Consequence of absorptive plasma on heavy quark energy loss and jet evolution in ultrarelativistic heavy ion collisions

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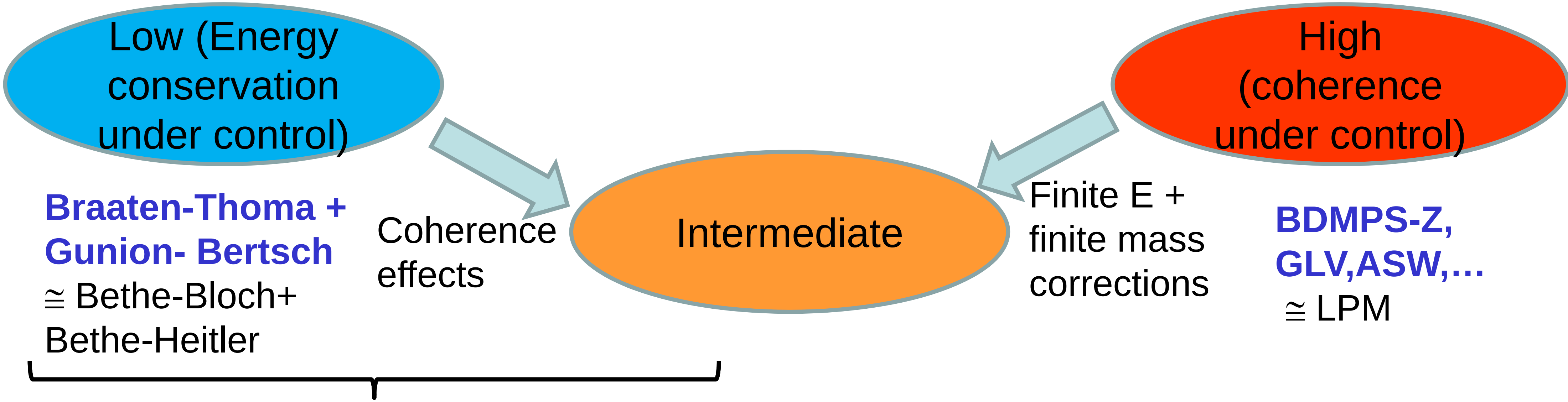
with

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

Motivation and context

- Most of the *interesting* HF observables so far: located at *intermediate* p_T (≈3 GeV-50 GeV)
- 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

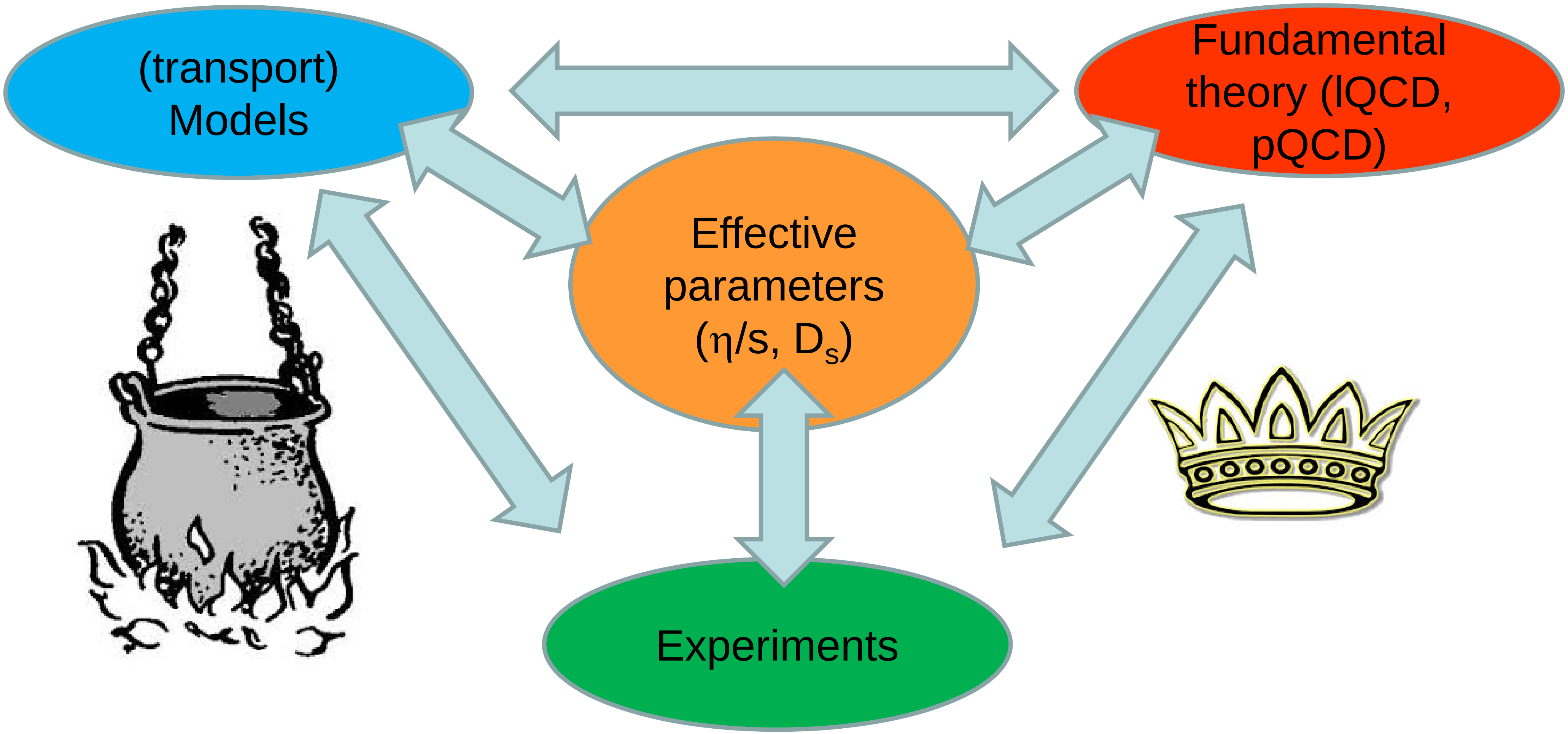


Approach pursued in our **models…** Unfortunately too many of them

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

Motivation and context

=> Need for classification and effective parameters

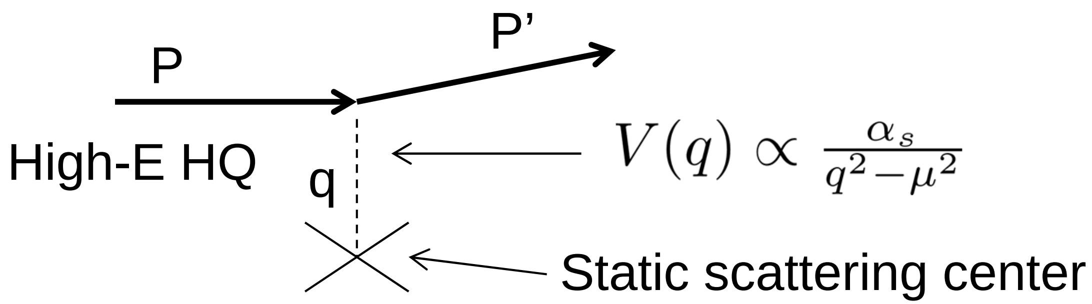


Insufficient control on energy loss theory in QCD

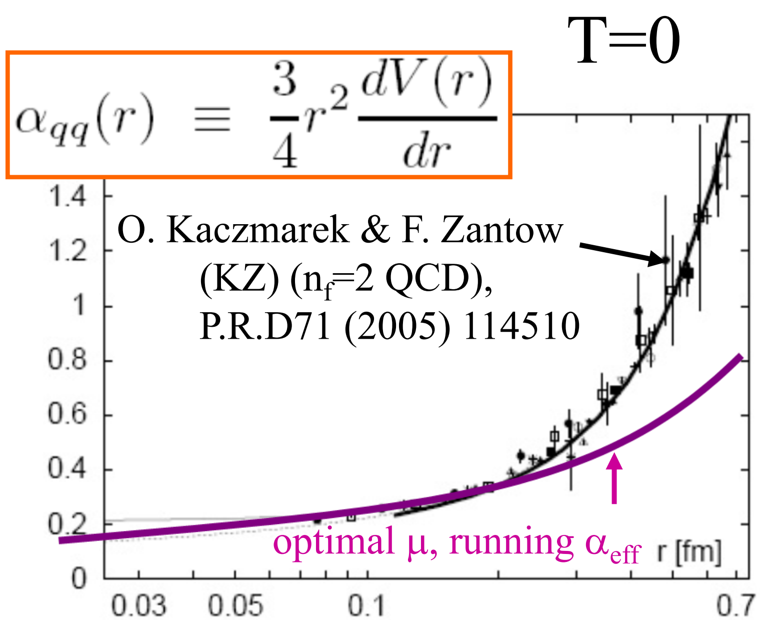
Basic ingredient in the derivation of QED collisional Eloss; transverse force

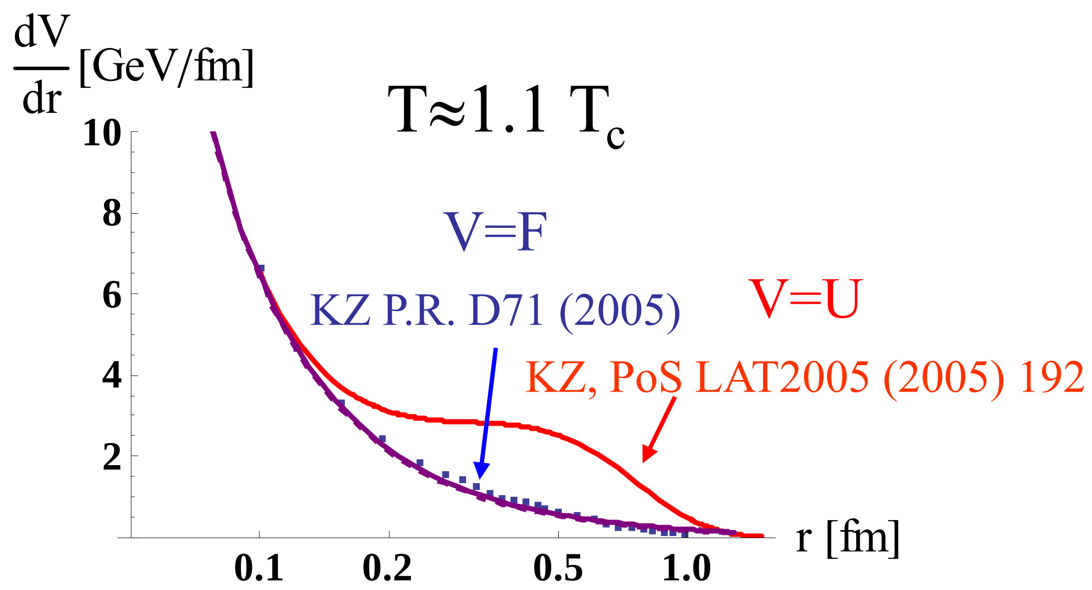
In QCD: non perturbative « corrections » even at large HQ energy

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

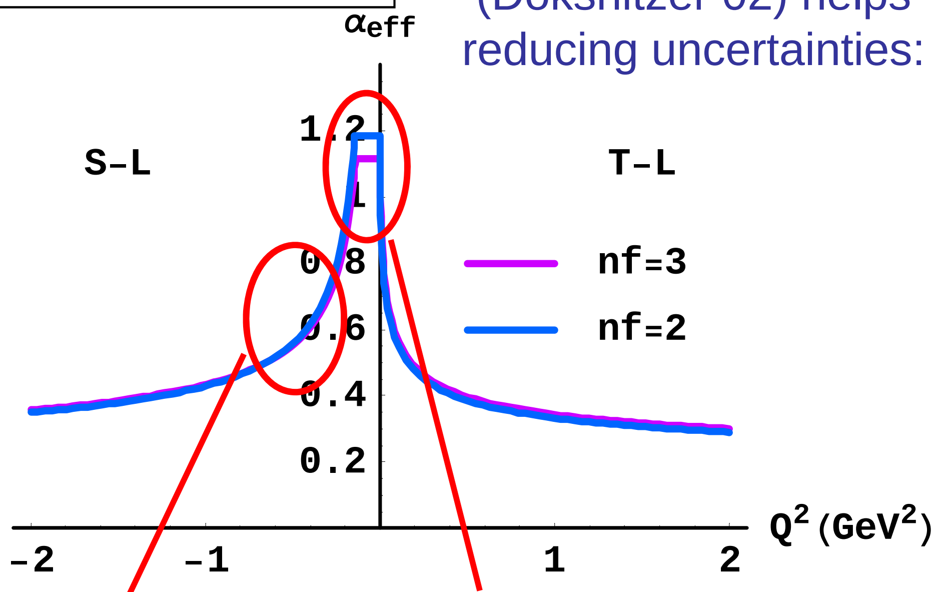
Elastic

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)

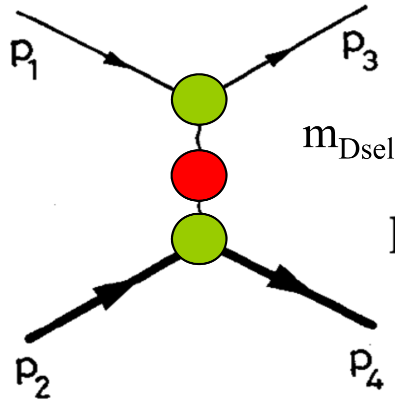
$$\frac{1}{Q_u}\int_{|Q^2|\le Q_u^2} dQ\,\alpha_s(Q^2) \approx 0.5$$

"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

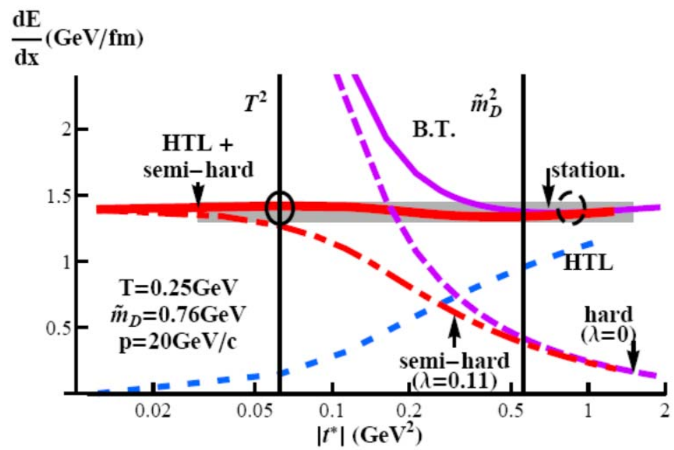


$$m_{Dself}^2(T) = (1+n_f/6)\,4\pi\alpha_{eff}(m_{Dself}^2)\,T^2$$

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

+ u and s channels

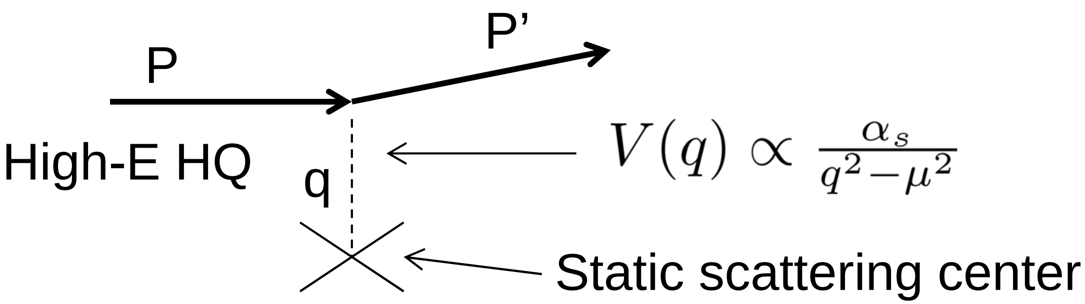
One gluon exchange effective propagator, designed in order to guarantee maximal insensitivity of dE/dx in Braaten-Thomas scheme



Insufficient control on energy loss theory

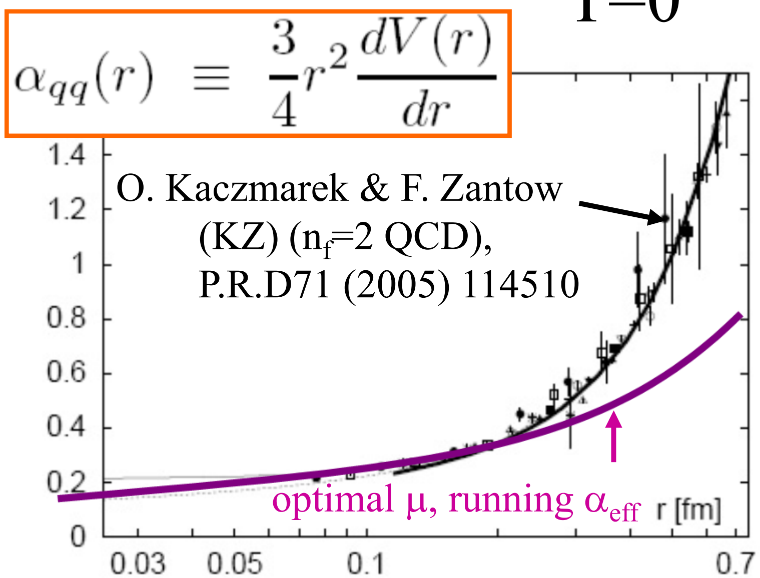
Non perturbative « corrections » even at large HQ energy

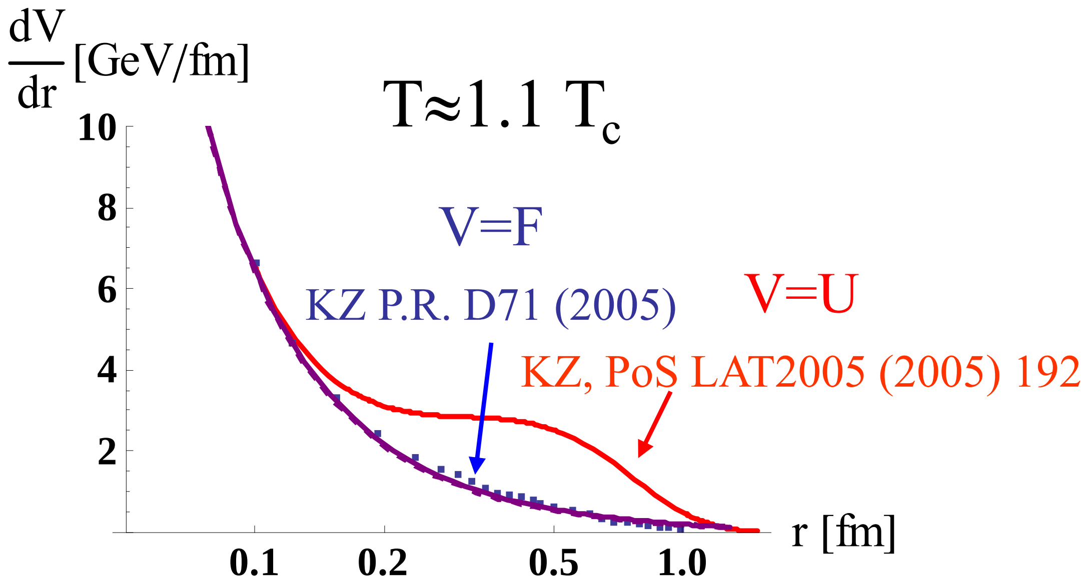
In most models:



Lattice QCD :

T=0





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

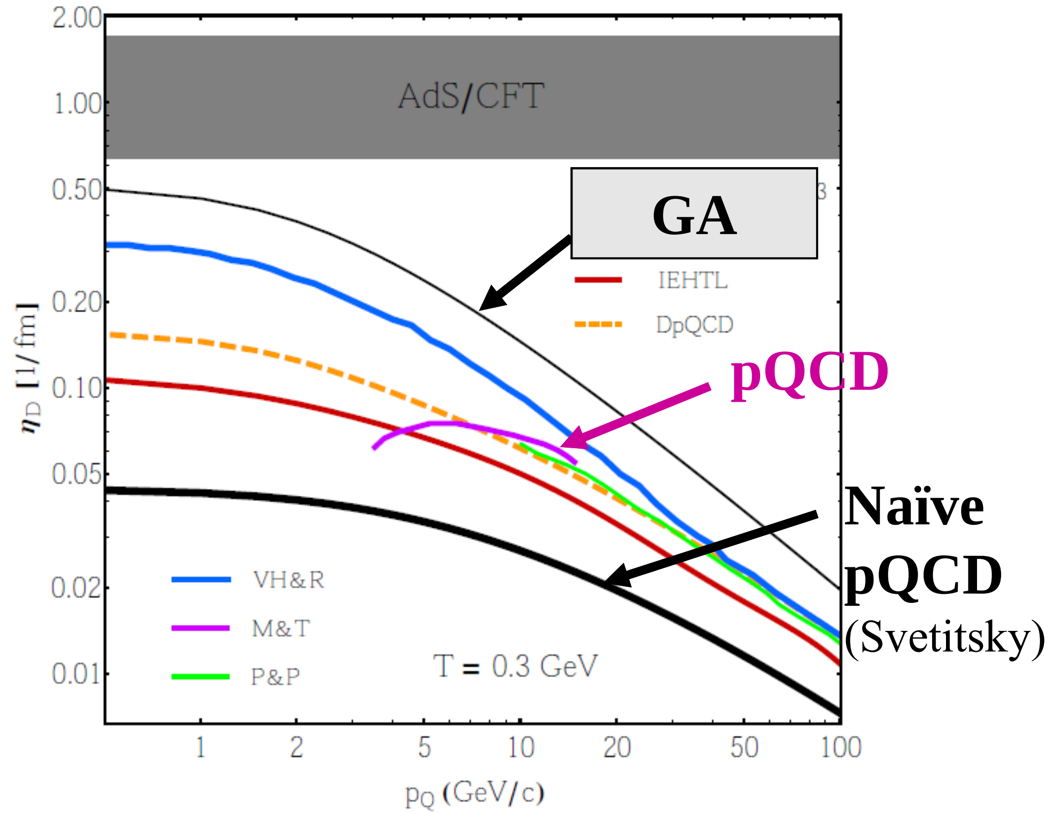
Running α_s : some Energy-Loss values

$$\frac{dE_{coll}(c/b)}{dx}$$

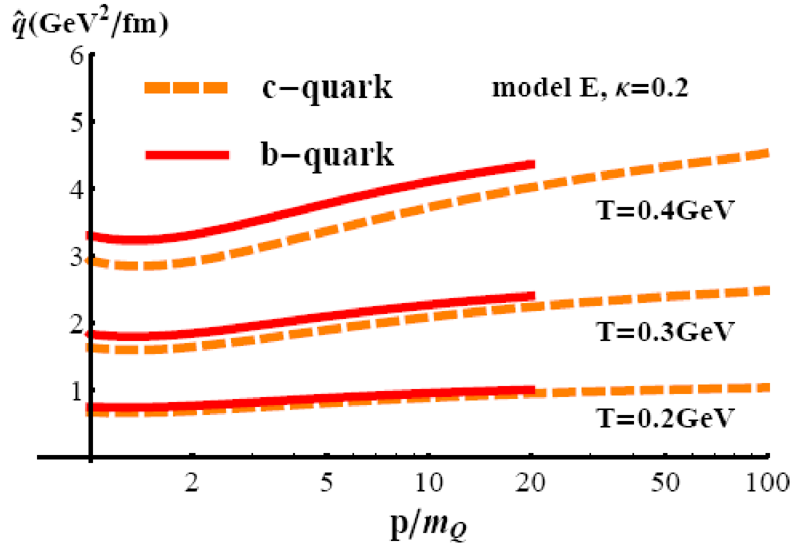
T(MeV) \p(GeV/c)	10	20
200	**1 / 0.65**	**1.2 / 0.9**
400	**2.1 / 1.4**	**2.4 / 2**

≈ 10 % of HQ energy

Drag coefficient (inverse relax. time)

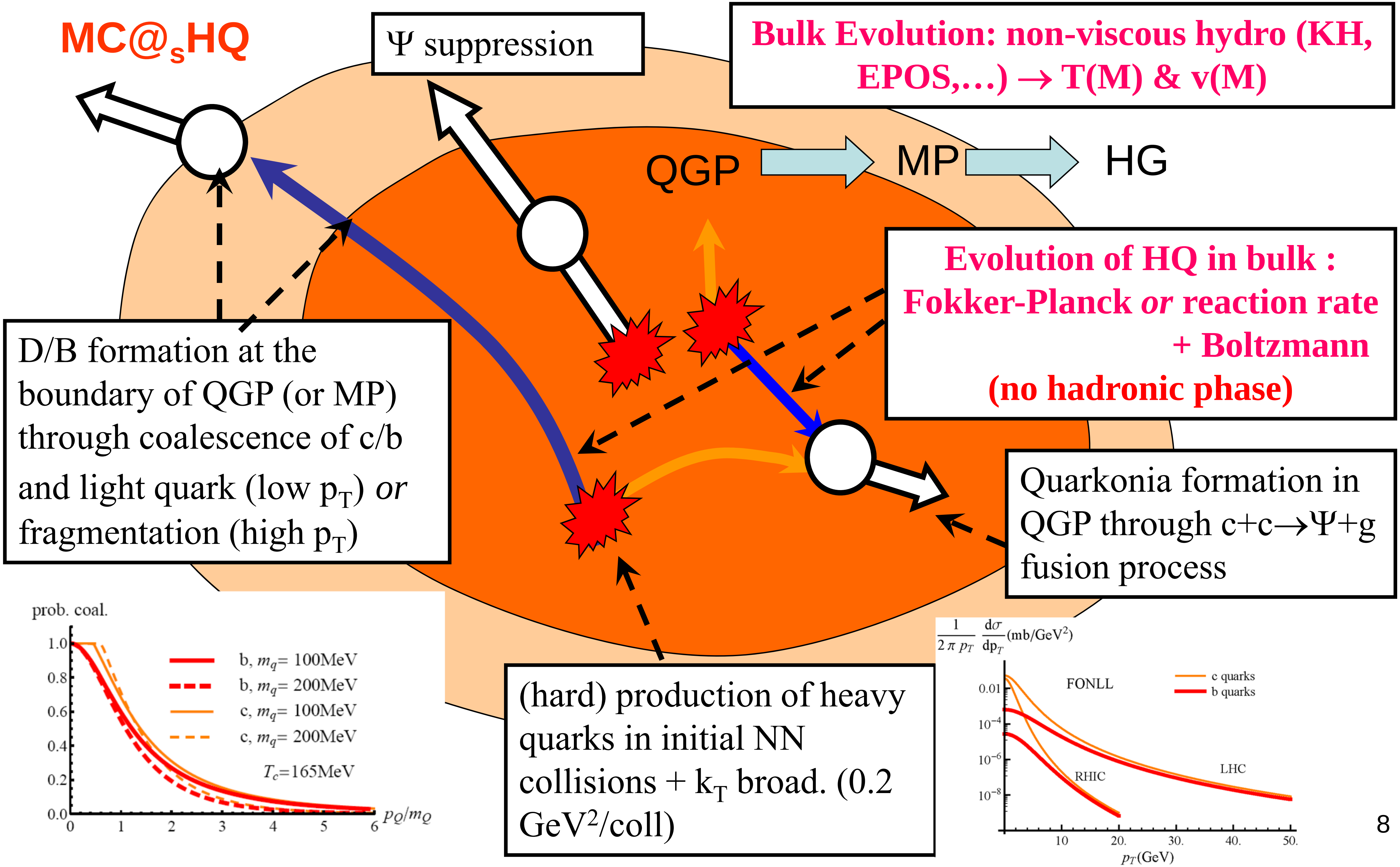


Transport Coefficient



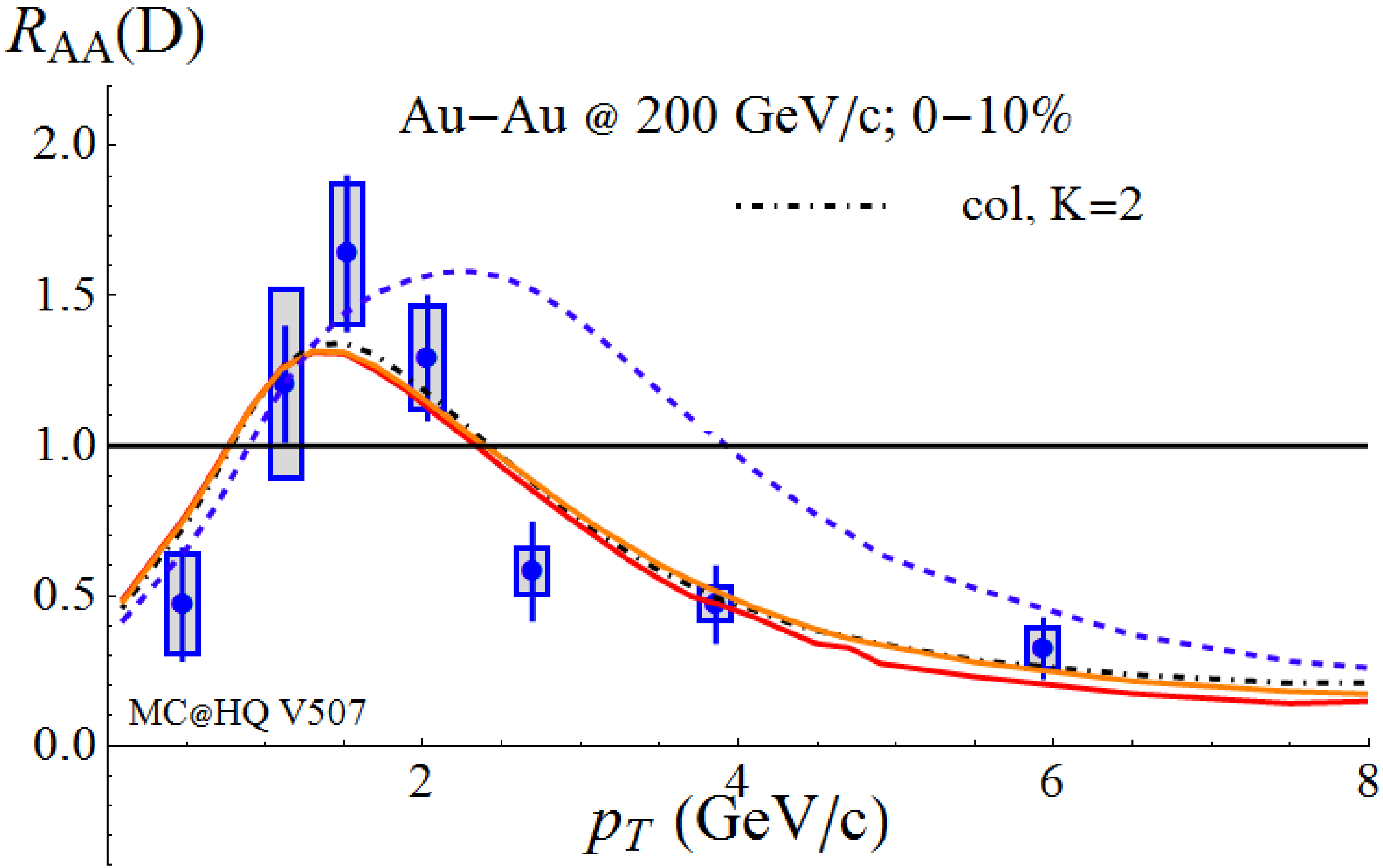
… of expected magnitude to reproduce the data (we "explain" the transp. coeff. in a rather parameter free approach).

Schematic view of « Monte Carlo @ Heavy Quark » generator

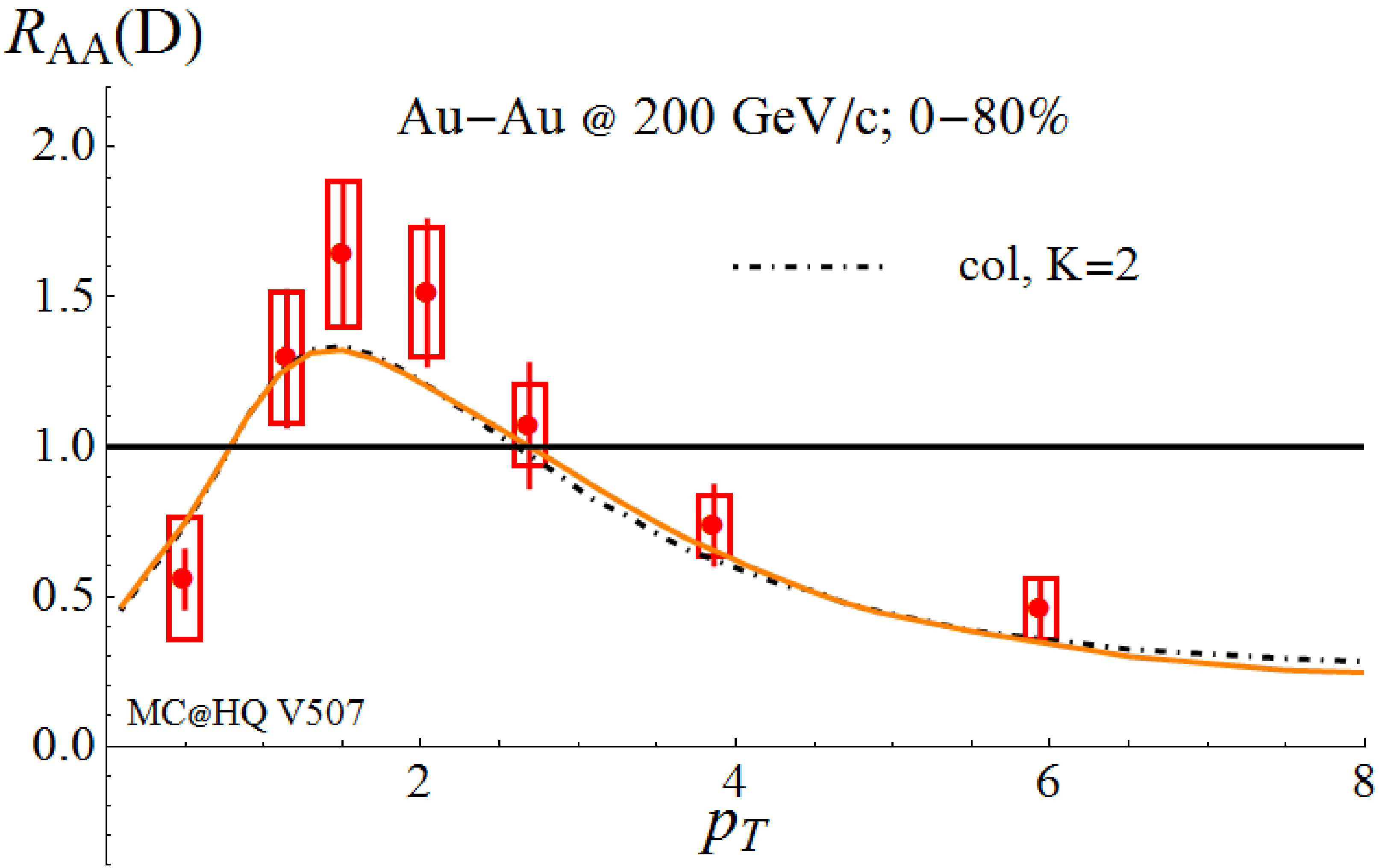


Elastic D mesons @ RHIC

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



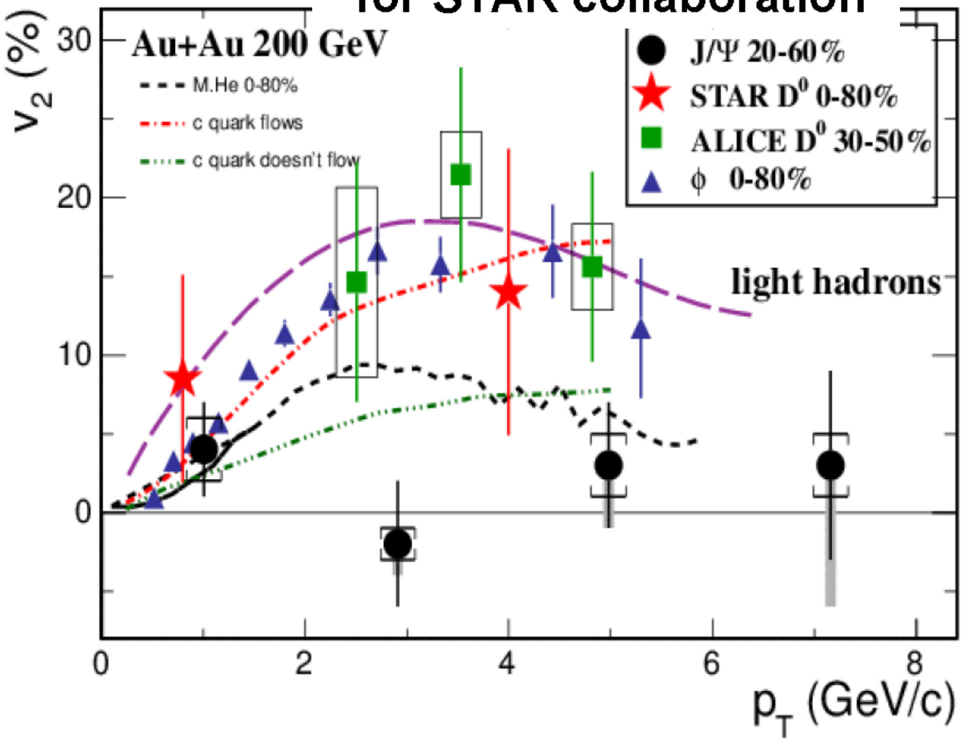
Elastic D mesons @ RHIC

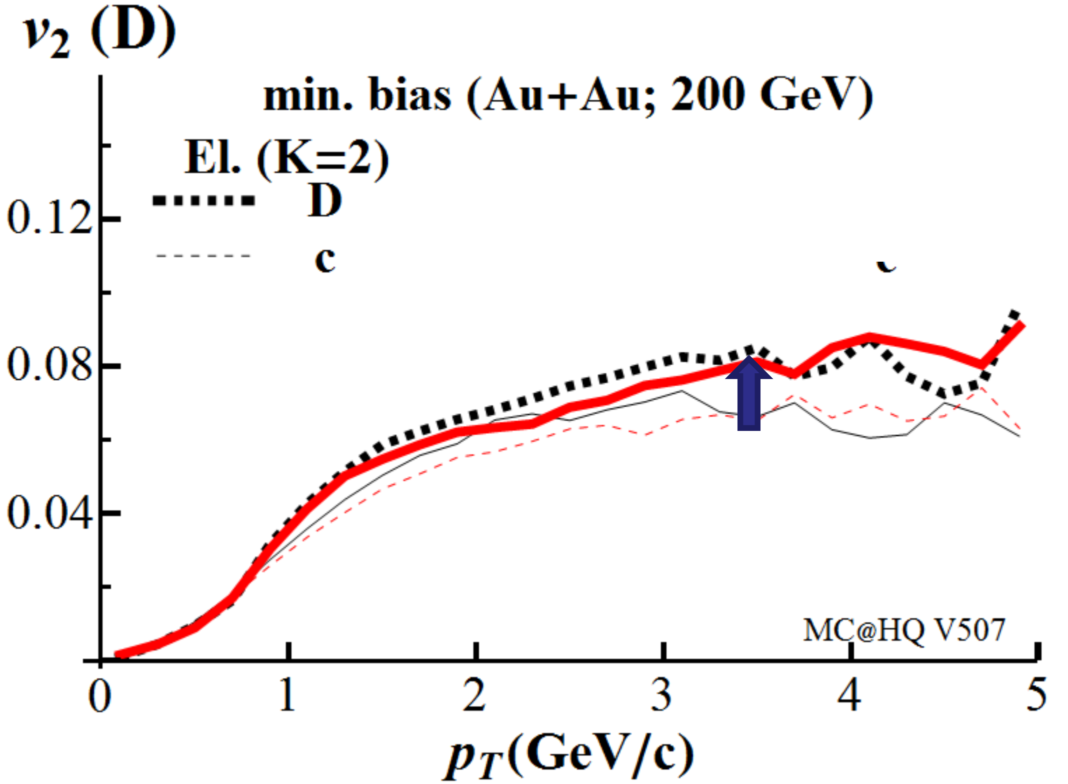


Elastic D mesons @ RHIC

Jaroslav Bielčík

for STAR collaboration





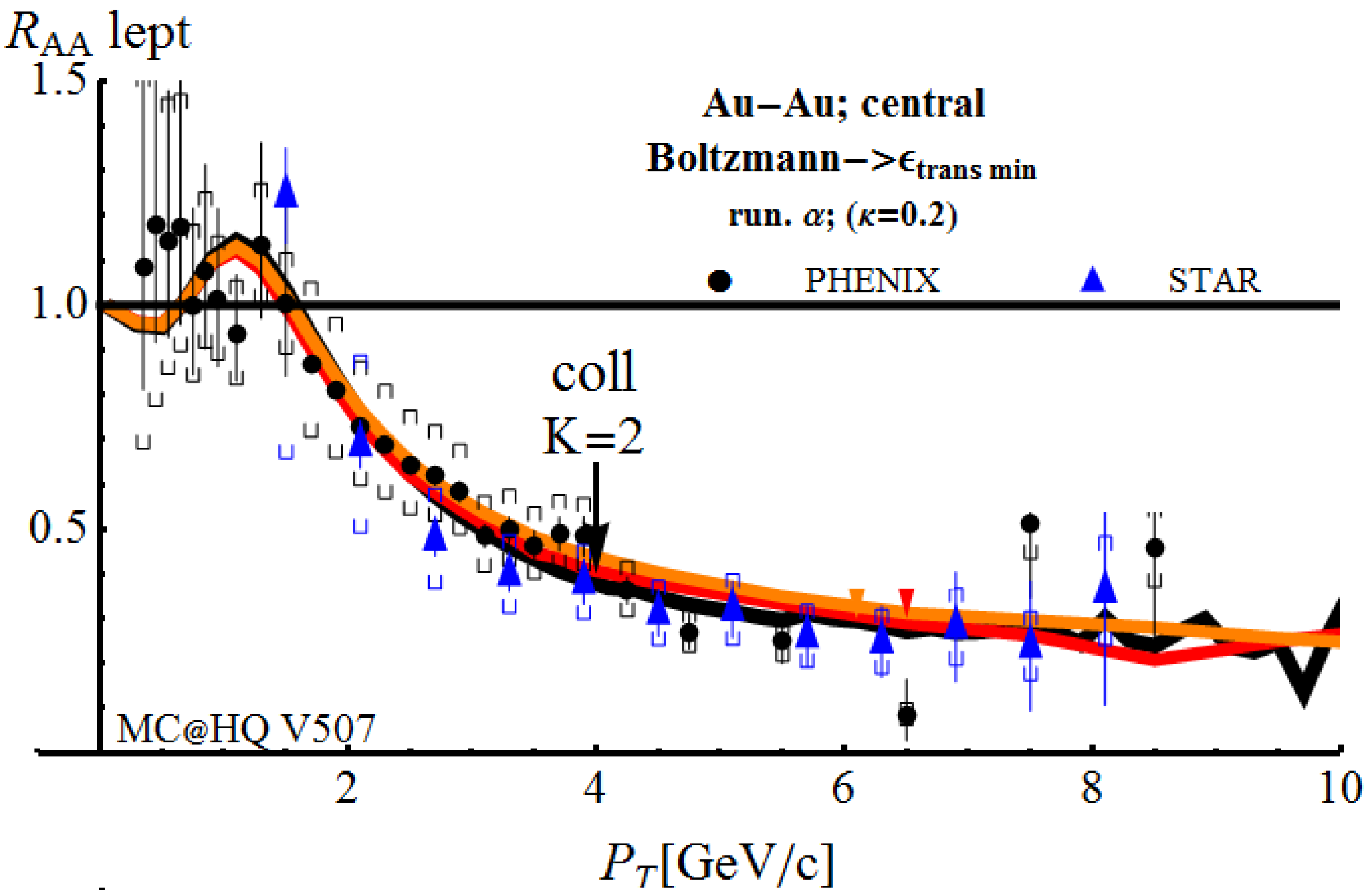
Rather little contribution from the light quark in our treatment… but conclusion may depend on the parameters (m_q, wave function)

Coalescence according to extended Dover framework

(PRC 79 044906)

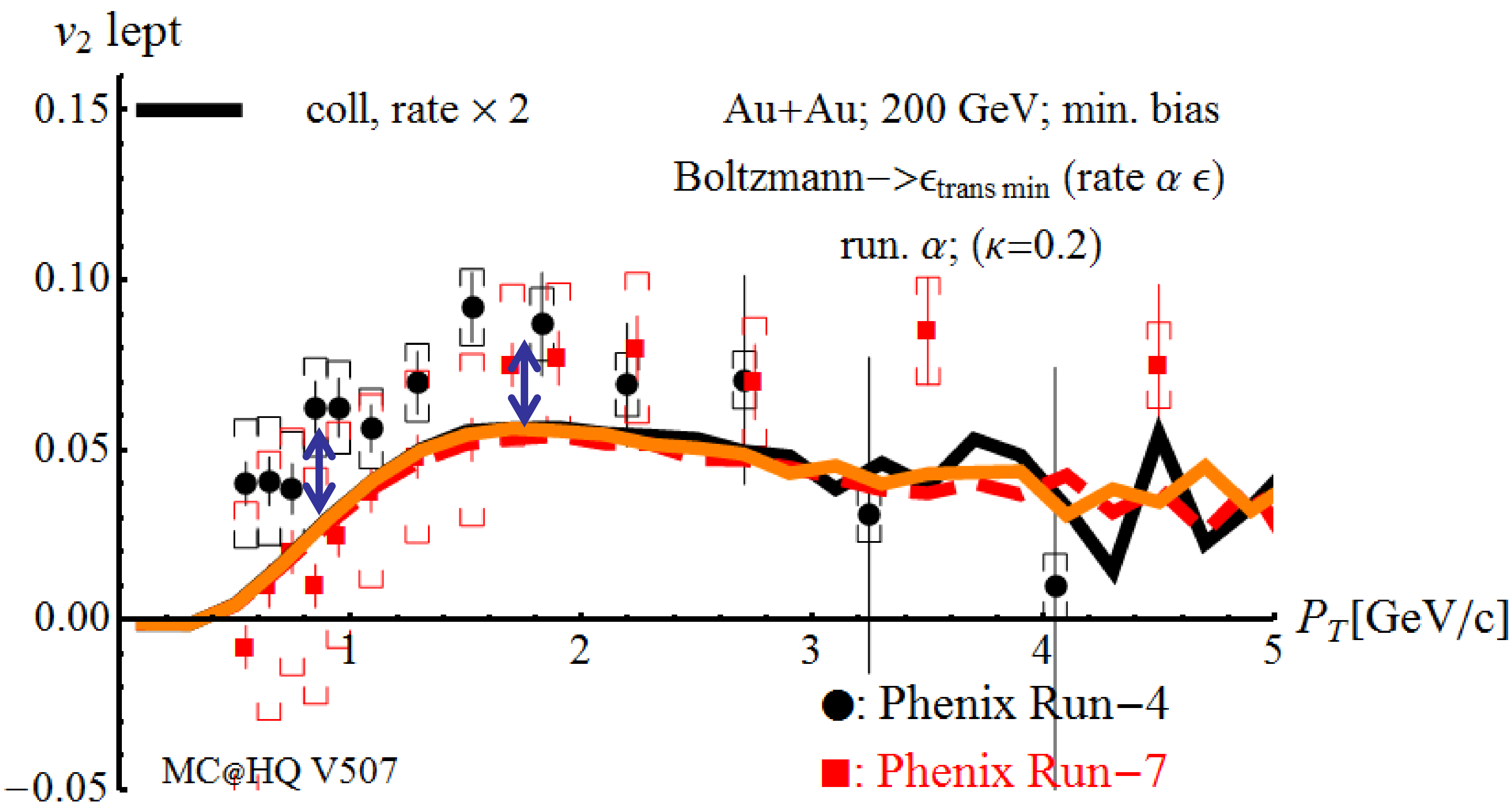
$$N_\Phi = \int \frac{d^3 p_q}{(2\pi\hbar)^3 E_q} \frac{p_q \cdot d\hat{\sigma}}{u_Q \cdot d\hat{\sigma}} f_q(x_Q, p_q)(\sqrt{2\pi} R_c)^3 \times F_\Phi(p_Q, p_q),$$

Elastic for leptons @ RHIC



Good agreement for NPSE as well

Elastic for leptons @ RHIC



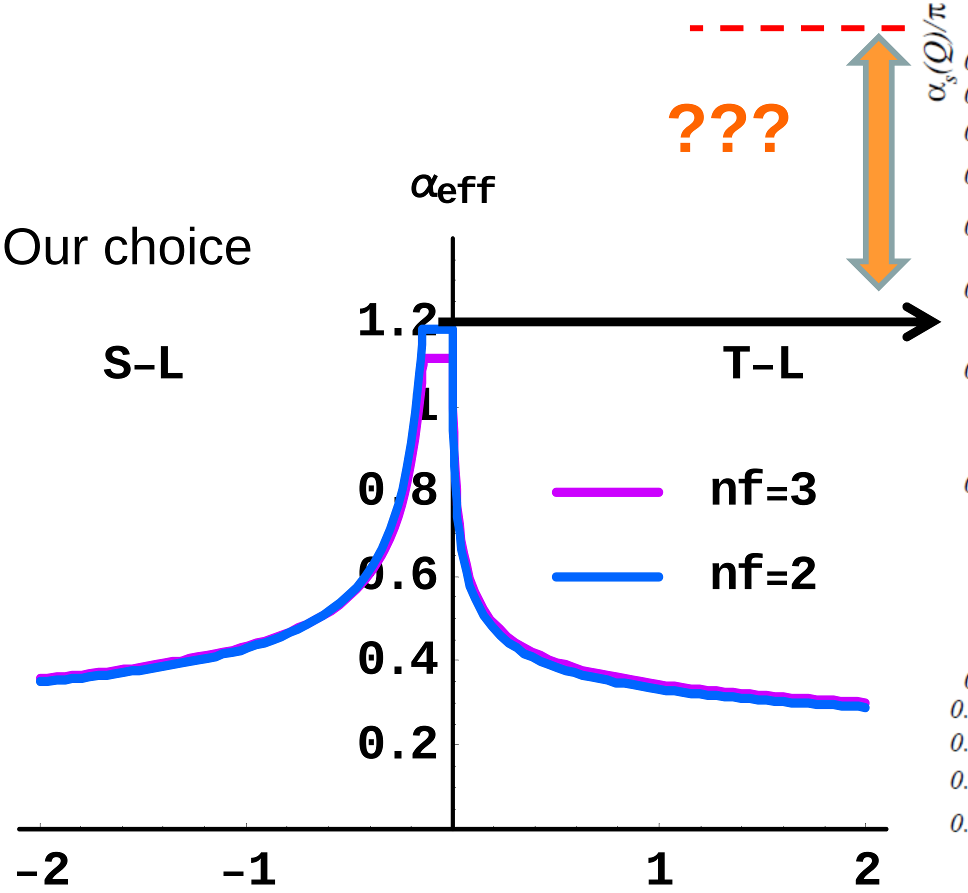
Some contribution from D meson rescattering ?

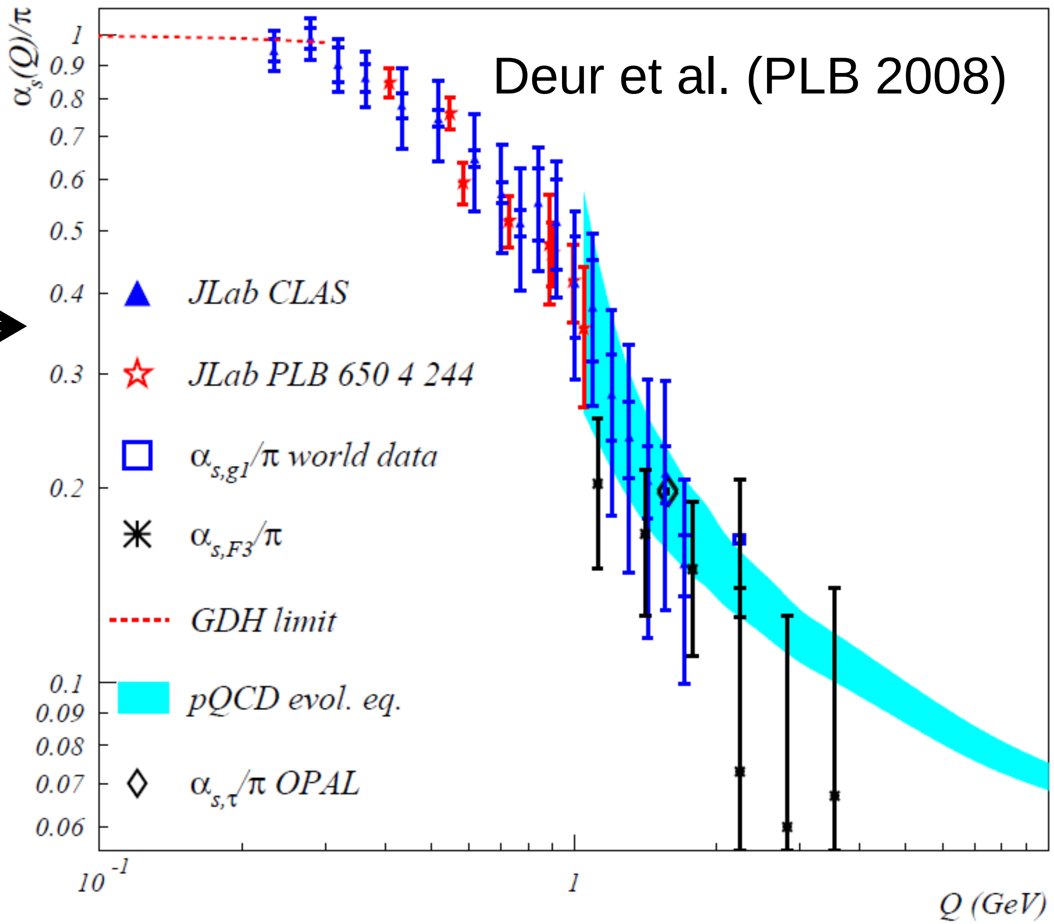
(see J. Aichelin's talk)

Elastic Eloss @ RHIC

We "explain" it all provided we allow for a multiplication of our pQCD (inspired) cross section by a factor 2…

Our choice

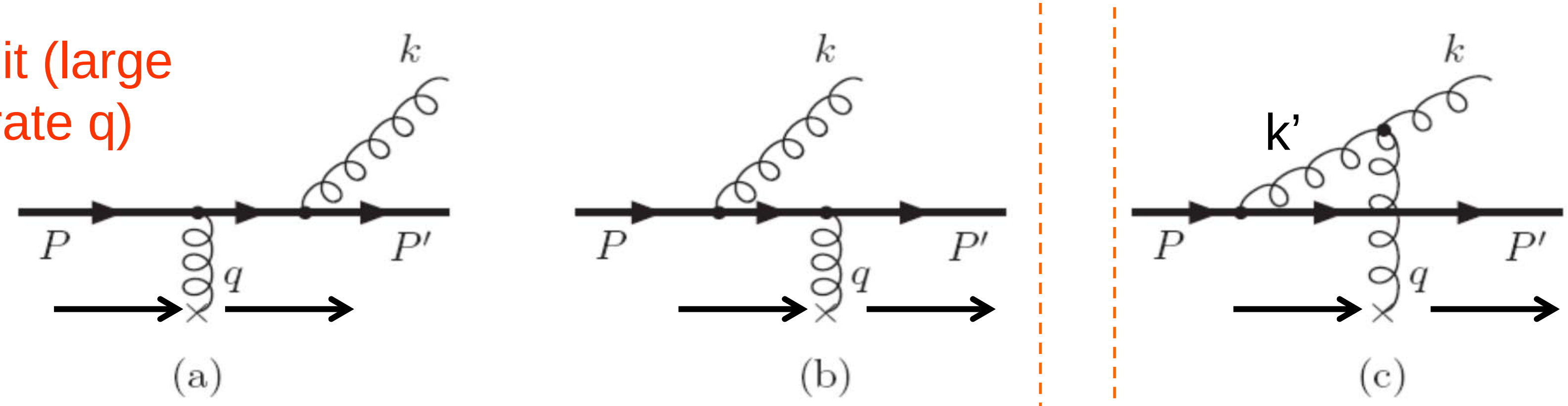




Induced Energy Loss

Generalized Gunion-Bertsch (NO COHERENCE) for finite HQ mass, dynamical light partons

Eikonal limit (large E, moderate q)



Dominates as small x as one “just” has to scatter off the virtual gluon k’

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

with

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

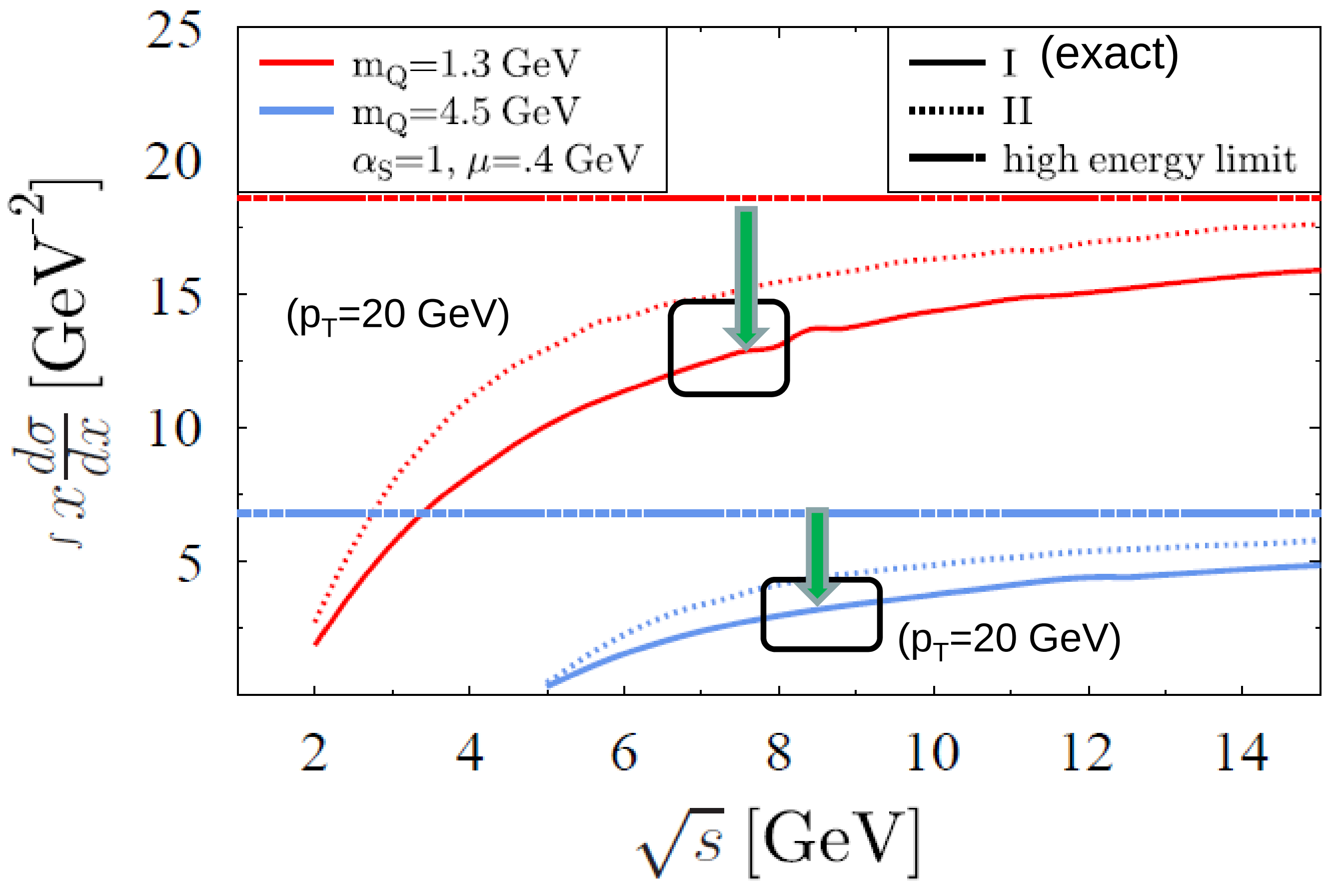
Gluon thermal mass ~2T (phenomenological; not in BDMPS)

Quark mass

Both cures the collinear divergences and influence the radiation spectra (dead cone effect)

Incoherent Induced Energy Loss

… & finite energy !



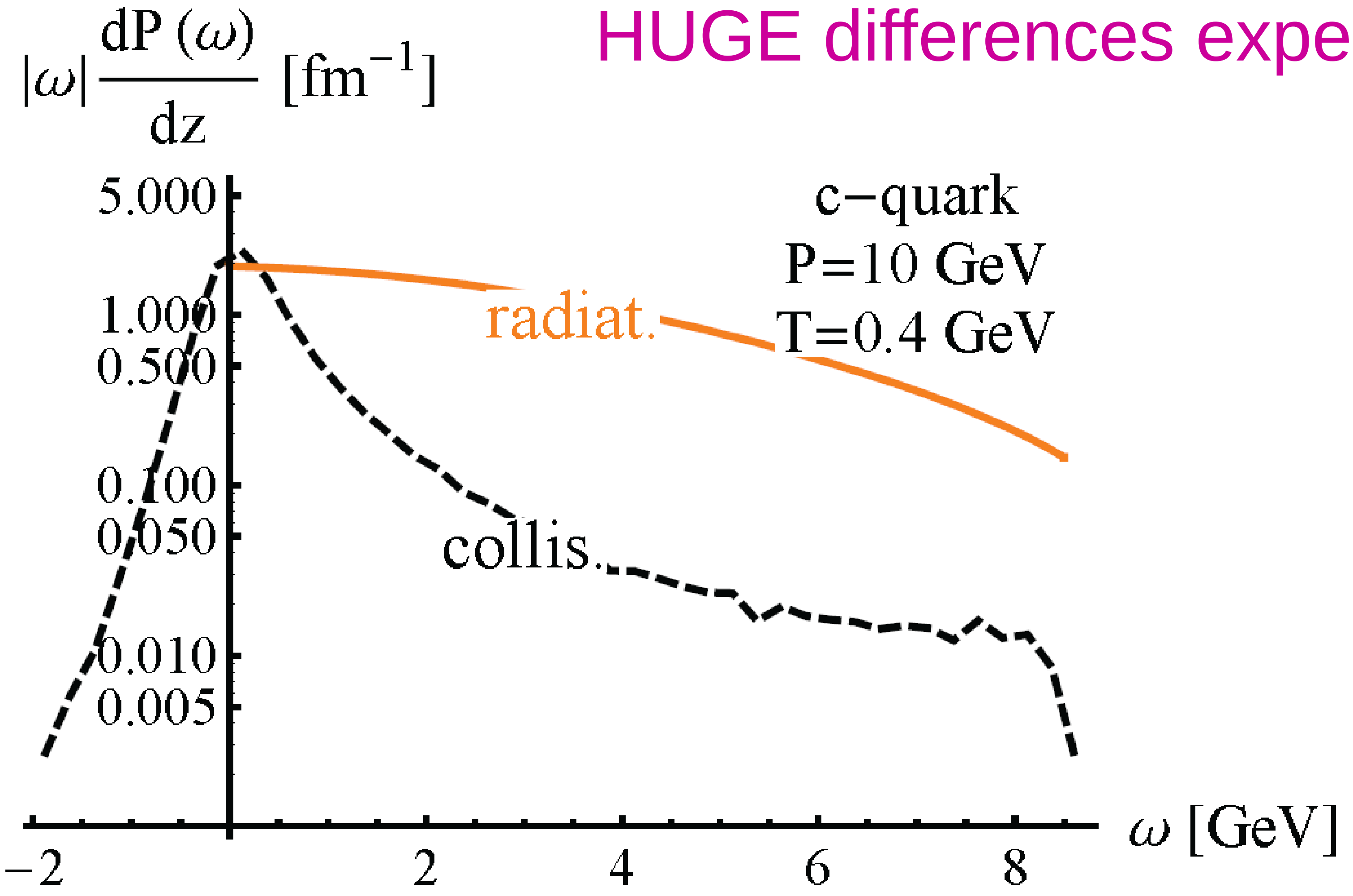
Gousset, Gossiaux & Aichein, arxiv 1307.5270

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

Incoherent Induced Energy Loss

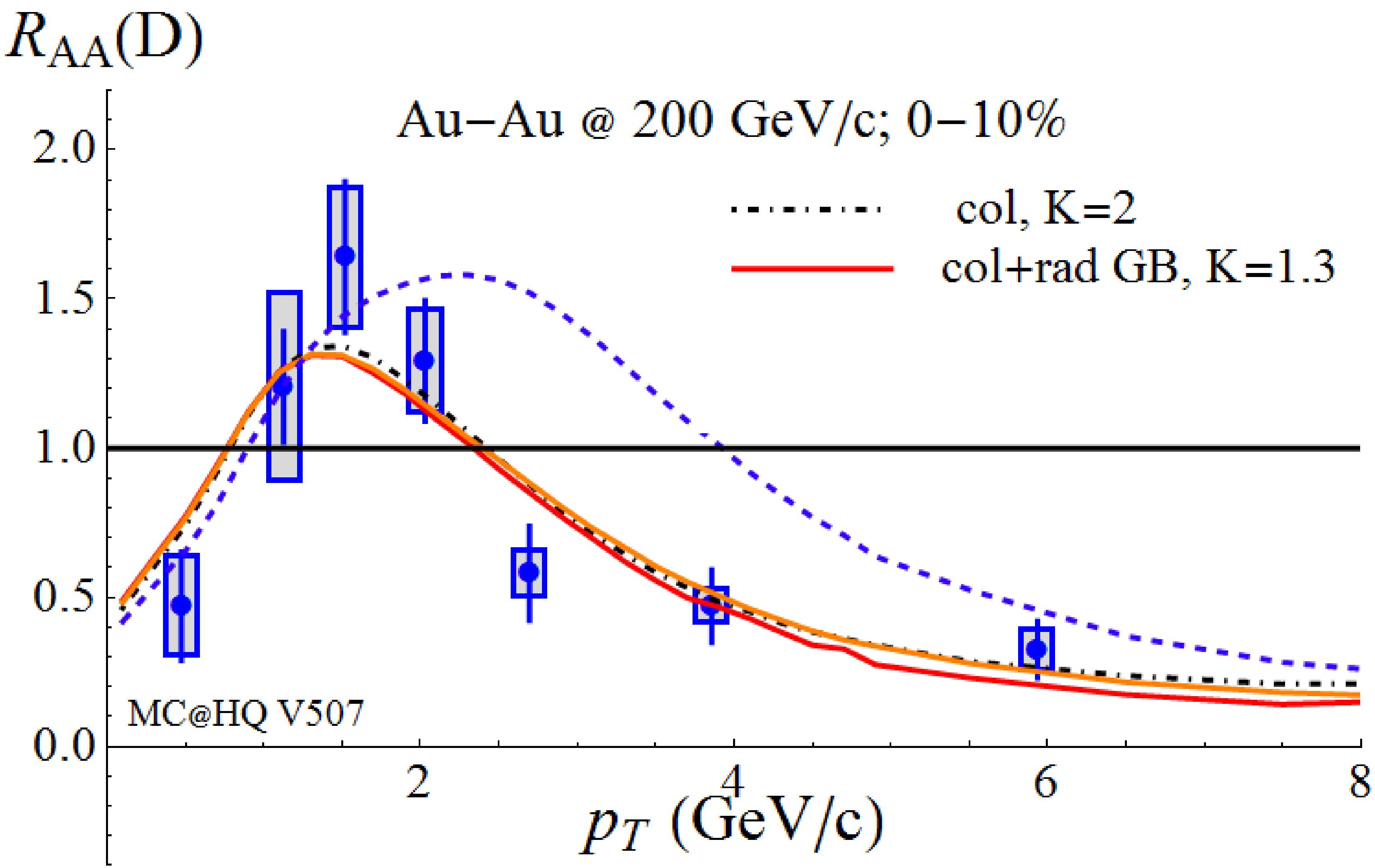
Probability P of energy loss ω per unit length (T,M,…):

HUGE differences expected



Caveat: no detailed balance implemented yet

{Radiative + Elastic} vs Elastic for D mesons @ RHIC



K coming closer to unity if radiation included

{Radiative + Elastic} vs Elastic for D mesons @ RHIC

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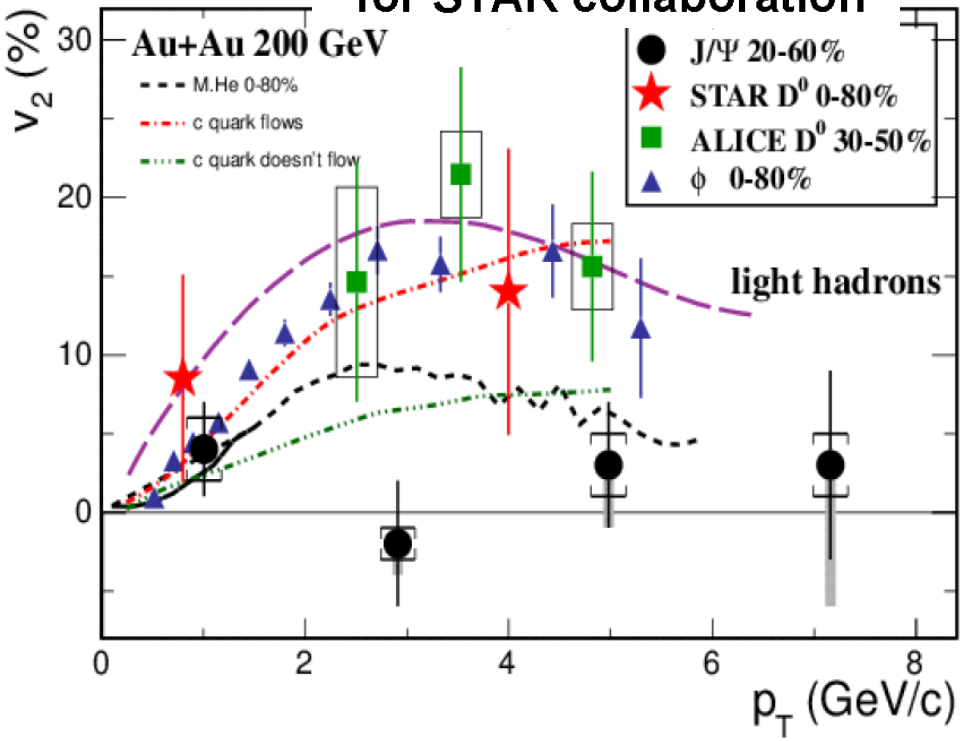

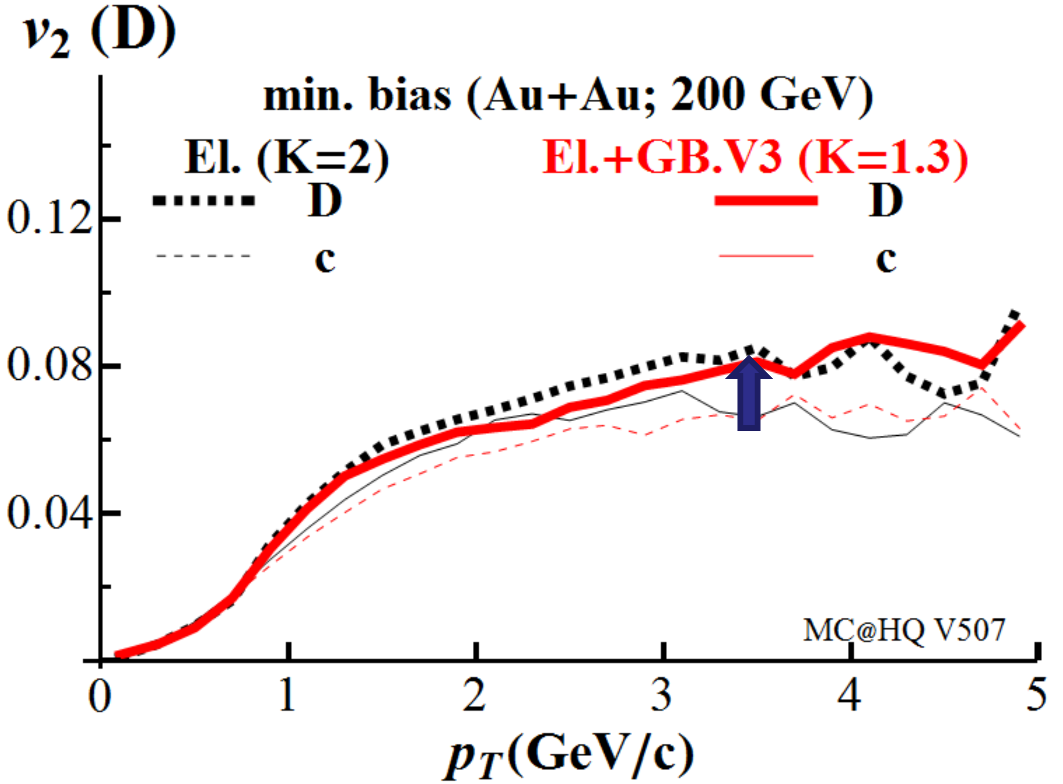

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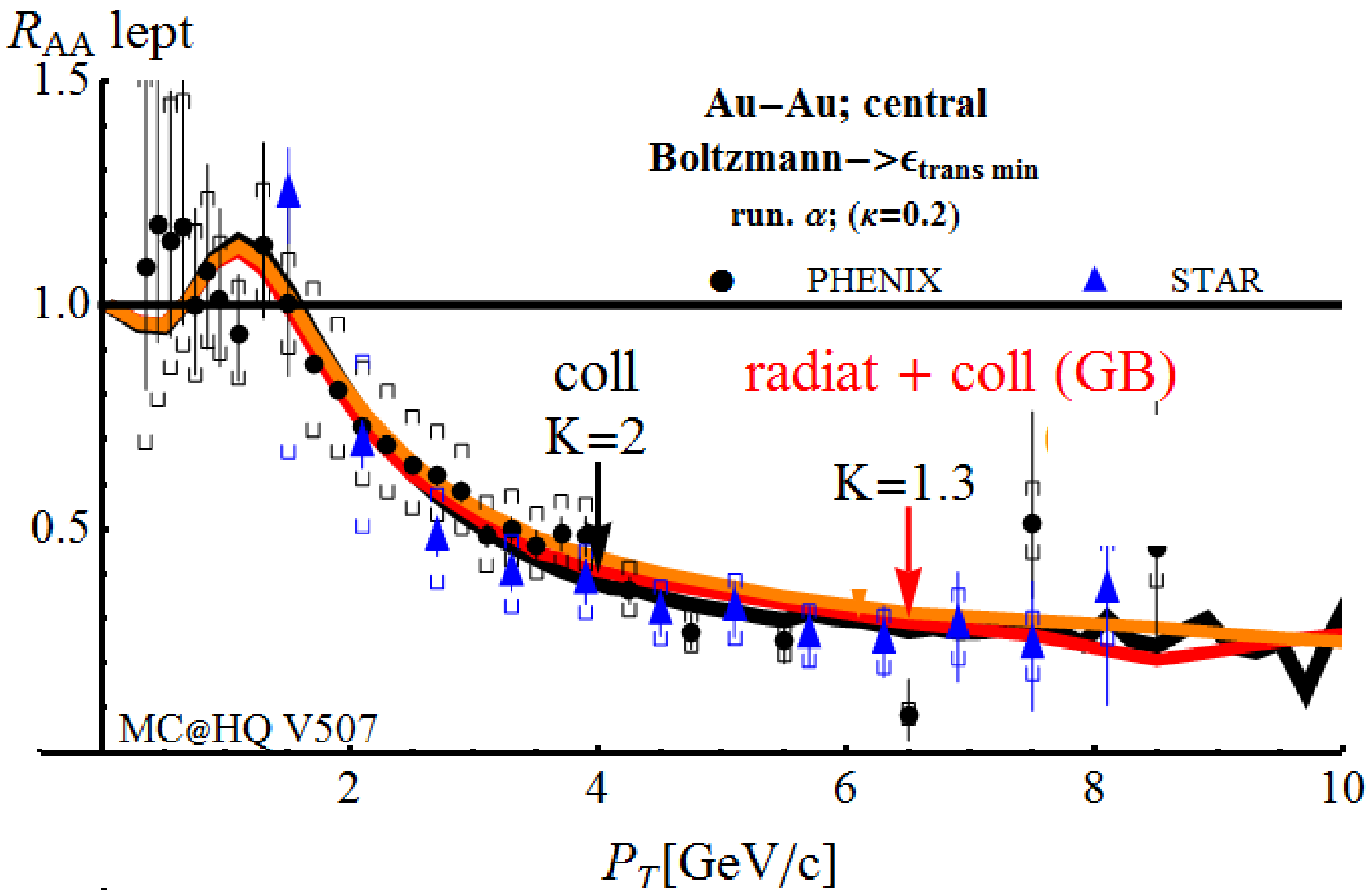
{Radiative + Elastic} vs Elastic for leptons @ RHIC



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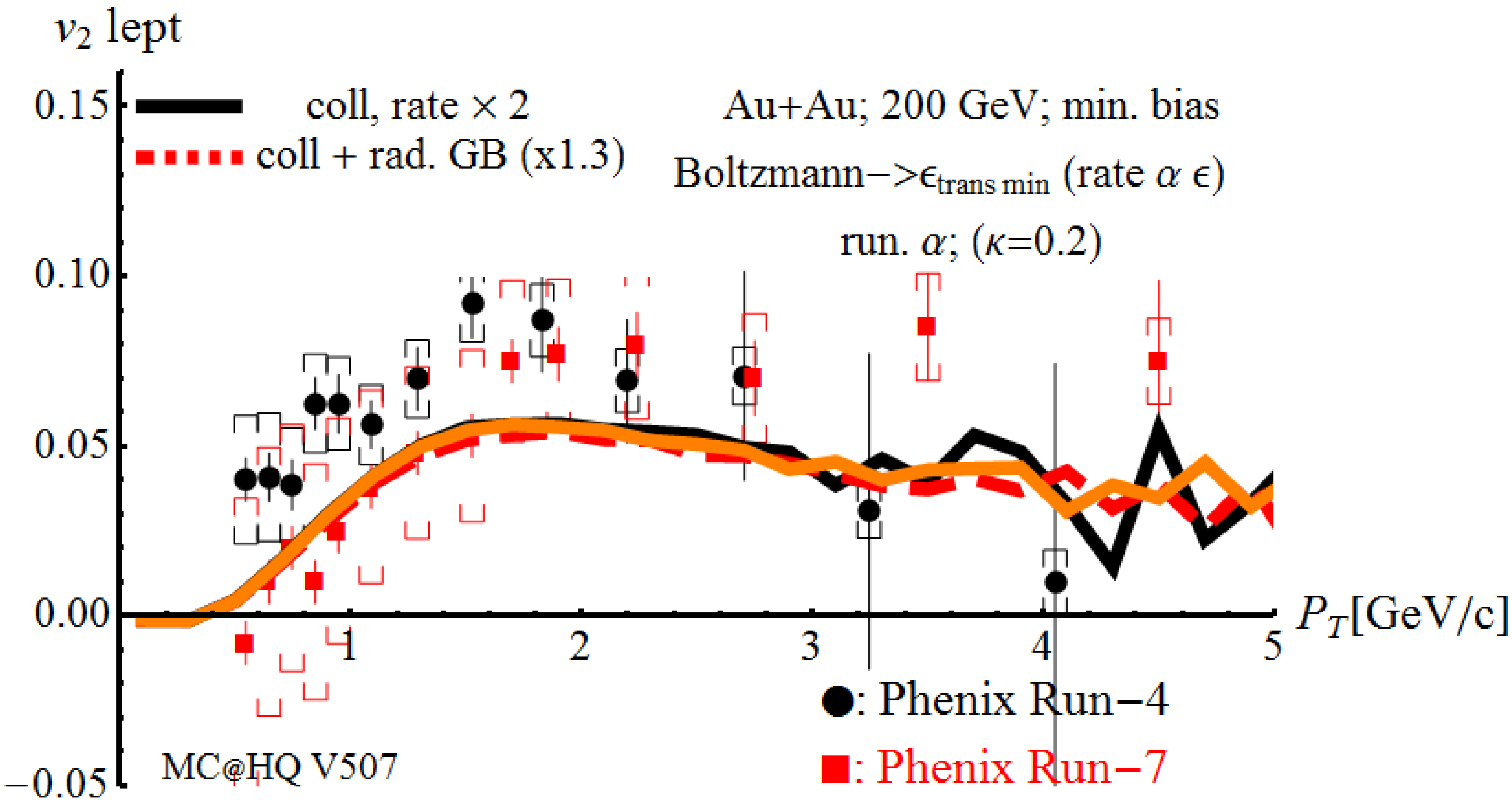

No lack of elliptic flow wrt pure elastic processes

Incoherent Induced Energy Loss

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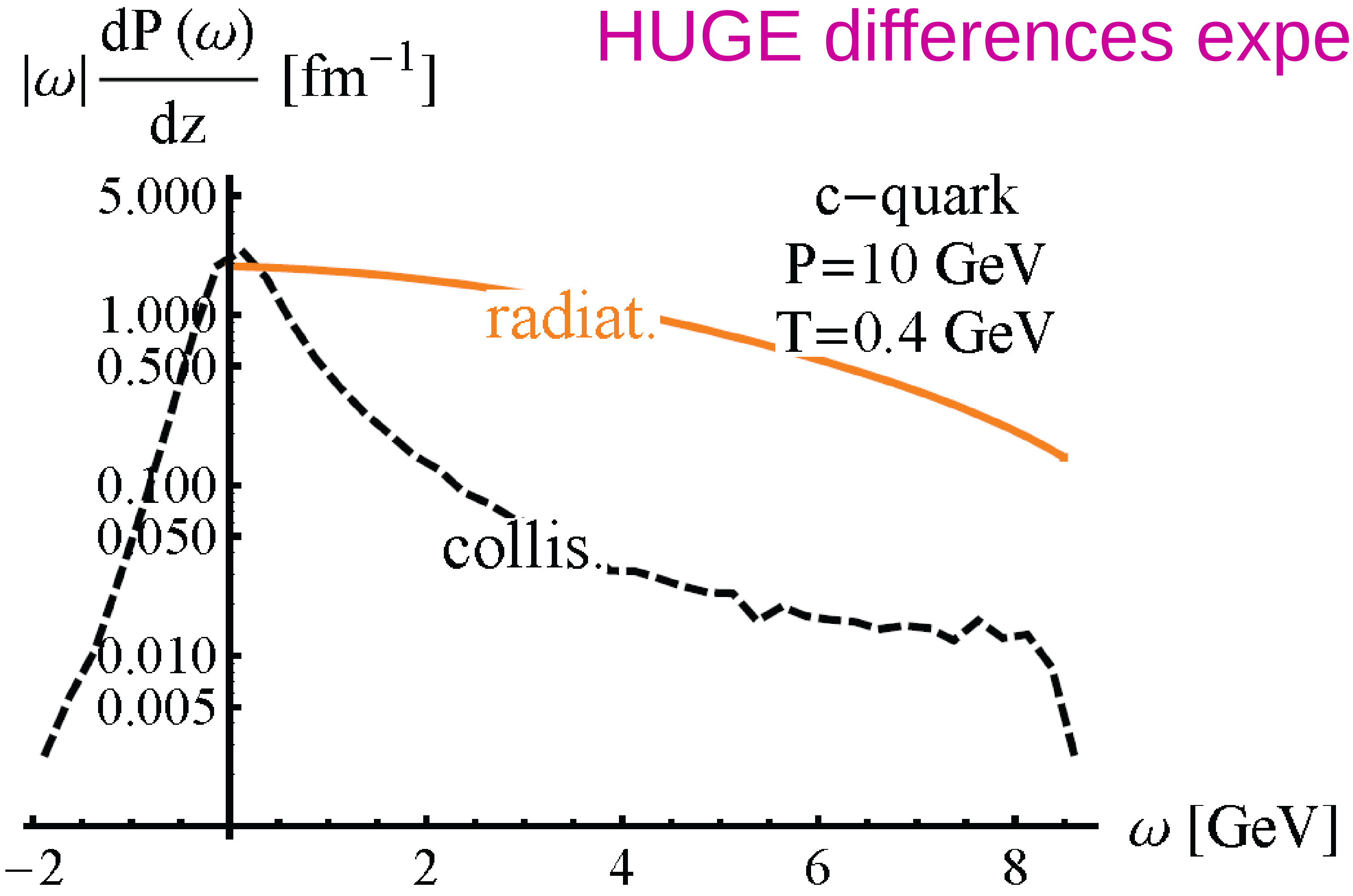
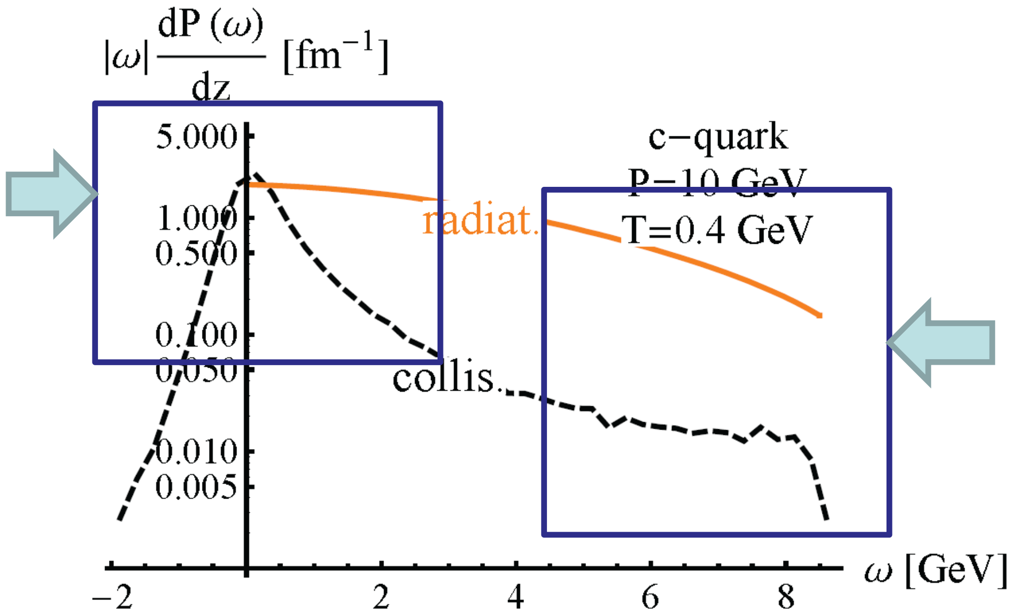


Where are they ?

Conclusions from RHIC

- Good consistency between NPSE and D mesons (10% difference in K values)…
- … within a model with mass hierarchy
- ΔE radiative < ΔE elastic
- Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB) $\Rightarrow$ Not sensitive to the large-ω tail of the Energy-loss probability (thanks to initial HQ distribution)

“Fokker Planck” regime

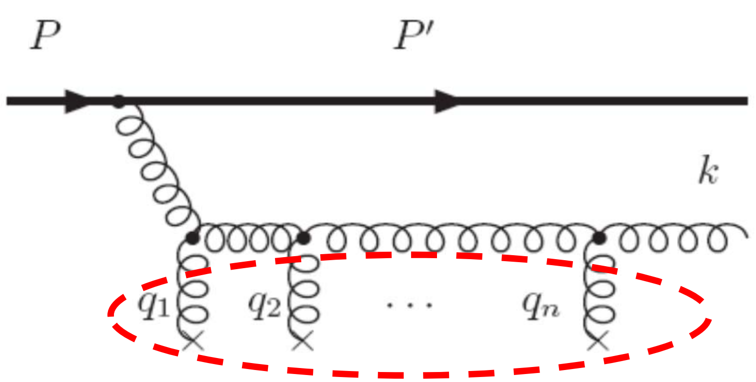


“hard scattering” regime

Giving coherence a chance

Coherent Induced Radiative

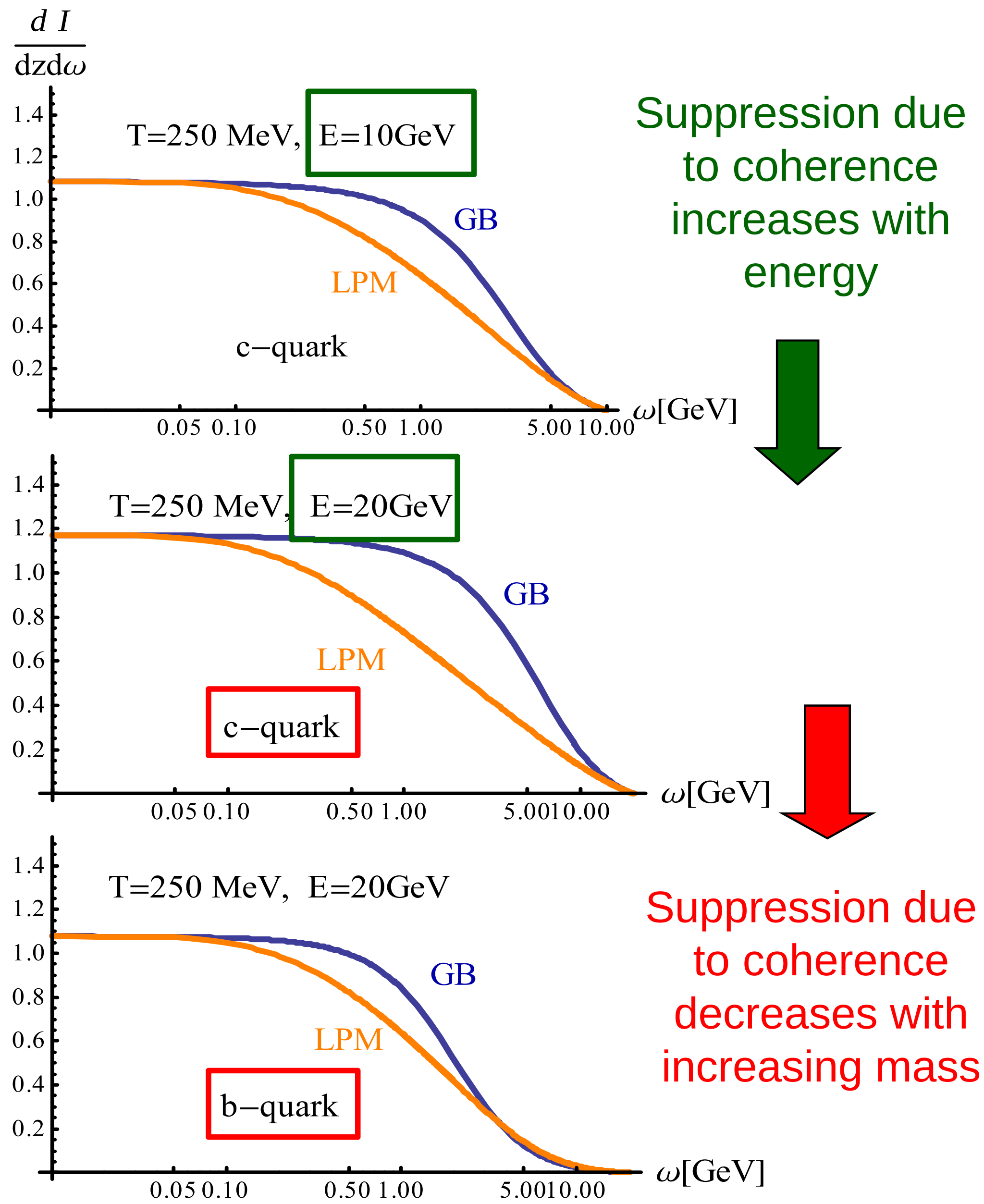
Formation time picture: for $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



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

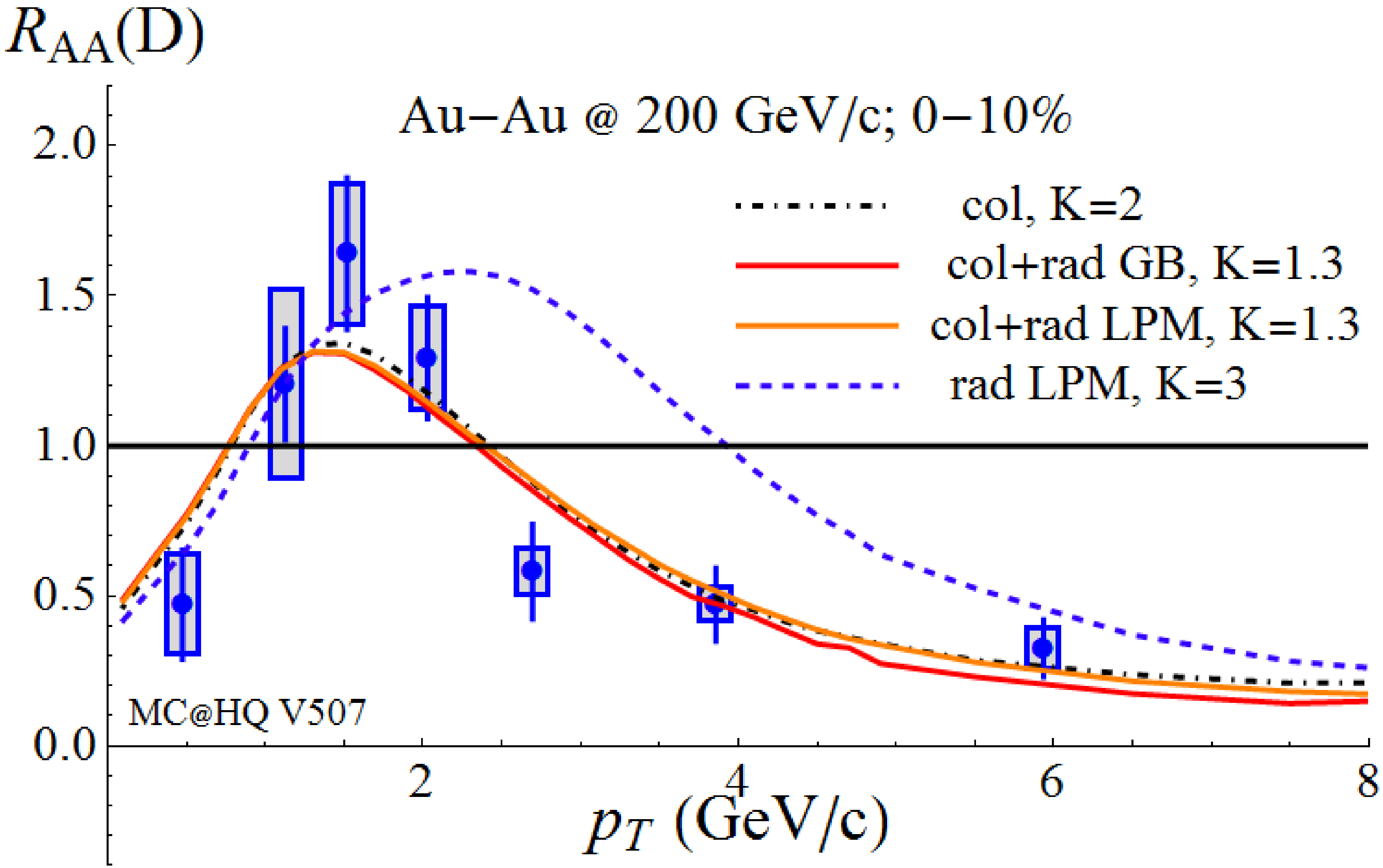
$$\frac{d^2 I_{\rm eff}}{dz\, d\omega} \sim \frac{\alpha_s}{N_{\rm coh}\tilde{\lambda}} \ln\left(1 + \frac{N_{\rm coh}\mu^2}{3\left(m_g^2 + x^2 M^2 + \sqrt{\omega \hat{q}}\right)}\right)$$

arXiv:1209.0844



{Radiative + Elastic} vs Elastic for D mesons @ RHIC

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



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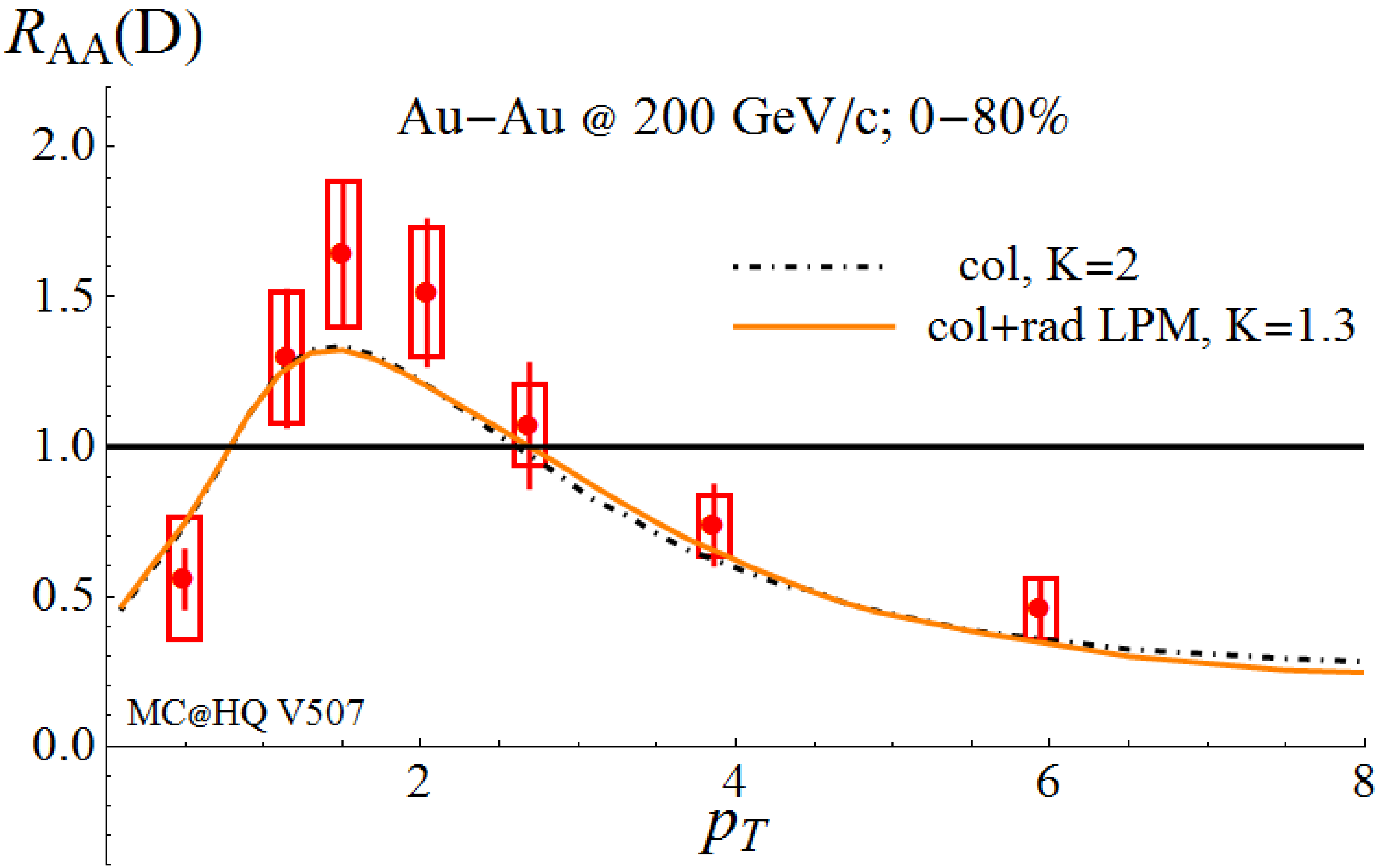
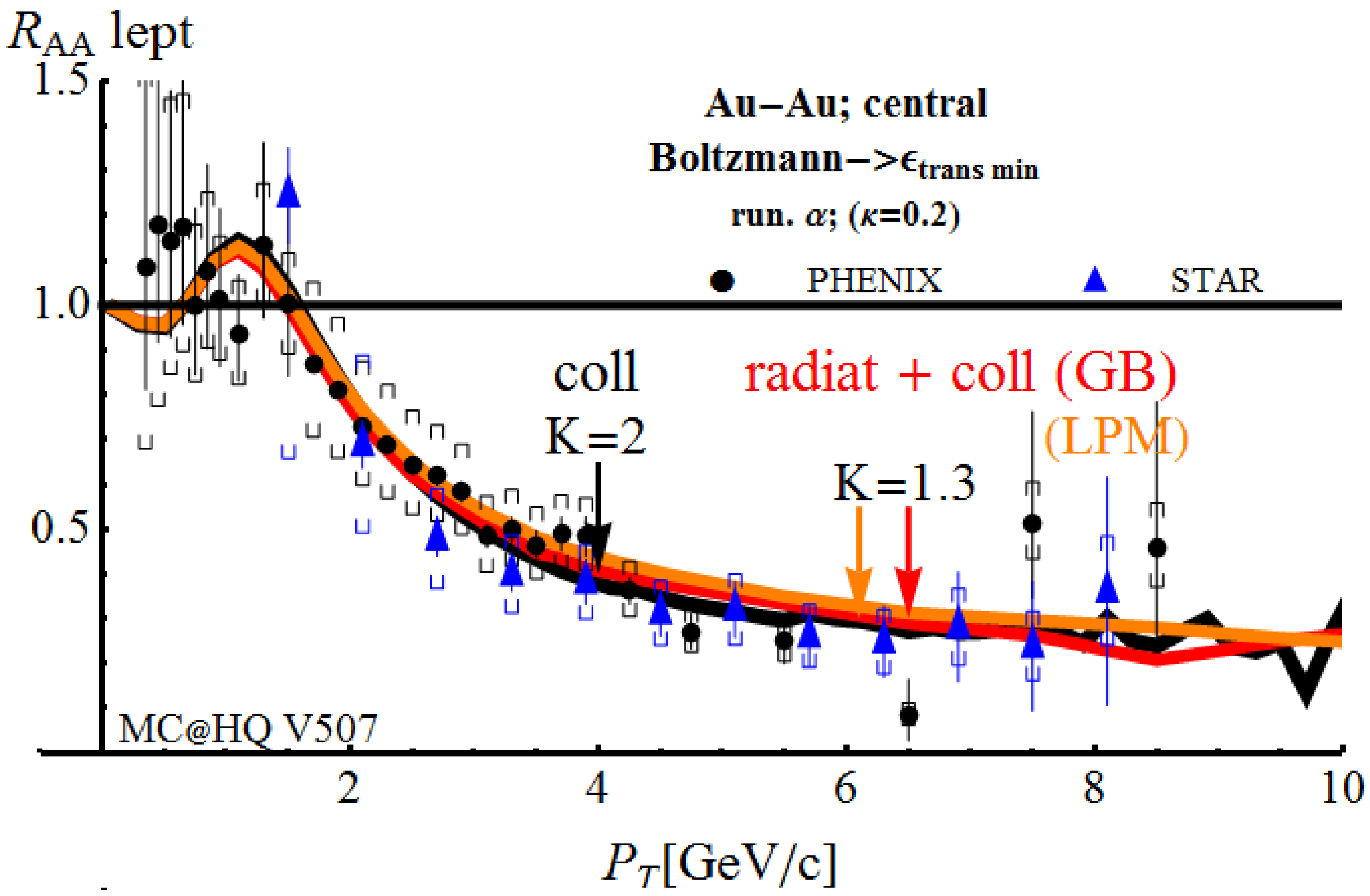
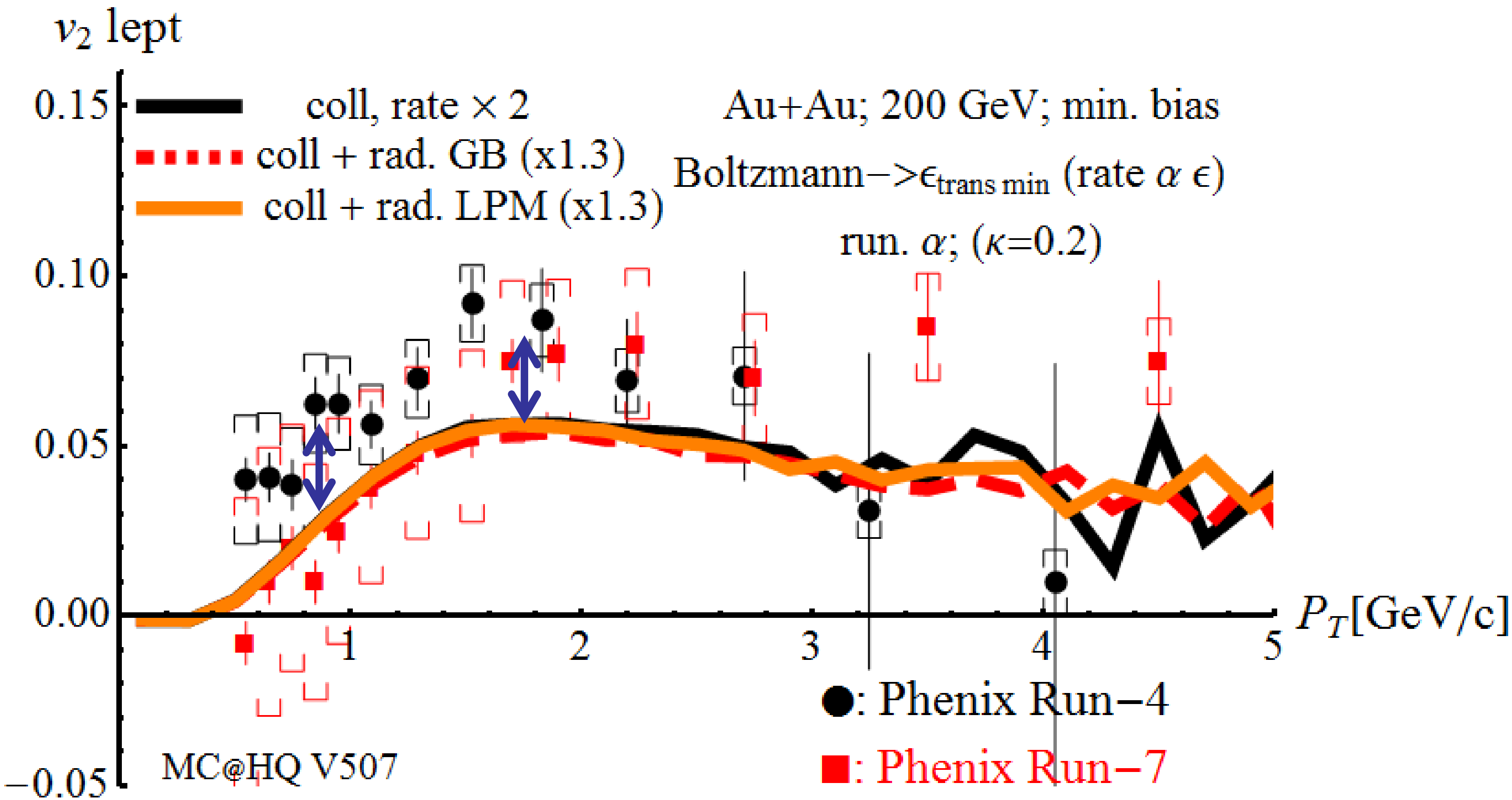


{Radiative + Elastic} vs Elastic for leptons @ RHIC

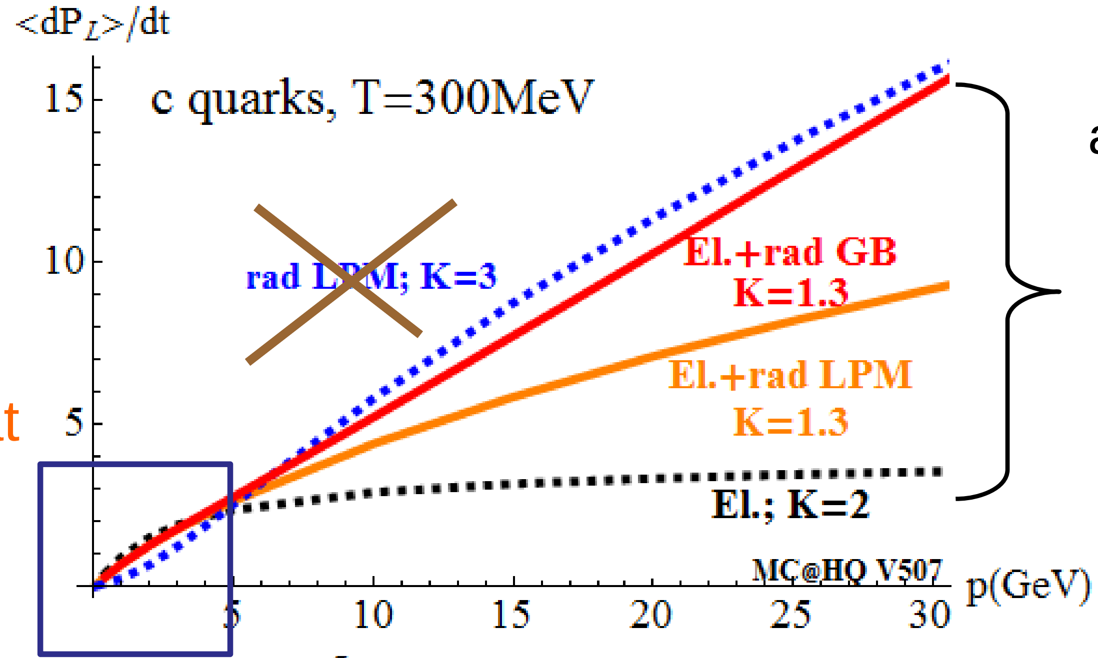


{Radiative + Elastic} vs Elastic for leptons @ RHIC



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* ~ 1

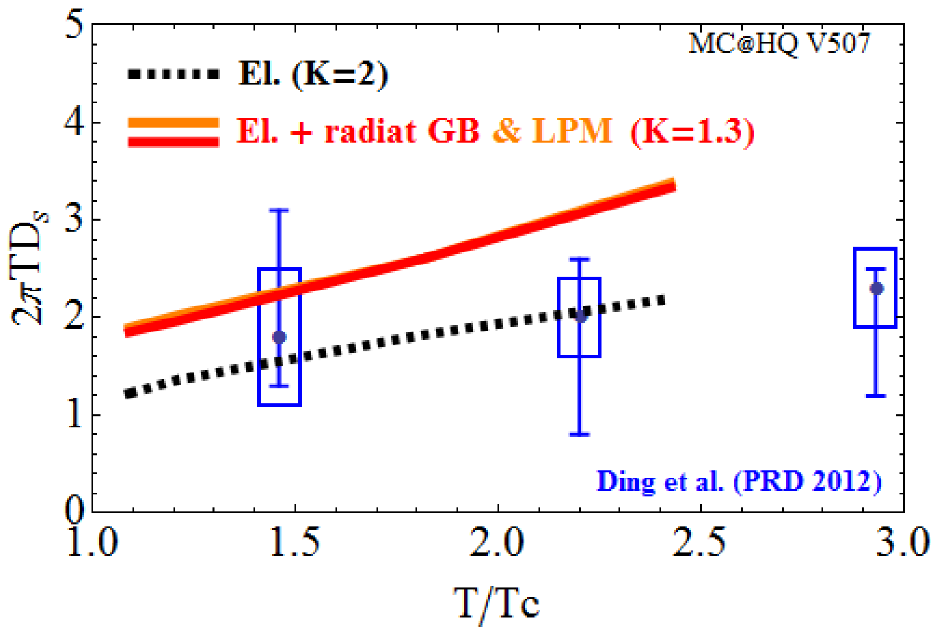
Present RHIC experiments cannot resolve between those various trends

Hope that LHC can do !!!

We extract it from data

(starting from SQM 2008)

We compare with recent lattice results

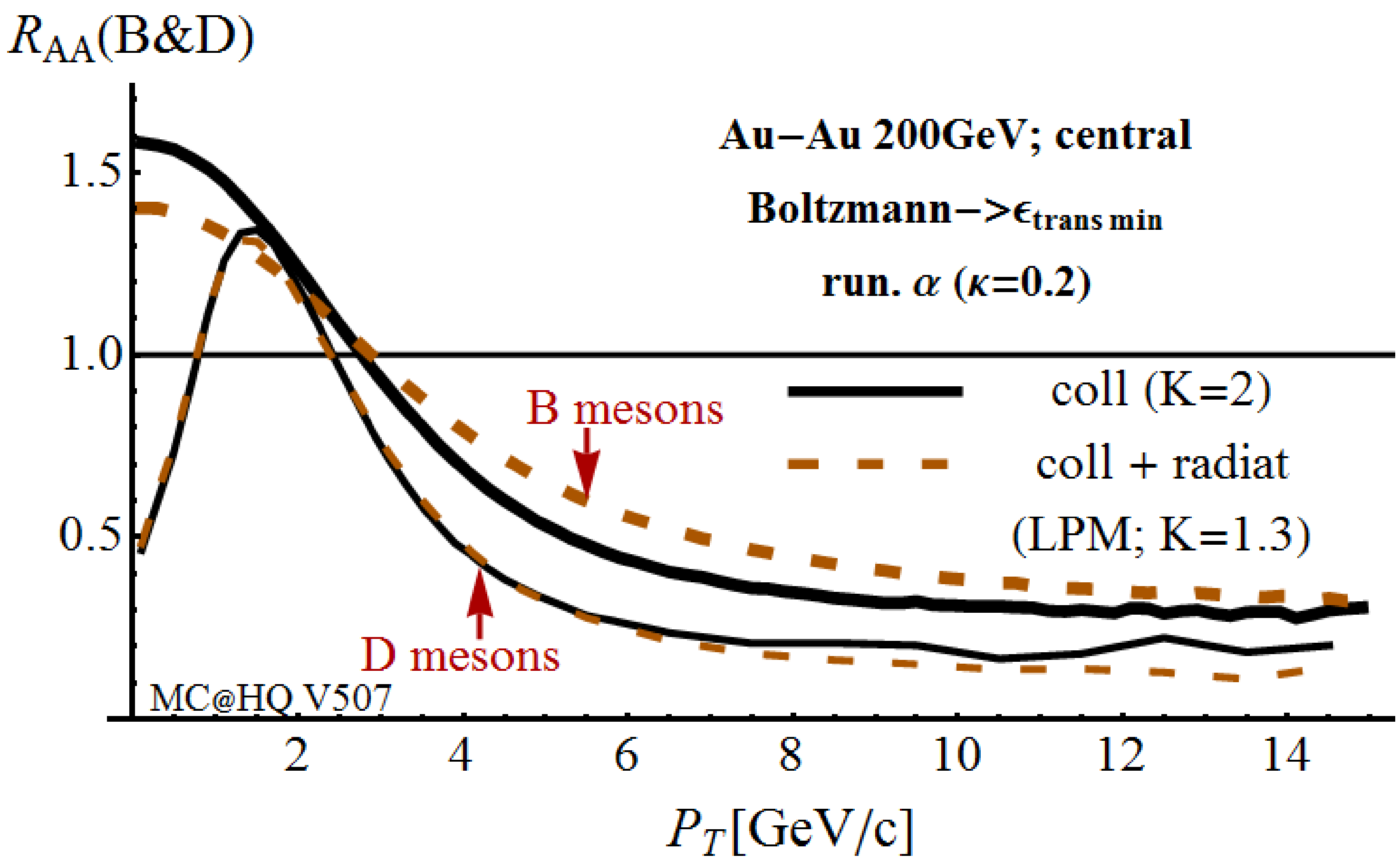


Main message

It is possible to reveal some fundamental property of QGP using HQ probes

Bright future of RHIC

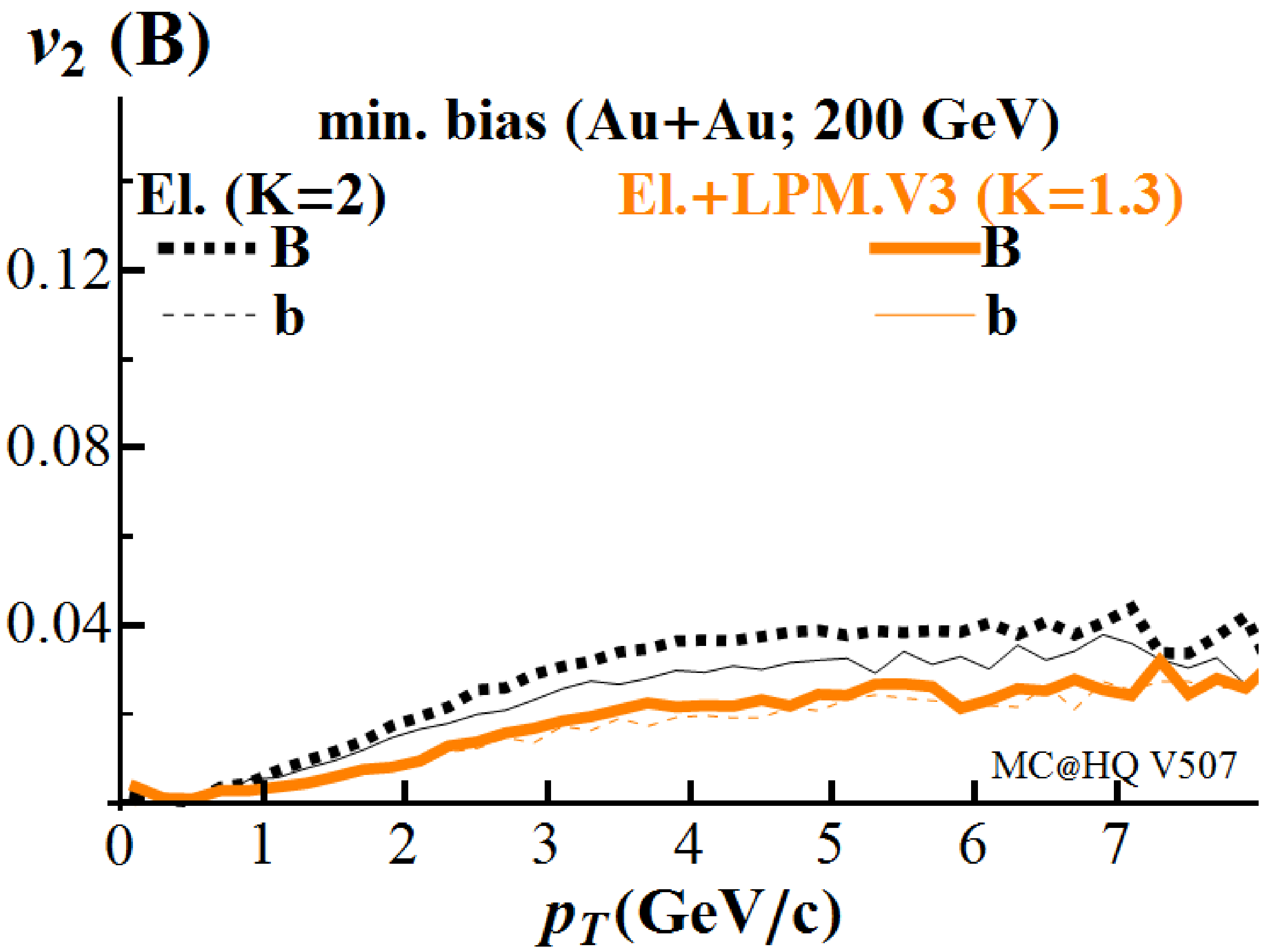
=> Discriminating power of B mesons



Larger mass hierarchy for radiative Eloss

Bright future of RHIC

=> Discriminating power of B mesons

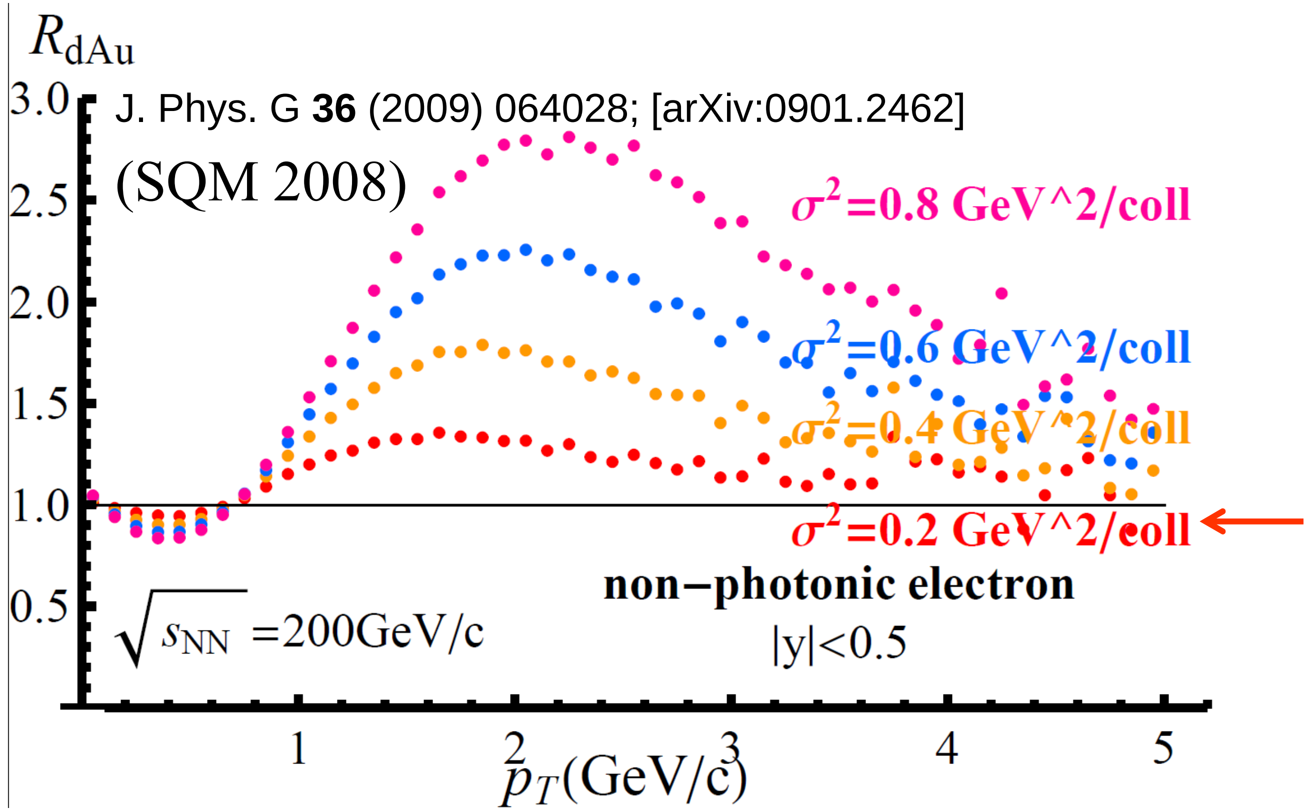


Larger mass hierarchy for radiative Eloss

Bright future of RHIC

=> BES, dAu, Cu + Cu, Cu + Au

Still in our "to do list"… however:

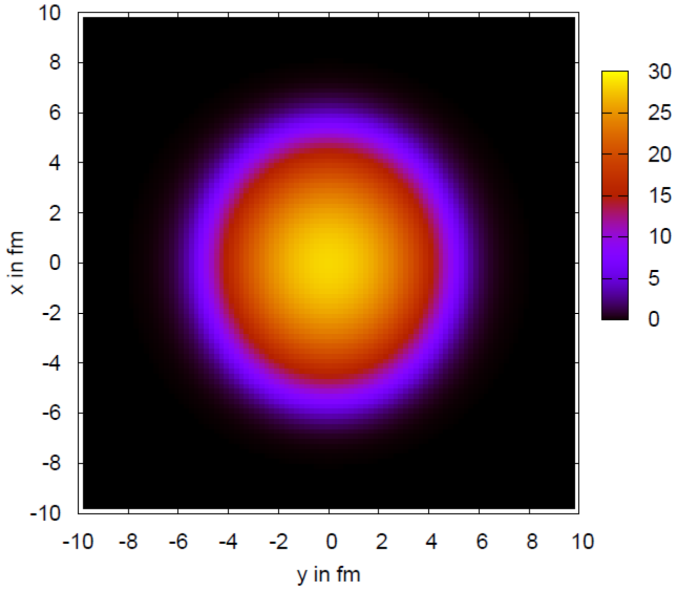


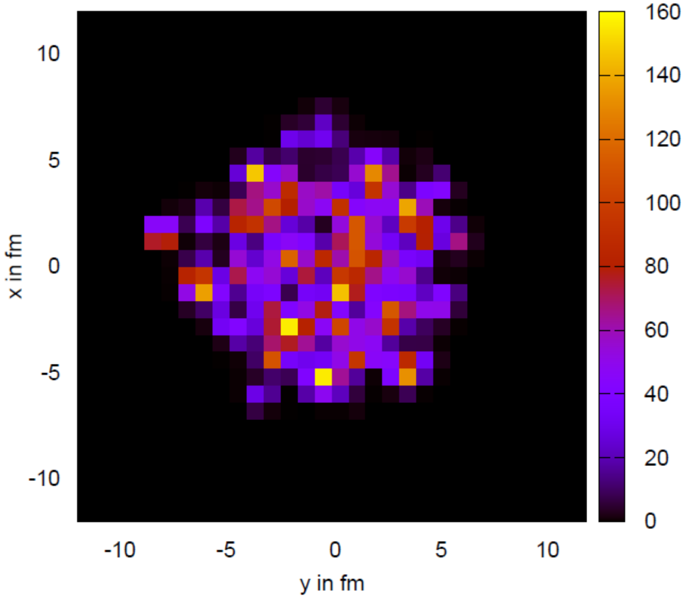
Selected values; good agreement with recent RHIC measurement

Going LHC: 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: $\neq$ color scales

Kolb Heinz (used previously)

EPOS

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

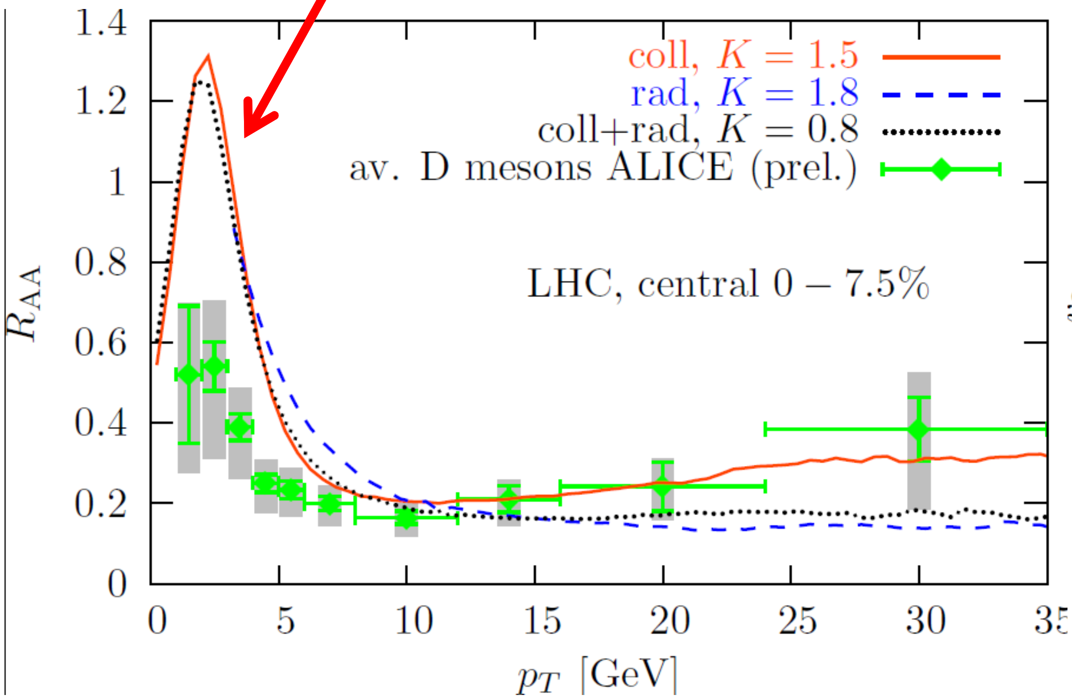
1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)

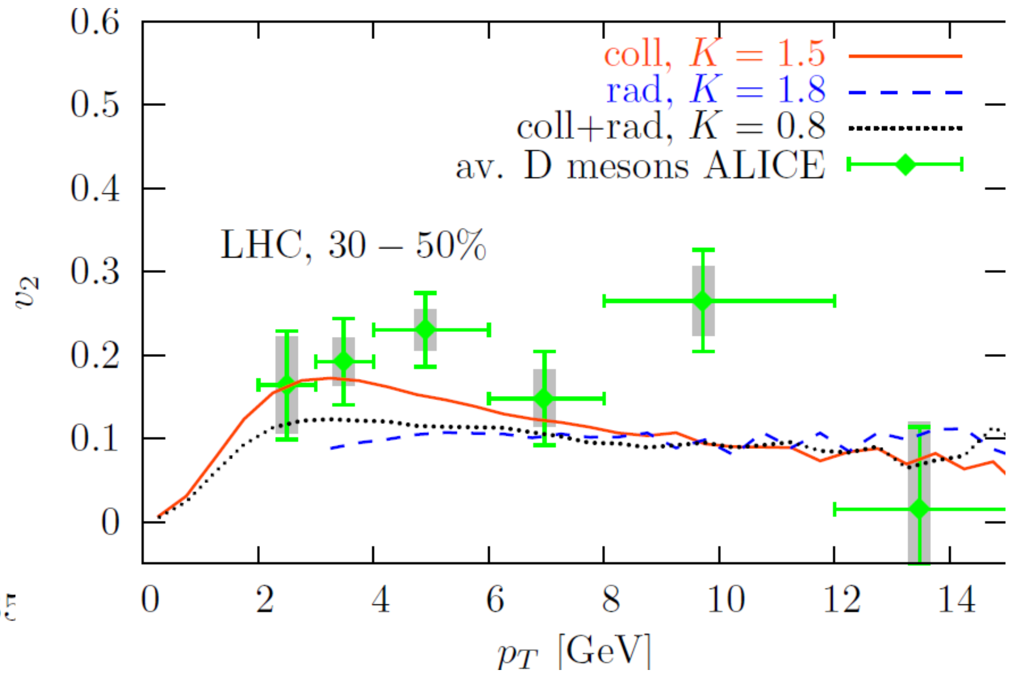
2) correlations between HF and light hadrons

Going LHC: EPOS as a background for MC@sHQ

Same microscopic ingredients as for RHIC (ΔE α L);

NO SHADOWING (yet)





Three options : Collisional only K factor = 1.5

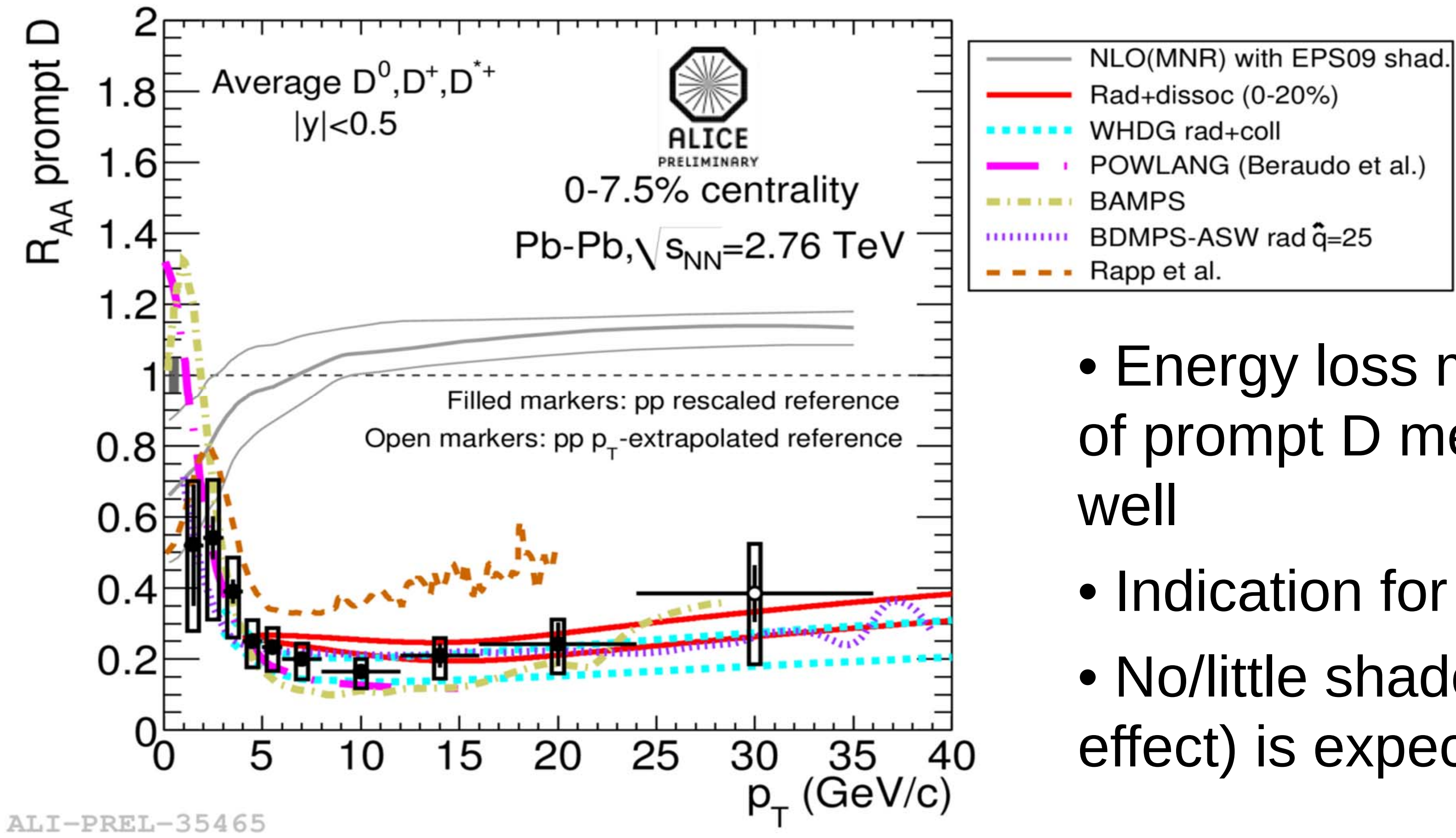
Collisional and radiative K = 0.8

Radiative only K= 1.8

N.B.: K values: slightly smaller then what obtained from RHIC

Data at large pT seems to favor « Collisional only ». Counter intuitive

Comparison with model calculations (A Mischke)



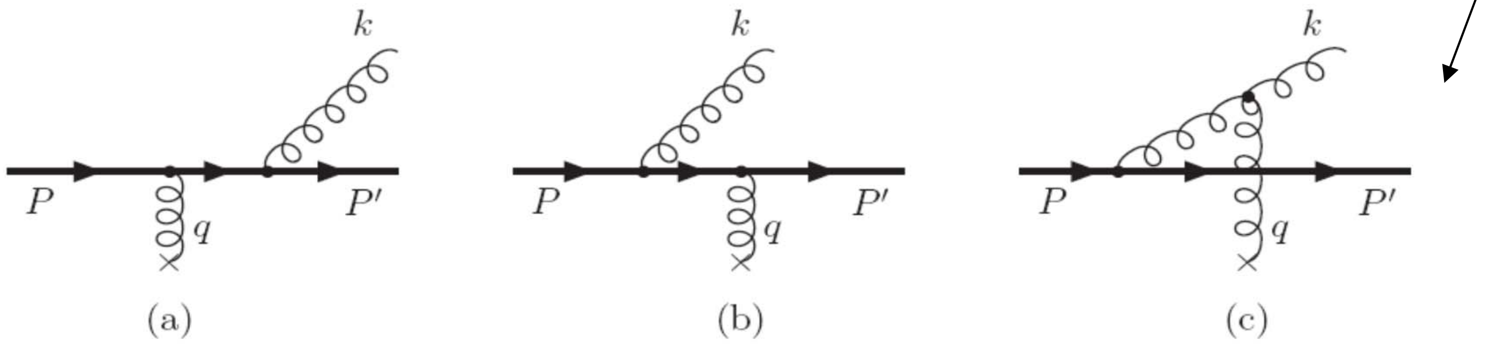
- Energy loss models describe R_{AA} of prompt D mesons reasonably well
- Indication for rising R_{AA}?
- No/little shadowing (initial-state effect) is expected in this p_T range

- Rad.+dissoc.: R. Sharma, I. Vitev and B.W. Zhang, Phys. Rev. C80 (2009) 054902, Y. He, I. Vitev and B.W. Zhang, arXiv: 1105.2566 (2011)
- WHDG (coll.+rad. Eloss in anisotropic medium): W.A. Horowitz and M. Gyulassy, J. Phys. G38 (2011) 124114
- POWLANG (coll. Eloss using Langevin approach): W.M. Alberico, et al., Eur. Phyis J. C71,1666 (2011)
- BAMPS (coll. Eloss in expanding medium): O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. G38 (2011) 124152
- Coll. + LPM rad. energy loss: J. Aichelin et al., Phys. Rev. C79 (2009) 044906
- BDMPS-ASW: N. Armesto, A. Dainese, C.A. Salgado and U.A. Wiedemann, Phys. Rev. D71 (2005) 054027
- Coll. Eloss via D mesons resonances excitation + Hydro evolution: M. He, R.J. Fries and R. Rapp, arXiv:1204.4442

Important facts about radiative *induced* energy loss

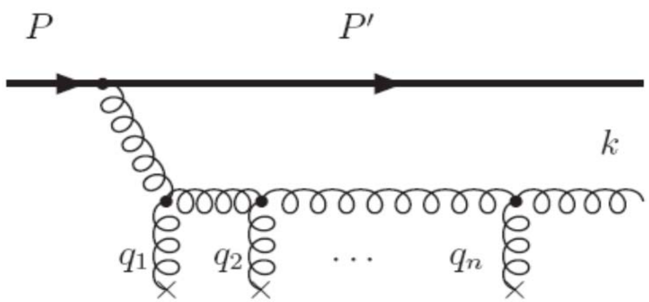
QCD:

1. QCD analog of Bethe Heitler result established by Gunion & Bertsch (M=0) at high energy; third diagram involved…



… important as it contributes to populate the mid rapidity gap (large angle radiation)

2. QCD analog of LPM effects: BDMPS; main difference: dominant process are the ones for which the emitted gluon is rescattered:



$$\Delta E \propto \hat{q} L^2$$

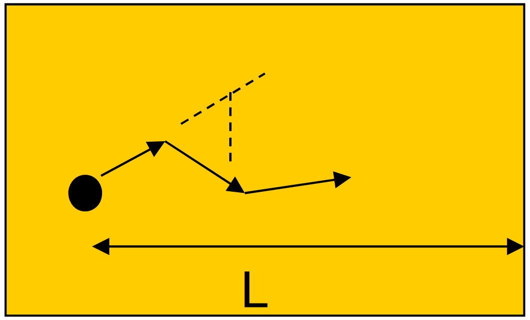
Yes, but…

… leads to a complete modification of the formation times and radiation spectra, but these concepts still apply

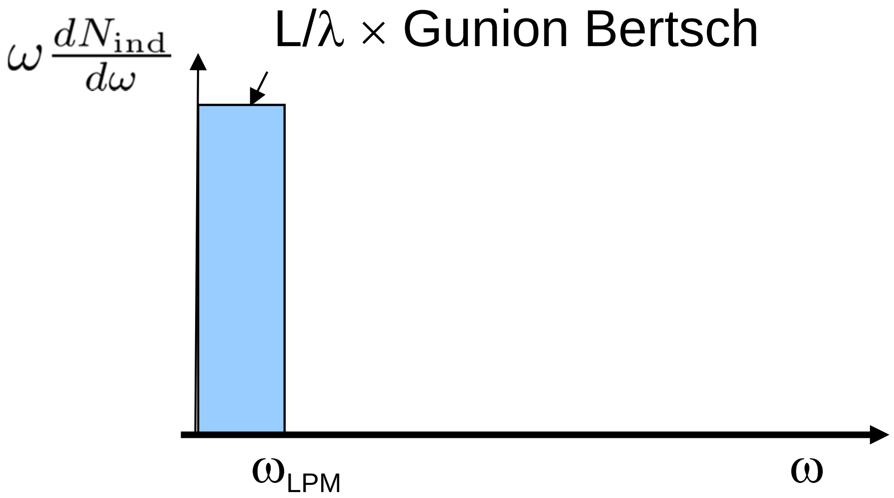
Important facts about radiative *induced* energy loss

LHC: the realm for coherence !

3 regimes and various path length (L) dependences : (light q)



QGP brick



→ a) Low energy gluons: Typical formation time ω/k_t^2 is smaller than mean free path λ:

$\omega < \omega_{\mathrm{LPM}} := \frac{\hat{q}\lambda^2}{2}$ Incoherent Gunion-Bertsch radiation

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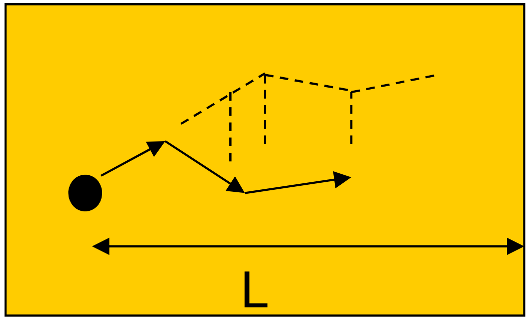
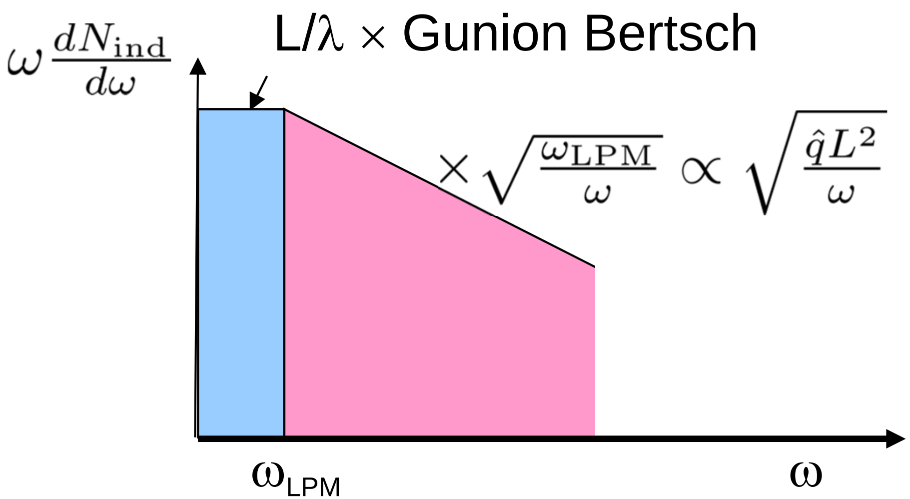


QGP brick



a) Low energy gluons: Typical formation time ω/k_t^2 is smaller than mean free path λ:

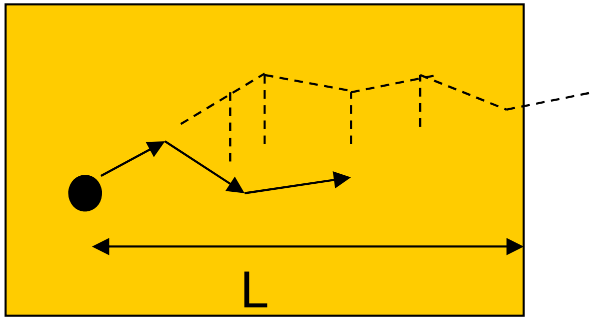
$\omega < \omega_{\rm LPM} := \frac{\hat{q}\lambda^2}{2}$ **Incoherent** Gunion-Bertsch radiation

→ b) Inter. energy gluons: Produced **coherenty** on $N_{\rm coh}$ centers after typical formation time $t_f = \sqrt{\frac{\omega}{\hat{q}}} \Rightarrow N_{\rm coh} = \frac{t_f}{\lambda} = \sqrt{\frac{\omega}{\omega_{\rm LPM}}}$ leading to an effective reduction of the GB radiation spectrum by a factor $1/N_{\rm coh}$

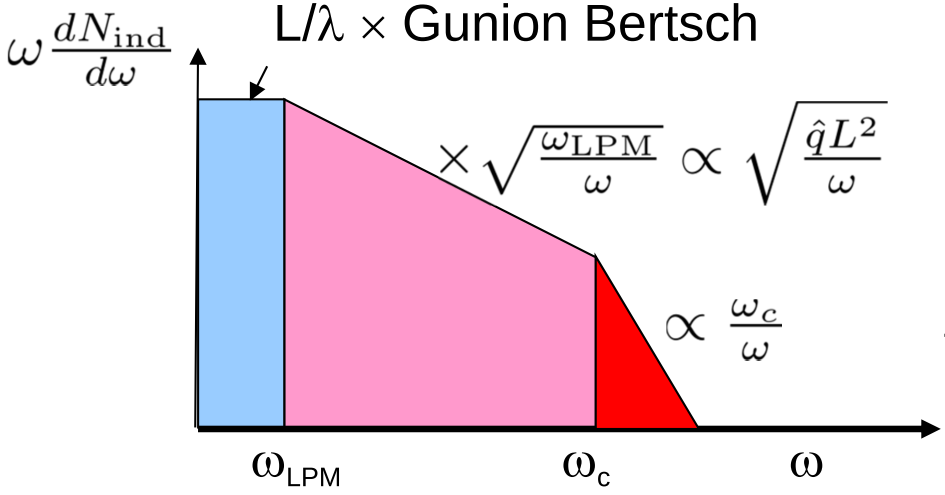
Important facts about radiative *induced* energy loss

LHC: the realm for coherence !

3 regimes and various path length (L) dependences : (light q)



QGP brick



GLV (2001),
Zakharov (2001)

a) Low energy gluons: **Incoherent** Gunion-Bertsch radiation

b) Inter. energy gluons: Produced **coherenty** on $N_{\rm coh}$ centers after typical formation time $t_f = \sqrt{\frac{\omega}{\hat{q}}}$

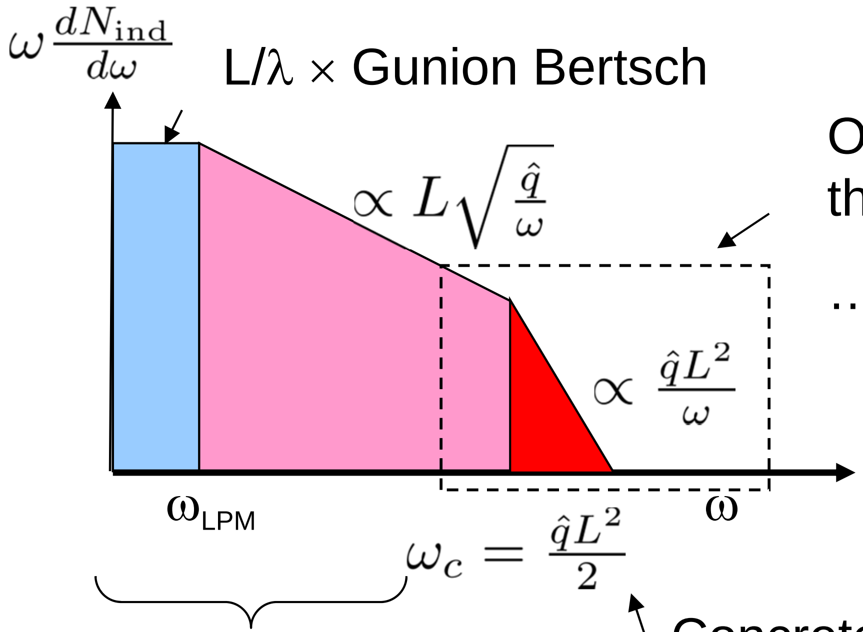
→ c) High energy gluons: Produced mostly outside the QGP… nearly as in vacuum **do not contribute significantly to the induced energy loss**

$\sqrt{\frac{\omega}{\hat{q}}} > L \Rightarrow \omega > \omega_c := \frac{\hat{q}L^2}{2}$

Important facts about radiative *induced* energy loss

LHC: the realm for coherence !

3 regimes and various path length (L) dependences : (light q)



Only this tail makes the L^2 dependence in the average Eloss integral …

…provided the higher boundary ω=E > ω_c.

Otherwise, everything α L

Concrete values @ LHC $\begin{cases} \hat{q} \sim 5\mathrm{GeV}^2/\mathrm{fm} \\ L \sim 2\mathrm{fm} \end{cases}$

Bulk part of the spectrum still scales like path length L

$\omega_c \sim 100\mathrm{GeV}$ Huge value !

A large part of radiative energy loss @ LHC still scales like the path length
=> **Still makes sense to speak about energy loss per unit length (for a typical event)**

$$\Delta E \simeq \pi C_s C_A \alpha^3 \mathcal{N} L^2 \left[\ln\left(\frac{\hat{q}_A L}{m_D^2}\right) + \ln\left(\frac{E}{\hat{q}_A L^2}\right)\right]$$

Consequences of radiation damping on energy loss

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

Concepts

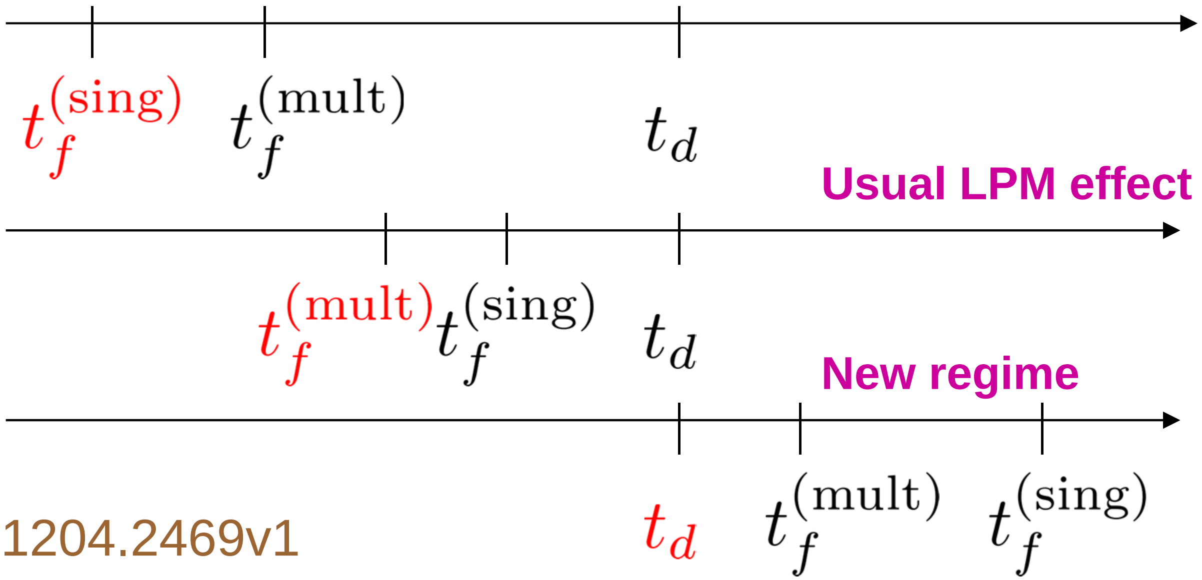
- In QED or pQCD, damping is a NLO process (damping time $t_d \gg \lambda$); neglected up to now.
- However: formation time of radiation t_f increases with boost factor γ of the charge
- Expected effects when $t_f \approx t_d$ or $t_f > t_d$: in this regime, t_d should become the relevant scale (gluons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

γ - hierarchy:

Small γ:

Interm. γ:

Large γ:

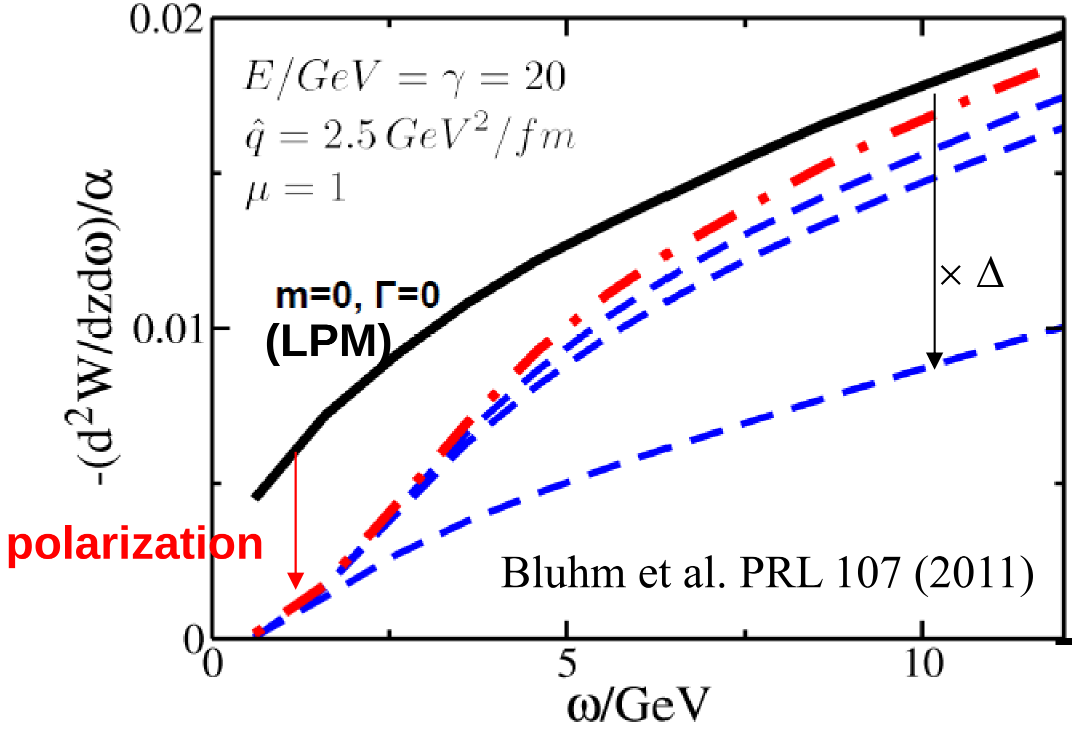


M. Bluhm, PBG & J. Aichelin, arXiv:1204.2469v1

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

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

No “BH” limit

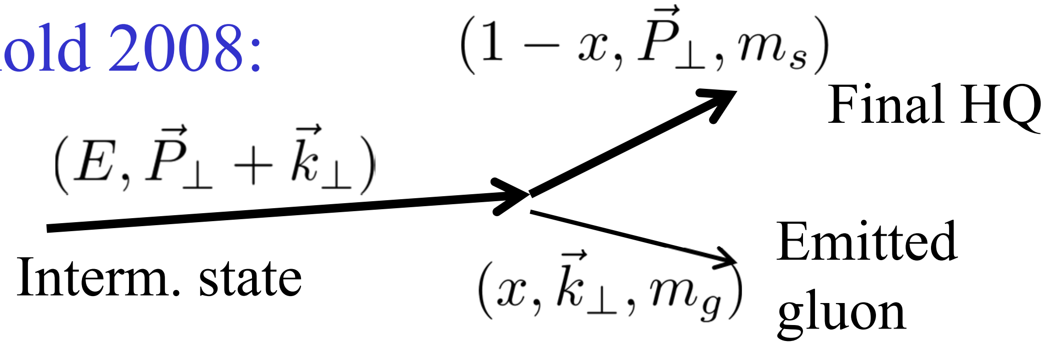
Scaling law:

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

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

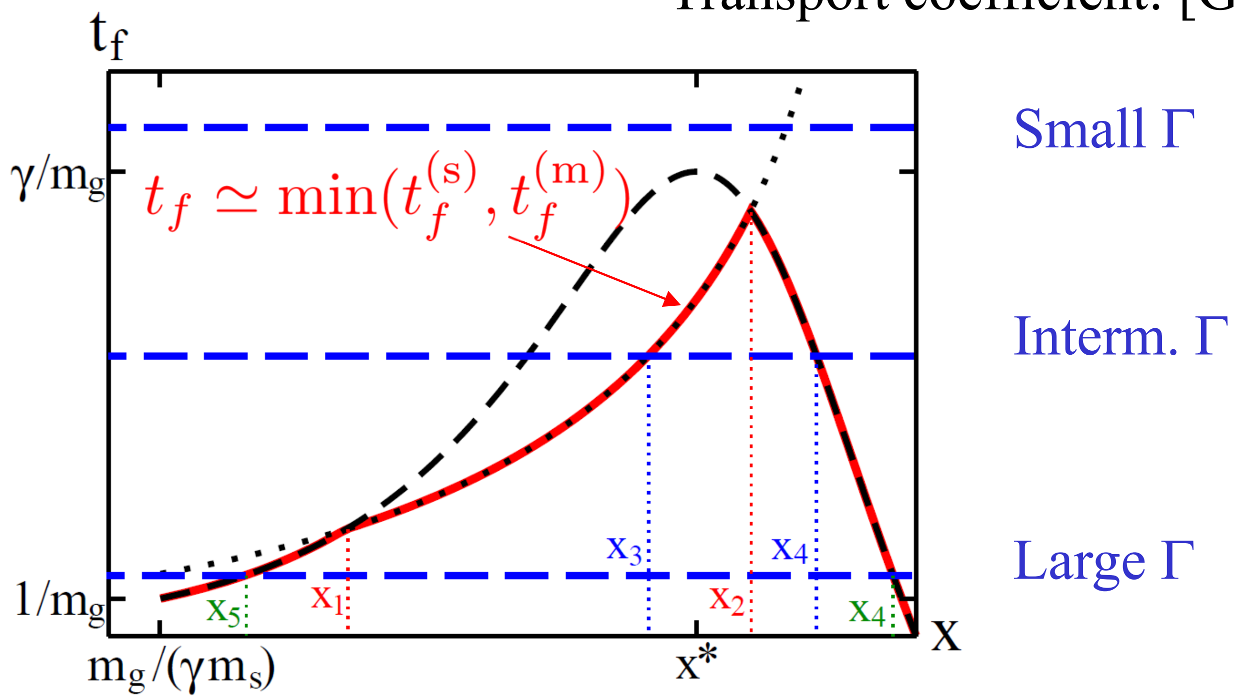
$\hat{q}_g$ ↑ Transport coefficient: [GeV^2/fm]

=> Self consistent expression for t_f

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

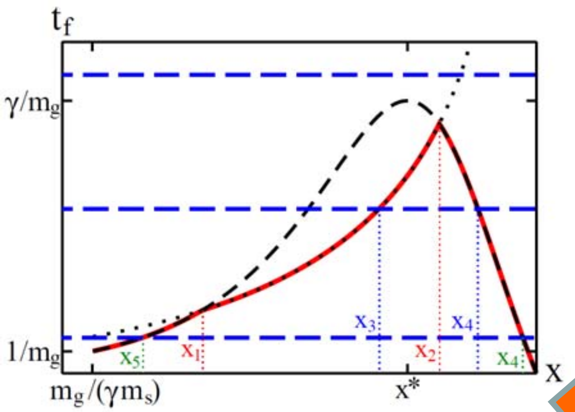
········ $t_f^{(m)} \simeq \sqrt{\dfrac{2xE}{(1-x)\hat{q}_g}}$

— — $t_d = \frac{1}{\Gamma}$

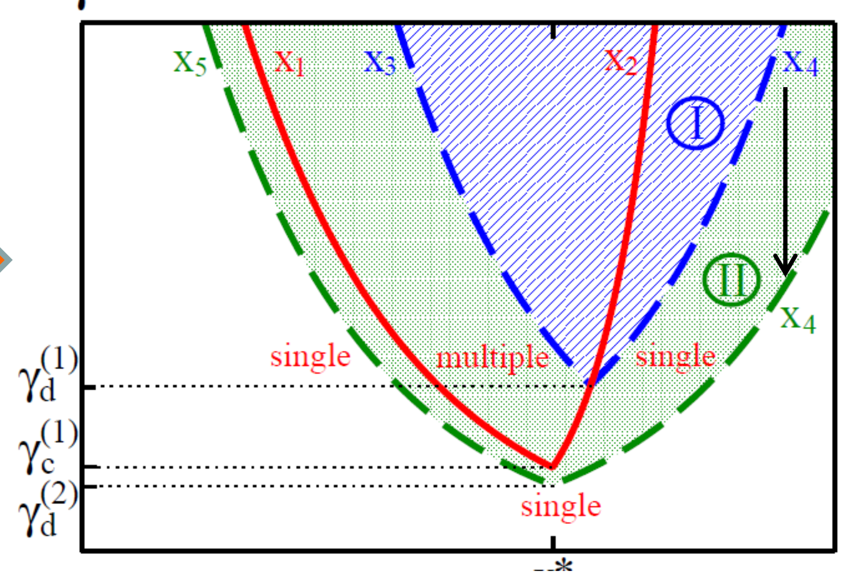


New regimes when including gluon damping

x-γ space for $\hat{q} < m_g^3$



Larger damping effect at large γ

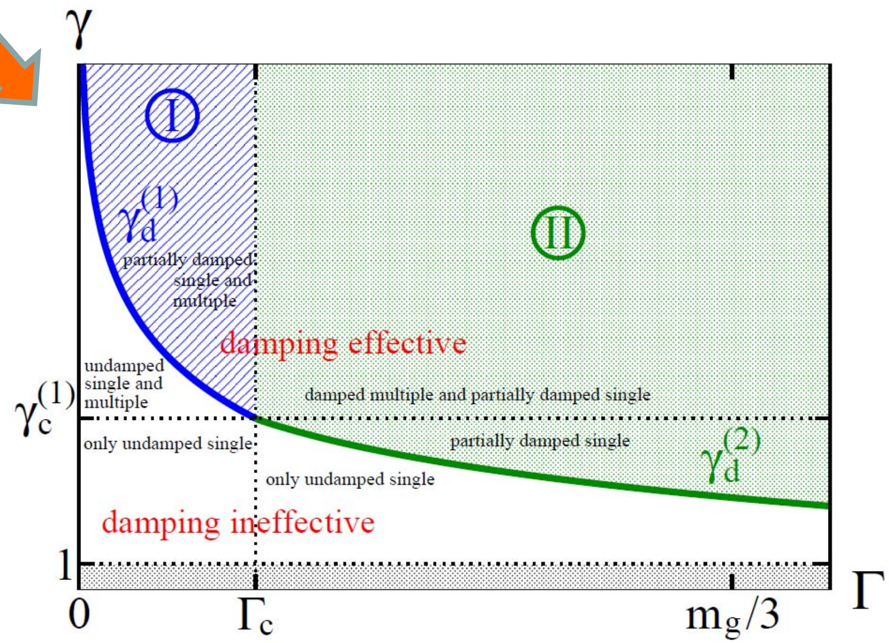


$x = \frac{\omega}{E}$

Increasing Γ

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

Γ–γ space



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

γ-scales

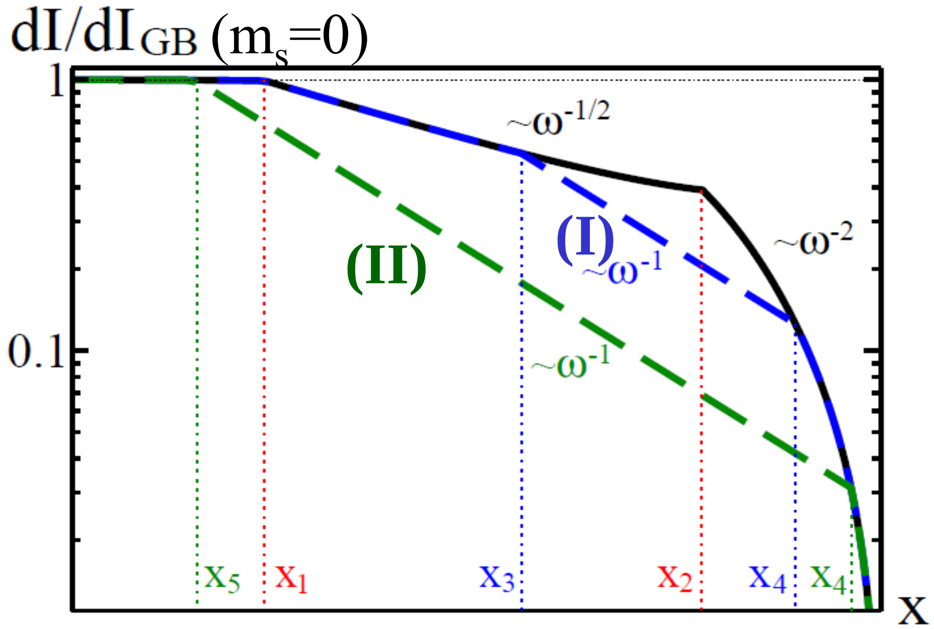
$\gamma_c^{(1)} \sim m_g^3/\hat{q}_g$

$\gamma_d^{(1)} \sim \sqrt{\hat{q}_g/\Gamma^3}$

$\gamma_d^{(2)} \sim m_g/\Gamma$

Consequences on the power spectra

$\hat{q} < m_g^3$



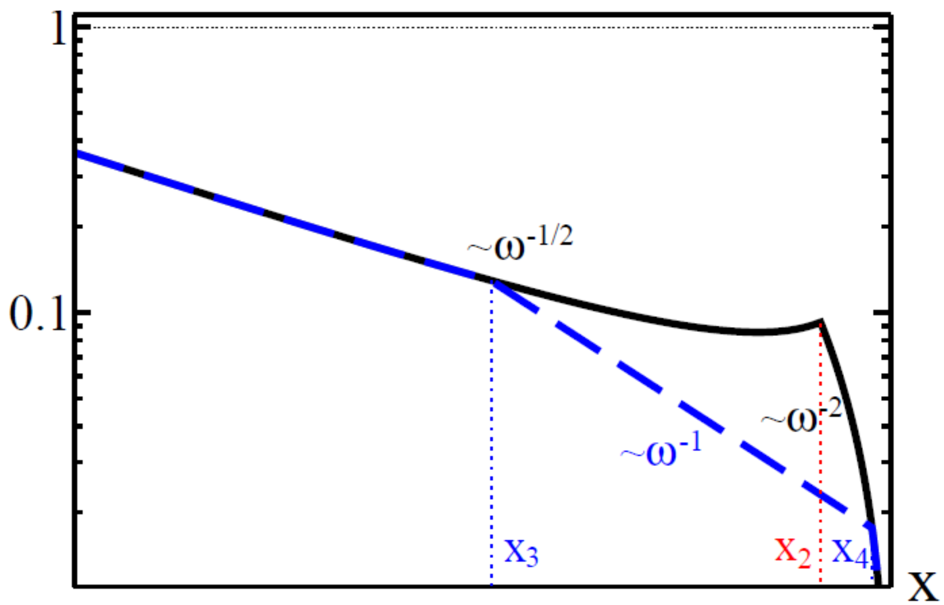
(I) and (II): moderate and large damping (see previous slide)

E= 45 GeV, m_s=1.5 GeV

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

Γ=0.05 GeV (I) & 0.15 GeV (II)

$\hat{q} > m_g^3$

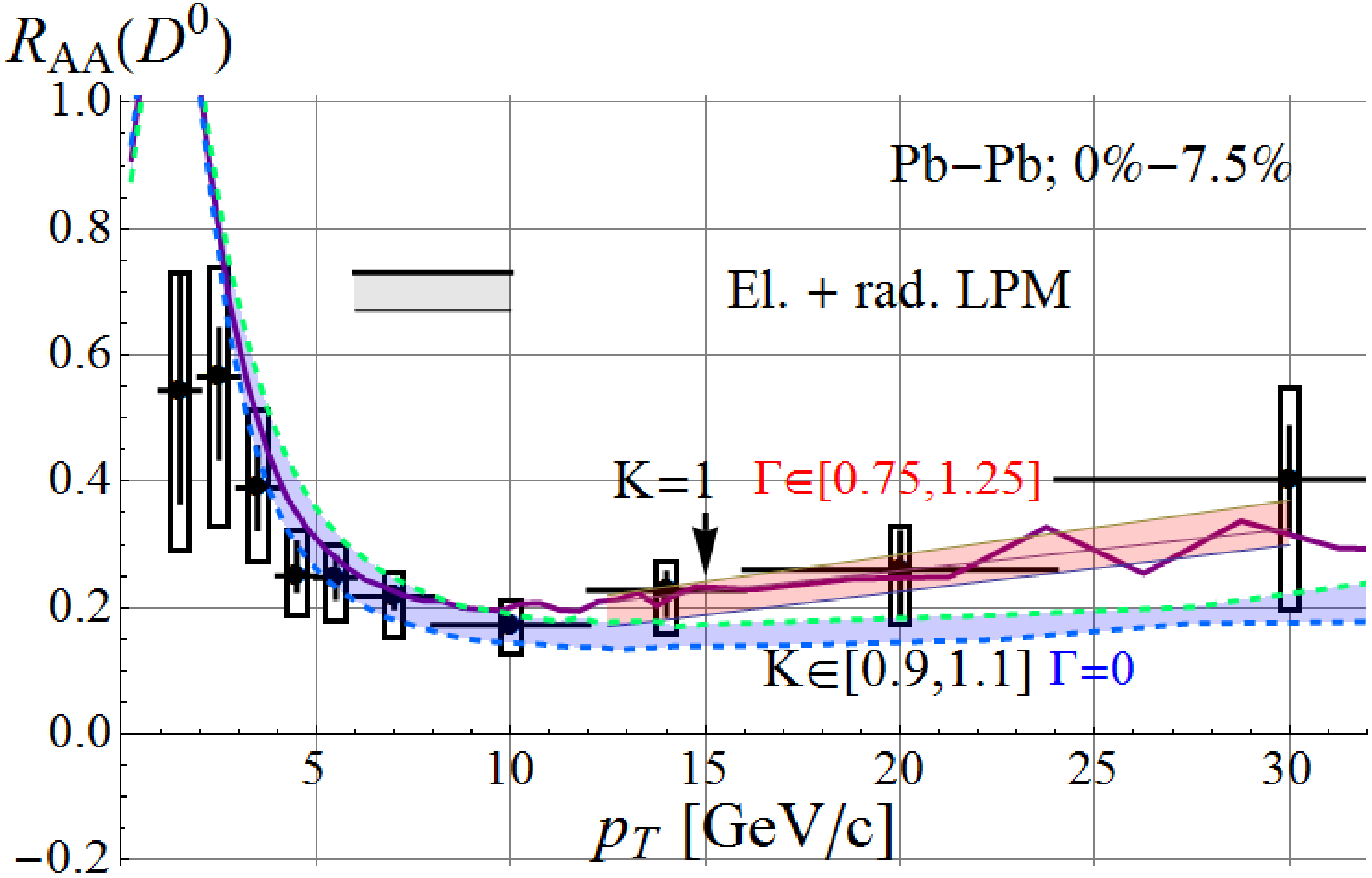


Same but

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

Γ=0.25 GeV

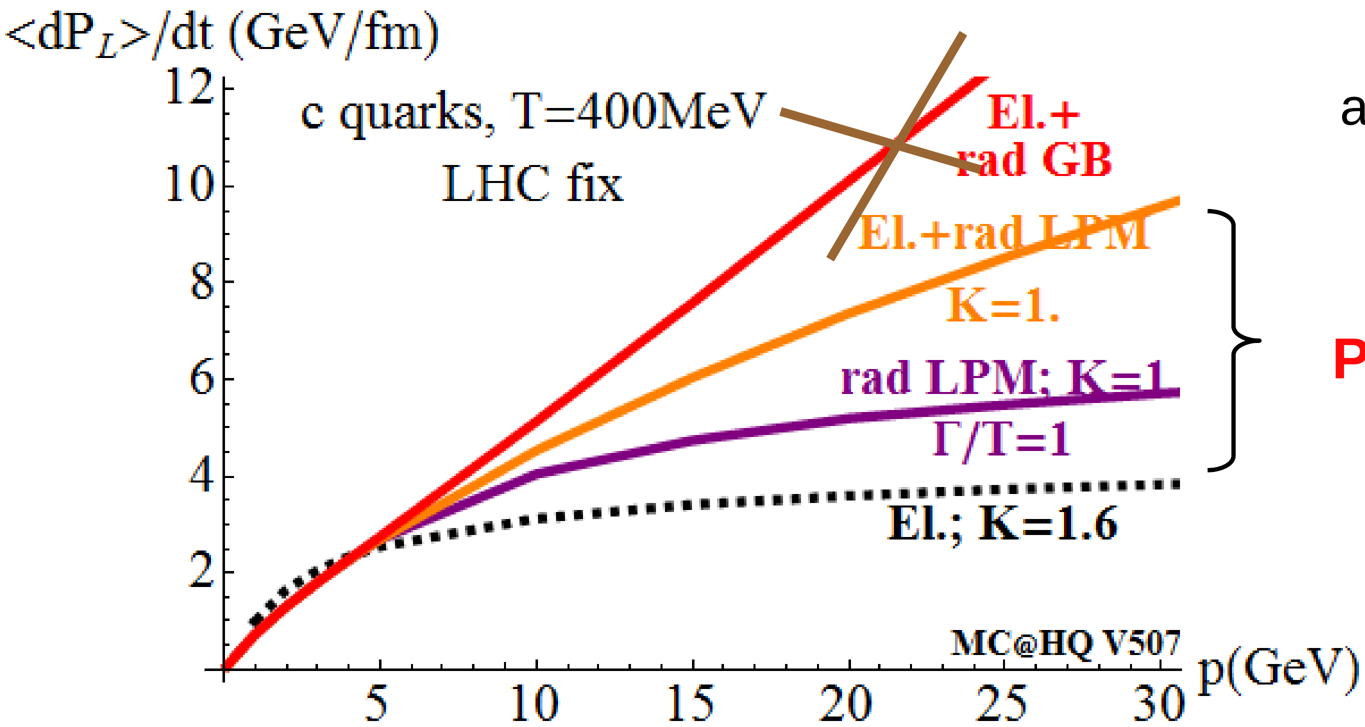
Consequences for mesons at LHC (central)



Damping of radiated gluons reduces the quenching of D mesons

QGP properties from HQ probe at LHC

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



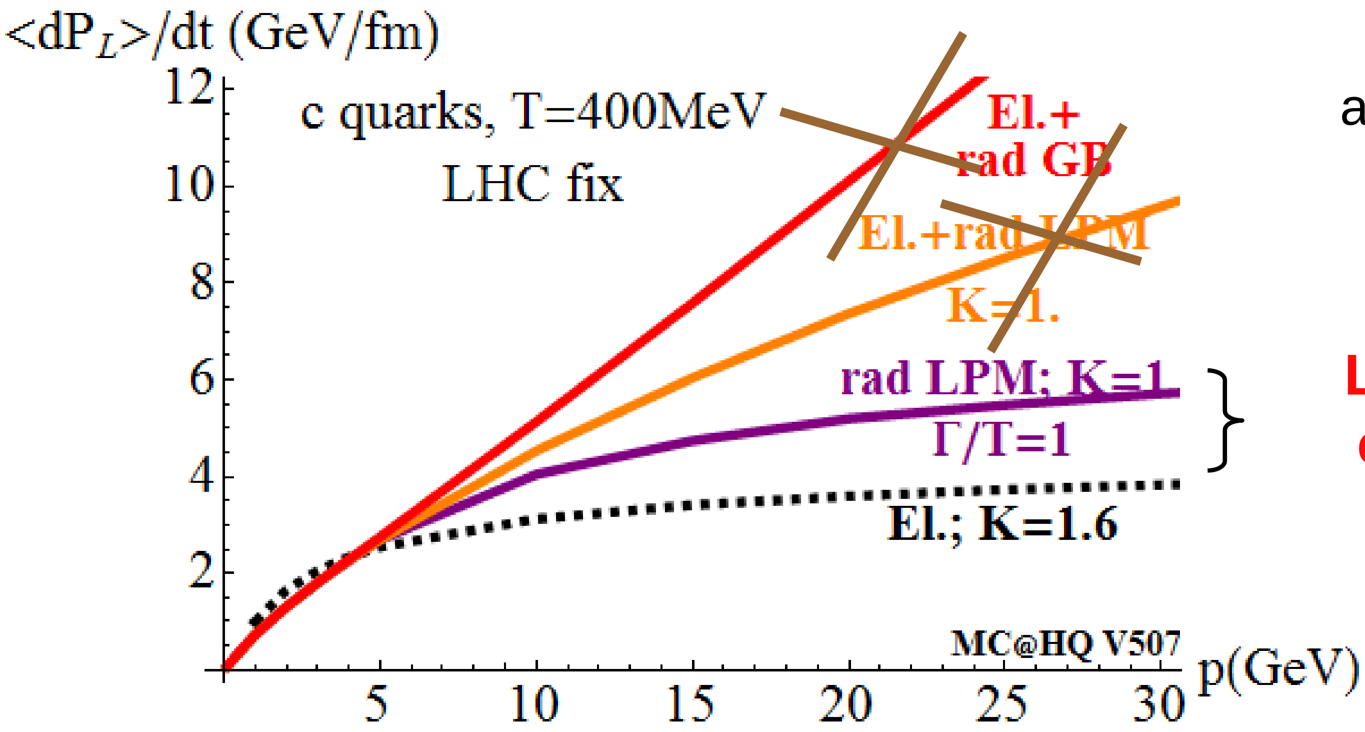
(starting from QM 2012)

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

Present LHC data

QGP properties from HQ probe at LHC

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



(starting from QM 2012)

the drag coefficient reflects the average momentum loss (per unit time) => large weight on *x* ~ 1

LHC has the potentiality to constrain further the drag coefficient!!!

We extract it from data

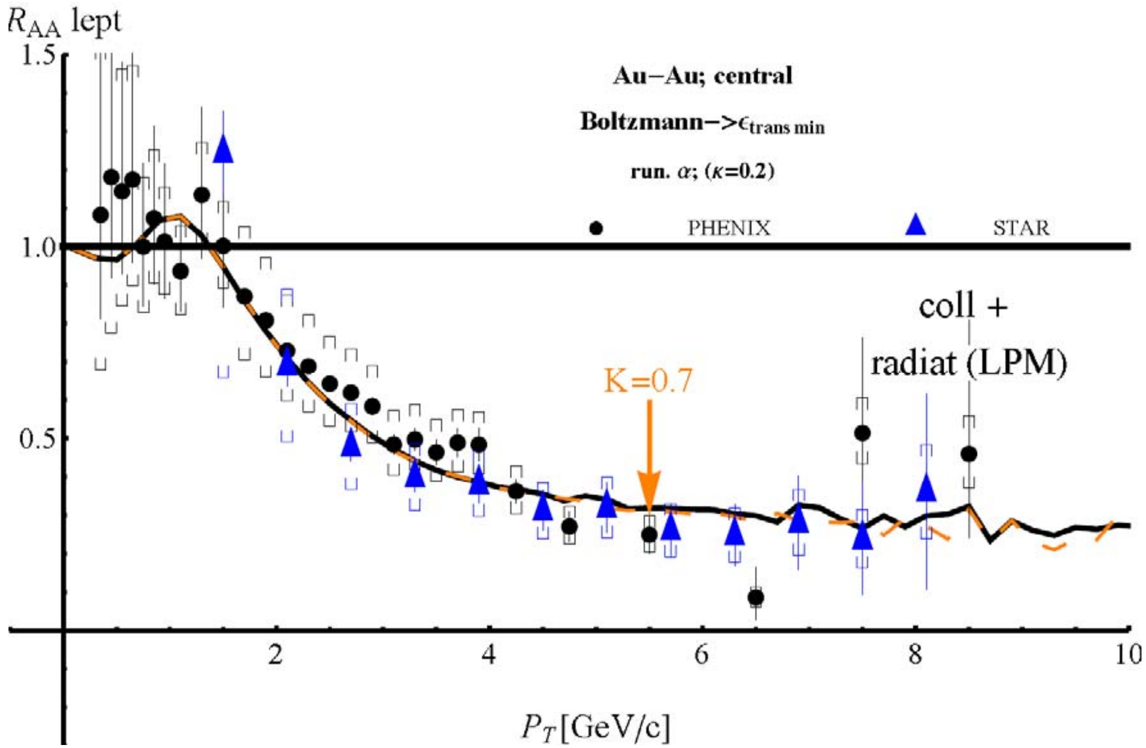
We are eager to compare with future lattice results

Main message

It is possible to reveal some fundamental property of QGP using HQ probes

Self consistency

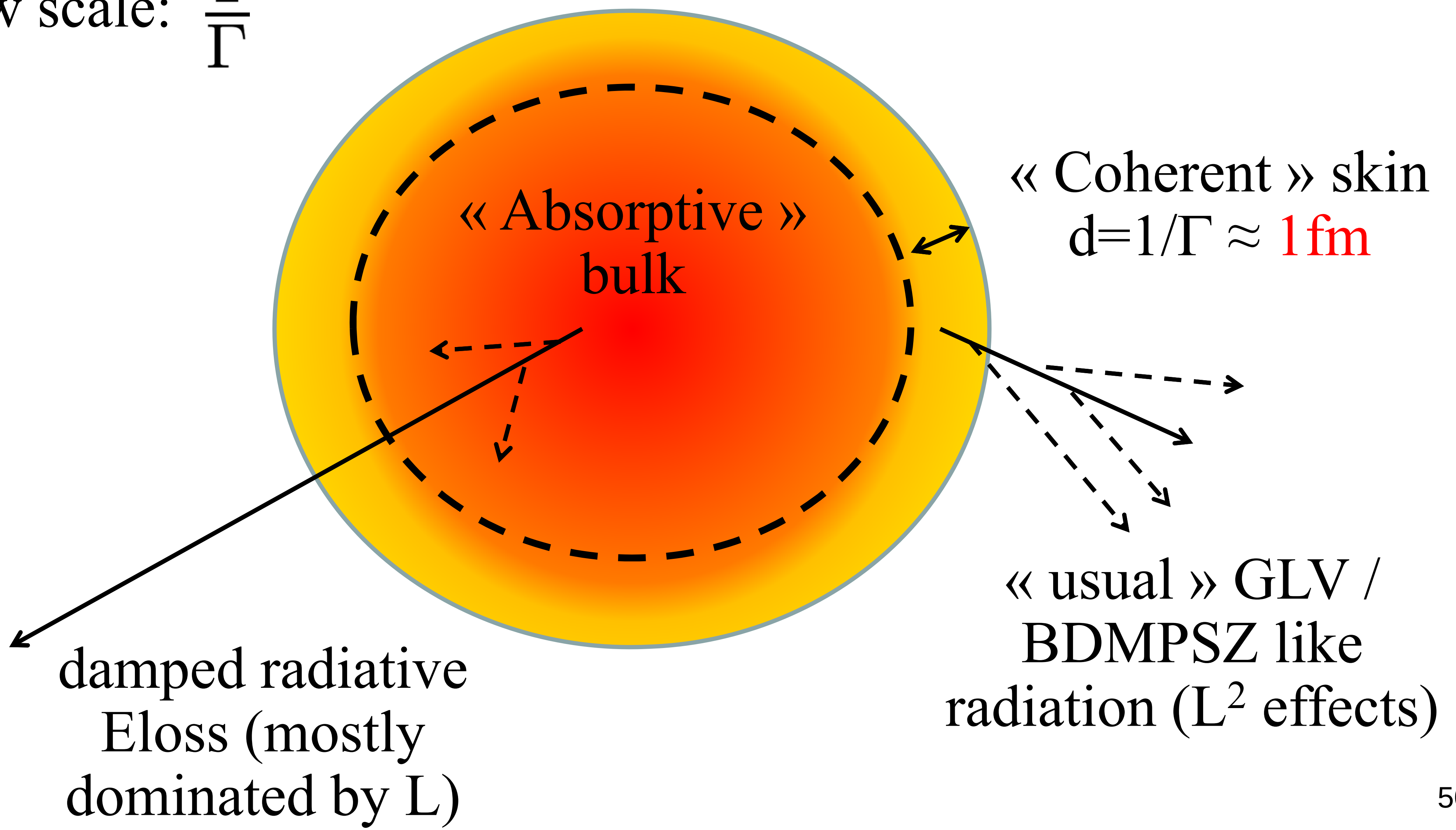
RHIC « reference »: no effect seen for Γ=0.75T



Conclusion: Global picture for finite path length L Eloss

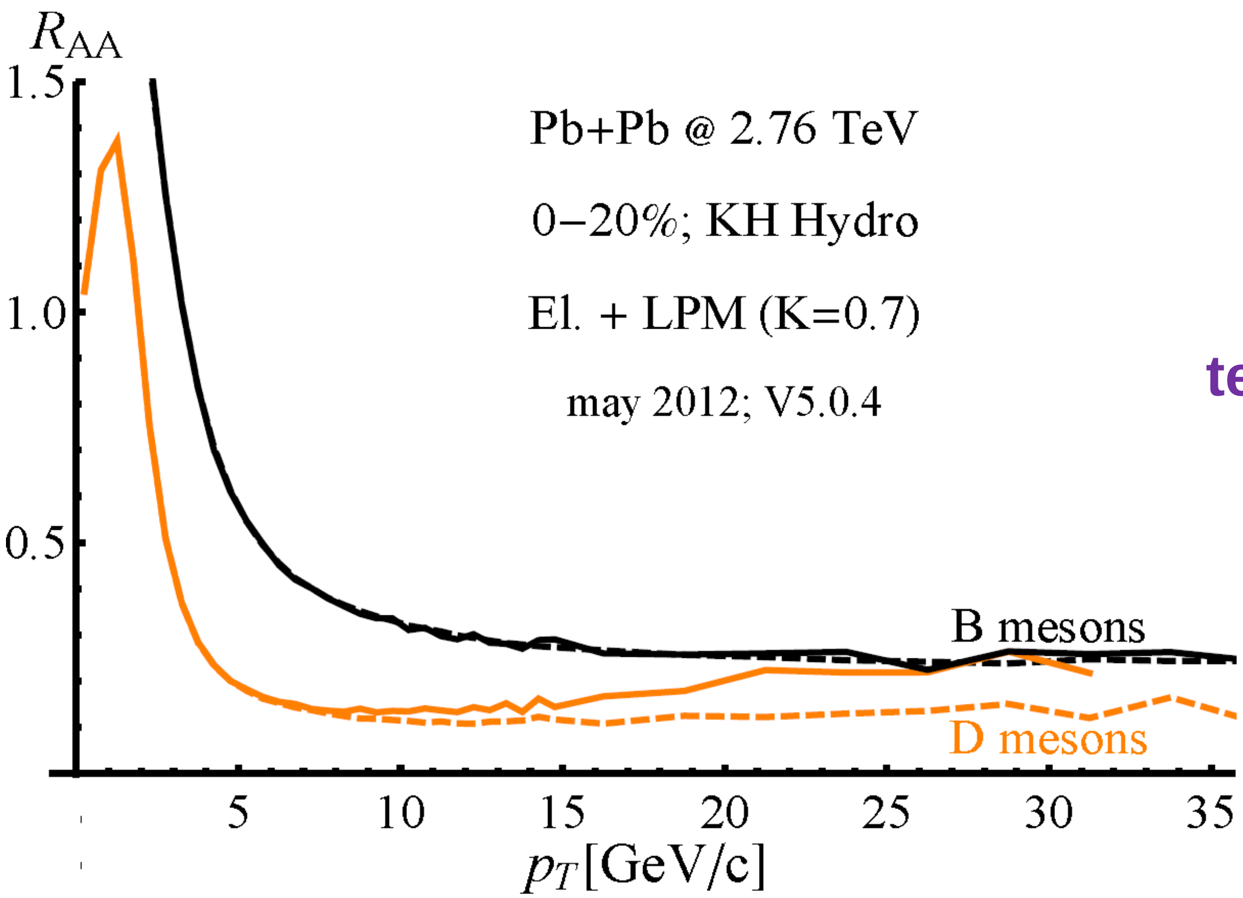
Usually: competition btwn L vs $L_\infty = \sqrt{\frac{E}{\hat{q}}}$

New scale: $\frac{1}{\Gamma}$



Consequences on the c vs b observable

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



Γ=0

Γ/T=0.75

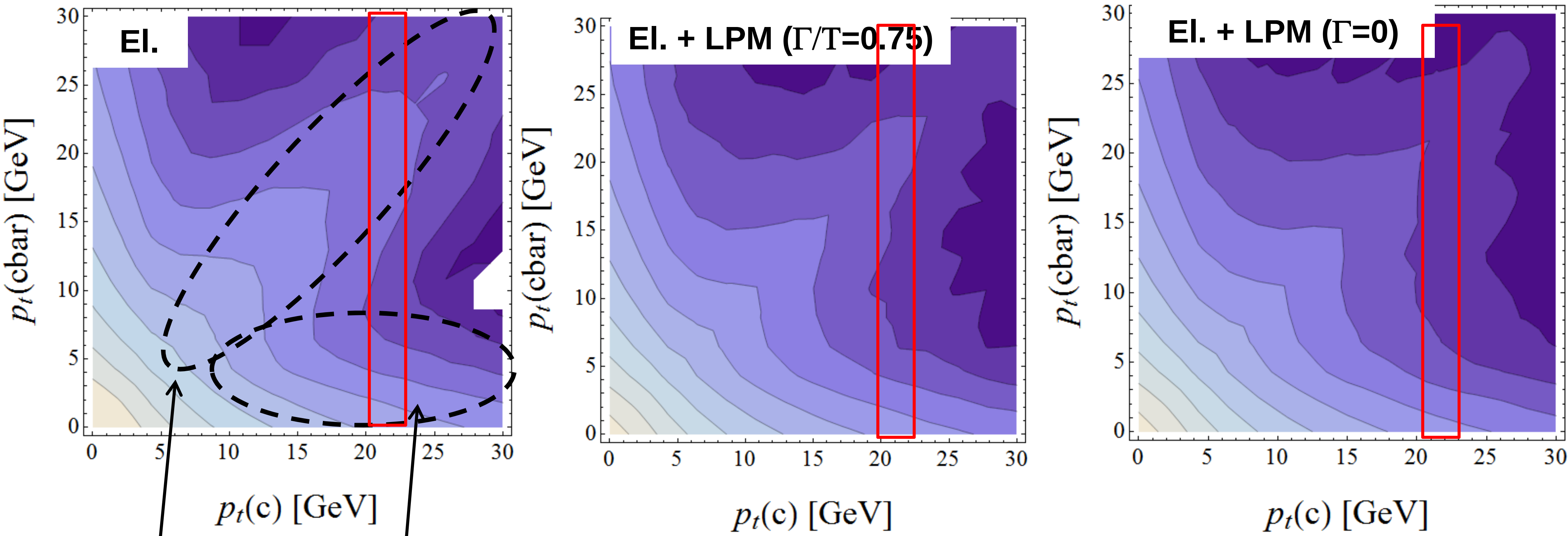
Damping of radiated gluons tempers the mass hierarchy at intermediate p_T

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**



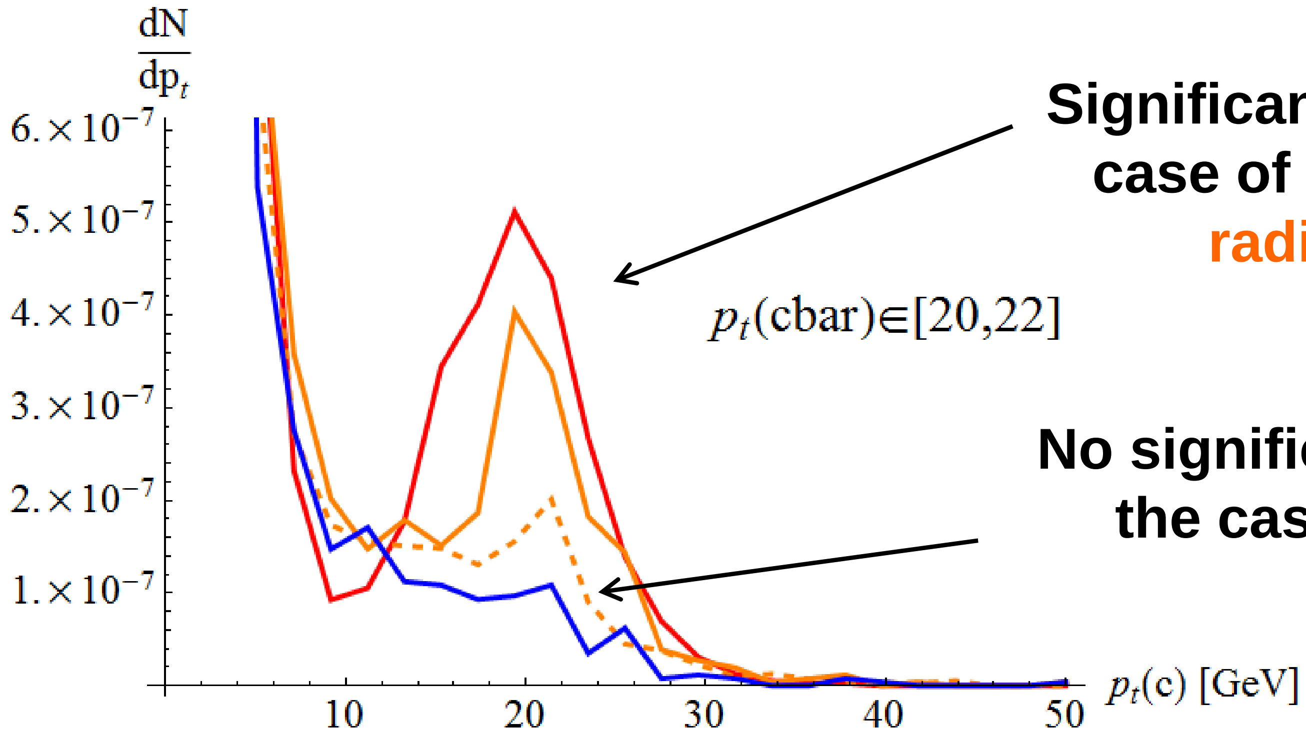
Background at small p_t

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