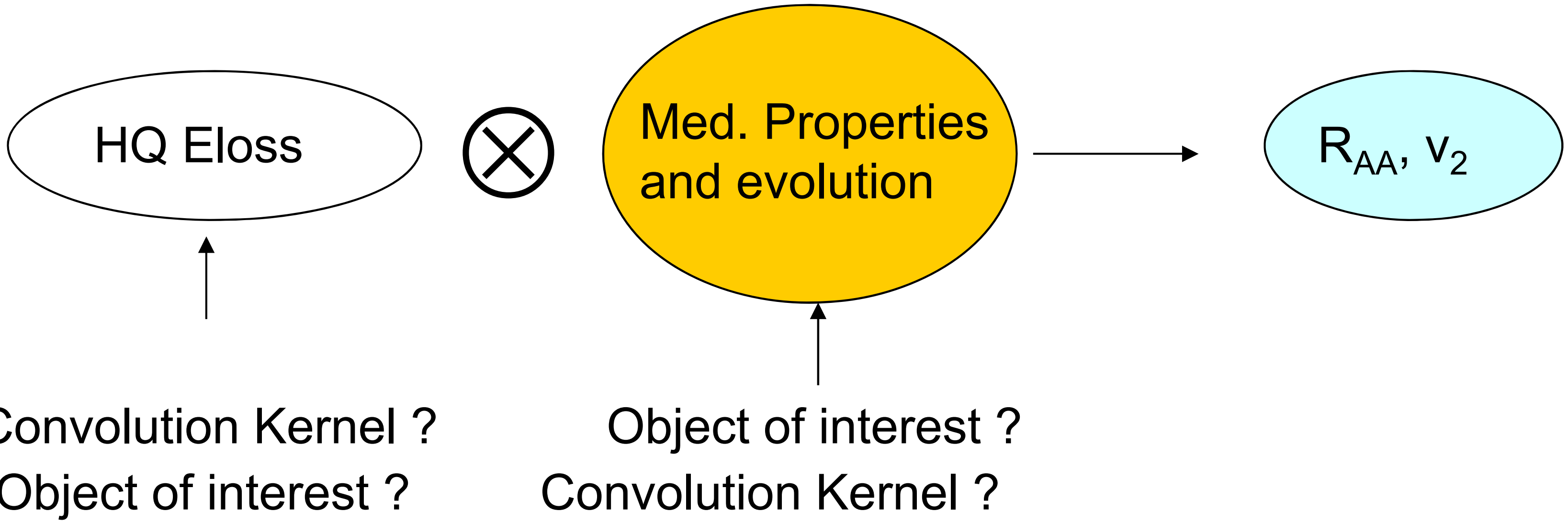
How to go from measured R_{AA} to the quark energy-loss ..., from the theory viewpoint

GDR-PH-QCD meeting, WG 3

P.B. Gossiaux (gossiaux@subatech.in2p3.fr)
SUBATECH, UMR 6457
Université de Nantes, Ecole des Mines de Nantes, IN2P3/CNRS

Questions

Q1: Does HQ Eloss really allows to probe the system, or more a subject of study in itself ?

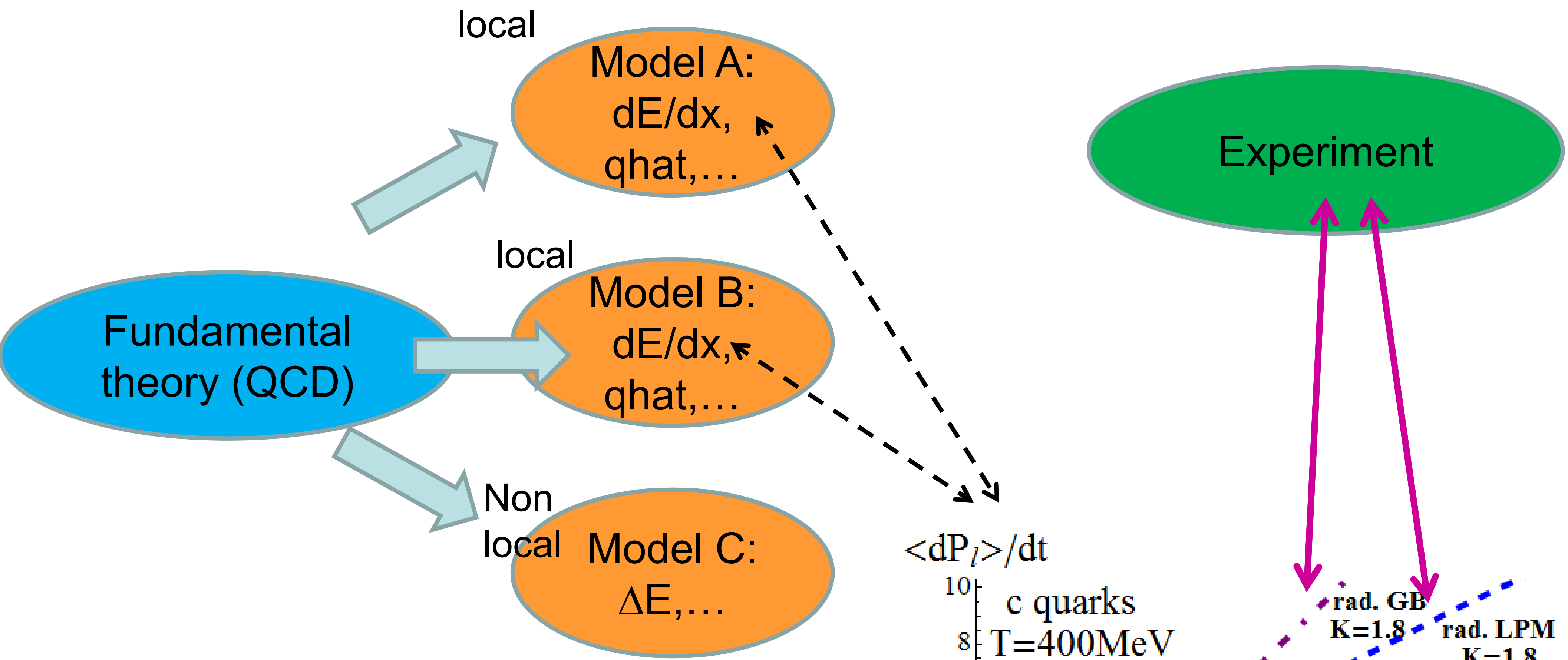


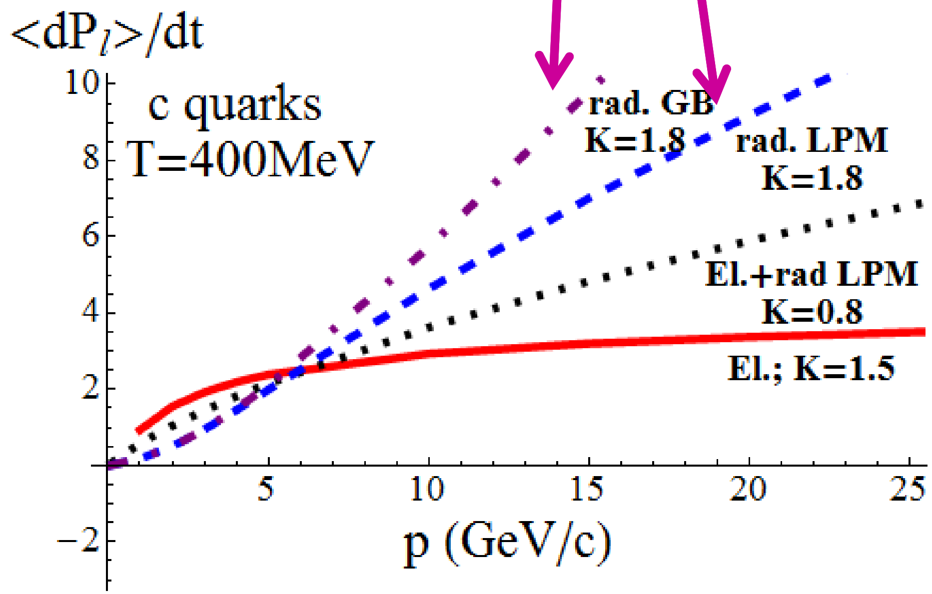
Q2: To make progress: decipher the most "correct" model/theory for Eloss:

- Various path length dependences: $\Delta E \alpha$ L, L^2, L^3,
- Various energy dependences: $\Delta E(E)$
- Various mass dependences: $\Delta E(M)$

From comparison with data: Not a clear view emerging for HQ… simply due to the convolution devil ? Some kind of fragility ?

Motivation and Context

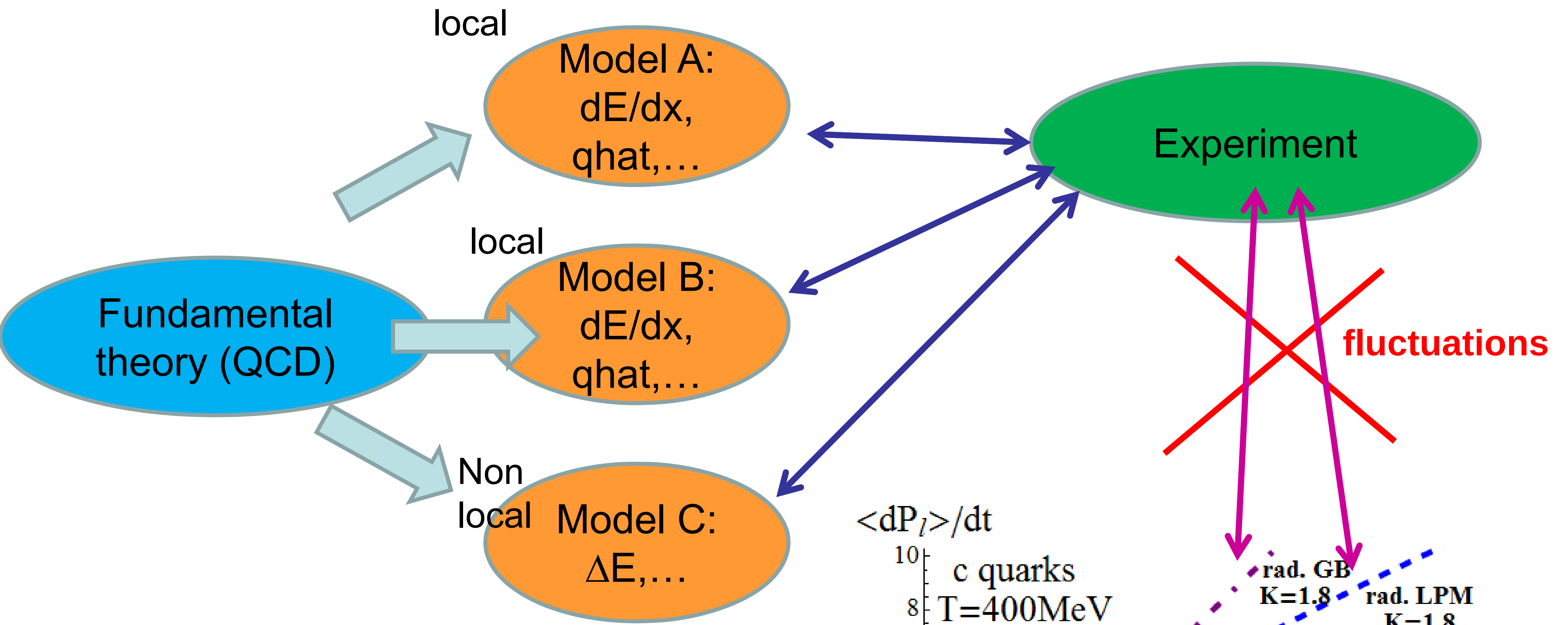




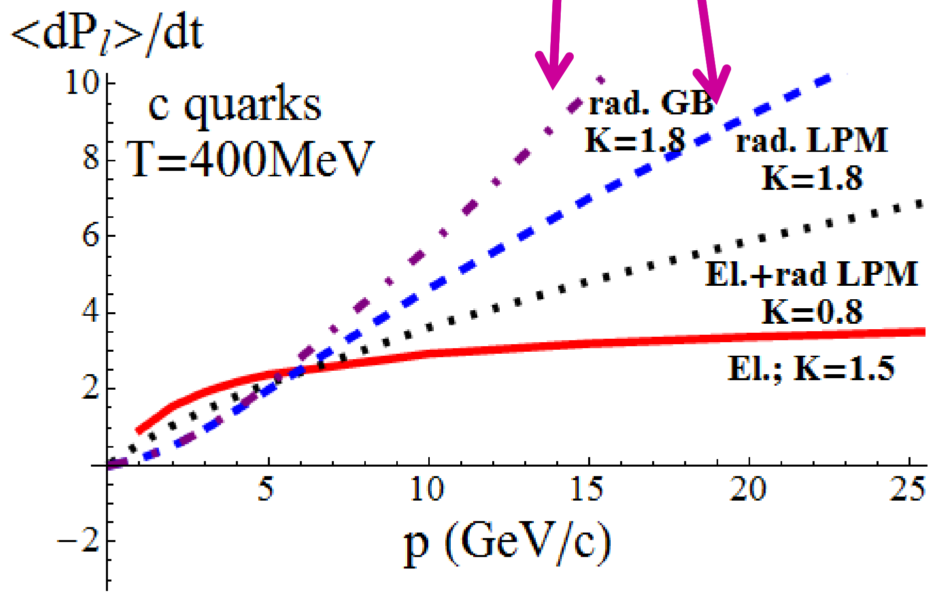
Constraining the energy loss ?

Or, if you prefer, trying to extract <Δp>/p
(as some experiments did)

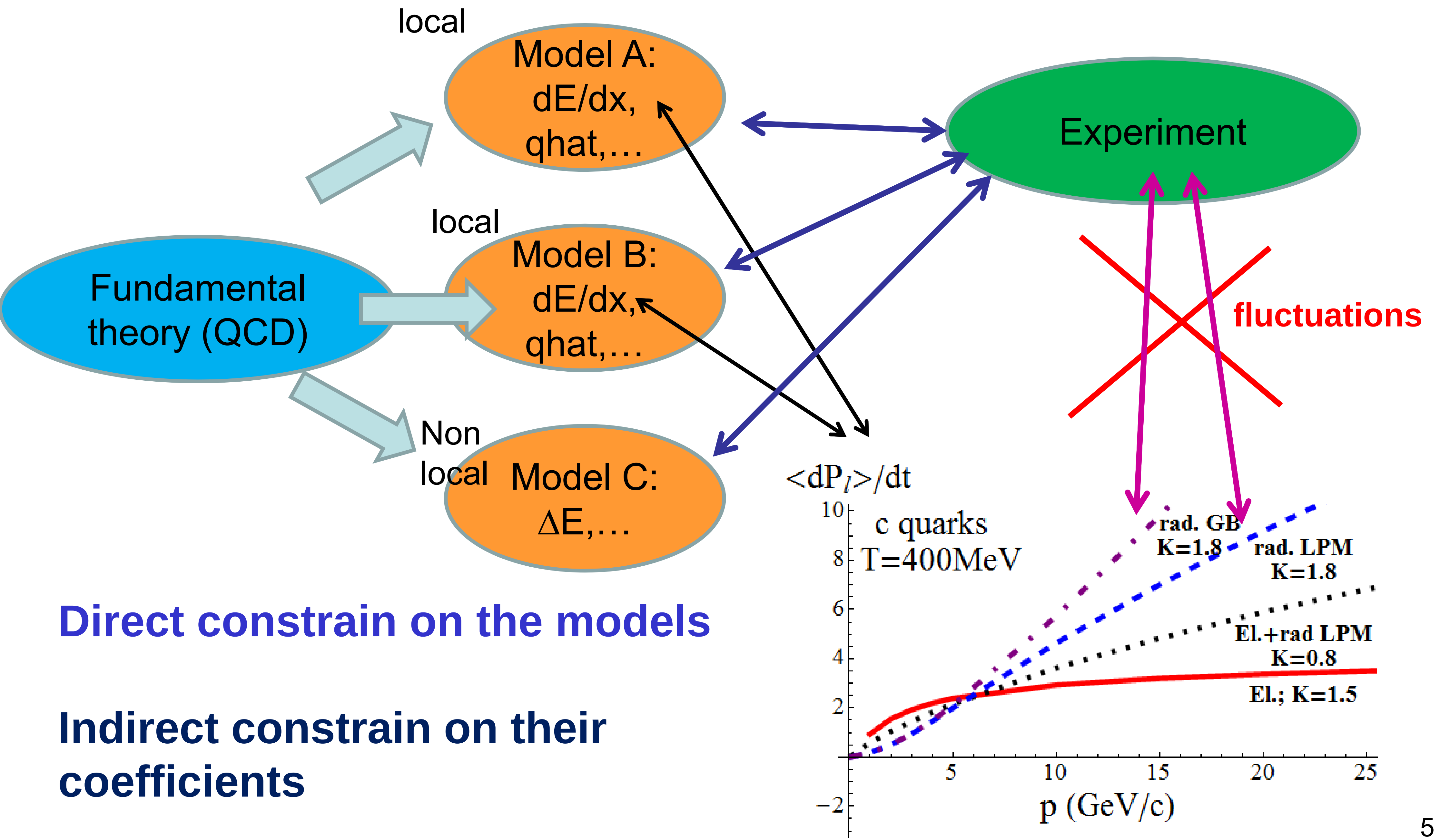
Motivation and Context



Direct constrain on the models



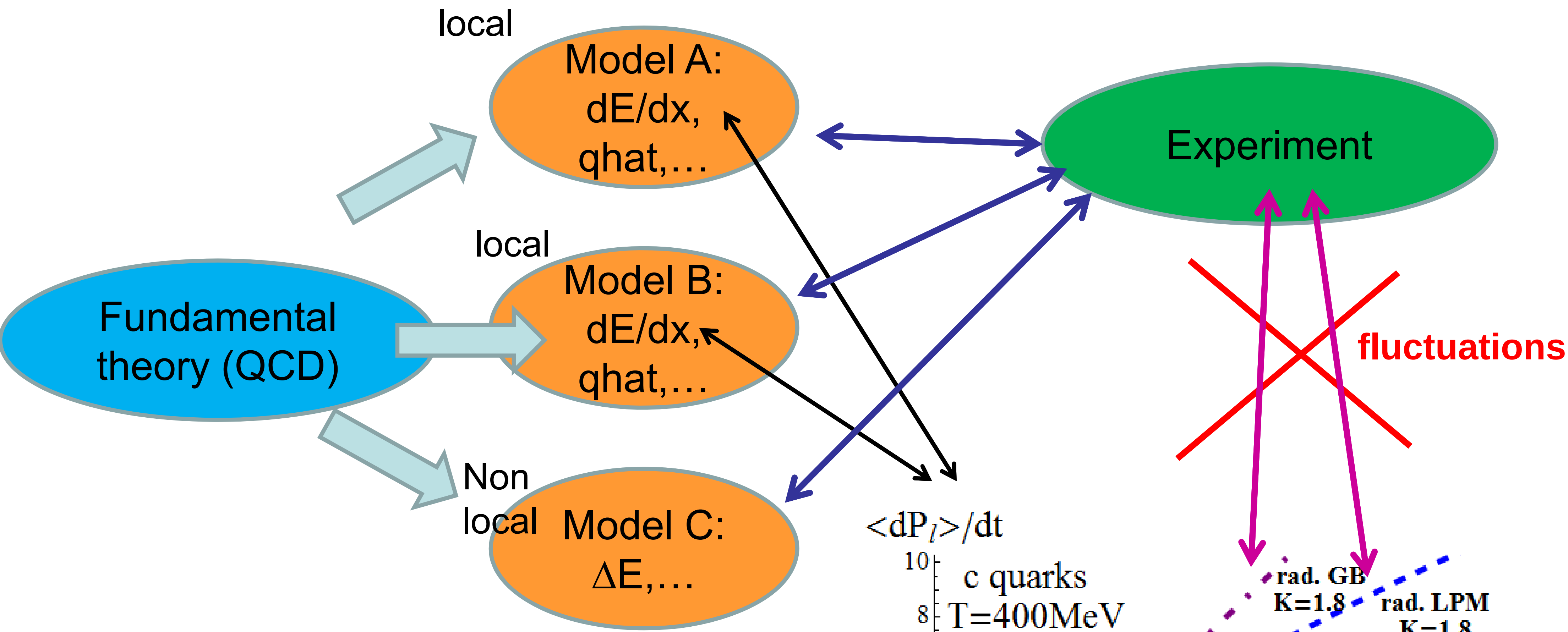
Motivation and Context

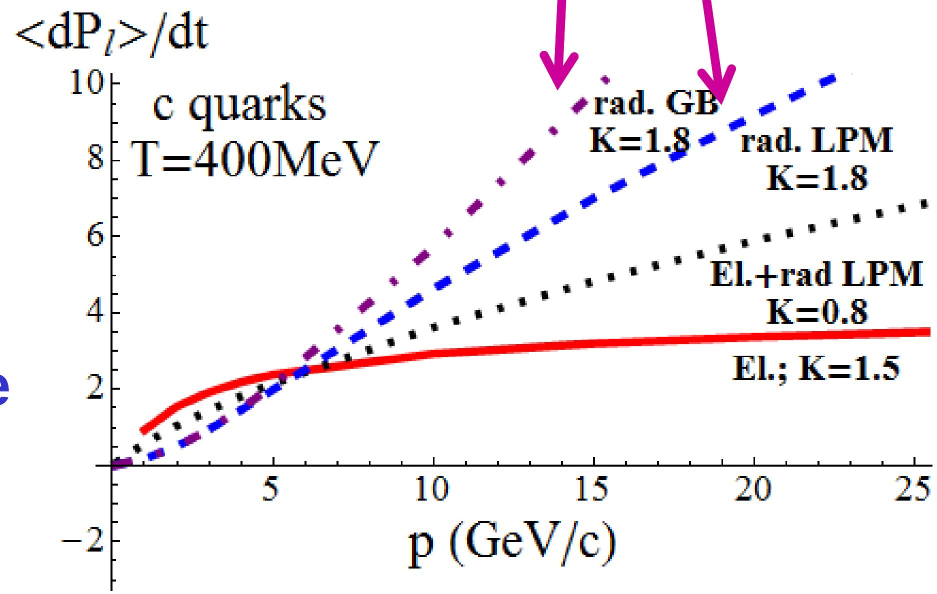


Direct constrain on the models

Indirect constrain on their coefficients

Motivation and Context





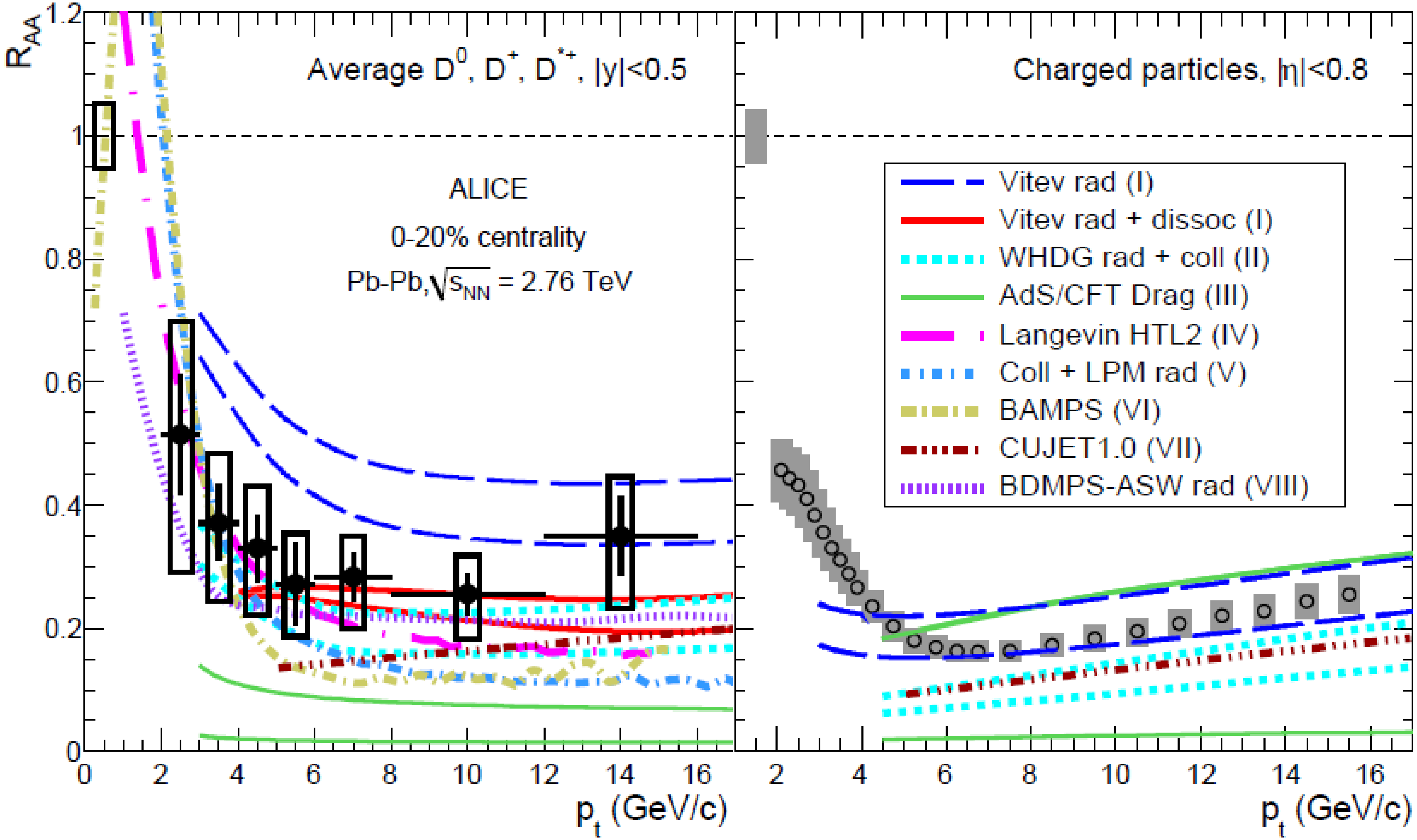
My falsifiability criteria: 2 microscopic models satisfying (l)QCD "constrains" and both "explaining" the data should be considered as UNRESOLVABLE

Wished Structure

- Weak to strong coupling
- Basic facts about Eloss (qualit and semi-quantitative) + classification
- Beware of average Eloss
- Excluding & Classifying the models (from their eloss content)
- Puzzles and systematics:
  - puzzles (BAMPS vs MC@HQ, POWLANG vs MT, v2…)
  - Beware of model background
  - Comparing what can be compared (coll with coll, rad with rad,…), including the RAA of ΔE
- Our own approach and how we proceed to answer the asked question
- How to move further ?

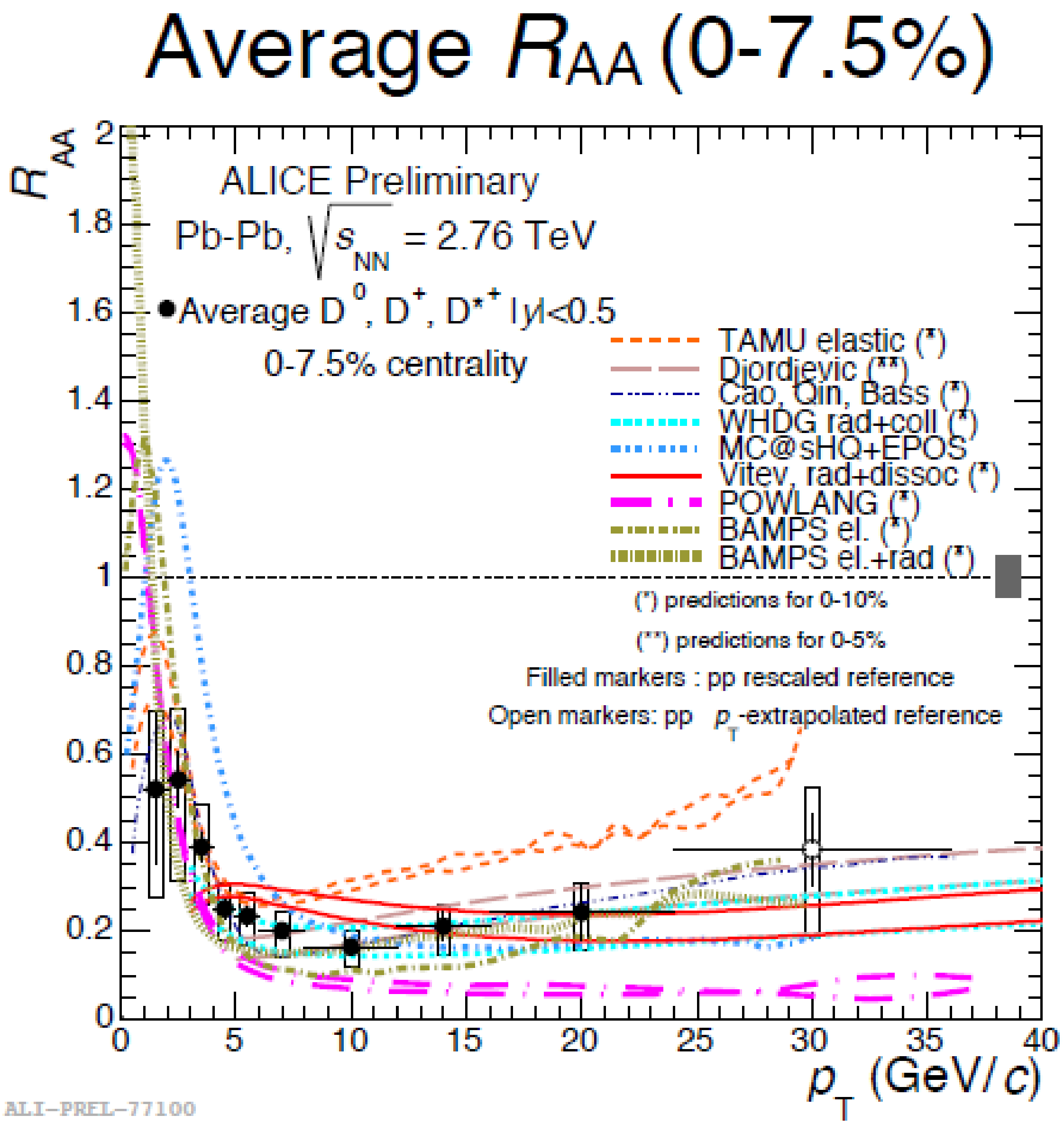
Models vs data: RAA

2012



Models vs data: RAA

2014



Some classification needed !

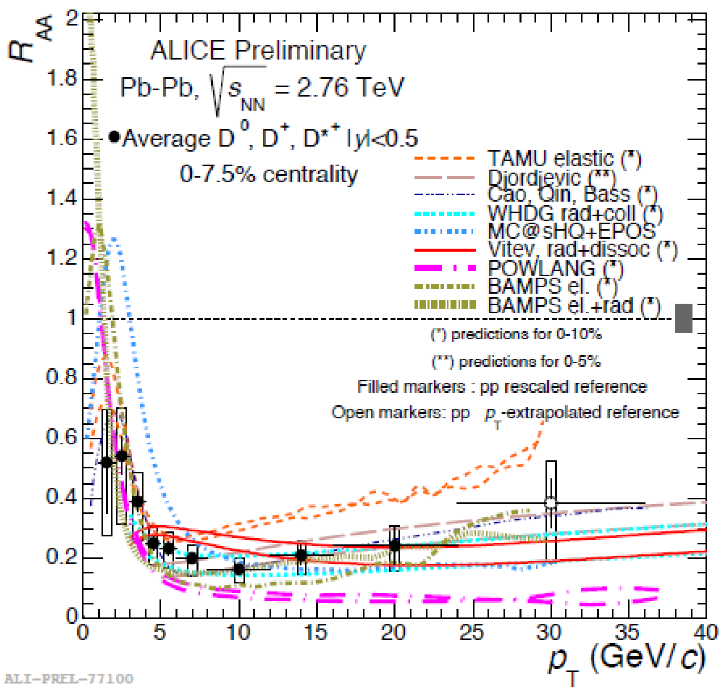
Most of the models contain some energy loss ingredient

Shopping list of issues

- Weak or strong coupling ?
- Fraction of Radiative and Elastic (whether it makes sense) ?
- Mass hierarchy and its origins
- Path length dependence and how to reveal it at best ?
- Taking into account medium effects in the calculations
- Initial off-shellness and its effect on Eloss
- Q->hadrons Fragmentation in medium or off medium
- Role of the fluctuations
- MC vs FP
- Model control ? lQCD

Setting the scene: E-Loss and thermalization

Average R_{AA} (0-7.5%)



(init) $P_t \approx m_Q$	(init) $P_t >> m_Q$

(init) $P_t \approx m_Q$

- Bulk part of Q production
- E gain becomes probable
- HQ scatter and can thermalize with the medium
- very ≠ from light quarks
- *Dominated by collisional processes and diffusion*
- Non perturbative effect (small momentum transfert, coalescence with light quark)
- 1 dominant parameter: D_s

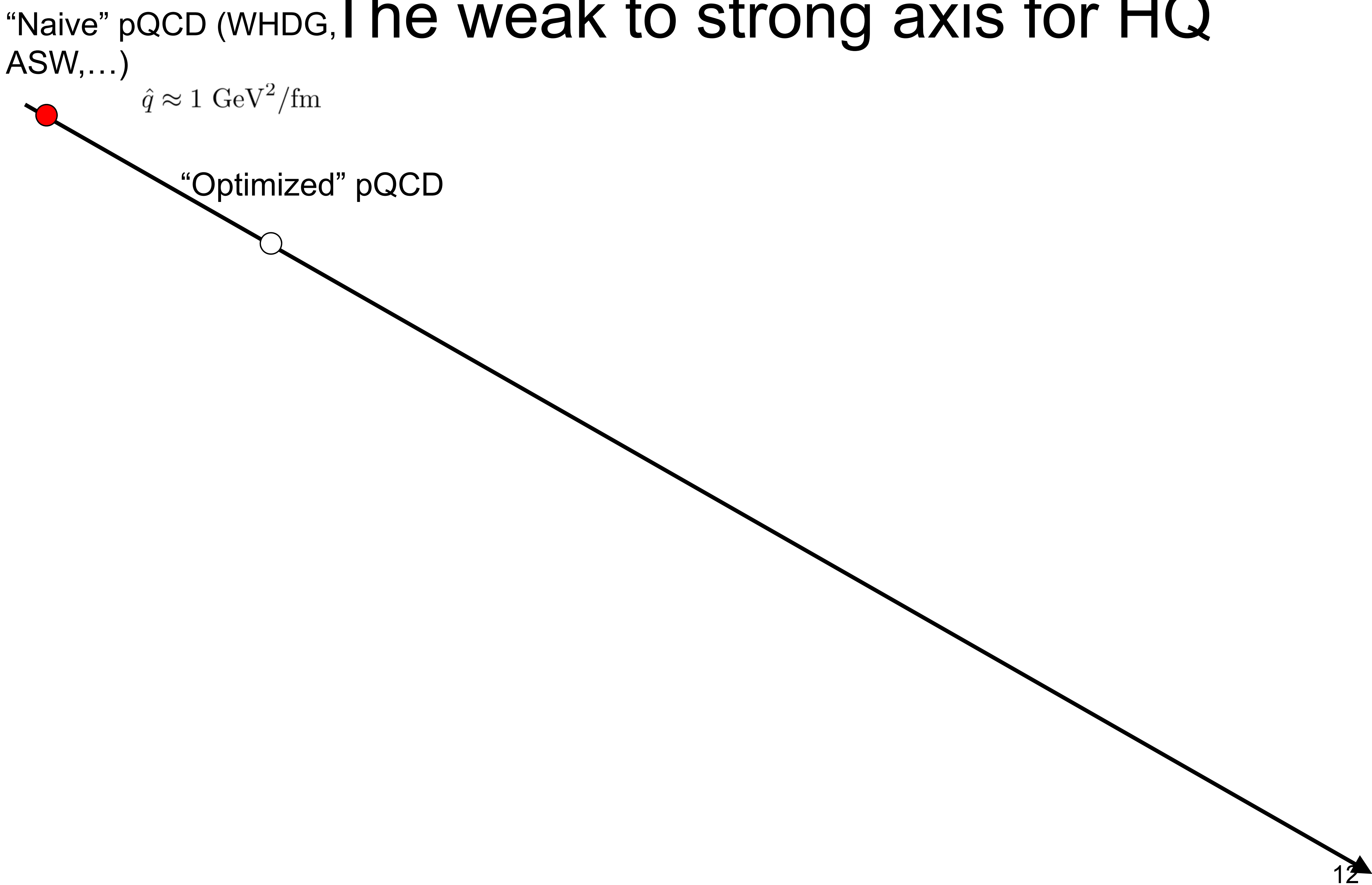
(init) $P_t >> m_Q$

- Rare processes
- Mostly E loss
- HQ go on straight lines and probe the opacity of matter. Little thermalization
- **~ light quarks (s.e.p.)**
- *Coherent radiative + collisional processes*
- Good test of pQCD and eikonal expansion… Theory at work (a priori)
- Several transport coeff implied (dE/dx, B_T,…)

… but one should however avoid do mixing those two worlds !!!

Intermediate p_T ?

The weak to strong axis for HQ



Fragility and surface emission (light hadrons)

"Once upon a time…": everything comes from the surface => not possible to probe the energy loss in a systematic way

More reasonable picture (Phenix 08: "*Quantitative Constraints on the Transport Properties of Hot Partonic Matter from Semi-Inclusive Single High Transverse Momentum Pion Suppression*"): the models are constrained by 20-25%.

Models and outcome:

TABLE II: Quantitative constraints on the model parameters from the PQM, GLV, WHDG, and ZOWW models and a linear functional form fit.

Model Name	Model Parameter	One Standard Deviation Uncertainty	Two Standard Deviation Uncertainty	Maximum p-value
PQM	$\langle \hat{q} \rangle = 13.2$ GeV^2/fm	$+2.1$ -3.2	$+6.3$ -5.2	9.0%
GLV	$dN^g/dy = 1400$	$+270$ -150	$+510$ -290	5.5%
WHDG	$dN^g/dy = 1400$	$+200$ -375	$+600$ -540	1.3 %
ZOWW	$\epsilon_0 = 1.9$ GeV/fm	$+0.2$ -0.5	$+0.7$ -0.6	7.8 %
Linear	b (intercept) $= 0.168$	$+0.033$ -0.032	$+0.065$ -0.066	11.6%
	m (slope) $= 0.0017$ (c/GeV)	$+0.0035$ -0.0039	$+0.0070$ -0.0076	

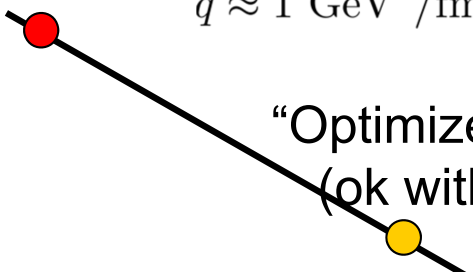
Challenge

Nevertheless, one has to get the "right" parameter (for instance the transport coefficient) from QCD before claiming one "understands"

A nice interpolation is not an explanation

The weak to strong axis for HQ

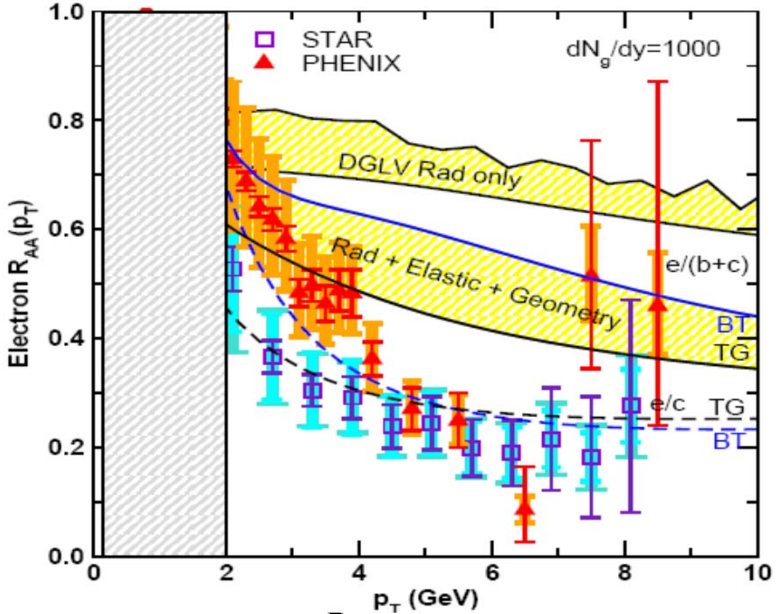
“Naive” pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$



“Optimized” pQCD
(ok with pions)

So-called “Failure of pQCD approach” aka “the non photonic single electron puzzle”

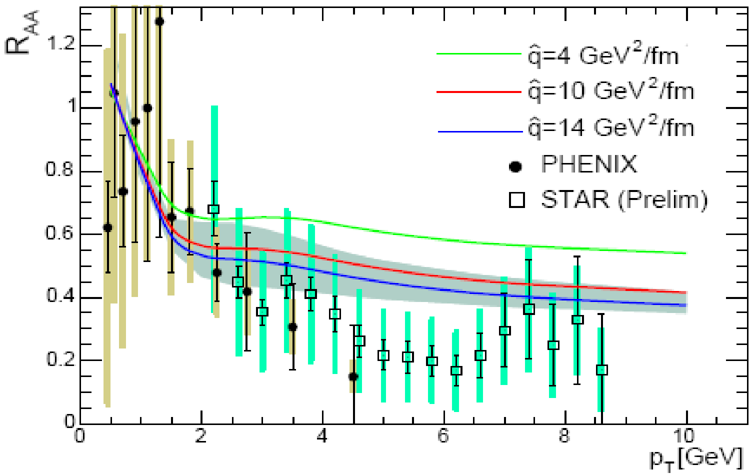
coll Eloss (BT and TG) + radiative Eloss



WHDG

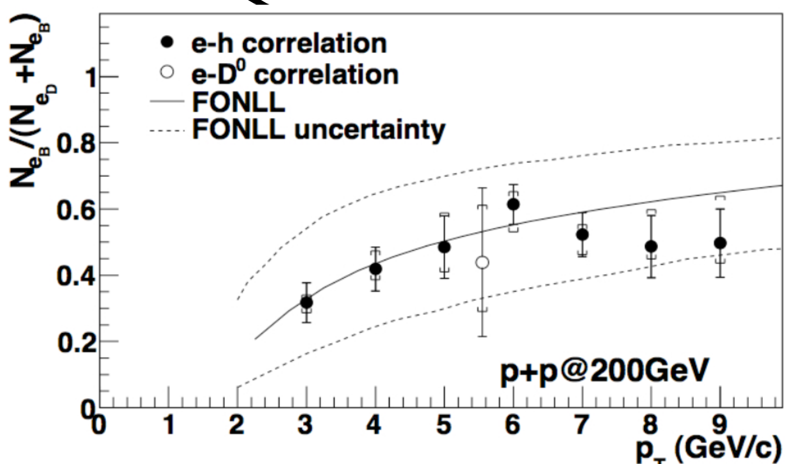
Beauty is the problem… but beauty is found to contribute

ASW (pure rad. energy loss; extended BDMPS)



Armesto et al Dainese, Phys. Rev D (hep-ph/0501225) & Phys.Lett. B637 (2006) 362-366 hep-ph/0511257

Conclude to rough agreement, subjected to b/c ratio in p-p



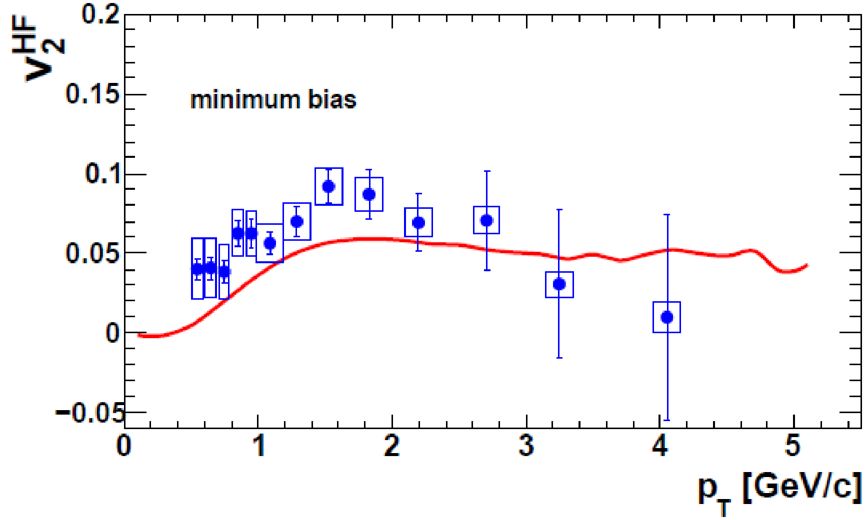
M Aggarwal et al, STAR, PRL 105 202301

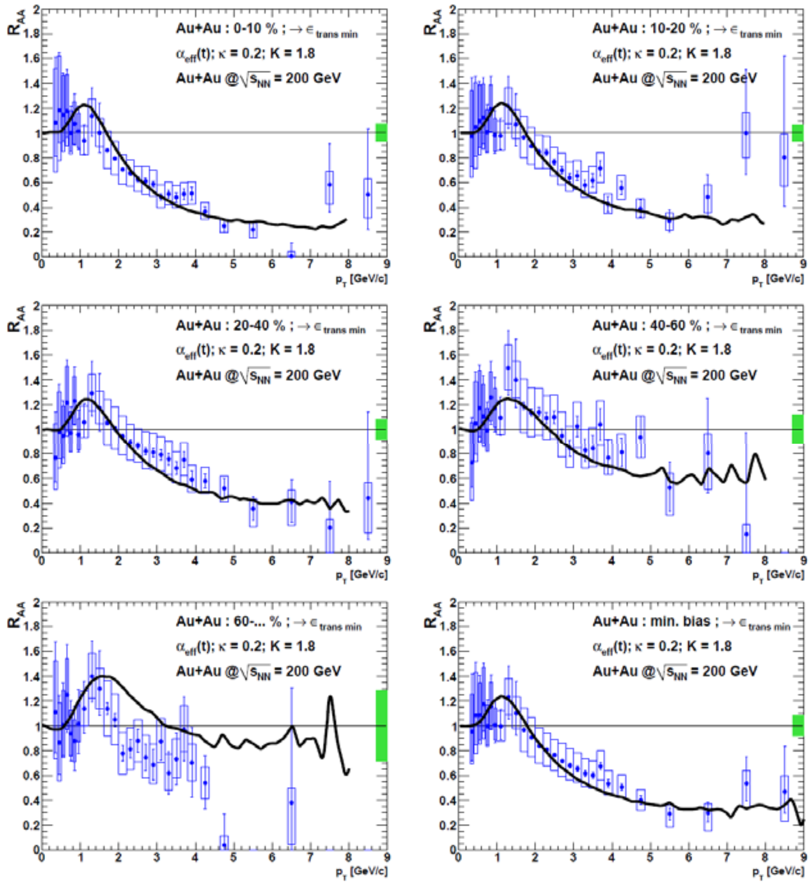
The weak to strong axis for HQ

"Naive" pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

"Optimized" pQCD

Collisional model with running α_s and optimized gluon propagator (Peshier, Gossiaux and Aichelin, BAMPS)





The weak to strong axis for HQ

"Naive" pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1 \text{ GeV}^2/\text{fm}$

"Optimized" pQCD

Running α_s (Peshier, Gossiaux and Aichelin, Uphoff)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang 0904.0032v1 [hep-ph]

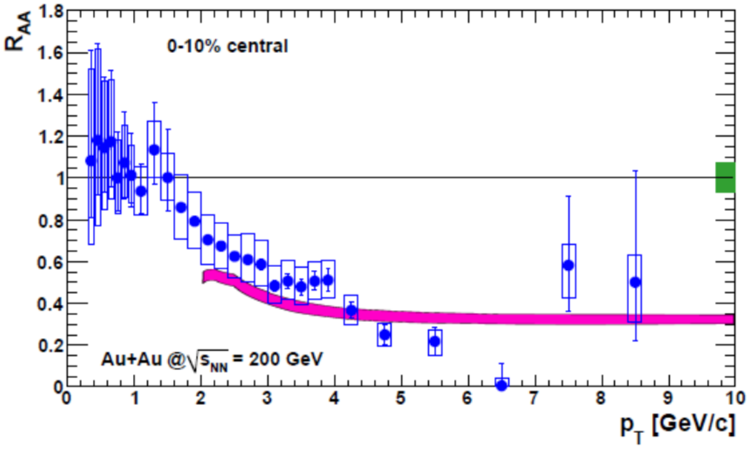


FIG. 41: (Color online) R_{AuAu} in 0–10% centrality class compared with a collisional dissociation model [78] (band) in Au+Au collisions.

The weak to strong axis for HQ

"Naive" pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

"Optimized" pQCD

Running α_s (Peshier, Gossiaux and Aichelin, Uphoff)

Distorsion (
fragmentat
existence c
R. Sharma
0904.0032

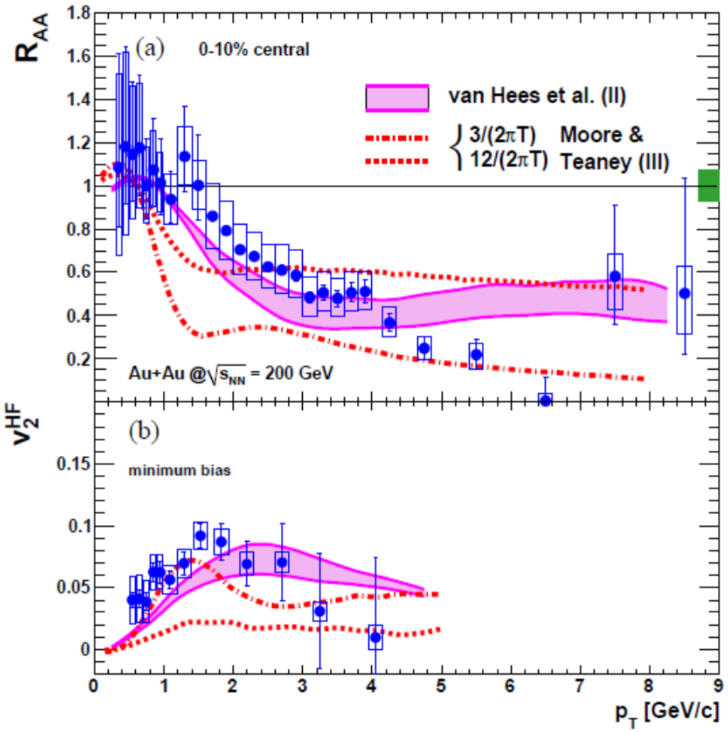


FIG. 40: (Color online) Comparison of Langevin-based models from [74–76] to the heavy flavor electron R_{AuAu} for 0–10% centrality and v_2 for minimum-bias collisions.

Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

The weak to strong axis for HQ

"Naive" pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

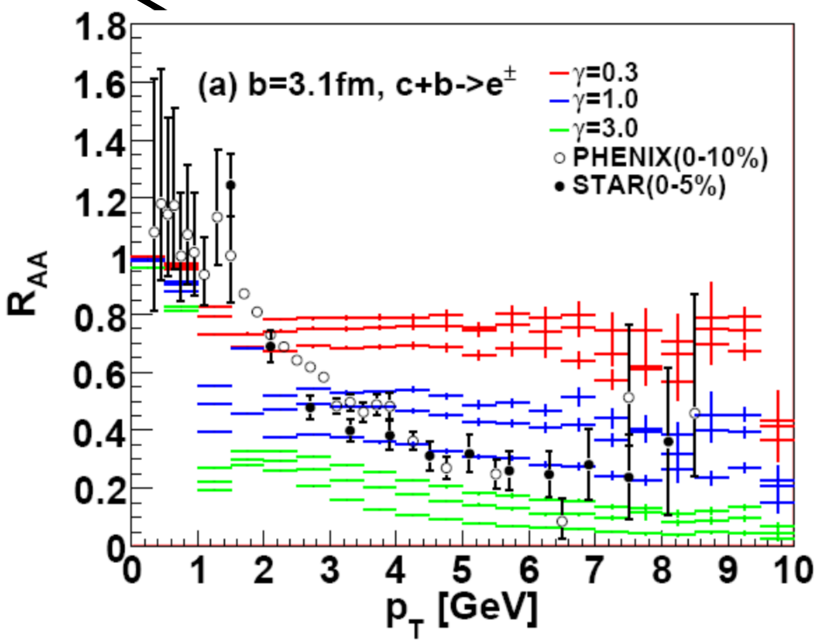
So-called "Failure of pQCD approach"

"Optimized" pQCD

Running α_s (Peshier, Gossiaux and Aichelin, Uphoff)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang 0904.0032v1 [hep-ph]

Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees ...r a review)



ADS/CFT
(akamatsu et al)

The weak to strong axis for HQ

“Naive” pQCD (WHDG, ASW,…)

$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

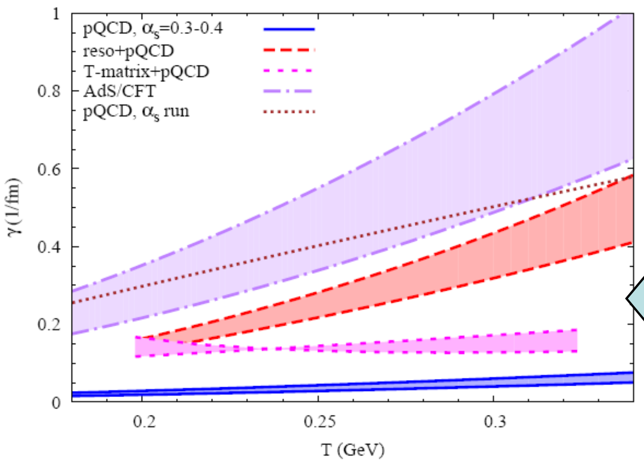
“Optimized” pQCD

Running α_s (Peshier, Gossiaux and Aichelin, Uphoff)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang 0904.0032v1 [hep-ph]

Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

Non perturbative equivalent for g+Q ?
No radiative !



from Rapp & Van Hees 0903.1096

Lesson n°1:

Several models containing either non perturbative features or tunable parameters are able to reproduce the HQ data, but many questions remain… and how to reconcile them all stays a challenge

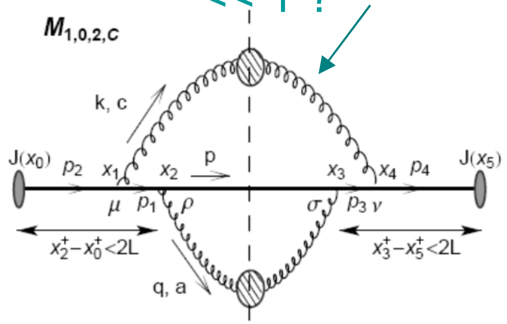
ADS/CFT (akamatsu et al)

Revival of the weak

"Naive" pQCD (WHDG, ASW, POWLANG, Djordjevic)

$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

HTL for x not << 1 ?



Beyond the static scatterer limit: M. Djordjevic, Preprint arXiv:0903.4591 [nucl-th] (2009) and previous work with U. Heinz

"Optimized" pQCD

Running α_s (Peshier, Gossiaux and Aichelin, Uphoff)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang 0904.0032v1 [hep-ph]

Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

Non perturbative equivalent for g+Q ? No radiative !

ADS/CFT

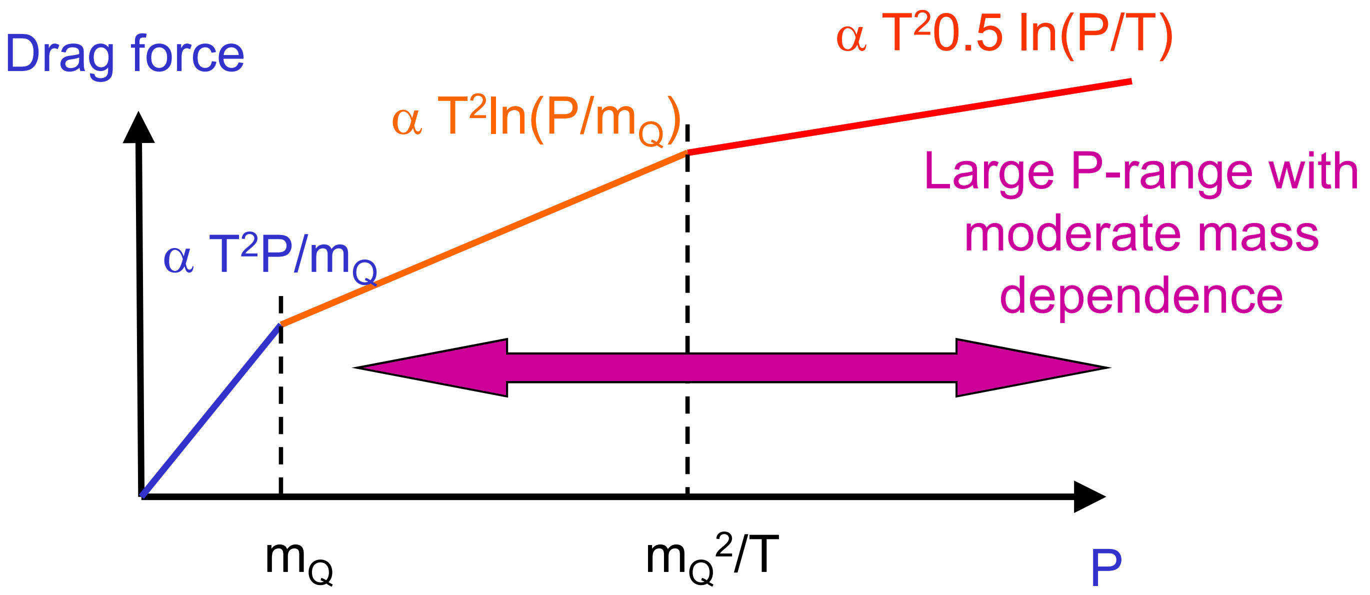
Now considering both light and heavy

!!! Not Akamatsu !!!

Parametric dependences in the realm of LHC

2 extreme cases

a. Collisional E loss:



b. AdS/CFT: Various results from our holographic friends (trailing string):

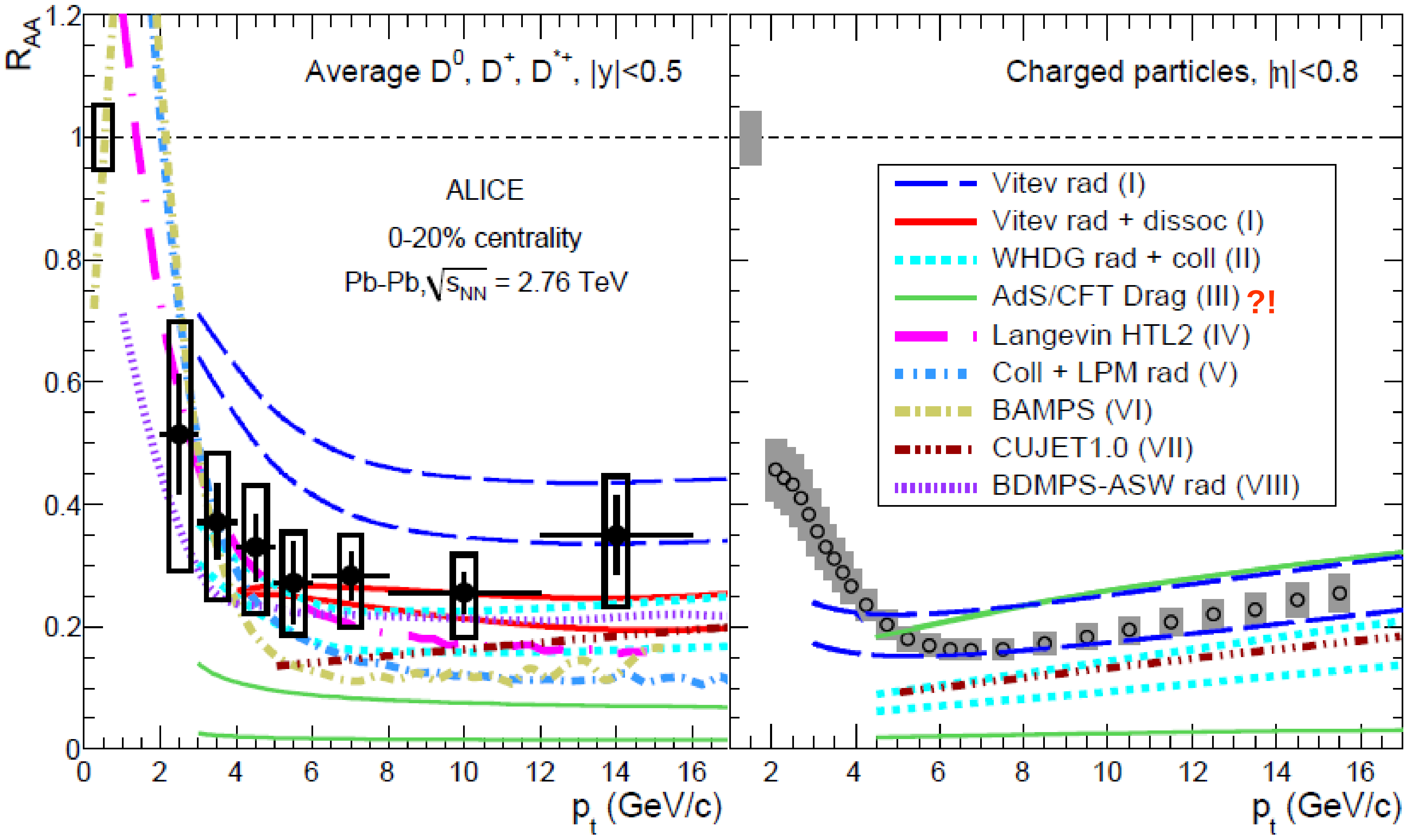
Drag coefficient →

Pretty strong $1/m_Q$ dependence on the mass for all p range: NOT compatible with the data

coefficient	$v \approx 0$	ref.	finite v	ref.
$\eta_D := \frac{A}{p}$	$\frac{\pi\sqrt{\lambda}T^2_{\rm sym}}{2m_Q}$	[Cas06]	$\frac{\pi\sqrt{\lambda}T^2_{\rm sym}}{2m_Q}$	[Her06, Gub06]
$\kappa_T = 2B_T = \frac{\hat{q}}{2}$	$\pi\sqrt{\lambda}T^3_{\rm sym}$	[Cas06]	$\pi\sqrt{\lambda}T^3_{\rm sym}\gamma^{\frac{1}{2}}$	[Cas07, Gub08]
$\kappa_L = 2B_L$	"		$\pi\sqrt{\lambda}T^3_{\rm sym}\gamma^{\frac{5}{2}}$	[Gub08]

Models vs data: RAA

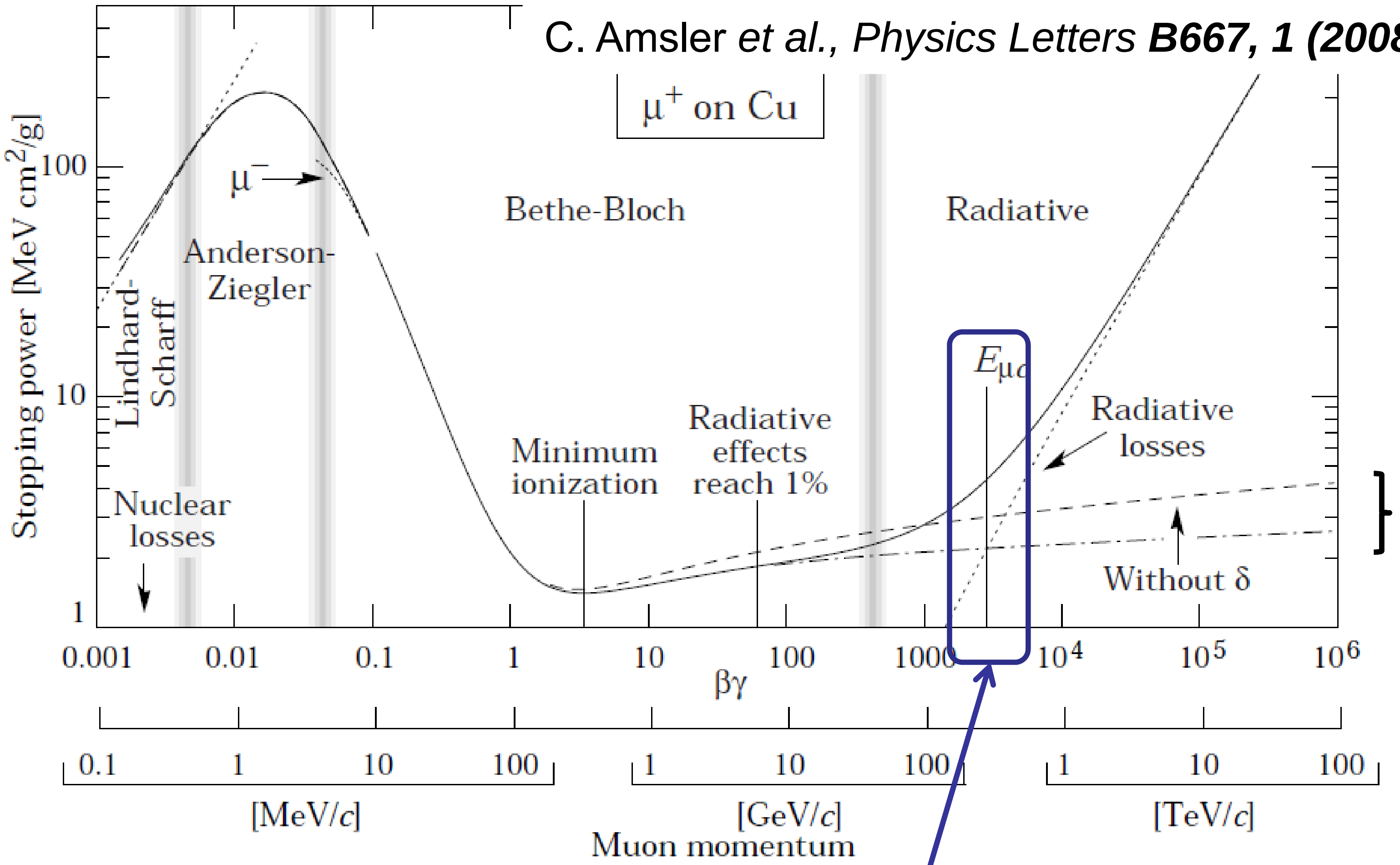
2012



Quenching – Energy loss in cold atomic matter

Energy loss of a charged particles passing through cold atomic matter: extensive field of research in the XXth century

C. Amsler *et al.*, *Physics Letters* ***B667, 1 (2008)***



Cold Matter Effects (Fermi)

$$\left(\frac{\frac{dE_{\rm BH}}{dz}}{\frac{dE_{\rm col}}{dz}}\right)_{V\approx c} \sim Zz^2 \times \alpha_{\rm QED} \times \frac{m_e}{M} \times \gamma \Rightarrow \gamma_{\mu\,c} \approx \frac{M}{m_e} \times \frac{1}{\alpha_{\rm QED}} \times \frac{1}{Zz^2} \rightarrow \frac{M}{g^3 T} \quad ???$$

Qualitative and semi-quantitative features of the models

(Assuming σ is defined; 0 mass parton q)

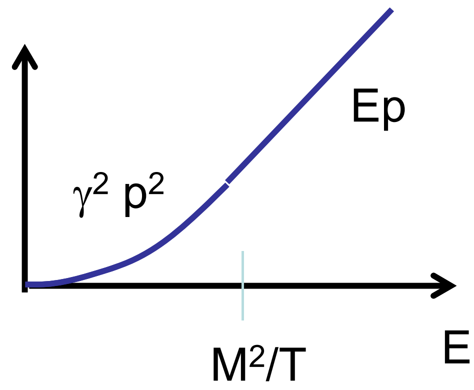
$$\frac{dE}{dx} = \int d^3p f(\vec{p})[\text{flux}] \int dt \frac{d\sigma}{dt}(-\omega)$$

$$[\text{flux}] := \frac{\sqrt{(P\cdot p)^2 - M^2 m^2}}{Ee} \approx \frac{P\cdot p}{Ee} = 1 - \cos\theta\,,$$

$$\omega = \frac{-t + \vec{p}_\perp \cdot \vec{q}_\perp}{2e(1-\cos\theta)}$$

$$\frac{dE}{dx} \sim \int pf(p)\, dp d\cos\theta \underbrace{\int_{|t|_{\text{inf}}}^{|t|_{\text{sup}}} |t| \frac{d\sigma}{dt}\, d|t|}_{\langle\sigma|t|\rangle}$$

$$|t|_{\text{sup}} \approx \frac{4E^2p^2}{M^2 + 2Ep}$$



Mass effect for a fixed E up to E≈M^2/T

Coulomb like $\langle\sigma|t|\rangle \approx \alpha_s^2 \ln\left(\frac{|t|_{\text{sup}}}{m_D^2}\right)$

$$\frac{dE}{dx} \approx \alpha_s^2 \int pe^{-\frac{p}{T}}\, dp \times \ln\left(\frac{|t|_{\text{sup}}}{m_D^2}\right)_{p=T} \approx \alpha_s^2 T^2 \times \ln\left(\frac{|t|_{\text{sup}}}{m_D^2}\right)_{p=T}$$

Qualitative and semi-quantitative features of the models

$$\frac{dE_{\mathrm{el}}}{dx} \propto \alpha_s^2 T^2 \times \ln\left(\frac{ET}{m_D^2}\right)$$

Typical HTL result…although hard scatterings contribute the most (in HTL)

- ❑ Mild mass-dep., Mild increase with energy (even saturation if running α_s)
- ❑ Local
- ❑ E loss fluctuations in a single scattering: not gaussian, tail α ω^{-2}
- ❑ Rather strong dep. on the coupling (regular claims that it could be enough to "explain" the data). Less strong dep. on the coupling through m_D.

Qualitative and semi-quantitative features of the models

Other models ? For instance, role of the light-parton mass (higher order in HTL)

$$\frac{d\langle p_L\rangle}{dt} = A \propto \frac{g_p}{8\pi^2}\frac{T}{u}\boxed{\int_0^{+\infty}\frac{q\,dq}{q^0}e^{-\frac{u^0 q^0 - uq}{T}}\langle\sigma\,|t|\rangle}$$

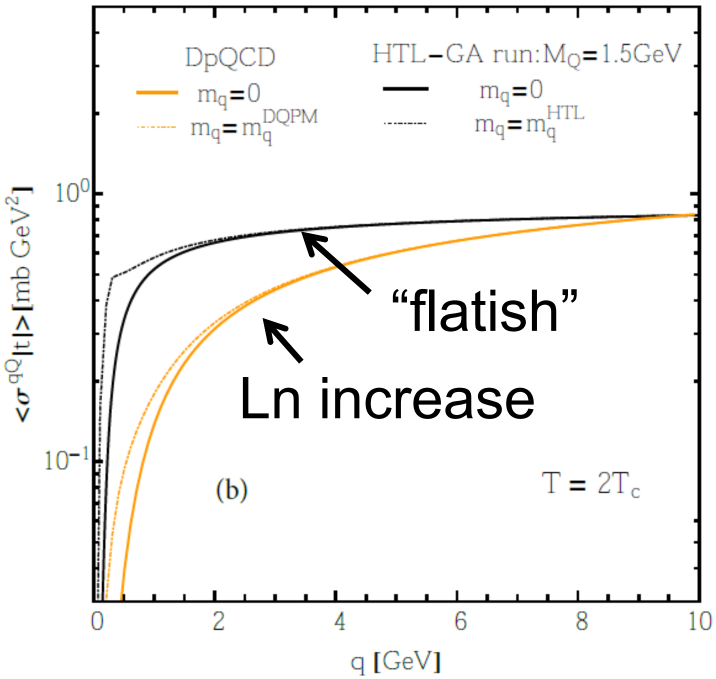
Evaluated In HQ rest frame

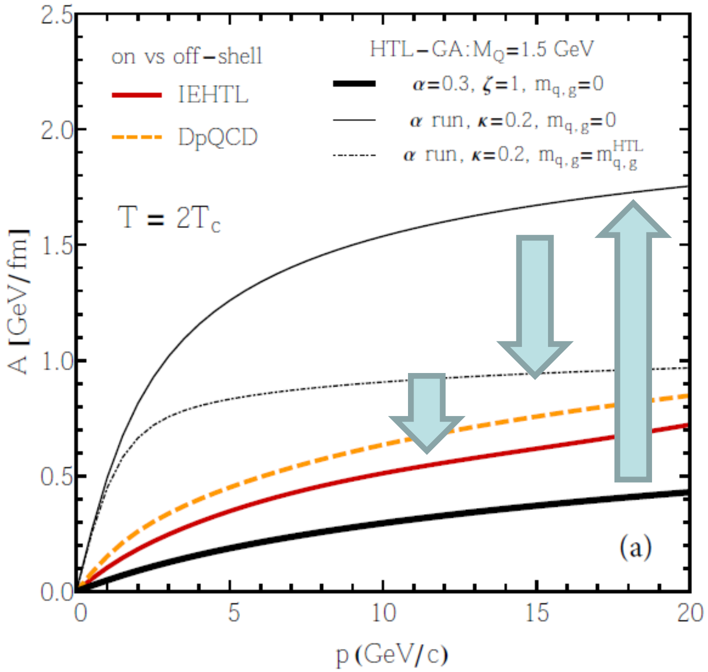
$$|t|_{\rm sup} \approx \frac{4M^2q^2}{M^2+m_q^2+2Mq^0}$$

For $m_q \gg T$:

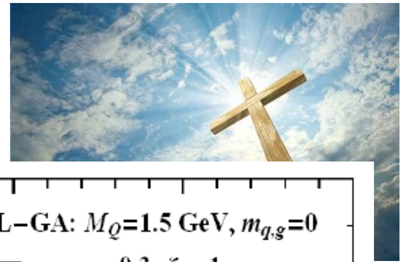
$$\boxed{\propto \sqrt{m_q T^3}\times e^{-m_q/T}\times\langle\sigma|t|\rangle_{q=\frac{m_q p}{M}}}$$

QGP dof are massive => less populated. New dep on the coupling constant $g^{2.5}$ Exp(-g) !

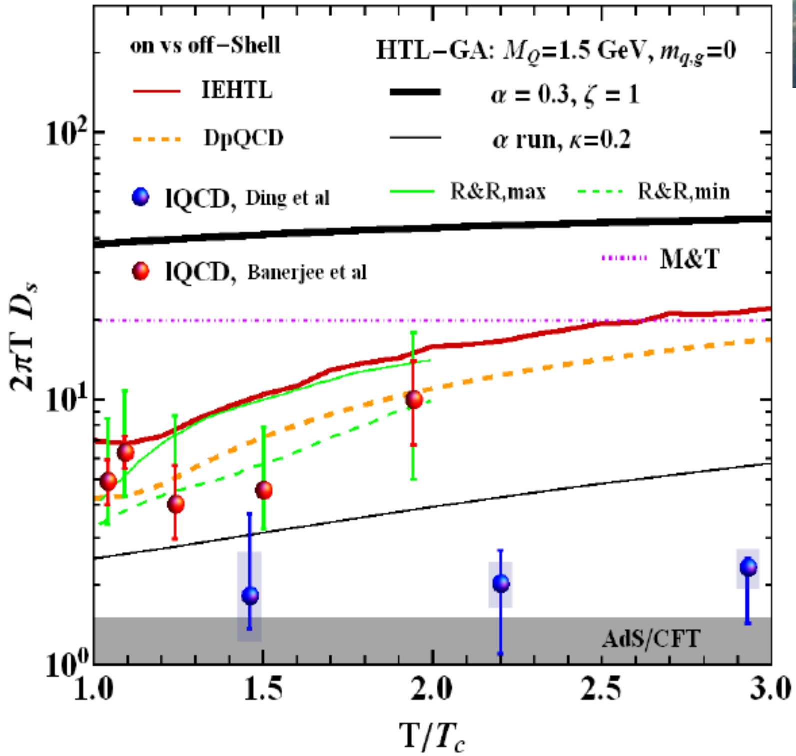




Elastic Energy loss: model control



$$D_s = \frac{T}{\eta_D m_Q} \quad \text{with} \quad \underbrace{\eta_D = \lim_{p\to 0} \frac{d\langle p_L\rangle/dt}{p_L}}_{\text{Drag (or drift) coefficient}}$$



Soft part… the most debated one !!! Start from HTL:

$$\langle\frac{dp}{dt}\rangle = \eta_D p \simeq v\left(N_c+\frac{N_f}{2}\right)\frac{C_F g^4 T^2}{24\pi}\underbrace{\left(\frac{1}{v^2}-\frac{1-v^2}{2v^3}\ln\frac{1+v}{1-v}\right)}_{2/3+O(v^2)}\ln(T/m_D)$$

$$\frac{d\langle p\rangle}{dt} = \mathrm{cste}(T,\alpha_s)\times\ln\frac{T}{m_D}\times\begin{cases}\frac{2p}{3m_Q} & v\approx 0\\ 1 & v\approx 1\end{cases} \Rightarrow \eta_D = \frac{2}{3m_Q}\mathrm{cste}(T,\alpha_s)\times\ln\frac{T}{m_D} = \frac{T}{m_Q D_s}$$

$$\Rightarrow \mathrm{cste}(T,\alpha_s)\times\ln\frac{T}{m_D} = \frac{3T}{2D_s} = \frac{3\pi T^2}{2\pi T D_s} \approx \frac{10T^2}{2\pi T D_s}$$

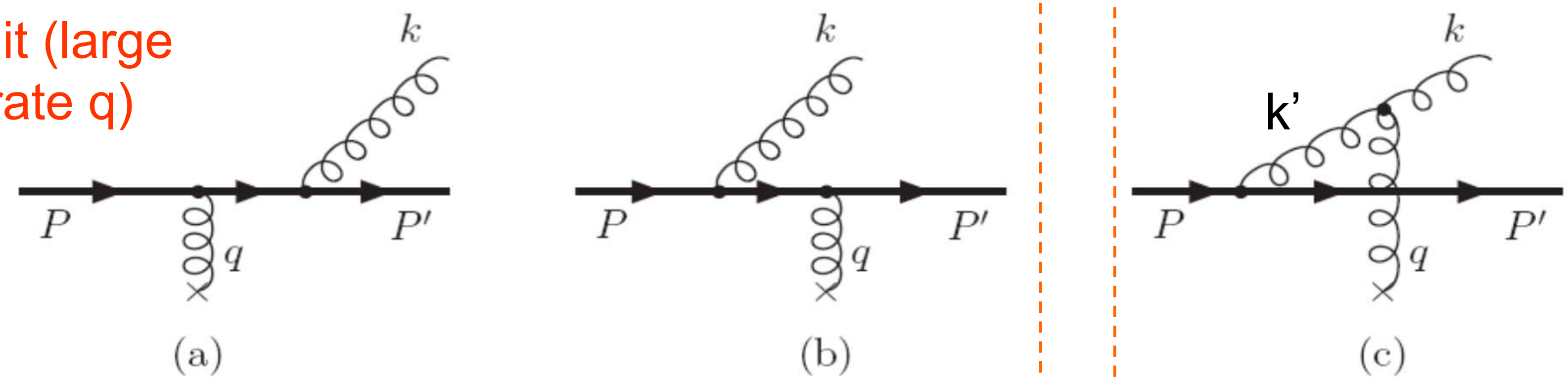
Proposal for a lQCD Constrained Eloss: $\frac{d\langle p\rangle}{dt} = \frac{10T^2}{2\pi T D_s}\left(\frac{1}{v^2}-\frac{1-v^2}{2v^3}\ln\frac{1+v}{1-v}\right)v + \text{hard part}\left(\propto \ln\frac{E}{T}\right)$

Of course needs better precision from the lattice calculations

Basic radiation:(massive) Gunion-Bertsch

Radiation α deflection of current (semi-classical picture)

Eikonal limit (large E, moderate q)



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

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

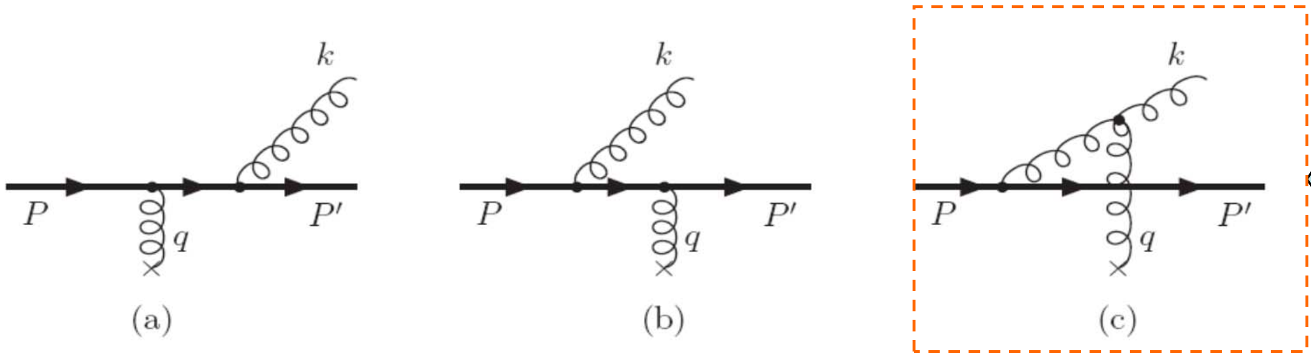
with
$$\frac{J^2_{\rm QCD}}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2 + x^2M^2 + (1-x)m_g^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{\left(\vec{k}_\perp - \vec{q}_\perp\right)^2 + x^2M^2 + (1-x)m_g^2}\right)^2$$

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

Quark mass

Both cures the colinear divergences and will influence the radiation spectra

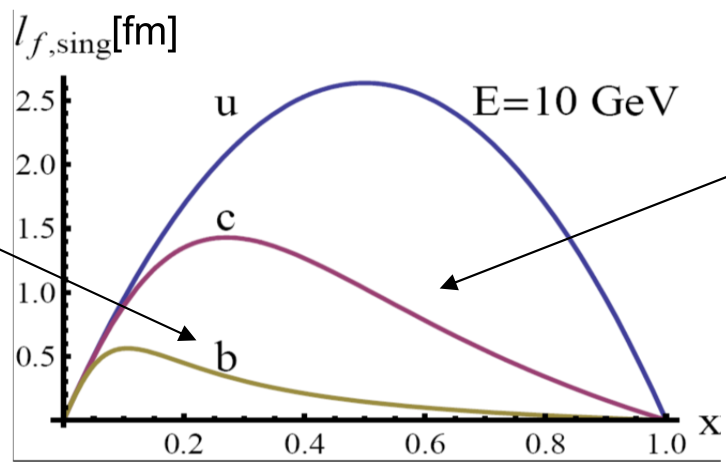
Formation time for a single coll.



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

At 0 deflection: $$l_{f,\mathrm{sing}} \approx \frac{2x(1-x)E}{m_g^2 + x^2 M^2}$$

For $x<x_{cr}=m_g/M$, basically no mass effect in gluon radiation

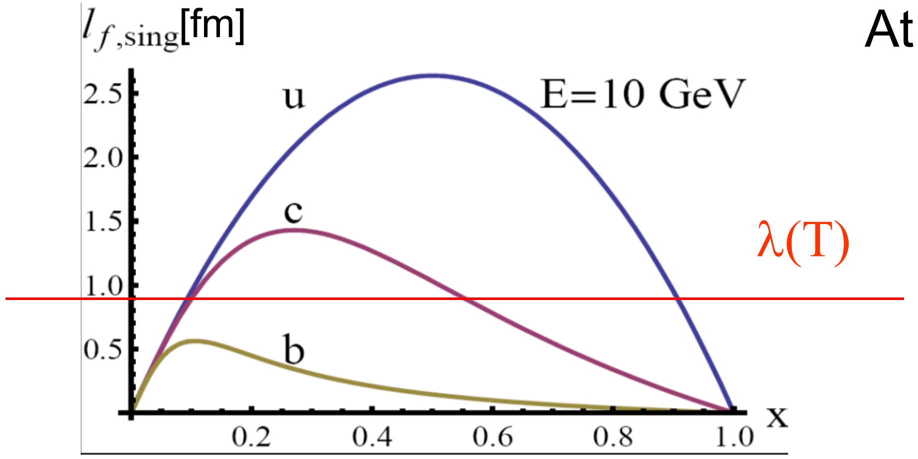


For $x>x_{cr}=m_g/M$, gluons radiated from heavy quarks are resolved in less time then those ← light quarks and gluon => radiation process less affected by coherence effects in multiple scattering

Dominant region for quenching

Dominant region for average E loss

Formation time for a single coll.



At 0 deflection:

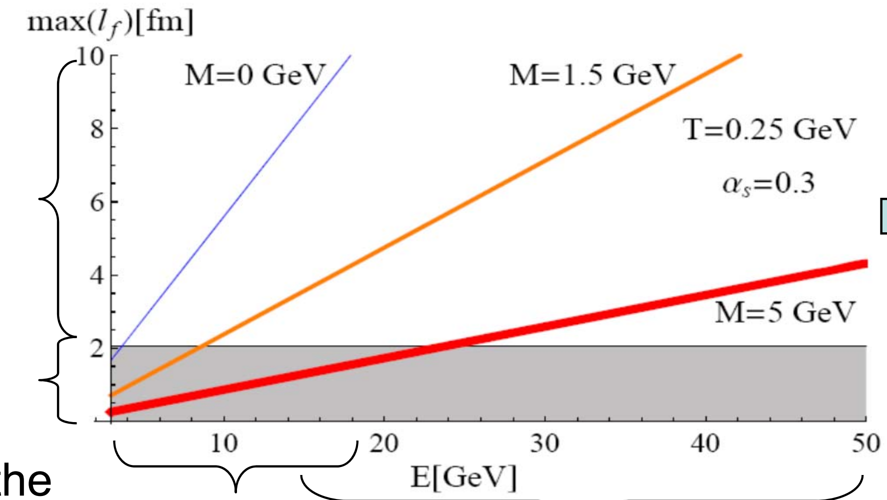
Comparing the formation time (on a single scatterer) with the mean free path:

Coherence effect for HQ gluon radiation : $\Leftrightarrow \quad \frac{E}{M} \gtrsim m_g \lambda_Q \sim \frac{1}{g_s}$

Mostly coherent

Mostly incoherent

(of course depends on the physics behind λ_Q)



RHIC

LHC

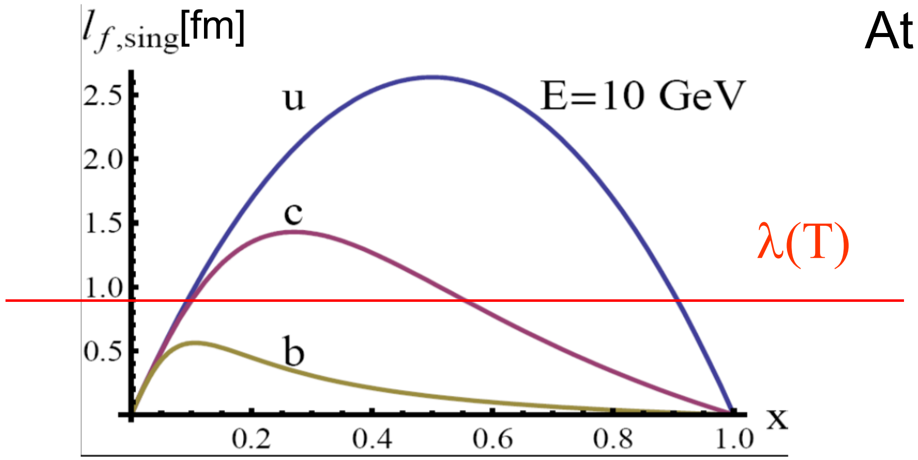
Coherence effect (equiv. LPM in QED) mandatory for high p_T HQ.

(and even more for high p_T light quark)…

That will mostly affect the radiation pattern at intermediate x

LHC: the realm for coherence !

Formation time for a single coll.



At 0 deflection:

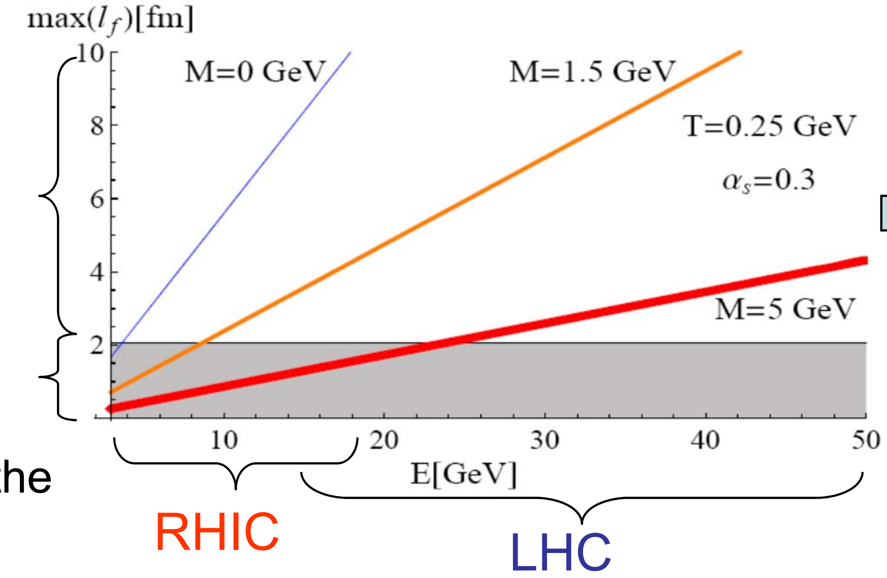
Comparing the formation time (on a single scatterer) with the mean free path:

Coherence effect for HQ gluon radiation : $\Leftrightarrow \quad \frac{E}{M} \gtrsim m_g \lambda_Q \sim \frac{1}{g_s}$

Mostly coherent

Mostly uncoherent

(of course depends on the physics behind λ_Q)



Maybe not completely foolish to neglect coherence effect in a first round for HQ.

(will provide at least a maximal value for the quenching)

Radiation spectra

$$\omega\frac{d^2\sigma^{x\ll 1}_{\mathrm{rad}\,''\mathrm{QCD}''}}{d\omega\, dq_\perp^2} \approx \frac{2N_c\alpha_s}{\pi}\ln\left(1+\frac{q_\perp^2}{3\tilde{m}_g^2}\right)\times\frac{d\sigma^{Qq}_{\mathrm{el}}}{dq_\perp^2}$$

… to convolute with your favorite elastic cross section

$$\tilde{m}_g^2 = (1-x)m_g^2 + x^2M^2$$

$$\omega\frac{d\sigma^{x\ll 1}_{\mathrm{rad\,QCD}}}{d\omega} \approx 4C_F\alpha_s^3 \times \frac{\ln\left[3(m_g^2+x^2M^2)\right]-\ln\mu^2}{3(m_g^2+x^2M^2)-\mu^2}$$

If typical $q_\perp \approx \mu$:

$$\frac{d^2 I^{x\ll 1}_{\mathrm{GB}}}{dz\, d\omega} \sim \frac{2N_c\alpha_s}{3\pi}\times\frac{1}{m_g^2+x^2M^2}\times\underbrace{\frac{\langle q_\perp^2\rangle}{\lambda}}_{\hat{q}}$$

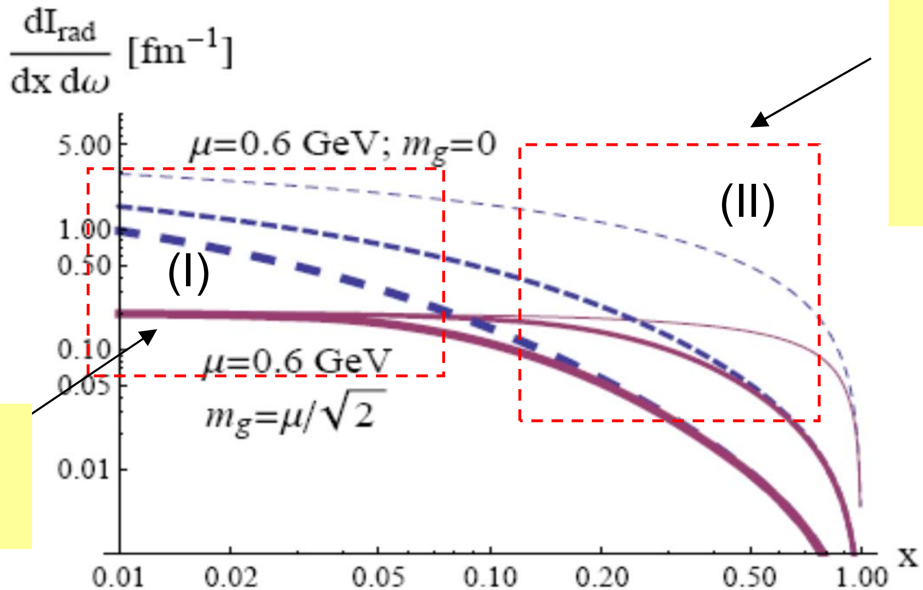
(Evaluated with $q_\perp^2 \leq m_g^2 + x^2M^2$)

For coulomb scattering:

Light quark

c-quark

b-quark



Strong mass hierarchy for $x > m_g/M_Q$ (but NO dead cone)

Little mass dependence (especially from $q \to c$)

2010 J. Phys. G: Nucl. Part. Phys. 37 094019

PRD 89

Thermal gluon have a large impact for $x < m_g/M$

Average Energy loss

$$m_g = \frac{\mu}{\sqrt{2}}$$

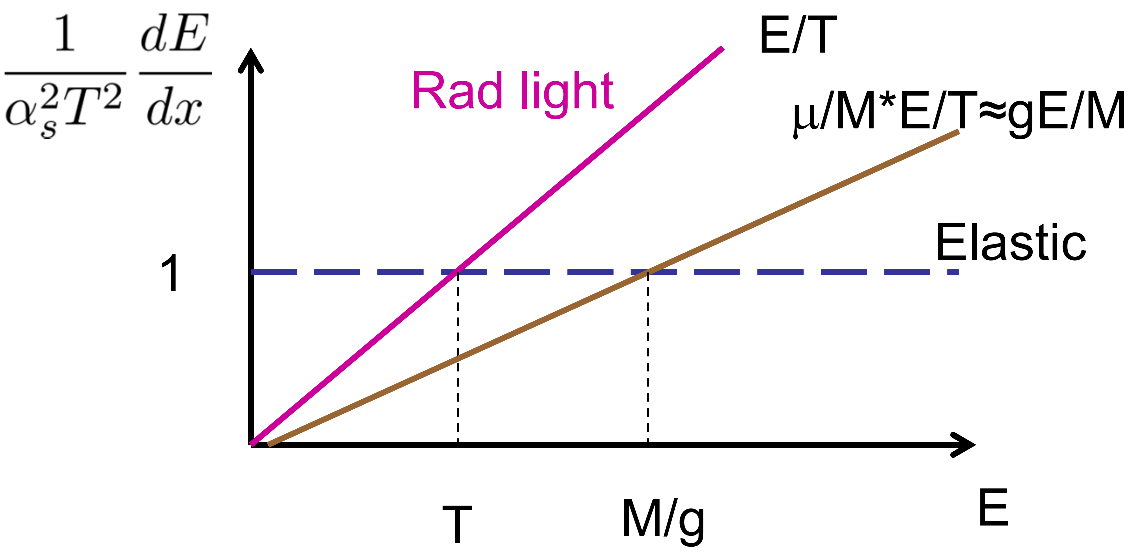
$$\boxed{\frac{dE_{\mathrm{GB}}(Q)}{dz} \approx \frac{4N_c\alpha_s}{\pi} \times \frac{0.8\mu}{M+\mu} \times \frac{E}{\lambda_Q}}$$

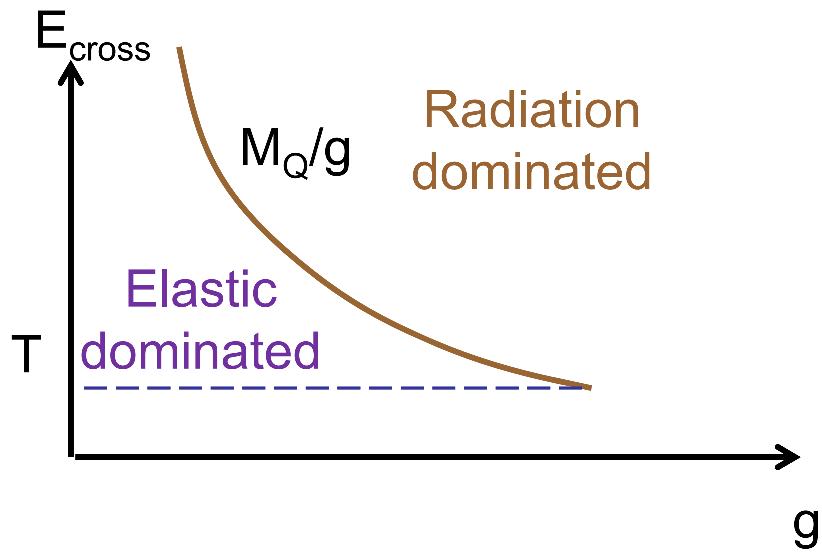
Strong mass effect in the average Eloss (mostly dominated by region II), similar to AdS/CFT

Interesting *per se*, but not intimately connected to the quenching or R_{AA}.

$$\frac{dE_{GB}}{dz} \sim \frac{\mu}{\mu+M}\boxed{\alpha_s^2 TE} \quad \text{vs} \quad \frac{dE_{\mathrm{el}}}{dx} \propto \alpha_s^2 T^2 \times \ln\left(\frac{ET}{m_D^2}\right)$$

Usual GB for light partons (one loses α_s E per elastic collision)



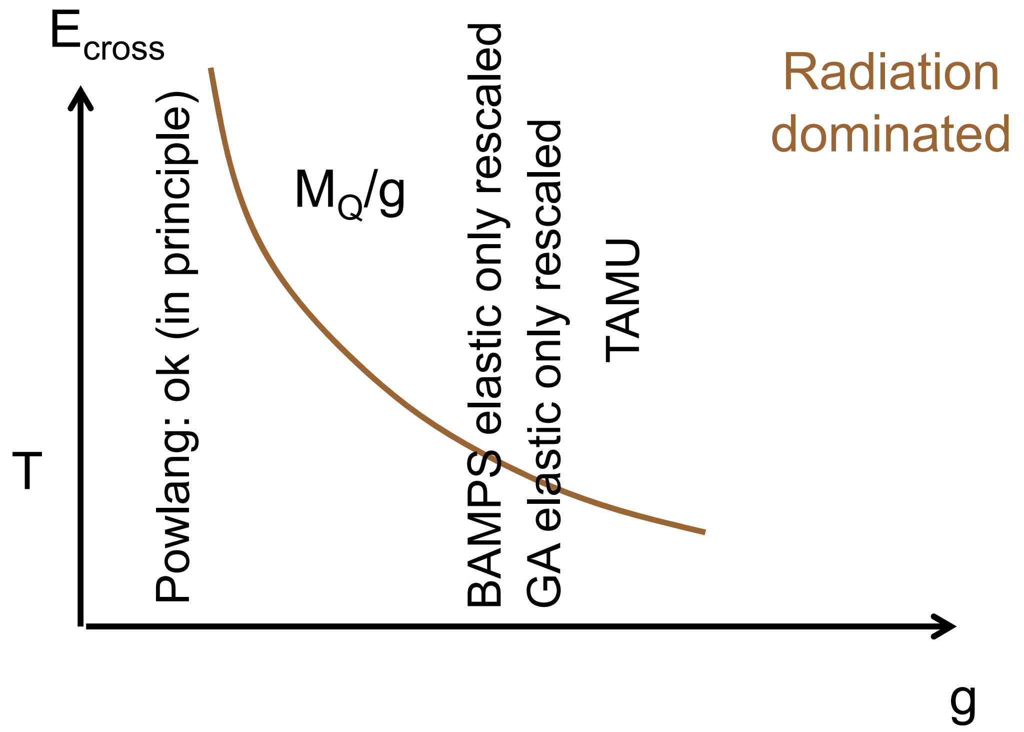


Well known fact: heavier quarks are more dominated by the elastic energy loss

Elastic vs GB radiative

Less trivial: Accomodating data using some strongly coupled model exclusively relying on elastic energy loss on full pT range and neglecting radiative Eloss seems a nonsense…

Lesson n°2



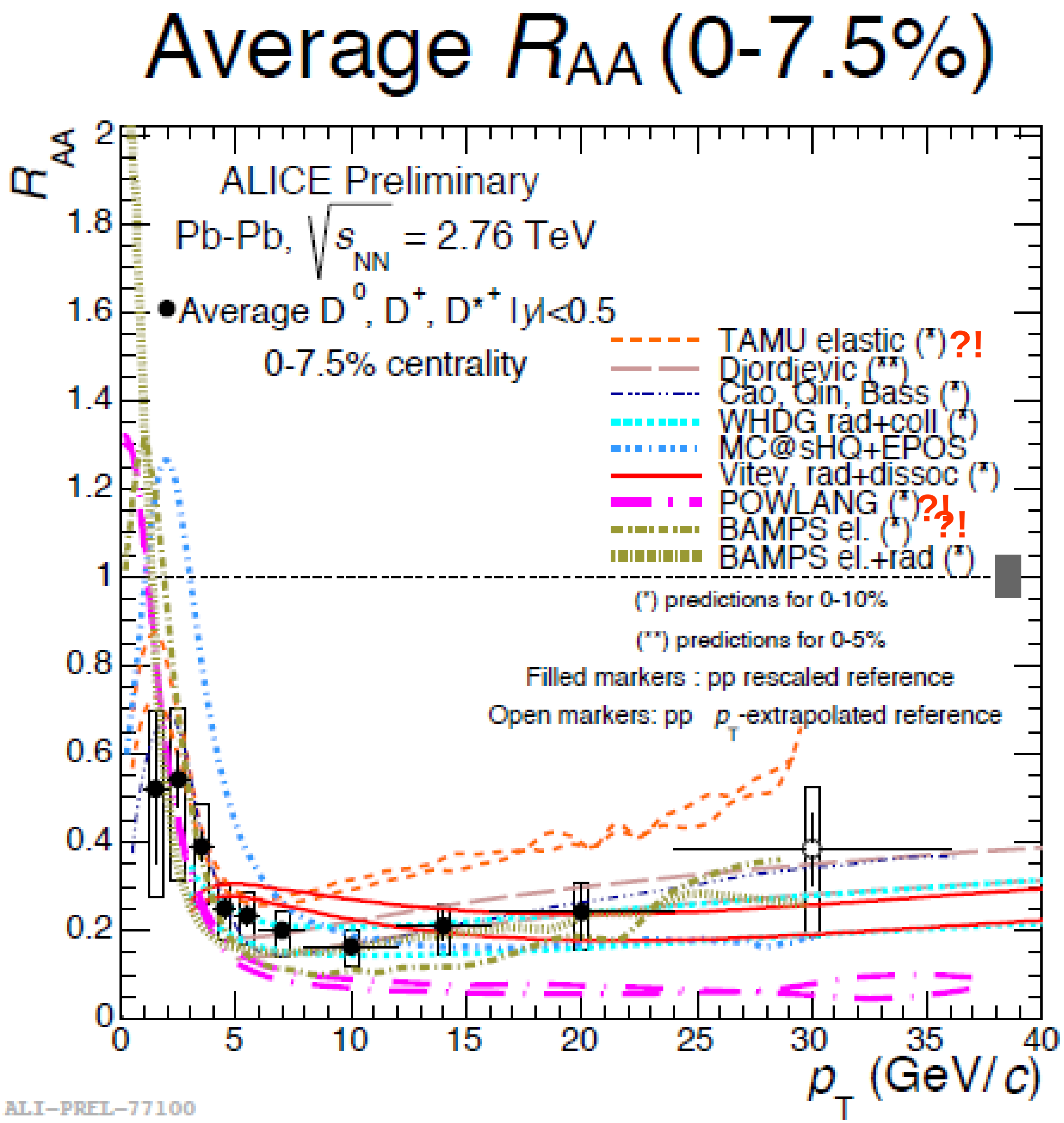
Rescaling may obscure the physics… especially because the parametric dependences of various eloss laws are not clear cut

… unless you come with a very good reason to explain why radiative Eloss should not be there ! … Coherence

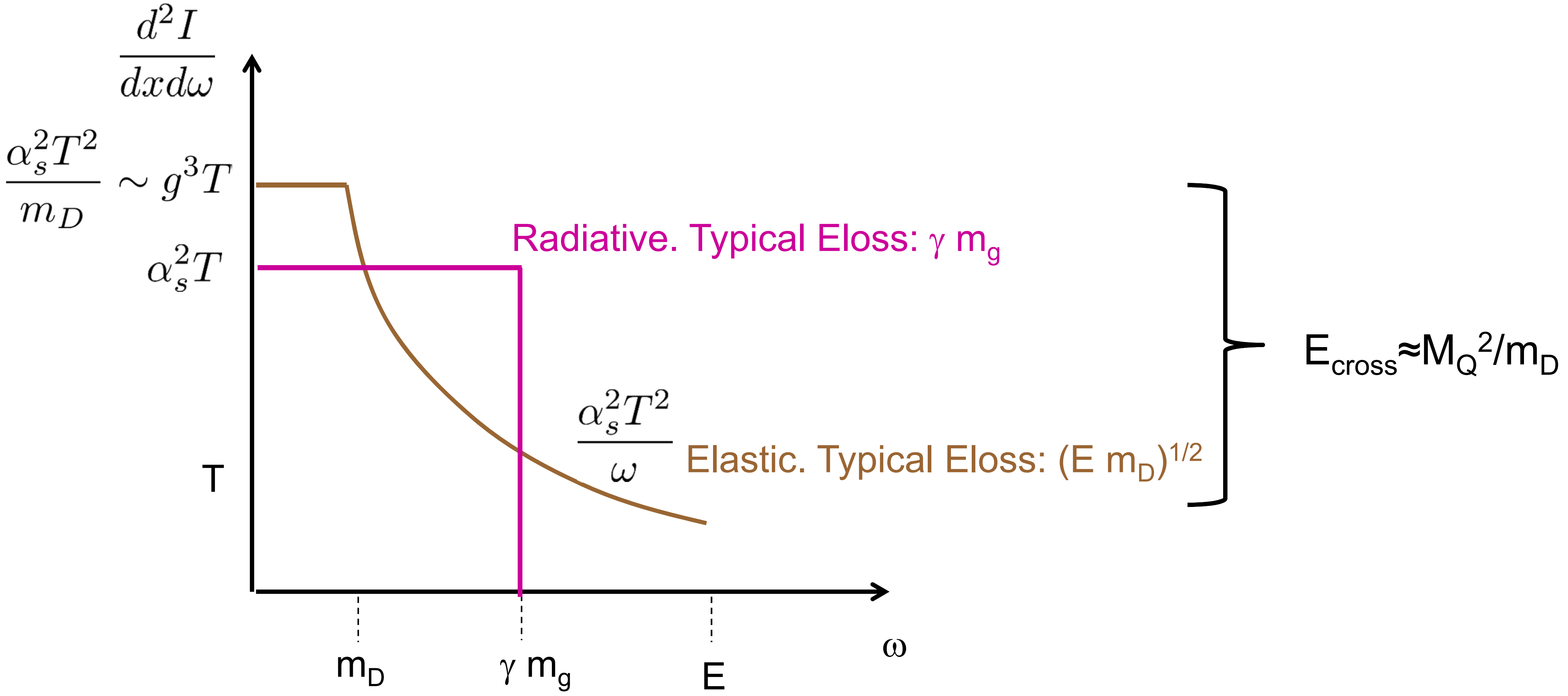
Models vs data: RAA

2014

How can HTL (pQCD) lead to the strongest suppression ?



Elastic vs GB radiative (spectra)



Same conclusions as the ones based on the average Eloss

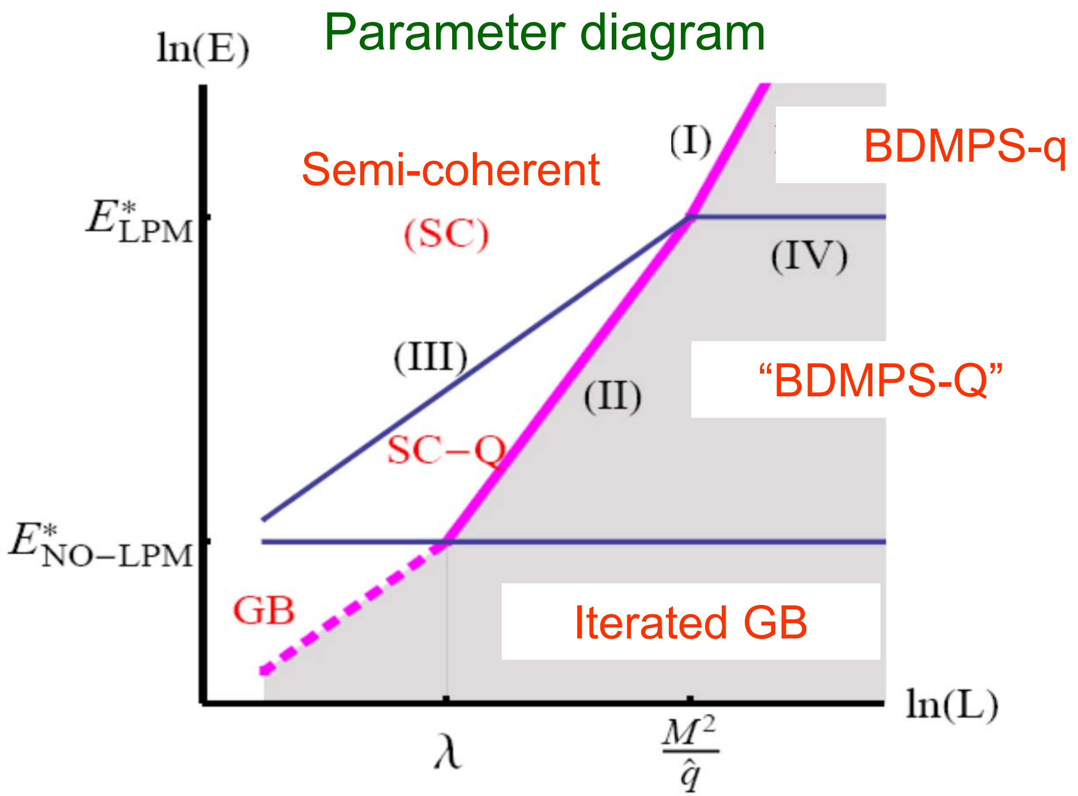
Coherent radiative energy loss

Much more complicated in many respects:

- Radiated gluon produced on several scattering centers (assumed infinitely heavy) => complicated numerical procedures (especially in the large opacity case) relying on uncontrolable hypothesis (l>1/mu)
- As a consequence, not many compact analytical results ("pocket formulas")

Thx Stephane & Andrei; see as well PB HDR

- For HQ especially: rather complicated parametric diagram



No mass dependence

$1/M^{0<a<1}$ or ln(..;/M) mass dependence

1/M mass dependence (what we have just covered)

Large variety of regimes depending on:

For a review: Peigné & Smilga 2008

- Particle energy E
- Path length L
- Production point (-∞ or in QGP)
- Opacity (# of collisions L/λ)

Light interlude

Formation time and radiation spectra

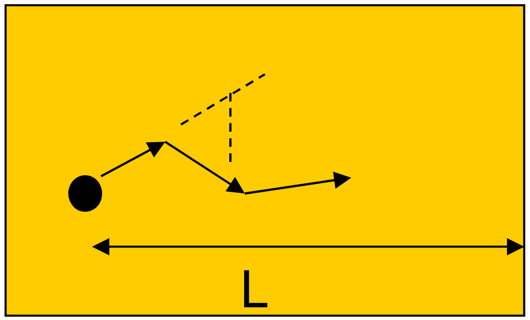
(light q)

Application for radiative energy loss in the eikonal limit

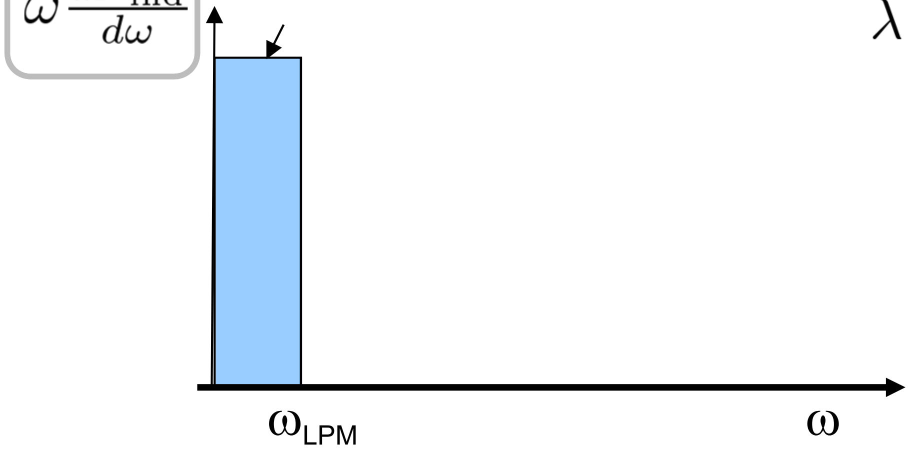
Total radiation through path length L

3 regimes:

L/λ × Gunion Bertsch $\approx \frac{L}{\lambda}\alpha_s \approx \alpha_s^2 T L$



QGP brick



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

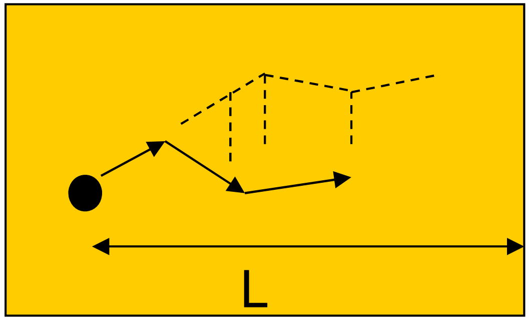
$\omega < \omega_{\rm LPM} := \frac{\hat{q}\lambda^2}{2} \approx T$ Incoherent Gunion-Bertsch radiation

Where $\hat{q} = \frac{\langle \delta q_\perp^2 \rangle}{\lambda}$ (transport coefficient) is the average square momentum increase of the partons per unit time… Very important quantity, in principle calculable from lattice QCD

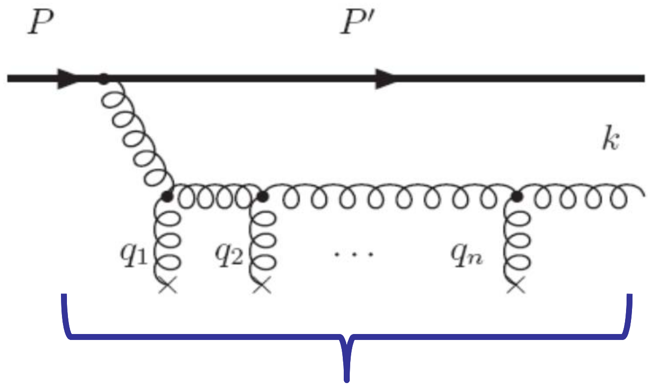
Formation time and radiation spectra

(light q) Application for radiative energy loss in the eikonal limit

3 regimes:



QGP brick



Production on N_{coh} scatterings => reduction of the GB radiation by a factor $1/N_{coh}$

→ b) Inter. energy gluons:

Produced **coherenty** on N_{coh} centers after typical formation time t_f such

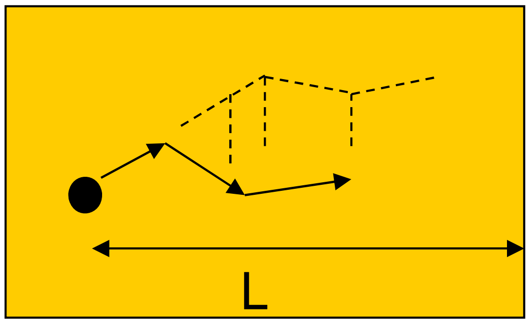
$t_f = \frac{\omega}{k_t^2}$ (as usual) but also $k_t^2 = \hat{q} t_f$ (stochastic propagation of the gluon)

$$=> \underbrace{t_f = \sqrt{\frac{\omega}{\hat{q}}}}_{\text{Multiple formation time}} \Rightarrow N_{\mathrm{coh}} = \frac{t_f}{\lambda} = \sqrt{\frac{\omega}{\omega_{\mathrm{LPM}}}}$$

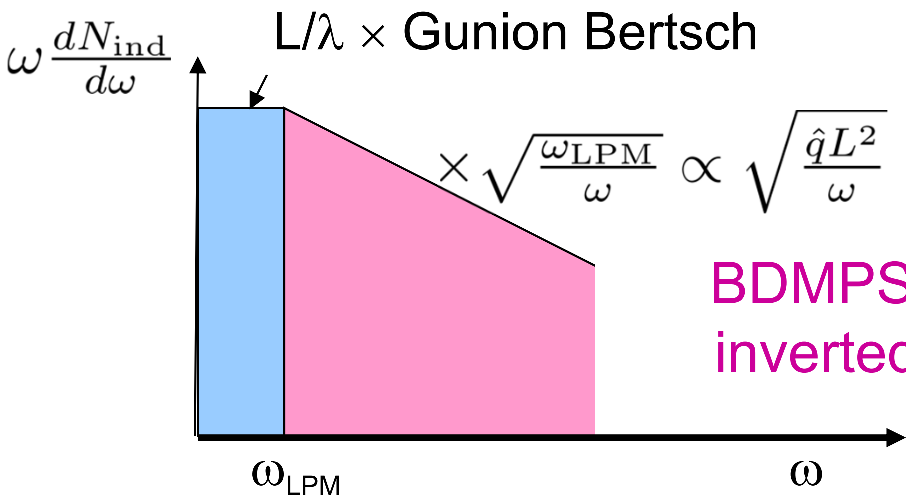
Formation time and radiation spectra

(light q) Application for radiative energy loss in the eikonal limit

3 regimes:



QGP brick



BDMPS (96-00); pattern inverted wrt LPM (gluon charged)

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

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

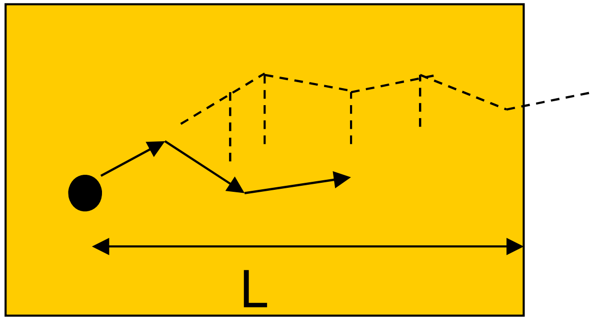
Especially important for av. energy loss

$$\frac{dE_{\mathrm{BDMPS}}(q)}{dz} \sim \boxed{\sqrt{\frac{\omega_{\mathrm{LPM}}}{E}}} \times \frac{dE_{\mathrm{GB}}(q)}{dz}$$

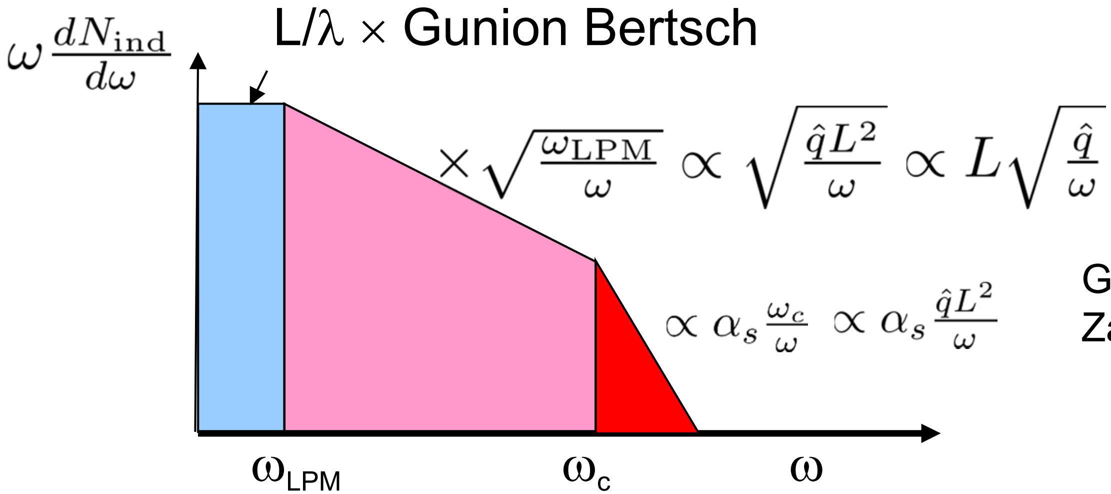
Formation time and radiation spectra

(light q) Application for radiative energy loss in the eikonal limit

finite path length:



QGP brick



GLV (2001), Zakharov (2001)

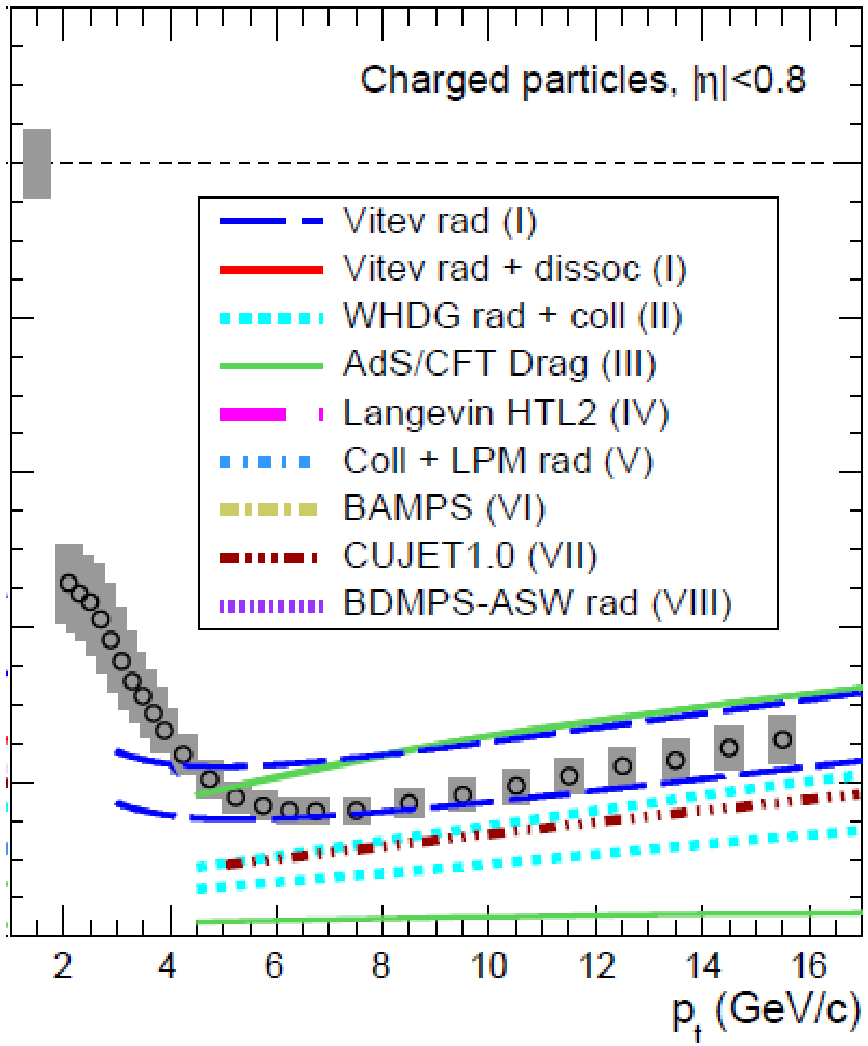
a) Low energy gluons: **Incoherent** Gunion-Bertsch radiation

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: $\sqrt{\frac{\omega}{\hat{q}}} > L \Rightarrow \omega > \omega_c := \frac{\hat{q}L^2}{2}$ Produced mostly outside the QGP… nearly as in vacuum **do not contribute significantly to the induced energy loss**

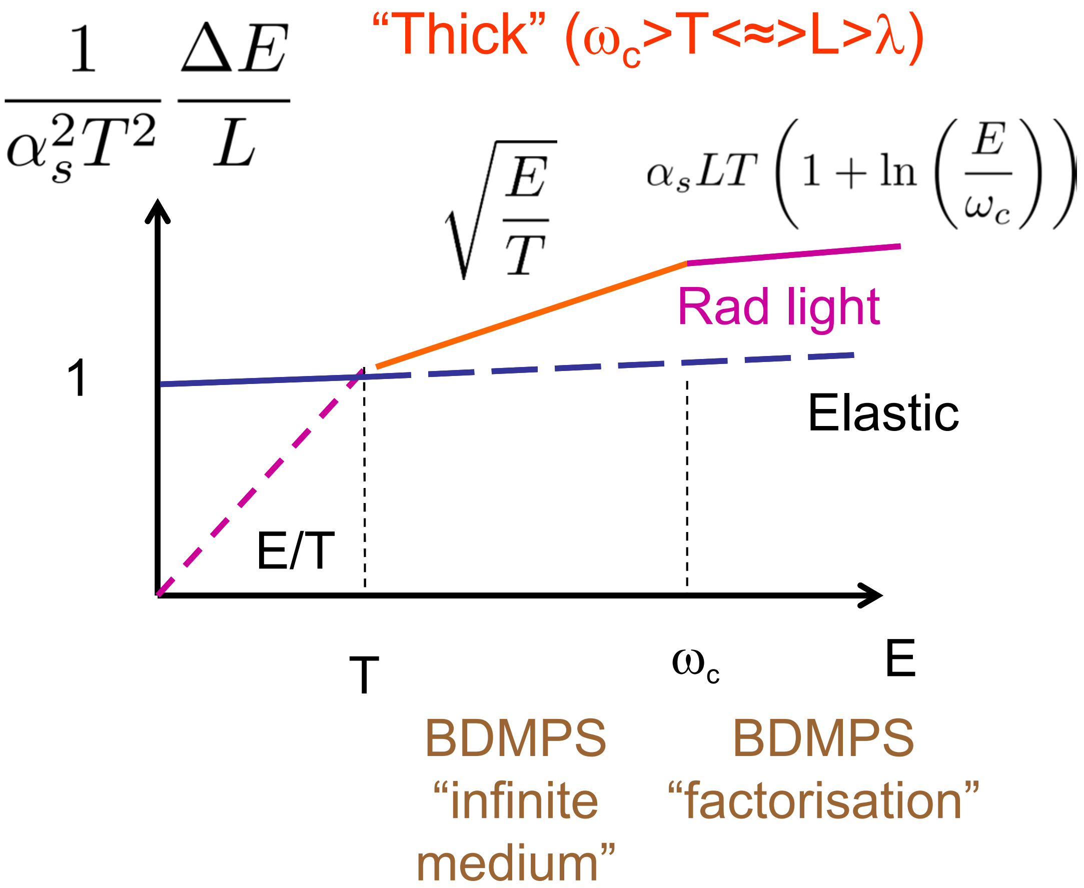
=> Average Energy loss along the path way: $\langle \Delta E \rangle \sim \alpha_s \hat{q} L^2 \ln\left(\frac{E}{m_D}\right)$ often the only result retained

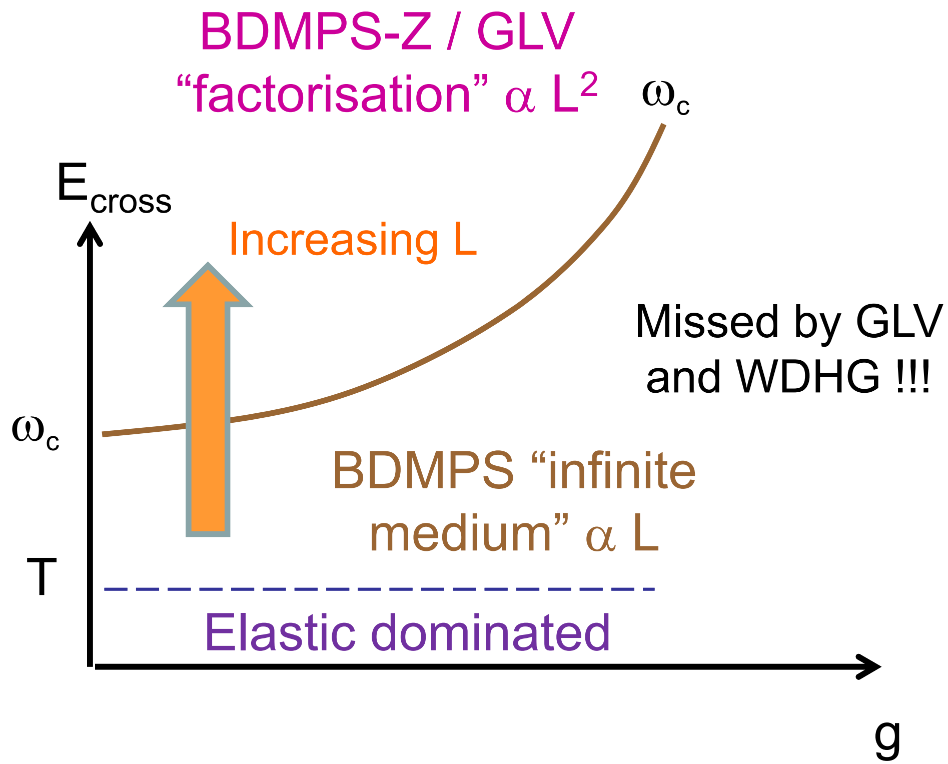
Model vs Experiment



Some of the models based on energy loss mechanism which explain the quenching reduction at large p_T include those finite path length effects… but the counter part is that they do not include proper medium evolution

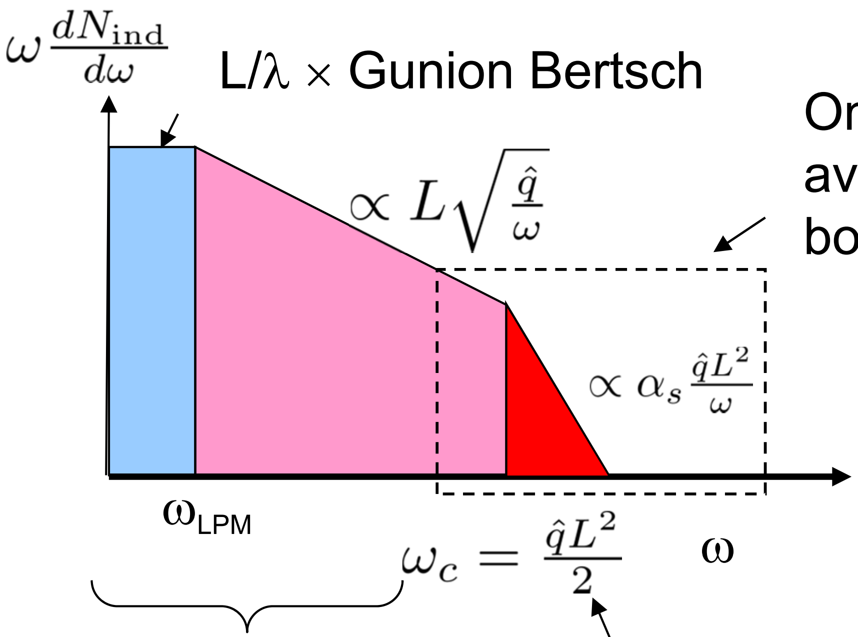
Radiative vs Elastic (average eloss)





- Dominant radiative only comes through coherent processes
- The BDMPS "infinite medium" domain increases with g and L => relevance of the factorisation regime for bulk sQGP ?

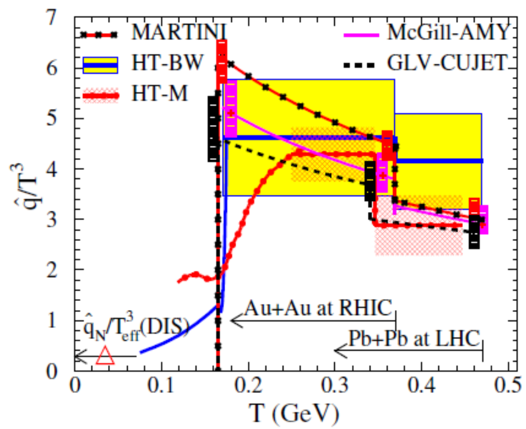
Formation time and radiation spectra



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

Bulk part of the spectrum still scales like path length L



$$\hat q = \frac{4 \times (0.3-0.5)^2}{0.2}$$

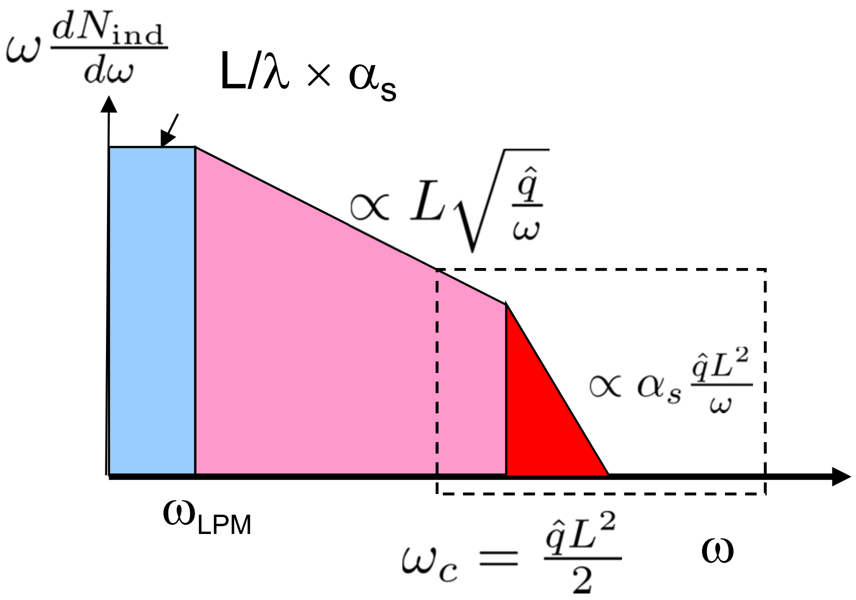
$$\approx 0.5 - 2.5\ \mathrm{GeV}^2/\mathrm{fm}$$

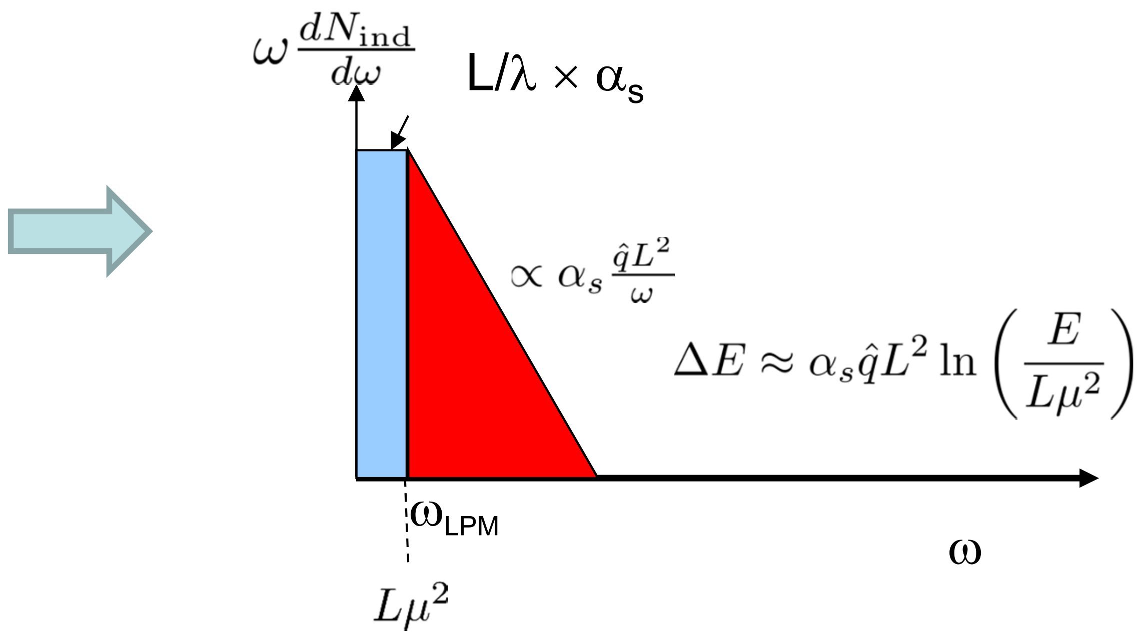
Concrete values @ LHC $\begin{cases} \hat q \sim 1\mathrm{GeV}^2/\mathrm{fm} \\ L \sim 5\mathrm{fm} \end{cases}$

$\omega_c \sim 50\mathrm{GeV}$ Large value !

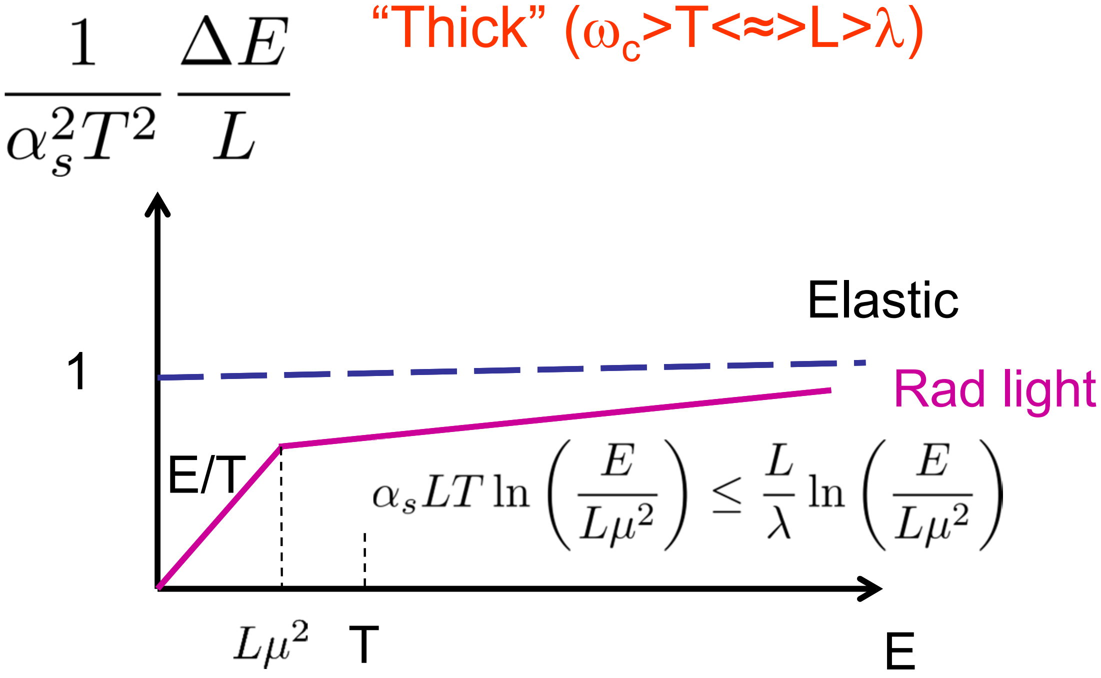
Personal opinion: a large part of radiative energy loss @ LHC still scales like the path length L… unless L≈ 1–2 fm

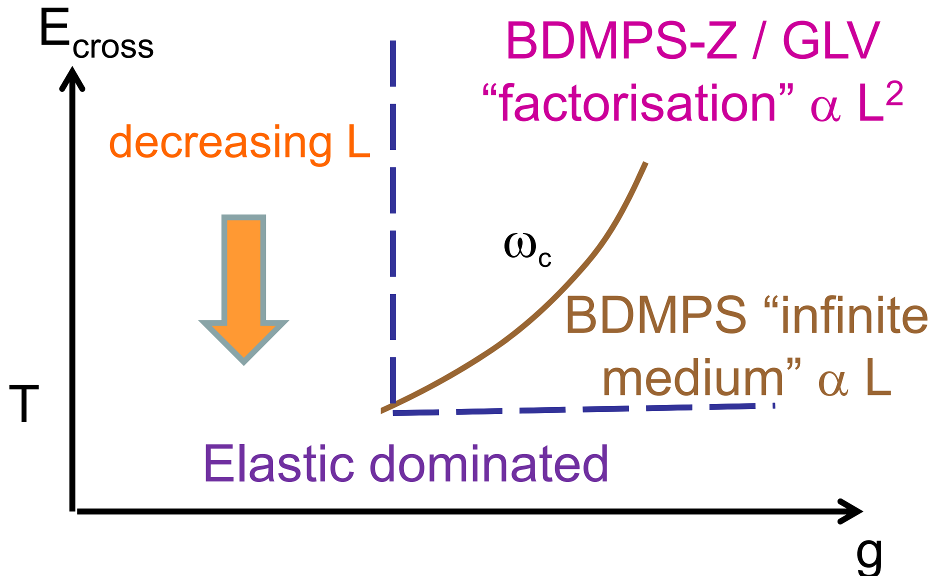
Case of small path length





"Thick" (ω_c>T<≈>L>λ)

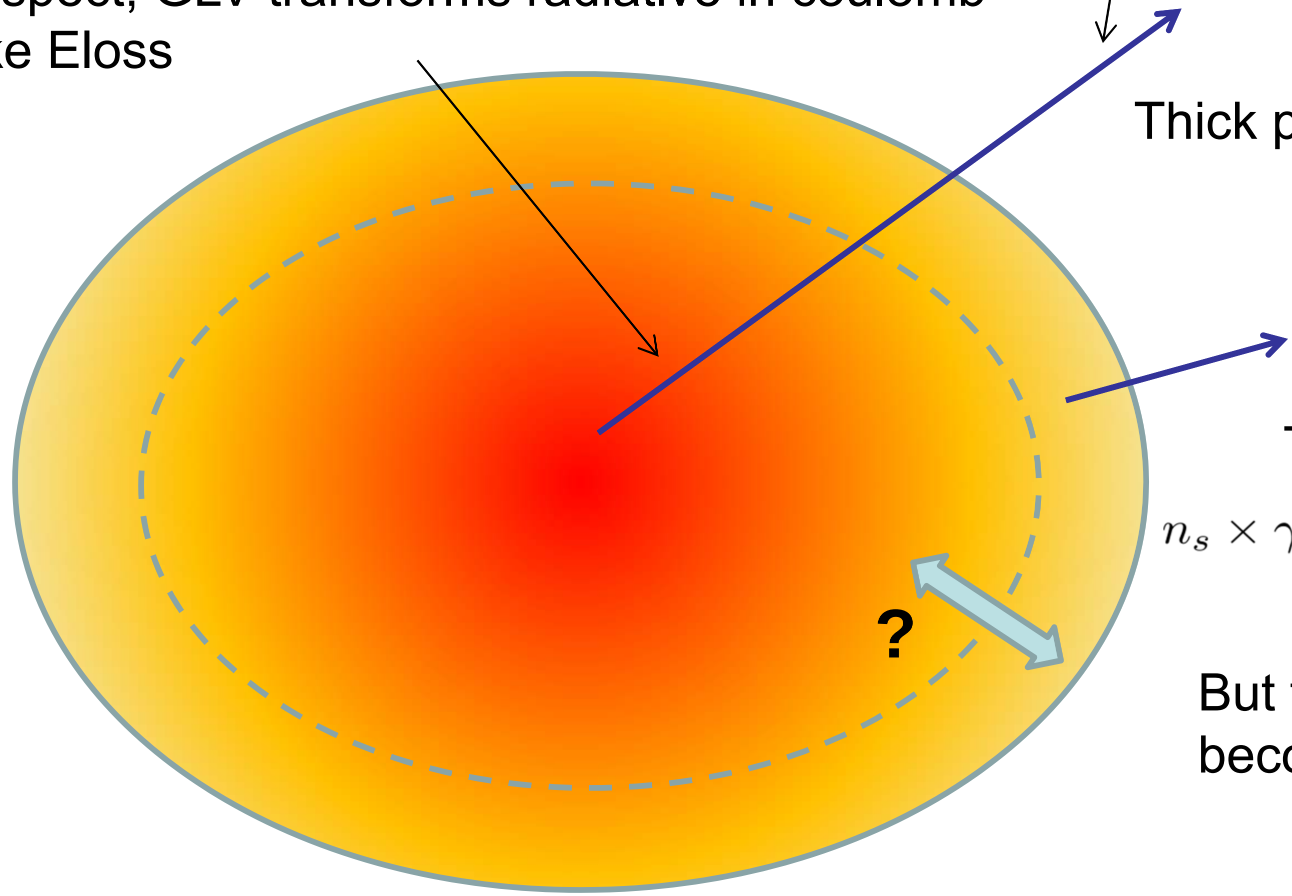




General overview

Not legitimate to use models relying on 1rst opacity expansion for thick plasma…

… especially because one misses the √E part of BDMPS-Z part of the Eloss. In this respect, GLV transforms radiative in coulomb-like Eloss



Thick plasma

Thin plasma. condition (GLV):

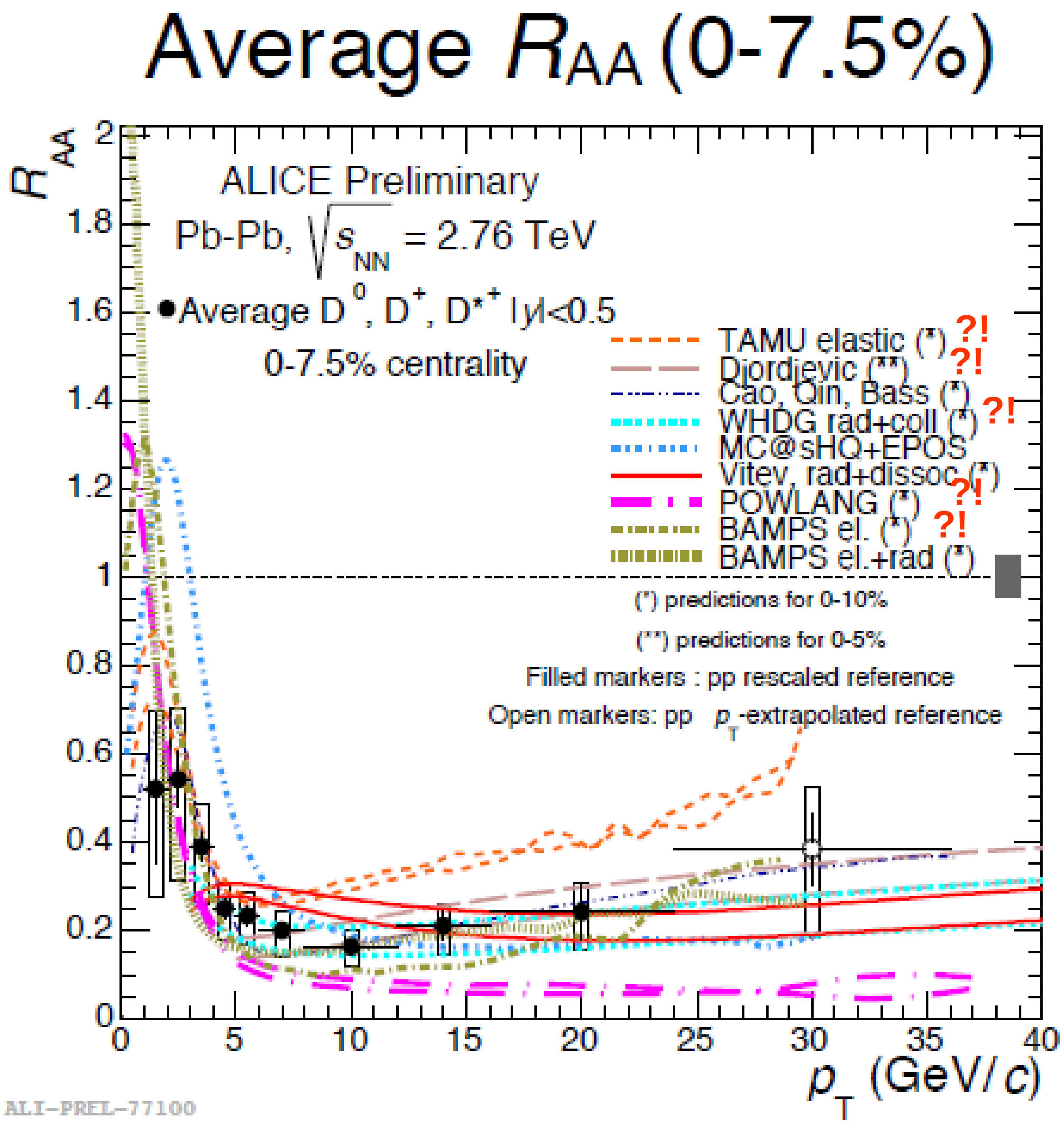
$$n_s \times \gamma = \frac{L}{\lambda} \times \frac{L\mu^2}{4x(1-x)E} \ll 1 \Leftrightarrow \omega \gg \frac{L^2\hat{q}}{4}$$

But then, elastic energy loss becomes the dominant mechanism

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

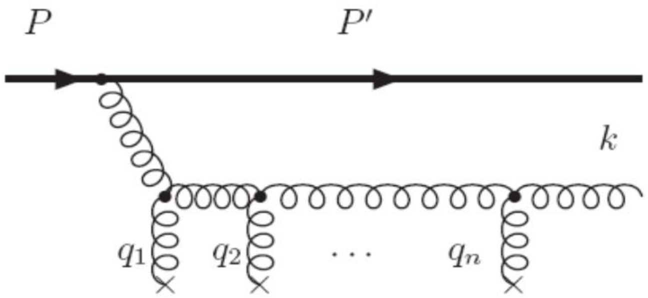
Models vs data: RAA

2014



End of light interlude

Formation time in a random walk



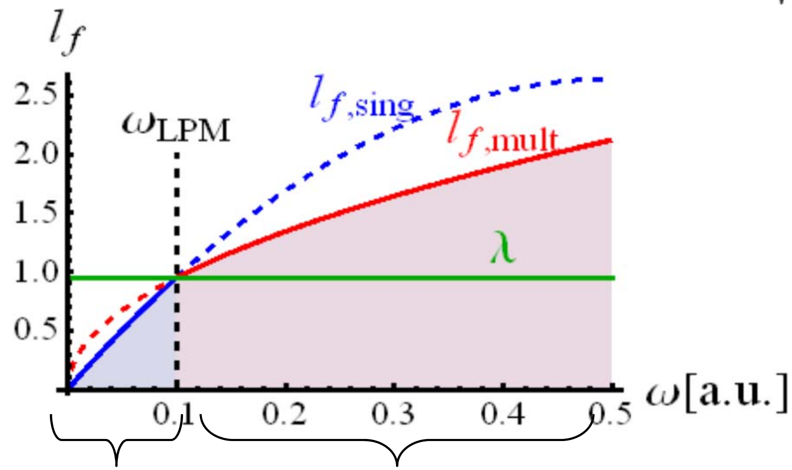
Phase shift at each collision

Following Landau-Pomeranchuk: one obtains an effective formation time by imposing the cumulative phase shift to be Φ_{dec} of the order of unity

For light quark (infinite matter):

$$l_{f,\mathrm{mult}}(q+g) = l_{f,\mathrm{scat}}(q+g) \approx 2\sqrt{\frac{\omega\Phi_{\mathrm{dec}}}{\hat{q}}}$$

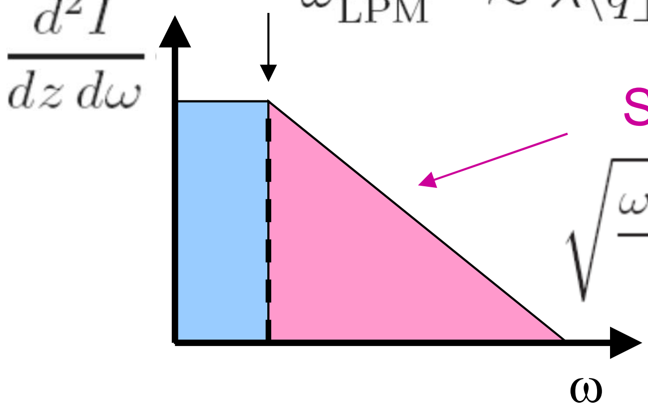
=> 3 scales: $l_{f,mult}$, $l_{f,sing}$ & λ



Incoherent radiation

Coherent radiation (BDMPS)

$$\omega_{\mathrm{LPM}}^{(\mathrm{QCD})} \approx \tilde{\lambda}\langle q_\perp^2\rangle \sim \lambda_q\mu^2 \sim T$$



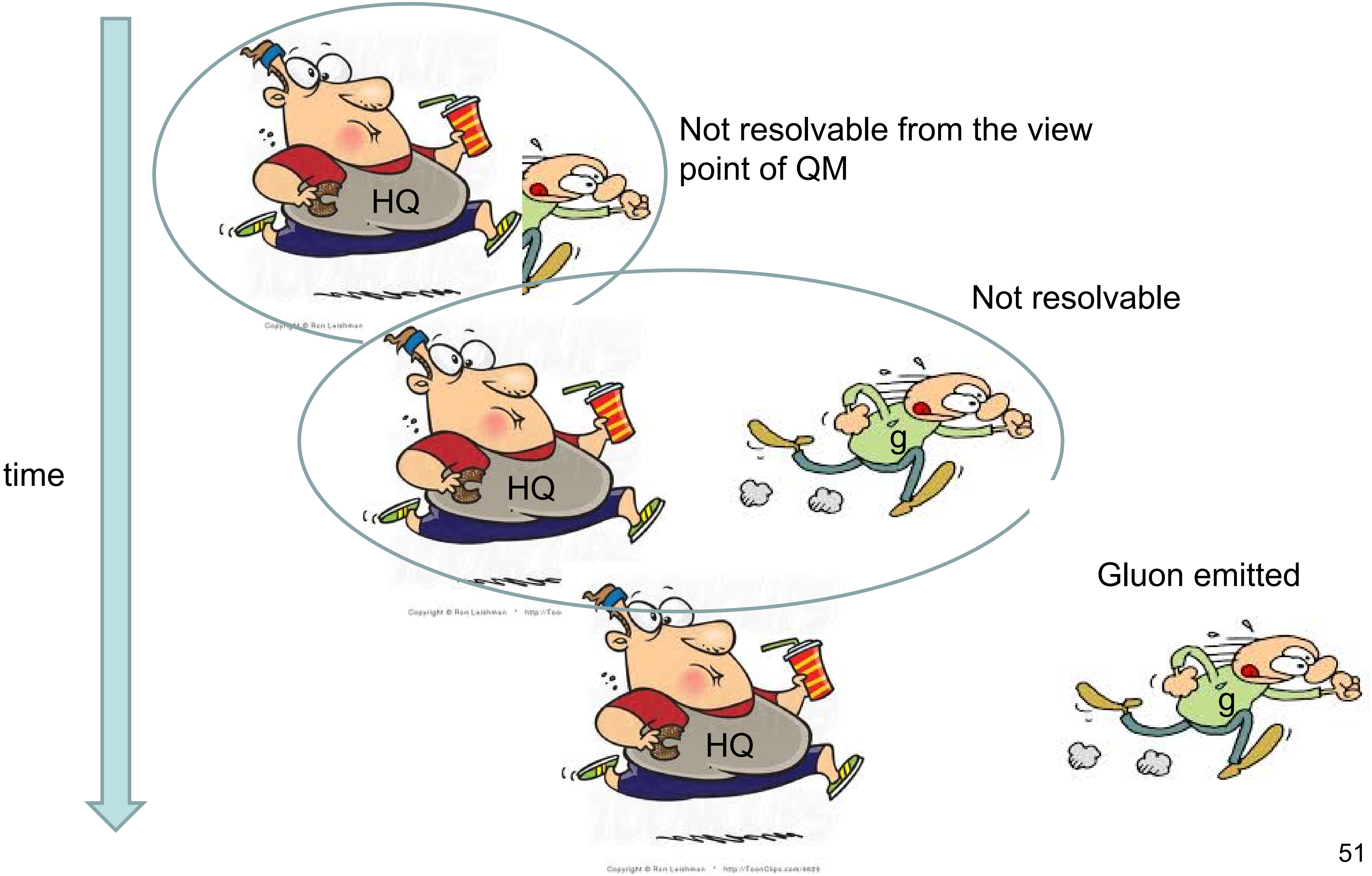
Suppression:

$$\sqrt{\frac{\omega_{\mathrm{LPM}}}{\omega}\ln\left(\frac{\omega}{\omega_{\mathrm{LPM}}}\right)}$$

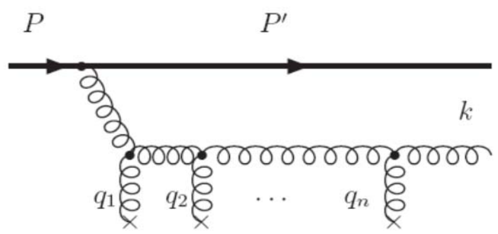
Especially important for av. energy loss

$$\frac{dE_{\mathrm{BDMPS}}(q)}{dz} \sim \boxed{\sqrt{\frac{\omega_{\mathrm{LPM}}}{E}}} \times \frac{dE_{\mathrm{GB}}(q)}{dz}$$

Gluon emission from HQ



Formation time and decoherence for HQ



$$l_{f,\mathrm{mult}}(Q+g) = \frac{2\omega\Phi_{\mathrm{dec}}}{\sqrt{\omega\hat{q}\Phi_{\mathrm{dec}} + \left(\frac{M^2\omega^2}{2E^2}\right)^2} + \frac{M^2\omega^2}{2E^2}}$$

"Competition" between

- decoherence" due to the masses: $m_g^2 + x^2 M^2$
- decoherence due to the transverse kicks $\langle Q_\perp^2 \rangle = l_{f,\mathrm{mult}}\,\hat{q}$

Special case: $\lambda < l_{f,\mathrm{mult}} < L^{\star\star}_{\mathrm{QCD}} := \dfrac{m_g^2 + x^2 M^2}{\hat{q}}$

One has a possibly large coherence number $N_{coh} := l_{f,mult}/\lambda$ but the radiation spectrum per unit length stays mostly unaffected:

Radiation on an effective center of length $l_{f,mult} = N_{coh}\,\lambda$ $\longrightarrow$ $$\frac{d^2 I}{dz\,d\omega}$$ $\longleftarrow$ Radiation at small angle $\propto \langle Q_\perp^2 \rangle$ i.e. $\propto N_{coh}$

Compensation at leading order !

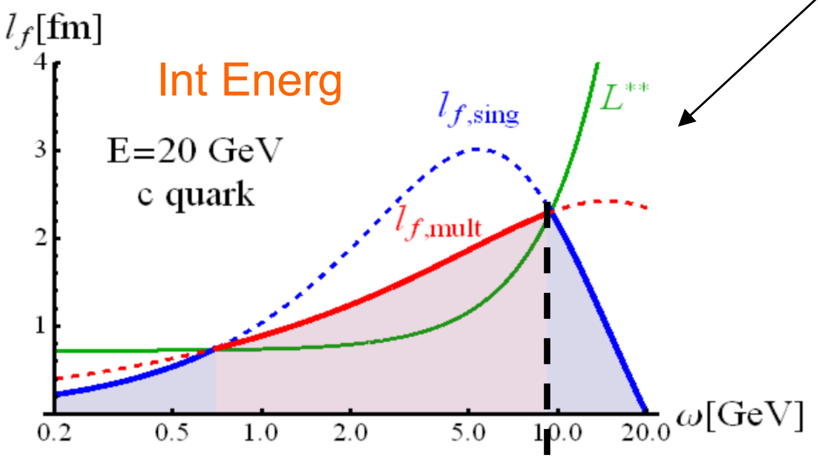
LESSON: HQ radiate less, on shorter times scales and are less affected by coherence effects than light ones !!! (dominance of 1rst order in opacity expansion)

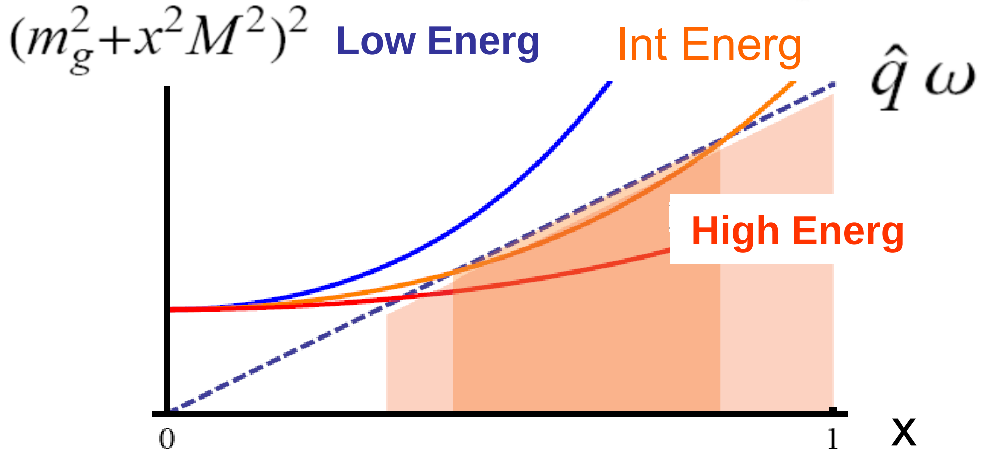
Formation time and decoherence for HQ

Criteria: HQ radiative E loss strongly affected by coherence provided:

$$l_{f,\text{mult}}(Q) \gtrsim L^{\star\star}_{\text{QCD}} := \frac{m_g^2 + x^2 M^2}{\hat{q}}$$

Equivalent to: $l_{f,\text{sing}}(Q) \gtrsim 2L^{\star\star}_{\text{QCD}} \Leftrightarrow \left(m_g^2 + \frac{\omega^2 M^2}{E^2}\right)^2 \lesssim \omega \hat{q}$





$$\omega^\star_{\text{LPM}}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$$

3 regimes (2 for light quarks)

Low energy: radiation from HQ unaffected by coherence

Intermediate energy: coherence affects radiation on an increasing part of the spectrum (up to ω_{LPM}^*)

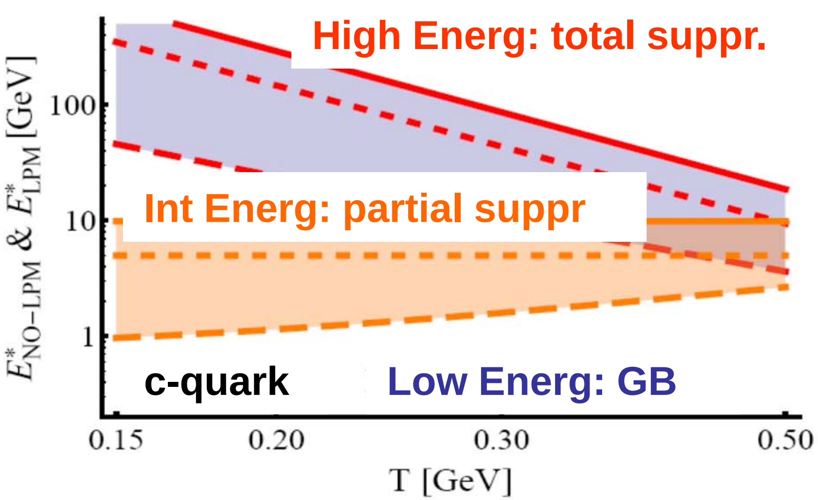
High energy: HQ behaves like a light one; coherence affects radiation from ω_{LPM} on.

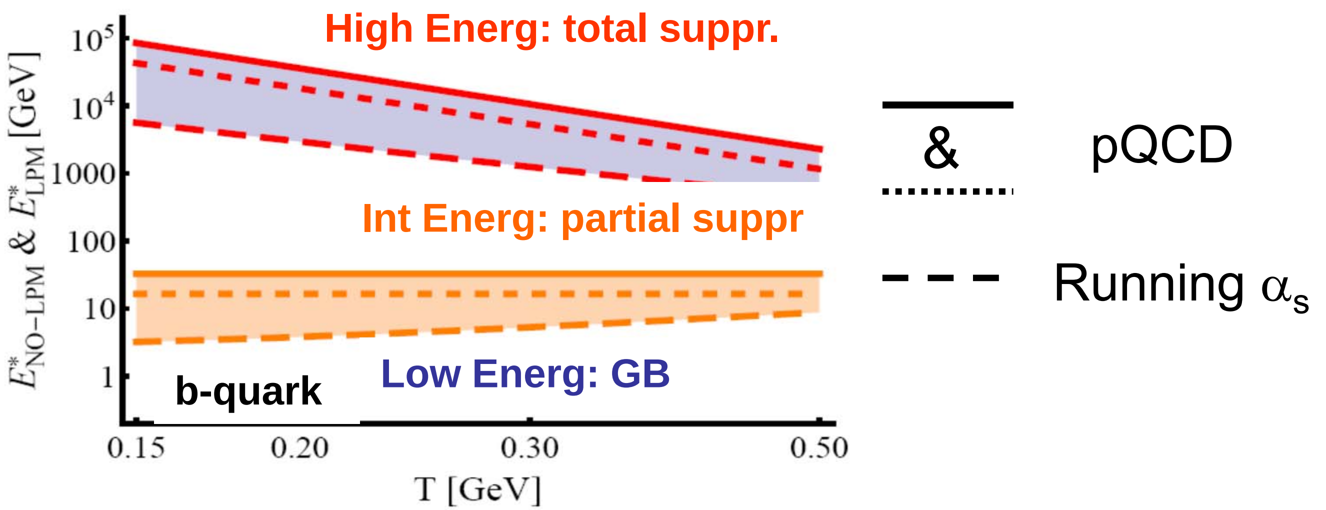
$$E^\star_{\text{NO-LPM}} := 3\frac{M m_g^3}{\hat{q}} \sim \frac{M}{g_s} \qquad E^\star_{\text{LPM}} := \frac{M^4}{\hat{q}}$$

Regimes and radiation spectra

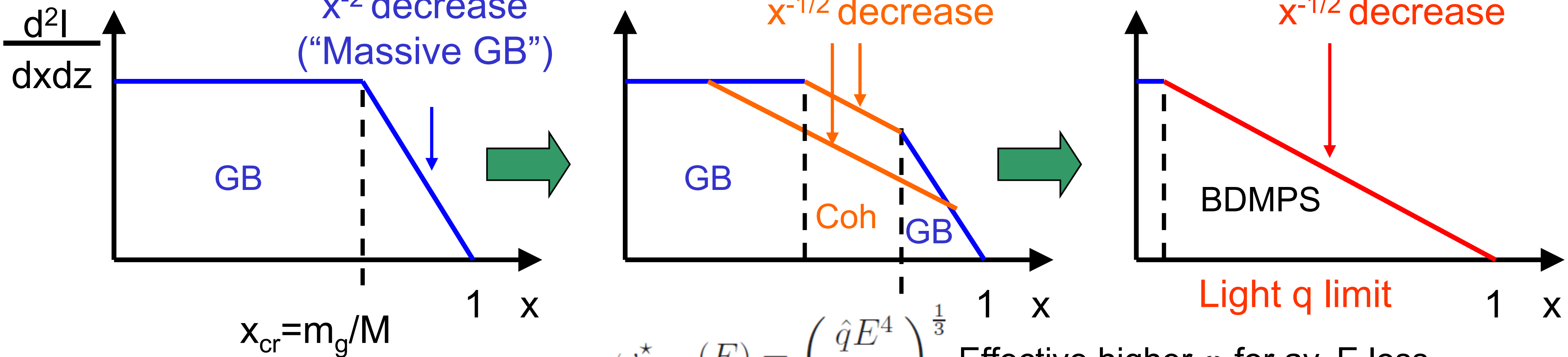
Hierarchy of scales: $\underbrace{E_{\rm LPM}(q)}_{T} \ll \underbrace{E^\star_{\rm NO-LPM}(Q)}_{\frac{M}{g_s T}\times T} \ll \underbrace{E^\star_{\rm LPM}(Q)}_{\left(\frac{M}{g_s T}\right)^4\times T}$

larger coupling ⇒ Larger coherence effects



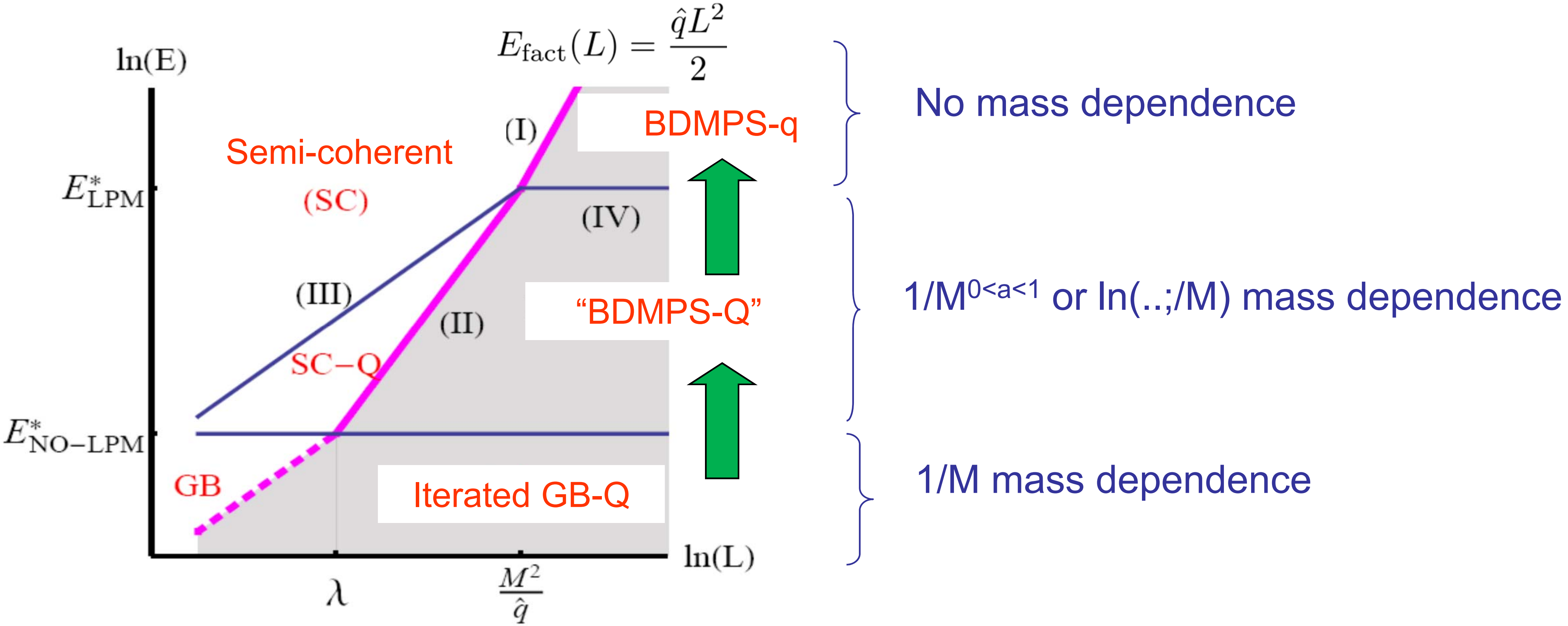


Spectra



$\omega^\star_{\rm LPM}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$ Effective higher ω for av. E loss

Regimes and radiation spectra

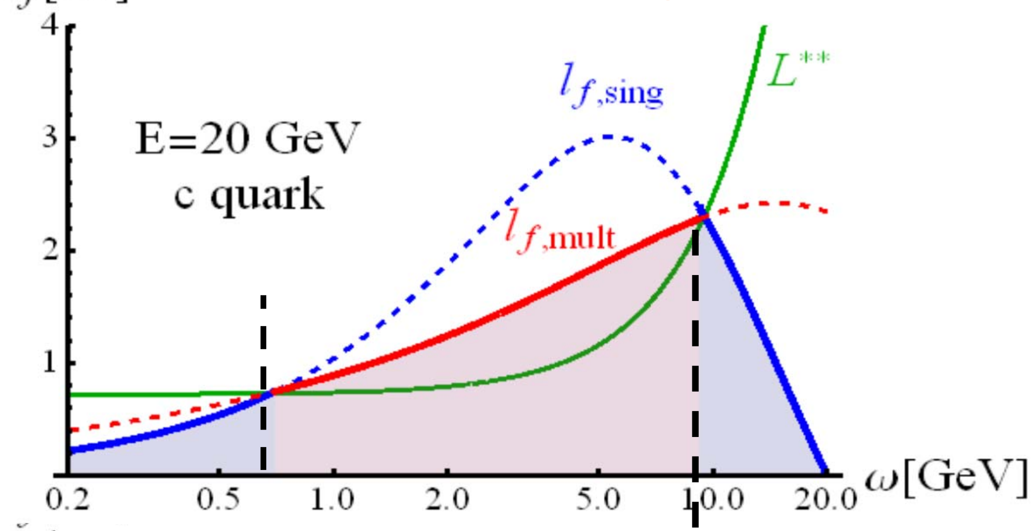


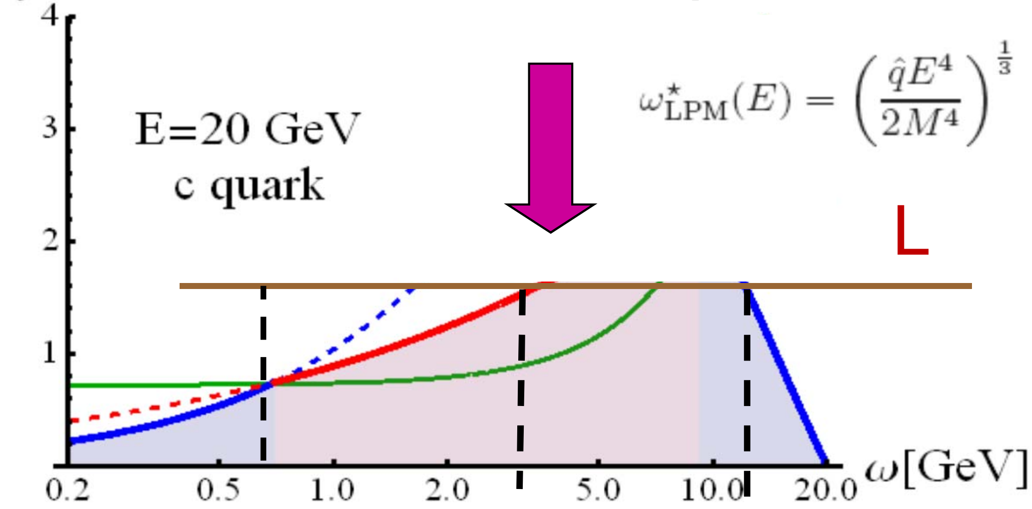
	E_{LPM}		$E^\star_{\text{NO-LPM}}$		$E^\star_{\text{LPM}}$
$\frac{1}{\alpha_s}\frac{dE^q_{\text{rad}}}{dz} \sim$	$\frac{E}{\lambda_Q}$	$\nearrow$			$\sqrt{\hat{q}E}$
$\frac{1}{\alpha_s}\frac{dE^Q_{\text{rad}}}{dz} \sim$	$\frac{\mu}{M} \times \frac{E}{\lambda_Q}$	$\nearrow$	$\left(\frac{\hat{q}E}{M}\right)^{\frac{2}{3}}$	$\nearrow$	$\sqrt{\hat{q}E}$

Now considering the finite path length…

Finite path length for HQ

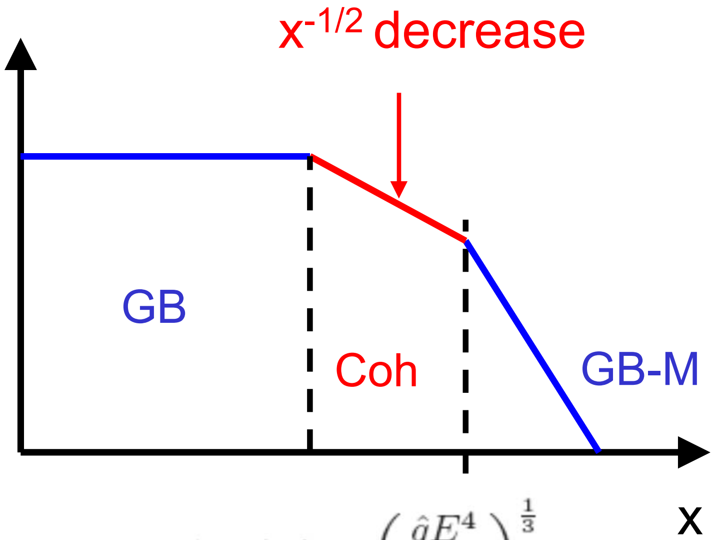
Intermediate Energy



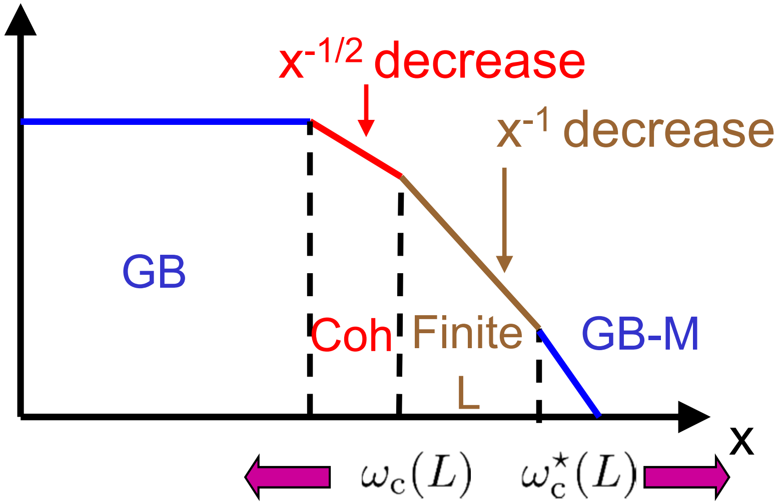


$$\omega^\star_{\mathrm{LPM}}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$$

$$\omega_c(L) = \frac{\hat{q}L^2}{2} \quad \omega^\star_c(L) = \frac{E^2}{M^2 L}$$



$$\omega^\star_{\mathrm{LPM}}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$$



Decreasing L

Finite L window opens for $L < L^\star_{\mathrm{fact}} = \left(\frac{E^2}{\hat{q}M^2}\right)^{1/3} \Rightarrow \Delta E^{\mathrm{SC-Q}}_{\mathrm{rad}} \approx \alpha_s \hat{q} L^2 \ln\left(\frac{\omega^\star_c}{\omega_c}\right) \approx \alpha_s \hat{q} L^2 \ln\left(\frac{E^2}{\hat{q}L^3M^2}\right)$

Finite path length for HQ

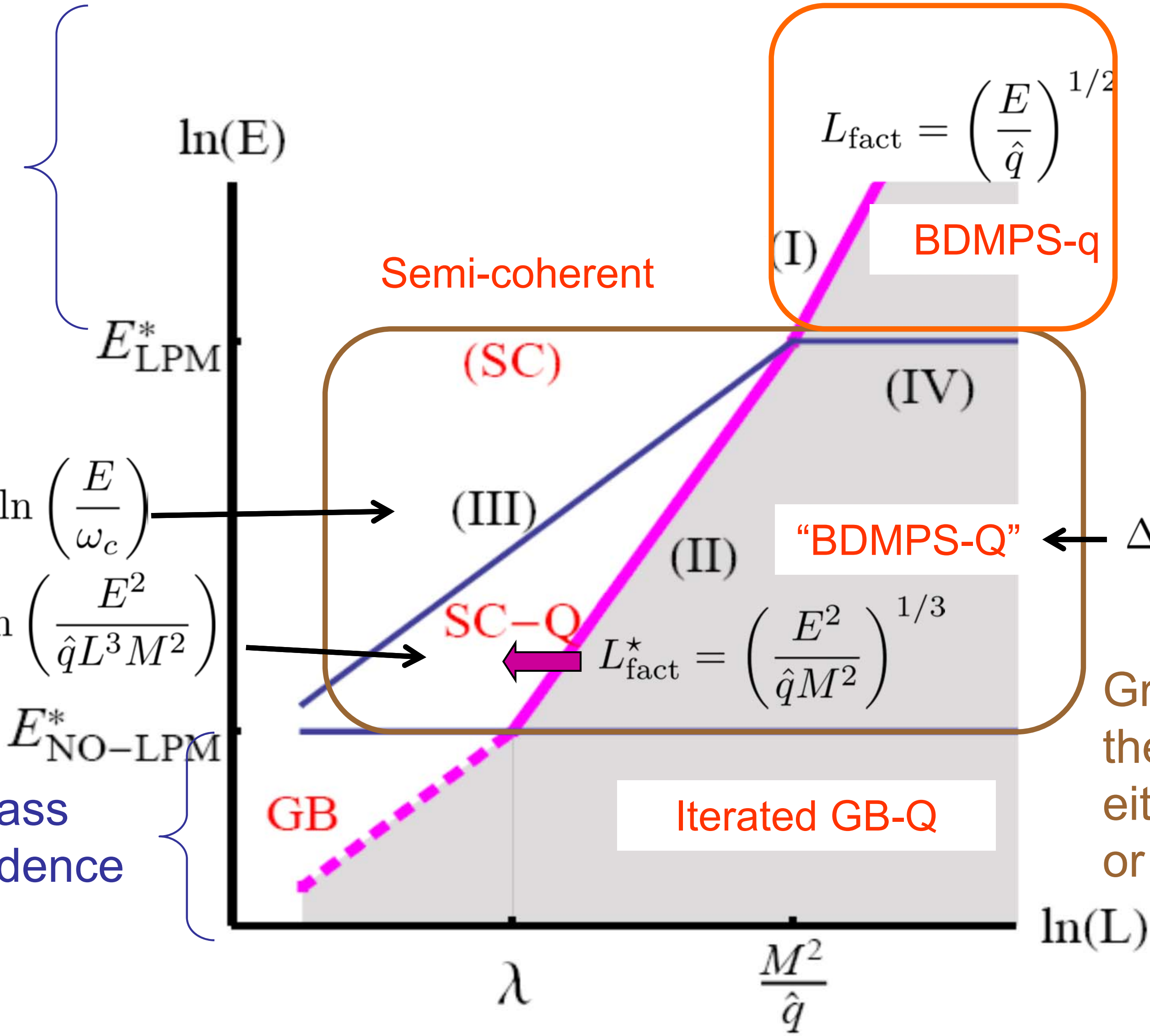
For L>M²/$\hat{q}$, radiation from HQ and lq similar in BDMPS-q regime and above (have a chance to behave like lq while still being in the medium); Typical for c quarks

No mass dependence

$\Delta E_{\rm rad}^{\rm SC} \sim \alpha_s \hat{q} L^2 \ln\left(\frac{E}{\omega_c}\right)$

$\Delta E_{\rm rad}^{\rm SC-Q} \approx \alpha_s \hat{q} L^2 \ln\left(\frac{E^2}{\hat{q} L^3 M^2}\right)$

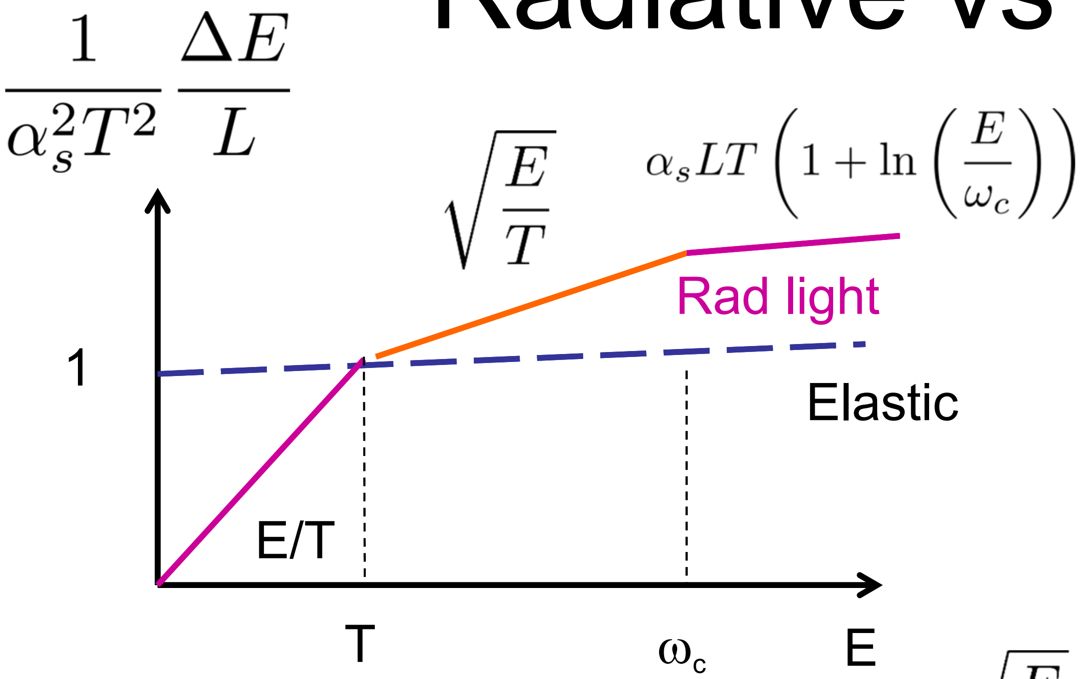
1/M mass dependence



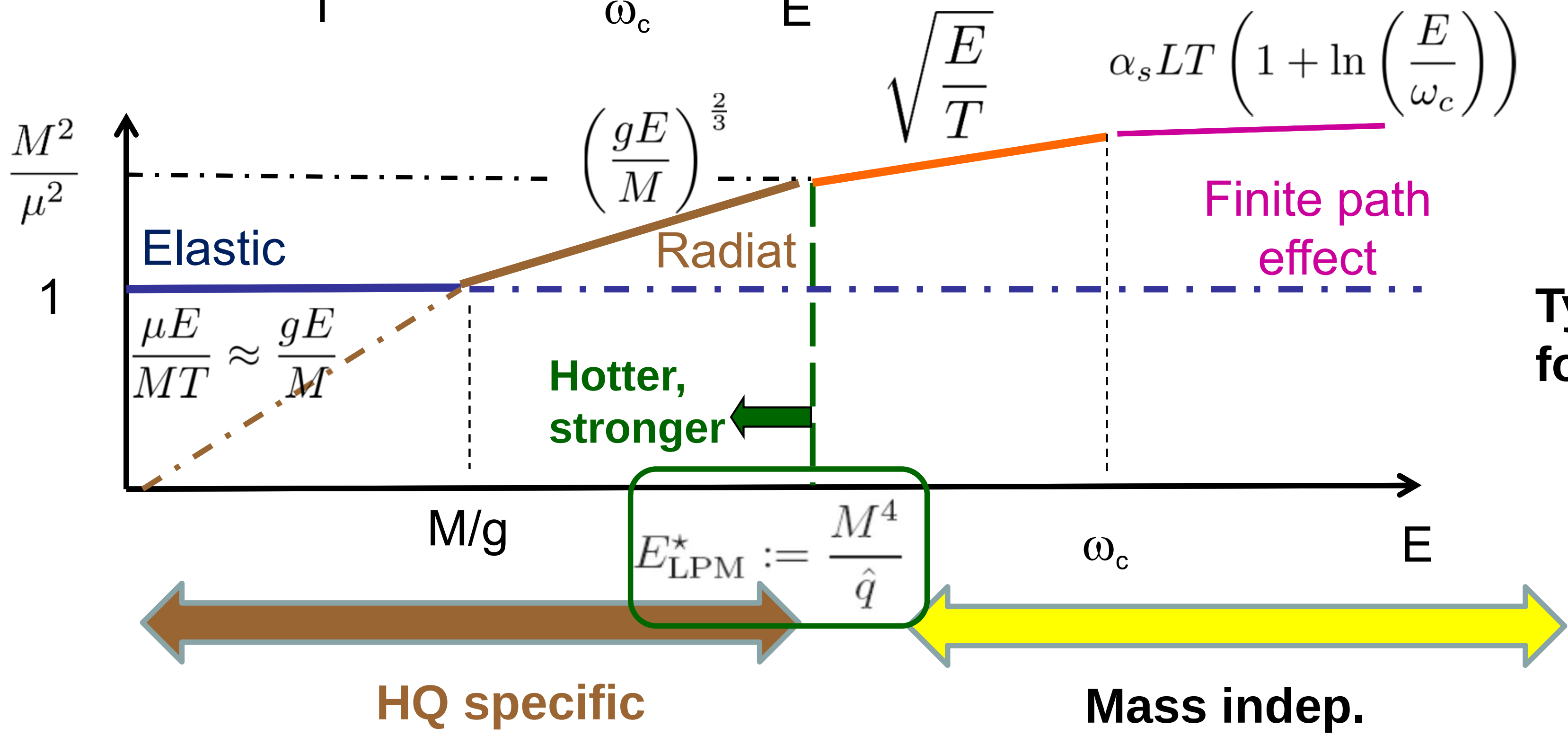
$\Delta E_{\rm rad}^{\rm BDMPS-Q} \sim \alpha_s \left(\frac{\hat{q}E}{M}\right)^{\frac{2}{3}} L$

Gradual disappearance of the mass dependence for either increasing energy or decreasing path length

Radiative vs Elastic



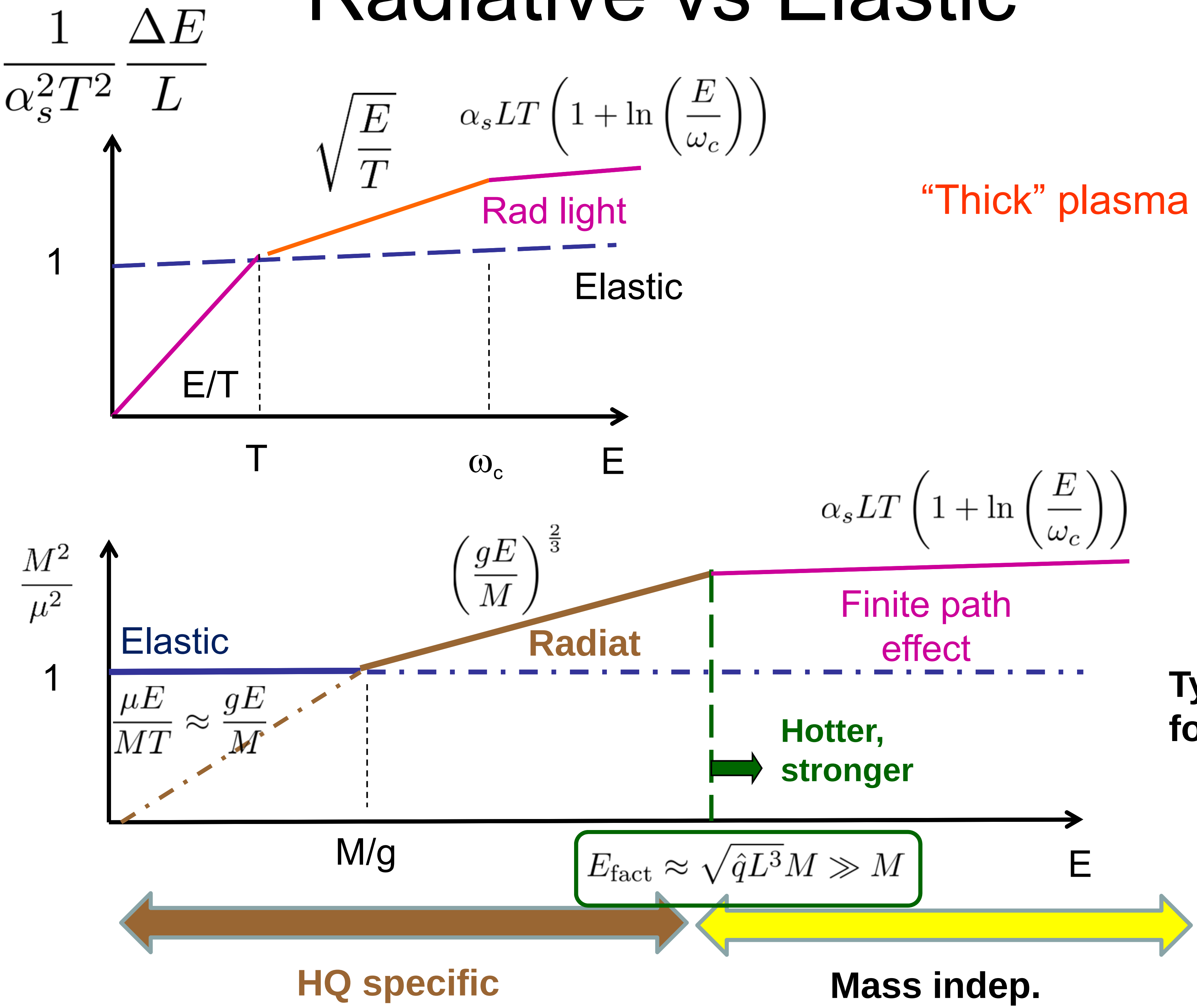
"Thick" plasma



$$L > \frac{M^2}{\hat{q}}$$

Typical picture for c quarks

Radiative vs Elastic



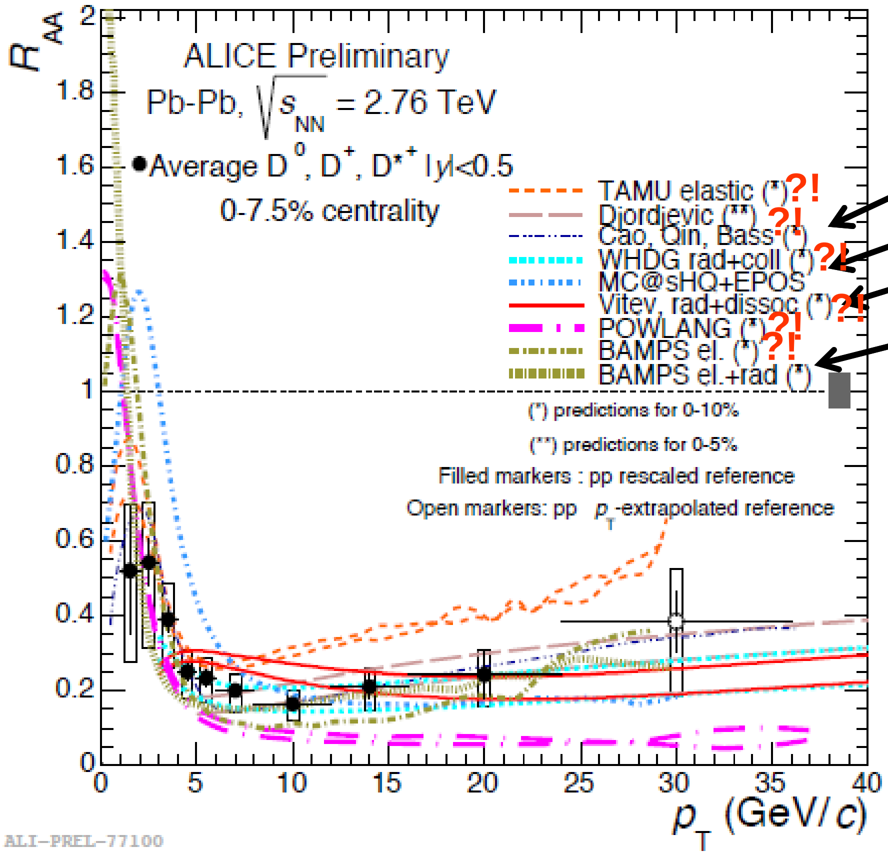
"Thick" plasma

$$\lambda < L < \frac{M^2}{\hat{q}}$$

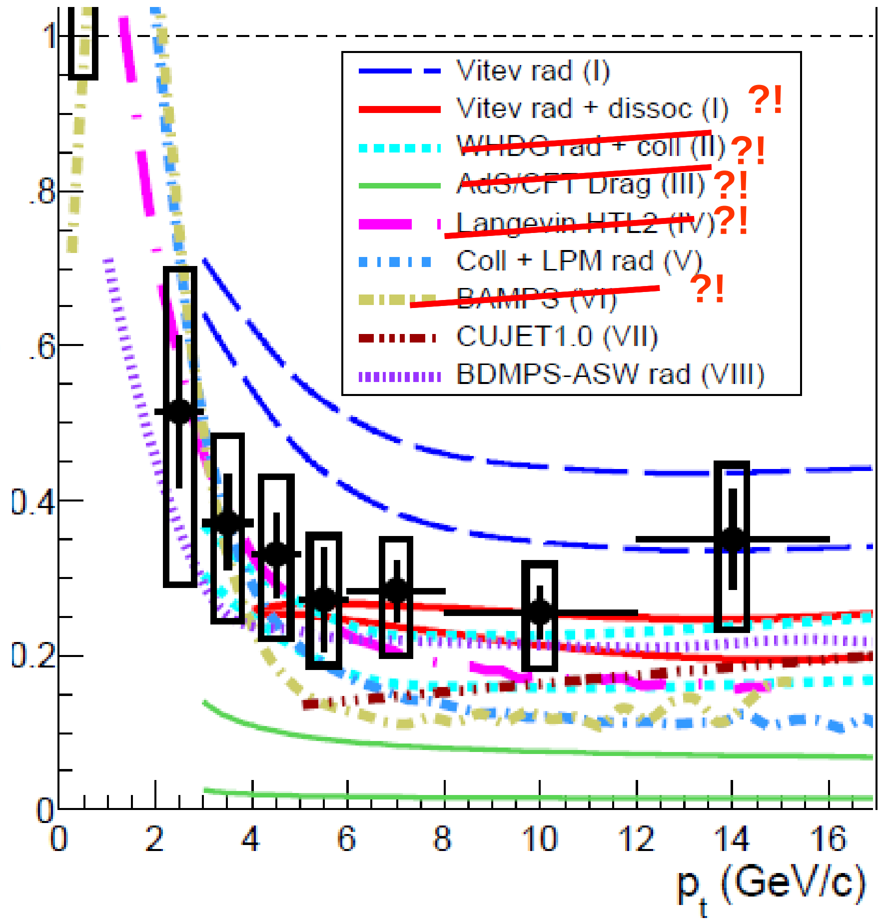
Typical picture for b quarks

Models vs data: RAA

Average R_{AA} (0-7.5%)



Radiative with Langevin ?!
No finite path length
Issue with mass hierarchy ?
Oversimplistic treatment of coherence



Constraining heavy-quark energy loss with the joint analysis of D-mesons and non-prompt J/Psi nuclear modification factors

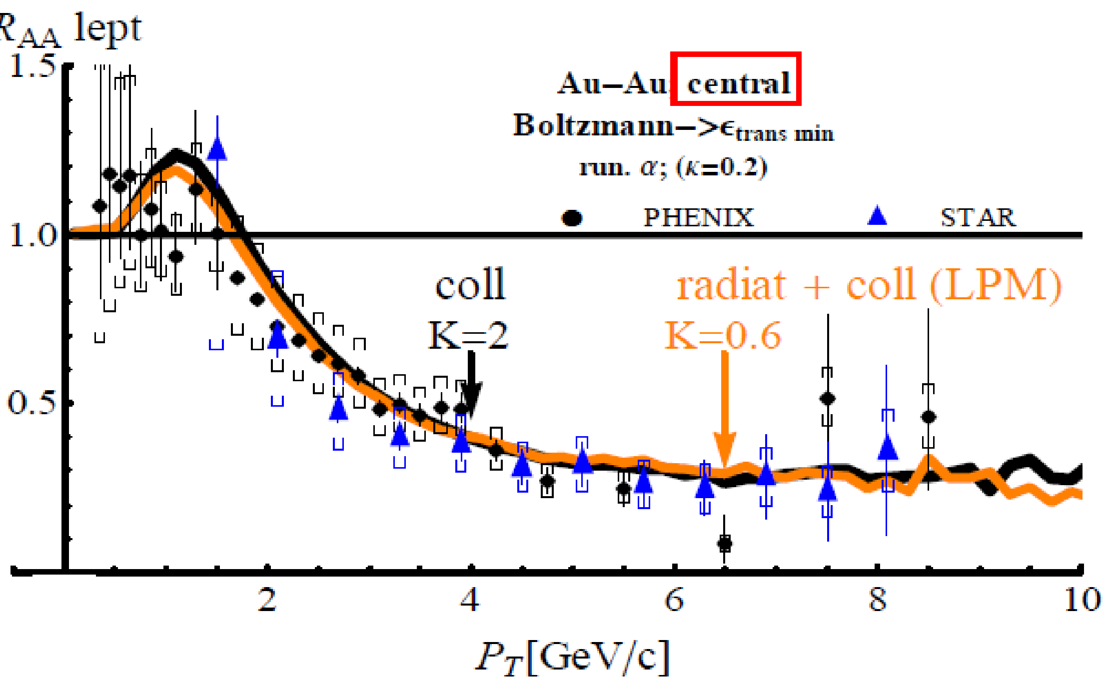
Motivation and Context

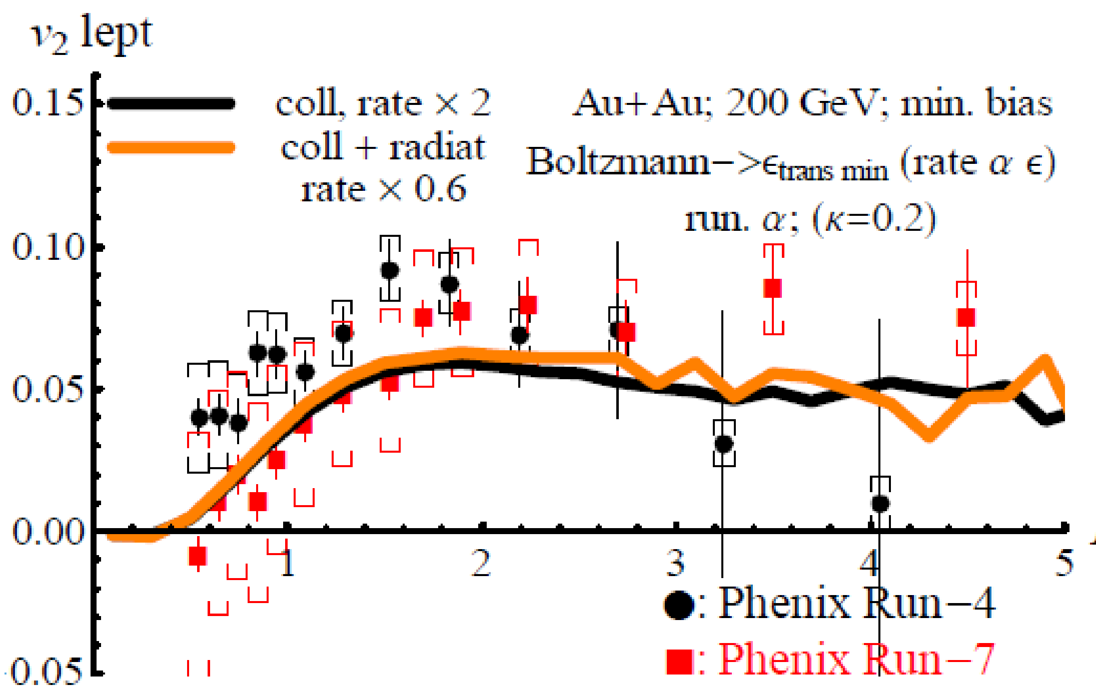
- It all started at RHIC (Gossiaux, SQM 2009; J. Phys. G: Nucl. Part. Phys. 37 (2010)):

Round 1

Round 6

Elliptical Flow

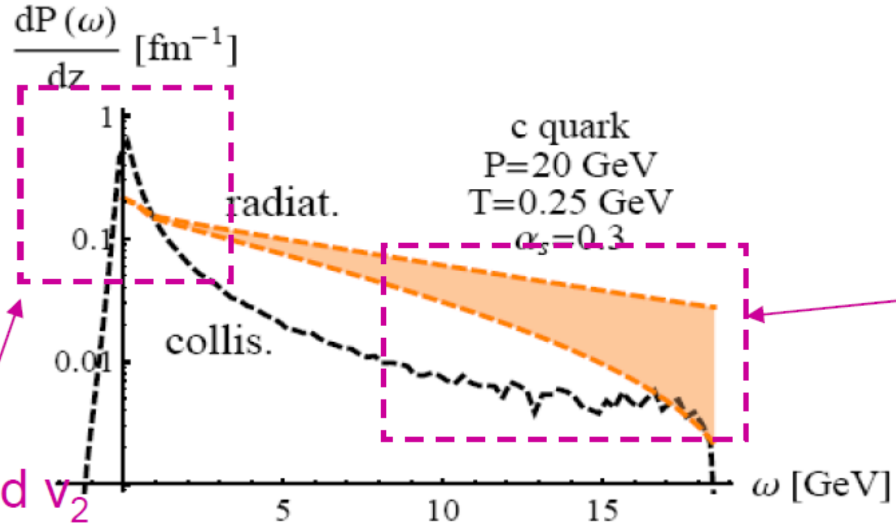




Motivation and Context

➤ It all started at RHIC (Gossiaux, SQM 2009; J. Phys. G: Nucl. Part. Phys. 37 (2010)):

However, it seems difficult to kill the Devil with the present measurements (and present control on the theory). In other words, the (present) winner is the one you have bet on



R_{AA} and v_2 physics

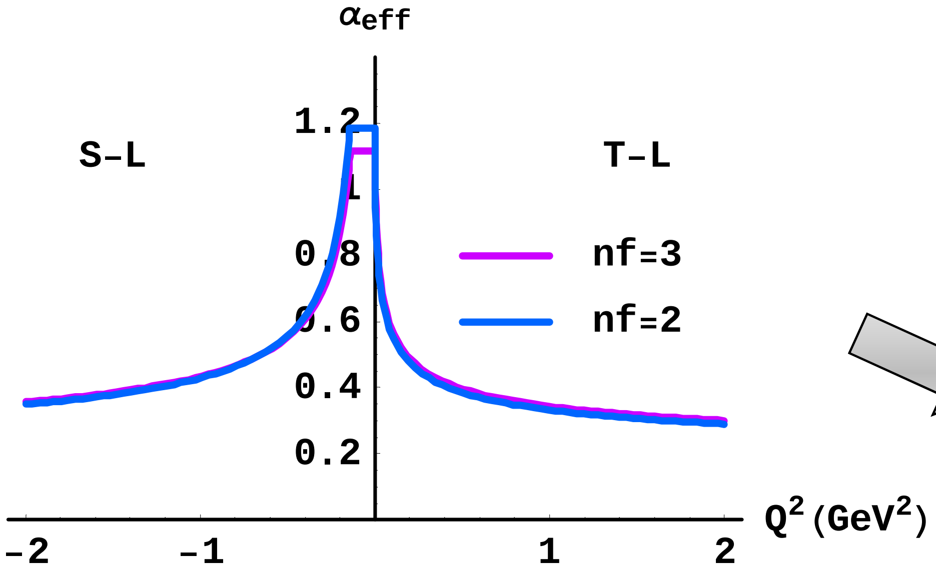
What we need

- D and B separately (in any case)
- tagged HQ jets and I_{AA} (and other correlations)

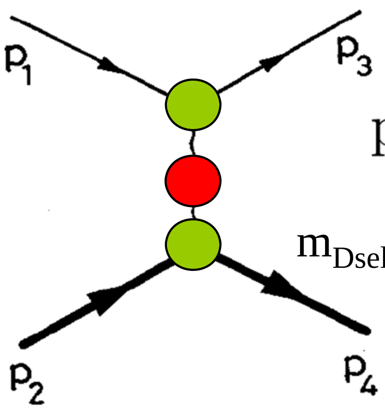
Now the competition strikes back !!!

Our Basic Ingredients for HQ Collisional Energy Loss

I. Effective running $\alpha_s(Q^2)$



II. One gluon exchange with self-consistent Debye mass



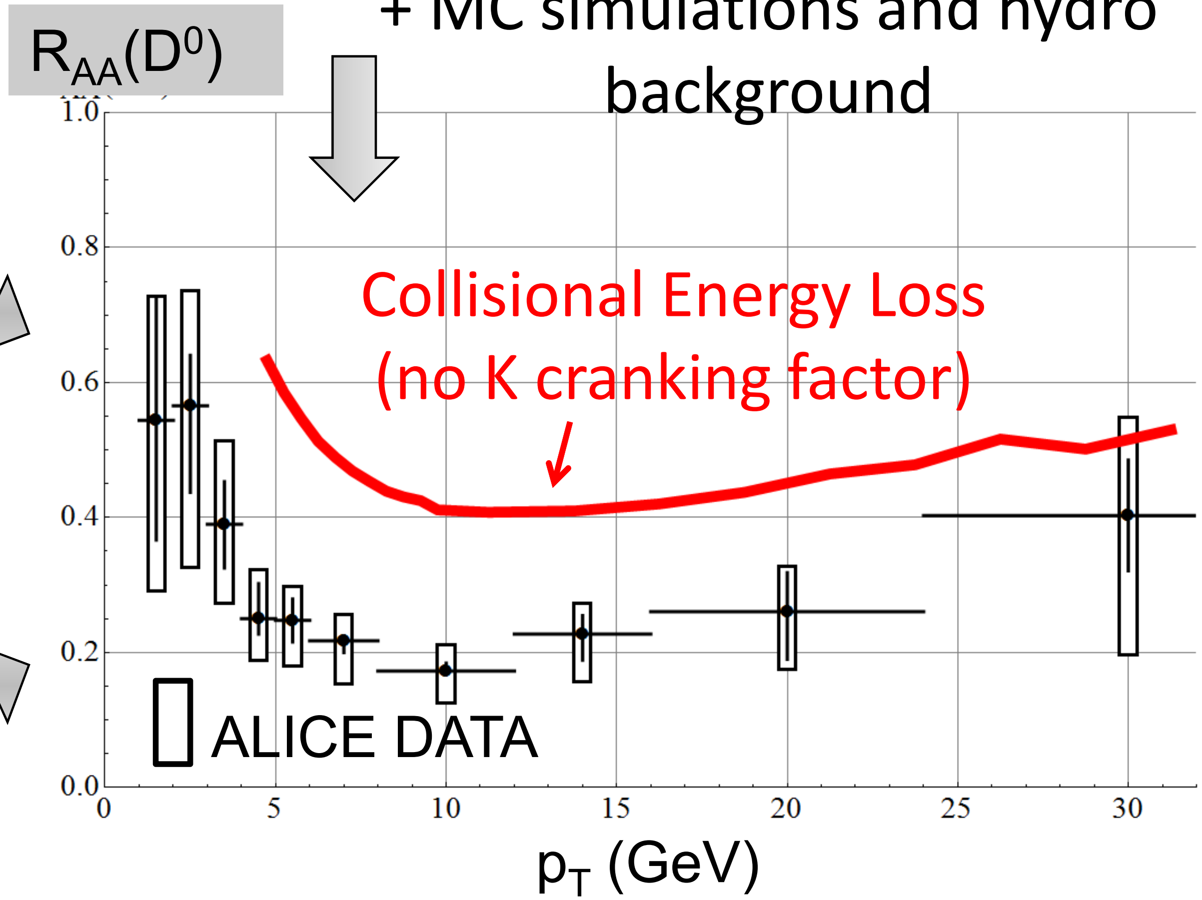
$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{\text{Dself}}(T)}$$

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

+ u and s channels

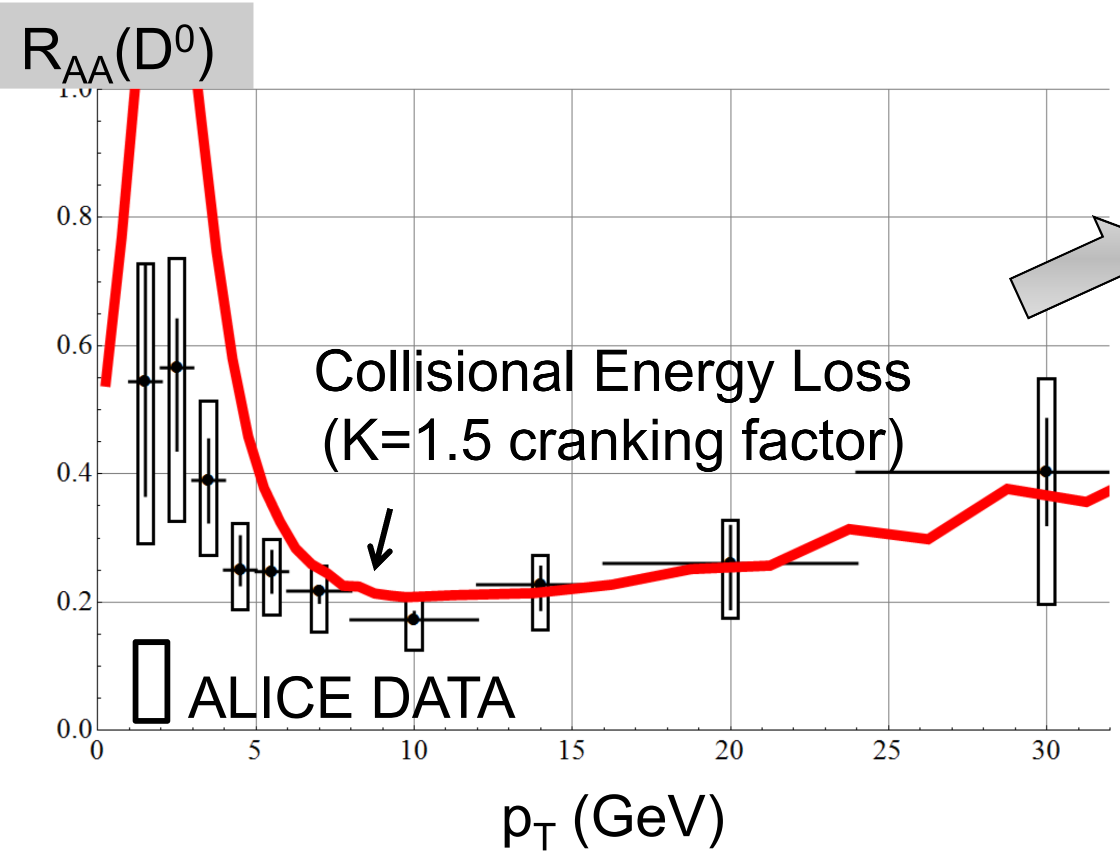
"running α_s" model for $\frac{d\sigma_{\text{el}}}{dt}$

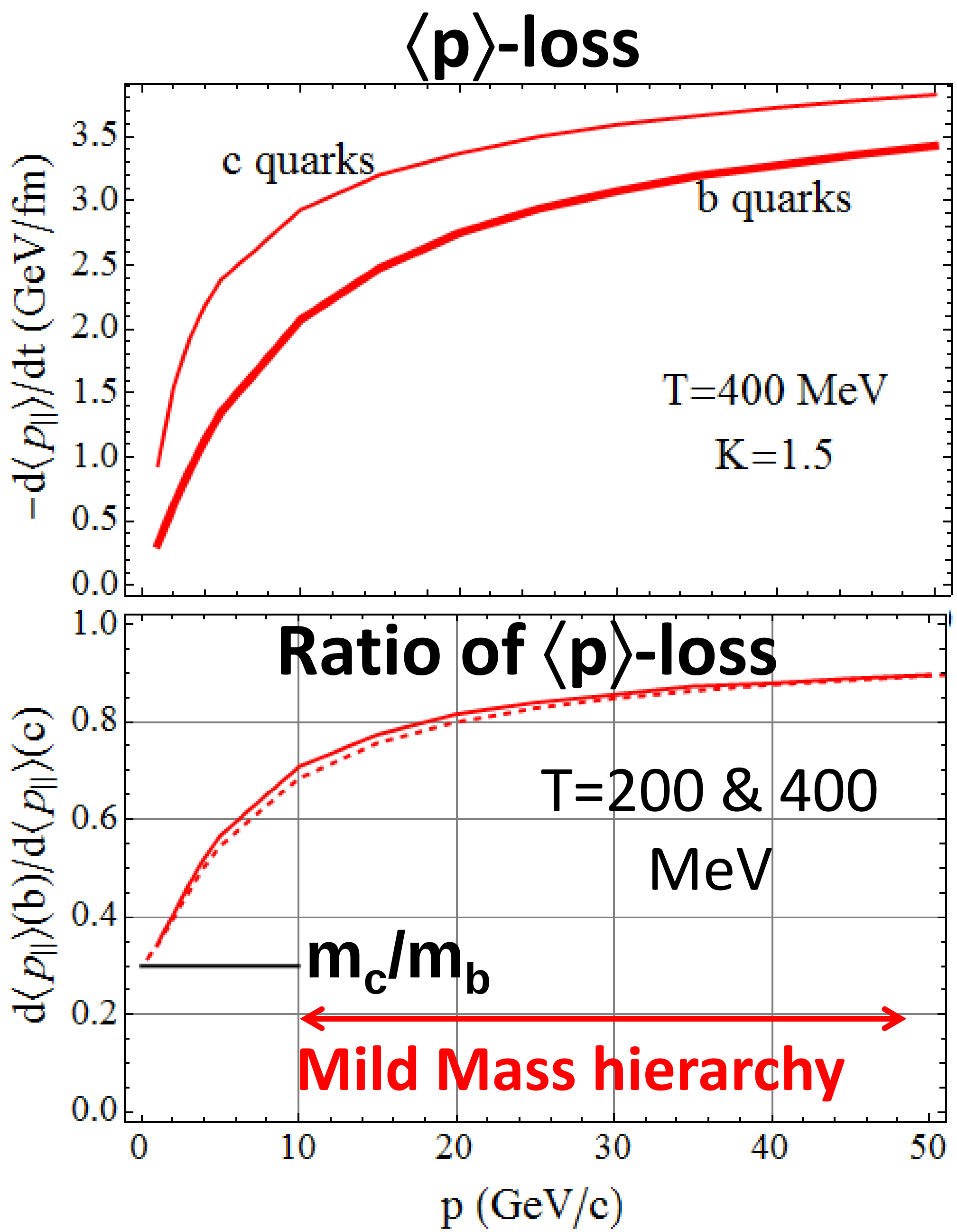
+ MC simulations and hydro background



Lack of quenching as compared with the data

HQ Collisional Energy Loss and Mass Hierarchy



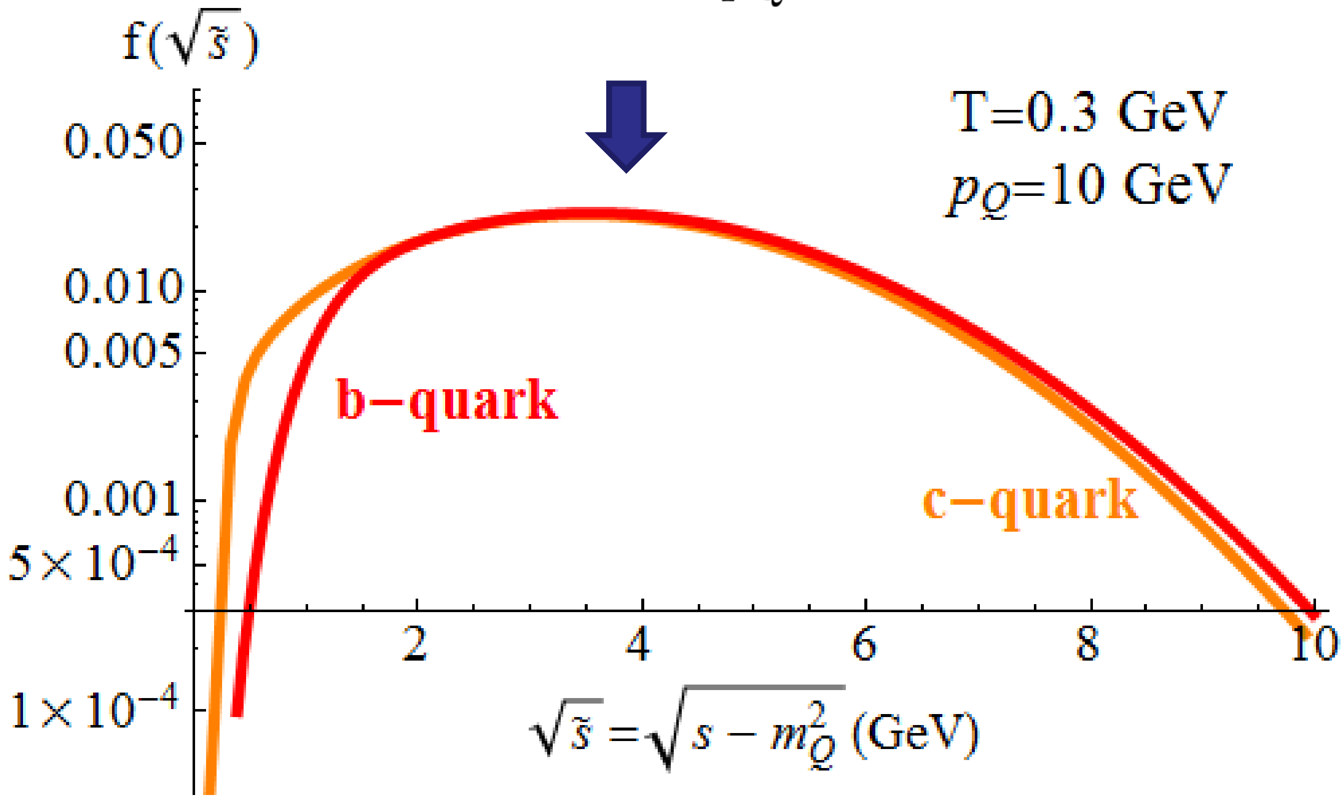


Quenching ok (at intermediate and large p_T) at the price of a K=1.5-2 cranking factor

Radiation at Intermediate Energies ?

Max at $\tilde{s} \approx 2 p_Q T$

Distribution *f* of invariant mass for some HQ of given p_Q in a (weak) QGP



For most of the scatterings: $\tilde{s} \gg \{l_t^2, k_t^2\}$ (typical scales in the direction $\perp$ to HQ propagation)

But NOT $s \gg m_Q^2$ (source of many simplifications)

(Induced) Radiative Energy Loss

In the literature:

From naïve "dead cone" effect $$\frac{d\sigma_{\rm rad}}{\theta d\theta} \propto \frac{\theta^2}{\left(\theta^2+\frac{M_Q^2}{E_Q^2}\right)^2}$$ ...

... To rather involved formalisms implementing coherence effects at high energy, but relying on simplifying assumptions (fixed scattering centers, $\lambda >> 1/m_D$,...) : parametric dependences not always easy to unravel

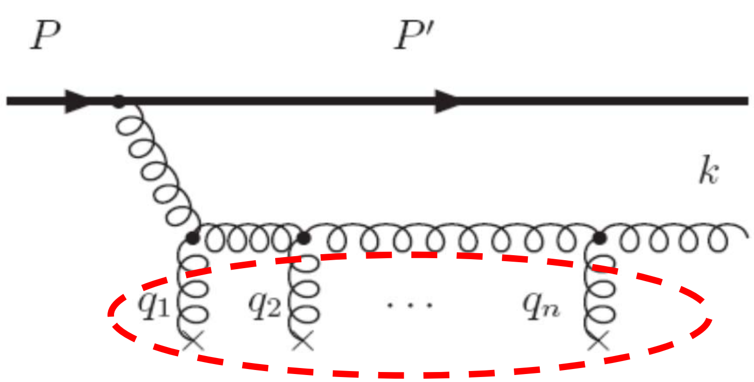
Our approach: Phys. Rev. D **89** (2014) 074018; arXiv:1307.5270.

- Study radiation ↔ Gunion-Bertsch who proposed a pQCD model for light quark radiation phenomenology in high-energy collisions
- Consider relativistic HQ, but intermediate energy where coherence effects are not dominant (HQ => smaller formation time)
  - extension of the Gunion-Bertsch model to heavy quarks
  - investigating the influence of a finite energy

Corrections from Coherence

Coherent Induced Radiative

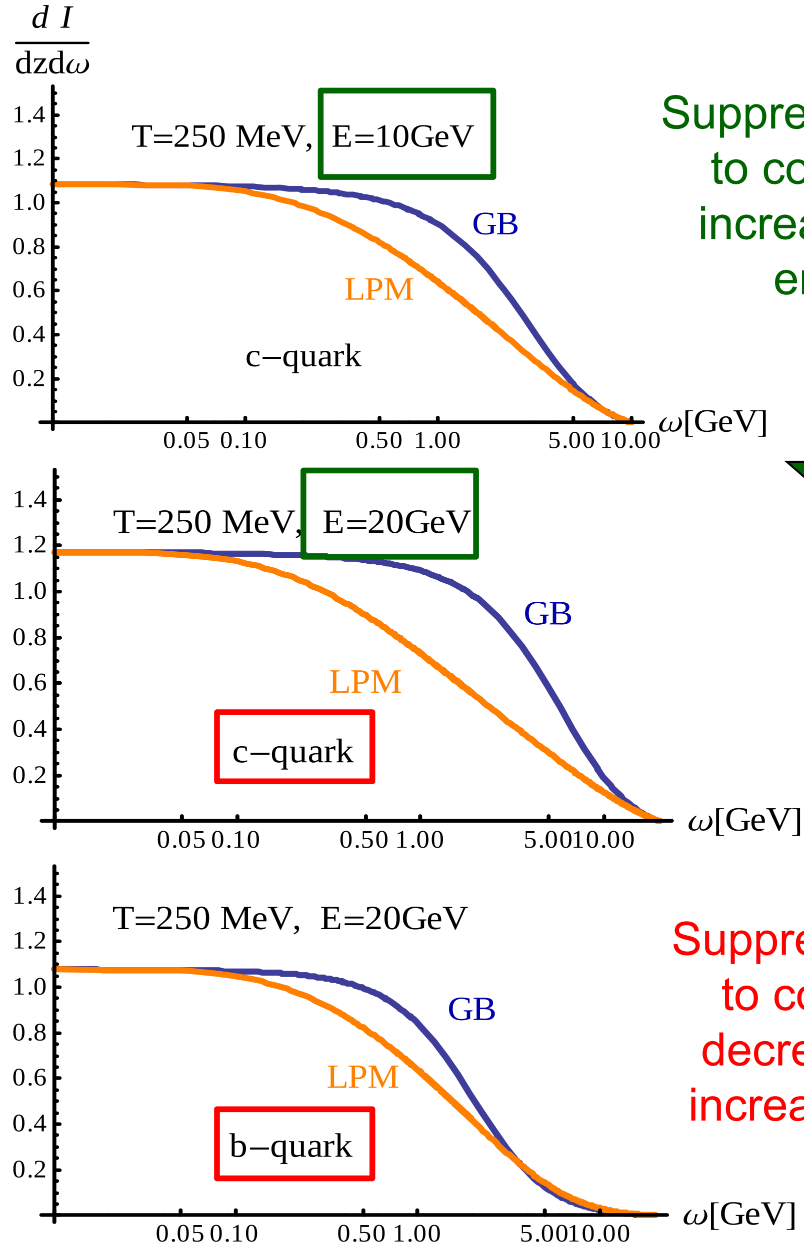
Formation time picture: for $l_{f,mult}>\lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



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

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

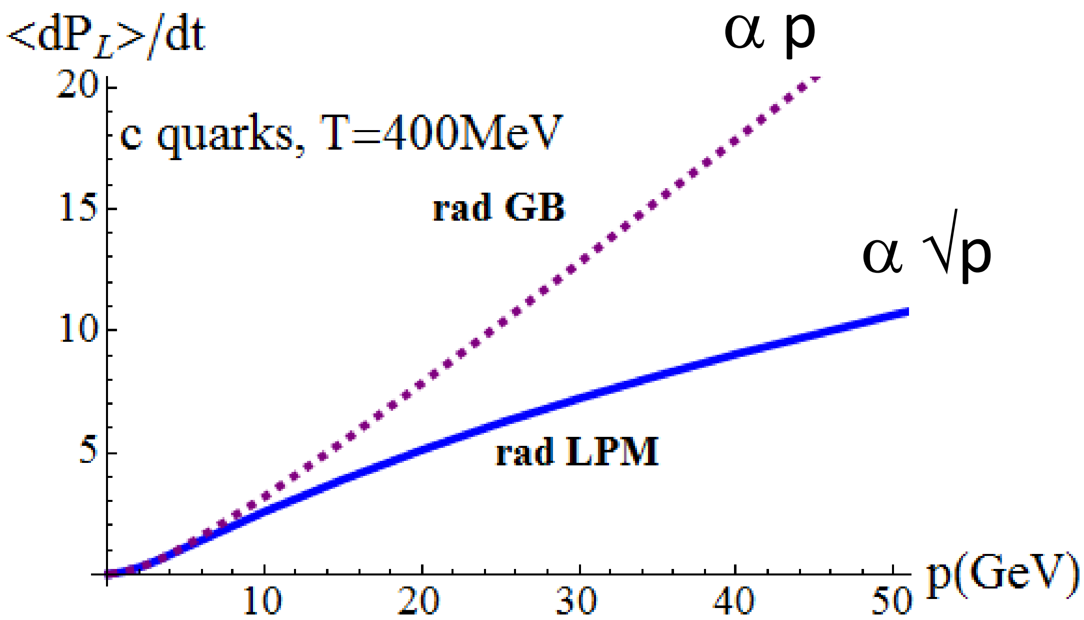
Nuclear Physics A (2013), 301, [arXiv:1209.0844]



Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

Radiative Momentum Loss with Running α_s $d\sigma_{el}$



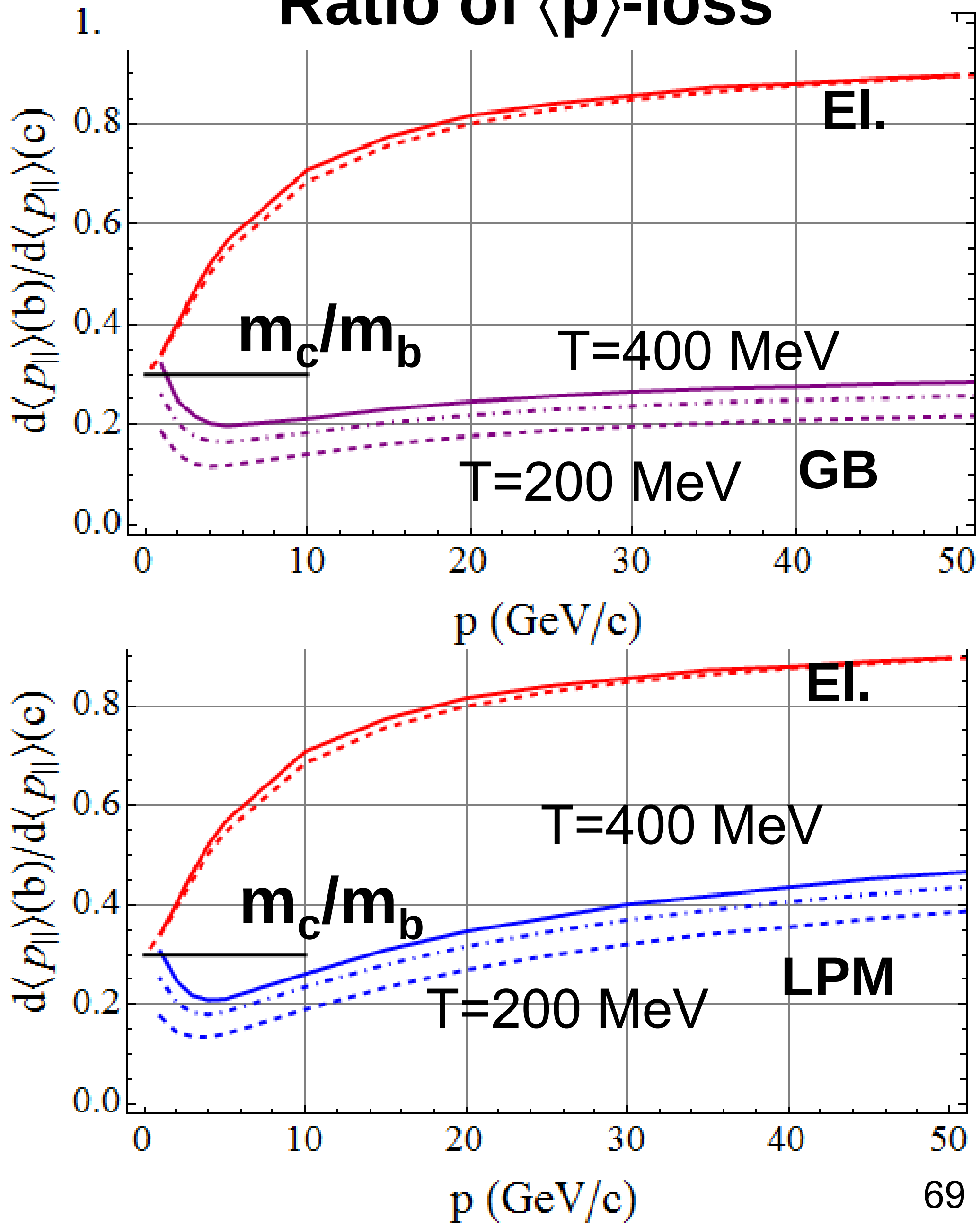
Mass hierarchy:

Elastic < rad LPM < rad GB

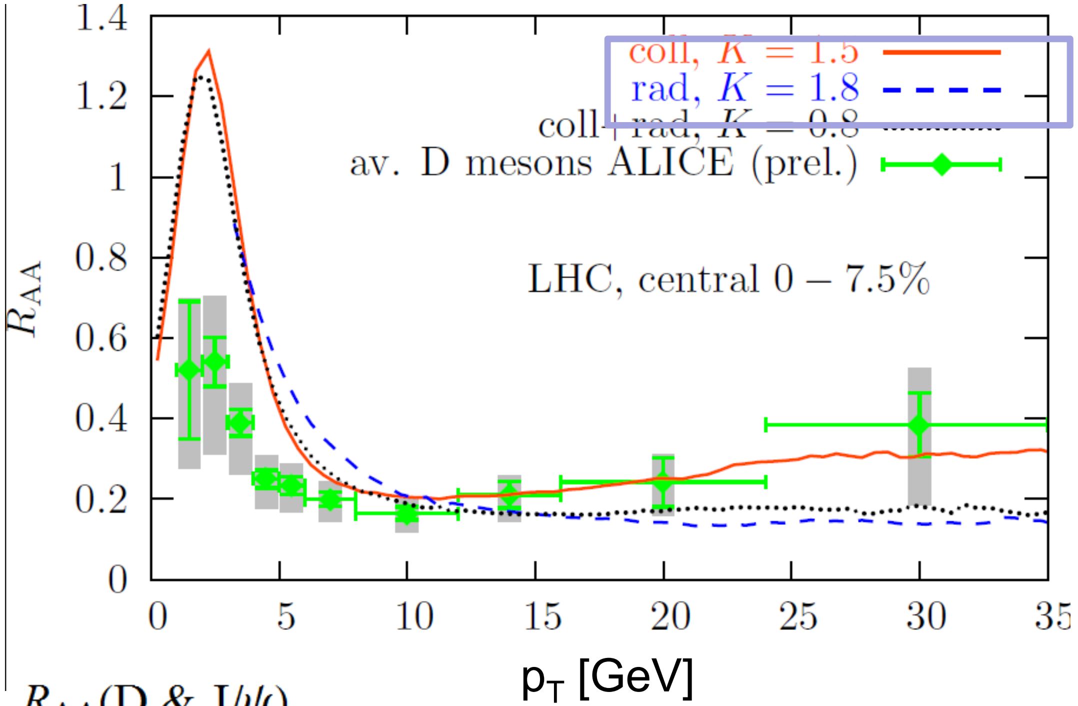
(weak) (strong) (strong)

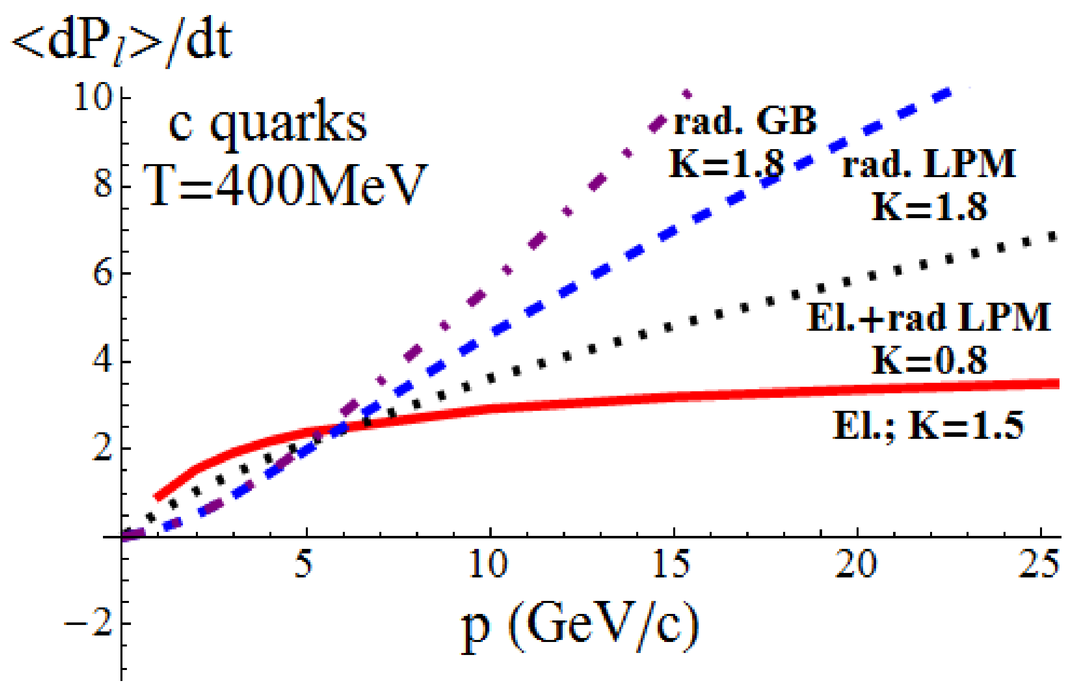
in the available exp range

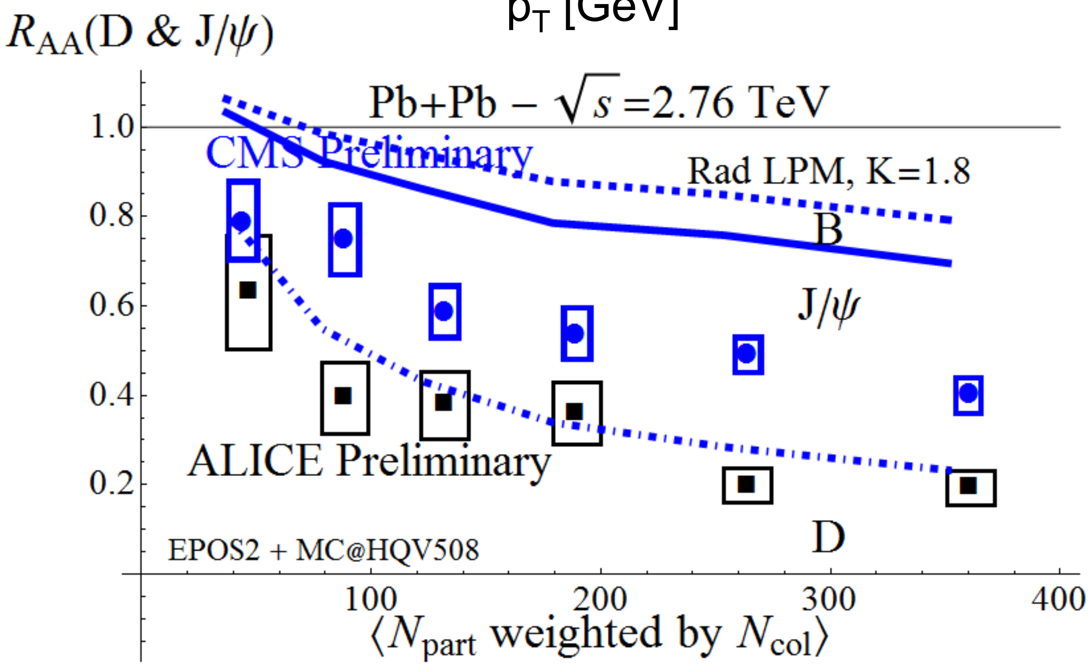
Ratio of ⟨p⟩-loss



Contact with LHC Data: I. Pure radiative w LPM





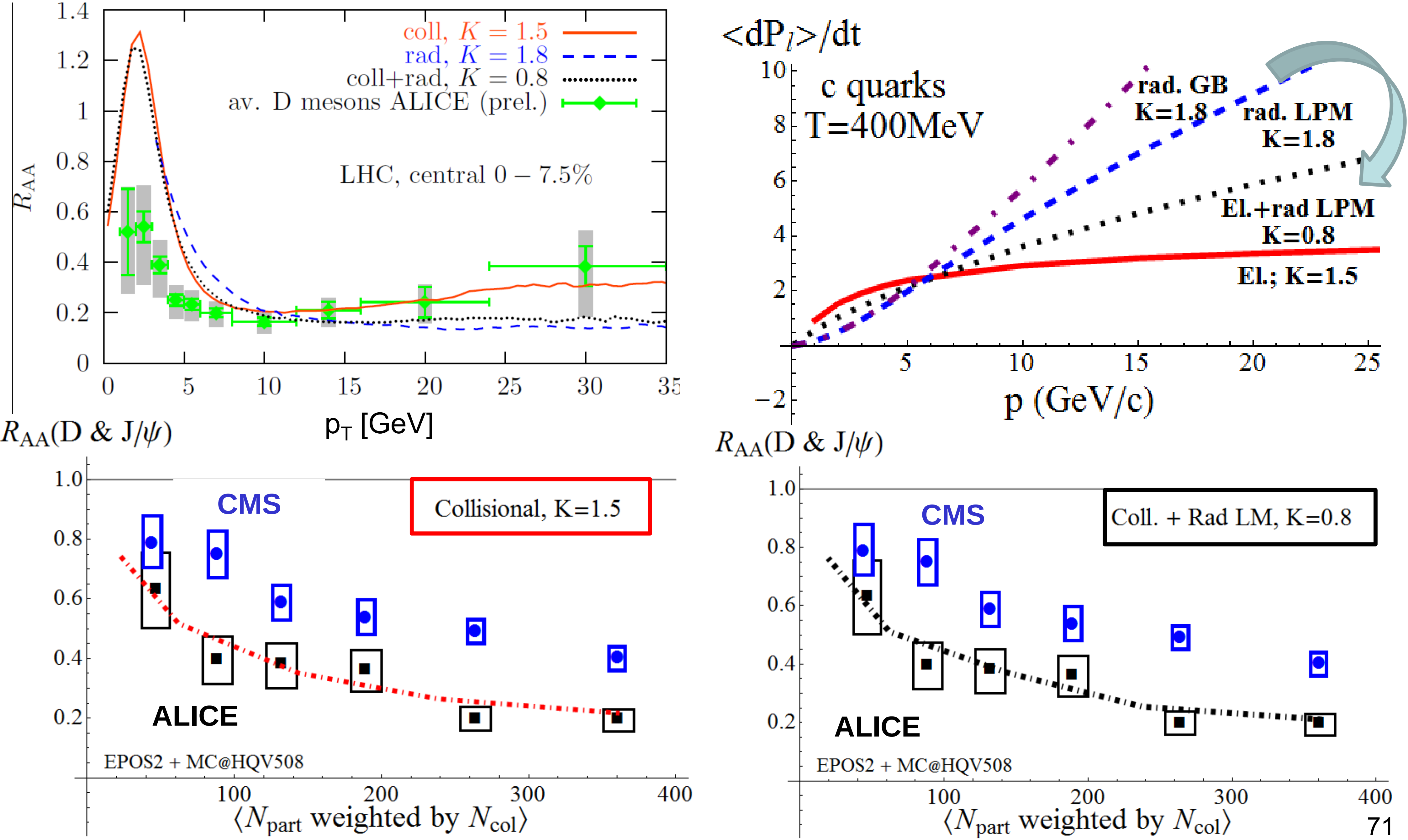


Combined CMS + ALICE data not compatible with a strong mass hierarchy

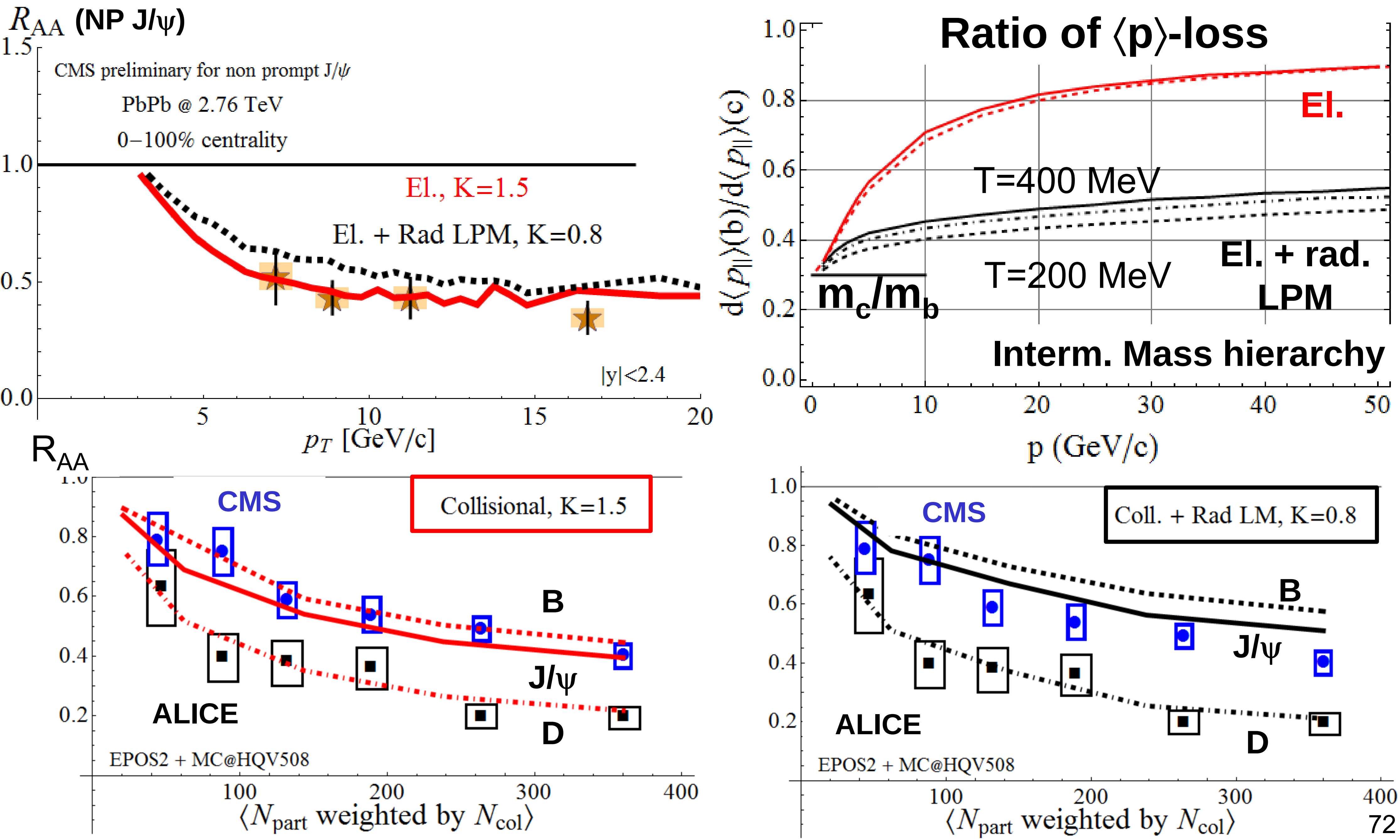
$$\left(\frac{dE}{dz} \propto \frac{1}{\mu m_Q}\right)$$

…also found in AdS/CFT

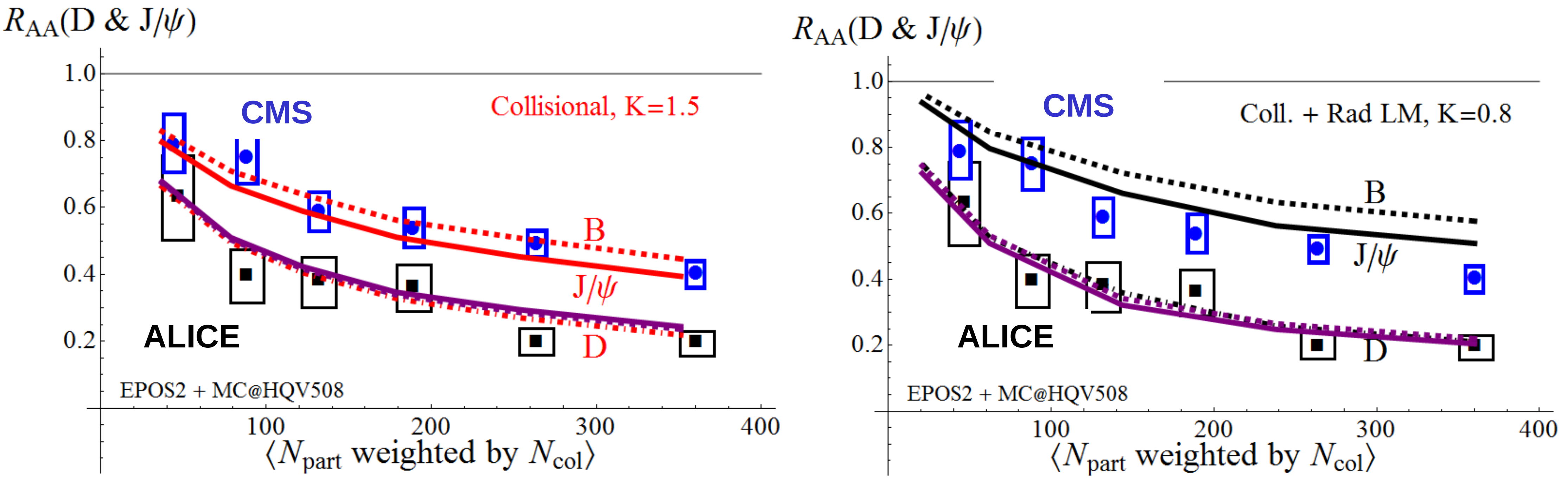
II with collisional component: a) for c-quarks…



… b) for b-quarks (& Non-Prompt J/ψ)



… c) for b-quarks with c-quark mass Eloss



Purple: B and non-prompt J/ψ with mb=1.5 GeV for Eloss

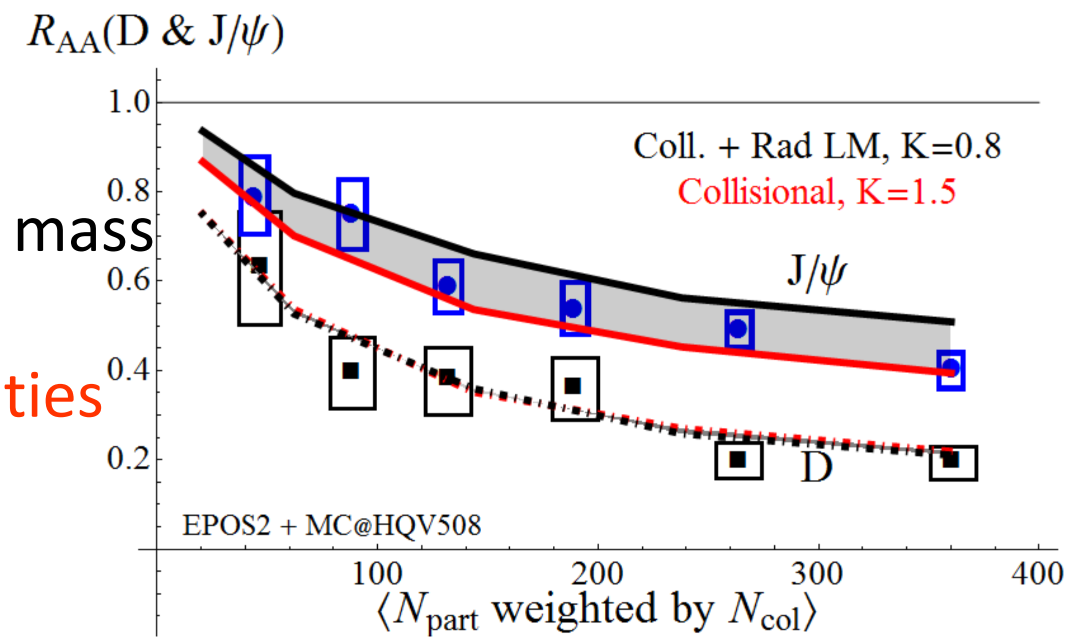
Confirms that the mass hierarchy in the Eloss (model) is the key ingredient for the observed R_{AA}

Conclusions and Perspectives

➢ dynamical light quarks and finite energy effects are mandatory for the quantitative understanding of heavy quarks production in ultrarelativistic nucleus-nucleus collisions

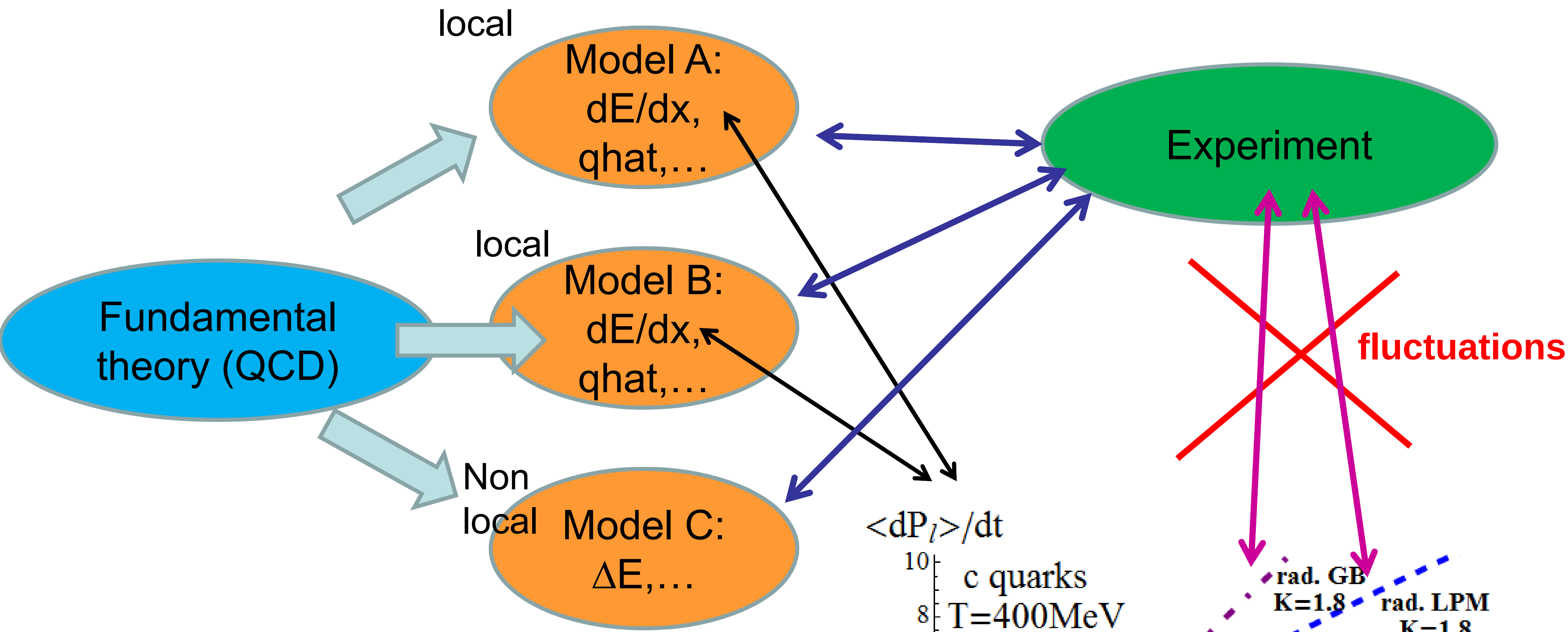
➢ A large part of the mass hierarchy in seen in radiative energy loss does not originate from the "dead cone" effect (interference at play)

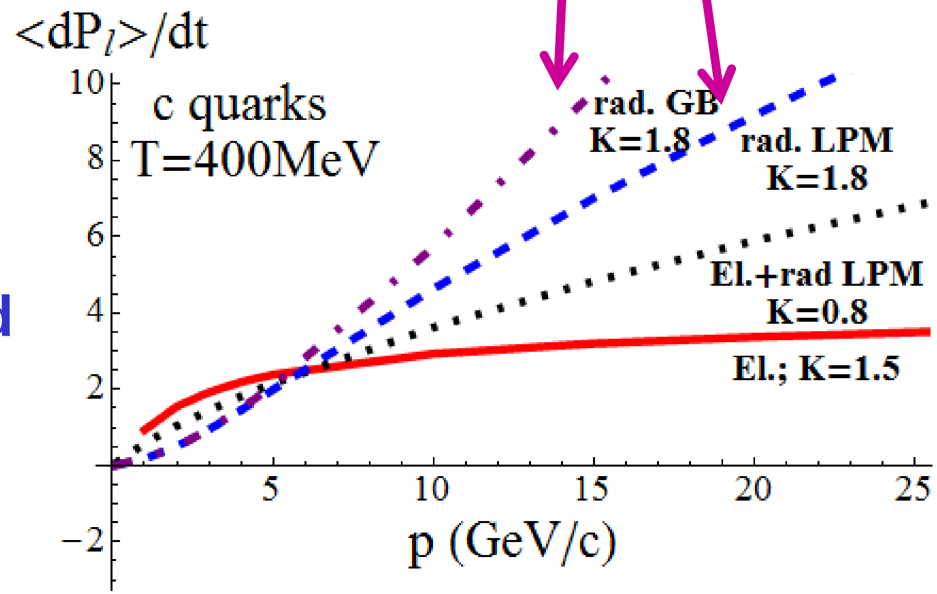
➢ (In our models), combined LHC data from ALICE and CMS is found in slightly better agreement with the rather weak mass hierarchy observed (f.i.) in collisional Eloss… but various sources of uncertainties and better data needed



➢ Perspectives: coherence and finite path lengths in dynamical media

Motivation and Context

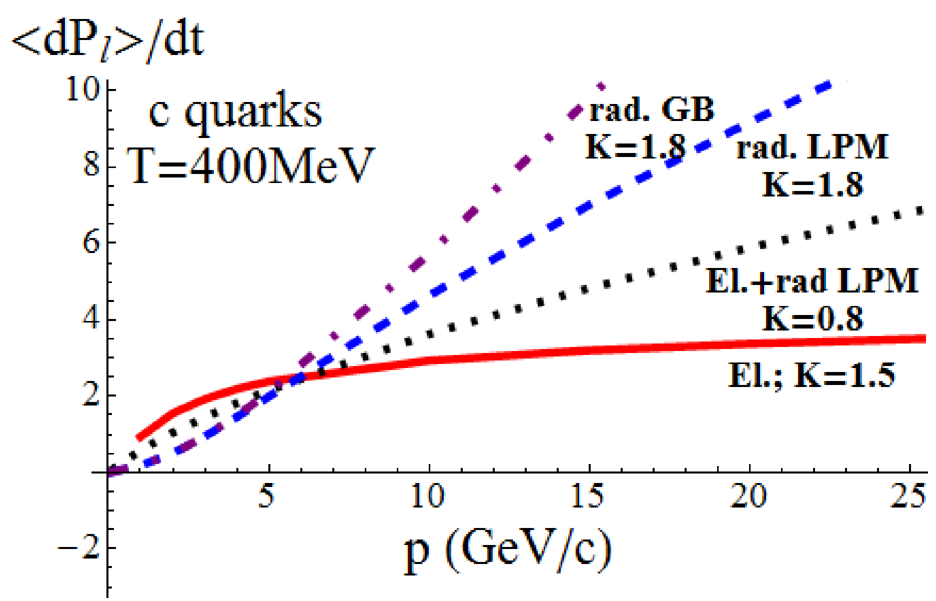




My falsifiability criteria: 2 microscopic models satisfying lQCD "constrains" and both "explaining" the data should be considered as UNRESOLVABLE

Perspective: to move further

Global view



Excluded by LHC -> 2014]

Jury is still out

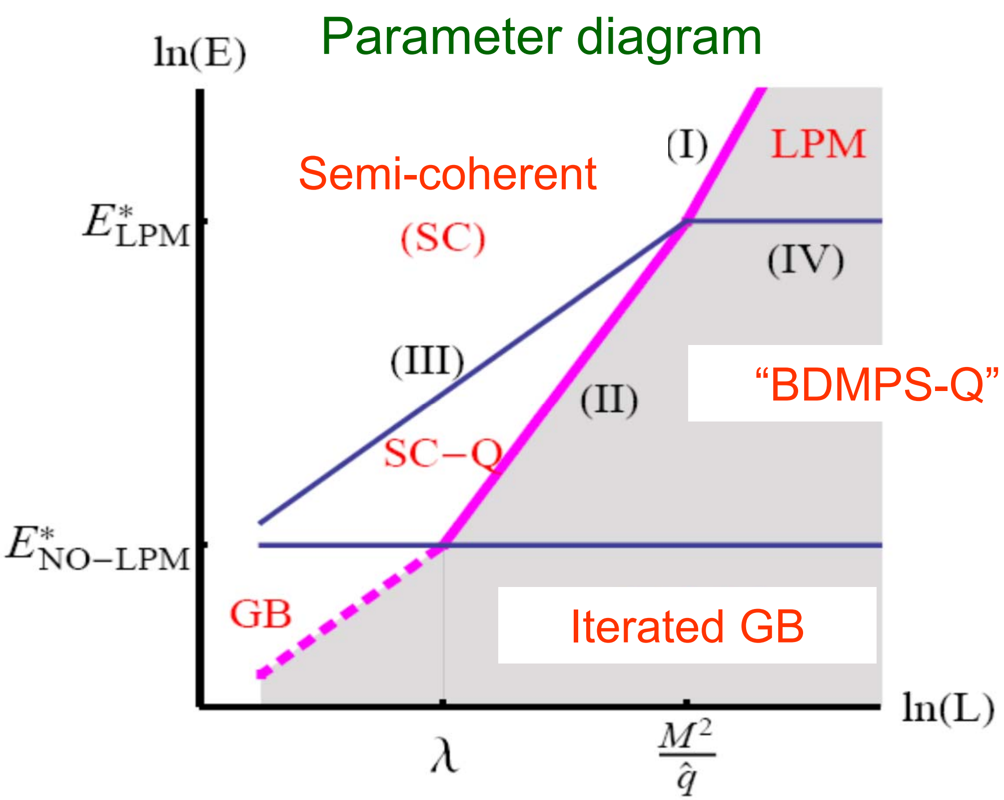
“fixed” by RHIC

Not “fixed” by RHIC

Full lattice calculation of (at least) drag coefficient at γ=5-10 is mandatory in order to rule out some theories

Perspective: to move further

1) Agree on basic physical regimes:



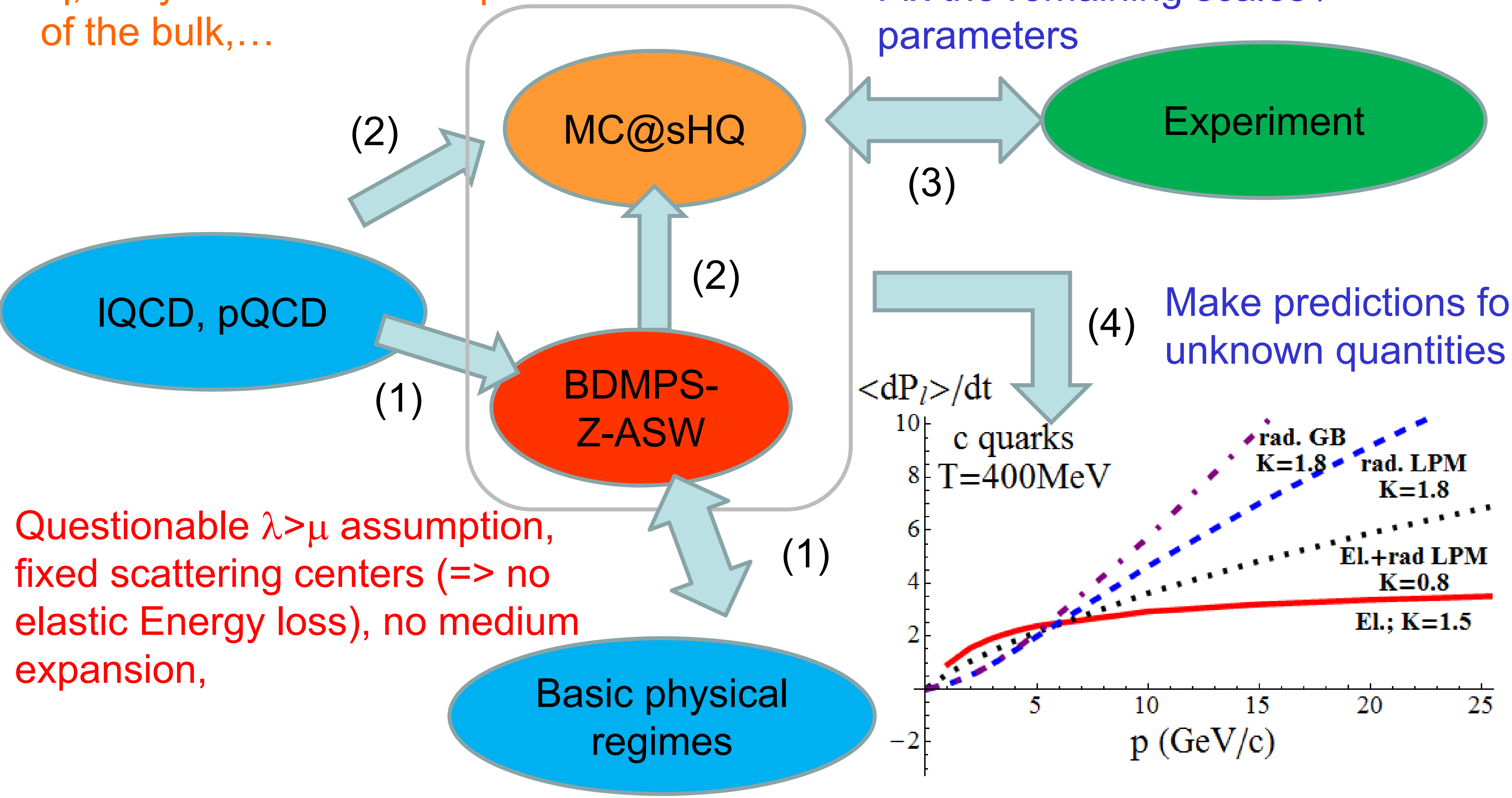
$\hat{q}$ is not the only coefficient !

2) Program If no further lQCD

Phenomenological but: dynamical lq, easy to follow time-dependence of the bulk,…

Fix the remaining scales / parameters

Make predictions for unknown quantities



Questionable λ>μ assumption, fixed scattering centers (=> no elastic Energy loss), no medium expansion,