EMMI Rapid Reaction Task Force

GSI, 18-22 July 2016

Microscopic Models of Energy Loss and transport coefficients: The Nantes Approach

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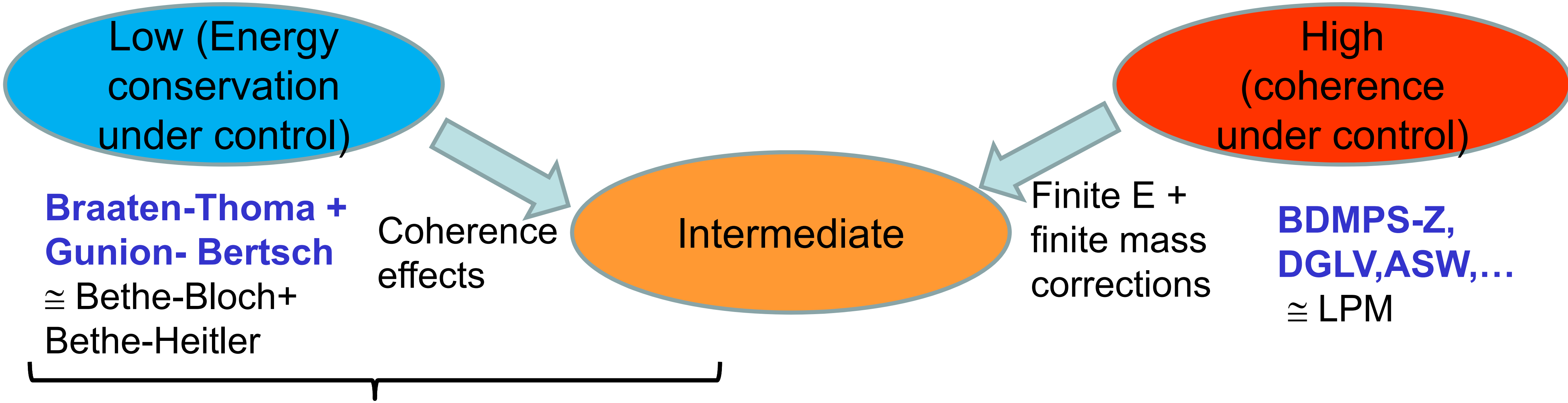
Subatech

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

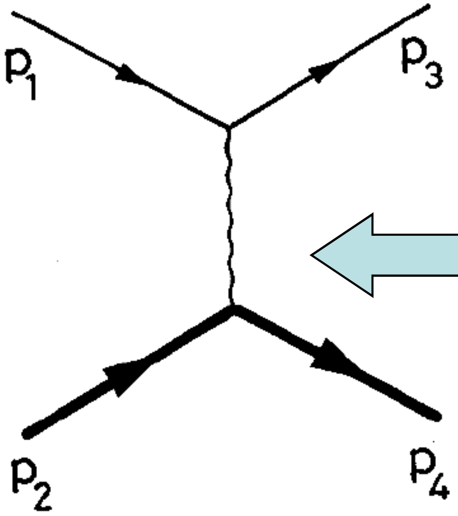


Approach pursued in our **models…** Unfortunately too many of them

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

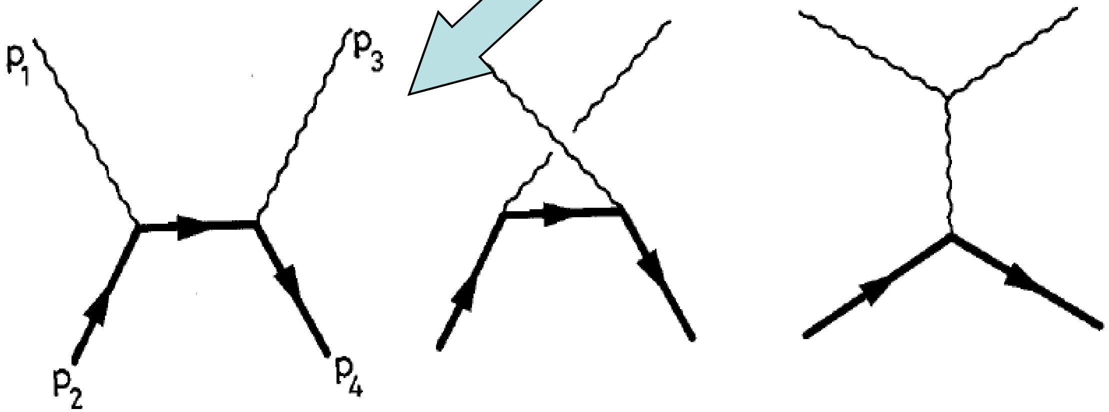
Cross sections

Starting from Combridge (79) as a basis:



$$\sum |\mathcal{M}|^2 = \frac{64\pi^2\alpha^2(Q^2)}{9}\,\frac{(M^2-u)^2+(s-M^2)^2+2M^2t}{t^2}$$

$$\sum |\mathcal{M}|^2 = \pi^2\alpha^2(Q^2)\Big[\frac{32(s-M^2)(M^2-u)}{t^2} + \frac{64}{9}\,\frac{(s-M^2)(M^2-u)+2M^2(s+M^2)}{(s-M^2)^2} + \frac{64}{9}\,\frac{(s-M^2)(M^2-u)+2M^2(M^2+u)}{(M^2-u)^2} + \frac{16}{9}\,\frac{M^2(4M^2-t)}{(s-M^2)(M^2-u)} + 16\,\frac{(s-M^2)(M^2-u)+M^2(s-u)}{t\,(s-M^2)} - 16\,\frac{(s-M^2)(M^2-u)-M^2(s-u)}{t\,(M^2-u)}\Big]$$



However, t-channel is IR divergent => modelS

Naïve regulating of IR divergence:

$$\frac{1}{t} \to \frac{1}{t-\mu^2}$$

With μ(T) or μ(t)

OBE model, NOT pQCD at finite T !!!

Models A/B: 2 customary choices

$\mu^2(T) = m_D^2 = 4\pi\alpha_s(1+3/6)xT^2$

(Svetitsky: 0.5; equil time of 1fm/c) !!!

$$\alpha_s(Q^2) \to \begin{cases} 0.3 \text{ (mod A)} \\ \alpha_s(2\pi T) \text{ (mod B)} \end{cases} (\approx 0.3)$$

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

T(MeV) \p(GeV/c)	10	20
200	0.18	0.27
400	0.35	0.54

… of the order of a few % !

Educated: Calibrating on HTL….

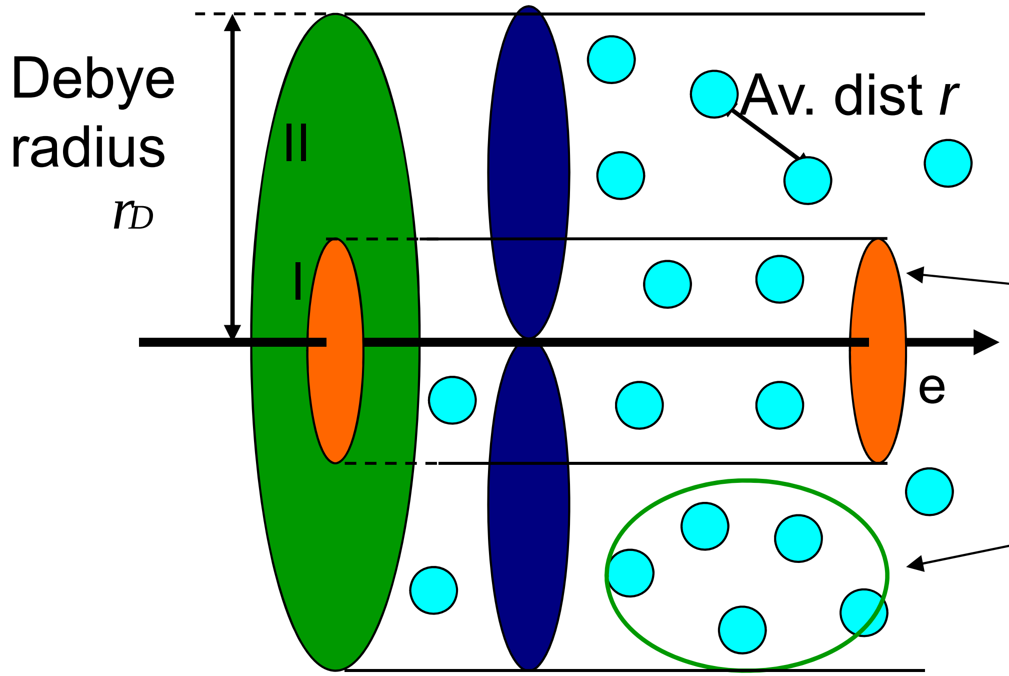
permits to fix the effective mass μ

Heavy fermion Energy loss in a relativistic plasma

Braaten – Yuan scheme

Relying on the smallness of the coupling constant

$$\frac{1}{M} << r = \frac{1}{T} << \frac{1}{q^*} << r_D \approx \frac{1}{eT} << \lambda \approx \frac{1}{e^2 T}$$



Heavy fermion of mass M probes the medium via virtual fermion of momentum q

Region I: $q>q^*$: hard; close collisions; individual; incoherent.

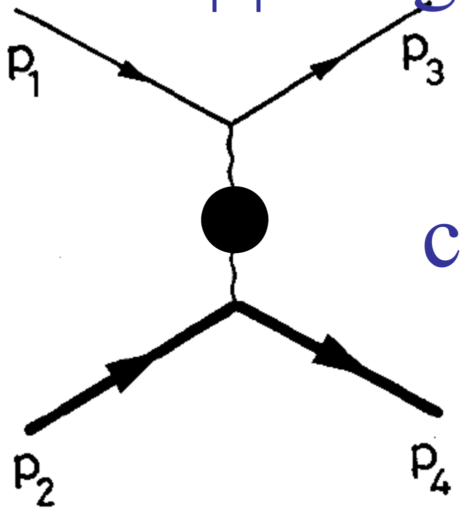
Region II: $q<q^*$: soft; far collisions; collective; coherent; macroscopic.

Braaten-Thoma:

(Peshier – Peigné)

HTL: convergent kinetic
(matching 2 regions)

Low |t|: large distances

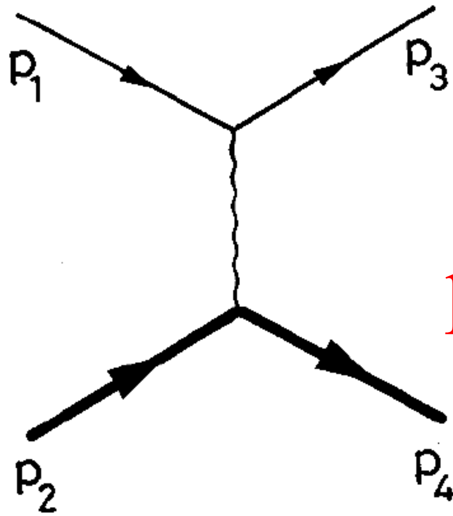


HTL:
collective
modes

$|t^*|$

+

Large |t|: close coll.



Bare
propagator

$$G_{\mu\nu}(Q) = \frac{-\delta_{\mu 0}\delta_{\nu 0}}{q^2 + \Pi_{00}} + \frac{\delta_{ij} - \hat{q}_i \hat{q}_j}{q^2 - \omega^2 + \Pi_T}$$

$$G_{\mu\nu}(Q) = \frac{-\delta_{\mu\nu}}{q^2 - \omega^2}$$

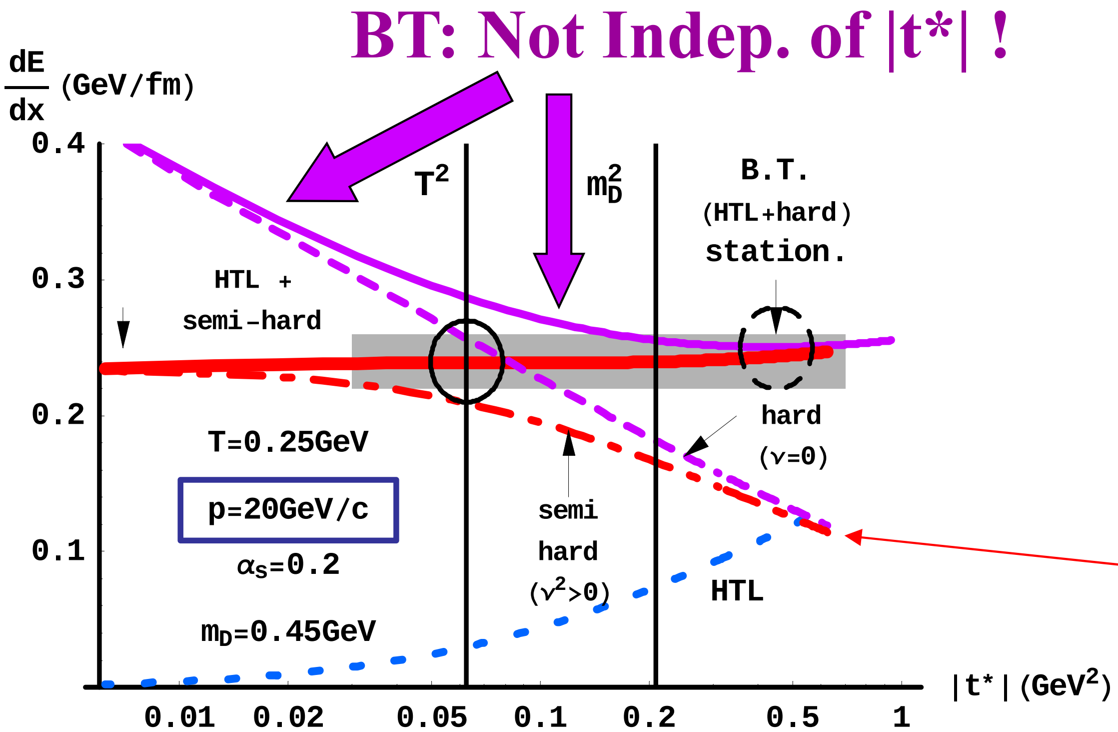
$$\frac{dE_{soft}}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{t^*}}{m_D/\sqrt{3}}\right) + \ldots$$

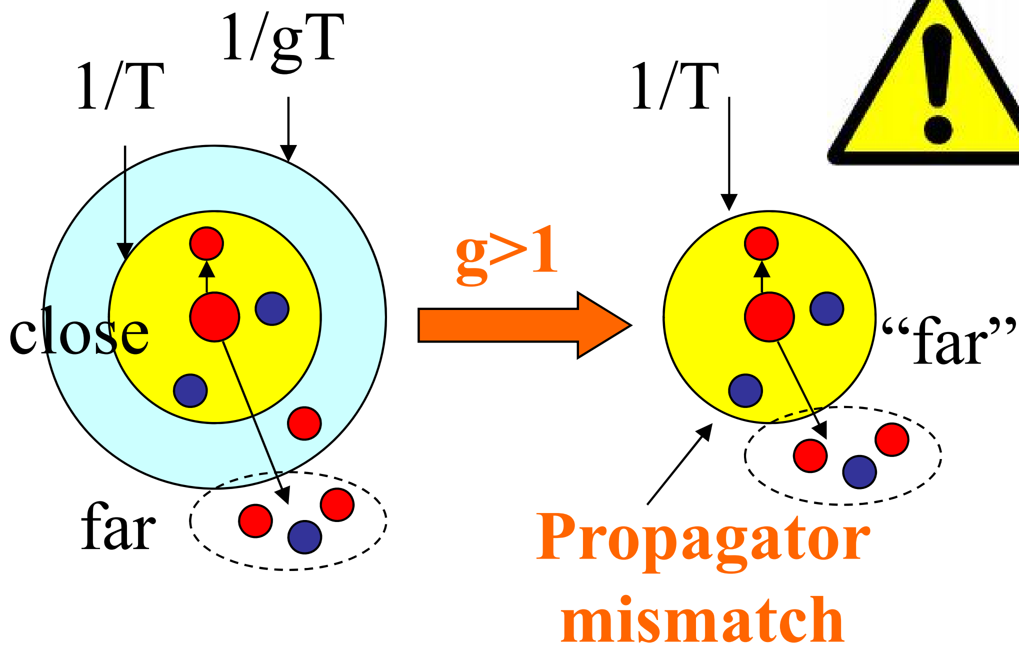
$$\frac{dE_{hard}}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{ET}}{\sqrt{t^*}}\right) + \ldots$$

SUM: $\dfrac{dE}{dx} = \dfrac{2}{3}\alpha\, m_D^2 \ln\left(\dfrac{\sqrt{ET}}{m_D/\sqrt{3}}\right)$

Indep. of |t*| !
(provided $g^2T^2 \ll |t^*| \ll T^2$)

In QGP: $g^2T^2 > T^2$!!!





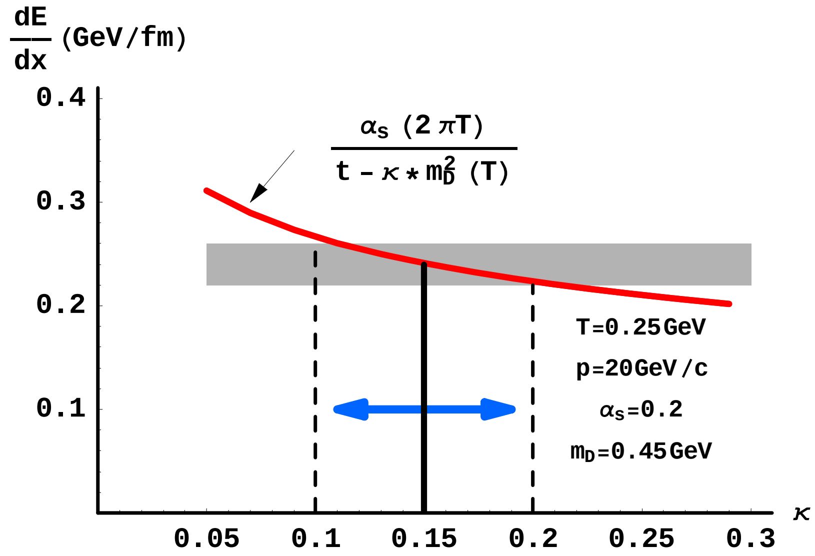
Our solution: Introduce a semi-hard propagator --$1/(t-\nu^2)$-- for $|t|>|t^*|$ to attenuate the discontinuities at t^* in BT approach.

Prescription: ν^2 in the semi-hard prop. is *chosen* such that the resulting E loss is maximally $|t^*|$-independent.

This allows a matching at a natural value of $|t^*| \approx T$... Not an increase wrt Braaten-Thoma

Model C: optimal μ^2

THEN: Optimal choice of μ in our OBE model:



$$\frac{\alpha_s(2\pi T)}{t-\mu^2}$$

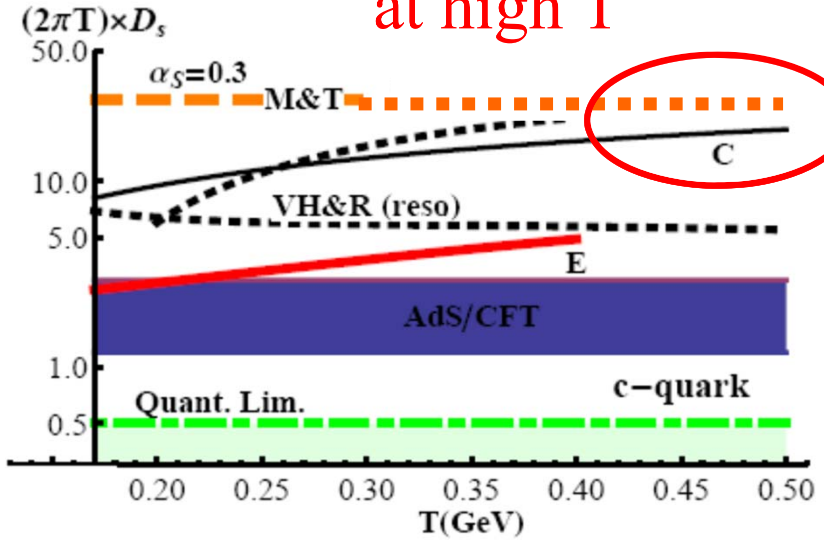
$$\boxed{\begin{array}{c}\mu^2(T) = \kappa\, m_D^{\,2}(T) \\ \text{With } \kappa \approx 0.15\end{array}}$$

with $m_D^{\,2} = 4\pi\alpha_s(2\pi T)(1+3/6)xT^2$

$\frac{dE_{coll}(c)}{dx}$ … factor 2 increase w.r.t. mod B (not enough to explain R_{AA})

T(MeV) \p(GeV/c)	10	20
200	0.36 (0.18)	0.49 (0.27)
400	0.70 (0.35)	0.98 (0.54)

Convergence with "pQCD" at high T



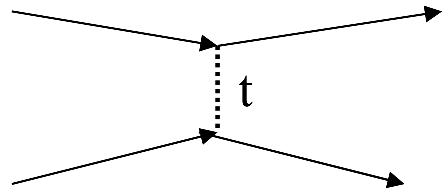
Refined: *running coupling constant*

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

Open question: long range behaviour and renormalisation at finite temperature

A Peshier: α_S not fixed at the right scale

Running of α_s (Peshier 06) in collisional E loss



Usually
$$\frac{dE_j}{dx} = \sum_s \int_{k^3} \rho_s(k)\, \Phi \int dt\, \frac{d\sigma_{js}}{dt}\, \omega$$

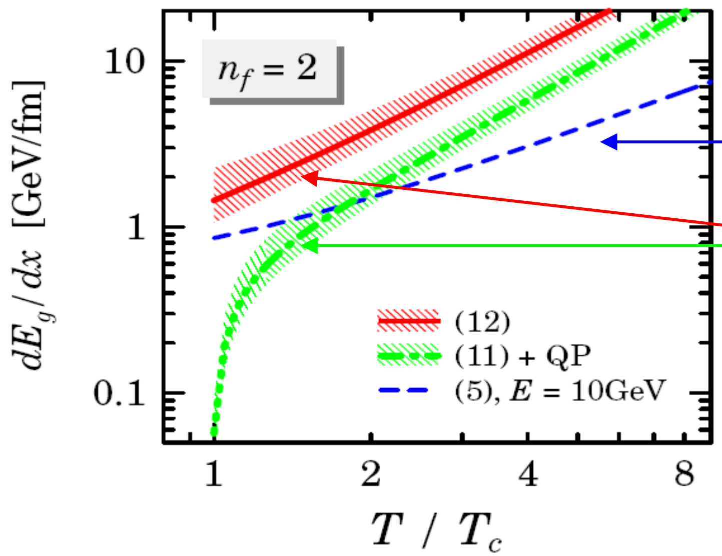
with
$$\Phi \int_{t_1}^{t_2} dt\, \frac{d\sigma_{js}}{dt}\, \omega = \frac{\pi C_{js} \alpha^2}{-k} \int_{t_1}^{t_2} \frac{dt}{t} = \frac{\pi C_{js} \alpha^2}{k} \ln \frac{t_1}{t_2}$$
and $\alpha_S(2\pi T)$

Doing it more cautiously

$$\Phi \int_{t_1}^{t_2} dt\, \frac{d\sigma_{js}}{dt}\, \omega = -\frac{\pi C_{js}}{k\, b_0^2} \int_{t_1}^{t_2} \frac{dt}{t \ln^2(|t|/\Lambda^2)}$$
Dominated by the soft scale

$$= \frac{\pi C_{js}}{k\, b_0^2} \left. \frac{1}{\ln(|t|/\Lambda^2)} \right|_{t_1}^{t_2} = \frac{\pi C_{js}}{k\, b_0} \left[\alpha(\mu^2) - \alpha(|t_1|)\right]$$
No log(E) increase. UV conv. for $t_1 \to \infty$

Softer scale $\Rightarrow$ larger E loss !!!

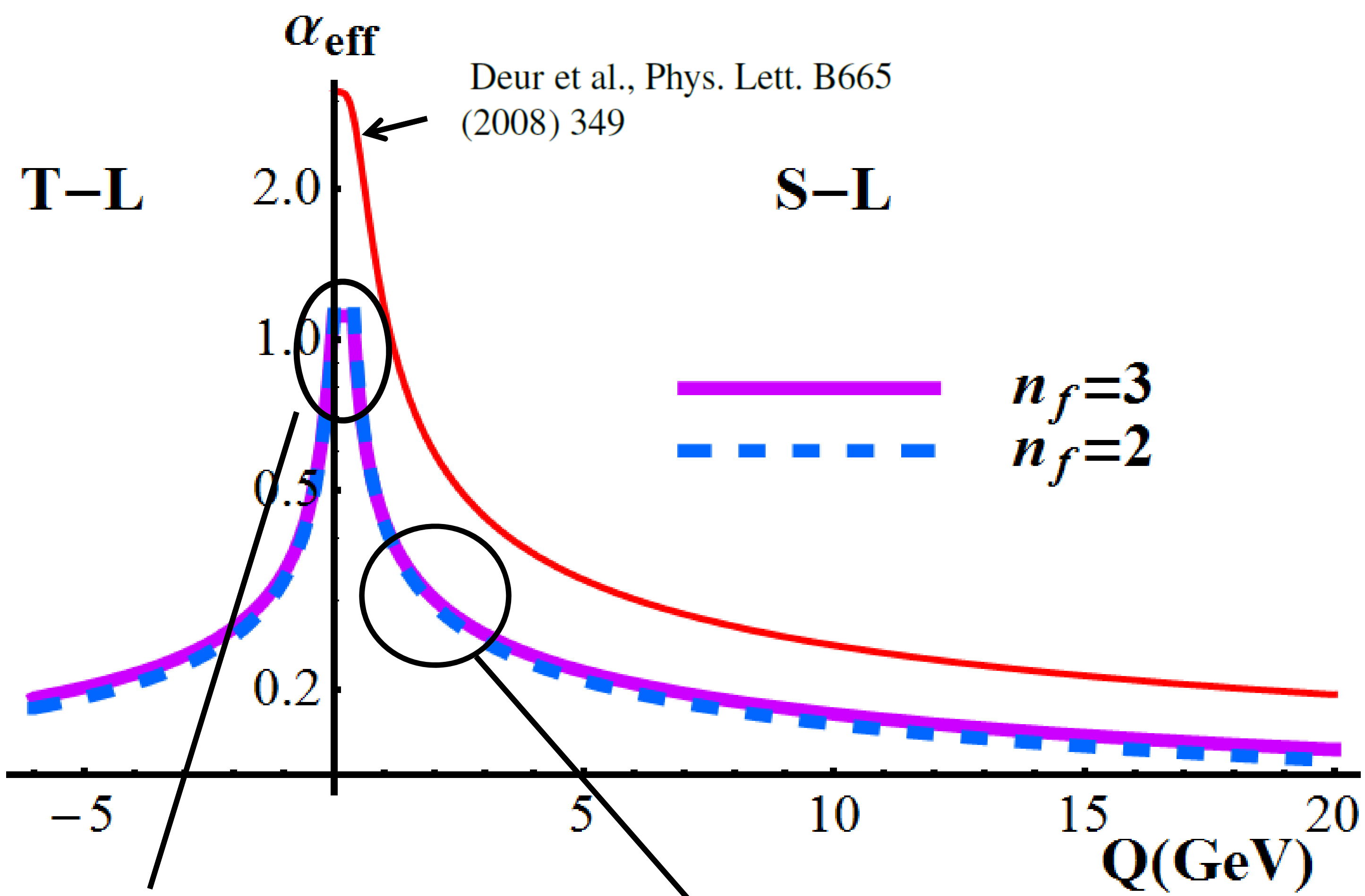


Bjorken

Peshier

"In fact, σ with running coupling … an order of magnitude larger than expected from the widely used expression $\sigma_{\alpha\ \mathrm{fix}} \propto \alpha^2(Q^2T)/\mu^2$. Thus, the present approach gives a consistent and simple explanation of phenomenologically inferred large cross sections found in transport models."

running α_s

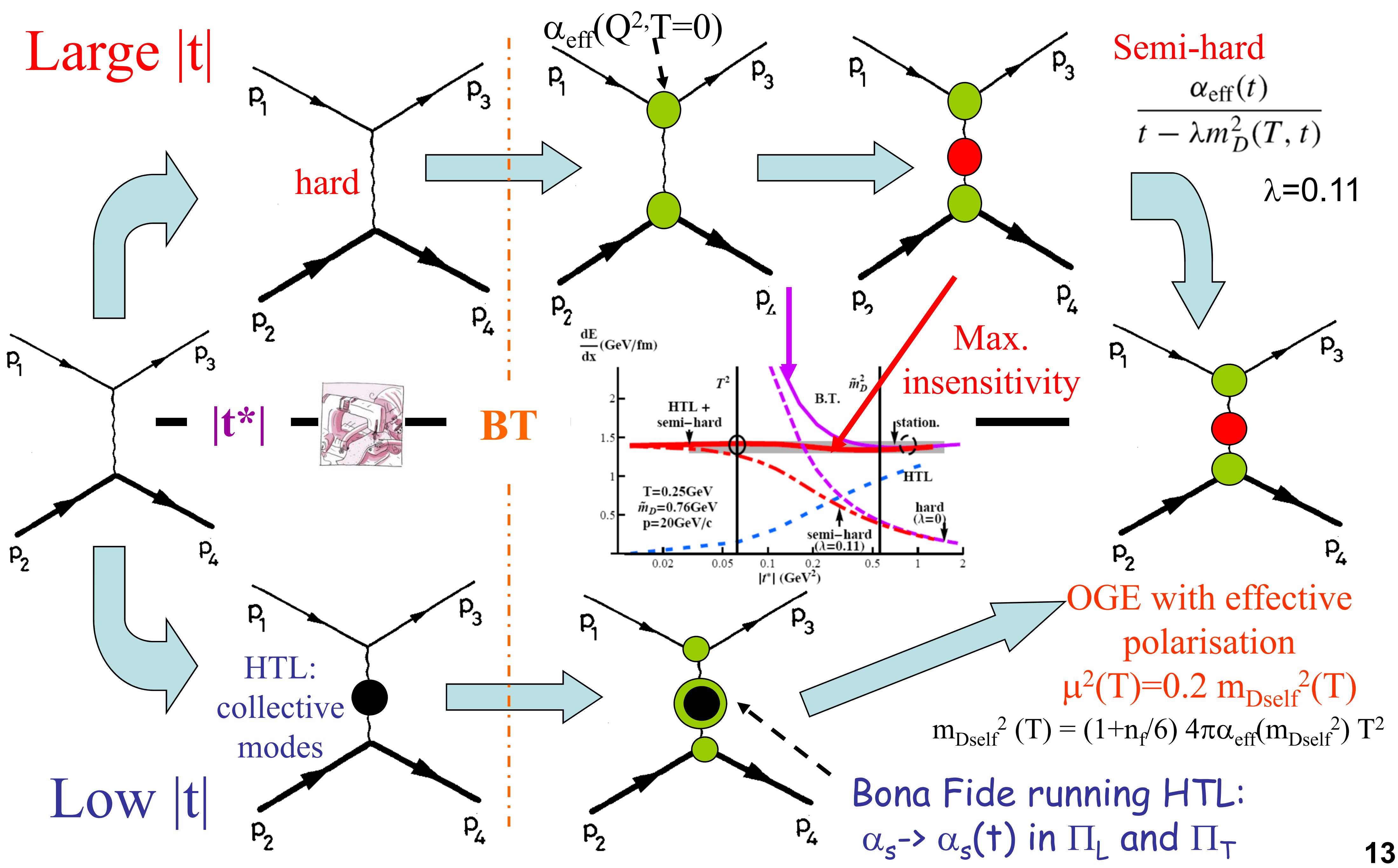


IR safe. The detailed form very close to Q^2 =0 is not important does not contribute to the energy loss

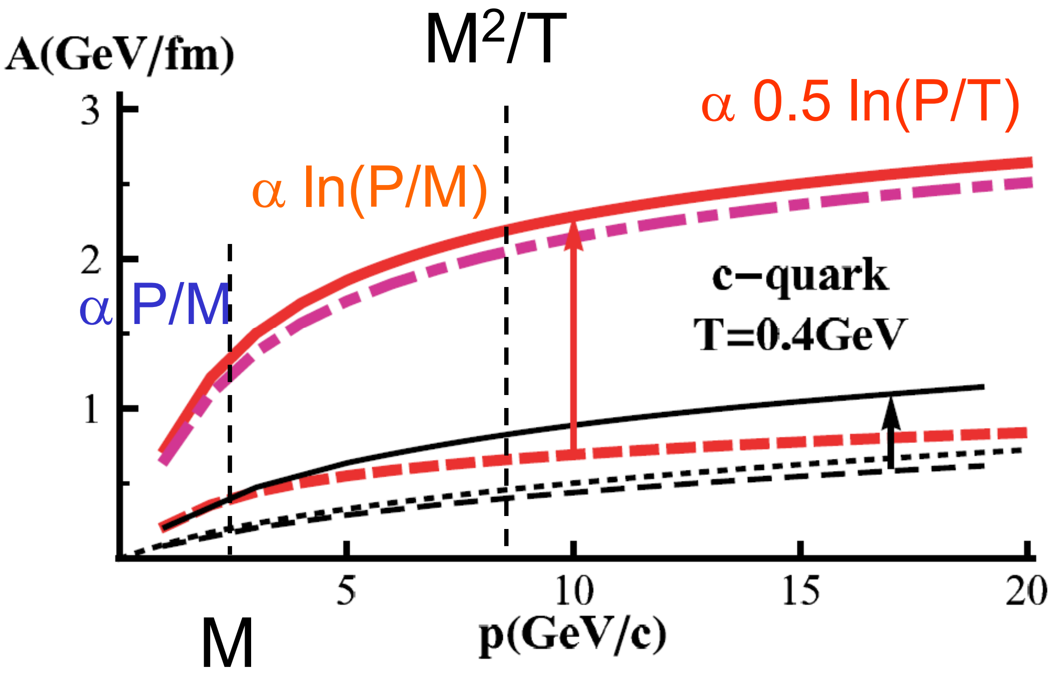
Large values for intermediate momentum-transfer => larger cross section

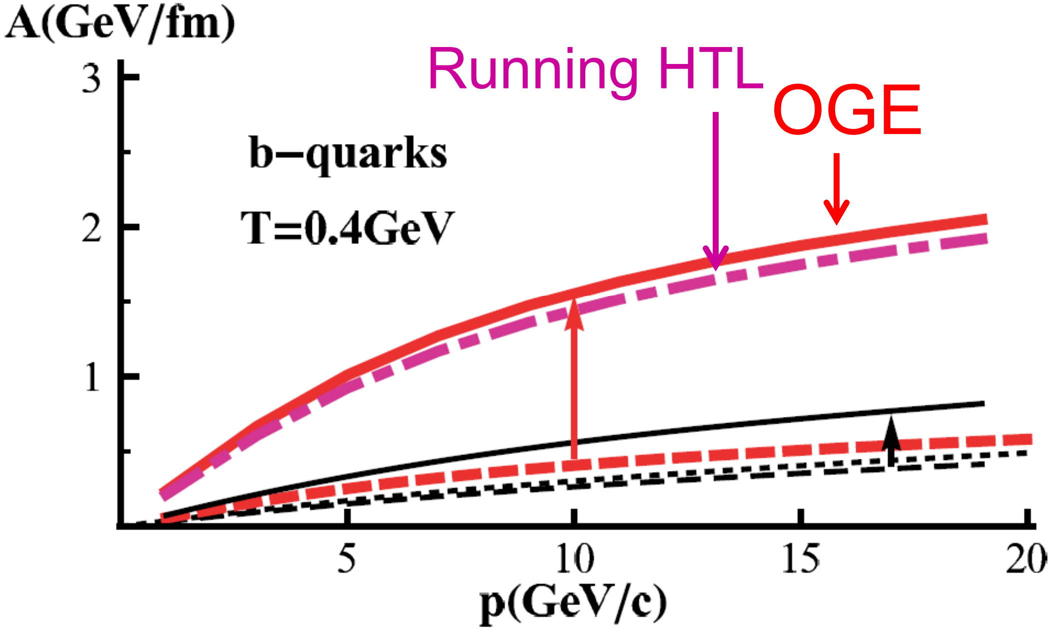
Of course, still a lot of uncertainties in the choice of this essential quantity !!!

μ-local-model: medium effects at finite T in t-channel



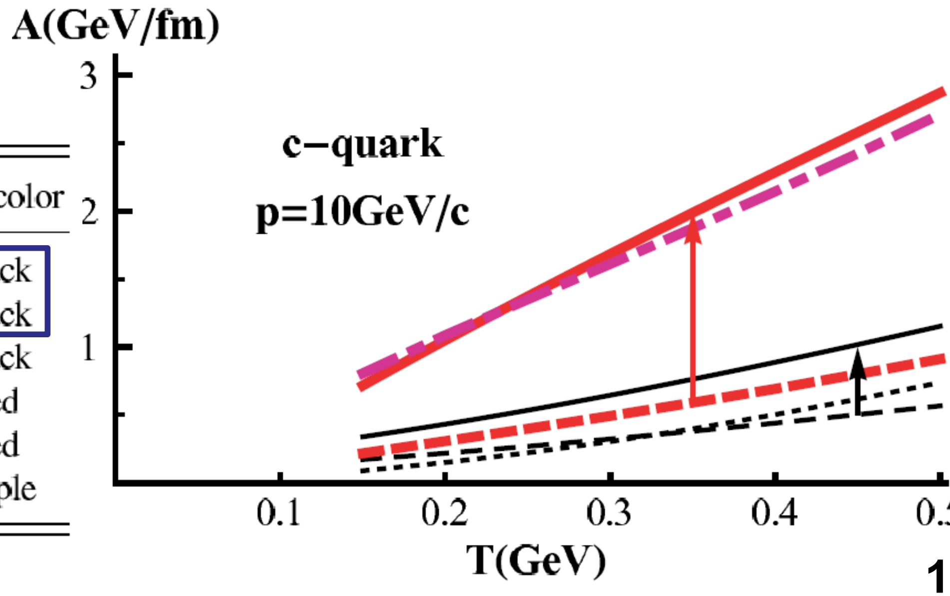
Drag coefficient A (d<p>/dt)





At large p: moderate mass dependence

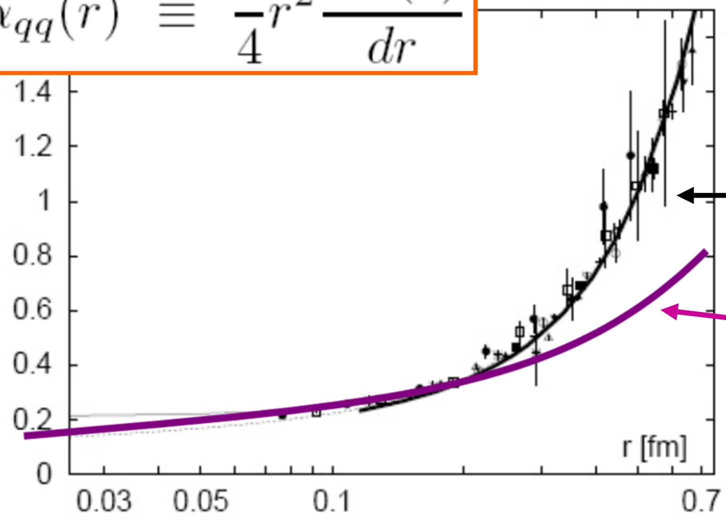
	α_S	μ^2	Line form	Line color
A	0.3	m_D^2	Dotted thin	Black
B	$\alpha_S(2\pi T)$	m_D^2	Dashed thin	Black
C	$\alpha_S(2\pi T)$	$0.15 m_D^2$	Full thin	Black
D	Running, Eq. (17)	$\tilde{m}_D^2$	Dashed bold	Red
E	Running, Eq. (17)	$0.2\tilde{m}_D^2$	Full bold	Red
F	Running, Eq. (17)	$0.11(6\pi\,\alpha_{\rm eff}(t)\,T^2)$	Dashed dotted bold	Purple



μ-local-model: Eff. Running α_s vs lQCD

T=0

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



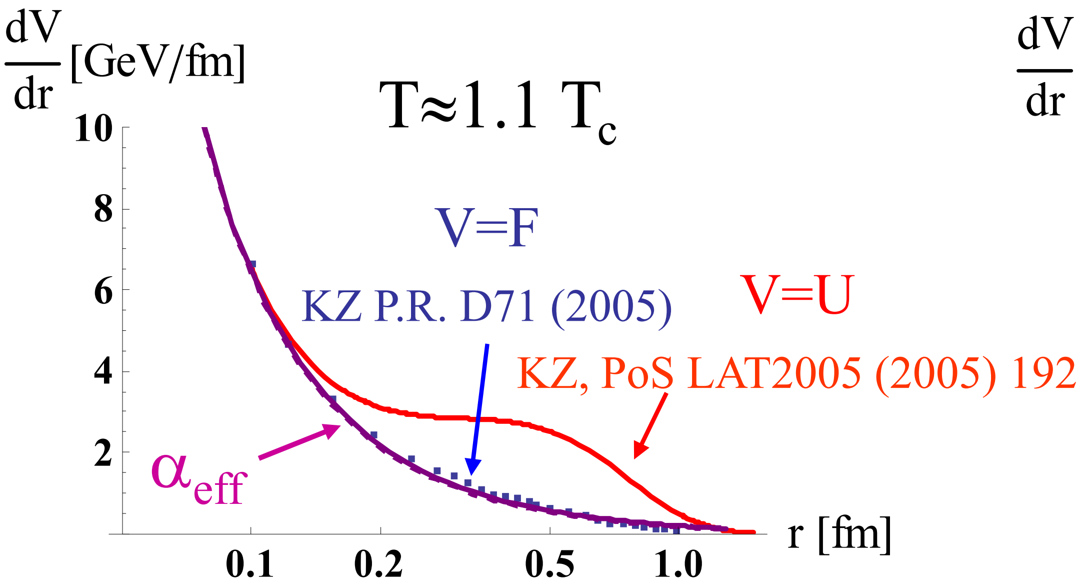
O. Kaczmarek & F. Zantow (KZ) (n_f=2 QCD), P.R.D71 (2005) 114510

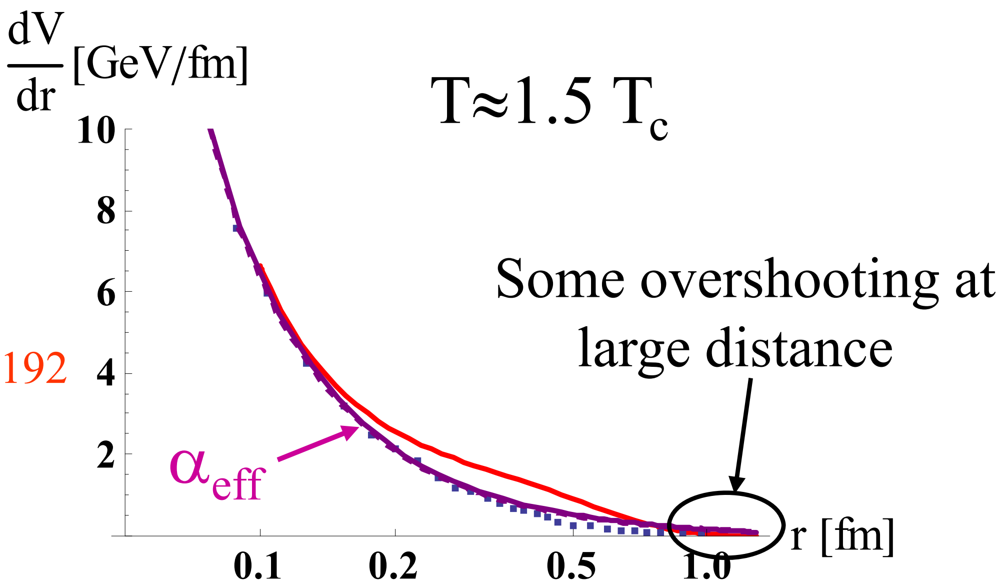
Genuine non-pert (string)

optimal μ, running α_{eff}

V:ω=0 sector; dE/dx: finite ω

Finite T

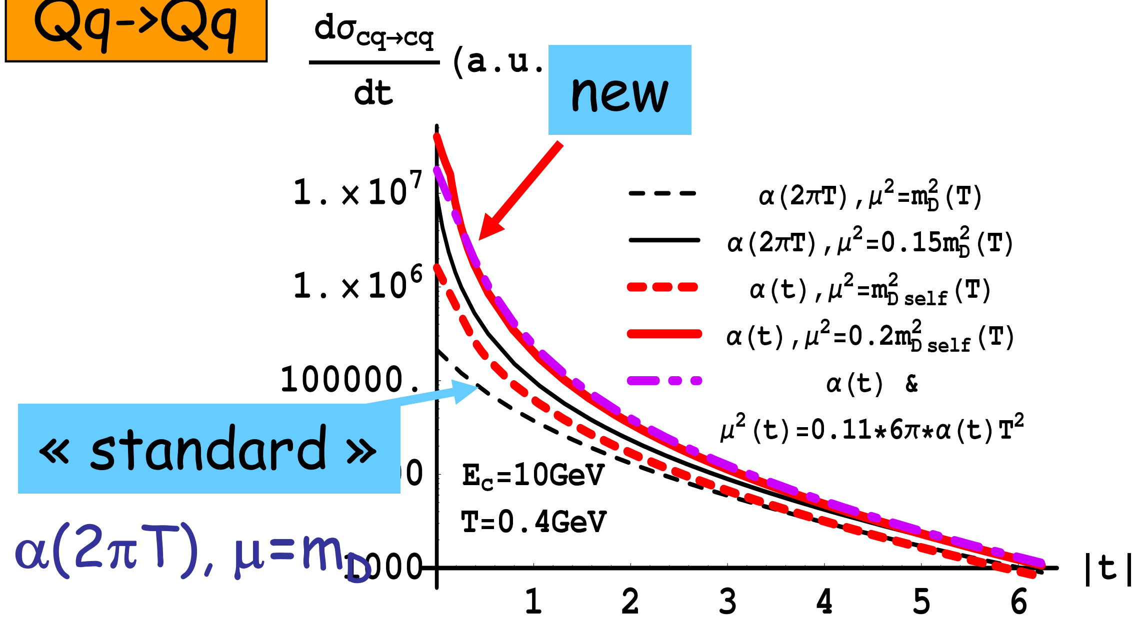




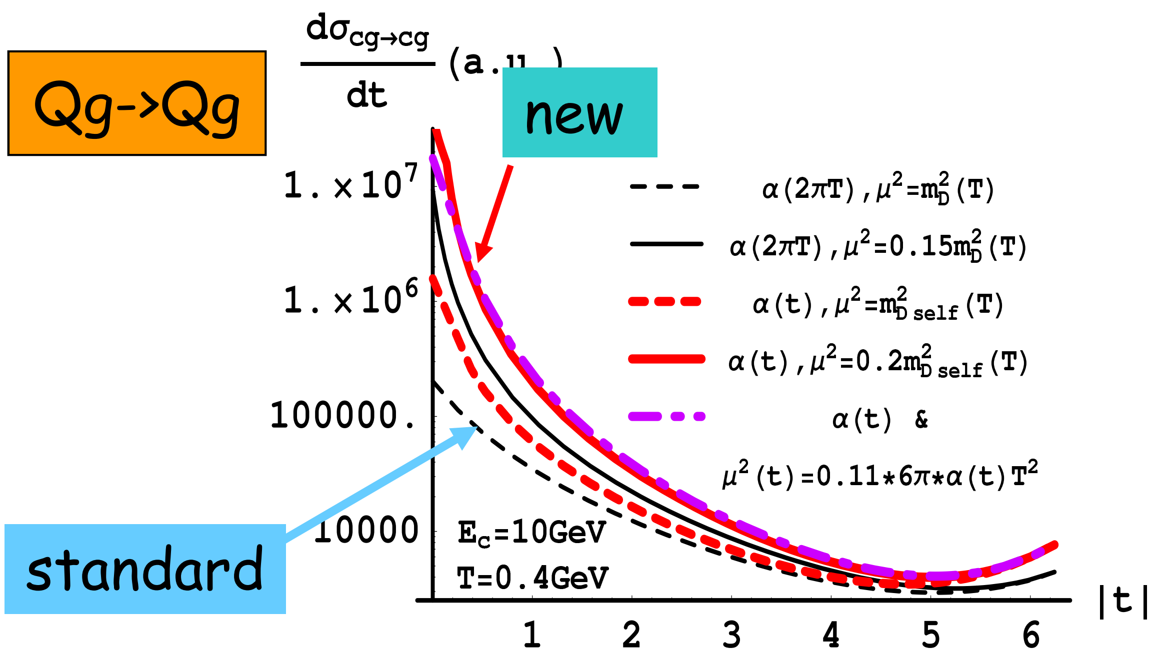
Merging at ≈2 T_c

Differential cross sections

Qq->Qq



Qg->Qg



Large enhancement of both cross sections at small and intermediate |t|

Little change at large |t|

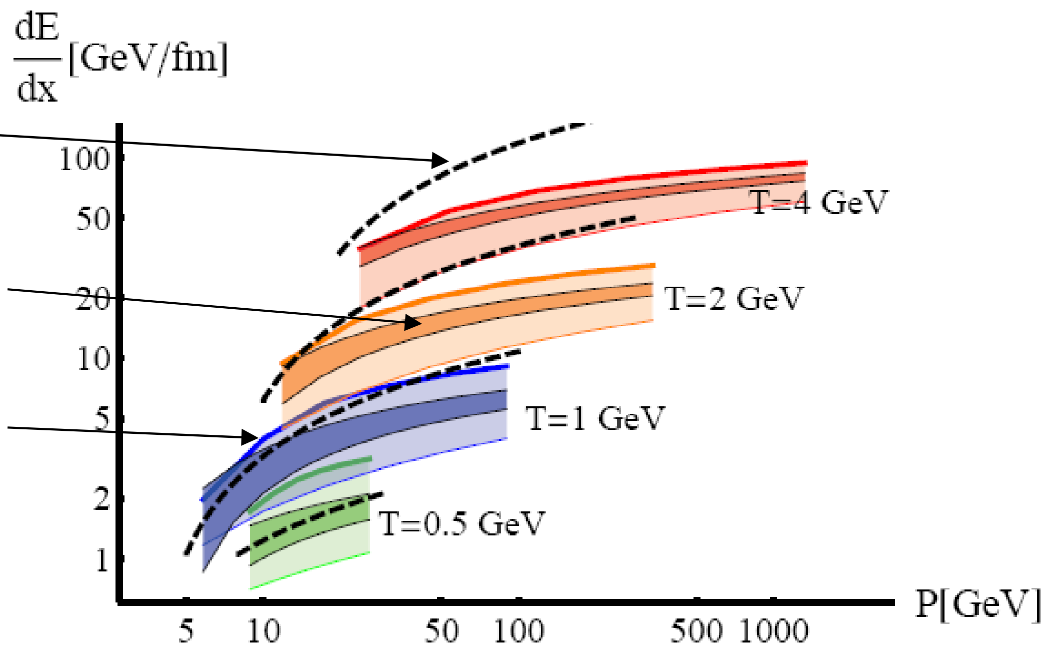
μ-local-model: Eff. Running vs fixed α_s

BT

Dark bands: Peshier & Peigné (2008)

E: optimal μ, running α_{eff}

Light bands: theoretical uncertainty related to the prescription for the HTL-hard transition



Conclusions:

- Good agreement with PP for large T and large P
- Running α_s is more than a cranking of BT (different shapes and T-dependences)

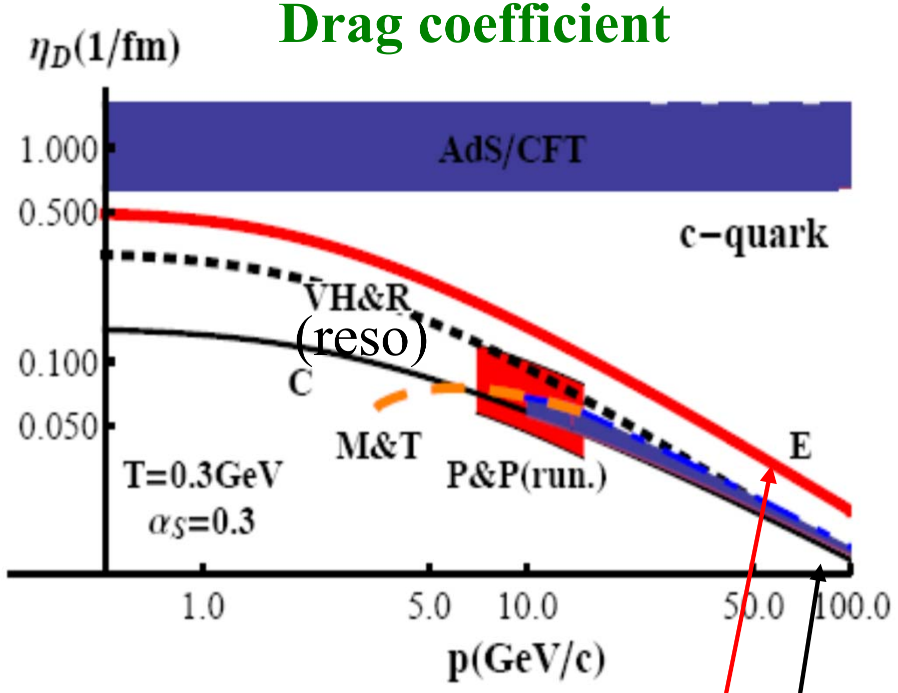
Running α_s : some Energy-Loss values

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

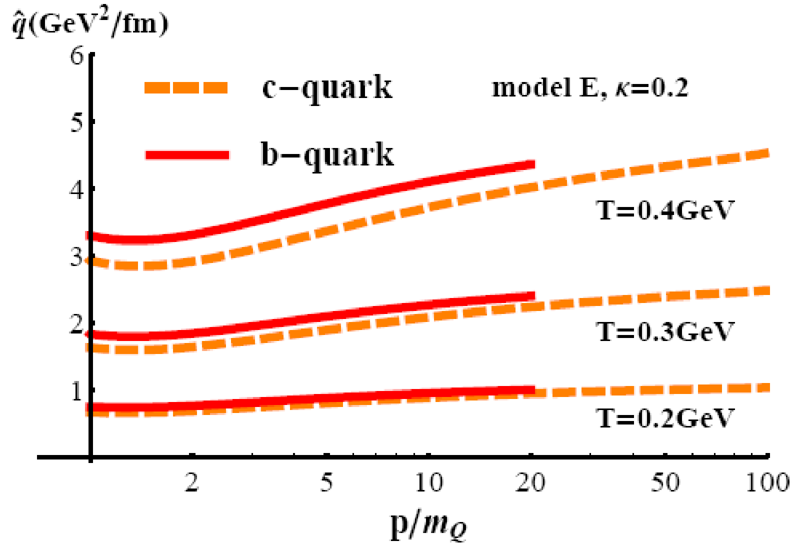
T(MeV) \p(GeV/c)	10	20
200	**1 / 0.65**	**1.2 / 0.9**
400	**2.1 / 1.4**	**2.4 / 2**

≈ 10 % of HQ energy

Drag coefficient



Transp. Coef …



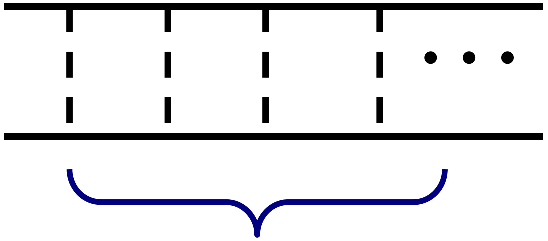
E: optimal μ, running α_{eff}

C: optimal μ, $\alpha_s(2\pi T)$

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

Several issues

1.Non perturbative aspects (beyond Born). Usually in convergent kinetic:

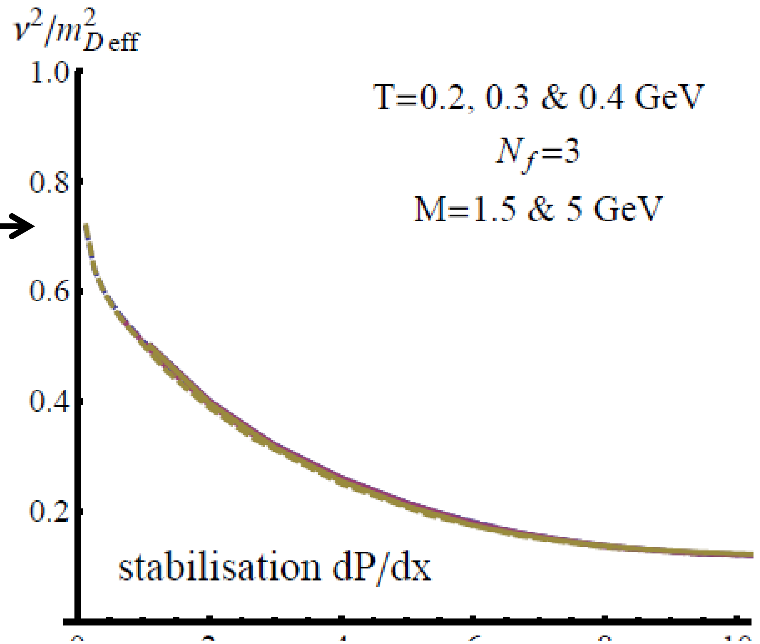
RPA + 

Ladders necessary at short distance (large force)

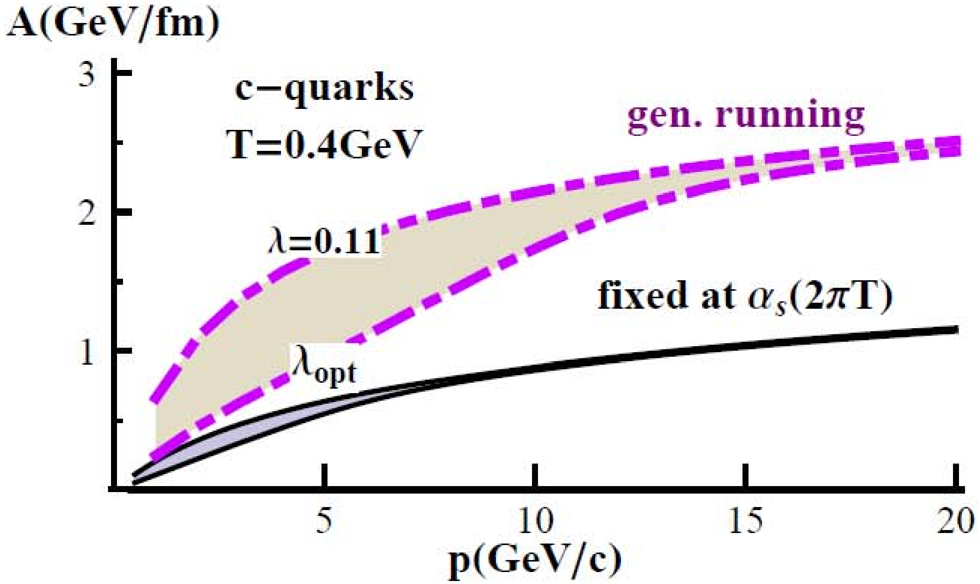
Several issues

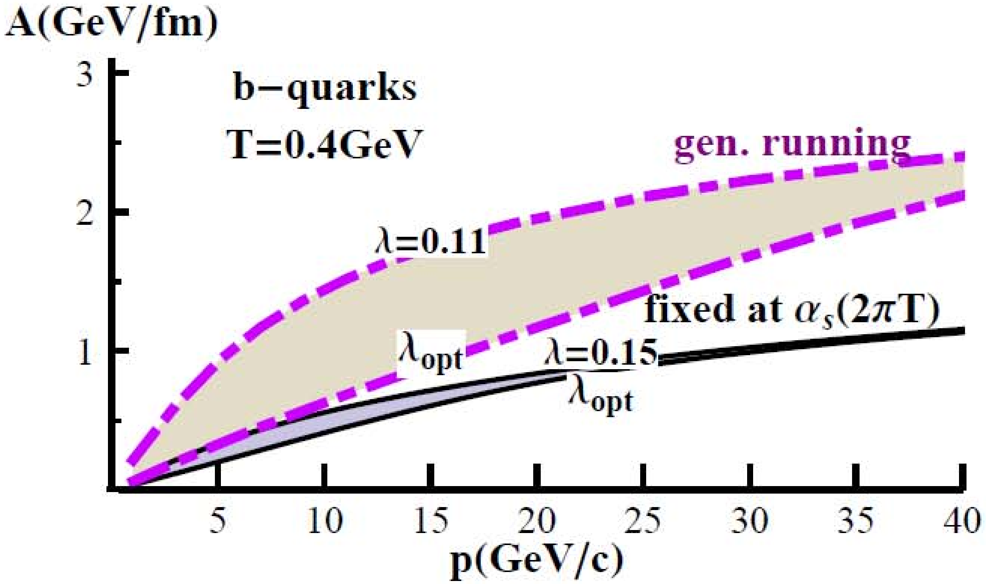
2. λ at small momentum ?

Reduction of the interaction range



λ=0.11

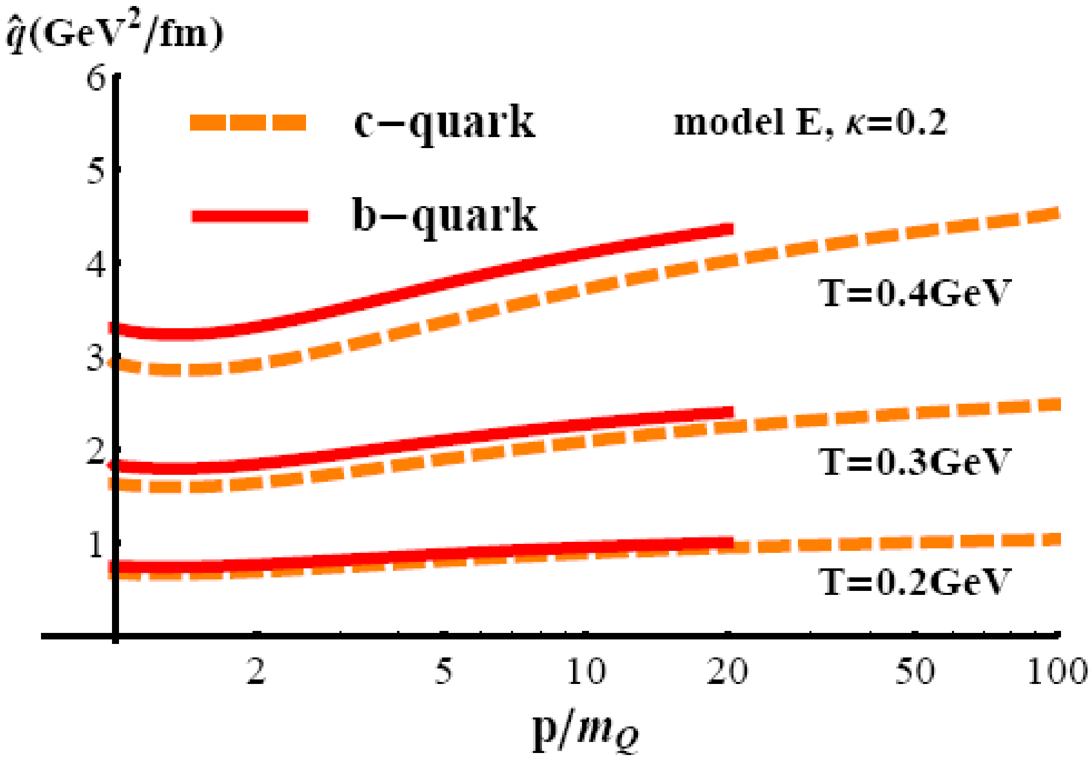




Several issues

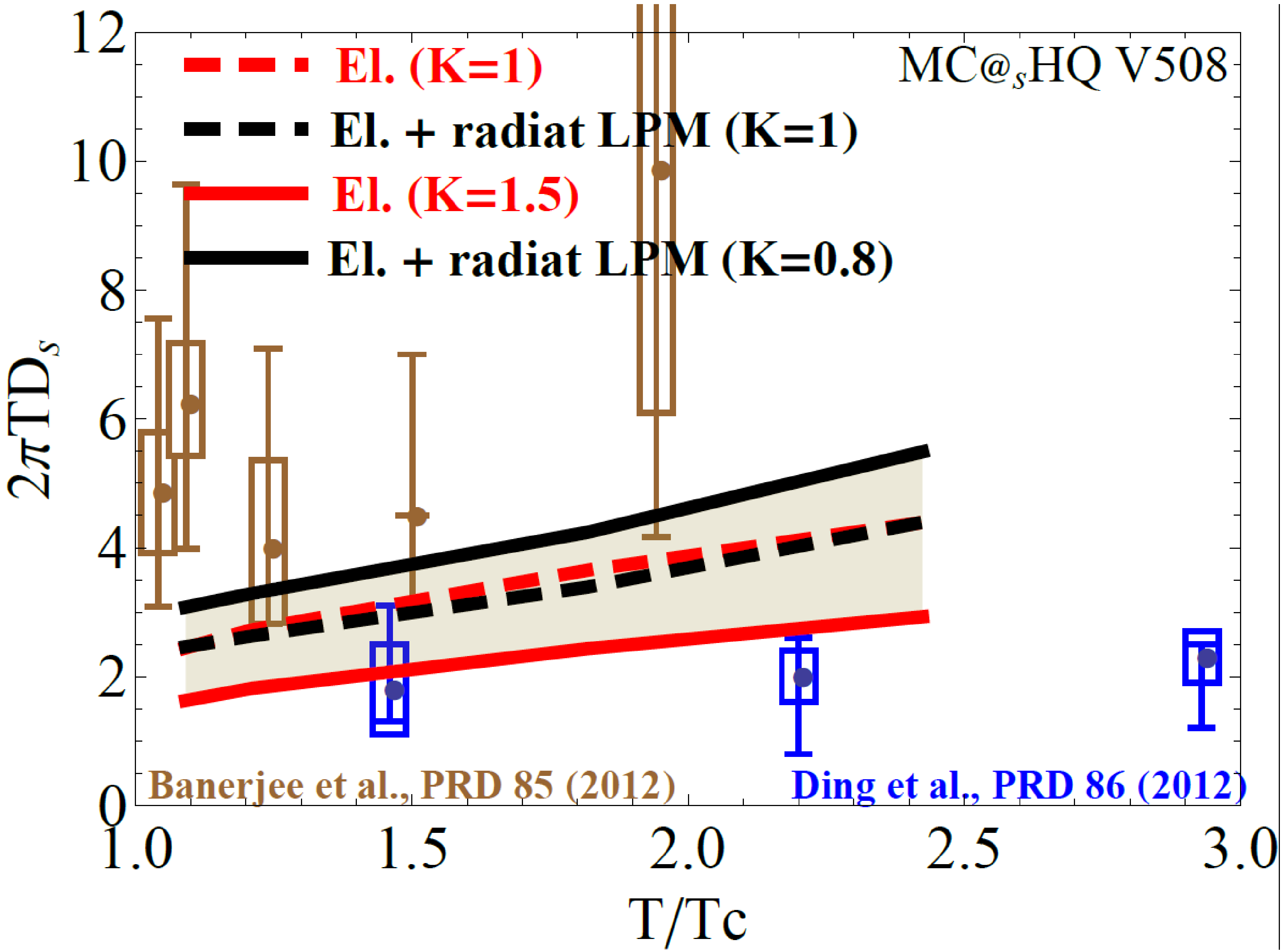
3. How to deal with the genuinely NP part ?

Transport coefficients (1)



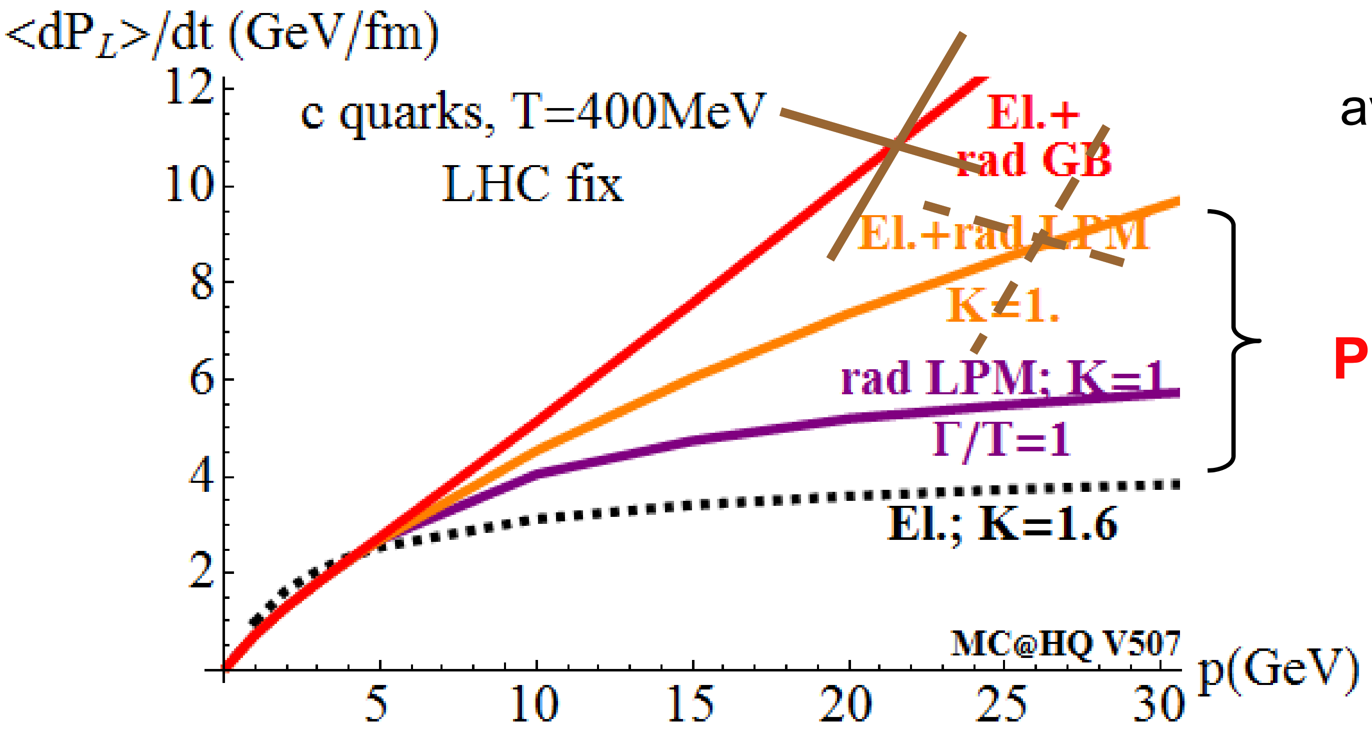
Only the elastic contribution

Transport coefficients (2)



Transport coefficients (3)

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



(starting from QM 2012)

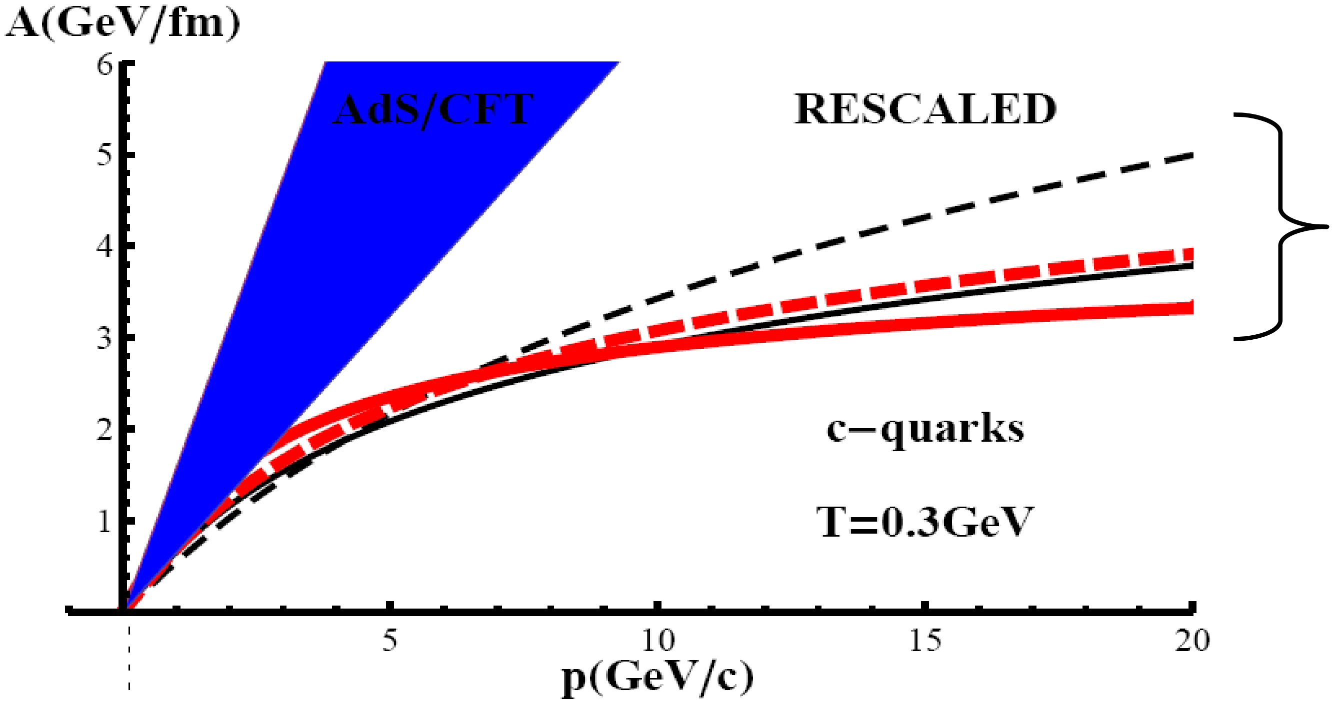
the drag coefficient reflects the average momentum loss (per unit time) => large weight on $x \sim 1$

Present LHC data

For too large p_T, L^2 terms dominate => transport coefficients are not the relevant objects

Transport coefficients (4)

Gathering all rescaled models (various prescriptions for μ and α_s):



Similar trend for all collisional models

AdS/CFT too large to reproduce experimental data ?! Against the conclusion of Akamatsu et al (?)

A16

(E-loss plays a dominant role, but not the only parameter)

Diapositive 25

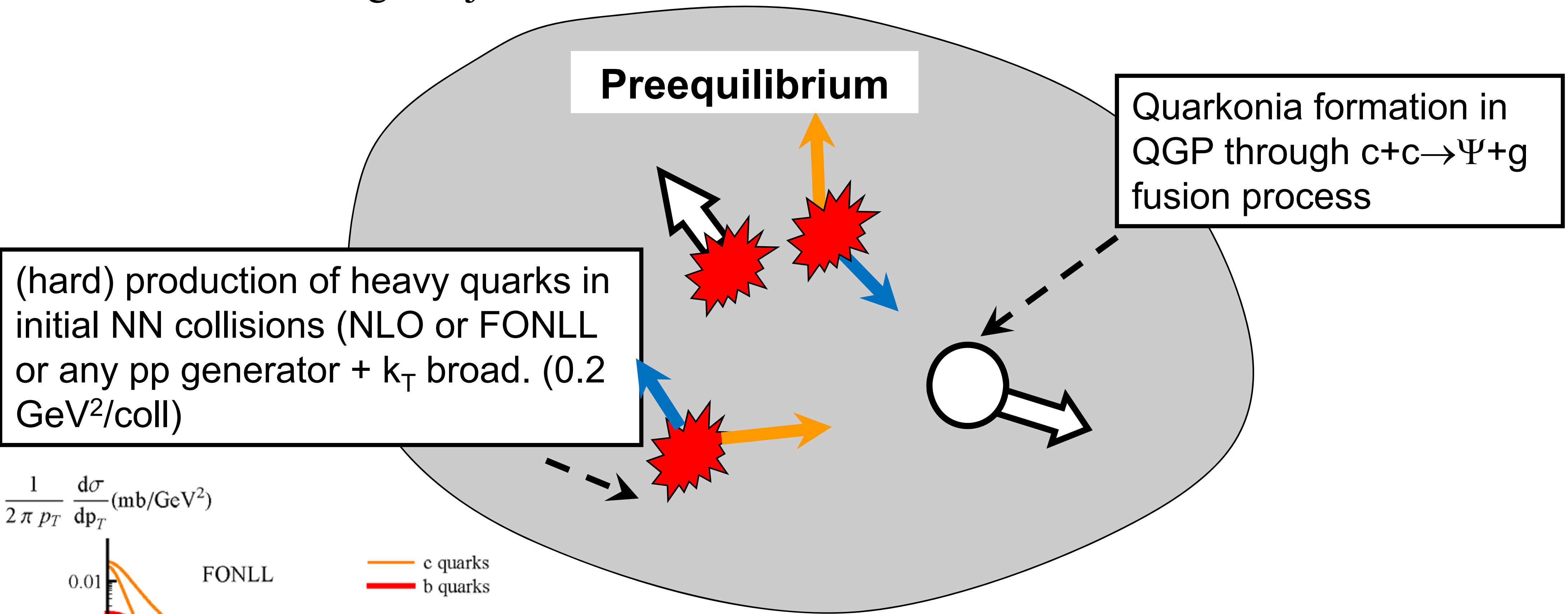
A16 comparer avec hirano et al qui parviendraient à reproduire le RAA

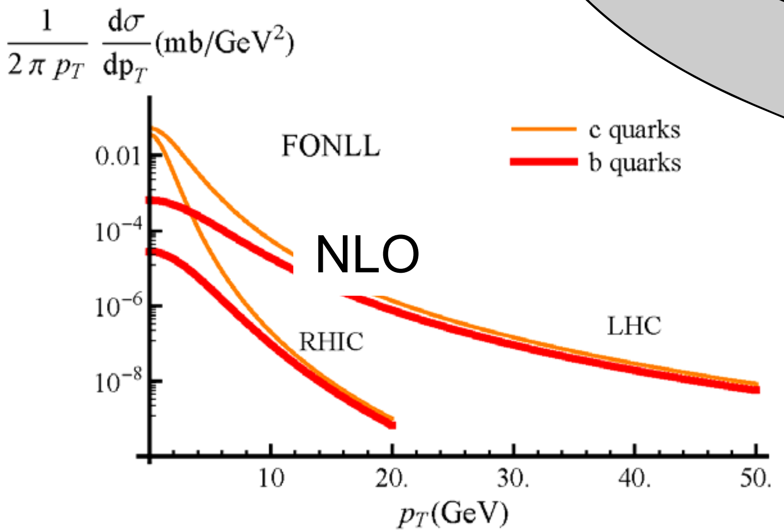
Administrateur; 19/07/2009

The Monte Carlo @ Heavy Quark Generator

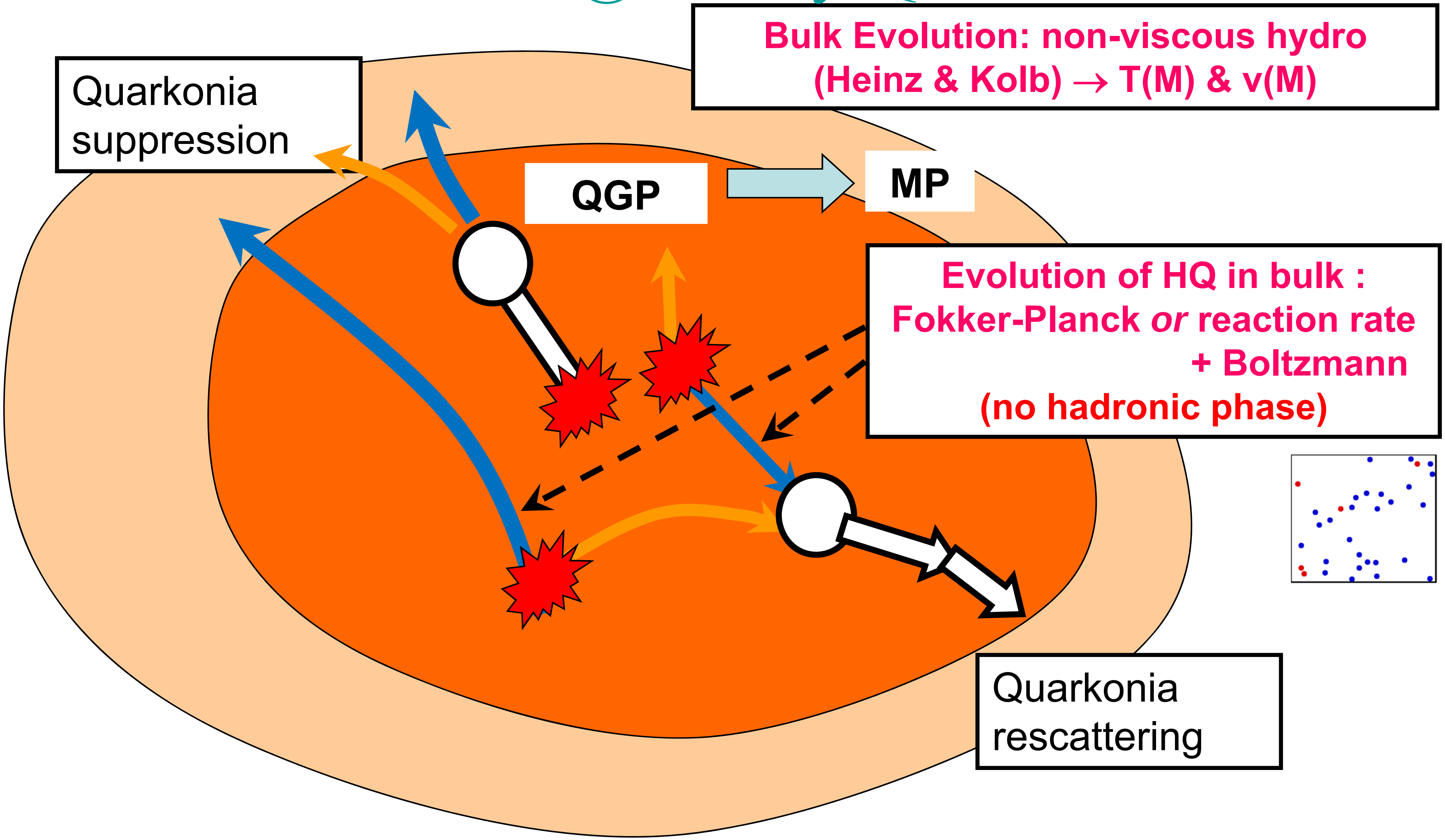
No force on HQ before thermalization of QGP (0.6 fm/c)

Evolution according to Bjorken time





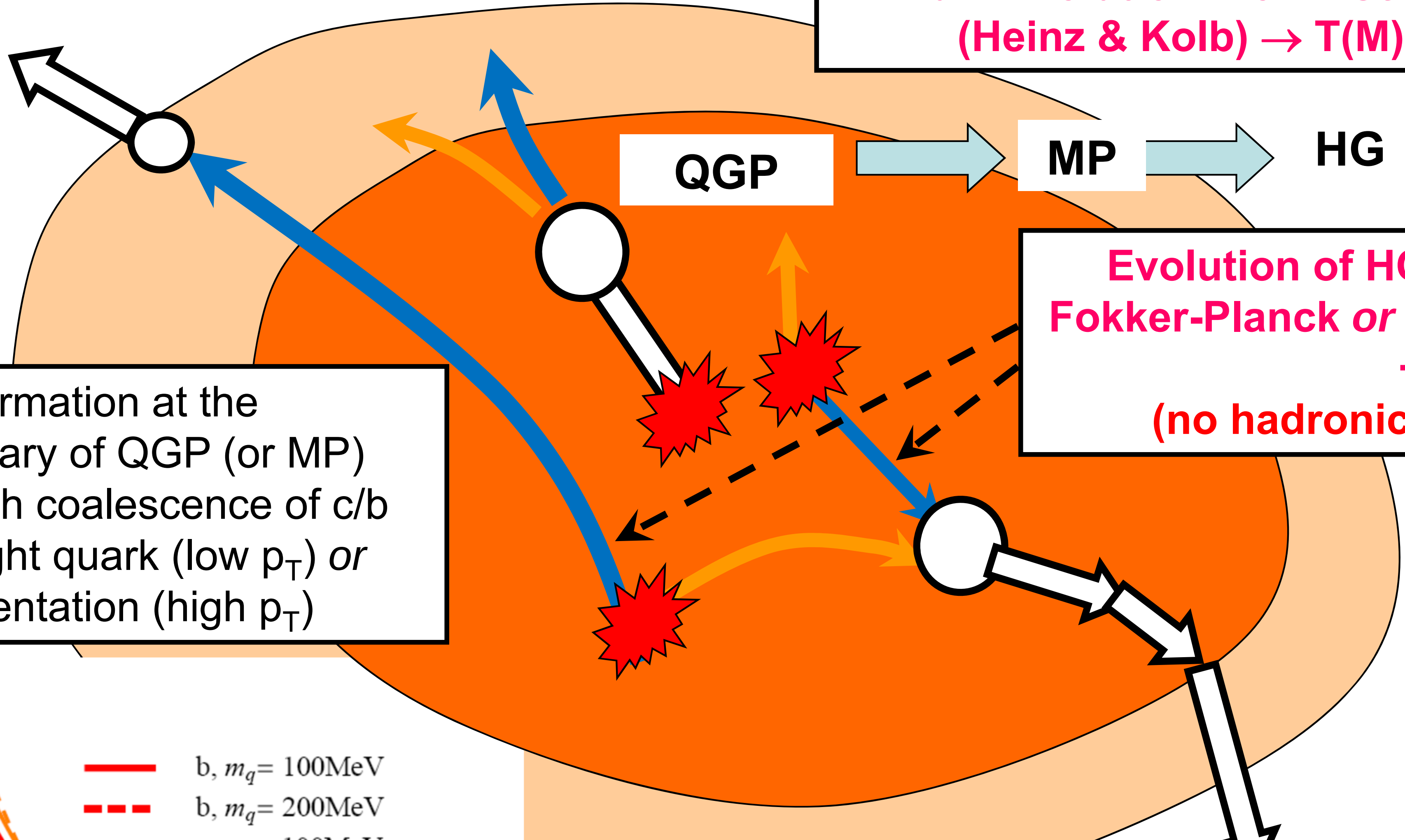
The Monte Carlo @ Heavy Quark Generator



Recently : coupling to EPOS2 (3) instead of KH

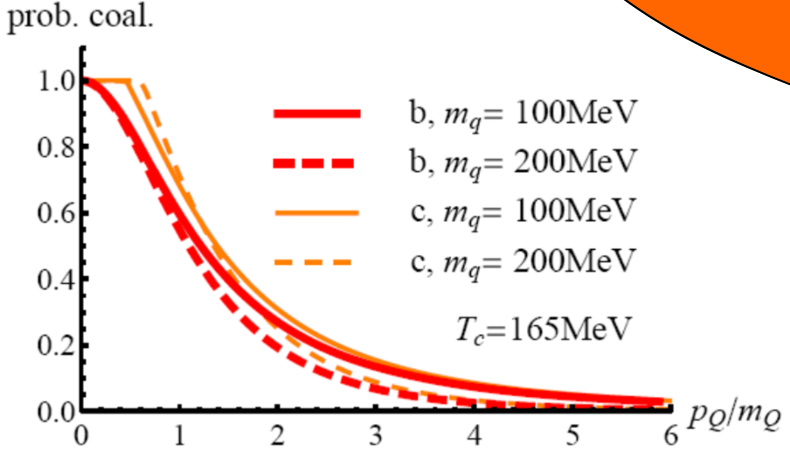
The Monte Carlo @ Heavy Quark Generator

Bulk Evolution: non-viscous hydro (Heinz & Kolb) → T(M) & v(M)



Evolution of HQ in bulk : Fokker-Planck *or* reaction rate + Boltzmann (no hadronic phase)

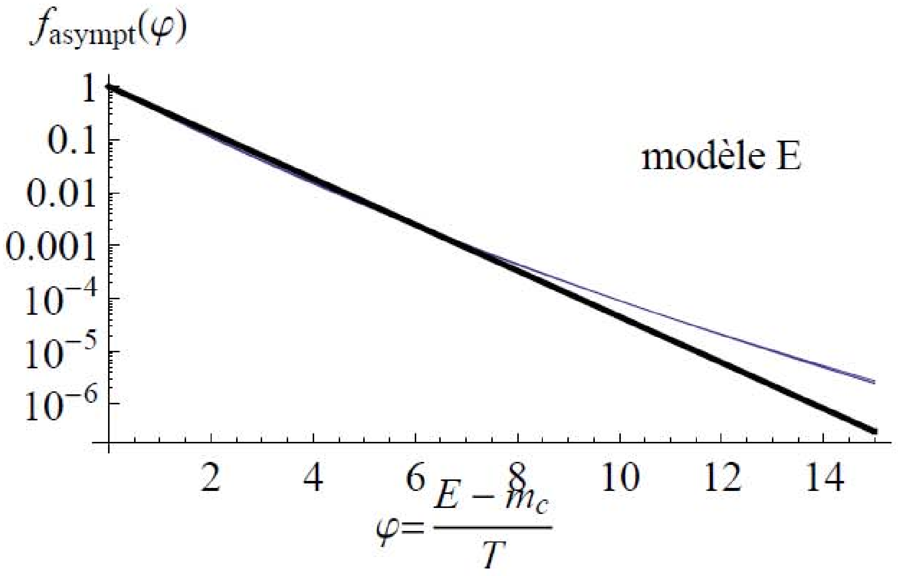
D/B formation at the boundary of QGP (or MP) through coalescence of c/b and light quark (low p_T) *or* fragmentation (high p_T)

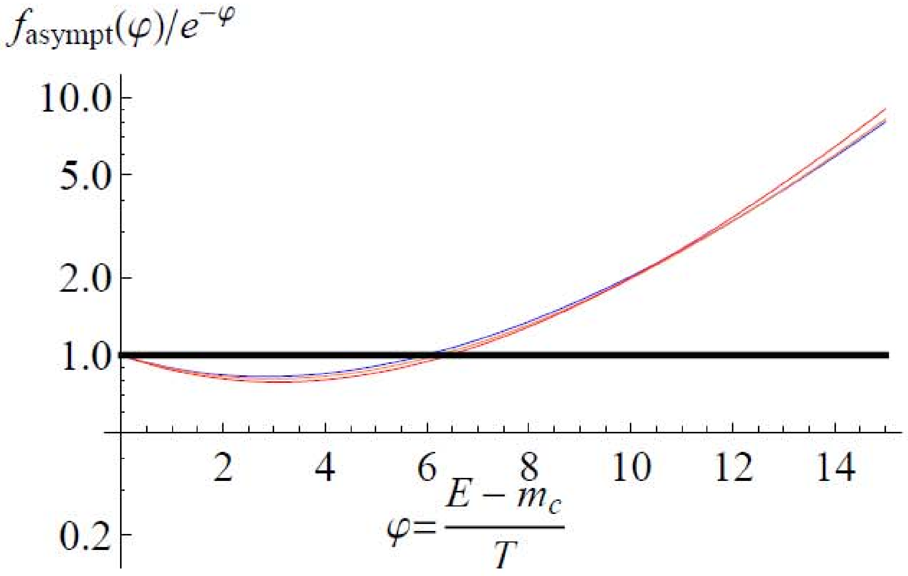


Nothing spectacular at freeze-out
(quarkonia are white objects already)

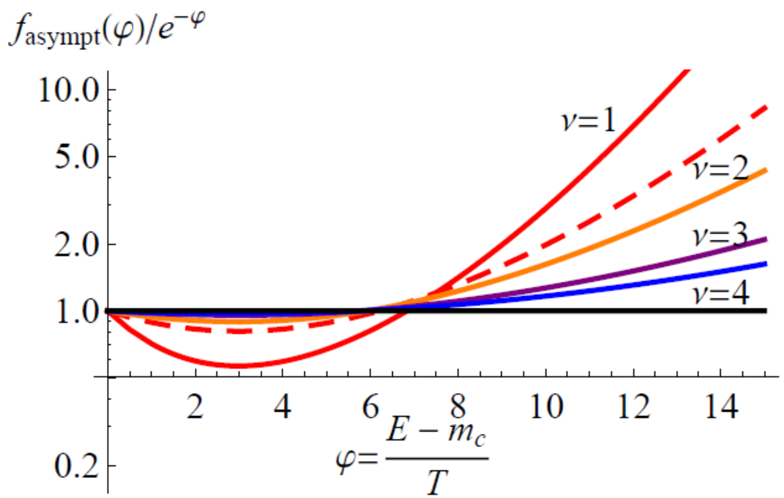
Boltzmann vs Langevin

Deviation from Einstein relation with native coefficients





$$|\mathcal{M}_{\text{grazing}}(s,t,\mu;\nu)|^2 = \frac{(s-m^2)^2\,\mu^{4(\nu-1)}}{(\mu^2-t)^{2\nu}}$$

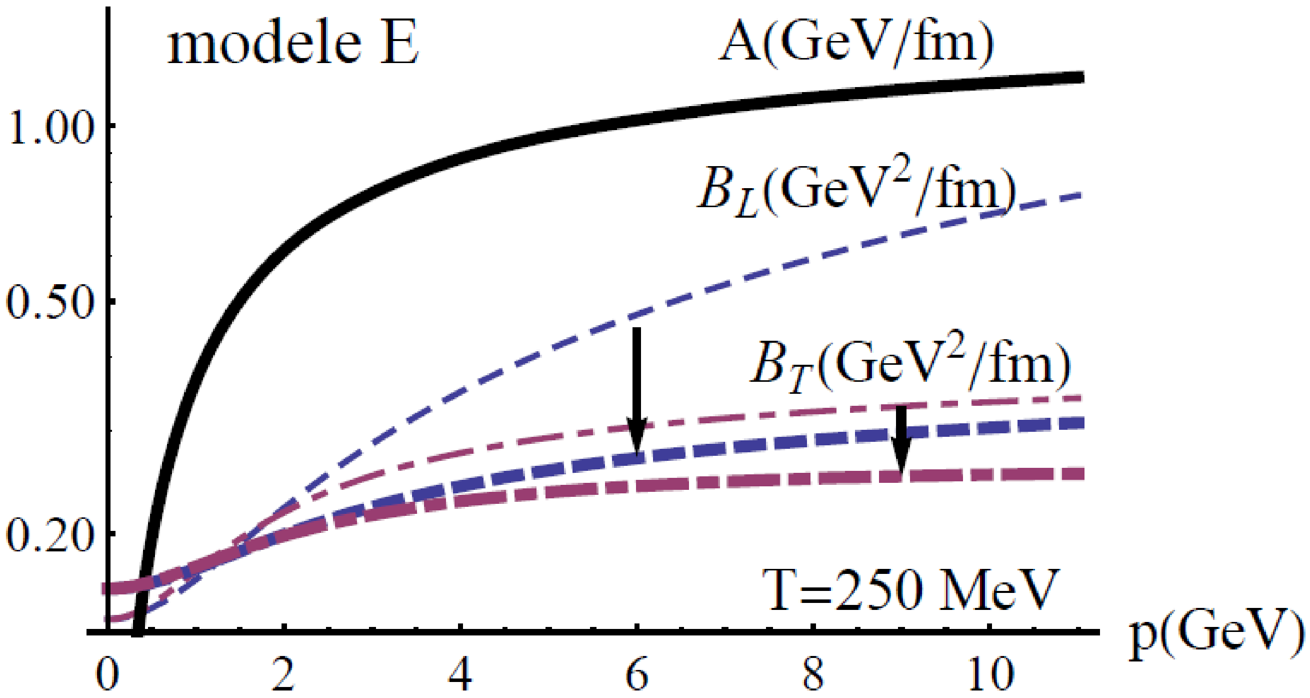


Boltzmann vs Langevin

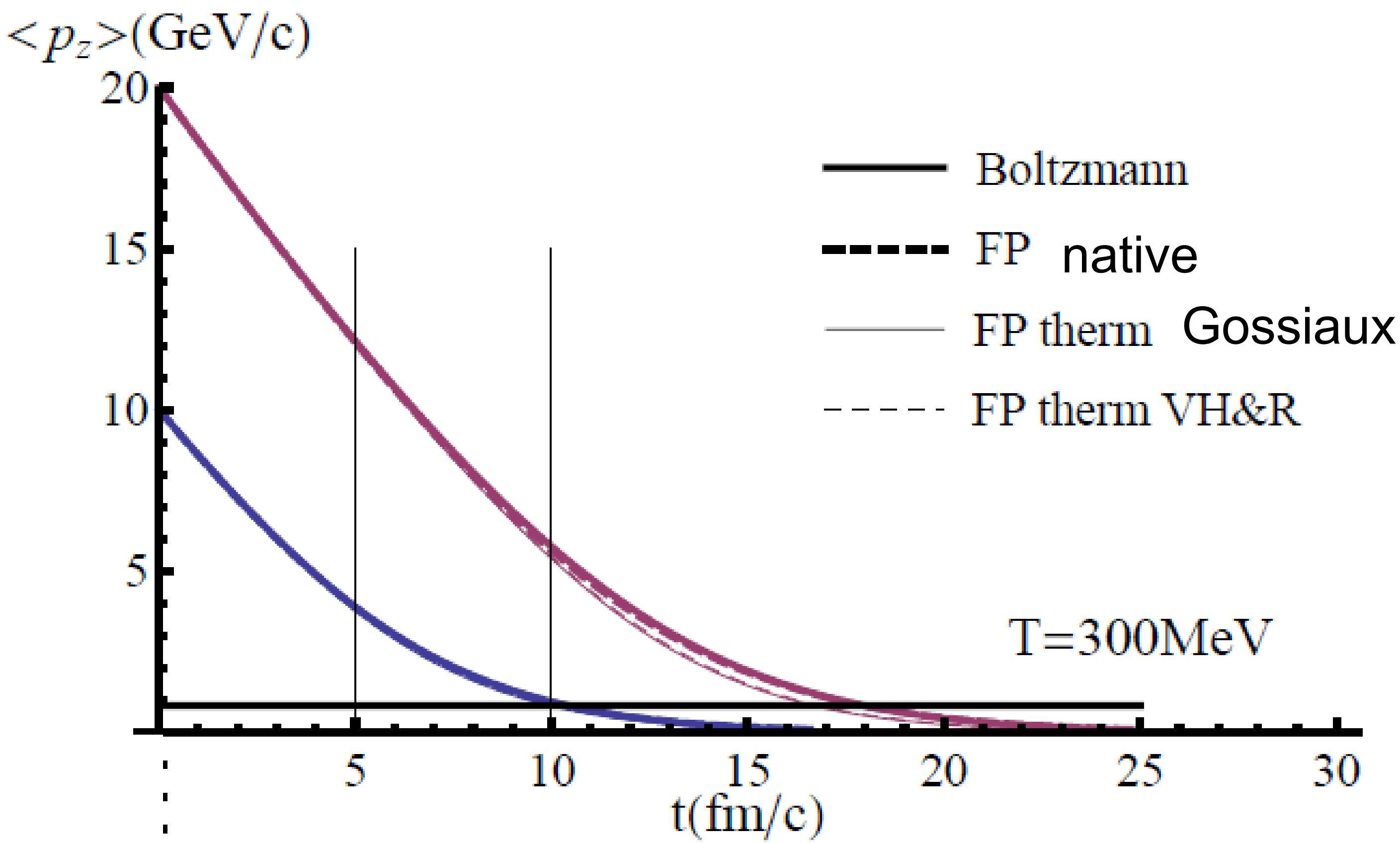
2 corrections prescriptions:

- VHR: $B_L^{\mathrm{therm\,VHR}}(p) = E_p T A$ /p

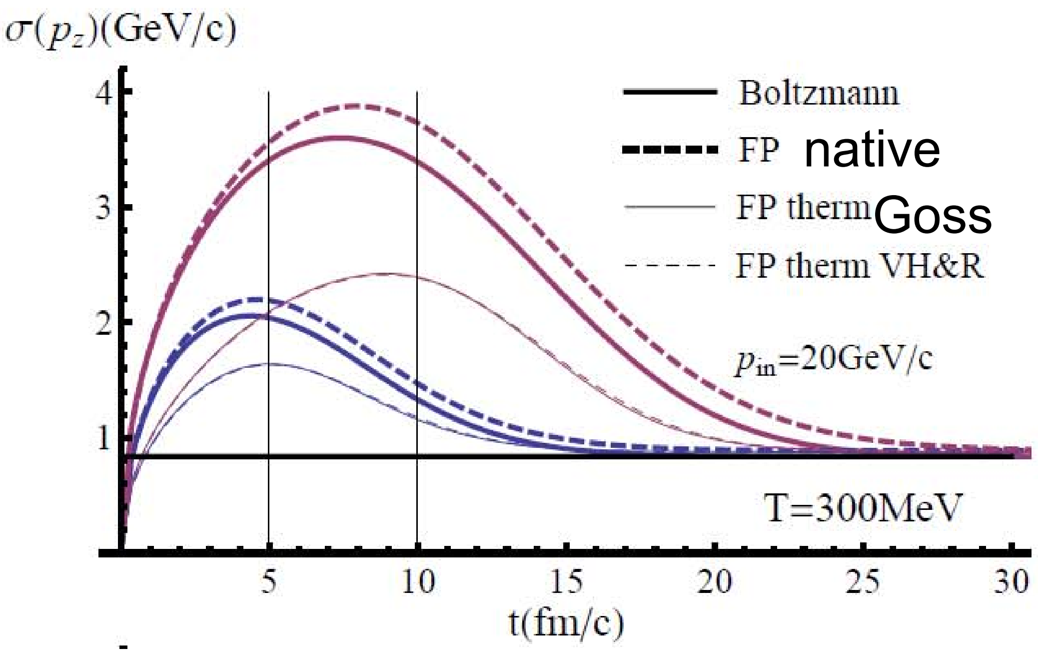
- Gossiaux (historical) $$\frac{B_L^{\mathrm{therm}}(p)}{B_T^{\mathrm{therm}}(p)} = \left(\frac{B_L(p)}{B_T(p)}\right)^{\beta} \qquad \beta = 0.25$$

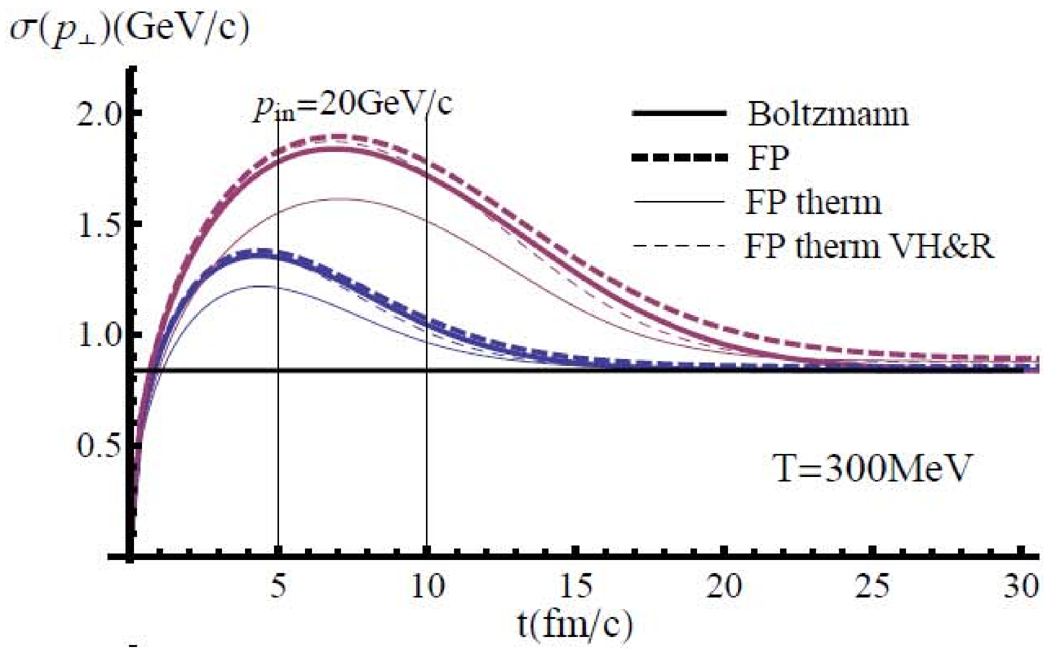


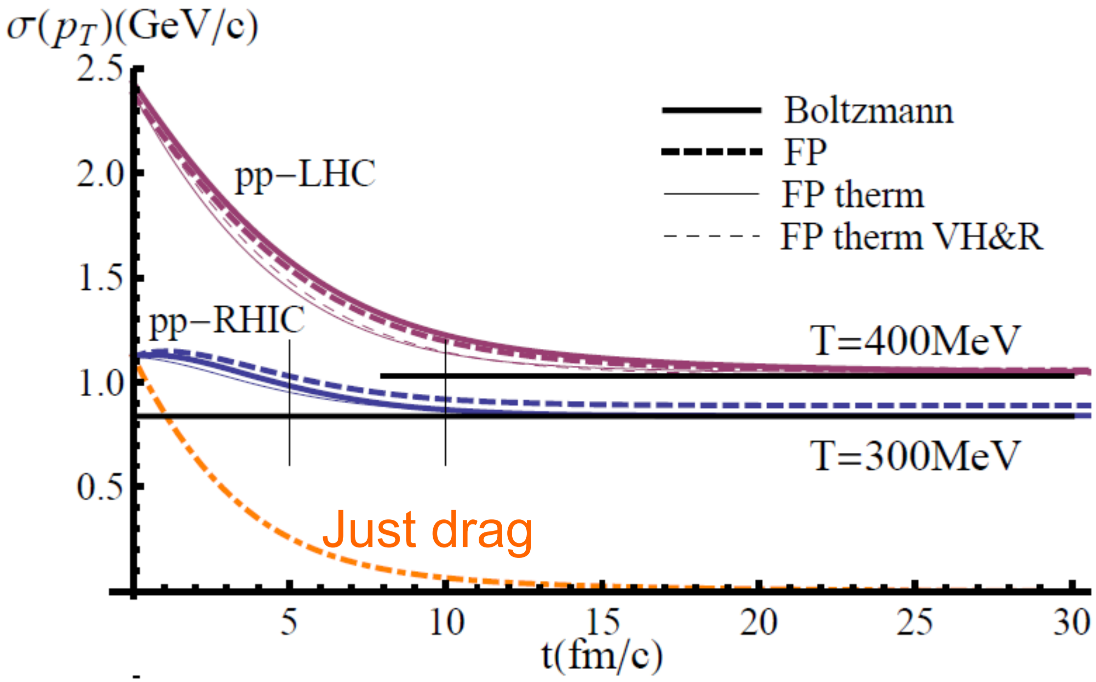
Boltzmann vs Langevin



Boltzmann vs Langevin

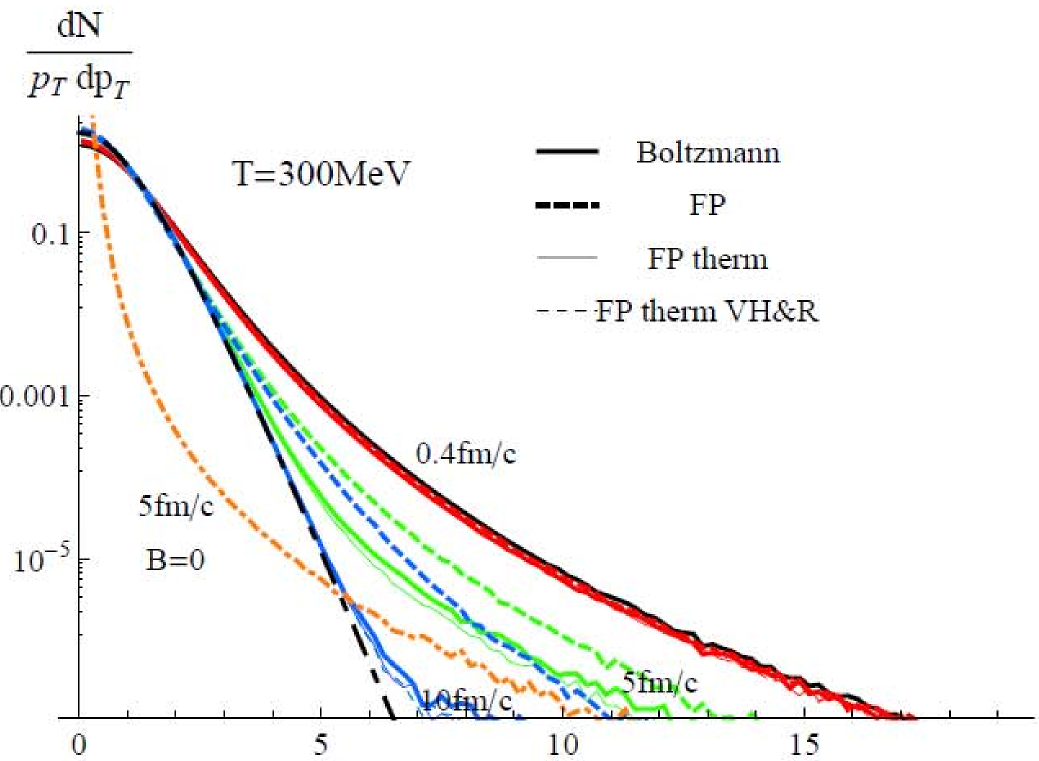


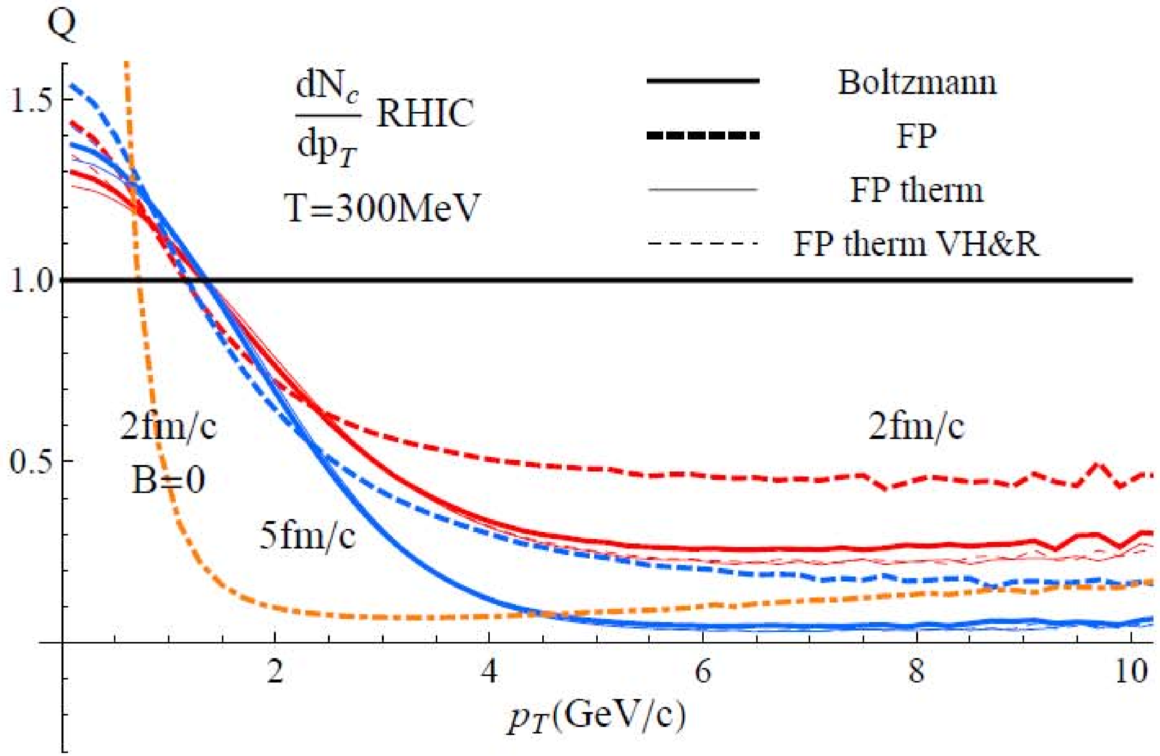




Boltzmann vs Langevin

Evolution in a finite T stationnary medium (infinite)



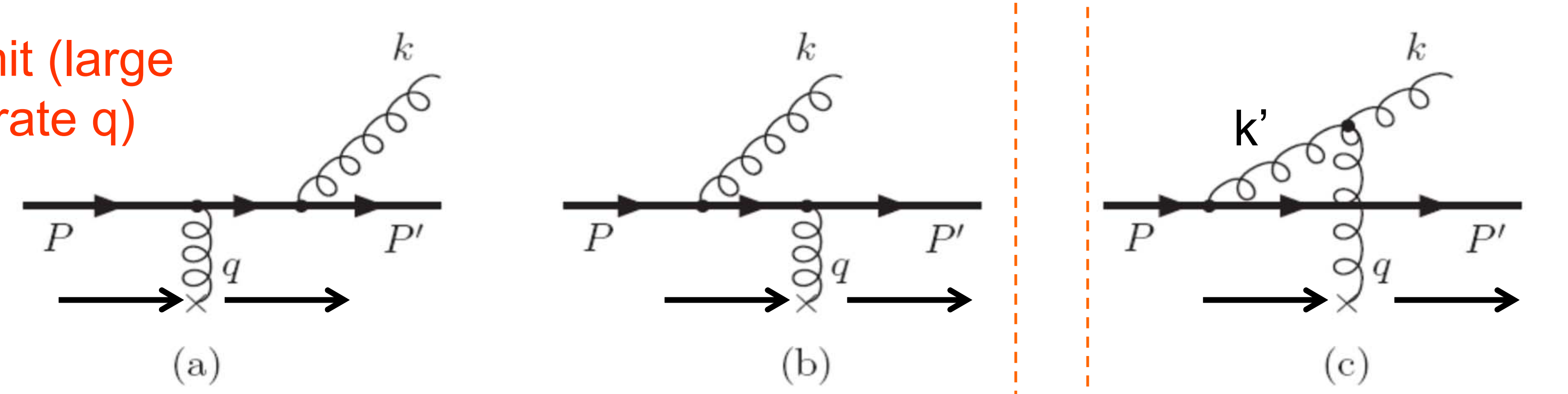


Both tuned FP ok,… Native FP has less RAA (more longitudinal fluctuations dating from Einstein violation)

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’

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

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

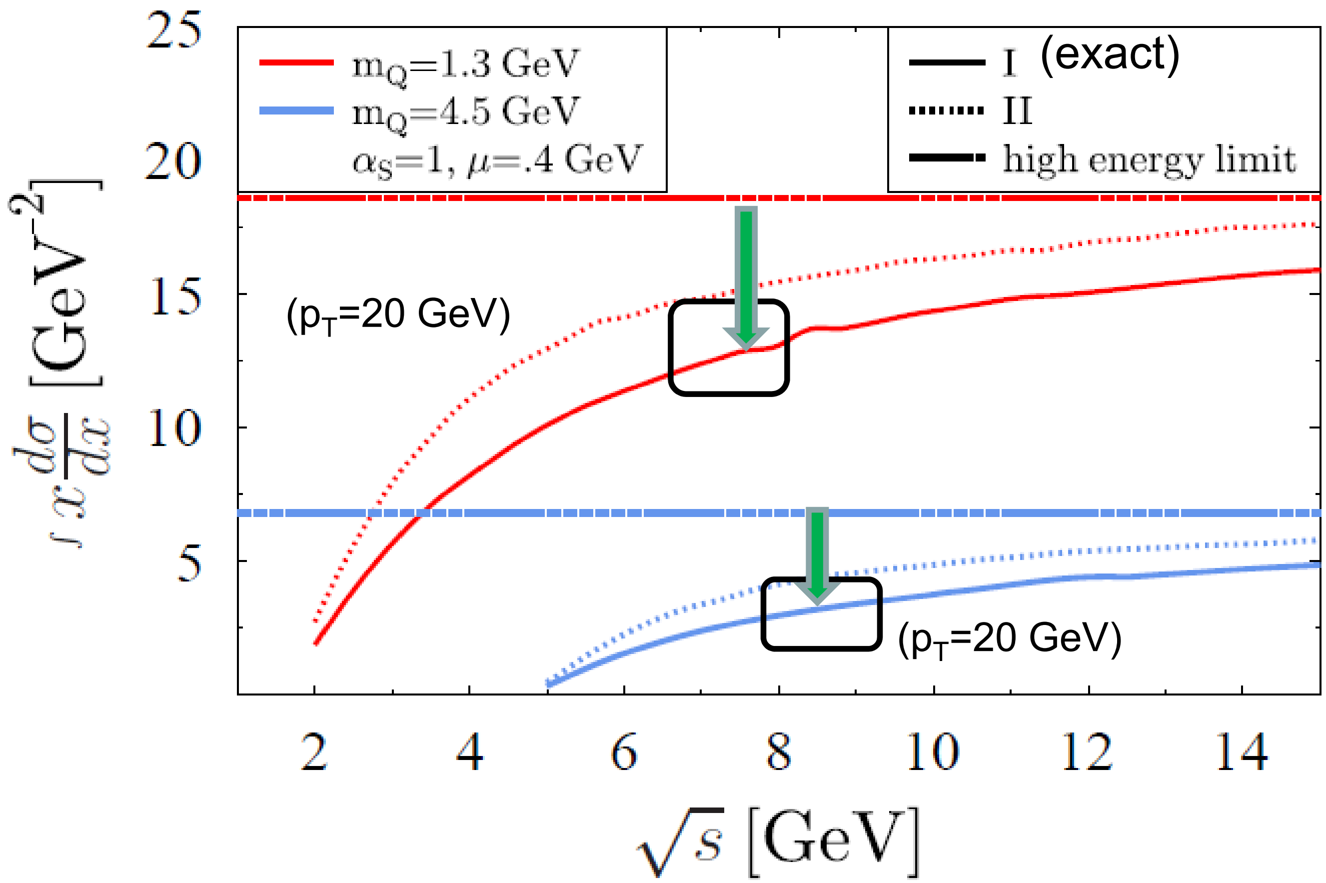
Gluon thermal mass ~2T (phenomenological; not in BDMPS)

Quark mass

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

Incoherent Induced Energy Loss

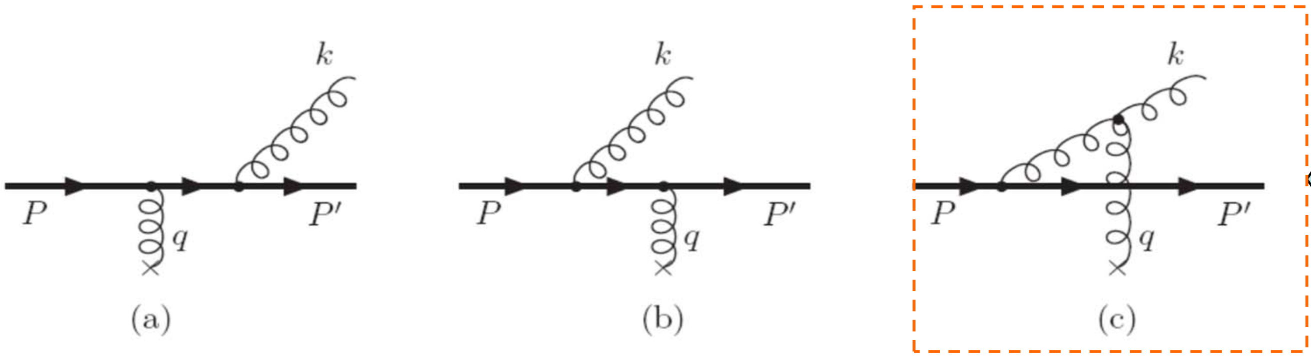
… & finite energy !



Gousset, Gossiaux & Aichelin, Phys. Rev. D 89, 074018 (2014)

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

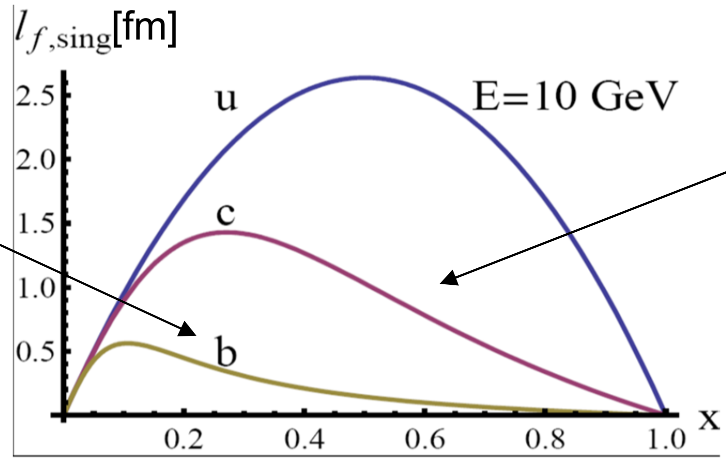
Formation time for a single coll.



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

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

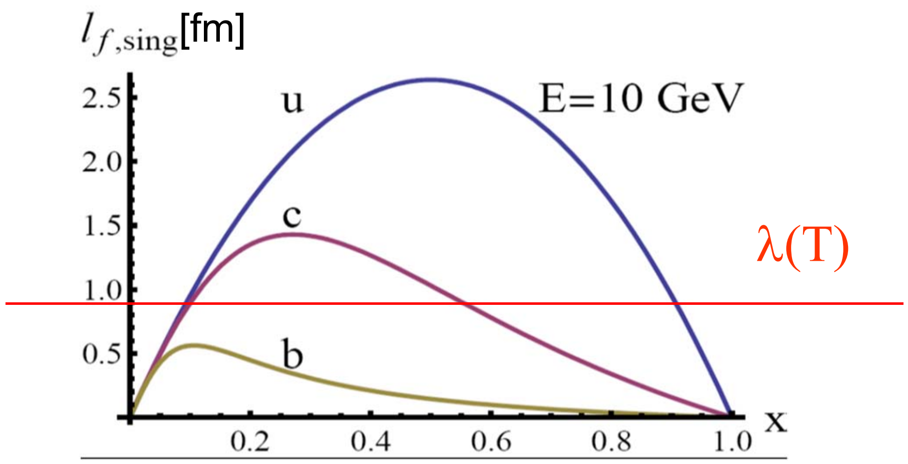


For $x>x_{cr}=m_g/M$, gluons radiated from heavy quarks are resolved in less time then those ← light quarks and gluon => radiation process less affected by coherence effects in multiple scattering

Dominant region for quenching

Dominant region for average E loss

A first criteria



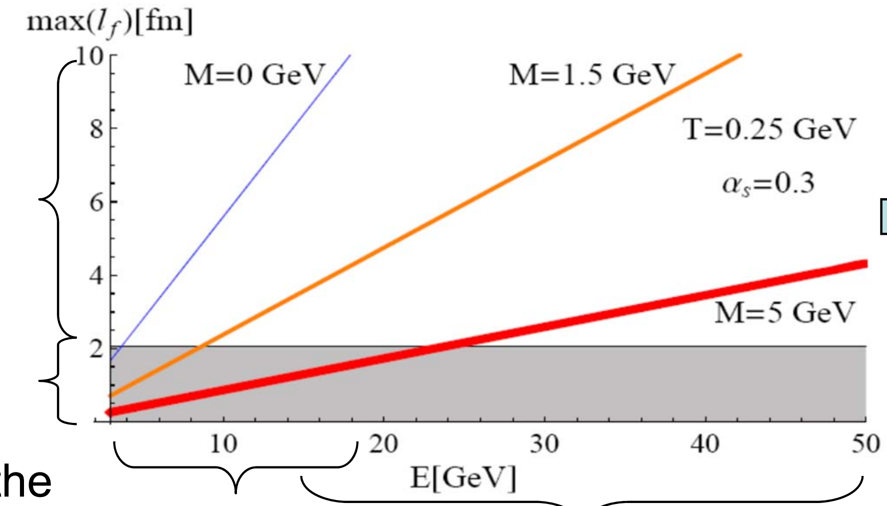
Comparing the formation time (on a single scatterer) with the mean free path:

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)



RHIC

LHC

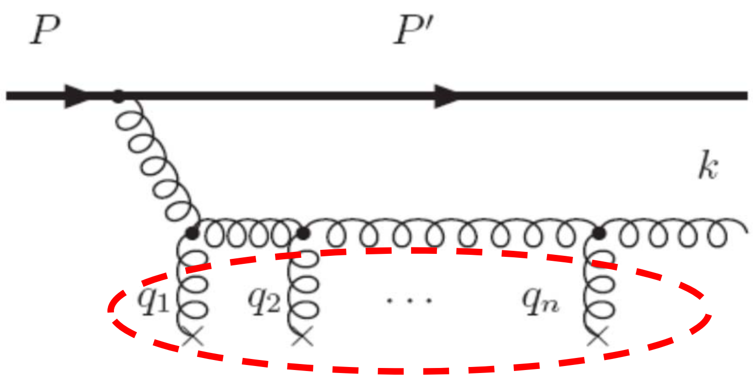
Maybe not completely foolish to neglect coherence effect in a first round for HQ.

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

Our basic ingredients for HQ energy loss

Coherent Induced Radiative

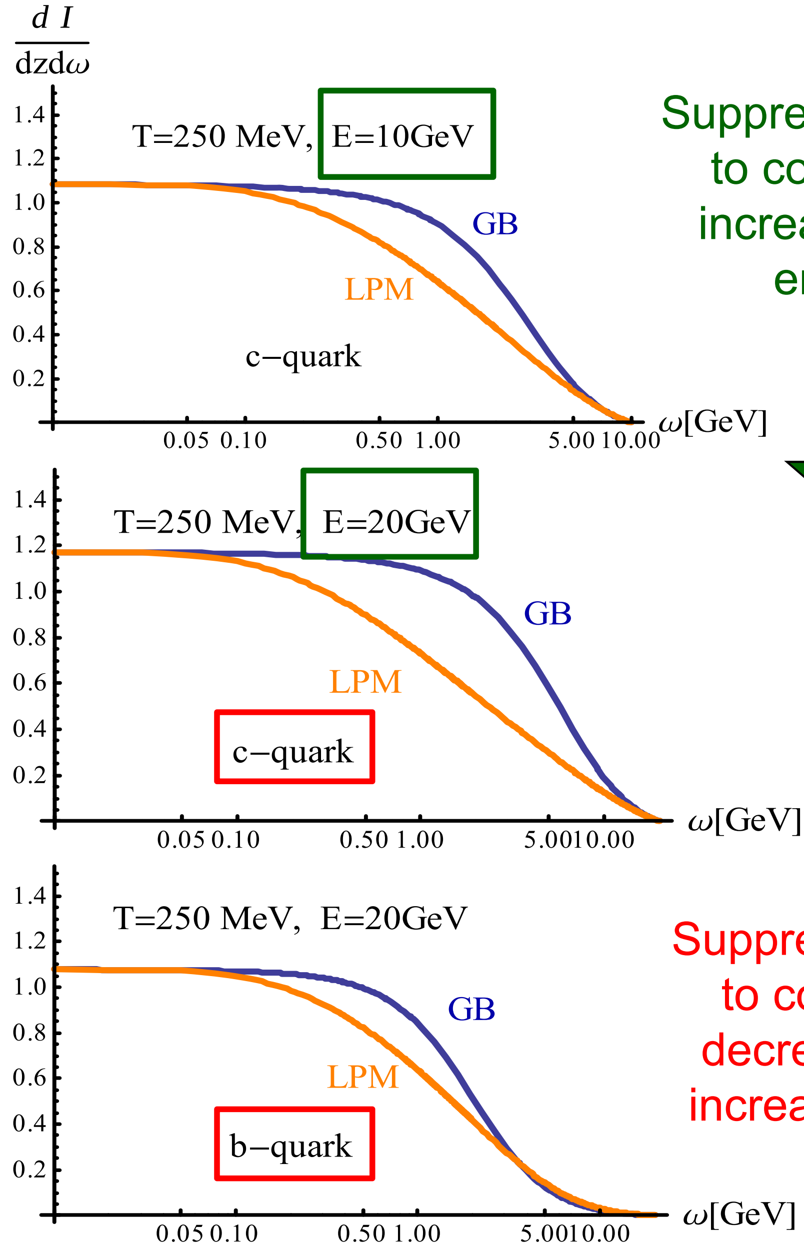
Formation time picture: for $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



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

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

[arXiv:1209.0844] (Hard Probes 2012)



Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

Monte Carlo Implementation (rad)

I) For each collision with a given $q_\perp$, we define the conditional probability of radiation:

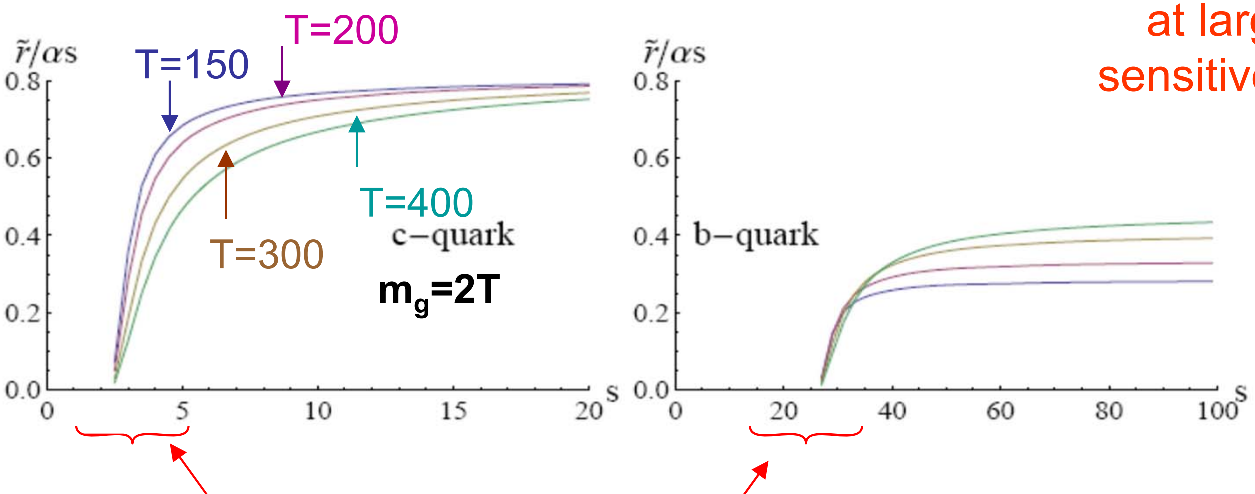
$$r(q_\perp) := \frac{\int_{\boxed{0}}^{+\infty} \frac{d^2\sigma_{\rm rad}}{d\omega dq_\perp^2} d\omega}{\frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}}$$

In practice, ω_{min}=5% E to avoid IR catastrophy

II) For each collision with a given invariant mass squared s, we define the conditional *total* probability of radiation:

$$\tilde{r}(s) = \frac{\sigma_{\rm rad}}{\sigma_{\rm el}} \approx \frac{\int_{-|t|_{\max}}^{0} r(\sqrt{-t}) \frac{d\sigma_{\rm el}^{Qq}(t)}{dt} dt}{\int_{-|t|_{\max}}^{0} \frac{d\sigma_{\rm el}^{Qq}(t)}{dt} dt}$$

Probes the elastic cross section at larger values of t => less sensitive to $\alpha_{\rm eff}$ at small t-values



Threshold for radiation

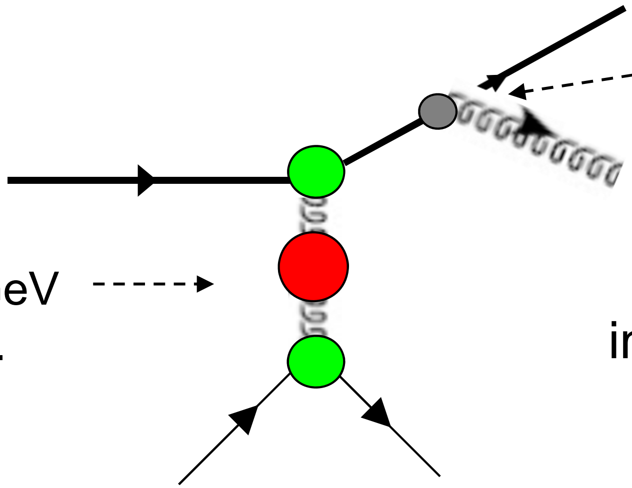
Monte Carlo Implementation (rad)

III) For a given HQ energy E, we sample the entrance channel according to the thermal distribution of light quarks and gluons and $\sigma_{el}(s)$ and accept according to the conditional probability $\tilde{r}(s)$

IV) We sample "downwards" $q_\perp$, ω and then $k_\perp$

Hard shocks with |t|>25% s are rejected (not treated properly in our formalism)

V) $P^+ \to (1-x)\, P^+$ and transverse kick of $\mathbf{q_\perp - k_\perp}$.



Fixed α_s

Approximation:

In "reality", several collisions at intermediate t-values accumulate

$<q_\perp>$ from 0.6 GeV (col) $\to$ 1.1 GeV (rad) for E=15GeV and T=400.

VI) Reject if out of phase-space