Heavy Quarks Messengers from QGP

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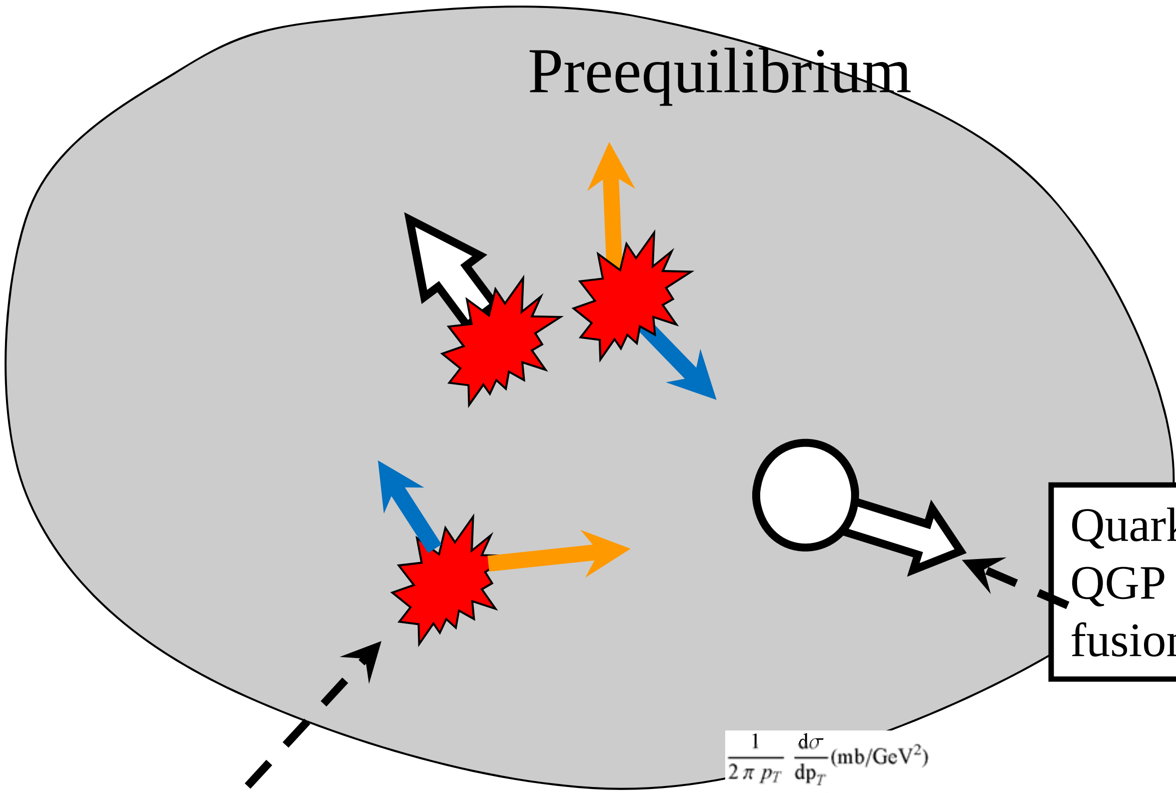
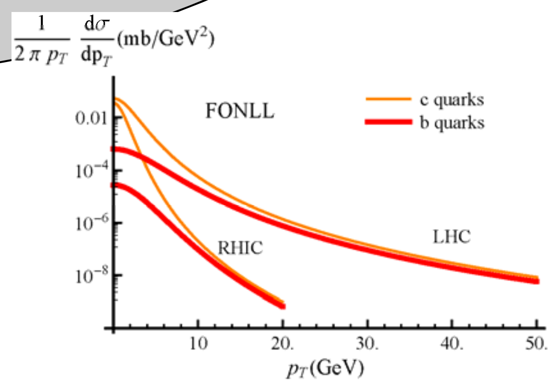
5 talks on strong interaction – SUBATECH – 14-18 January 2013

The Monte Carlo @ Heavy Quark Generator

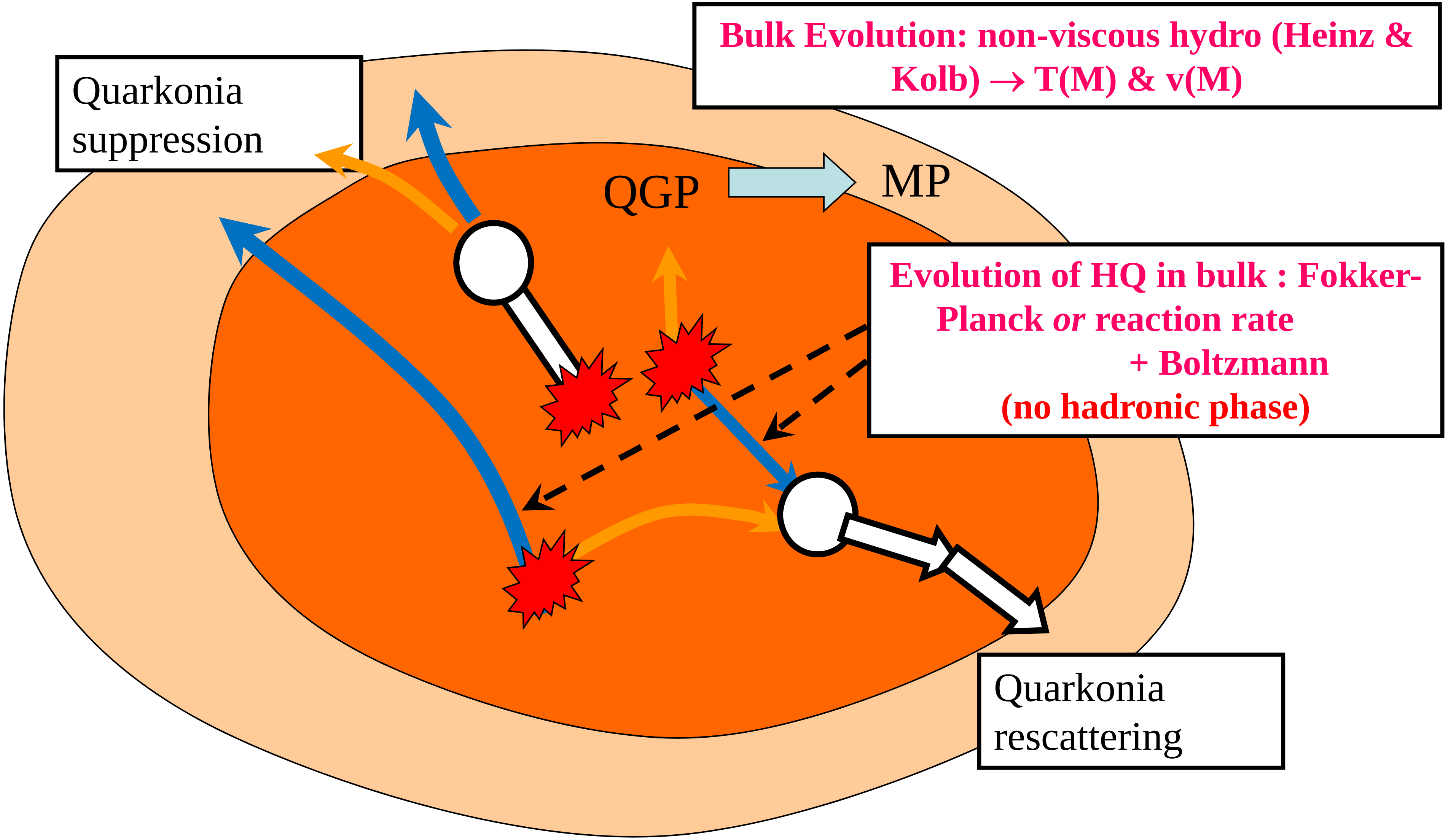


Quarkonia formation in QGP through c+c→Ψ+g fusion process

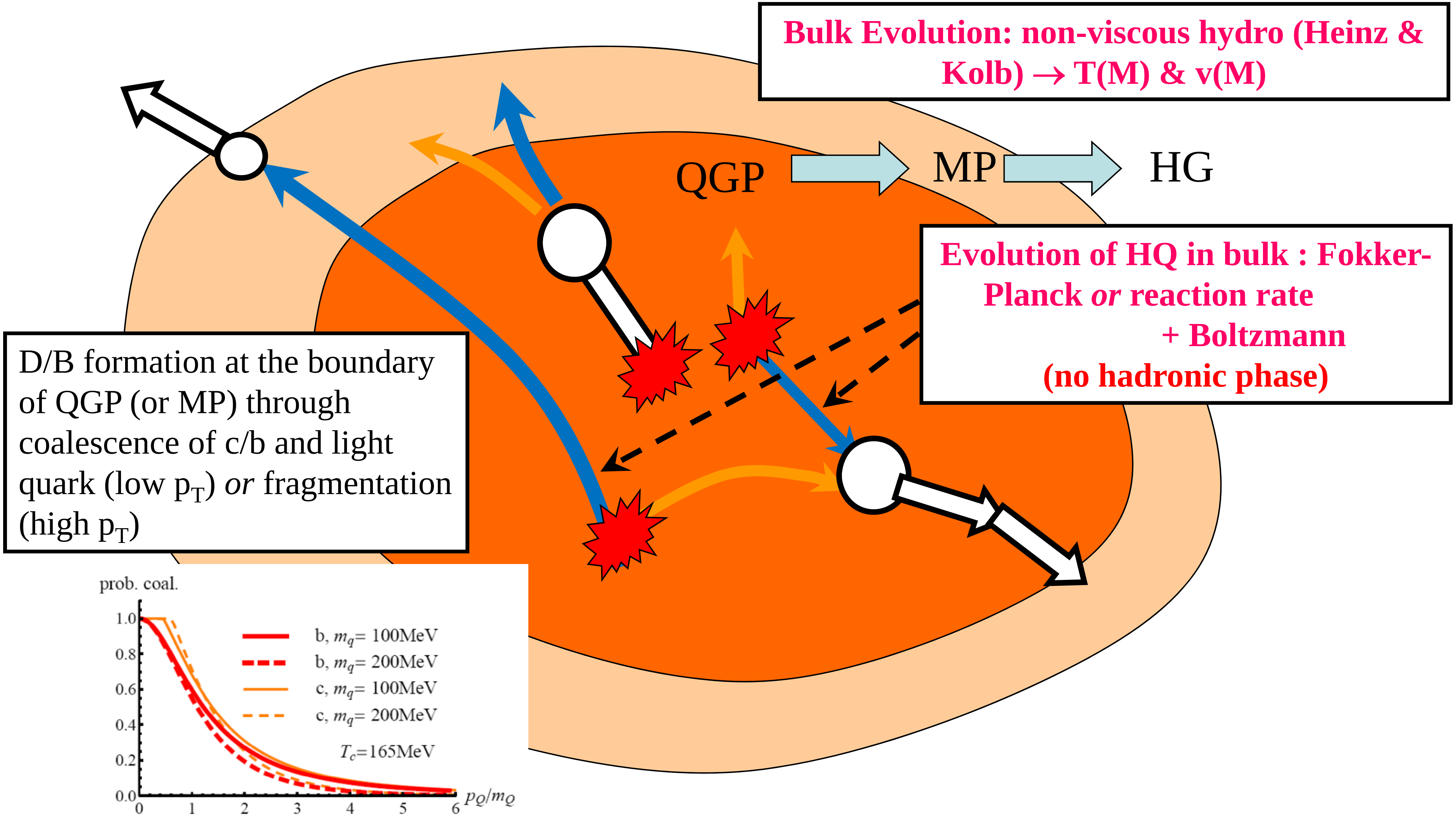
(hard) production of heavy quarks in initial NN collisions + k_T broad. (0.2 GeV^2/coll)



The Monte Carlo @ Heavy Quark Generator



The Monte Carlo @ Heavy Quark Generator



Model in a Nutshell: HQ Interaction with the bulk

- No force on HQ before thermalization of QGP
- Hydro evol => macroscopic parameters T(t,h,xT), **v**(t,h,xT), μ(t,h,xT),
- In QGP: heavy quarks are assumed to interact with partons of type "i" (massless quarks and gluons) with local 2→2 collisional rate:

$$R_i = \frac{1}{2E_p}\int\frac{d^3k}{(2\pi)^3 2k}\int\frac{d^3k'}{(2\pi)^3 2k'}\int\frac{d^3p'}{(2\pi)^3 2E'}$$
$$n_i(k)\times\ (2\pi)^4\delta^{(4)}(P+K-P'-K')\sum|\mathcal{M}_i|^2$$

Φ inside

…depends on the QGP macroscopic parameters at a given 4-position (t,x).

We follow the hydro evolution and sample the rates R_i "on the way", performing the Qq→Q'q' & Qg→Q'g' collisions according to Boltzmann:

Monte Carlo approach

- In mixed phase: Rate = $\varepsilon/\varepsilon_{\text{end QGP}}$ x Rate at end of QGP
- No D (B) interaction in hadronic phase

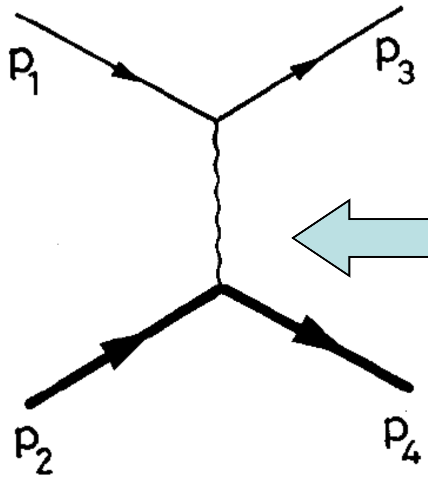
Oldies on

Collisional Energy Loss…

suffers from customary choices

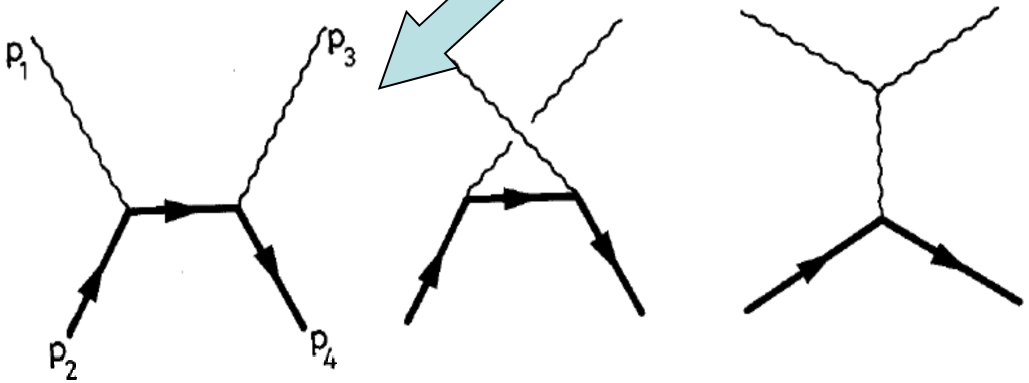
Cross sections

Starting from Combridge (79) as a basis:



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

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



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)

Models A/B: 2 customary choices

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

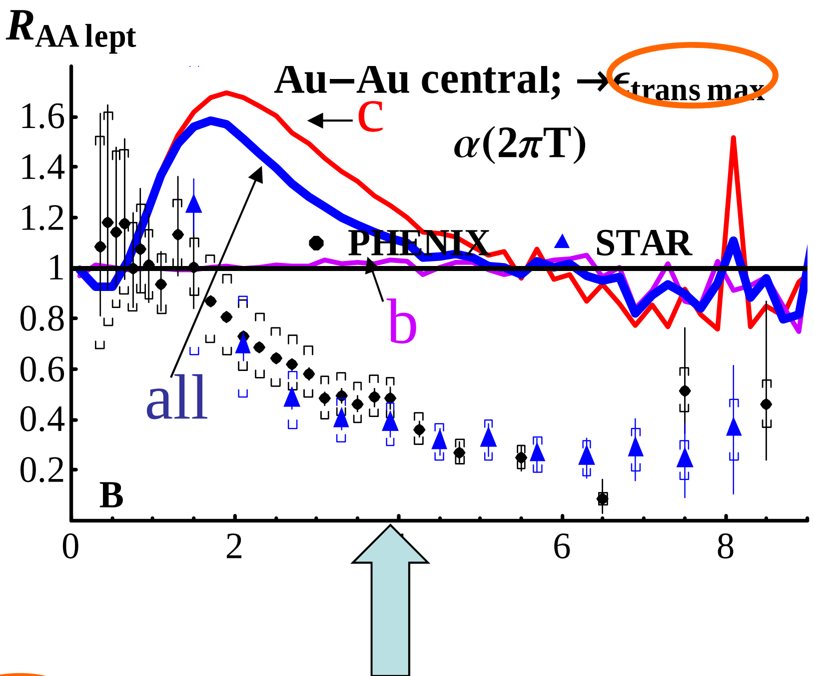
$\alpha_s(Q^2) \to \begin{cases} 0.3 \text{ (mod A)} \\ \alpha_s(2\pi T) \text{ (mod B)} \ (\approx 0.3) \end{cases}$

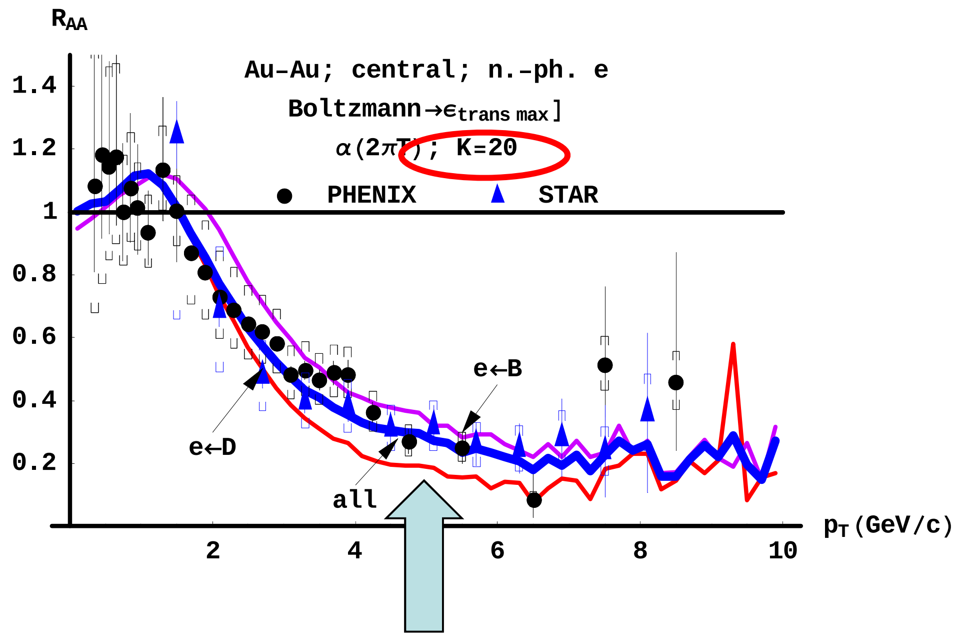
$$\frac{dE_{coll}(c)}{dx}$$

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

… of the order of a few % !

Results for model B:





Evolution → beginning of cross-over

: Cranking factor of the collisional rate

N.B.: Overshoot due to coalescence

One reproduces the R_{AA} shape at the price of a *huge cranking K-factor* !!!

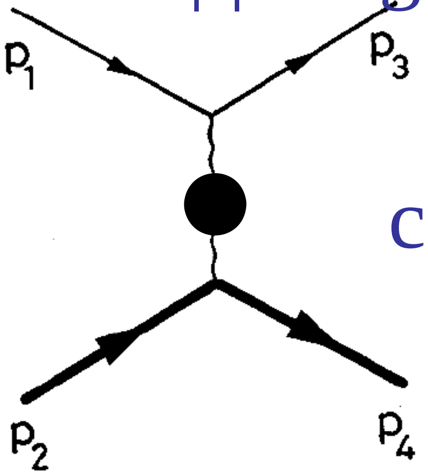
Calibrating on HTL… *permits to fix the effective mass* μ

Braaten-Thoma:

(Peshier – Peigné)

HTL: convergent kinetic
(matching 2 regions)

Low |t|: large distances

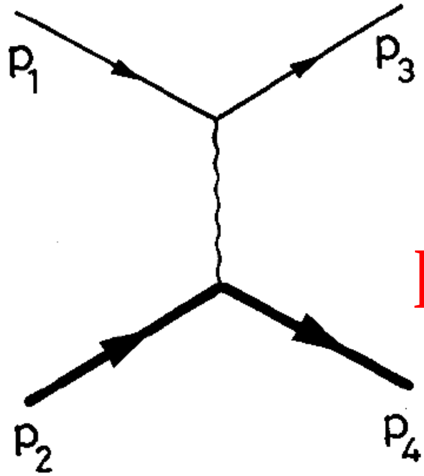


HTL:
collective
modes

$|t^*|$

+

Large |t|: close coll.



Bare
propagator

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

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

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

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

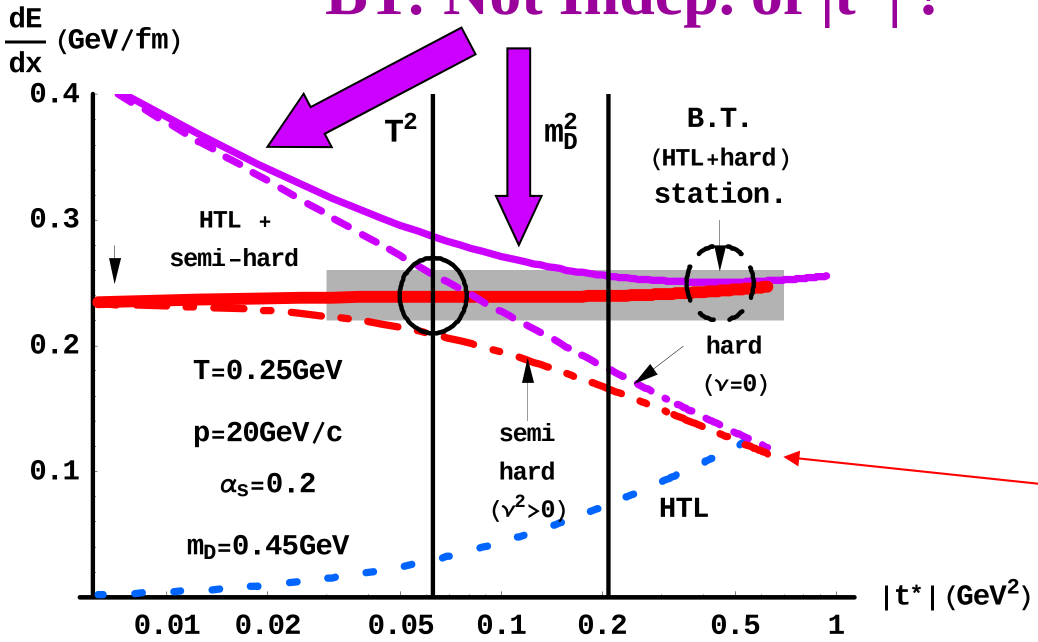
SUM: $\dfrac{dE}{dx} = \dfrac{2}{3}\alpha\, m_{\mathrm{D}}^2 \ln\left(\dfrac{\sqrt{ET}}{m_{\mathrm{D}}/\sqrt{3}}\right)$

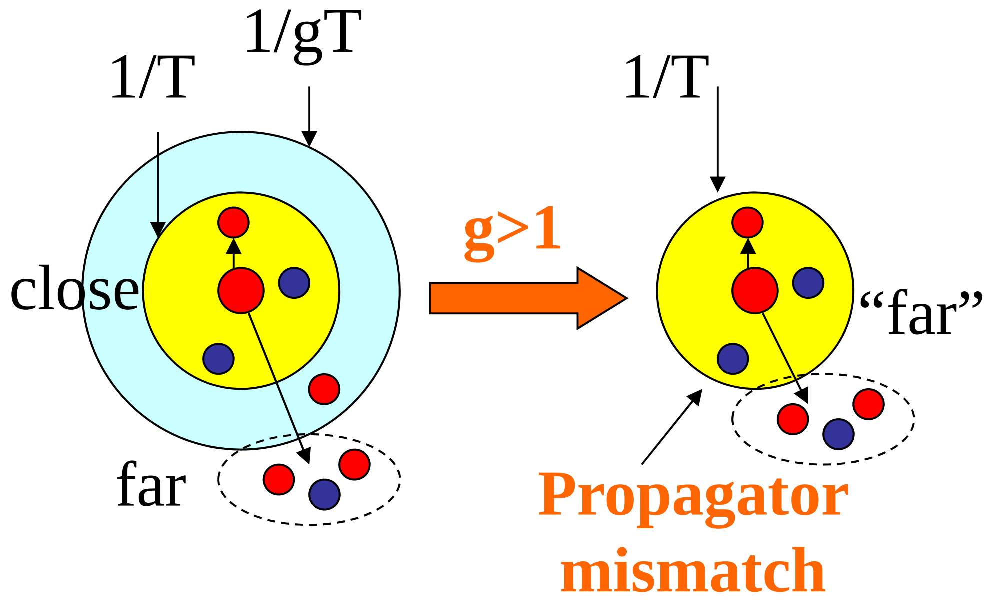
Indep. of |t*| !

(provided $g^2T^2 \ll |t^*| \ll T^2$)

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

BT: Not Indep. of |t*| !





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 sound value of $|t^*| \approx T$

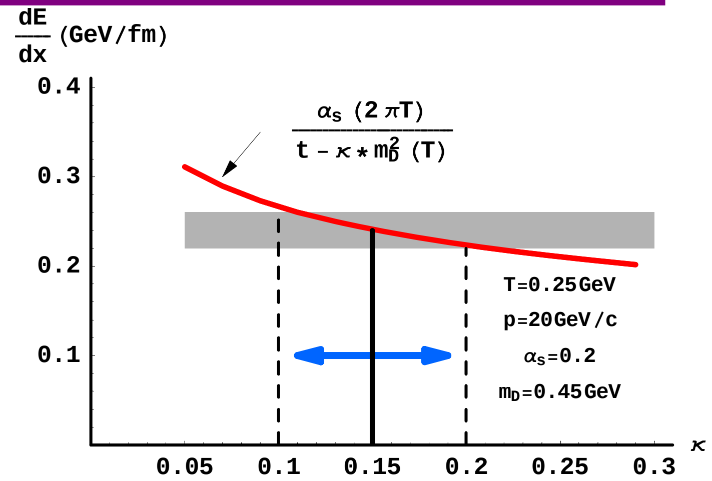
Model C: optimal μ^2

THEN: Optimal choice of μ in our OBE model:

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

$$\boxed{\mu^2(T) \approx 0.15\, m_D^2(T)}$$

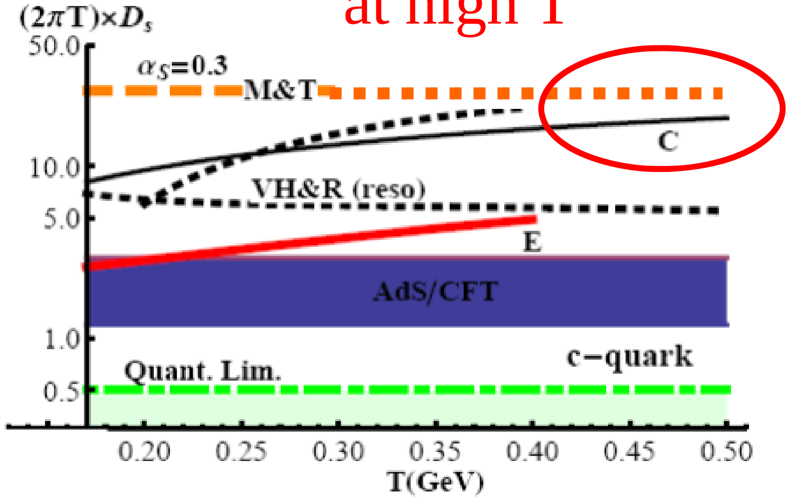
with $m_D^2 = 4\pi\alpha_s(2\pi T)(1+3/6)xT^2$



$$\frac{dE_{coll}(c)}{dx}$$ … 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



Running α_s …

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

…asymptotic freedom and infrared slavery

Strategy

1. Effective $\alpha_{eff}\,(Q^2)$

2. "generalized BT" / convergent-kinetic => dE/dx

3. Fix the optimal IR regulator in propagator
   i.e. in t-channel, fix the optimal κ

$$\frac{\alpha_{\text{eff}}(t)}{t - \kappa\underbrace{\tilde{m}_D^2(T)}_{\mu^2(T)}}$$

Self consistent m_D (Peshier hep-ph/0607275)

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

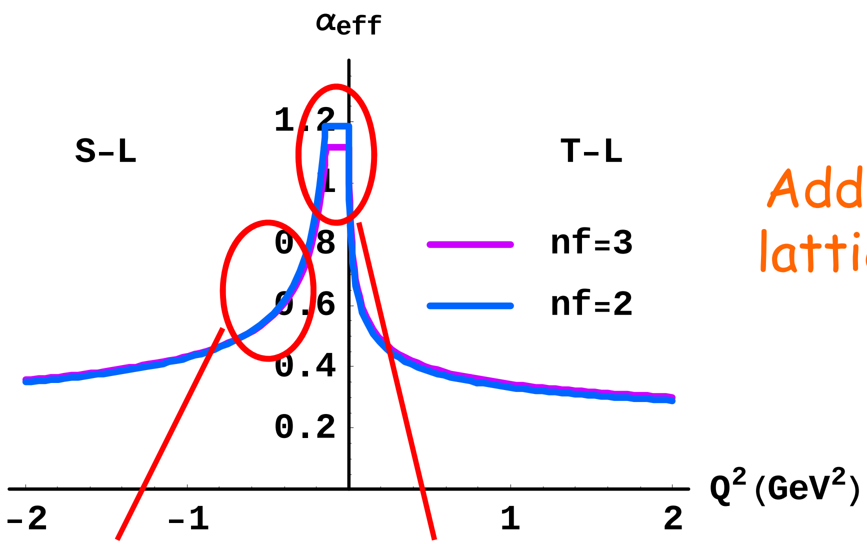
Model E : running α_s AND optimal μ^2

- Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)

Observable = T-L effective coupling * Process dependent fct

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

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



Additional inputs (from lattice) could be helpful

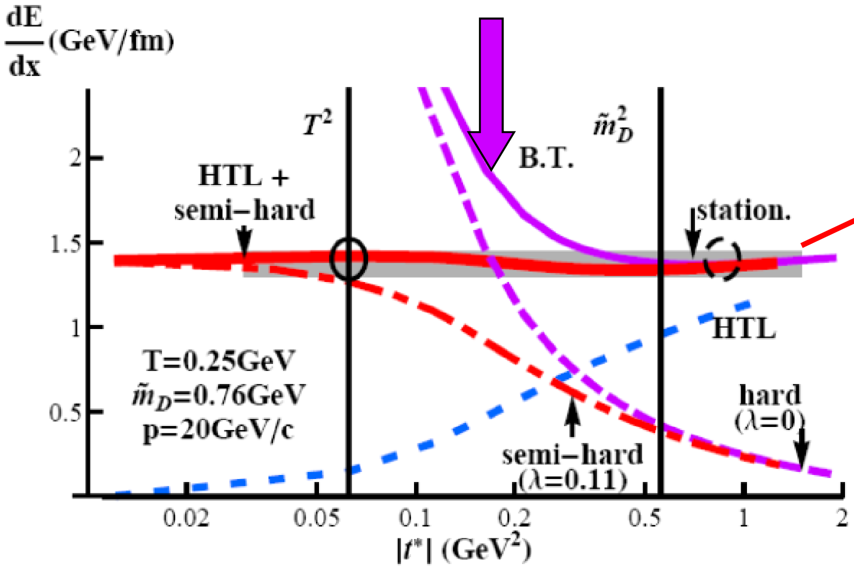
Large values for intermediate momentum-transfer

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

Model E : running α_s AND optimal μ^2

- Bona fide "running HTL": $\alpha_s \to \alpha_s(Q^2)$

Brute BT: Not Indep. of |t*| !



Introducing semi-hard propag…

$$\frac{\alpha_{\text{eff}}(t)}{t} \longrightarrow \frac{\alpha_{\text{eff}}(t)}{t - \lambda m_D^2(T,t)}$$

…leads to stationary results

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

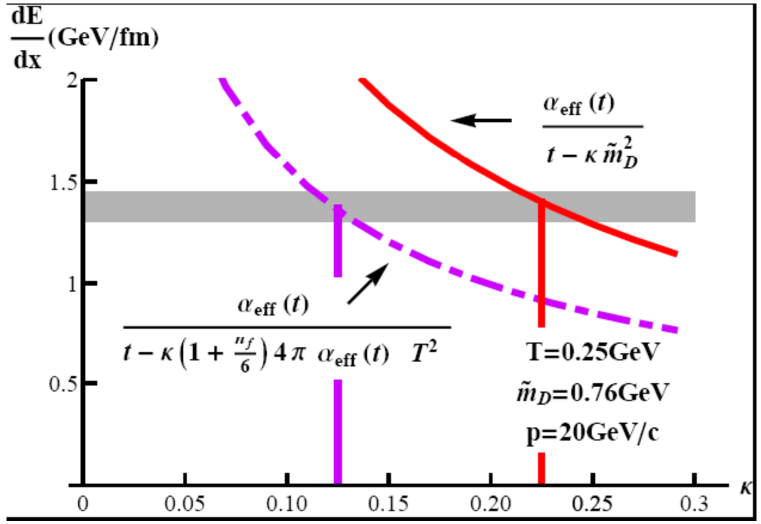
T(MeV) \p(GeV/c)	10	20
200	**1 / 0.65**	**1.2 / 0.9**
400	**2.1 / 1.4**	**2.4 / 2**

Of the order of 10 % of energy

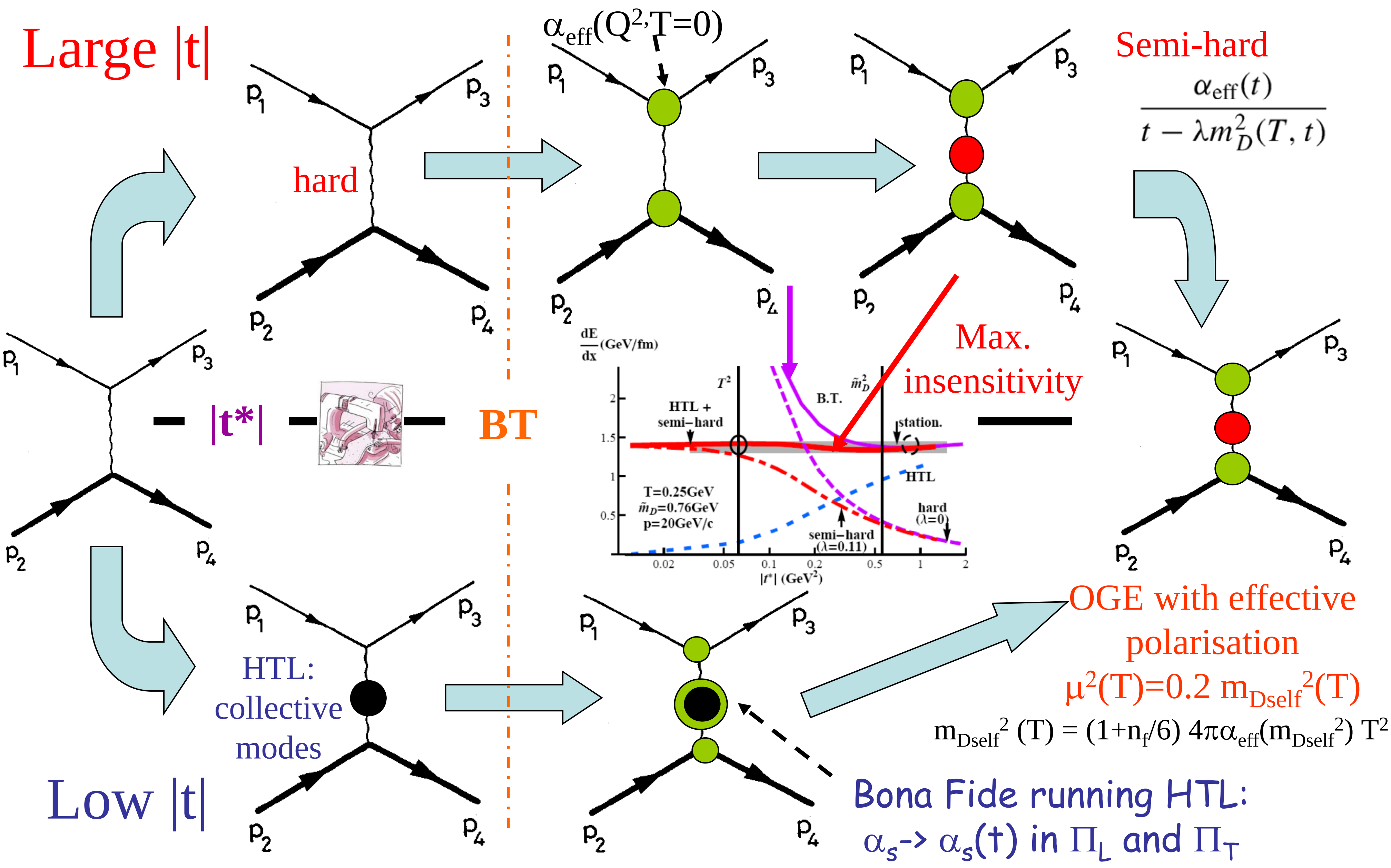
Model E : running α_s AND optimal μ^2

- Optimal regulator:

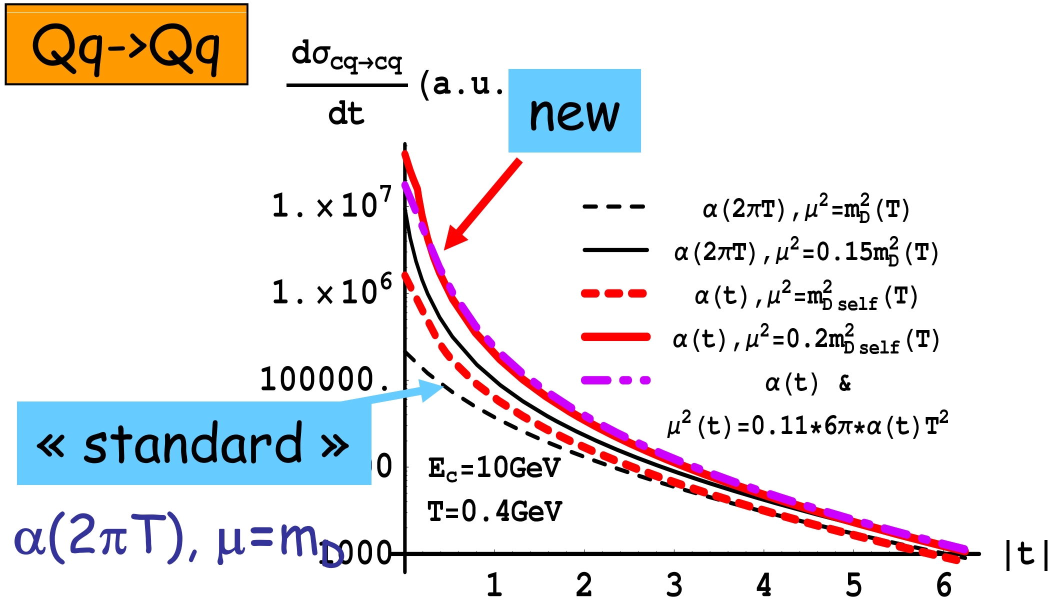
$$\mu^2(T) \approx 0.2\ m_{Dself}{}^2(T)$$

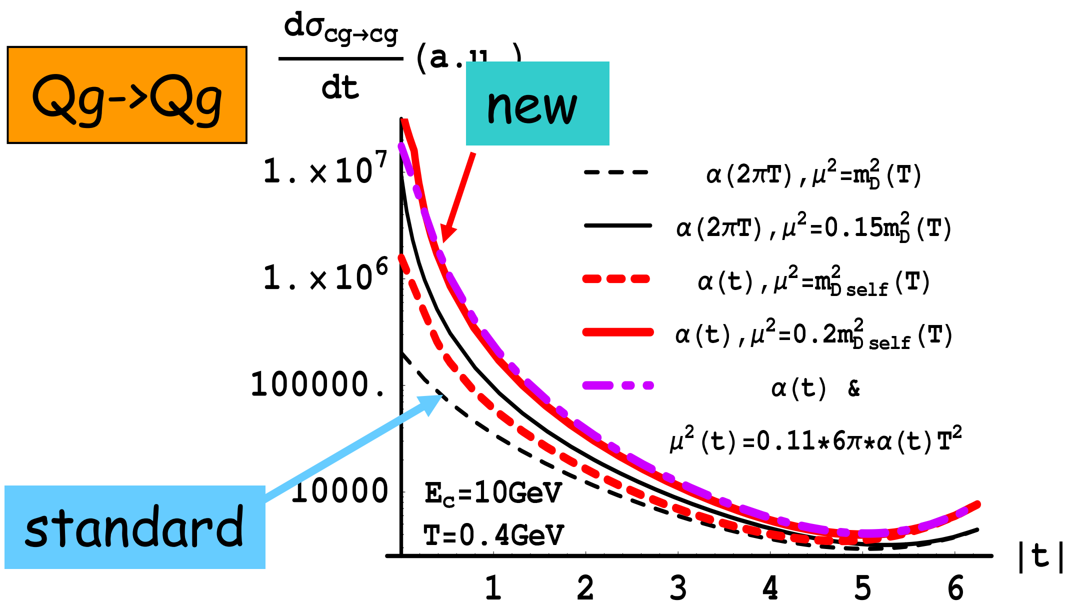


μ-local-model: medium effects at finite T in t-channel



Differential cross sections

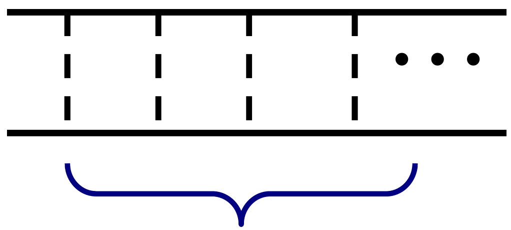




Large enhancement of both cross sections at small and intermediate |t|

Little change at large |t|

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

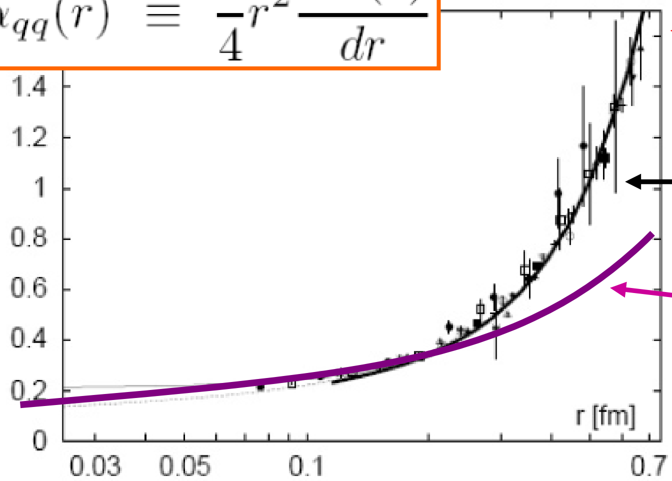
RPA + 

Ladders necessary at short distance (large force)

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

T=0

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



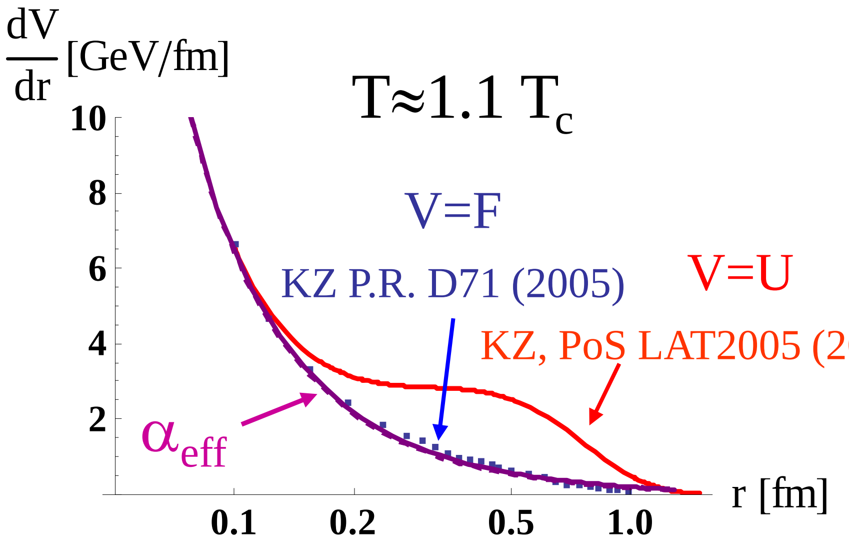
O. Kaczmarek & F. Zantow (KZ) (n_f=2 QCD), P.R.D71 (2005) 114510

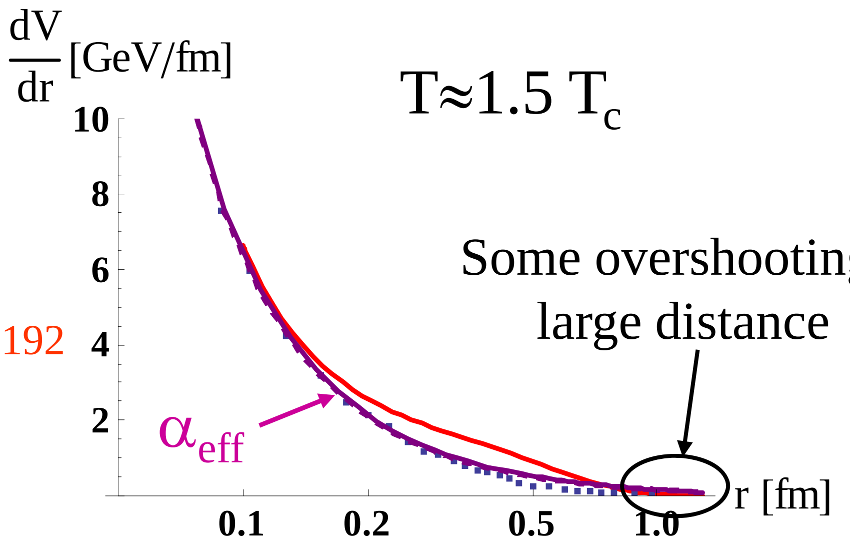
Genuine non-pert (flux tube)

optimal μ, running α_{eff}

V:ω=0 sector; dE/dx: finite ω

Finite T





Merging at ≈2 T_c

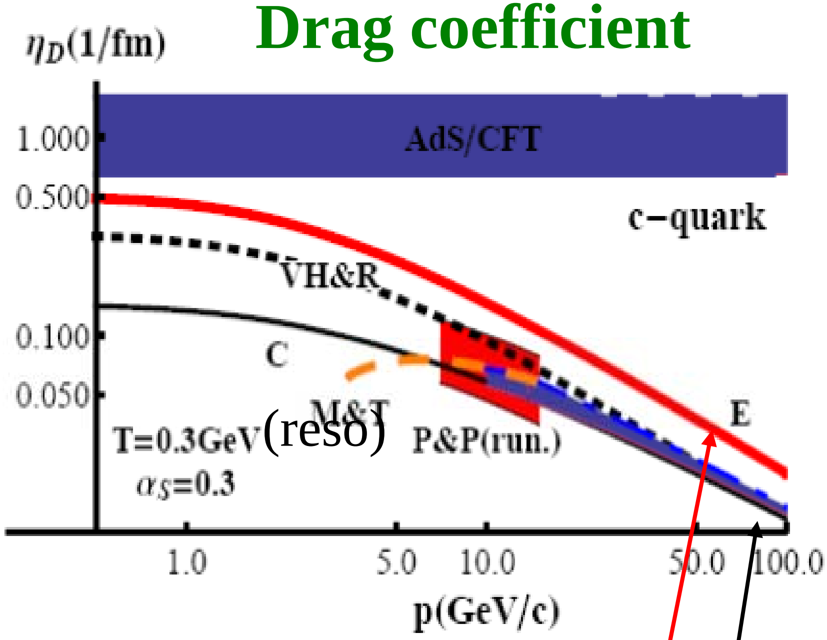
Running α_s : some Energy-Loss values

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

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

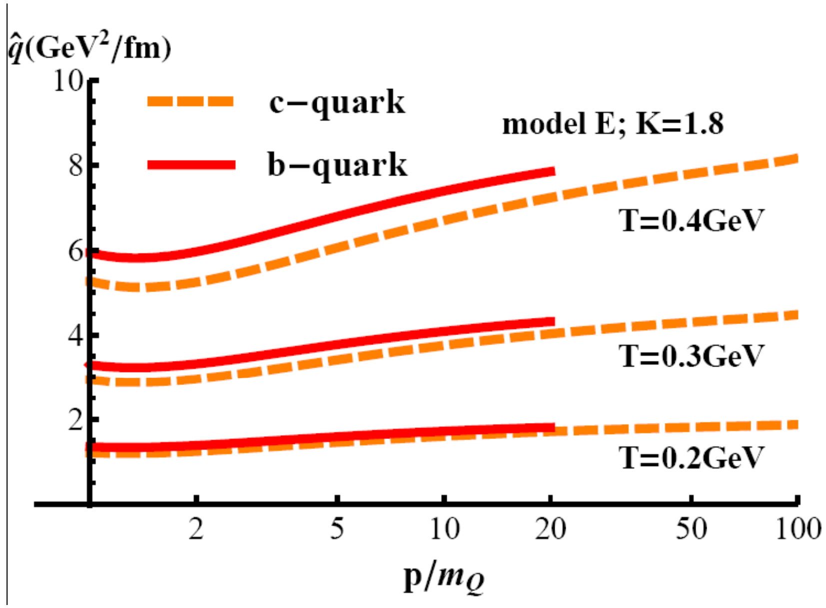
Drag coefficient



E: optimal μ, running α_{eff}

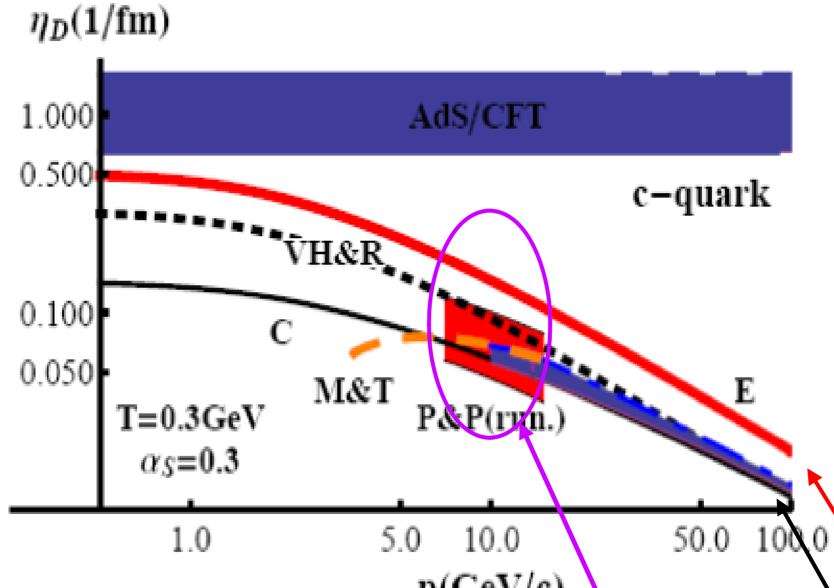
C: optimal μ, $\alpha_s(2\pi T)$

Transp. Coef …

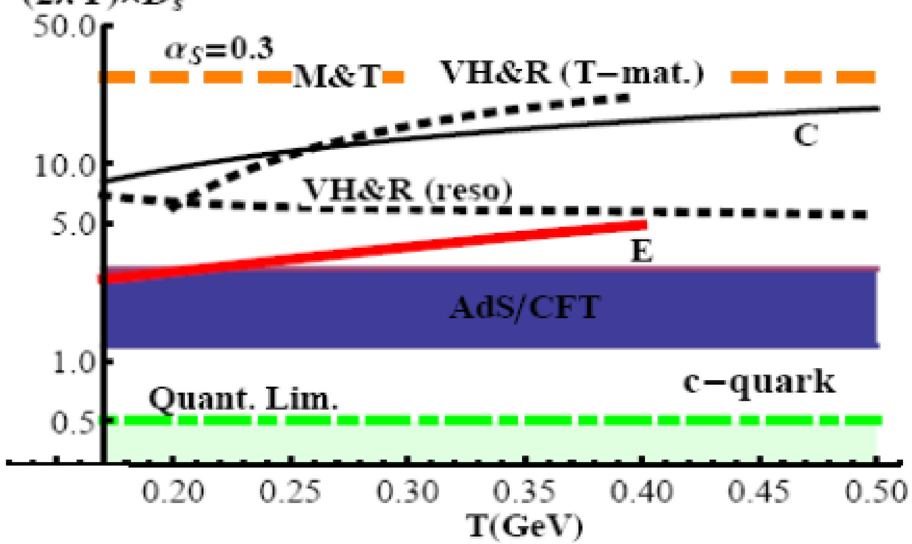


… of expected magnitude

Transport coefficients



Diff. coefficient

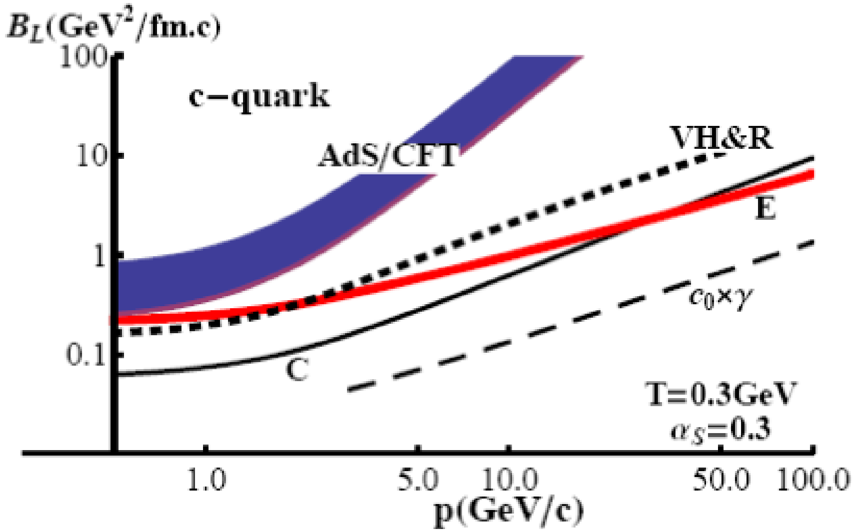


Long. fluctuations

Caution: *One* way of implementing running α_s

E: optimal μ, running $\alpha_{s,eff}$

C: optimal μ, $\alpha_s(2\pi T)$

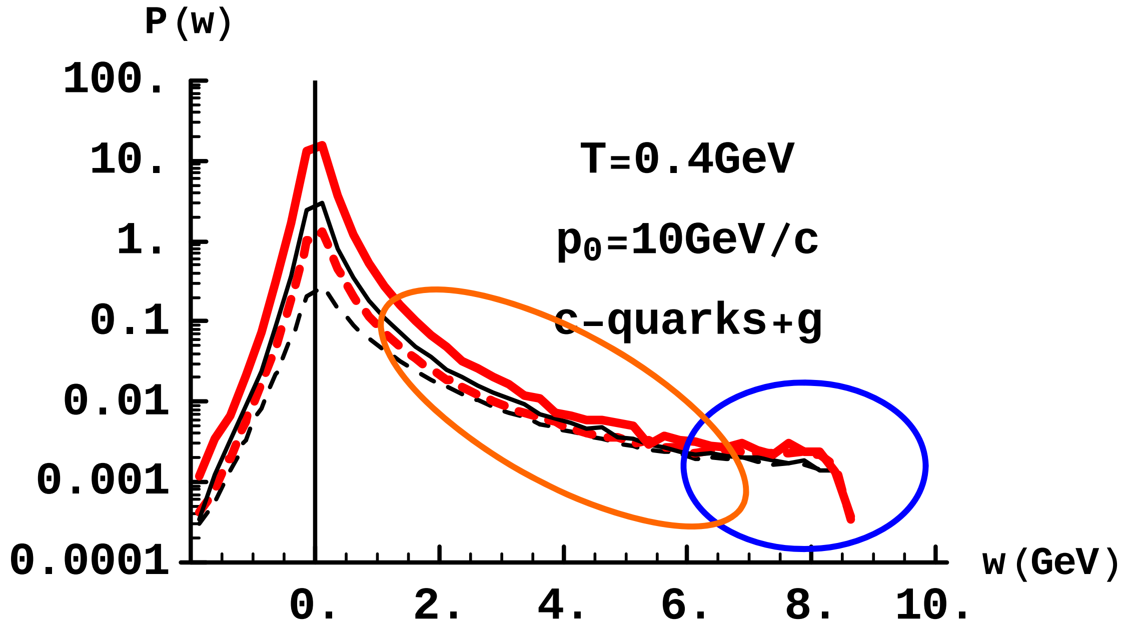


Running α_s and Van Hees &Rapp: roughly same trend

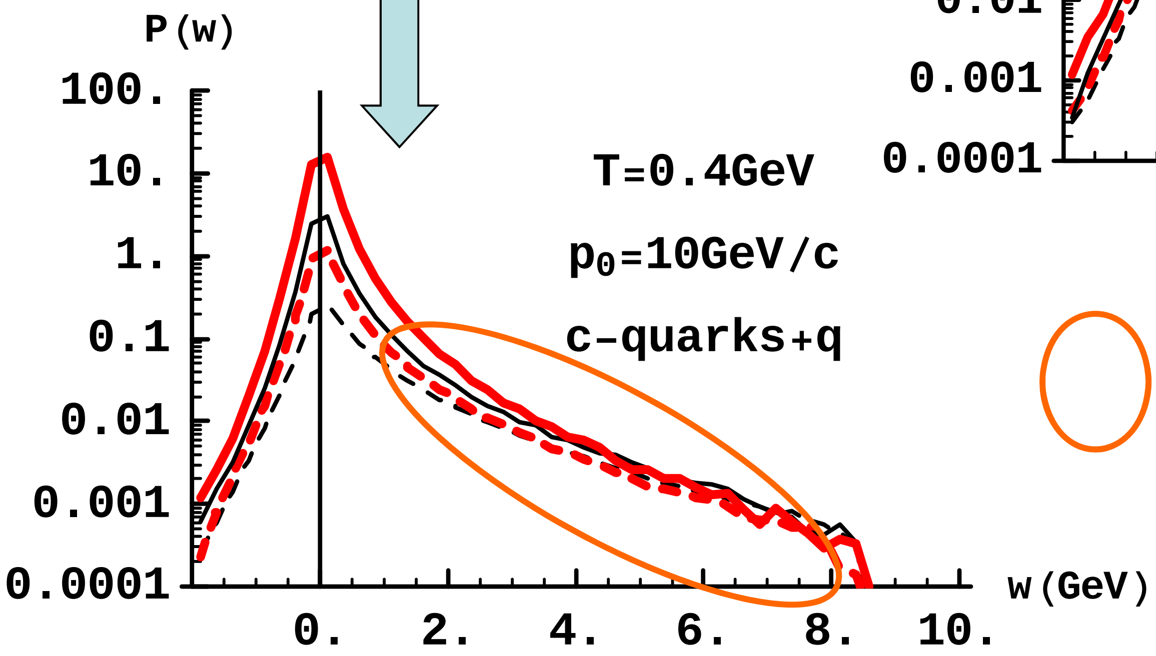
mod C – mod E - AdS/CFT
Evolution ? Not so clear

Probability P(w) of energy loss per fm/c:

With gluons



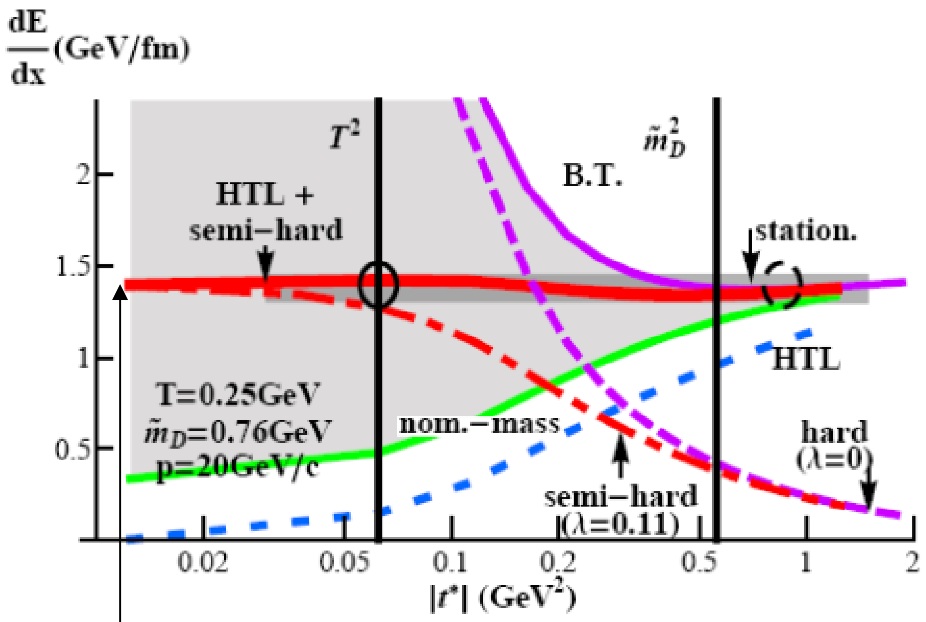
With quarks



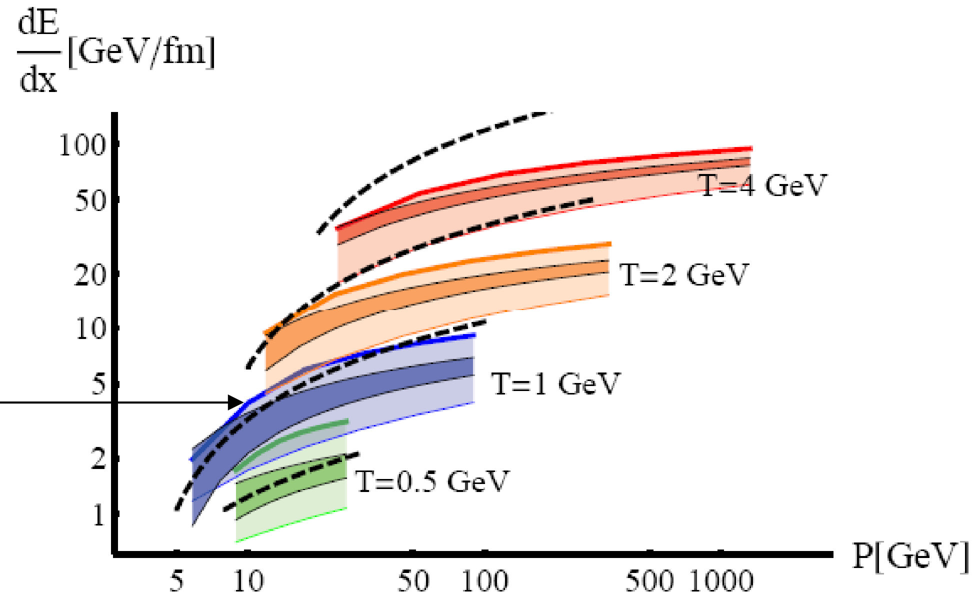
: Large fluctuation tail

: hard transfer due to u-channel

Running α_s : theoretical uncertainties



E: optimal μ, running α_{eff}

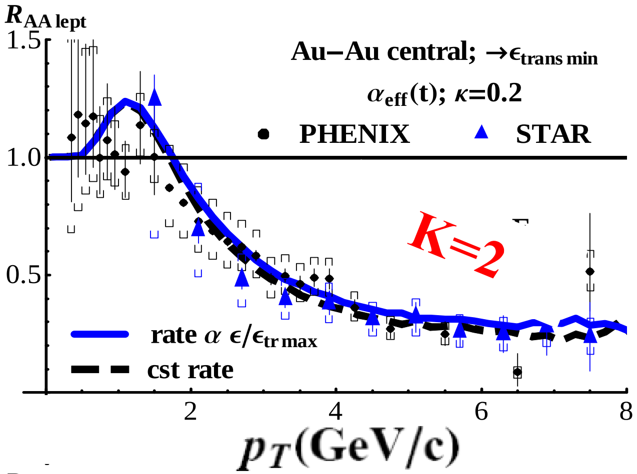


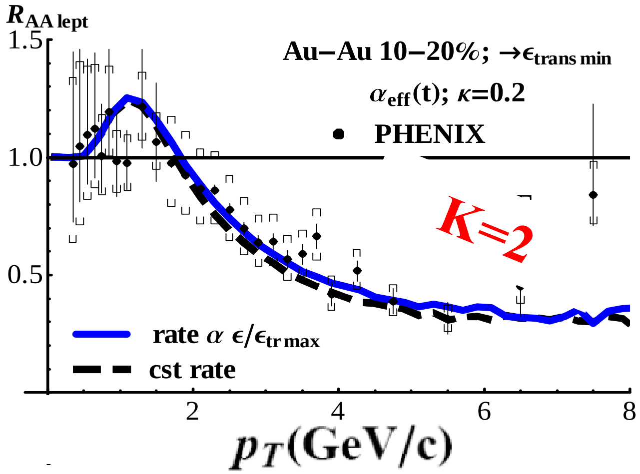
Dark zones: PP

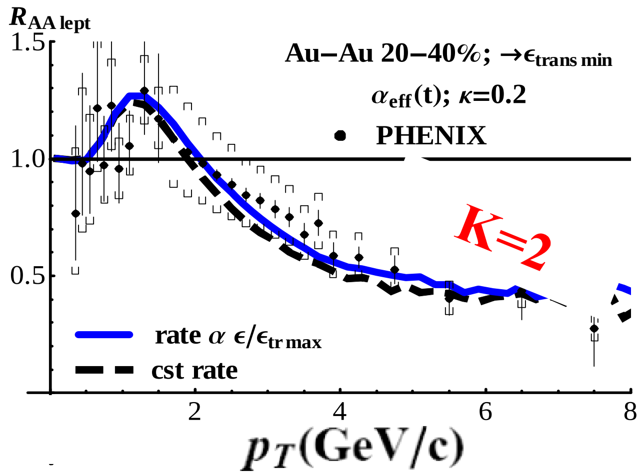
Experimental observables

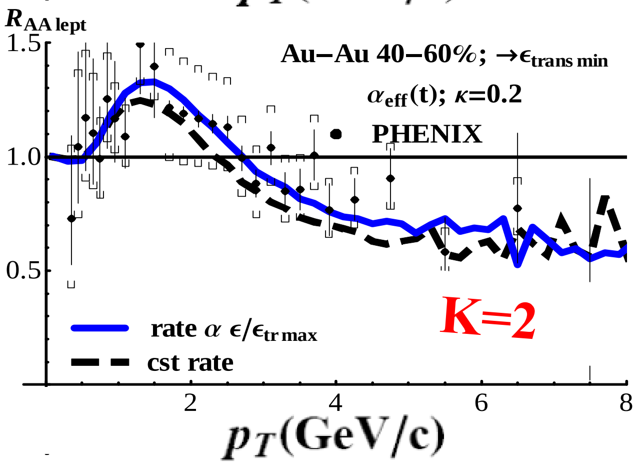
Model vs R_{AA} (Au-Au, all centralities)

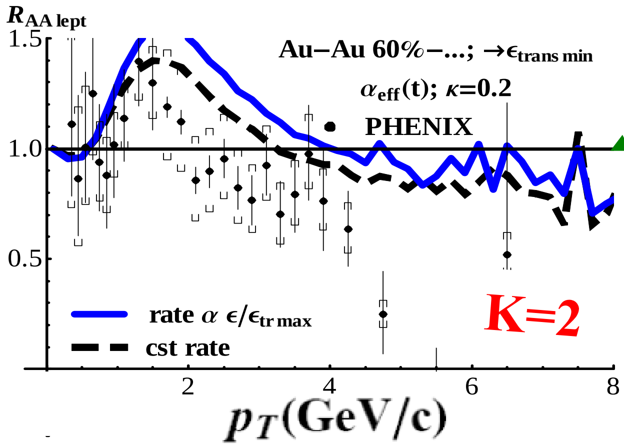
Tuning: Cranking the interaction rates by “empirical” K-factor











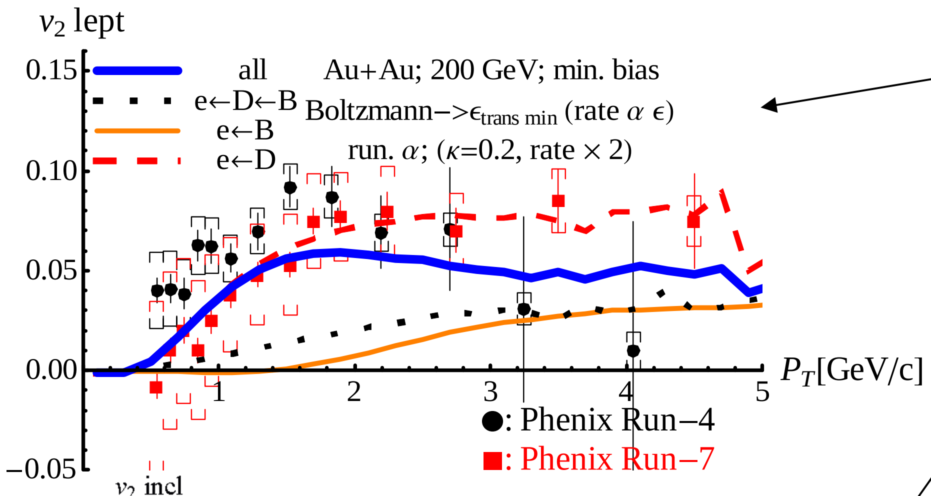
Syst. Error due to p-p

Customary choice for our present analysis

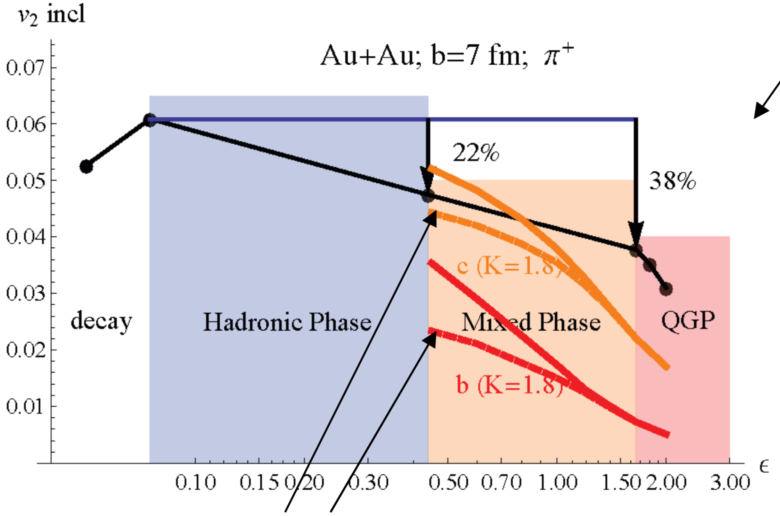
* One reproduces R_{AA} *on all p_T range* with cranking K-factor ≈2

* Data compatible with ΔE α path-length L in stationnary QGP.

v_2 for tuned model :

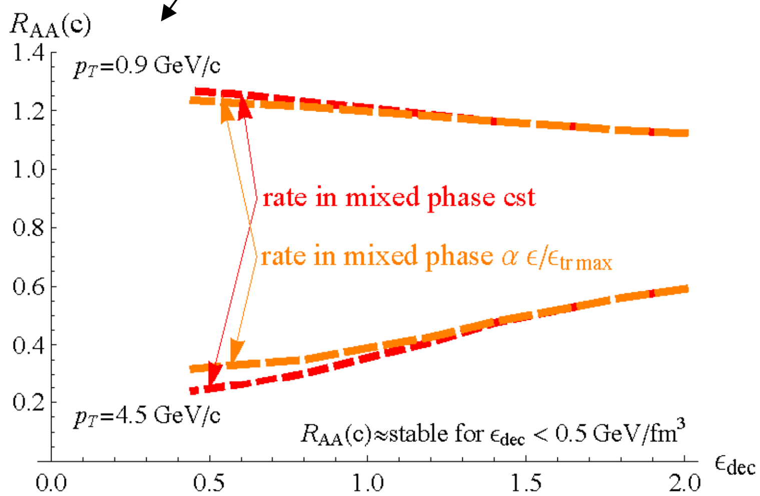


v_2 (nearly) compatible with experimental data (20% missing)



Rate α ϵ in MP

v_2 builds until very late times, while R_{AA} has already saturated



Reasonable hope that v_2 will agree with data when hadronic phase implemented

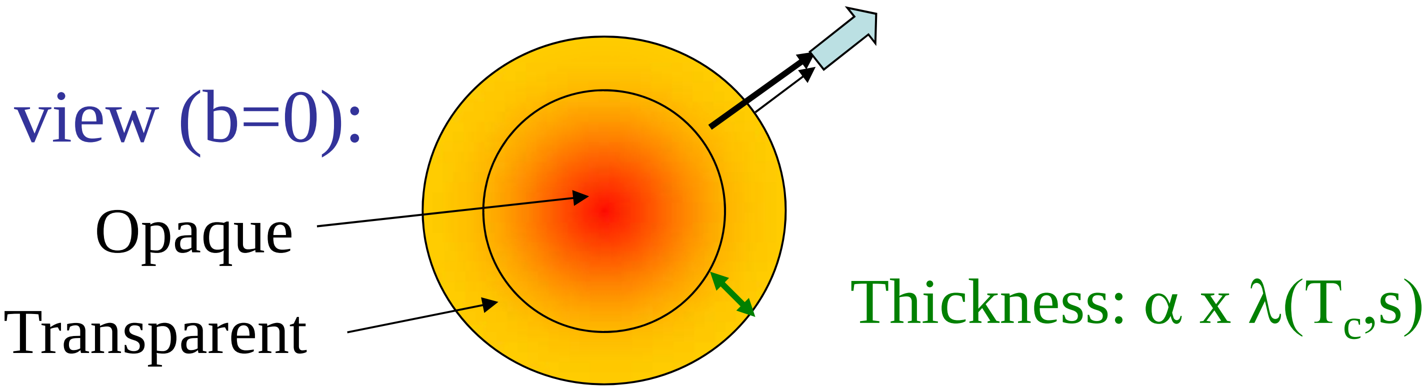
Corona effect and Beyond

How Opaque (or Translucid) is the (s)QGP ?

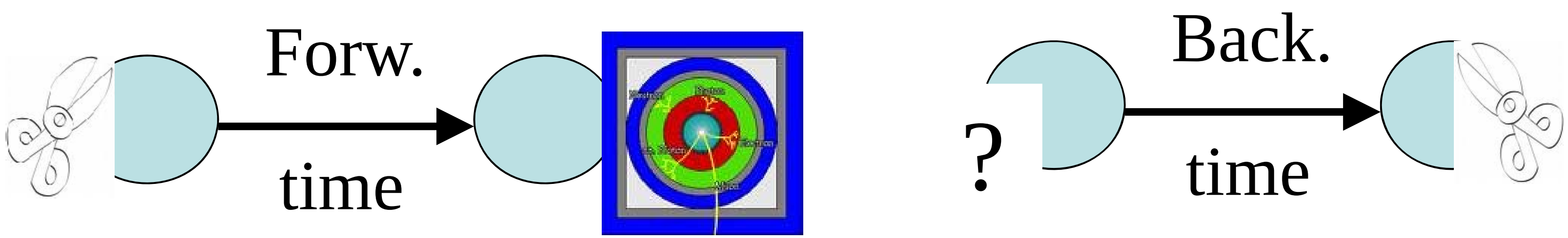
Probing the energy loss with R_{AA} at large p_T:

* **large p_T**: mostly corona effect (?)

* Naïve view (b=0):



- Two kinds of (theoretical) “observables” to understand:
  - «Forward»: Cuts on initial variables (position, momentum,…) and look at consequences for final quantities
  - Backward: Cuts on final variables and observe initial quantities

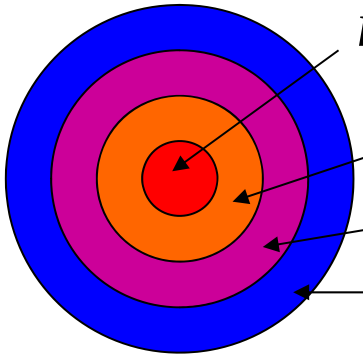


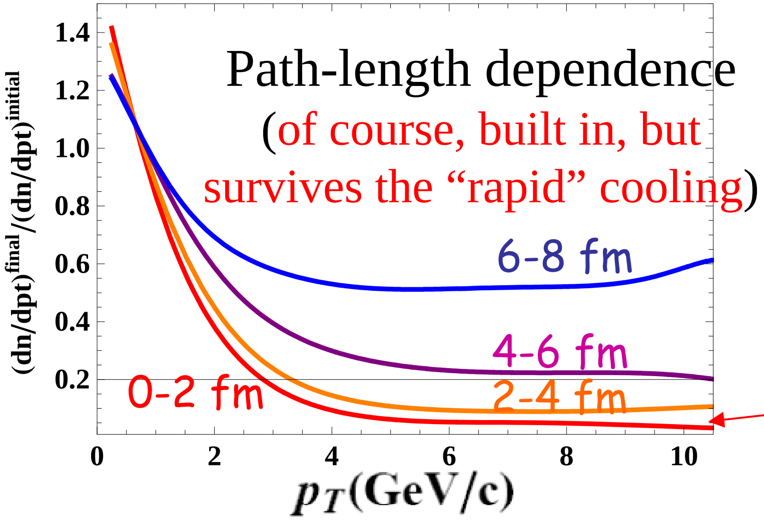
Probing the energy loss with R_{AA} at large p_T

All analysis: Au+Au at 200 A GeV & b=0 fm

* Forward: focus on c-quarks produced within various coronas

Transverse plane



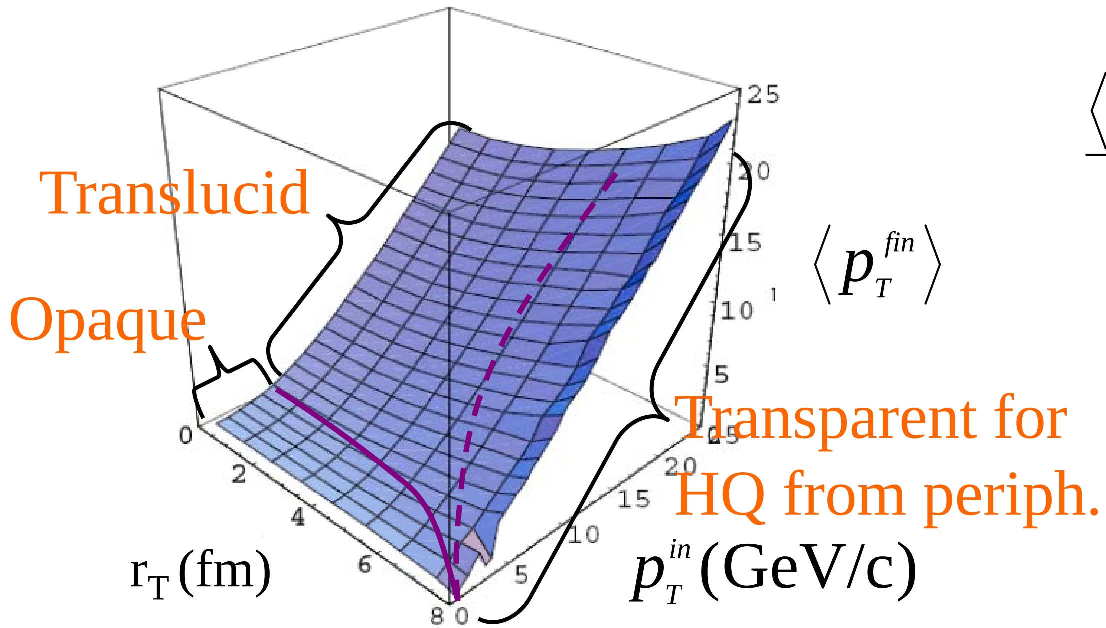


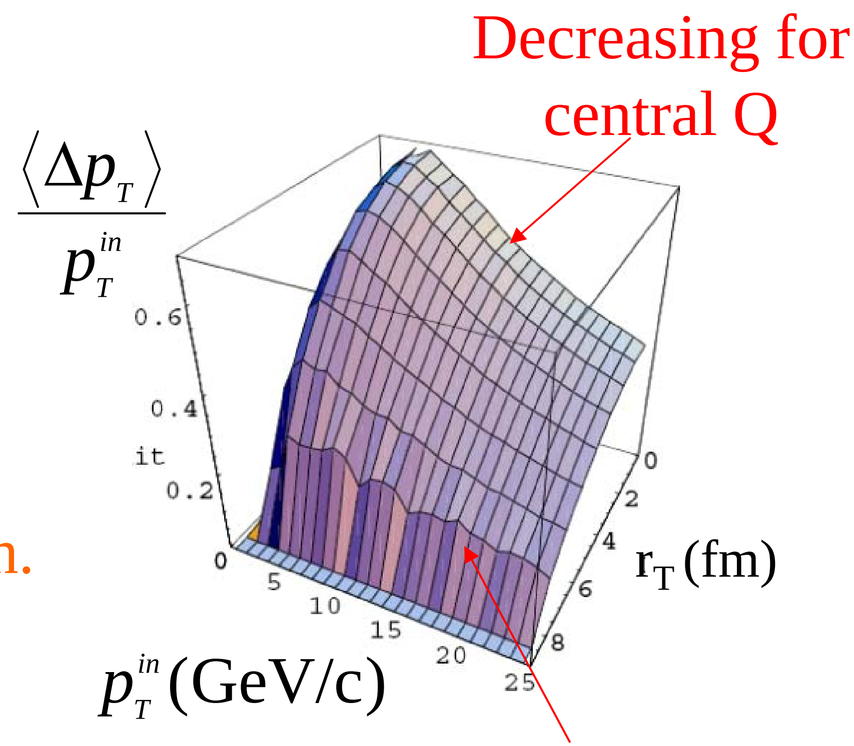
The stopping depends strongly on the position where the HQ's are created

The spectra at large p_T are insensitive to the HQ's produced in the center of the plasma

Very few Q produced in central zone come out… however, more quarks produced than at periphery

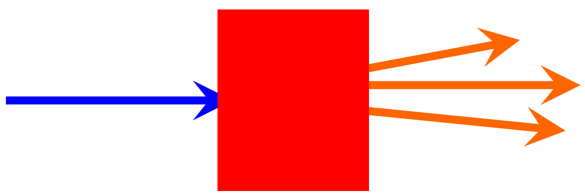
…answers may vary depending on T and p





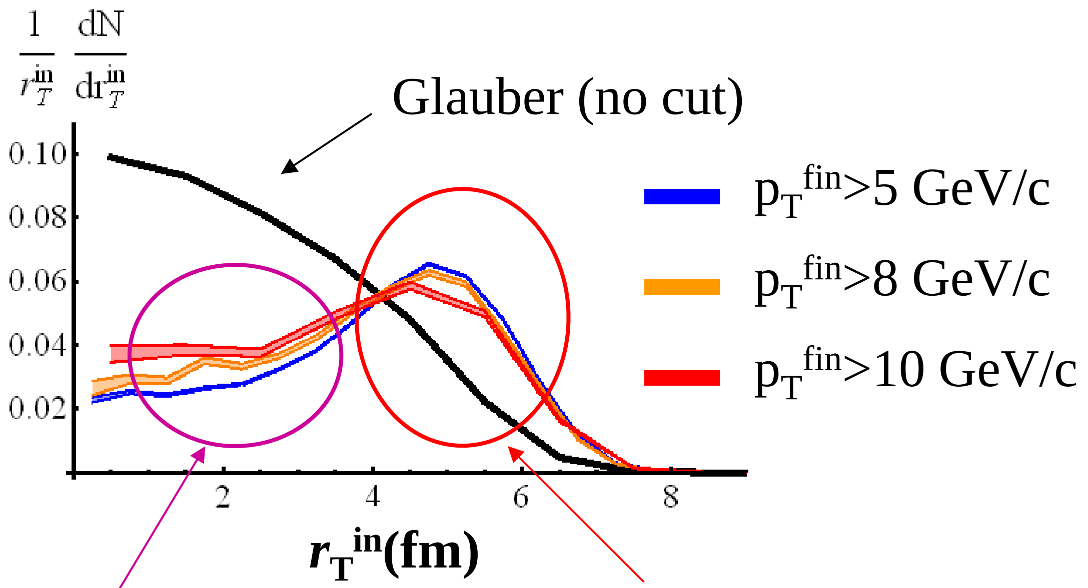
≈ cst at periphery => robust corona

* Challenge: tagging on the "central" Q, i.e. getting closer to the ideal "penetrating probe" concept:



Probing the Energy Loss with R_{AA} at large p_T

* Backward Analysis: tag on final p_T and builds the distribution of *initial positions* in transverse plane

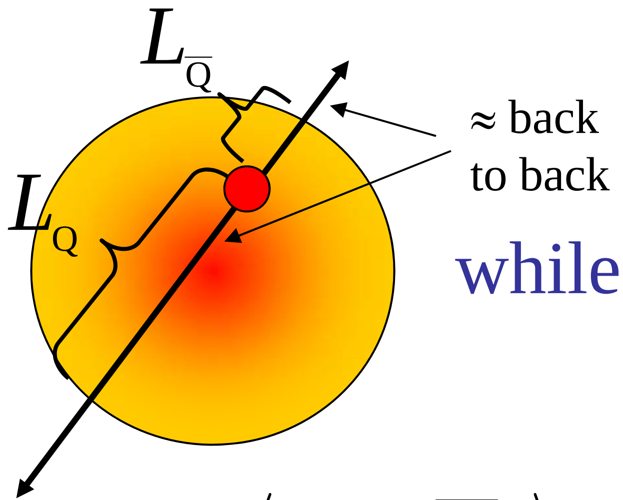


Probability peak for $r_T^{in} \approx$ 5fm: STRONG CORONA EFFECT

However: finite contribution from the center (hot zone), larger and larger at high p_T

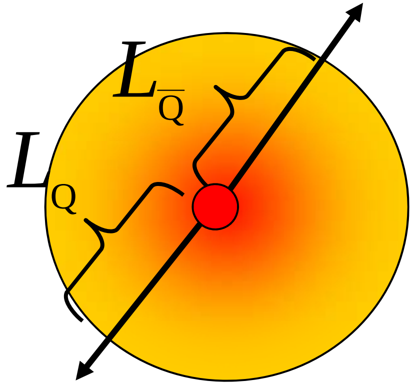
How to *better* access them ?

Q-Qbar Correlations



$$L_{\overline{Q}} < L_Q \Rightarrow \langle \Delta p_T(\overline{Q}) \rangle < \langle \Delta p_T(Q) \rangle$$

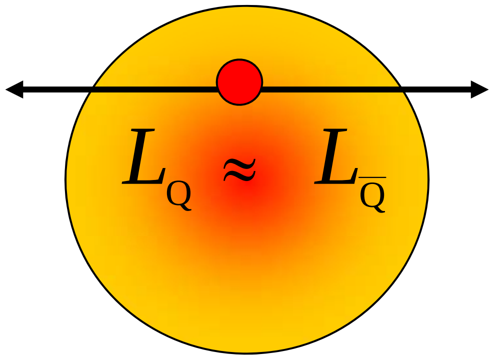
while



$$L_{\overline{Q}} \approx L_Q \Rightarrow$$
$$\langle \Delta p_T(\overline{Q}) \rangle \approx \langle \Delta p_T(Q) \rangle$$

* Reversing the argument: selecting $\langle \Delta p_T(\overline{Q}) \rangle \approx \langle \Delta p_T(Q) \rangle$ might bias the data in favor of "central" pairs

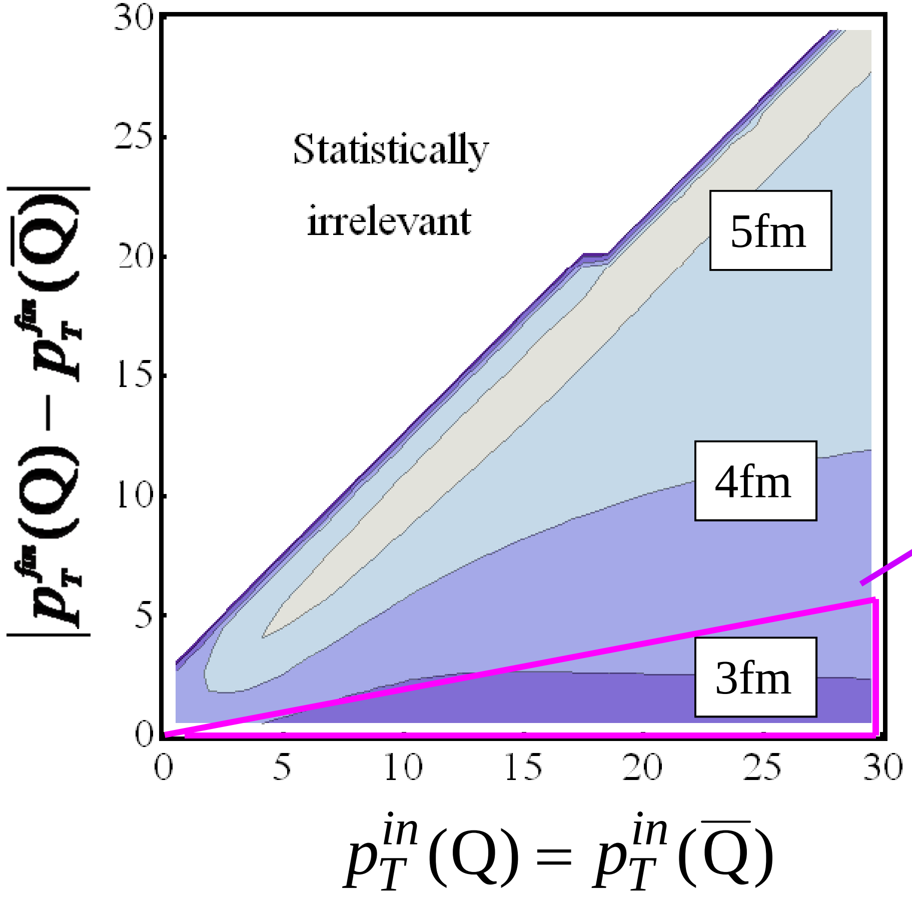
Possible caveat: tangential events



$\Rightarrow$ Need for a detailed study

Q-Qbar Correlations

Average transv.-dist. to center as a function of Δp_T^{fin} *for various* p_T^{in}



Indeed some (favorable) bias for init $p_T^{in} > 5$GeV/c and "small" Δp_T^{fin}

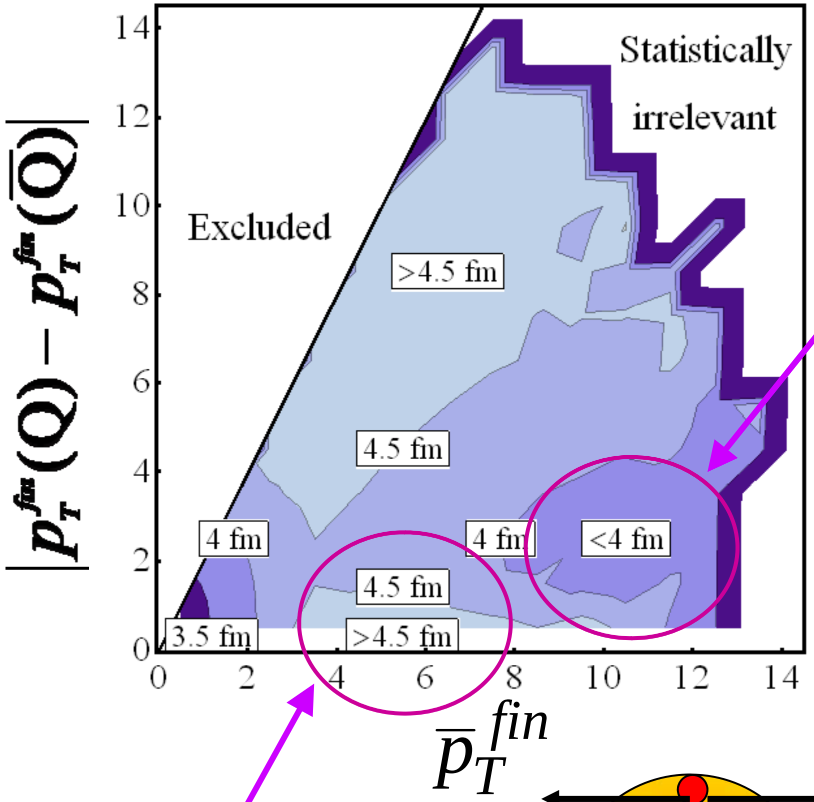
Hope to probe hotter regions of the QGP

<u>However</u>: No access to p_T^{in} !!!

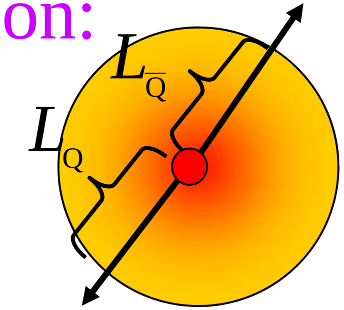
Q-Qbar Correlations

Best ansatz: $p_T^{in}(\mathrm{Q}) \rightarrow \overline{p}_T^{fin} := \dfrac{p_T^{fin}(\mathrm{Q}) + p_T^{fin}(\overline{\mathrm{Q}})}{2}$

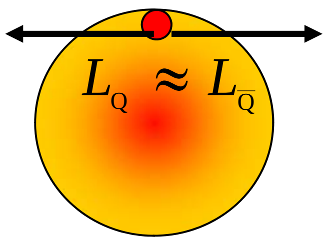
Average transv.-dist. to center as a function of $\Delta p_T^{\mathrm{fin}}$ *for various* $\overline{p}_T^{fin}$



Bias towards Central production:

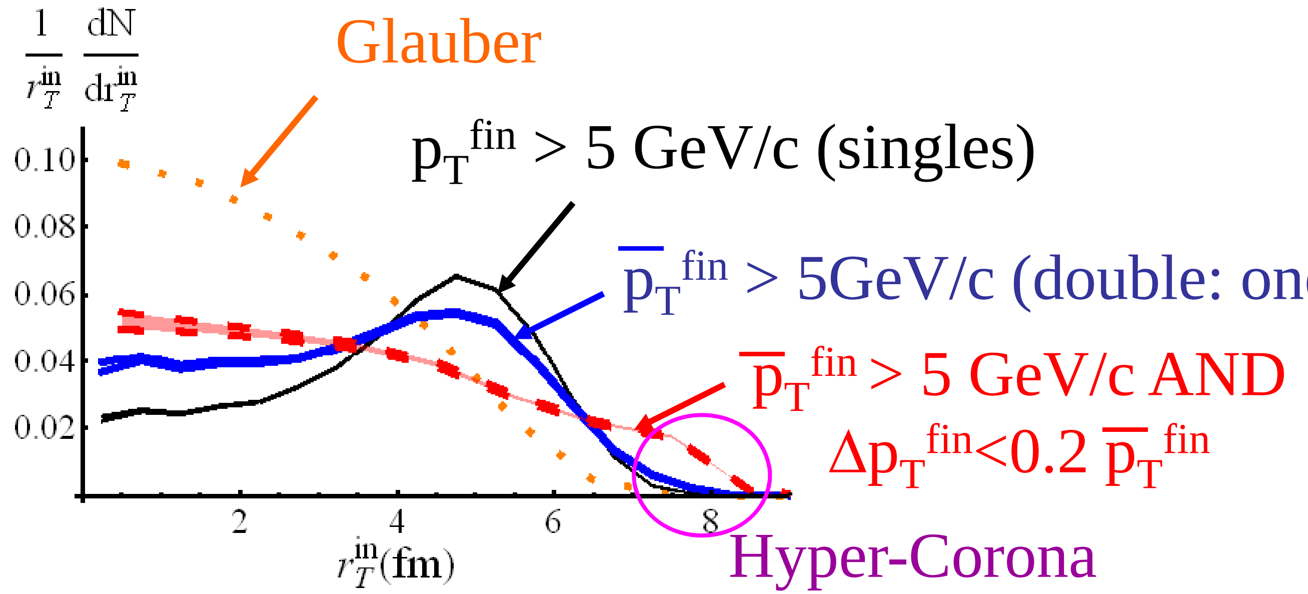


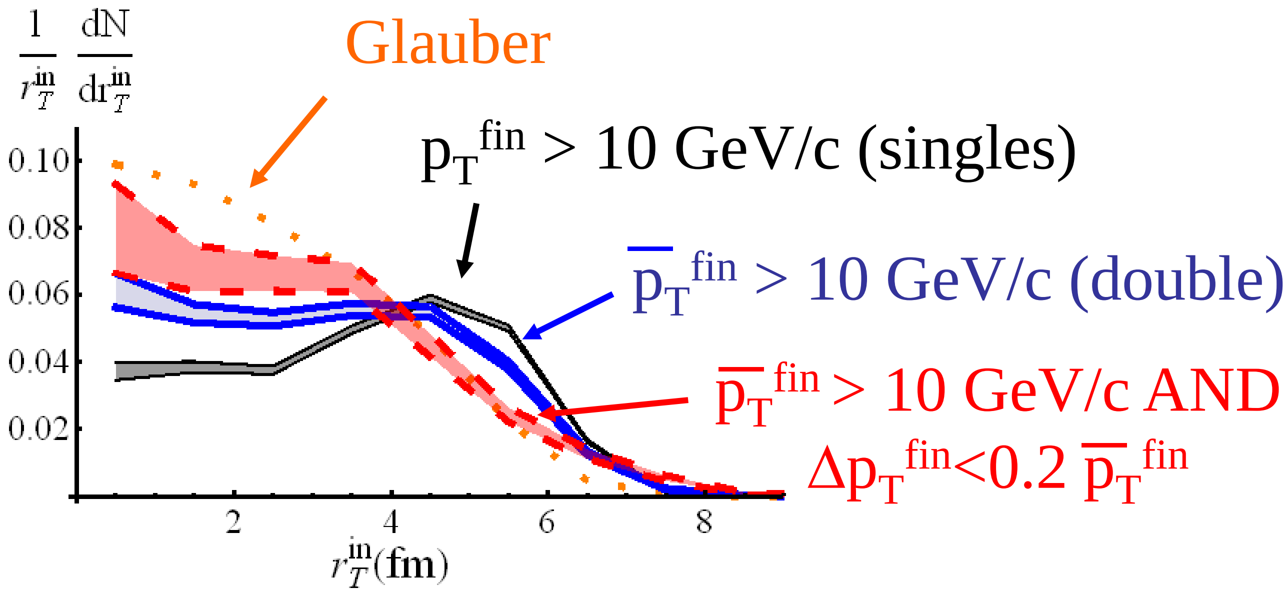
Bias towards Tangential production



Conclusion: Favorable bias for av. $p_T^{\mathbf{fin}} > 8$ GeV/c and "small" $\Delta p_T^{\mathbf{fin}}$

Q-Qbar Correlations: back to r_T distributions

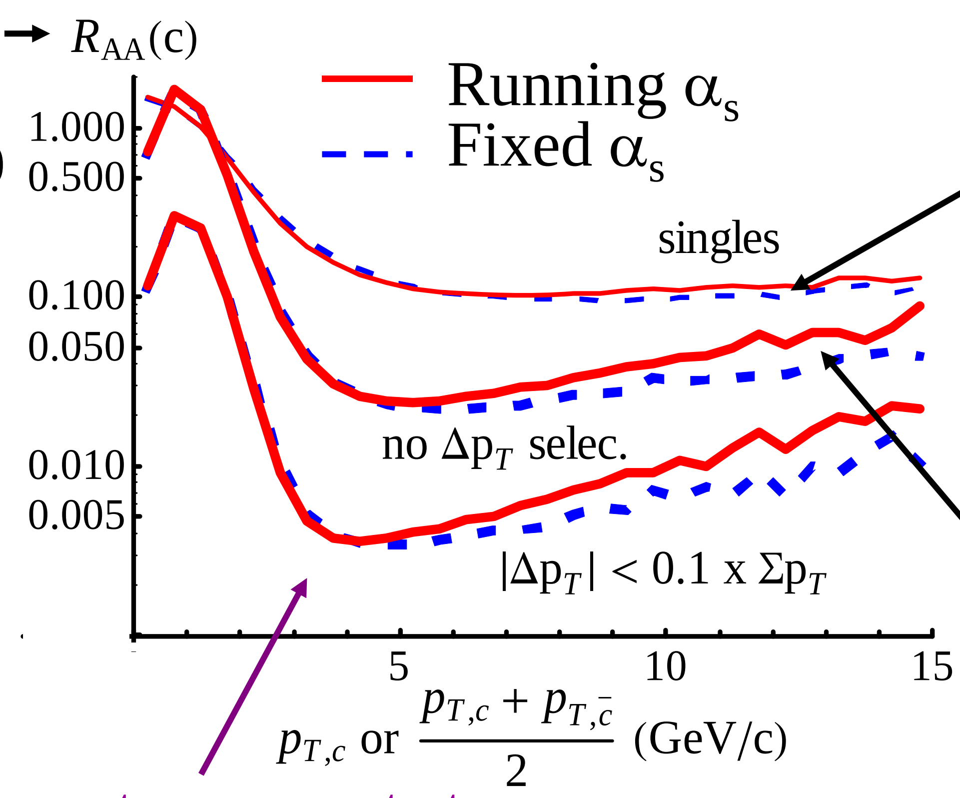




- Final cuts lead to various distributions of initial position
- One nearly recovers the Glauber profile for most severe cut

R_{AA} with Q-Qbar Correlations

Usual ratio: Nb(Au+Au)/ Nb_{coll}*Nb(pp)



Usual flat

double

Rise with p_T although no selection ! Different behaviors are due to fluctuations

More and more transparent at large p_T for HQ from center

Close to experimental prediction but not yet (Hadronization, NLO at the time of production, background substraction,…)

(Induced) Radiative for HQ

I) Approach of increasing sophistication

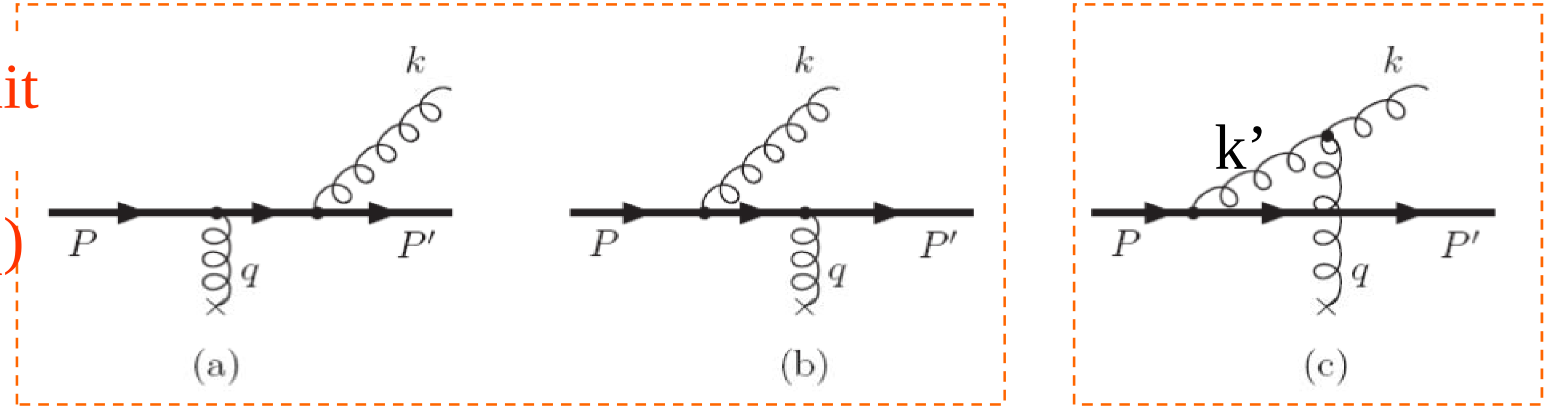
II) Ultimate goal is to have “simple” effective model that can be implemented in Monte Carlo simulations => need for analytical formula

III) Mostly centered on HQ

Basic (massive) Gunion-Bertch

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'

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

with

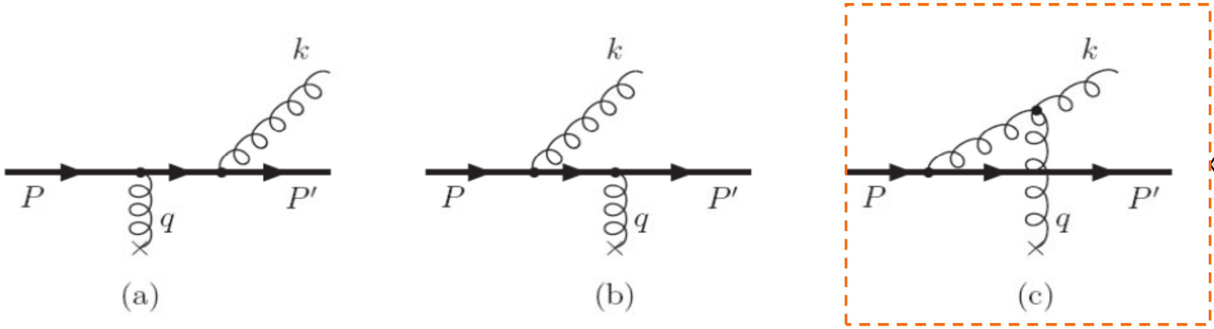
$$\frac{J_{\rm QCD}^2}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2 + x^2M^2 + \underbrace{(1-x)m_g^2}_{}} - \frac{\vec{k}_\perp - \vec{q}_\perp}{\left(\vec{k}_\perp - \vec{q}_\perp\right)^2 + x^2\underbrace{M^2}_{} + (1-x)m_g^2} \right)^2$$

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

Quark mass

Both cures the collinear divergences and will influence the radiation spectra

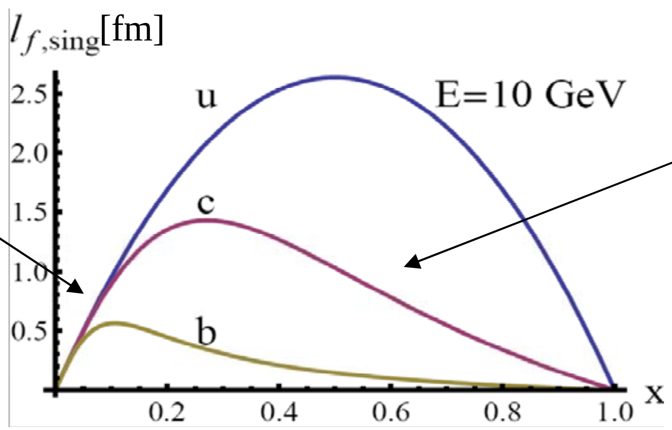
Formation time for a single coll.



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

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

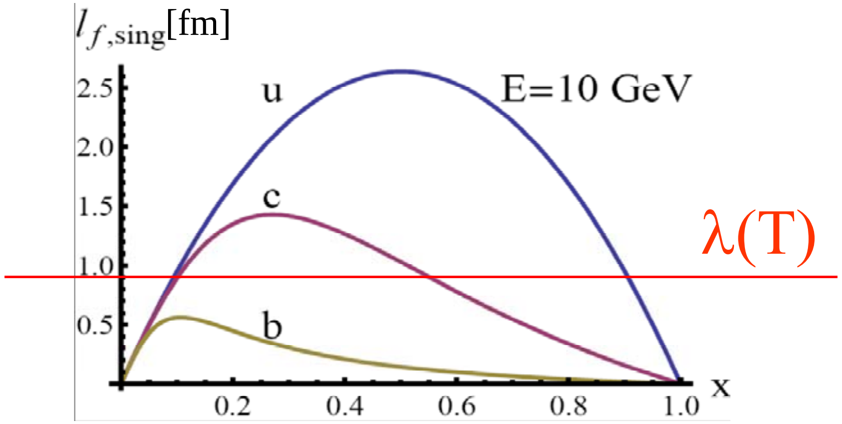


For $x > x_{cr} = m_g/M$, gluons radiated from heavy quarks are resolved in less time then those ← light quarks and gluon => radiation process less affected by coherence effects in multiple scattering

Dominant region for quenching

Dominant region for average E loss

A first criteria



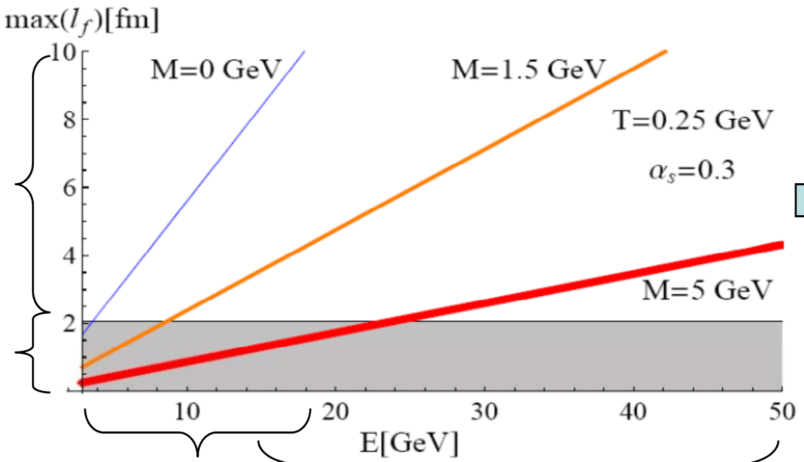
Comparing the formation time (on a single scatterer) with the mean free path:

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

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)

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

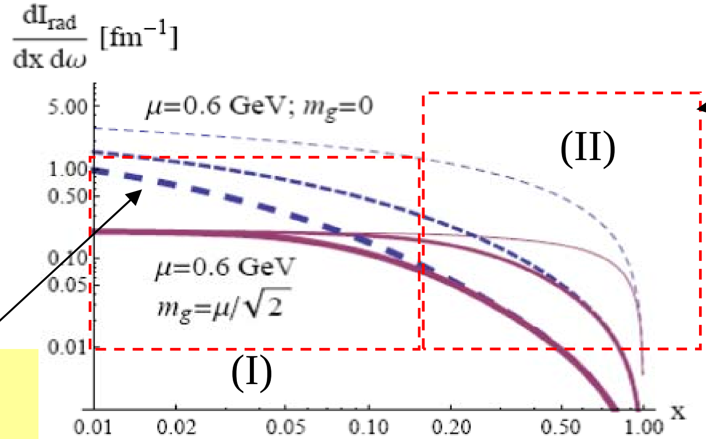
$$\tilde{m}_g^2 = (1-x)m_g^2 + x^2 M^2$$

For coulomb scattering:

Light quark

c-quark

b-quark



Strong dead cone effect for $x>m_g/M_Q$ (mass hierarchy)

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

If typical $q_\perp \approx T$:

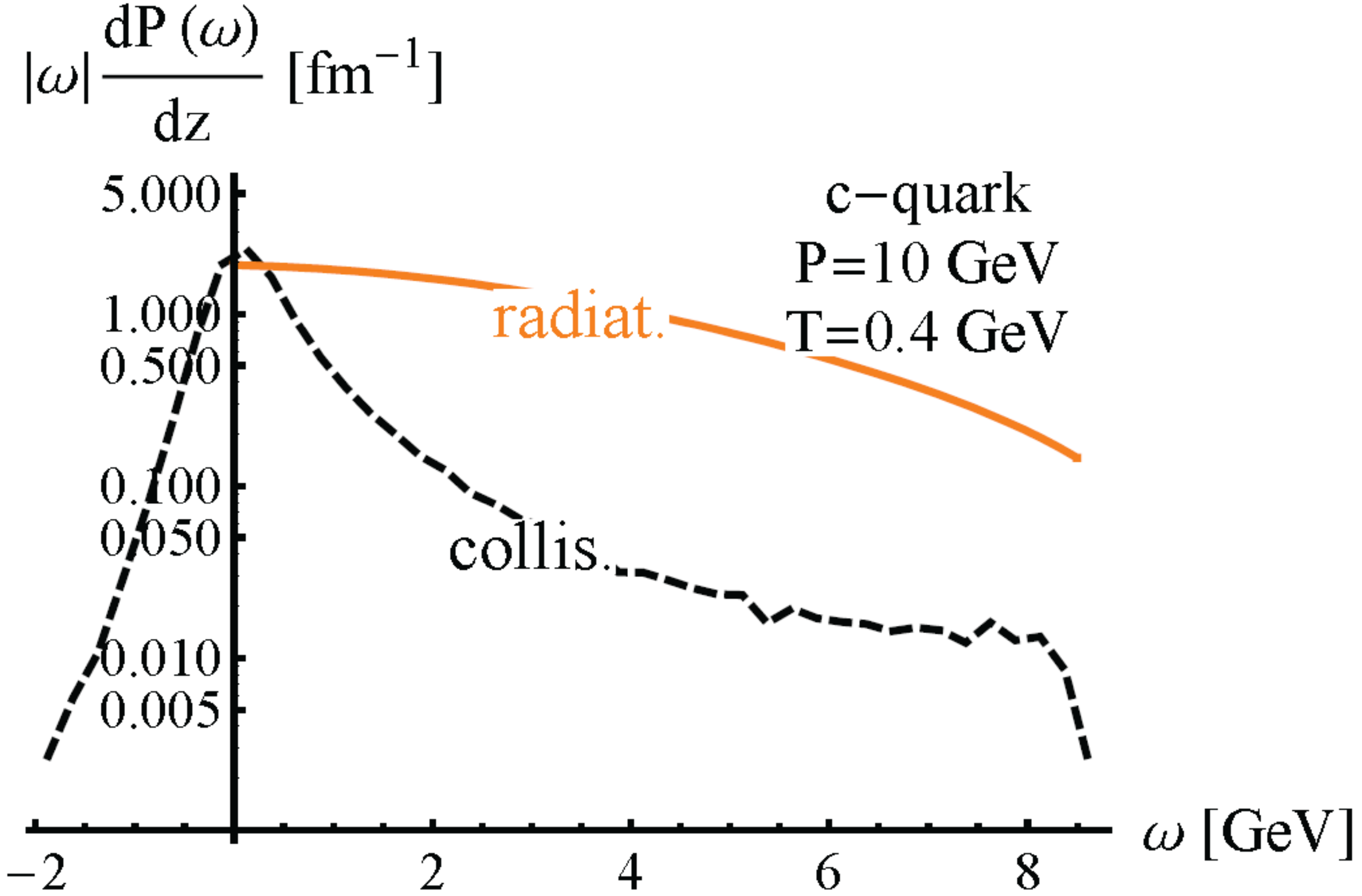
$$\frac{d^2 I^{x\ll 1}_{\mathrm{GB}}}{dz\, d\omega} \sim \frac{2N_c\alpha_s}{3\pi} \times \frac{1}{m_g^2 + x^2M^2} \times \underbrace{\frac{\langle q_\perp^2\rangle}{\lambda}}_{\hat{q}}$$

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

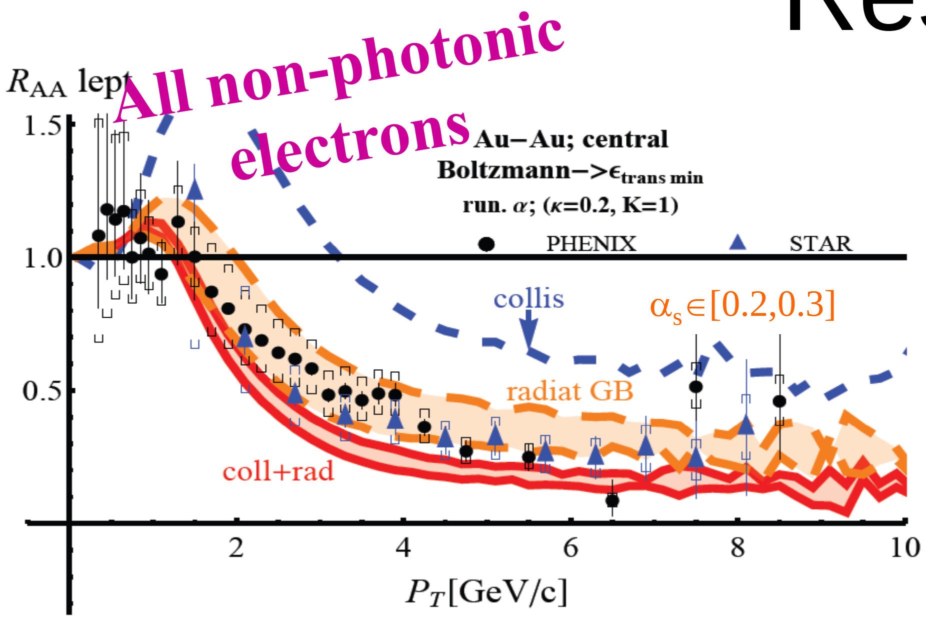
Strong mass effect in the average Eloss (mostly dominated by region II)

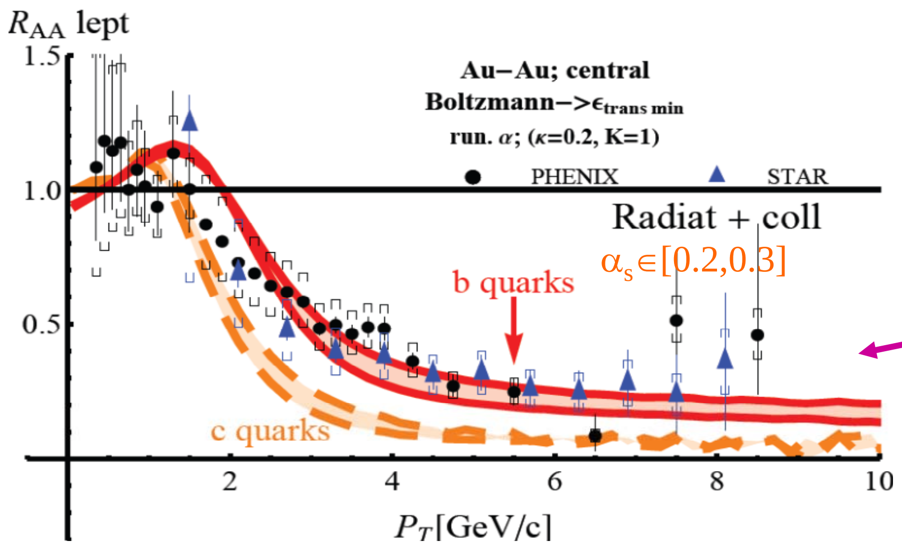
Interesting *per se*, but not much connected to the quenching or R_{AA}.

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



Results

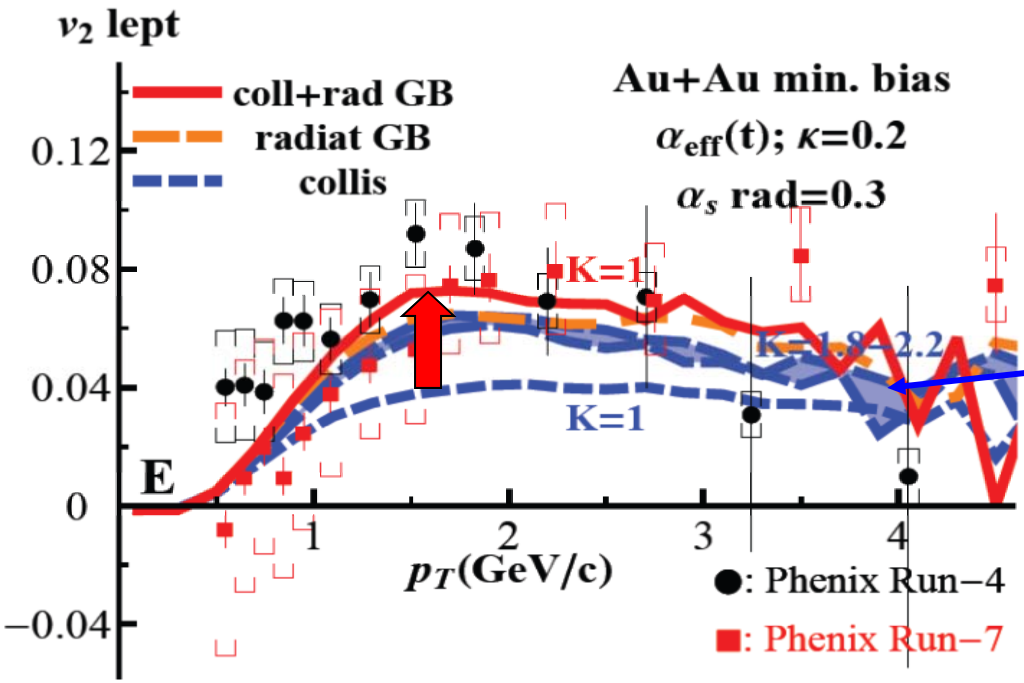




1. Too large quenching; good as we obviously overestimate the radiative Eloss
2. Radiative Eloss indeed dominates the collisional one
3. Flat experimental shape is well reproduced

separated contributions e ← D and e ← B.

Results



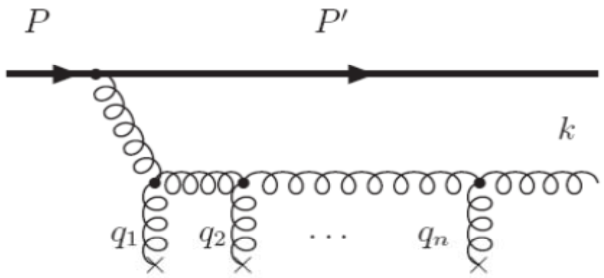
1. Collisionnal + radiative energy loss + dynamical medium : *compatible* with data
2. Shape for radiative E loss and *rescaled* collisional E loss are pretty similar
3. To my knowledge, one of the first model using radiative Eloss that reproduces v_2

Basics of Coherent Radiation

Subject of numerous (mosty numerical) investigations

See Peigné & Smilga (2008) for some analytical results pertaining to HQ

Formation time in a random walk



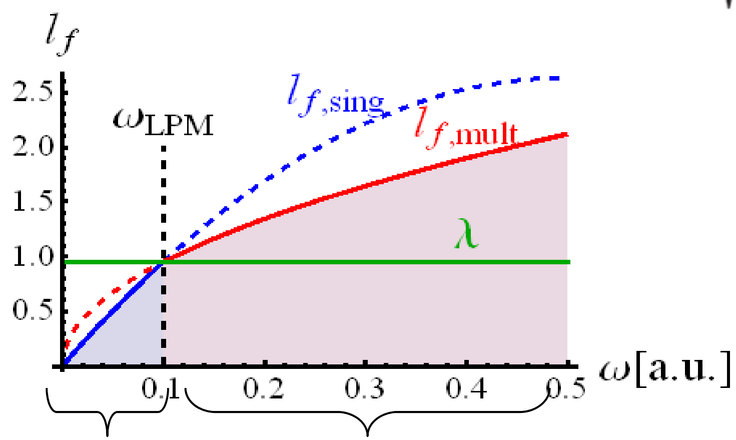
Phase shift at each collision

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):

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

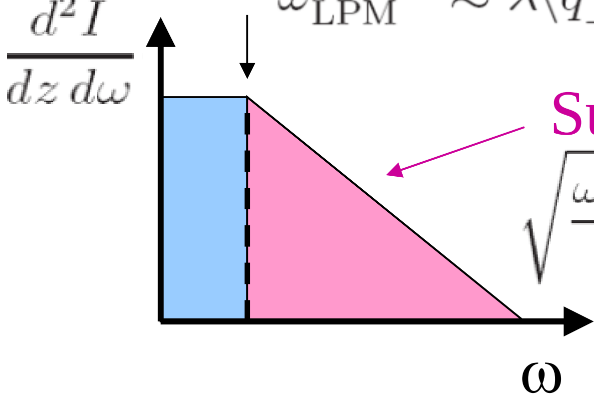
=> 3 scales: $l_{f,mult}$, $l_{f,sing}$ & λ



Uncoherent radiation

Coherent radiation (BDMPS)

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

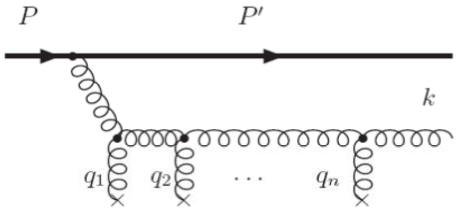


Suppression: $\sqrt{\frac{\omega_{\mathrm{LPM}}}{\omega}\ln\left(\frac{\omega}{\omega_{\mathrm{LPM}}}\right)}$

Especially important for av. energy loss

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

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: $\lambda < l_{f,\mathrm{mult}} < L_{\mathrm{QCD}}^{\star\star} := \frac{m_g^2 + x^2 M^2}{\hat{q}}$

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 $l_{f,mult} = N_{coh}\,\lambda \longrightarrow \frac{\boxed{d^2 I}}{\boxed{dz}\,d\omega} \longleftarrow$ Radiation at small angle α $\langle Q_\perp^2 \rangle$ i.e. α N_{coh} Compensation at leading order !

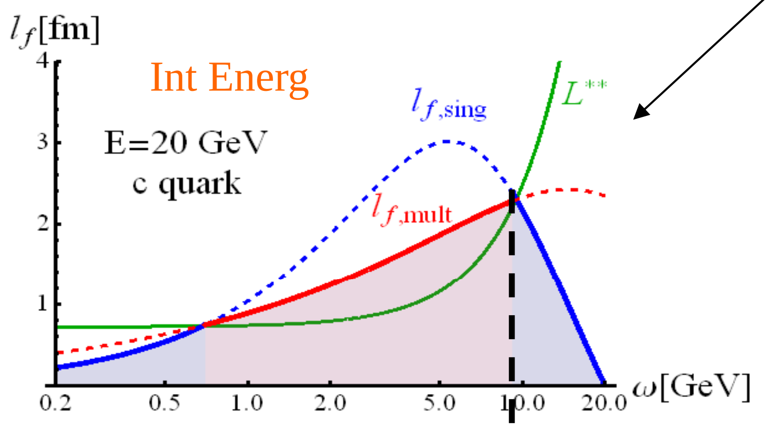
LESSON: HQ radiate less, on shorter times scales but are less affected by coherence effects than light ones !!! (dominance of 1rst order in opacity expansion)

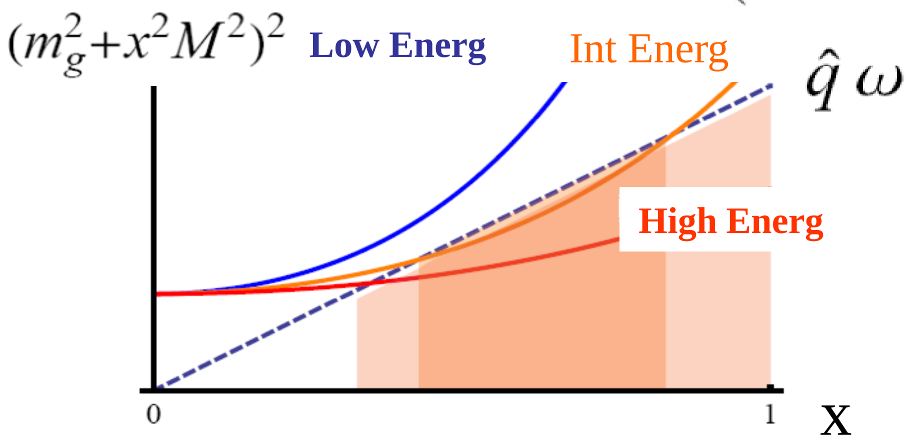
Formation time and decoherence for HQ

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

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

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





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

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.

$$E^{\star}_{\mathrm{NO-LPM}} := 3\frac{M m_g^3}{\hat{q}} \sim \frac{M}{g_s}$$

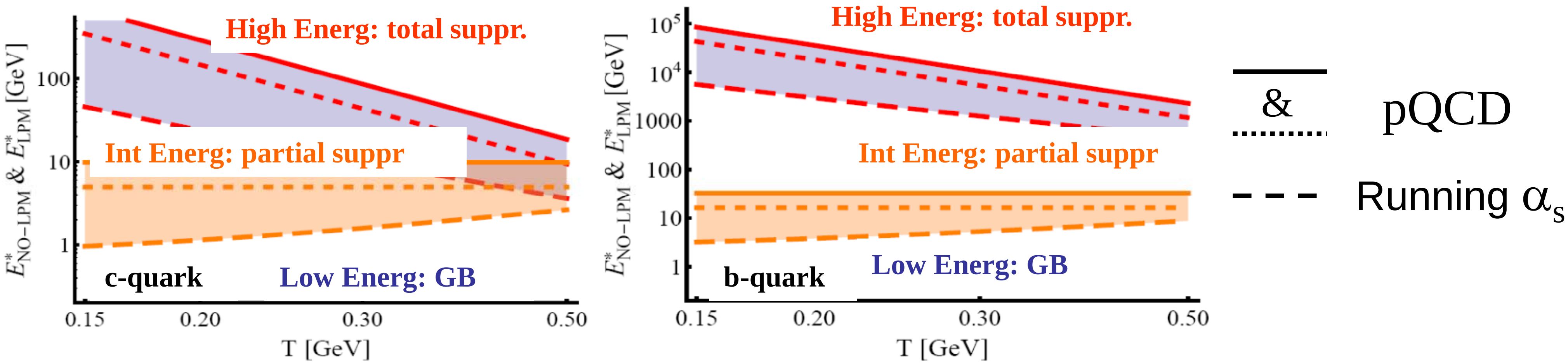
$$E^{\star}_{\mathrm{LPM}} := \frac{M^4}{\hat{q}}$$

Regimes and radiation spectra

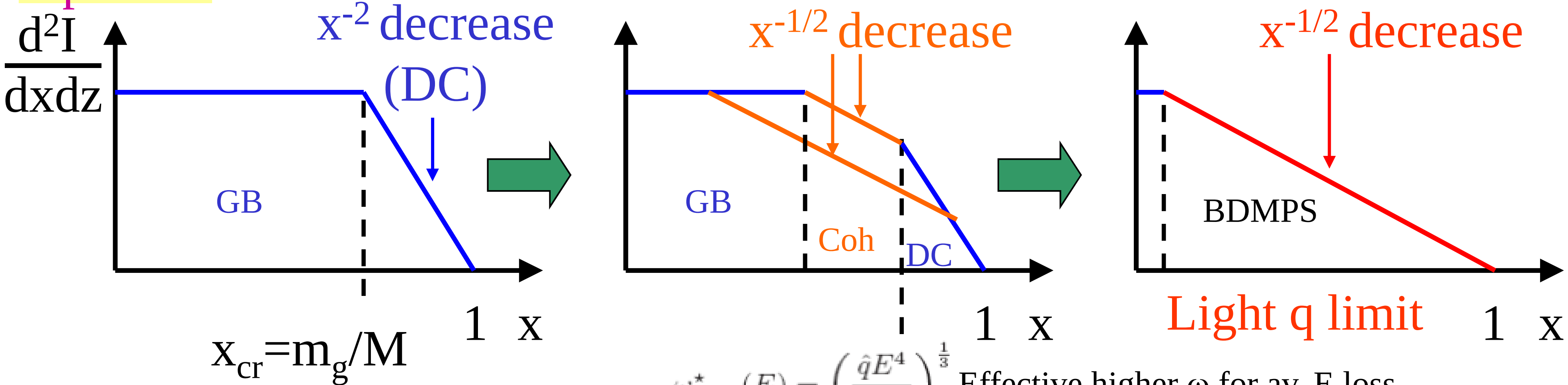
Hierarchy of scales:

$$\underbrace{E_{\mathrm{LPM}}(q)}_{T} \ll \underbrace{E^{\star}_{\mathrm{NO-LPM}}(Q)}_{\frac{M}{g_s T}\times T} \ll \underbrace{E^{\star}_{\mathrm{LPM}}(Q)}_{\left(\frac{M}{g_s T}\right)^4\times T}$$

larger coupling ⇒ Larger coherence effects

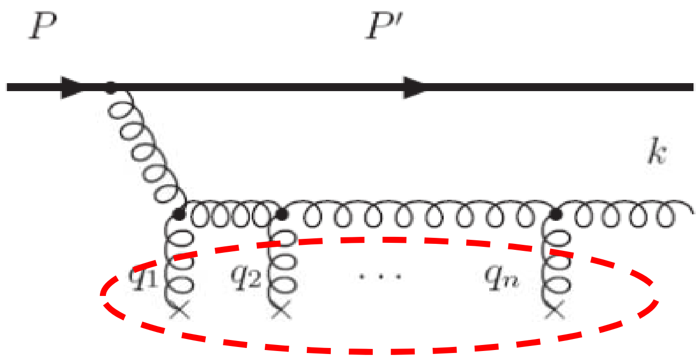


Spectra



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

Semi-quantitative model:



For $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$

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

$$\left(\frac{d^2 I^{x\ll 1}_{\text{"QCD"}}}{dz\,d\omega}\right)_{\mathrm{coh}} \approx \frac{2N_c\alpha_s}{\pi l_{f,\mathrm{mult}}}\left\langle \ln\left(1+\frac{Q_\perp^2}{3\tilde{m}_g^2}\right)\right\rangle_{p_{N_{\mathrm{coh}}}} \quad \text{with} \quad \tilde{m}_g^2 \approx m_g^2 + x^2 M^2 + \sqrt{\frac{\hat{q}\omega}{\Phi_{\mathrm{dec}}}}$$

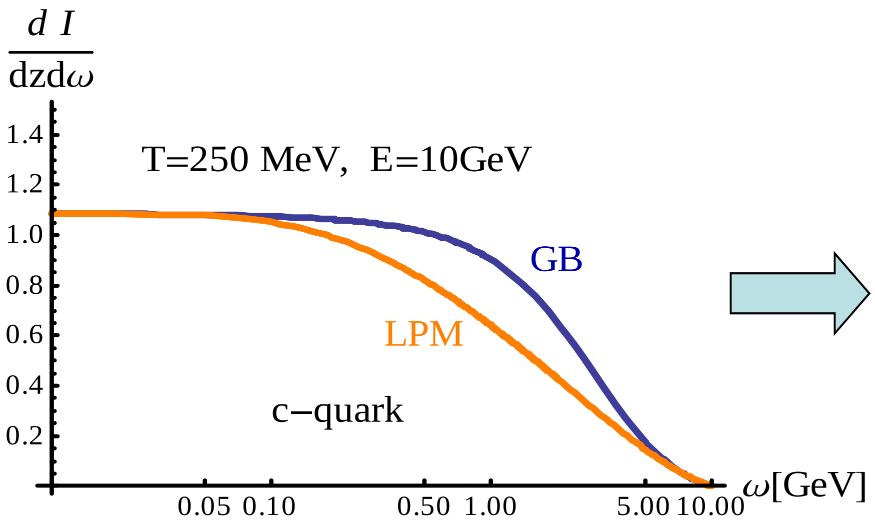
Prevents radiation of gluon of formation time $> l_{f,mult}$

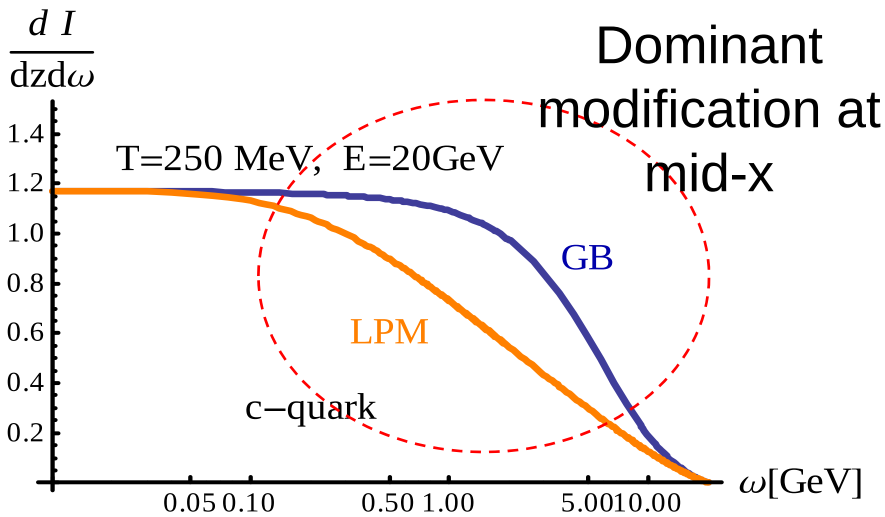
After averaging:

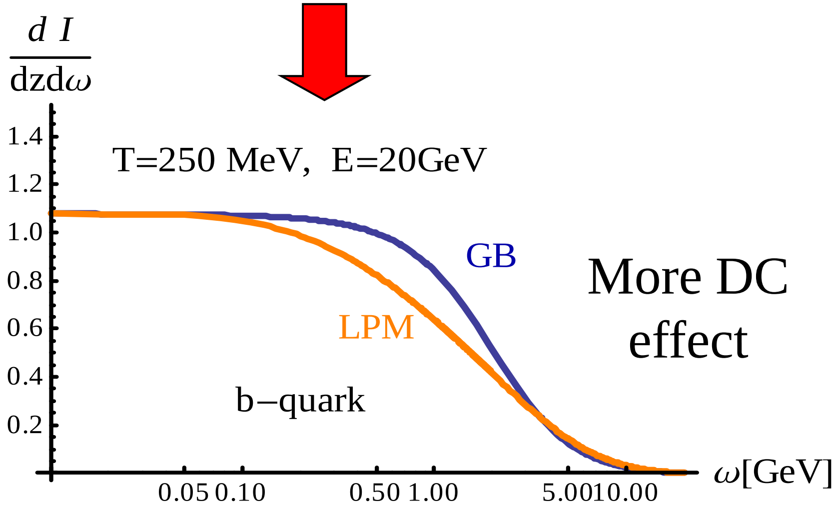
$$\frac{d^2 I_{\mathrm{eff}}}{dz\,d\omega} \sim \frac{\alpha_s}{N_{\mathrm{coh}}\lambda}\ln\left(1+\frac{N_{\mathrm{coh}}\mu^2}{3\left(m_g^2+x^2M^2+\sqrt{\omega\hat{q}}\right)}\right)$$

- Compares well to the BDMPS result ($N_{coh} \gg 1$) for light quark (up to some color factor => rescaling), including the coulombian logs.
- Naturally interpolates to the massive-GB regime for $N_{coh} \lesssim 1$.
- Incorporates all regimes discussed above.

Reduced spectra from coherence





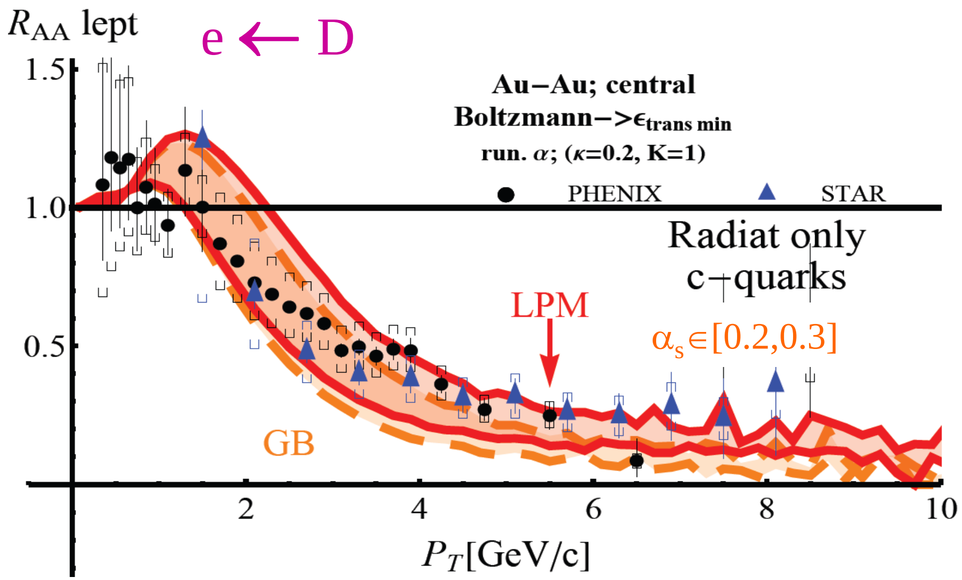


: Suppression due to coherence increases with increasing energy

: Suppression due to coherence decreases with increasing mass

In (first) Monte Carlo implementation: we quench the probability of gluon radiation by the ratio of coherent spectrum / GB spectrum

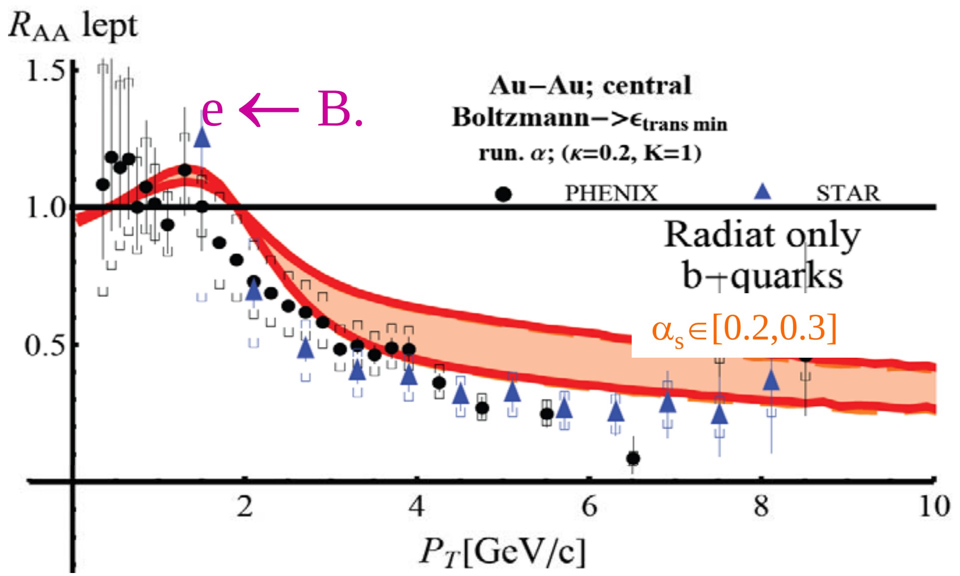
Results with Coherence Included

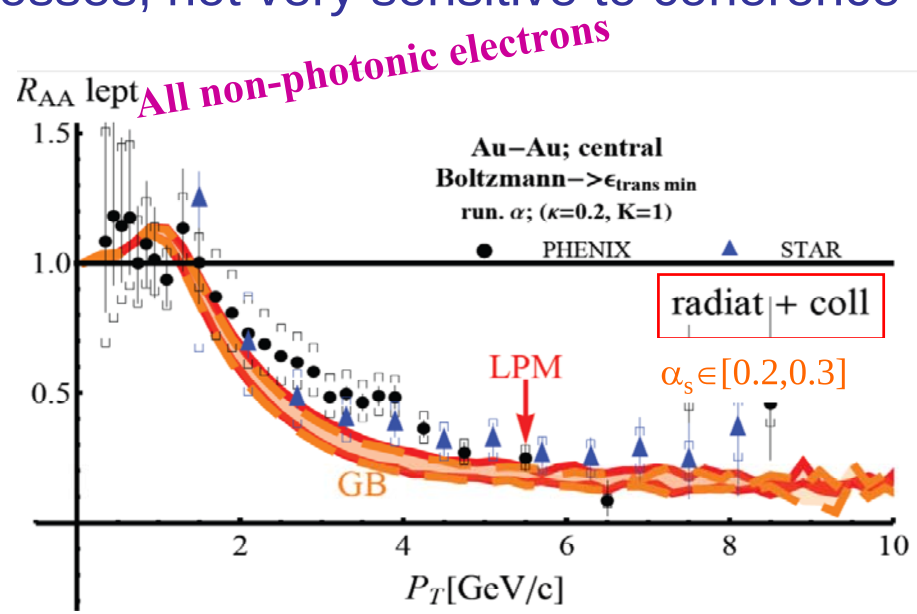


1. Some moderate increase of R_{AA} for D at large p_T.
2. No effect seen for B

Conclusions can vary a bit depending on the value of the transport coefficient

Confirms that RAA at RHIC is mostly the physics of rather numerous but small E losses, not very sensitive to coherence .





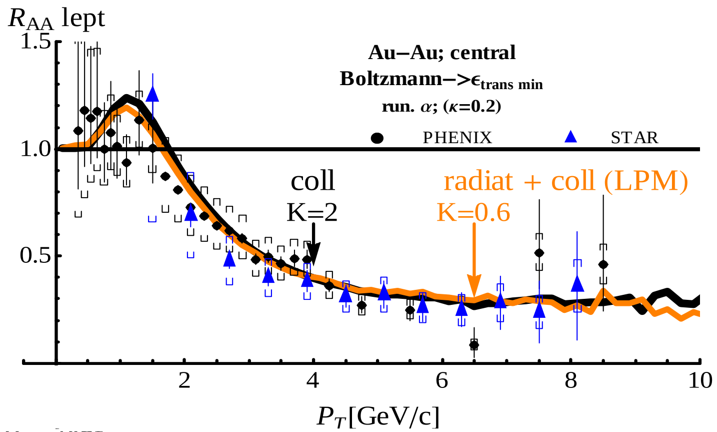
What is (really) missing ?

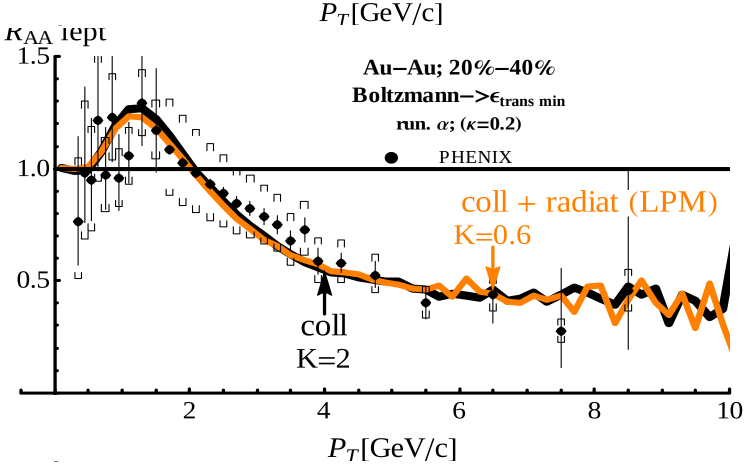
- 0-opacity correction and transition radiation that partly compensates and lead to an effective retardation of the energy loss.
- Better Monte Carlo implementation for radiation caused by multiple collisions.
- Finite path Length effects : In practice, formation length are of the order of a couple of fm => HQ emanating from the corona have a path length $L < l_{f,mult}$

{Radiative + Elastic} vs Elastic for leptons @ RHIC

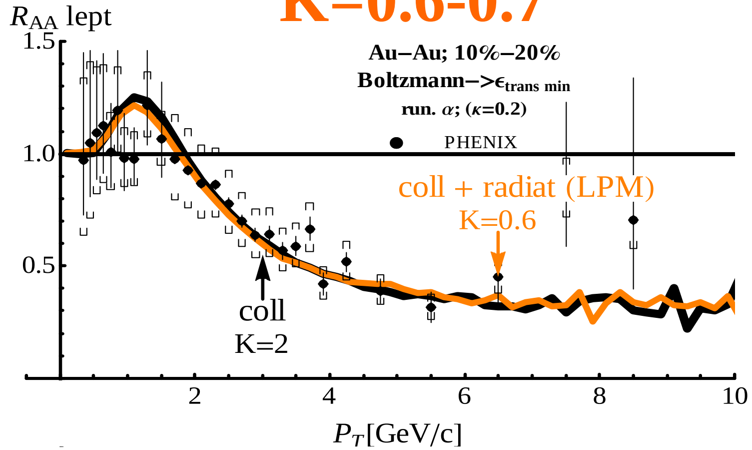
El. and rad. Eloss exhibit very different E and mQ dependences. However…

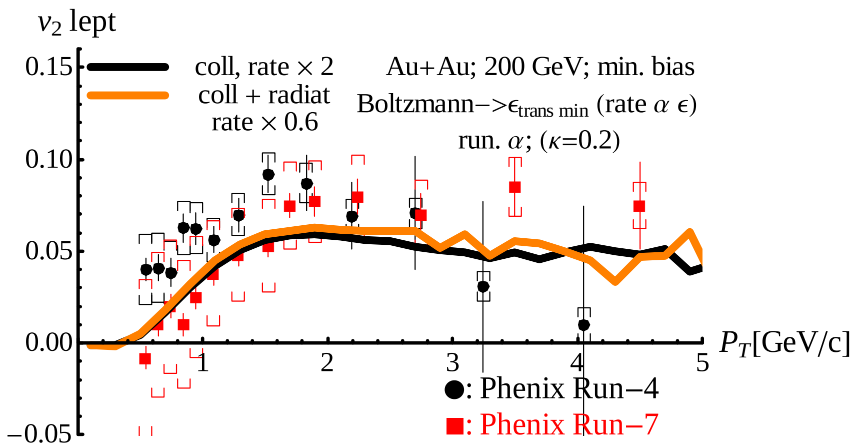
σ_{el} alone rescaling: K=1.8-2.2





σ_{el} & σ_{rad} cocktail: rescaling by K=0.6-0.7

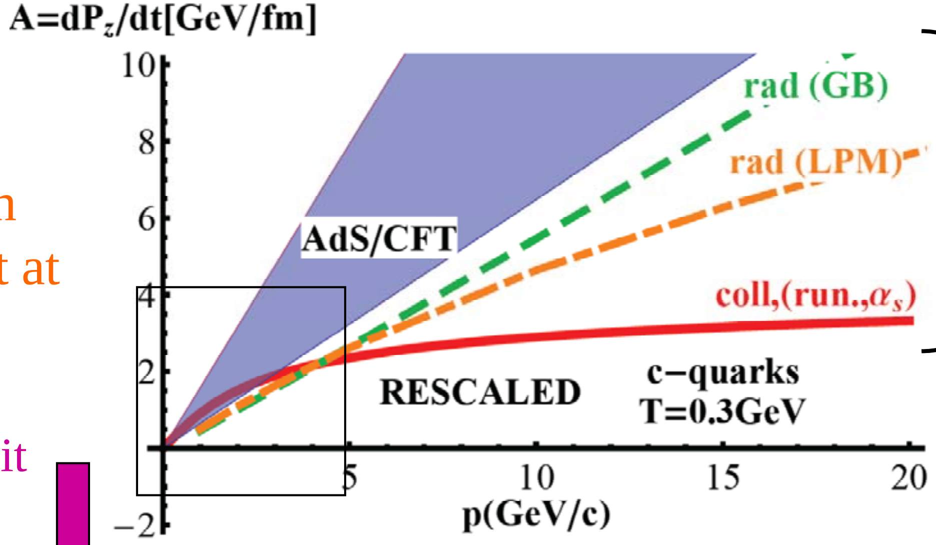




QGP properties from HQ probe at RHIC (the bad and the good news from our messengers)

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

Similar diffusion coefficient at low p



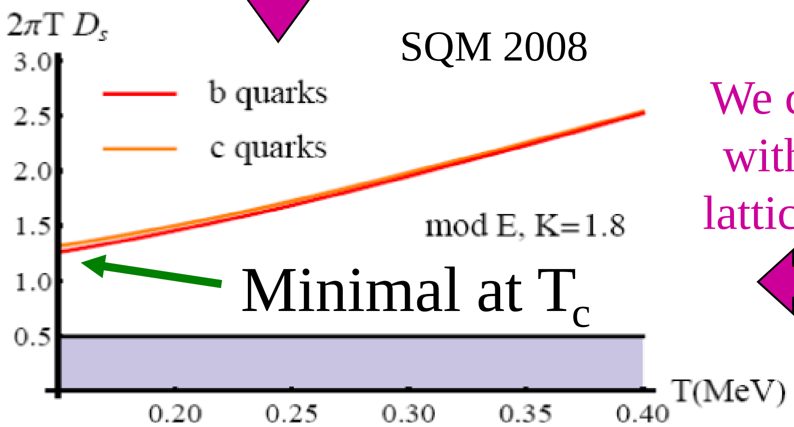
the drag coefficient reflects the average momentum loss (per unit time) => large weight on $x \sim 1$

Present RHIC experiments cannot resolve between those various trends (model fragility)

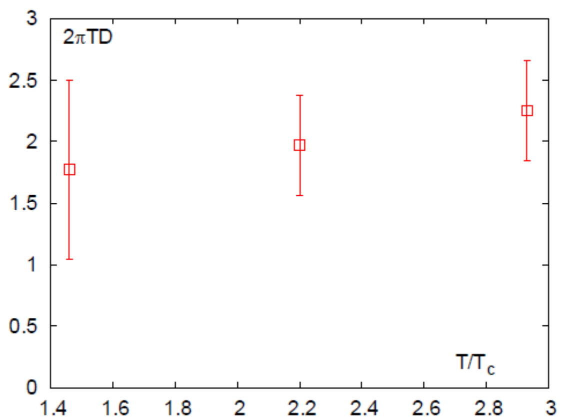
We extract it from data

Hope that LHC will do !!!

SQM 2008



We compare with recent lattice results



Kaczmarek Bad Honnef 2011