Heavy quark Energy loss (in QGP): from RHIC towards LHC

Theory @ LHC (Lyon; 6 April 2010)

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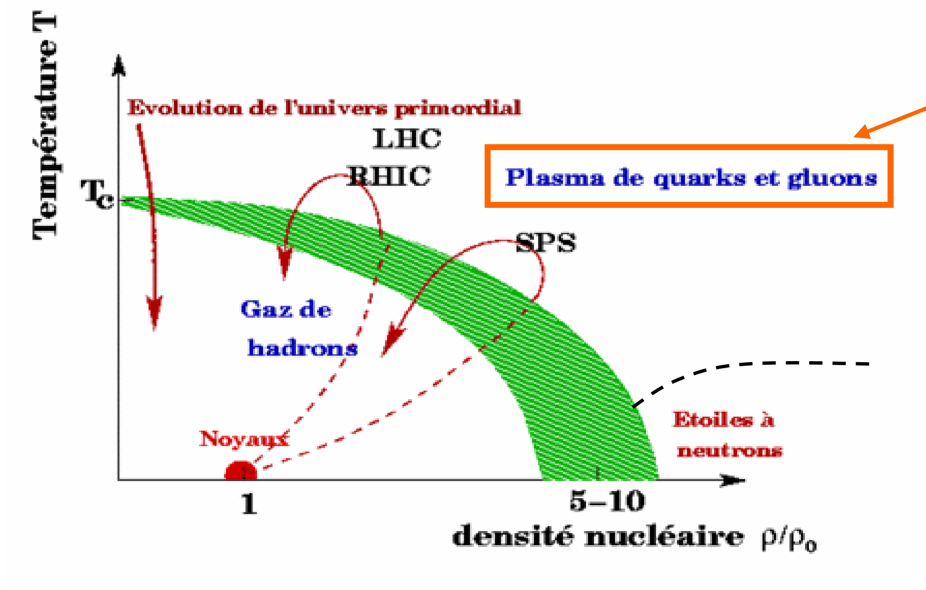
With: J. Aichelin & Th Gousset

I. Panoramic Introduction to the QGP Physics

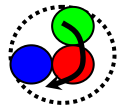
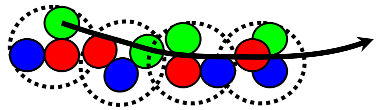
II. Understanding (partly) the present RHIC data

III. LHC will (could) tell

Object under study: Phase Diagram of Hadronic Matter & Quark Gluon “Plasma” (QGP)

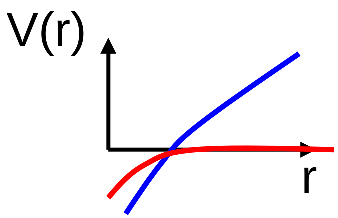


Naive view: larger temperature T (or larger baryonic density ρ_B) $\Rightarrow$ larger hadronic density $\Rightarrow$ overlapping of individual hadrons $\Rightarrow$ possible tunneling of single quarks:

From  to 

(Hadron Gas) (QGP)

2-body potential:

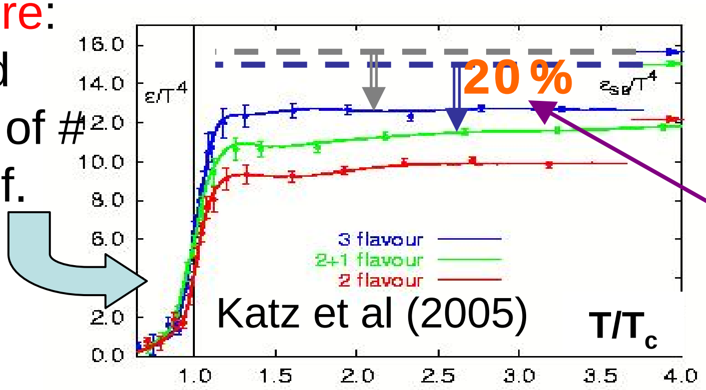


Vacuum

QGP: string melting and Debye screening

Rigorous Theoretical prediction (QCD on Lattice at finite T)

Signature: Rapid increase of # of d.o.f.



Usual plasma (pQCD):

- $E_{pot} << E_{kin}$
- no bound state

Weak coupling; Applicable for high T (asympt. Freedom)

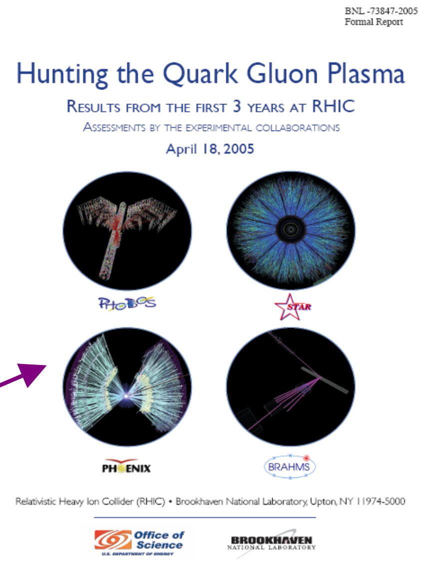
(s)QG“P”:

Strong (at least, not weak) coupling (2004 $\rightarrow$)

Investigating the Quark Gluon Plasma

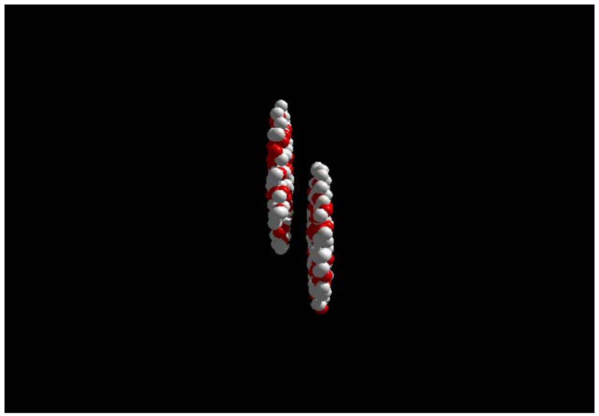
Possible interests (intrinsic & extrinsic) of QGP study:

- One of the strongest coupled many-body system (new techniques, new concepts) $\Rightarrow$ Challenging per se
- Could help in understanding *some aspects* of confinement
- Ingredient of the astrophysical “standard model”
- It has probably been (re)created in earth during the last decade thanks to URHIC: it *EXISTS* !



Ultra-Relativistic Heavy Ion Collisions

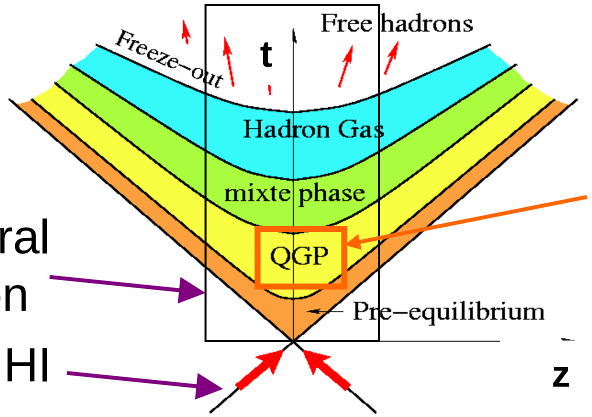
Schematic view I (URQMD):



Schematic view II (time – long. direction)

Central region

Initial HI



One of the smallest macroscopic system (≈100 fm³) surviving for a couple of fm/c only.

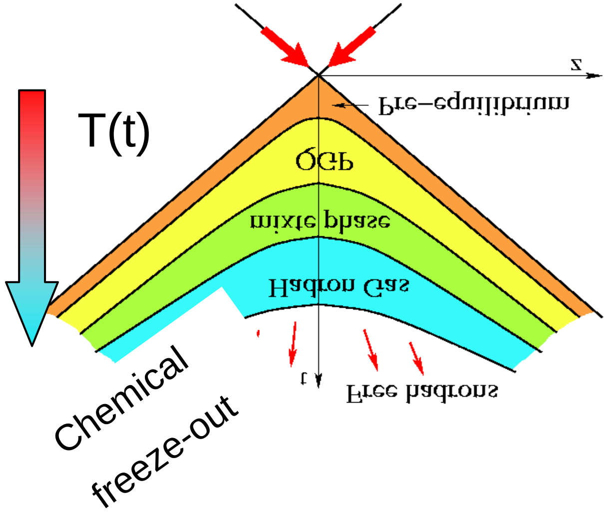
Since mid-80’s $\rightarrow$ now (AGS, SPS, RHIC, LHC): more and more energy deposit in the central overlapping region.

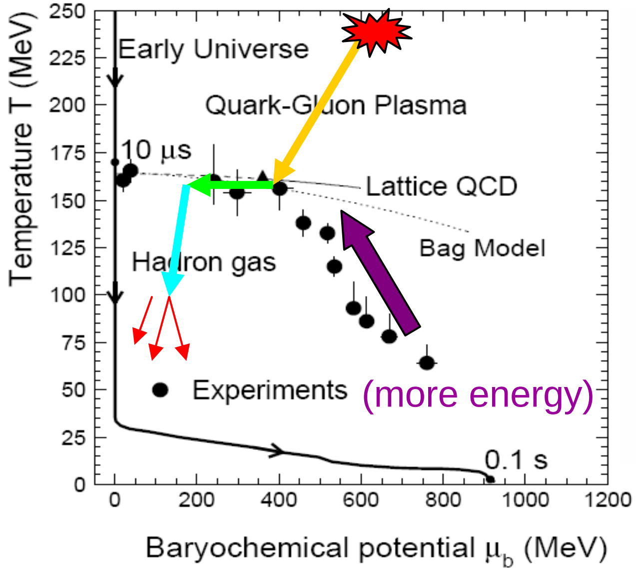
One system, many questions

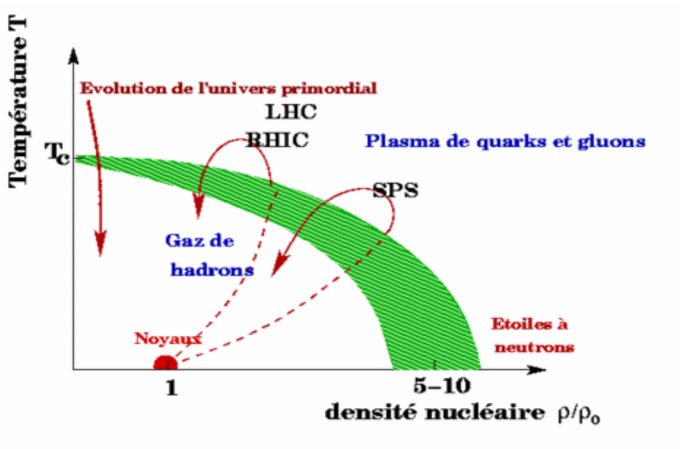
I. Does the system created in central region reach and maintain equilibrium long enough to be understood in terms of a quasi-stationnary state ?

Hadro-chemistry as a *thermometer* (# and spectra):

P. Braun-Munzinger & J. Wambach (arXiv:0801.4256)







One recovers the naïve view

Experiments seem to reveal the chemical freeze-out horizon, i.e. the frontier between a hadron gas and a state “beyond”

One system, many questions

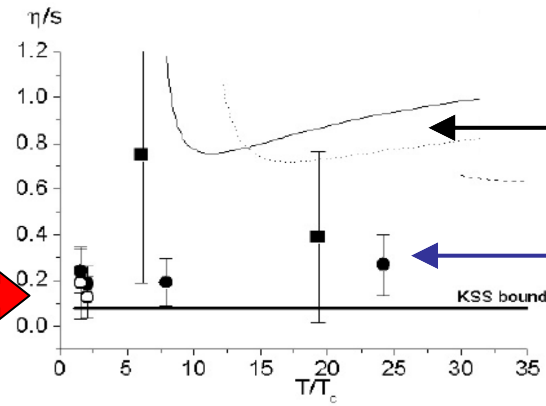
II.a Ok, there is a state "beyond"… How can we characterize it ?

≡ quantifying *properties:*

- Structure of the phase diagram (nature of transition lines, existence of critical points), equation of state,…
- Surface tension
- Transport coefficients : response to various perturbations inhomogeneousities:
  - *viscosity* – bulk and shear (η) – : velocity gradient
  - heat conductivity: temperature gradient
  - spatial diffusivity D_s: concentration gradient
- Stopping power

and Link between fundamental theory and experiment (α mean free path λ)

…"Easy" to evaluate for weakly coupled plasma. (Example: AMY calculation of η and D_S), with limited success, though



pQCD

Recent lattice calculations… (large uncertainties)

One system, many questions

II.b *Measuring* various properties (as theory not mature enough)

- Extremely short-lived (10^{-23} s) and tiny (10^{-14} m) system $\Rightarrow$ no traditional instrumentation and/or experimental protocol; no external probe as well

Need for *probes* created WITH the QGP during the URHIC collision

- Thermalized system $\Rightarrow$ (by definition) memory loss $\Rightarrow$ difficult to probe the system beyond the freeze-out horizons

Probes should:

1. accumulate history of QGP
2. couple to QGP strongly enough to be affected by this hot and dense phase but weakly enough not to reach equilibrium
3. be sensitive to the achievement of some critical condition

Examples:

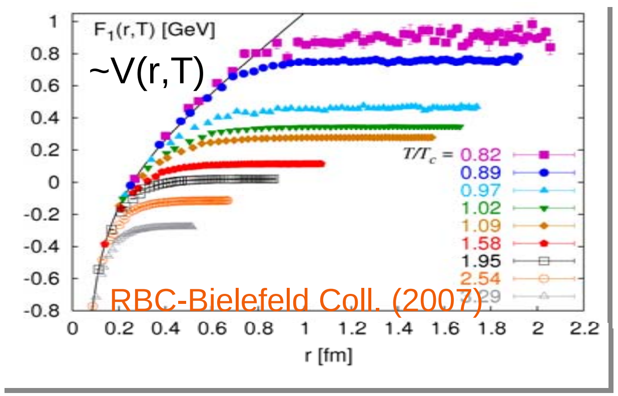
- Global observables (flow, blue-shift of particle spectra): sensitive to final velocities, i.e. to pressure gradients $\equiv$ barometer (1)
- Energy loss of ultrarelativistic particles and jet quenching $\equiv$ densitometer (1,2)
- Chemical abundance (PBM plot) , diff. p_T spectra $\equiv$ thermometer… of T_c ! (3)

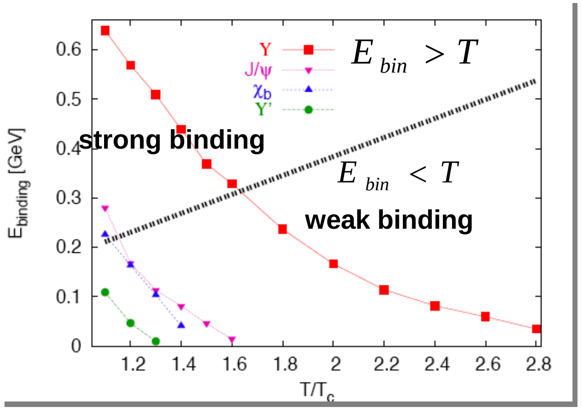
One system, many questions

III How can we prove (at best) it is really *deconfined* state of matter ?

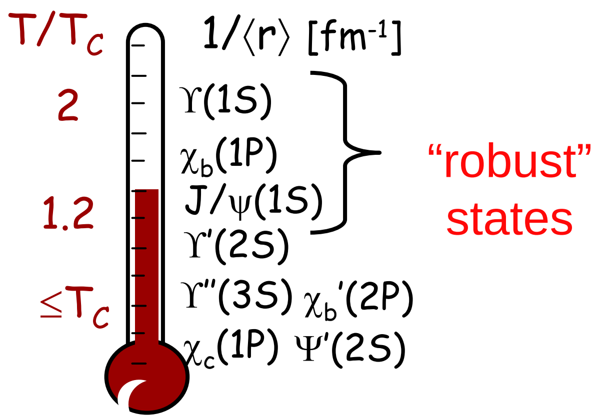
"deconfinometer" ≡
- Color fluctuations
- Propagation of quarks over large distances

Best candidate: Quarkonia (Q-Qbar bound state) sequential "suppression", i.e. melting and/or dissociation (Matsui & Satz 86)





From A. Mocsy (Bad Honnef 2008)



QGP Thermometer (3)

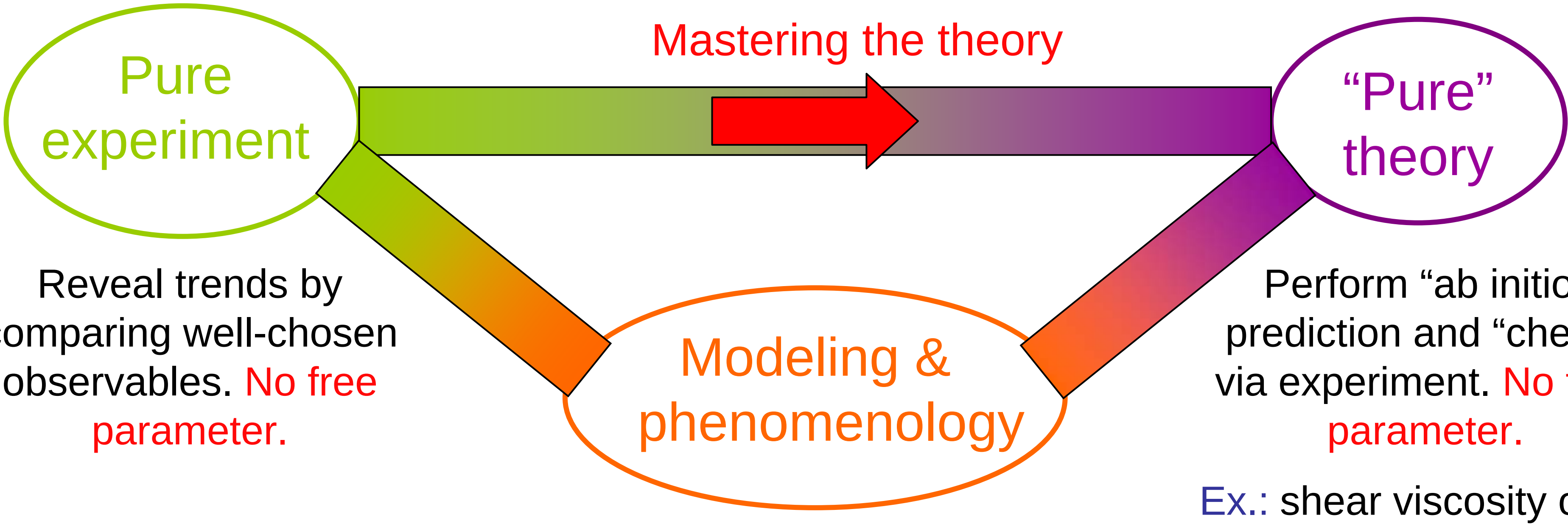
Indeed observed at SPS (CERN) and RHIC (BNL) experiments. However:

- alternative explanations, lots of unknown (also from theory side)
- no additional suppression at RHIC w.r.t. SPS !

Nevertheless: Still best candidate and dedicated (di-μ) program at LHC

Some point of scientific method

One *complex* system, several ways of analyzing



Reveal trends by comparing well-chosen observables. No free parameter.

Perform "ab initio" prediction and "check" via experiment. No free parameter.

Ex.: shear viscosity or drag coefficient

Explain larger and larger classes of phenomenon with simplifying assumptions and calibrated models. Free parameters

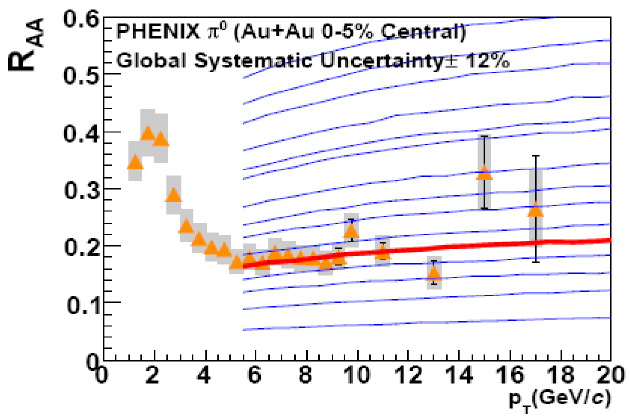
Some point of scientific method (con't)

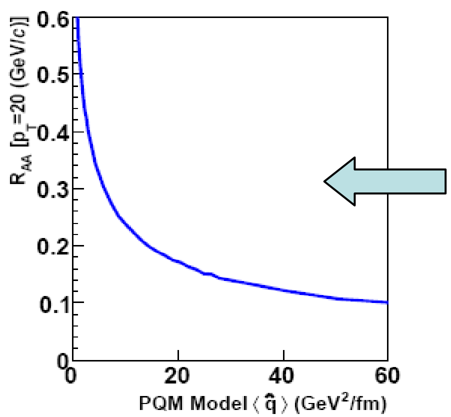
"Once upon a time…": everything comes from the surface => not possible to probe the energy loss in a systematic way

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:

- PQM (BDMPS ; *radiative* only, large formation times; parameter: qhat) ; static medium
- GLV (opacity expansion of *radiative* Eloss; dN_g/dy); av. Path lengh
- WHDG: as GLV + collisional and distribution of path lengh.; no modified PDF
- ZOWW: modification of fragmentation function by the medium; ε_0; no collisional





Everything but parameter free

Linear in log-log

Why heavy flavors in A-A ?

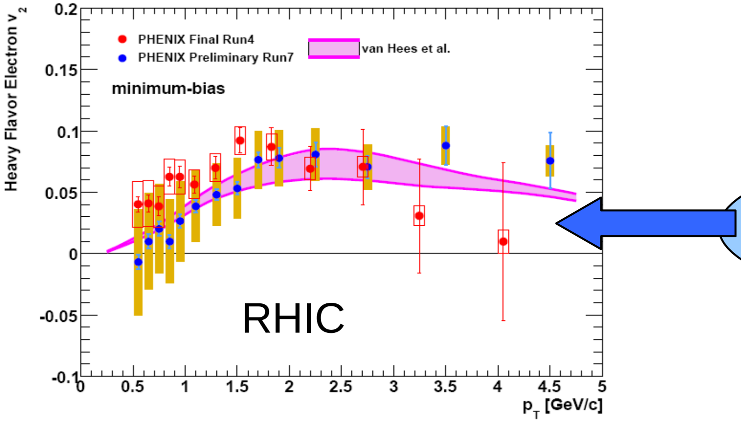
1. Produced early, number conserved through time evolution (even at LHC) $\Rightarrow$ signature of early (hot) phase
2. Weakly affected by late time evolution (heavy, colour transparency)
3. Allows some pQCD calculations
4. Clear decay channel of quarkonia in leptons

Seems to be an ideal probe of dense matter…

What is true and what is wishfull thinking ?

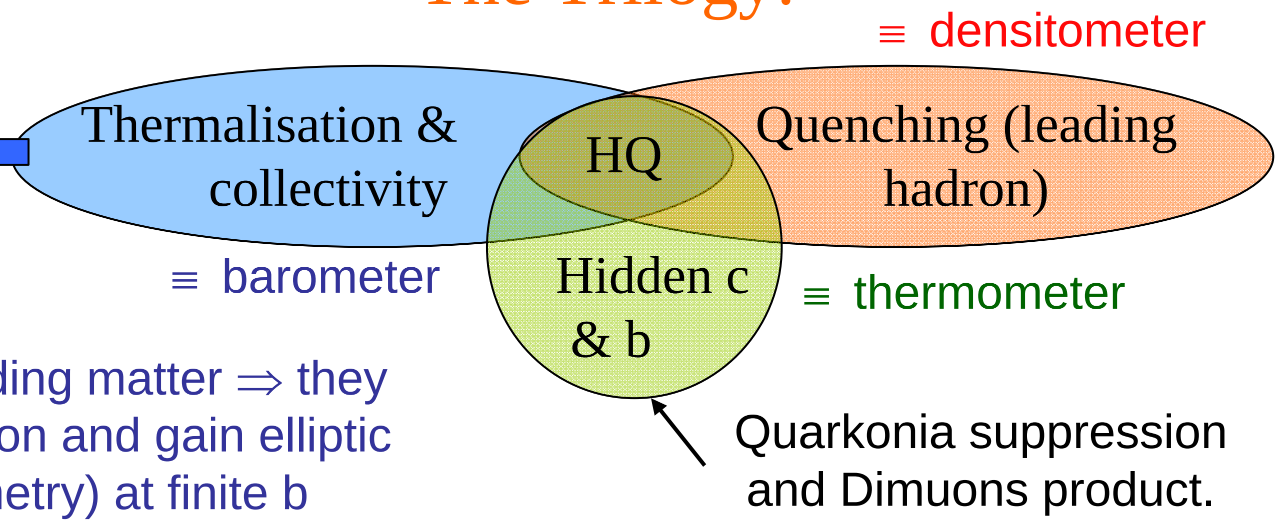
Why *open* heavy flavors in A-A ?

- Those are for sure sensitive to the early stages
- Much simpler then quarkonia and also sensitive to the medium properties (t_{equil} (α M_Q/T^2) $\Rightarrow$ clear hierarchy for s, c and b).
- Mandatory to understand Q-Qbar evolution in QGP & quarkonia product.



HQ are imbedded in expanding matter $\Rightarrow$ they participate to collective motion and gain elliptic flow (v_2:azimutal asymmetry) at finite b

The Trilogy:



Challenges:

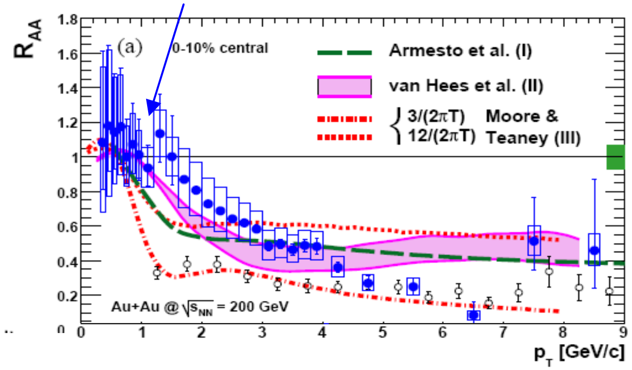
- Description of HQ E-loss / equilibration from fundamental theory
- Joint v_2-R_{AA} explanation …will help to better constrain free parameters

Setting the scene: E-Loss and thermalization

(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

Phenix data (hep-ex 0611018)



(init) $P_T >> m_Q$

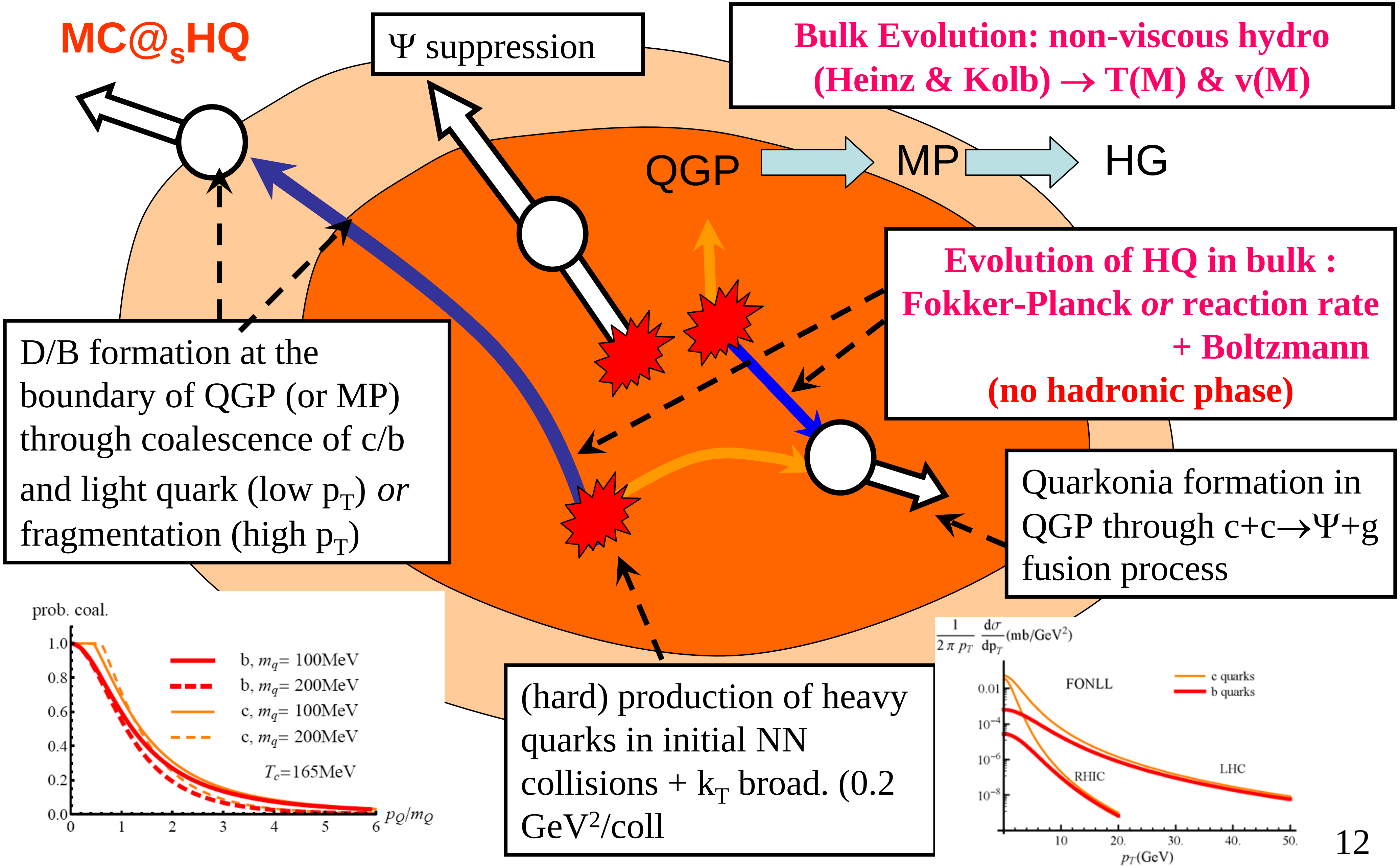
- Rare processes
- Mostly E loss
- HQ go on straight lines and probe the opacity of matter. Little thermalization
- **~ light quarks (s.e.p.)**
- *Coherent radiative + collisional processes*
- Good test of pQCD… Theory at work
- Several transport coeff implied (dE/dx, B_T,…)

…do not mixt those two worlds !!!

II. Understanding the RHIC HQ-data

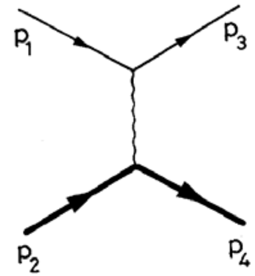
What is the dominant E loss mechanism @ RHIC ?

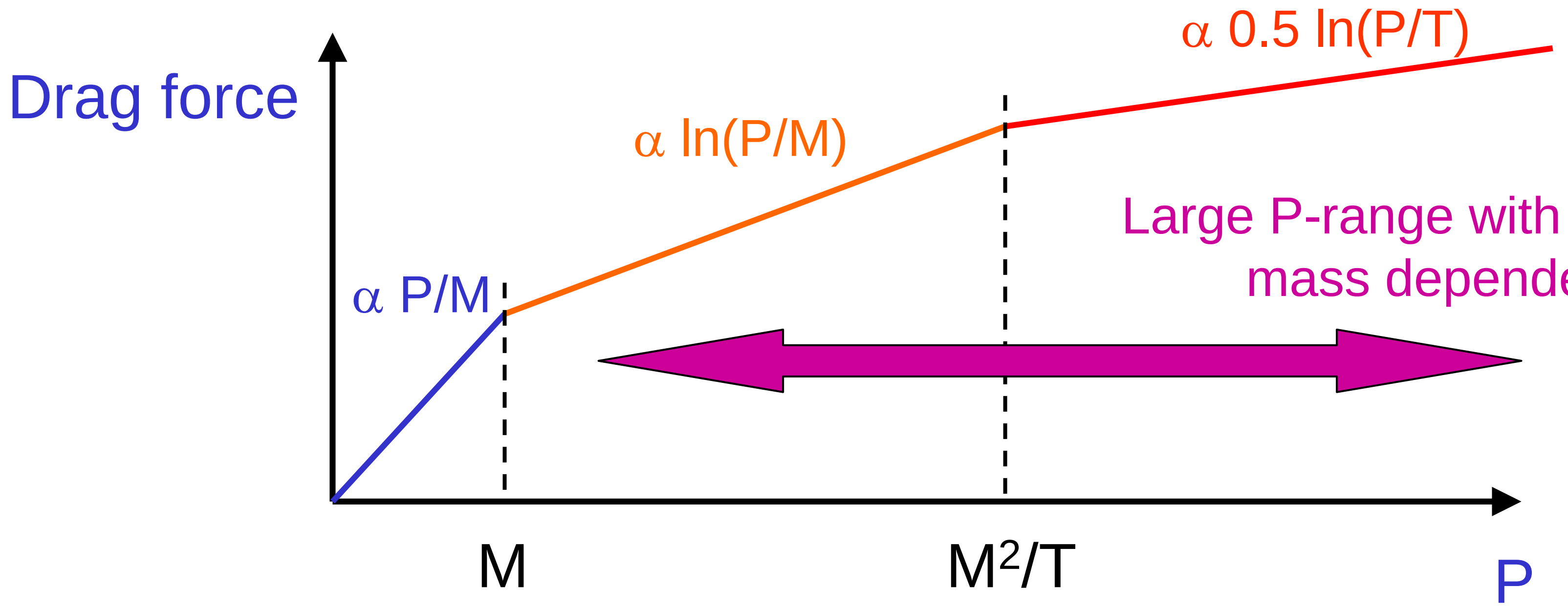
Schematic view of the global framework



Collisional E loss

Revived by Mustafa & Dutt Mazumber (2005) and then by Peshier (2006). Also: data-driven motivation: Mass Hierarchy





Other (main) interest: the seed of the radiation emanating from HQ

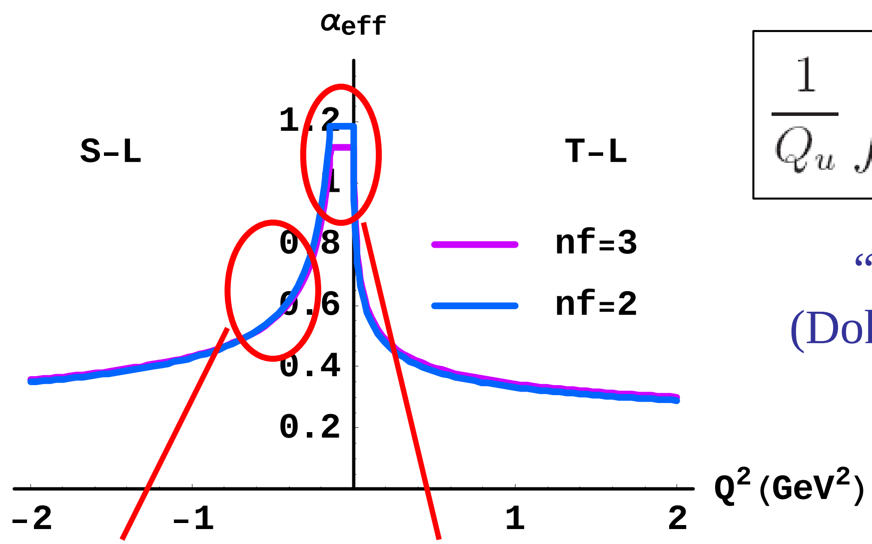
Open question: long range behaviour and renormalisation at finite temperature

The (Peshier) – Gossiaux – Aichelin approach

The reader digest of SQM08 & QM09

Motivation: Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$. The running aspect of the coupling constant has been "forgotten/neglected" in most of approaches

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



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

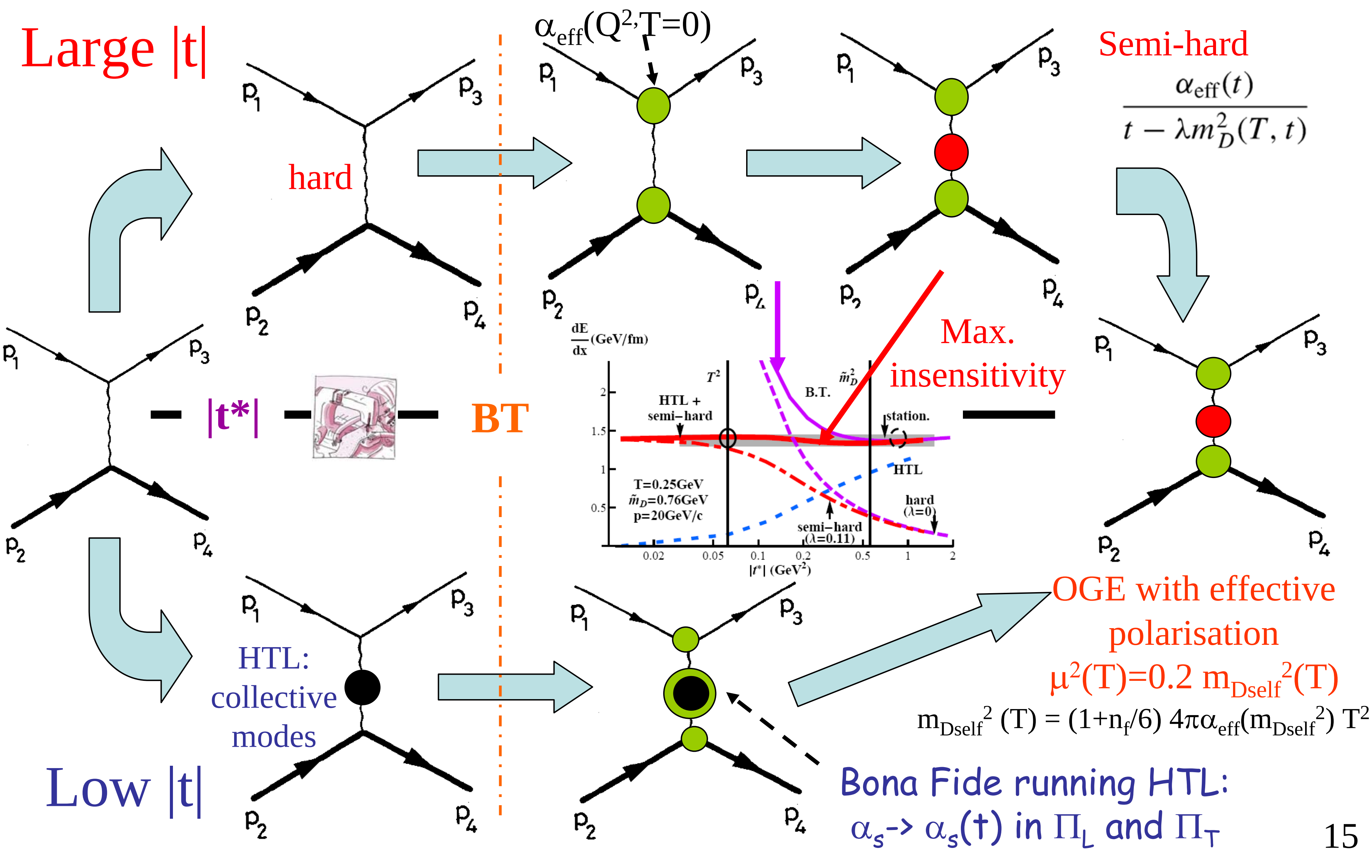
"Universality constrain" (Dokshitzer 02) helps reducing uncertainties:

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

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

A model; not a renormalizable theory

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



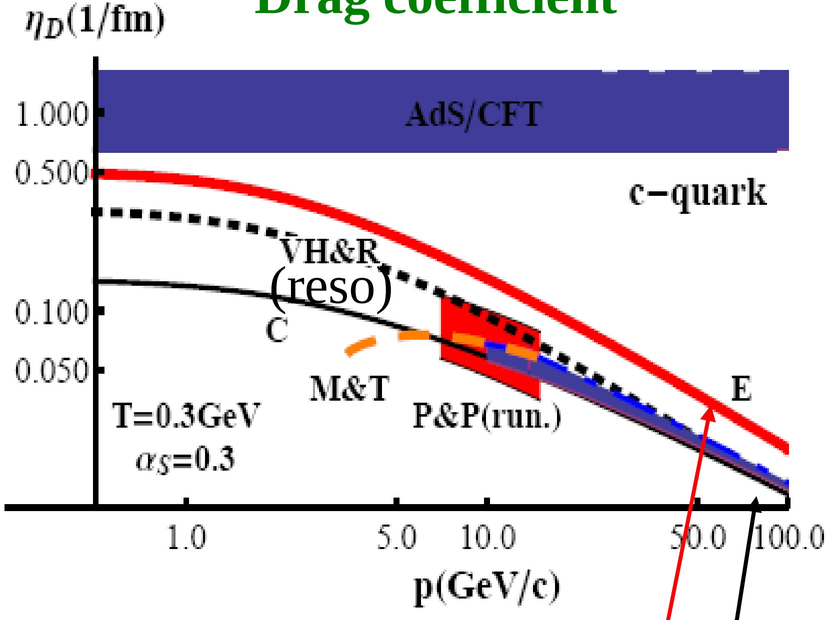
Running α_s : some Energy-Loss values

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

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

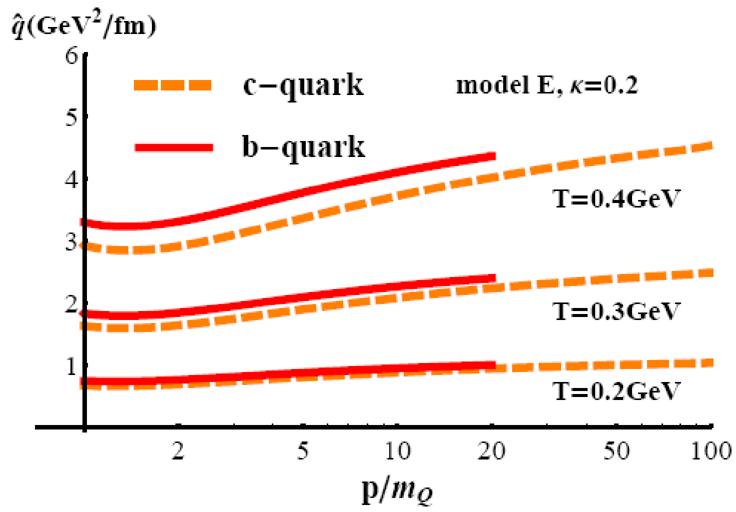
Drag coefficient



E: optimal μ, running α_{eff}

C: optimal μ, $\alpha_s(2\pi T)$

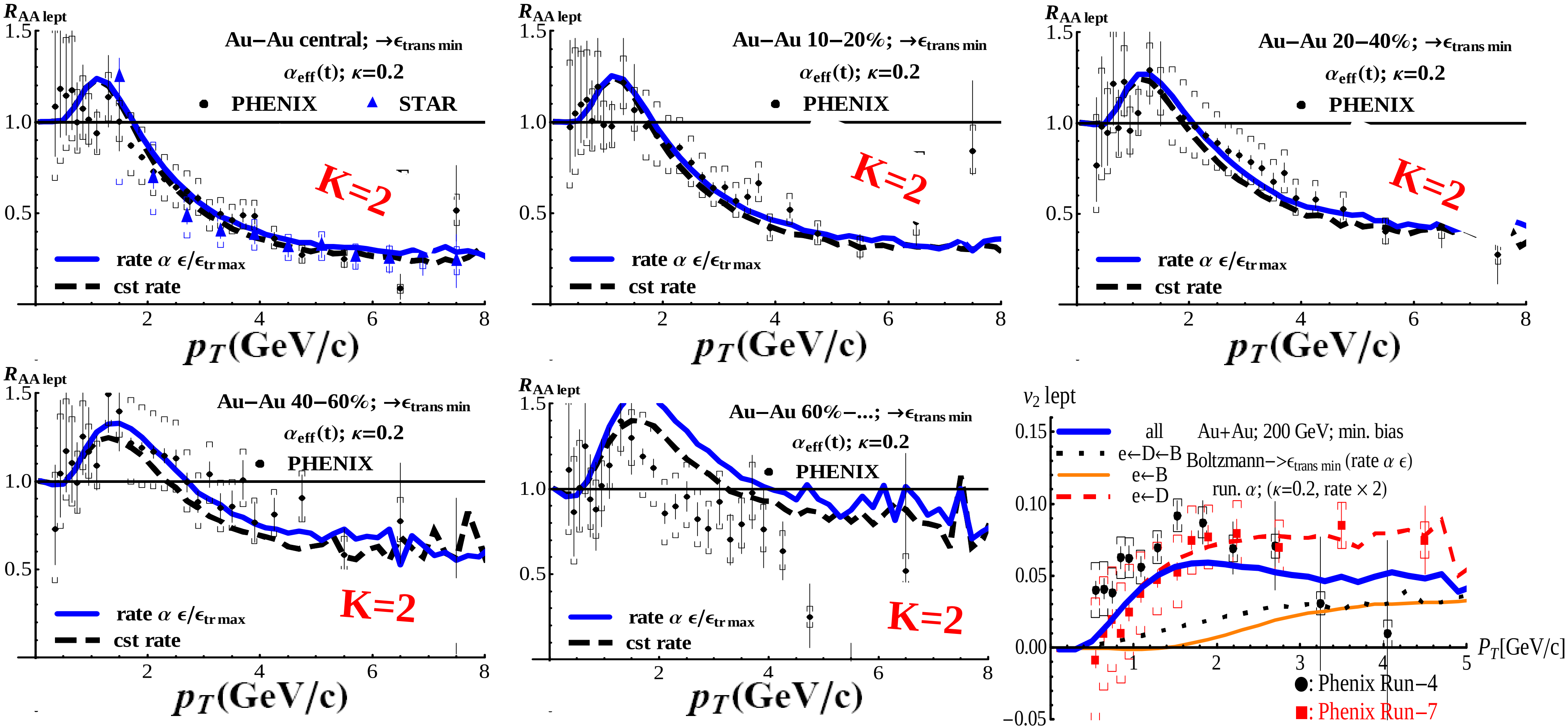
Transp. Coef …



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

Observables (Au-Au) vs (rescaled) Model

Best observable so far: R_{AA} for single non-photonic electrons



One reproduces R_{AA} *on all* p_T *range* with cranking K-factor ≈2 which permits to accommodate the “unknowns”

QGP properties: low momentum

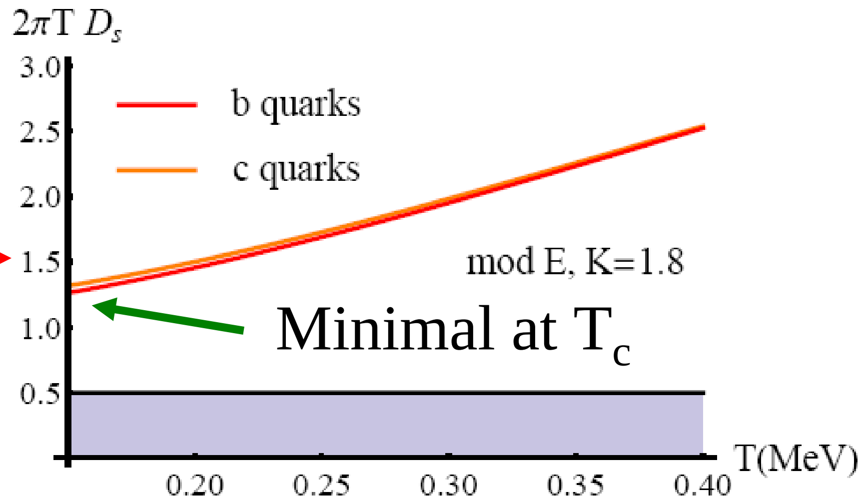
As we reproduce experimental data with rescaled model:

Moore-Teaney:

$$\frac{D}{\eta/(e+p)} \approx 6 \quad \Rightarrow \eta/s \approx DT/6 \approx \frac{2\pi T\, D}{3 \times 4\pi}$$

"robust"pQCD

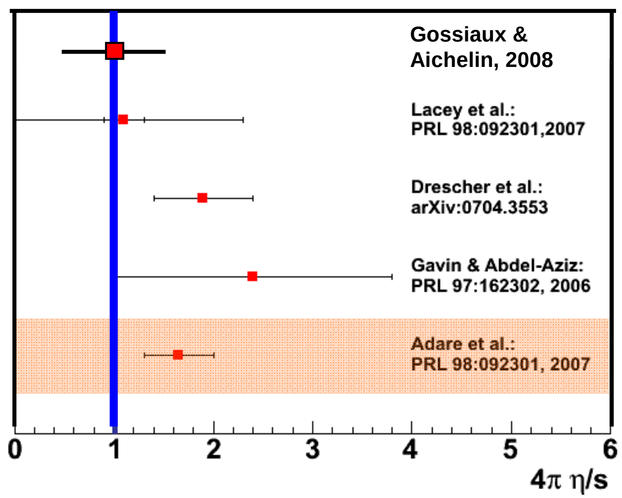
$$\boxed{\Rightarrow \eta/s \approx \frac{0.5}{4\pi}} \quad \text{at } T_c$$



Strong coupling; AdS/CFT:

$$\eta/s \approx DT/2 \approx \frac{2\pi T\, D}{4\pi}$$

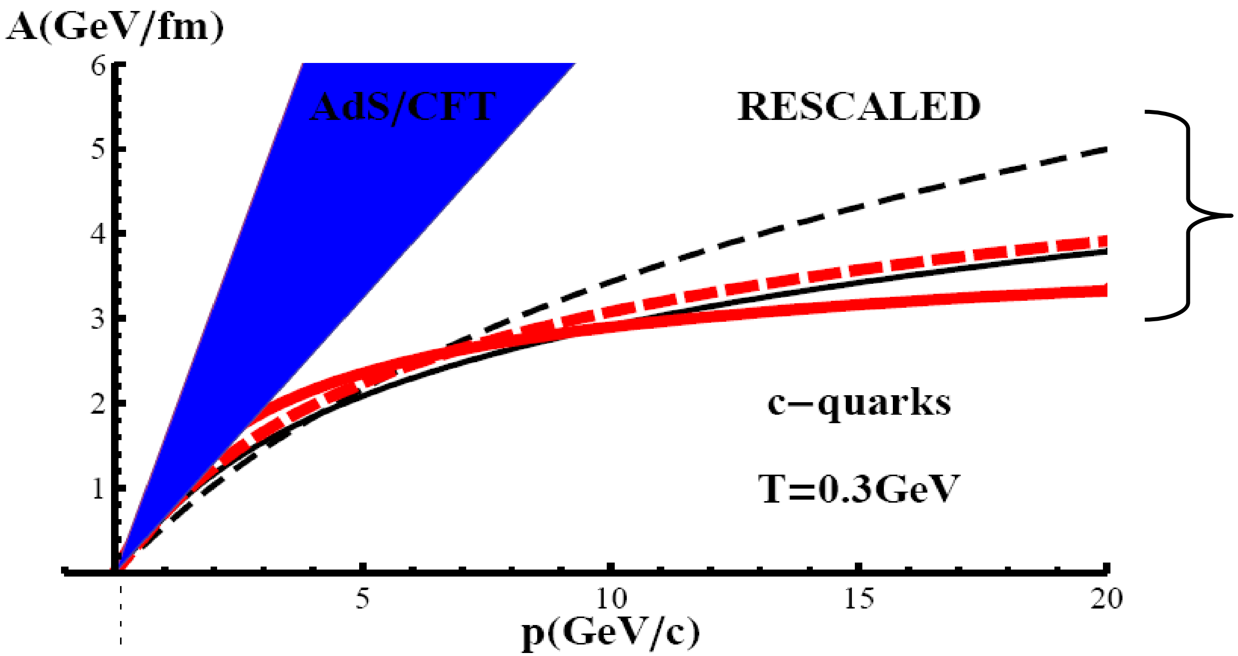
$$\boxed{\Rightarrow \eta/s \approx \frac{1.5}{4\pi}} \quad \text{at } T_c$$



But diffusion constant of heavy quark is already an interesting quantity in itself and could be evaluated on the lattice !!!

QGP properties: stopping power

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 ?!

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

(Induced) Radiative for HQ

I) Approach of increasing sophistication

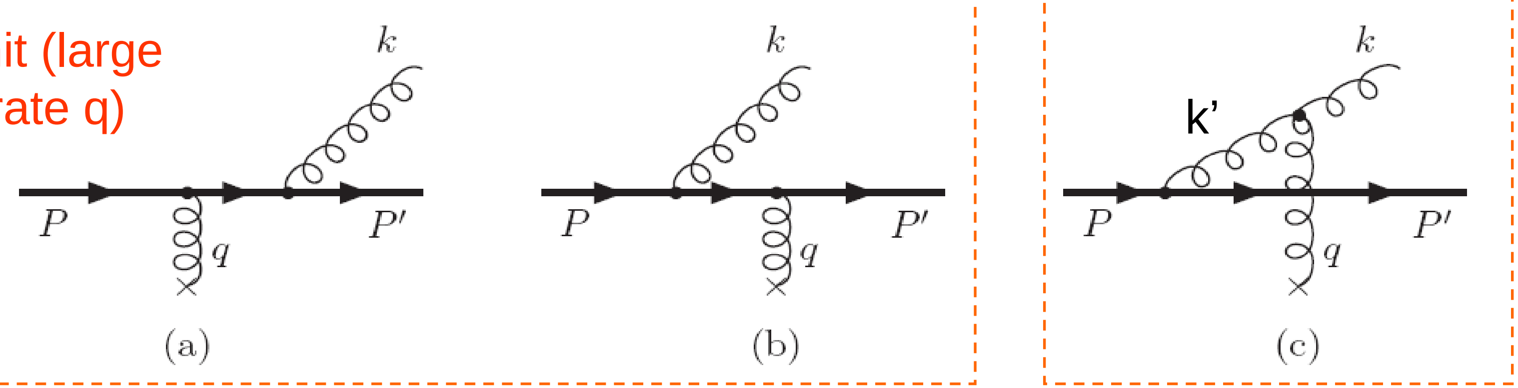
II) Ultimate goal is to have “simple” effective model that can be implemented in Monte Carlo simulations => need for analytical formula

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’

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

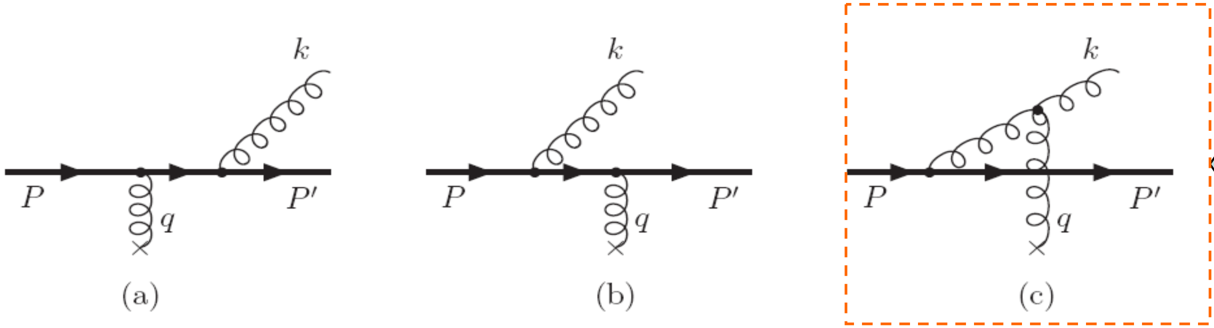
with

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

(phenomenological; not in BDMPS)

Both cures the colinear divergences and will influence the radiation spectra

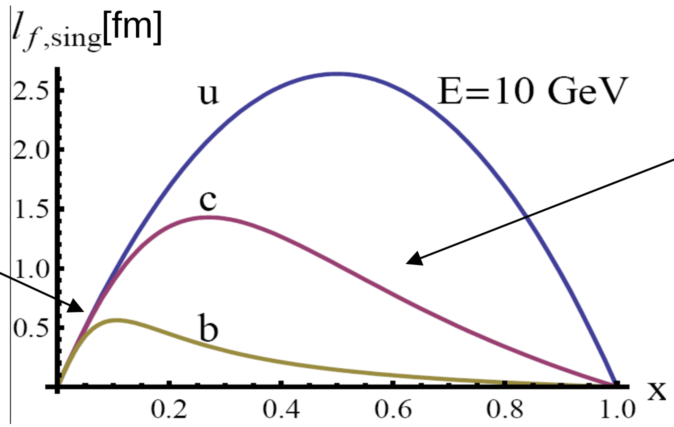
Formation time for a single coll.



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

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

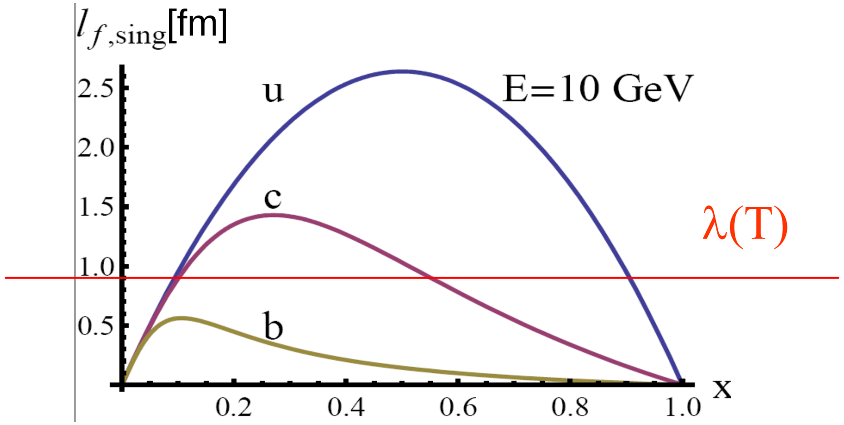


For $x > x_{cr} = m_g/M$, gluons radiated from heavy quarks are resolved in less time then those ← light quarks and gluon => radiation process less affected by coherence effects in multiple scattering

Dominant region for quenching

Dominant region for average E loss

A simplifying hypothesis



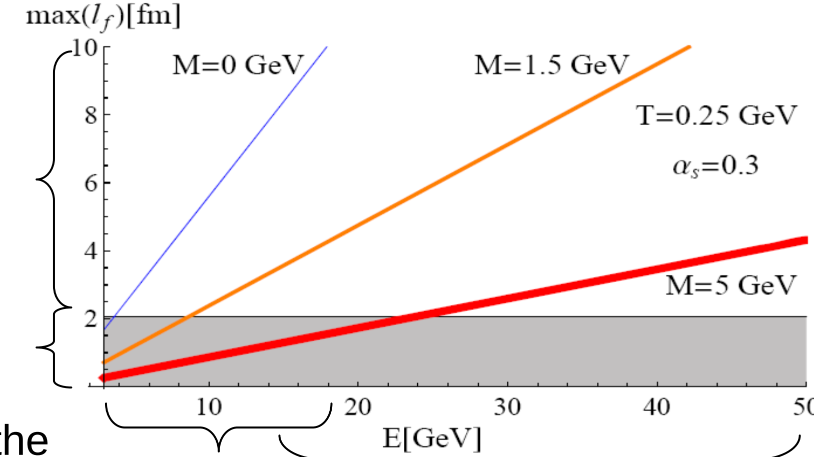
Comparing the formation time (on a single scatterer) with the mean free path:

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)

Radiation spectra

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

… to convolute with your favorite elastic cross section

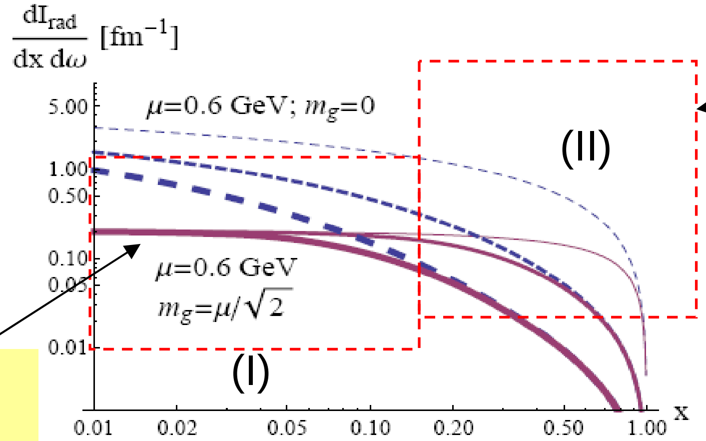
$$\tilde{m}_g^2 = (1-x)m_g^2 + x^2 M^2$$

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 $q\rightarrow c$)

If typical $q_\perp \approx T$:

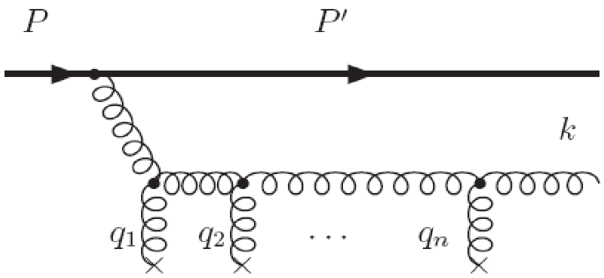
$$\frac{d^2 I^{x\ll 1}_{\mathrm{GB}}}{dz\, d\omega} \sim \frac{2N_c\alpha_s}{3\pi} \times \frac{1}{m_g^2 + x^2 M^2} \times \underbrace{\frac{\langle q_\perp^2\rangle}{\lambda}}_{\hat{q}}$$

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

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

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

Formation time in a random walk (LPM)



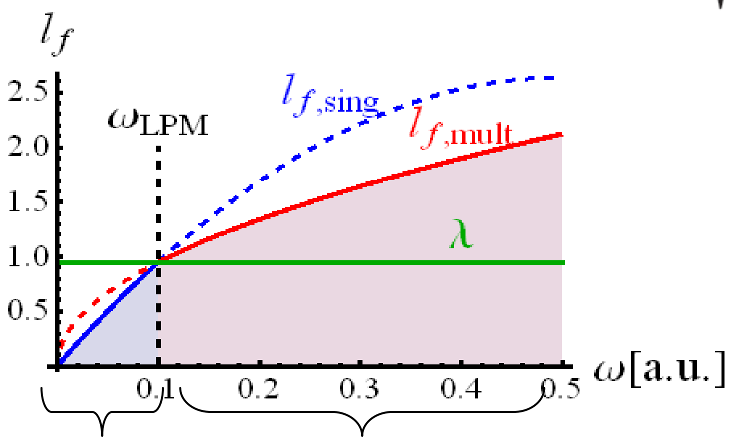
Phase shift at each collision

One obtains an effective formation time by imposing the cumulative phase shift to be $\Phi_{\rm dec}$ of the order of unity

For light quark (infinite matter):

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

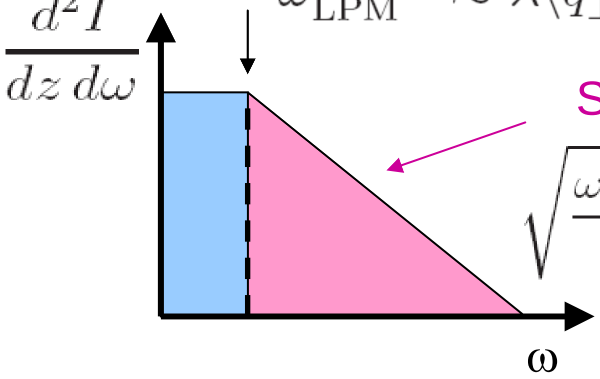
=> 3 scales: $l_{f,\rm mult}$, $l_{f,\rm sing}$ & λ



Uncoherent radiation

Coherent radiation (BDMPS)

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



Suppression:

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

Especially important for av. energy loss

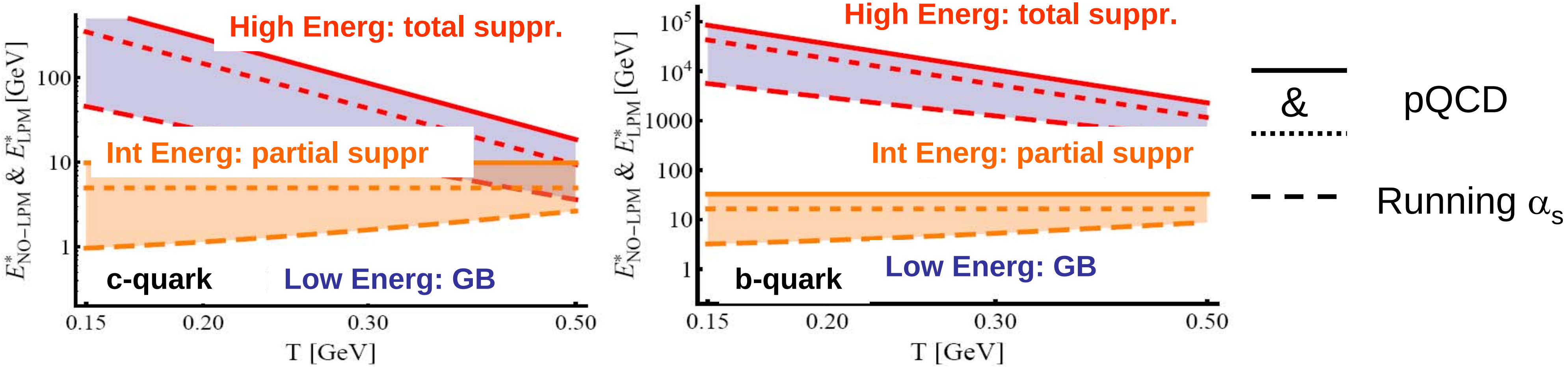
$$\frac{dE_{\rm BDMPS}(q)}{dz} \sim \boxed{\sqrt{\frac{\omega_{\rm LPM}}{E}}} \times \frac{dE_{\rm GB}(q)}{dz}$$

HQ: Regimes and radiation spectra

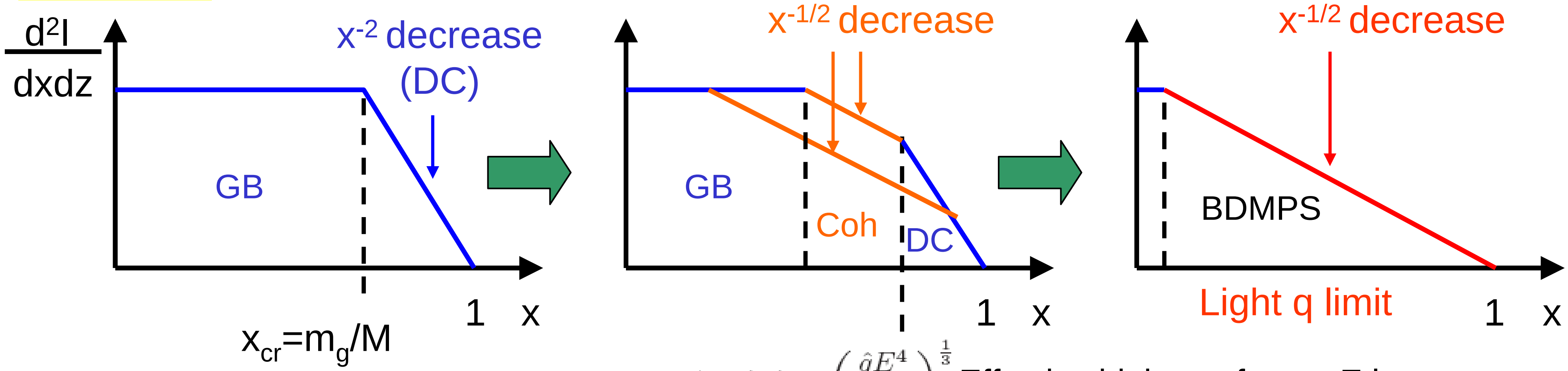
Hierarchy of scales:

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

larger coupling ⇒ Larger coherence effects

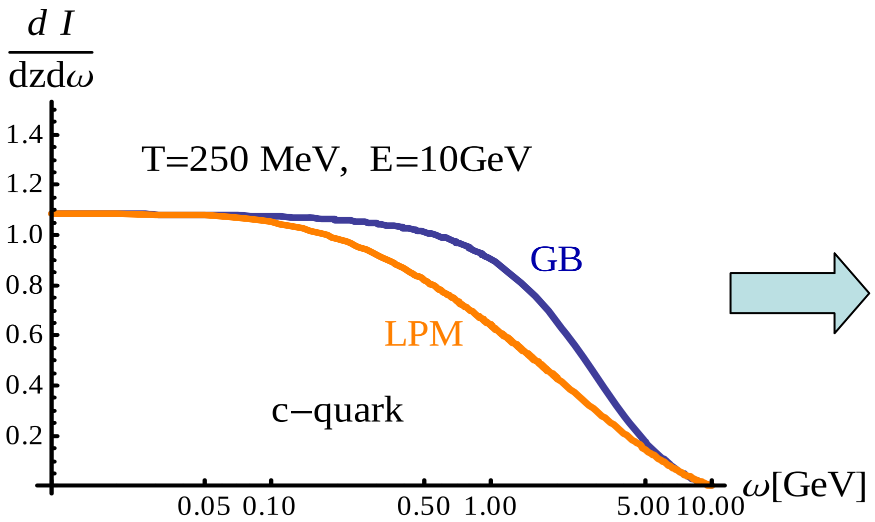


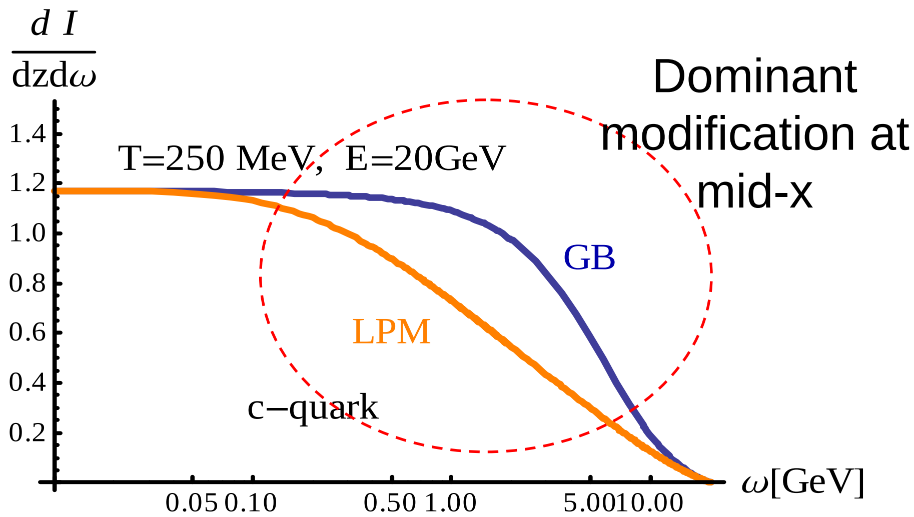
Spectra

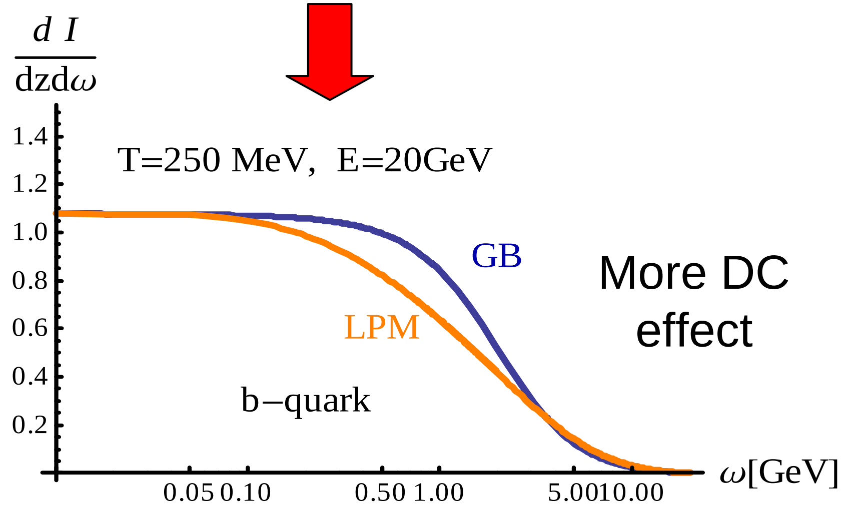


$$\omega^{\star}_{\rm LPM}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$$ Effective higher ω for av. E loss

Reduced spectra from coherence







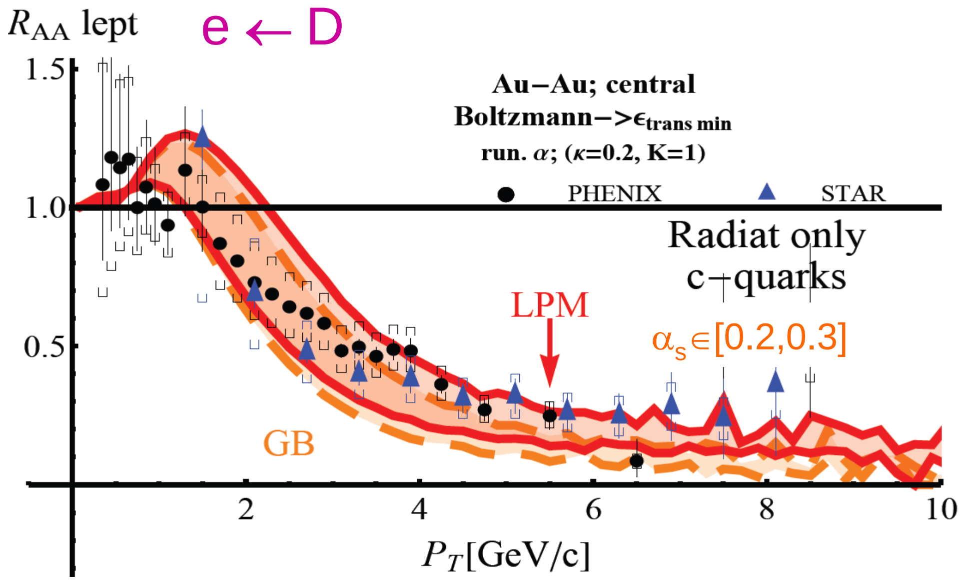
More DC effect

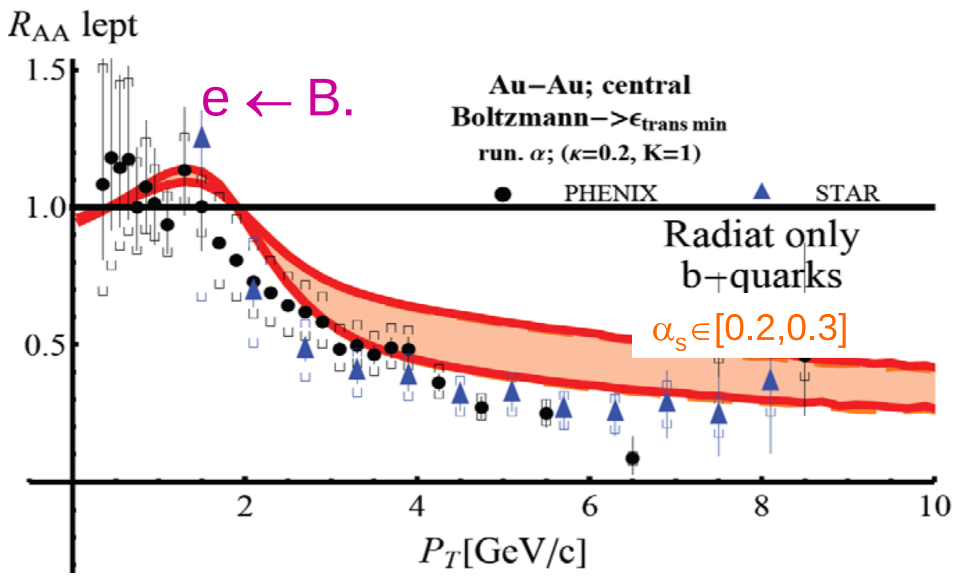
: Suppression due to coherence increases with increasing energy

: 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 (Coherent) Radiation Included

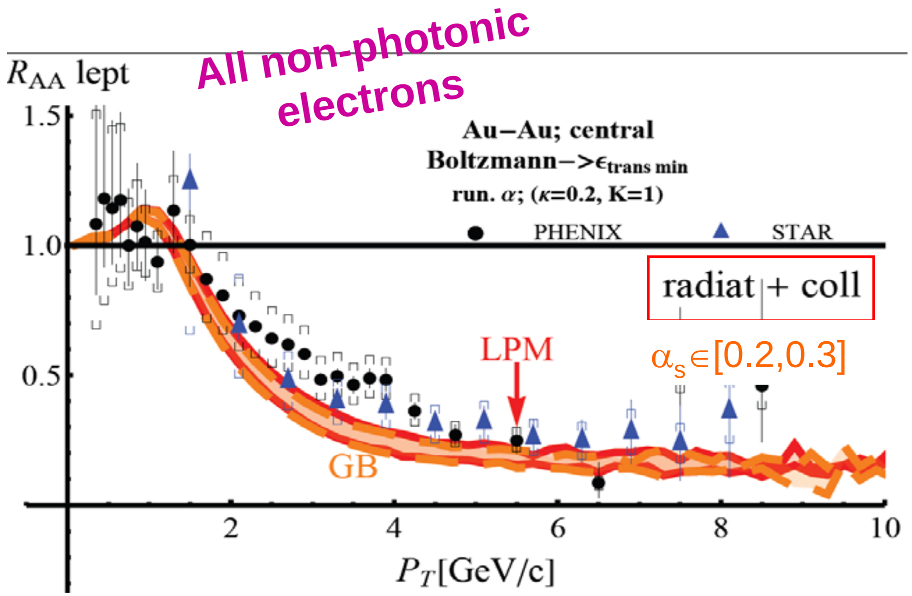




1. Coherence: Some moderate increase of R_{AA} for D at large p_T.
2. No effect seen for B

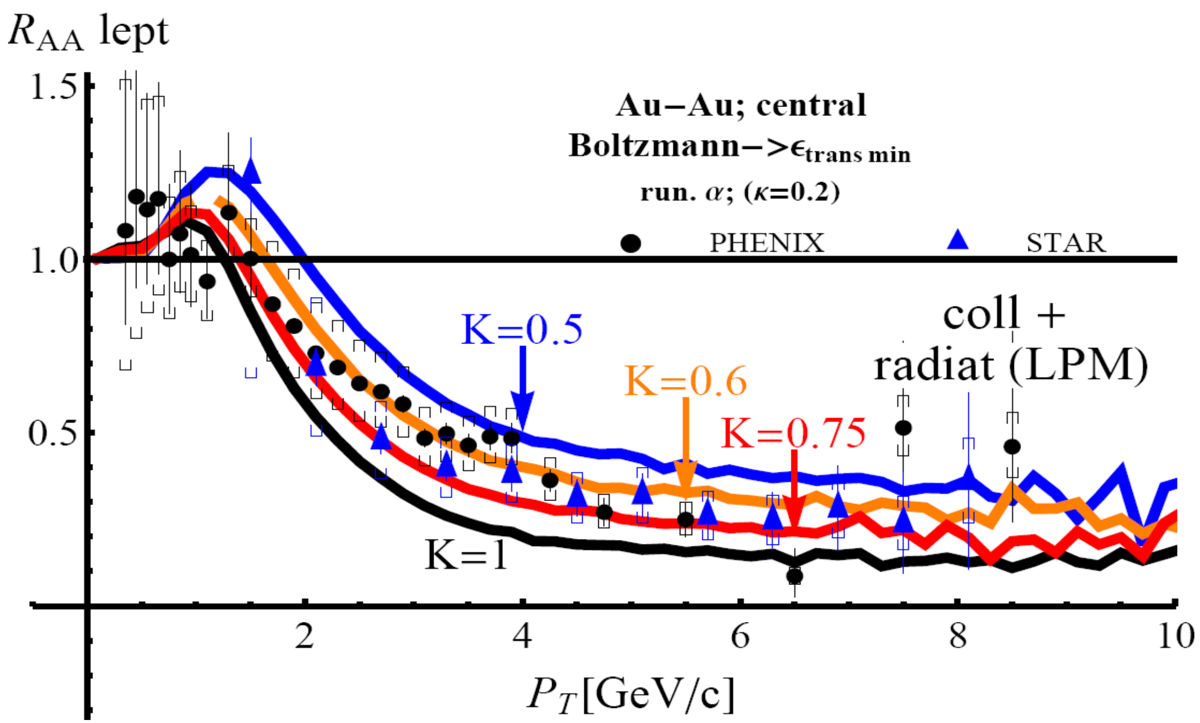
Conclusions can vary a bit depending on the value of the transport coefficient

Indication that R_{AA} at RHIC is mostly the physics of rather numerous but small E losses, not very sensitive to coherence .



Optimization of radiative + collisional

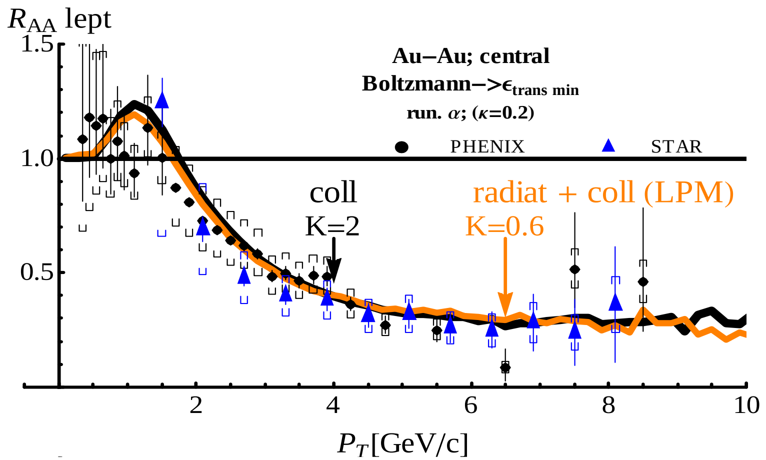
Same approach as by PHENIX

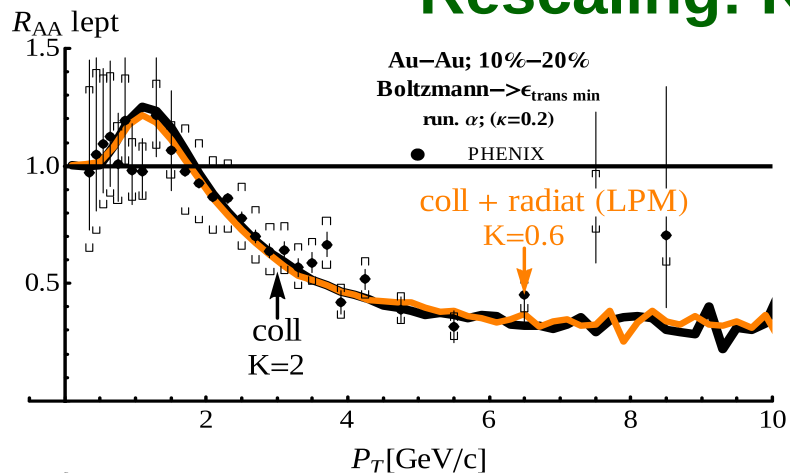


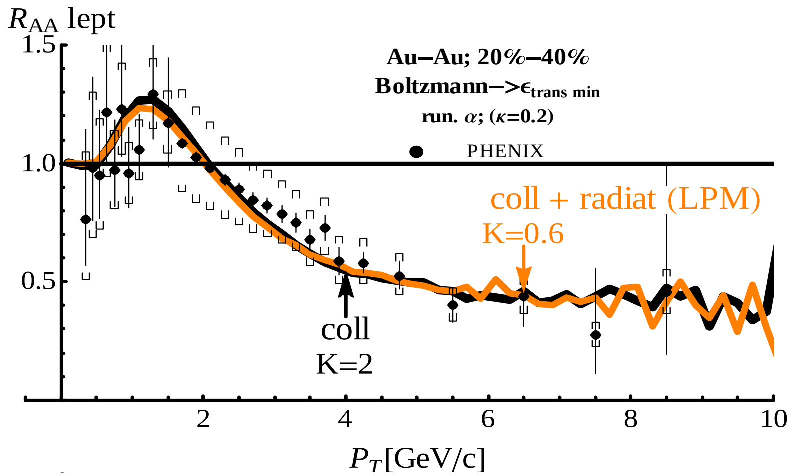
K: overall cranking factor. Optimal for K$\in$[0.6,0.75]

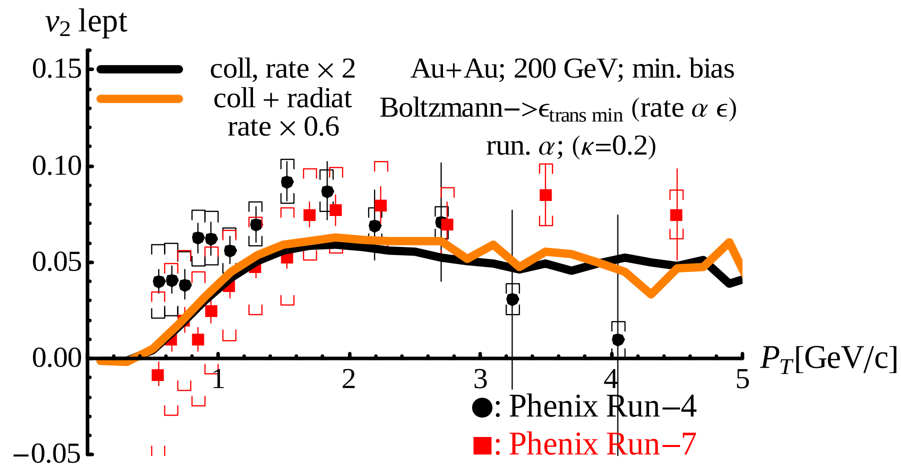
Collisional vs {Radiative + Coll}

Rescaling: K=0.6





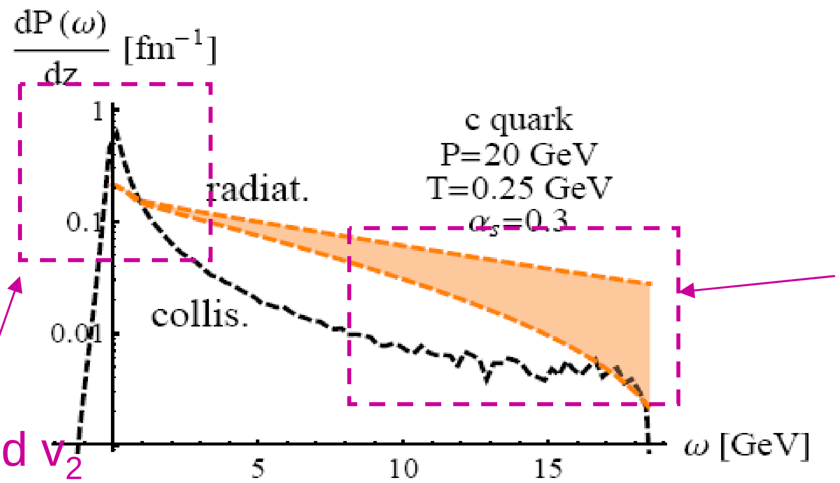




The present data cannot decipher between the 2 local microscopic E-loss scenarios

Interpretation

The heavy-quark physics at play for RHIC up to now is the one of small (relative) E-loss (and thus of the Fokker-Planck equation)… even at the largest p_T



R_{AA} and v_2 physics

What we need

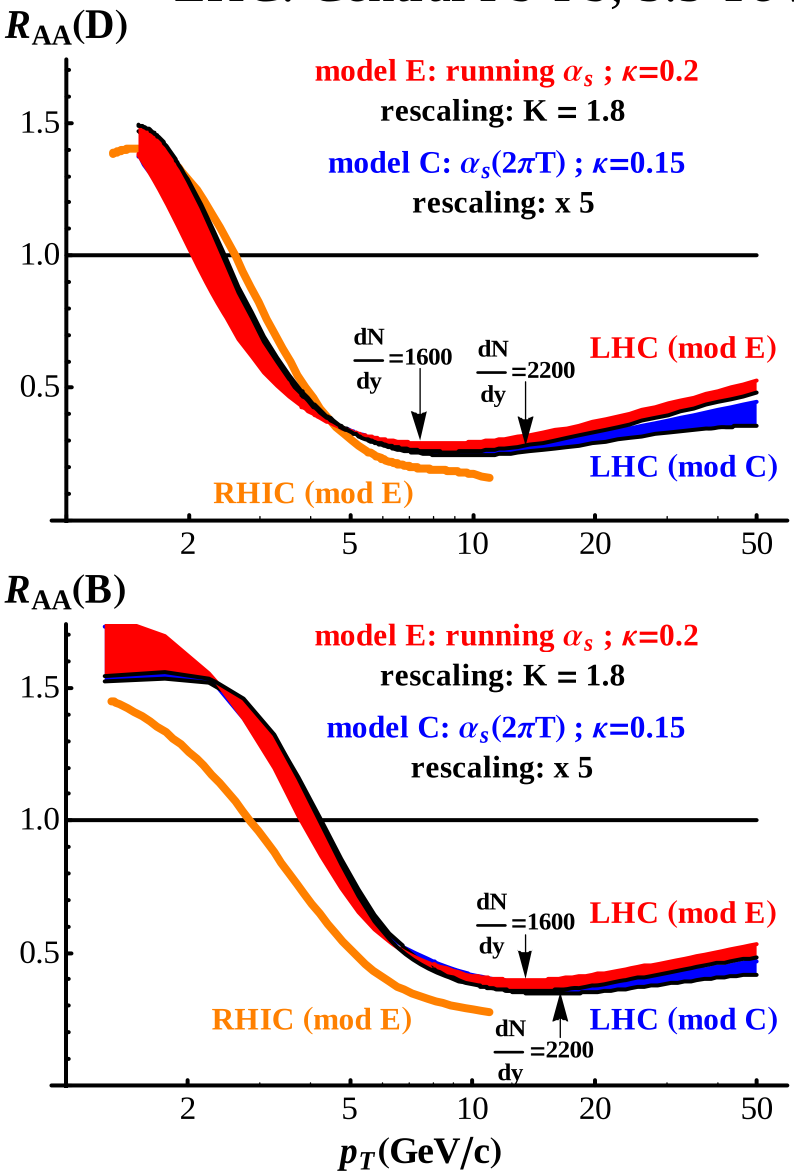
- D and B separately (in any case)
- tagged HQ jets and I_{AA} (and other correlations)

In our view, it is nevertheless more plausible to describe the physics in terms of a rather strong collisionnal energy loss supplied with an even stronger radiative energy loss (at least for γ “>>” 1).

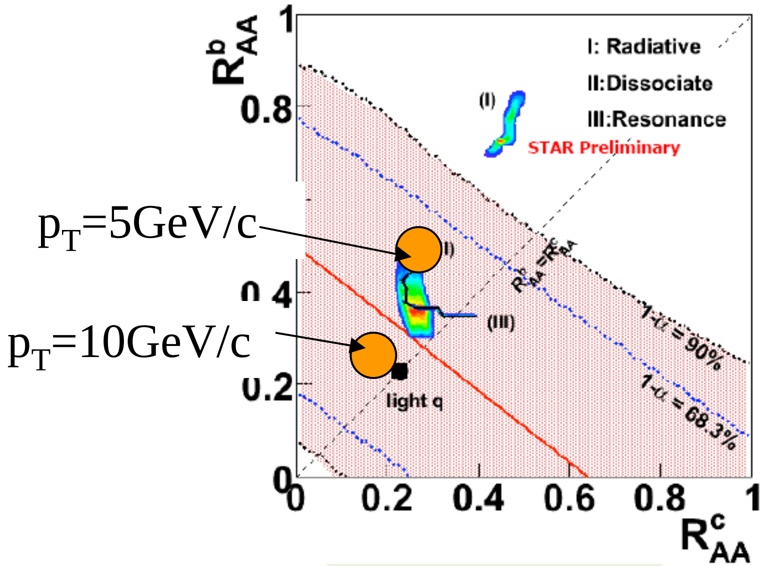
III. Future observables

D & B meson: RHIC II vs LHC (pure collisional)

LHC: Central Pb-Pb; 5.5 TeV



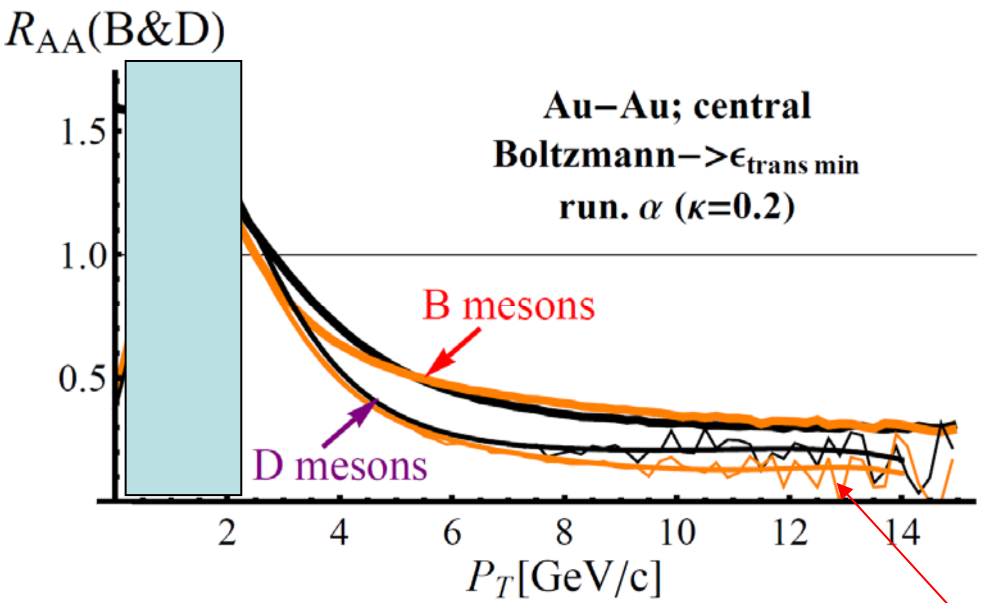
Rescaled collisional E loss



Z. Xu (sqm08)

- RAA $\rightarrow$ 1 at asymptotic p_T values, mostly seen in running α_s models.
- medium at LHC relatively less opaque that at RHIC

D & B meson: RHIC II (radiat + collisional)



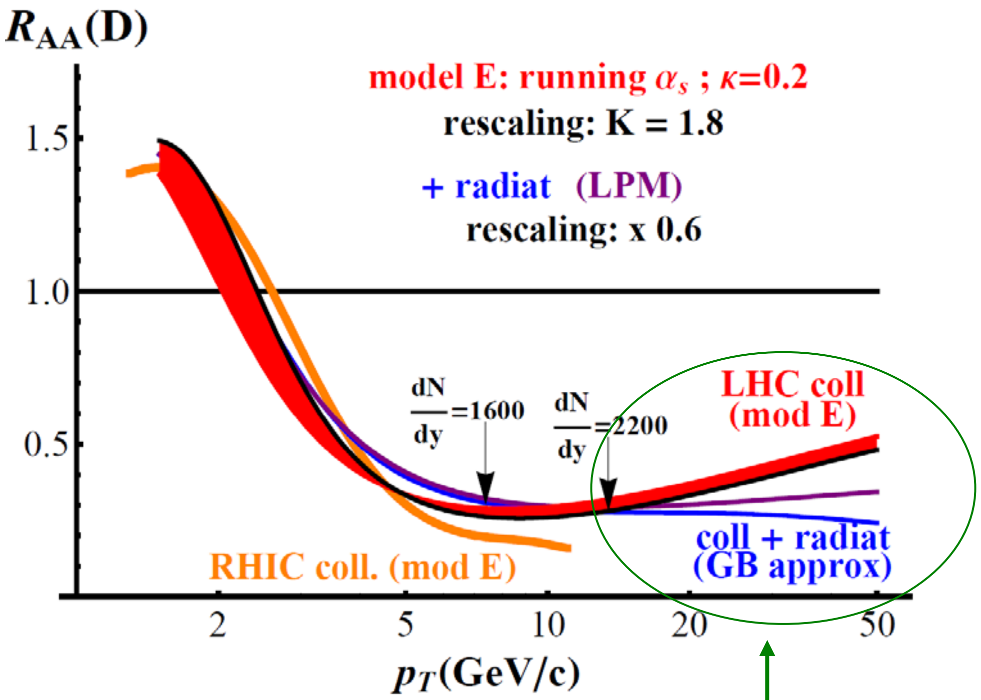
Collis., rate x 2

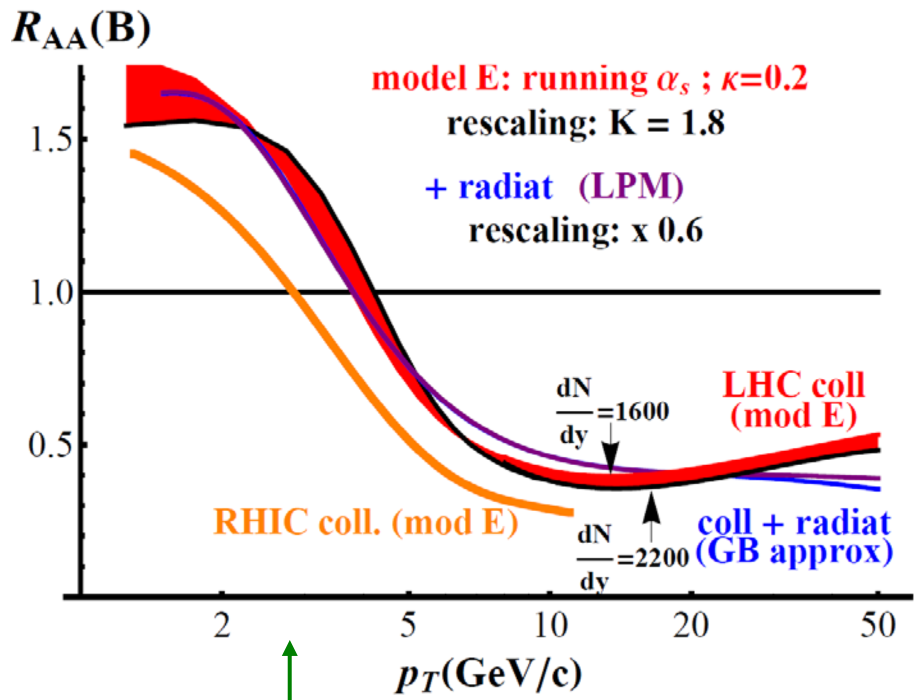
Collis. + Rad (LPM), rate x 0.6

α_s(rad)=0.3

… some small deviations for D spectra at large p_T

D & B meson: LHC (radiat + collisional)





D spectra in Pb-Pb (5.5 TeV): Some window to decipher between the various Energy-loss models, for $p_T > 20$ GeV/c

B spectra in Pb-Pb (5.5 TeV): Pretty independent of E-loss model (properly calibrated w.r.t. RHIC data)

Conclusions & Perspectives

- Enough E loss in (our effective) QCD model to explain both R_{AA} and v_2 of single non-photonic electrons (1/3 collisional and 2/3 radiative)
- Energy loss for R_{AA} is a question of moderate energy loss (i.e. small x, for rad energy loss), whatever radiative or collisional
- Bad news for deciphering the basic mechanism at RHIC I: central limit theorem prevents to distinguish => go for more exclusive probes (azimuthal correlation, tagged HQ-jets)
- Good news: RHIC II or (especially) LHC will help to resolve the ambiguities
- But: lots of aspects should be investigated / considered:
    - Evolution of the "QGP"
    - Initial production of heavy quarks
    - p-p reference
    - …