Gluon Radiation by Heavy Quarks at Intermediate Energies

24th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

Darmstadt, Germany

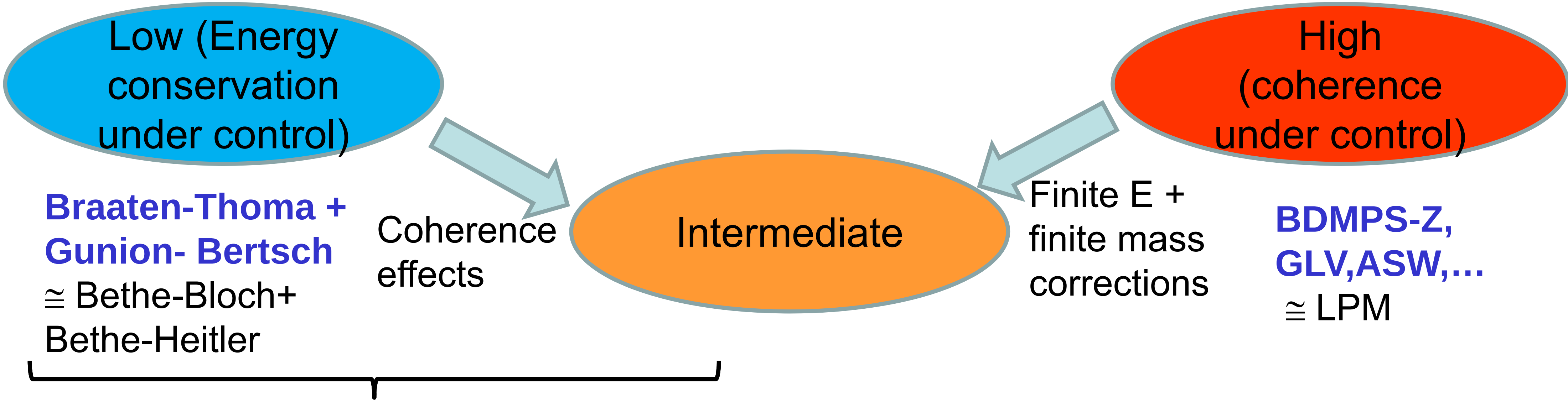
P.B. Gossiaux
SUBATECH, UMR 6457
Université de Nantes, Ecole des Mines de Nantes, IN2P3/CNRS

with

J. Aichelin, Th. Gousset, M. Nahrgang, V. Ozvenchuk
K. Werner

Motivation and Context

- Most of the *interesting* HF observables so far: located at *intermediate* p_T ($\approx$3 GeV-50 GeV)
- Intermediate p_T: mass effect still present and thus hope to learn something more as compared to large p_T



Approach pursued in our **models…** Still some “free choice”

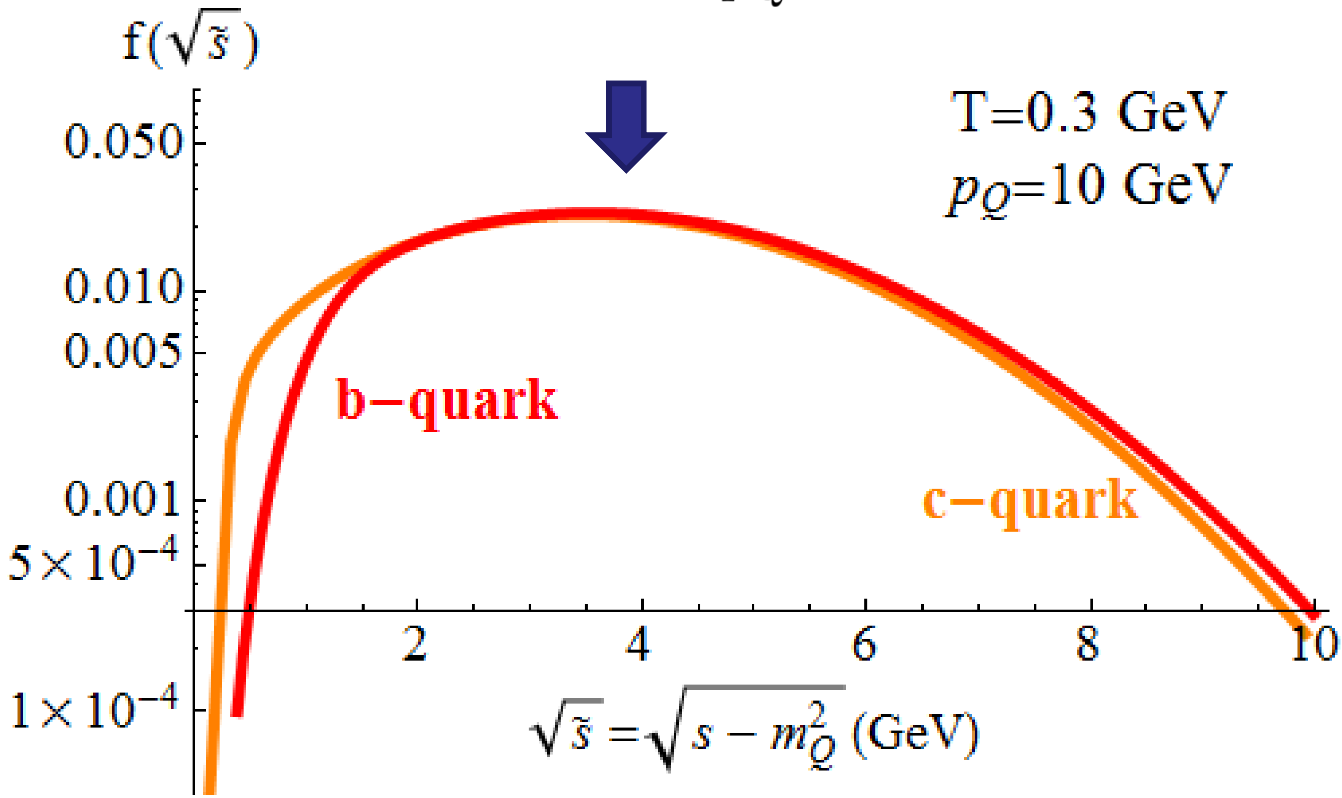
$\Rightarrow$ Need for falsification (more observables; lQCD): See M. Nahrgang’s talk

$\Rightarrow$ **Need for a better understanding of the parametric dependences, in particular the mass hierarchy**

Radiation at Intermediate Energies ?

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

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

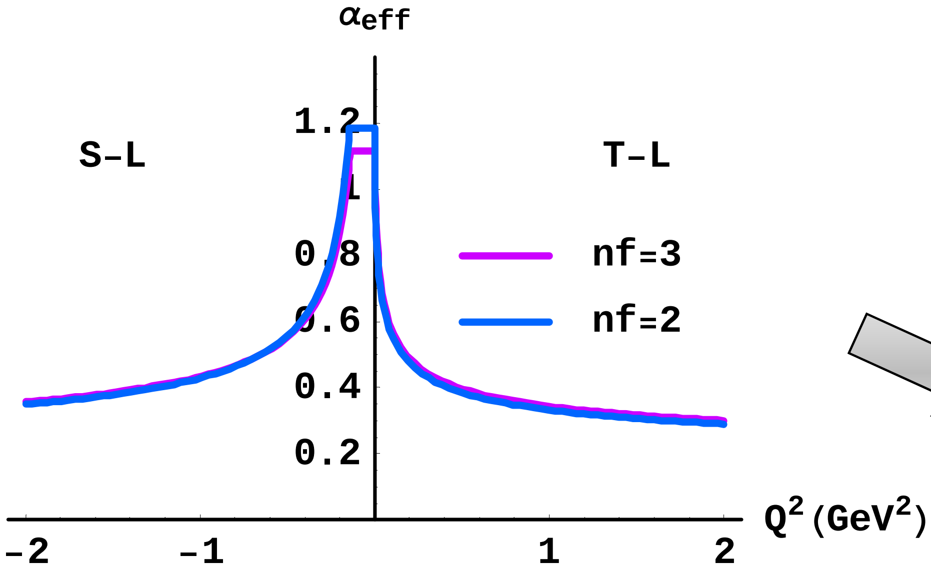


For most of the scatterings: $\tilde{s} \gg \{l_t^2, k_t^2\}$ (typical scales in the direction $\perp$ to HQ propagation)

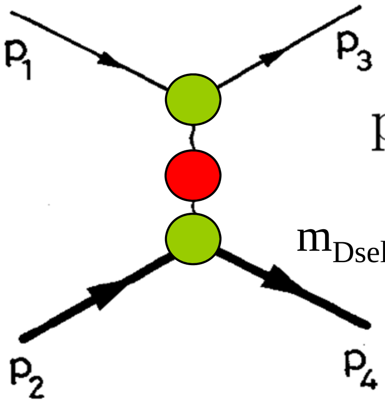
But NOT $s \gg m_Q^2$ (source of many simplifications)

Our Basic Ingredients for HQ Collisional Energy Loss

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



II. One gluon exchange with self-consistent Debye mass



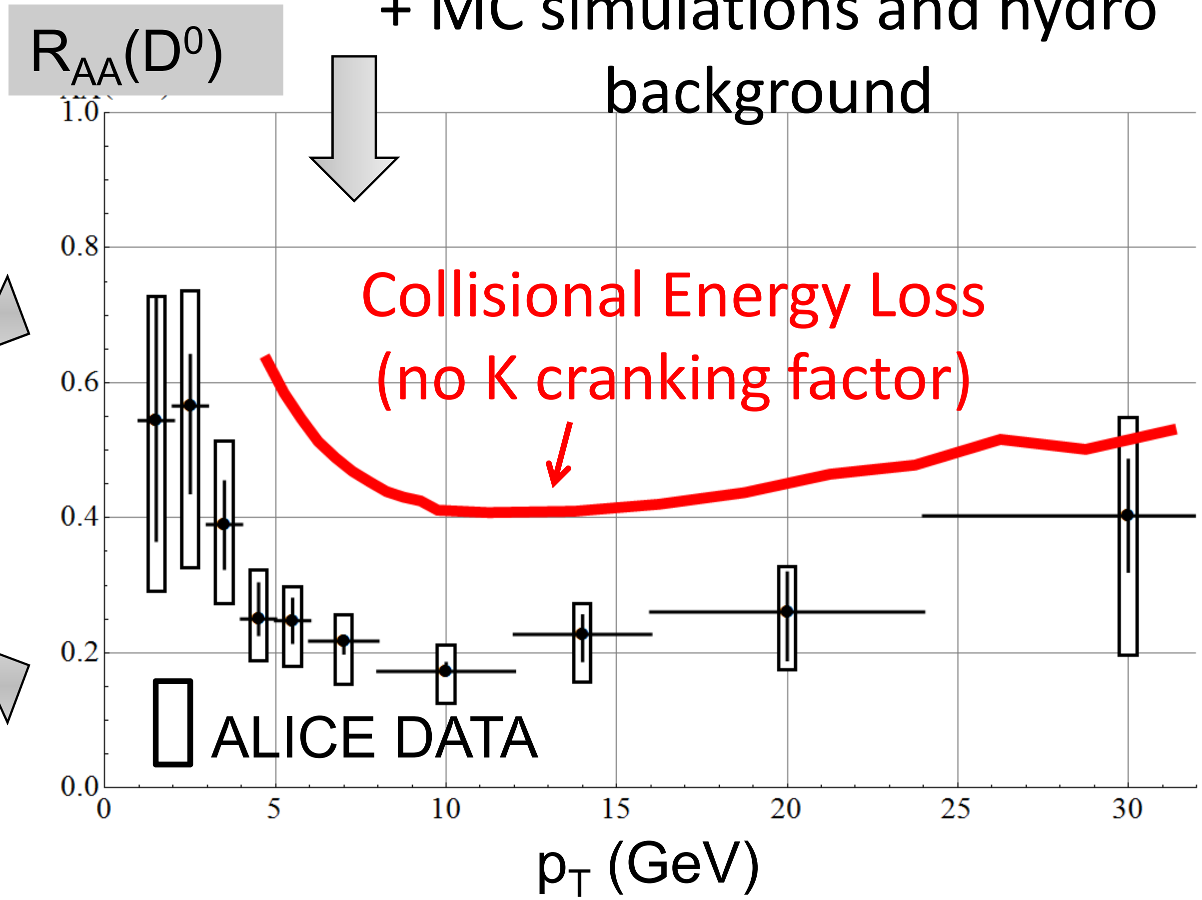
$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{\text{Dself}}(T)}$$

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

+ u and s channels

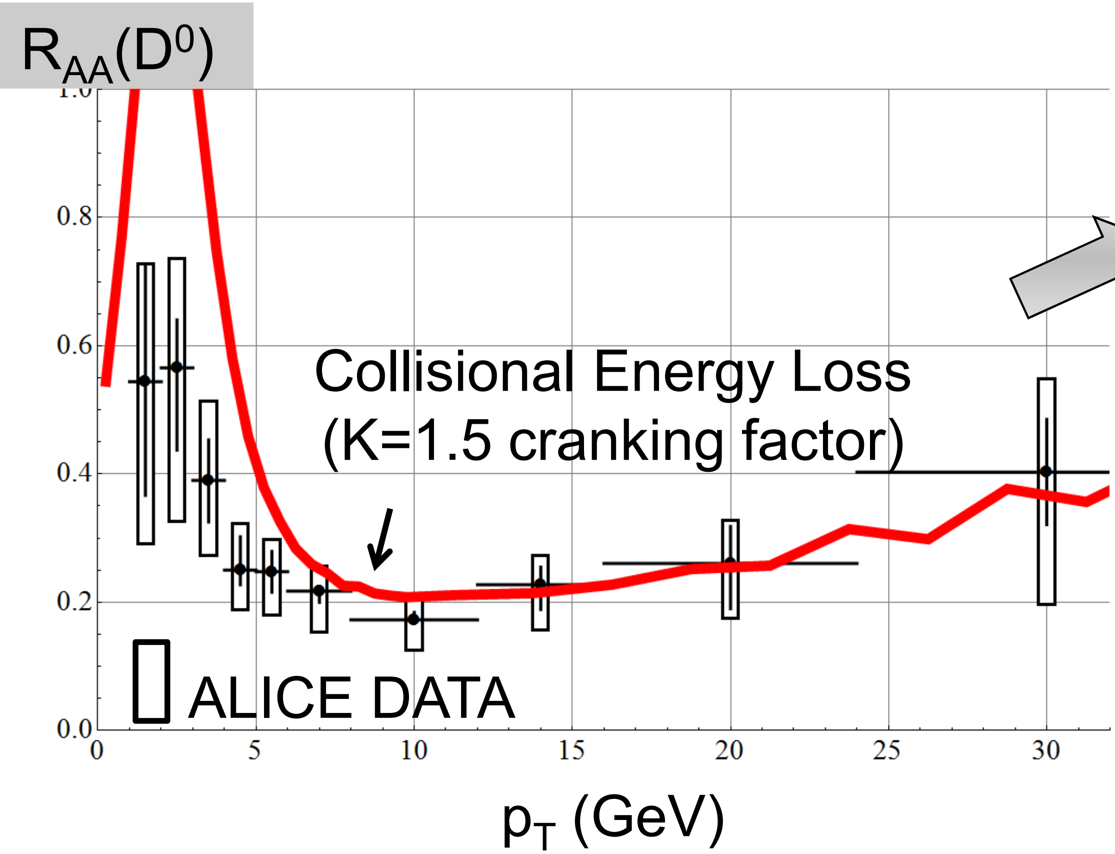
"running α_s" model for $\frac{d\sigma_{\text{el}}}{dt}$

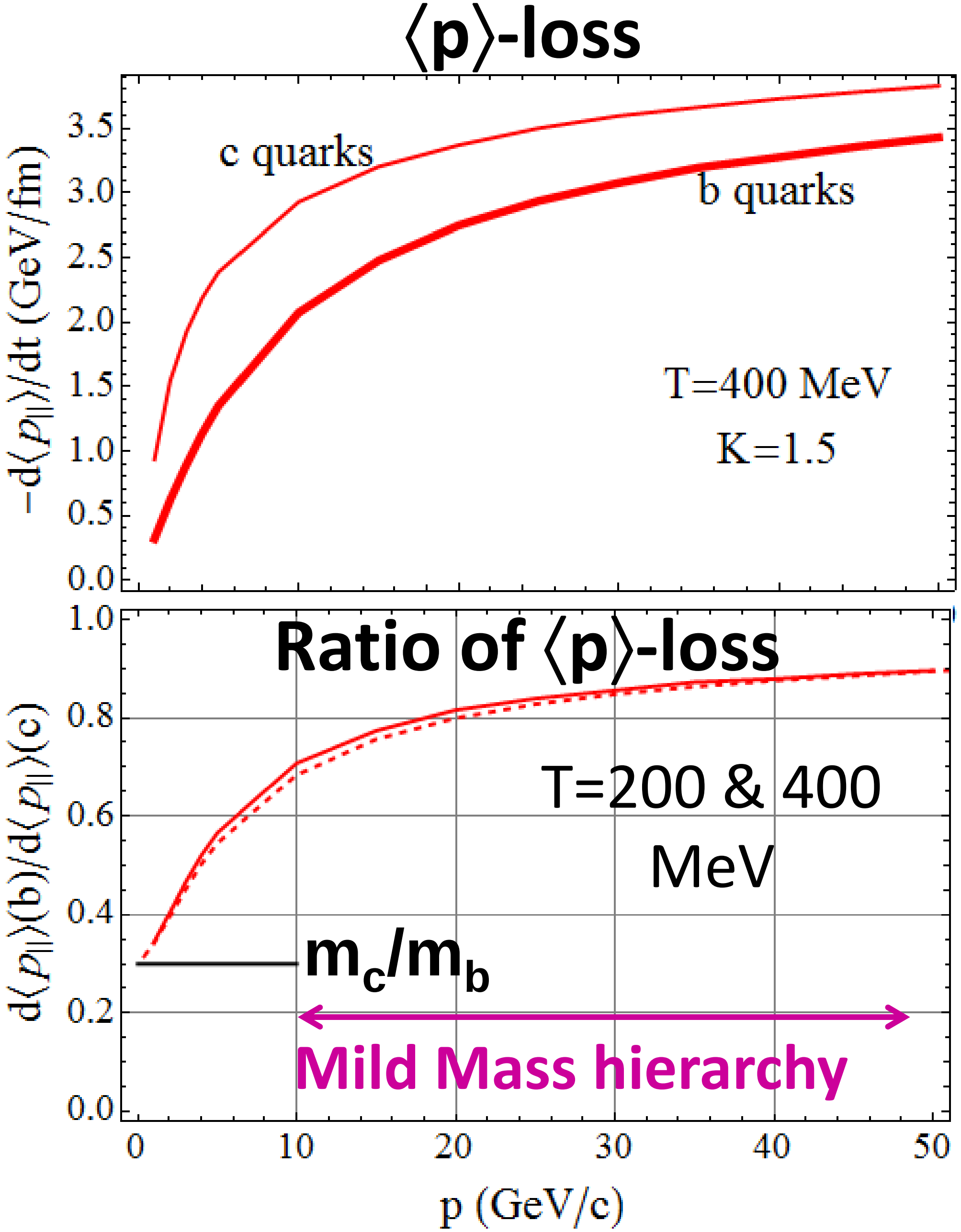
+ MC simulations and hydro background



Lack of quenching as compared with the data

HQ Collisional Energy Loss and Mass Hierarchy





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

(Induced) Radiative Energy Loss

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

In the literature:

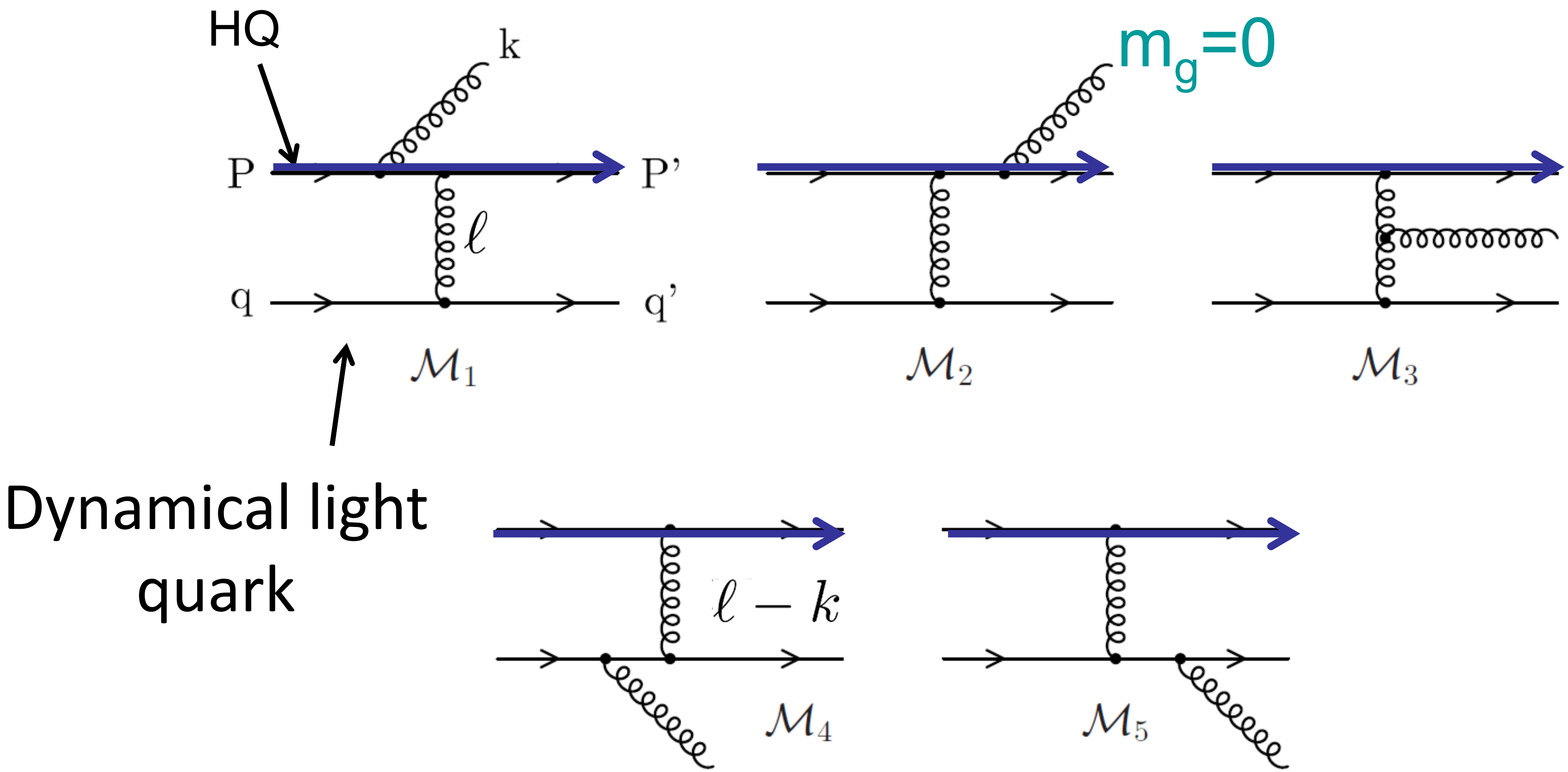
From naïve "dead cone" effect $\frac{d\sigma_{\rm rad}}{\theta d\theta} \propto \frac{\theta^2}{\left(\theta^2+\frac{M_Q^2}{E_Q^2}\right)^2}$ ...

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

Our goal:

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

qQ→qQg “in the Vacuum”



Sudakov decomposition: $P = p + \frac{m_Q^2}{s - m_Q^2} q$ $\quad p$ and q : light-like

$$k = xp + yq + \vec{k}_t$$

Momentum transfer: $\ell = q - q', \; t = \ell^2$

qQ→qQg "in the Vacuum": Exact Relation

Exact relation: $$\frac{d\sigma^{Qq\to Qgq}}{dx d^2k_t d^2\ell_t} = \frac{1}{2(s-M^2)}|\mathcal{M}|^2 \frac{1}{4(2\pi)^5\sqrt{\Delta}}\Theta(\Delta)$$

With:

Δ: phase-space

and $$\underset{\substack{\uparrow\\ \text{Rapidity-plateau}}}{\mathcal{M} = \mathcal{M}^{\rm QCD}} \oplus \underset{\substack{\uparrow\\ \text{Fragmentation region}}}{\mathcal{M}^{\rm QED-like}}$$

(subdominant for $\tilde{s} \gg \{l_t^2, k_t^2\}$)

$$\mathcal{M}^{\rm QCD} \simeq \mathcal{M}^{\rm SQCD} + \mathcal{O}(x^2)$$

$$\boxed{\mathcal{M} \simeq \mathcal{M}^{\rm SQCD} = g\, C_3 \left(\frac{-4\, g^2\, P\cdot q}{\ell^2}\right)\left(\frac{(2(1-x)-x')\,\vec{\epsilon}_t\cdot\vec{k}_t}{\vec{k}_t^2+x^2m_Q^2} - \frac{2(1-x-x')\,\vec{\epsilon}_t\cdot(\vec{k}_t-\vec{l}_t)}{(\vec{k}_t-\vec{l}_t)^2+(x+x')^2m_Q^2}\right).}$$

$x'(\vec{k}_t, \vec{l}_t, x)$ Recoil momentum of the l.q. (in the Sudakov decomposition)

Seeked extension of the Gunion-Bertsch model

qQ→qQg "in the Vacuum": High Energy Limit

One can show: $x'(\vec{k}_t, \vec{l}_t, x) \ll 1 \quad \Leftrightarrow \quad \underbrace{x(s - m_Q^2) \gg \{l_t^2, k_t^2\}}$

High energy condition
(when s disappears from the dσ : GB)

$$\frac{d\sigma^{Qq\to Qgq}}{dx d^2k_t d^2\ell_t} \underset{\text{HE}}{\rightarrow} \frac{d\sigma_{\rm el}}{d^2\ell_t} P_g(x, \vec{k}_t, \vec{\ell}_t)$$

with: $P_g = \frac{C_A \alpha_s}{\pi^2} \frac{1-x}{x} \left(\frac{\vec{k}_t}{\vec{k}_t^2 + x^2 m_Q^2} - \frac{\vec{k}_t - \vec{\ell}_t}{(\vec{k}_t - \vec{\ell}_t)^2 + x^2 m_Q^2} \right)^2$

No collinear divergence thanks to HQ mass (finite formation time), but (usual) IR divergence in the $d\sigma_{el}$ => prescription: IR regulator μ.

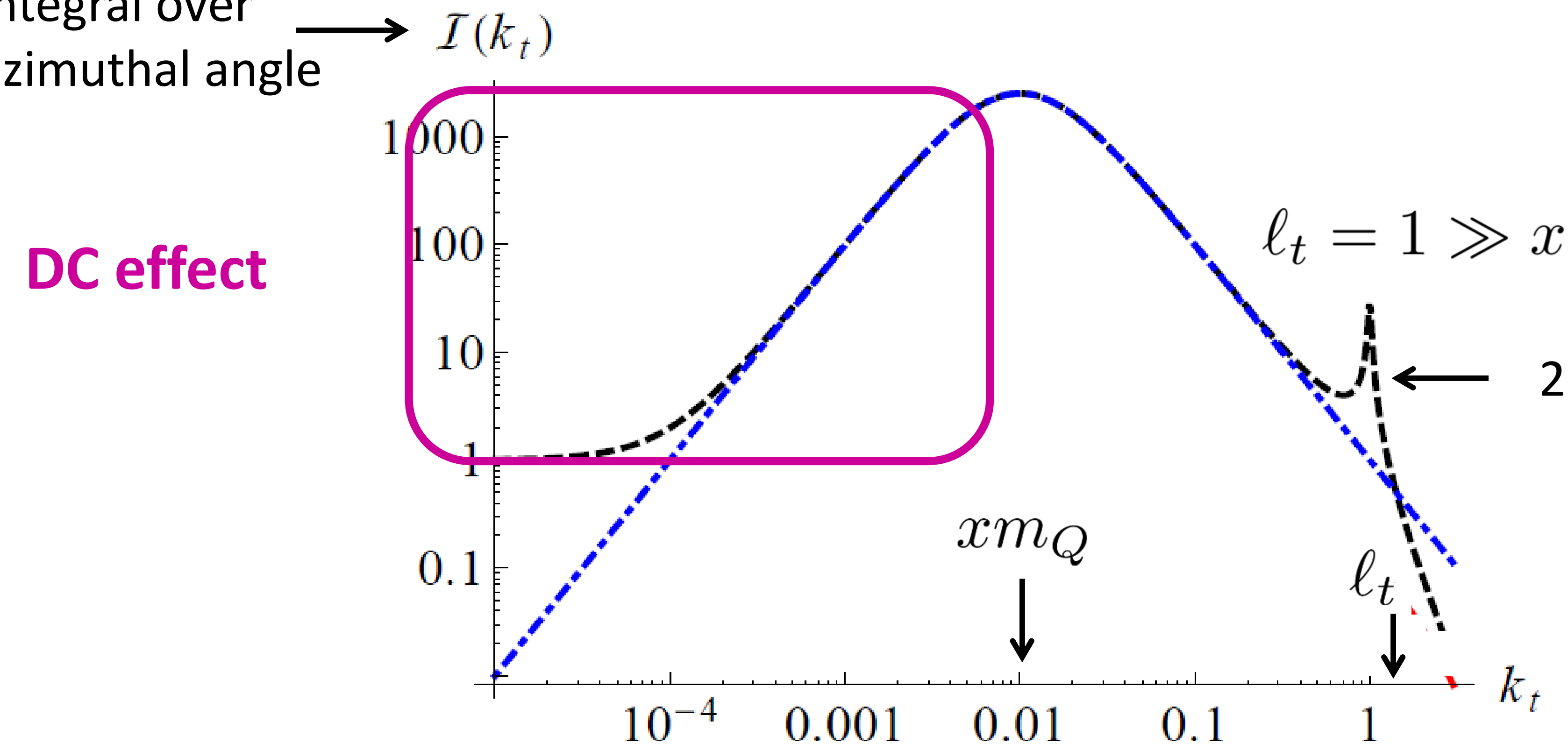
$$\frac{d\sigma_{\rm el}}{d^2\ell_t} \propto \frac{1}{t^2} \rightarrow \frac{1}{(t-\mu^2)^2}$$

μ : Natural scale for ℓ_t

qQ→qQg : Analysis of the Transverse Distributions

$$\text{I. } \ell_t \gg x m_Q \left(\Leftrightarrow x \ll x_M = \frac{\mu}{m_Q} \right)$$ Hard scattering regime

Integral over azimuthal angle



$$P_g \propto \left(\frac{\vec{k}_t}{\vec{k}_t^2 + x^2 m_Q^2} - \frac{\vec{k}_t - \vec{\ell}_t}{(\vec{k}_t - \vec{\ell}_t)^2 + x^2 m_Q^2} \right)^2$$ **vs** $$P_g \propto \left(\frac{\vec{k}_t}{\vec{k}_t^2 + x^2 m_Q^2} \right)^2$$ **DK**

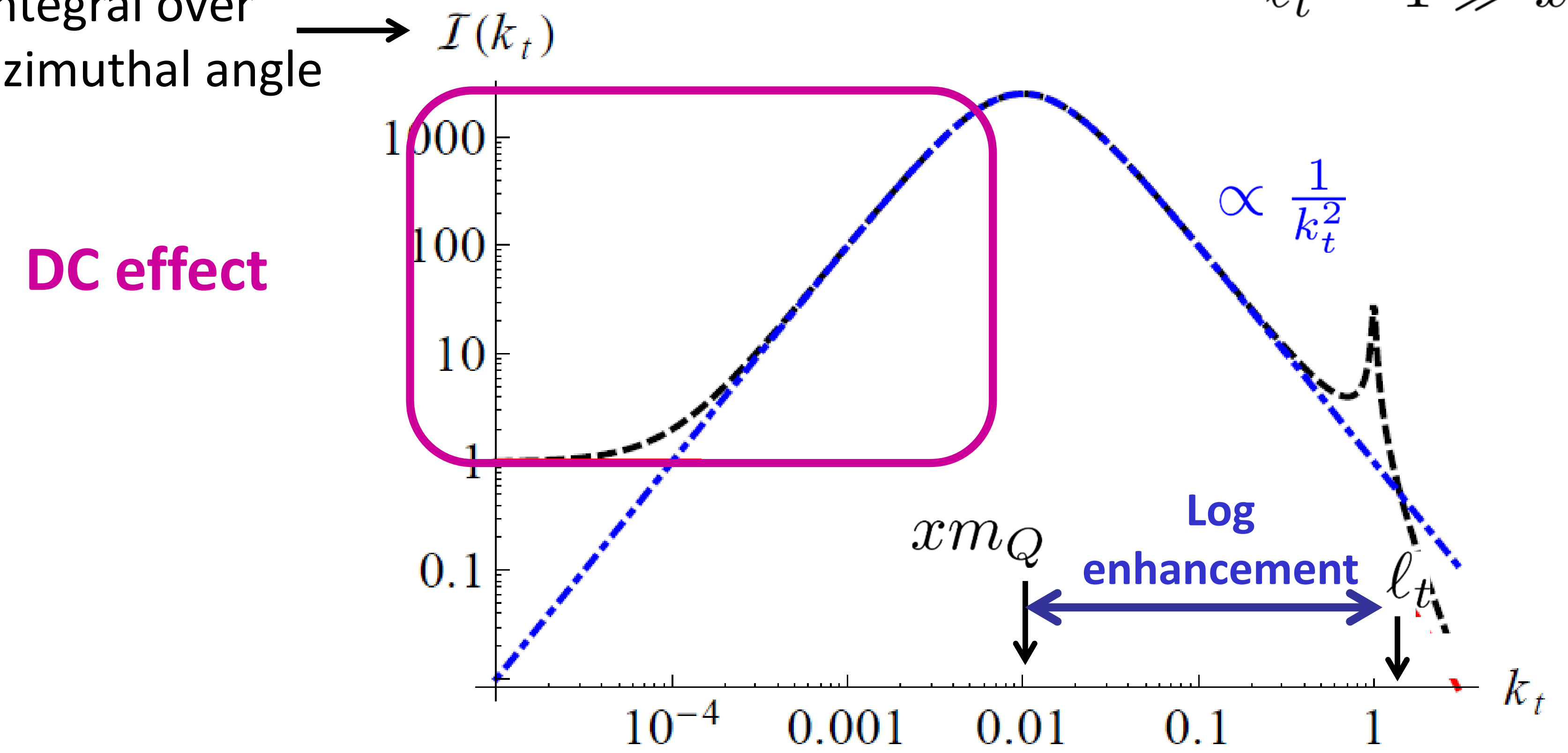
Little interference => as in HQ production

qQ→qQg : Analysis of the Transverse Distributions

I. $\ell_t \gg x m_Q \left(\Leftrightarrow x \ll x_M = \frac{\mu}{m_Q}\right)$ Hard scattering regime

$\ell_t = 1 \gg x m_Q = 0.01$

Integral over azimuthal angle



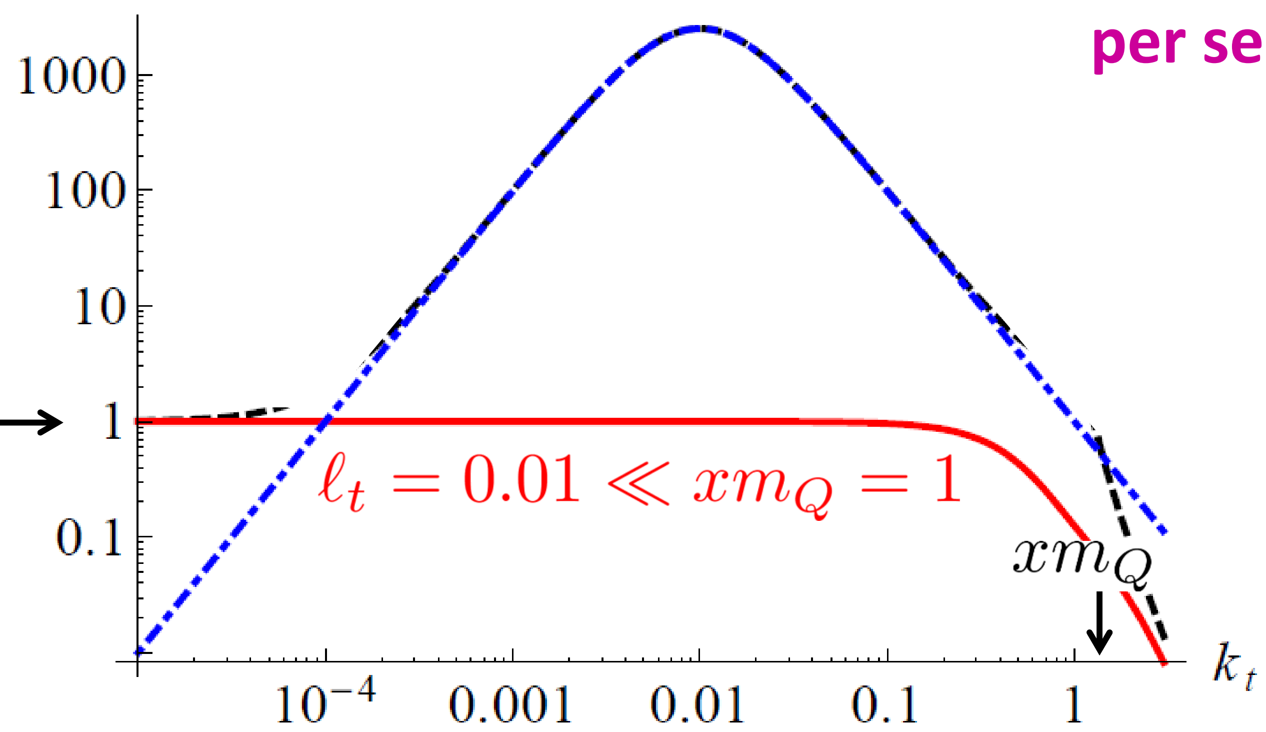
$$\int P_g d^2 k_t \propto \ln\left(\frac{l_t}{x m_Q}\right)$$

qQ→qQg : Analysis of the Transverse Distributions

$\mathrm{II.}\ \ell_t \ll x m_Q \left(\Leftrightarrow x \gg x_M = \frac{\mu}{m_Q}\right)$ soft scattering regime

Integral over azimuthal angle → $\mathcal{I}(k_t)$

NO DC effect per se



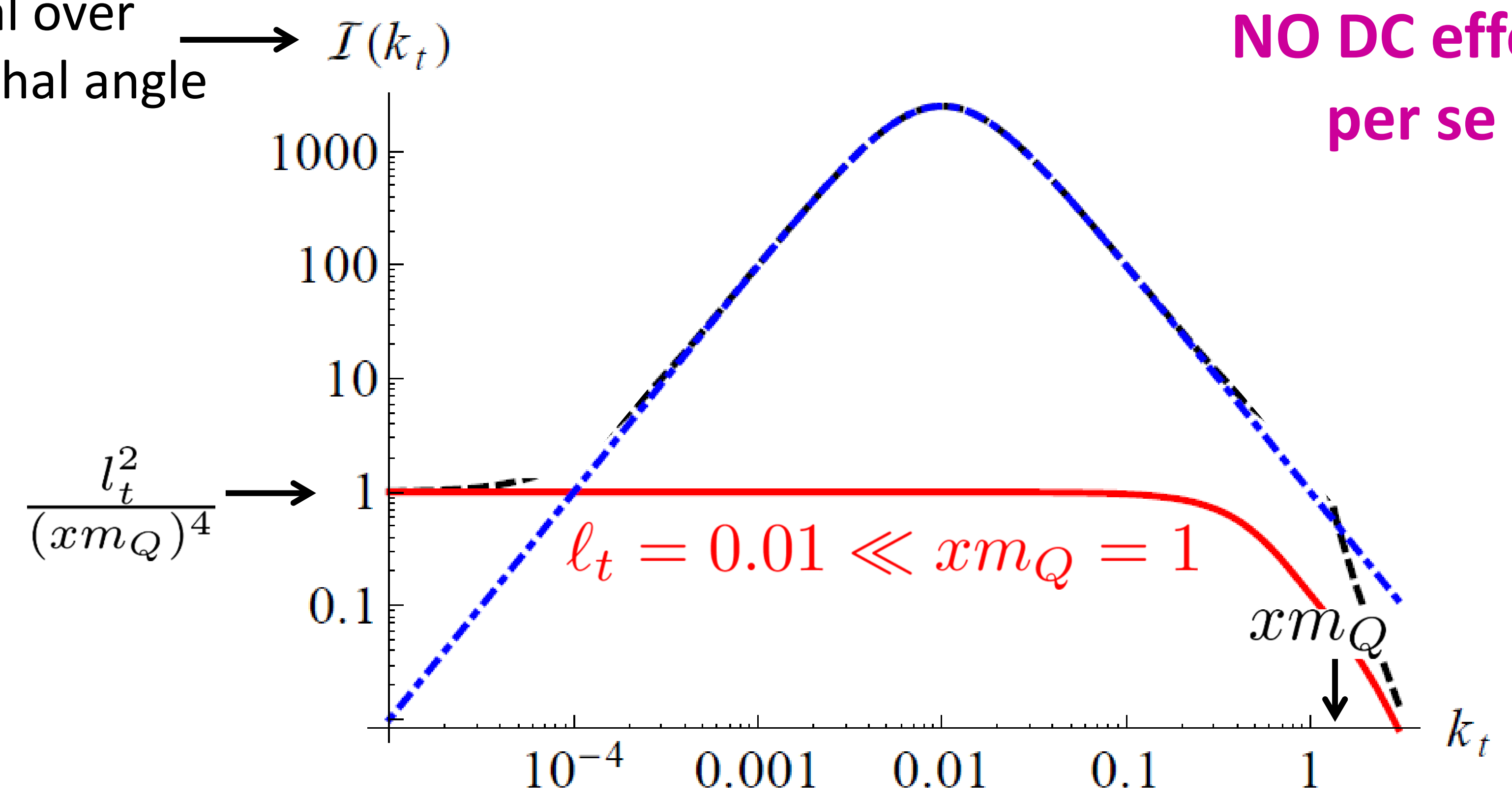
$$P_g \propto \left(\frac{\vec{k}_t}{\vec{k}_t^2 + x^2 m_Q^2} - \frac{\vec{k}_t - \vec{\ell}_t}{(\vec{k}_t - \vec{\ell}_t)^2 + x^2 m_Q^2}\right)^2 \quad \text{vs} \quad P_g \propto \left(\frac{\vec{k}_t}{\vec{k}_t^2 + x^2 m_Q^2}\right)^2 \ \ \textbf{DC}$$

Large interferences not found in HQ production

qQ→qQg : Analysis of the Transverse Distributions

$\text{II. } \ell_t \ll x m_Q \left(\Leftrightarrow x \gg x_M = \frac{\mu}{m_Q} \right)$ soft scattering regime

Integral over azimuthal angle



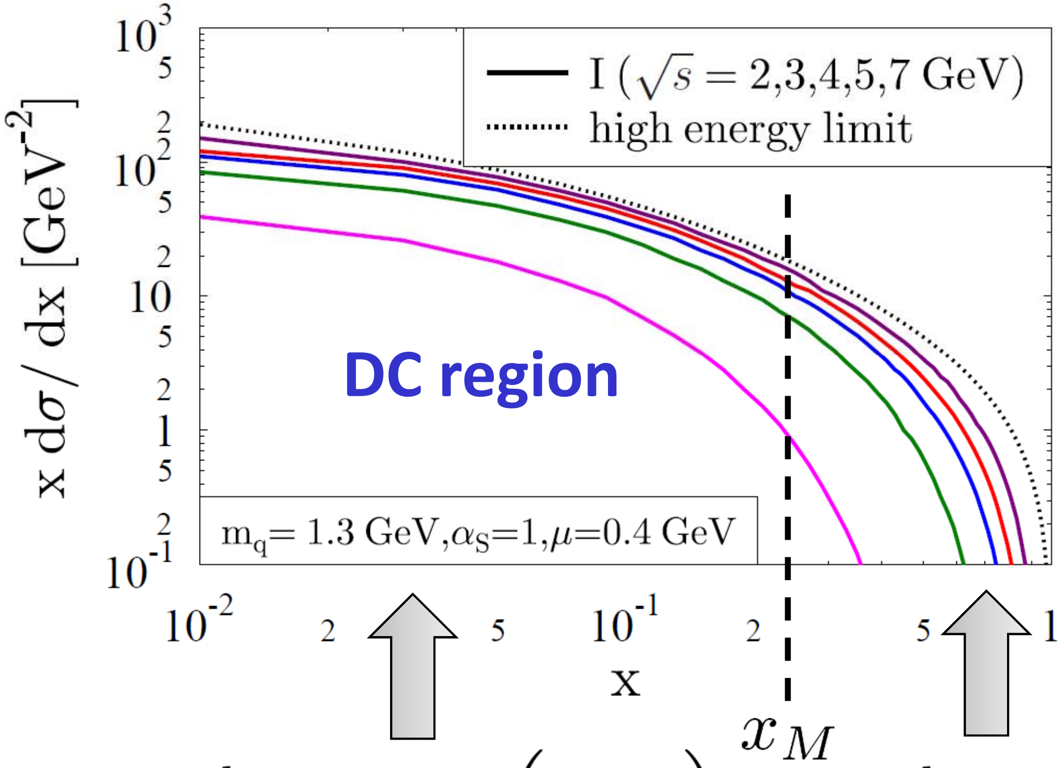
NO DC effect per se

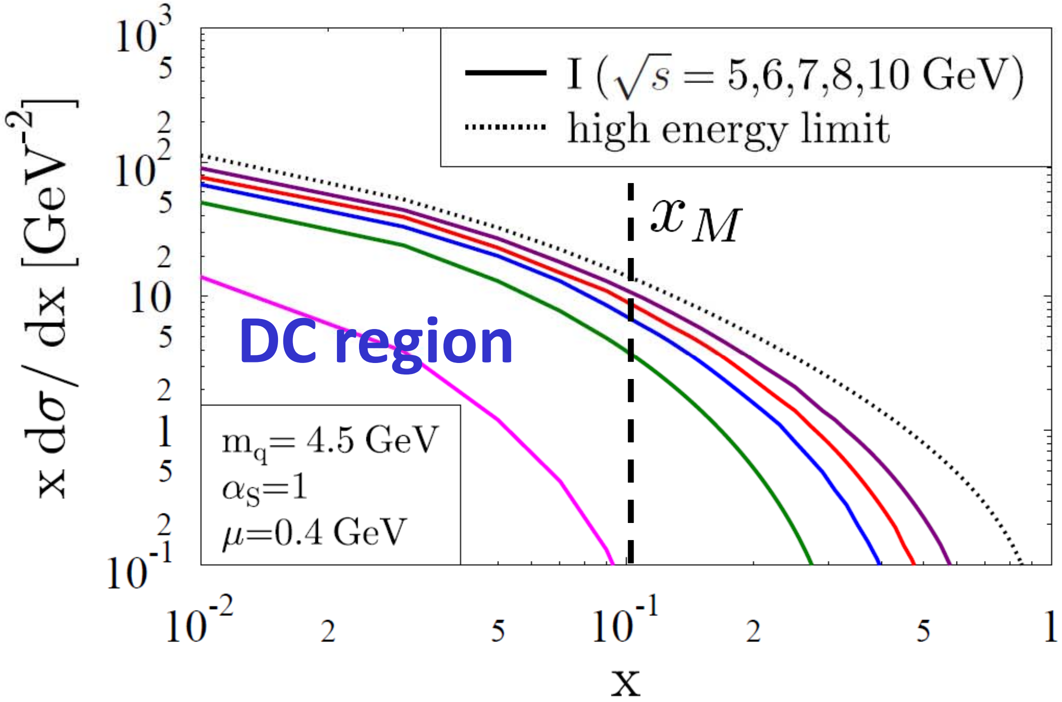
$$\int P_g d^2 k_t \propto \frac{l_t^2}{(x m_Q)^2}$$

… but strong reduction due to mass effects

qQ→qQg : Power Spectra

c-quark **b-quark**

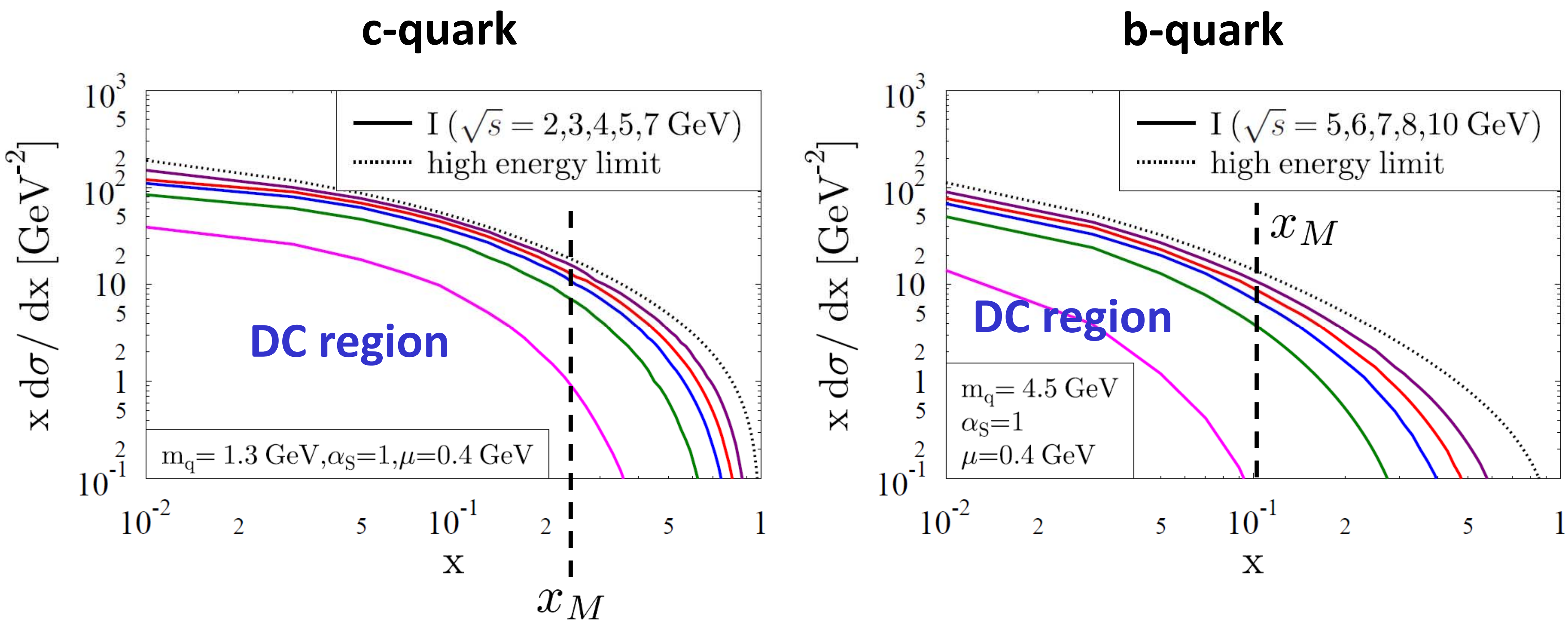




$$x\frac{d\sigma_{\rm rad}}{dx} \propto \ln\left(\frac{\mu}{x m_Q}\right) \qquad x\frac{d\sigma_{\rm rad}}{dx} \propto \left(\frac{\mu}{x m_Q}\right)^2$$

$$x\frac{d\sigma^{HE}_{\rm rad}}{dx} = \sigma_{\rm el} \times \frac{dI}{dx} \quad \text{with} \quad \frac{dI}{dx} = \frac{2C_A}{\pi}\alpha_s(1-x)\frac{\ln\left(\frac{3x^2 m_Q^2}{\mu^2}\right)}{\frac{3x^2 m_Q^2}{\mu^2}-1}$$

qQ→qQg : Power Spectra



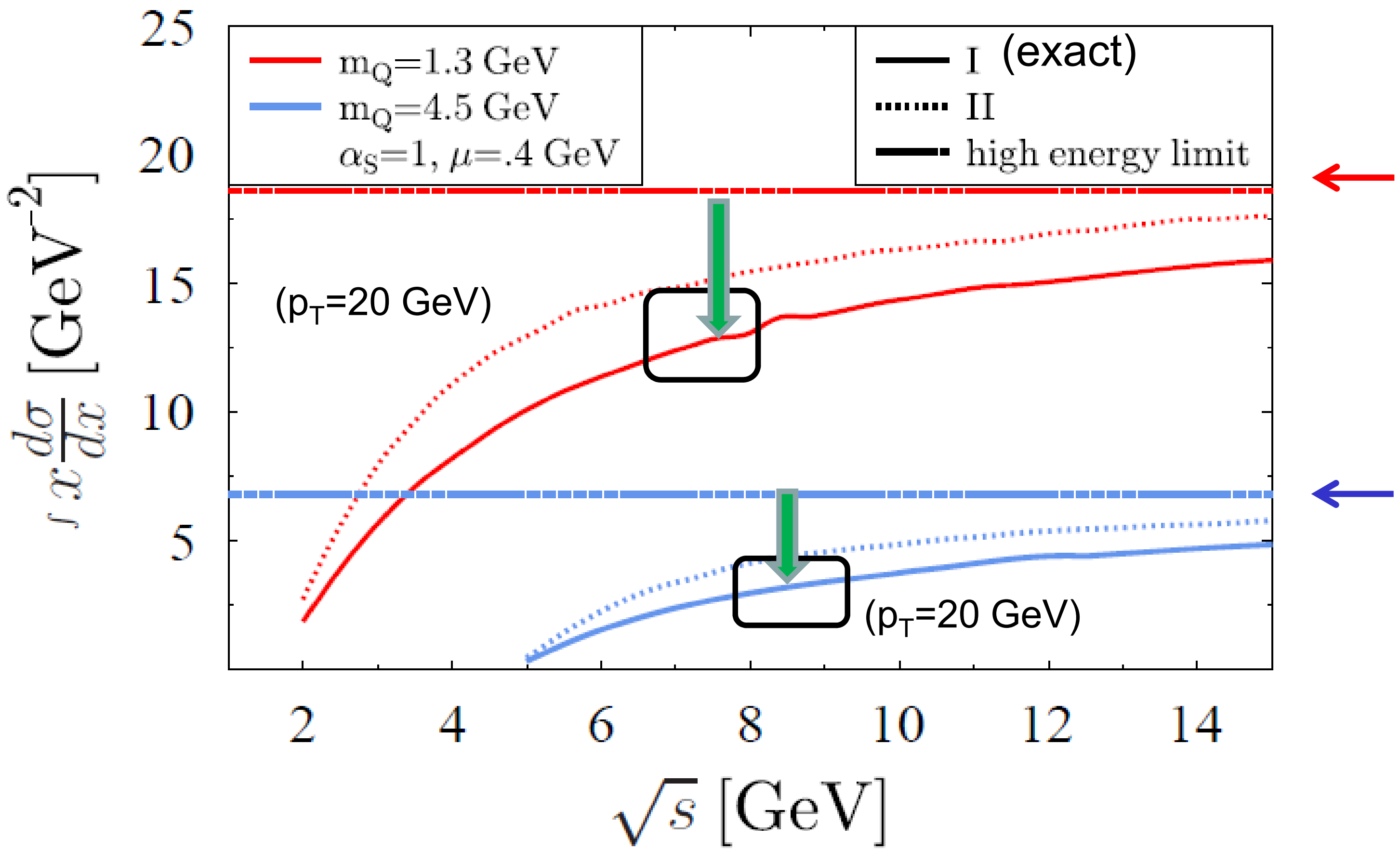
But significant finite energy corrections due both to:

- Non vanishing x' (light quark recoil)
- Finite phase space

Incoherent Induced Energy Loss at Finite Energy

$$\frac{dE_{\rm rad}}{dz} \approx \rho \int \omega \frac{d\sigma}{d\omega} d\omega \approx \rho E_{\rm beam} \int x \frac{d\sigma}{dx} dx.$$

Contribution from both $x<x_M$ and $x>x_M$

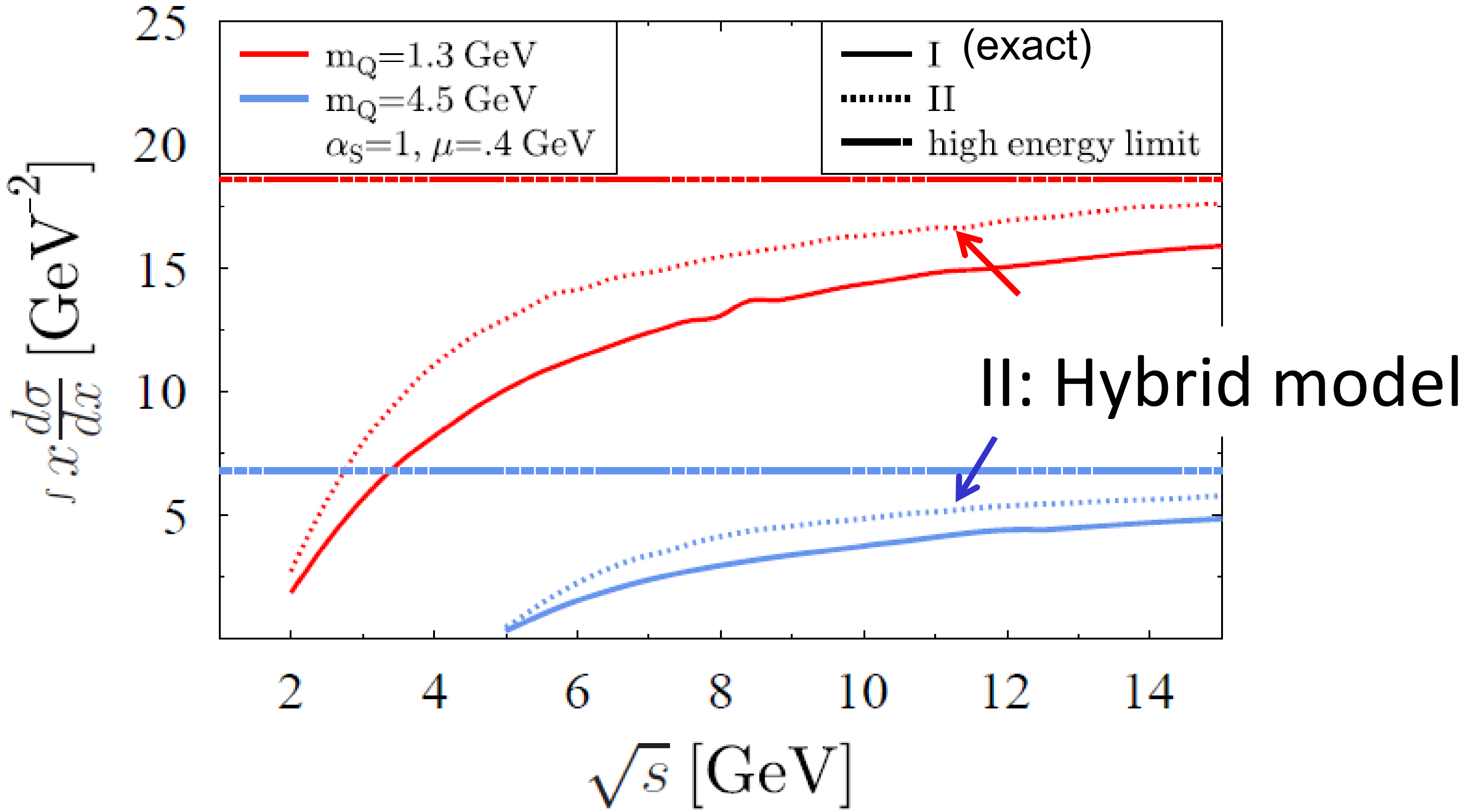


Asymptotic behaviour

$$\propto \frac{1}{\mu m_Q}$$

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

Incoherent Induced Energy Loss at Finite Energy



$$\frac{d\sigma_{II}^{Qq\to Qgq}}{dx d^2k_t d^2\ell_t} = \frac{d\sigma_{\rm el}}{d^2\ell_t} P_g(x, \vec{k}_t, \vec{\ell}_t)\Theta(\Delta)$$

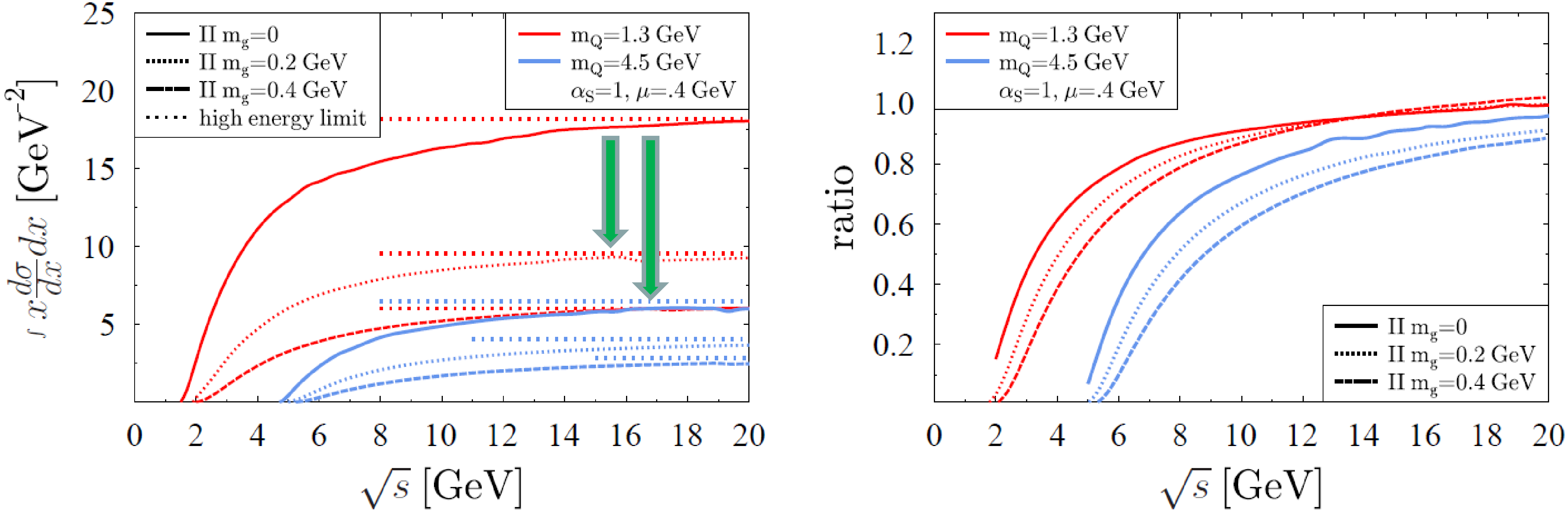
High energy P_g + finite phase space

Useful for a)MC simulations & b) gQ $\rightarrow$ gQg

Incoherent Induced Energy Loss at Finite T (m_g)

Our Prescription: Hybrid Model with

- modified phase space
- matrix el. P_g modified according to $x^2 m_Q^2 \rightarrow x^2 m_Q^2 + (1-x) m_g^2$

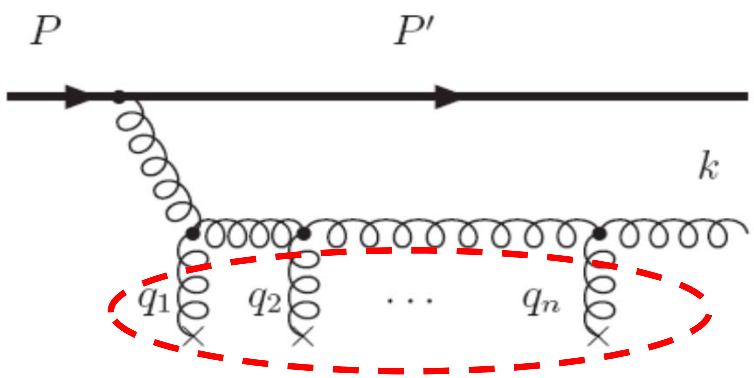


- Large reduction of the power spectra and average p-loss; scales roughly like asymptotic behaviour.
- $\Delta E_{rad} \approx \Delta E_{el.}$

Corrections from Coherence

Coherent Induced Radiative

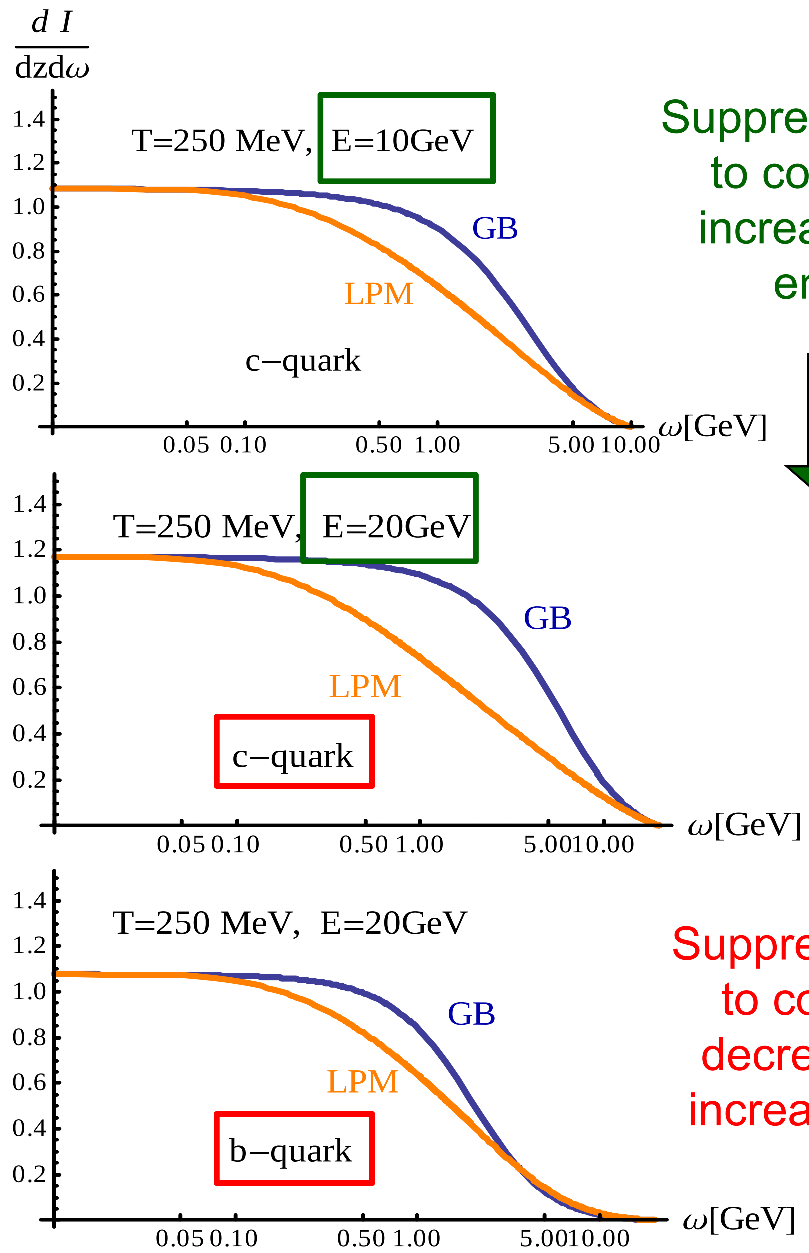
Formation time picture: for $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



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

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

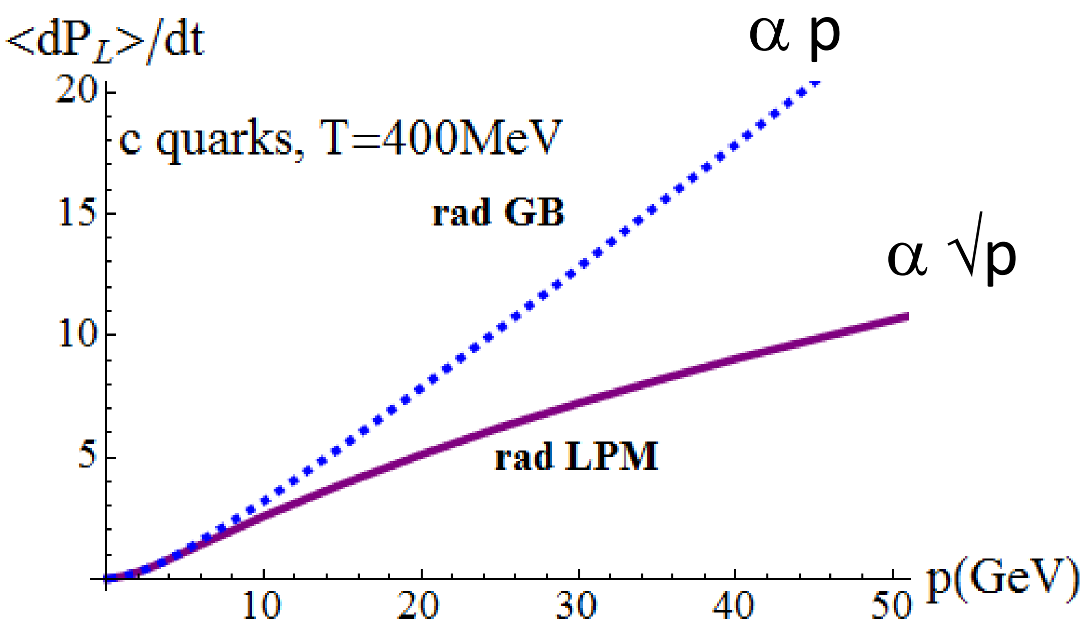
Nuclear Physics A (2013), 301, [arXiv:1209.0844]



Suppression due to coherence increases with energy

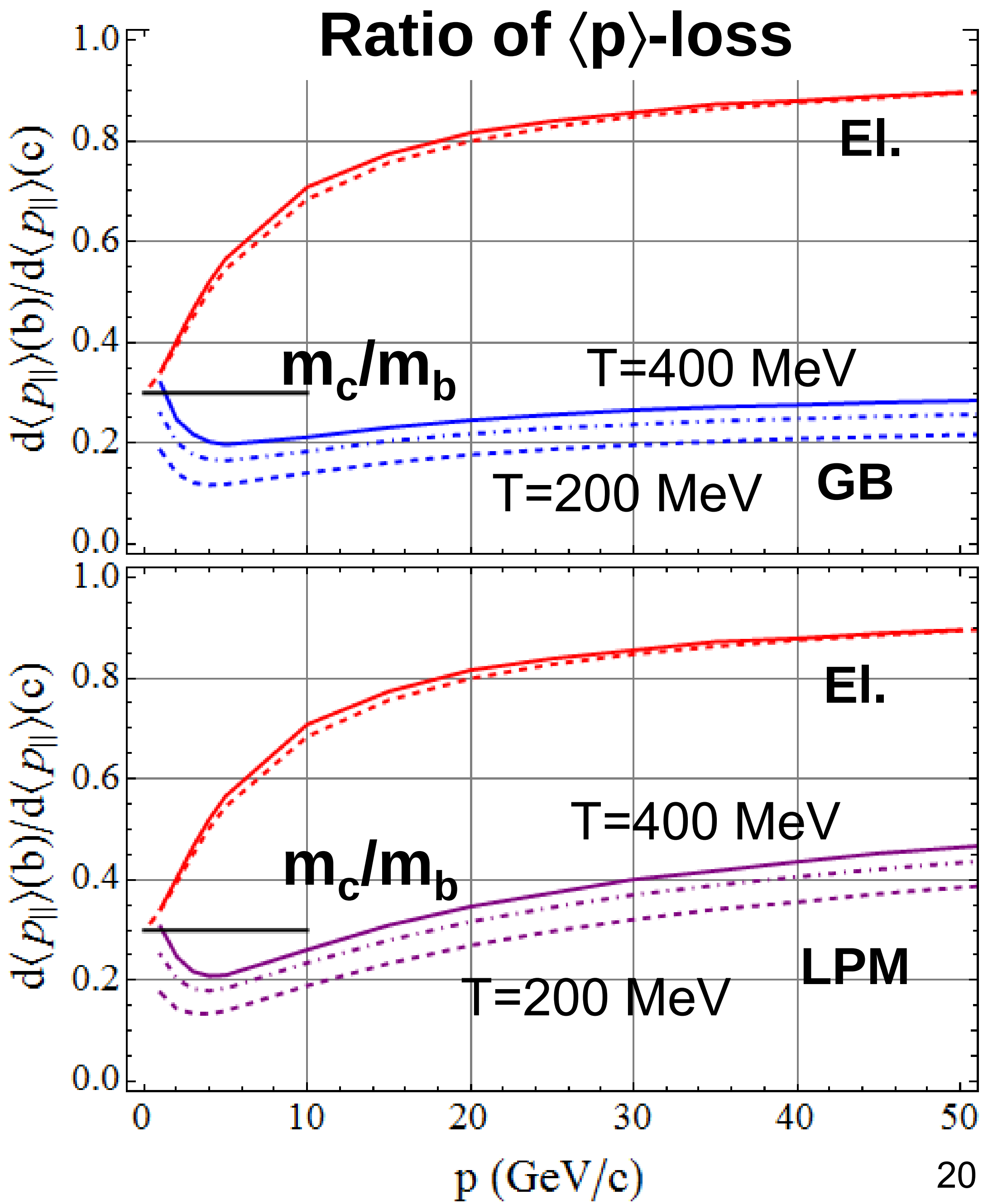
Suppression due to coherence decreases with increasing mass

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

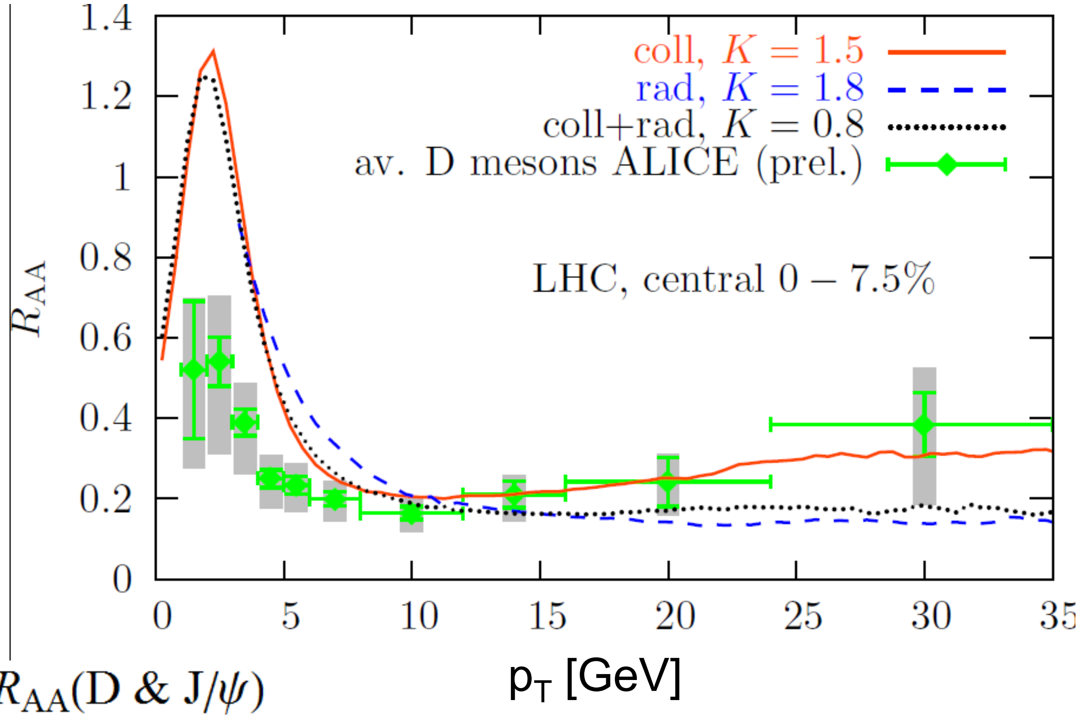


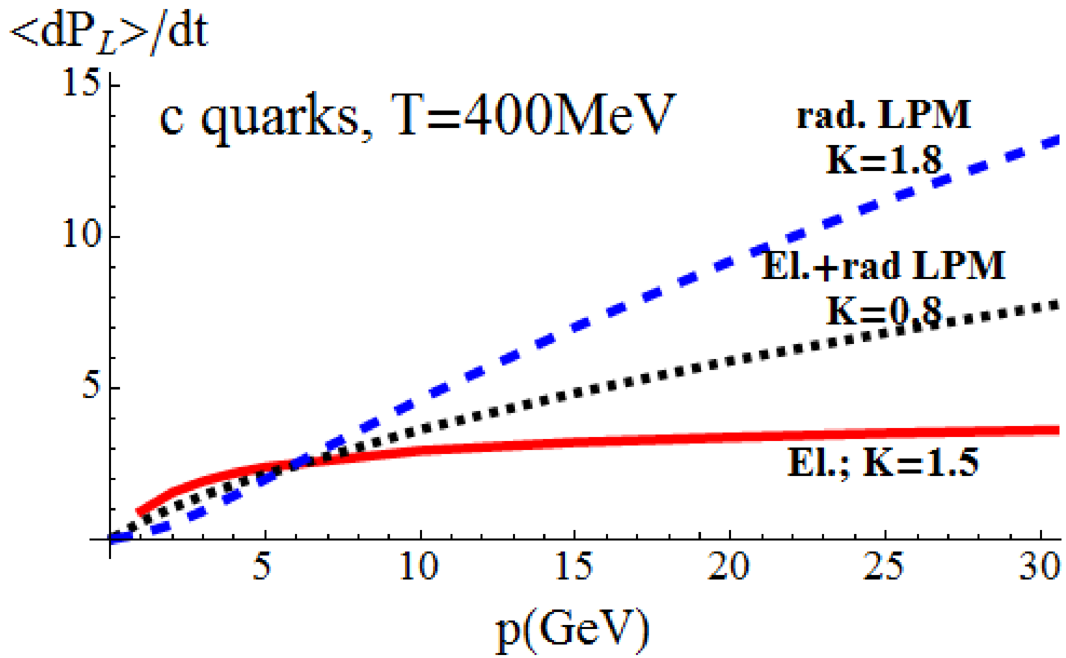
Mass hierarchy:

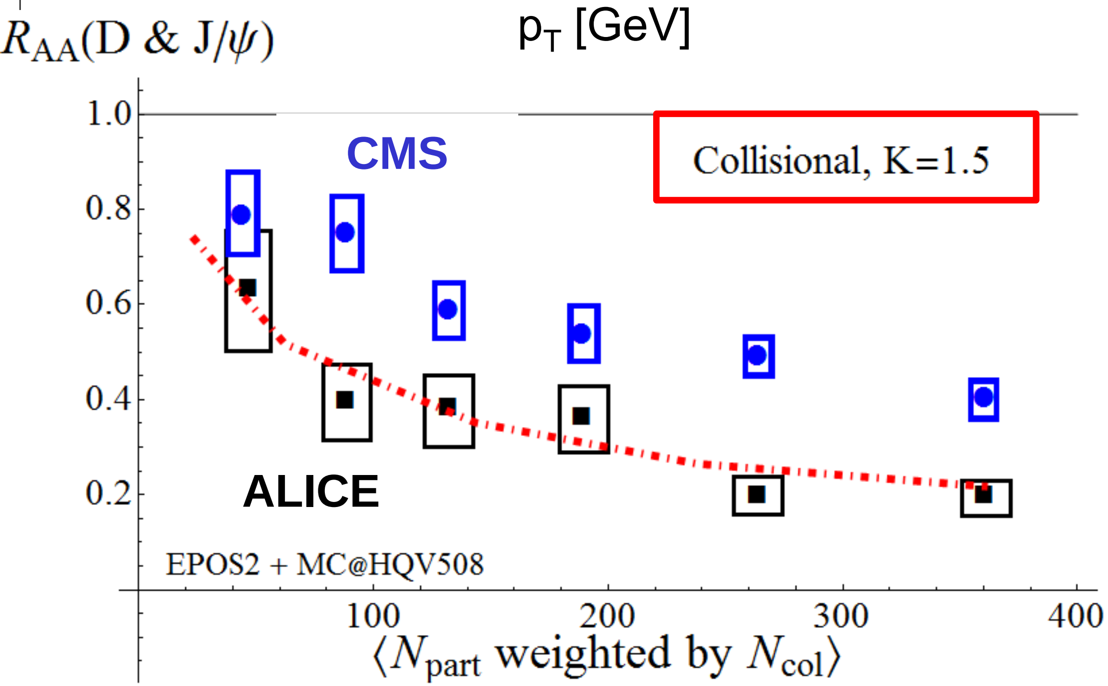
Elastic < rad LPM < rad GB

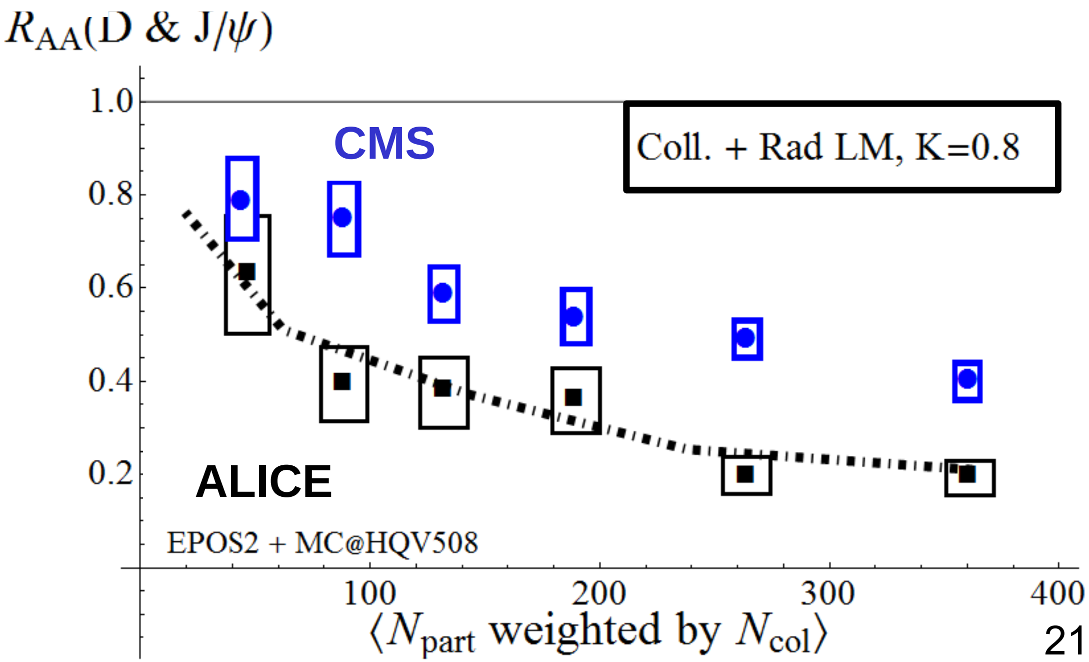


Contact with LHC Data: a) for c-Quarks…

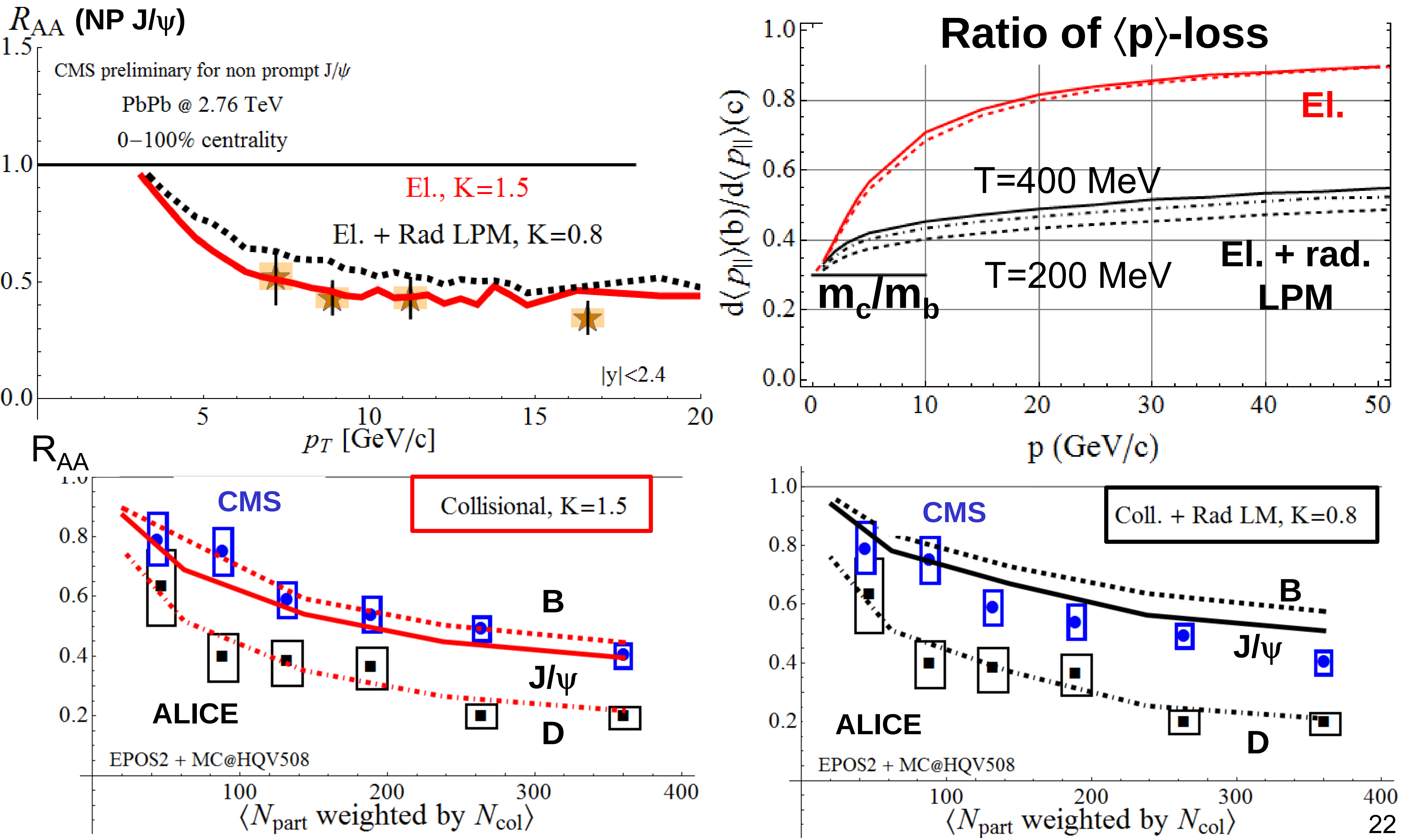








… b) for b-Quarks (& Non-Prompt J/ψ)



Conclusions and Perspectives

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

- A large part of the mass hierarchy in seen in radiative energy loss does not originate – strictly speaking – from the “dead cone” effect (interference at play)

- (In our models), combined LHC data from ALICE and CMS is found in slightly better agreement with the rather mild mass-hierarchy observed (f.i.) in collisional energy loss… but various sources of uncertainties and some effects not taken into account

- Perspectives: coherence and finite path lengths in dynamical media