Fragmentation of heavy flavors in a hot environment

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Specific features of heavy quarks

Heavy and light quarks radiate gluons differently

Gluon bremsstrahlung: Dead-cone effect

$$\frac{dn_g}{dx\,dk_T^2} = \frac{2\alpha_s(k_T^2)}{3\pi\,x}\,\frac{k_T^2[1+(1-x)^2]}{[k_T^2+x^2m_q^2]^2}$$

k_T and x are transverse momentum and fractional light-cone momentum of the radiated gluon

Small-angle radiation with $k_T^2 \ll x^2 m_q^2$ is suppressed.

The suppressed gluons have a long radiation (coherence) length (Landau-Pomeranchuk)

$$l_c = \frac{2E}{M_{qg}^2 - m_q^2} = \frac{2Ex(1-x)}{k_T^2 + x^2 m_q^2}$$

Neither the radiation length lc, nor quark energy E are Lorentz invariant, they must be taken within the same reference frame.

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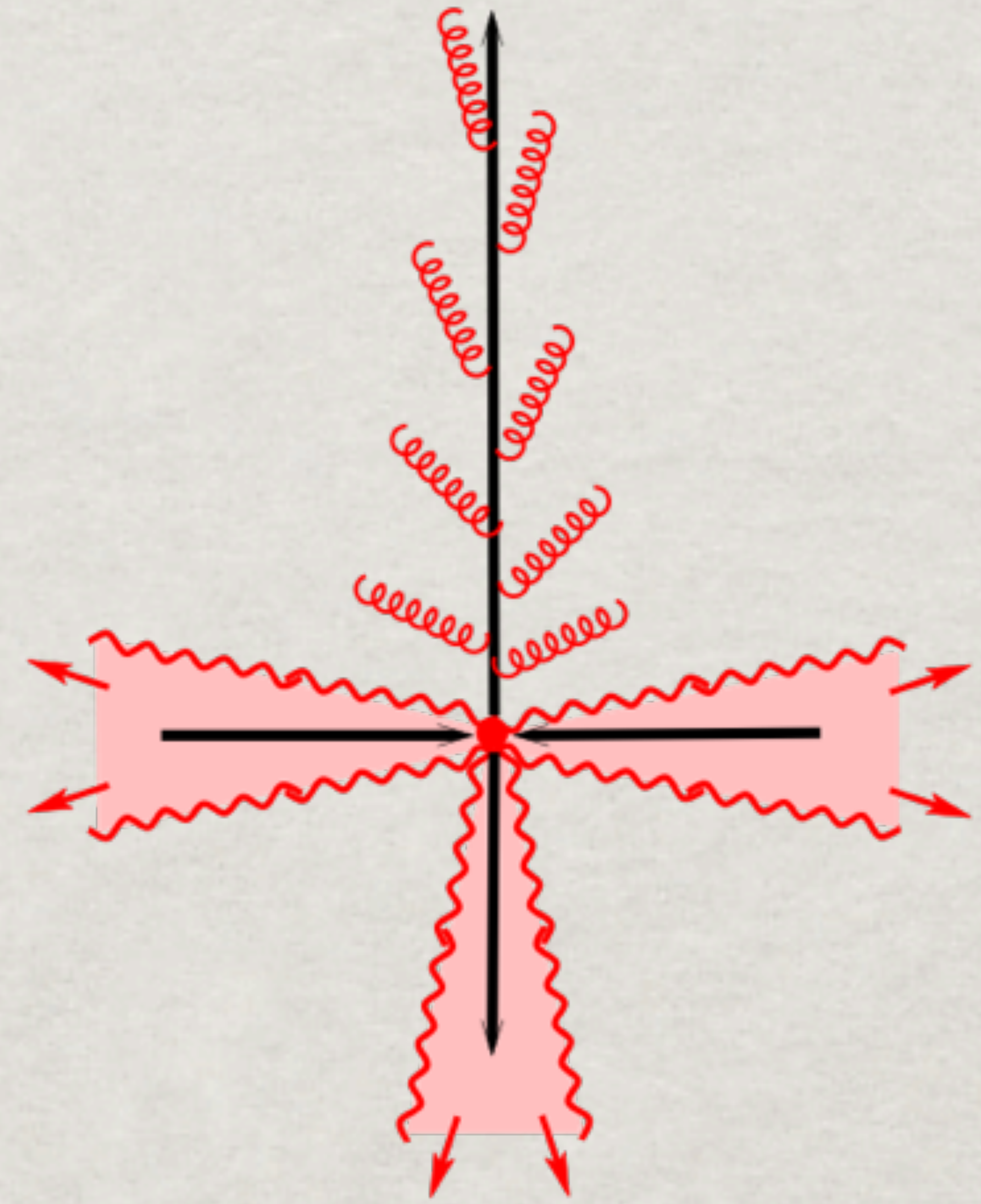
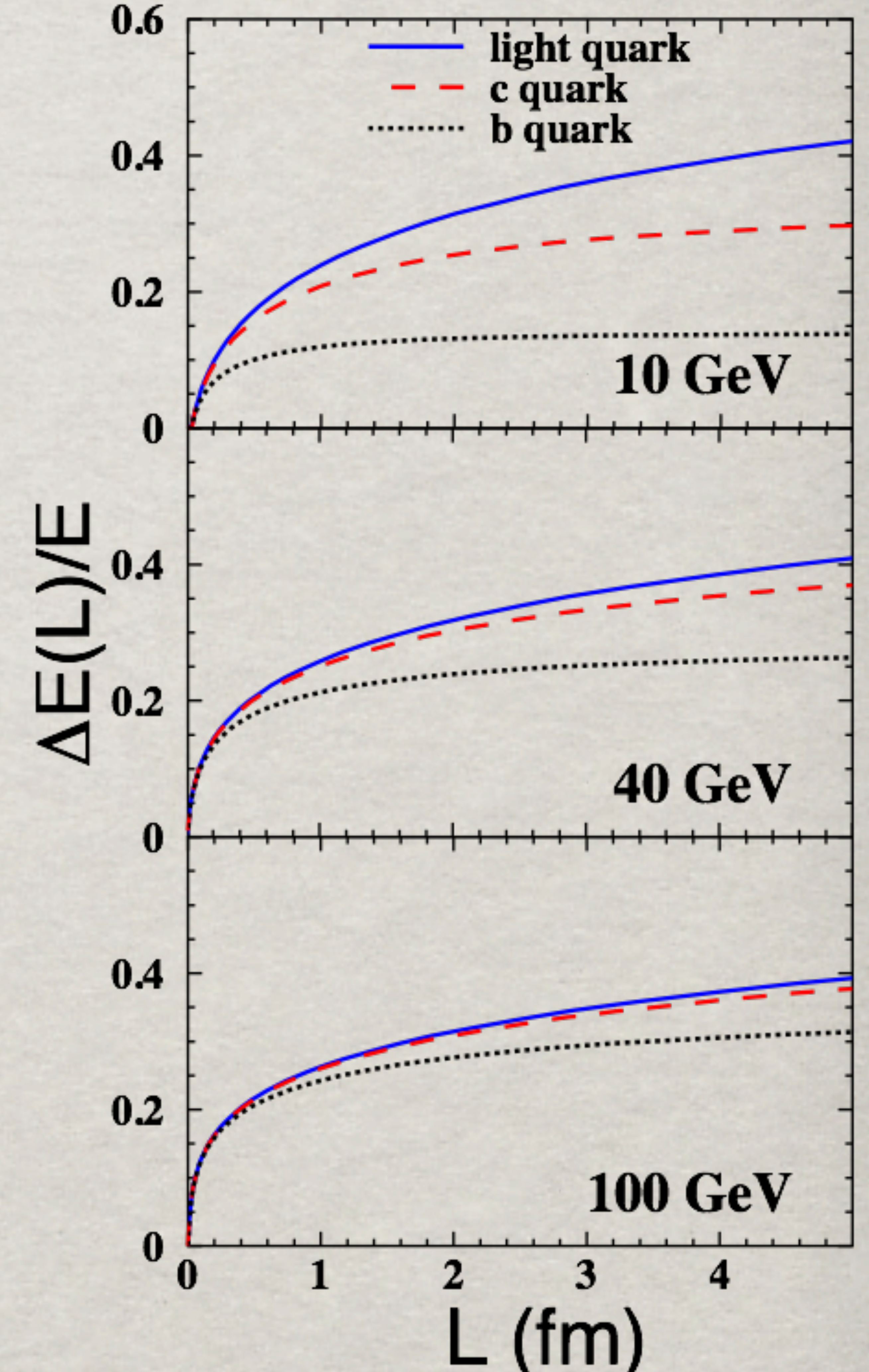
Radiated energy

The quark regenerates its stripped-off color field by means of gluon radiation, which are emitted sequentially, rather than burst simultaneously.



B.K., I.Potashnikova, I.Schmidt, PRC 82(2010)037901

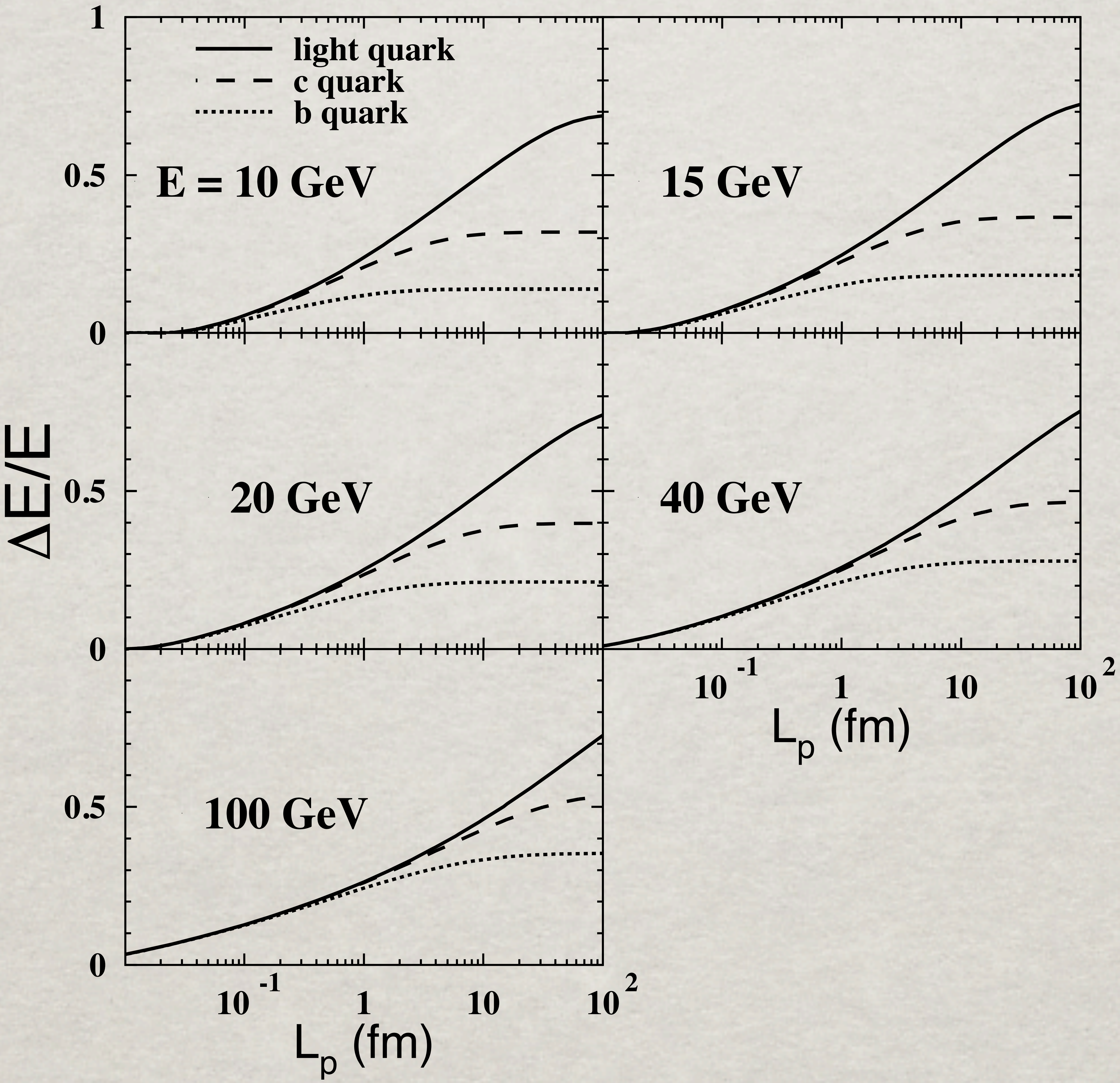


How much energy is radiated along path length L?

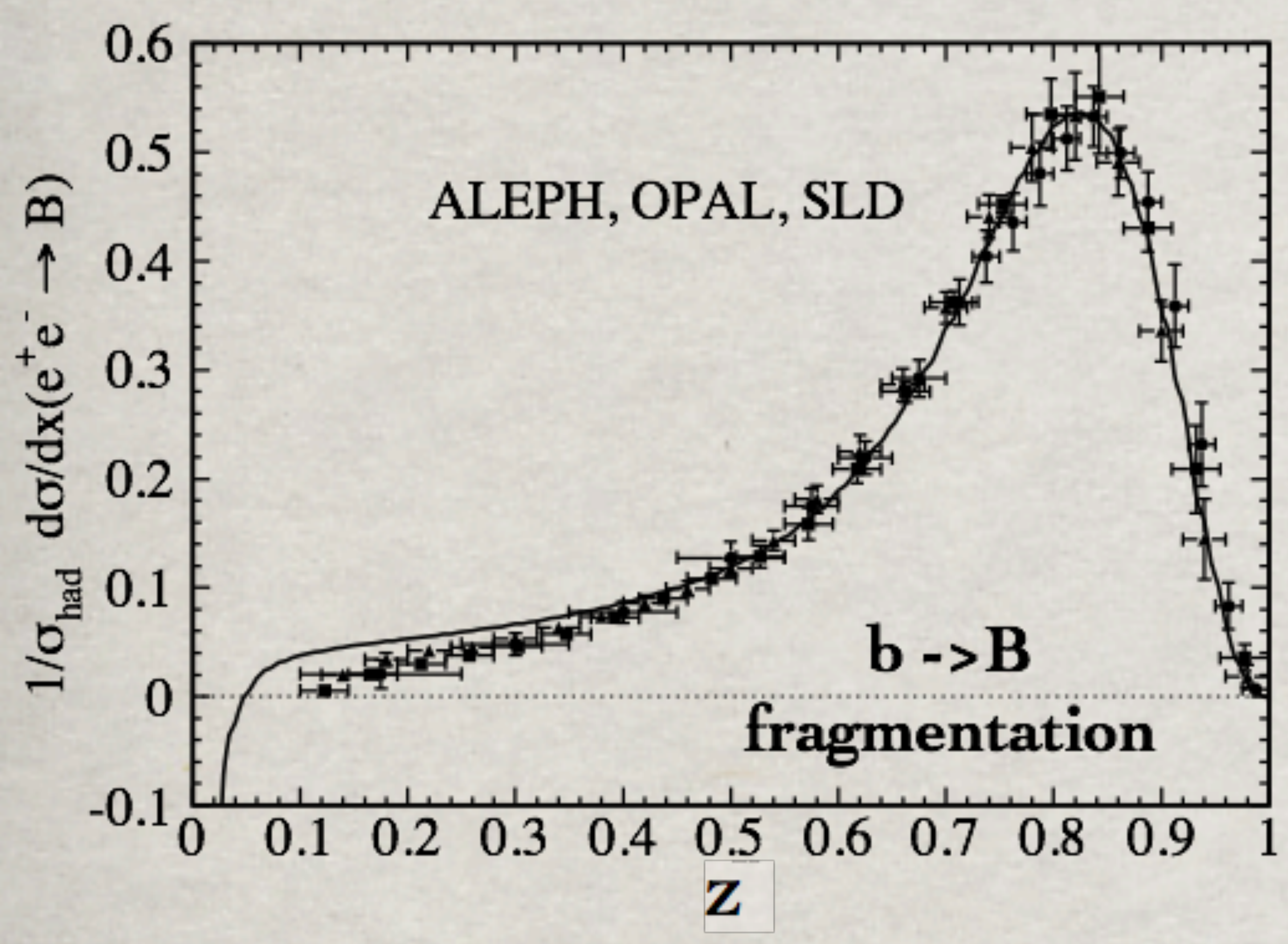
$$\Delta E(L) = E \int_{\Lambda^2}^{Q^2} dk^2 \int_0^1 dx\, x \frac{dn_g}{dx\, dk^2} \Theta(L - l_c)$$

Dead-cone: gluons with $k^2 < x^2 m_q^2$ are suppressed.

Heavy quarks radiate less energy than the light ones.

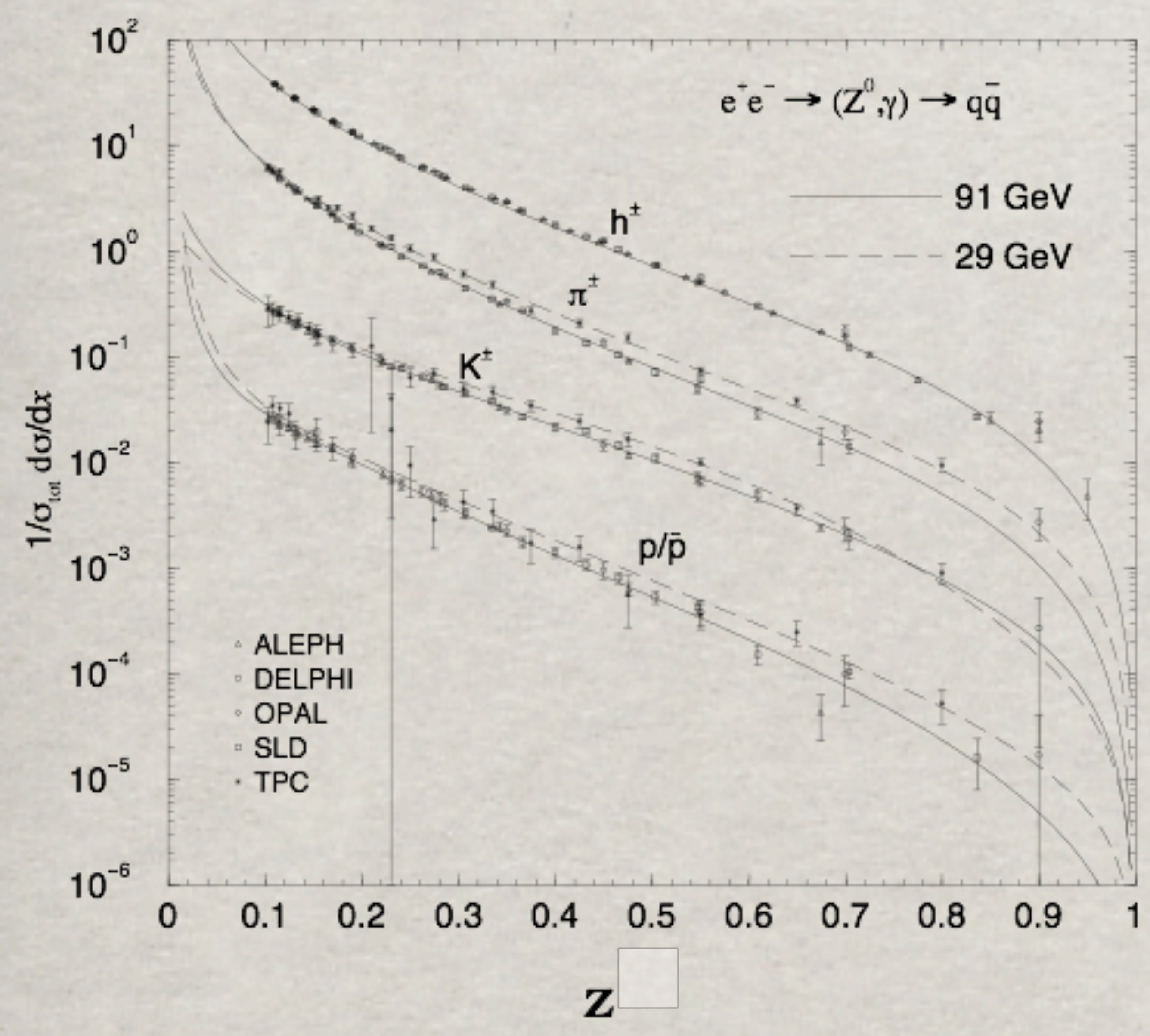

light quark
c quark
b quark
E = 10 GeV
15 GeV
20 GeV
40 GeV
100 GeV
ΔE/E
L_p (fm)
L_p (fm)
0
0.5
1
10^{-1}
1
10
10^{2}

Fragmentation functions



As far as a heavy quark radiates only a small fraction of its energy, **ΔE/E = Δz/z**, the fragmentation functions b->B, c->D should be enhanced at large **z**. This explains the observed specific shape of the fragmentation functions $\mathbf{D_{b/B}(z)}$ and $\mathbf{D_{c/D}(z)}$

On the contrary, the fragmentation functions of light quarks are strongly suppressed at large **z**.

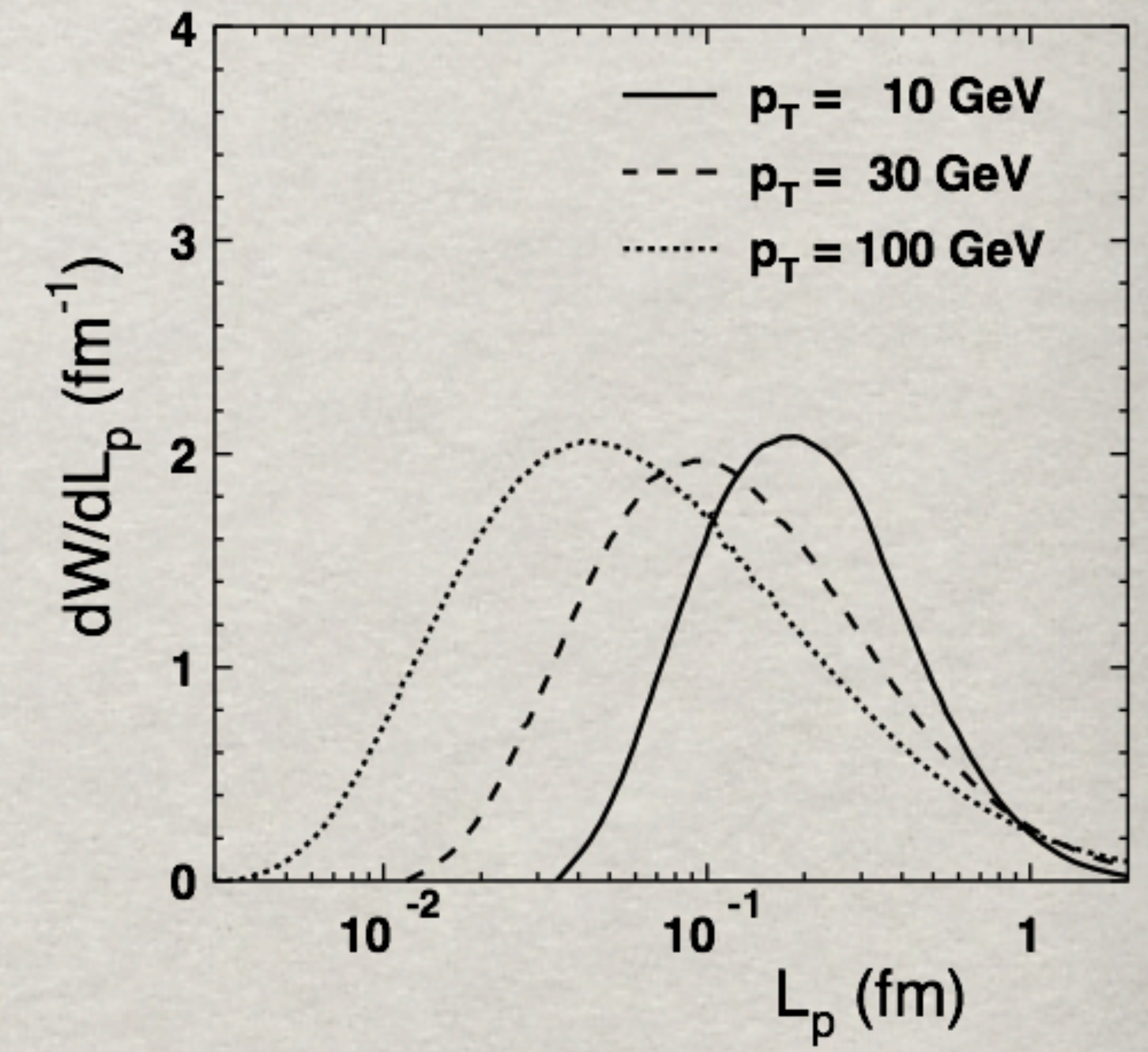


The fractional light-cone momentum

$$\mathbf{z \equiv \frac{p_+^B}{p_+^b} = 1 - \frac{\Delta p_+^b(L_p)}{p_+^b}}$$

Since we can calculate ΔE(L)/E, the production length distribution can be extracted from $\mathbf{D_{b/B}(z)}$

$$\mathbf{\frac{dW}{dL_p} = \frac{1}{p_+^b}\ \frac{\partial \Delta p_+^b}{\partial L}\bigg|_{L=L_p} D_{b/B}(z)}$$



B. Kopeliovich, HEP UTFSM 2023

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Counterintuitive shortness of the production length

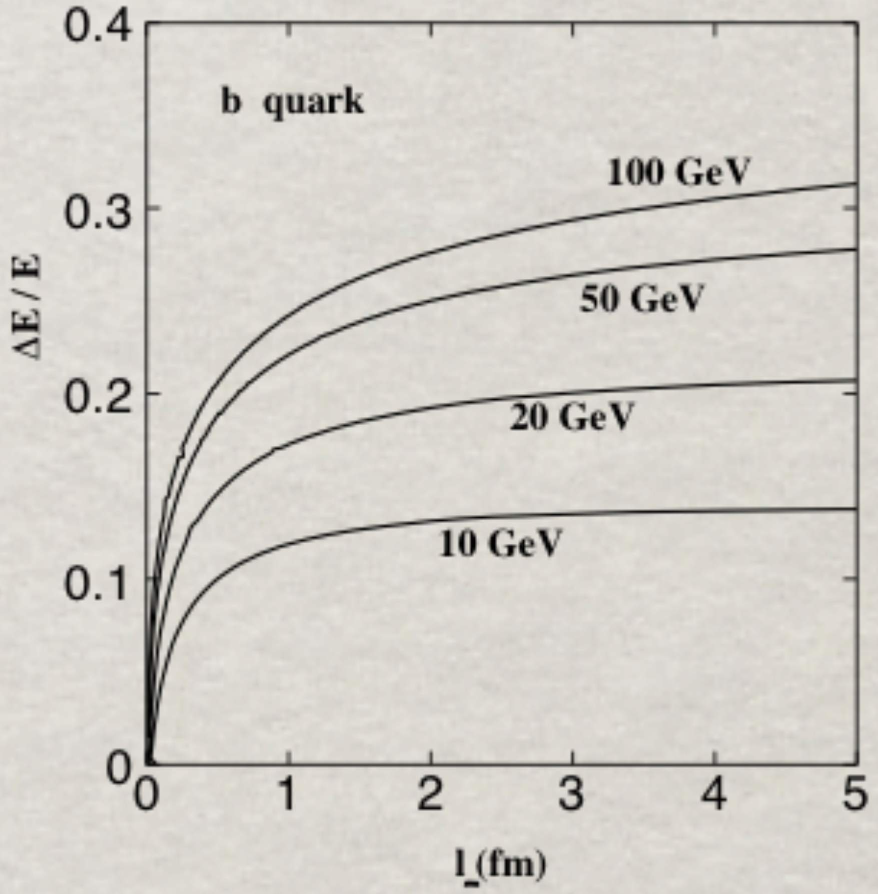
Gluon radiation by a heavy quark Q is lasting until color neutralization and production of a colorless dipole $Q\bar{q}$, which is not a bound state, has no wave function, even no certain mass. It takes much longer time to develop the hadronic wave function.

The production length distribution W(Lp) reveals remarkable features:

(i) <Lp> is much shorter than the confinement radius,
i.e the fragmentation mechanism is perturbative.

WHY?

- The calculated rate of radiation energy loss $\Delta E(L)/E$
- saturates at L less than 1fm.



(ii) <Lp> shrinks with rising quark energy.
This seems to contradict the usual expectation of <Lp> linearly rising with energy due to Lorentz time dilation. Usually jets in hard reactions have two scales, energy and virtuality (e.g. DIS). However, in e+e- annihilation, or high-pT parton scattering (in c.m.) the two scales coincide.
Increasing energy, one increases virtuality, what makes Lp shorter

Fast expansion of heavy-light dipole

The light quark in a $Q\bar{q}$ meson carries a small fraction m_q/m_Q of the momentum.

The produced Q-$\bar{q}$ dipole has a small transverse separation, which expands with a high speed, enhanced by m_Q/m_q. E.g. the expansion length and formation of the B-meson wave function (in the target rest frame) is very short,

$$l_f^B = \frac{\sqrt{p_T^2 + m_B^2}}{2 m_B \omega} \qquad (\omega=300\text{MeV})$$

The Q-$\bar{q}$ dipole quickly expands up to transverse separation $\langle r_T^2 \rangle = \frac{8}{3} \langle r_{ch}^2 \rangle$

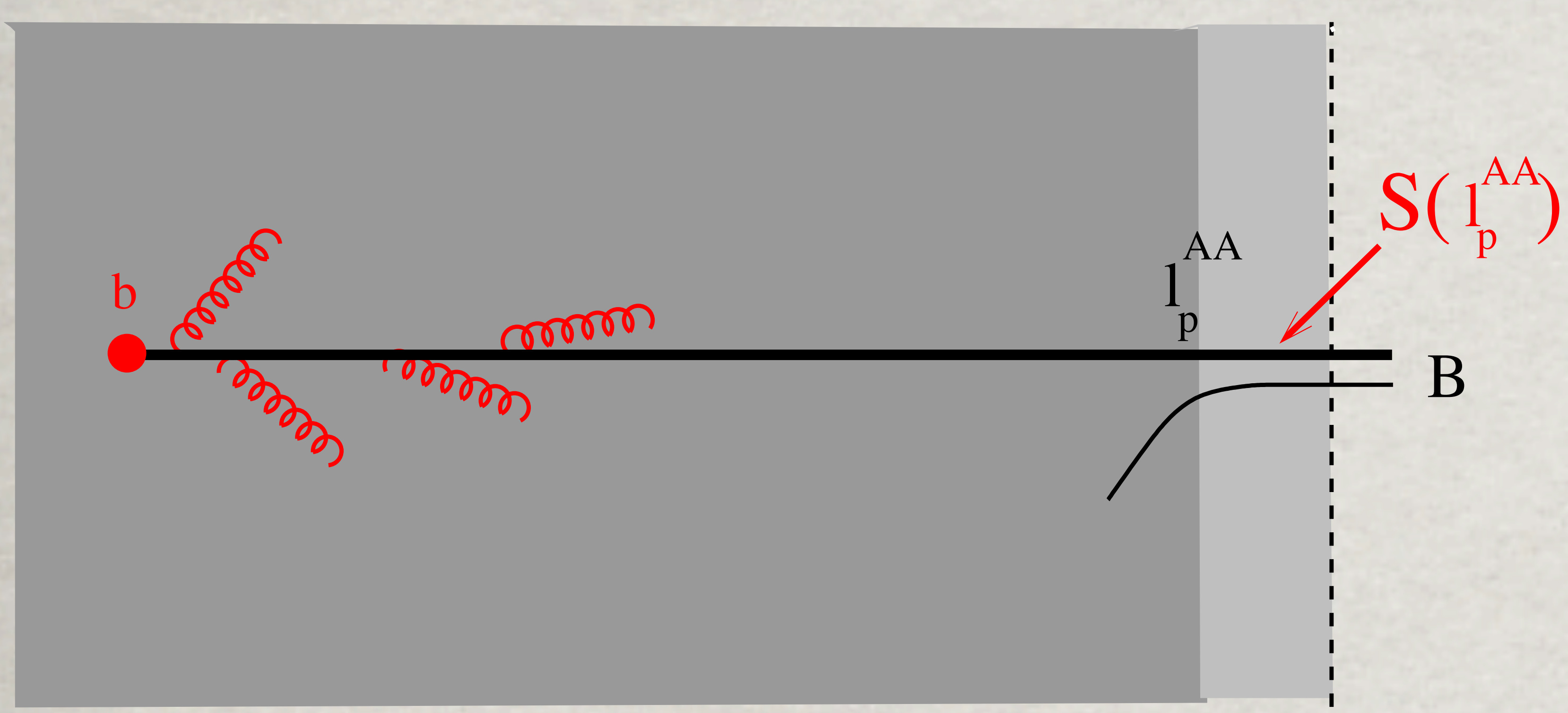
B meson is nearly as big as a pion, $\langle r_{ch}^2 \rangle_B = 0.378\,\text{fm}^2$ [Ch.-W. Hwang (2001)]

The mean free path of such a meson in a hot medium is very short $\lambda_B \sim \frac{1}{\hat{q}\,\langle r_T^2 \rangle}$

where $\hat{q}$ is the rate of broadening per 1fm (called "transport coefficient")

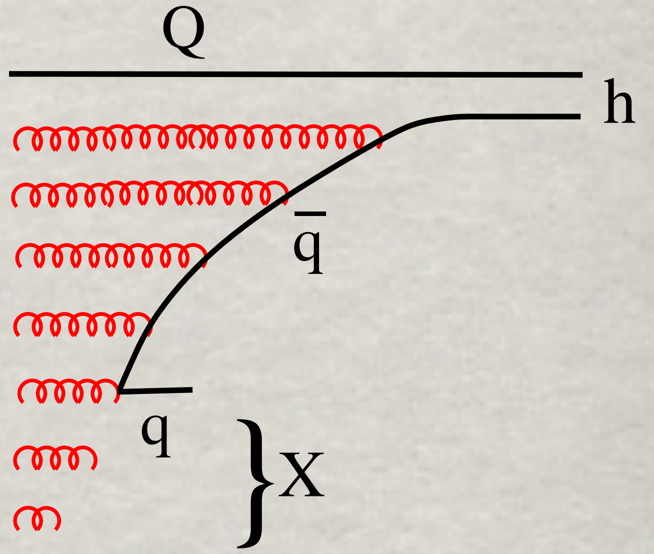
E.g. at $\hat{q} = 1\,\text{GeV}^2/\text{fm}$ $\lambda_B = 0.04\,\text{fm}$, i.e. the b-quark propagates through the dense medium, picking up and releasing light quarks. Meanwhile the b-quark keeps losing energy with a rate, enhanced by medium-induced effects. Eventually the detected B-meson is formed in the dilute surface of the medium.

In-medium propagation: E-loss vs absorption



Radiational energy loss like in vacuum, plus induced by the medium

However, hadronization cannot be completed at a very short distance Lp, like in vacuum, because the produced $Q\bar{q}$ meson is immediately broken-up by the dense medium



The heavy quark keeps losing energy even inside a colorless $Q\bar{q}$ dipole sharing it with the light quark. A considerable energy ΔE is dissipated on a long way to the medium periphery.

$$\frac{dE}{dL} = \frac{dE_{rad}}{dL} - \kappa$$

In-medium string tension $\kappa(T) = \kappa\,(1 - T/T_c)^{1/3}$

This leads to an effective renormalization of the fragmentation function D(z)->D($\tilde{z}$)

$$\tilde{z} = z\left(1 + \frac{\Delta E}{E}\right)$$

Attenuation in a hot medium

Assuming factorization and fragmentation mechanism of b->B production

$$\frac{d^2\sigma_{pp\to BX}}{d^2p_T} = \frac{1}{2\pi p_T E_T}\int d^2q_T \frac{d^2\sigma_{pp\to bX}}{d^2q_T}\int\limits_0^\infty dL_p \frac{dW}{dL_p}\frac{\Delta E(L_p)}{E}\,\delta\left(1 - z - \frac{\Delta E(L_p)}{E}\right).$$

Here the fragmentation function $D_{b/B}(z)$ is replaced by the production length distribution dW/dL_p, which peaks at extremely short distances Lp < 1fm.

In the case of AA collisions one can employ the same formula, but with a modified production length distribution.

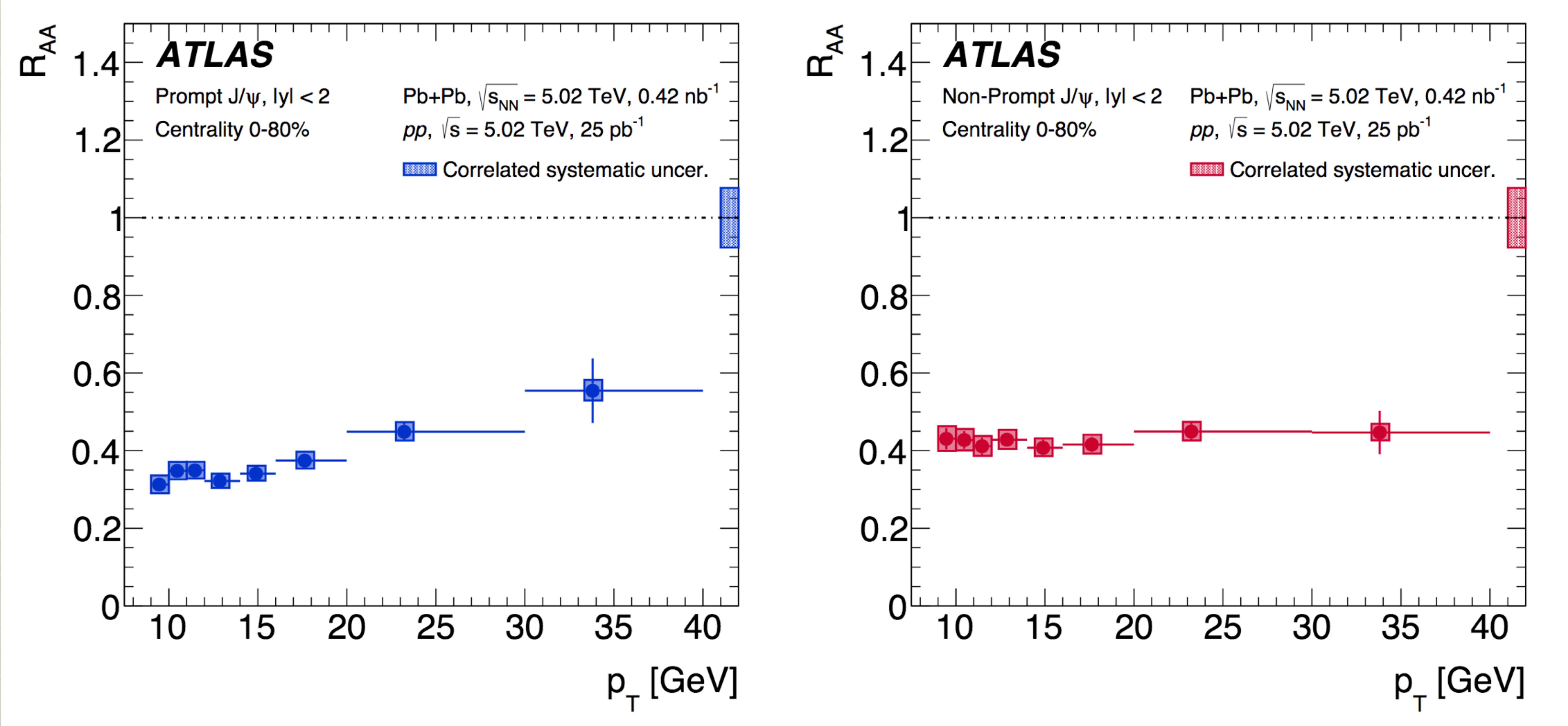
$$\frac{dW^{AA}}{dL_p} = \frac{\langle r_B^2\rangle}{2}\hat{q}(L_p)\exp\left[-\frac{\langle r_B^2\rangle}{2}\int\limits_{L_p}^\infty dL\,\hat{q}(L)\right]$$

Lp turns out to be much longer, because the B-meson is produced mainly at the medium border,

$$\frac{d^2\sigma_{AA\to BX}}{d^2p_T d^2s} = \frac{1}{2\pi p_T E_T}\int d^2q_T \frac{d^2\sigma_{pp\to bX}}{d^2q_T}\int d^2\tau\, T_A(s)T_A(\tilde{s}-\tilde{\tau})\int\limits_0^\infty dL_p \frac{dW^{AA}}{dL_p}\frac{\Delta E(L_p)}{E}\,\delta\left(z - \frac{\Delta E(L_p)}{E}\right)$$

Results: B mesons

M.Arratia, W.Brooks et al. ATLAS, *Eur.Phys.J.C* 78 (2018) 9



Why the AA/NN ratio rises with pT for prompt J/ψ, but is hardly varies for non-prompt?

Slow expansion of $\bar{Q}Q$ separation — Color transparency

Fast expansion of $\bar{q}Q$ separation — No color transparency

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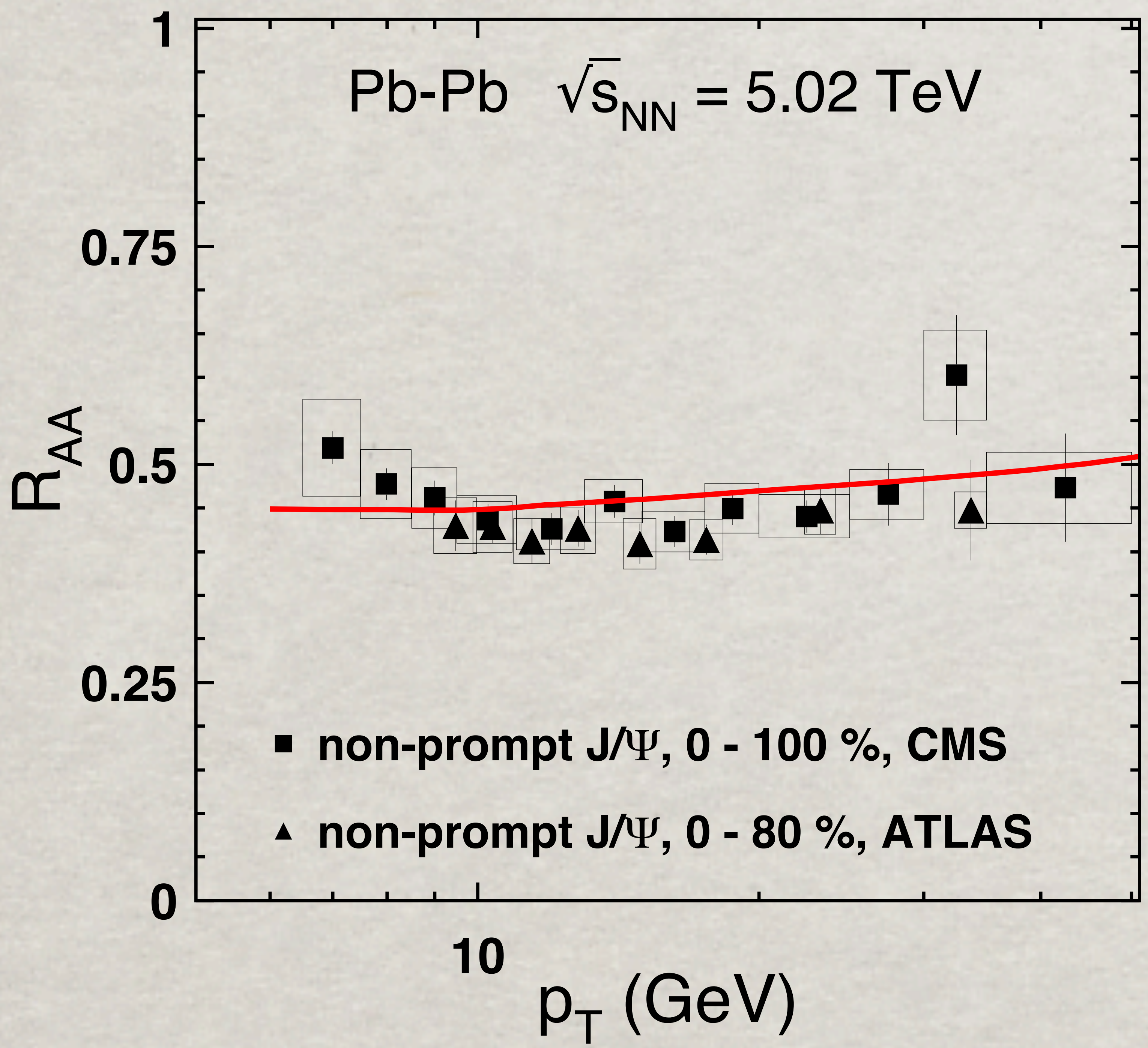
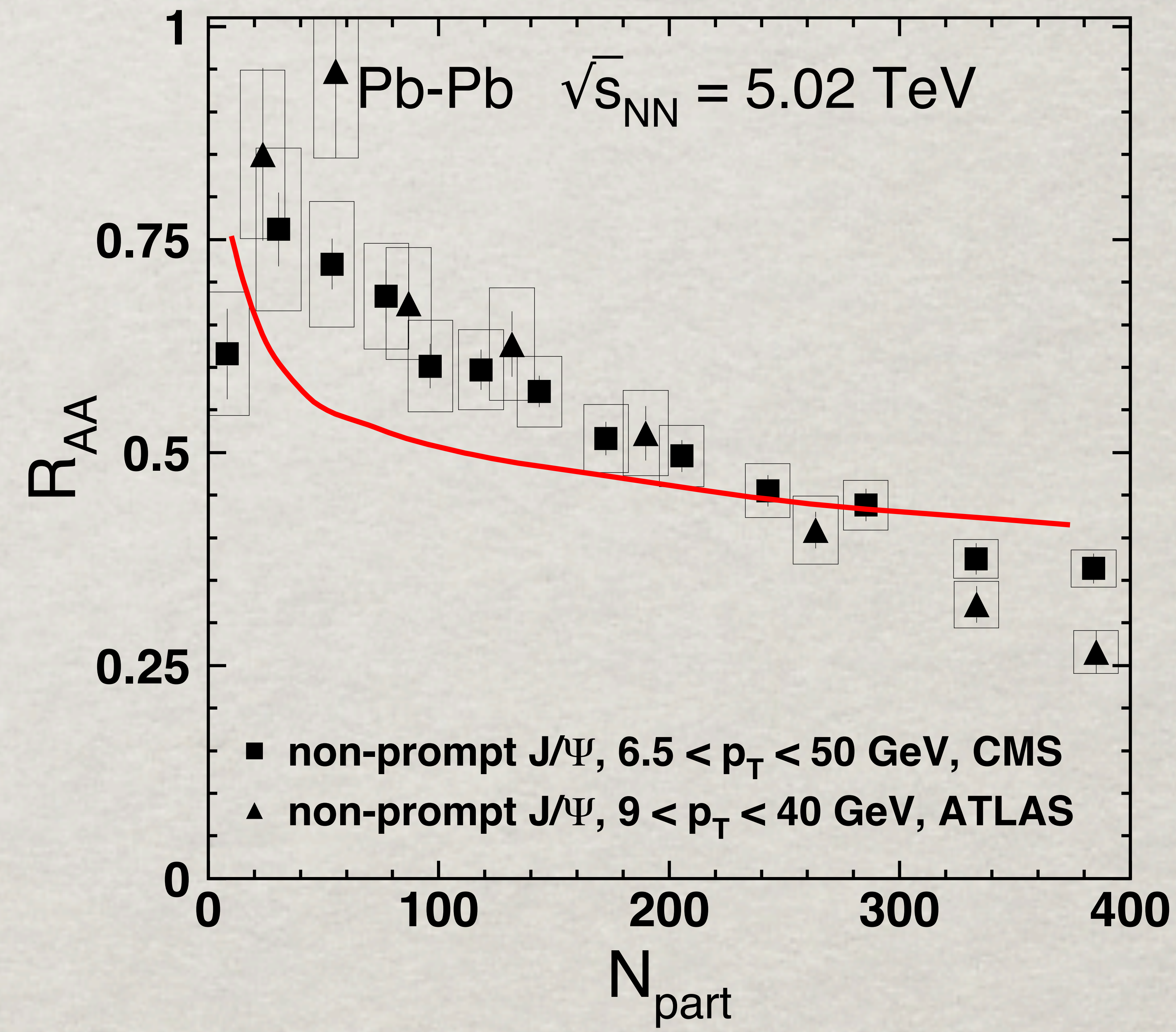
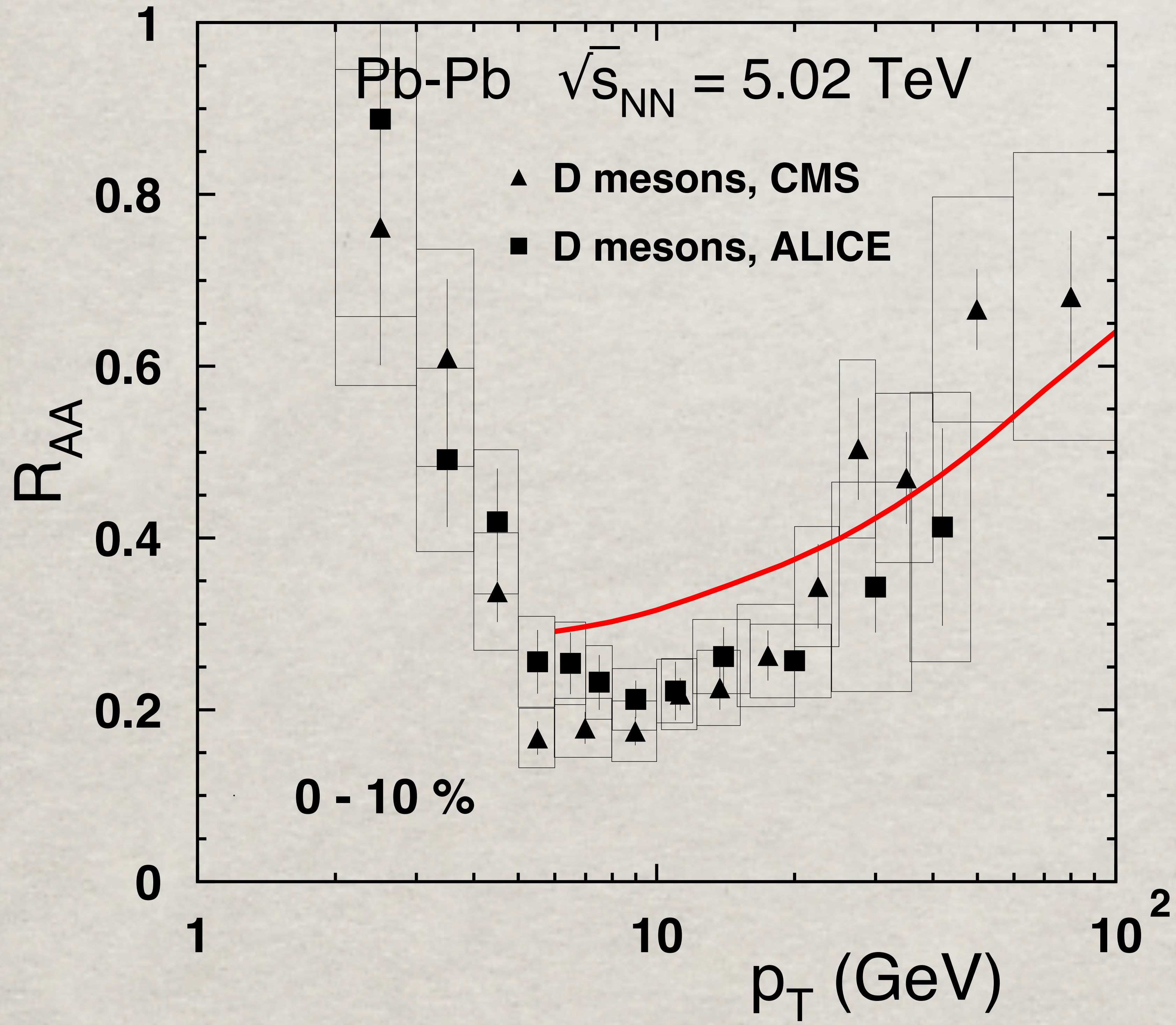
Results: B mesons

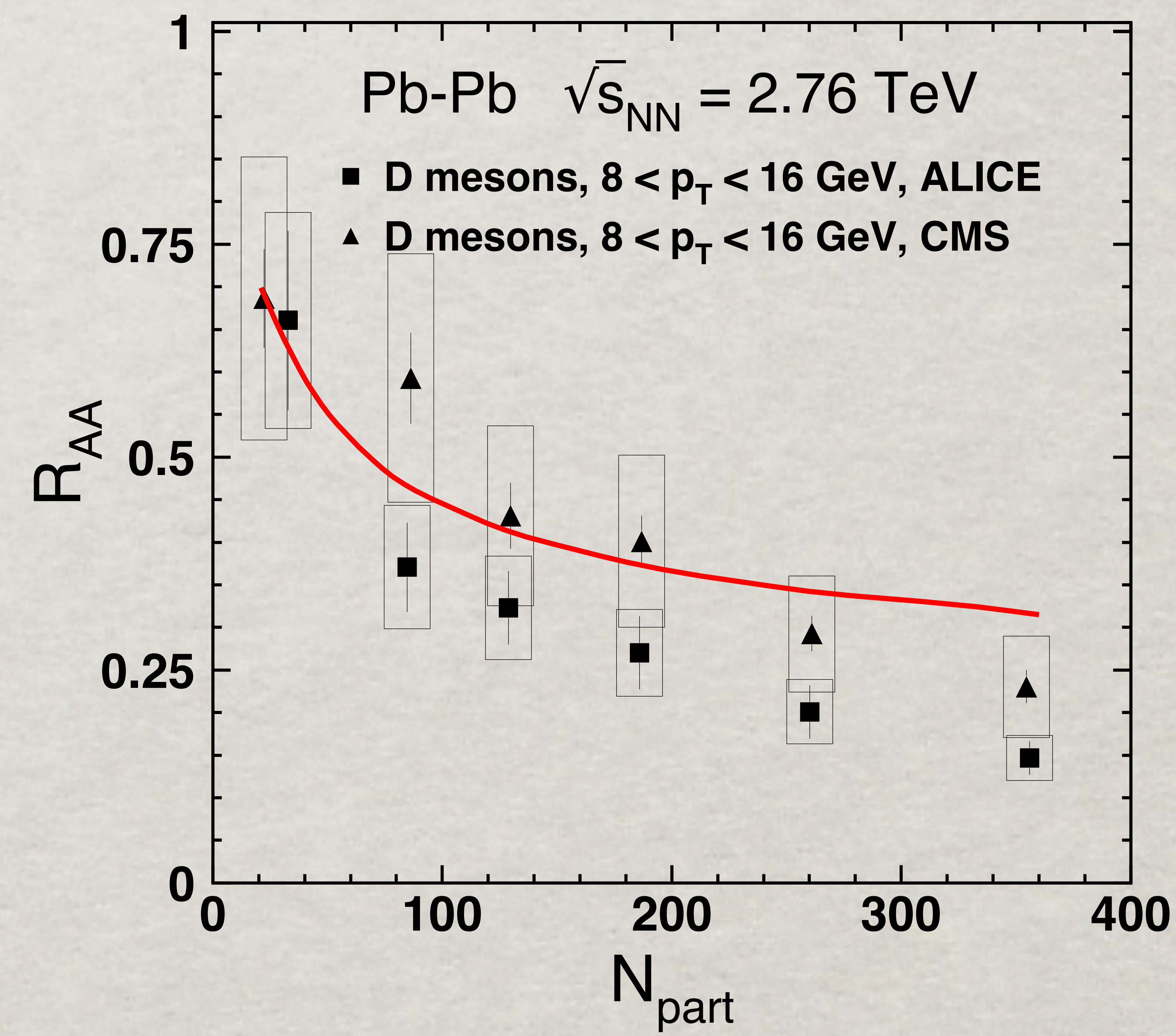




Results: D mesons

c-quarks radiate in vacuum much more energy than b-quarks, while the effects of absorption of c-qbar and b-qbar dipoles in the medium are similar. Therefore D-mesons are suppressed in AA collisions more than B-mesons.





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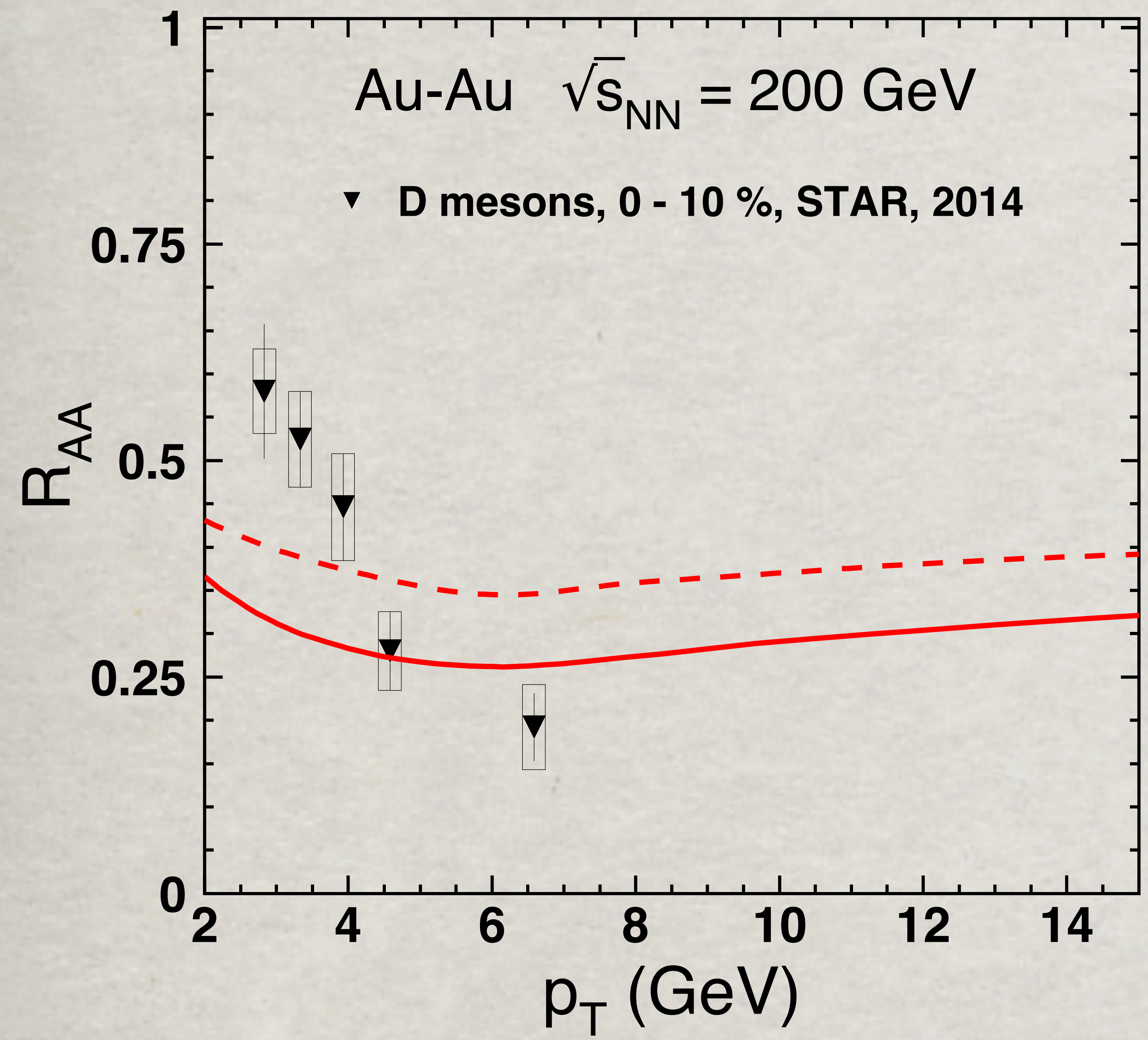
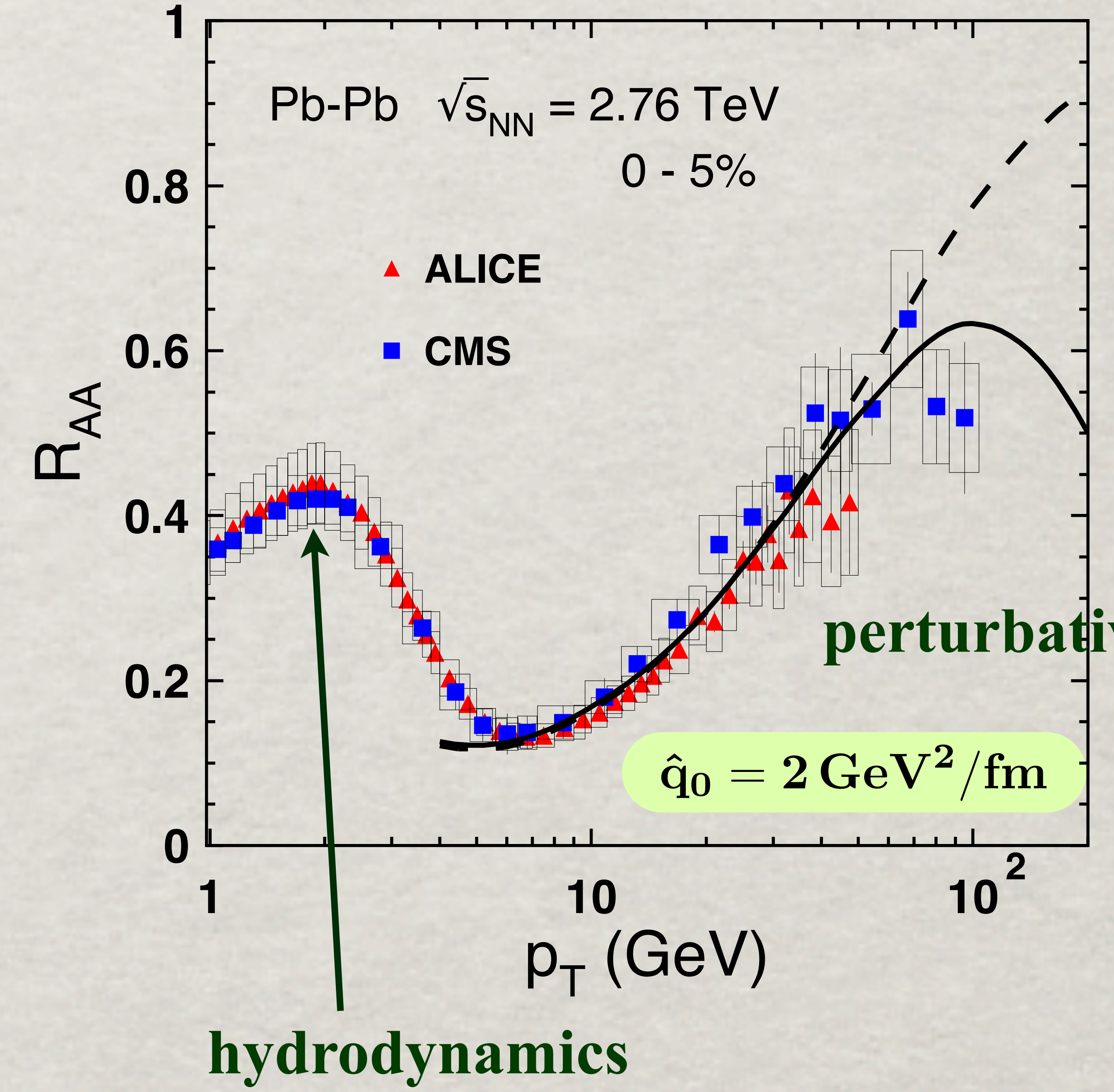
Results: D mesons



BK, J.Nemchik, I.Potashnikova, I.Schmidt
Phys.Rev. C86(2012)054904



Why $R_{AA}(p_T)$ **is falling at small pT?**

BK, J.Nemchik, I.Potashnikova,
Yu.Karpenko, Yu.Sinyukov
EDS 13, Arxiv 1310.3455

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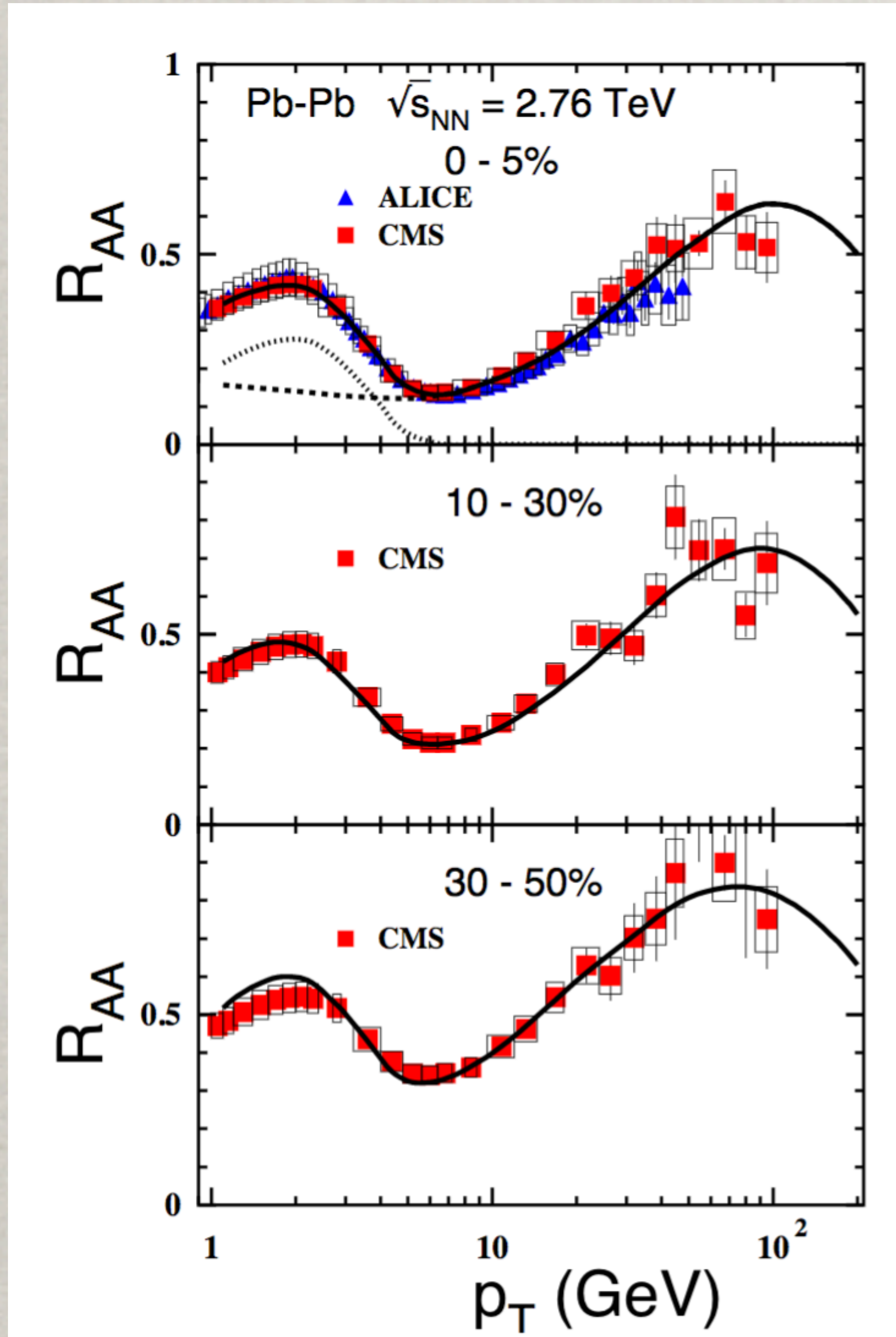
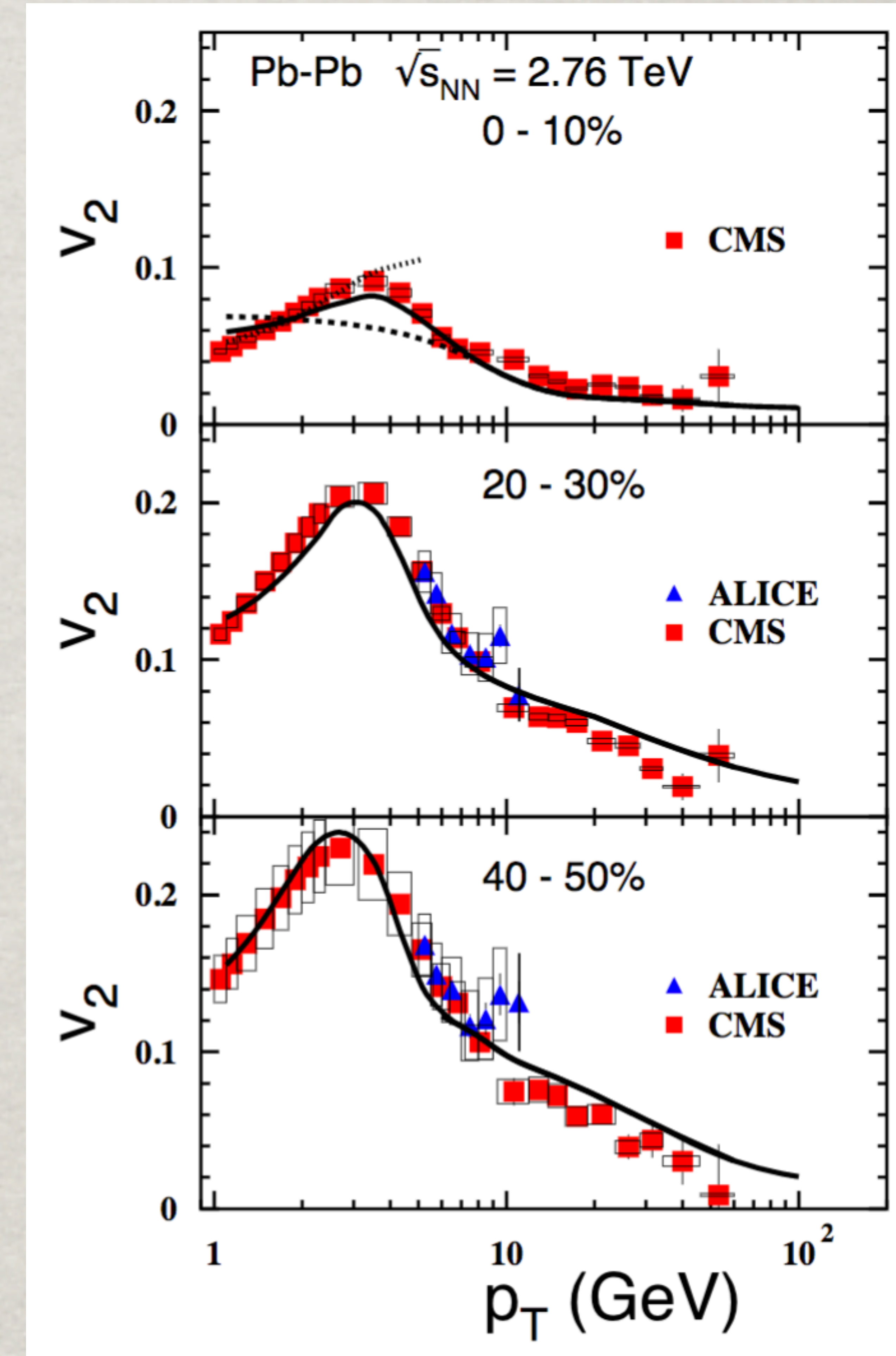
HYDRO + pQCD



J.Nemchik,Yu.Karpenko,I.Potashnikova
I.Schmidt, Yu.Sinyukov & B.K.
arXiv:1310.3455



Conclusions

- Heavy and light quarks produced in high-pT partonic collisions radiate differently. Heavy quarks regenerate their stripped-off color field much faster than light ones and radiate a significantly smaller fraction of the initial energy.

- This peculiar feature of heavy-quark jets leads to a specific shape of the fragmentation functions. Differently from light flavors, the heavy quark fragmentation function strongly peaks at large fractional momentum z, i.e. the produced heavy-light meson, B or D, carry the main fraction of the jet momentum. This is a clear evidence of a short production time of a heavy-light mesons.

- Contrary to the propagation of a small q-$\bar{q}$ dipole, which survives in the medium due to color transparency, a $\bar{q}$-Q dipole promptly expands to a large size. Such a big dipole has no chance to remain intact in a hot medium. On the other hand, a breakup of such a dipole does not suppress the production rate of $\bar{q}$-Q mesons, differently from light $q\bar{q}$ mesons.