Unconventional mechanisms of heavy quark fragmentation

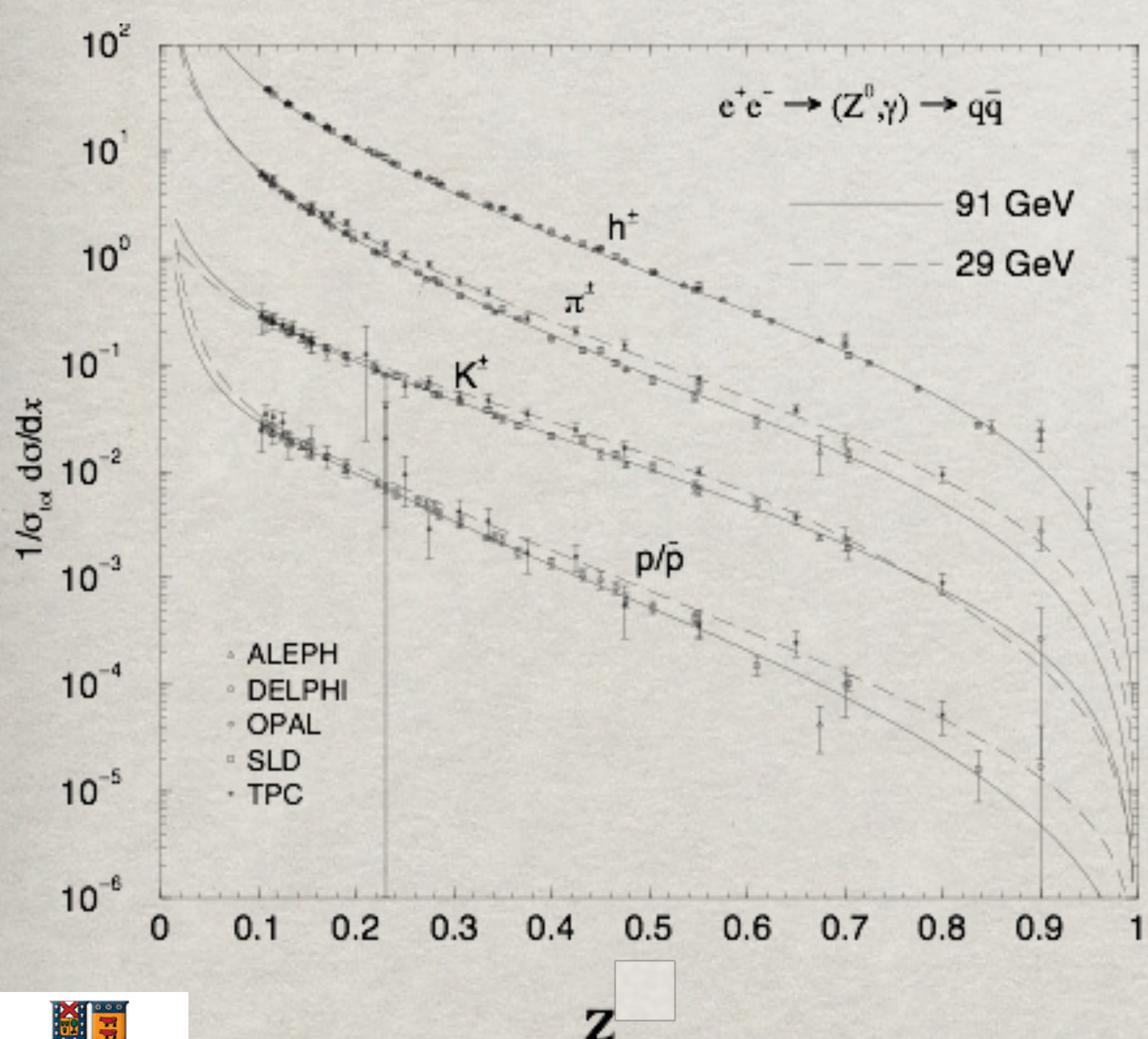
Boris Kopeliovich

In collaboration with:

Jan Nemchik
Irina Potashnikova
Ivan Schmidt

Measured fragmentation functions

Fragmentation function $\mathbf{D_{q/h}(z)}$ describes the distribution of hadrons over fractional light-cone momentum $\mathbf{z = p_h^+/p_q^+}$.



$\mathbf{D_{q/h}(z)}$ has been measured in semi-inclusive DIS;

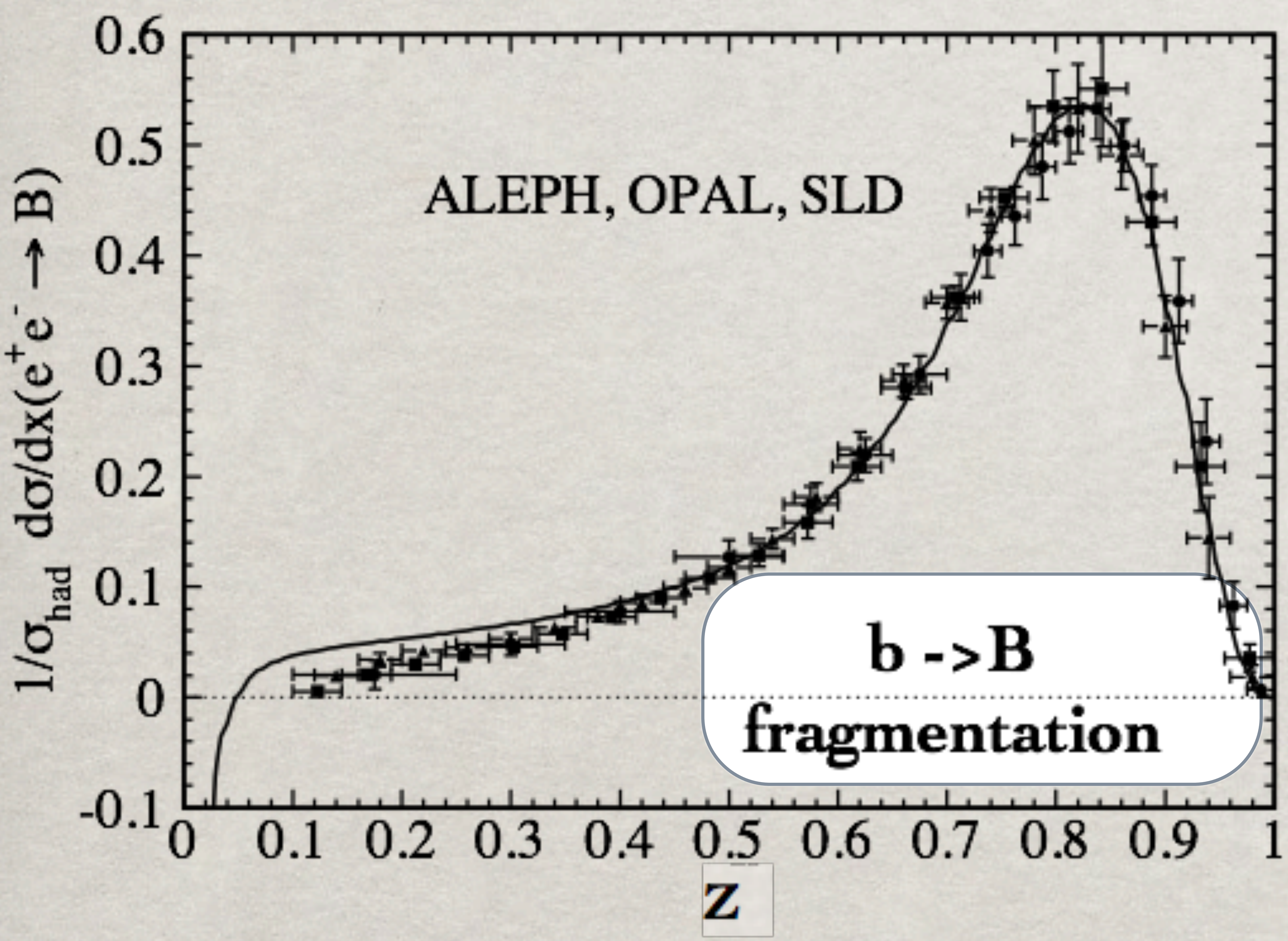
In high-pT hadronic jets;

In e+e- annihilation at LEP and SLAC.

The predominant part of light hadrons are produced at the mid-rapidities, i.e. z<<1, while they are strongly suppressed at large z.

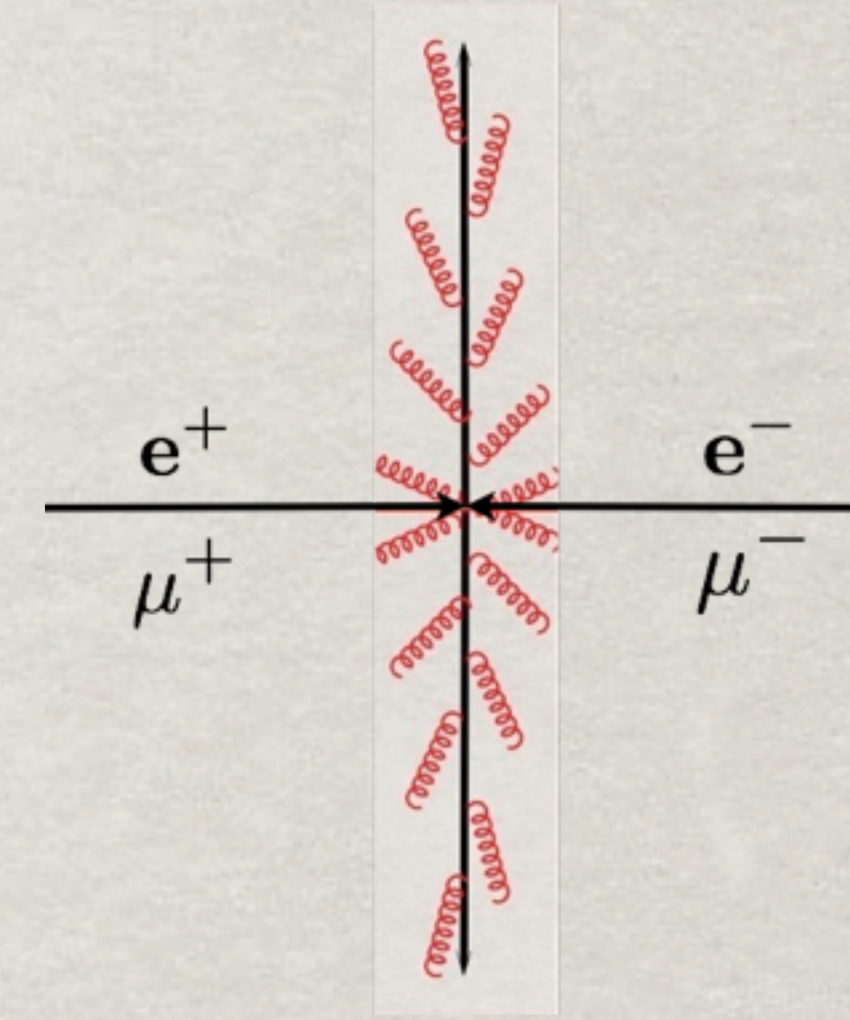
Measured fragmentation functions

Fragmentation functions of heavy quarks look quite differently



WHY ?

Perturbative fragmentation

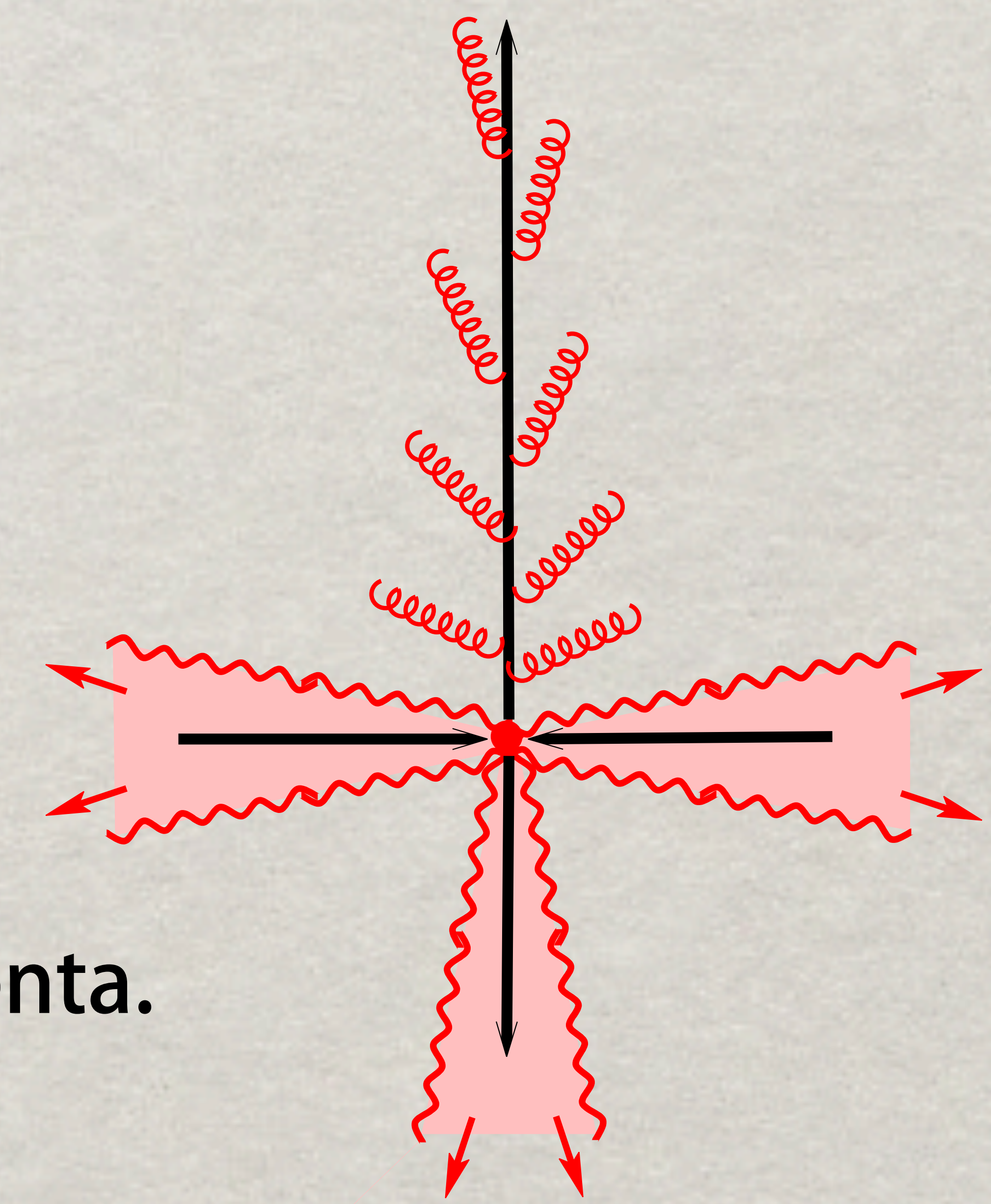


A quark, originated from a hard collision is lacking the soft component of its color field (equivalent gluons) with $\mathbf{k_T^2 \lesssim Q^2}$.
It regenerates the stripped off components of the field by radiating gluons.

The radiated gluons subsequently hadronize forming a jet of hadrons.

Gluons are radiated successively in accordance with the coherence length/time of gluon radiation

$$\mathbf{lc = \frac{2Ex(1-x)}{k_T^2 + x^2 m_q^2}}$$



First are radiated gluons with small longitudinal and large transverse momenta.

Radiational energy loss

How much energy is radiated over the path length L?

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

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

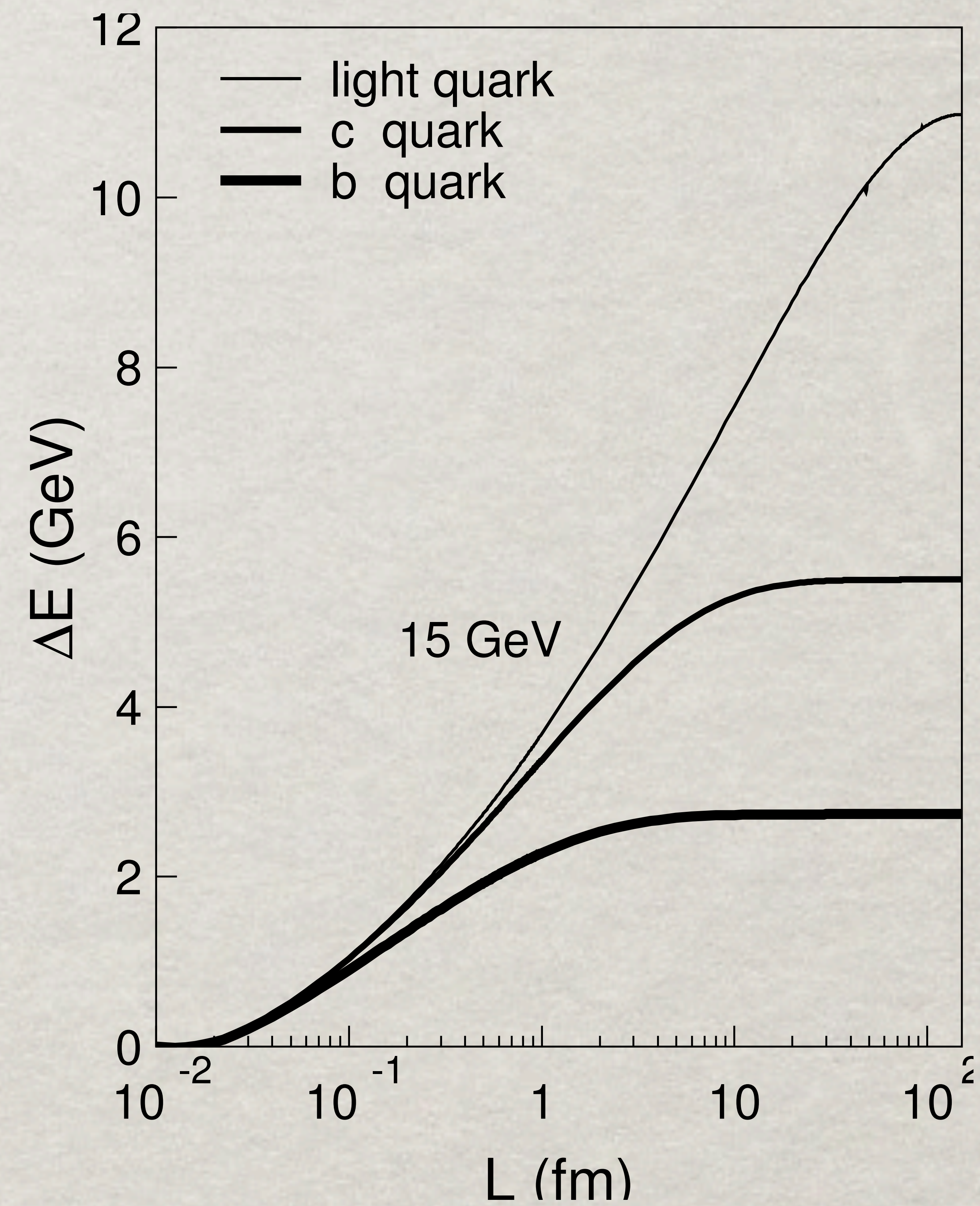
Light quarks: $dn_g/dk^2 \sim 1/k^2$

Heavy quarks $dn_g/dk^2 \sim k^2/m_Q^4$

Dead-cone effect: gluons with $k^2 < x^2 m_q^2$ are suppressed. Heavy quarks radiate less energy than the light ones. They promptly restore their color field and stop radiating.

B.K., I.Potashnikova, I.Schmidt

PRC 82(2010)037901



Heavy quarks radiate only a small fraction 10-20% of their momentum.

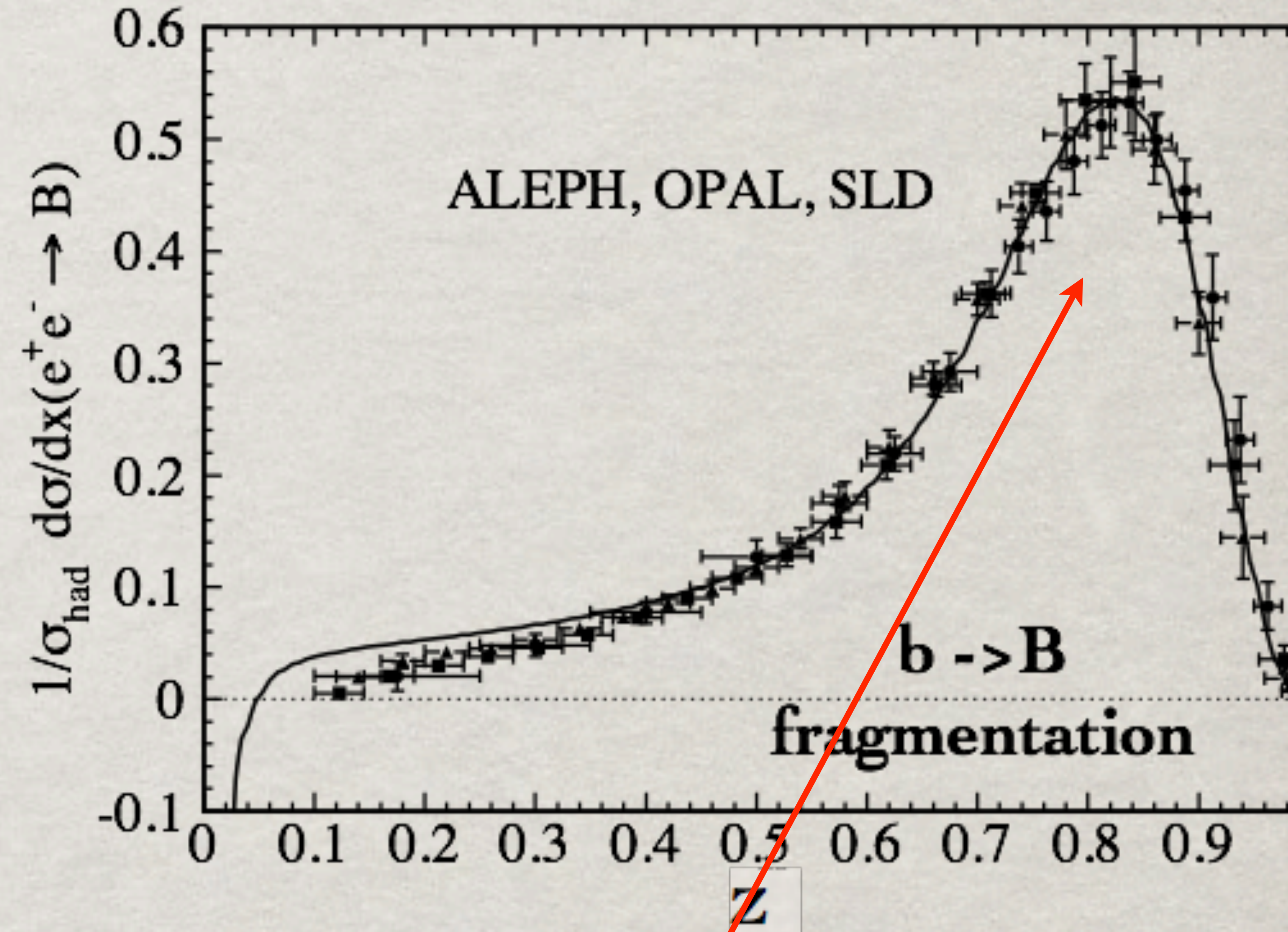
UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

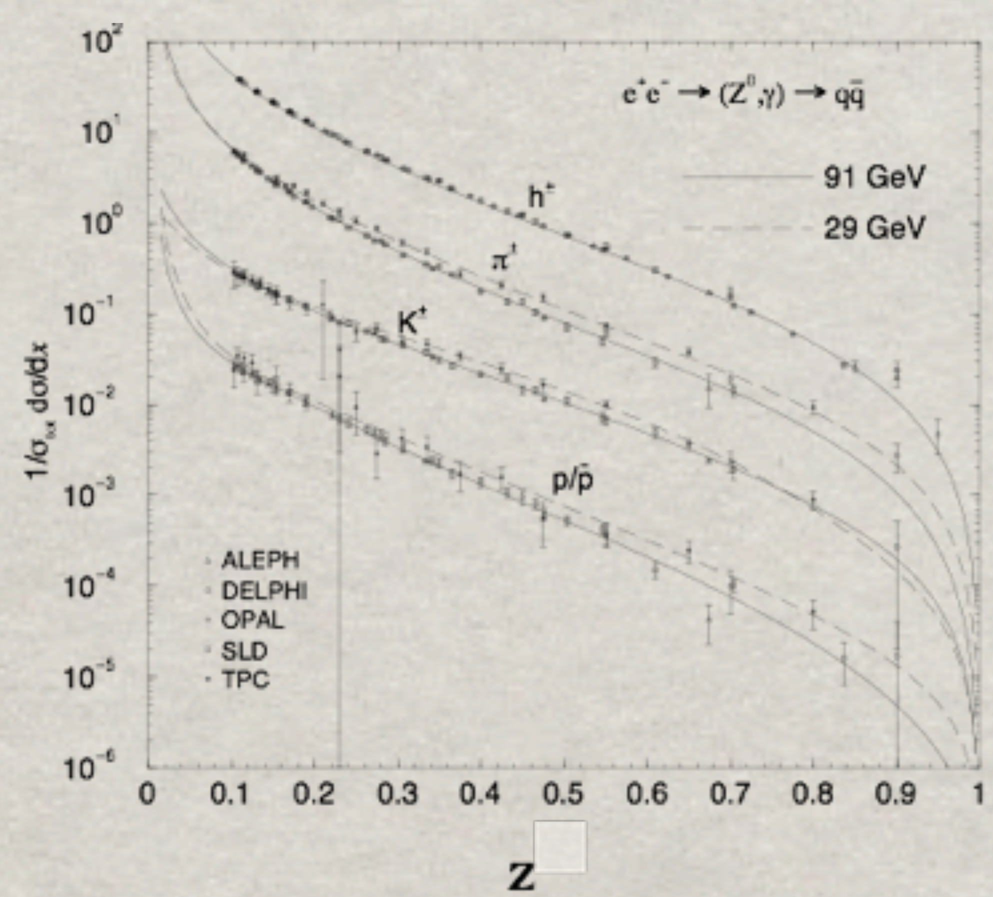
Radiational energy loss

Heavy quarks radiate only a small fraction 10-20% of their momentum.

This explains the quite unusual shape of the experimentally observed fragmentation function

It shows that only a small fraction (1-z) of the b-quark momentum, is lost.



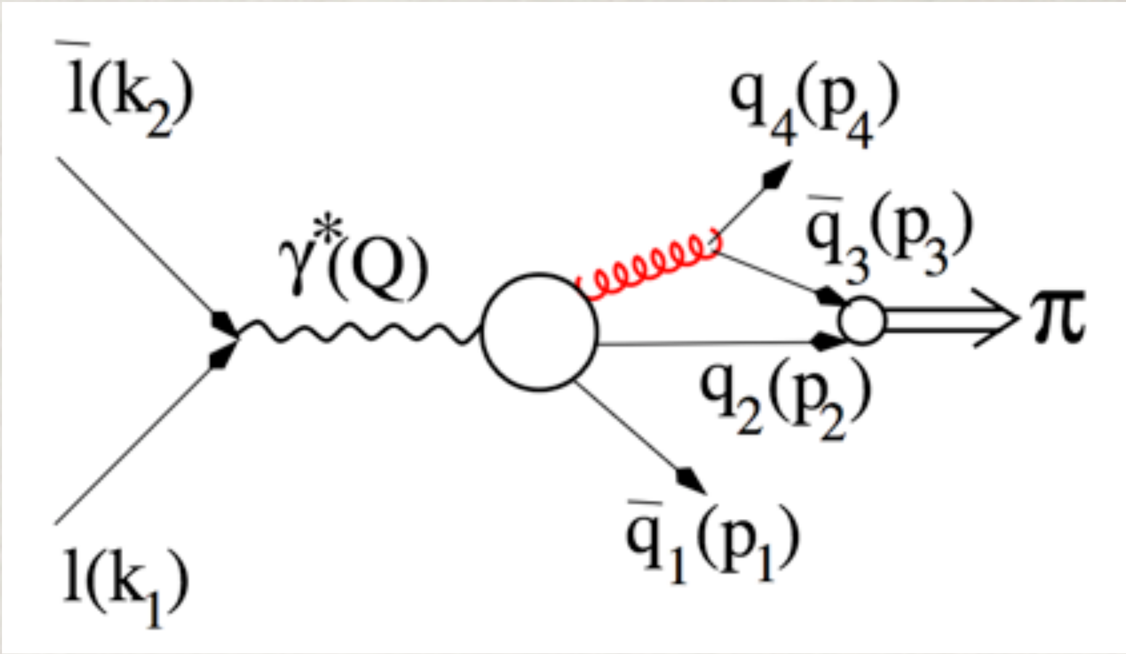


Such a specific shape of the fragmentation function is a direct consequence of the dead-cone effect.

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Production length

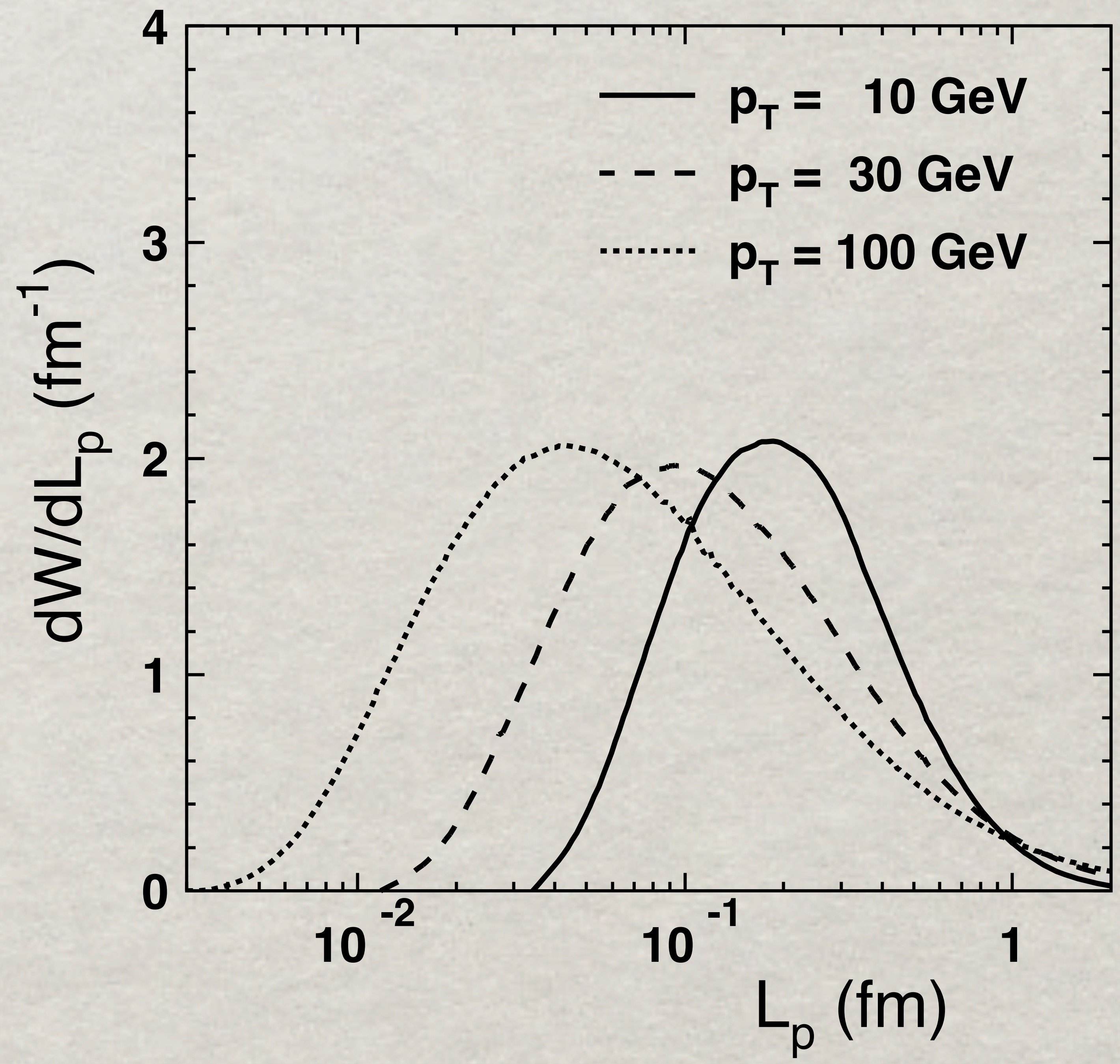
The gluon radiation process by a heavy quark Q ends up with color neutralization by a light antiquark and production of a Q-qbar dipole.



example of pion production

As far as we can calculate $\Delta E(L)/E$, the production length distribution can be extracted directly from $\mathbf{D_{q/h}(z)}$

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



Remarkably, the mean value of Lp is extremely short and shrinks with rising pT. This sounds counter intuitive, however, the process has maximal hard scale $p_T = W$

It is much shorter than the confinement radius, i.e the fragmentation mechanism is pure perturbative. At L=Lp, a small-size dipole, with no certain mass.

B. Kopeliovich, ISMD 2023

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Fragmentation in a dense medium

Formation length of a $Q\bar{q}$ meson

The light quark in a B-meson carries a tiny fraction of the momentum, $\mathbf{x \sim m_q/m_b \approx 5\%}$

The produced b-qbar dipole has a small transverse separation, but it expands with a high speed, enhanced by 1/x. It promptly reaches the large hadronic size.

$$\mathbf{L_f \sim \frac{1}{2} x(1-x)\langle r_T^2 \rangle p_T}$$ where $$\mathbf{\langle r_T^2 \rangle = \frac{8}{3}\langle r_{ch}^2 \rangle}$$ and $$\mathbf{\langle r_{ch}^2 \rangle_B = 0.378\, fm^2}$$

[Ch.-W. Hwang (2001)]

The B meson is nearly as big as a pion, since its radius is controlled by the mass of the light antiquark.

This is the early, perturbative stage of the dipole expansion.

The further evolution filters out the states with large relative phase shifts. The longest time takes discrimination between the two lightest hadrons, the ground state B and the first radial excitation B′ , which concludes the formation process. Correspondingly the full formation path length is,

$$\mathbf{L_f = \frac{2p_T}{m_{B'}^2 - m_B^2}}$$

Still, i is pretty short. E.g. for oscillatory potential mB− mB = 2ω = 0.6 GeV,

so Lf = 0.06 fm[pT /1 GeV].

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Attenuation in a dense medium

Mean free path in the medium

The mean free path of such a meson in a hot medium with transport coefficient (rate of broadening) $\hat{q}$

$$\lambda_B \sim \frac{1}{\hat{q}\,\langle r_T^2\rangle} = \frac{3}{8\hat{q}\langle r_{ch}^2\rangle}$$

E.g. at $\hat{q} = 1\,\mathrm{GeV^2/fm}$ $\lambda_B = 0.04\,\mathrm{fm}$ an extremely short path length

A b-quark propagates through the hot medium, easily picking up and losing accompanying light antiquarks. Meanwhile the b-quark keeps dissipating energy with a rate, slightly enhanced by medium-induced effects. Eventually the detected B-meson is produced in the dilute periphery of the medium.

Attenuation in a dense medium

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

Here the b-B fragmentation function is replaced by the Lp distribution applying the previously used relation

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

The medium-modified Lp distribution is

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

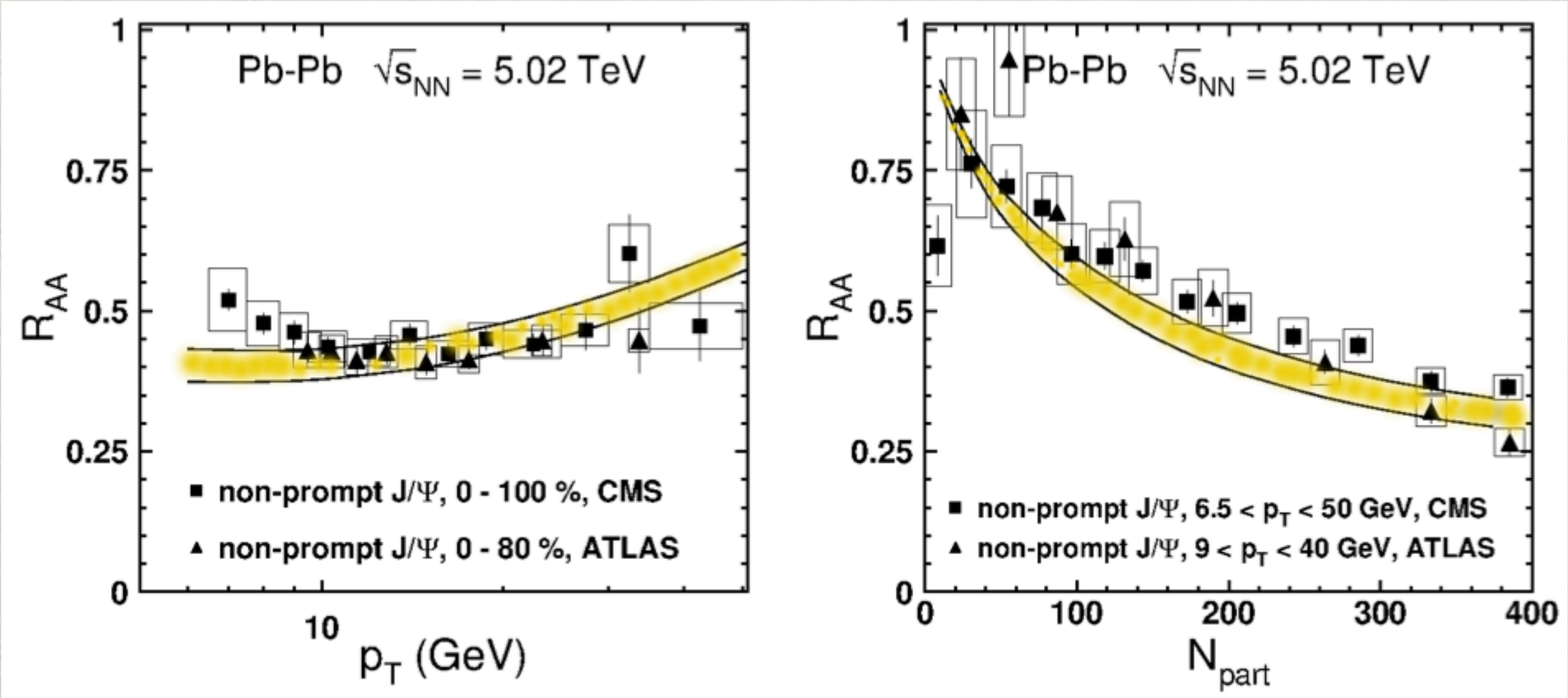
The in-medium Lp turns out to be much longer, because the B-meson is produced mainly at the periphery,

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

Results: B-meson

Different sources of energy loss should be added up. Medium-induced energy loss is much smaller than in vacuum. Besides, it is expected to be suppressed for heavy flavors by the dead-cone effect.

[Yu.Dokshitzer & D.Kharzeev (2001)]



UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

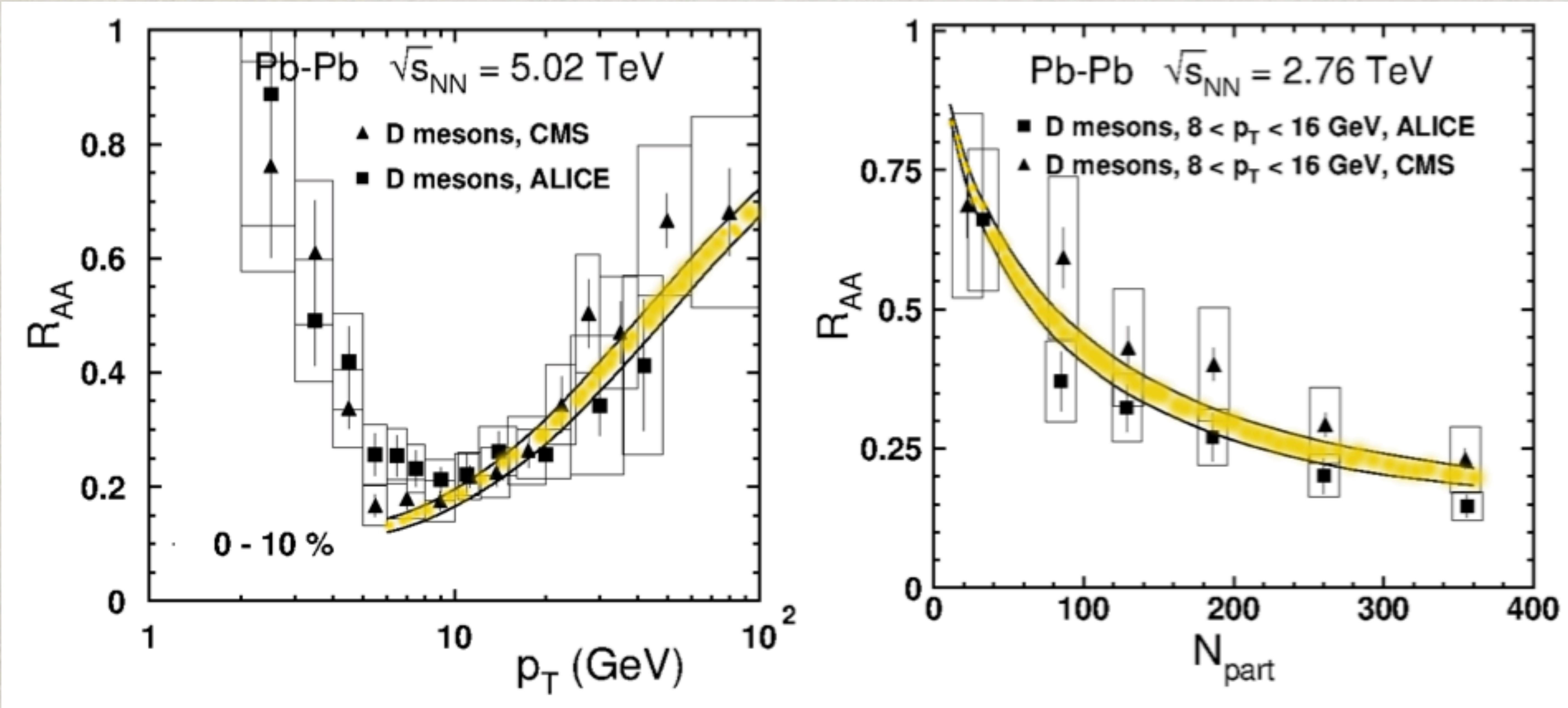
Results: D-meson

c-quarks radiate in vacuum 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.

$\mathbf{R_{AA}(p_T)}$ for D-mesons steeply rises due to color transparency.

Since $\mathbf{b\bar{q}}$ dipoles expand much faster than $\mathbf{c\bar{q}}$,

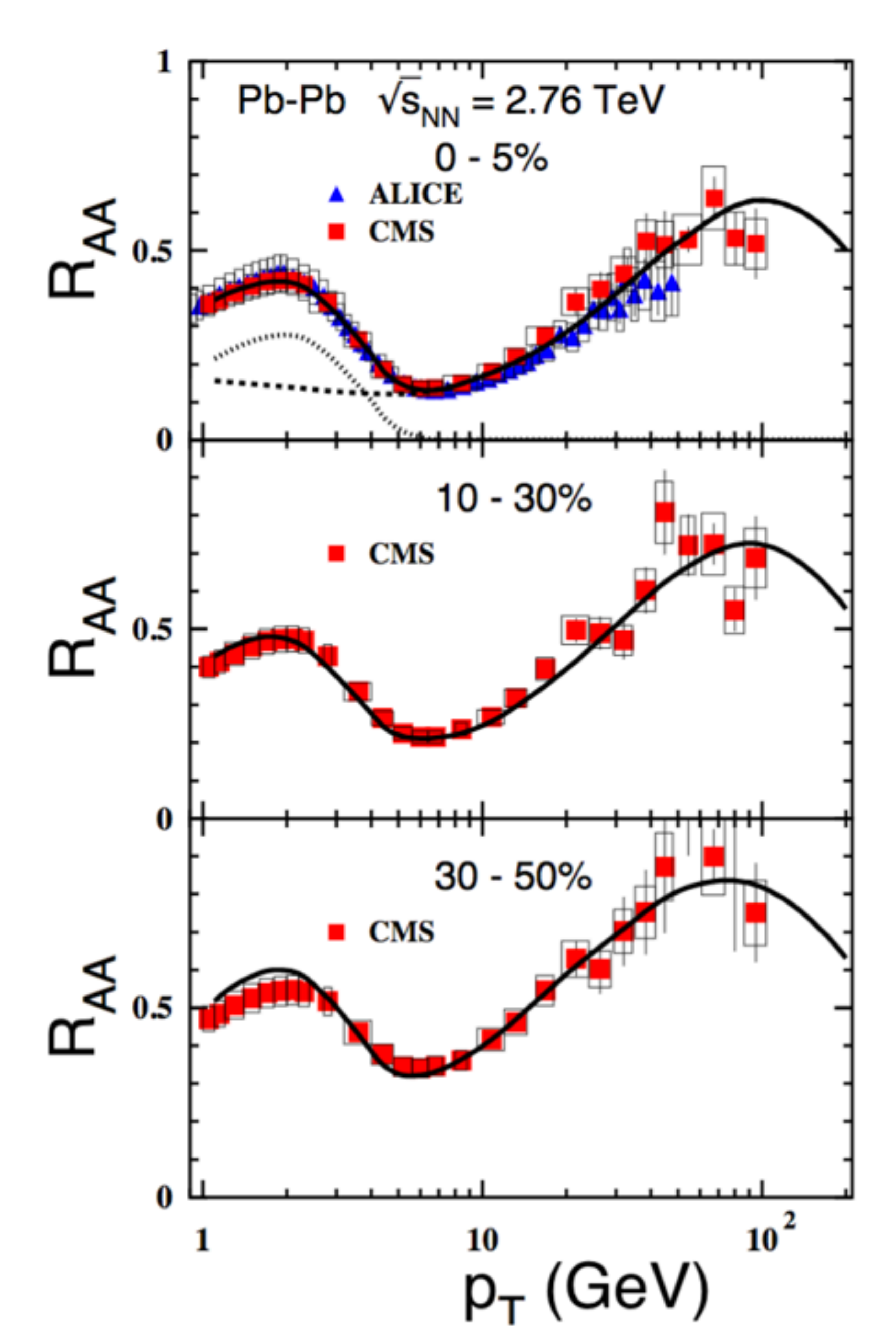
no color transparency effects are seen in $\mathbf{R_{AA}(p_T)}$ for B-mesons.

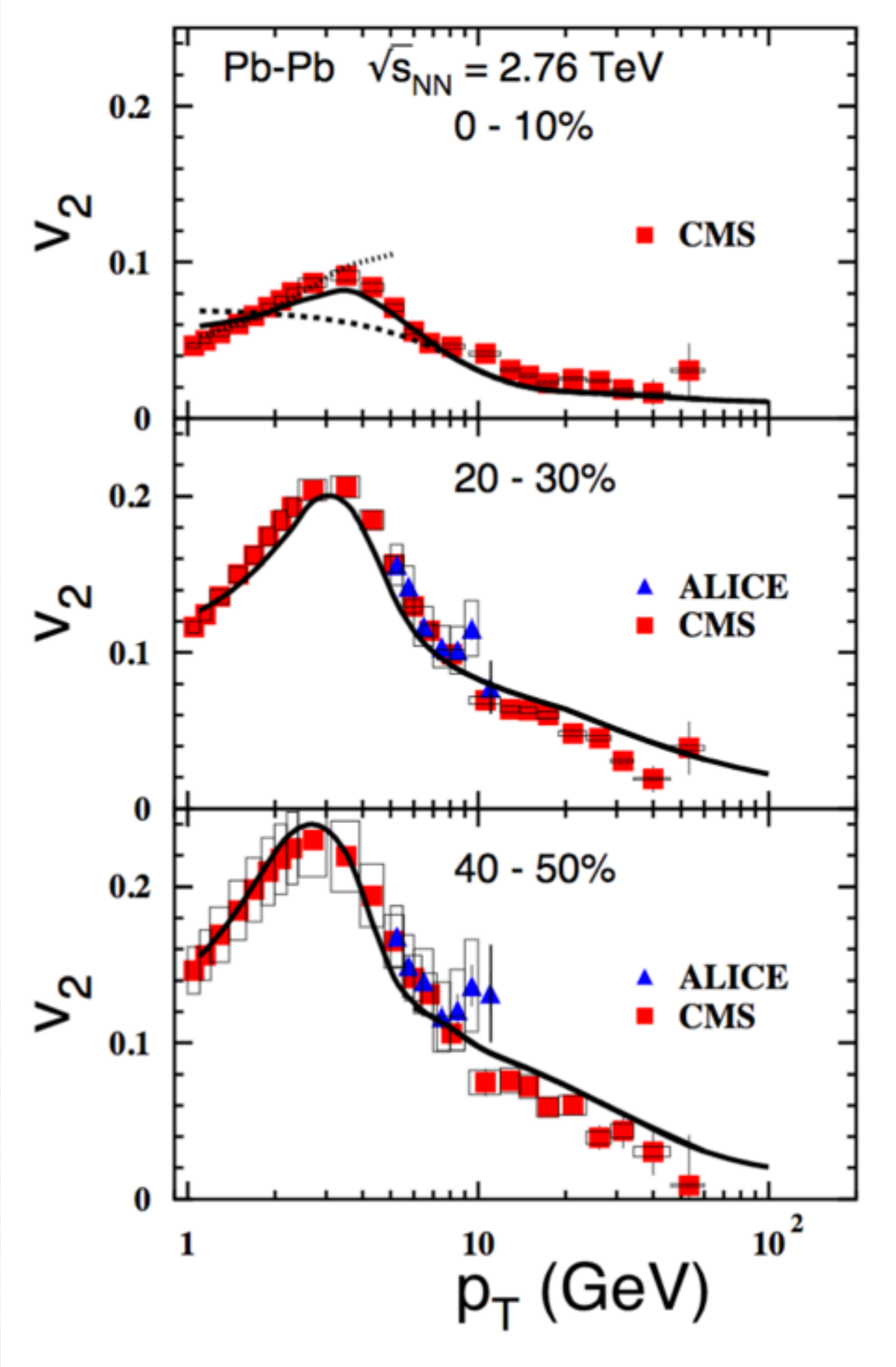


UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Light hadrons

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





UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

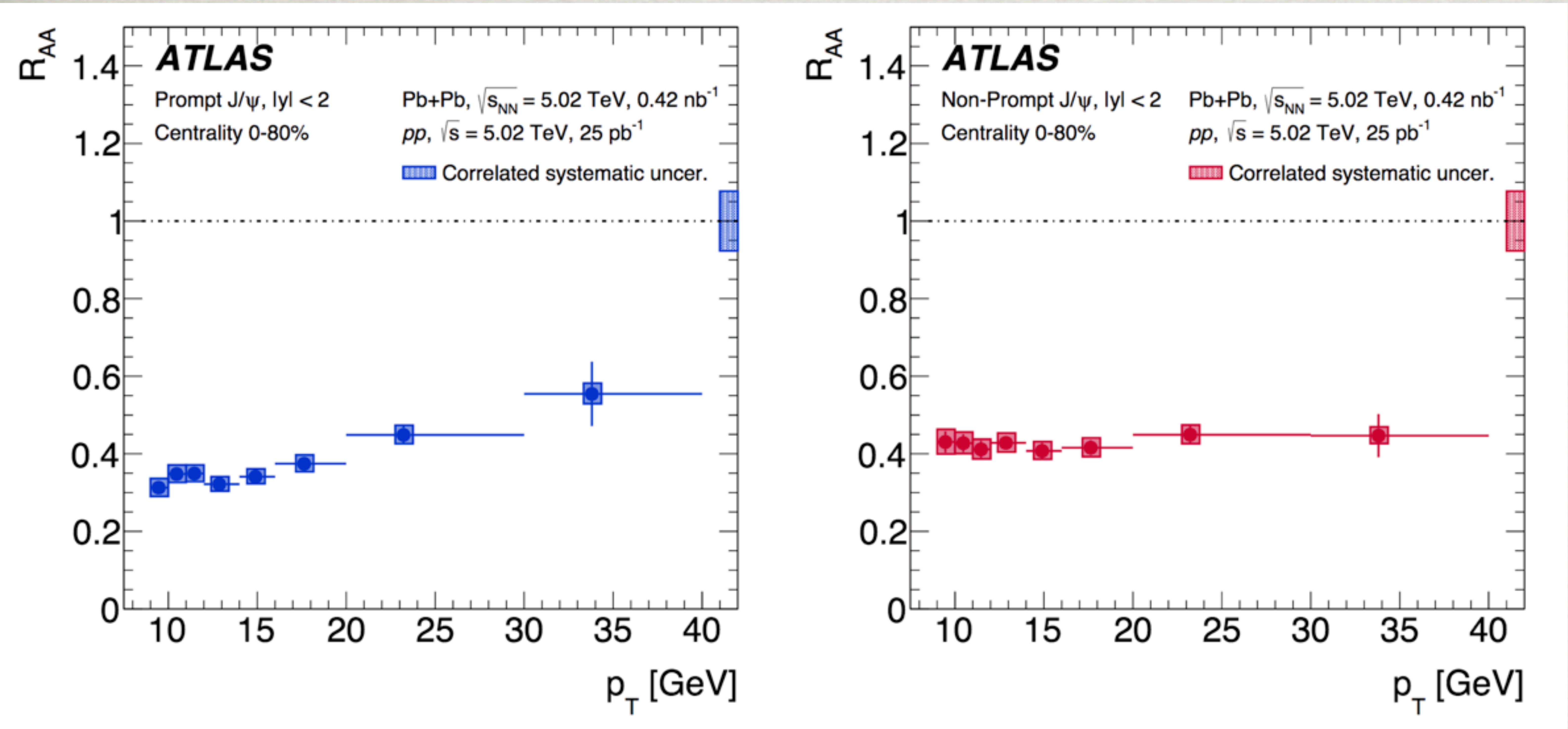
Summary

- Heavy and light quarks produced in high-pT partonic collisions radiate differently. Heavy quarks regenerate their stripped-off color field much faster and radiate a significantly smaller fraction of their 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 a large fractional momentum z, i.e. the produced heavy-light mesons, B or D, carry the main fraction of the jet momentum. This is a clear evidence of the dead-cone effect, and of a short production time of a heavy-light mesons.

- Contrary to propagation of a small q-q dipole, which survives in the medium due to color transparency, a 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 Q-qbar mesons, differently from symmetric q-qbar or Q-Qbar mesons.

Results: B-meson



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

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

Slow expansion of $\bar{Q}Q$ separation

Fast expansion of $\bar{q}Q$ separation

Color transparency

color opacity