Hadronization of highly virtual partons: perturbative vs nonperturbative mechanisms

Boris Kopeliovich

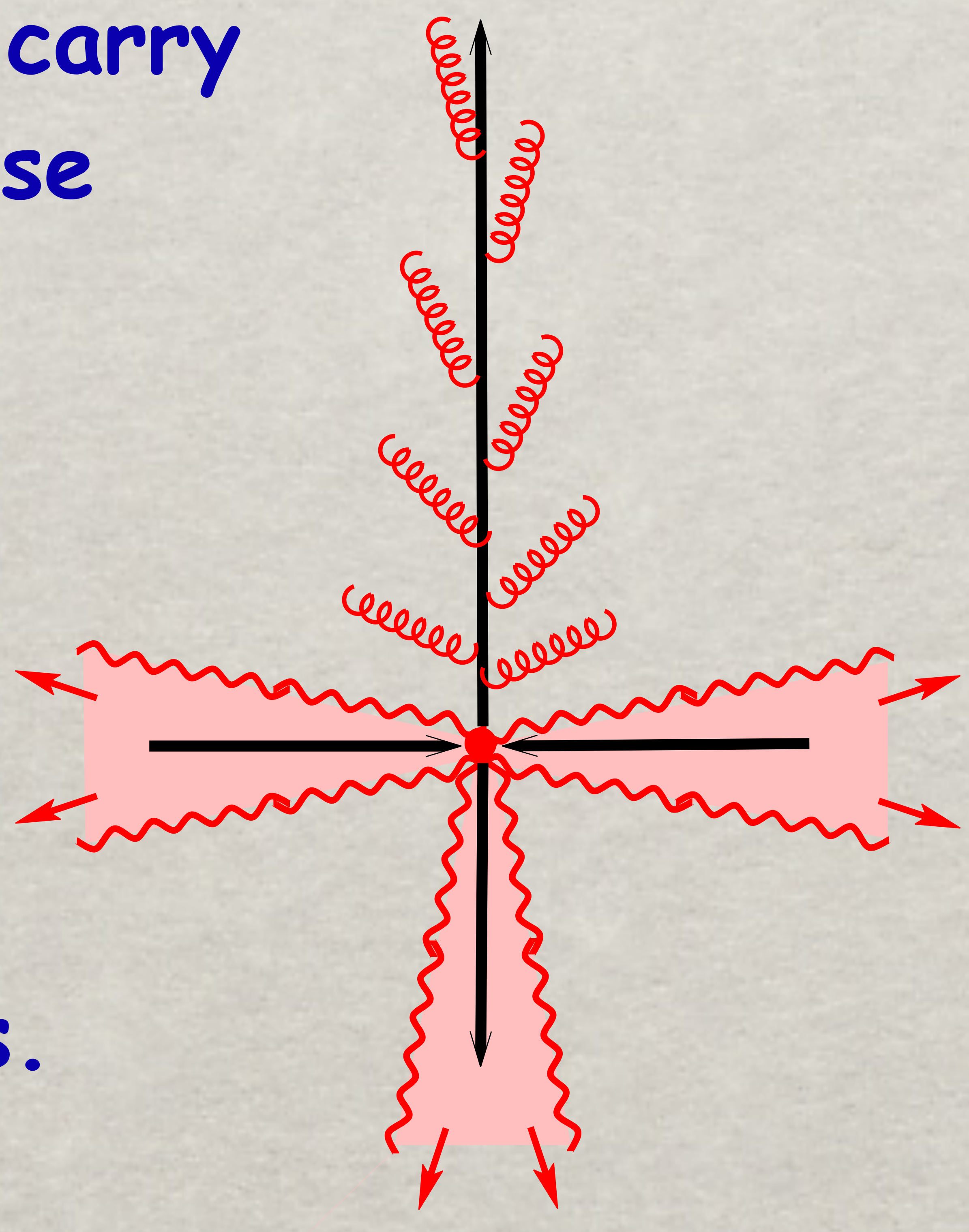
Hard parton collision

High-pt parton scattering leads to formation of 4 cones of gluon radiation:

(i) the color field of the colliding partons is shaken off in forward-backward directions.

(ii) the scattered partons carry no field up to transverse momenta kt<pt.

The final state partons are regenerating the lost color field by radiating gluons and forming the up-down jets.



The coherence length/time of gluon radiation

$$l_c = \frac{2E\,x(1-x)}{k_T^2 + x^2 m_q^2} \approx \frac{2\,\omega}{k_T^2}$$

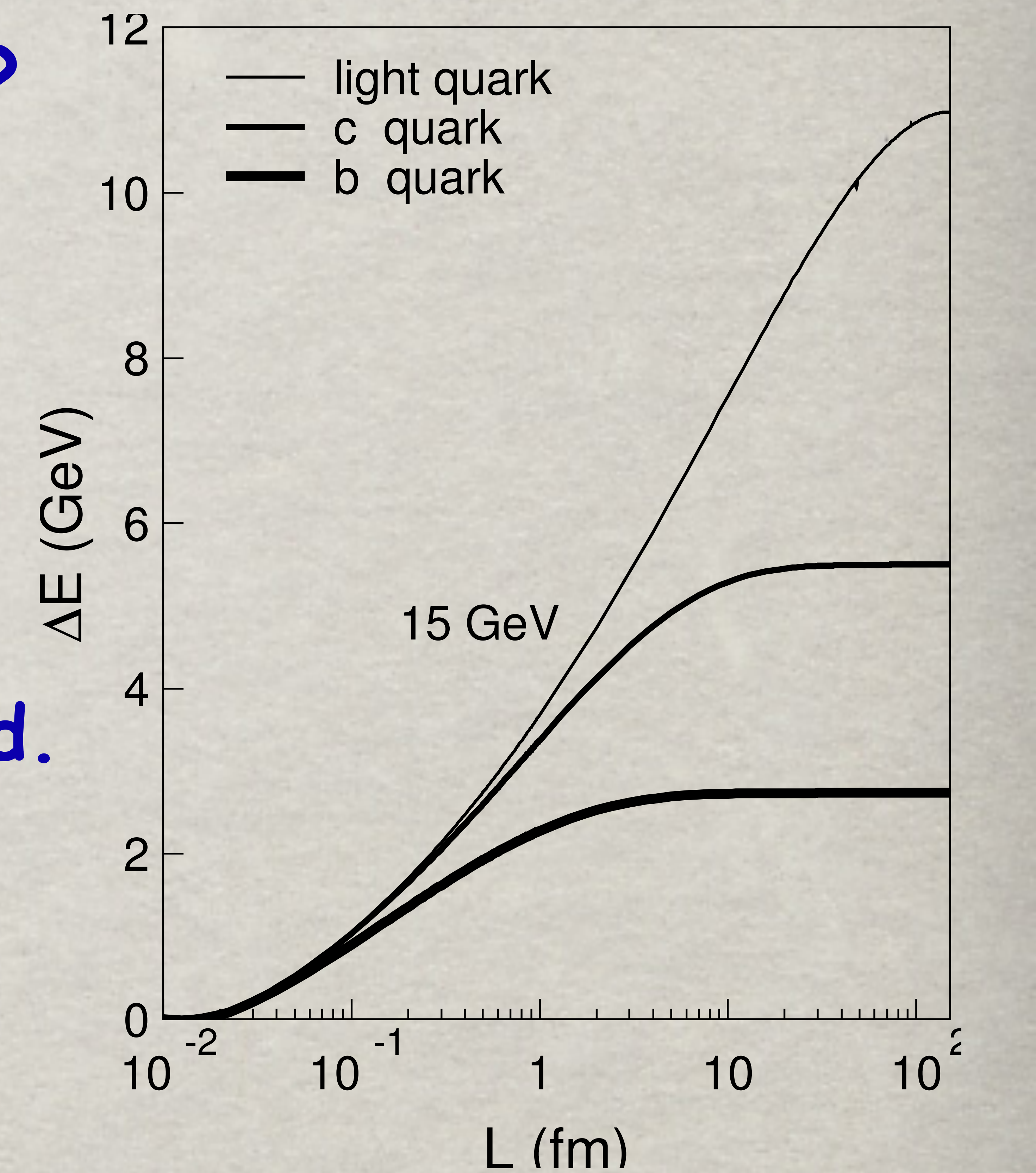
First are radiated gluons with small longitudinal and large transverse momenta.

Vacuum energy loss

How much energy is radiated over the path length L?

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

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



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

Dead-cone effect: gluons with $k^2 < x^2 m_q^2$ are suppressed.
Heavy quarks radiate less energy than the light ones.

Another dead cone: soft gluons
cannot be radiated at short path length

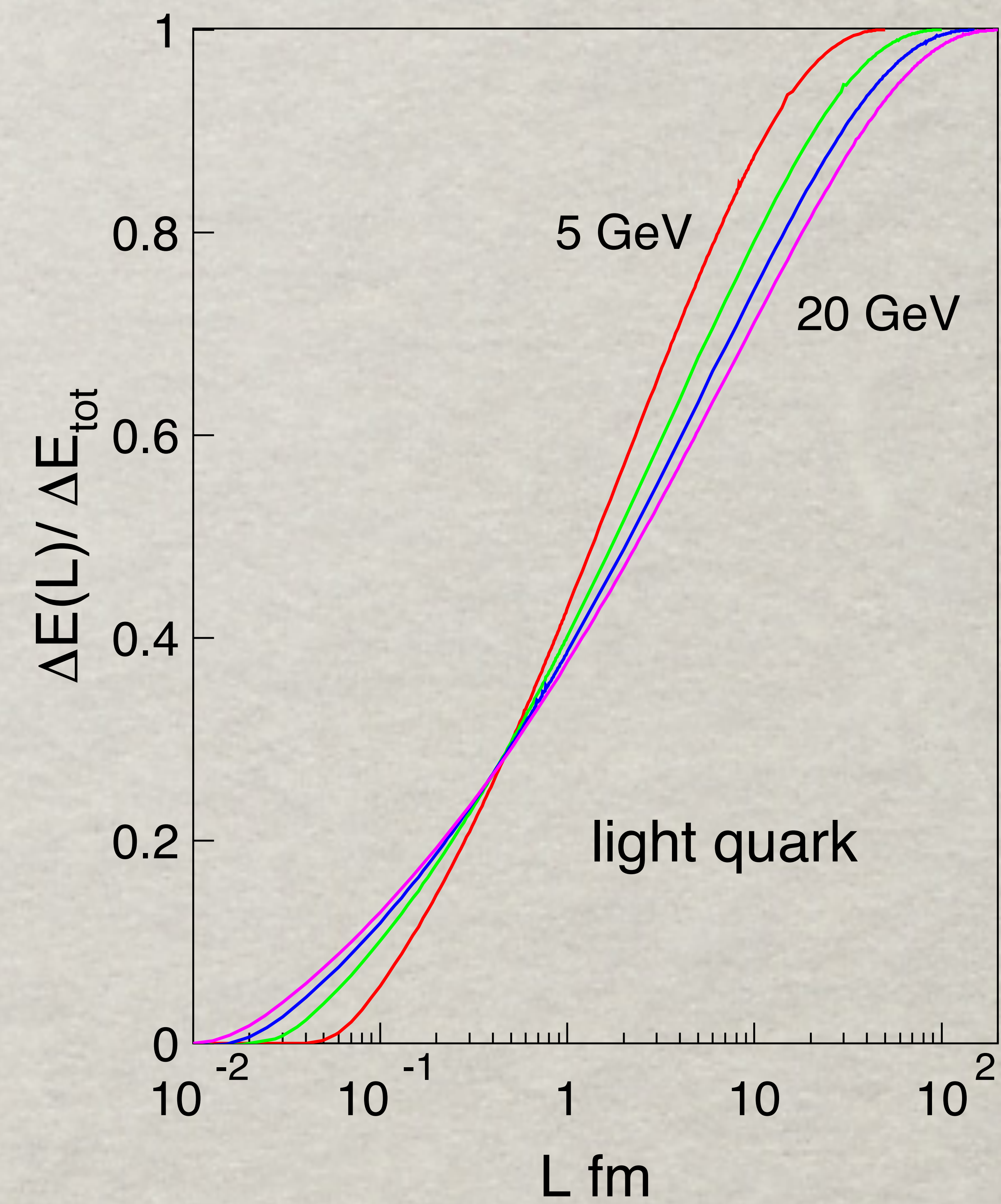
$$k^2 > \frac{2Ex(1-x)}{L} - x^2 m_q^2$$

This is why heavy and light quarks radiate with similar rates
at short time scales $L \lesssim \frac{Ex(1-x)}{x^2 m_q^2}$

Vacuum energy loss

How fast is energy dissipation?

A light quark loses 40% of the total radiated energy during the first 1fm.



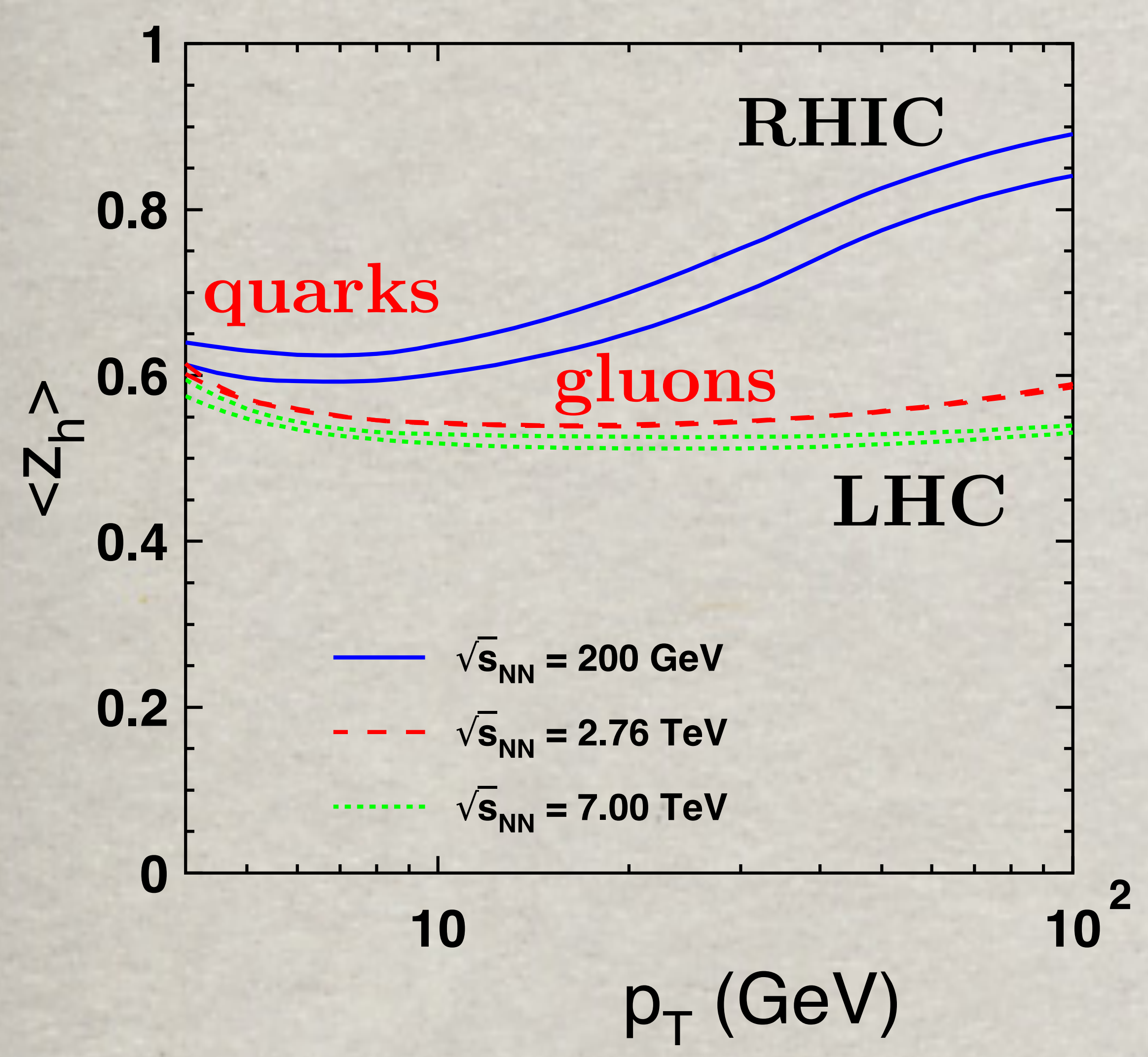
Energy conservation imposes severe restrictions on the production length l_p for hadrons with large fractional momentum z_h.

- Gluons with $\mathbf{x > 1 - z_h}$ are forbidden, This leads to Sudakov suppression

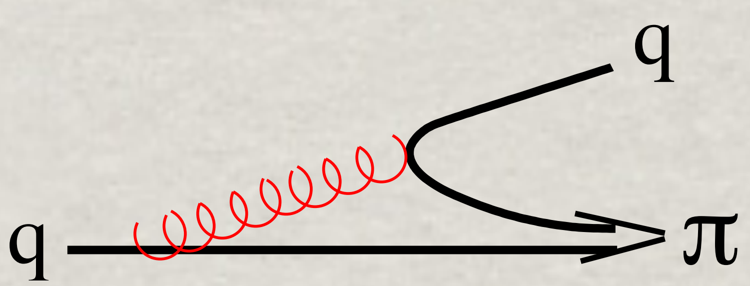
- The hadron cannot be produced after the parton momentum falls below $\mathbf{p_T}$, i.e. $\mathbf{\Delta E/E > 1 - z_h}$

Hadronization in vacuum

The mean value $\langle z_h \rangle$



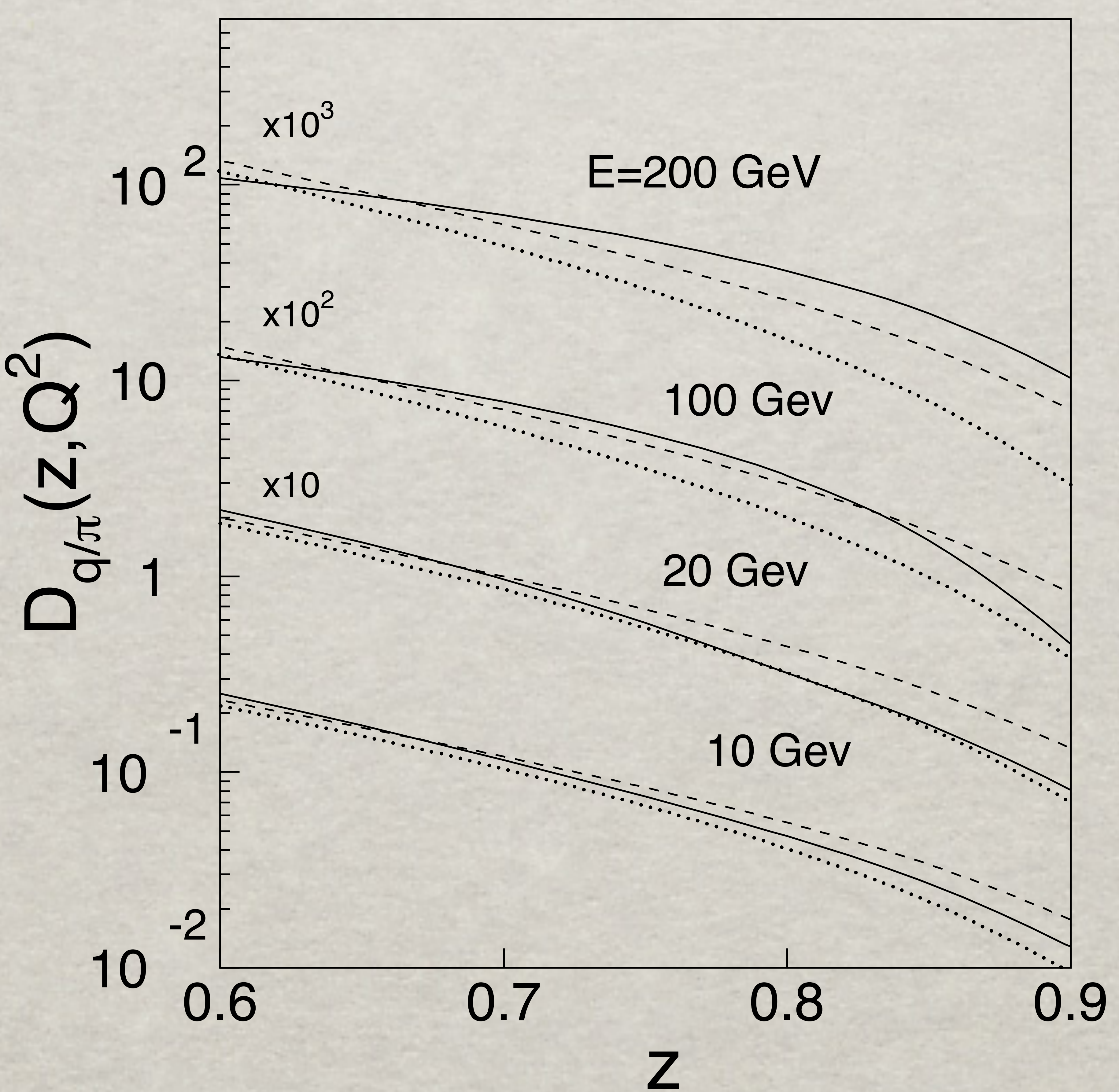
Perturbative hadronization at large z



E. Berger (1980)

B.K., H.J.Pirner,I.Schmidt,A.Tarasov (2008)

B.K., H.J.Pirner,I.Potashnikova,I.Schmidt,(20



Test vs KKP and BKK:

Production of heavy flavored mesons occur with larger z_h

$$\langle z_D \rangle = 0.76$$

$$\langle z_B \rangle = 0.89$$

$$(\sqrt{s} = 7\,\text{TeV})$$

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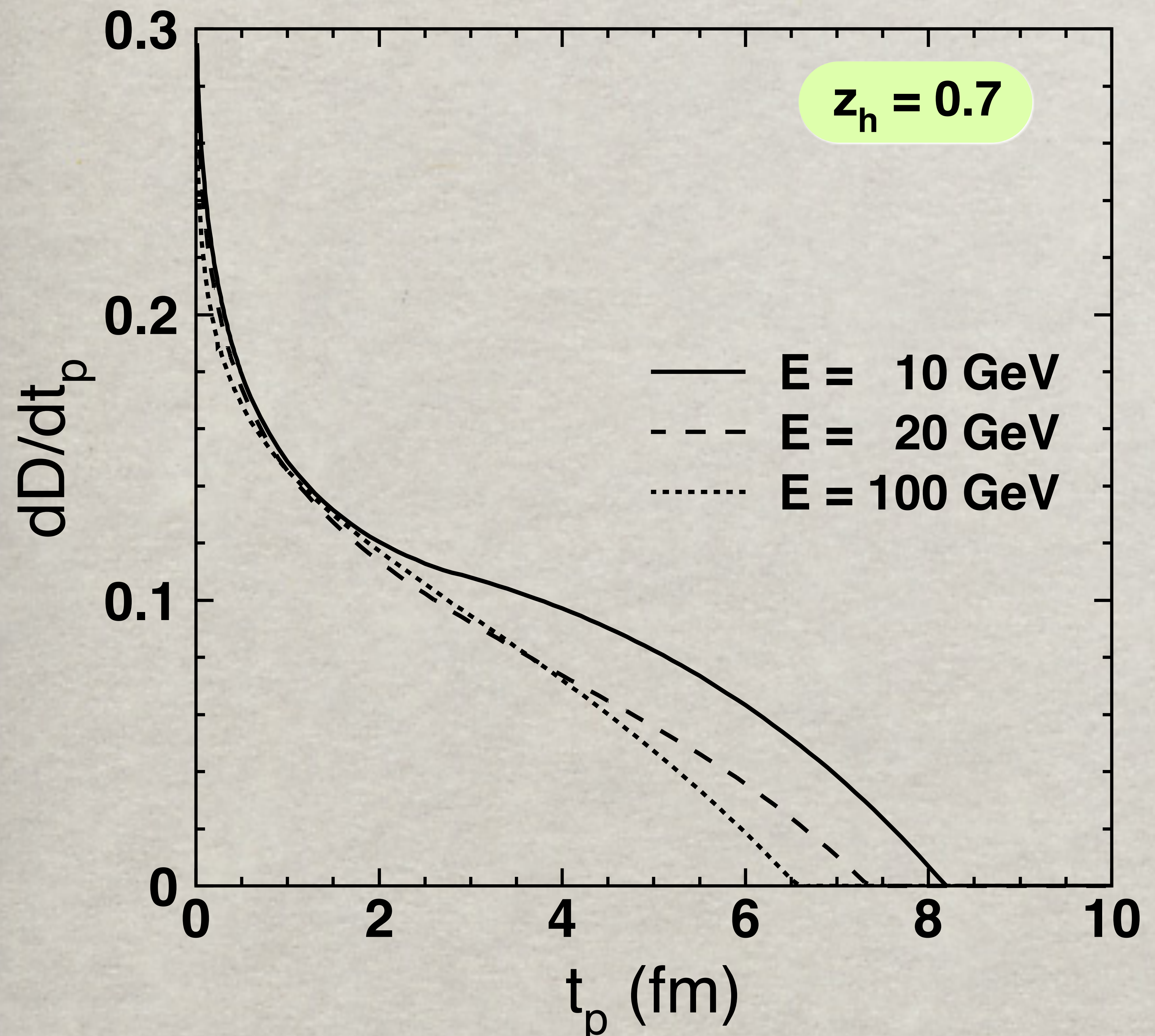
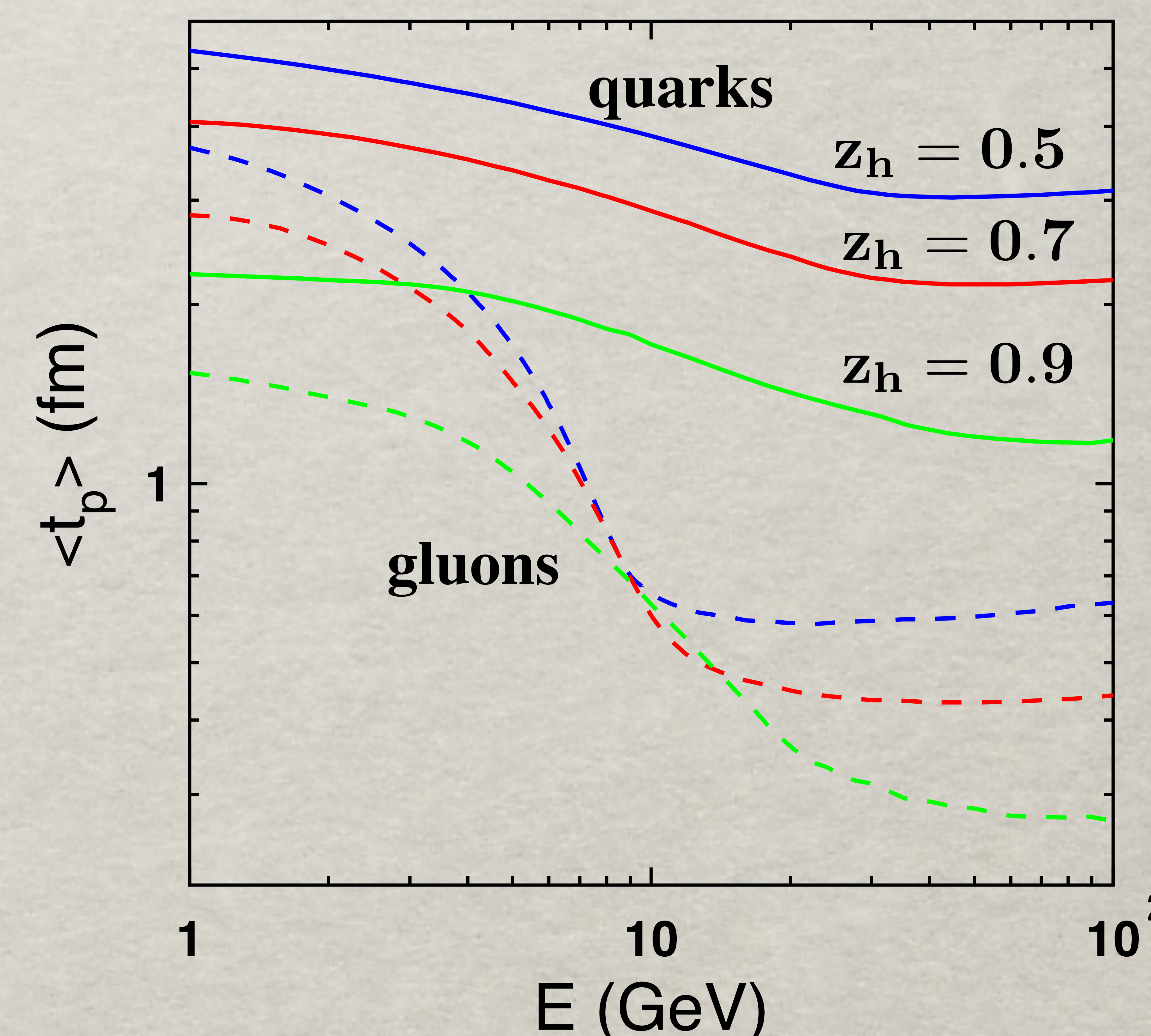
Production time/length

$\mathbf{t_p}$-dependent fragmentation function

$$\frac{\partial D_{\pi/q}(z_h, E)}{\partial t_p}$$

$$\langle t_p(z_h, E)\rangle = \frac{1}{D_{\pi/q}} \int dt_p\, t_p \frac{\partial D_{\pi/q}(z_h, E^2)}{\partial t_p}$$





B. Kopeliovich, WONPAQCD 2025

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Production time/length

Why the Lorentz factor does not make l_p longer at large p_T?

Jet features depend on two parameters, the hard scale Q^2 and jet energy E.

For the leading hadron energy conservation constraint: $l_p \lesssim \frac{E}{dE/dl}(1 - z_h)$

Energy and scale dependences of l_p in **SIDIS:**

(i) Energy dependence at fixed Q^2

$\langle dE/dl \rangle$ is fixed, so $l_p \propto E$

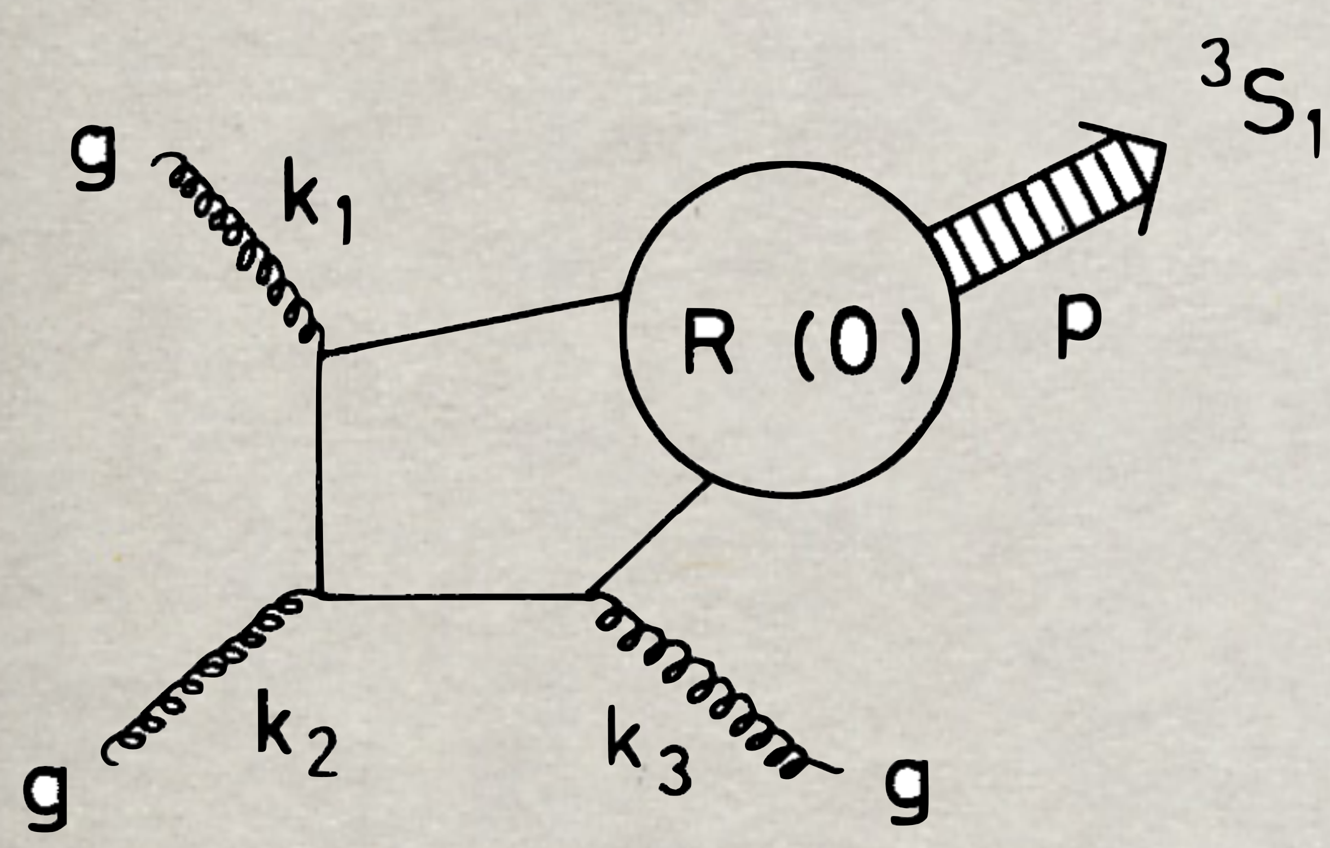
(ii) Scale dependence at fixed energy

$\langle dE/dl \rangle$ rises with Q^2, so $l_p(Q^2)$ is falling

★ **Specifics of high-pT jets: $E = p_T$; $Q^2 = p_T^2$**

Charmonium with high p_T

Color singlet mechanism

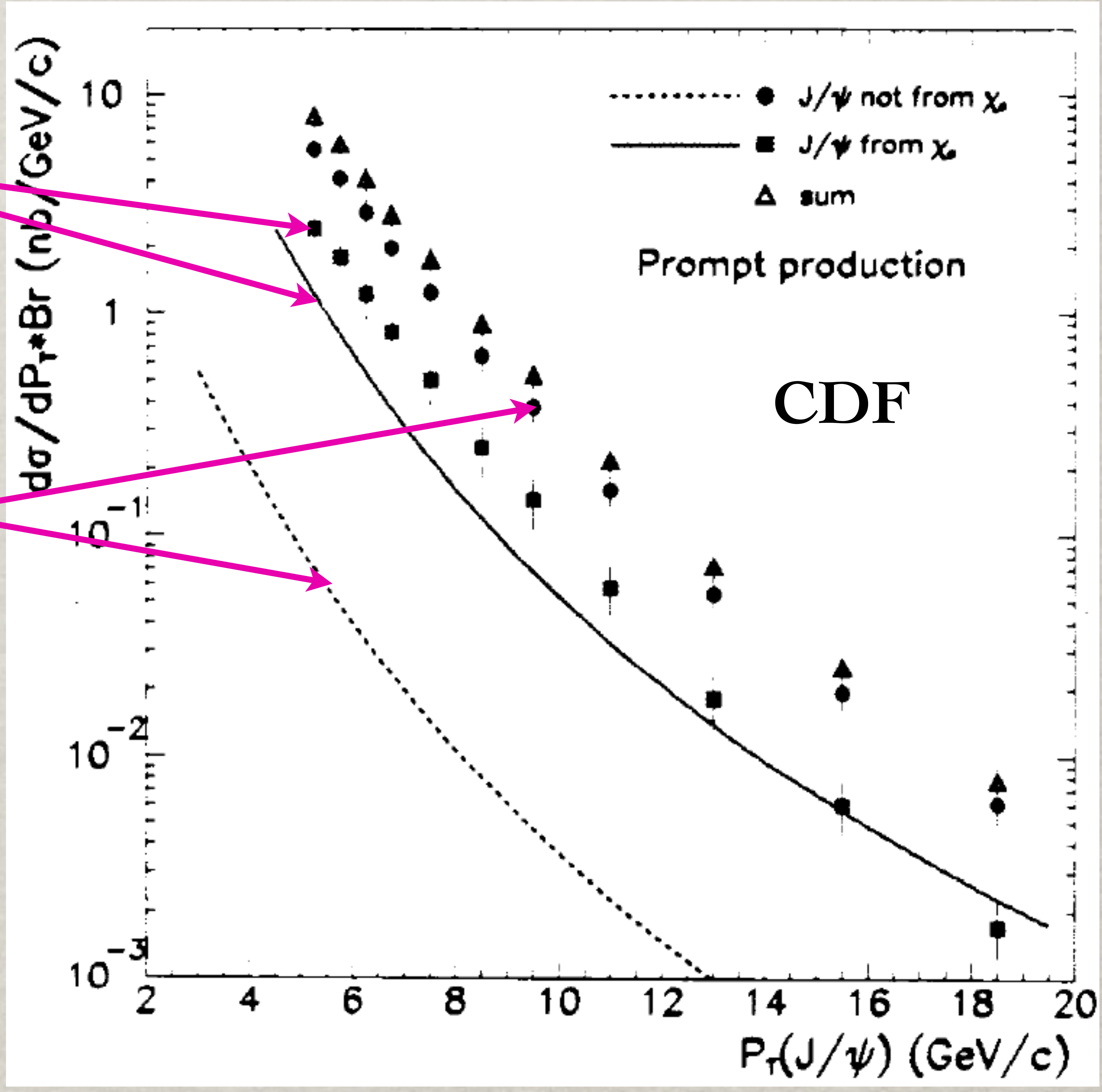


E.Berger & D.Jones (1981)
R.Baier & R.Ruckl (1981)

collinear factorization

from χ

direct J/Ψ



F. Abe et al., PRL 79(1997)572

Ph.Hagler, R.Kirschner, A.Schaefer,
L.Szymanowski, O.Teryaev(2001)

k_T factorization should not be applied at $k_T \sim p_T$

Charmonium with high p_T

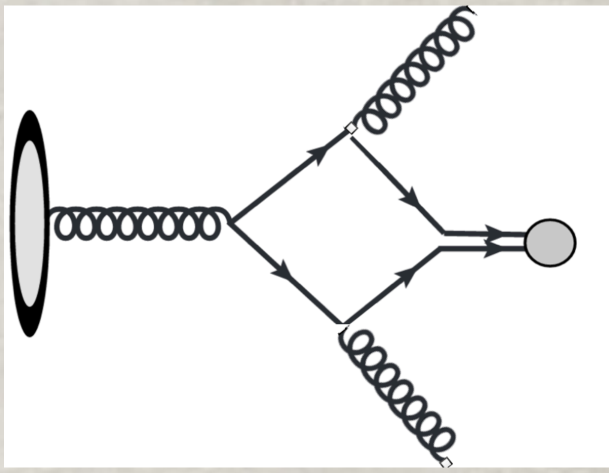
Color-singlet model fails, because the strong kick from the target breaks-up the c-cbar pair.

Color-octet model: the projectile gluon can easily accept a strong kick, and then fragment to J/ψ via production of a color-octet c-cbar. Fragmentation is assumed to happen on a long time scale, by a soft mechanism, which cannot be calculated, but fitted.

However, energy conservation restricts the time of color neutralization and the colorless c-cbar dipole is produced promptly, in the perturbative regime. Therefore this contribution can be evaluated.

Gluon fragmentation

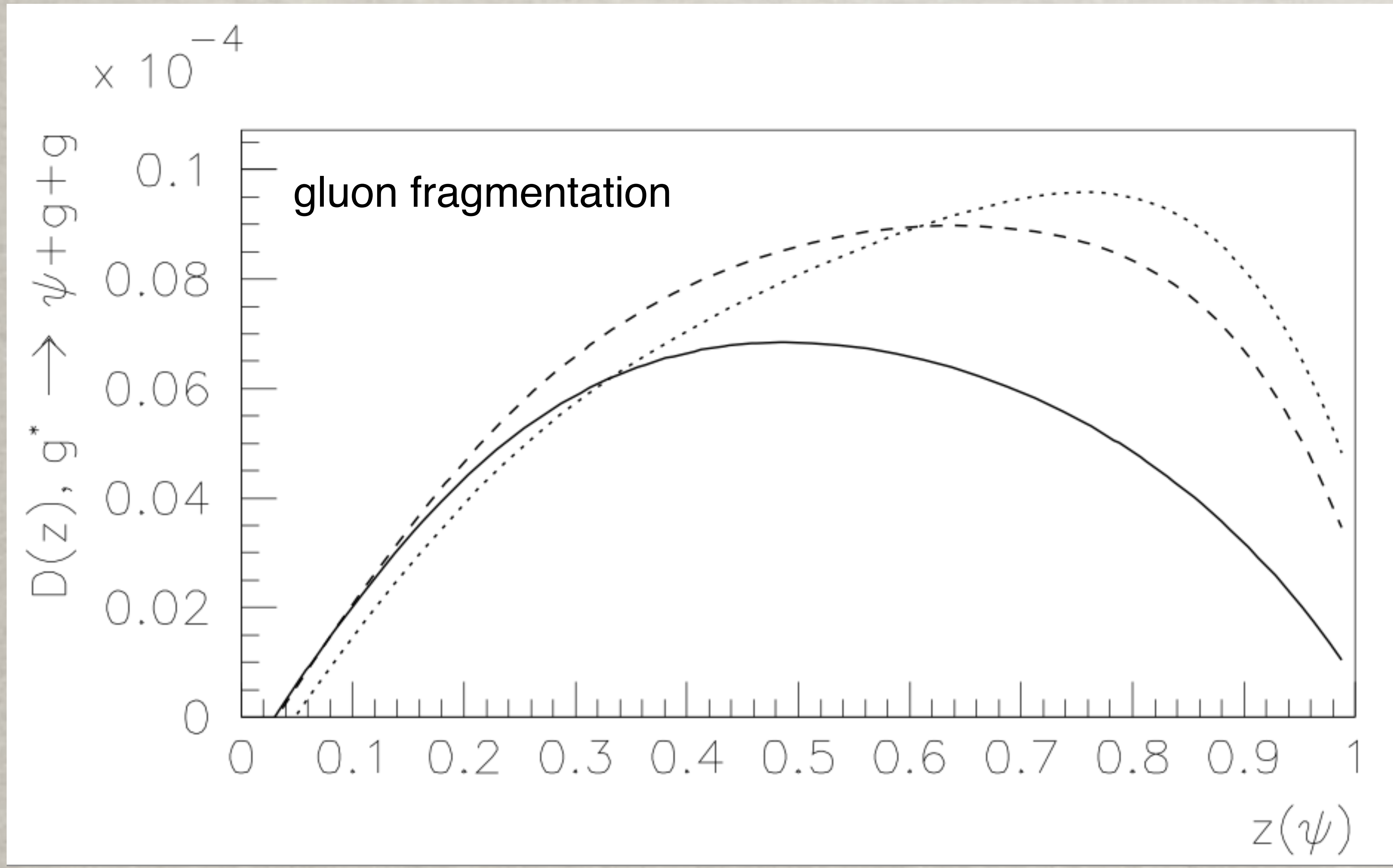
Perturbative fragmentation $\mathbf{g \to J/\psi + 2g}$

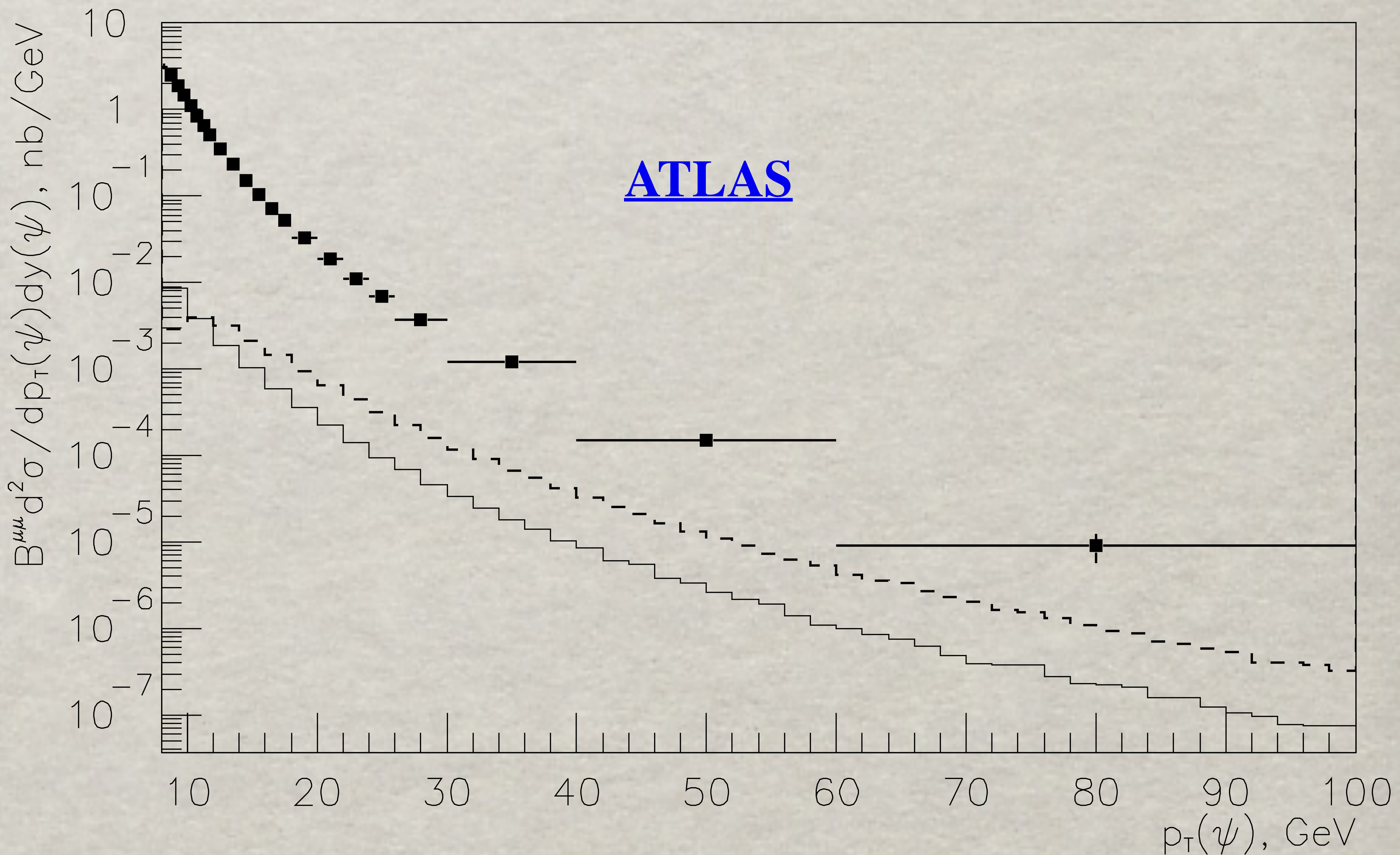


S. Baranov & B.K.

$$\mathbf{dD(g^* \to \psi gg) = \frac{1}{(2\pi)^6}\,\frac{1}{32\,m_g^6}\,|\mathcal{M}(g^* \to J/\psi gg)|^2 dm_g^2\, d\Omega_\psi\, d\phi\, ds_2\, ds_3}$$

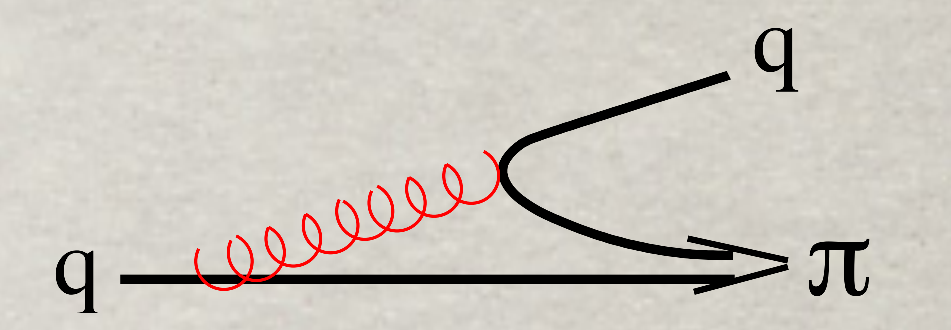
$$\mathbf{D(z) = \int D(g^* \to \psi gg)\,\delta(z - p_\psi^+/k_1^+)\,dm_g^2\, d\Omega_\psi\, d\phi\, ds_2\, ds_3.}$$





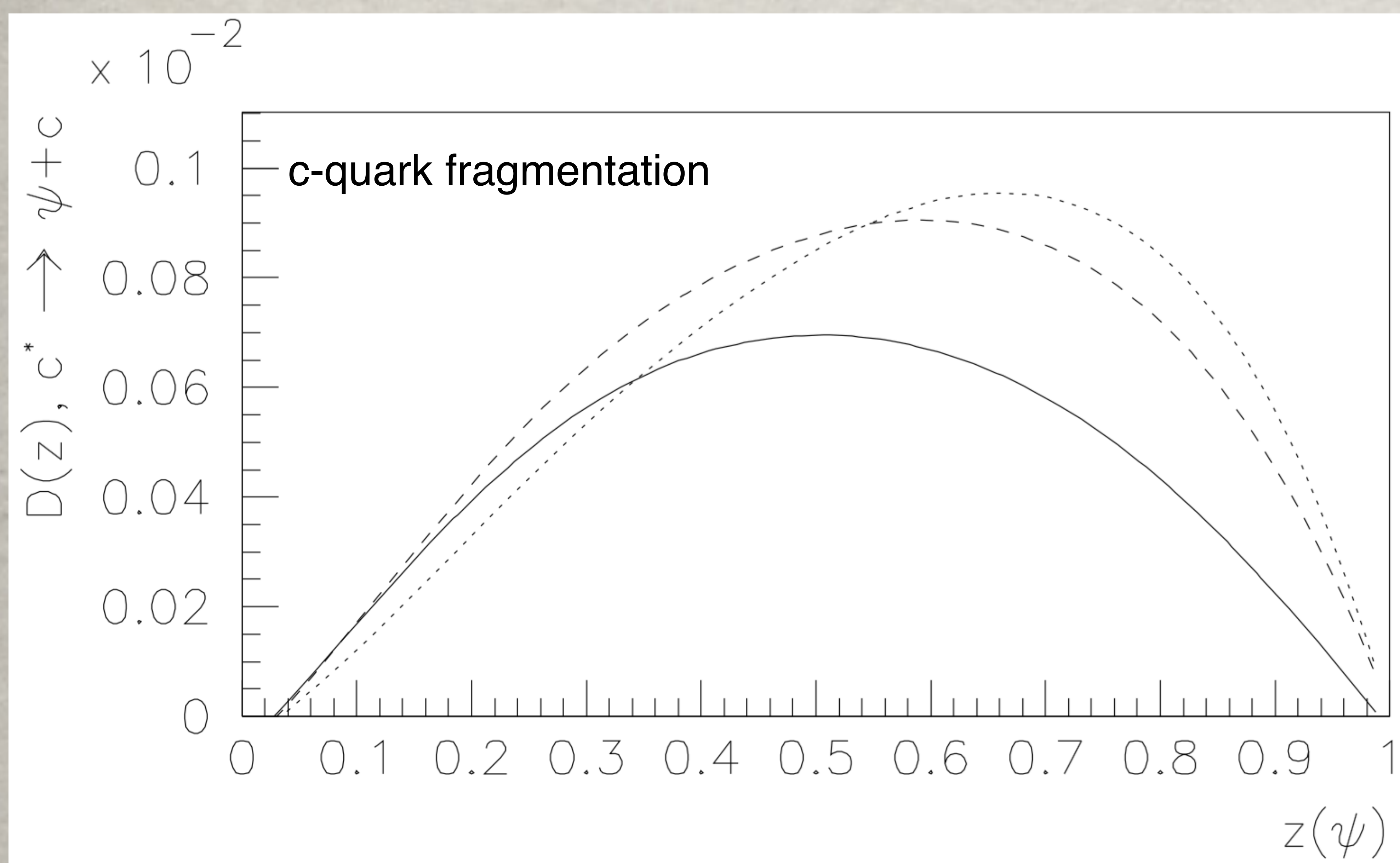
Quark fragmentation

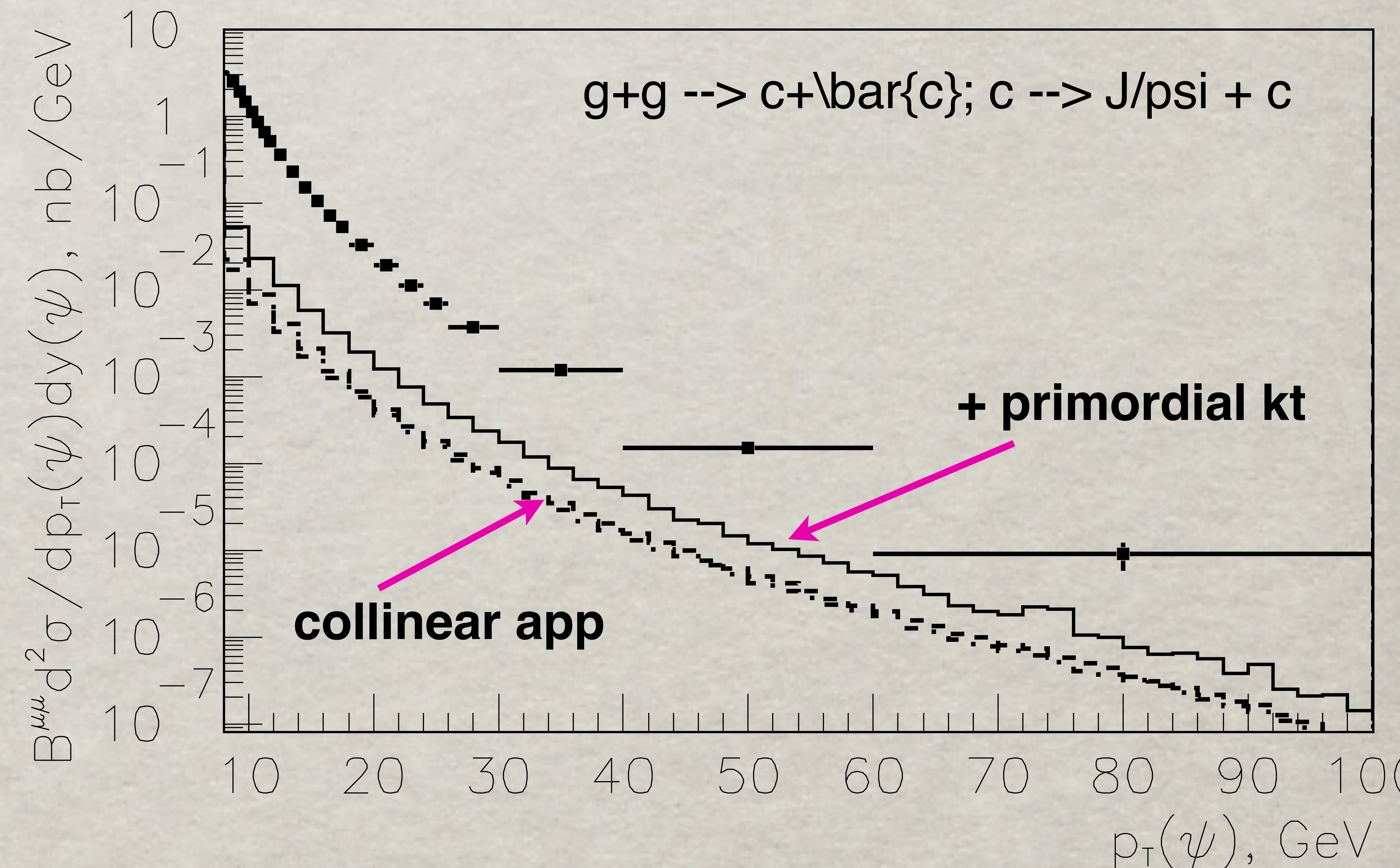
Even if a strong kick breaks-up the c-cbar pair, a single high-pT c-quark can fragment into J/ψ similar to q->πq transition



$$\mathbf{q} \to \mathbf{c} \qquad \pi \to \mathbf{J}/\psi$$

S. Baranov & B.K.





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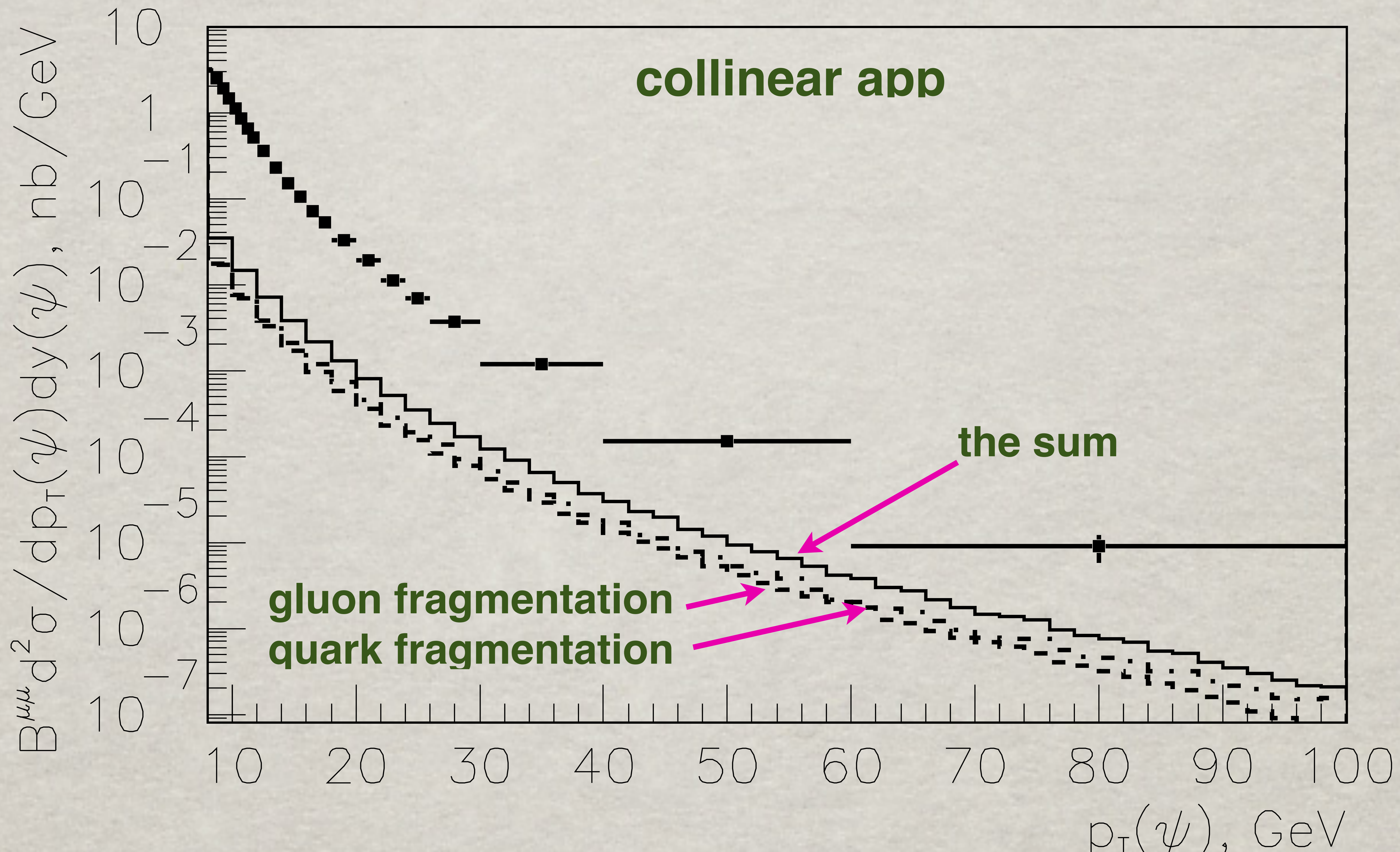
Gluon vs quark fragmentations



kt-factorization pulls the result up by about factor three

J/ψ's from X should be excluded from data, pulling it down by about 30%

Summary

- A high-p_T jet with virtuality equal to its energy dissipates energy so intensively, that has to produce a leading hadron (colorless dipole) with large z promptly, on a very short time scale, which does not rise with p_T.

- Production of a dipole on a short time scale can be treated perturbatively.

- A high-p_T J/ψ appears to result from perturbative fragmentation of either a gluon, or a quark

- Reasonable agreement with data at high p_T is achieved.