The Energy Dependence of $\hat{q}$ and Parton Saturation in QGP

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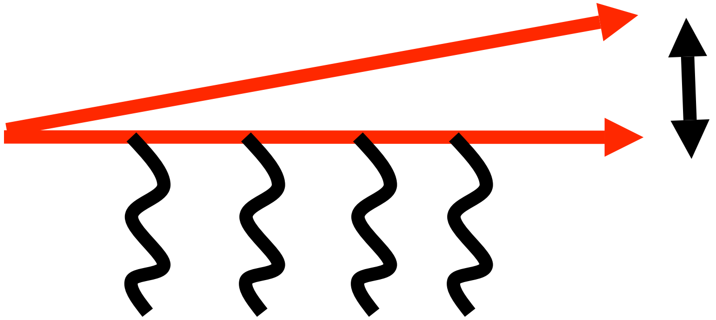
Introduction

Broadening of a probe in the medium



$$\langle p_{out}^2 \rangle = \hat{q} L$$

Jet transport parameter:

$\hat{q}$ = mean transferred momentum squared per unit length

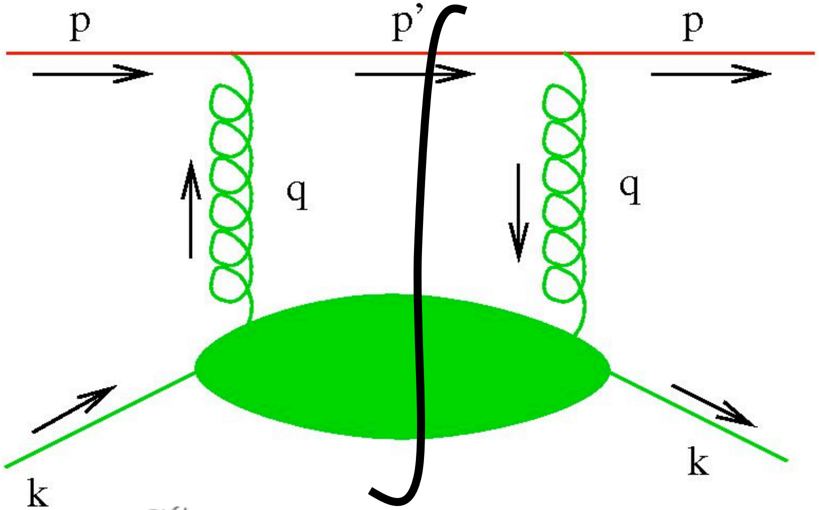
Fundamental medium property

Controls the (radiative) energy loss: $\Delta E = \frac{\alpha_s N_c}{4} \hat{q}_R L^2$

LHC allows to study jets in a large energy range

Does $\hat{q}$ depend on Energy?

$\hat{q}$ and the Gluon Distribution Function



Transverse broadening of the probe:

⇒scattering with thermal particles

$$\hat{q}_R = \rho \int dq_T^2 \frac{d\sigma_R}{dq_T^2} q_T^2$$

A closer look leads to

$$\hat{q}_R = \frac{4\pi^2 C_R}{N_c^2 - 1} \rho \int_0^{\mu^2} \frac{d^2 q_T}{(2\pi)^2} \int dx \delta\left(x - \frac{q_T^2}{2p^- \langle k^+ \rangle}\right) \alpha_s(q_T^2) \phi(x, q_T^2)$$

≀ E

≀ 3T

Unintegrated gluon distribution function

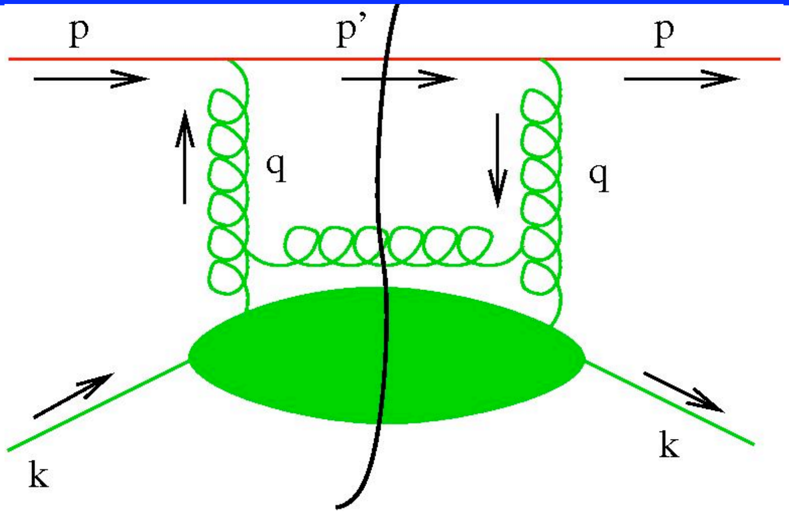
The value of x decreases with the probe energy!

If the gluon distribution is independent of x

$$\hat{q}_R \approx \frac{4\pi^2 C_R}{N_c^2 - 1} \rho \alpha_s(\mu^2) x G(x, \mu^2)$$

→ Gluon distribution per scattering center

Evolution



High Energy Jets

⇒ x is small

Large momentum transfer

⇒ large scales μ^2

The gluon distribution function grows = Evolution

Since both x^{-1} and the scale are large

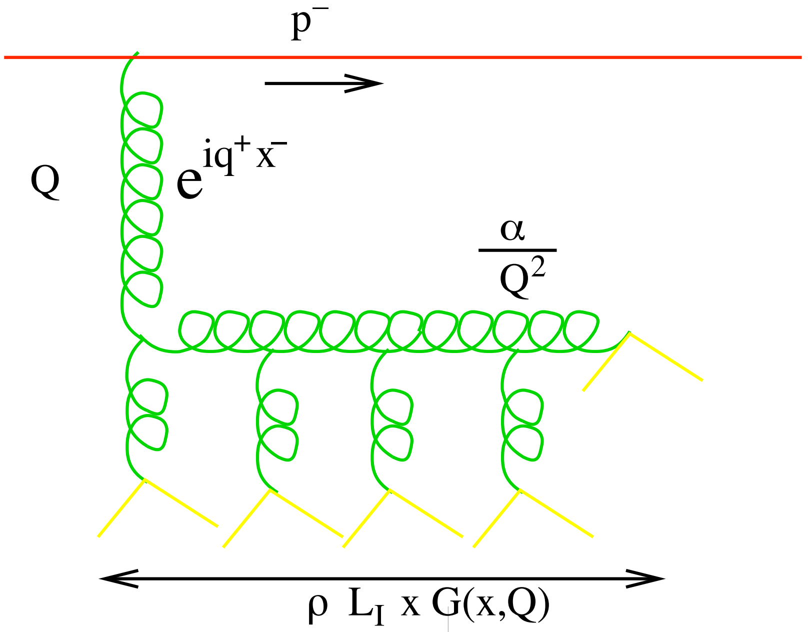
⇒ Evolution via the Double Logarithmic Approximation (DLA)

For scales $\mu \gg \mu_D$ the medium effects on the evolution are small

⇒ We use vacuum DLA evolution

Initial condition for evolution deduced from HTL.

Saturation



Multiple coherent scattering
$\Rightarrow$ saturation

Maximum length for interference

$$L_c = \frac{1}{q^+} = \frac{1}{xT} \approx \frac{6ET}{Q_s^2}\frac{1}{T}$$

Saturation scale is determined by:

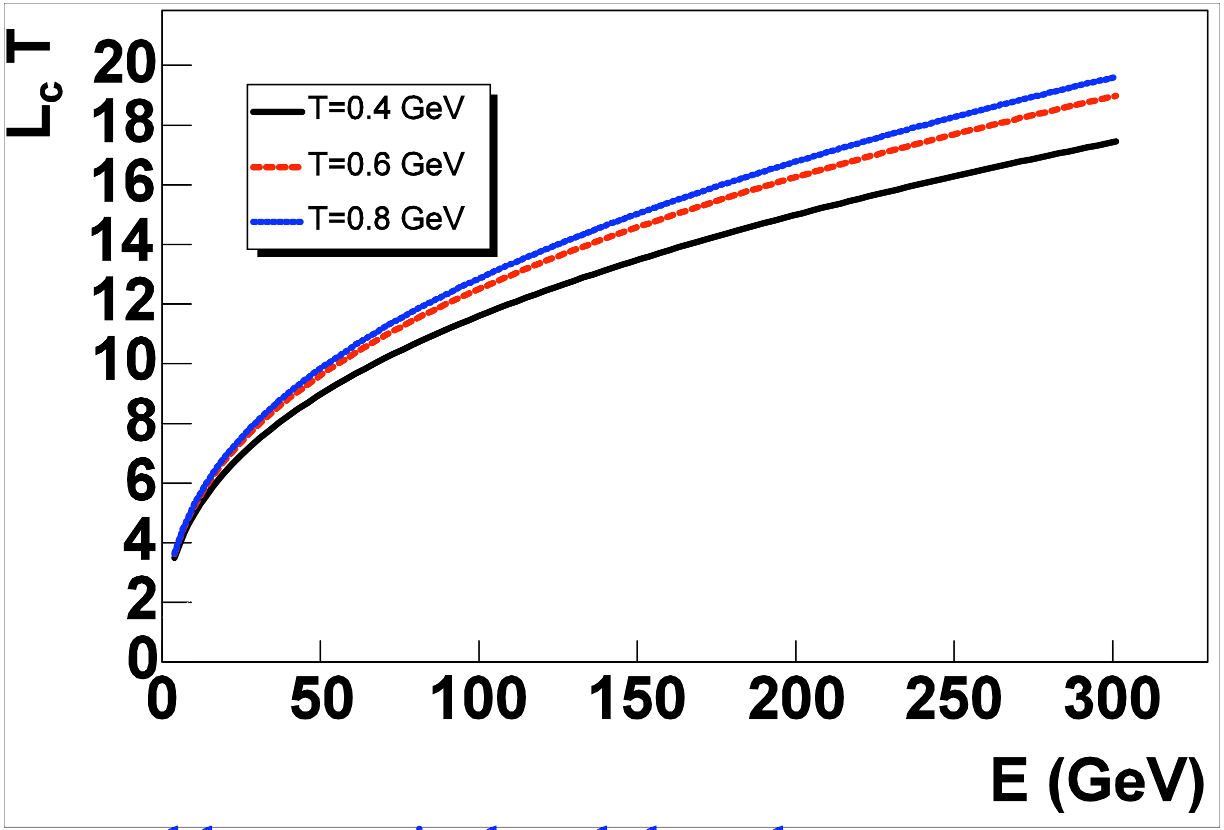
$$Q_s^2(x) = \frac{4\pi^2 N_c \alpha_s\left(Q_s^2\right)}{N_c^2-1}\rho x G(x,Q_s^2)\,\mathrm{min}(L,L_c)$$

The QGP density is much larger than nuclear density

Saturation sets at larger x

The saturation scale is larger

Coherence Length

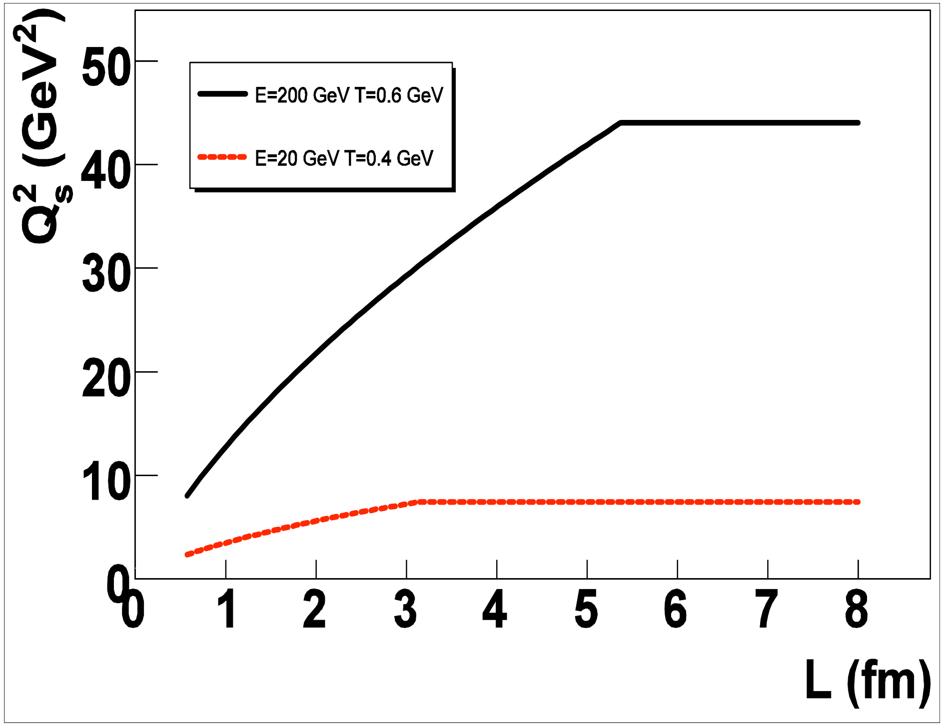


L_c is comparable to typical path length

L_c = 5 fm for E=300 GeV and T=0.6 GeV

The effect of Λ_{QCD} leads to non trivial scale dependence

Saturation: Length Dependence



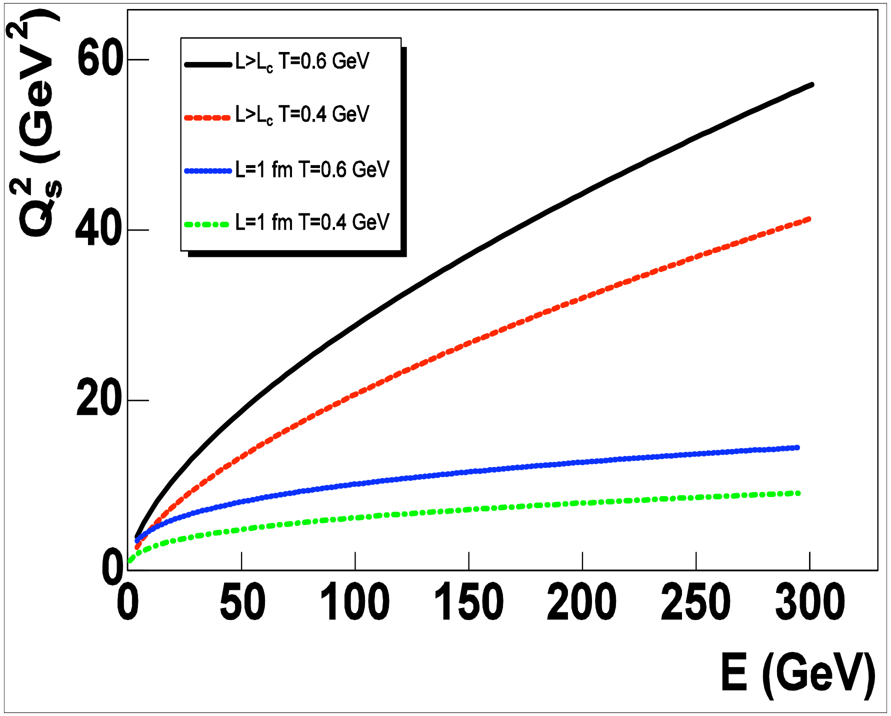
Q_s grows with path length. Coherence length stops the growth.

The abrupt change for $L=L_c$ is a consequence of simplified treatment

Evolutions leads to $Q_s^2 \sim L^p$, $p \approx 0.7$ (from numerics)

slower than linear!

Saturation: Energy Dependence



We obtain large values for the saturation scale (large density)

Significant energy dependence:

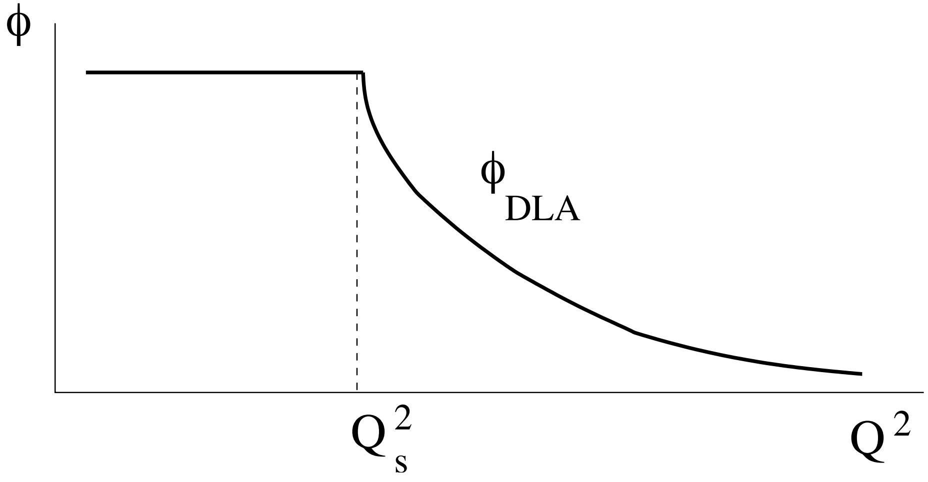
For L>L$_c$ fast grow $Q_s^2 \sim \dfrac{ET}{Q_s^2 T} \Rightarrow Q_s^2 \sim \sqrt{E}$

$\hat{q}$ from the Thermal Gluon Distribution

Simplified treatment of the unintegrated gluon distribution

Constant for $Q^2 < Q^2_s$

Linear evolution for $Q^2 > Q^2_s$

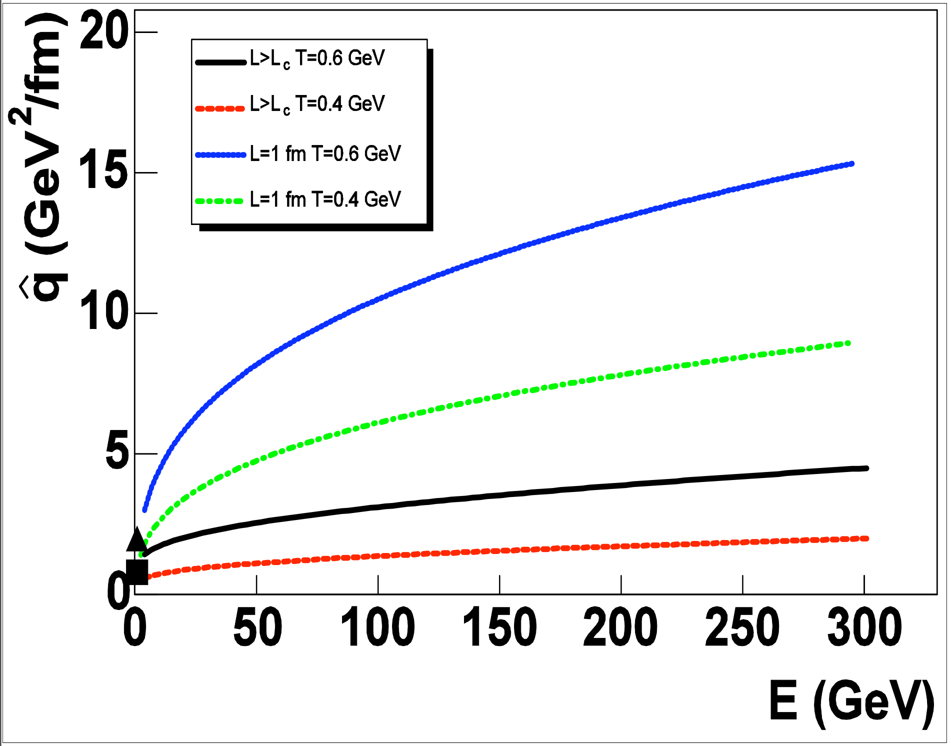


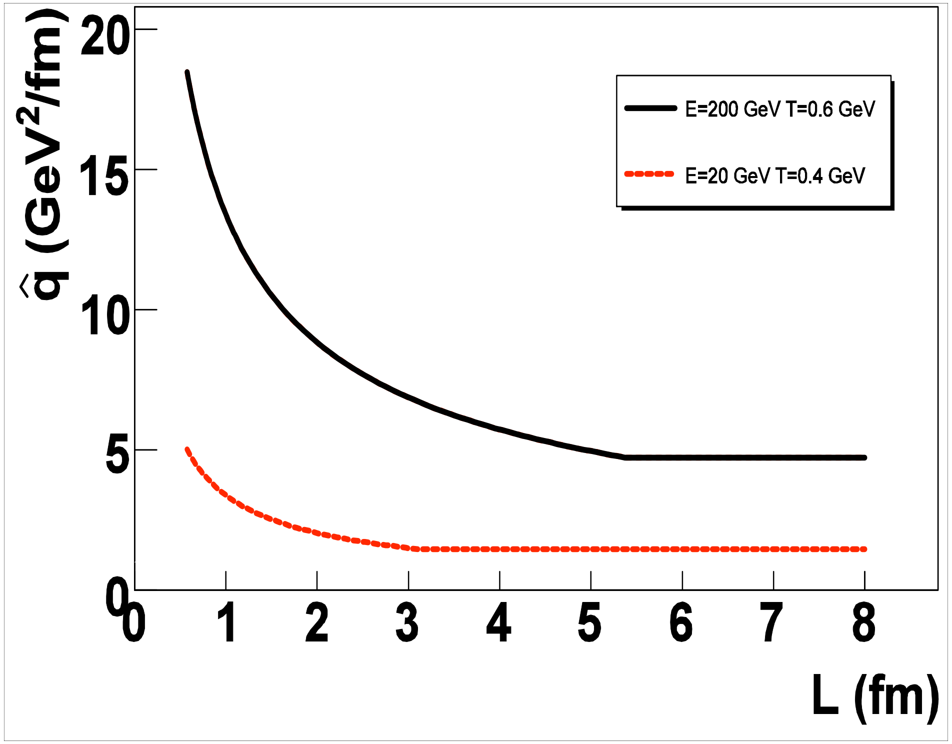
We find

$$\hat{q}_R = \frac{C_R}{N_c}\frac{Q_s^2}{\min(L, L_c)}\frac{\ln\frac{1}{x_m}}{\ln\frac{Q_s^2(x_m)}{\Lambda^2}} \times \left[\frac{\delta_L}{\sqrt{\pi\frac{b}{N_c}\ln\frac{1}{x_m}\ln\left(\ln\frac{Q_s^2}{\Lambda^2}\Big/\ln\frac{\mu^2}{\Lambda^2}\right)}} + \frac{1}{\ln\left(\ln\frac{Q_s^2}{\Lambda^2}\Big/\ln\frac{\mu^2}{\Lambda^2}\right) - \frac{\ln(1/x_m)}{\ln(Q_s^2(x_m)/\Lambda^2)}}\right]$$

The transport coefficient is determined by the saturation scale (as expected)

$\hat{q}$





Evolution leads to energy dependence

Non trivial lenght dependence

Apparent divergence of $\hat{q}$ is due to $Q_s^2 \sim L^p$, $p \approx 0.7$ (from numerics)

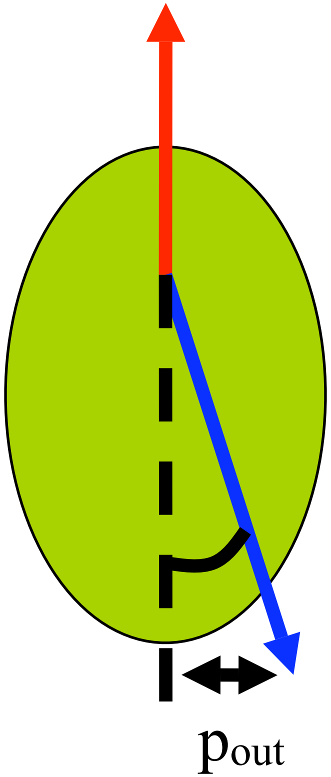
Jet Acoplanarity

Look for γ + jet events

γ gives the initial direction

The back-jet broadens in its propagation

The jet acoplanarity is sensitive to the transferred momentum

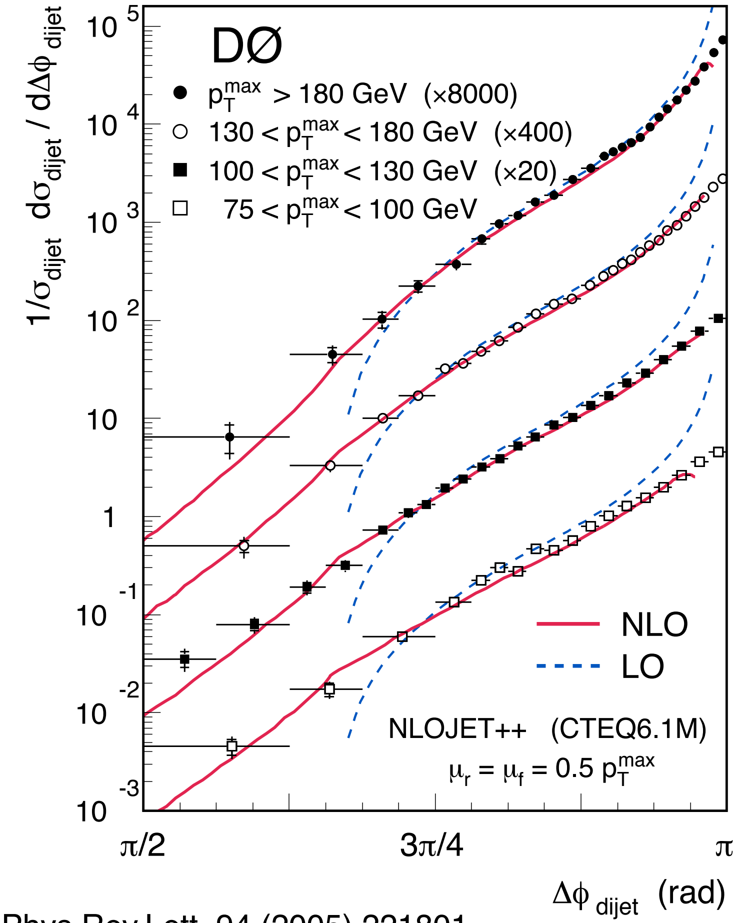


Since γ does not lose energy, the typical length is the average length

Cross check for the jet energy loss since it depends on the broadening

Large Vacuum Acoplanarity

Acoplanarity in p+p



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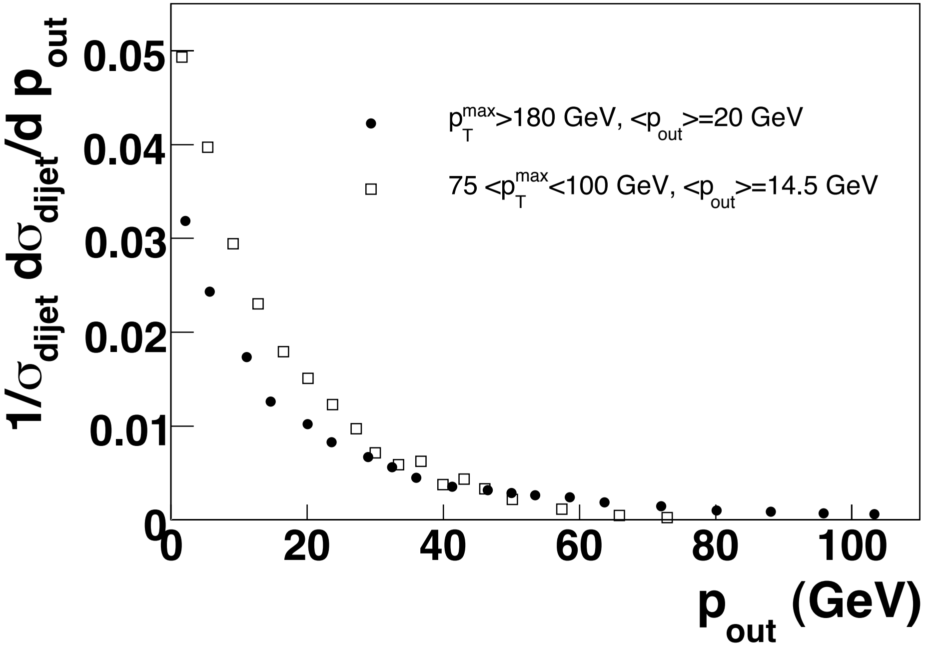
$$p_{out} = p_T^{max} \sin(\Delta\theta)$$



Medium effect (Gaussian)

$$\langle p_{out} \rangle = \sqrt{\frac{Q_s^2}{4\pi}} \approx \sqrt{\frac{35\,\mathrm{GeV}^2}{4\pi}} \approx 1.3\,\mathrm{GeV}$$

Thanks to: I. Dominguez Jimenez, G. Paic

Conclusions

Ø $\hat{q}$ is determined from the unintegrated gluon distributions

High energy jets probe the small x region

Ø The growth of the gluon distribution leads to saturation (in the plasma)

Large densities lead to large Q_s

Ø q depends on the saturation scale (as expected)

Rapidity dependent Q_s leads to energy dependent $\hat{q}$

Ø The energy and length dependence of $\hat{q}$ is significant in the kinematic range of LHC jets.

Back up

Large Vacuum Acoplanarity

Initial state radiation ⇒ Large vacuum acoplanarity

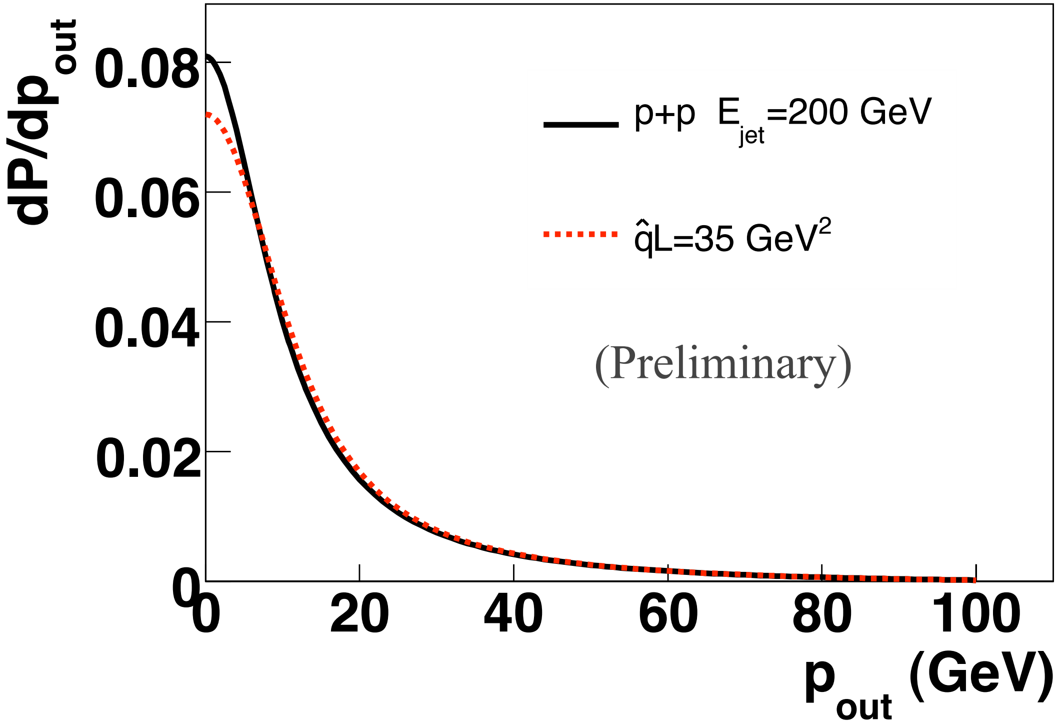
(estimated via LO-PQCD:
Davis, Webber and Stirling, 85)

$$\langle p_{out}^2 \rangle_{vac} \approx 400 GeV^2$$

Medium effect

⇒ gaussian broadening

$$\langle p_{out}^2 \rangle_{me} \approx 35 GeV^2$$



Thanks to: I. Dominguez Jimenez, G. Paic

Broadening of Thermal Particles

For thermal particles, $\hat{q}$ is computed via HTL

$$\hat{q}_R = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\rho\int dx\frac{dq_T^2}{(2\pi)^2}\delta\left(x-\frac{q_T^2}{2p^-\langle k^+\rangle}\right)\overbrace{2N_c\alpha_s\frac{\pi^2}{6\zeta(3)}q_T^2|\mathcal{M}_{Rb}|^2}^{\phi(x,q_T)}$$

With the HTL propagator:

$$\mathcal{M}_{Rb}\approx\left[\frac{1}{q^2+\mu_D^2\pi_L(x_q)}-\frac{(1-x_q^2)\cos\phi}{q^2(1-x_q^2)+\mu_D^2\pi_T(x_q)+\mu_{\mathrm{mag}}^2}\right]$$

$$x_q=\frac{\omega}{q}\approx\frac{3xT}{q_T}$$

For a maximum momentum transfer of order T

$$xG(x,\mu)=\int^{\mu}\frac{d^2q_T}{(2\pi)^2}\phi(x,q_T^2)$$

$$xG(x,\mu^2)\approx C_A\frac{\alpha_s}{\pi}\frac{\pi^2}{6\zeta(3)}\frac{1}{2}\left[\frac{3}{2}\ln\frac{\mu^2}{\mu_D^2}+\frac{1}{3}\ln\frac{\mu_D}{xT}\right]$$

We use this as initial condition at $\mu=T$