Jet quenching in an EFT framework

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Outline

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   - the jet quenching parameter $\hat{q}$
   - energy scales and degrees of freedom
   - SCET

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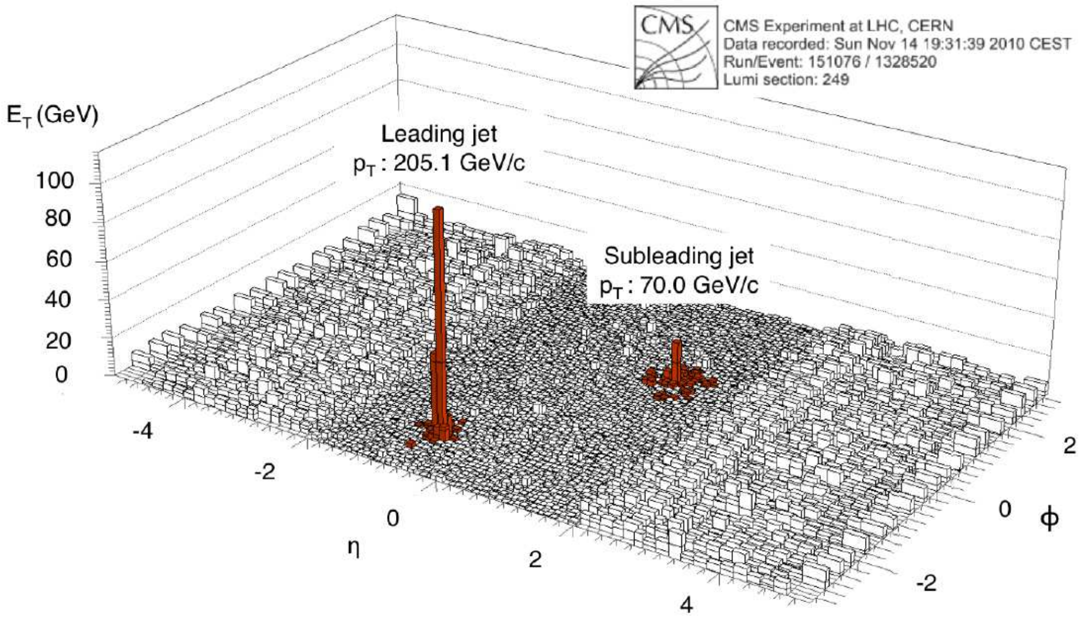
1. INTRODUCTION

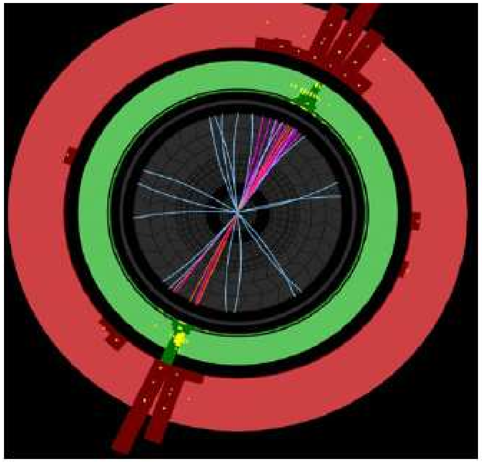
Jet quenching

Jet quenching was first observed at RHIC and then confirmed at LHC.

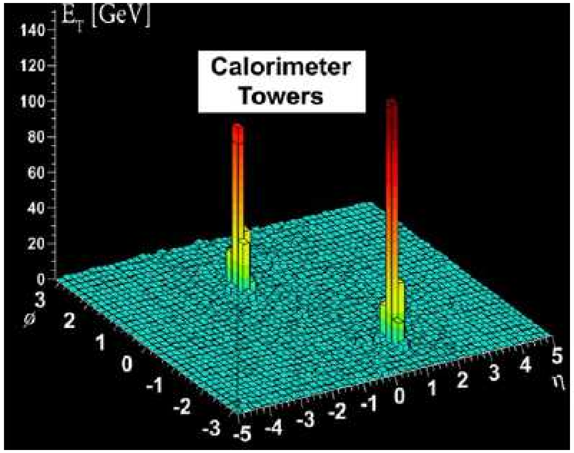
This phenomenon happens when a very energetic quark or gluon, $Q \gg T$, which in vacuum would manifest itself as a jet, going through a strongly coupled plasma loses sufficient energy that few high momentum hadrons are seen in the final state.

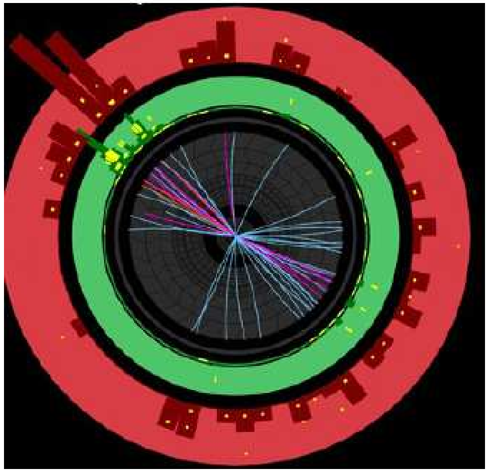


Jet quenching

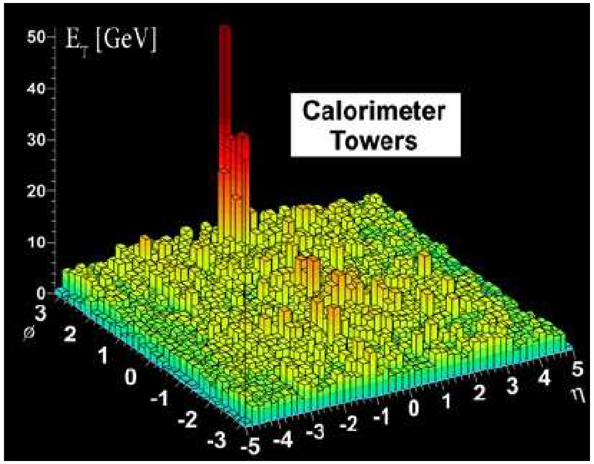


p+p event





Pb+Pb event
(very central)

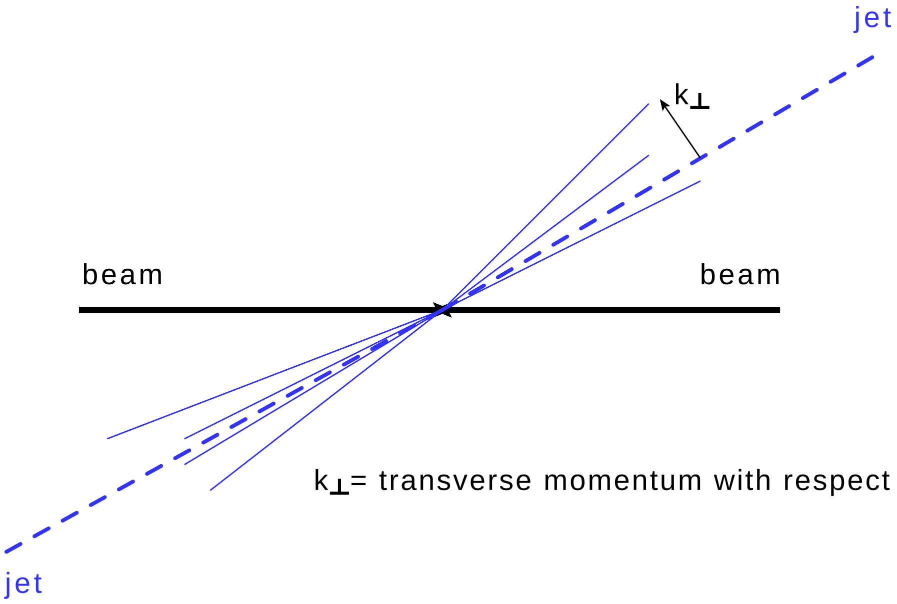


Jet quenching

Jet quenching manifests itself in many observables.

In particular, the hard partons produced in the collision

- lose energy;
- change direction of their momenta: transverse momentum broadening.



$k_\perp$= transverse momentum with respect to the original hard parton direction

Jet quenching parameter $\hat{q}$

$P(k_\perp)$ is the probability that after propagating through the medium for a distance L the hard parton acquires transverse momentum $k_\perp$,

$$\int \frac{d^2 k_\perp}{(2\pi)^2} P(k_\perp) = 1$$

$\hat{q}$ is the jet quenching parameter, i.e. the mean square transverse momentum picked up by the hard parton per unit distance traveled,

$$\hat{q} = \frac{\langle k_\perp^2 \rangle}{L} = \frac{1}{L} \int \frac{d^2 k_\perp}{(2\pi)^2} k_\perp^2 P(k_\perp)$$

Jet quenching: early literature

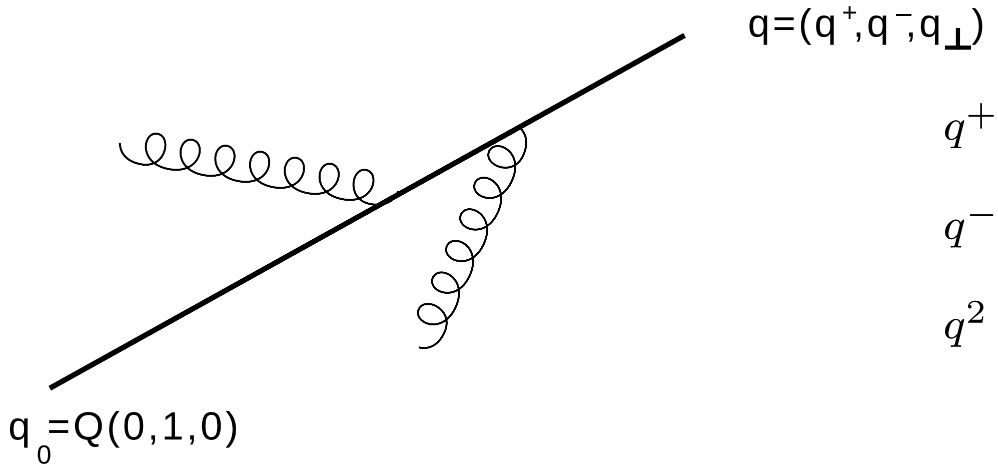
There has been a long-time effort to determine $\hat{q}$ from QCD.

- The relation of $\hat{q}$ to the expectation value of two Wilson lines oriented along one of the light-cone directions has been established over the last fifteen years.
  - `Baier Dokshitzer Mueller Peigne Schiff NP B483 (1997) 291`
    `Zakharov JETPL 63 (1996) 952`
    `Casalderrey-Solana Salgado APP B38 (2007) 3731`
    `Liang Wang Zhou PR D77 (2008) 125010`

- Effective field theories (EFTs) taking advantage in a systematic way of the many scales involved in the problem have been used more recently.
  - `D'Eramo Liu Rajagopal PR D84 (2011) 065015`
    `Ovanesyan Vitev JHEP 1106 (2011) 080`

Energy scales: kinematics and medium

A highly energetic parton, $Q > 100$ GeV, propagates along the light-cone direction $\bar{n}$.



$$q^+ = \bar{n} \cdot q \qquad \bar{n} = (1,0,0,-1)/\sqrt{2}$$

$$q^- = n \cdot q \qquad n = (1,0,0,1)/\sqrt{2}$$

$$q^2 = 2q^- q^+ - q_\perp^2$$

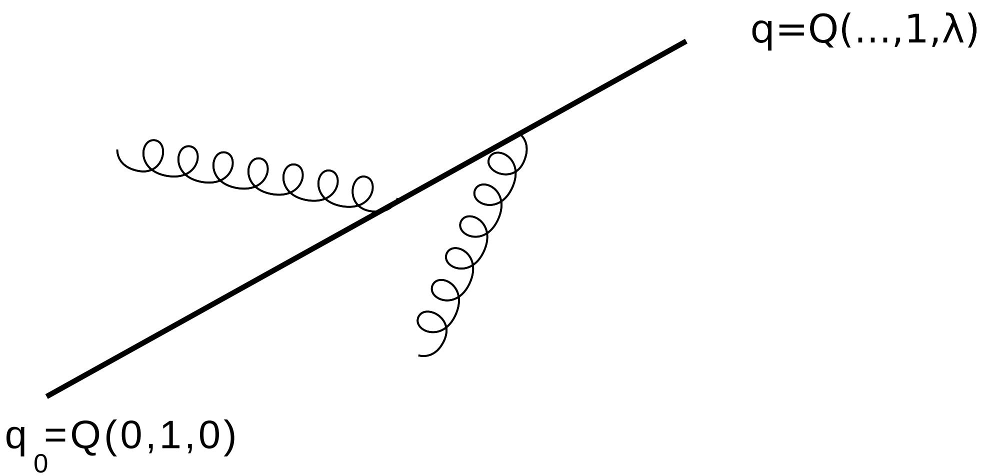
In a medium characterized by a scale (e.g. temperature) $T \ll Q$:

$$\lambda \equiv \frac{T}{Q} \ll 1$$

λ will be the relevant expansion parameter.

Energy scales: collinear partons

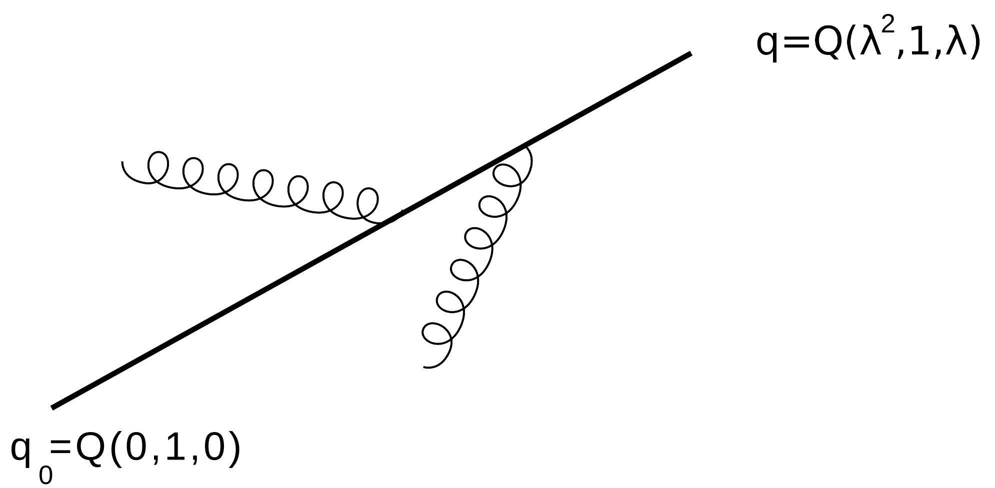
We consider partons that undergo a transverse momentum broadening of order $Q\lambda$:



- if $q = Q(\lambda, 1, \lambda)$, the parton is off shell by $\sim Q^2\lambda$: the parton is hard-collinear;
- if $q = Q(\lambda^2, 1, \lambda)$, the parton is off shell by $\sim Q^2\lambda^2$: the parton is collinear.

Energy scales: Glauber gluons

We consider the transverse momentum broadening of a collinear parton:



It may happen through

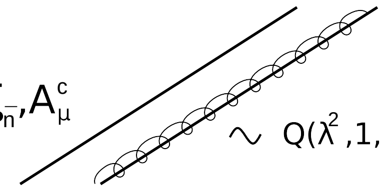
- fragmentation into collinear partons (gluons, quarks) of momentum $q = Q(\lambda^2, 1, \lambda)$;
- scattering by soft gluons of momentum $q = Q(\lambda, \lambda, \lambda)$;
- scattering by Glauber gluons of momentum $q = Q(\lambda^2, \lambda, \lambda)$ or $q = Q(\lambda^2, \lambda^2, \lambda)$.

○ Idilbi Majumder PR D80 (2009) 054022

Degrees of freedom

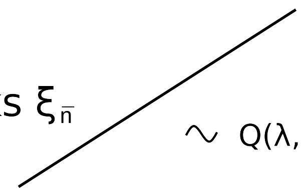
The relevant degrees of freedom are:

- Collinear partons $\xi_{\bar{n}}, A_\mu^c$



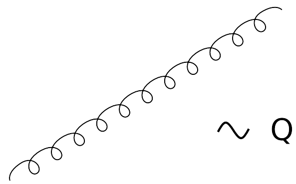
$\sim Q(\lambda^2, 1, \lambda)$

- Hard-collinear quarks $\xi_{\bar{n}}$



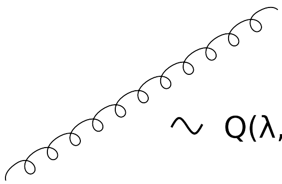
$\sim Q(\lambda, 1, \lambda)$

- Glauber gluons A_μ



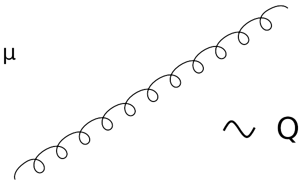
$\sim Q(\lambda^2, \lambda^2, \lambda)$ or $Q(\lambda^2, \lambda, \lambda)$

- Soft gluons A_μ



$\sim Q(\lambda, \lambda, \lambda)$

- Ultrasoft gluons A_μ

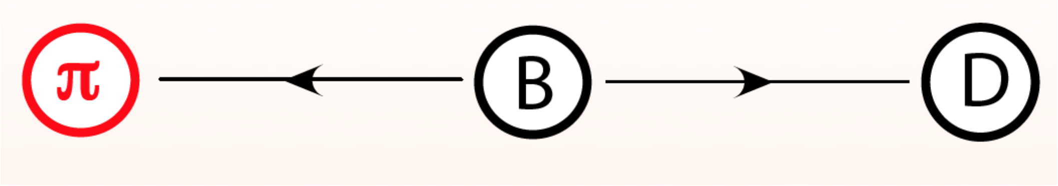


$\sim Q(\lambda^2, \lambda^2, \lambda^2)$

Soft Collinear Effective Theory (SCET)

SCET is the suitable EFT for processes that involve a large energy transfer (larger than any other scale including masses).

- B decays by weak interactions:
  $B \to X_u \ell \bar{\nu}$, $B \to D\pi$, $B \to K^*\gamma$, $B \to \pi\ell\nu$, $B \to X_s\gamma$, $B \to \rho\gamma$, $B \to \rho\gamma$, $B \to \rho\rho$, $B \to \pi\pi$, $B \to D^*\eta'$, $B \to K\pi$, $B \to \gamma\ell\bar{\nu}$, $\Upsilon \to X\gamma$, ...
  Ex. $B \to D\pi$



$$p_\pi^\mu \approx (2.3\,\mathrm{GeV}, 0, 0, -2.3\,\mathrm{GeV}) \sim Q\bar{n}^\mu \sim Q(0,1,0)$$

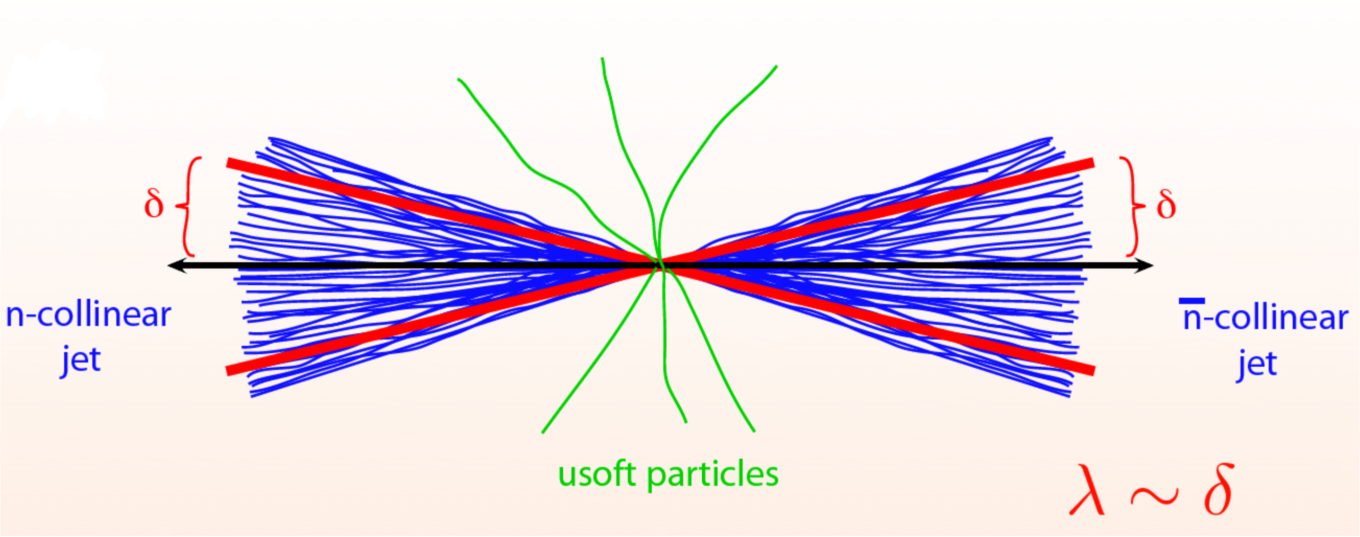
$Q \gg \Lambda$, hence $\lambda \sim \Lambda/Q$

- soft constituent (of B and D): $p_s^\mu \sim (\Lambda, \Lambda, \Lambda) \sim Q(\lambda, \lambda, \lambda)$
- collinear constituent (after boost): $p_c^\mu \sim (\Lambda^2/Q, Q, \Lambda) \sim Q(\lambda^2, 1, \lambda)$

∘ Bauer Fleming Pirjol Stewart PR D63 (2001) 114020

Soft Collinear Effective Theory (SCET)

- High-energy collisions and jets:
  $e^- p \to e^- X$, $p\bar{p} \to X e^+ e^-$, $e^- \gamma \to e^- \pi^0$, $e^- e^+ \to \text{jets}$, $p\bar{p} \to \text{jets}$, $e^- e^+ \to J/\psi X$, ...
  Ex. $e^- e^+ \to \text{jets}$



$Q \gg \Delta$, hence $\lambda \sim \Delta/Q$

- Jet constituents: $p^\mu \sim (\Delta^2/Q, Q, \Delta) \sim Q(\lambda^2, 1, \lambda)$

2. GAUGE INVARIANT $P(k_\perp)$

SCET for transverse momentum broadening

The EFT that describes the propagation of a collinear quark in the $\bar{n}$-direction is SCET coupled to collinear, soft, Glauber and ultrasoft gluons:

$$\mathcal{L}_{\bar{n}} = \bar{\xi}_{\bar{n}} \, i \not{n} \bar{n} \cdot D \, \xi_{\bar{n}} + \bar{\xi}_{\bar{n}} \, i \not{D}_{\perp} \frac{1}{2 i n \cdot D} i \not{D}_{\perp} \not{n} \, \xi_{\bar{n}}$$

We will consider now the contribution of soft, Glauber and ultrasoft gluons only and rescale $\bar{\xi}_{\bar{n}} \to e^{-iQx^{+}} \bar{\xi}_{\bar{n}}$. The Lagrangian, organized as an expansion in λ, is then

$$\mathcal{L}_{\bar{n}} = \bar{\xi}_{\bar{n}} \, i \not{n} \bar{n} \cdot D \, \xi_{\bar{n}} + \bar{\xi}_{\bar{n}} \frac{D_{\perp}^{2}}{2Q} \not{n} \, \xi_{\bar{n}} + \bar{\xi}_{\bar{n}} \, i \frac{g F_{\perp}^{\mu\nu}}{4Q} \gamma_{\mu} \gamma_{\nu} \not{n} \, \xi_{\bar{n}} + \dots$$

- Idilbi Majumder PR D80 (2009) 054022

Power-counting in covariant gauges

In a covariant gauge and in the presence of covariant soft sources, it is ($q^+ \sim Q\lambda^2$)

$$A^+ \sim A_\perp \sim Q\lambda^2$$

which follows from the equation of motion of a collinear parton and Lorentz symmetry.

- Note, however, that the fields are not homogeneous in the energy scales.

For $\partial_\perp \sim \lambda$ (when acting on collinear quarks), the leading order Lagrangian in λ is

$$\mathcal{L}_{\bar{n}} = \bar{\xi}_{\bar{n}}\, i\not{n}\bar{n} \cdot D\, \xi_{\bar{n}} + \bar{\xi}_{\bar{n}}\, \frac{\partial_\perp^2}{2Q} \not{n}\, \xi_{\bar{n}}$$

Decoupling of ultrasoft gluons

- Ultrasoft gluons decouple at lowest order from collinear quarks trough

$$\xi_{\bar{n}} \to \mathrm{P}\ \exp\left\{ ig \int_{-\infty}^{x^-} dy\, \bar{n} \cdot A_{\mathrm{us}}(x^+, y, x_\perp) \right\} \xi_{\bar{n}}$$

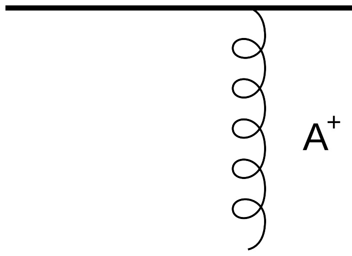
- The field redefinition works for ultrasoft gluons because, at lowest order, the kinetic energy, $\nabla_\perp^2/(2Q)$, commutes with ultrasoft gluons. For the opposite reason, the field redefinition would not decouple, even at lowest order, Glauber gluons from collinear quarks.

- We may consider in the Lagrangian soft and Glauber gluons only.

∘ Bauer Pirjol Stewart PR D65 (2002) 054022

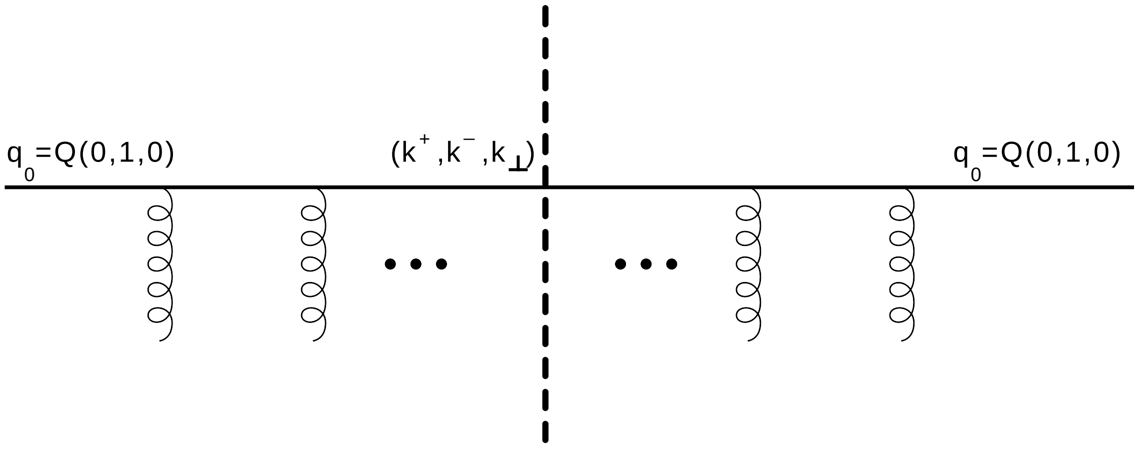
Jet broadening in covariant gauges

Only one relevant vertex



$$= igT^a \bar{n}^\mu \not{n}$$

for the scattering amplitude



$$= P(k_\perp)$$

for $k_\perp \neq 0$ and normalizing by the number of particles in the medium ($= \Delta t/L$).

Glauber and soft gluons in covariant gauge

- Glauber gluon propagators may be approximated by (e.g. in Feynman gauge)

$$D_{\mu\nu}(k) = D(k^2) g_{\mu\nu} \approx D(k_\perp^2) g_{\mu\nu}$$

- This implies that the scattering amplitude has the form

$$\int \prod_i \frac{d^4 q_i}{(2\pi)^4} \cdots \frac{iQ\bar{n}\!\!\!/}{2Qq_2^+ - q_{2\perp}^2 + i\epsilon} A^+(q_2 - q_1) n\!\!\!/ \frac{iQ\bar{n}\!\!\!/}{2Qq_1^+ - q_{1\perp}^2 + i\epsilon} A^+(q_1 - q_0) n\!\!\!/ \xi_{\bar{n}}(q_0)$$

$$\approx \int dy^+ d^2 y_\perp \prod_i dy_i^- \cdots \theta(y_3^- - y_2^-) A^+(y^+, y_2^-, y_\perp)\, \theta(y_2^- - y_1^-) A^+(y^+, y_1^-, y_\perp) \xi_{\bar{n}}(q_0)$$

where $\bar{n}\!\!\!/ \xi_{\bar{n}}(q_0) = 0$ and $\xi_{\bar{n}}^\dagger(q_0)\, \xi_{\bar{n}}(q_0) = \sqrt{2}Q$.

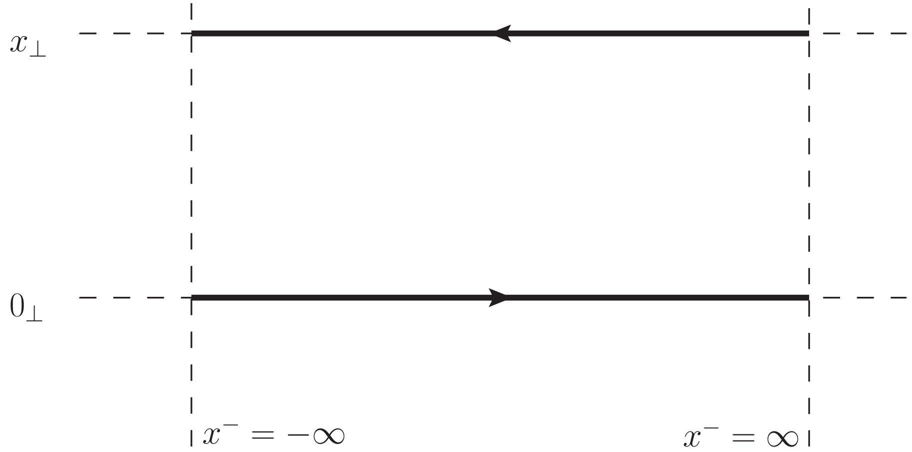
- The same result holds if one considers the interaction of soft gluons with collinear and hard-collinear quarks. In this case, one has to recall that the hard-collinear quark propagator reads $\dfrac{i}{2q^+ + i\epsilon} \bar{n}\!\!\!/$.

Jet broadening in covariant gauges

$$P(k_\perp) = \frac{1}{N_c} \int d^2x_\perp e^{ik_\perp \cdot x_\perp} \left\langle \mathrm{Tr} \left\{ W^\dagger[0^+, x_\perp] W[0^+, 0_\perp] \right\} \right\rangle$$

where $\langle \ldots \rangle$ is a medium average

and $W[0^+, x_\perp] = \mathrm{P}\exp\left\{ ig \int_{-L/\sqrt{2}}^{L/\sqrt{2}} dx^- \, A^+(0^+, x^-, x_\perp) \right\}$, for $L \to \infty$.



- The fields are path ordered (P) but not time ordered;
- the expression is not gauge invariant (e.g. for $A^+ = 0$, $W = 1$).

- Baier et al NP B483 (1997) 291, Zakharov JETPL 63 (1996) 952
  Casalderrey-Solana Salgado APP B38 (2007) 3731
  D'Eramo Liu Rajagopal PR D84 (2011) 065015

Power-counting in light-cone gauge

Consider the light-cone gauge $A^+ = 0$:

$$D_{\mu\nu}(k) = D(k^2)\left(g_{\mu\nu} - \frac{k_\mu \bar{n}_\nu + k_\nu \bar{n}_\mu}{[k^+]}\right)$$

for Glauber gluons $k_\perp/[k^+] \sim 1/\lambda$, which leads to on enhancement of order λ in the singular part of the propagator.

Moreover, because of the $k_\perp/[k^+]$ singularity,

$$A_\perp(x^+, x^-, x_\perp) = A_\perp^{\rm cov}(x^+, x^-, x_\perp) + \theta(x^-)A_\perp(x^+, \infty^-, x_\perp) + \theta(-x^-)A_\perp(x^+, -\infty^-, x_\perp)$$

where $A_\perp^{\rm cov}$ vanishes at infinity and $A_\perp(x^+, \pm\infty^-, x_\perp) = \partial_\perp \phi^\pm(x^+, x_\perp)$:

- $A_\perp$ does not vanish at infinity where it becomes pure gauge,
- but the field tensor does (because the energy of the gauge field is finite).

∘ Belitsky Yuan NP B656 (2003) 165
Garcia-Echevarria Idilbi Scimemi PR D84 (2011) 011502

Power-counting in light-cone gauge

In the $A^+ = 0$ light-cone gauge, the scaling of the Glauber fields appearing in the Lagrangian goes like

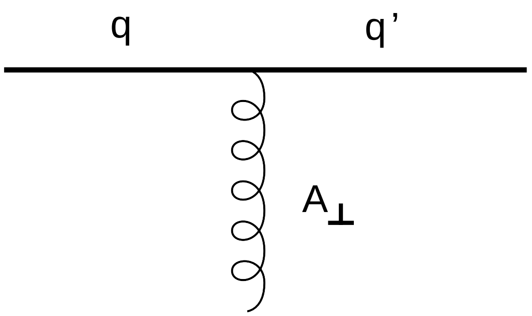
$$A^+ = 0 \qquad A_\perp^{\rm cov} \sim Q\lambda^2 \qquad \partial_\perp \phi^\pm \sim Q\lambda$$

The leading order Lagrangian in λ is

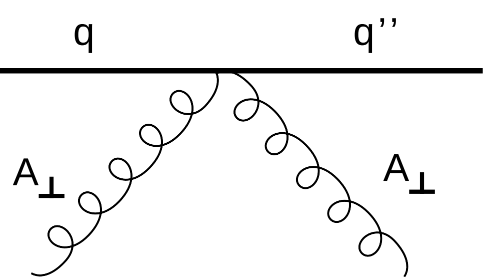
$$\mathcal{L}_{\bar{n}} = \bar{\xi}_{\bar{n}}\, i\not{n}\bar{n}\cdot\partial\,\xi_{\bar{n}} + \bar{\xi}_{\bar{n}}\,\frac{(\partial_\perp - ig\theta(x^-)\partial_\perp\phi^+ - ig\theta(-x^-)\partial_\perp\phi^-)^2}{2Q}\not{n}\,\xi_{\bar{n}}$$

Jet broadening in light-cone gauge

The relevant vertices are two



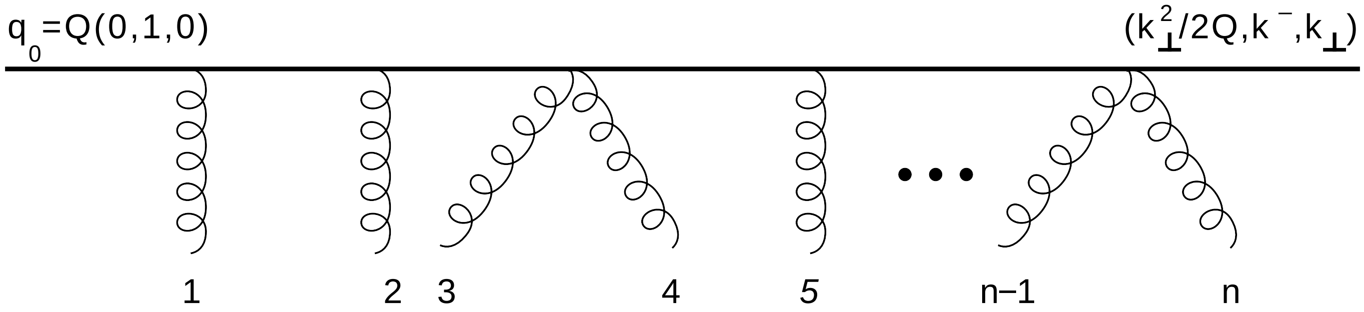
$$= -ig\,\frac{q'_\perp \cdot A_\perp(q'-q) + A_\perp(q'-q)\cdot q_\perp}{2Q}\,\not{n}$$



$$= -\frac{ig^2}{2Q}\int \frac{d^4q'}{(2\pi)^4}\,A^i_\perp(q''-q')A^i_\perp(q'-q)\not{n}$$

Jet broadening in light-cone gauge

From the vertices one constructs the amplitude (on the left of the cut)



$= G_n(k^-, k_\perp)$

G_n is a convolution of G^+_{n-j}, which involves only fields at $x^- = \infty$ and G^-_j, which involves only fields at $x^- = -\infty$:

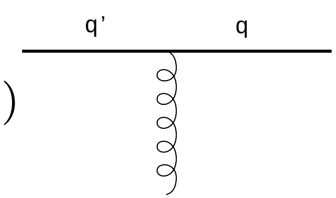
$$G_n(k^-, k_\perp) = \sum_{j=0}^{n} \int \frac{d^4q}{(2\pi)^4}\, G^+_{n-j}(k^-, k_\perp, q)\, \frac{iQ\not{n}}{2Qq^+ - q_\perp^2 + i\epsilon}\, G^-_j(q)$$

Jet broadening in light-cone gauge

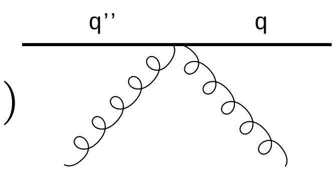
The computation is done by

- solving recursively (analogously for $G_n^+(q)$)

$$G_n^-(q) = \int \frac{d^4q'}{(2\pi)^4}\, G_{n-1}^-(q')$$



$$+\int \frac{d^4q''}{(2\pi)^4}\, G_{n-2}^-(q'')$$



- writing the differential amplitude as

$$\frac{1}{L^3\sqrt{2}Q}\int\frac{dk^+}{2\pi}\int\frac{dk^-}{2\pi}\, 2\pi\, Q\, \delta(2Qk_+ - k_\perp^2)\; \bar{\xi}_{\bar{n}}(q_0)\, G_m^\dagger(k^-, k_\perp)\bar{n}\!\!\!/ G_n(k^-, k_\perp)\, \xi_{\bar{n}}(q_0)$$

- eventually summing over all m and n.

Jet broadening in light-cone gauge

$$P(k_\perp) = \frac{1}{N_c}\int d^2x_\perp e^{ik_\perp\cdot x_\perp} \left\langle \mathrm{Tr}\left\{T^\dagger[0^+,-\infty^-,x_\perp]T[0^+,\infty^-,x_\perp] \right.\right.$$
$$\left.\left. \times\; T^\dagger[0^+,\infty^-,0_\perp]T[0^+,-\infty^-,0_\perp]\right\}\right\rangle$$

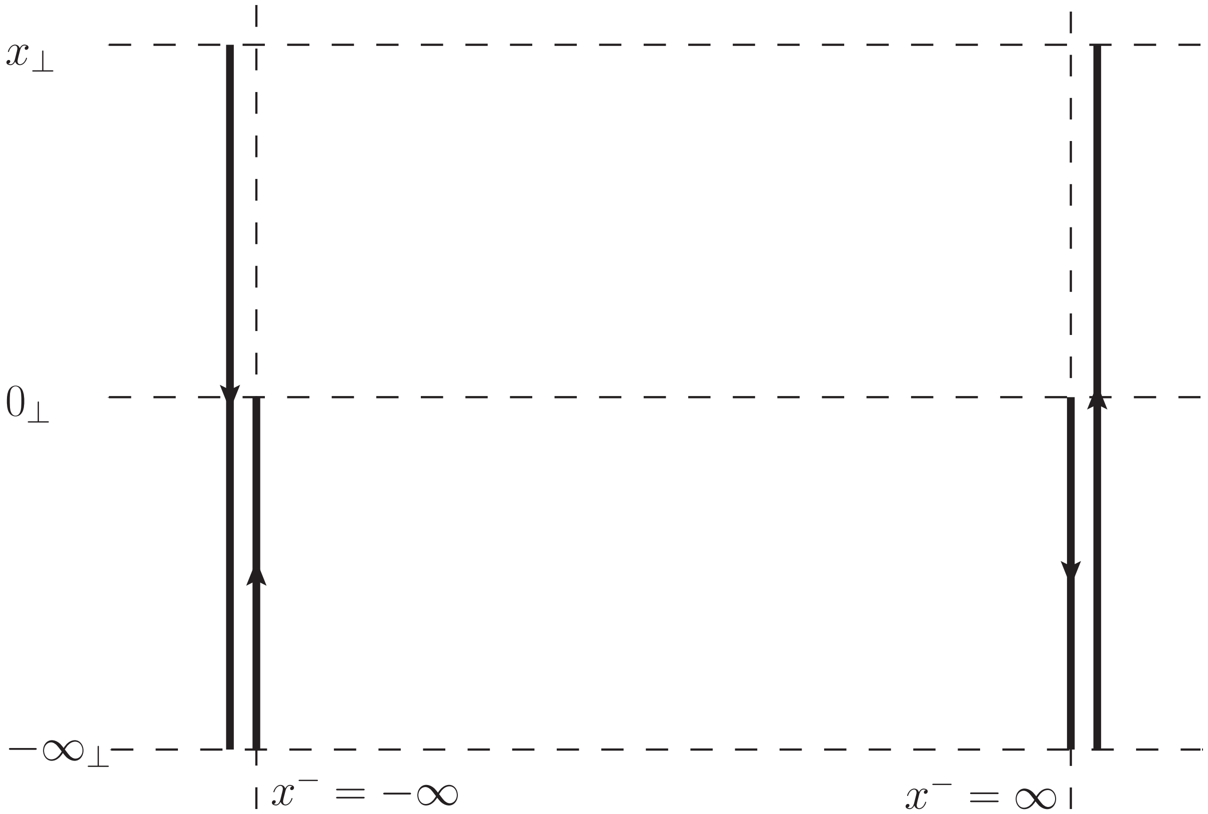
where $T[0^+,\pm\infty^-,x_\perp] = \mathrm{P}\exp\left\{-ig\int_{-L/\sqrt{2}}^{0} ds\, l_\perp\cdot A_\perp(0^+,\pm\infty^-,x_\perp+sl_\perp)\right\}$

- `Benzke Brambilla Escobedo Vairo JHEP 1302 (2013) 129`

The relevance of the Wilson line T in light-cone gauge SCET has been discussed in

- `Idilbi Scimemi PL B695 (2011) 463`

Jet broadening in light-cone gauge



The gauge-invariant expression of $P(k_\perp)$

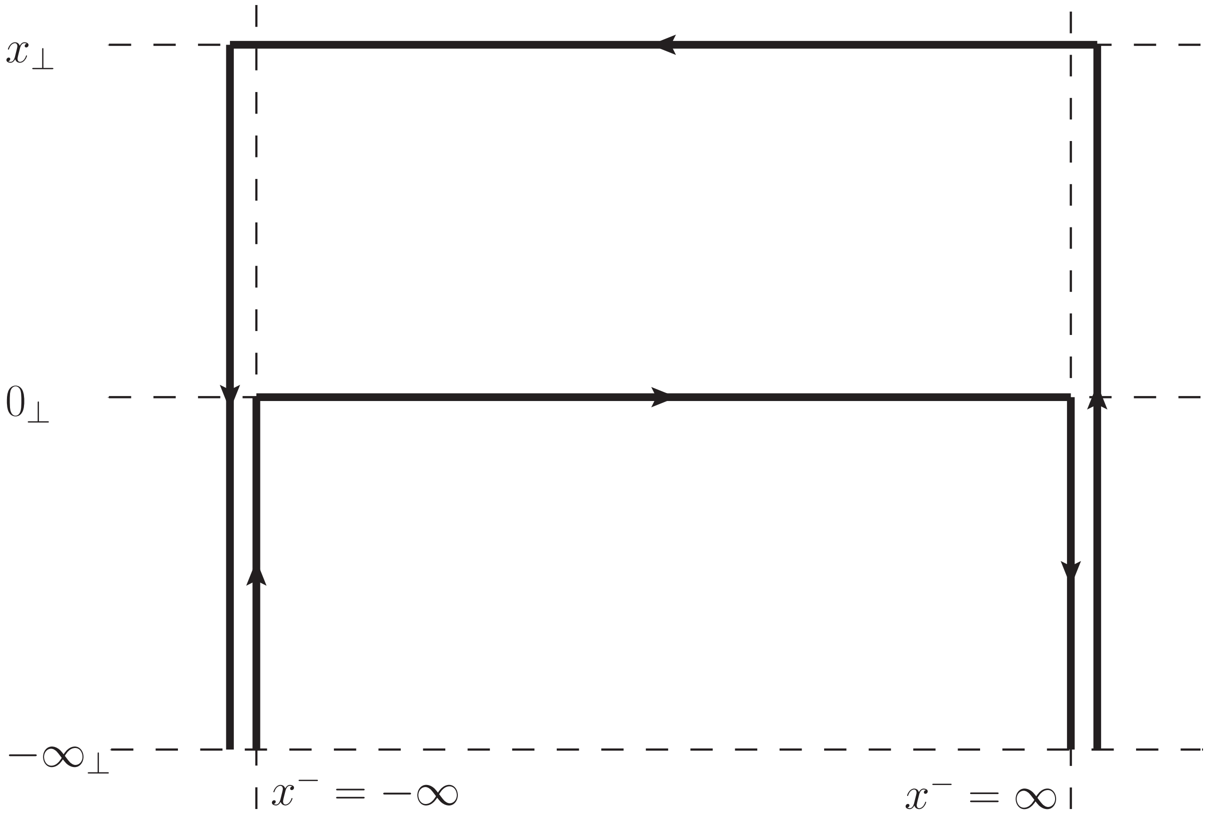
The gauge invariant expression of $P(k_\perp)$ then reads

$$P(k_\perp) = \frac{1}{N_c}\int d^2x_\perp e^{ik_\perp\cdot x_\perp} \left\langle \mathrm{Tr}\left\{T^\dagger[0^+,-\infty^-,x_\perp]W^\dagger[0^+,x_\perp]T[0^+,\infty^-,x_\perp]\right.\right.$$
$$\left.\left.\times\ T^\dagger[0^+,\infty^-,0_\perp]W[0^+,0_\perp]T[0^+,-\infty^-,0_\perp]\right\}\right\rangle$$

The path ordering prescription implies that fields in the first line are anti-time ordered while fields in the second line are time ordered.

- Benzke Brambilla Escobedo Vairo JHEP 1302 (2013) 129

The gauge-invariant expression of $P(k_\perp)$

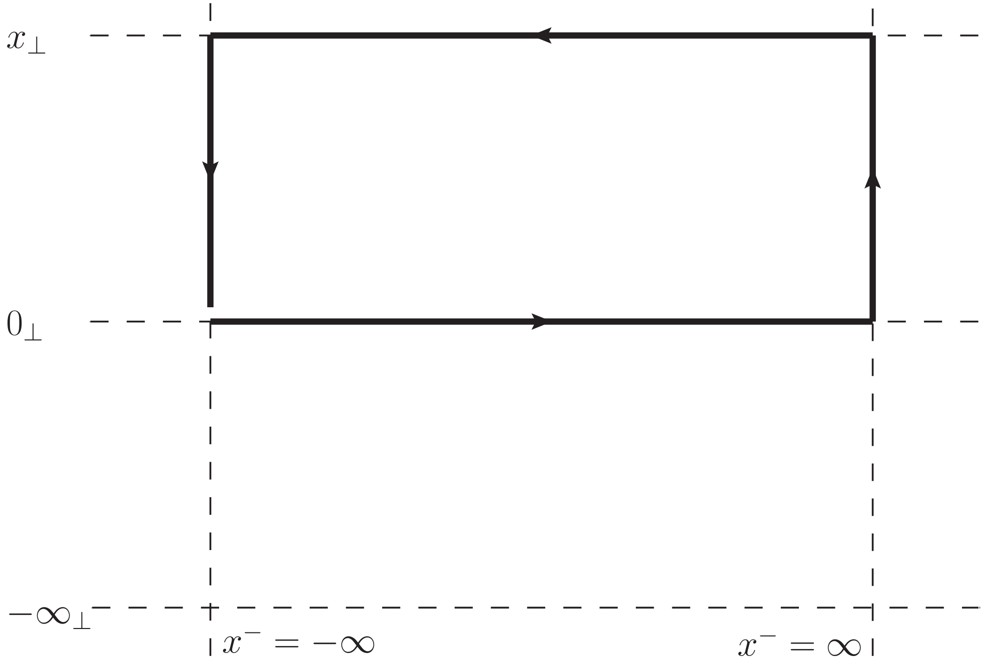


- Note that the Wilson lines at $x^- = \infty$ are contiguous while those at $x^- = -\infty$ are not. This is because the fields are not time ordered.

The gauge-invariant expression of $P(k_\perp)$

The expression of $P(k_\perp)$ may be simplified because:

- contiguous adjoint (unitary) lines cancel;
- fields separated by space-like intervals commute;
- the cyclicity of the trace.



- Note that the fields in $(0^+, -\infty^-, 0_\perp)$ are not contiguous.

Gauge invariance

Under a gauge transformation Ω

$$\mathrm{Tr}\,\left\{T^\dagger[0^+,-\infty^-,x_\perp]W^\dagger[0^+,x_\perp]\cdots T[0^+,-\infty^-,0_\perp]\right\}$$

$$\longrightarrow \mathrm{Tr}\,\left\{\Omega(0^+,-\infty^-,-\infty\, l_\perp)T^\dagger[0^+,-\infty^-,x_\perp]W^\dagger[0^+,x_\perp]\cdots \right.$$
$$\left. \times T[0^+,-\infty^-,0_\perp]\Omega^\dagger(0^+,-\infty^-,-\infty\, l_\perp)\right\}$$

$$= \mathrm{Tr}\,\left\{T^\dagger[0^+,-\infty^-,x_\perp]W^\dagger[0^+,x_\perp]\cdots T[0^+,-\infty^-,0_\perp]\right\}$$

for the fields in $\Omega(0^+,-\infty^-,-\infty\, l_\perp)$ commute with all the others (space-like separations) and the cyclicity of the trace.

- Benzke Brambilla Escobedo Vairo JHEP 1302 (2013) 129

3. DISCUSSION

Jet quenching: recent literature

- One can express $P(k_\perp)$ as a two particle (time ordered) Wilson loop by modifying the partition function according to the Keldysh–Schwinger contour and by identifying the anti-time ordered fields with fields on the imaginary time line of the Keldysh–Schwinger contour.
  - D'Eramo Liu Rajagopal PR D84 (2011) 065015
- $\hat{q}$ may be written in terms of field correlators as

$$\hat{q} = \int^{k_{\max}} \frac{d^2k_\perp}{(2\pi)^2} \int d^2x_\perp \, e^{ik_\perp \cdot x_\perp} \int dx^- \\ \times \frac{\sqrt{2}}{N_c} \left\langle \mathrm{Tr} \left\{ [0, x_\perp]_- U^\dagger_{x_\perp}[x^-, -\infty] \, gF_\perp^{+i}(0, x^-, x_\perp) \right.\right. \\ \left.\left. \times U^\dagger_{x_\perp}[\infty, x^-][x_\perp, 0]_+ U_{0_\perp}[\infty, 0] \, gF_\perp^{+i}(0,0,0) \, U_{0_\perp}[0, -\infty] \right\} \right\rangle$$

where $Q\lambda \lesssim k_{\max} \ll Q$ and $U_{x_\perp}[x^-, y^-] = \mathrm{P}\,\exp\left[ig \int_{y^-}^{x^-} dz^- \, A^+(0, z^-, x_\perp) \right]$.

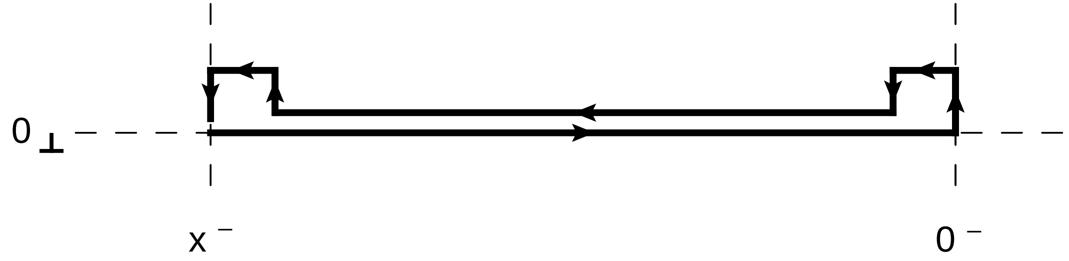
Jet quenching: recent literature

- Similar (but not gauge invariant) expressions can be found in the literature.

  E.g. ○ Majumder arXiv:1202.5295

  They seem to require $k_{\rm max} \to \infty$, which is only justified, under some circumstances, in dimensional regularization. In this case, the gauge invariant expression reads

$$\hat{q} = \int dx^- \frac{\sqrt{2}}{N_c} \Big\langle {\rm Tr} \Big\{ U_{0_\perp}[-\infty, x^-]\, g F_\perp^{+i}(0, x^-, 0) \times\; U_{0_\perp}[x^-, 0]\, g F_\perp^{+i}(0,0,0)\, U_{0_\perp}[0, -\infty] \Big\} \Big\rangle$$



The contribution from the scale g^2T

The gauge invariant expression of $\hat{q}$ allows for the use of lattice data.

E.g. Suppose a weakly coupled plasma characterized by the thermodynamical scales:

$$T \gg gT \gg g^2T \quad \text{(non-perturbative)}$$

At relative order g^2

- one can analytically continue from Minkowski to Euclidean space-time;
- time ordering is irrelevant;
- the partition function at the energy scale g^2T is described by an EFT (MQCD) that is three-dimensional SU(3) (with coupling g^2T).

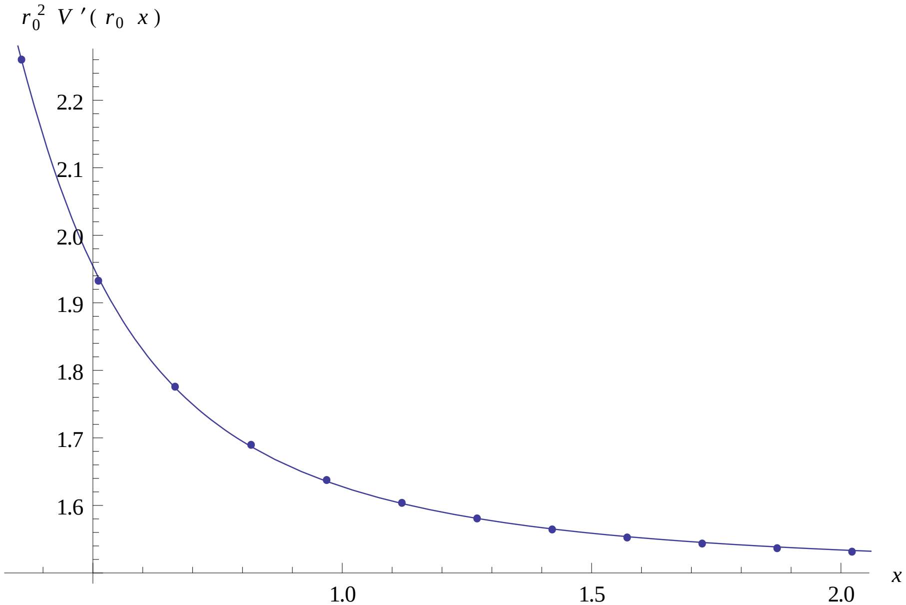
○ Caron-Huot PR D79 (2009) 065039

The contribution from the scale g^2T may be extracted from the behaviour of the Wilson loop, $\sim e^{-LV}$, in three-dimensional QCD.

○ Laine EPJ C72 (2012) 2233

The contribution from the scale g^2T at large distances

At large distances, $r \gtrsim r_0 = 2.2/(g^2T)$,



$$V(r) = \frac{1}{r_0}\left(a\,\frac{r}{r_0} - b\,\frac{r_0}{r} + \ldots\right)$$

$$a \approx 1.5, \qquad b = \pi/24 \approx 0.13$$

this implies $\delta\hat{q} = \dfrac{aq^*}{r_0^2} + \dfrac{b(q^*)^3}{3} + \ldots$

where $k_{\rm max} \gg gT \gg 1/r_0 \gtrsim q^*$

is the cut off in the $k_\perp$ integration.

For $\alpha_{\rm s} \approx 0.5$ and $T \approx 300$ MeV, $\delta\hat{q} \approx 5$ GeV^2/fm.

- Lüscher Weisz JHEP 0207 (2002) 049 (for the lattice data)
  see also Mykkanen JHEP 1212 (2012) 069 (for new lattice data)
  and Pineda Stahlhofen PR D81 (2010) 074026 (for PT)

Conclusions and outlook

A systematic treatment of a complex phenomenon like jet quenching is possible in an EFT framework owning to the hierarchy of scales that characterize the system. These are the typical SCET scales, Q, $Q\lambda$, $Q\lambda^2$, with $\lambda = T/Q$, which characterize the propagation of a very energetic parton in the medium and the thermal scales that characterize the medium itself, T, m_D, magnetic mass.

Many contributions still need to be computed both on the SCET side and on the thermal side of the theory. Work in progress includes:

- inclusion of collinear gluons;
  - `D'Eramo Liu Rajagopal JP G38 (2011) 124162`
- extended perturbative analysis of the thermal bath.
  - `Benzke Brambilla Escobedo Vairo TUM-EFT 32/12`