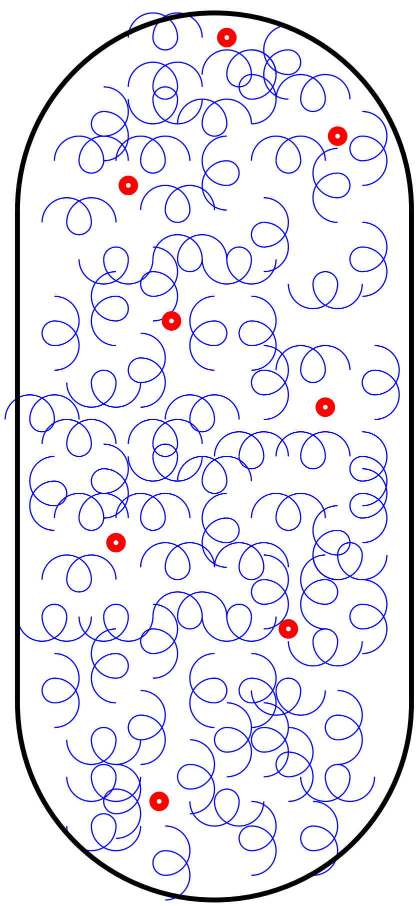
Jet-Medium Interactions at NLO

With Jacopo Ghiglieri, Derek Teaney

- Reminder: jets in a Heavy Ion environment
- The ways a jet can interact with a medium
- The power of light-like propagation
- The power of analyticity
- Results and conclusions

“Why move from Montréal to Darmstadt?”

Nucleus as seen at high energy

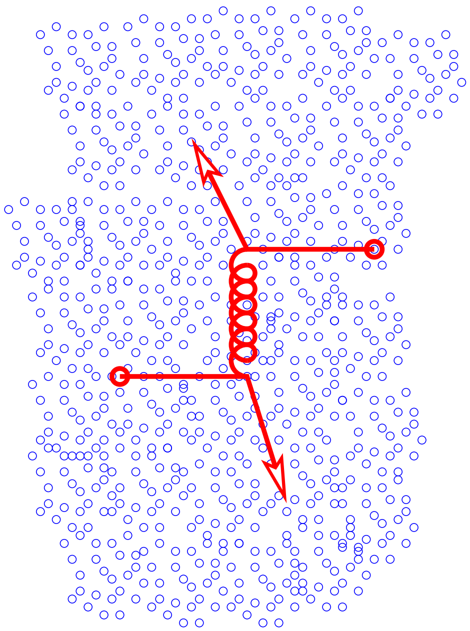


Lots of soft low-energy partons, mostly gluons,

a few hard high-energy partons, mostly quarks.

Low-energy also easier to scatter.

Hard partons and Collisions

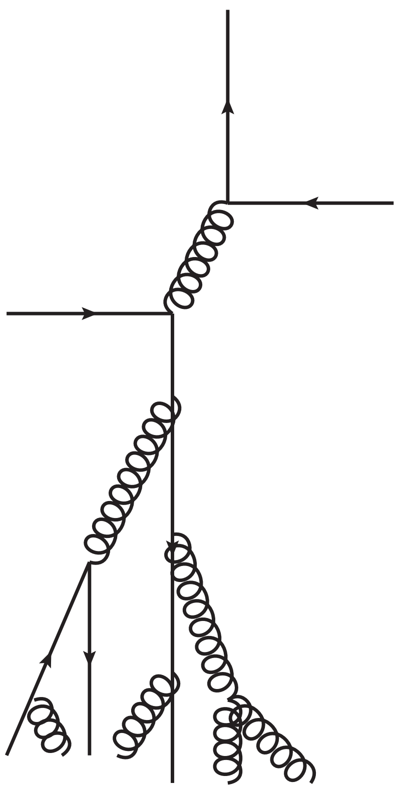


Collision: soft partons scatter and form a medium.

Most hard partons fly through, but a few scatter with large transfer and become jets-to-be.

Croutons in the Quark-Gluon Soup

If the Scattering were in Vacuum



Propagators are off-shell.

Breaks into fragments, which fragment further.

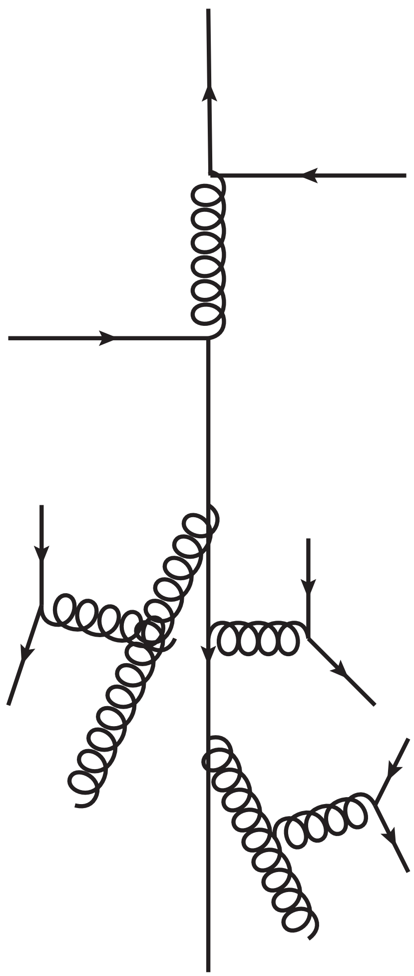
Coord-space Distance for a propagator is $\sim 1/\Delta q^0 \simeq q^0/Q^2$

At end, fragments hadronize.

Occurs when virtuality $Q^2 \sim \Lambda_{QCD}{}^2$

Distance $E/\Lambda_{QCD}{}^2$, 10's of Fermi for > 50GeV jet

Jet formation in medium



Each component scatters with medium.

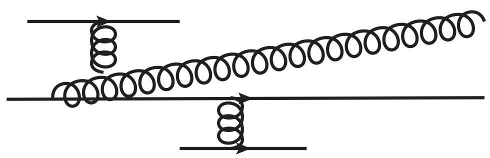
This "keeps them off-shell"

Allows more, larger-Q^2 splittings.

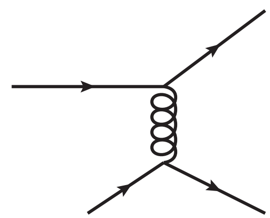
Jet fragments more, fragments also fragment and scatter with medium.

Softest fragments get lost in the medium.

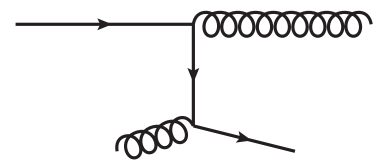
3 Medium Effects



Induced splitting

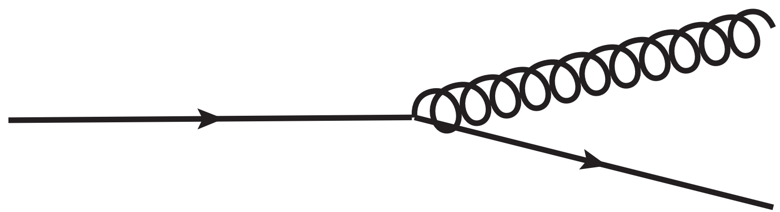


Hard scattering



Identity change

Splitting



Probably main effect:

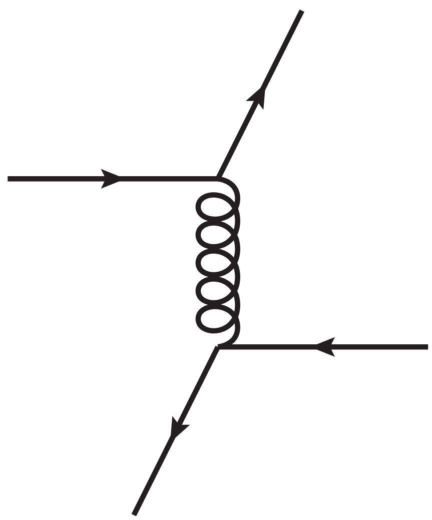
high-energy, small opening-angle splitting.

Clothed with lots of soft medium scatterings (not shown)

- Need medium interaction – $p_\perp$ exchange (how often how much)
- Splitting process itself – formation time, geometry, interference with vacuum process, overlapping emissions?
  Large active literature

I focus on medium interaction

Hard scattering



Most important for large Q^2 exchange.

Should be perturbative (safe).

But rate goes as $\int dQ^2/Q^4$.

Soft exchanges just as important as hard.

Coupling stronger.

medium effects important.

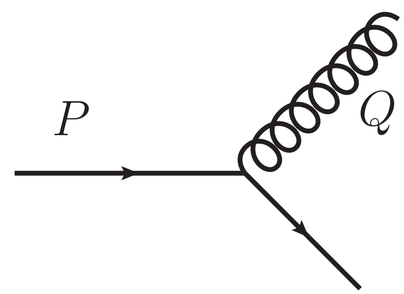
Must address IR end!!

Define $\hat{q}_L = \int d^4Q \frac{d\Gamma}{d^4Q} q_z^2 \, , \qquad \hat{q} = \int d^4Q \frac{d\Gamma}{d^4Q} q_\perp^2 \, .$

Relating these Effects

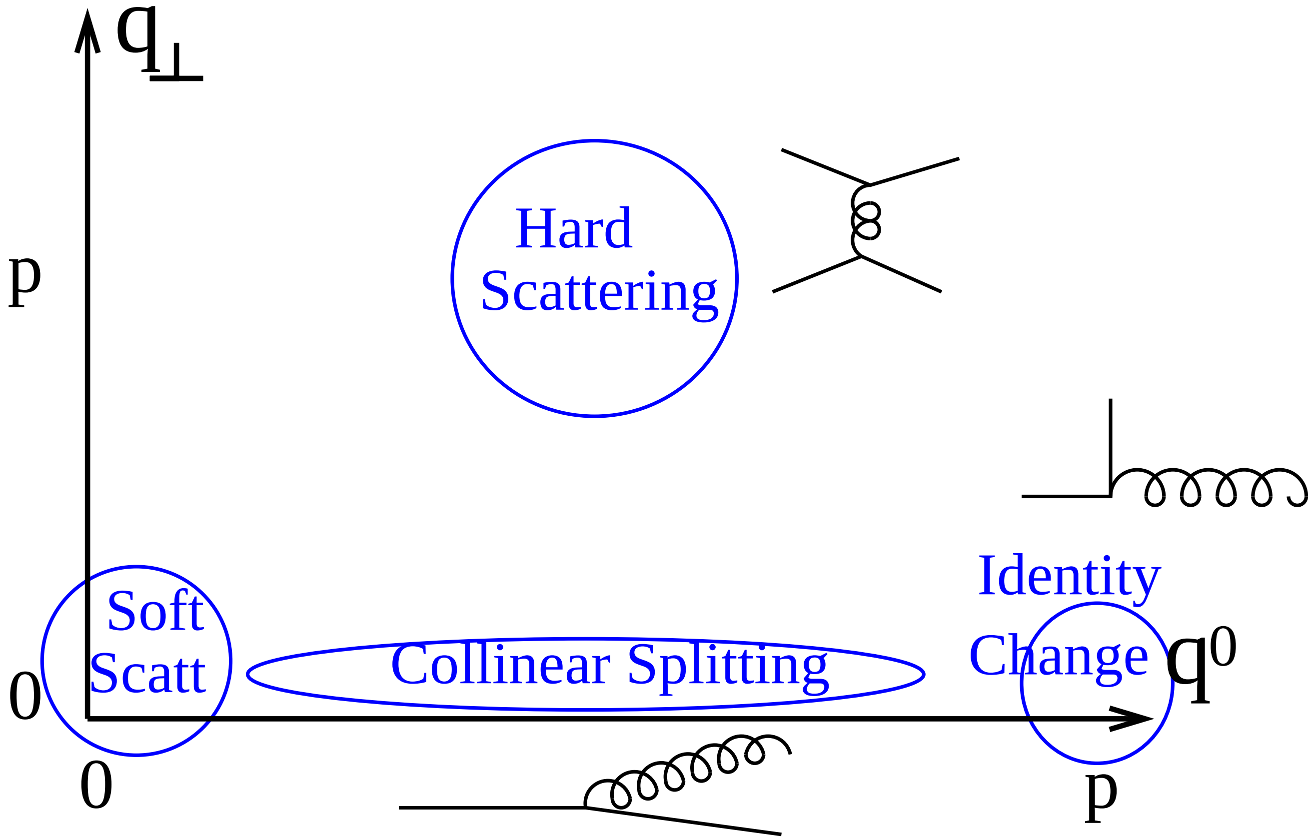
To show the relation between these effects, look at the vertex the hard particle attaches to:

My hard quark has a vertex with a gluon. Define incoming momentum P, choose it as z-axis. gluon's momentum Q: describe in terms of $q_\perp$ and q^0 (really q^-)

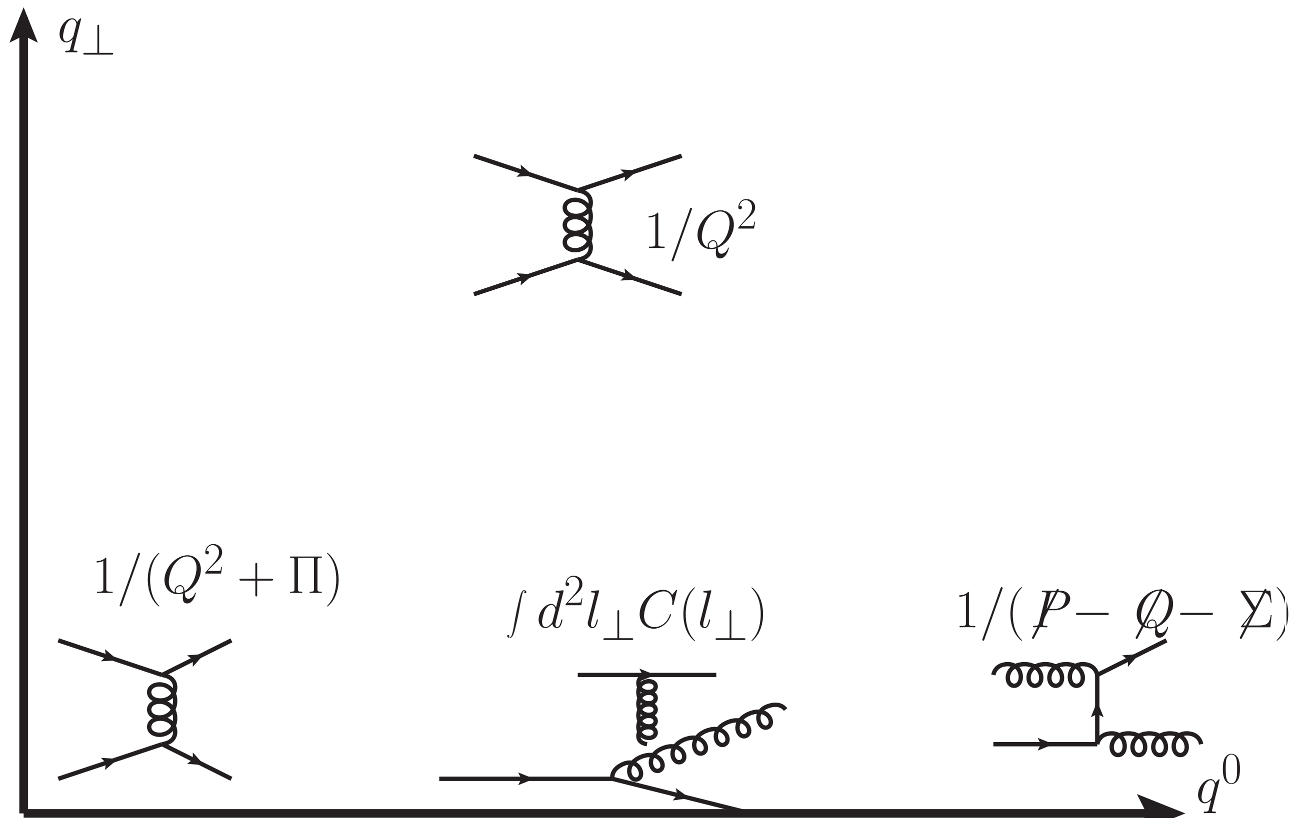


Hard scattering: large $q_\perp$, q^0.
Splitting: small $q_\perp$, large q^0.
Identity change: $q^0 \simeq p^0$, $q_\perp$ small.

All effects in One Picture



Leading-order Calculation Requires:



Collinear: transverse scattering strength *and* resummation of many scatterings.

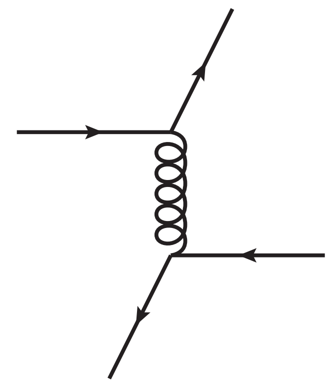
Assumptions I made

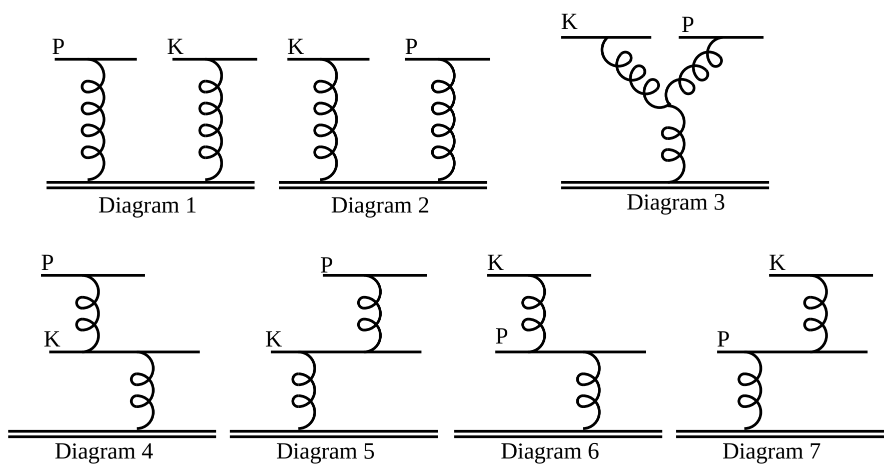
- Assumed that these processes are *distinct*
- Assumed that interaction with medium is *perturbative*
- I will also assume that the medium is *thermal* and *perturbative*.

All these are questionable. I will stick with perturbative assuption, as a framework. To test it I must go to NLO – where the first assumption will *fail*.

Why NLO is a challenge!

Basic scattering happens every $1/g^2T$ time, and lasts $1/gT$.





$O(g)$ correction: two scatterings can overlap. Many processes enter in the interference!!!

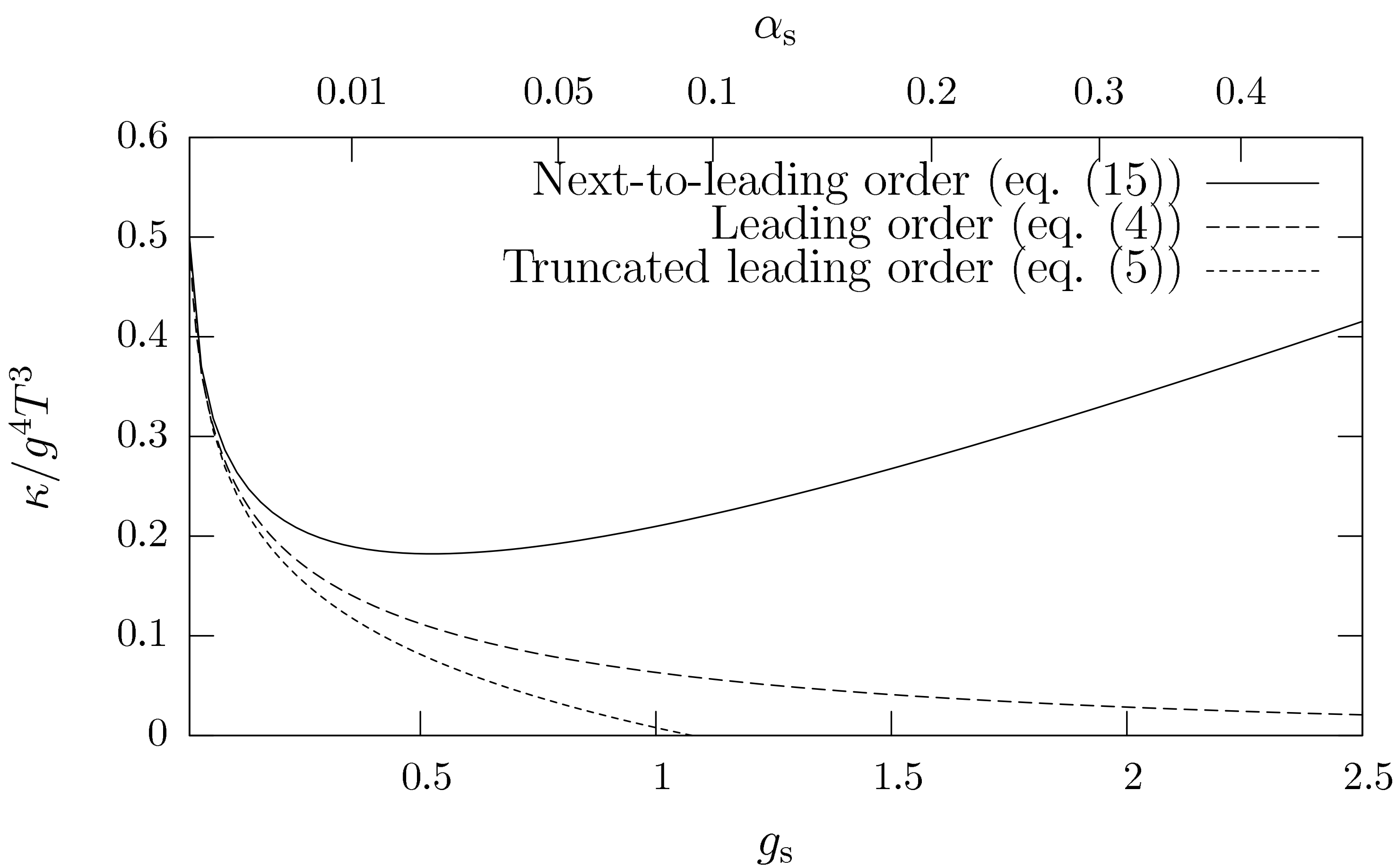
Oh–and everything in sight is HTL resummed!

Heavy quarks near rest

Years ago Simon Caron-Huot and I did the NLO calculations for heavy quark diffusion, including these overlapping-collision processes.

- At the time, argued that this was structurally the *simplest* of all transport processes
- Calculation was just as awful as it sounds
- Required new advances in HTL pert. theory
- Large corrections.

Heavy Quarks: Results

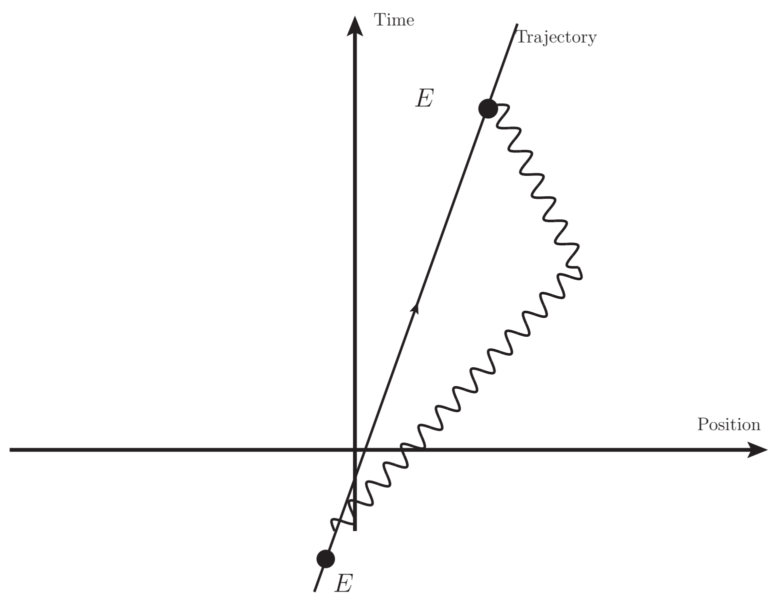


Perturbation theory is a **DISASTER!**

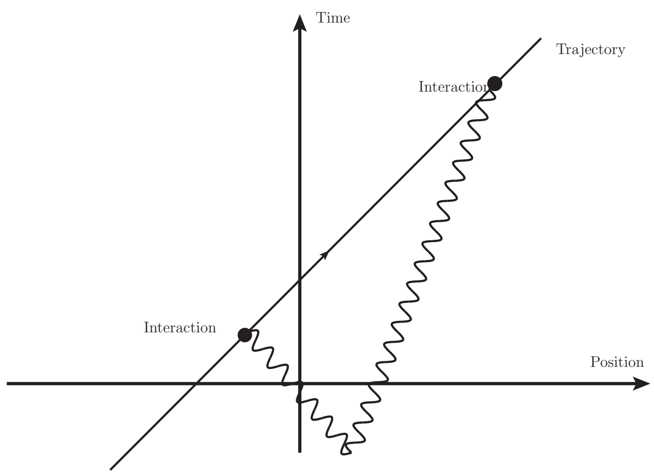
For this quantity.

Why heavy quarks were hard

Correlation of two E-fields.
Disturbed heavy quark disturbs medium.
Medium evolves in complex way
Effects get back to heavy quark line



Why light fast things are easier



Particle takes lightlike path. Correlation between two medium-interactions can only arise because medium was already correlated at those points. Only explores **PRE-EXISTING** correlations in plasma.

Remarkably, light-separated correlators essentially *the same as* equal-time correlators (!!!)

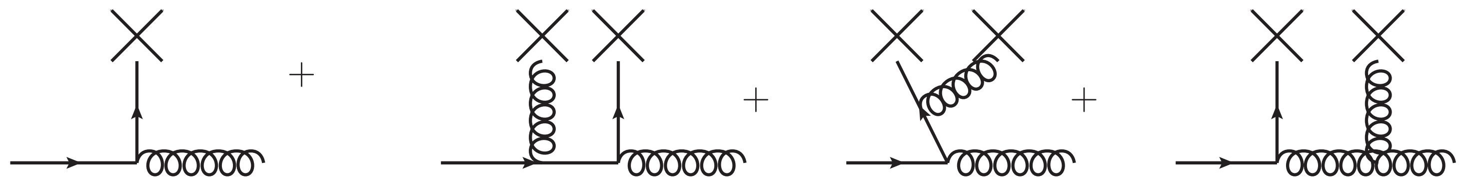
Causality in Field Theory

Spacetime: operators at spacelike-separated *and if* $m \neq 0$*, light-like separated* positions (anti)commute.

K**-space:** Retarded correlation functions, in terms of k^0 or any energy-like *and if* $m \neq 0$*, null* variable, are analytical in the upper half-plane.

Light-like propagation: exploit this analyticity.

Identity change



Leading — Various NLO effects

Call incoming 4-momentum P, outgoing $P+Q$.

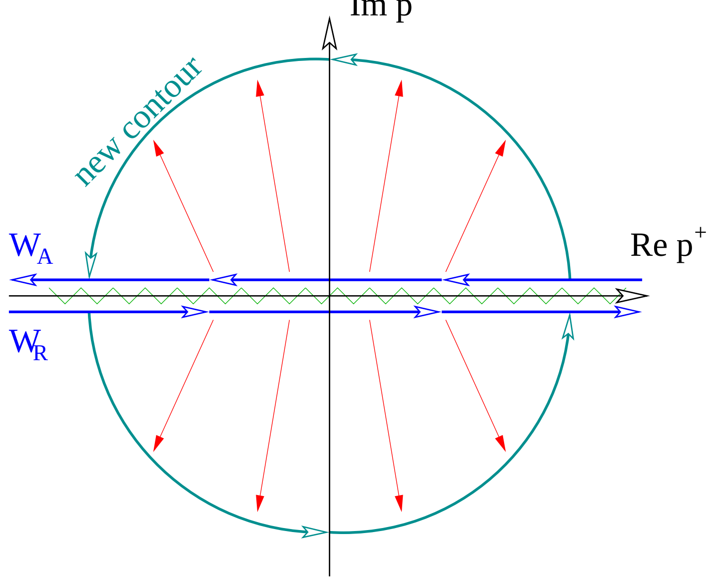
Both on-shell. So for small Q, $q^+ = 0$.

Which ensures q^- is light-like

So I can use analyticity tricks in computing $\int dq^-$

Identity change

Organize as $\int d^2q_\perp \int dq^-|\mathcal{M}|^2$



q^- lightlike. Deform contour!

Now q^- is large–expand.

$|\mathcal{M}|^2 = A + \frac{B}{q^-} + \mathcal{O}(q_-^{-2})$

A subtracted in matching

B dominates. Physical interpretation: correction to hard dispersion.

Identity change

Leading-order result turns out to be simple:

$$\Gamma^{\rm conv}_{q\to g}(p) = \frac{g^2 C_F}{4p} \int \frac{d^2 q_\perp}{(2\pi)^2} \frac{m_Q^2}{q_\perp^2 + m_Q^2} \,.$$

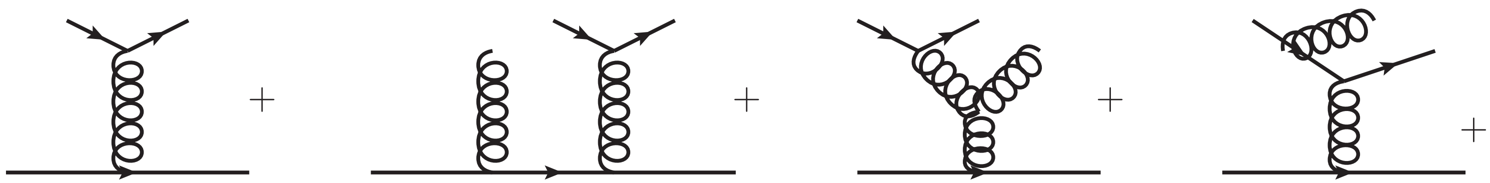
m_Q^2 is large-p correction to dispersion.
Known numerically since 1991 but not understood.
NLO is just:

$$\Gamma^{\rm conv}_{q\to g}(p) = \frac{g^2 C_F}{4p} \int \frac{d^2 q_\perp}{(2\pi)^2} \frac{m_{Q,\rm NLO}^2}{q_\perp^2 + m_{Q,\rm NLO}^2} \,.$$

Longitudinal Momentum Diffusion

Effect of many small scatterings: shift around energy.

Consider LO and NLO scattering processes:



Leading

Various NLO

Label incoming, outgoing P and $P+Q$ again.

Both on-shell. For small Q, $q^+ = 0$

Analyticity opportunities the same as for identity-change!

Longitudinal momentum diffusion

Mean-squared momentum exchange per unit time:

$$\hat{q}_L = g^2 C_F T \int \frac{d^2 q_\perp}{(2\pi)^2} \frac{m_G^2}{q_\perp^2 + m_G^2}$$

with m_G^2 the gluonic dispersion correction ($m_G^2 = m_D^2/2$).
At NLO, no surprise:

$$\hat{q}_L = g^2 C_F T \int \frac{d^2 q_\perp}{(2\pi)^2} \frac{m_{G,\mathrm{NLO}}^2}{q_\perp^2 + m_{G,\mathrm{NLO}}^2}$$

Transverse-momentum diffusion

Need differentially: $C(q_\perp)$ = differential rate to exchange transverse-momentum $q_\perp$ with medium.

$$\hat{q} \equiv \int \frac{d^2 q_\perp}{(2\pi)^2} \, q_\perp^2 \, C(q_\perp)$$

NLO form of $C(q_\perp)$ found in 2008 by Caron-Huot.

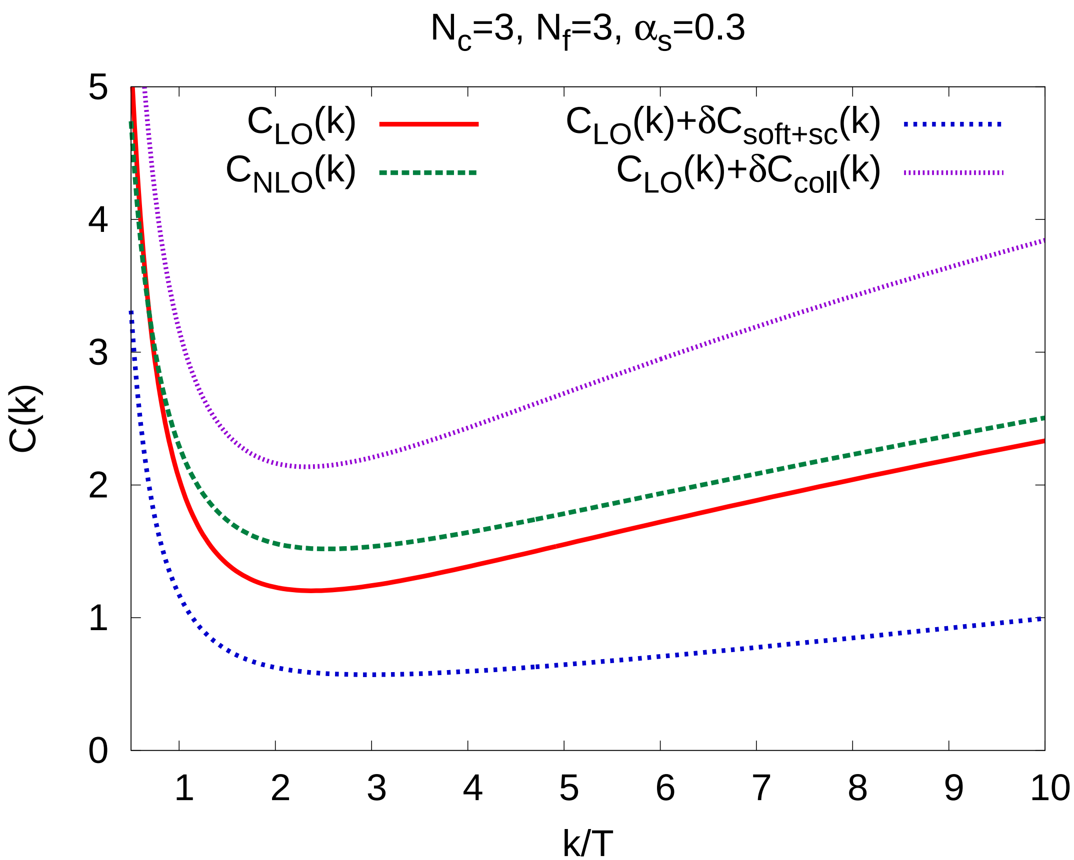
Also used lightlike-propagation tricks.

Written in terms of light-like Wilson loops...

Possibility of nonperturbative lattice determination!

Photon production

All results available for jet modification. Phenomenological study not yet complete. Same tools also work for photons:



Perturbation theory OK at factor-2 level!

Conclusions

- Jet particles experience medium at speed of light.
- Particle does not see its own influence on the medium; Only see pre-existing perturbations – huge simplification
- Analyticity gives strikingly simple results for jet-medium interaction. Longitudinal diffusion / number change related to gluon / quark medium-dispersion corrections.
- Perturbative expansion not *that* bad: NLO only $\sim 100\%$ corrections compared to leading order for $\alpha_{\rm s} \sim 0.3$