Are parton showers in a quark-gluon plasma strongly coupled?

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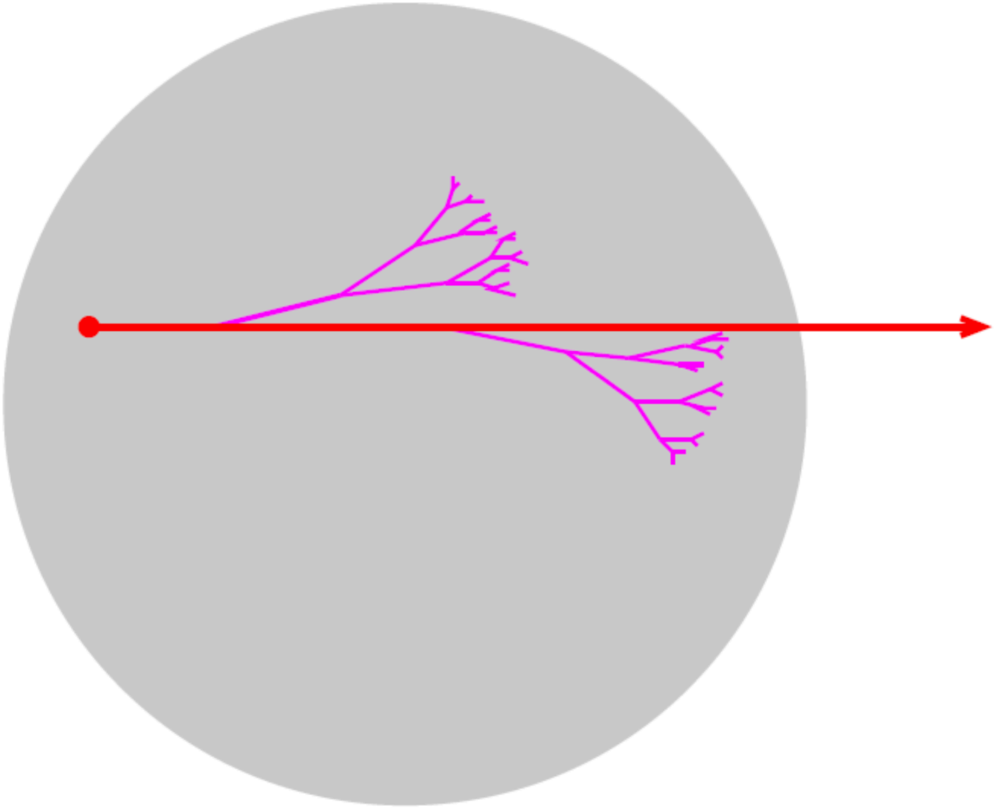
Reporting on work done in collaboration with Peter Arnold and Omar Elgedawy

The Problem of Overlapping formation times

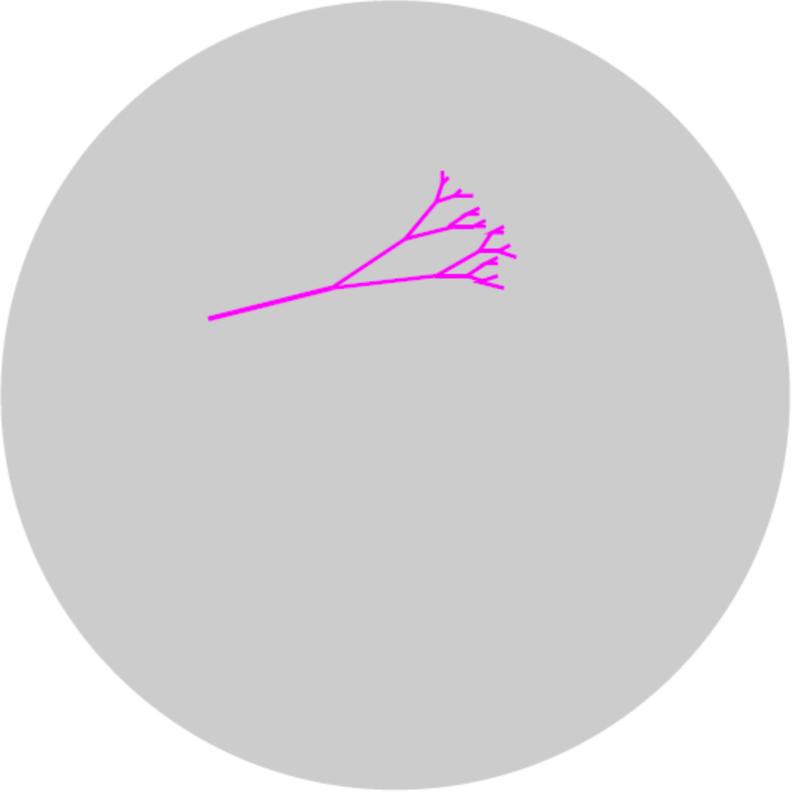
Energy loss of high energy parton in a QGP



Consider the energy loss of a high energy gluon in a QGP

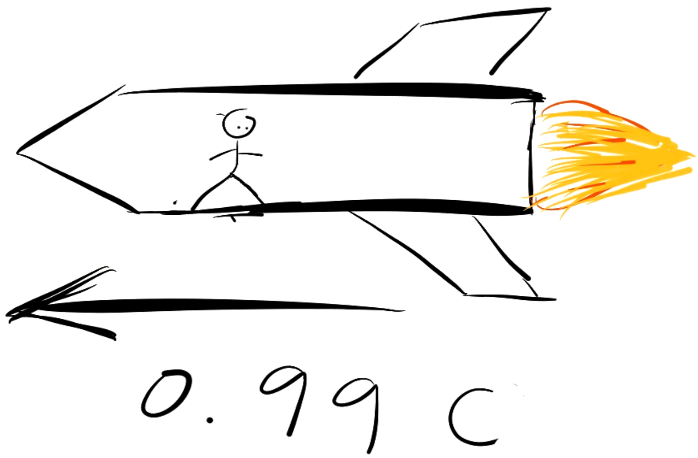
Assumptions:

- Thick, homogenous medium. Imagine a cascade that stops in the medium!
- Multiple scattering aka. $\hat{q}-$approximation.
- Large-Nc limit of QCD.
- Will be looking at $p_\perp-$integrated rates.
- Initial particle is approximately on-shell.

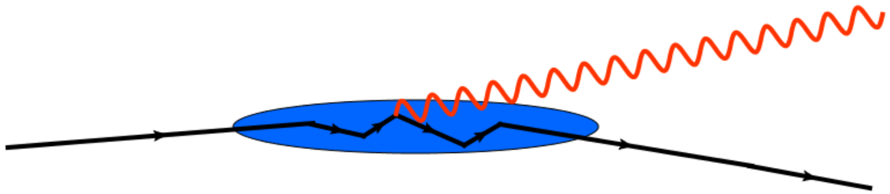


Theoretically the simplest situation for now, although the formalism is not restrictive.

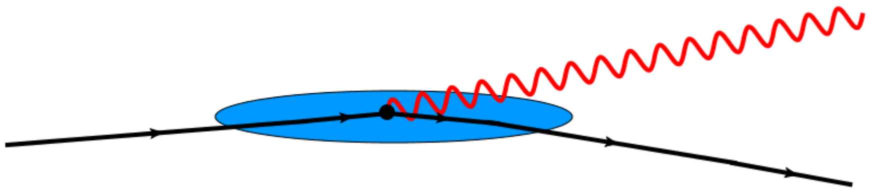
Landau-Pomeranchuk-Migdal effect

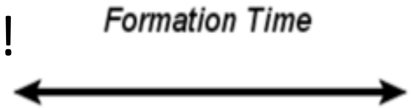


Light cannot resolve details smaller than its wavelength!



Indistinguishable from



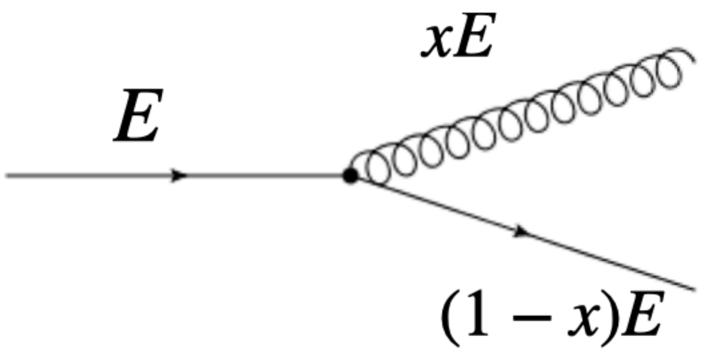


LPM effect: actual rate is smaller than the naive expectation!
LPM effect for QED developed in 1950s.
QCD generalization in 1990s.

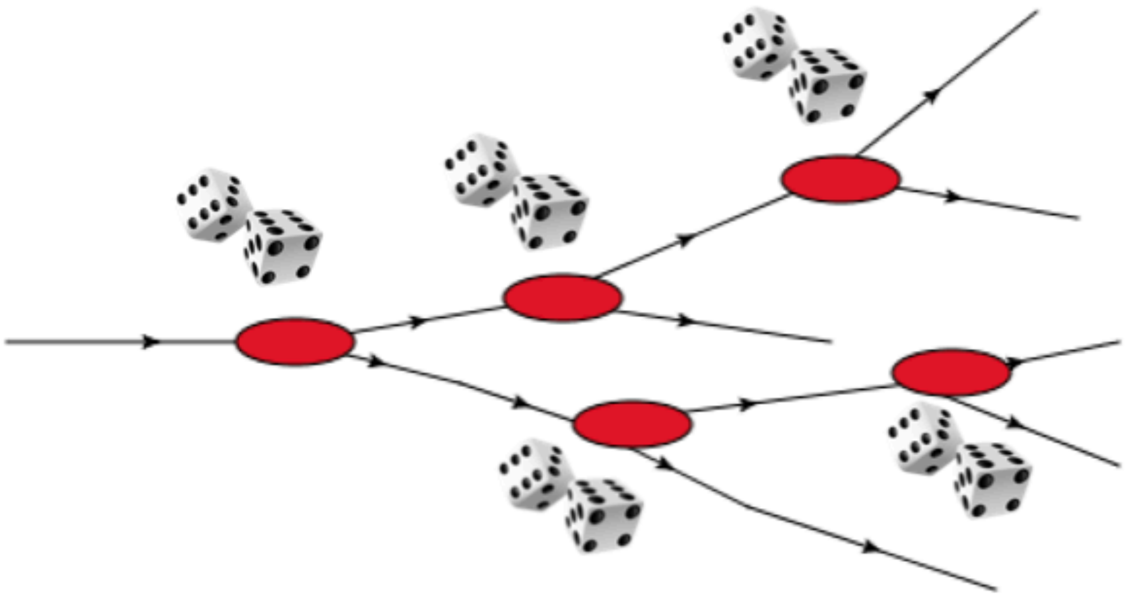
LPM effect in QCD

- LPM effect in QCD is qualitatively different than in QED.
- LPM suppression is smaller for softer gluons.
- Formation times grow with gluon energy as

$$t_F \sim \sqrt{\frac{xE}{\hat{q}}}$$



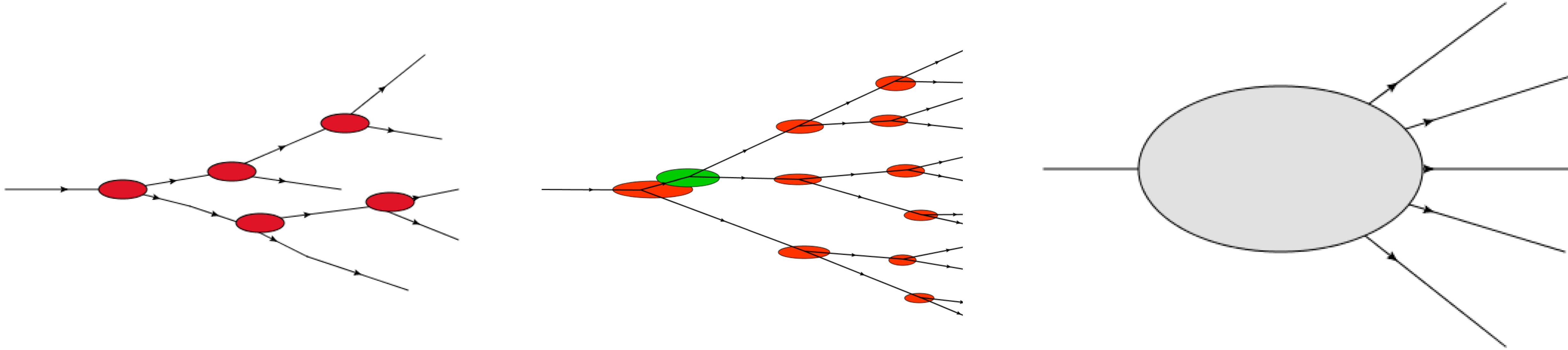
Idealized Monte-Carlo?



- Rolls a classical dice for each time-step with the splitting probability weighted by the LPM splitting rate.

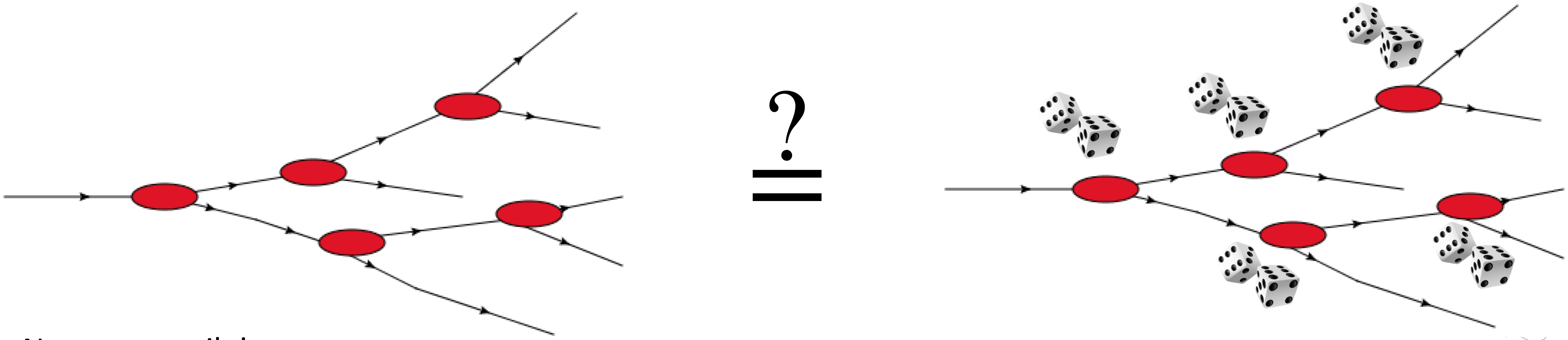
Weakly- vs. Strongly-coupled showers

Parametrically the time between democratic splittings $t_{rad} \sim \frac{t_{form}}{\alpha}$.



$\alpha \ll 1$ $\alpha \sim \textit{not too small}$ $\alpha \to \textit{large}$

Naively, Idealized Monte-Carlo is really just weak-coupling

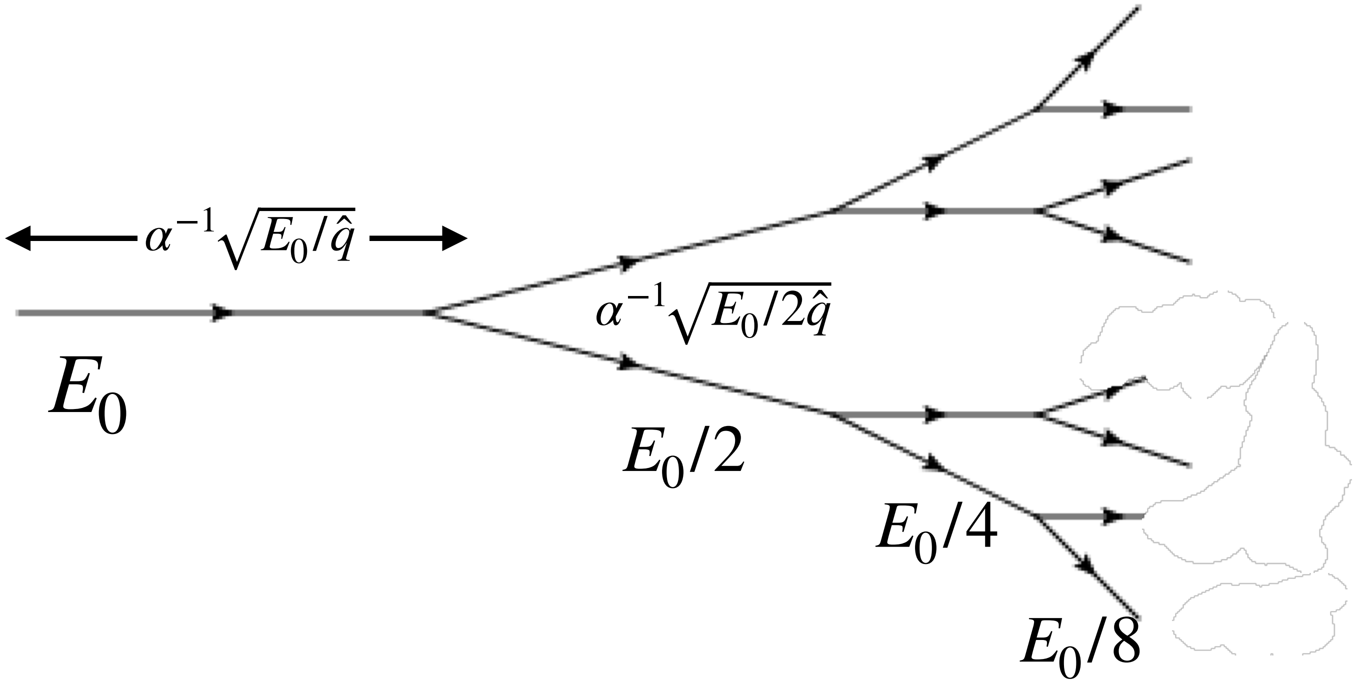


Not necessarily!

- The QCD coupling α_s is only moderately small at energy scales reached in real-life heavy-ion collisions.
- Previous authors have shown that corrections from soft bremsstrahlung give large double logarithmic enhancements, however these corrections can be absorbed into an effective value of $\hat{q}$. (Mehtar-Tani, Wu, Blaizot, Iancu)

Refined Question: Overlap effects that can't be absorbed into an effective $\hat{q}$?

- Consider democratic splittings i.e. each daughter carries off roughly equal energy.
- Distance between subsequent splittings decreases parametrically.
- Shower will stop/thermalize with the medium after $l_{stop} \sim \alpha^{-1}\sqrt{E_0/\hat{q}}$.



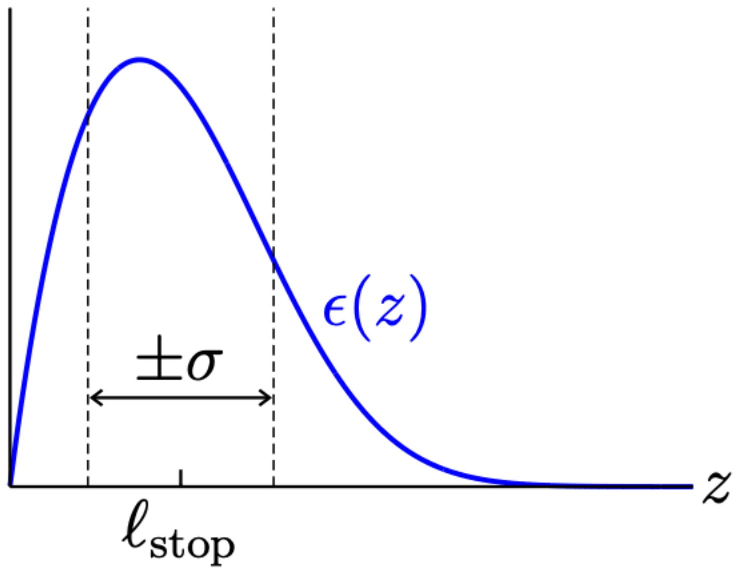
Depends on $\hat{q}$!

Energy deposition distribution

- As a theorist's thought experiment, imagine measuring the distribution of energy deposited by the shower as it moves and evolves in time (or z-direction).

$$l_{stop} = \langle z \rangle = E_0^{-1} \int_z z\epsilon(z) = \text{First moment of } \epsilon(z)$$

- The width σ is same order i.e. $\sigma \sim \alpha^{-1}\sqrt{E_0/\hat{q}}$
- Any ratio of such quantities e.g. $\dfrac{\sigma}{l_{stop}}$ will be independent of $\hat{q}$.



A measure of overlap effects that cannot be absorbed into an effective q-hat

- We calculate overlap effects on the ratio $\frac{\sigma}{l_{stop}}$ for a high energy gluon shower.
- In large-Nf QED, $\frac{\sigma}{l_{stop}} \approx \frac{\sigma}{l_{stop}}^{LO}(1+\chi\alpha+O(\alpha^2))$ with $\chi\alpha \approx -0.87 N_f \alpha_{QED}(\mu)$, i.e. **nearly a $100\,\%$ correction.**

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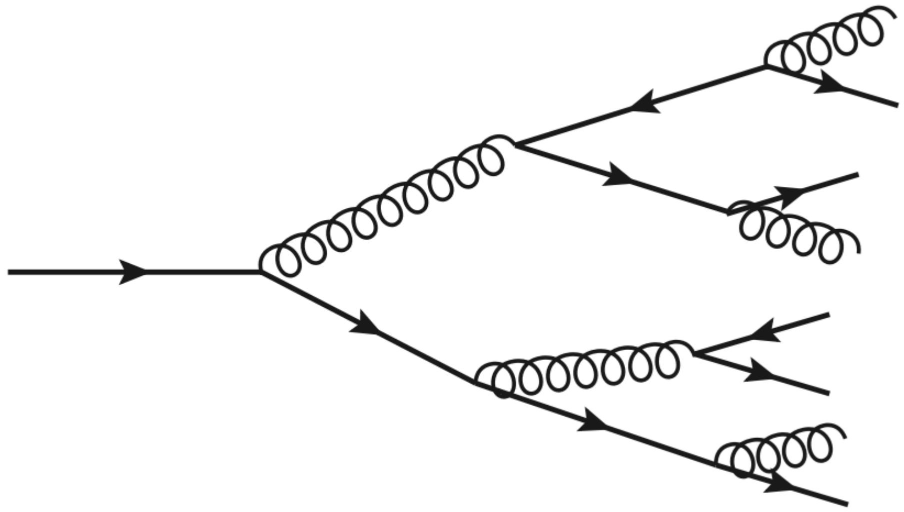
- In stark contrast, for an all gluon Nf=0, large-Nc QCD, $\chi\alpha \sim 0.1 N_c \alpha_s$, i.e barely a 1% correction.
- Why is the correction so radically different between QED and QCD?

QCD with $N_f \gg N_c \gg 1$

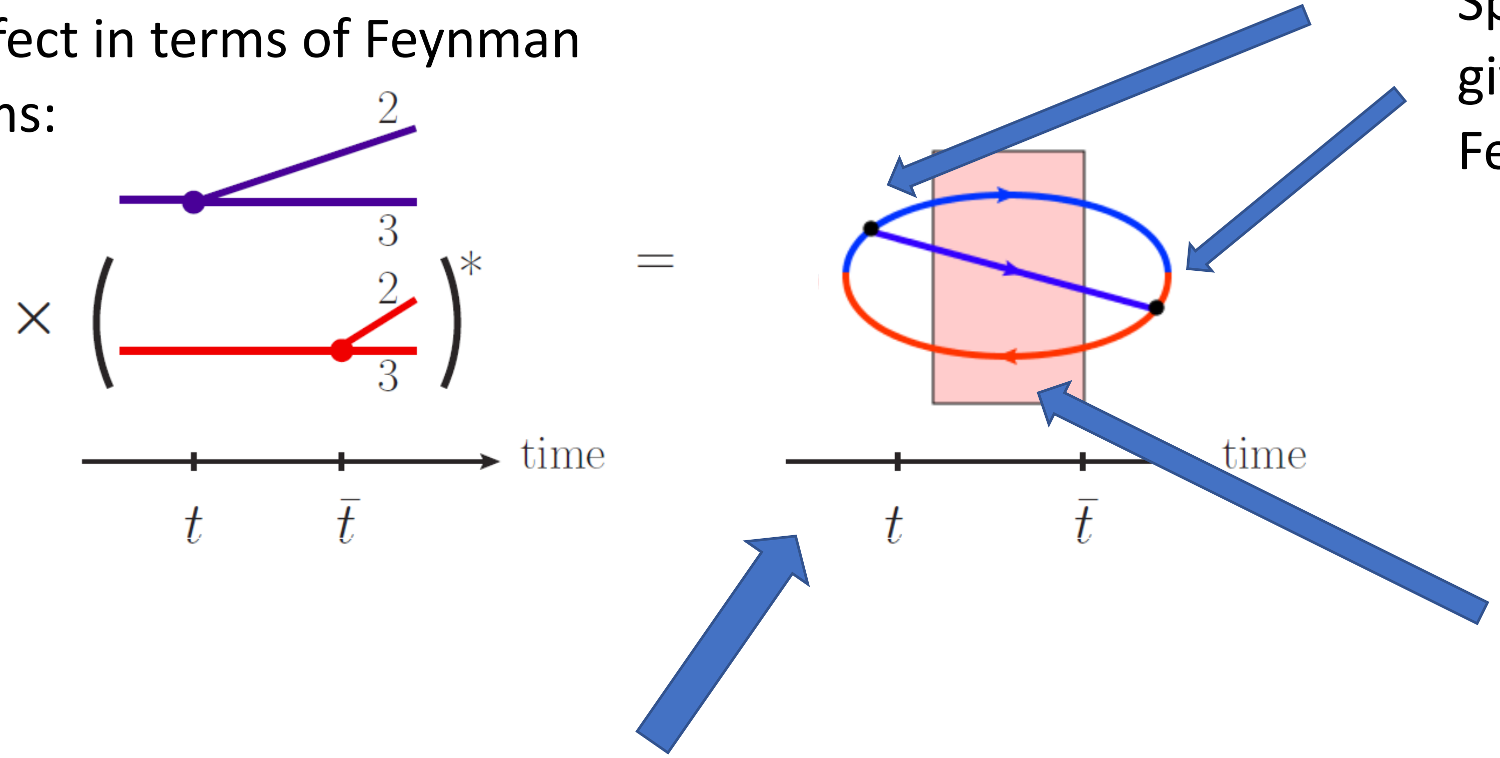
Overlap corrections for QCD in $N_f \gg N_c \gg 1$ limit



- We consider now QCD in the opposite limit of very large number of quarks.
- QCD showers made up entirely of $q \to qg$ and $g \to q\bar{q}$ processes.
- Goal: To decide if the small correction in QCD was an accidental cancellation in no quarks limit, or a broader property of QCD itself.

Review of Single splitting result.

LPM effect in terms of Feynman diagrams:

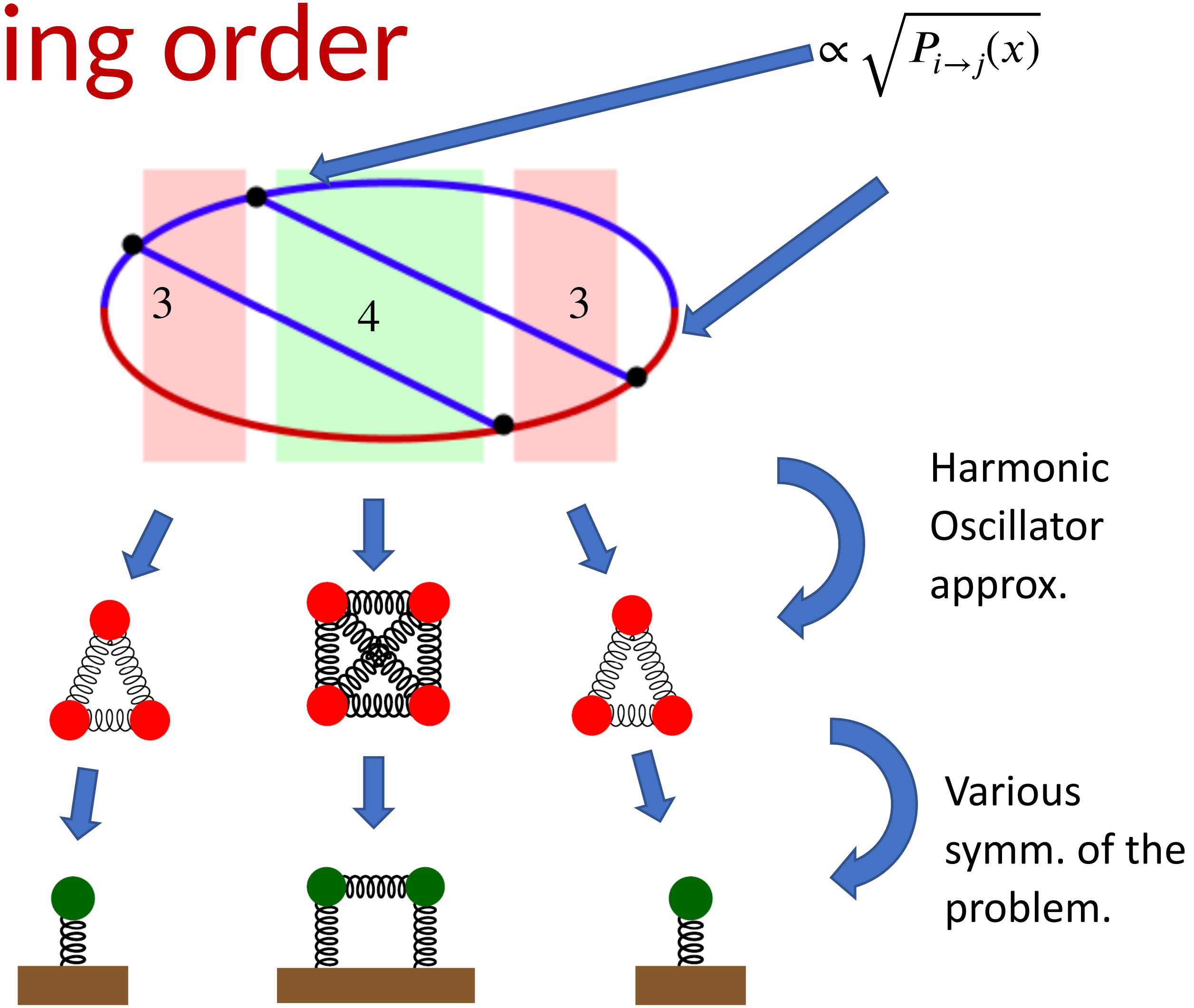


Splitting vertices given by QCD Feynman rules.

Medium effects given by non-Hermitian Hamiltonian.

$$rate \propto \int (\text{Splitting matrix element at } \bar{t}) \times (\text{3-particle evolution}) \times (\text{Splitting matrix element at } t)$$

LPM at next-to-leading order



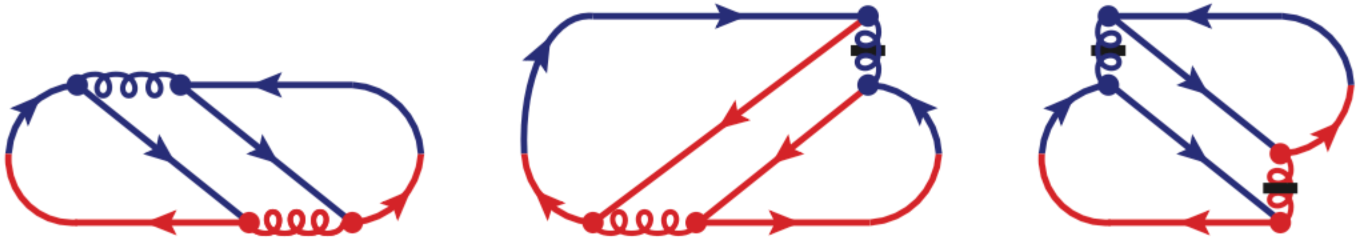
Same idea, but a lot more complicated!

- Many different time orderings and permutations.
- Non-trivial helicity structure. Splitting matrix elements related to *Helicity dependent* DGLAP splitting functions.
- Use Harmonic Oscillator (a.k.a. multiple scattering approx. or $\hat{q}$ approx.) and Large-Nc limit to simplify things.
- The final result

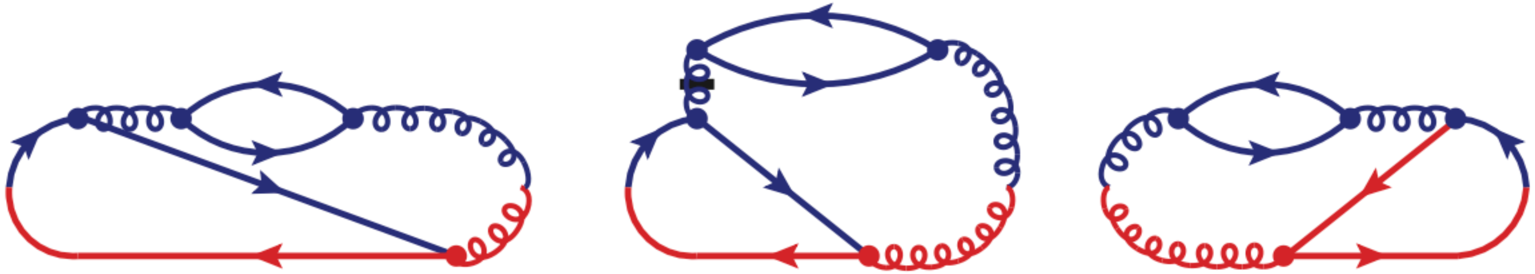
$$\frac{d\Gamma}{dxdy} = \int d\Delta t\ (complicated\ ..)$$

Many, many contributions....

$q \to qQ\bar{Q}$ ....



$q \to qg$ virtual corrections



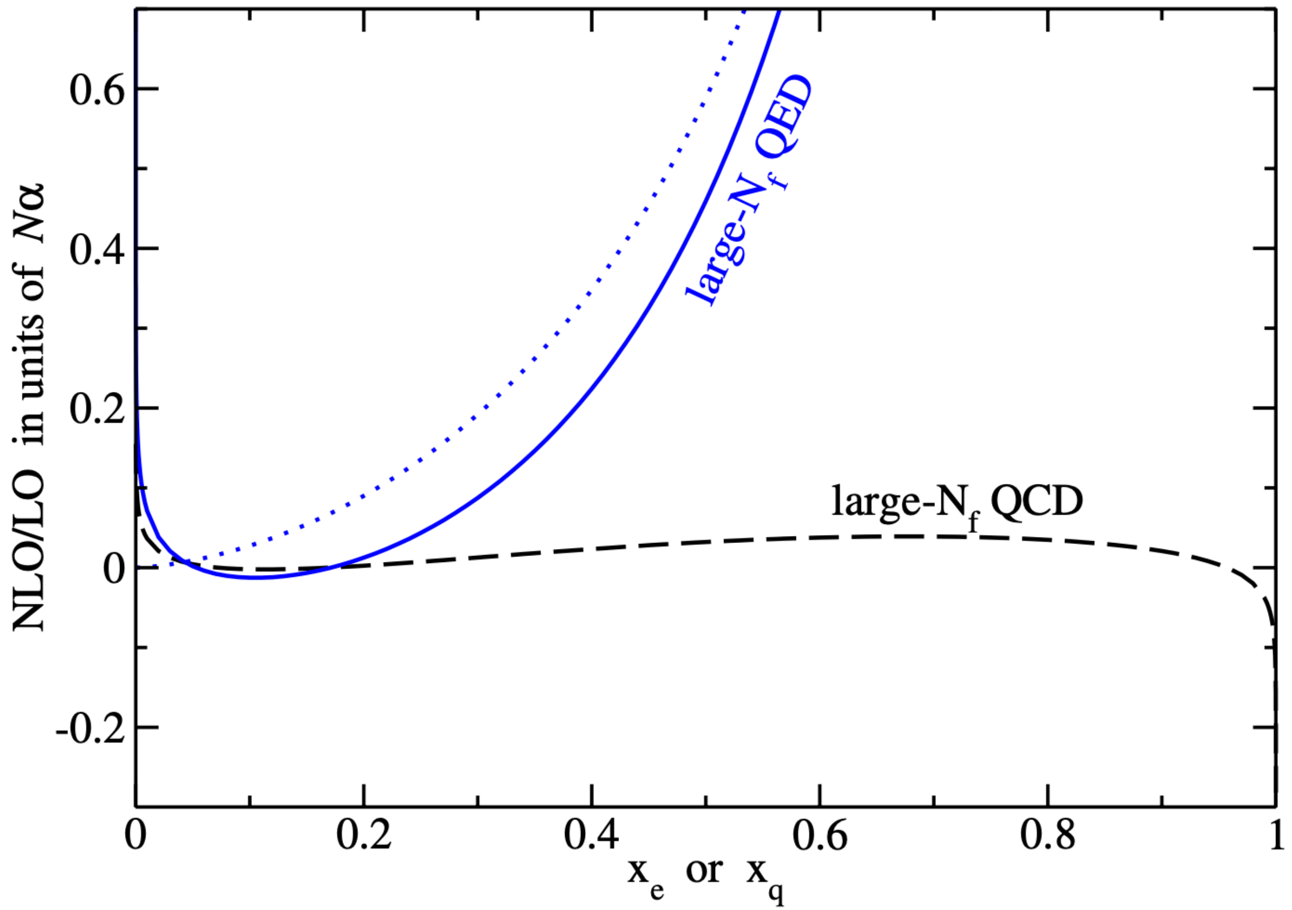
With the result……..

???

With the result……..

$$\chi\alpha \sim 0.5\% \times N_f \alpha_s$$

How is QCD different? A qualitative explanation

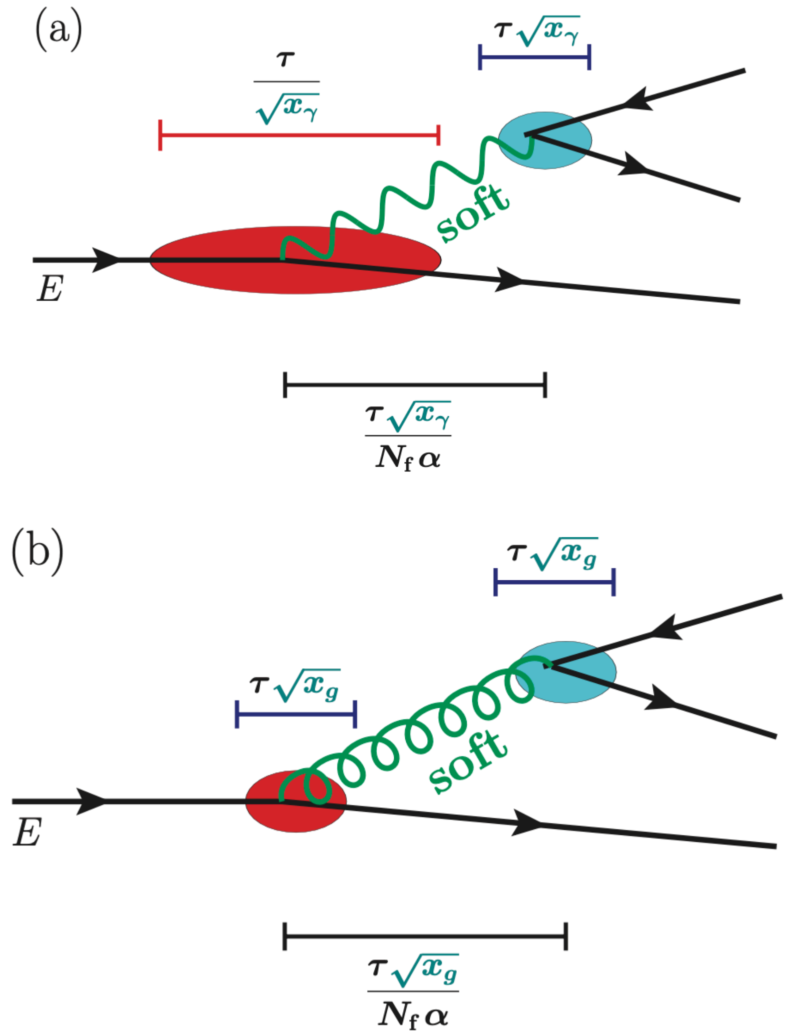


$$\text{Ratio}(x) \equiv \frac{[d\Gamma/dx]^{\text{NLO}}_{\underline{e\to e}}}{[d\Gamma/dx]^{\text{LO}}_{\underline{e\to e}}}$$

How is QCD different? A qualitative explanation

For QED $t_{form}(x_\gamma) \sim \sqrt{\frac{E^2}{\omega_{rad}\hat{q}}} \sim \sqrt{\frac{E}{x_\gamma \hat{q}}}$ for $x_\gamma \ll 1$.

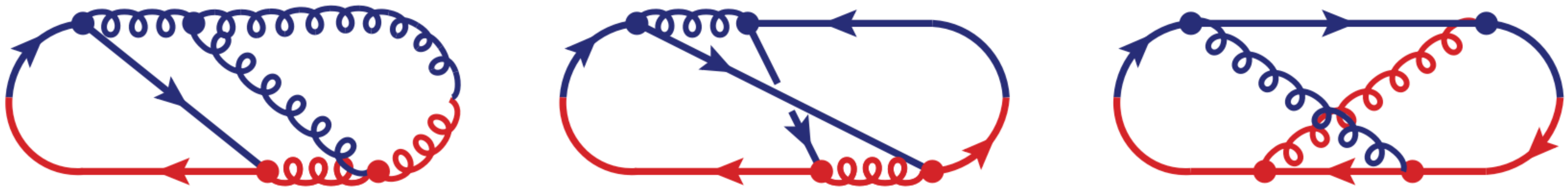
For QCD $t_{form}(x_g) \sim \sqrt{\frac{\omega_{rad}}{\hat{q}}} \sim \sqrt{\frac{x_g E}{\hat{q}}}$ for $x_g \ll 1$.



Conclusion

- Small size of overlap effects for pure gluon ($N_f = 0$) showers was NOT a numerical accident : Soft photons are affected much more significantly by a subsequent pair production than soft gluons are.
- Take away for now: Overlap correction effects that cannot be absorbed into an effective value of $\hat{q}_{eff}$ are small for QCD for both $N_f \gg 1$ and $N_f = 0$.
- Could $N_f \sim N_c$ change the situation?

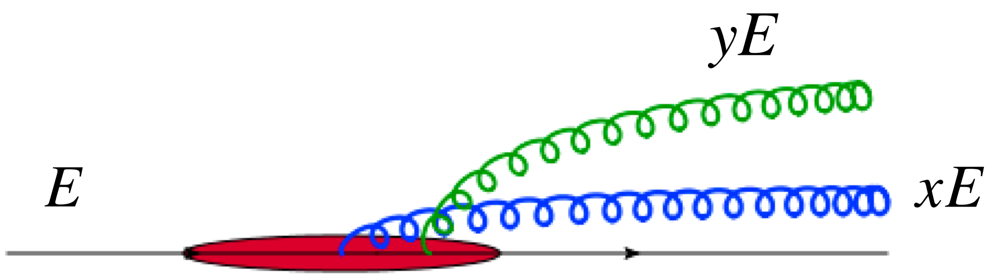
$$N_f \sim N_c ?$$



Thank You!

Double logarithmic enhancement from soft bremsstrahlung

- Probability of hard splittings overlapping with soft bremsstrahlung is enhanced by large logarithms.
- Even if $\alpha_s(\mu)$ is small, the probability can be large when the double log is large.
- In our case, $E \gg T$.
- These effects can be absorbed into $\hat{q}_{eff}$.



$\propto \alpha_s(\mu)\ln^2(xE/T)$

$y \ll x$

Overlap corrections for QCD in $N_f \gg N_c \gg 1$ limit