# Jet evolution in a dense QCD medium

Linnéa Gräns Samuelsson

Internship at CEA Saclay
Supervisors: Edmond Iancu and Gregory Soyez

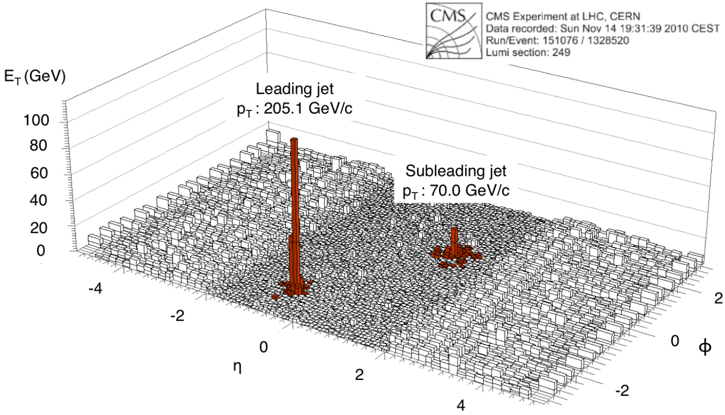
June 30, 2017

- *the medium: a quark gluon plasma created in a heavy ion collision*
- *the jet: a collimated spray of particles generated via successive branchings of a parton with high energy produced in the collision*

Structure of presentation:

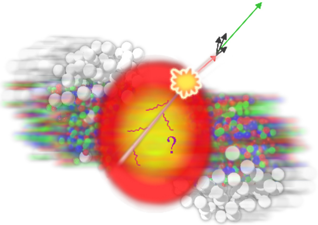
- Context
- Physical picture
- Markov process
- Monte Carlo simulation

# Heavy ion collisions, quark gluon plasma and jets, what we observe:

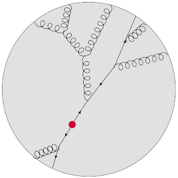


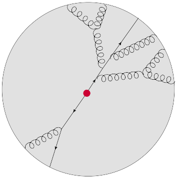

Di-jet asymmetry. Missing energy found among soft hadrons propagating at large angles ⇒ different from in vacuum jet evolution.

Heavy ion collisions, quark gluon plasma and jets, the stereotypical picture:




Implicit assumption: small energy fluctuations.





We need a model that answers:

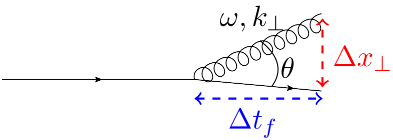
- How can the lost energy end up at such large angles?
- How large are the energy fluctuations?

# Physical picture

*In medium* scattering triggers emissions:

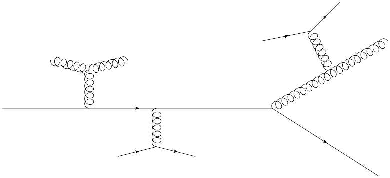
- Destroys quantum coherence
- Gives broadening of transverse momentum

Formation time: $\lambda_\perp < \Delta x_\perp \Rightarrow \frac{1}{k_\perp} < \frac{k_\perp}{\omega}\Delta t_f$.




Note: we have mostly gluon emissions so we consider only these.

$\Delta t_f \gg$ mean free path $\gg$ Debye length $\Rightarrow$ multiple scatterings lead to one emission and scattering centers are independent $\Rightarrow$ random walk $\Rightarrow \langle k_\perp^2 \rangle \sim \hat{q}\Delta t$.



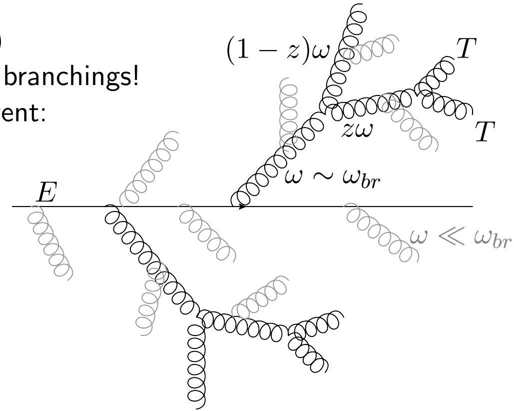
All together: $\Delta t_f \sim \sqrt{\frac{\omega}{\hat{q}}}$ and $\theta_f = \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$

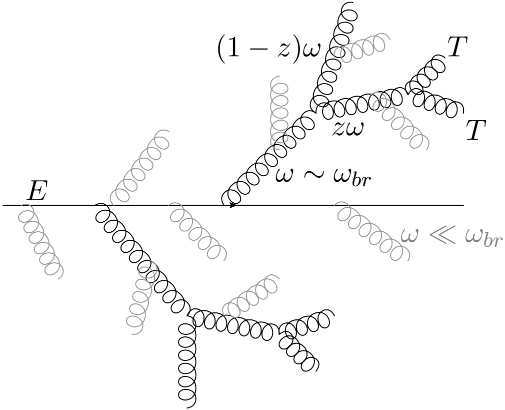
$\Rightarrow$ we favour soft gluons at large angles!

If instead $\omega$ energy of parent: $\Delta P(z,\omega,\Delta t) \sim \alpha_s \Delta t/[\Delta t_f(z\omega)]$

- For $z\omega \sim \omega_{br}$, $\Delta P(z,\omega) \sim \mathcal{O}(1)$ at $\Delta t = L$
- For $\omega_{br}$, $P(z,\omega_{br}) \sim \mathcal{O}(1)$ for $\Delta t < L$, even for $z \sim 1/2$

$\Delta P \sim \mathcal{O}(1)$
$\Rightarrow$ multiple branchings!
A typical event:






- A number of $\mathcal{O}(1)$ of primary gluons with $\omega \sim \omega_{br}$ emitted from leading particle.
- They then branch democratically, transferring away all energy.
- Hence both energy loss and its fluctuations on the scale $\omega_{br}$.
- Time between branchings $>$ formation time $\Rightarrow$ branchings are independent $\Rightarrow$ Markov process

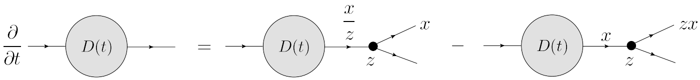
# Markov process

Branching rate from BDMPSZ spectrum:

$$\frac{\mathrm{d}^2 P(z,\tau)}{\mathrm{d}z\mathrm{d}\tau} = \frac{K(z)}{2\sqrt{x}} \equiv K(x,z).$$

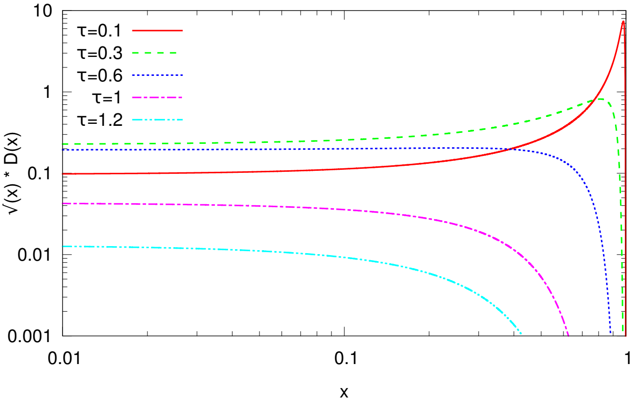
- $\tau$ = time scaled by the time needed for the leading particle to branch democratically.
- Splitting kernel: $K(z) = \frac{[1-z(1-z)]^{5/2}}{[z(1-z)]^{3/2}}$.
  Simplified: $K(z) = \frac{1}{[z(1-z)]^{3/2}}$.

Get equation for the one point function $D(x,\tau) \equiv xn(x,\tau)$




and similarly (but longer) for the two-point function $D^{(2)}(x,x'\tau) \equiv xx'n^{(2)}(x,x',\tau)$.

Simple kernel:



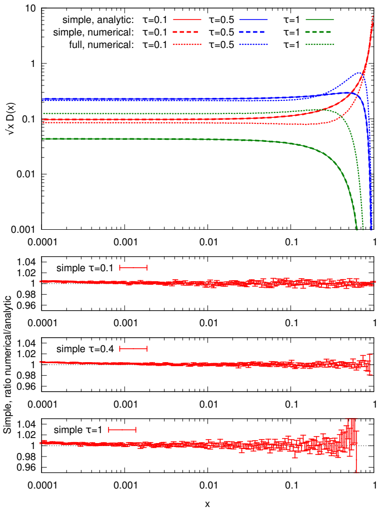

- Energy fraction left in gluon cascade: $\int_0^1 \mathrm{d}x\, D(x,\tau) = e^{-\pi\tau^2} \Rightarrow$ decreasing in time.
- Formally: condensate at $x = 0$. Physically: thermalization.
- At small $\tau$, loss $\simeq \pi\omega_{br}$.
- $D^{(2)}(x, x'\tau)$ used to find fluctuations. To order $\tau^4$:

$$\sigma_\epsilon(\tau) \simeq \langle \epsilon(\tau) \rangle / \sqrt{3}$$

# Monte Carlo simulation

Result: full kernel $\Rightarrow$ less efficient branching

$\sqrt{x}D(x)$




Simple splitting kernel, numerical versus analytic:

- Good agreement overall
- Bias at small x (pileup)

Corrections from the full splitting kernel:

- Leading peak still present at $\tau = 0.5$
- Less energy lost at $\tau = 1$

Recall:

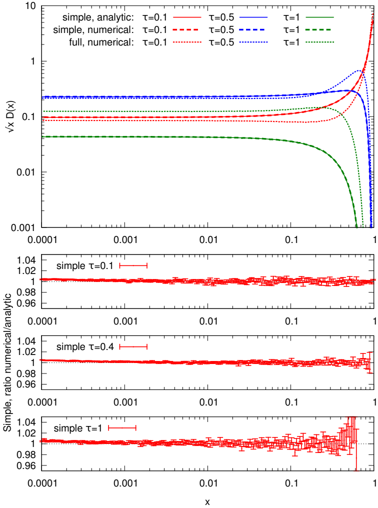
Simple $K(z) = \frac{1}{[z(1-z)]^{3/2}}$

Full $K(z) = \frac{[1-z(1-z)]^{5/2}}{[z(1-z)]^{3/2}}$

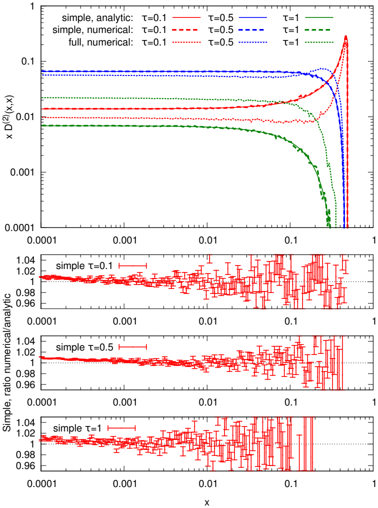
# Monte Carlo simulation

## Result: full kernel $\Rightarrow$ less efficient branching

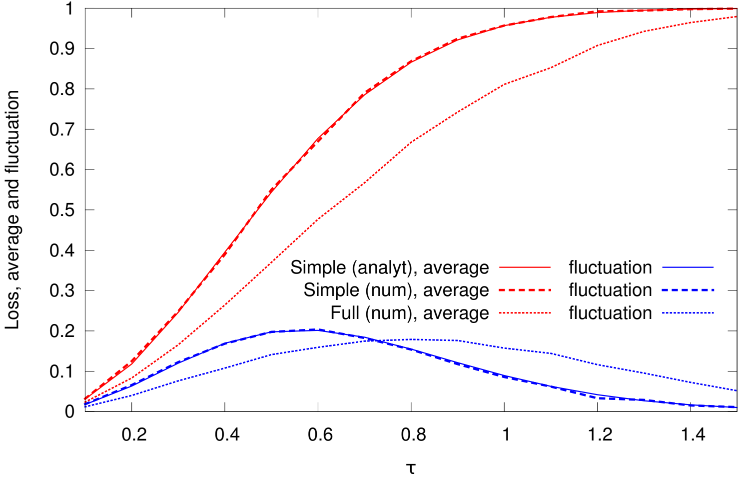
$$\sqrt{x}D(x)$$




$$xD^2(x,x)$$



## Energy loss: $1 - \int_0^1 \mathrm{d}x\, D(x,\tau) = 1 - e^{-\pi\tau^2}$



Summary:

- Democratic branchings $\Rightarrow$ energy found at large angles
- Prediction: large fluctuations in energy loss
- Possible to make Monte Carlo simulation
- Full kernel $\Rightarrow$ less efficient branching
- Full and simple kernel have same behaviour *qualitatively*

THE END

Questions?