

Recent developments in the theory of jet quenching

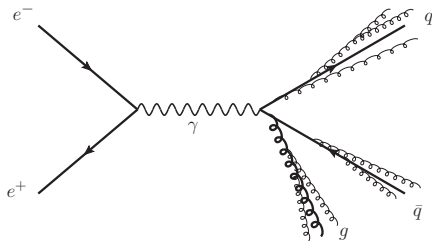
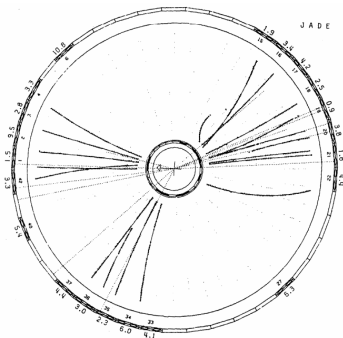
Paul Caucal

Brookhaven National Laboratory

SEWM 2021 conference - July 1st - online

Final state parton evolution: QCD jets

- Jets are collimated spray of energetic hadrons.



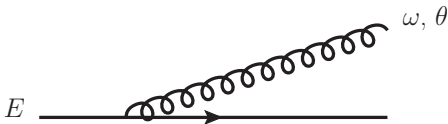
- Predicted and well described by QCD in e^+e^- and pp collisions.
- Collinear/soft radiations enhanced at high energy.
- Jets result from successive collinear emissions from a virtual parton.

Jets in the vacuum

- **Vacuum-like emissions (VLEs)** = Bremsstrahlung triggered by the virtuality:

$$d^2\mathcal{P}_{\text{vle}} \simeq \frac{\alpha_s C_R}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

- Includes soft and collinear divergences.



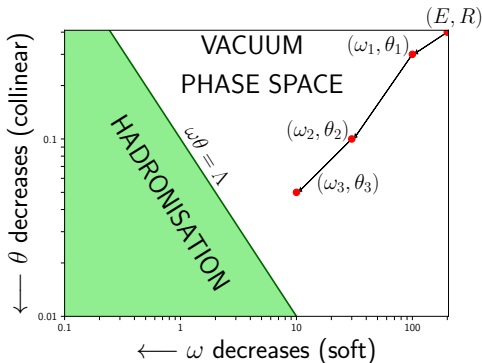
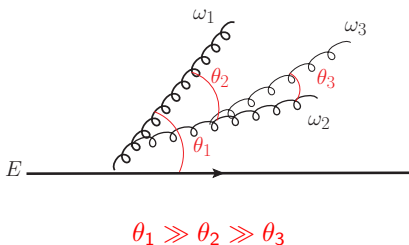
- Duration of the process: $t_f \sim 1/(\omega\theta^2)$.

Jets in the vacuum

- **Vacuum-like emissions (VLEs)** = Bremsstrahlung triggered by the virtuality:

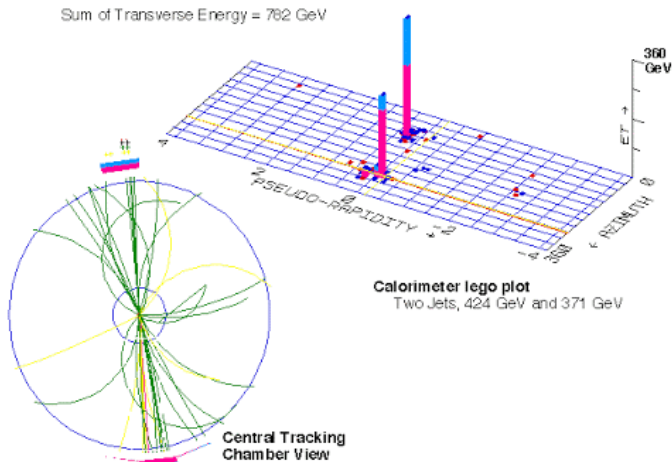
$$d^2\mathcal{P}_{\text{vle}} \simeq \frac{\alpha_s C_R}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

- Markovian process with **angular ordering** to account for **quantum** interferences.



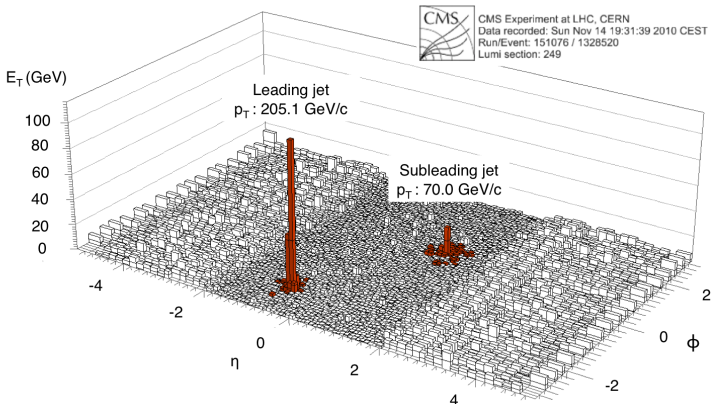
Jets in PbPb collisions: jet quenching

- Illustrative example: **dijet asymmetry**.
- In e^+e^- annihilation: typical events have $p_{T1} \sim p_{T2}$:



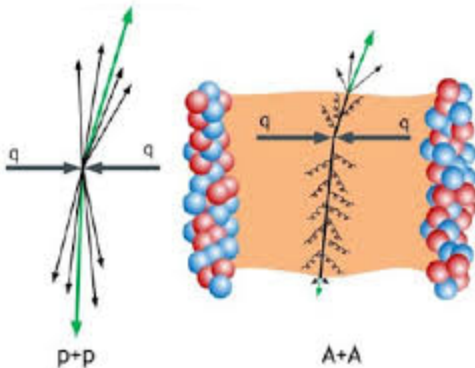
Jets in PbPb collisions: jet quenching

- Illustrative example: **dijet asymmetry**.
- In PbPb collisions: one jet loses more energy
 $\Rightarrow p_{T2} \ll p_{T1}$ much more frequent than in pp or e^+e^- .



Hard probes: jets in heavy-ion collisions

- A hard scattering produces a pair of highly energetic partons.
- The subsequent evolution of the parton \Rightarrow jets.

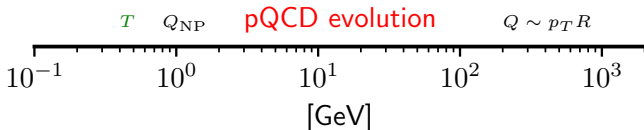


- In PbPb, interaction with the plasma during propagation.

General pQCD picture of jet quenching

Jets in dense QCD plasma: basic processes

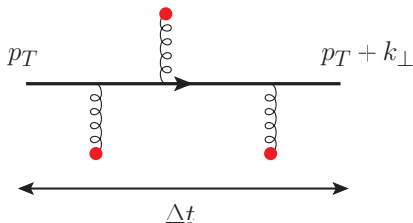
- Jet physics involves a broad range of physical scales



- Transverse momentum broadening
 - Medium-induced emissions
 - Color decoherence
- } pQCD regime
- Many more: hadronization, thermalization, medium response...
See review by Cao, Wang, 2002.04028 See also Schlichting, Soudi, 2008.04928

Parton propagation in dense media (1/3)

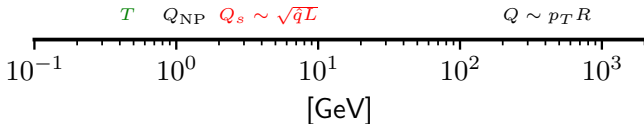
Transverse momentum broadening



- In the multiple soft scattering regime $\Rightarrow \mathcal{P}(k_\perp)$ is Gaussian.

$$\langle k_\perp^2 \rangle = \hat{q} \Delta t$$

- For a jet path length L , typical “saturation scale” $Q_s^2 = \hat{q}L$.



Parton propagation in dense media (2/3)

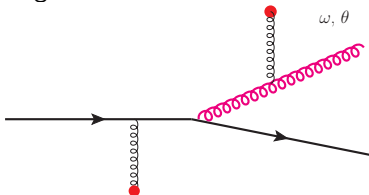
Medium induced emissions

- Medium-induced spectrum: Baier, Dokshitzer, Mueller, Peigne, Schiff, 1997 - Zakharov, 1997

$$d^3\mathcal{P}_{\text{mie}} = \frac{\alpha_s C_R}{\pi} \frac{d\omega}{\omega} \frac{dt}{t_{f,\text{med}}} \underbrace{\mathcal{P}_{\text{broad}}(\theta)}_{\text{Gaussian}} d\theta, \quad \text{with} \quad t_{f,\text{med}} = \sqrt{\omega/\hat{q}}$$

See Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk 2106.07402 beyond the MS approx.

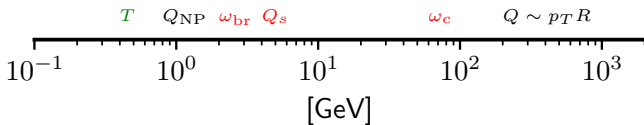
- Typical scale for hardest MIE over L : $\omega_c \sim \hat{q}L^2$.
- **No** collinear divergence when $\theta \rightarrow 0$.



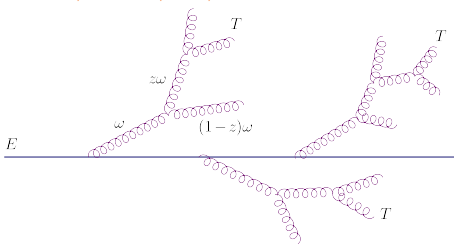
See talk by Omar Elgedawy beyond the single emission process

Parton propagation in dense media (2/3)

Medium induced emissions



- Soft divergence resummed via an evolution equation with rate $d\mathcal{P}_{\text{mie}}/dt$ [Blaizot, Dominguez, Iancu, Mehtar-Tani, 1311.5823](#)
- Multiple branching regime for $\omega \sim \omega_{\text{br}} = \bar{\alpha}_s^2 \hat{q} L^2$.
- Turbulent energy flow from hard to soft sector, **at large angles.**
[Blaizot, Iancu, Mehtar-Tani, 1301.6102, Iancu, Fister 1409.2010](#)



Parton propagation in dense media (3/3)

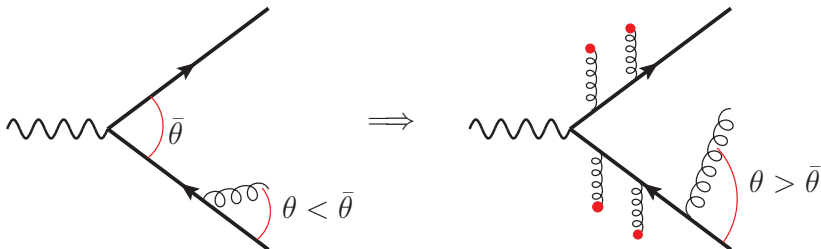
Color decoherence

- Quantum color decoherence: independent sources.

⇒ Characteristic time scale $t_d = (\hat{q}\bar{\theta}^2)^{-1/3}$.

Mehtar-Tani, Salgado, Tywoniuk, 2011 - Casalderrey-Solana, Iancu, 2011

⇒ $t_d = L \Leftrightarrow \bar{\theta}^2 = \theta_c^2 \equiv 1/(\hat{q}L^3)$.

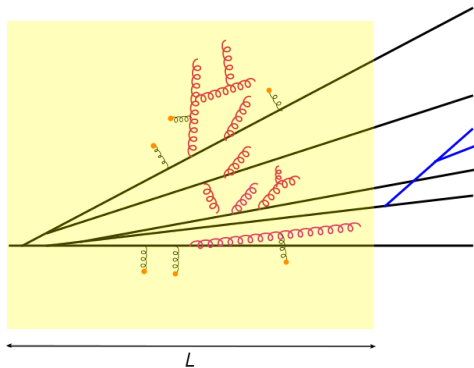


In medium jet evolution to leading-log accuracy

- The evolution of a jet **factorizes** into three steps:
 - (1) An **angular ordered vacuum-like shower inside the medium**,
 - (2) **medium-induced emissions** triggered by previous sources,
 - (3) finally, a **vacuum-like shower outside the medium**.
- Re-opening of the phase space for the first emission outside the medium.

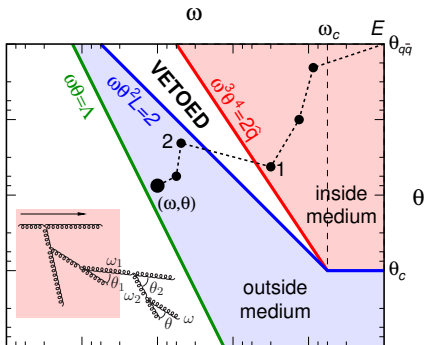
“Factorized” picture

PC, Iancu, Mueller, Soyeur, 1801.09703



In medium jet evolution to leading-log accuracy

- The evolution of a jet **factorizes** into three steps:
 - (1) An **angular ordered vacuum-like shower inside the medium**,
 - (2) **medium-induced emissions** triggered by previous sources,
 - (3) finally, a **vacuum-like shower outside the medium**.
- Re-opening of the phase space for the first emission outside the medium.



- Red line:

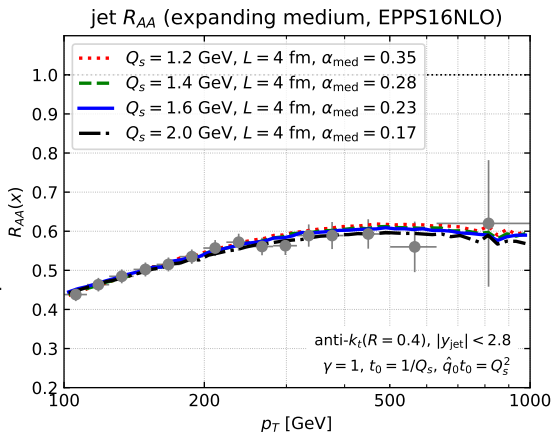
$$t_f = t_{f,\text{med}} = \sqrt{\omega/\hat{q}}$$
- Blue line: $t_f = L, \theta = \theta_c$

Numerical results using Monte-Carlo methods

- 3 medium parameters: \hat{q} , L , $\alpha_{s,med}$ (vertex for MIEs), parton level.

$$R_{AA} \sim \frac{\text{x-section in PbPb}}{\text{x-section in pp}}$$

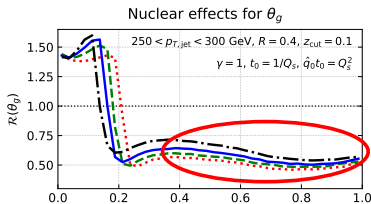
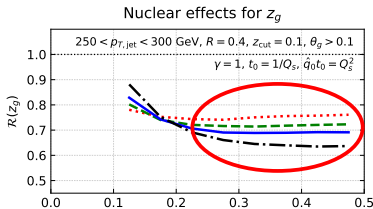
⇒ Results including the **medium expansion** and nPDF. [PC, Iancu, Soyez 2012.01457](#).



- Large p_T suppression due to the increase of vacuum-like sources.
- R_{AA} mainly controlled by $\alpha_{s,med}^2 \hat{q} L^2$ [PC, Iancu, Soyez, 1907.04866](#)

Other IRC safe jet observables

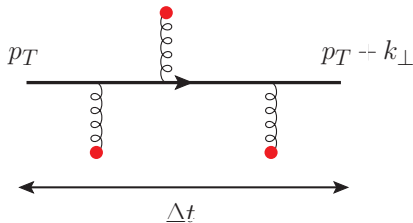
- Framework successfully applied to jet substructure observables such as Soft Drop z_g and θ_g . Larkoski, Marzani, Soyez, Thaler 1402.2657
- z_g (θ_g) \sim typical momentum fraction (angle) of a hard splitting in a jet.



PC, Iancu, Soyez, 1907.04866-2012.01457

- Suppression of large z_g , θ_g jets since they lose more energy.
 \Rightarrow see talk by Yilun Du for machine learning study of this bias effect.

Transverse momentum broadening beyond leading-order



Transverse momentum broadening at tree-level

- Fourier transform of the dipole S-matrix

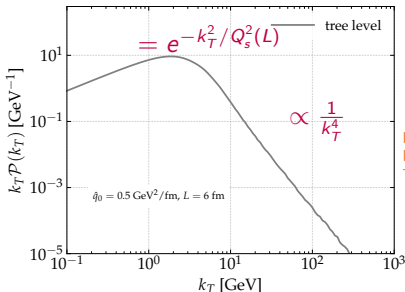
$$\mathcal{P}(\mathbf{k}_\perp) = \int d^2\mathbf{x}_\perp e^{-i\mathbf{k}_\perp \cdot \mathbf{x}_\perp} e^{-\frac{1}{4}\hat{q}(1/x_\perp^2)Lx_\perp^2}$$

⇒ beyond homogeneous isotropic plasma, [see talk by Sigtryggur Hauksson](#).

- Tree level quenching parameter depends on the size of the dipole

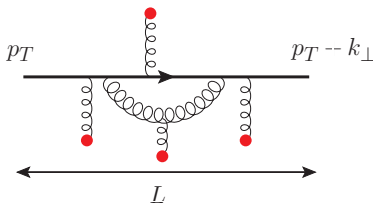
$$\hat{q}_{\text{LO}}(\mathbf{x}_\perp) = \hat{q}_0 \ln \frac{1}{\mathbf{x}_\perp^2 \mu^2}$$

for $\mathbf{x}_\perp^2 \mu^2 \ll 1$. ⇒ [See talk by Niels Schlusser](#) for the NP determination of dipole cross-section.



For an analytic expression, see e.g. Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk 2009.13667 .

NLO corrections and double-logarithmic resummation



- Double logarithmic enhancement of the NLO corrections

$$\hat{q}_{\text{NLO}} \sim \hat{q}_{\text{LO}} \left[1 + \frac{\bar{\alpha}_s}{2} \ln^2(L/\tau_0) \right]$$

Liou, Mueller, Wu, 1304.7677 Blaizot, Mehtar-Tani, 1403.2323, Iancu 1403.1996

- Resummation to all orders via the evolution equation:

$$\frac{\partial \hat{q}(\tau, \mathbf{k}_\perp^2)}{\partial \tau} = \bar{\alpha}_s \int_{Q_s^2(\tau)}^{k_\perp^2} \frac{d\mathbf{k}'_\perp{}^2}{\mathbf{k}'_\perp{}^2} \hat{q}(\tau, \mathbf{k}'_\perp{}^2)$$

with $Q_s^2(\tau) \equiv \hat{q}(\tau, Q_s^2(\tau))\tau$.

See also Iancu, Triantafyllopoulos, 1405.3525, Blaizot, Dominguez, 1901.01448

Extended geometric scaling

- At tree-level, $\mathcal{P}(k_T) = f(k_T/Q_s)$ around the peak $k_T \sim Q_s$ but not at large k_T .
- After DL resummation, for $\ln(L/\tau_0) \gg 1$

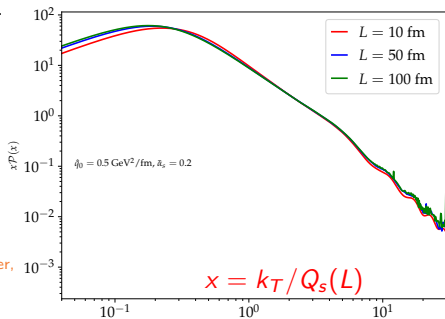
$$\frac{\hat{q}(k_{\perp}^2)L}{Q_s^2(L)} = \begin{cases} e^{\frac{c-1}{c} \ln\left(\frac{k_{\perp}^2}{Q_s^2(L)}\right)} & \text{if } k_{\perp}^2 \leq Q_s^2(L) \\ e^{\frac{c-1}{2c} \ln\left(\frac{k_{\perp}^2}{Q_s^2(L)}\right)} \left[1 + \frac{c-1}{2c} \ln\left(\frac{k_{\perp}^2}{Q_s^2(L)}\right) \right] & \text{else} \end{cases}$$

with $c = 1 + 2\sqrt{\bar{\alpha}_s + \bar{\alpha}_s^2} + 2\bar{\alpha}_s$.

PC, Y. Mehtar-Tani, to appear

⇒ extended **geometric scaling**
beyond the peak!

~ saturation physics in DIS, see Mueller,
Triantafyllopoulos, Iancu, McLerran, Itakura, Munier,
Peschanski (2002-2004)

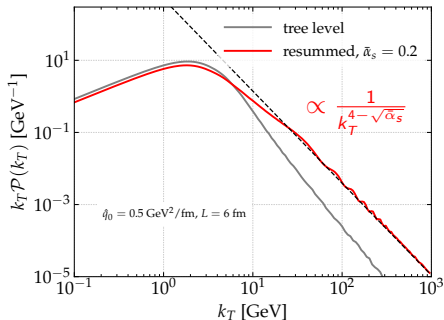


New emergent phenomenon: anomalous diffusion in k_T

- The median of the distribution scales like

$$\mathcal{M} \sim L^{1/2 + \sqrt{\bar{\alpha}_s}}$$

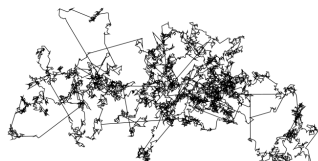
- \Rightarrow super-diffusive behaviour. NLO corrections yields super-diffusion in momentum space.
- Heavy tailed distribution $\mathcal{P}(\mathbf{k}_\perp) \sim (k_T/Q_s(L))^{-4 + \sqrt{\bar{\alpha}_s}}$



PC, Y. Mehtar-Tani, to appear



Brownian
motion



Levy flight

Conclusion and perspectives

- A factorized picture for jet quenching derived from pQCD.
- For precise phenomenology, one should:
 - (1) Go beyond leading-log for the determination of the phase space boundaries.
 - (2) Go beyond the multiple soft scattering approximation for the treatment of the medium-induced radiations.
 - (3) Include NP modeling into this picture: hadronization, thermalization, medium-response,...
 - (4) (non exhaustive list)
- Transverse momentum broadening in QCD plasma beyond leading order exhibits extended geometric scaling and share similarities with super-diffusive random walks.

THANK YOU!