Recent developments in the theory of jet quenching

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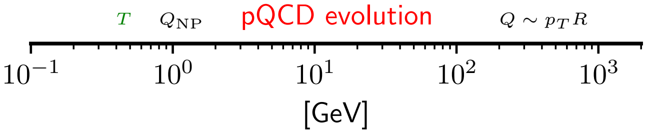
General pQCD picture of jet quenching

Jets in dense QCD plasma: basic processes

- Jet physics involves a broad range of physical scales



- Transverse momentum broadening
- Medium-induced emissions
- Color decoherence

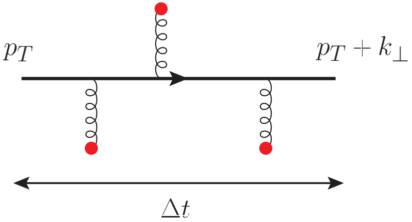
} pQCD regime

- 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)

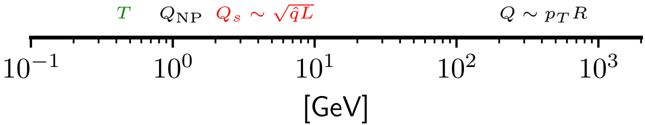
Transverse momentum broadening



- 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 lentgh L, typical "saturation scale" $Q_s^2 = \hat{q}L$.



Parton propagation in dense media (2/3)

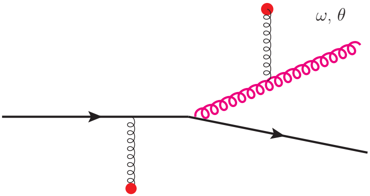
Medium induced emissions

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

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

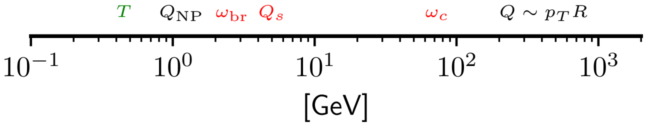
See Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk 2106.07402 beyond the MS approx.

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

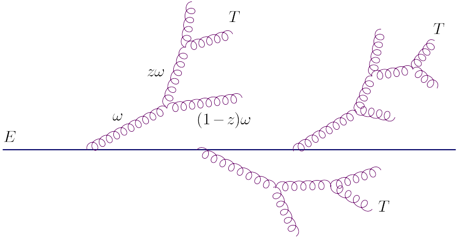


Parton propagation in dense media (2/3)

Medium induced emissions



- Soft divergence resummed via an evolution equation with rate $\mathrm{d}\mathcal{P}_{\rm mie}/\mathrm{d}t$ Blaizot, Dominguez, Iancu, Mehtar-Tani, 1311.5823
- Multiple branching regime for $\omega \sim \omega_{\rm br} = \bar{\alpha}_s^2 \hat{q} L^2$.
- 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)

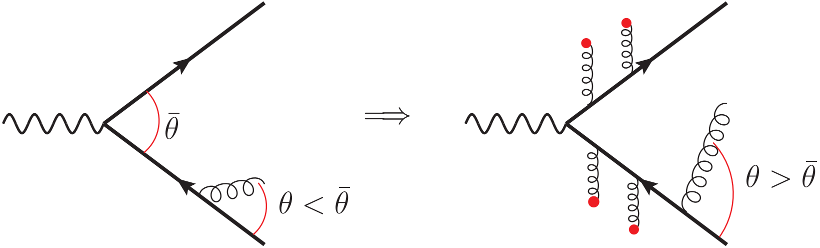
Color decoherence

- 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

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

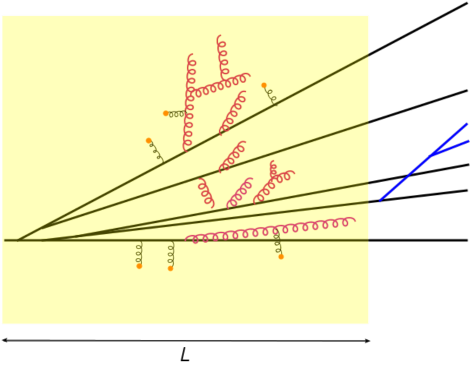


In medium jet evolution to leading-log accuracy

- 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, Soyez, 1801.09703



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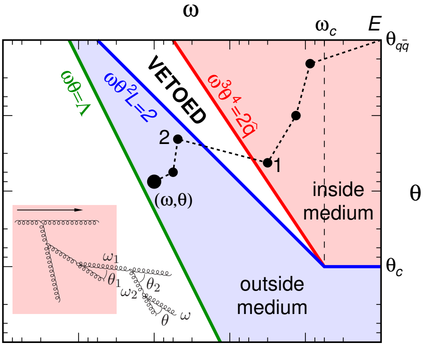


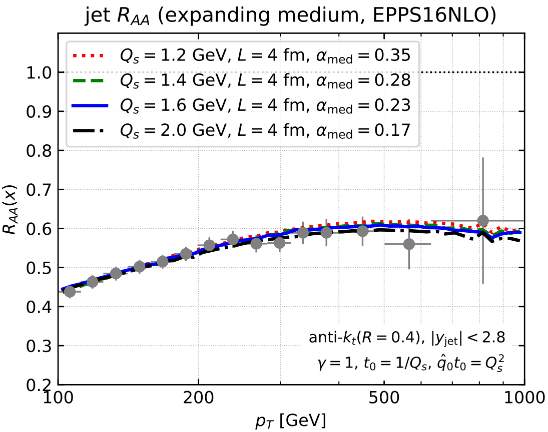
- Red line: $t_f = t_{f,\text{med}} = \sqrt{\omega/\hat{q}}$
- Blue line: $t_f = L$, $\theta = \theta_c$

Numerical results using Monte-Carlo methods

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

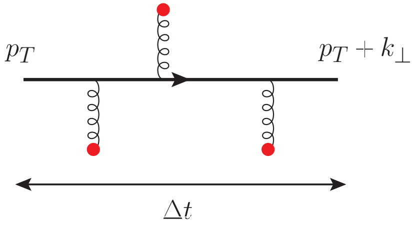
$$R_{AA} \sim \frac{\text{x-section in PbPb}}{\text{x-section in pp}}$$

$\Rightarrow$ 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 $\alpha_{s,\mathrm{med}}^2 \hat{q} L^2$ PC, Iancu, Soyez, 1907.04866

Transverse momentum broadening beyond leading-order



Transverse momentum broadening at tree-level

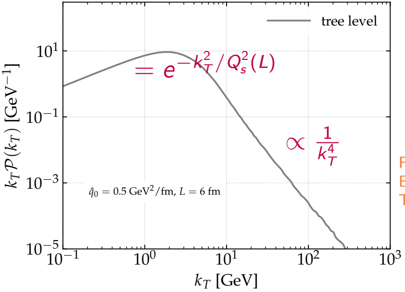
- Fourier transform of the dipole S-matrix

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

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

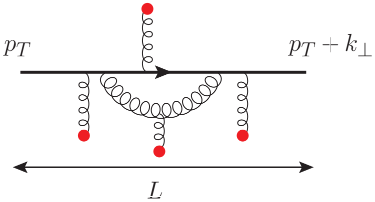
$$\hat{q}_{\rm LO}(\boldsymbol{x}_\perp) = \hat{q}_0 \ln \frac{1}{\boldsymbol{x}_\perp^2 \mu^2}$$

for $\boldsymbol{x}_\perp^2 \mu^2 \ll 1$.



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

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

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

- Resummation to all orders via the evolution equation:

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

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 $\ln(L/\tau_0) \gg 1$

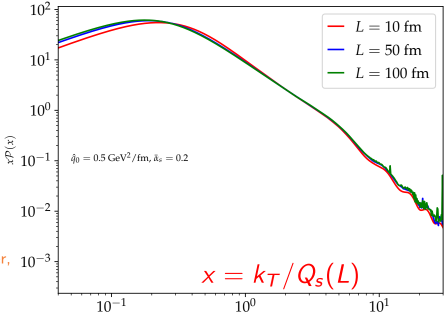
$$\frac{\hat{q}(\boldsymbol{k}_\perp^2)L}{Q_s^2(L)} = \begin{cases} e^{\frac{c-1}{c}\ln\left(\frac{\boldsymbol{k}_\perp^2}{Q_s^2(L)}\right)} & \text{if } \boldsymbol{k}_\perp^2 \leq Q_s^2(L) \\ e^{\frac{c-1}{2c}\ln\left(\frac{\boldsymbol{k}_\perp^2}{Q_s^2(L)}\right)}\left[1+\frac{c-1}{2c}\ln\left(\frac{\boldsymbol{k}_\perp^2}{Q_s^2(L)}\right)\right]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

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

PC, Y. Mehtar-Tani, to appear

$\Rightarrow$ extended **geometric scaling** beyond the peak!

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

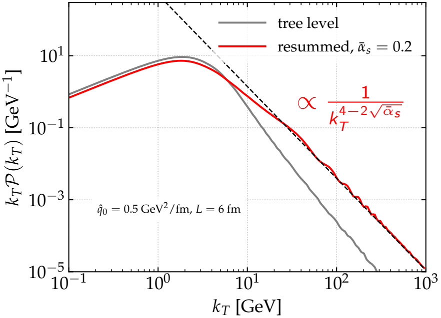


New emergent phenomenon: anomalous diffusion in k_T

- The typical width of the distribution scales like

$$\langle \boldsymbol{k}_\perp^2 \rangle_{\rm med} \sim L^{1/2+\sqrt{\bar{\alpha}_s}}$$

- $\Rightarrow$ super-diffusive behaviour. NLO corrections yields super-diffusion in momentum space.
- Heavy tailed distribution $\mathcal{P}(\boldsymbol{k}_\perp) \sim (1/k_T)^{4-2\sqrt{\bar{\alpha}_s}}$



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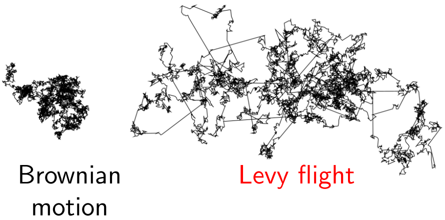


Conclusion and perspectives

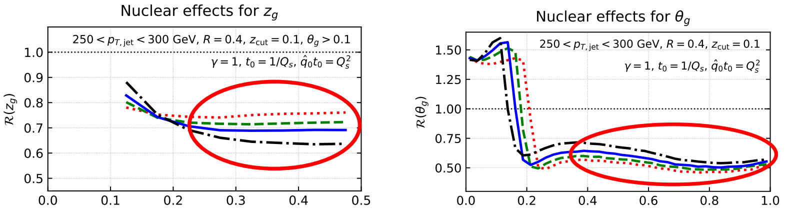
- A factorized picture for jet quenching derived from pQCD.
- For precise phenomenology, one should:
  (1) Go beyond leading-log for the determination of the phase space boundaries.
  (2) Go beyond the multiple soft scattering approximation for the treatment of the medium-induced radiaitons.
  (3) Include 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!

Back-up

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.