From Jet Quenching to Turbulence

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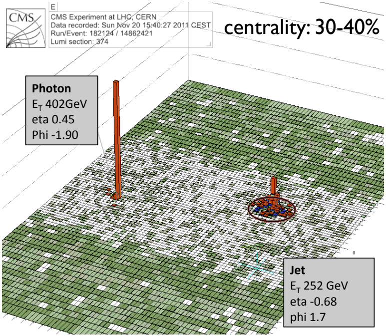
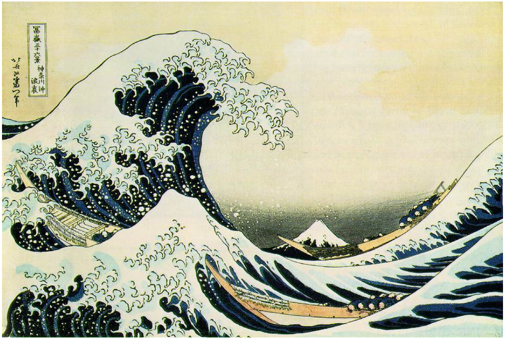
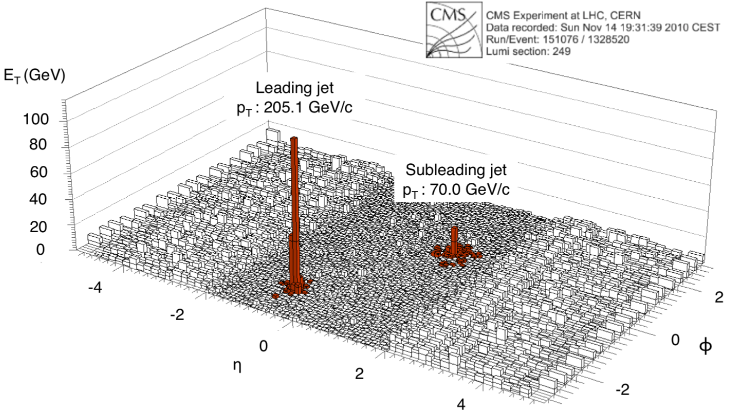


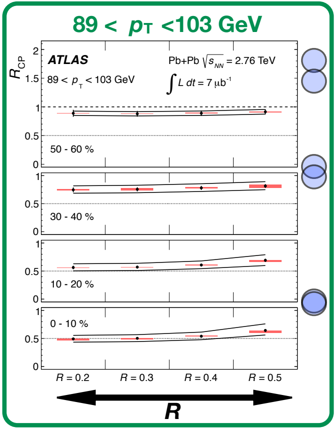


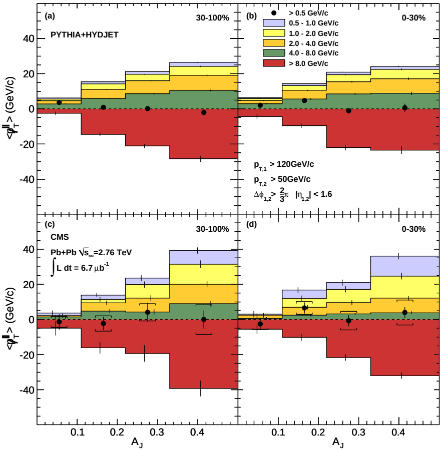
Motivation: **Di–jet asymmetry at the LHC**



- Additional energy imbalance as compared to p+p : 20 to 30 GeV
- Detailed studies show that the 'missing energy' is associated with the additional radiation of many soft quanta at large angles *(cf. the talks by Stefan Bathe, Guenther Roland, and Aaron Angerami)*

Motivation: **Di–jet asymmetry at the LHC**





- Can we understand that from first principles ?
- Is there a natural mechanism in pQCD to radiate soft quanta at large angles alone ?

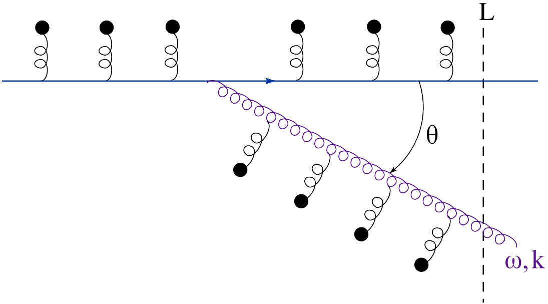
Medium–induced jet evolution

- We need to understand medium–induced jet evolution within pQCD
- Previous studies restricted to a single, medium–induced, emission
  - 'BDMPS–Z mechanism', 'opacity expansion', 'higher–twist' ...
    Baier, Dokshitzer, Mueller, Peigné, and Schiff; Zakharov (96–97); Wiedemann (2000); Guylassy, Levai, Vitev (2000); Arnold, Moore, Yaffe (2002); Wang and Wang (2002) ...
- Already complicated, due to coherent multiple scattering (LPM effect)
- Generalization to multiple branchings even more complicated
  - interference between different emitters
  - correlations induced by multiple scattering (many Wilson lines) ...
- Color decoherence via medium rescattering simplifies the problem
  Mehtar-Tani, Salgado, Tywoniuk (10-12); Casalderrey-Solana, E. I. (11)
- Factorization of multiple branchings & first physical consequences
  Blaizot, Dominguez, E.I., Mehtar-Tani (2012–13)

pQCD : the BDMPSZ mechanism

- Gluon radiation triggered by interactions in the medium

  Baier, Dokshitzer, Mueller, Peigné, and Schiff; Zakharov (96–97)



- Gluon emission is linked to transverse momentum broadening

$$\Delta k_\perp^2 \simeq \hat{q}\,\Delta t \quad \text{with} \quad \hat{q} \simeq \frac{m_D^2}{\lambda} = \frac{(\text{Debye mass})^2}{\text{mean free path}}$$

  - destroys the coherence between the gluon and its parent parton
  - increases the emission angle

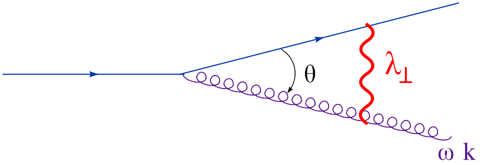
The formation time

- The gluon must lose quantum coherence with respect to its source
- The quark–gluon transverse separation $r_\perp$ at the formation time τ_f should be comparable with the gluon transverse wavelength $\lambda_\perp$

$$r_\perp \simeq \theta\,\tau_f \gtrsim \lambda_\perp \simeq 1/k_\perp$$

$$k_\perp \simeq \omega\,\theta$$

$$\Longrightarrow \tau_f \simeq \frac{\omega}{k_\perp^2} \simeq \frac{1}{\omega\theta^2}$$



- The transverse momentum increases via collisions: $k_\perp^2 \simeq \hat{q}\,\tau_f$

$$\tau_f \simeq \frac{\omega}{\hat{q}\,\tau_f} \Longrightarrow \tau_f \simeq \sqrt{\frac{\omega}{\hat{q}}} \;\;\&\;\; k_f \simeq (\omega\hat{q})^{1/4}$$

- Actually, this is an upper limit on τ_f : $k_\perp$ can be larger than $k_f(\omega)$

Formation time (τ_f) & angle (θ_f)

$$\tau_f(\omega) \simeq \sqrt{\frac{\omega}{\hat{q}}} \qquad \& \qquad \theta_f(\omega) \gtrsim \frac{k_f}{\omega} \simeq \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$

- Soft gluons : short formation times & large emission angles ✓

  ... but what does 'soft' really mean ?

  - maximal ω for this mechanism : $\tau_f \simeq L \Rightarrow \omega \lesssim \omega_c \equiv \hat{q}L^2$
  - minimal ω : $\tau_f \simeq \lambda_{\rm mfp} \Rightarrow \omega \gtrsim \omega_{\rm BH} \equiv \hat{q}\lambda^2_{\rm mfp}$ (Bethe–Heitler)

- The gluon can be emitted anywhere within the size L of the medium

  ... but its emission takes some time τ_f

  - BDMPSZ gluon spectrum (probability for one gluon emission)

$$\omega\frac{{\rm d}N}{{\rm d}\omega} \simeq \alpha_s\frac{L}{\tau_f(\omega)} \simeq \alpha_s\sqrt{\frac{\omega_c}{\omega}}$$

  - Bremsstrahlung times the available longitudinal phase

The BDMPSZ spectrum

$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \simeq \alpha_s \frac{L}{\tau_f(\omega)} \simeq \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

- LPM effect : the emission rate decreases with increasing ω
  - coherence: many soft collisions contribute to a single, hard, emission
- Relatively hard emissions with $\omega \sim \omega_c$:
  - rare events : probability of $\mathcal{O}(\alpha_s)$
  - control energy loss by the leading particle (and observables like R_{pA})

$$\Delta E = \int^{\omega_c} \mathrm{d}\omega \, \omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \sim \alpha_s \omega_c$$

  - small emission angles $\theta_c = \theta_f(\omega_c) \Rightarrow$ the energy remains inside the jet
- Arguably, not so important for the di–jet asymmetry

The BDMPSZ spectrum

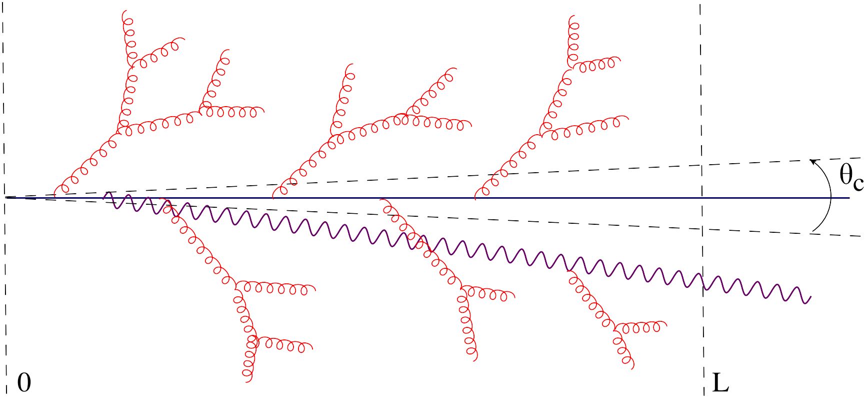
$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \simeq \alpha_s \frac{L}{\tau_f(\omega)} \simeq \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

- LPM effect : the emission rate decreases with increasing ω
  - coherence: many soft collisions contribute to a single, hard, emission
- Relatively soft emissions with $\omega \ll \omega_c$:
  - small formation times : $\tau_f \ll L$
  - quasi–deterministic : probability of $\mathcal{O}(1)$ for $\omega \lesssim \alpha_s^2 \omega_c$

    $\Longrightarrow$ they show up in a typical event !
  - relatively small contribution to energy loss : $\Delta E_{\rm soft} \sim \alpha_s^2 \omega_c$
  - ... but this can be lost at arbitrarily large angles
- Potentially relevant for the di–jet asymmetry

A typical gluon cascade

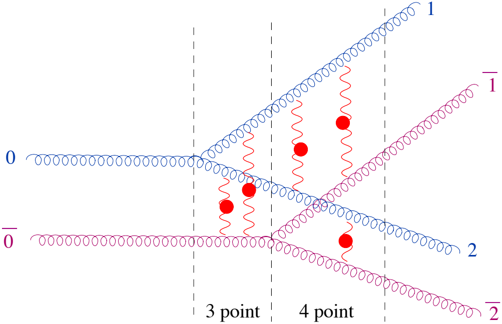
- One needs to understand multiple medium–induced branchings



- A rain of soft gluons ($\omega \ll \omega_c$) plus (sometimes) a harder one ($\omega \sim \omega_c$)
- From now on, we shall focus on the 'rain' !

A few words on the formalism

- Quantum emission: amplitude $\times$ the complex conjugate amplitude



- 'Medium' = randomly distributed scattering centers (Gaussian)
  - Coulomb scattering with Debye screening
  - multiple scattering in eikonal approximation (one Wilson line per gluon)
  - $1 \to 2$ gluon branching $\Rightarrow$ 3–p and 4–p functions of the Wilson lines
- *See also the talk by Fabio Dominguez*

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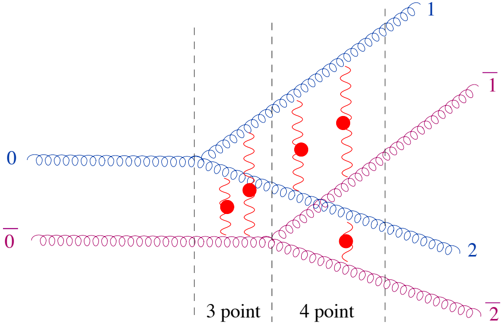


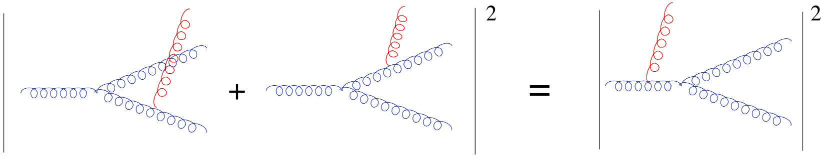
- Contains and extends the original BDMPSZ/AMI formalisms already at the level of a single medium–induced emission ...

  ▷ transverse momentum dependence for the emission vertex, correct inclusion of single scattering, color (de)coherence after emission ...

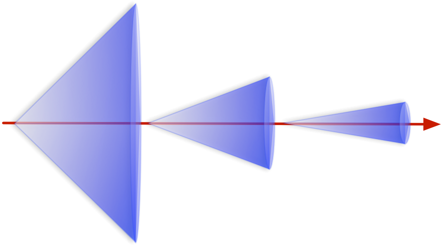
- Permits the treatment of interference & multiple branchings

Multiple emissions : vacuum

- After a splitting, the daughter gluons remain in the same overall color state until the next emission : they are color coherent
- A subsequent emission at large angles sees the overall color charge

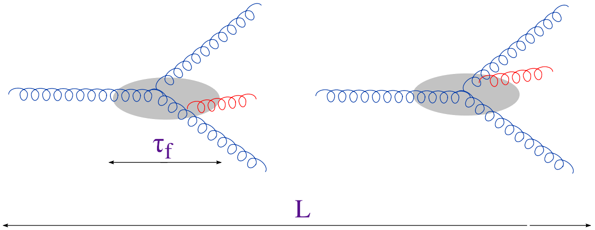


- Equivalent classical branching process, but with angular ordering



Multiple emissions : medium

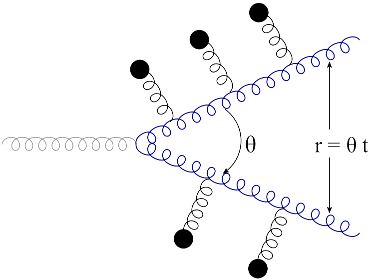
- In the medium, color coherence is rapidly lost via rescattering
  Mehtar-Tani, Salgado, Tywoniuk (arXiv: 1009.2965; 1102.4317); Casalderrey-Solana, E. I. (arXiv: 1106.3864)



- By the time of their emission, the daughter gluons have already lost their color coherence $\Rightarrow$ they cannot interfere with each other
  Blaizot, Dominguez, E.I., Mehtar-Tani (arXiv: 1209.4585)
- The interference effects are suppressed by a factor $\tau_f/L \ll 1$

Color decoherence in the medium

- A 'color antenna' : two gluons propagating at a fixed angle
  - at $\tau = 0$, the two gluons start in a color singlet state ('dipole')
  - how fast do they lose their color coherence via rescattering ?



$$S(\tau,\theta) = \frac{1}{N_g}\left\langle \mathrm{Tr}\left[U(\tau,\boldsymbol{v}_1)U^\dagger(\tau,\boldsymbol{v}_2)\right]\right\rangle$$

$$U^\dagger(\tau,\boldsymbol{v}) = \mathrm{T}\exp\left[\mathrm{i}g\int_0^\tau \mathrm{d}x^+ A^-(x^+,\boldsymbol{v}x^+)\right]$$

Gaussian average over $A^- \Longrightarrow \hat{q}$

$$S(\tau,\theta) \simeq \exp\left\{-\,\hat{q}\int_0^\tau \mathrm{d}t\, r_\perp^2(t)\right\} \simeq \exp\left\{-\,\hat{q}\theta^2\tau^3\right\}$$

- Color coherence is lost for $\tau \gtrsim \tau_{\rm coh} \sim \frac{1}{(\hat{q}\theta^2)^{1/3}}$

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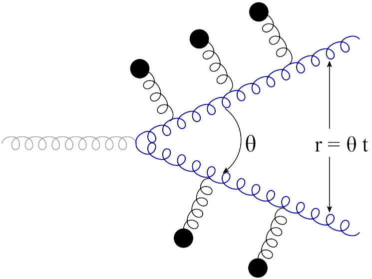

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Gaussian average over $A^- \Longrightarrow \hat{q}$

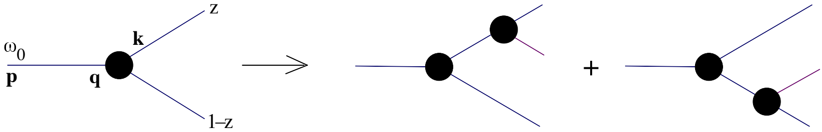
- If the antenna is generated via gluon splitting: $\theta = \theta_f(\omega) \sim (\hat{q}/\omega^3)^{1/4}$

$$\tau_{\rm coh} \sim \frac{1}{(\hat{q}\theta_f^2)^{1/3}} \simeq \sqrt{\frac{\omega}{\hat{q}}} = \tau_f(\omega)$$

- Successive emissions can be treated as independent

A classical branching process

- Markovian process in $D = 3 + 1$: ω, $k_\perp$, time t (or medium size L)



- The $g \to gg$ splitting vertex (the 'blob') : the BDMPSZ spectrum

$$\mathcal{K}(\boldsymbol{Q}, z, \omega_0) = \frac{2}{\omega_0} \frac{P_{gg}(z)}{z(1-z)} \sin\left[\frac{\boldsymbol{Q}^2}{2k_f^2}\right] \exp\left[-\frac{\boldsymbol{Q}^2}{2k_f^2}\right], \quad \boldsymbol{Q} \equiv \boldsymbol{k} - z\boldsymbol{q}$$

▷ strongly peaked at $\boldsymbol{Q}^2 = k_f^2 \equiv \sqrt{z(1-z)\omega_0 \hat{q}}$

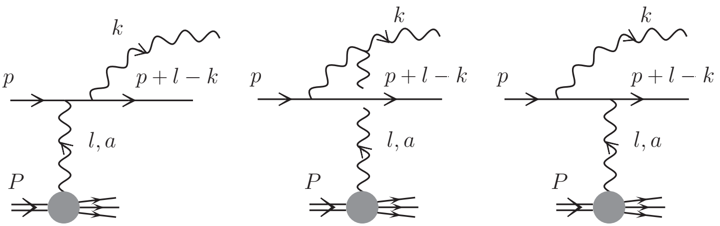
- The propagator (the 'line') : transverse momentum broadening

$$\mathcal{P}(\Delta \boldsymbol{k}; \Delta t) = \frac{4\pi}{\hat{q}\Delta t} \exp\left[-\frac{\Delta \boldsymbol{k}^2}{\hat{q}\Delta t}\right]$$

- Multiple emissions of the BDMPSZ type : multiple soft scattering

Radiative transverse momentum broadening

- Emissions triggered by a single scattering are important as well:
  - unusually hard emissions, with very short formation time $\omega/k_\perp^2$



- Gunion–Bertsch spectrum $\Longrightarrow$ power tail at high $k_\perp$

$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega\, \mathrm{d}^2\boldsymbol{k}} \simeq \frac{\alpha_s N_c}{\pi^2} \frac{\hat{q}L}{k_\perp^4} \qquad \text{(N.B. : linear in } \hat{q}\text{)}$$

- Via their recoil, such high–$k_\perp$ emissions contribute to the momentum broadening of the emitter $\Longrightarrow$ radiative correction to $\hat{q}$

Radiative transverse momentum broadening

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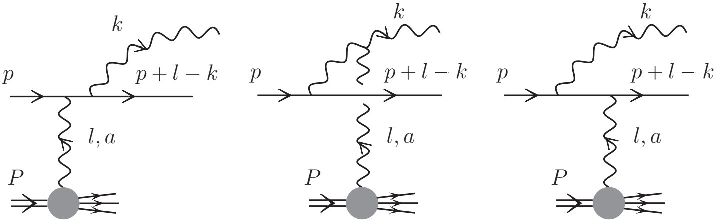
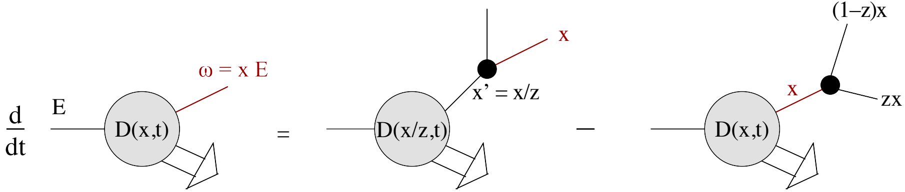


- Formally NLO but enhanced by a double-log *(Liou, Mueller, Wu, 13)*

$$\langle p_\perp^2 \rangle_{\rm RAD} = \int_{\omega,\boldsymbol{k}} \boldsymbol{k}^2 \frac{{\rm d}N}{{\rm d}\omega\, {\rm d}^2\boldsymbol{k}} \sim L\, \alpha_s \hat{q} \int \frac{{\rm d}\omega}{\omega} \int \frac{{\rm d}^2 k_\perp}{k_\perp^4} \equiv L\, \Delta\hat{q}$$

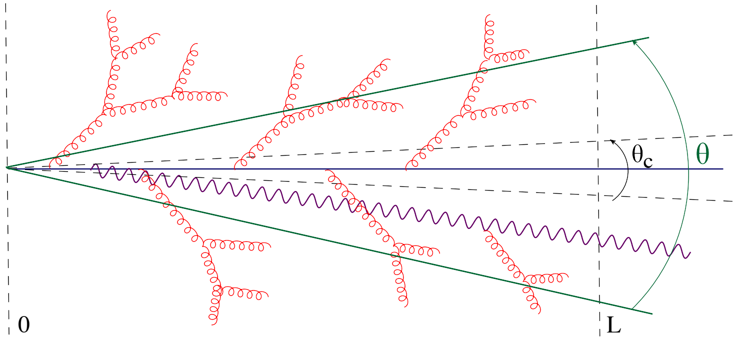
- Also visible in our formalism: *see next talk by Fabio Dominguez*

- From now on: focus on the energy flow alone (integrate over $k_\perp$)
- Rate equation for the gluon spectrum: $D(x,t) \equiv x\frac{dN}{dx}$ $(x = \omega/E)$



- $t \rightarrow t + \mathrm{d}t$: one additional branching with splitting fraction z
- $\partial D/\partial t$ = Gain - Loss (obvious for independent branchings)
  - *Baier, Mueller, Schiff, Son, 2001 : thermalization*
  - *Jeon, Moore, 2003 : jet quenching $\Longrightarrow$ MARTINI*
- Numerical solution *(Jeon, Moore)*: energy loss by the leading particle
- Our focus: energy flow towards soft quanta $(x \ll 1)$ & large angles

Out–of–cone energy



- How much of the jet energy goes outside a given angle θ ?

  ▷ exploit the correlation between energy (x) and the emission angle (θ_f)

  ▷ after emission, the angles are further enhanced by collisions

- A new, efficient, mechanism for angular spreading : wave turbulence

The rate equation

J.-P. Blaizot, E. I., Y. Mehtar-Tani, PRL 111, 052001 (2013)

$$\frac{\partial D(x,t)}{\partial t} = \int \mathrm{d}z \left[2\mathcal{K}\left(z, \frac{x}{z}\right) D\left(\frac{x}{z}, t\right) - \mathcal{K}\left(z, x\right)\, D\left(x, t\right) \right]$$

$$\mathcal{K}(z,x) \equiv \frac{1}{\sqrt{x}} \frac{P_{gg}(z)}{\sqrt{z(1-z)}}\,, \qquad t = \alpha_s \sqrt{\frac{\hat{q}}{E}}\, L$$

- Compare to DGLAP equation: $\mathcal{K}_{\rm DGLAP} = P_{gg}(z) \sim 1/[z(1-z)]$
  - emission kernel depends not only upon the splitting fraction z, but also upon the parent energy x (LPM effect)
  - stronger singularities at $z=0$ and $z=1$ (exponent 3/2 vs. 1)
- DGLAP is controlled by asymmetric splittings : $z \ll 1$ or $1-z \ll 1$
- For the medium–induced radiation, one would expect this bias to be even stronger (since stronger singularities) ...

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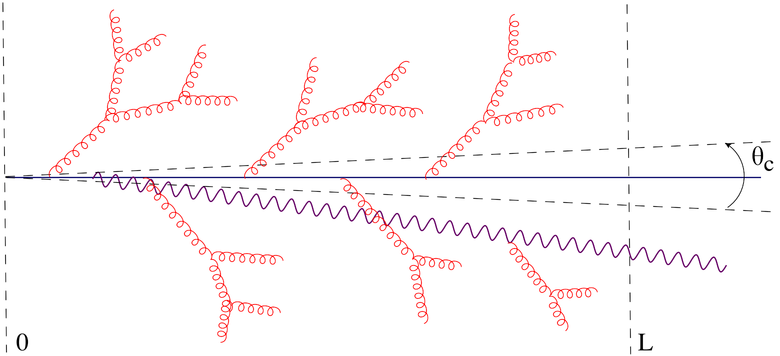
  - stronger singularities at $z = 0$ and $z = 1$ (exponent 3/2 vs. 1)
- DGLAP is controlled by asymmetric splittings : $z \ll 1$ or $1 - z \ll 1$
- For the medium–induced radiation, one would expect this bias to be even stronger (since stronger singularities) ...
- ... but this is actually not the case !

Quasi–democratic branching

- Medium–induced branchings are quasi–democratic ($z \sim 1/2$)



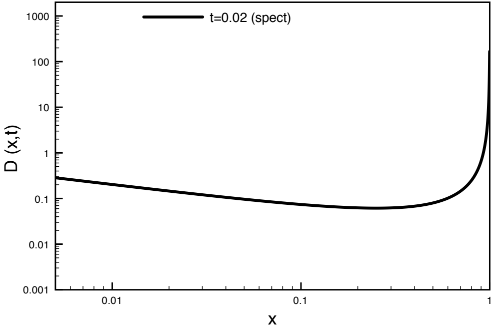
  - the leading particle ($x \sim 1$) emits mostly soft gluons ($z \ll 1$)
  - the subsequent branchings of these soft gluons are quasi–democratic

- When $x \ll 1$, the emission probability is of $\mathcal{O}(1)$ already for $z \sim 1/2$

Small time behaviour

- Initial condition: $D(x, t = 0) = \delta(x - 1)$ (leading particle)
- First iteration $\Longrightarrow$ BDMPSZ spectrum (by construction)

$$D^{(1)}(x,t) \simeq \frac{t}{\sqrt{x}} = \alpha_s \frac{L}{\tau_f(\omega)} \qquad \text{(for } x \ll 1\text{)}$$



- The leading particle populates via direct radiation all the bins at $x < 1$, and preponderantly those at small $x \ll 1$

Small time behaviour

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- First iteration $\Longrightarrow$ BDMPSZ spectrum (by construction)

$$D^{(1)}(x,t) \simeq \frac{t}{\sqrt{x}} = \alpha_s \frac{L}{\tau_f(\omega)} \qquad \text{(for } x \ll 1)$$

- Energy fraction radiated at large angles $\theta_f(x) > \theta_0$, or small $x < x_0$

$$\mathcal{E}^{(1)}(\theta_f > \theta_0, t) = \int_0^{x_0} \mathrm{d}x D^{(1)}(x,t) \simeq 2t\sqrt{x_0}\,, \qquad \theta_0 \propto \frac{1}{x_0^{3/4}}$$

  - the larger $\theta_0 \Rightarrow$ the smaller $x_0 \Rightarrow$ the smaller the energy loss

- BDMPS radiation by the leading particle is not very efficient in transporting the jet energy towards large angles ☹
- Will the situation improve after including multiple branching ?

A fake scenario inspired by DGLAP

- Via successive branchings, gluons fall at smaller and smaller values of x
- Naively, energy conservation seems to imply the sum-rule

$$\int_0^1 \mathrm{d}x\, D(x,t) \,=\, 1 \quad \text{for any } t$$

  - 'all the energy is stored in the spectrum'
  - this is indeed what happens for the DGLAP evolution

- If that was true, then with increasing t the spectrum should become steeper and steeper at small x, but in such a way to remain integrable
- The energy fraction contained in the modes with $x < x_0$, that is,

$$\mathcal{E}(x < x_0, t) \,\equiv\, \int_0^{x_0} \mathrm{d}x\, D(x,t)$$

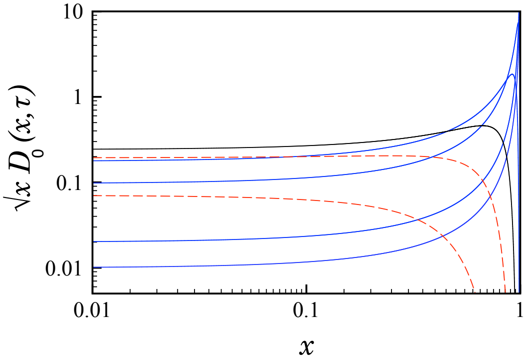
  - would be dominated by the upper limit x_0
  - would rapidly vanish when $x_0 \to 0$

- The out-of-cone energy would rapidly decrease with increasing the angle ☹

The scaling spectrum

- However, this is not what actually happens ! Rather, one finds

$$D(x \ll 1, t) \simeq \frac{t}{\sqrt{x}}\,\mathrm{e}^{-\pi t^2} \qquad \& \qquad \int_0^1 \mathrm{d}x\, D(x,t) = \mathrm{e}^{-\pi t^2}$$



- The spectrum does not get steeper at small x !
- The energy sum–rule is not obeyed !

Where does the energy flow ?

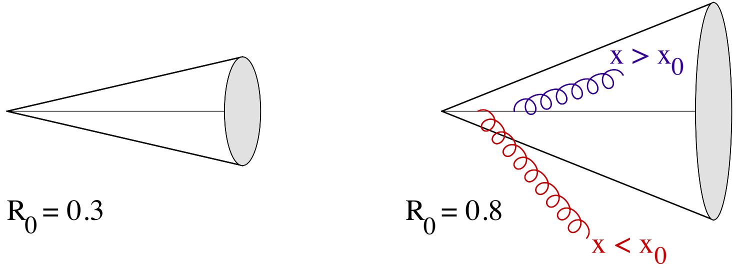
- The 'scaling' spectrum $\frac{1}{\sqrt{x}}$: a fixed point for the branching process
  - precise cancellation between 'gain' and 'loss' terms at any $x \ll 1$
- Via successive branchings, the energy flows from large x to small x, without accumulating in any bin $x > 0$
  - formally, it accumulates into a 'condensate' at $x = 0$
  - physically, it goes below $x_{\rm th} = T/E \ll 1$, meaning it thermalizes
- In principle, an arbitrary large fraction of the jet energy can flow out to arbitrarily large angles

$$E_{\rm flow}(t) \equiv 1 - \int_0^1 {\rm d}x\, D(x,t) = 1 - {\rm e}^{-\pi t^2}$$

- In practice, $t = \alpha_s \sqrt{2\omega_c/E} \sim 0.3$ is not that large ($E = 100$ GeV)
  - $1 - {\rm e}^{-\pi t^2} \sim 0.25 \Rightarrow$ about 25% of the energy is lost at large angles
  - ... independently of the jet angle & and the medium temperature

Energy flow at large angles

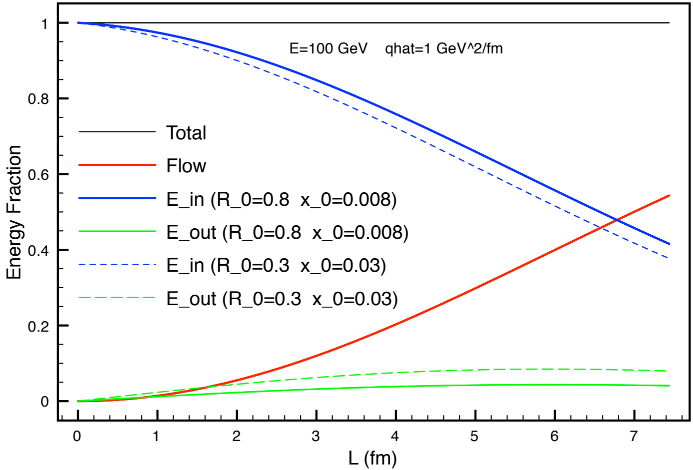
- The energy inside the jet is only weakly increasing with the jet angular opening R_0, within a wide range of values for R_0 ☺



- The energy inside the jet $E_{\rm in}$: the energy in the spectrum at $x > x_0$
- The energy outside the jet : $E_{\rm out}(x_{\rm th} < x < x_0) + E_{\rm flow} \simeq E_{\rm flow}$
- $E_{\rm flow}$: independent of R_0, $x_{\rm th}$, and the original energy E

$$E_{\rm flow} \simeq v\,\alpha_s^2\,\hat{q}L^2 \qquad (\sim 20\,\text{GeV for } L = 5 \text{ fm})$$

Energy flow at large angles



- Qualitative and semi-quantitative agreement with ATLAS and CMS
- No fit, rather a first–principle calculation

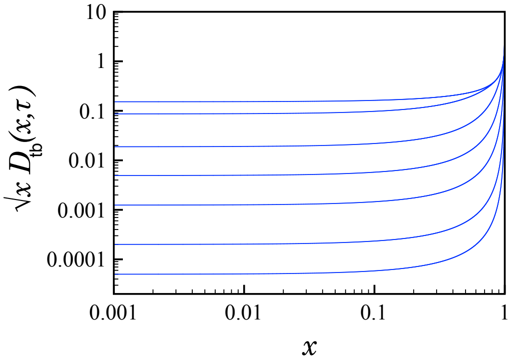
Wave turbulence

- A branching process in which the energy flux is independent of x
  - the energy uniformly flows through the entire spectrum (like water through a pipeline)
- It requires interactions to be quasi–local in energy
  - our 'democratic branching'
  - generally associated with scalar field theories, but not with gauge ones
- It implies the existence of a scaling spectrum $1/k^{\nu}$ where the exponent ν is independent of time ('Kolmogorov power')
  - for medium–induced jet evolution: $\nu = 1/2$
- Generally formulated for steady situations, in which there is a 'source' (at high frequency) and a 'sink' (at low frequency)
  - replace the 'leading particle' by a steady source $\propto \delta(x-1)$ ...
  - ... and the medium by a 'sink' at $x = x_{\rm th}$

The usual turbulence set-up

- Steady source at $x = 1$ and sink at $x = x_{\rm th}$ (here $x_{\rm th} = 0$)

$$D_{\rm tb}(x,t) = \frac{1}{2\pi\sqrt{x(1-x)}} \left(1 - {\rm e}^{-\pi\frac{t^2}{1-x}}\right)$$



- The spectrum approaches a steady shape when $\pi t^2 \gtrsim 1$

With due respect to Wikipedia ...

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Wave turbulence

From Wikipedia, the free encyclopedia

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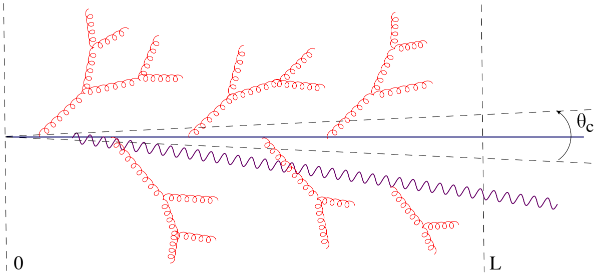
- *V. Zakharov, V. L´vov, and G. Falkovich, Kolmogorov Spectra of Turbulence, Wave Turbulence (Springer-Verlag, 1992)*

Conclusions

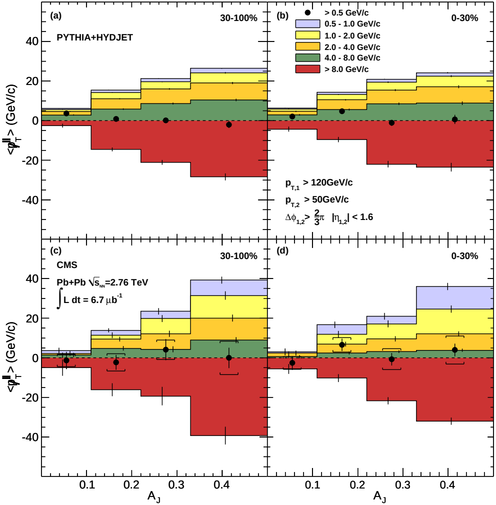
- 3+1 space-time picture for medium–induced jet evolution in pQCD
  - hard emissions at small angles (energy loss by leading particle, R_{AA})
  - multiple soft branchings leading to turbulent flow (di-jet asymmetry)



- Anomalously large value for $\hat{q}$ due to pQCD evolution
  (see the next talk by Fabio Dominguez)
- Encouraging estimates, but still a long way to phenomenology
  - to be implemented in MC event generators like MARTINI

- … but a pronounced difference in the distribution of the total energy in bins of $\omega \equiv p_T$ and in the angle w.r.t. the jet axis

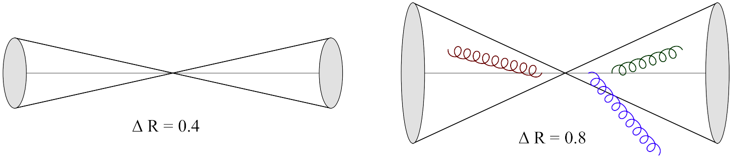
- $p_T^{\parallel}$: projection of the (transverse) energy along the jet axis
- $p_T^{\parallel} < 0$: same hemisphere as the trigger jet
- $p_T^{\parallel} > 0$: same hemisphere as the secondary jet
- all hadrons with $p_T > 0.5$ GeV are measured

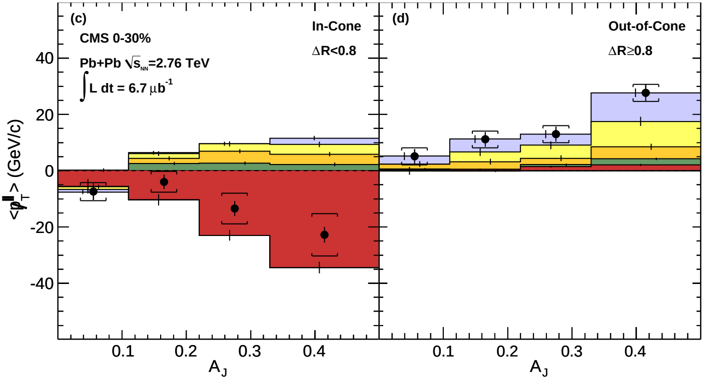


- Excess of soft quanta (≤ 4 GeV) in the hemisphere of secondary jet

In–out asymmetry

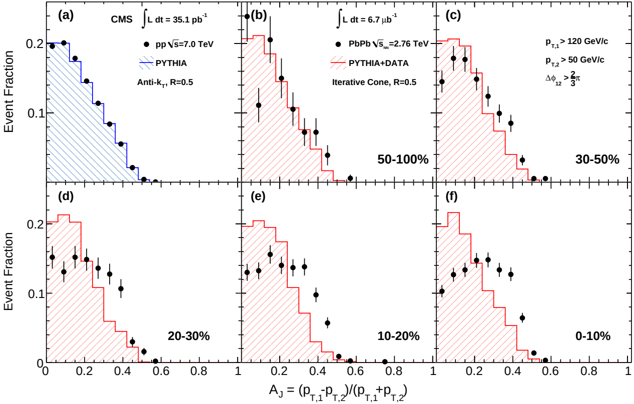
- Increase the angular opening ΔR of the jet





- The soft energy in excess is found at very large angles

Di–jet asymmetry : $A_{\rm J}$ (CMS)

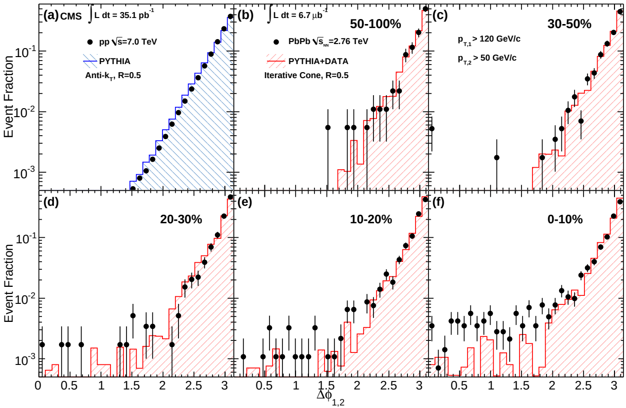


- Event fraction as a function of the di–jet energy imbalance in p+p (a) and Pb+Pb (b–f) collisions for different bins of centrality

$$A_{\rm J} = \frac{E_1 - E_2}{E_1 + E_2} \qquad (E_i \equiv p_{T,i} = \text{ transverse energy})$$

- Additional energy loss of 20 to 30 GeV due to the medium

Di–jet asymmetry : $\Delta\phi$ (CMS)

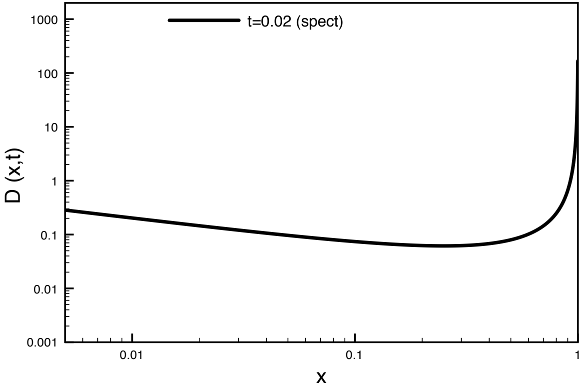


- Event fraction as a function of the azimuthal angle $\Delta\phi$
- Typical event topology: still a pair of back–to–back jets
- The secondary jet loses energy without being deflected
- The additional in–medium radiation is relatively soft

Would-be DGLAP

- One branching $\Longrightarrow$ BDMPSZ spectrum by the leading particle

$$D^{(1)}(x,L) \simeq \alpha_s \frac{L}{\tau_f(\omega)} = \frac{t}{\sqrt{x}} \qquad (t = L \text{ in appropriate units})$$



- What happens when including multiple branchings ?

Would-be DGLAP

- One branching $\Longrightarrow$ BDMPSZ spectrum by the leading particle

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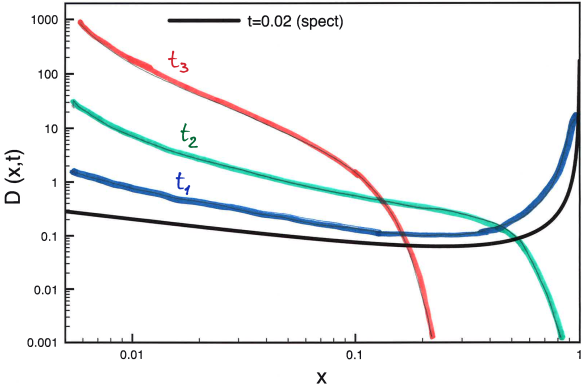
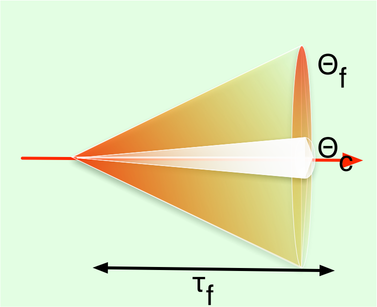


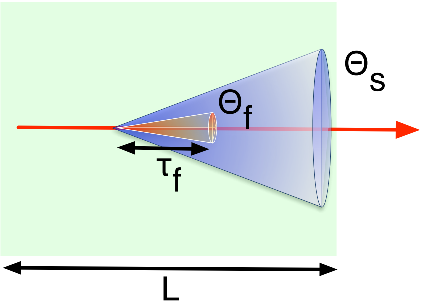
- DGLAP–like evolution: the spectrum is depleted at large x but becomes steeper at small x : $\int_0^1 \mathrm{d}x\, D(x,t) = 1$

Formation time (τ_f) & angle (θ_f)

$$\tau_f \simeq \sqrt{\frac{\omega}{\hat{q}}} \qquad \theta_f \equiv \frac{\Delta k_\perp}{\omega} \simeq \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$

- Soft gluons (small ω) : short formation times & large emission angles
- Maximal ω for this mechanism : $\tau_f \simeq L \Rightarrow \omega_c = \hat{q}L^2$





- Soft gluons ($\omega \ll \omega_c$) have $\tau_f \ll L$ & $\theta_f \gg \theta_c$

Formation time (τ_f) & angle (θ_f)

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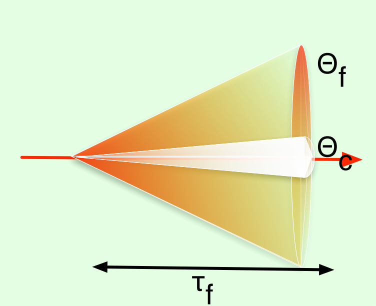
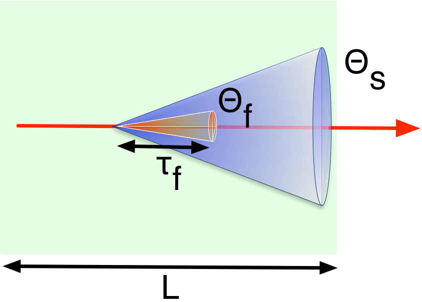
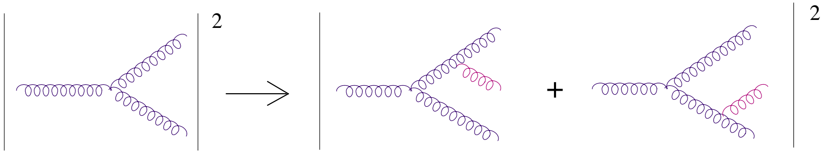




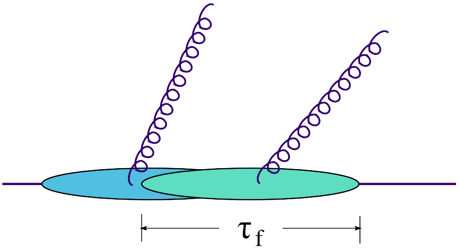
- After emission, the angle can further increase via medium rescattering

Multiple emissions : difficulties

- New complications specific to multiple emissions:
  - interference effects between different emitters



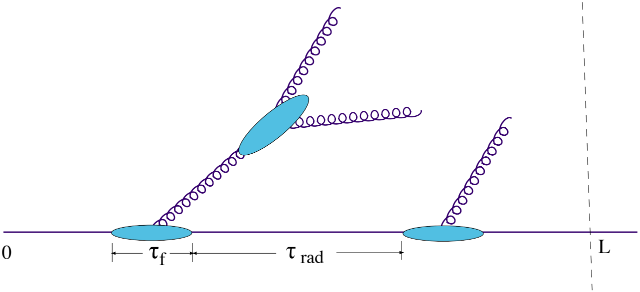
  - overlapping between successive emissions



A classical branching process

- By the time of their emission, the daughter gluons have already lost their color coherence $\Rightarrow$ they cannot interfere with each other
- Subsequent emissions do typically not overlap with each other :

$$P(\tau) \sim \alpha_s \frac{\tau}{\tau_f} \sim 1 \implies \tau_{\rm rad} \sim \frac{\tau_f}{\alpha_s} \gg \tau_f$$



- No interference, no overlapping $\Longrightarrow$

  successive emissions are effectively independent from each other

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Jet quenching

From Wikipedia, the free encyclopedia

- *Collisions of ultra-relativistic heavy-ion beams create a hot and dense medium comparable to the conditions in the early universe, and then these jets interact strongly with the medium, leading to a marked reduction of their energy. This energy reduction is called jet quenching.*

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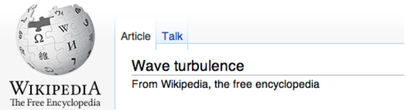
- A familiar concept, hiding a complex reality

With due respect to Wikipedia ...



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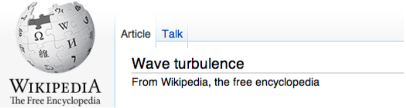
- A rather elusive concept, with an unambiguous mathematical signature

With due respect to Wikipedia ...



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