Event-by-event picture for medium-induced jet evolution

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based on recent work by the Saclay collaboration

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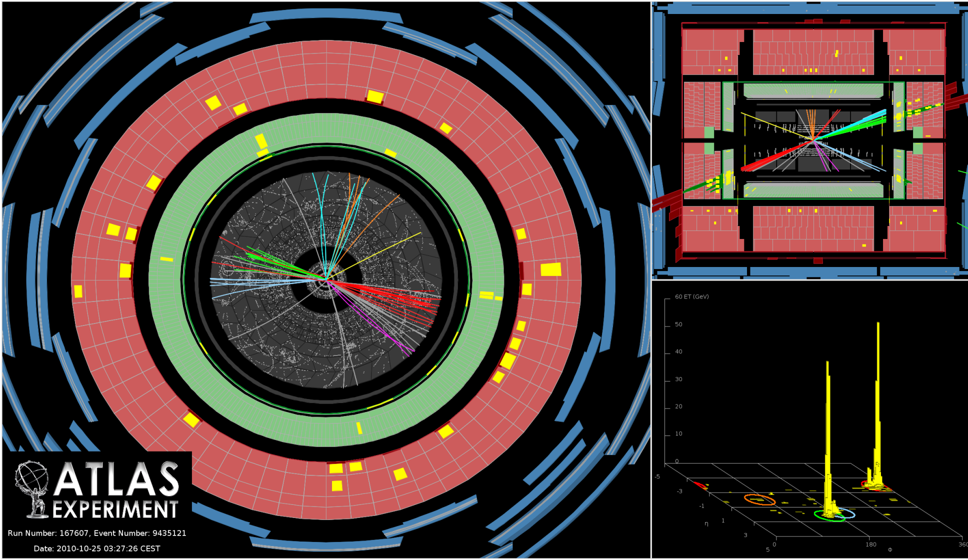
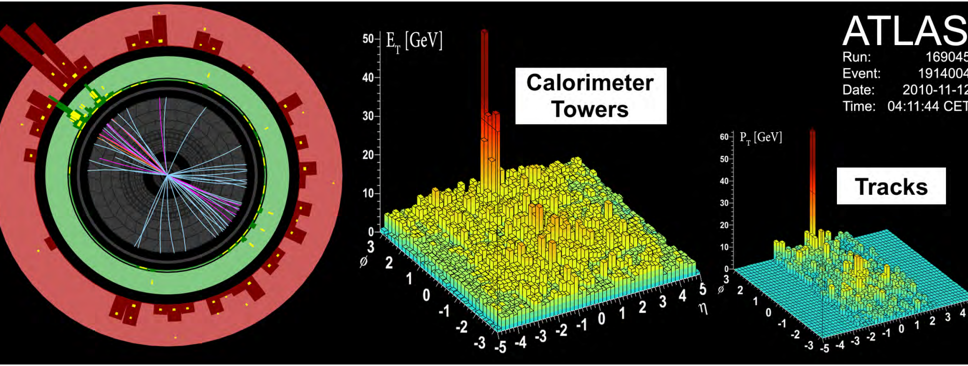
Bon anniversaire à QGP France !

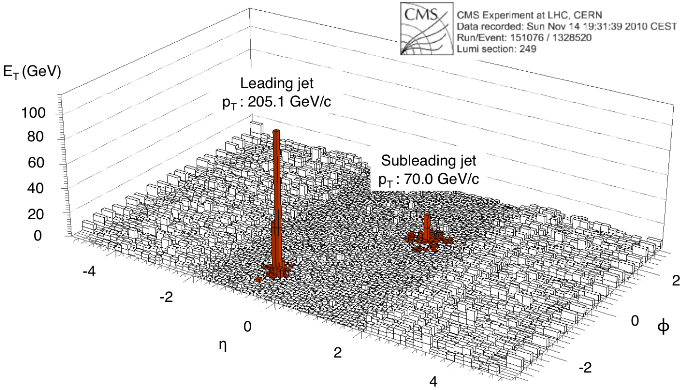
From di–jets in p+p collisions ...





- Central Pb+Pb: 'mono–jet' events
- The secondary jet can barely be distinguished from the background: $E_{T1} \geq 100$ GeV, $E_{T2} > 25$ GeV

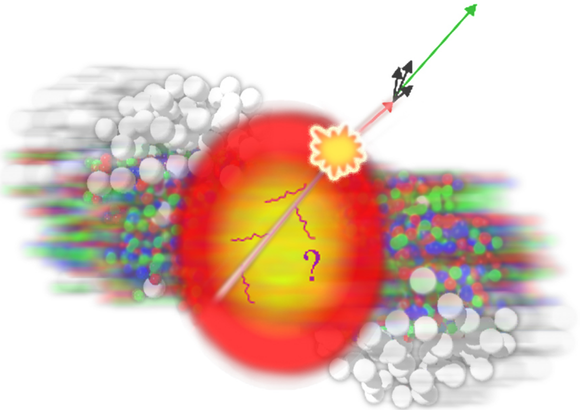
Di–jet asymmetry *(CMS)*



- Average energy imbalance between the 2 jets: $E_1 - E_2 \simeq$ 20 to 30 GeV
- Compare to the typical scale in the medium: $T \sim 1$ GeV (average $p_\perp$)
- Many soft ($p_\perp < 2$ GeV) hadrons propagating at large angles
- Very different from the usual jet fragmentation pattern in the vacuum

The generally expected picture

- Interactions between the jets and the surrounding medium: jet quenching

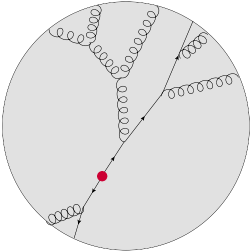


- "One jet crosses the medium along a distance longer than the other"

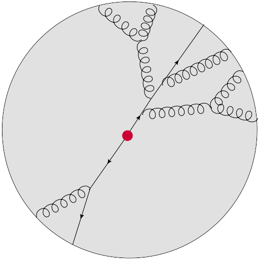
Fluctuations in the branching process

- Implicit assumptions: fluctuations in energy loss are small
  - "the energy loss is always the same for a fixed medium size"

- Different path lengths



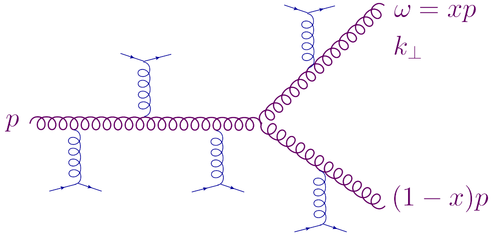
- Fluctuations in the branching pattern



- A recent Monte-Carlo study *(Milhano and Zapp, arXiv:1512.08107)*
  - fluctuations compete with path-length difference
- Analytic studies *(M. Escobedo and E.I., arXiv:1601.03629 & 1609.06104)*
  - fluctuations in the energy loss are as large as the average value

Medium-induced radiation

- Additional radiation triggered by interactions in the medium: BDMPSZ
  Baier, Dokshitzer, Mueller, Peigné, and Schiff; Zakharov (96–97)
- Gluon emission is linked to transverse momentum broadening
- Independent multiple scattering $\Longrightarrow$ a random walk in $k_\perp$



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

$$t_{\rm f} \simeq \frac{1}{\Delta E} \simeq \frac{\omega}{k_\perp^2}$$

- The scatterings destroy quantum coherence and favor gluon emissions

$$t_{\rm f} \simeq \frac{\omega}{k_\perp^2} \quad \& \quad k_\perp^2 \simeq \hat{q} t_{\rm f} \quad \Longrightarrow \quad t_{\rm f}(\omega) \simeq \sqrt{\frac{\omega}{\hat{q}}}$$

Multiple branchings

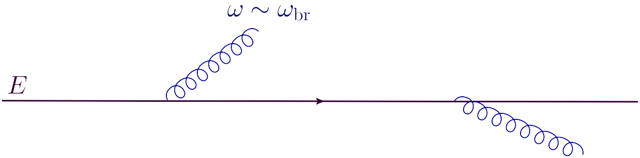
- Probability for emitting a gluon with energy $\geq \omega$ during a time L

$$\mathcal{P}(\omega, L) \simeq \alpha_s \frac{L}{t_{\rm f}(\omega)} \simeq \alpha_s L \sqrt{\frac{\hat{q}}{\omega}}$$

- When $\mathcal{P}(\omega, L) \sim 1$, multiple branching becomes important

$$\omega \lesssim \omega_{\rm br} \equiv \alpha_s^2 \hat{q} L^2 \quad : \text{the fundamental scale for what follows}$$

- LHC: the leading particle has $E \sim 100\,\mathrm{GeV} \gg \omega_{\rm br} \sim 5 \div 10\,\mathrm{GeV}$



- In a typical event, the LP emits ...
  - a number of $\mathcal{O}(1)$ of gluons with $\omega \sim \omega_{\rm br}$

Multiple branchings

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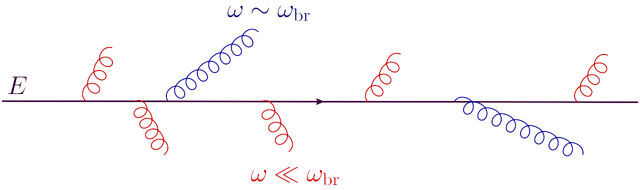

- In a typical event, the LP emits ...
    - a large number of softer gluons with $\omega \ll \omega_{\rm br}$

Multiple branchings

- Probability for emitting a gluon with energy $\geq \omega$ during a time L

$$\mathcal{P}(\omega, L) \simeq \alpha_s \frac{L}{t_{\rm f}(\omega)} \simeq \alpha_s L \sqrt{\frac{\hat{q}}{\omega}}$$

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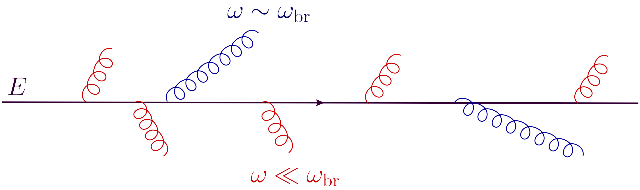
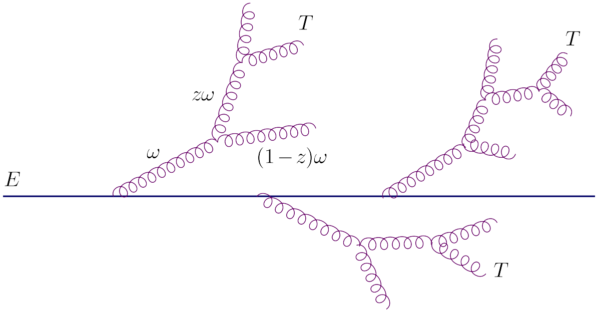


- The energy loss is controlled by the hardest primary emissions

Democratic branchings

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

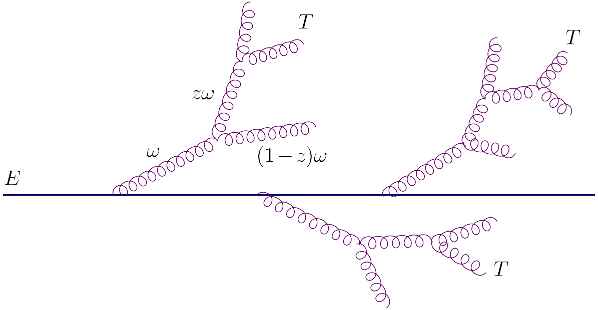
- The primary gluons generate 'mini-jets' via democratic branchings
  - daughter gluons carry comparable energy fractions: $z \sim 1 - z \sim 1/2$
  - contrast to asymmetric splittings in the vacuum: $z \ll 1$



- Democratic branchings lead to wave turbulence
  - energy flows from one parton generation to the next one, at a rate which is independent of the generation

Energy loss at large angles

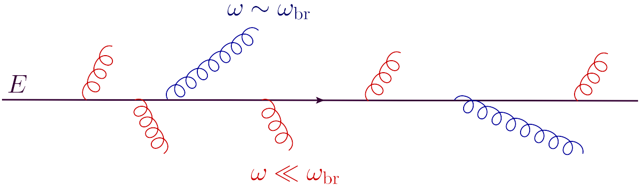
- Via successive democratic branchings, the energy is efficiently transmitted to softer and softer gluons, down to $\omega \sim T$
  - the soft gluons thermalize *(E.I. and Bin Wu, arXiv:1506.07871)*
- Energy appears in many soft quanta propagating at large angles



- Medium-induced jet evolution $\approx$ a Markovien stochastic process
- What is the average energy loss and its fluctuations ?

The average energy loss

- Recall: energy loss is controlled by the primary emissions with $\omega \sim \omega_{\rm br}$



  - softer emissions ($\omega \ll \omega_{\rm br}$) carry very little energy
  - harder gluons ($\omega \gg \omega_{\rm br}$) do not suffer democratic branchings
    $\Longrightarrow$ their energy remains at small angles $\longrightarrow \Delta E_{\rm LPM}$

- Confirmed by an exact calculation *(Blaizot, E. I., Mehtar-Tani, 2013)*

$$\langle \Delta E \rangle = E\left[1 - {\rm e}^{-\pi \frac{\omega_{\rm br}}{E}}\right] \simeq \pi \omega_{\rm br}$$

The average energy loss

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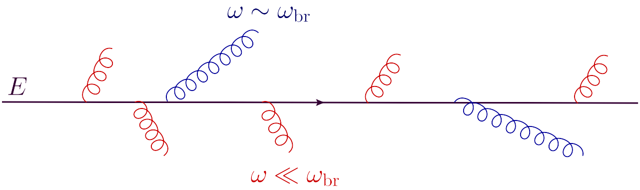

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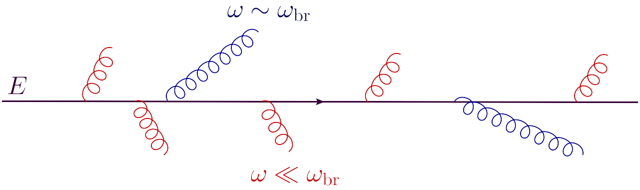
$$\langle \Delta E \rangle = E \left[1 - \mathrm{e}^{-\pi \frac{\omega_{\rm br}}{E}} \right] \simeq \pi \omega_{\rm br} = \pi \alpha_s^2 \hat{q} L^2$$

  - independent of the energy E of the leading particle
  - rapidly increasing with the medium size $\propto L^2$

Fluctuations in the energy loss at large angles

- Recall: the probability for a primary emissions with $\omega \sim \omega_{\rm br}$ is of $\mathcal{O}(1)$



  - the average number of such emissions is of $\mathcal{O}(1)$ (indeed, it is π)
  - successive such emissions are quasi-independent $(E \gg \omega_{\rm br})$

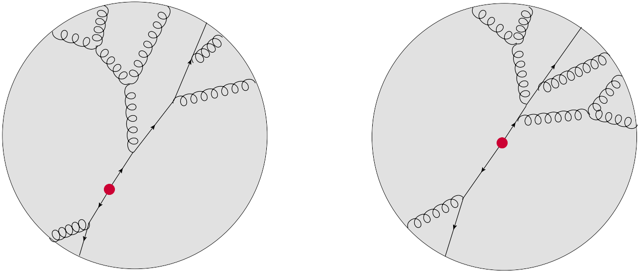
- Fluctuations in the number of such emissions must be of $\mathcal{O}(1)$ as well

- Confirmed by exact calculations *(M. Escobedo and E. I., arXiv:1601.03629)*

$$\sigma^2 \equiv \langle \Delta E^2 \rangle - \langle \Delta E \rangle^2 \simeq \frac{\pi^2}{3}\,\omega_{\rm br}^2 = \frac{1}{3}\langle \Delta E \rangle^2$$

- Variance is comparable to expectation value: large fluctuations

Di-jet asymmetry from fluctuations



- Average asymmetry is controlled by the difference in path lengths

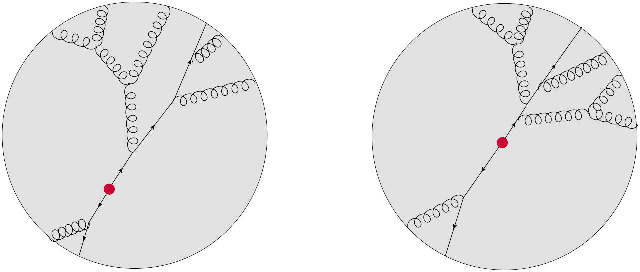
$$\langle E_1 - E_2 \rangle = \langle \Delta E_2 - \Delta E_1 \rangle \propto \langle L_2^2 - L_1^2 \rangle$$

- In experiments though, one rather measures $|E_1 - E_2|$

$$\langle (E_1 - E_2)^2 \rangle - \langle E_1 - E_2 \rangle^2 = \sigma_1^2 + \sigma_2^2 \propto \langle L_2^2 + L_1^2 \rangle$$

- Fluctuations dominate whenever $L_1 \sim L_2$ (the typical situation)

Di-jet asymmetry from fluctuations



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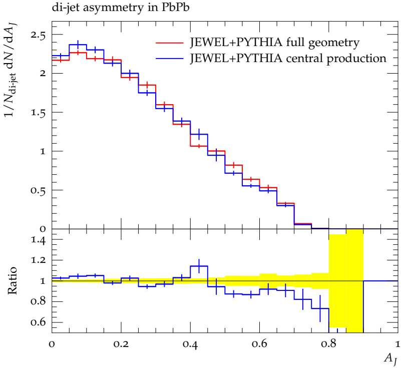
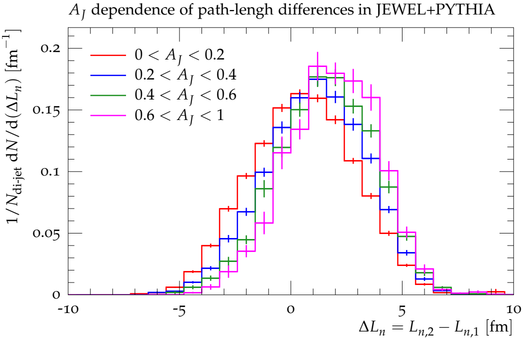
$$\langle (E_1 - E_2)^2 \rangle - \langle E_1 - E_2 \rangle^2 = \sigma_1^2 + \sigma_2^2 \propto \langle L_2^2 + L_1^2 \rangle$$

- Difficult to check: no direct experimental control of L_1 and L_2

Monte-Carlo generated events (central collisions)

(Milhano and Zapp, JEWEL, arXiv:1512.08107) $A_{\rm J} = \frac{|E_1 - E_2|}{E_1 + E_2}$





- Left: Central production $(L_1 = L_2)$ vs. randomly distributed production points ("full geometry")
- Right: Distribution of $\Delta L \equiv L_1 - L_2$ for di-jet events with different values for the asymmetry A_J
  - the width of the distribution is a measure of fluctuations

Gluon multiplicities

- Average number of gluons with $\omega \geq \omega_0$
  - $\omega_0 \ll E$ is the 'resolution scale'

$$\langle N(\omega_0)\rangle = \int_{\omega_0}^{E} \mathrm{d}\omega \, \frac{\mathrm{d}N}{\mathrm{d}\omega} \simeq 1 + 2\left[\frac{\omega_{\rm br}}{\omega_0}\right]^{1/2} \quad \text{(LP + radiation)}$$

  - would be divergent if $\omega_0 \to 0$
  - in experiments too, one has a non-zero resolution scale
  - independent of the energy E of the LP
  - $\langle N(\omega_0)\rangle \simeq 1$ when $\omega_0 \gg \omega_{\rm br}$: just the leading particle
  - $\langle N(\omega_0)\rangle \gg 1$ when $\omega_0 \ll \omega_{\rm br}$: multiple branching
  - amusingly enough: $\langle N(\omega_{\rm br})\rangle = 3 \simeq \pi$
- Multiplicities are high for soft gluons: $\omega_0 \ll \omega_{\rm br}$

Koba-Nielsen-Olesen scaling

- One has similarly computed all the higher moments $\langle N^p \rangle$ with $p \geq 2$ *(M. Escobedo and E. I., arXiv:1609.06104)*
- For soft gluons, $\omega_0 \ll \omega_{\rm br}$, they are all determined by the 1-point function:

$$\frac{\langle N^2 \rangle}{\langle N \rangle^2} \simeq \frac{3}{2}, \qquad \frac{\langle N^p \rangle}{\langle N \rangle^p} \simeq \frac{(p+1)!}{2^p}$$

- KNO scaling : the reduced moments are pure numbers
  - independent of any of the physical parameters of the problem
- A special negative binomial distribution (parameter $r = 2$)
  - huge fluctuations (say, as compared to a Poissonian distribution)

$$\left.\frac{\sigma_N}{\langle N \rangle}\right|_{\rm KNO} = \frac{1}{\sqrt{2}} \qquad \text{vs.} \qquad \left.\frac{\sigma_N}{\langle N \rangle}\right|_{\rm Poisson} = \frac{1}{\sqrt{\langle N \rangle}}$$

- KNO scaling also holds for a jet in the vacuum ...
- ... but the medium-induced distribution is much wider !

Conclusions

- Effective theory and physical picture for jet quenching from pQCD
  - event-by-event physics: multiple branching
  - democratic branchings leading to wave turbulence
  - thermalization of the soft branching products with $p \sim T$
  - efficient transmission of energy to large angles
  - wide probability distribution, strong fluctuations, KNO scaling
- Fluctuations compete with the difference in path lengths in determining the di-jet asymmetry
- Qualitative and semi-quantitative agreement with the phenomenology of di-jet asymmetry at the LHC
- Important dynamical information still missing: vacuum-like radiation (parton virtualities), medium expansion ...