From Jet Quenching to Turbulence

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(arXiv: 1209.4585; 1301.6102)

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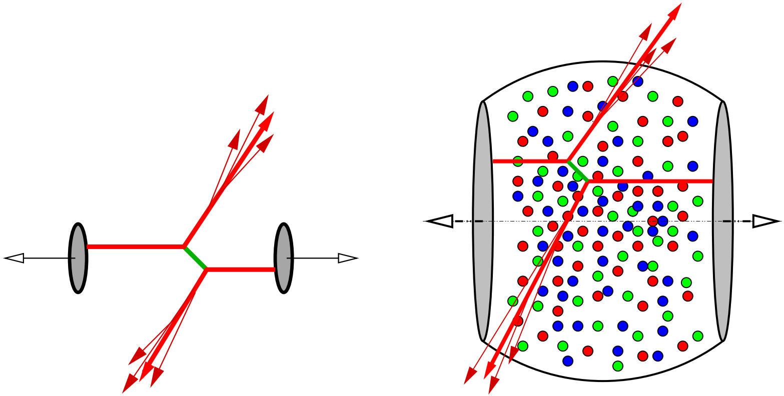
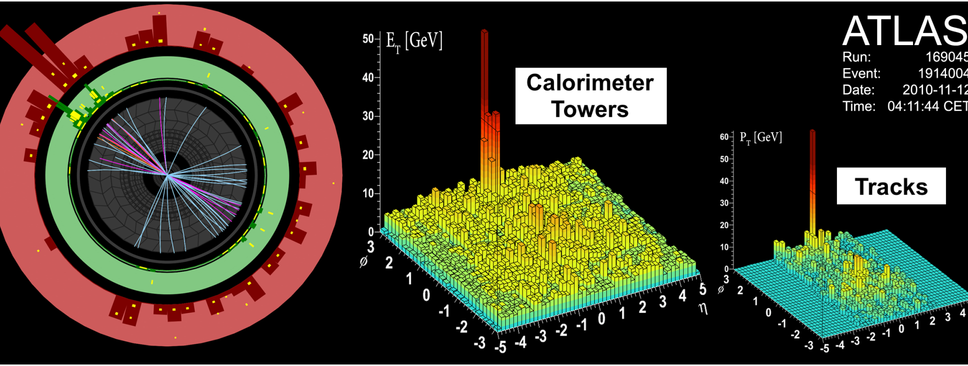
Di–jet correlations in A+A collisions

- A powerful tool to scrutinize the 'quark gluon plasma'
- Similar studies for p+p provide the benchmark



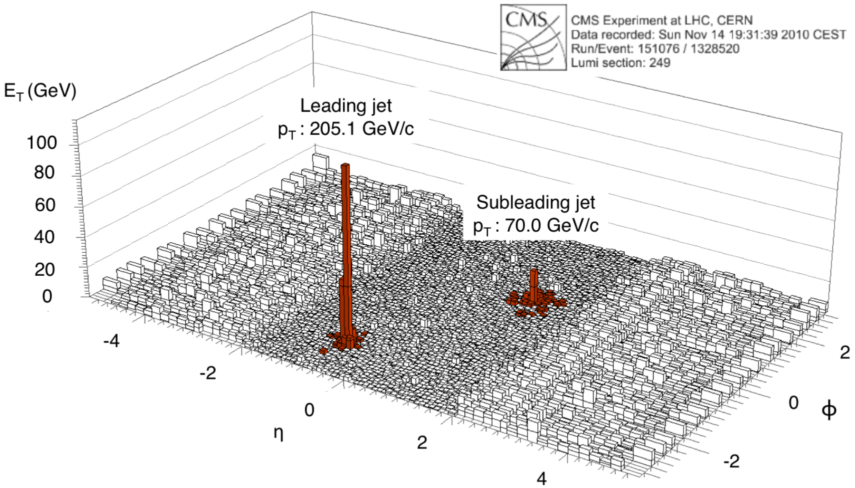
- Jet quenching: energy loss, momentum broadening, di–jet asymmetry

Di–jet asymmetry *(ATLAS)*



- Central Pb+Pb: 'mono–jet' events
- The secondary jet cannot be distinguished from the background: $E_{T1} \geq 100$ GeV, $E_{T2} > 25$ GeV
- Additional energy imbalance as compared to p+p : 20 to 30 GeV

Di–jet asymmetry *(CMS)*

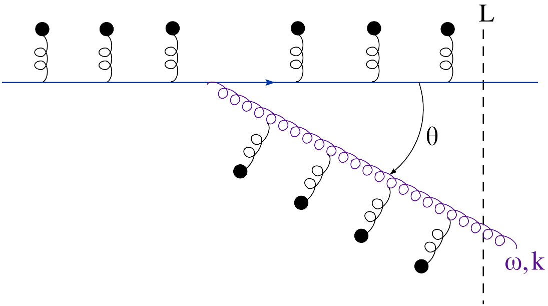


- Central Pb+Pb: the secondary jet is barely visible
- Detailed studies show that the 'missing energy' is associated with the additional radiation of many soft quanta at large angles

pQCD : the BDMPSZ mechanism

- Gluon radiation triggered by interactions in the medium

  Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov ∼ 1996



- 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

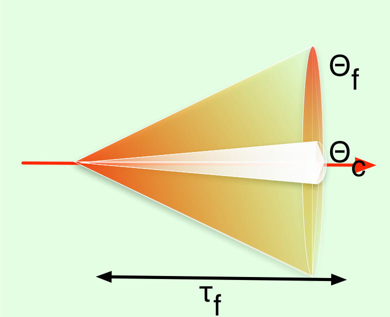
The formation time

- Formation time (τ_f) & angle (θ_f) are determined by ω and $\hat{q}$

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

- Maximal energy of a gluon emitted in this way: $\tau_f \simeq L \Rightarrow \omega_c = \hat{q}L^2$
- Typical range: $T \simeq 1\,\text{GeV} < \omega \leq \omega_c \simeq 50\,\text{GeV}$
- Hard emissions ($\omega \sim \omega_c$) control energy loss at small angles ($\theta_f \sim \theta_c$)

- Soft gluons ($\omega \ll \omega_c$)
  - large emission angles $\theta_f \gg \theta_c$
  - small formation times $\tau_f \ll L$
  - high probability to be emitted (large phase space : $L/\tau_f \gg 1$)



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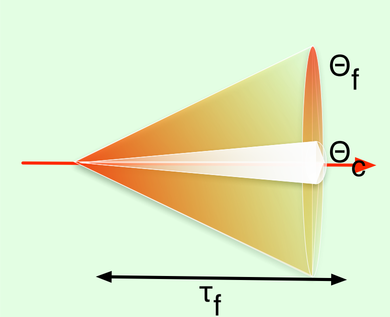
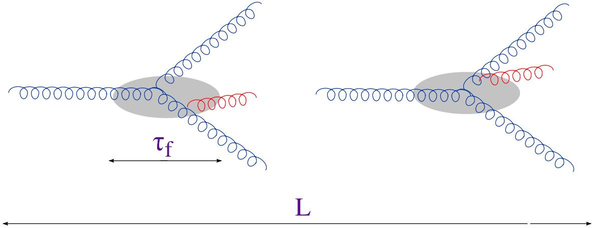


Multiple emissions

$$\omega \frac{dN}{d\omega} \simeq \alpha_s \frac{L}{\tau_f(\omega)} \gtrsim 1 \quad \text{when} \quad \omega \lesssim \alpha_s^2 \omega_c \sim 5\,\text{GeV}$$

- Successive medium–induced branchings are independent
  - Non–trivial ! Not true for jet evolution in the vacuum, where interference effects lead to angular ordering
- Color coherence is lost via scattering with the medium

Mehtar-Tani, Salgado, Tywoniuk (1009.2965; 1102.4317); E. I., Casalderrey-Solana (1106.3864)

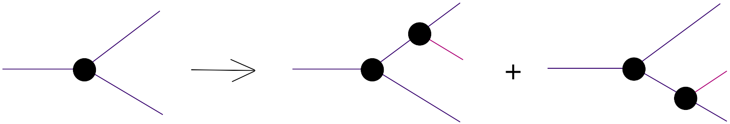


- Interference effects are suppressed by a factor $\tau_f/L \lesssim \alpha_s$

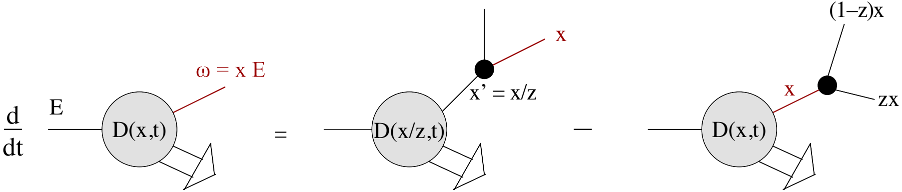
Blaizot, Dominguez, E.I., Mehtar-Tani (arXiv: 1209.4585)

A classical branching process

- Successive branchings are independent and quasi–local ($\tau_f \ll L$)



- A stochastic process well suited for Monte–Carlo implementation
- Rate eq. for the gluon spectrum : $D(x,t) \equiv x\frac{\mathrm{d}N}{\mathrm{d}x}$ where $x = \omega/E$



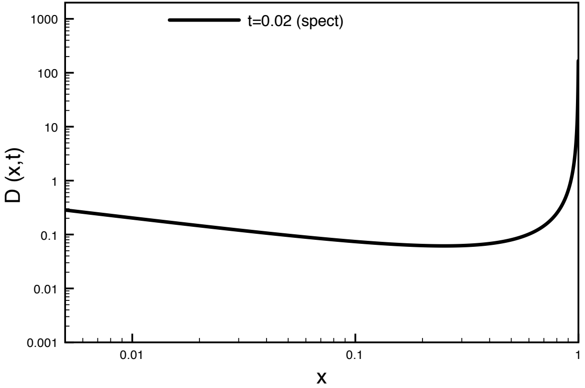
- Formally similar to DGLAP ... but very different kernel & physics !

First iteration

- 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 increasing the time t ?
  (i.e., when including the effects of multiple branchings)



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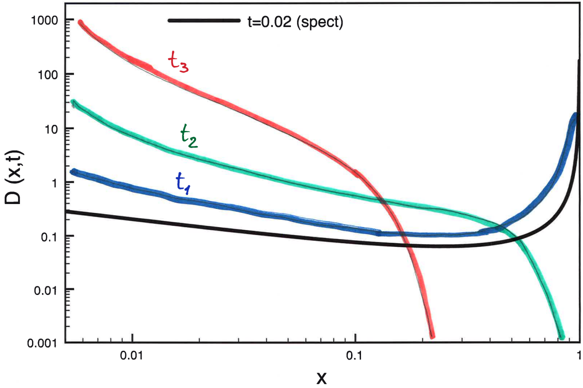
$$D^{(1)}(x,L) \simeq \alpha_s \frac{L}{\tau_f(\omega)} = \frac{t}{\sqrt{x}} \qquad (t = L \text{ in appropriate units})$$

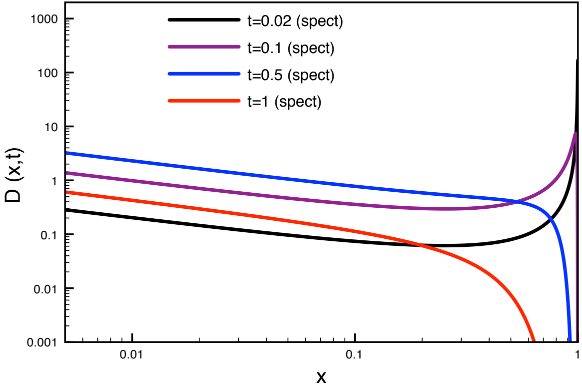
- One may expect the spectrum to become steeper at small x (as happens for DGLAP) : $\int_0^1 \mathrm{d}x\, D(x,t) = 1$ for any t



The scaling spectrum

- But this is not what happens ! One rather finds (exact result)

$$D(x,t) \simeq \frac{t}{\sqrt{x}}\, \mathrm{e}^{-\pi t^2} \qquad \text{for } x \ll 1 \text{ and any } t$$



- The spectrum in $1/\sqrt{x}$ is a fixed point of the evolution

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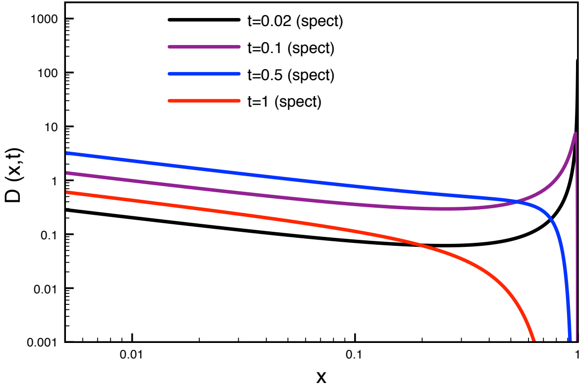
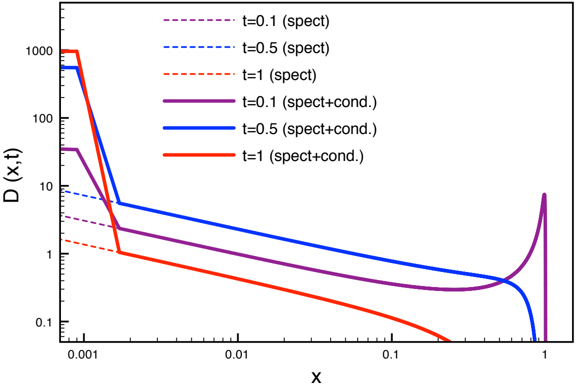


- The spectrum in $1/\sqrt{x}$ is a fixed point of the evolution
- With increasing time, the energy disappears from the spectrum

Wave turbulence

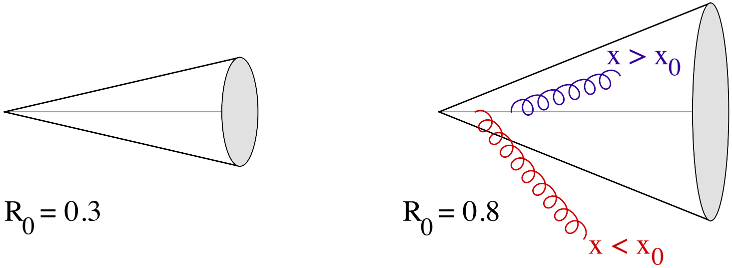
- Fine cancellations between ‘gain’ and ‘loss’ terms : turbulent flow
- The energy accumulates into a ‘condensate’ at $x = 0$
  (truly, at the ‘thermalization’ scale: $x_{\rm th} = T/E \ll 1$)



- Small x branchings are quasi–democratic: $z \sim 1/2$ (unusual in QCD)

Energy flow at large angles

- Remember : small $x \Longrightarrow$ large emission angle
- For a jet with angular opening $R_0 \Longrightarrow$ intermediate value x_0



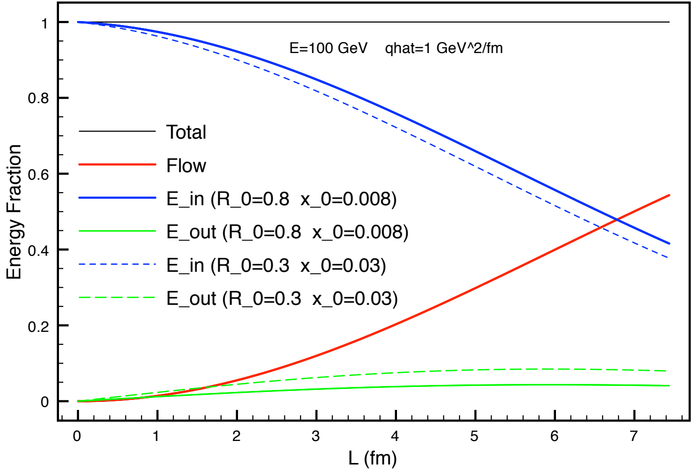
- Total jet energy $= E_{\rm in}\,(x > x_0) + \underbrace{E_{\rm out}\,(x_{\rm th} < x < x_0) + E_{\rm flow}}$

  spectrum + condensate

- The flow component: independent of x_0 and the original energy E

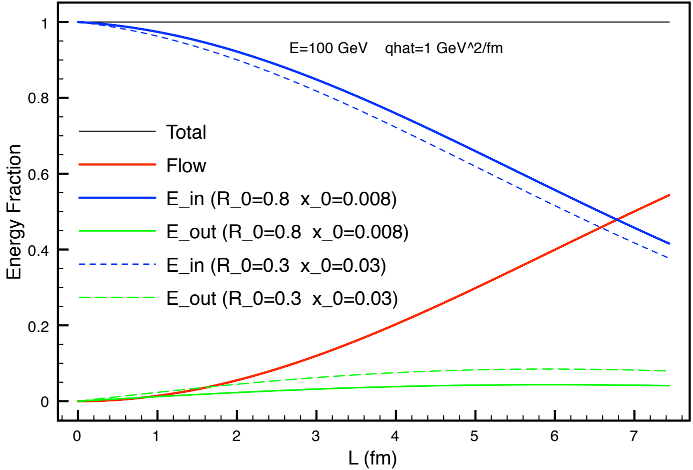
$$E_{\rm flow} = v\,\alpha_s^2\,\hat{q}L^2 \qquad (\sim 20\,\text{GeV for } L = 5\text{ fm})$$

Energy flow at large angles



- When increasing the jet opening $(R_0 = 0.3 \rightarrow 0.8)$, the 'missing energy' is not found inside the (larger) jet, but it is still outside it !

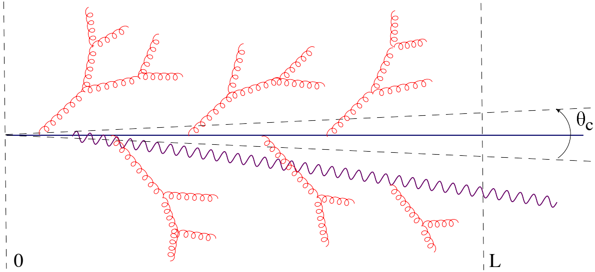
Energy flow at large angles



- When increasing the jet opening $(R_0 = 0.3 \to 0.8)$, the 'missing energy' is not found inside the (larger) jet, but it is still outside it !
- Good agreement with the analysis by CMS (arXiv:1102.1957)

Conclusions

- The problem of medium–induced jet evolution is by now solved
- The associated energy loss involves two components
  - hard emissions at small angles (energy loss by leading particle, R_{AA})
  - multiple soft branchings leading to turbulent flow (energy loss at large angles, di–jet asymmetry)



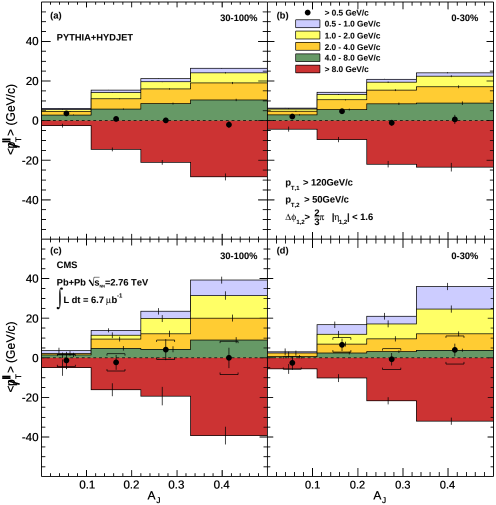
- The flow component has been recognized only very recently

  J.-P. Blaizot, E. I., Y. Mehtar-Tani, arXiv: 1301.6102

No missing energy ! *(CMS, arXiv:1102.1957)*

- ... but a pronounced difference in the distribution of the transverse energy in p_T and in the angle w.r.t. the jet axis

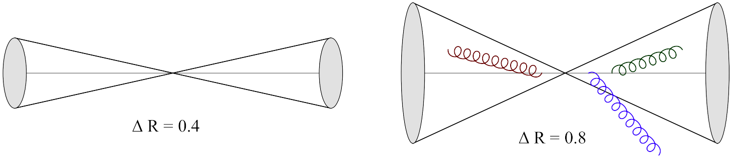
- $p_T^{\parallel}$: projection of the (transverse) energy along the jet axis
- $p_T^{\parallel} < 0$: same hemisphere as the trigger jet
- $p_T^{\parallel} > 0$: same hemisphere as the secondary jet
- all hadrons with $p_T > 0.5$ GeV are measured

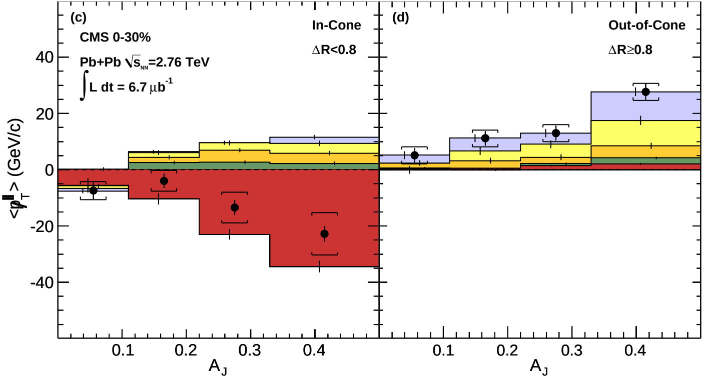


- Excess of soft quanta (≤ 4 GeV) in the hemisphere of secondary jet

In–out asymmetry

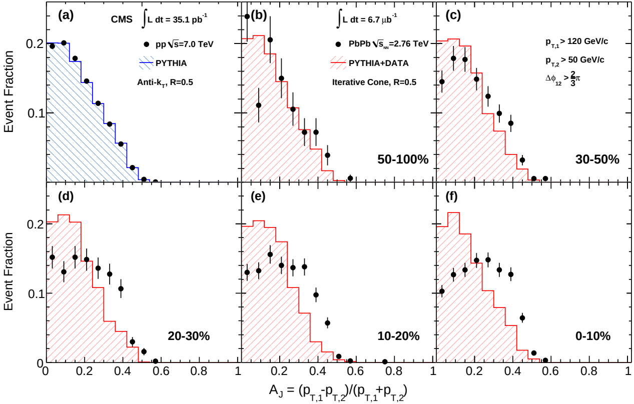
- Increase the angular opening ΔR of the jet





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

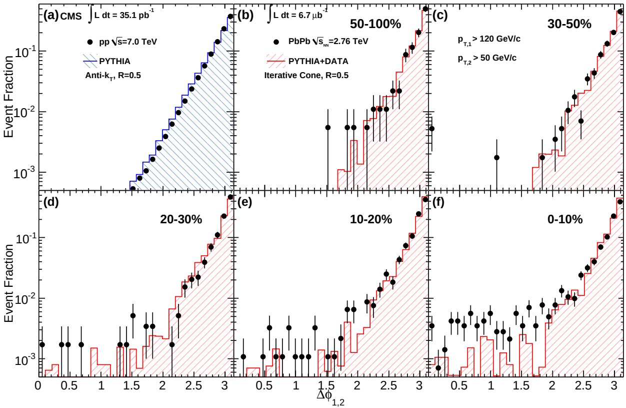
Di–jet asymmetry : A_J (CMS)



- 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

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

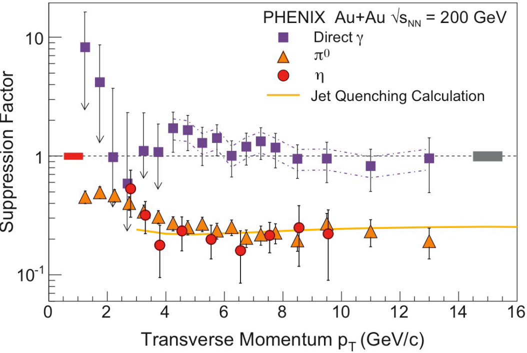
- Additional energy loss of 20 to 30 GeV due to the medium

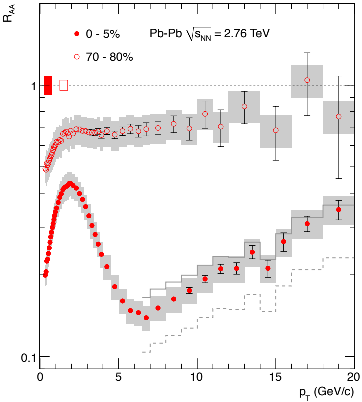


- Event fraction as a function of the azimuthal angle $\Delta\phi$
- Typical event topology: still a pair of back–to–back jets
- The secondary jet loses energy without being deflected
- The additional in–medium radiation is relatively soft

Nuclear modification factor at RHIC & the LHC

$$R_{\mathrm{A+A}} \equiv \frac{1}{A^2} \frac{\mathrm{d}N_{\mathrm{A+A}}/\mathrm{d}^2p_{\perp}\mathrm{d}\eta}{\mathrm{d}N_{\mathrm{p+p}}/\mathrm{d}^2p_{\perp}\mathrm{d}\eta}$$





- Strong suppression $(R_{AA} \lesssim 0.2)$ at moderate $p_{\perp}$
- Probing the energy loss by the leading particle