# *From Jet Quenching to Turbulence*

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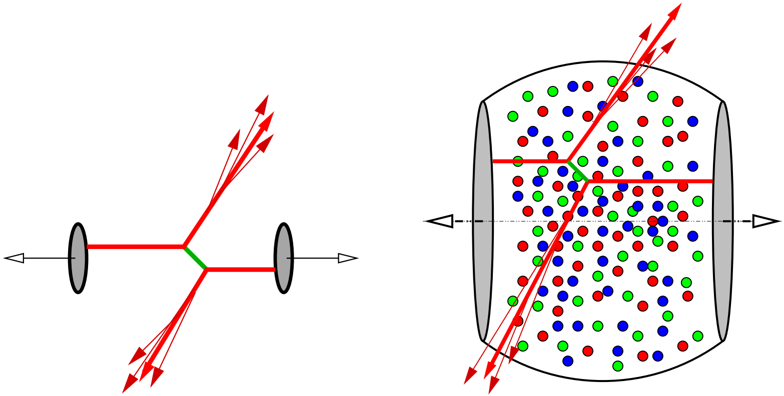
(arXiv: 1209.4585; 1301.6102)

March 28, 2013

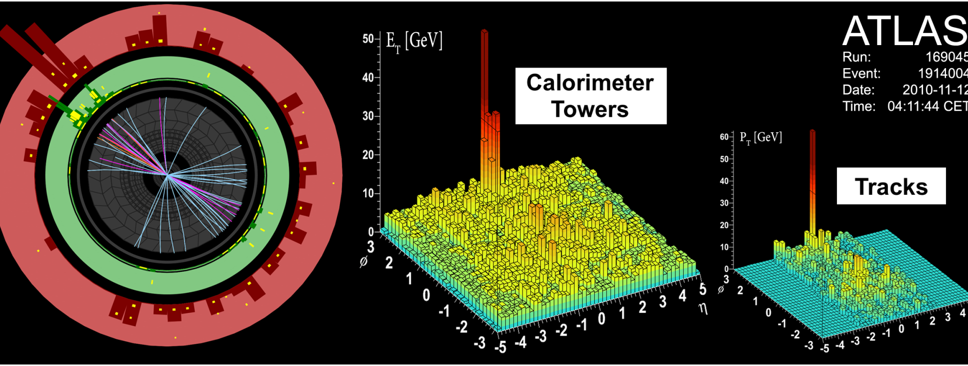
# Di–jet correlations in A+A collisions

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



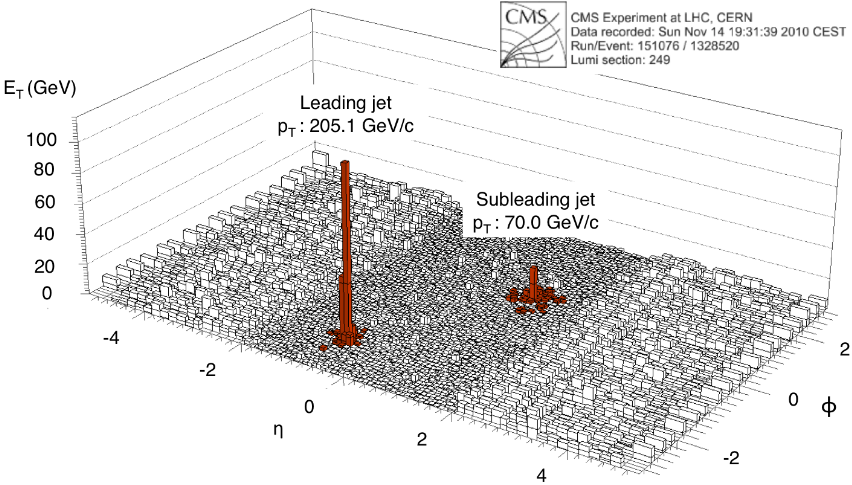
- Jet quenching: energy loss, momentum broadening, di–jet asymmetry

# 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)*

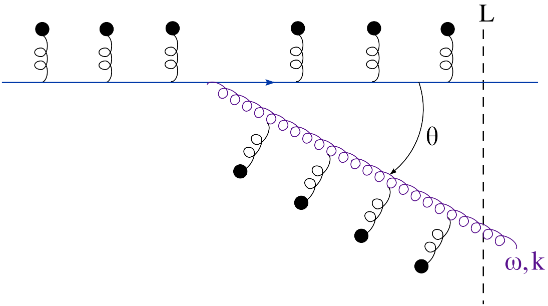



- Central Pb+Pb: the secondary jet is barely visible
- Detailed studies show that the 'missing energy' is associated with the additional radiation of many soft quanta at large angles

# pQCD : the BDMPSZ mechanism

- Gluon radiation triggered by interactions in the medium

  *Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov* $\sim$ *1996*




- Gluon emission is linked to transverse momentum broadening

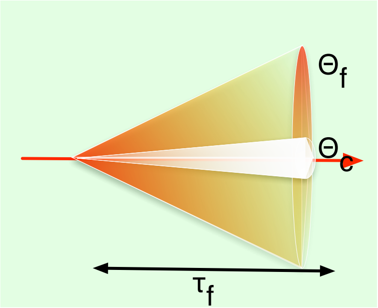
$$\Delta k_\perp^2 \simeq \hat{q}\,\Delta t \quad \text{with} \quad \hat{q} \simeq \frac{m_D^2}{\lambda} = \frac{(\text{Debye mass})^2}{\text{mean free path}}$$

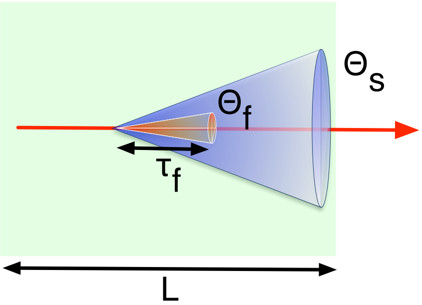
  - destroys the coherence between the gluon and its parent parton
  - increases the emission angle

# Formation time ($\tau_f$) & angle ($\theta_f$)

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

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




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

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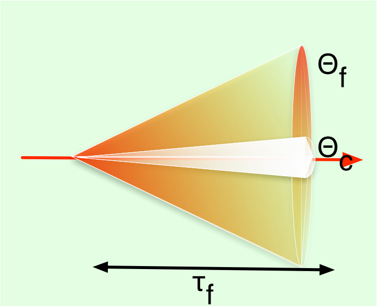


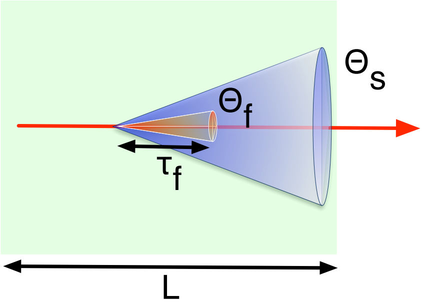


- After emission, the angle can further increase via medium rescattering

# Hard vs. soft emissions

- The BDMPSZ gluon spectrum (probability for one gluon emission)

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

- Typical range: $T \simeq 1\,\text{GeV} < \omega \leq \omega_c \simeq 50\,\text{GeV}$

  $T$ ('temperature') : typical momentum scale of the medium ('QGP')

- Relatively hard emissions with $\omega \sim \omega_c$ :
  - rare events : probability of $\mathcal{O}(\alpha_s)$
  - dominate energy loss by the leading particle $(R_{AA})$ : $E_{\text{hard}} \sim \alpha_s \omega_c$
  - small angles though $(\theta_f \sim \theta_c) \Longrightarrow$ the energy remains inside the jet
  - arguably, not so important for the di–jet asymmetry

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- Soft emissions with $\omega \ll \omega_c$ :
  - quasi–deterministic : probability of $\mathcal{O}(1)$ for $\omega \lesssim \alpha_s^2\,\omega_c \sim 5\,\mathrm{GeV}$
  - less energy is lost in this way : $E_{\mathrm{soft}} \sim \alpha_s^2 \omega_c$
  - ... but this can be lost at arbitrarily large angles
  - control the di–jet asymmetry

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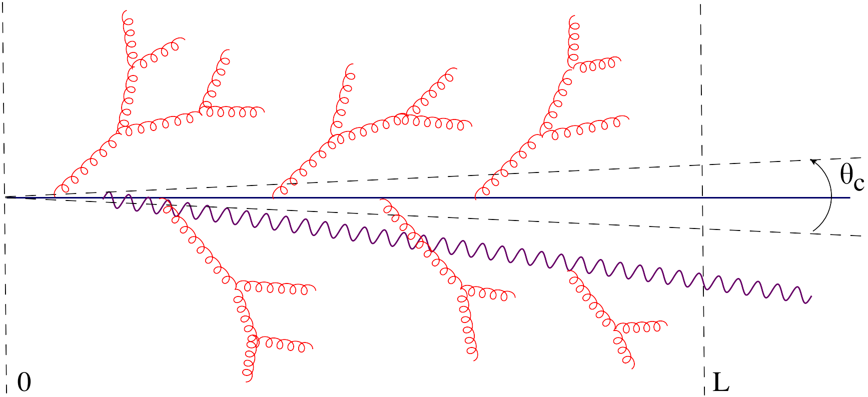
  - ... but this can be lost at arbitrarily large angles
  - control the di–jet asymmetry
- One needs to understand mutiple medium–induced branchings

# Multiple emissions

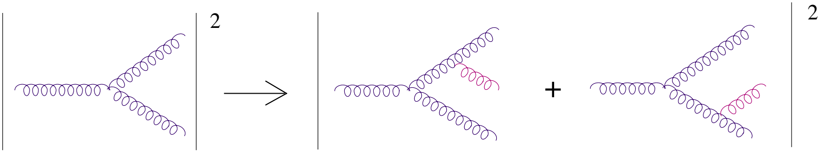



- A typical event:

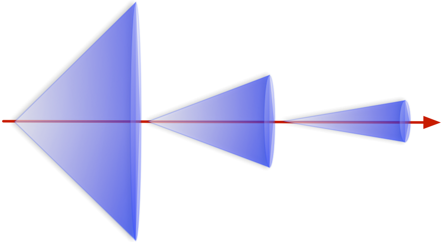
  many soft cascades plus (sometimes) a harder emission

# Multiple emissions

- Successive medium–induced branchings are independent
- Non–trivial ! Not true for jet evolution in the vacuum !



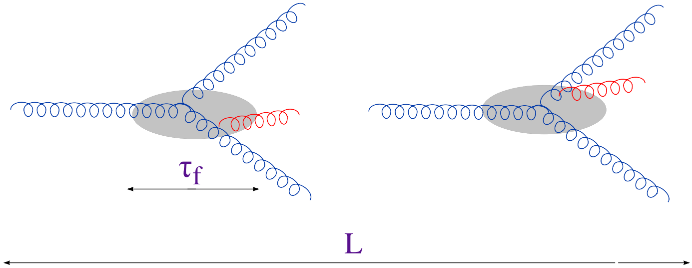

- In vacuum, interference effects lead to angular ordering



# Multiple emissions

- Successive medium–induced branchings are independent
- Non–trivial ! Not true for jet evolution in the vacuum !
- In the medium, color coherence is rapidly lost via rescattering

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

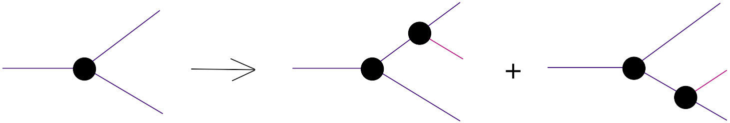



- The interference effects are suppressed by a factor $\tau_f/L \ll 1$

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

# A classical branching process

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




  - the $g \to gg$ splitting vertex (the 'blob') : the BDMPSZ spectrum
  - the propagator (the 'line') : transverse momentum broadening in between successive splittings

- A stochastic process well suited for Monte–Carlo implementation

- Similar Monte–Carlo's have been already used for phenomenological studies, on a heuristic basis.

  *MARTINI (Schenke, Gale, Jeon); Q-PYTHIA (Armesto, Salgado et al.); Wiedemann, Zapp, Stachel*

- No previous derivation, nor study of the gluon spectrum at small $x$

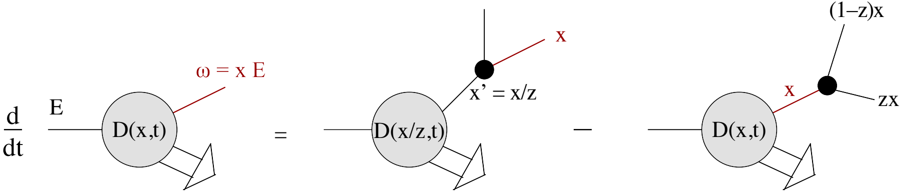
# The spectrum from multiple branchings

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

- Evolution equation for the gluon spectrum (integrated over $k_\perp$)

$$D(x,t) \equiv x\frac{\mathrm{d}N}{\mathrm{d}x} \quad \text{where} \quad x = \frac{\omega}{E} \quad \text{(energy fraction)}$$

- $t$ : the time/distance traveled by the jet inside the medium

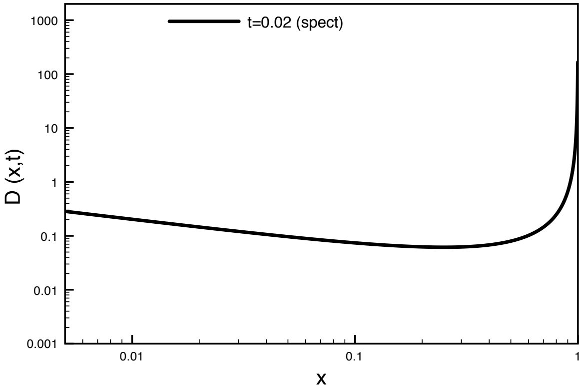



- $t \to t + \mathrm{d}t$ : one additional branching with splitting fraction $z$
- Rate for change = 'Gain' - 'Loss'
- Formally similar to DGLAP ... but very different kernel & physics !

# 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)

# First iteration

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

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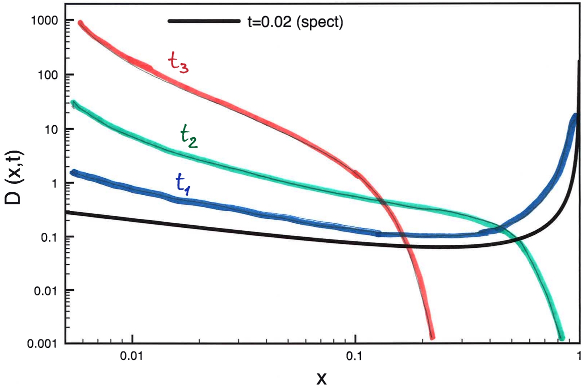


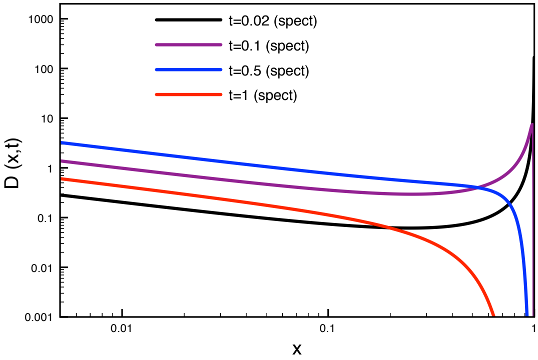

- One may expect the spectrum to be depleted at large $x$ and to increase faster at small $x$ (as for DGLAP) : $\int_0^1 \mathrm{d}x\, D(x,t) = 1$ for any $t$

# The scaling spectrum

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

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

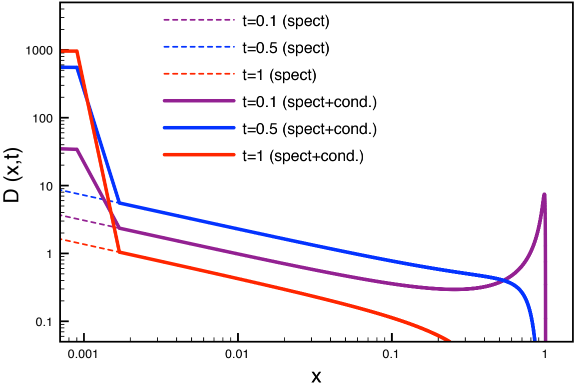
"single emission by the leading particle" $\times$ "survival probability"




- Fine cancellations between 'gain' and 'loss' terms : turbulent flow
- Scaling spectrum in $1/\sqrt{x}$ emerges as a fixed point (Kolmogorov)

# Energy flow

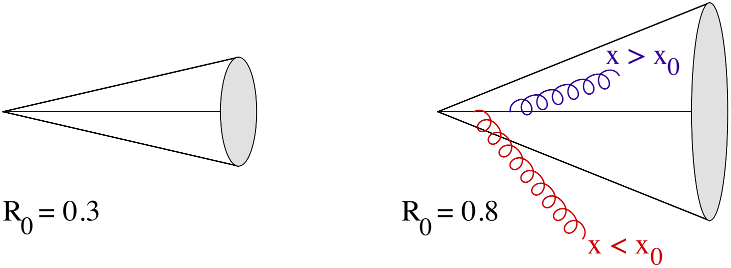
- The energy disappears from the spectrum: $\int_0^1 \mathrm{d}x\, D(x,t) = \mathrm{e}^{-\pi t^2}$
- Energy flows (large $x \rightarrow$ small $x$) w/o accumulating in any bin $x > 0$
- It accumulates into a 'condensate' at $x = 0$ (truly at $x_{\rm th} = T/E \ll 1$)




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

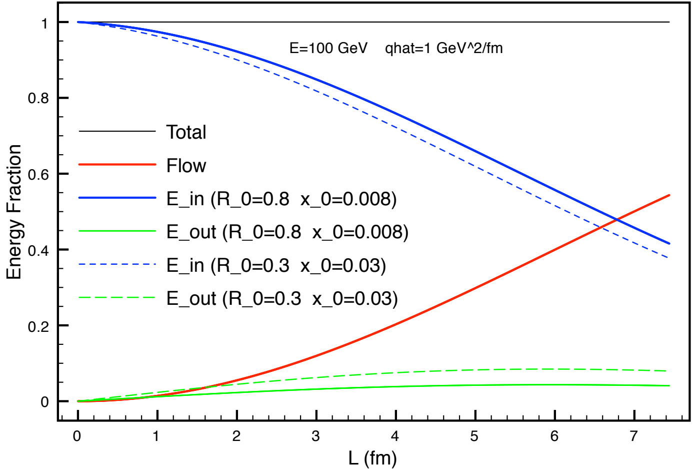
# Energy flow at large angles

- Remember : small $x \Longrightarrow$ large emission angle
- The energy which flows goes at very large angles !
- The energy inside the jet is only weakly dependent upon the jet angular opening $R_0$, within a wide range of values for $R_0$




- The energy inside the jet $E_{\text{in}}$ : the energy in the spectrum at $x > x_0$
- The energy outside the jet : $\underbrace{E_{\text{out}}\,(x_{\text{th}} < x < x_0) + E_{\text{flow}}}_{\text{spectrum} \; + \; \text{condensate}}$

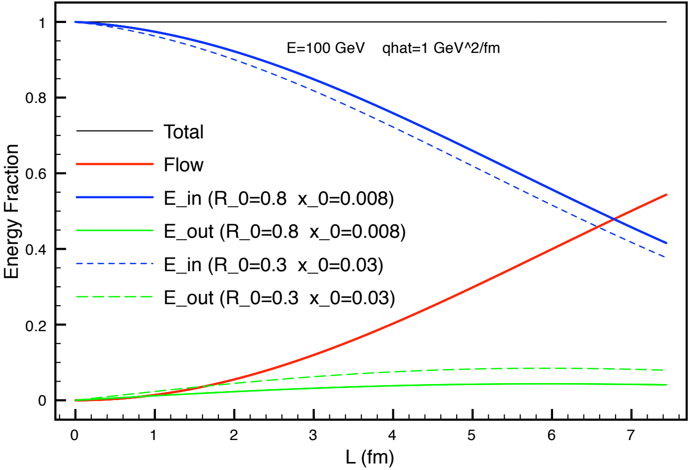
# Energy flow at large angles




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

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

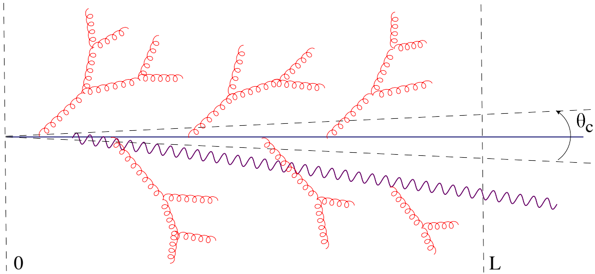
# Energy flow at large angles




- Good agreement with the analysis by CMS (arXiv:1102.1957)

# Conclusions

- Medium–induced jet evolution is by now understood in pQCD
- 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)




- A Monte–Carlo implementation is currently under way

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

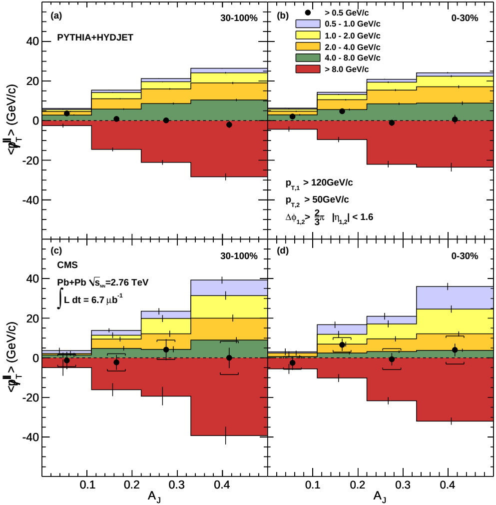
- ... but a pronounced difference in the distribution of the total energy in bins of $\omega \equiv p_T$ and in the angle w.r.t. the jet axis

- $p_T^{\parallel}$ : projection of the (transverse) energy along the jet axis

- $p_T^{\parallel} < 0$ : same hemisphere as the trigger jet

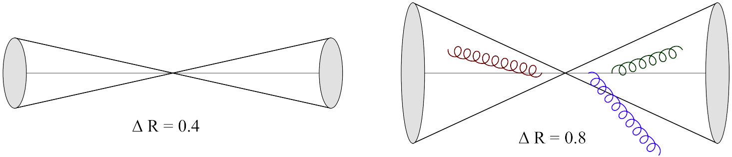
- $p_T^{\parallel} > 0$ : same hemisphere as the secondary jet

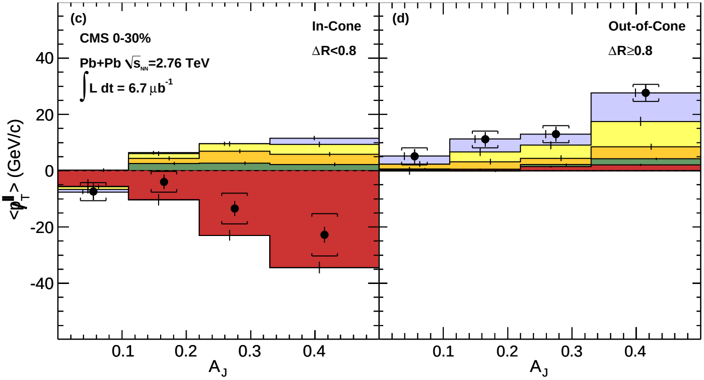
- all hadrons with $p_T > 0.5$ GeV are measured




- Excess of soft quanta ($\leq 4$ GeV) in the hemisphere of secondary jet

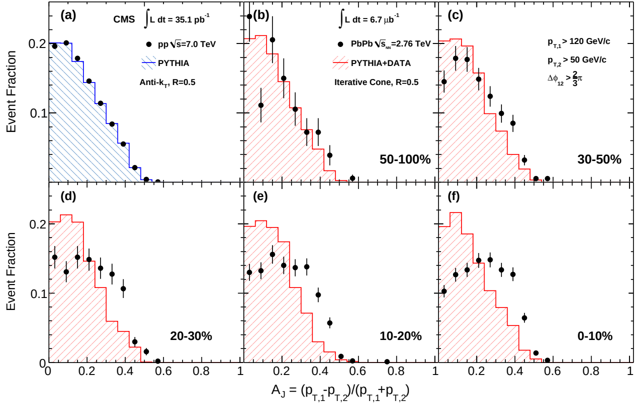
- Increase the angular opening $\Delta R$ of the jet




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

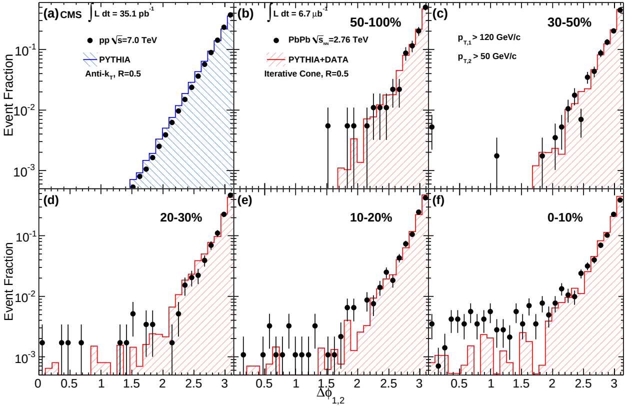
# Di–jet asymmetry : $A_{\rm J}$ (CMS)




- 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

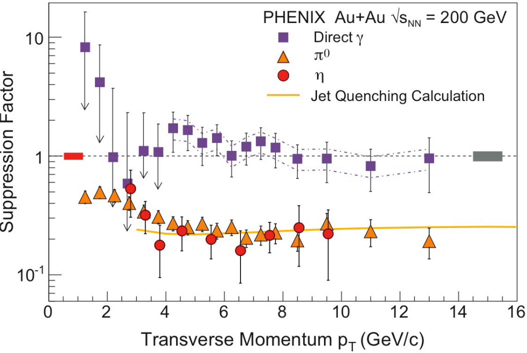
$$A_{\rm J} = \frac{E_1 - E_2}{E_1 + E_2} \qquad (E_i \equiv p_{T,i} = \text{ transverse energy})$$

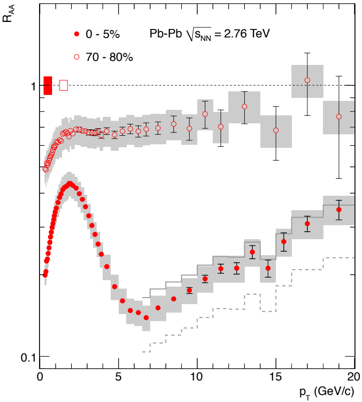
- Additional energy loss of 20 to 30 GeV due to the medium




- 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

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




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