Interference effects in medium–induced gluon radiation

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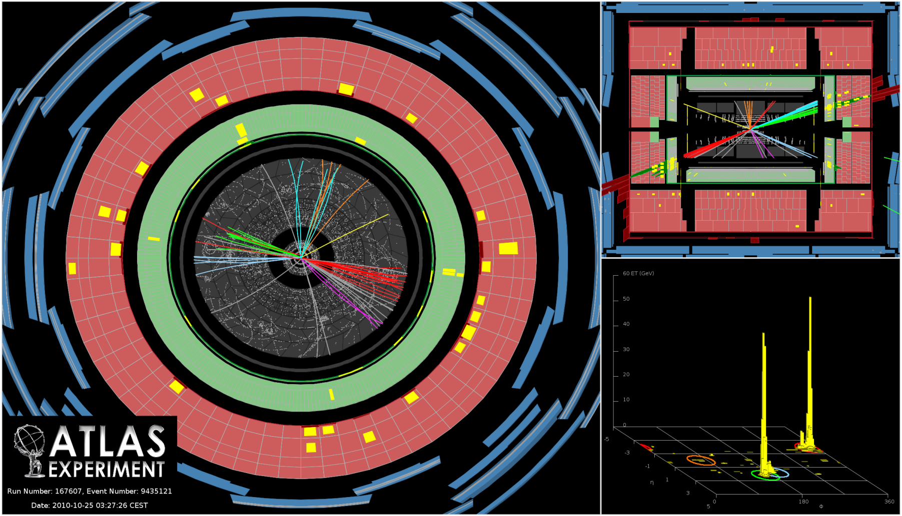
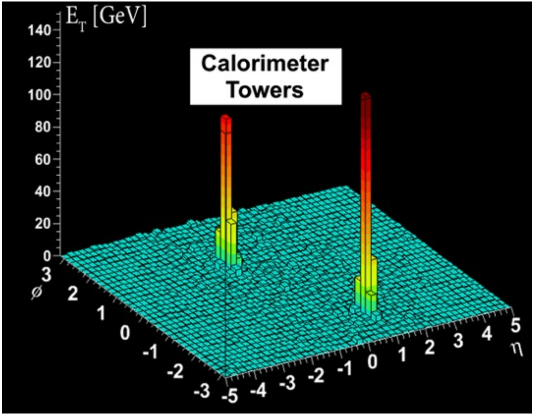
Di–jet production at the LHC



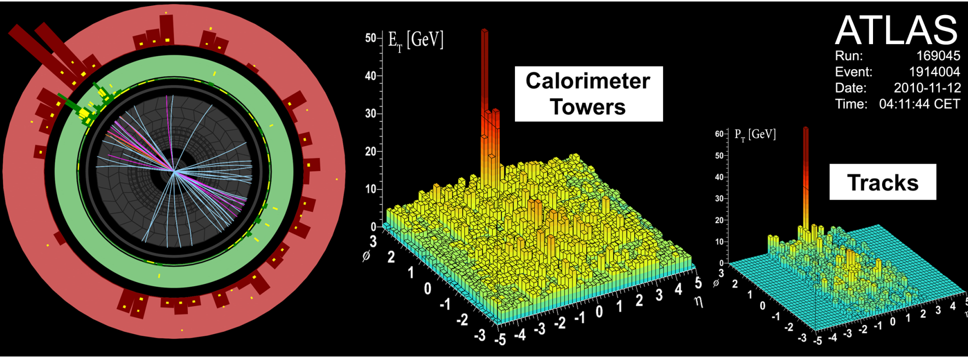
- p+p collisions, or peripheral Pb+Pb collisions

Di–jet production at the LHC



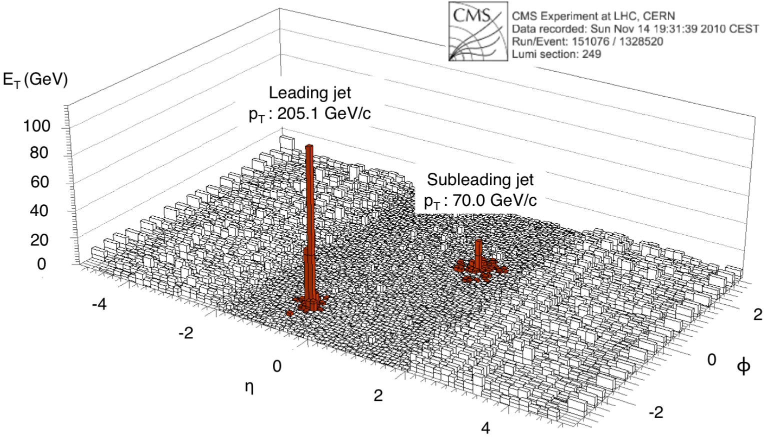
- p+p collisions, or peripheral Pb+Pb collisions
- A pair of well collimated, back to back, jets

Di–jet asymmetry *(ATLAS)*



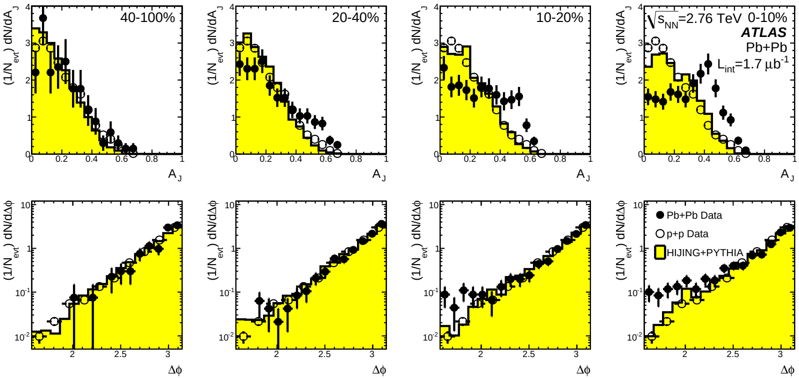
- Central Pb+Pb: mono–jet events
- The secondary jet cannot be distinguished from the background: $E_{T1} \geq 100$ GeV, $E_{T2} > 25$ GeV

Di–jet asymmetry *(CMS)*



- Central Pb+Pb: the secondary jet is barely visible
- The jet energy has been redistributed in the transverse plane

Di–jet asymmetry *(ATLAS)*

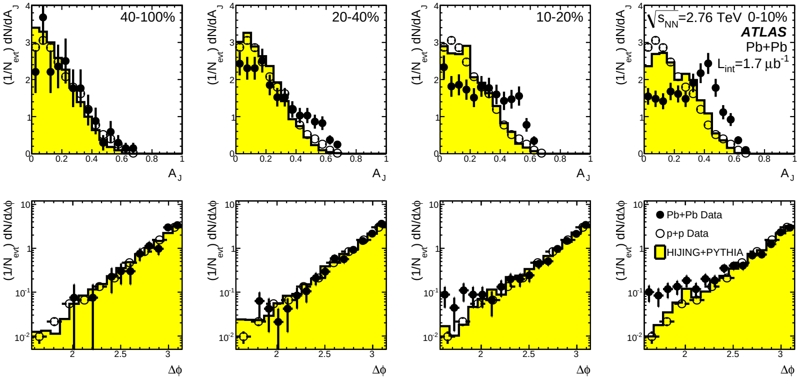


- Event fraction as a function of the di–jet energy imbalance

$$A_{\rm J} = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T1}}$$

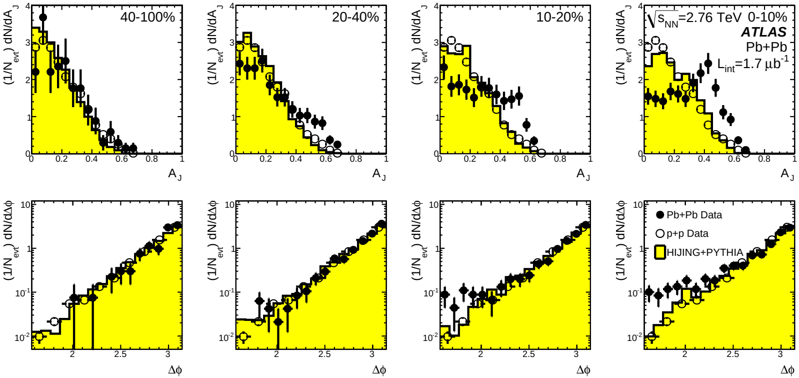
- ...and of the azimuthal angle $\Delta\phi$, for different centralities.

Di–jet asymmetry *(ATLAS)*



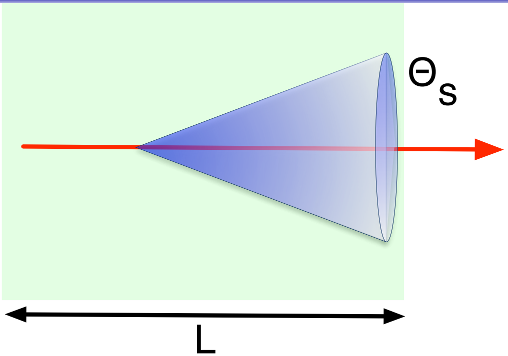
- Appreciable asymmetry already for p+p (e.g., 3–jet events)
- Additional energy loss of 20 to 30 GeV due to the medium
- Typical event topology: still a pair of back–to–back jets

Di–jet asymmetry *(ATLAS)*



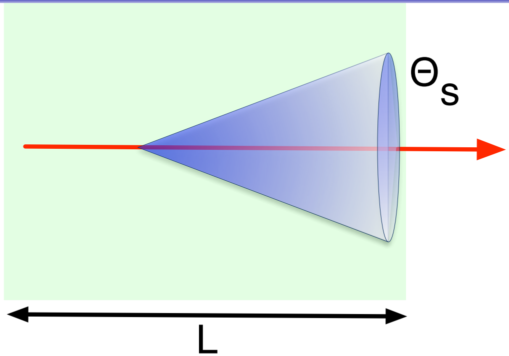
- Appreciable asymmetry already for p+p (e.g., 3–jet events)
- Additional energy loss of 20 to 30 GeV due to the medium
- Typical event topology: still a pair of back–to–back jets
- The secondary jet loses energy without being deflected

Medium–induced gluon radiation



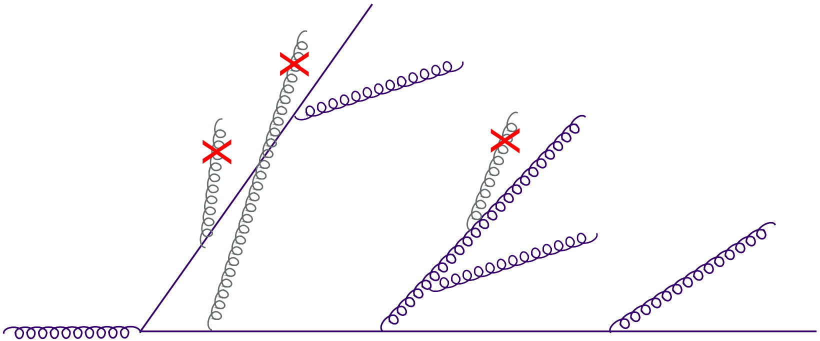
- Medium–induced, soft, gluon emissions at large angles
- Natural in perturbative QCD: the BDMPS–Z mechanism
  Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov

Medium–induced gluon radiation



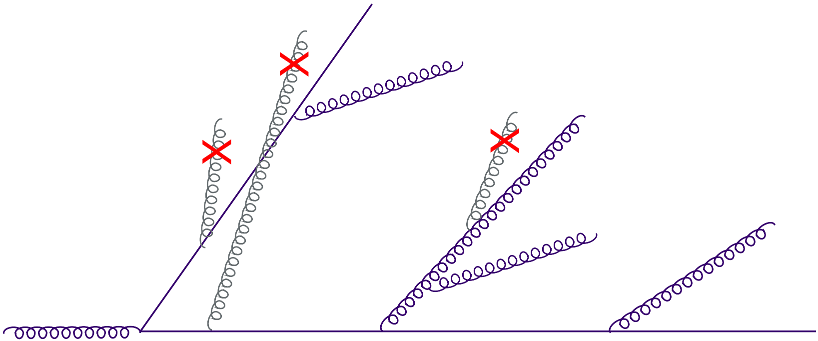
- Medium–induced, soft, gluon emissions at large angles
- Natural in perturbative QCD: the BDMPS–Z mechanism
  Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov
- This could be spoilt by angular ordering of successive emissions

Angular ordering (in the vacuum)



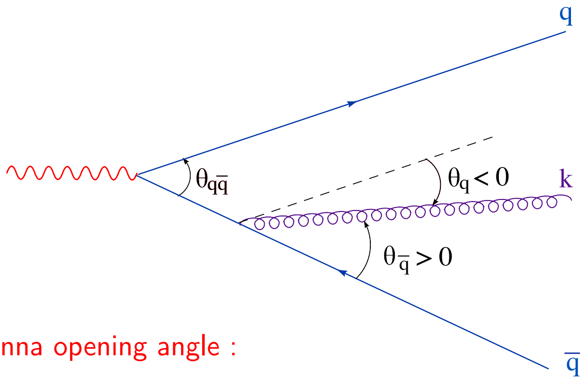
- Destructive interference between different sources
- The only surviving emissions are those inside the antenna

Angular ordering (in the vacuum)



- Destructive interference between different sources
- The only surviving emissions are those inside the antenna
- What about medium–induced radiation ?

A color antenna



- Antenna opening angle :

  $\theta_{q\bar{q}} = \theta_{\bar{q}} - \theta_q$

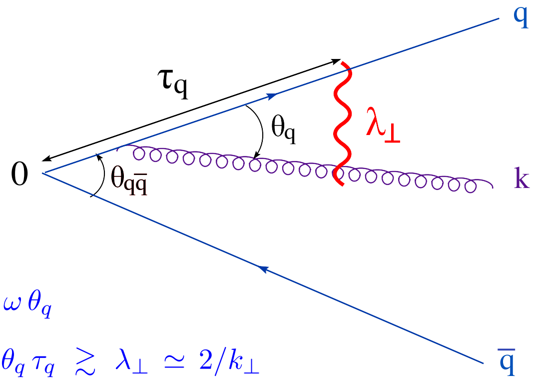
- The simplest device to study interferences

  the two sources (the quark and antiquark leg) already exist !

- Color singlet ('dipole') and color octet are quite similar

The formation time

- The gluon must lose coherence with respect to its source



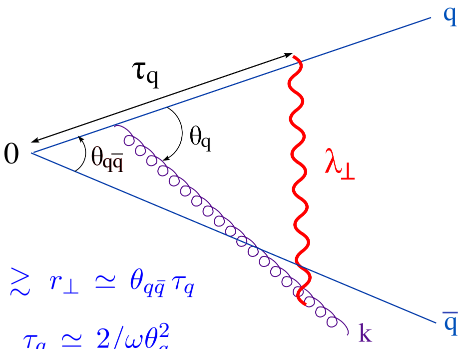
$$k_\perp \simeq \omega\,\theta_q$$

$$b_\perp \simeq \theta_q\,\tau_q \gtrsim \lambda_\perp \simeq 2/k_\perp$$

$$\tau_q \simeq \frac{2\omega}{k_\perp^2} \simeq \frac{2}{\omega\theta_q^2}$$

Interference (vacuum)

- The gluon must be coherent (overlap) with both sources



$$\lambda_\perp \simeq 2/k_\perp \gtrsim r_\perp \simeq \theta_{q\bar{q}}\,\tau_q$$

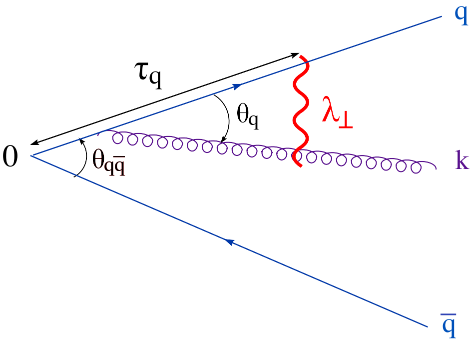
$$k_\perp \simeq \omega\,\theta_q\,, \quad \tau_q \simeq 2/\omega\theta_q^2$$

$\theta_q \gtrsim \theta_{q\bar{q}}$: large angle emission (out of cone)

- Large angle gluons see only the total color charge (here, zero)

Longitudinal phase–space

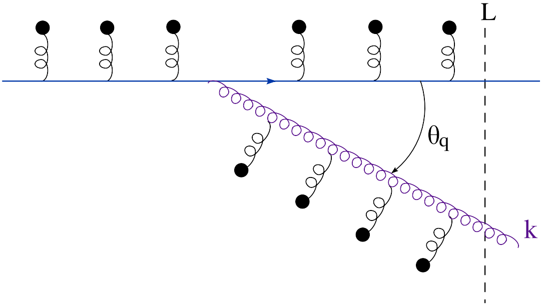
- A parton in the vacuum radiates within an interval τ_q after a hard scattering



- The longitudinal phase–space is proportional to τ_q
- This is true for both direct emissions and interference terms

Medium–induced gluon radiation

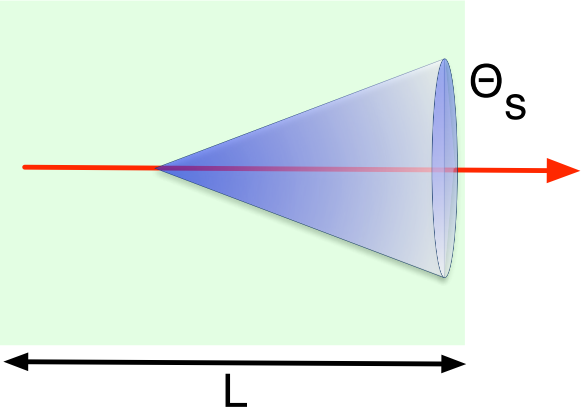
- A parton in the medium can radiate at any point within the medium size L, due to medium rescattering



- Each scattering acts as a kick allowing for radiation.
- This is the BDMPS–Z mechanism

The BDMPS–Z phase–space

- The longitudinal phase–space is proportional to L



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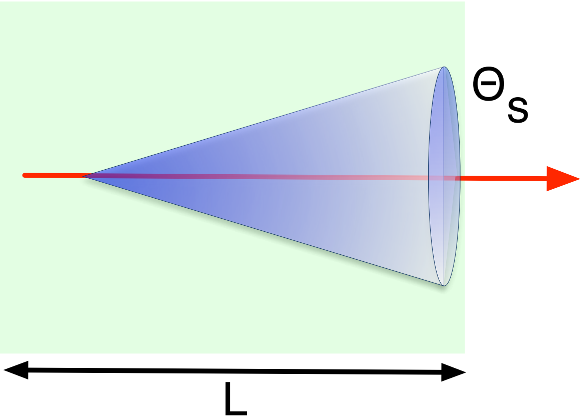

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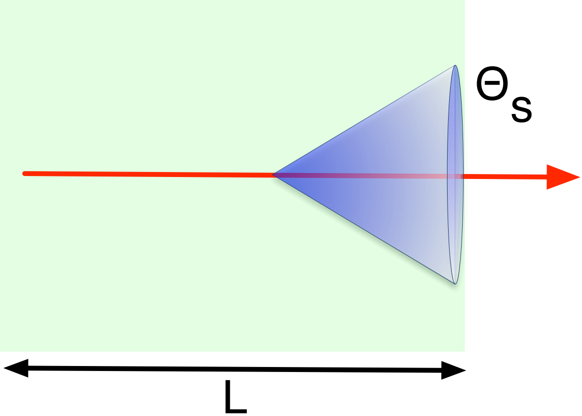

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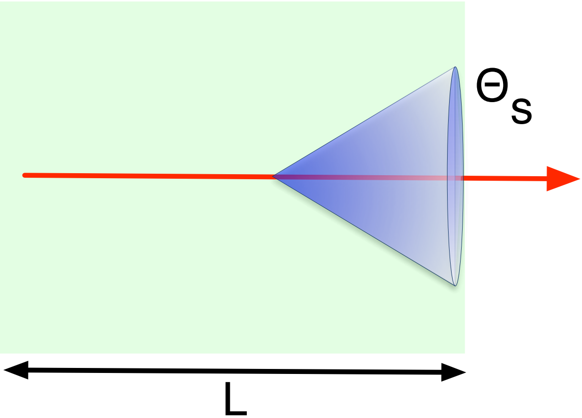
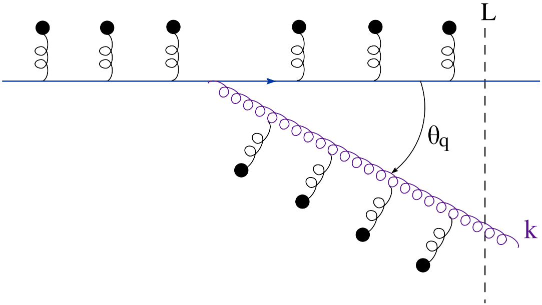


- What about the corresponding interference terms ?

Transverse momentum broadening

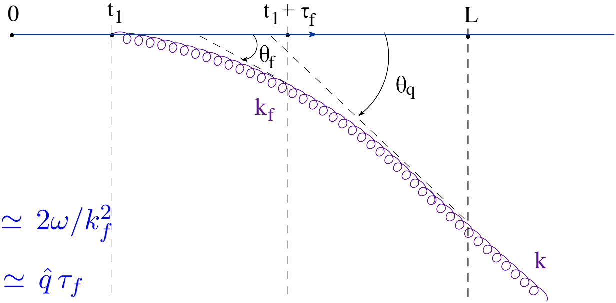
- Parton mean free path ℓ ($\ell \sim 1/g^2 T$ for a QGP)
- Average (momentum)^2 transfer per scattering μ_D^2 ($\mu_D \sim gT$)



$$\frac{\mathrm{d}\langle k_\perp^2\rangle}{\mathrm{d}t} \simeq \frac{\mu_D^2}{\ell} \equiv \hat{q} \sim \alpha_s^2 T^3$$ (jet quenching parameter)

In–medium formation time

- Via medium rescattering, the gluon decoheres from its source



$\tau_f \simeq 2\omega/k_f^2$

$k_f^2 \simeq \hat{q}\,\tau_f$

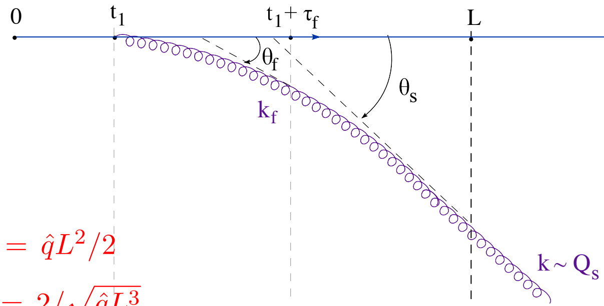
$$\tau_f \simeq \sqrt{\frac{2\omega}{\hat{q}}}, \qquad \theta_f \equiv \frac{k_f}{\omega} \simeq \left(\frac{2\hat{q}}{\omega^3}\right)^{1/4}$$

- The smaller the energy ω, the shorter τ_f and the larger the formation angle θ_f

Kinematical limits

- The in–medium formation time cannot be larger than L :

$\tau_f^{max} = L \implies$ maximal energy (ω_c) & minimal angle (θ_c)



$\omega_c = \hat{q}L^2/2$

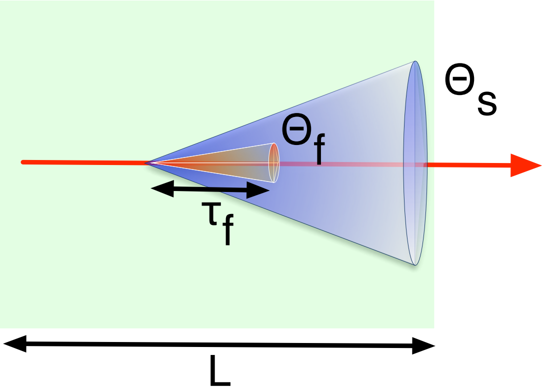
$\theta_c = 2/\sqrt{\hat{q}L^3}$

- After formation, the gluon can still acquire momentum:

final momentum $Q_s^2 = \hat{q}L$ & final angle $\theta_s = Q_s/\omega$

The BDMPS–Z spectrum

- $\omega \ll \omega_c \implies$ prompt emission: $\tau_f \ll L$



- ... and well separated angles: $\theta_s \gg \theta_f \gg \theta_c$

The BDMPS–Z spectrum

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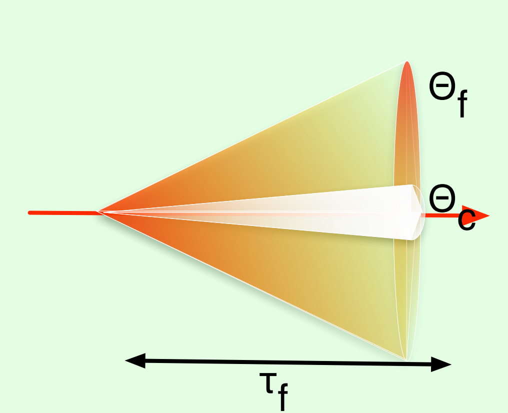
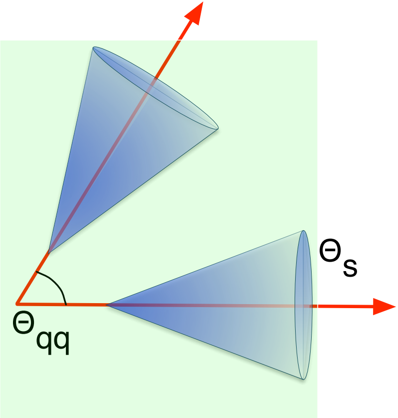


- ... and well separated angles: $\theta_s \gg \theta_f \gg \theta_c$

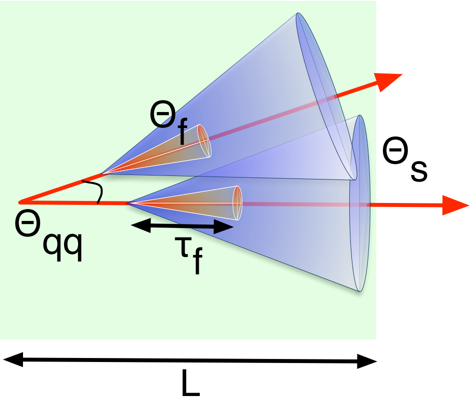
Very large dipole angle $\theta_{q\bar{q}} \gg \theta_s$

- The gluon must be coherent (overlap) with both sources



- No overlap between the BDMPS–Z spectrum by one parton and the other parton $\Rightarrow$ no interference

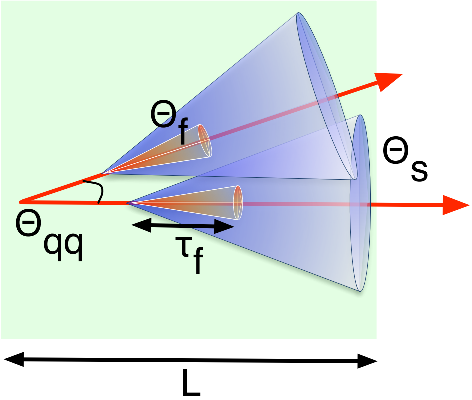
Relatively large dipole angles: $\theta_s \gtrsim \theta_{q\bar{q}} \gtrsim \theta_f$



- The two BDMPS–Z spectra overlap with both sources ...

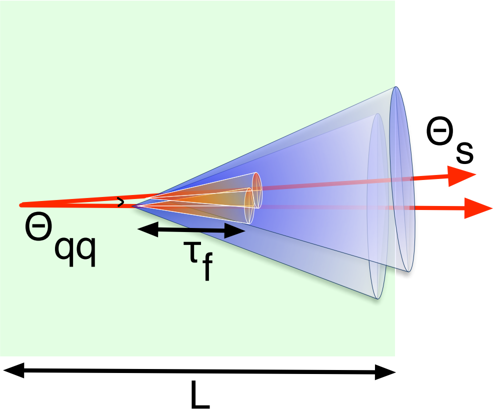
  ... but can they interfere ?

Relatively large dipole angles: $\theta_s \gtrsim \theta_{q\bar{q}} \gtrsim \theta_f$



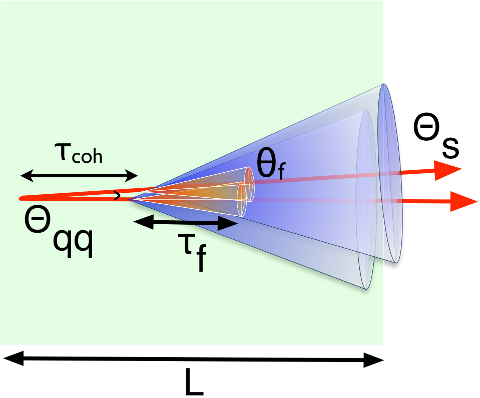
- The two BDMPS–Z spectra overlap with both sources ...
  ... but can they interfere ?
- No, they cannot ! (no overlap during formation)

Relatively small dipole angles: $\theta_f \gg \theta_{q\bar{q}} \gg \theta_c$



- The spectra overlap with both partons during formation.
- Naively : "The typical emission angles being much larger than $\theta_{q\bar{q}}$, there should be destructive interference."

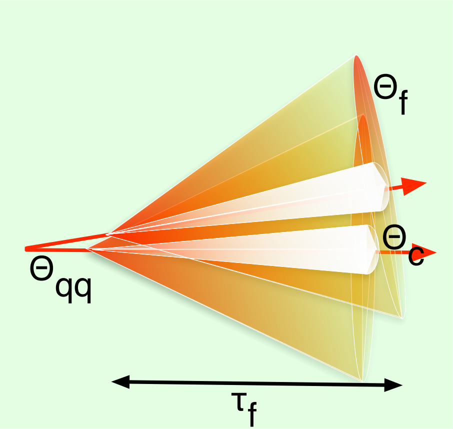
Relatively small dipole angles: $\theta_f \gg \theta_{q\bar{q}} \gg \theta_c$



- But this is spoilt by color rotations which wash out the color coherence of the $q\bar{q}$ pair over a time

$$\tau_{coh} \simeq \left(\frac{\theta_c}{\theta_{q\bar{q}}}\right)^{2/3} L \ll L$$

Very small dipole angles: $\theta_{q\bar{q}} \lesssim \theta_c$



- Color coherence is preserved throughout the medium.
- Quantum coherence is ensured during formation.
- Destructive interference ⇒ vanishing overall contribution

Summary

- So long as $\theta_{q\bar{q}} \gg \theta_c$, interference is parametrically suppressed
  - when $\theta_{q\bar{q}} \gtrsim \theta_f$, it is suppressed by quantum decoherence
  - when $\theta_f > \theta_{q\bar{q}} \gg \theta_c$, it is suppressed by color decoherence
- When $\theta_{q\bar{q}} \ll \theta_c$, the total medium–induced radiation vanishes
- When non–zero, the medium–induced radiation by the dipole

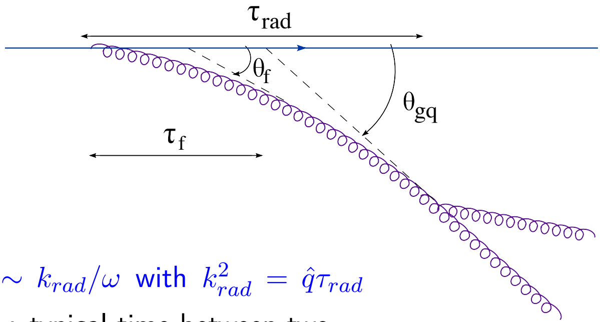
  $\simeq$

  the incoherent sum of the 2 contributions by the q and the $\bar{q}$
- This paves the way to Monte–Carlo generators

  (J. Stachel, U. Wiedemann, C. Zapp, 2011, w.i.p.)
- Can pQCD describe the di–jet asymmetry seen at the LHC ?

In–medium jet evolution

- The second gluon is emitted from a quark–gluon antenna



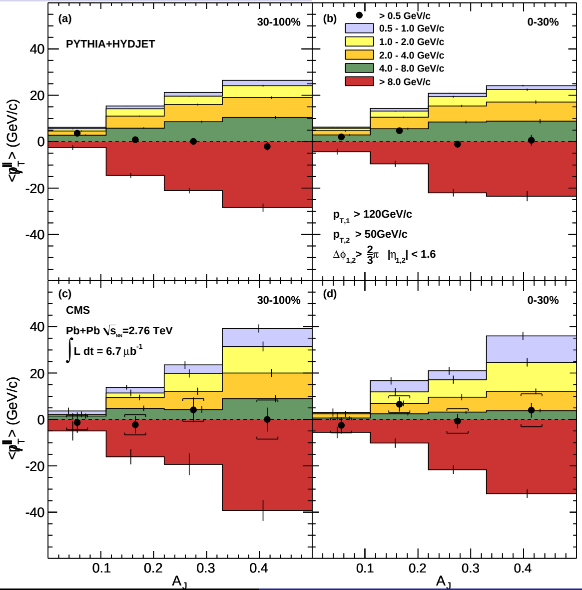
- $\theta_{gq} \sim k_{rad}/\omega$ with $k_{rad}^2 = \hat{q}\tau_{rad}$

  τ_{rad} : typical time between two successive emissions

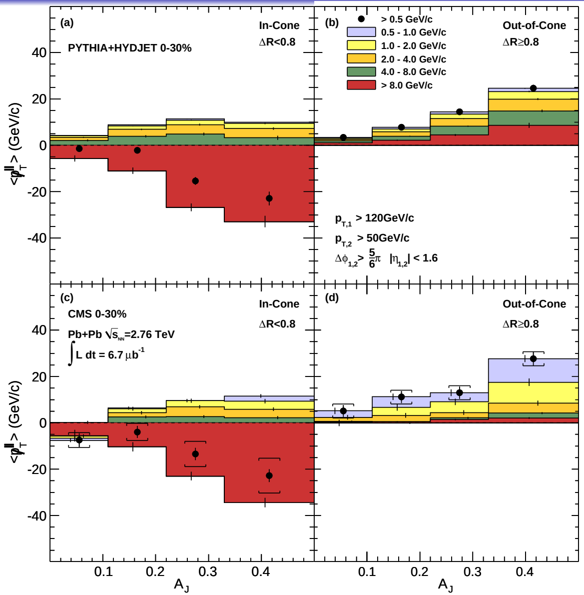
$$\mathcal{P}_{rad}(\tau) \sim \alpha_s C_R \frac{\tau}{\tau_f} \quad \Rightarrow \quad \tau_{rad} \sim \frac{\tau_f}{\alpha_s C_R} \quad \Rightarrow \quad \theta_{gq} \sim \frac{\theta_f}{g}$$

- In–medium jet evolution proceeds via independent emissions

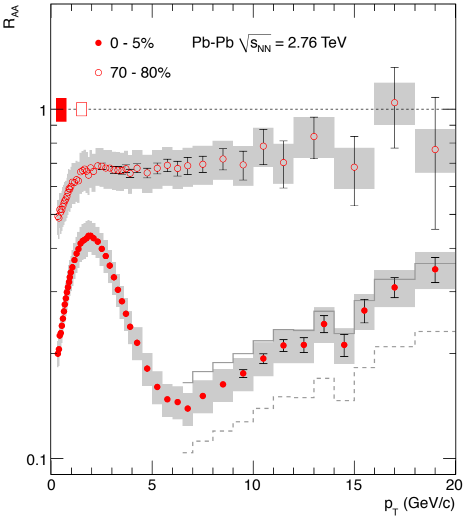
$p_T^{\parallel}$–asymmetry *(CMS)*



In–out asymmetry *(CMS)*



R_{AA} at RHIC & the LHC : **ALICE**



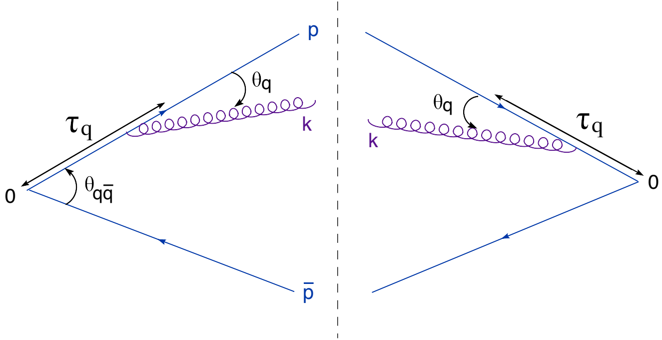
- Nuclear modification factor

$$R_{AA}(p_\perp) \equiv \frac{\text{Yield}(A+A)}{\text{Yield}(p+p)\,\times\,A^2}$$

- Strong suppression at moderate p_T
- Rapid increase for larger p_T
- Current models do not account for all these features

The bremsstrahlung spectrum

- Direct emission by a quark in the vacuum

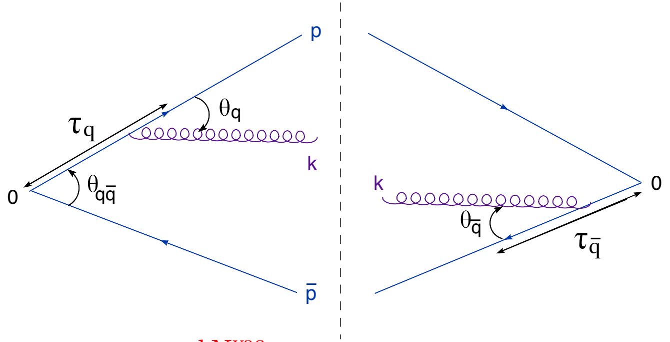


$$\omega \frac{dN^{vac}}{d\omega dk_\perp^2} \simeq \frac{\alpha_s C_F}{k_\perp^2} \simeq \alpha_s C_F \theta_q^2 \tau_q^2$$

- Vertex squared (θ_q^2) $\times$ longitudinal phase–space (τ_q^2)
- Mostly soft $(\omega \to 0)$ and collinear gluons $(\theta_q \to 0)$

Angular ordering

- Direct emissions plus interferences in the vacuum

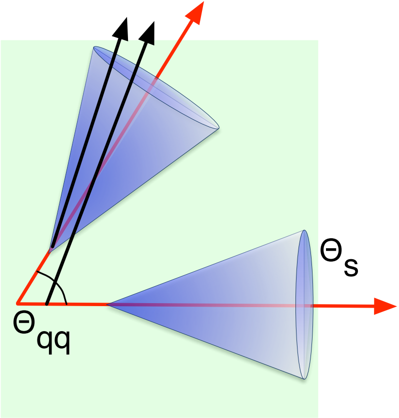


$$\omega \frac{dN^{vac}_{dip}}{d^3\boldsymbol{k}} \simeq \alpha_s C_F \left(\theta_q \tau_q - \theta_{\bar{q}} \tau_{\bar{q}}\right)^2$$

- The interference term $(-2\theta_q \theta_{\bar{q}} \tau_q \tau_{\bar{q}})$ cancels direct emissions when $\theta_q, \theta_{\bar{q}} \gg \theta_{q\bar{q}}$ $\Longrightarrow$ angular ordering

‘Vacuum–medium’ interference

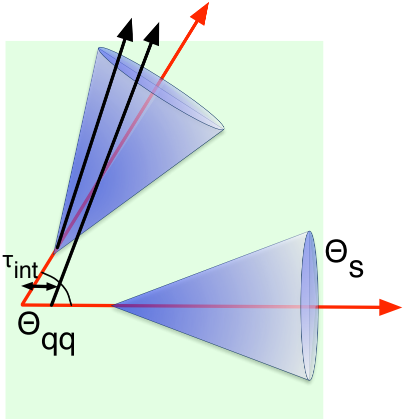
- A vacuum–like gluon emitted at a large angle $\gtrsim \theta_{q\bar{q}}$ by one of the partons can interfere with the other parton.



- This provides a BDMPS–Z–like contribution to the spectrum.

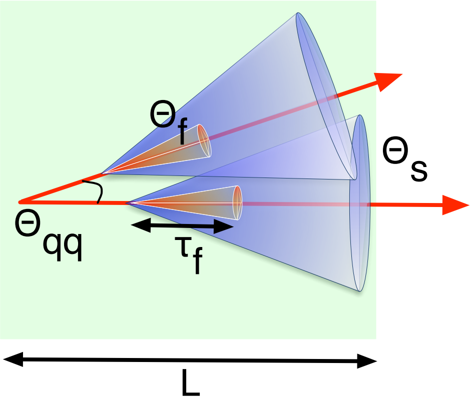
'Vacuum–medium' interference

- A vacuum–like gluon emitted at a large angle $\gtrsim \theta_{q\bar{q}}$ w.r.t. one parton can interfere with the second parton



- ... but this has a very small phase–space: $\tau_{int} = \frac{1}{\omega\theta_{q\bar{q}}^2} \ll L$

Relatively large dipole angles: $\theta_s \gtrsim \theta_{q\bar{q}} \gtrsim \theta_f$



- 'Vacuum–medium' interference is still possible ...
  but it is again suppressed by its small phase–space $(\tau_{int} \ll L)$