# *Medium–induced jet evolution*

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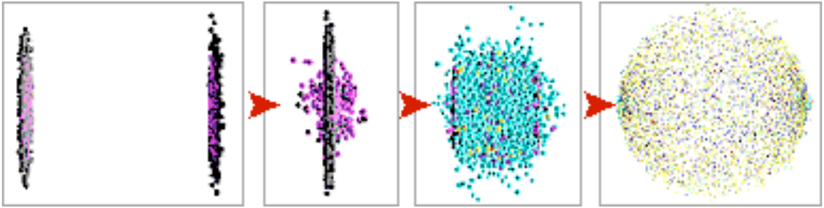
# Heavy Ion Collisions @ RHIC & the LHC


# New forms of partonic matter



- Prior to the collision: 2 Lorentz–contracted nuclei ('pancakes')
  - 'Color Glass Condensate' (CGC)
- Right after the collision: non–equilibrium partonic matter
  - 'Glasma' (from 'Glass' + 'Plasma')
- At later stages ($\Delta t \gtrsim 1$ fm/c) : local thermal equilibrium
  - 'Quark–Gluon Plasma' (QGP)

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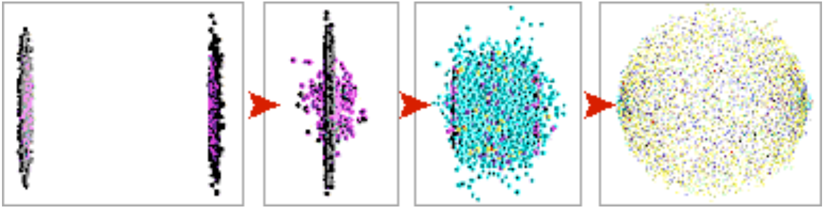

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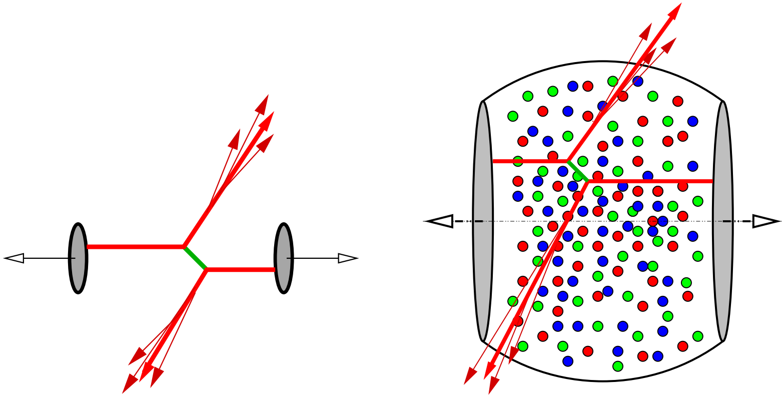
- At later stages ($\Delta t \gtrsim 1$ fm/c) : local thermal equilibrium
  - 'Quark–Gluon Plasma' (QGP)
- How to probe the intermediate stages (Glasma, QGP) ?

# Jet quenching

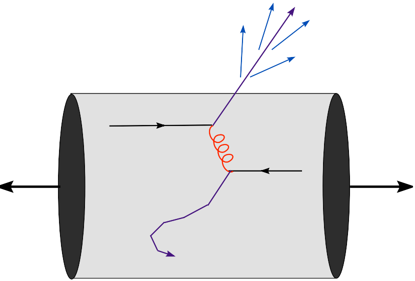
- Two–hadron (or 'di–jets') correlations :

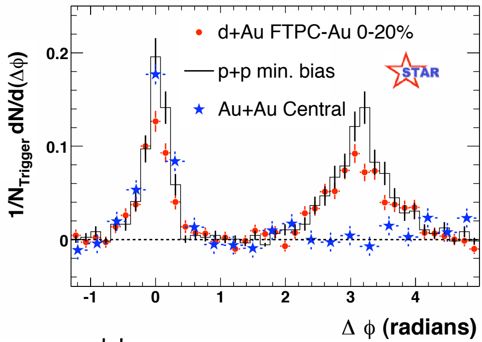
  a measurement of the medium (QGP ?) created at intermediate stages



- 'Jet': 'leading particle' + 'products of fragmentation'

- Studies of jet quenching at RHIC have focused on 'leading particles'





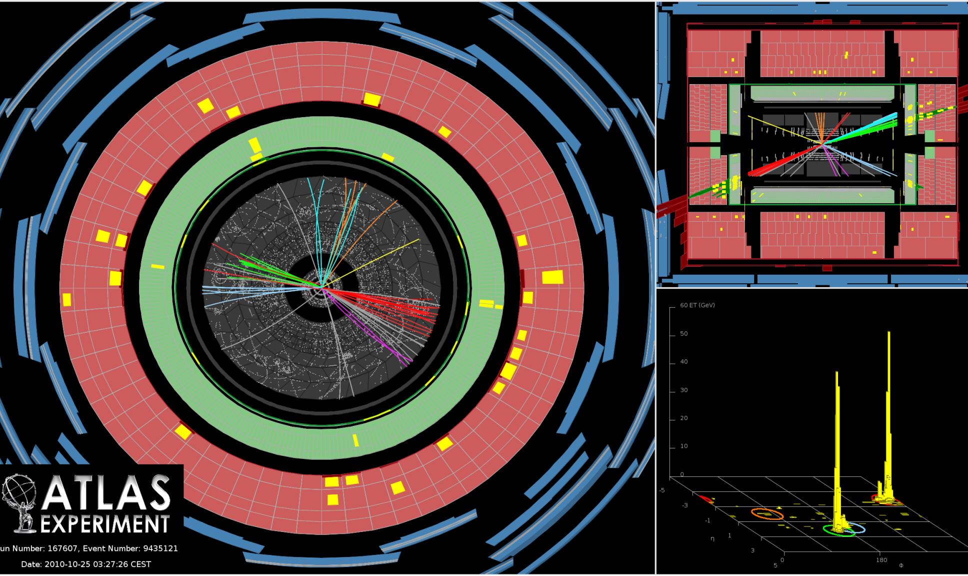

- The "away–side" peak has disappeared !

  absorbtion (or energy loss, or "jet quenching") in the medium

- The matter produced in a heavy ion collision is opaque

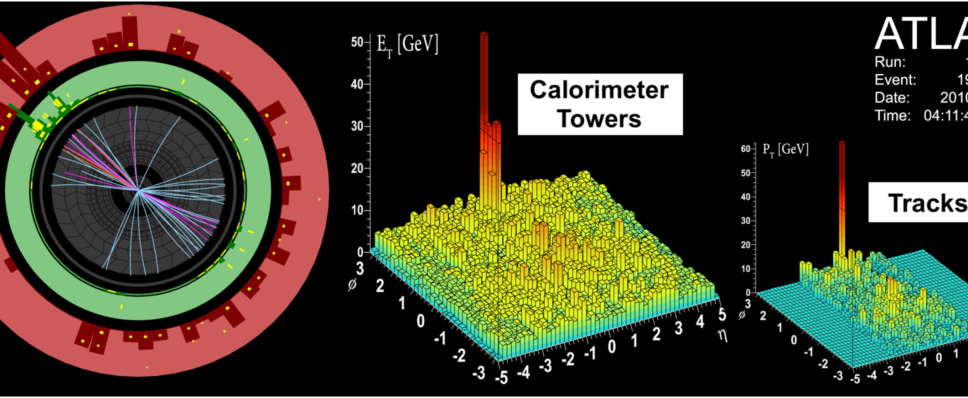
  high density, or strong interactions ('sQGP'), ... or both

# Jet production at the LHC



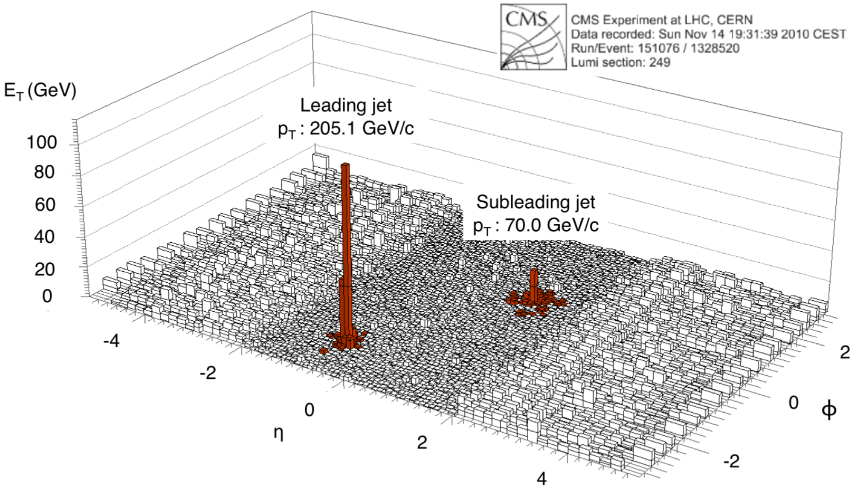

- The LHC gives us access to real jets

# 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)*

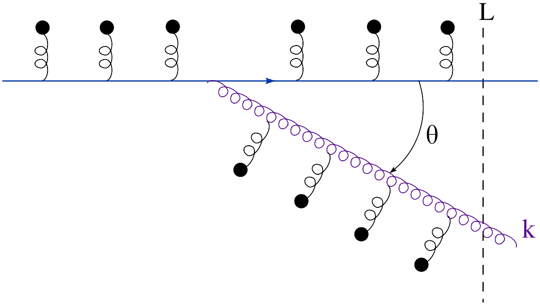



- Central Pb+Pb: the secondary jet is barely visible
- In–medium radiation of relatively soft quanta at large angles

# Medium–induced gluon radiation

- Additional radiation triggered by interactions in the medium

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




- Naturally leads to emissions at large angles

  the emitted gluons receive transverse kicks from the medium

- How to compute multiple gluon emissions / jet evolution ?

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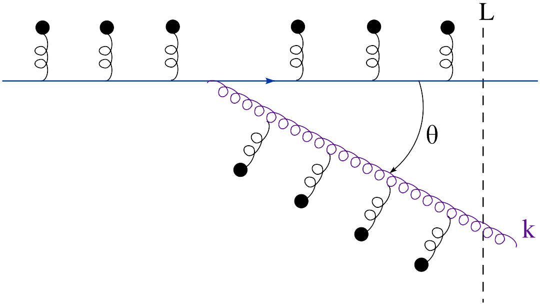
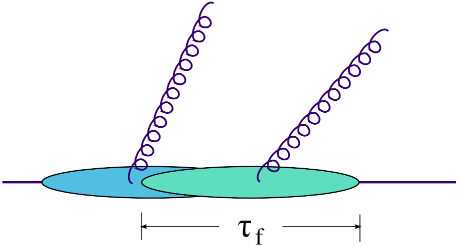


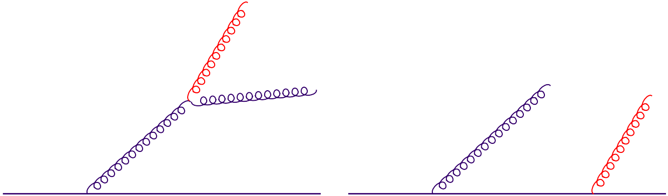

- Naturally leads to emissions at large angles
  the emitted gluons receive transverse kicks from the medium
- How to compute multiple gluon emissions / jet evolution ?
- Ideally: Monte Carlo generator $\Longrightarrow$ classical branching process

# Factorization issues

- Parton branching is a quantum phenomenon, which implies ...
  - a finite formation (or branching) time $\tau_f$

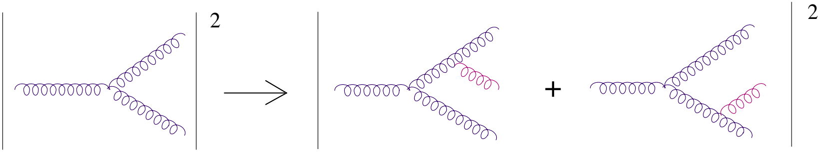



  - interference between emissions by different sources

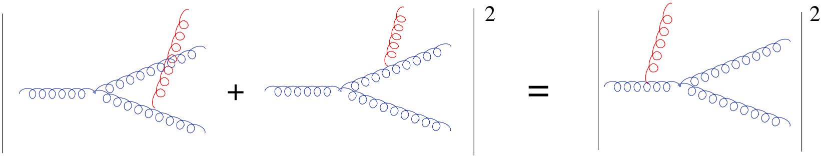


# Interferences in the vacuum

- $1 \to 2$ gluon splitting: the daughter gluons remain in the same overall colour state until the next emission — they are colour coherent

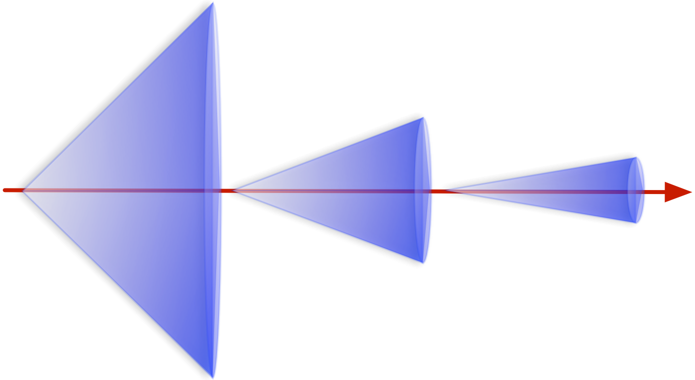


- A large angle emission sees the overall colour charge
  $\Longrightarrow$ it can be formally treated as an emission by the parent dipole



- Equivalent classical branching process but with angular ordering

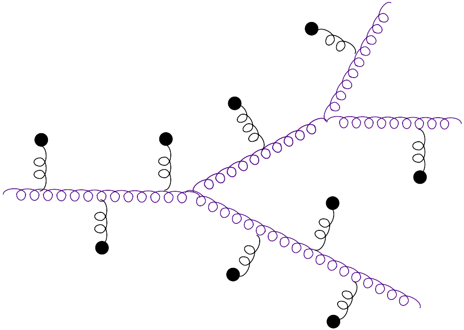
# Angular ordering (vacuum)



- For a jet propagating through the vacuum, destructive interference between different sources leads to angular ordering : $\theta_1 > \theta_2 > \theta_3 > \ldots$.
- What about medium–induced radiation ?

# Medium–induced jet evolution

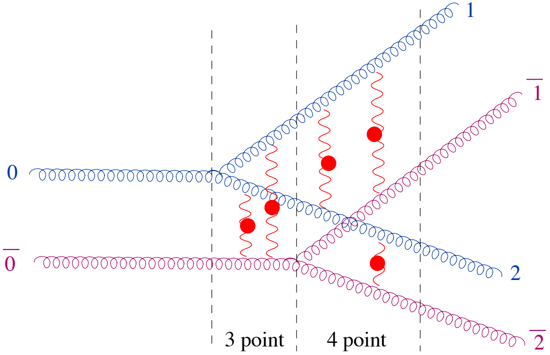
- The mathematical problem looks very complicated ...
  - medium rescattering and gluon emissions should be treated to all orders



- ... but there is hope that the physical answer could be simple !
- Medium rescattering destroys the coherence of the radiating system and thus can enhance radiation and reduce interferences

# A few words on the formalism

- Quantum emission: amplitude × the complex conjugate amplitude



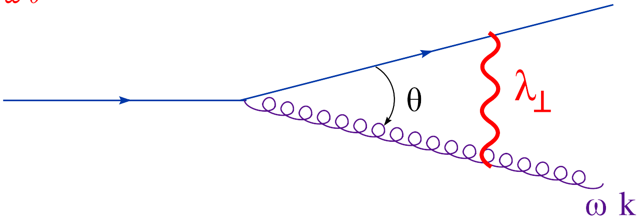

- 'Medium' = independent scattering centers with Debye screening
- Medium rescattering resummed to all orders in the eikonal approximation (Wilson lines, one for each gluon)
- $1 \rightarrow 2$ gluon branching $\Leftrightarrow$ 3–point and 4–point correlation functions of the Wilson lines (Gaussian average)

# 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 $\tau_f$ should be comparable with the gluon transverse wavelength $\lambda_\perp$

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

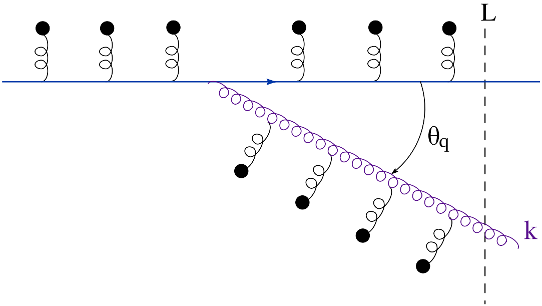
$$k_\perp \simeq \omega\,\theta$$




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

# Transverse momentum broadening

- The loss of coherence is accelerated by medium rescattering
- Random kicks leading to transverse momentum broadening




- Parton mean free path $\ell$
- Average (momentum)$^2$ transfer per scattering $m_D^2$ (Debye mass)

$$\frac{\mathrm{d}\langle k_\perp^2 \rangle}{\mathrm{d}t} \simeq \frac{m_D^2}{\ell} \equiv \hat{q}$$ 'jet quenching parameter'

# In–medium formation time

- The gluon acquires a (momentum)$^2 \sim \hat{q}$ per unit time ...
- ... and hence a momentum $k_f^2 \simeq \hat{q}\,\tau_f$ during its formation.
- The condition of quantum decoherence requires $\tau_f \simeq \omega/k_f^2$

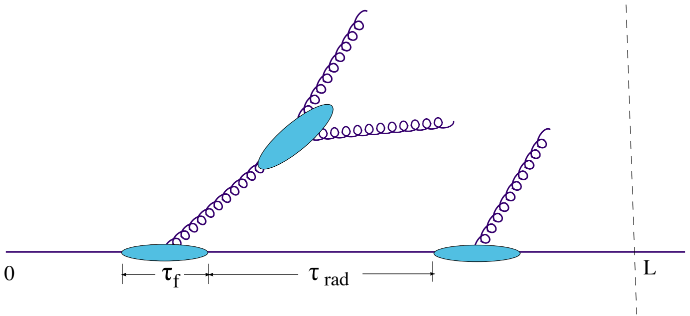
$$\tau_f \simeq \sqrt{\frac{\omega}{\hat{q}}}, \qquad \theta_f \equiv \frac{k_f}{\omega} \simeq \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$

- N.B. The energy $\omega$ and the transverse momentum $k_\perp$ are not independent kinematical variables anymore !
- Medium favors the emission of soft gluons (small $\omega$) at large angles

  $\Longrightarrow$ the right trend to explain the LHC data !

- $P(L) \simeq \alpha_s (L/\tau_f)$ : probability for one emission over a distance $L$
- When $P(L) \gtrsim 1$, multiple emissions are bound to occur

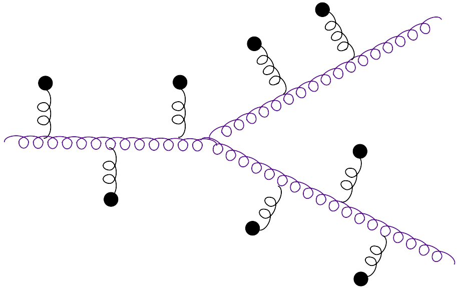
$$P(L) \sim \alpha_s \frac{L}{\tau_f} \gtrsim 1 \implies \tau_f \lesssim \alpha_s L \ll L$$




- Successive in–medium emissions do not overlap with each other ✓

# Decoherence & interferences

- Already during formation, the daughter gluons independently scatter off (and exchange colour with) the medium constituents.



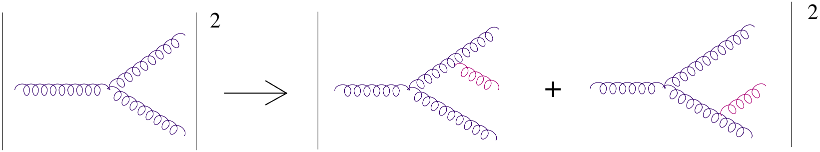
- By definition, the 'formation time' $\tau_f$ is when the daughter gluons have lost coherence w.r.t. their parent gluon
- By that time, they also lose coherence w.r.t. each other !

  $\Longrightarrow$ interference effects are suppressed by a factor $\tau_f/L \ll 1$ ✓

- By the same token, the branching process looks quasi–local

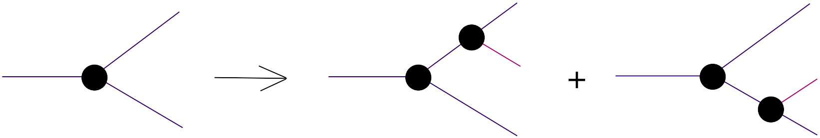
# Towards Monte–Carlo generators

- In–medium jet evolution : a classical, probabilistic, branching process
- One additional emission : quantum process




  - direct emissions plus interference effects

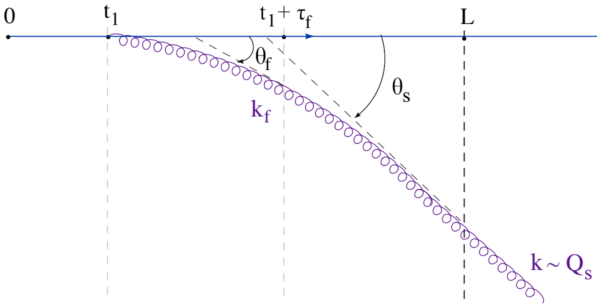
- One additional emission : classical process



  - medium effects explicit in effective vertices and propagators

# The BDMPS–Z spectrum

- So long as $\omega \ll \omega_c \equiv \hat{q}L^2$, one has $\tau_f \ll L$

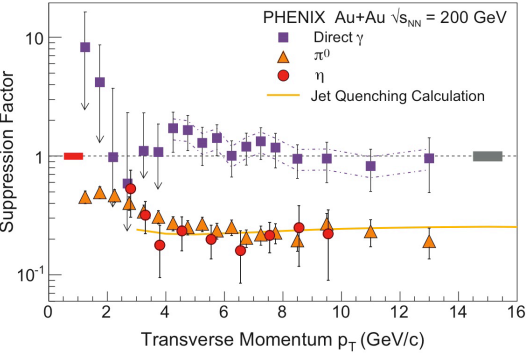


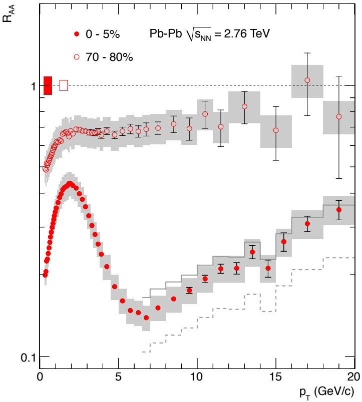

- After formation, the gluon can still acquire momentum via scattering in the plasma (transverse momentum broadening)

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

# Nuclear modification factor at RHIC & the LHC

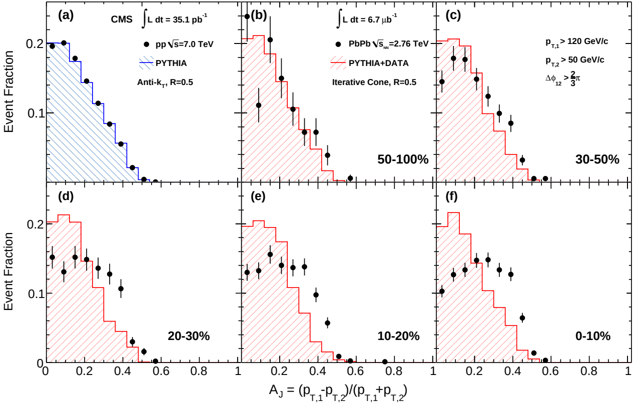
$$R_{\mathrm{A+A}} \equiv \frac{1}{A^2} \frac{\mathrm{d}N_{\mathrm{A+A}}/\mathrm{d}^2p_\perp \mathrm{d}\eta}{\mathrm{d}N_{\mathrm{p+p}}/\mathrm{d}^2p_\perp \mathrm{d}\eta}$$




- Strong suppression $(R_{AA} \lesssim 0.2)$ in central collisions
- Large energy loss in the medium

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

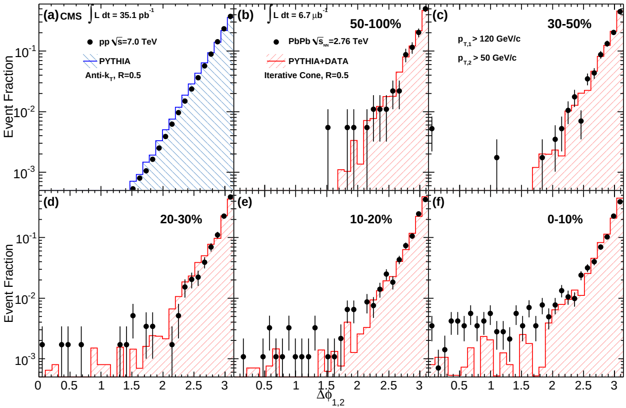



- Event fraction as a function of the di–jet energy imbalance in p+p (a) and Pb+Pb (b–f) collisions for different bins of centrality

$$A_\mathrm{J} = \frac{E_1 - E_2}{E_1 + E_{21}}$$

- 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

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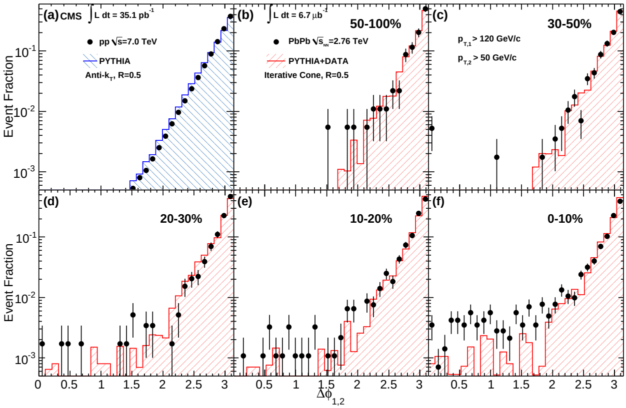
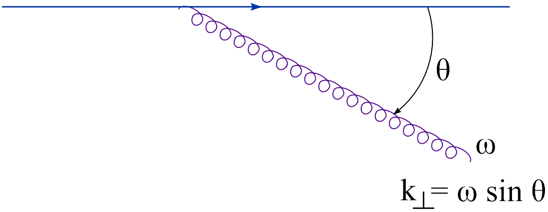



- Event fraction as a function of the azimuthal angle $\Delta\phi$.
- Typical event topology: still a pair of back–to–back jets
- The secondary jet loses energy without being deflected
- Additional radiation of relatively soft quanta at large angles

- Gluon emission by an off–shell quark in the vacuum !



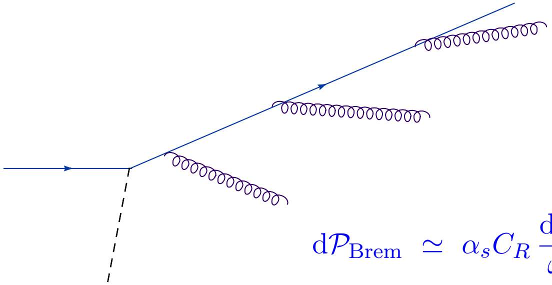

$$\mathrm{d}\mathcal{P}_{\rm Brem} \;\simeq\; \alpha_s C_R \,\frac{\mathrm{d}\omega}{\omega}\,\frac{\mathrm{d}^2 k_\perp}{k_\perp^2} \,\propto\, \alpha_s \,\frac{\mathrm{d}\omega}{\omega}\,\frac{\mathrm{d}\theta}{\theta}$$

- Phase–space enhancement for the emission of
  - soft (low–energy) $(\omega \to 0)$
  - and/or collinear $(\theta \to 0)$ gluons
- No similar enhancement for the emission of soft quarks

# In–vacuum fragmentation

- Radiation requires acceleration

  $\Longrightarrow$ in–vacuum emissions occur only after a hard scattering



$$\mathrm{d}\mathcal{P}_{\mathrm{Brem}} \simeq \alpha_s C_R \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta}{\theta}$$

- Successive emissions are ordered in energy and in angle, hence in time

$$\omega_1 > \omega_2 > \omega_3 \ldots \quad \& \quad \theta_1 > \theta_2 > \theta_3 \ldots \quad \Longrightarrow \quad \tau_1 < \tau_2 < \tau_3 \ldots$$

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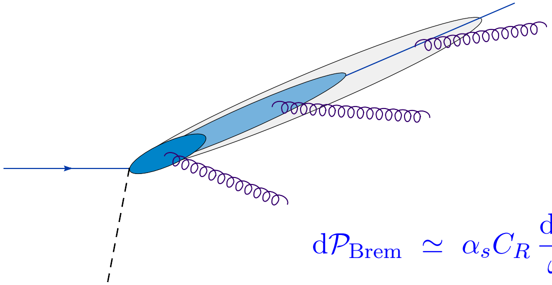

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- This ordering is typically strong ($\omega_1 \gg \omega_2$, etc)

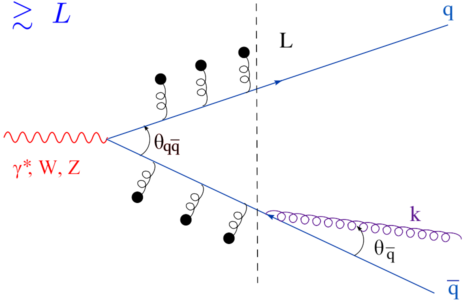
  $\Longrightarrow$ the overlapping between successive emissions is negligible

# Out–of–medium emissions

*(C. Salgado, Y. Mehtar-Tani & K. Tywoniuk, arXiv:1105.1346)*

- If the emission angle is sufficiently small (for a given $\omega$), then the gluon can be also emitted outside the medium:

$$\tau_q \simeq \frac{2}{\omega\theta_q^2} \gtrsim L$$




- The coherence between the sources is washed out by color rotations
  $\Longrightarrow$ no interference, no angular ordering
- Additional bremsstrahlung outside the antenna: $\theta_q \gtrsim \theta_{q\bar{q}}$
  $\Longrightarrow$ $\theta_{q\bar{q}}$ itself must be relatively small