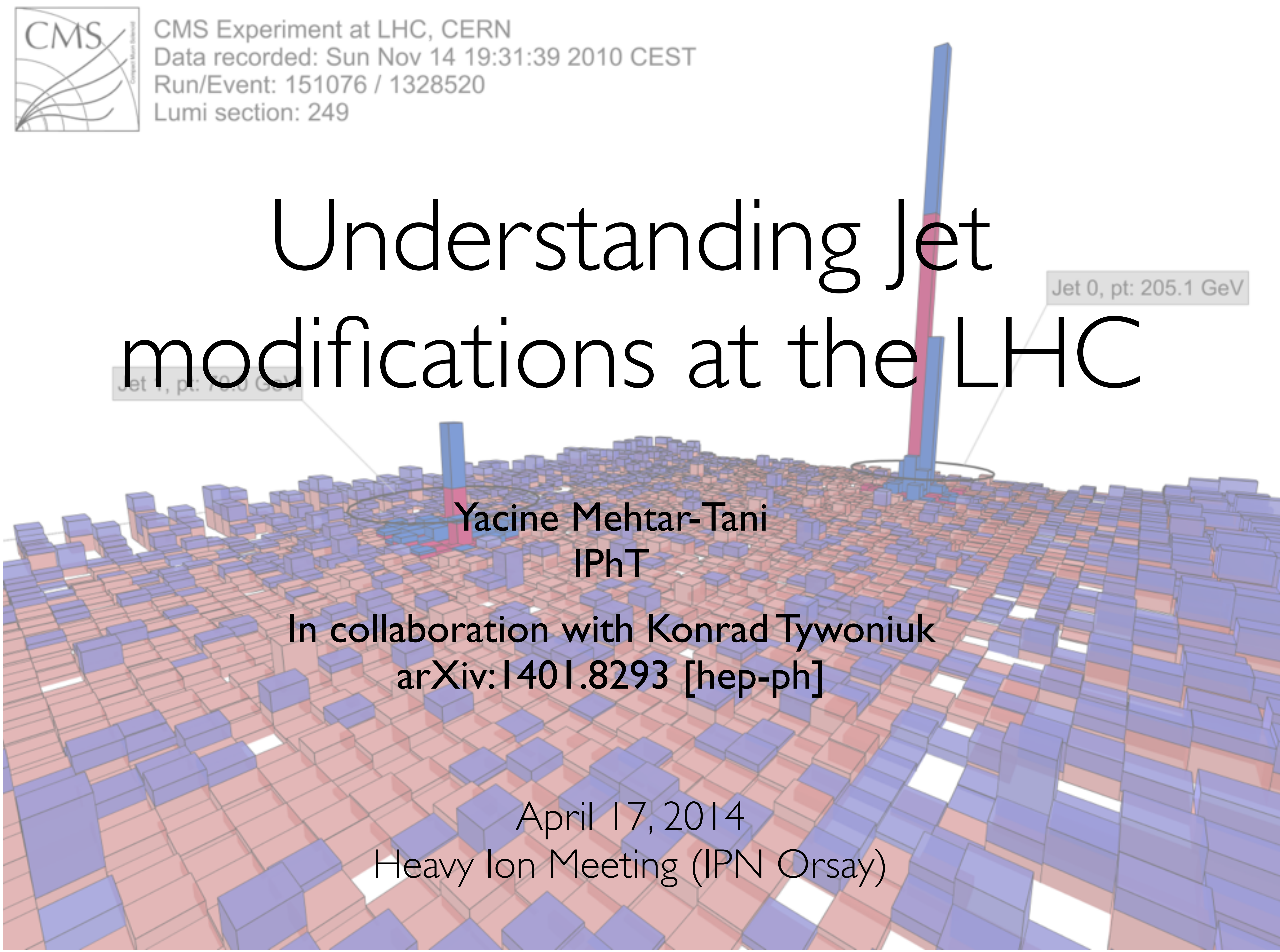


Understanding Jet modifications at the LHC

Yacine Mehtar-Tani
IPhT

In collaboration with Konrad Tywoniuk

arXiv:1401.8293 [hep-ph]

April 17, 2014
Heavy Ion Meeting (IPN Orsay)

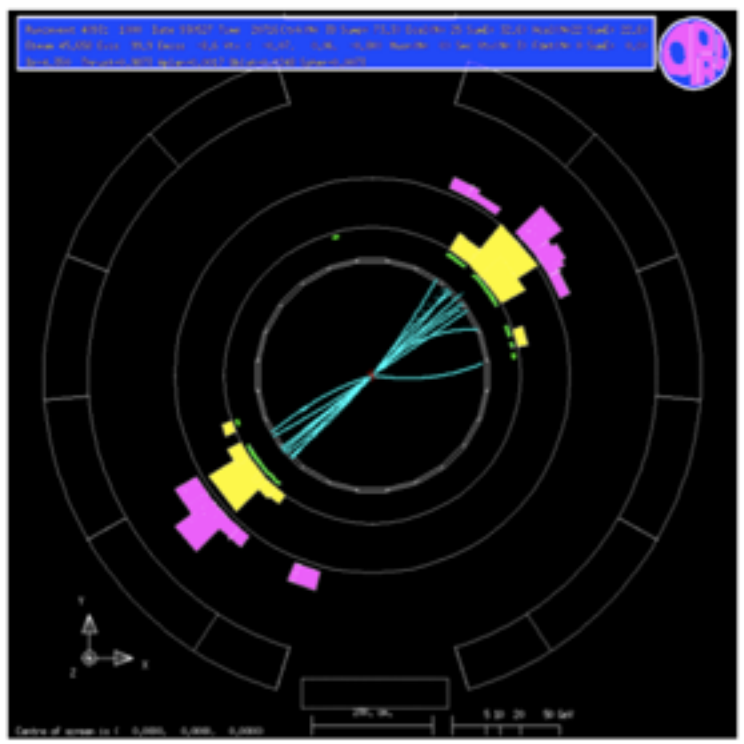
Jets in QCD

a Jet is an energetic and collimated bunch of particles produced in a high-energy collision

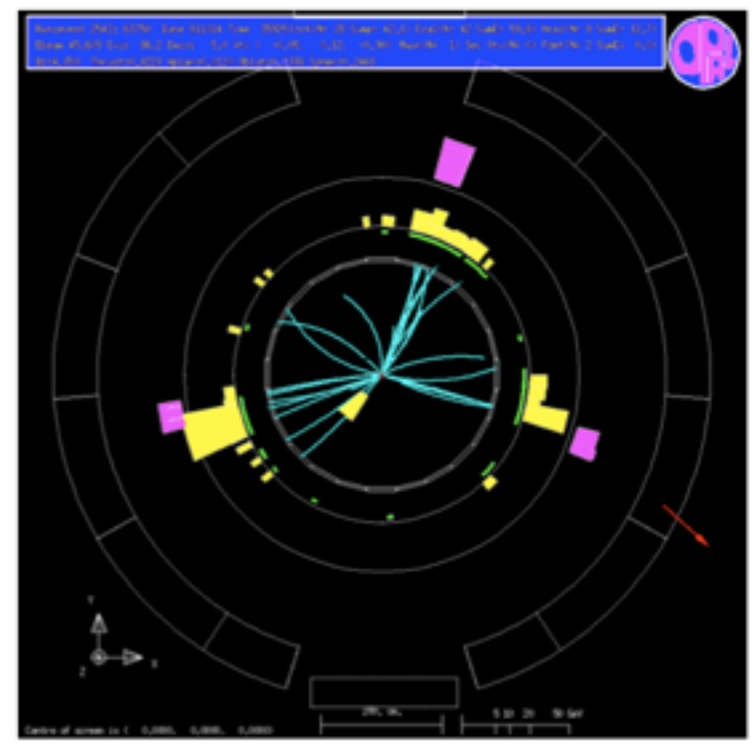
LEP (OPAL)

events

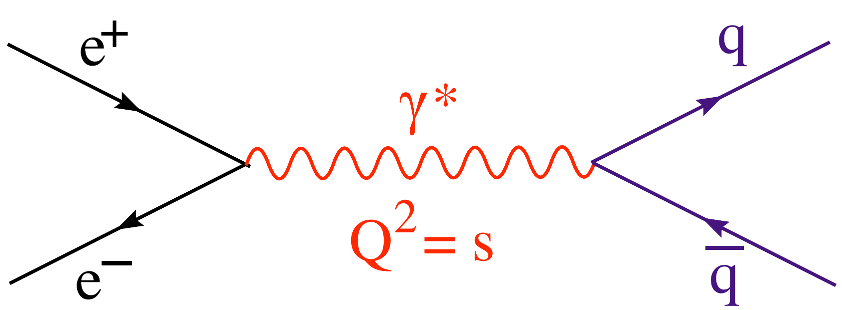
1993

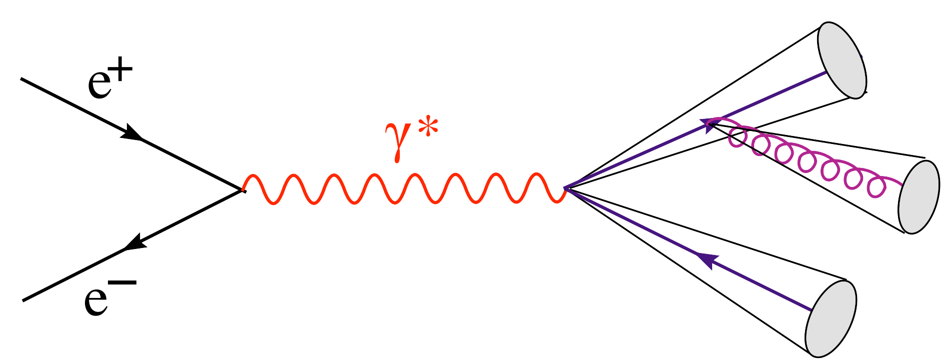


2 jets



3 jets



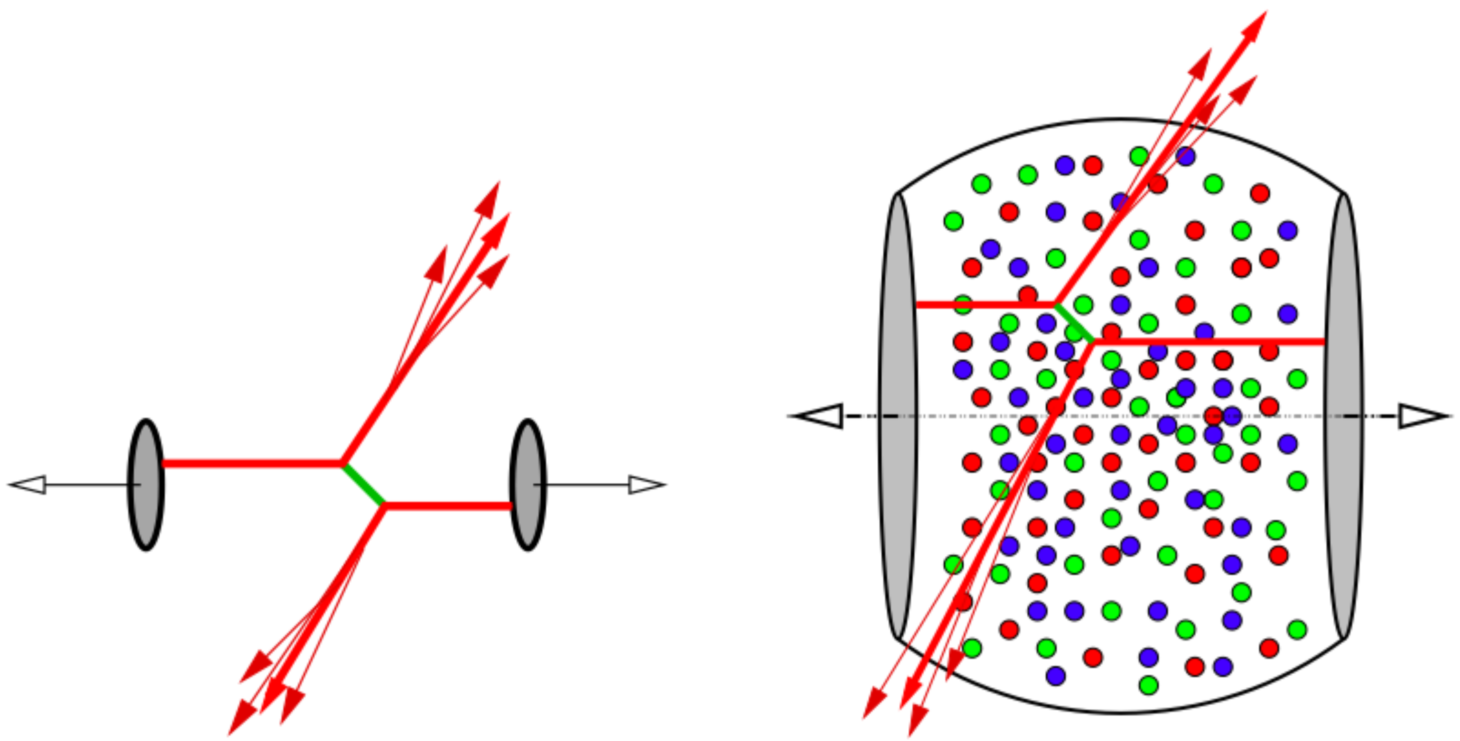


Jets in QCD

- From gluons/quarks to hadrons: at high energy large separation between short and large distance physics (QCD-factorization). Hard scale: $Q \gg \Lambda_{QCD}$
- Perturbative QCD successfully predicted jet observables (accounts also for the soft particle activity surrounding a jet) $\Longrightarrow$ test of QCD (precision physics)

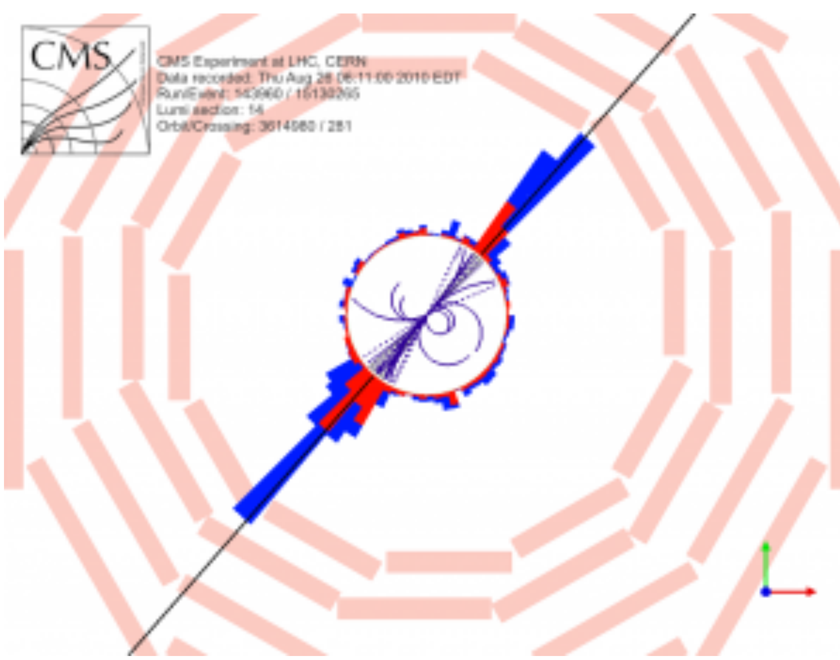
Heavy-Ion Collisions

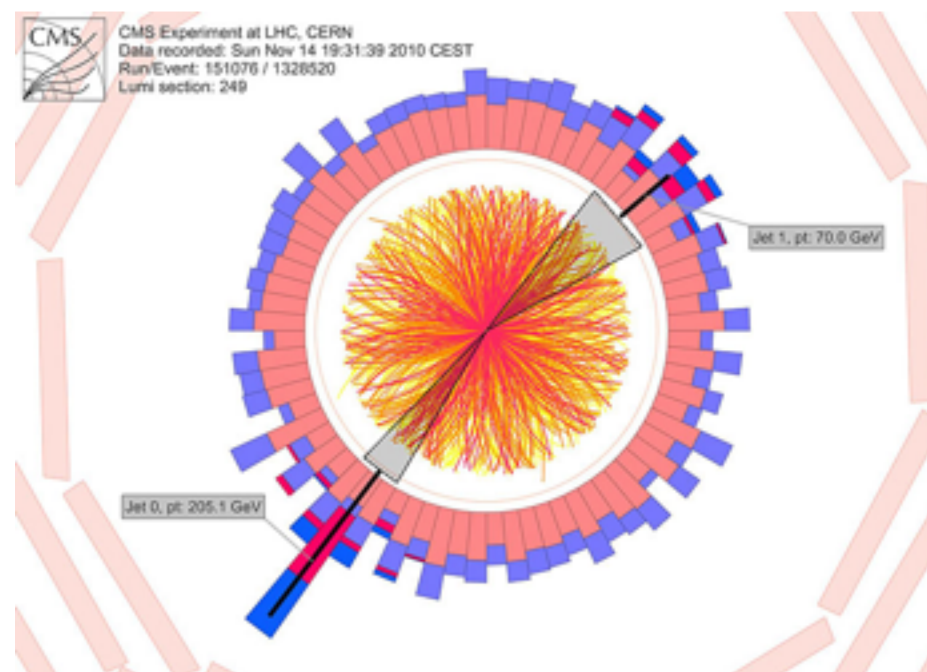
- What happens to the jets embedded in a very dense QCD medium, the quark-gluon plasma (QGP)?



Heavy-Ion Collisions

- Di-jet asymmetry observed at the LHC (jets are quenched due to interactions with the QGP)

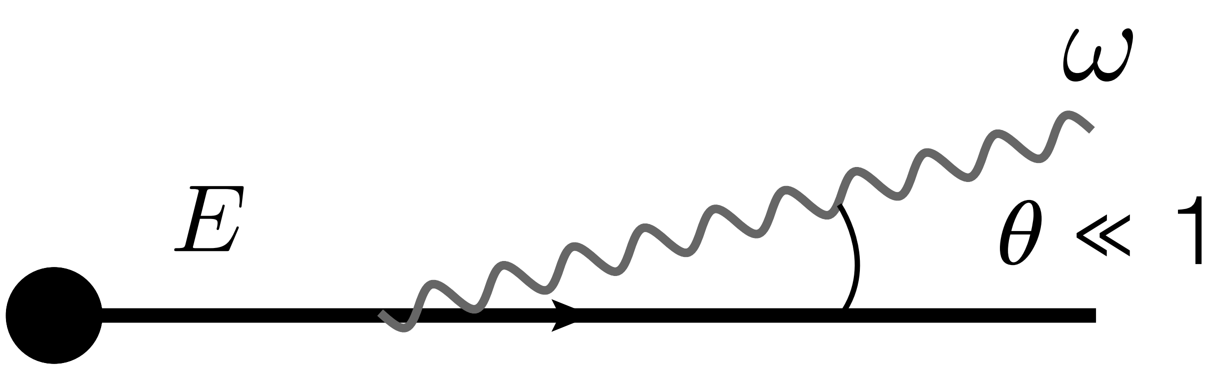




Collisions : proton - proton Pb-Pb

Jets in vacuum

- Jets originate from energetic partons that successively branch (similarly to an accelerated electron that radiates photons)
- Elementary branching process is enhanced in the collinear region $\Longrightarrow$ Collimated jets



branching prob.

$$dP \sim \alpha_s \, C_R \, \frac{d\theta}{\theta} \, \frac{d\omega}{\omega}$$

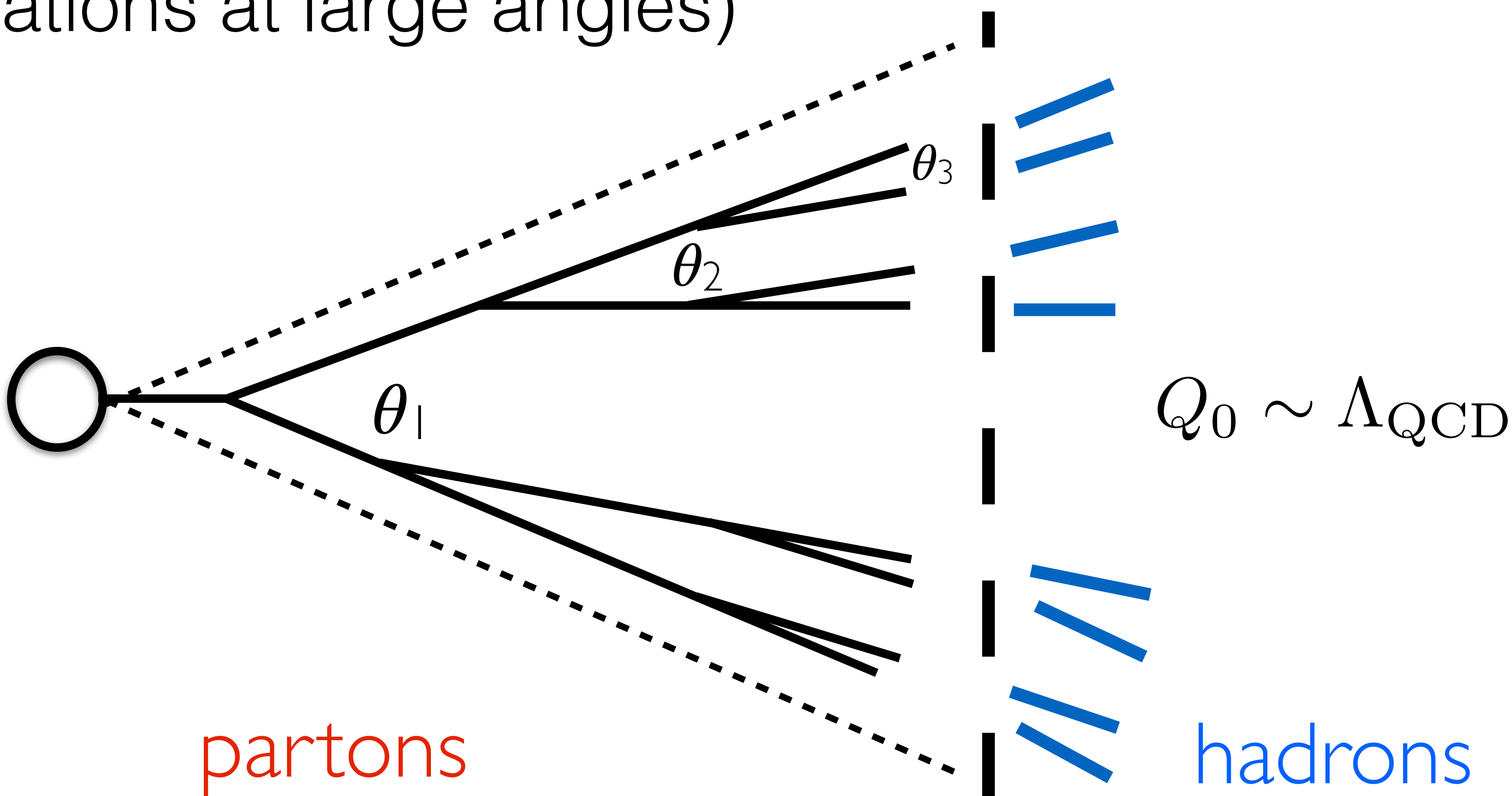
Jets in vacuum

The jet is a coherent object, successive branchings are ordered from larger to smaller angles $\theta_1 > \theta_2 > \ldots > \theta_n$

(coherence leads to destructive interferences between radiations at large angles)

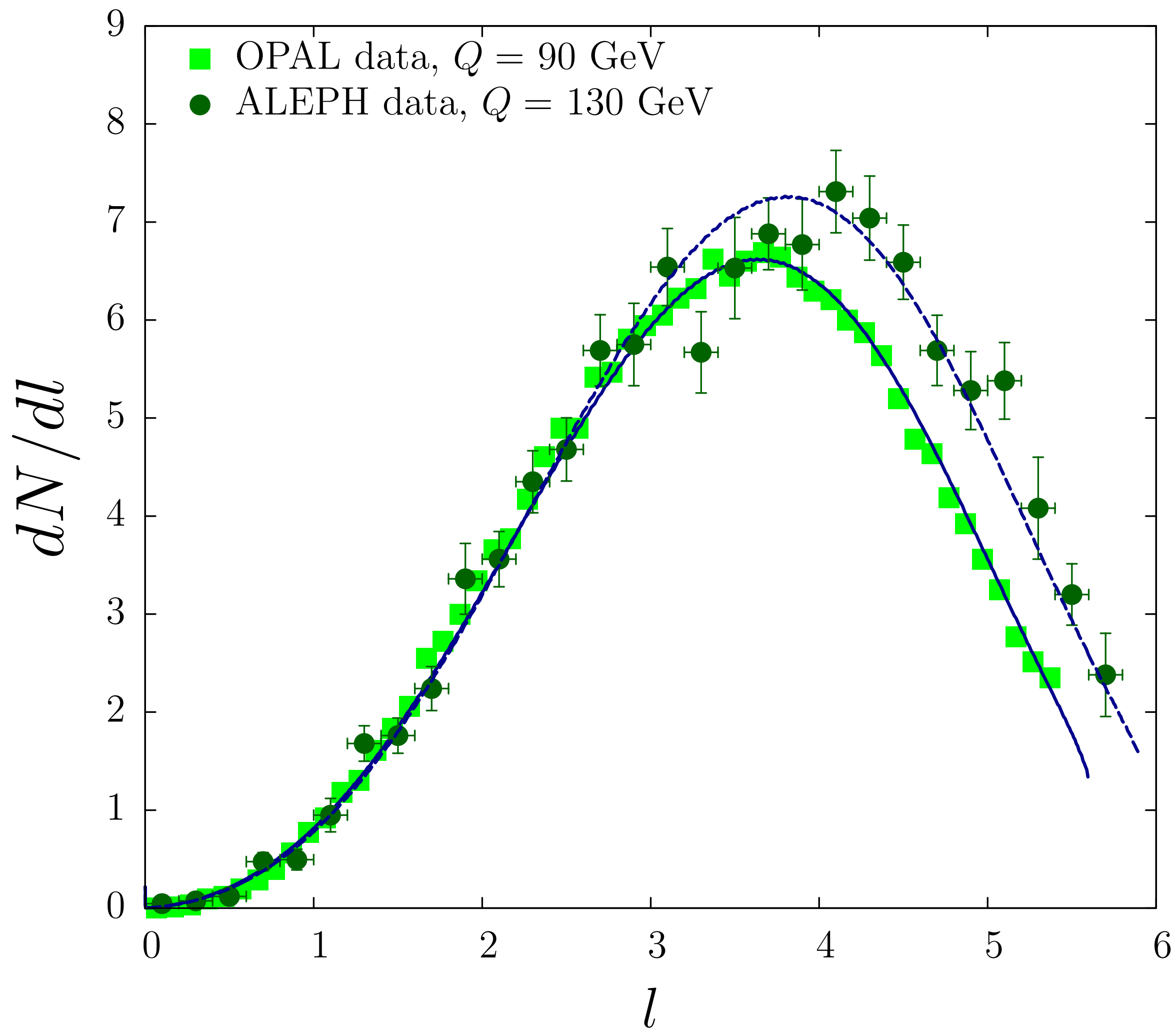
$$Q \equiv E\,\theta_{\rm jet}$$

Jet transverse mass



Jets in vacuum

Fragmentation Function



$$l = \ln(E_{\rm jet}/E_{\rm h})$$

- Perturbative QCD prediction for the distribution of hadrons in a jet
- 2 scales: non-perturbative scale $Q_0 = \Lambda_{QCD}$ and the jet transverse scale $Q = E\,\theta_{\rm jet}$
- Angular Ordering (AO) ⇒

soft gluon emissions (large l) are suppressed

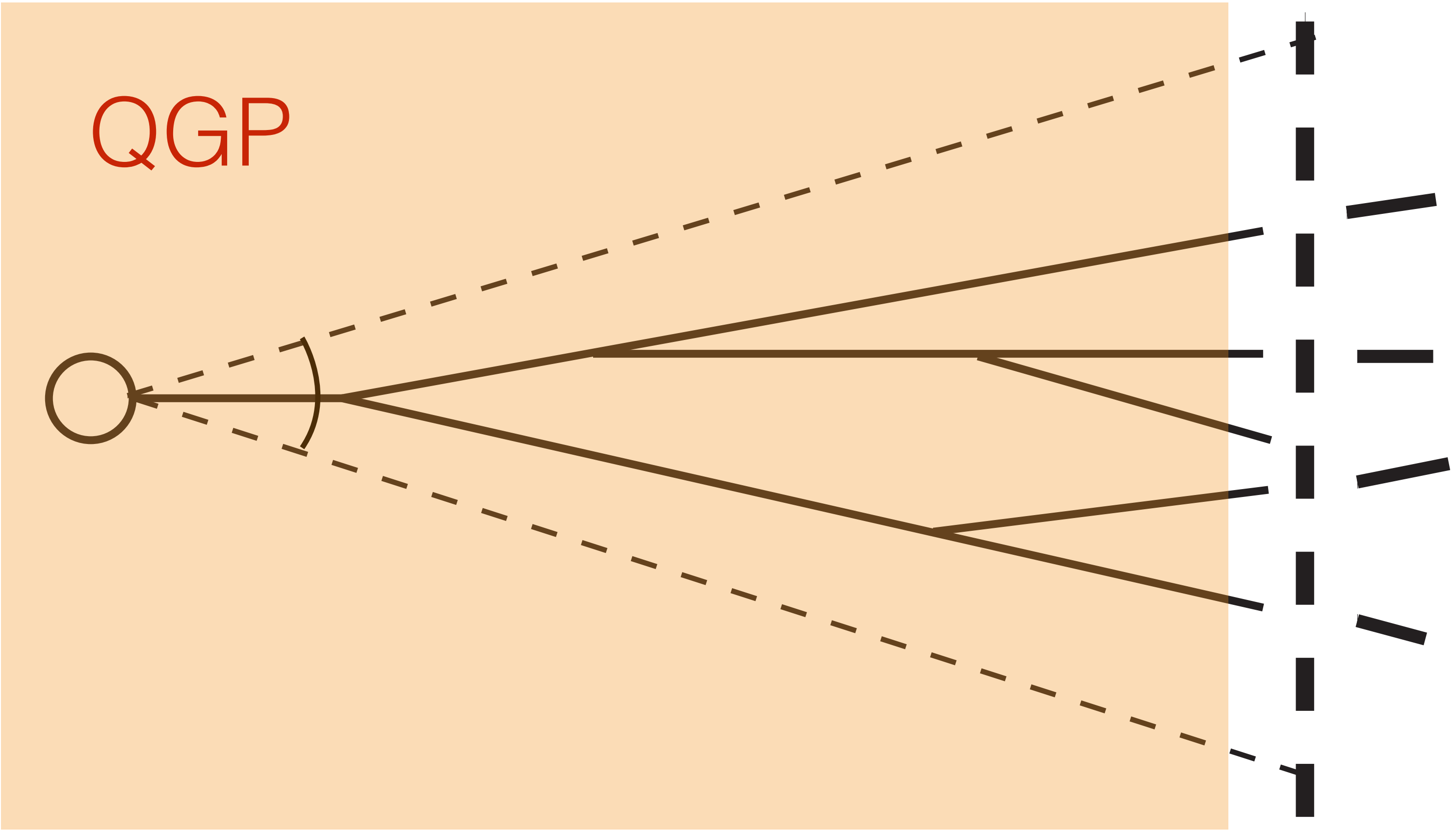
[Dokshitzer, Khoze, Mueller, Troyan, Kuraev, Fong, Webber…80']

Jets in the QGP

- How does the medium interact with a jet?

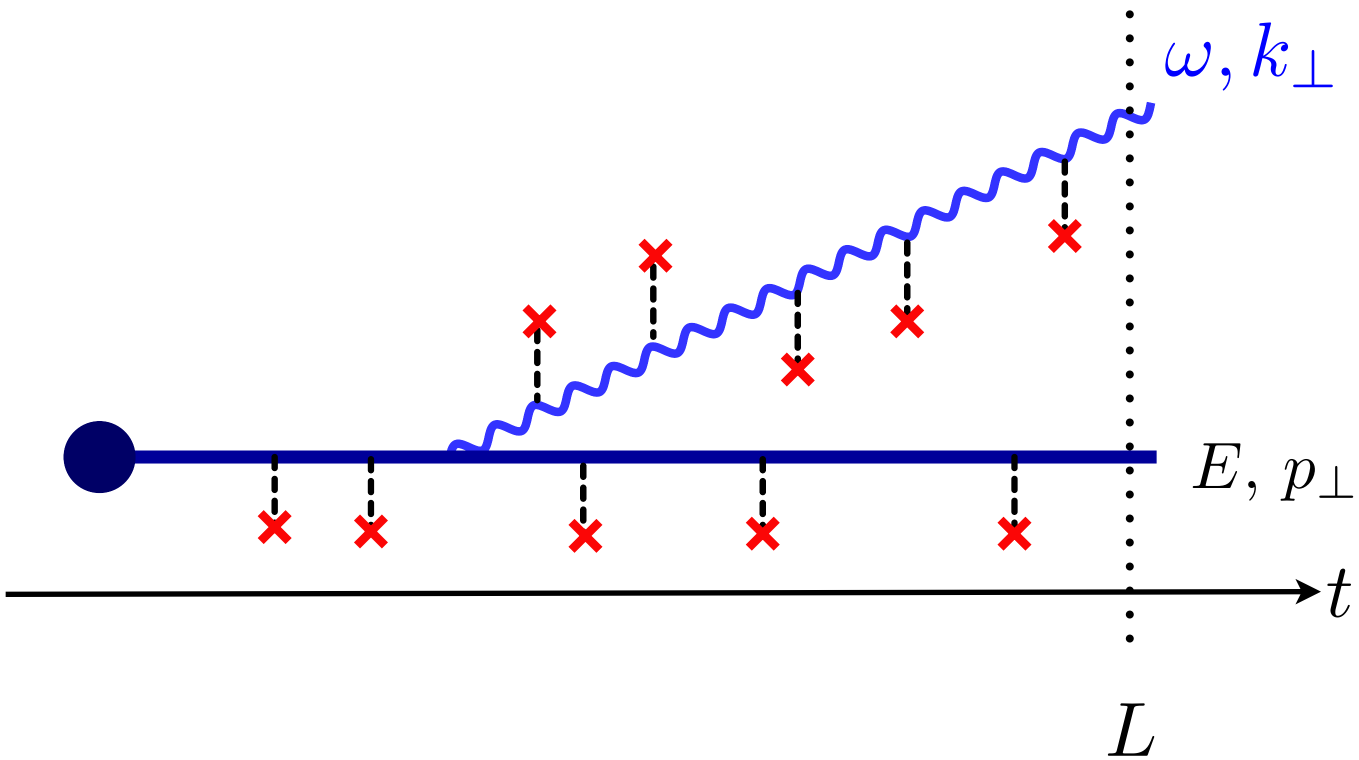
Medium-induced soft gluon radiations

Color coherence is altered (decoherence)



Medium-induced radiation

- Scatterings with the medium can induce gluon radiation
- The radiation mechanism is linked to transverse momentum broadening



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

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

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)]

Medium-induced radiation

How does it happen? After a certain number of scatterings coherence between the parent quark and gluon fluctuation is broken and the gluon is formed (decoherence is faster for soft gluons)

$$t_f \equiv \frac{\omega}{\langle q_\perp^2 \rangle} \simeq \frac{\omega}{\hat{q}\, t_f} \quad \Rightarrow \quad t_f = t_{\rm br} \equiv \sqrt{\frac{\omega}{\hat{q}}}$$

maximum frequency for this mechanism $\omega_c = \frac{1}{2}\hat{q}\, L^2$

corresponding to $t_{\rm br} \sim L$

Medium-induced radiation

soft gluon emissions $\omega \ll \omega_c$

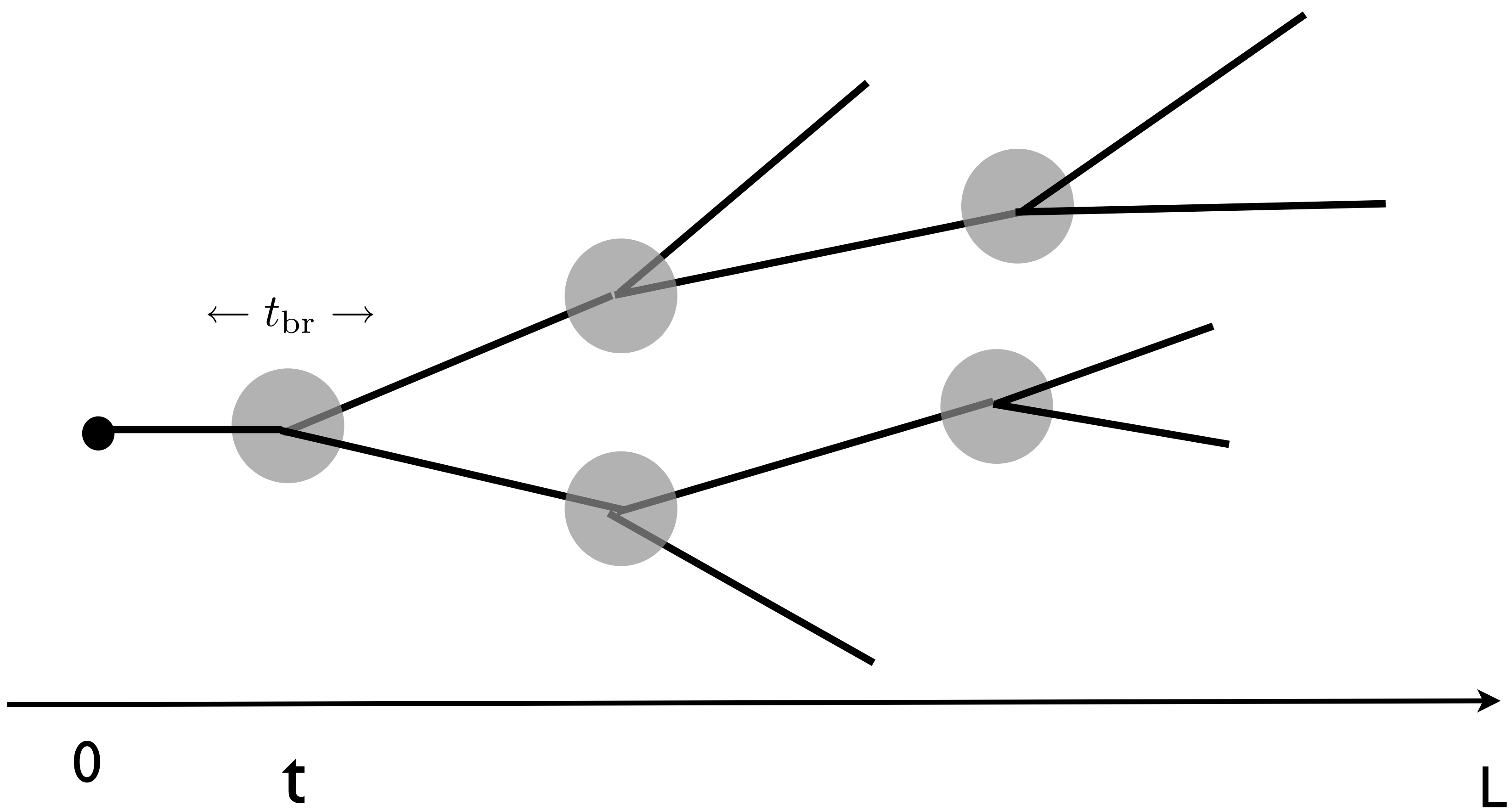
(energy loss at larger angles)

➡ high gluon multiplicity regime:
dominant in jet shapes and differential energy loss

➡ short branching times $t_{\rm br} \ll L$ and large phase-space

when $\alpha_s \dfrac{L}{t_{\rm br}} \gtrsim 1$ multiple branchings are no longer negligible

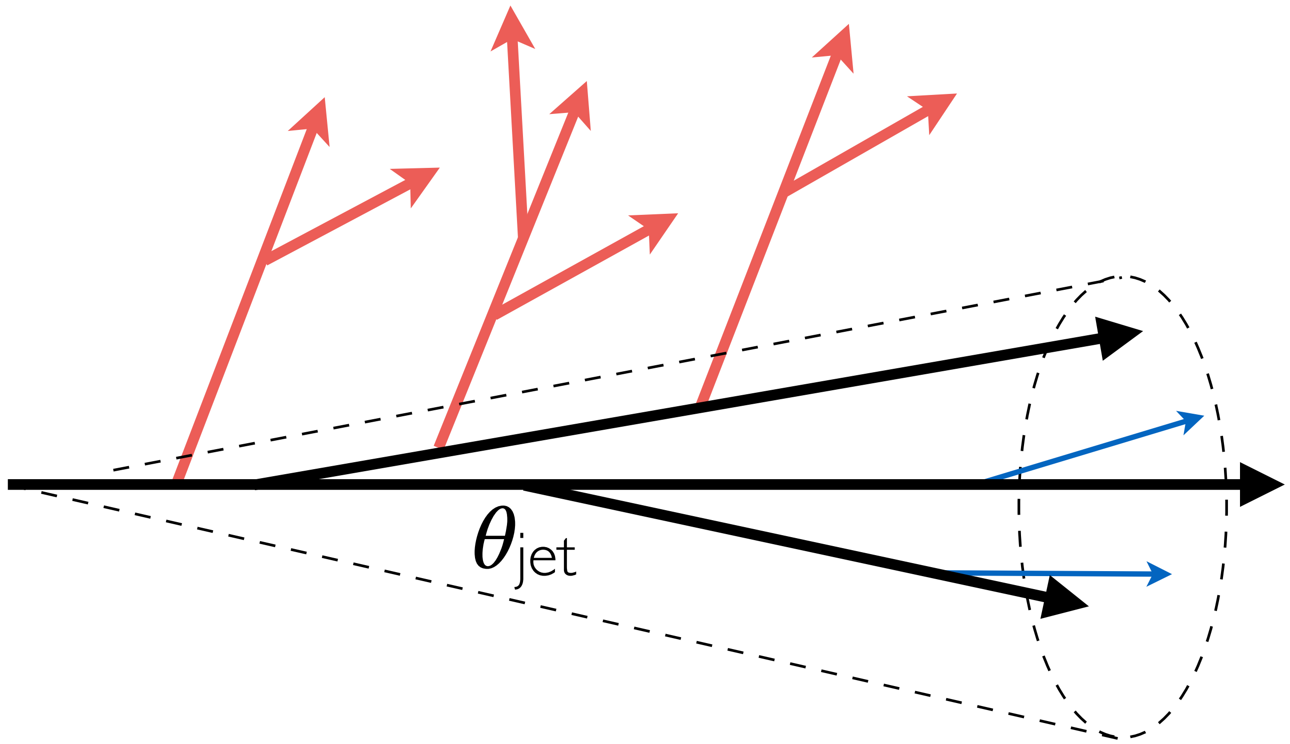
Decoherence of multi-g branching



successive branchings are then independent and quasi-local (Interferences are suppressed)

time-scale separation: $t_{\rm br} \ll t \sim L$

General Picture



- For collimated jets the medium only resolves the total color charge $\langle C_{jet} \rangle \neq 0$

two main medium effects:

- medium-induced radiation off the total jet charge at large angles: onset of rapid branching & broadening (multiple-scatterings)

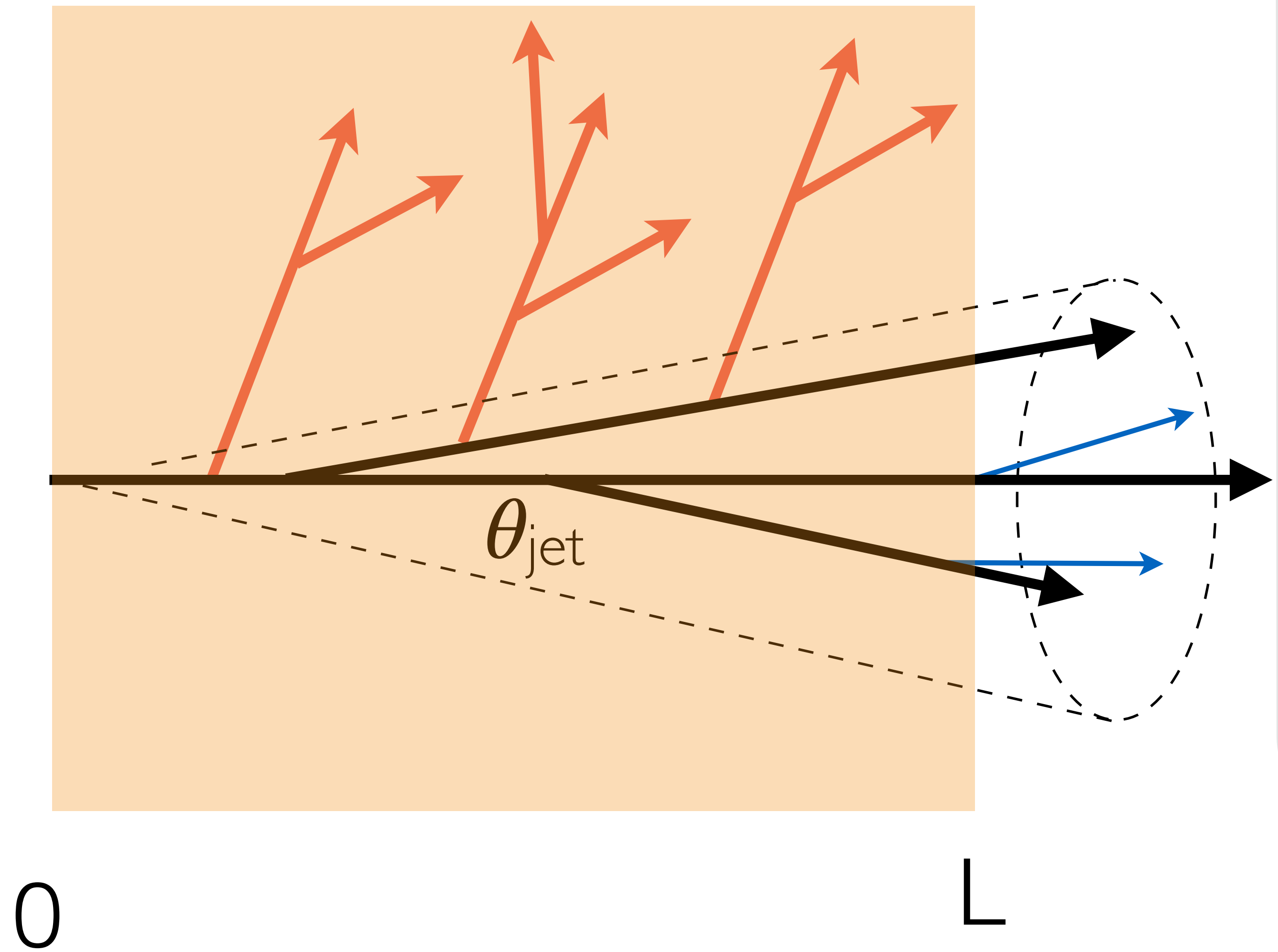
J. -P. Blaizot, F. Dominguez, E. Iancu, Y. M. -T. (2012-2013)

- coherent structure (AO) is weakened: decoherent vacuum radiation (quasi-collinear & long form times)

Y. M.-T, K. Tywoniuk, C. A. Salgado, PRL (2011)

Model: Jets as coherent objets

Multiple-scales:



Jet mass

$Q \equiv \theta_{\rm jet}\, E$

$Q_0 \sim \Lambda_{\rm QCD}$

pt-broadeding

$Q_{\rm med} \equiv (\hat{q}L)^{1/2}$

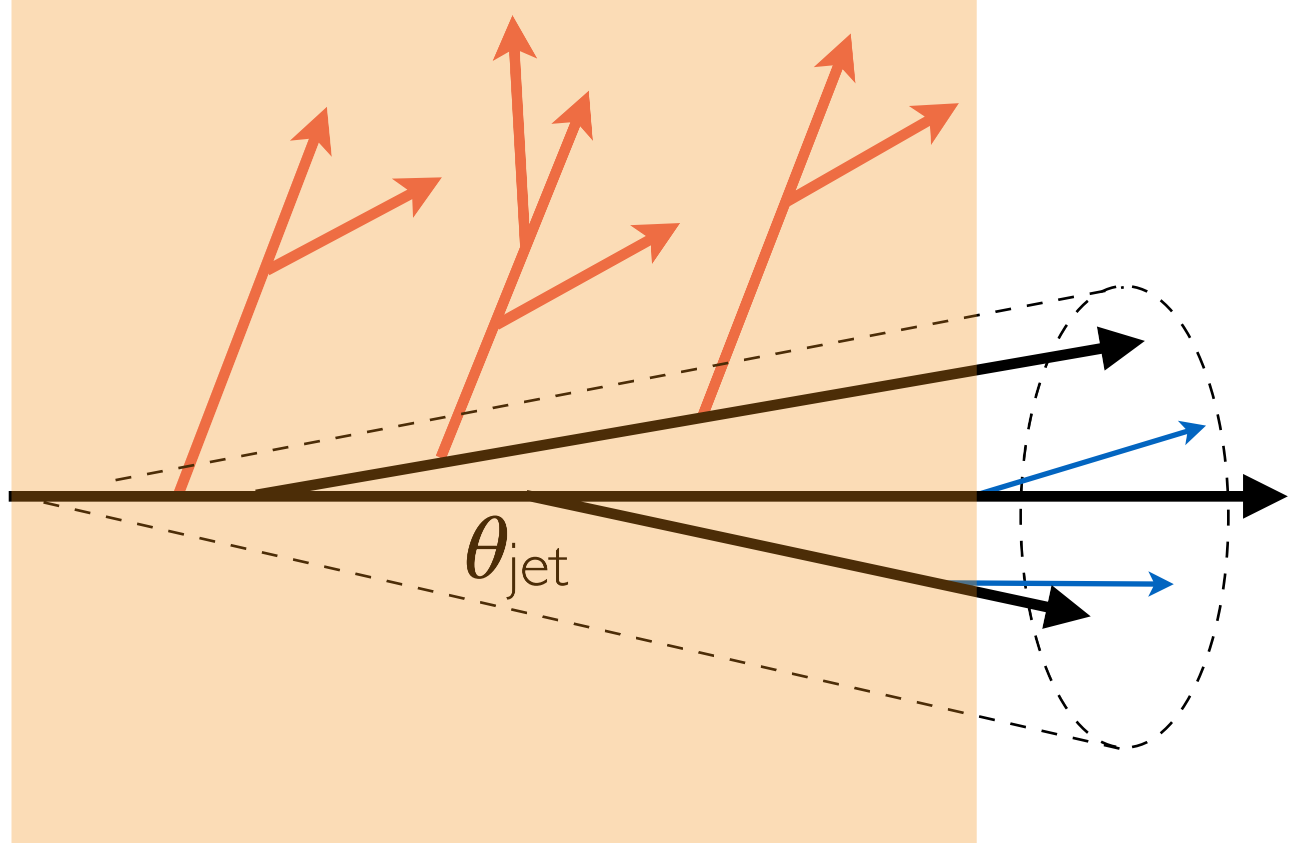
Jet seize

$r_\perp^{-1} \equiv (\theta_{\rm jet} L)^{-1}$

Model: Jets as coherent objets

$$Q \gg r_\perp^{-1} \gg Q_{\rm med} \gg Q_0$$

The medium interacts with the total charge (original parton)

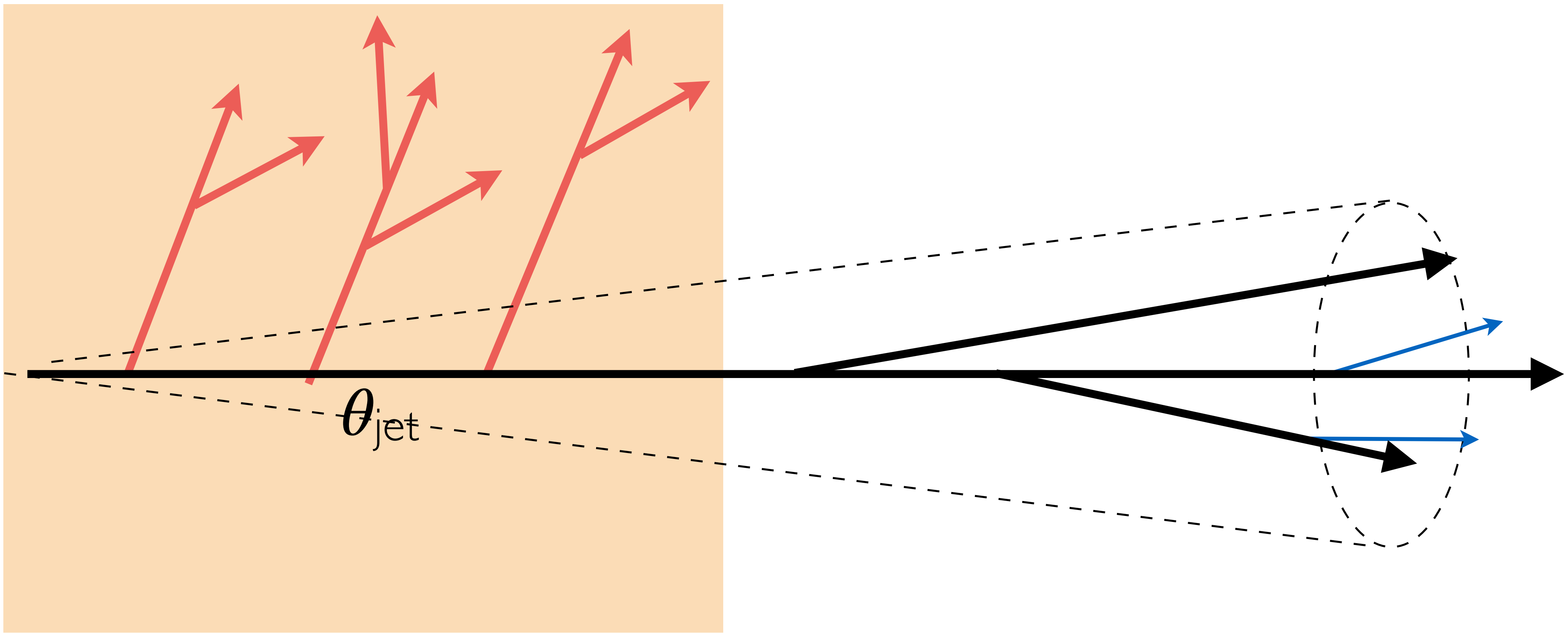


Color transparency: Well defined limit in pQCD

Model: Jets as coherent objets

$Q \gg r_\perp^{-1} \gg Q_{\mathrm{med}} \gg Q_0$

The medium interacts with the total charge (original parton)



Color transparency: Well defined limit in pQCD

Model: Jets as a coherent objets

Distribution of partons: Convolution of in-medium evolution with vacuum evolution

$$x = \frac{E_{\text{parton}}}{E}$$

$$x\frac{dN}{dx} \equiv D(x) \simeq D_{\text{med}} \otimes D_{\text{vac}}$$

The in-medium distribution obeys a rate equation

$$\frac{d}{dL}D_{\text{med}}(x) \equiv \text{Gain} + \text{Loss}$$

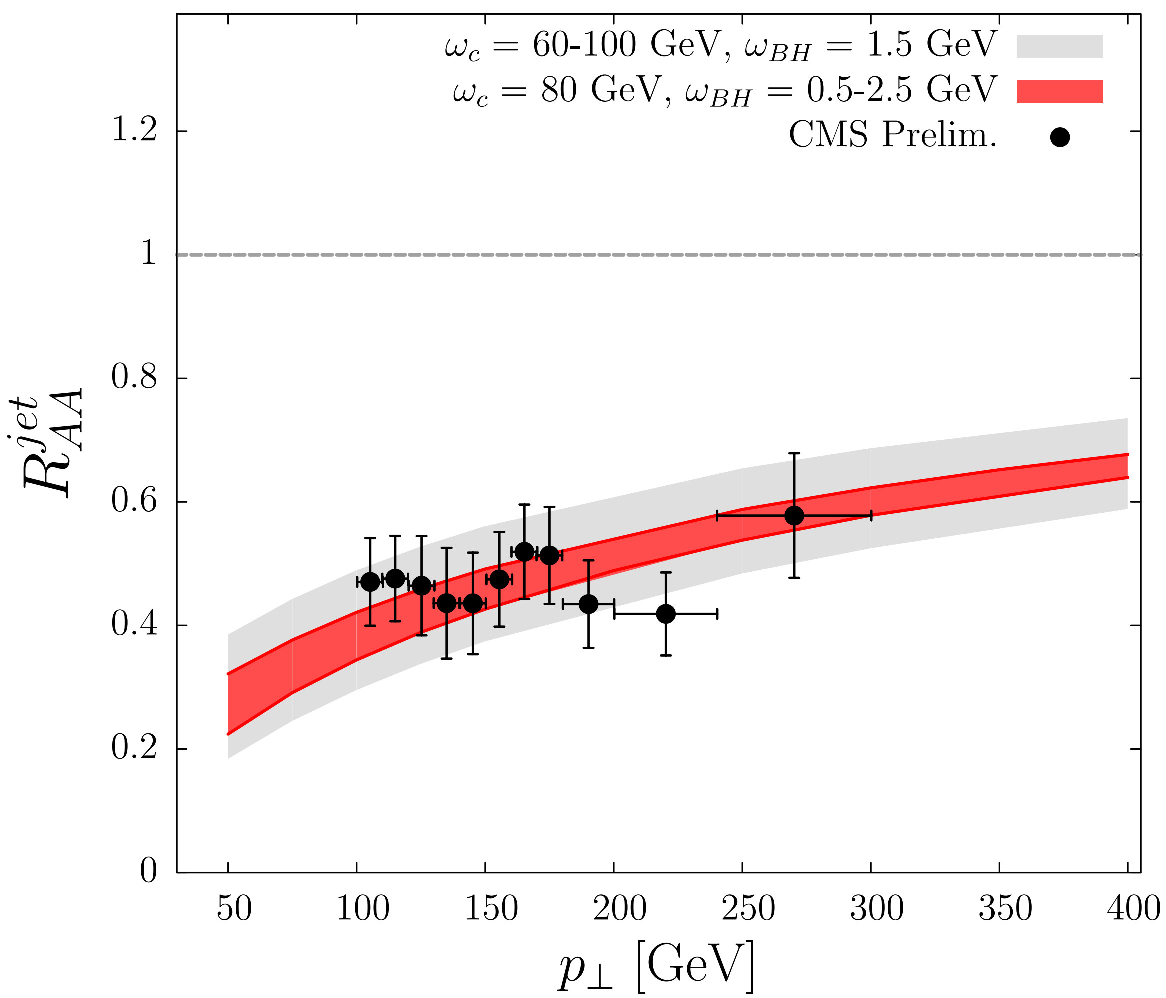
The evolution in vacuum obeys the MMLA equation

$$\frac{d}{d\log Q}D_{\text{vac}}(x) \equiv \text{Gain} + \text{Loss}$$

Understanding jet modifications at LHC (I)

The first inclusive measurement of jet quenching

Nuclear modification factor $R_{AA} = dN_{AA} / (dN_{pp} \times N_{coll})$

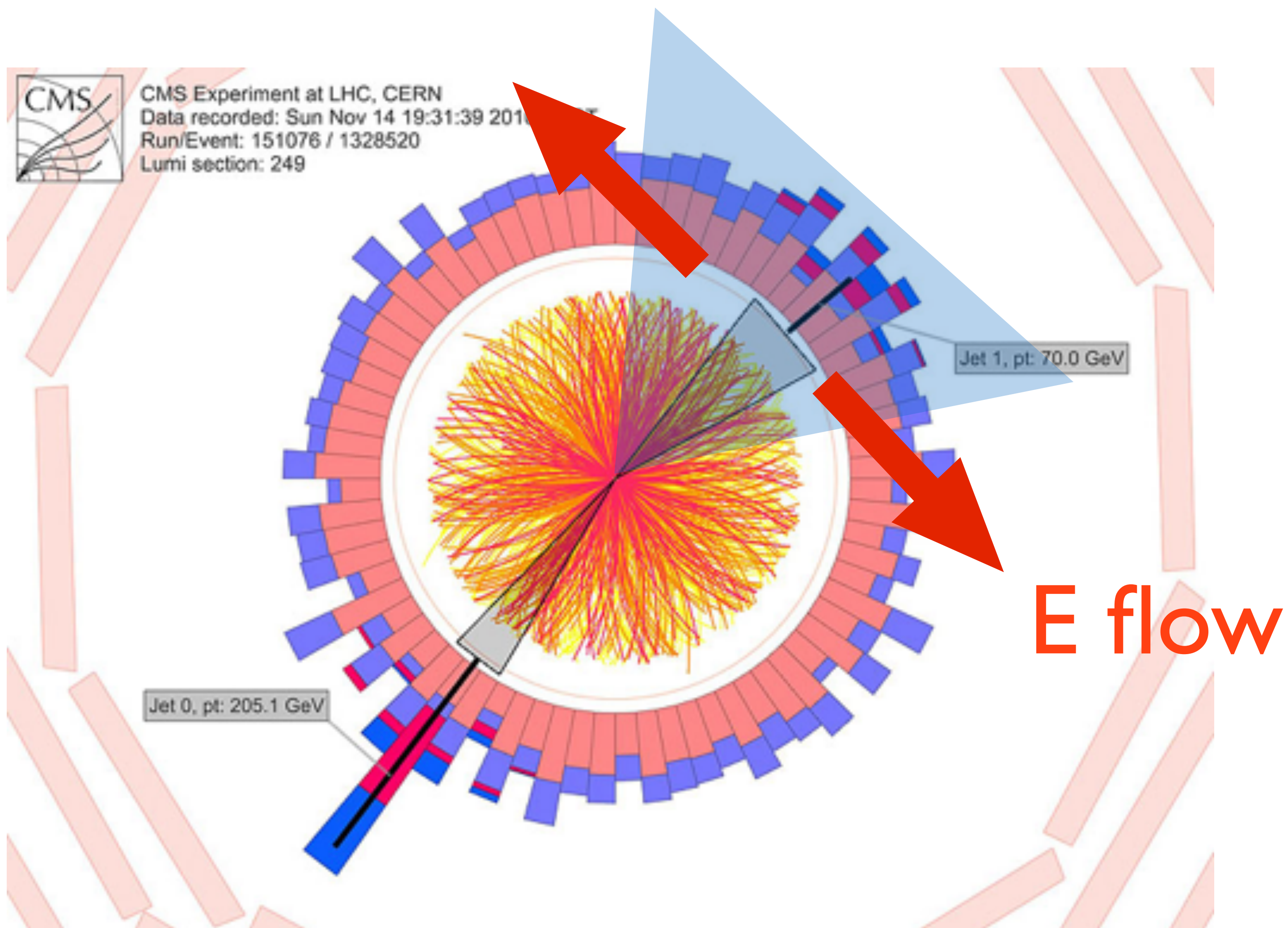


Solving the evolution equation for D convoluted with an initial power low spectrum $p_\perp^{-n}$

L = 2 - 3 fm
$\hat{q}$ = 2.5 - 6 GeV^2/fm

Understanding jet modifications at LHC (II)

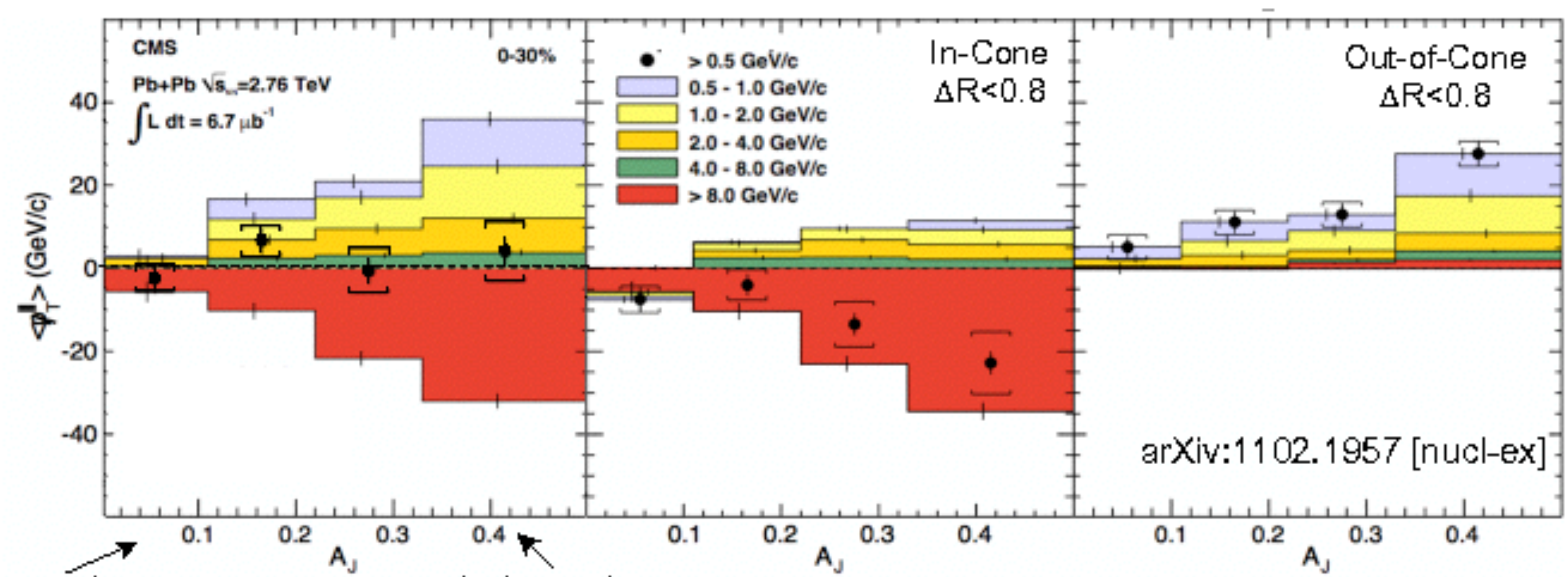
Di-jet asymmetry



CMS: energy is lost in soft particles at large angles

Understanding jet modifications at LHC (II)

Di-jet asymmetry



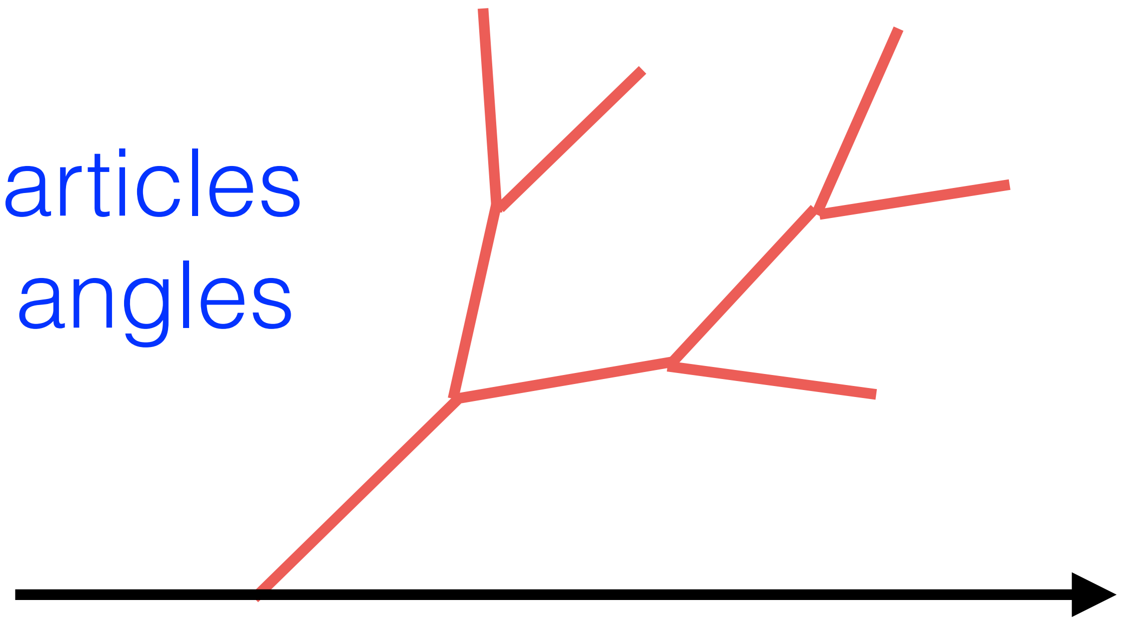
balanced jets unbalanced jets

CMS: energy is lost in soft particles at large angles

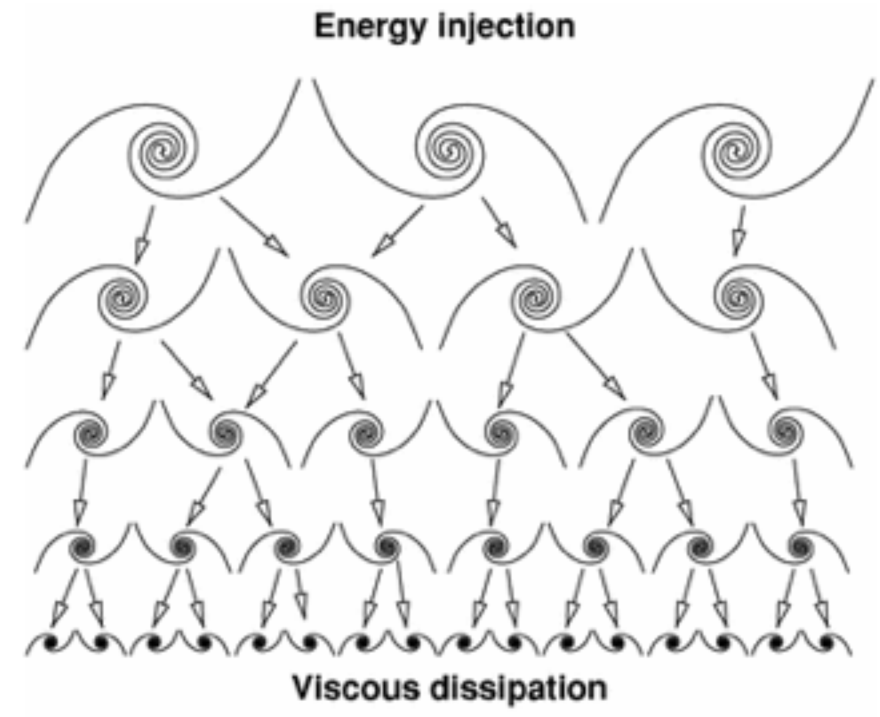
Di-jet asymmetry and turbulence

J. -P. Blaizot, E. Iancu, Y. M. -T. PRL 2013

soft particles
large angles



Richardson cascade 1921

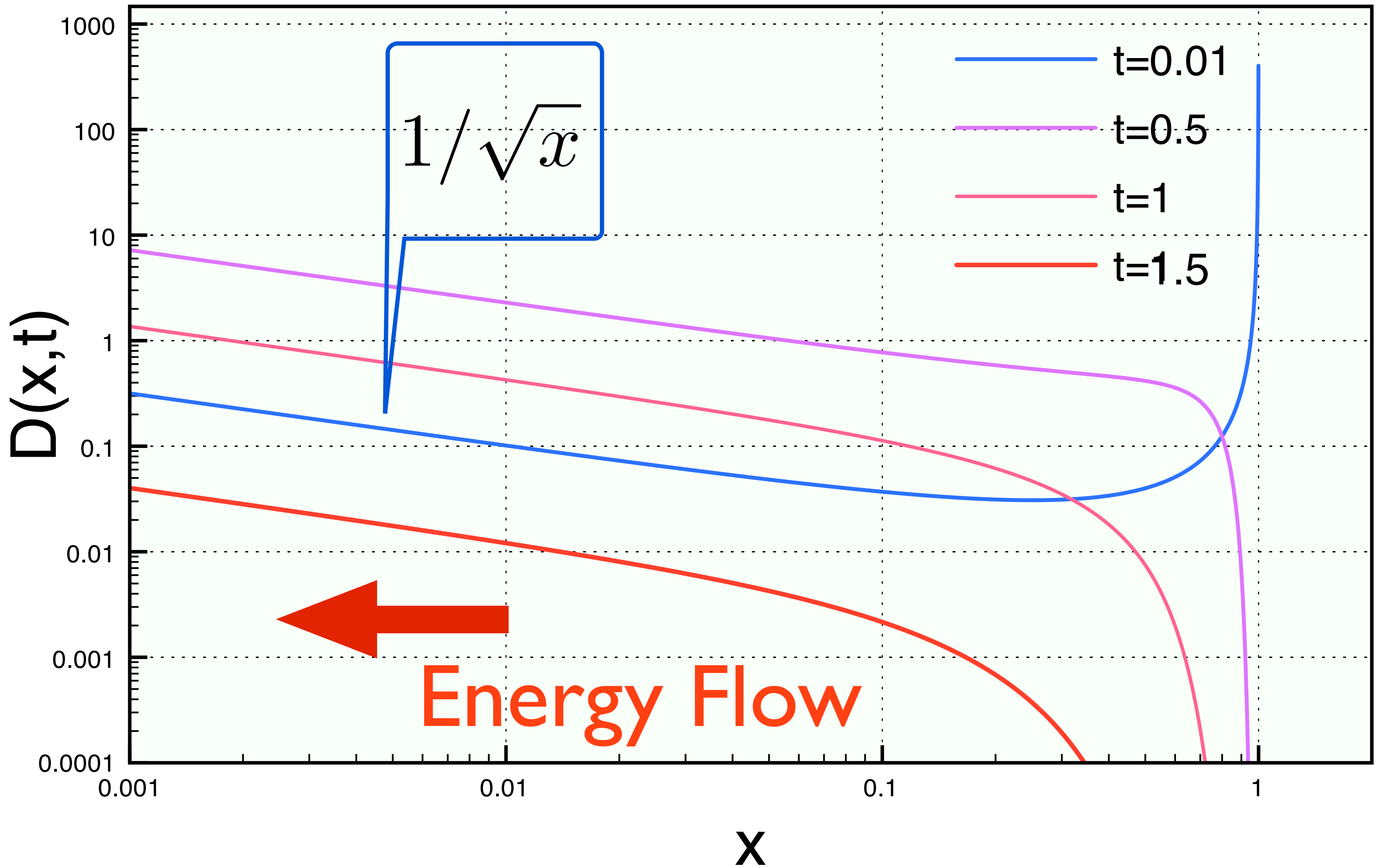


- gain = loss $\Longrightarrow$ the energy flux is independent of x
- Energy flows from large to low frequencies and large angles without accumulating (signature of wave turbulence

Efficient mechanism for energy transport at large angles

Di-jet asymmetry and turbulence

J. -P. Blaizot, E. Iancu, Y. M. -T. PRL 2013



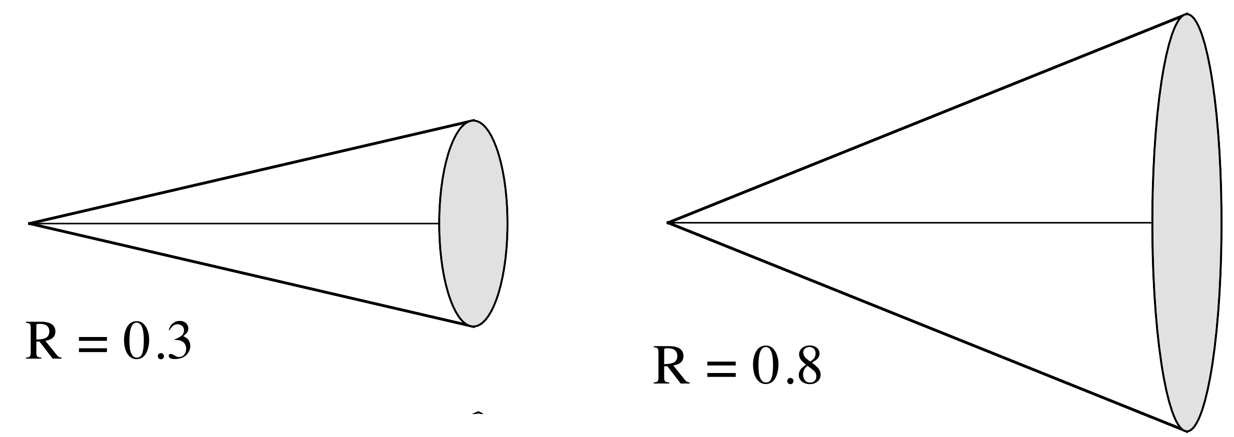
Efficient mechanism for energy transport at large angles

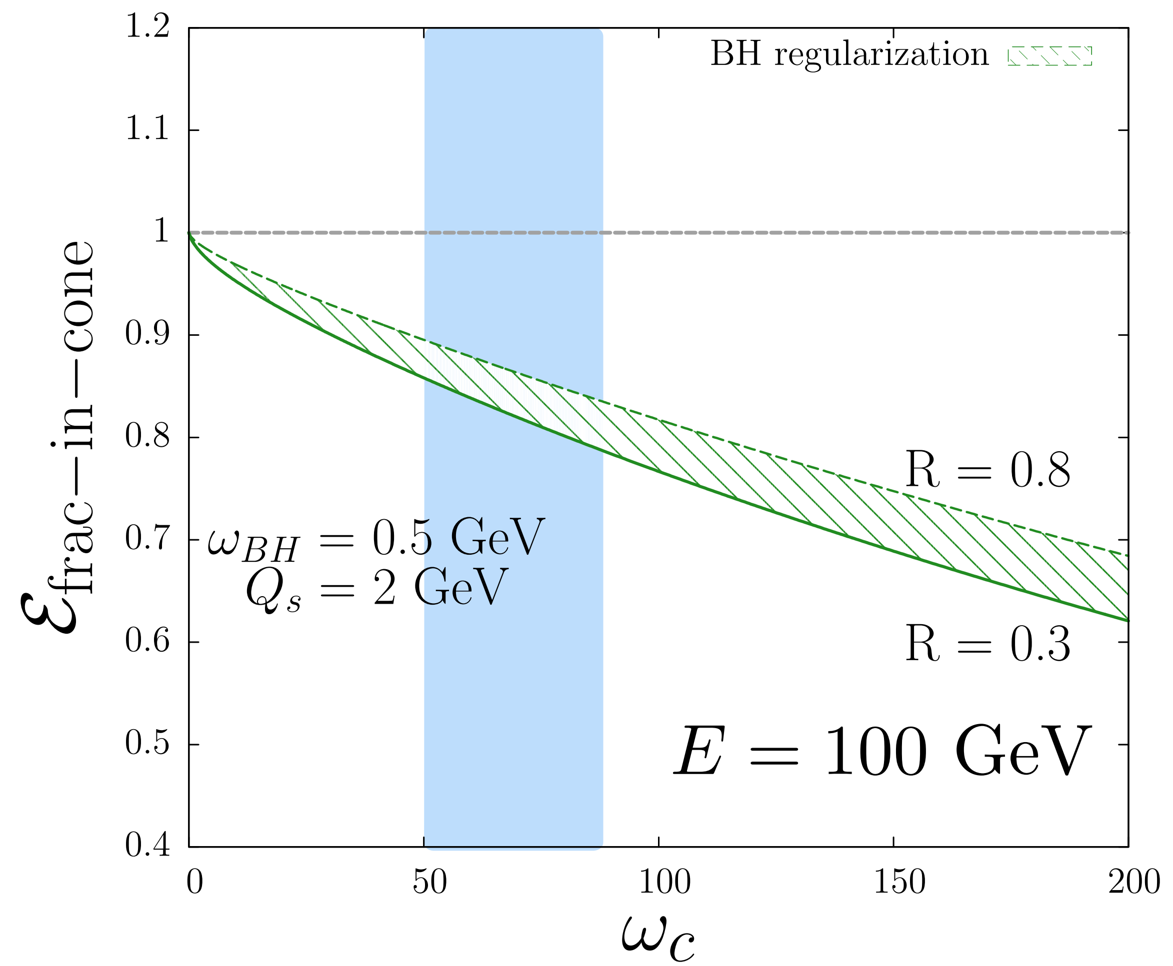
Understanding jet modifications at LHC (II)

Dijet asymmetry

integrating D and excluding out-cone gluons

$$\theta_{\mathrm{med}} \sim \frac{\sqrt{\hat{q}L}}{\omega} > R$$



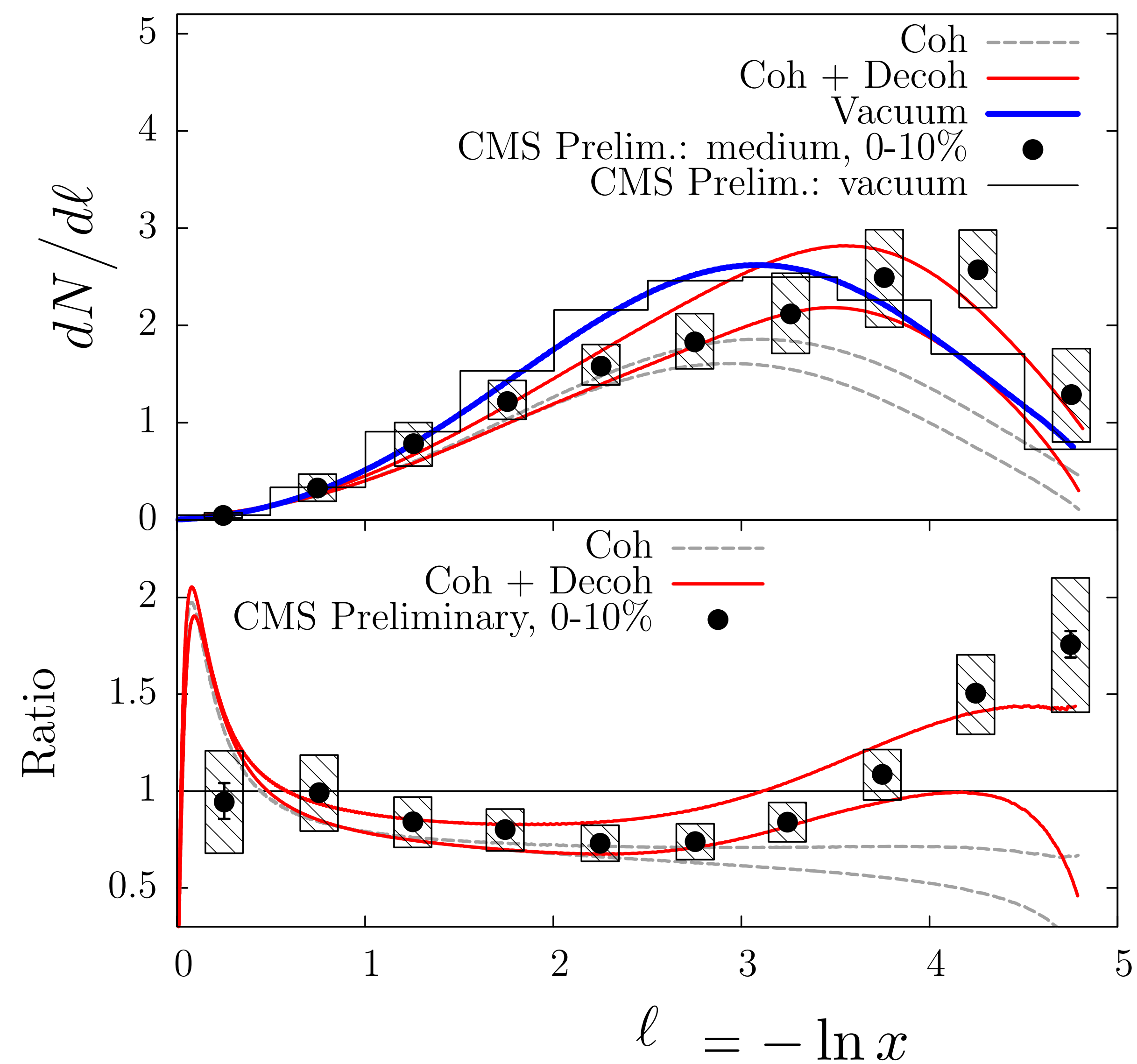


- little energy is recovered up to large cone angles, R~0.8
- striking effect due to multiple branching + broadening
- Possible explanation for energy transfer to large angles and soft modes in asymmetric dijet events observed by CMS (2012)

Understanding jet modifications at LHC (III)

Fragmentation functions

- vacuum baseline (blue)
- medium-induced energy loss at large angles depletes energy inside the cone. responsible for dip in the ratio
- small angle soft radiation due to decoherence of vacuum radiation: novel ingredient, responsible for enhancement at large l = shift of humpbacked plateau!



Summary and outlook

- Agreement with the observed Nuclear Modification Factor, Fragmentation Functions and the turbulent flow provides a natural explanation of the missing pt in dijet events
- Simplifications: study of limiting cases (useful for understanding bulk observables), no dynamical medium/geometry…
- Need for more detailed analysis and implementation in an event generator