Jet quenching theory …a brief introduction

Yacine Mehtar-Tani (BNL)

Open Symposium: The space-time structure of jet quenching: theory and experiment

August 12, 2019 @ GSI, Darmstadt

BROOKHAVEN NATIONAL LABORATORY

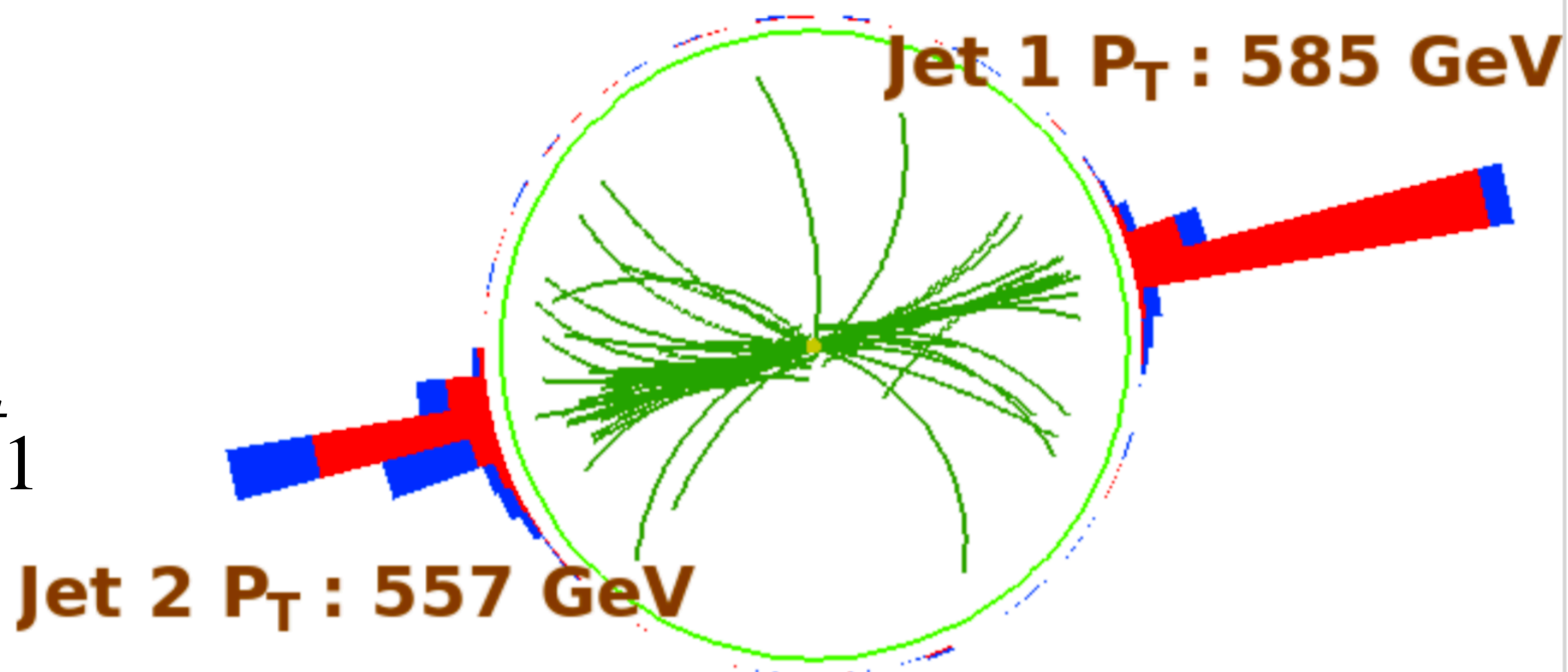
Outline

- Introduction to jets
- Jet quenching building blocks: momentum broadening and the LPM effect
- Soft components: medium induced turbulent cascade and medium response
- Color decoherence of jet substructure

Jets as footprints of quarks and gluons

- Jets are collimated spray of particles observed in high energy collisions (e+e-, electron-proton, proton-proton, ion-ion)

jet_1

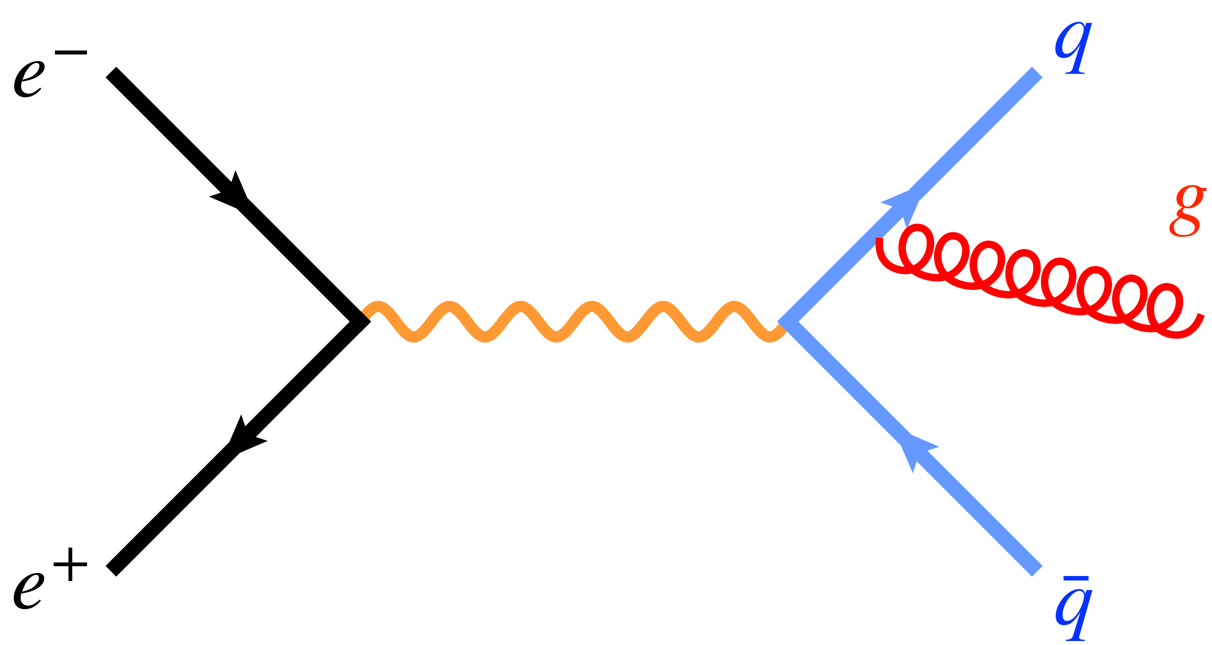


Dijet event in proton-proton collisions from CMS (LHC)

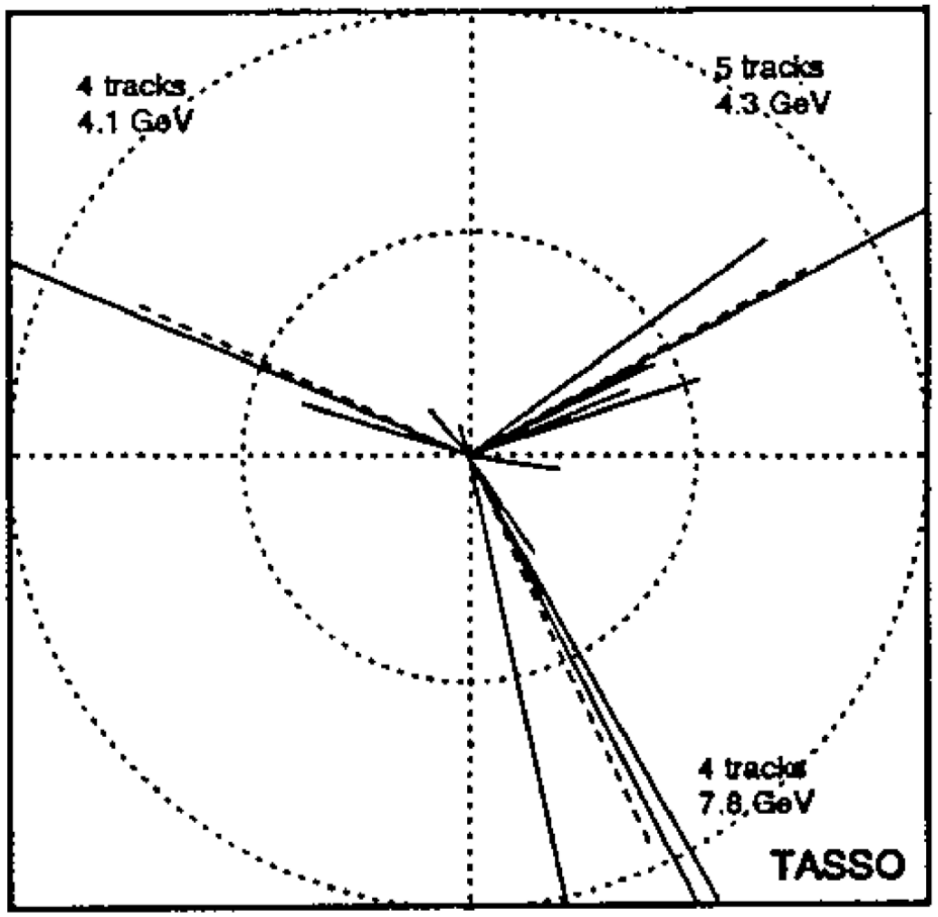
Jets as footprints of quarks and gluons

- Two jet events predicted to dominate the cross section in e^+e^- at high energy

Ellis, Gaillard and Ross (1976) Weinberg and Sterman (1977)



$$e^+e^- \rightarrow q\,\bar{q}\,g \rightarrow 2\ jets$$

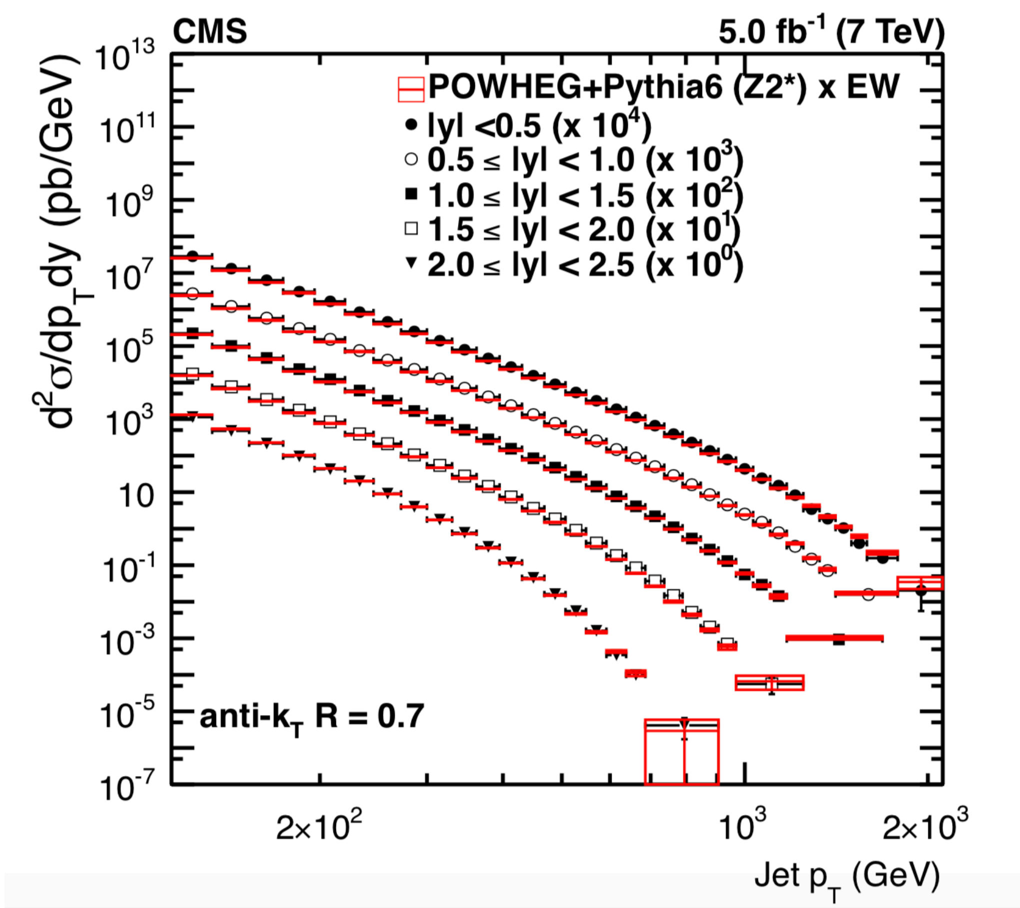


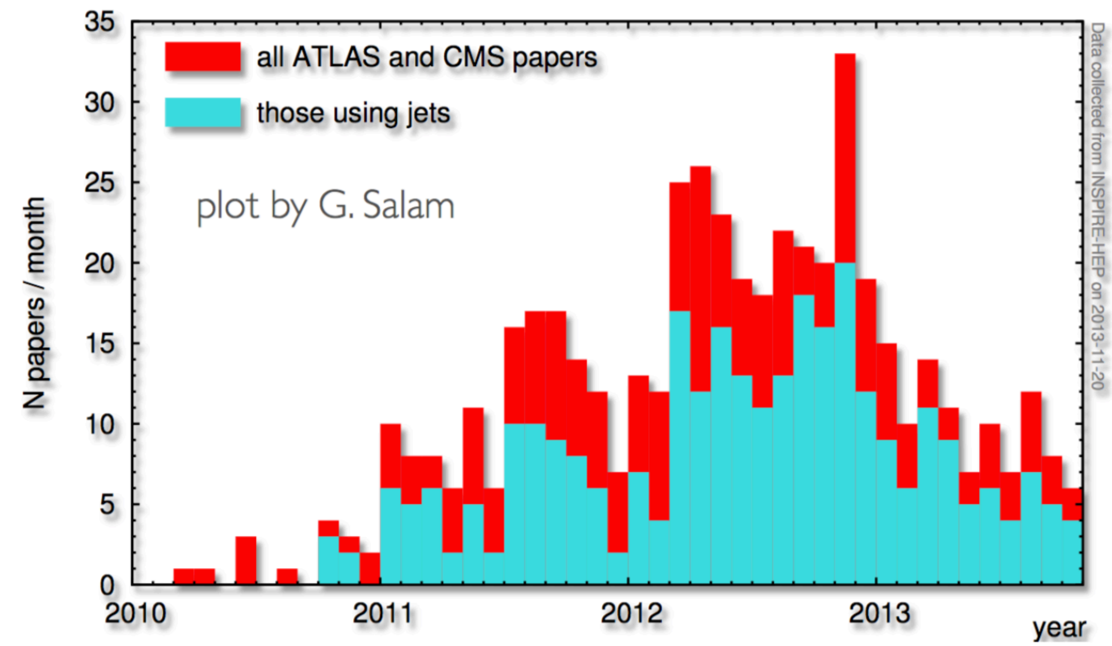
TASSO - PETRA (DESY) (1979)

- Evidence of the existence of the gluon: 3-jet topology

Jets in the LHC era (precision QCD)

- Jets are instrumental in BSM and Higgs search at the LHC





- **At the LHC, 60 - 70 % of ATLAS & CMS papers use jets in their analysis!**

- Monte Carlo Even Generators: such as Pythia, Herwig, Sherpa, etc. are important for QCD modeling and higher order computations. Include parton cascade and Hadronization models (Lund, Cluster)

QCD jets in a nutshell

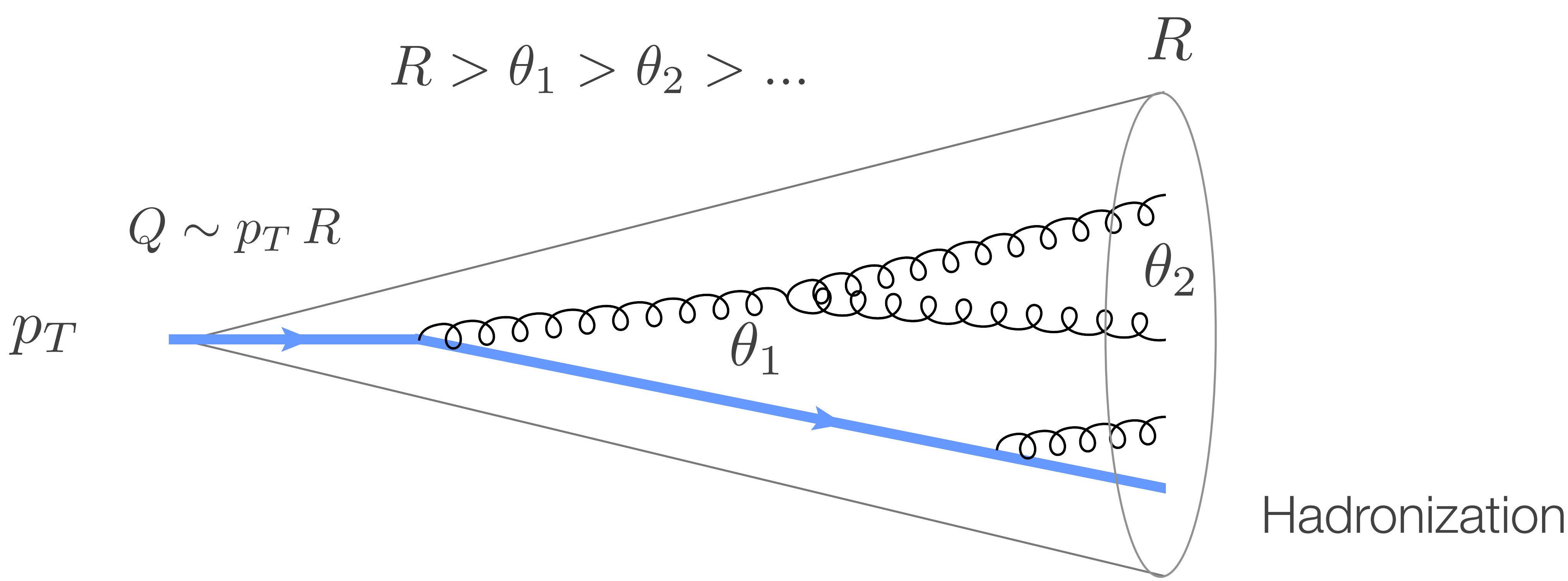
- Soft & Collinear divergences: high probability for branching

$$\mathrm{d}P \sim \alpha_s C_R \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}\omega}{\omega}$$

color factors (quark and gluon):

$$C_R \equiv C_F \quad \text{or} \quad C_A$$

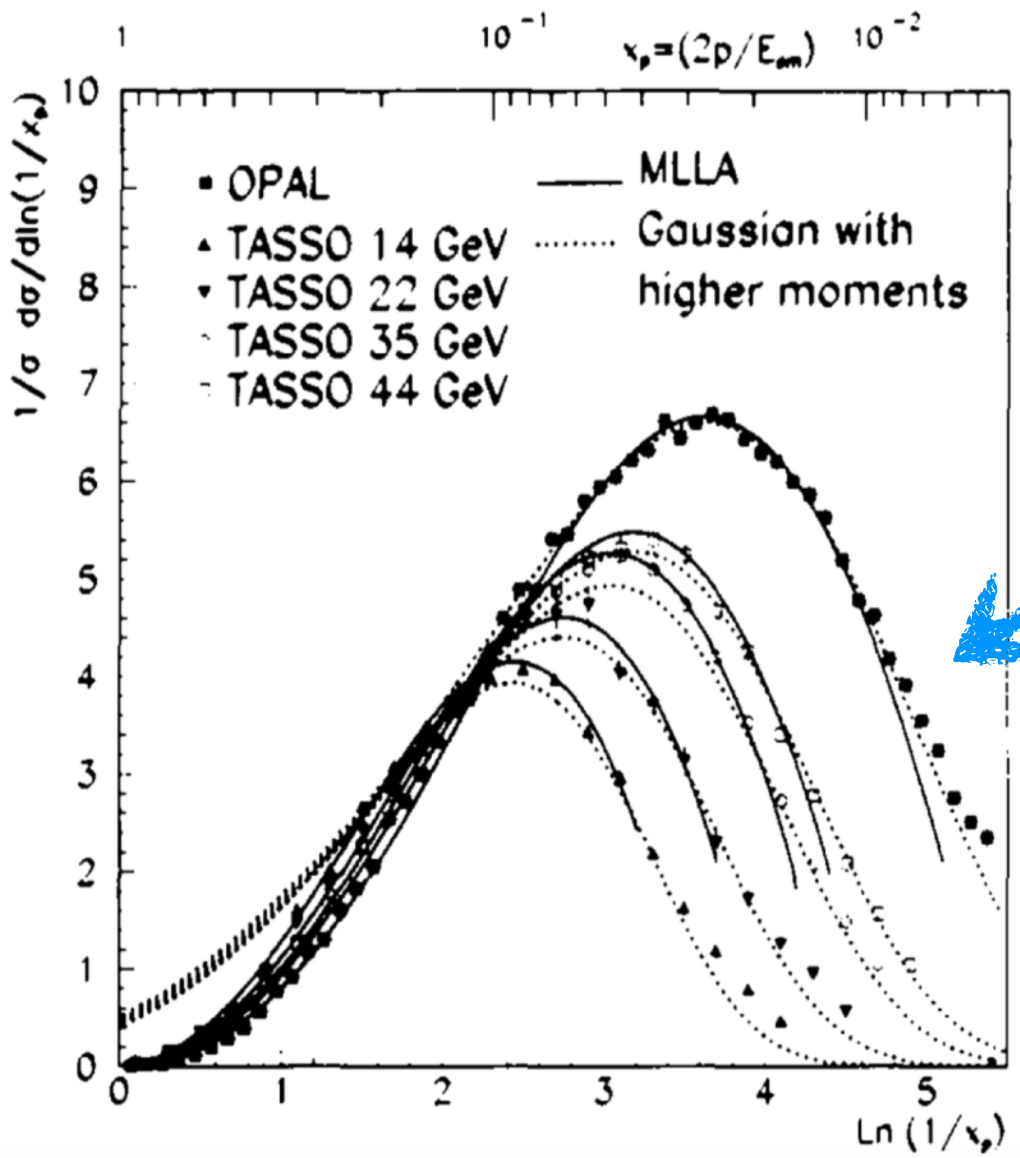
- Jet collimation: jets are dominated by collinear splittings
- Color coherence: soft radiation depleted due to destructive interference



[Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer, Khoze, Toyan, Collins, Soper, Sterman … 1980's]

QCD jets in a nutshell (color coherence)

$$\frac{1}{\sigma}\frac{d\sigma}{d\ln\frac{1}{x}}$$



Hard → Soft

Destructive interferences for large angle soft radiation: suppression of soft hadrons

$$\ln\frac{1}{x} \equiv \ln\frac{E_{\rm jet}}{p_{\rm hadron}}$$

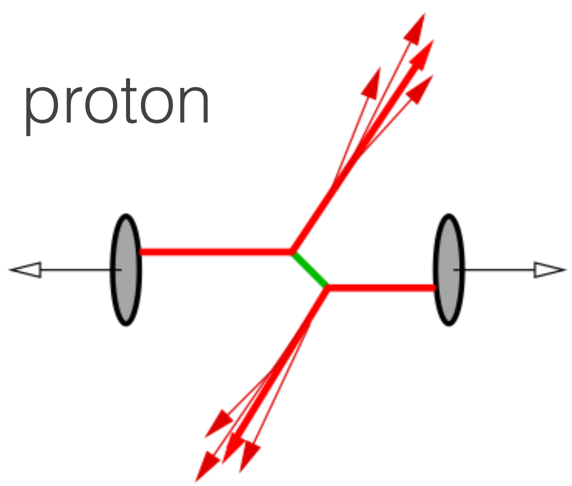
Fragmentation function: distribution of hadrons within jets

[Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer, Khoze, Toyan, Collins, Soper, Sterman … 1980's]

Jet quenching

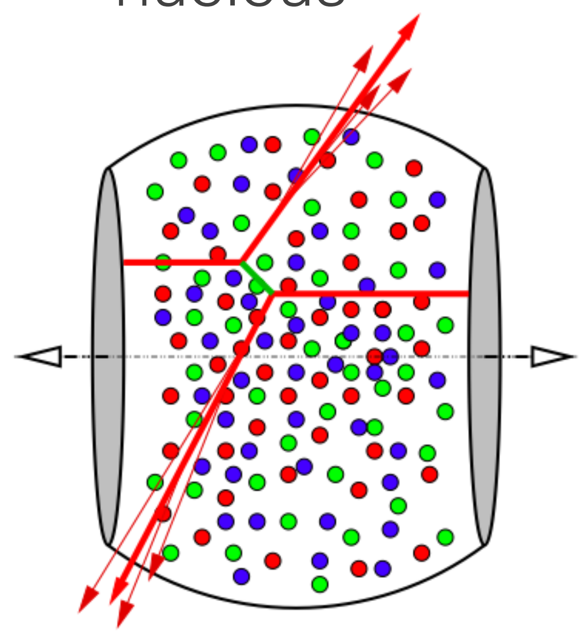
Jet physics at colliders
(T=0)

proton



Heavy Ion Collisions

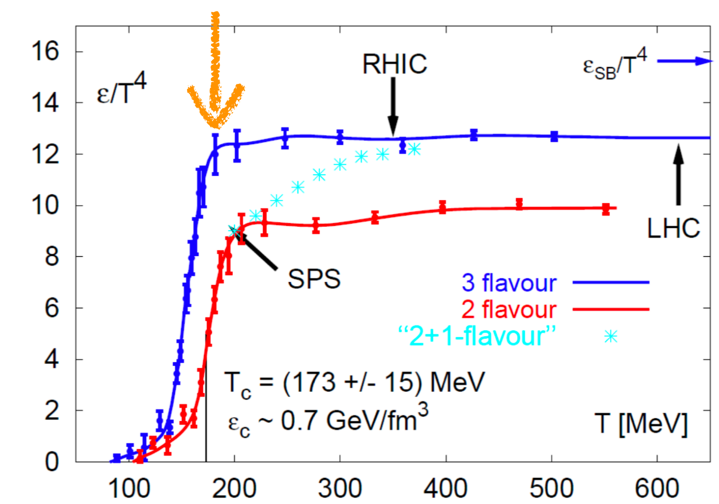
nucleus



QGP

Crossover phase transition
(from lattice QCD)

$T_c \simeq 173\,\mathrm{TeV}$



[F.Karsch, E.Laermann, arXiv:0305025]

LHC: $T \sim 600\,\mathrm{MeV}$

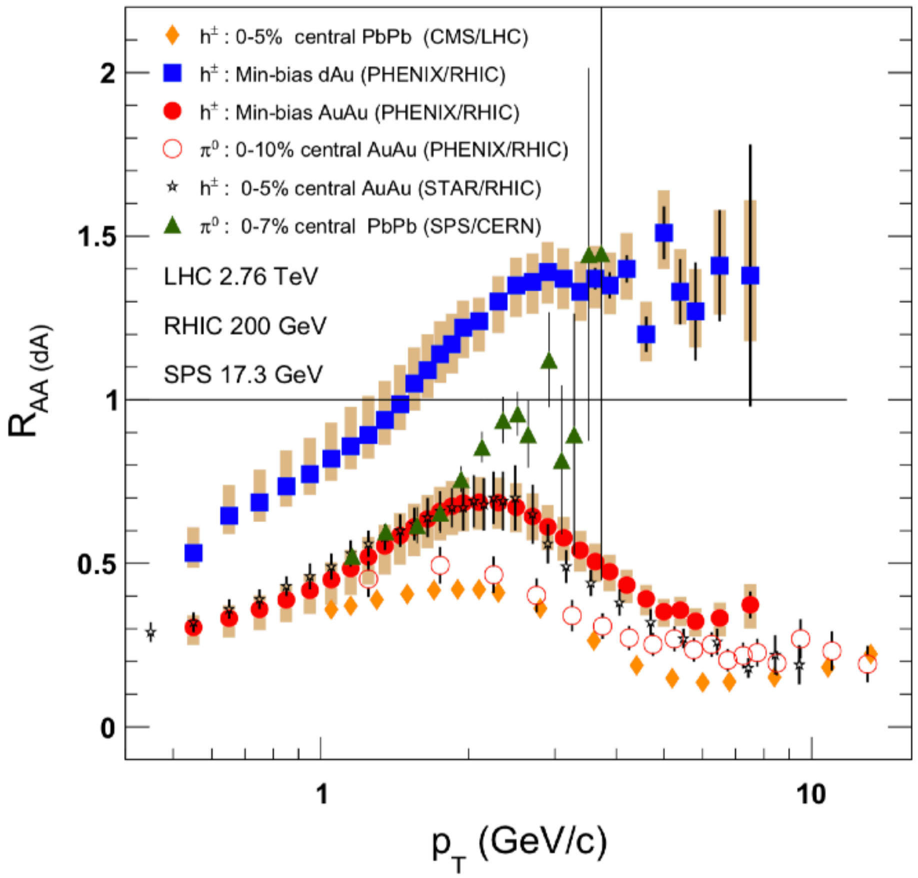
RHIC: $T \sim 350\,\mathrm{MeV}$

- Jet quenching refers to the suppression and modification of a jet as it propagates through hot QCD matter
- Strong final state interactions cause high pT jets to lose energy to the plasma

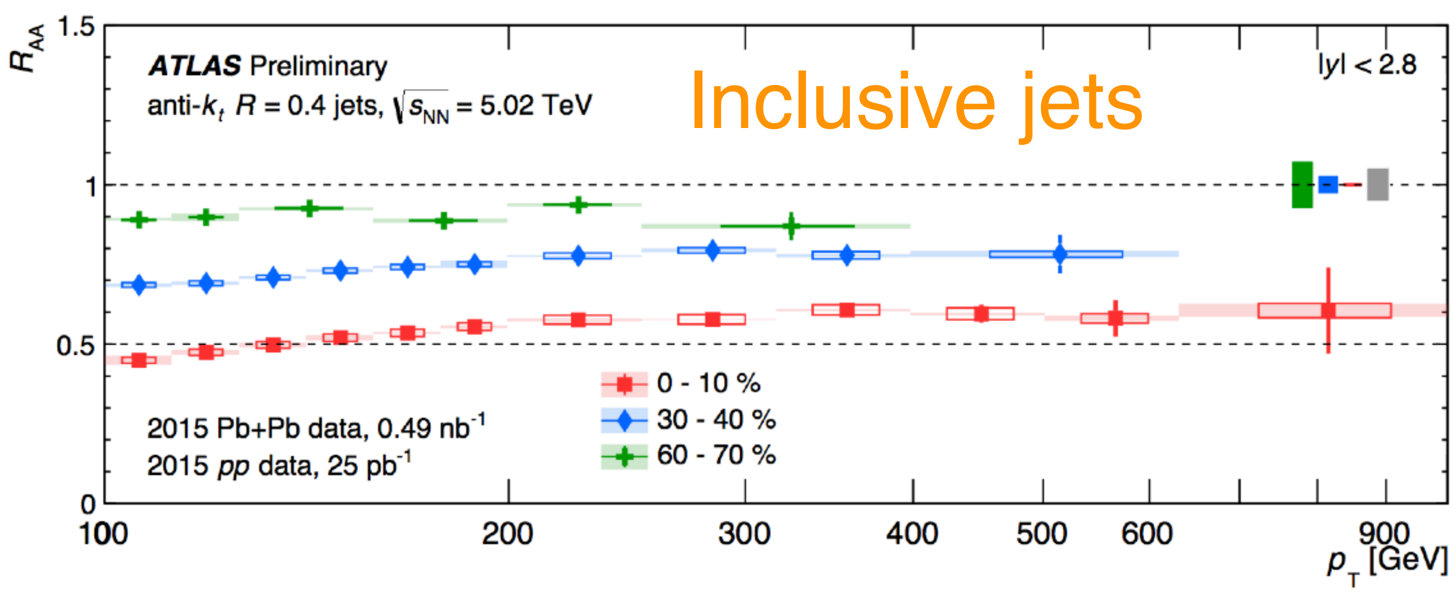
Jet quenching

- Two decades after Bjorken prediction of jet quenching, the suppression of high-pT hadrons was observed at RHIC and confirmed at LHC where a strong quenching of 1 TeV jets was observed
- **Goal:** Use jets as test particles to learn about the properties of of the Quark-Gluon-Plasma (QGP)

Inclusive hadrons



$$R_{AA} \equiv \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

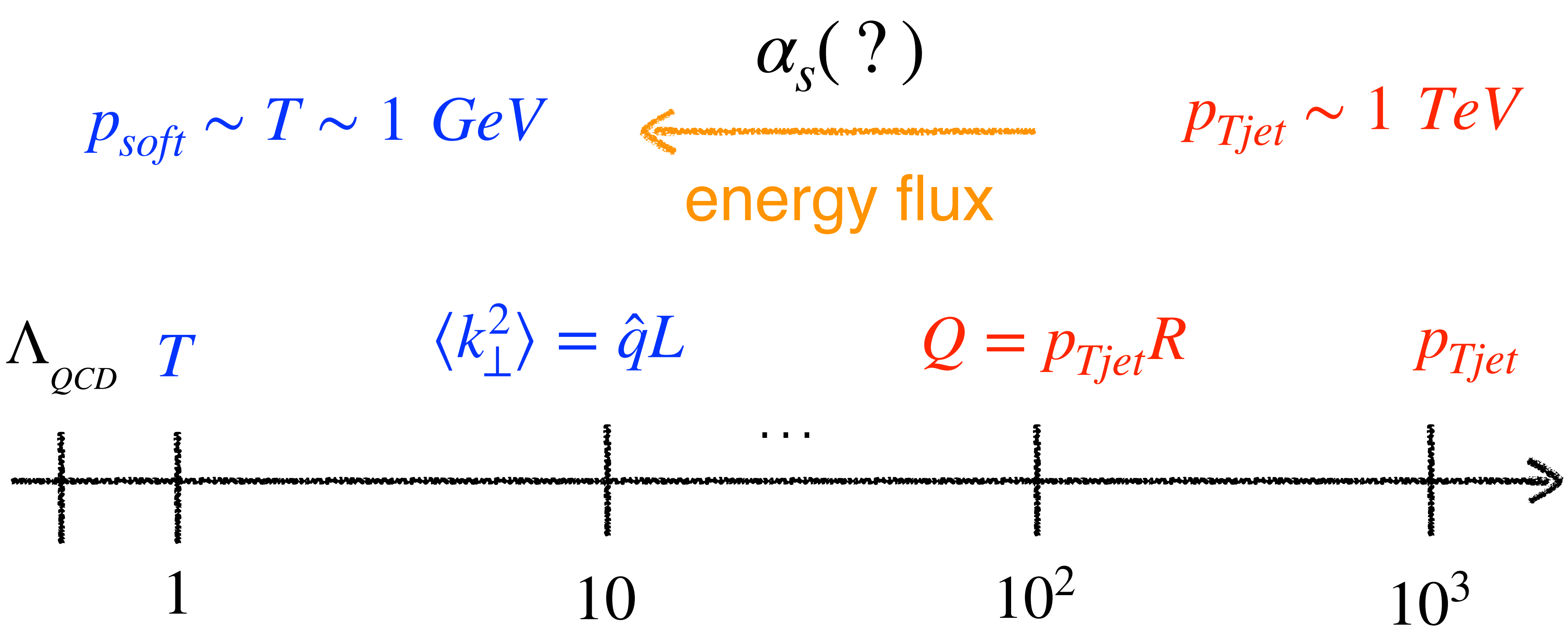


Probing high density QCD with jets

- Guidance from first principles: how does a jet as a multi-parton system interact with the QGP? Is it perturbative?

  → How is energy transported from energetic partons to low momenta and dissipated in the QGP?

  → How is the jet substructure modified?



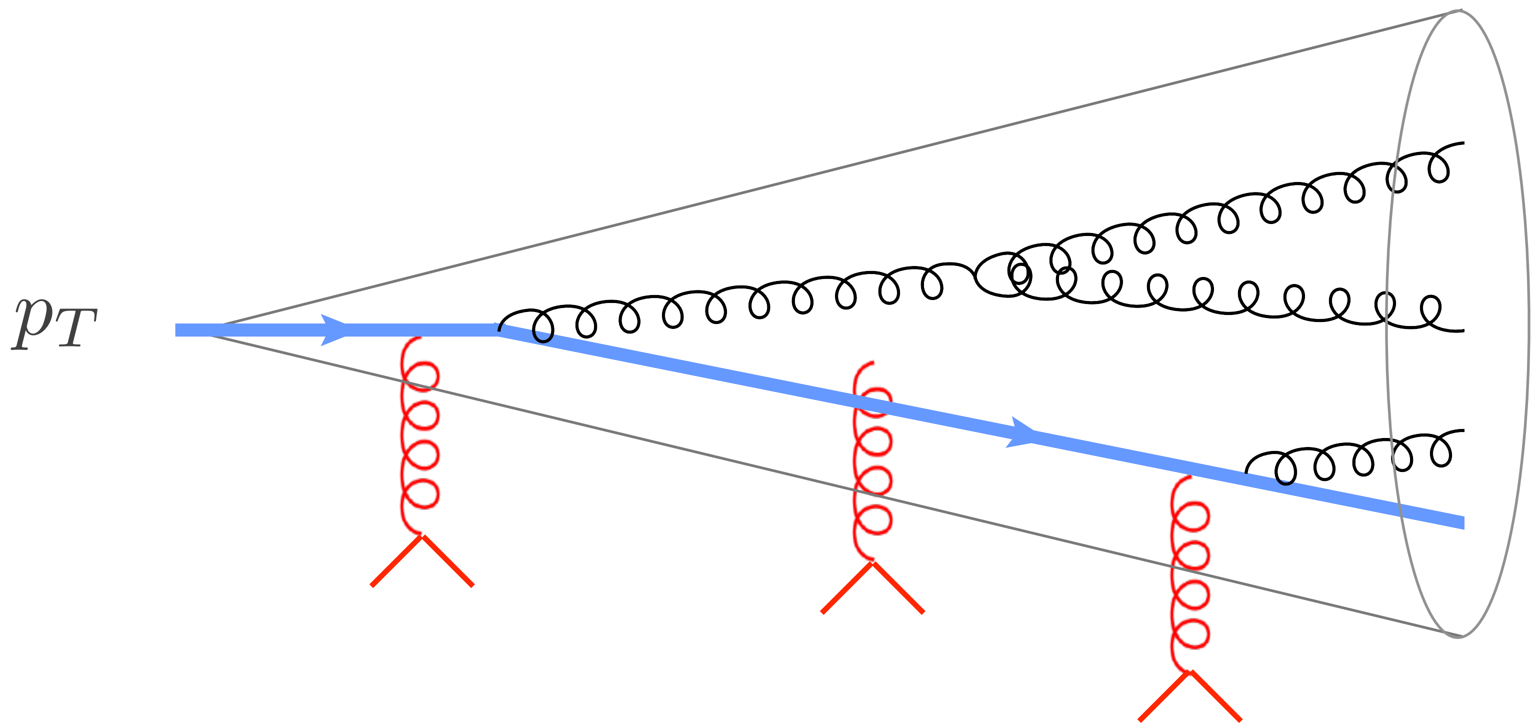
Multiple soft scattering and $\hat{q}$

- In a dense colored medium (QGP) a high energy parton produced in a hard collision undergoes multiple interactions with the plasma constituents

$$\frac{\mathrm{d}P}{\mathrm{d}z\,\mathrm{d}q_\perp^2} \sim \alpha_s^2\, C_R\, \frac{n}{q_\perp^4} \qquad \rightarrow \text{ Coulomb scattering}$$

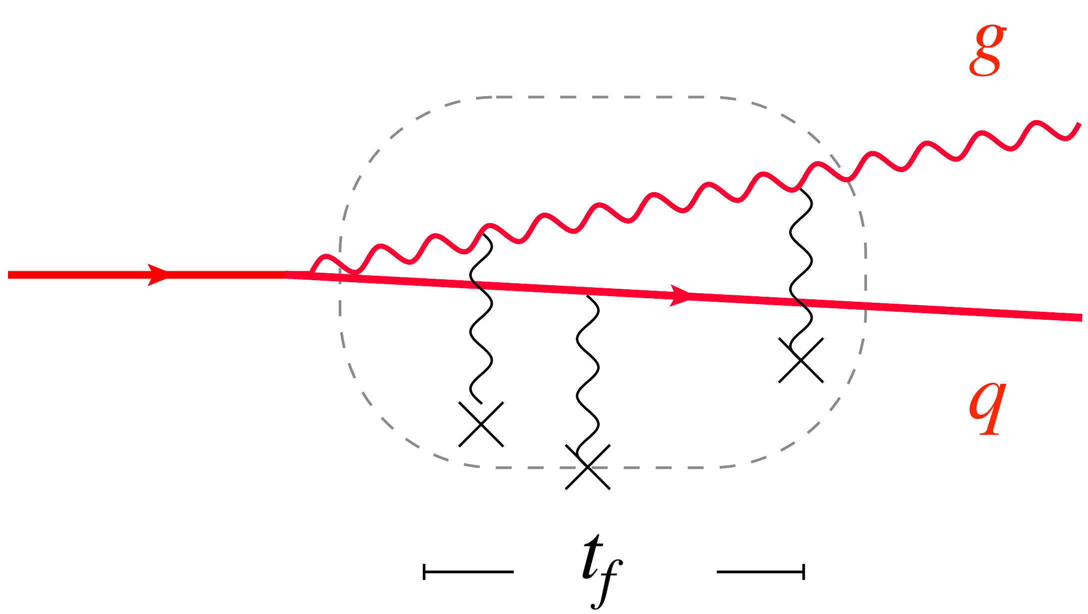
- Momentum boarding: the dominant collisions are soft. The effect is a diffusion in transverse momentum space

$$\langle k_\perp^2 \rangle \equiv \hat{q} L$$



The LPM effect on the back of the envelop

- The energy spectrum of photons caused by the propagation of a relativistic charge in a medium is suppressed due to coherence effects (Landau-Pomeranchuk Migdal 1953)



- The radiation formation time, together with transverse momentum broadening define the LPM time scale

$$t_f \sim \omega / k_\perp^2 \qquad k_\perp^2 \sim \hat{q}\, t_f \quad \Rightarrow \quad t_f(\omega) \equiv \sqrt{\frac{\hat{q}}{\omega}}$$

- The radiation spectrum: large multiplicity in the infrared and quadratic system size scaling of energy loss

$$\omega \frac{\mathrm{d}I^{LPM}}{\mathrm{d}\omega} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}}\, L \propto \frac{1}{\sqrt{\omega}}$$

$$\Delta E_{\mathrm{rad}} \sim \int \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_s \hat{q} L^2$$

Medium-induced turbulent cascade $T \ll \omega \ll p_T$

- Multiple scattering trigger abundant soft gluon with constant rate

$$\omega \frac{\mathrm{d}^2 P_{\mathrm{rad}}}{\mathrm{d}\omega\, \mathrm{d}z} \sim \alpha_s\, C_R \sqrt{\frac{\hat{q}}{\omega}}$$

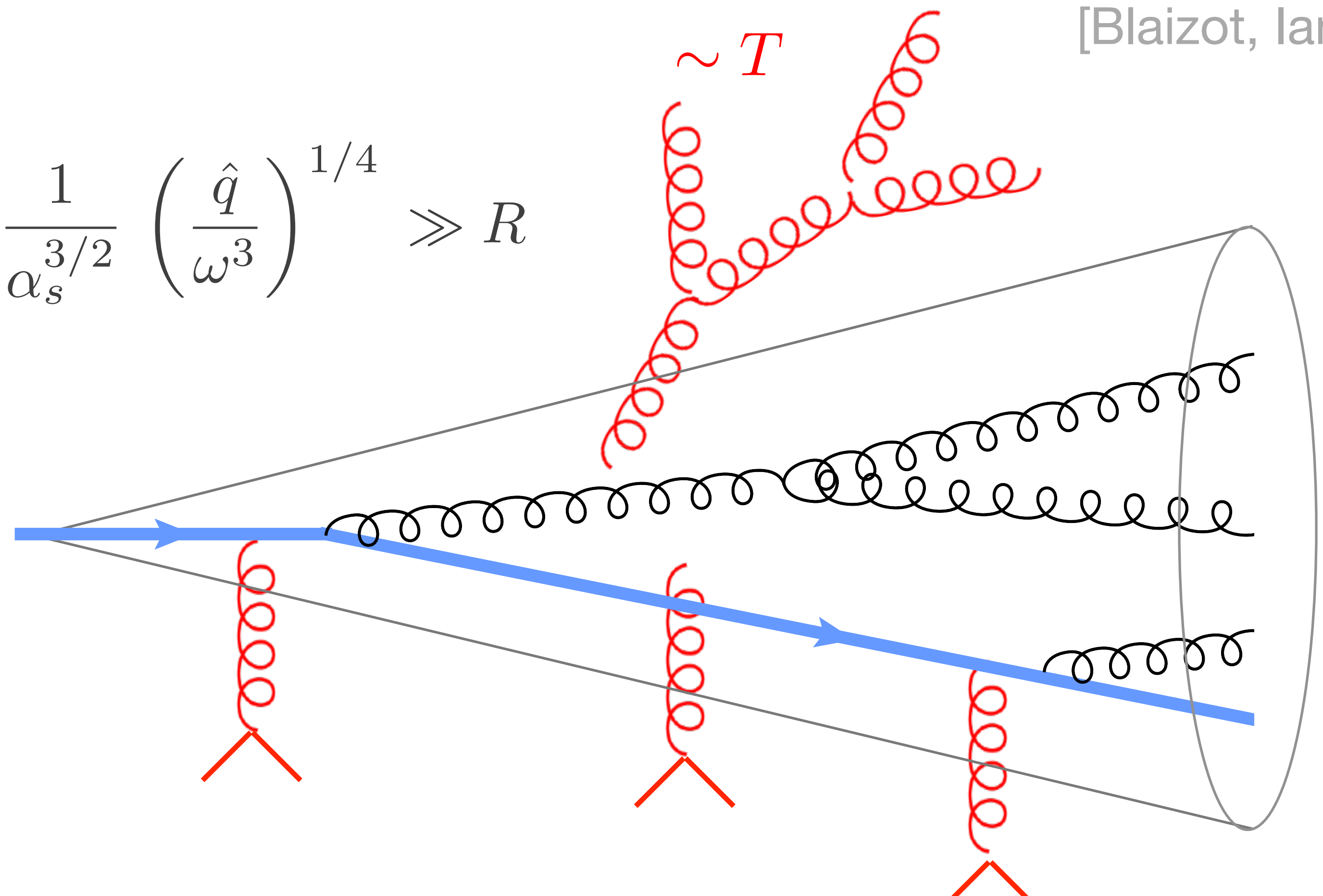
[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996) Wiedemann (2000) Arnold, Moore, Yaffe (2002), Gyulassy, Levai, Vitev (2000) Guo, Wang (2000)]

- Large angle cascade for $\omega \sim \alpha_s^2 \hat{q} L^2 \ll p_T$ → minijet thermalization

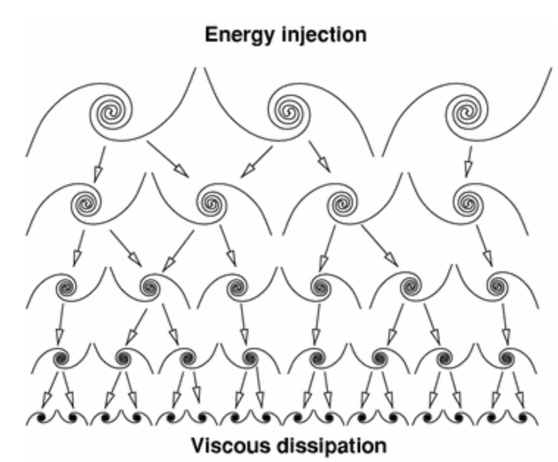
[Blaizot, Iancu, MT (2013), Iancu, Wu (2015)]

$$\theta_{\mathrm{br}} \sim \frac{1}{\alpha_s^{3/2}} \left(\frac{\hat{q}}{\omega^3}\right)^{1/4} \gg R$$

p_T



Richardson cascade

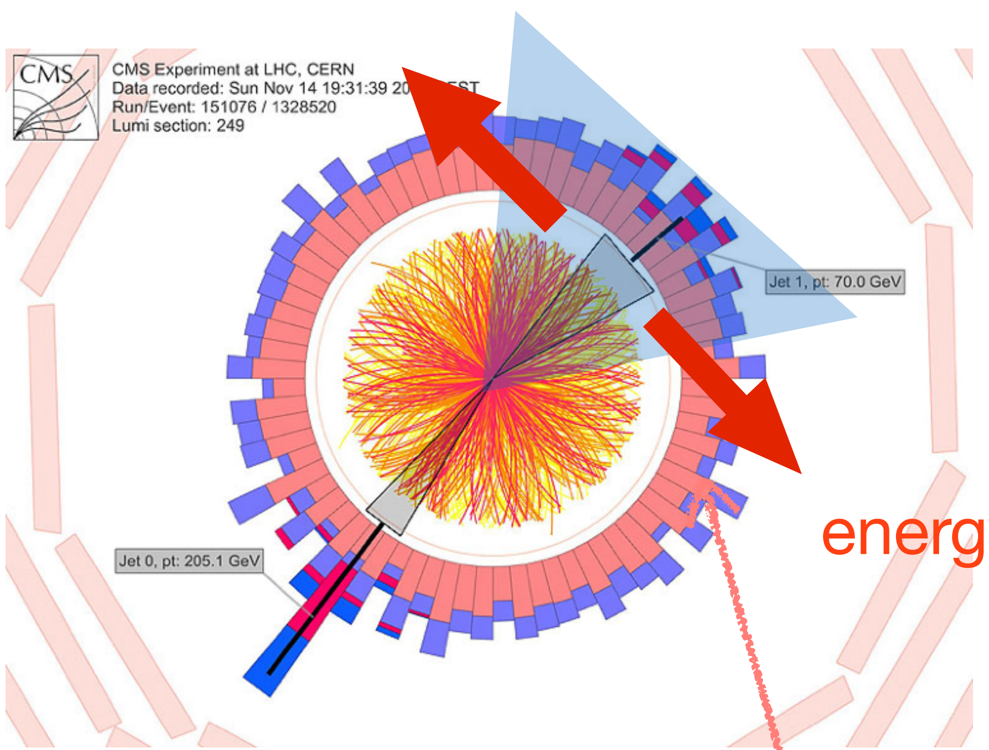


Missing pT in dijet events $\omega \sim T$

- Energy flows from high to low frequencies without accumulation: efficient mechanism for energy transport to large angles

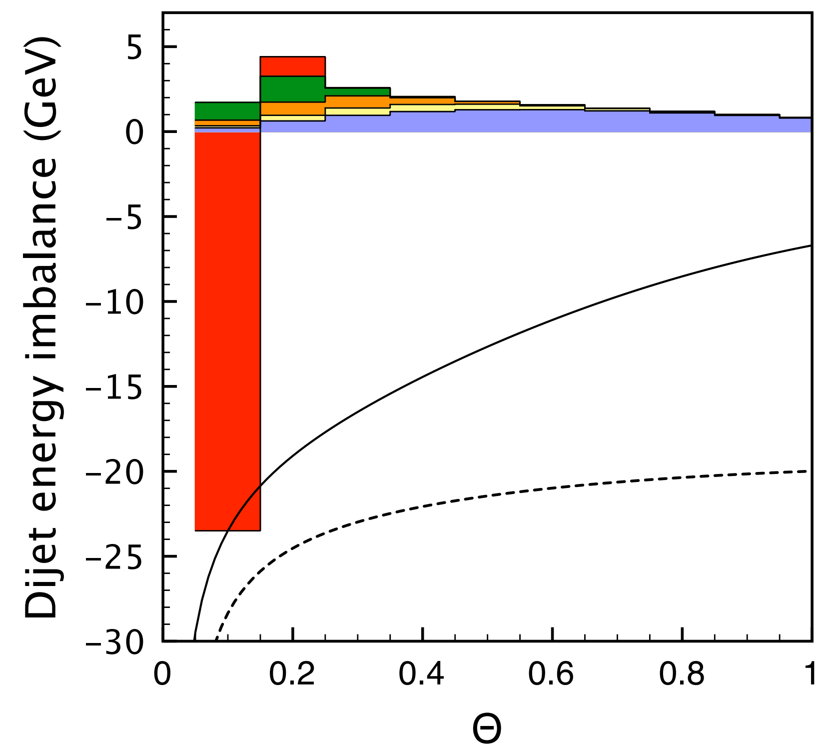
Blaizot, MT, Torres (2014)

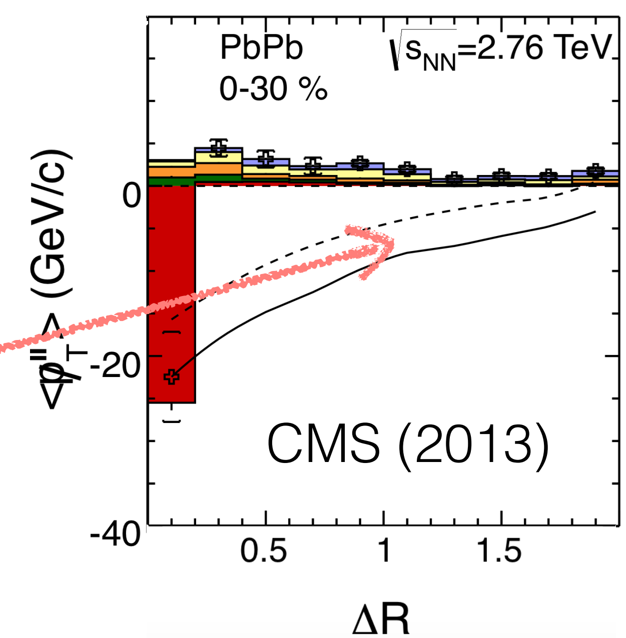
$$p_{T1} = 70\,GeV$$



energy flow

$$p_{T1} = 205\,GeV$$



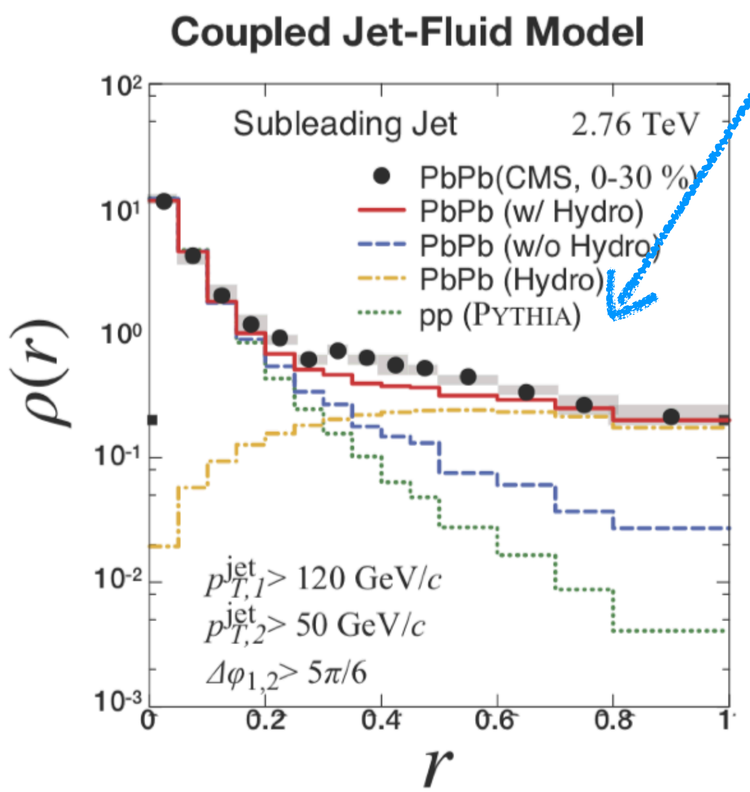


→ Energy is recovered at large angles in soft particles

Medium response $(\omega \sim T)$

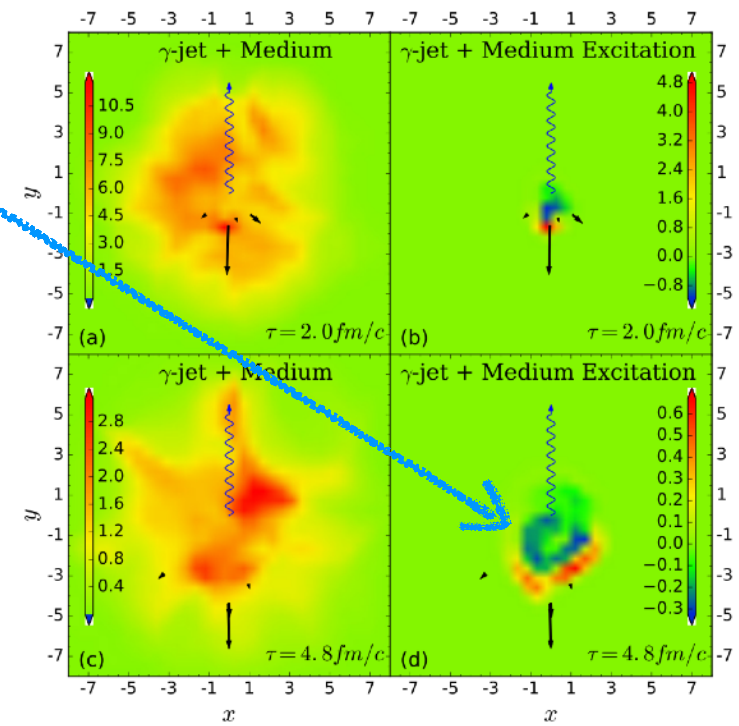
- Similar effect obtained by assuming direct energy deposition in the plasma: hydrodynamic response, linear Boltzmann

- Medium excitation correlated with the jet: may cause enhancement of soft radiation inside the jet



Y. Tachibana, N.-B. Chang, G.-Y. Qin (2017)

Hydro response



He, Liu Wang, Zhu (2015)

T. Luo, S. Cao, Y. He, X.-N. Wang (2018)

Wang, Wei, Zhang (2017)

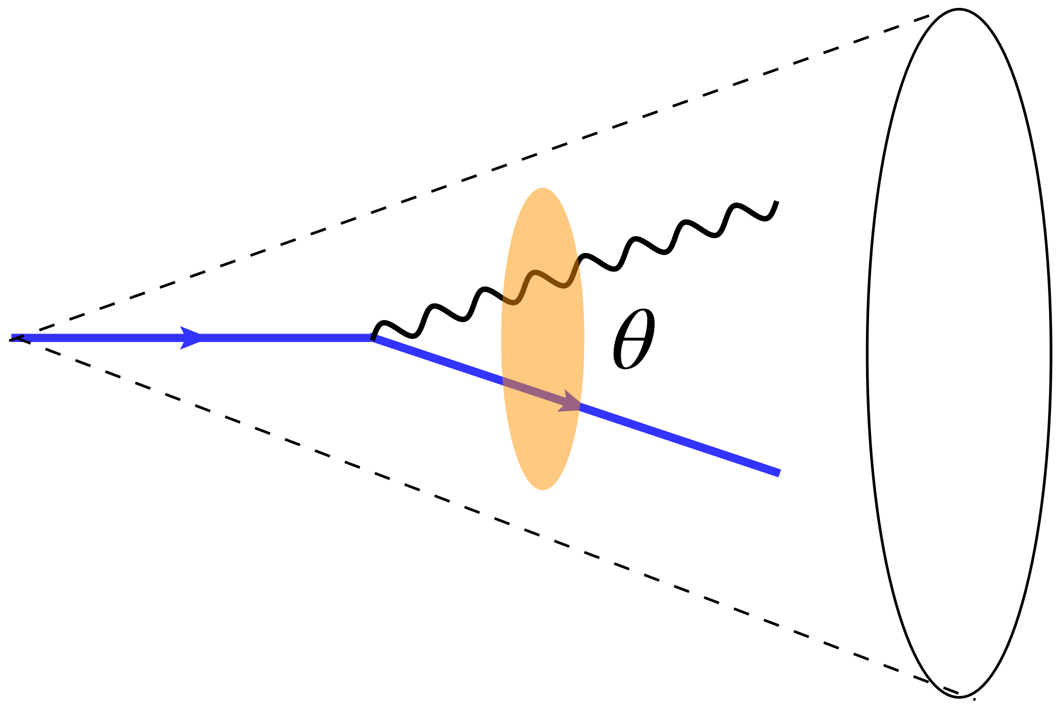
- Implemented in several MC event generators: JEWEL, HYBRID model, MARTINI (and available in JETSCAPE)

Color decoherence of jet substructure

- The jet is composed of many partons as it traverses the plasma — It is tempting to assume that jet constituents interact independently with the plasma.

- However, interactions are not point-like: the medium resolves jet fluctuations at transverse distances of order

$$l_{\rm med} \sim k_\perp^{-1} \sim (\hat{q}\, t)^{-1/2}$$



Color decoherence of jet substructure

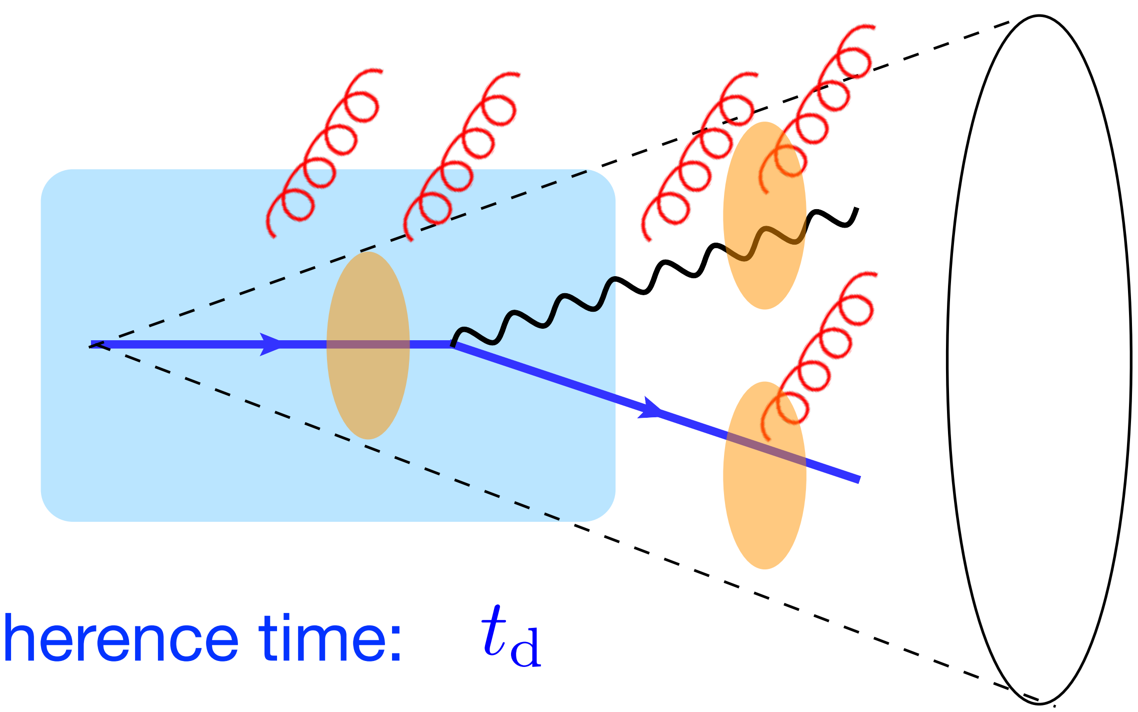
- Comparing the medium resolution scale to the transverse size of a partonic fluctuation defines a new time scale

$$l_{\rm med} \sim k_\perp^{-1} \sim (\hat q\, t)^{-1/2} \ll r_\perp \sim \theta\, t$$

- The medium resolves jet substructure (subjets) when

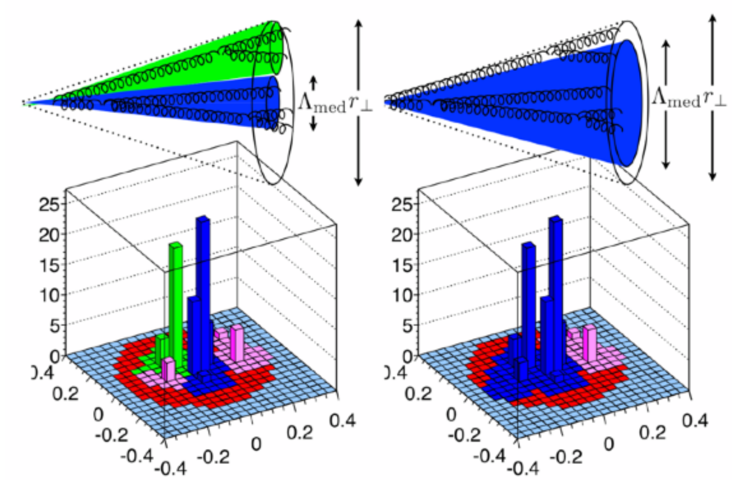
$$\theta > \theta_c \sim (\hat q L^3)^{-1/3}$$

$$t_{\rm d} \sim (\hat q\, \theta^2)^{-1/3} < L$$



The decoherence time: $t_{\rm d}$

MT, Salgado, Tywoniuk (2010-11)
Iancu, Casalderrey-Solana (2011)



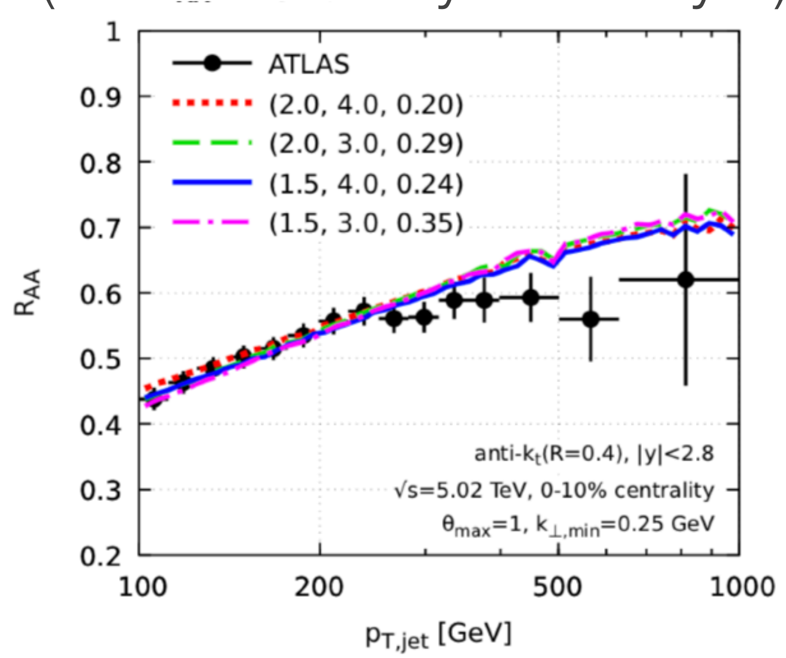
- Radiation intensity is proportional to the number of resolved color charges

Monte Carlo Event Generators and data

- Several Monte Carlo event generators in the market: JEWEL, Q-Pythia, MARTINI, CoLBT, LBT, Hybrid, MATTER (some available in a common platform, JETSCAPE) → More or less successful in describing substructure observables…do not account for color coherence yet

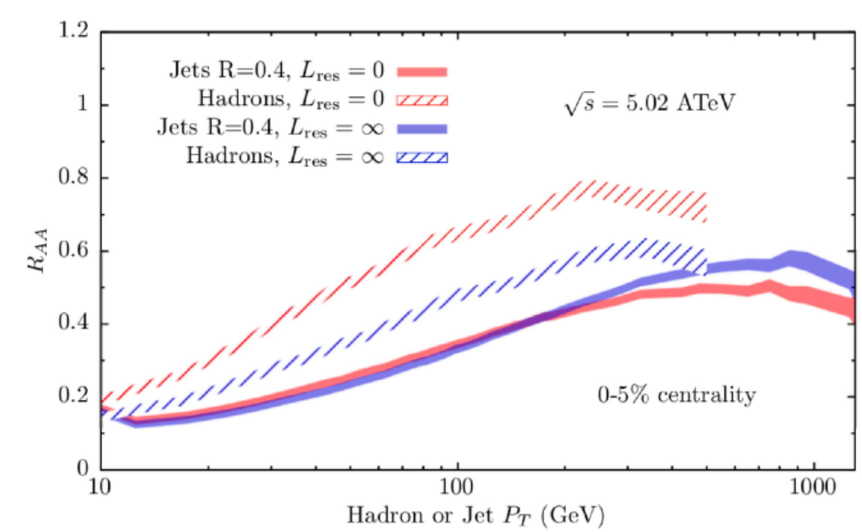
- Recent implementations of color decoherence:

Weak coupling QCD based MC (no medium dynamics yet)



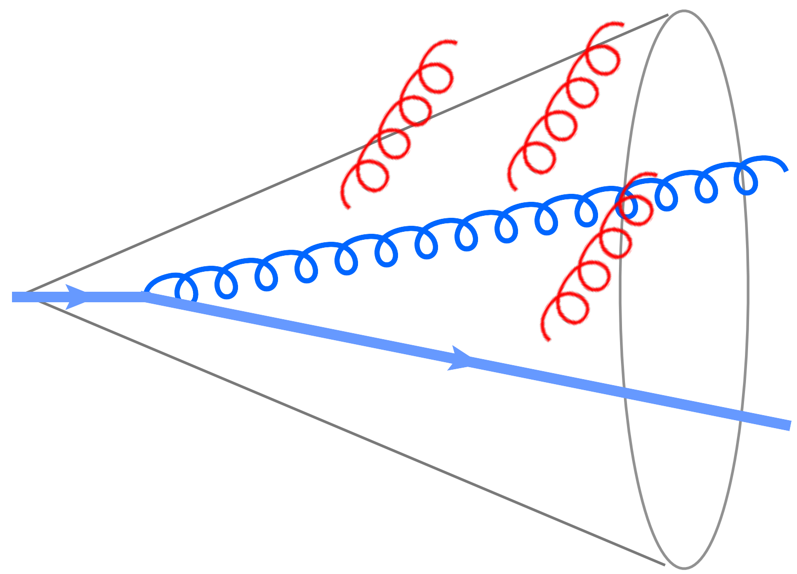
Iancu, Soyez, Caucal (2019)

Hybrid model: Pythia + strong coupling energy loss model

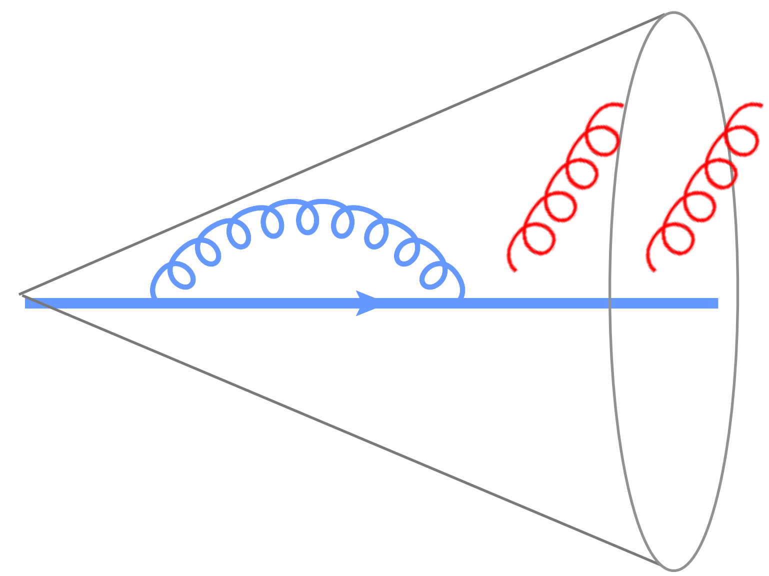


Casalderrey-Solana, Milhano, Pablos, Rajagopal (2017-2019)

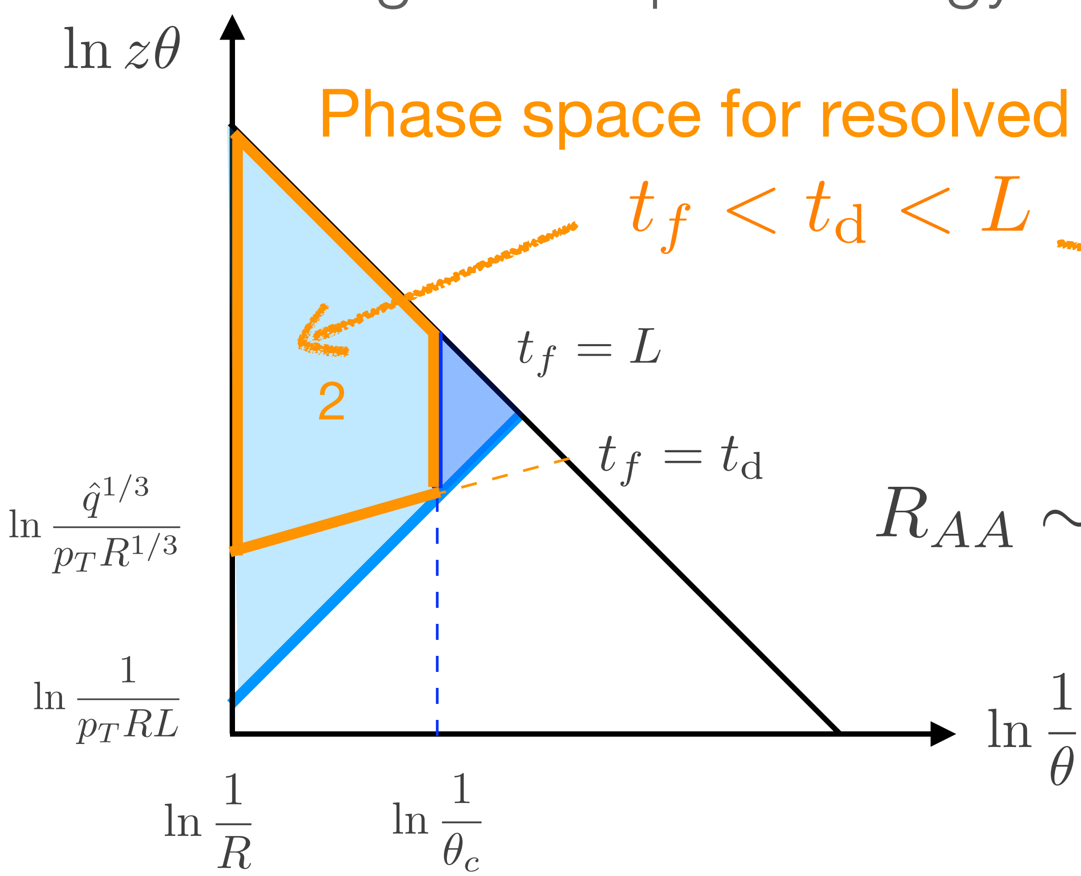
Higher order corrections to the jet spectrum



gluon + quark energy loss $\gg$



quark energy loss



Lund Plane

Sudakov suppression of jets due to jet substructure fluctuations

$$R_{AA} \sim Q_\mathrm{tot}(p_T) \times \exp\left[-2\bar{\alpha}\ \ln\frac{R}{\theta_c}\left(\ln\frac{p_T}{\omega_c} + \frac{2}{3}\ln\frac{R}{\theta_c}\right)\right]$$

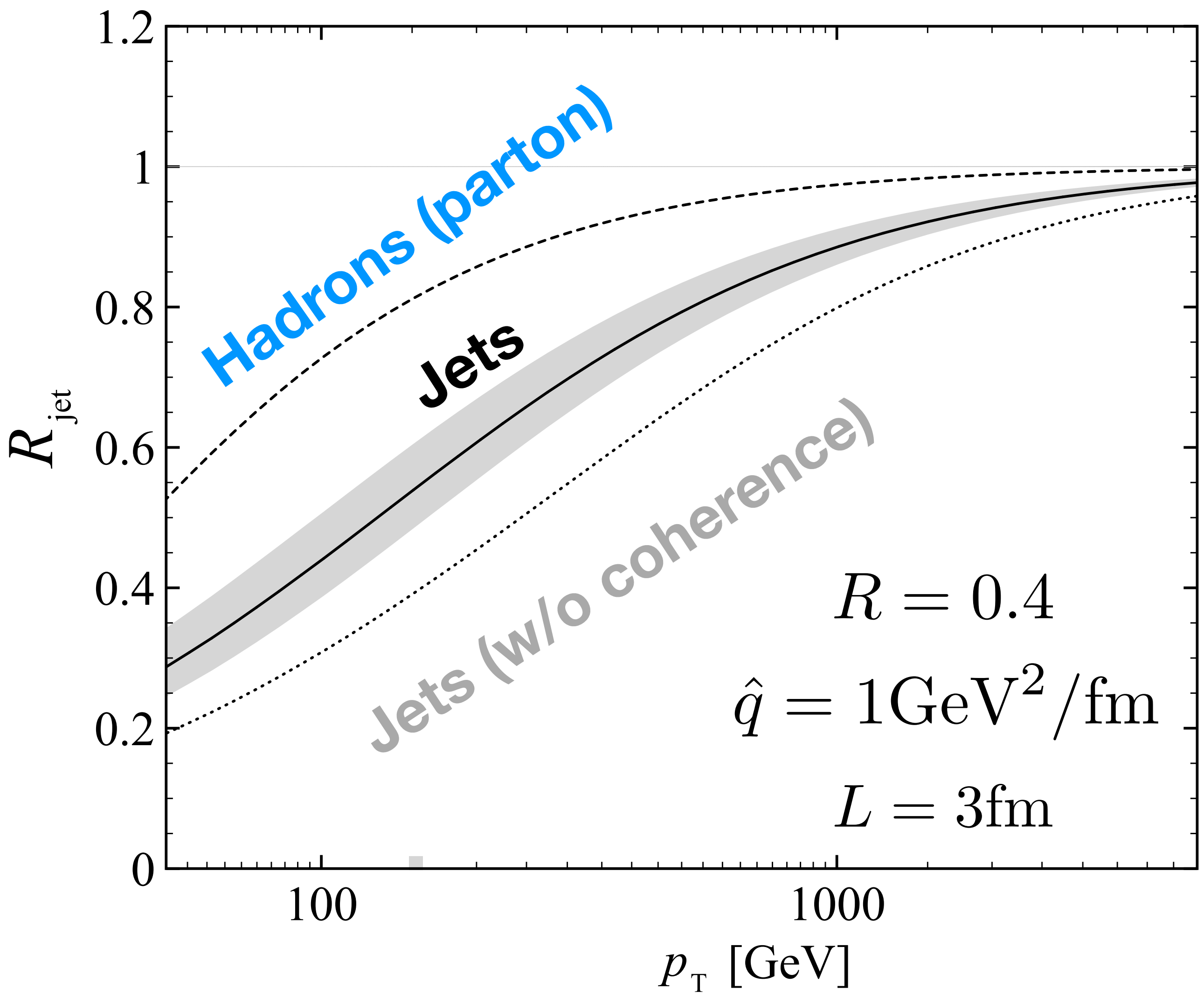
MT, Tywoniuk (2018)

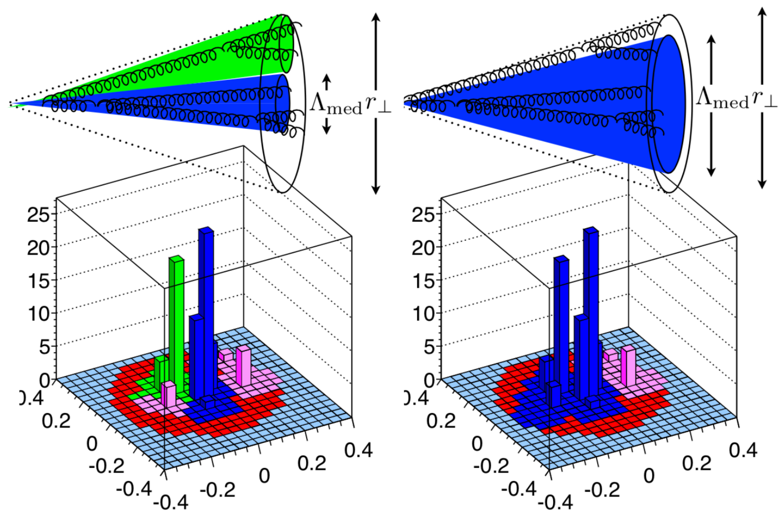
Note: θ_c sets the boundary between color coherence and decoherence

Higher order corrections to the jet spectrum

MT, Tywoniuk (2018)

- Sensitivity of the nuclear modification factor to color coherence





$\theta_c \sim (\hat{q}L^3)^{1/3} \sim 0.1$

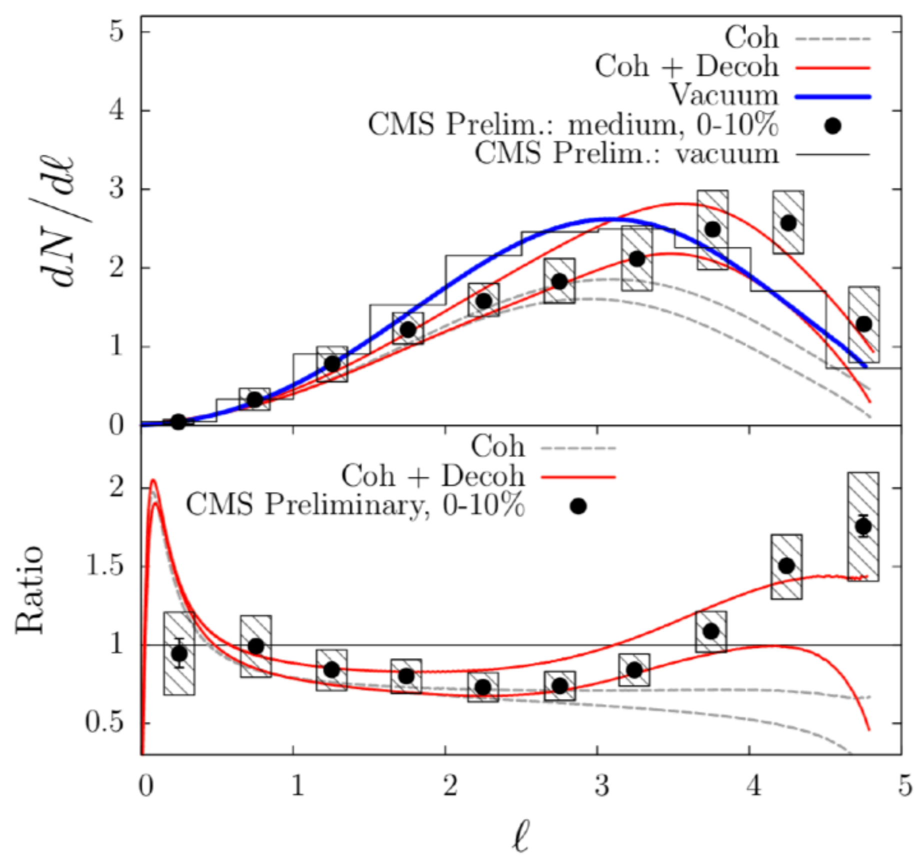
w/o color coherence: MC event generators: Hybrid Model, JEWEL and MARTINI

- **Caveat:** theoretical idealization

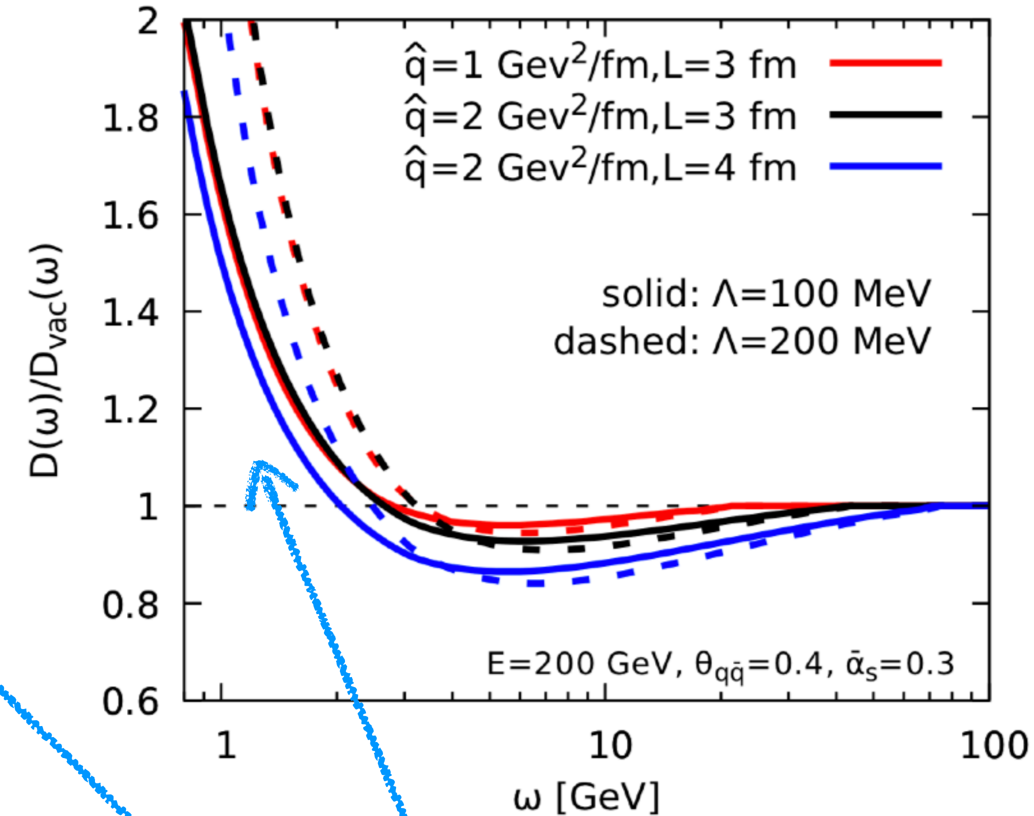
Softening of Fragmentation Function

- A softening of the Fragmentation function observed in the data

MT, Tywoniuk (2014)



Caucal, Iancu, Mueller Soyez (2018)



- Possible mechanism: in-cone decoherent vacuum radiation
- Other explanation: medium response

Summary

- QCD jet evolution in the presence of a QGP is multifaceted: in addition to the vacuum collinear cascade a medium induced shower responsible for jet quenching forms at large angles
- Jets in HIC are probes of the QGP and constitute a unique tool to study QCD far-from-equilibrium and thermalization
- QCD coherence phenomena such as the LPM effect and color (de)coherence play an important role in jet quenching and may be more directly investigated with substructure observables
- A plethora of MC event generators encoding different physics. A common picture of the perturbative component of jet evolution in a QGP remains to be achieved $\rightarrow$ Need analytic guidance to reduce dependence on modeling