New developments and challenges in the theory of jet quenching in heavy ion collisions

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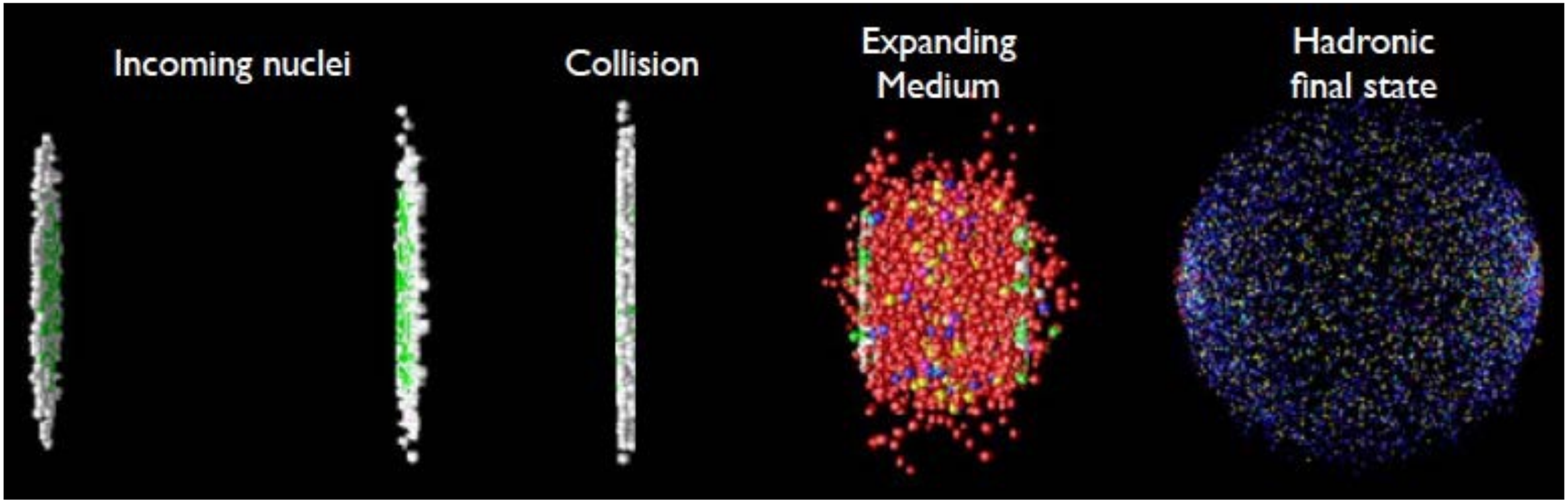
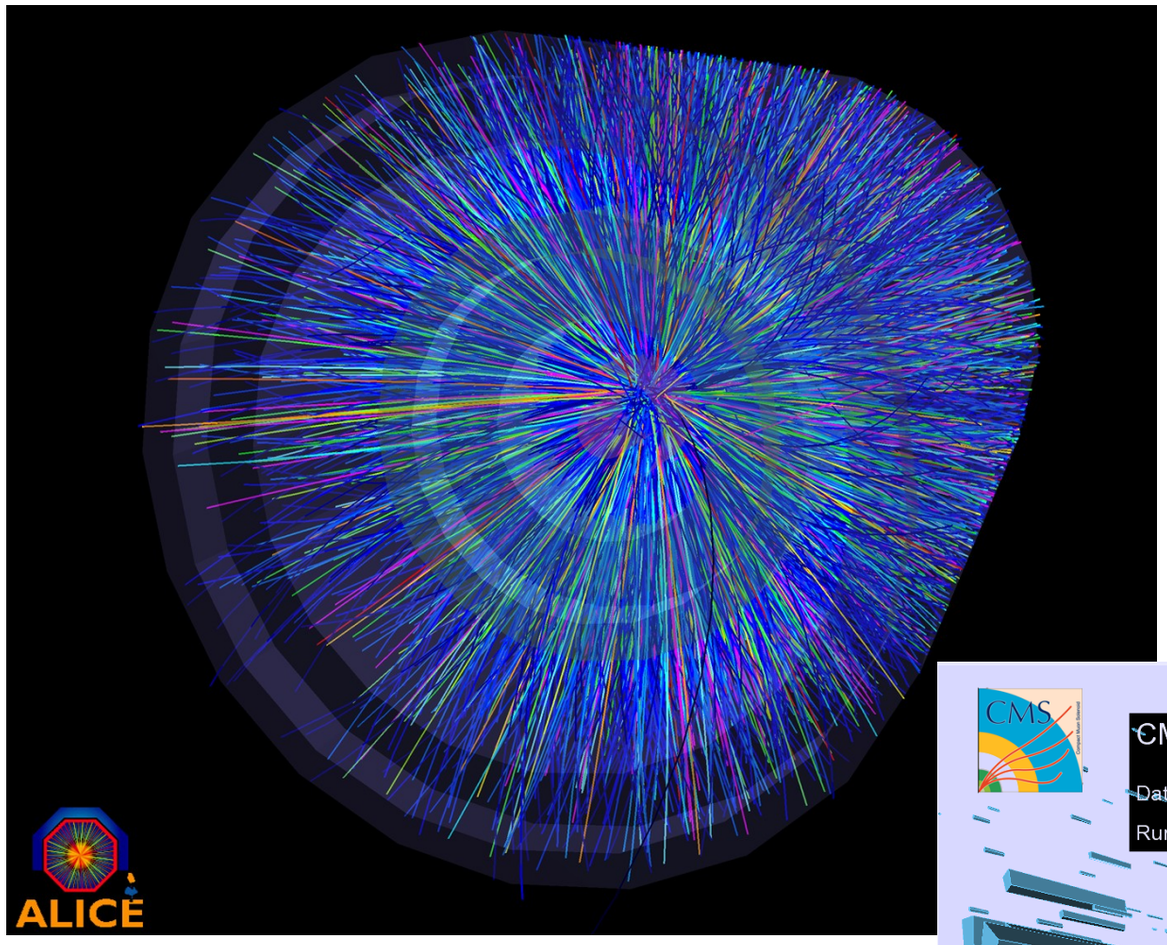
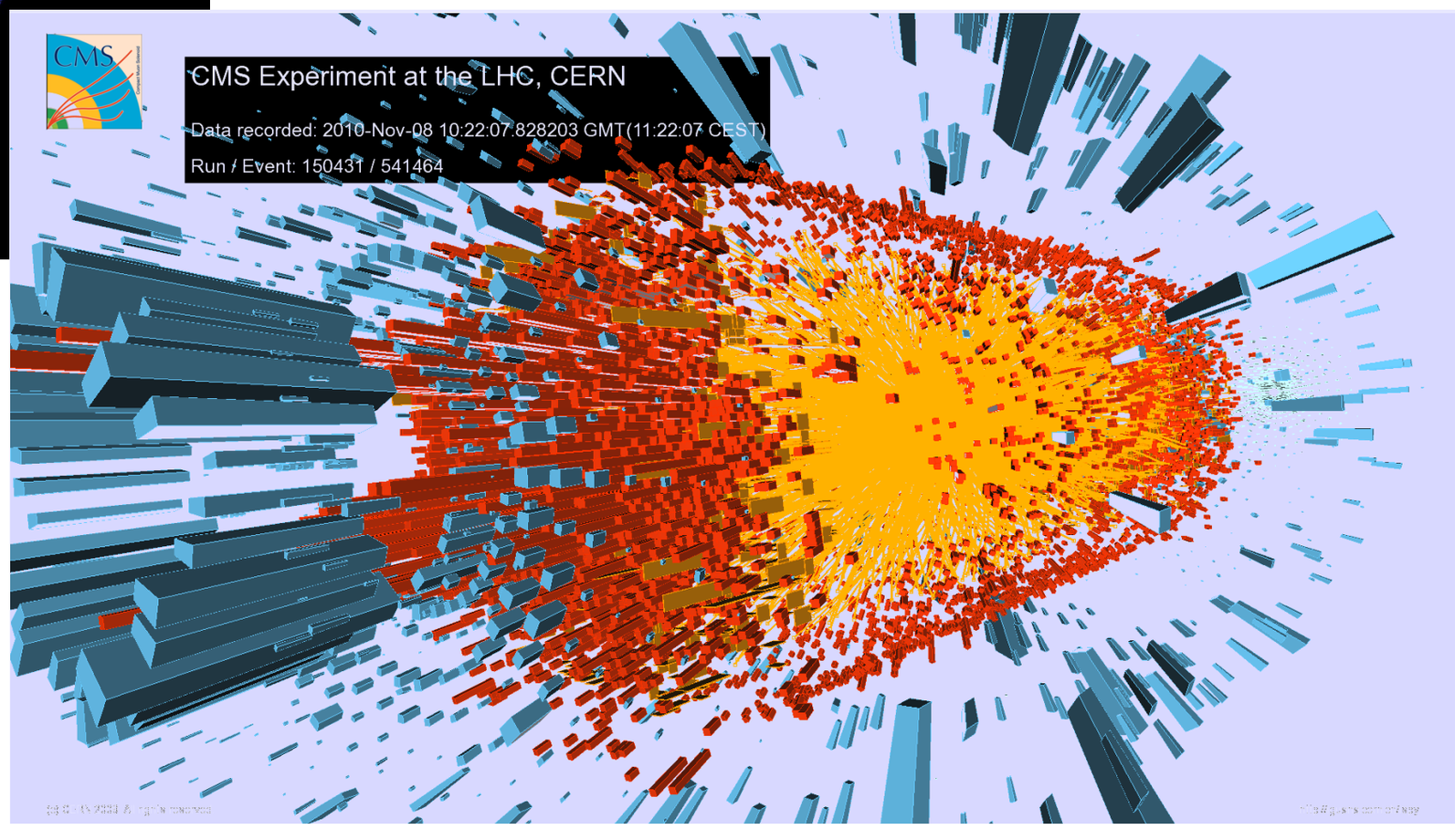
Heavy Ion Collisions



- High-energy nuclei collide producing thousands of particles
- A quark-gluon plasma (QGP) is created and is thought to behave like a liquid
- Unique opportunity to access deconfined quarks and gluons

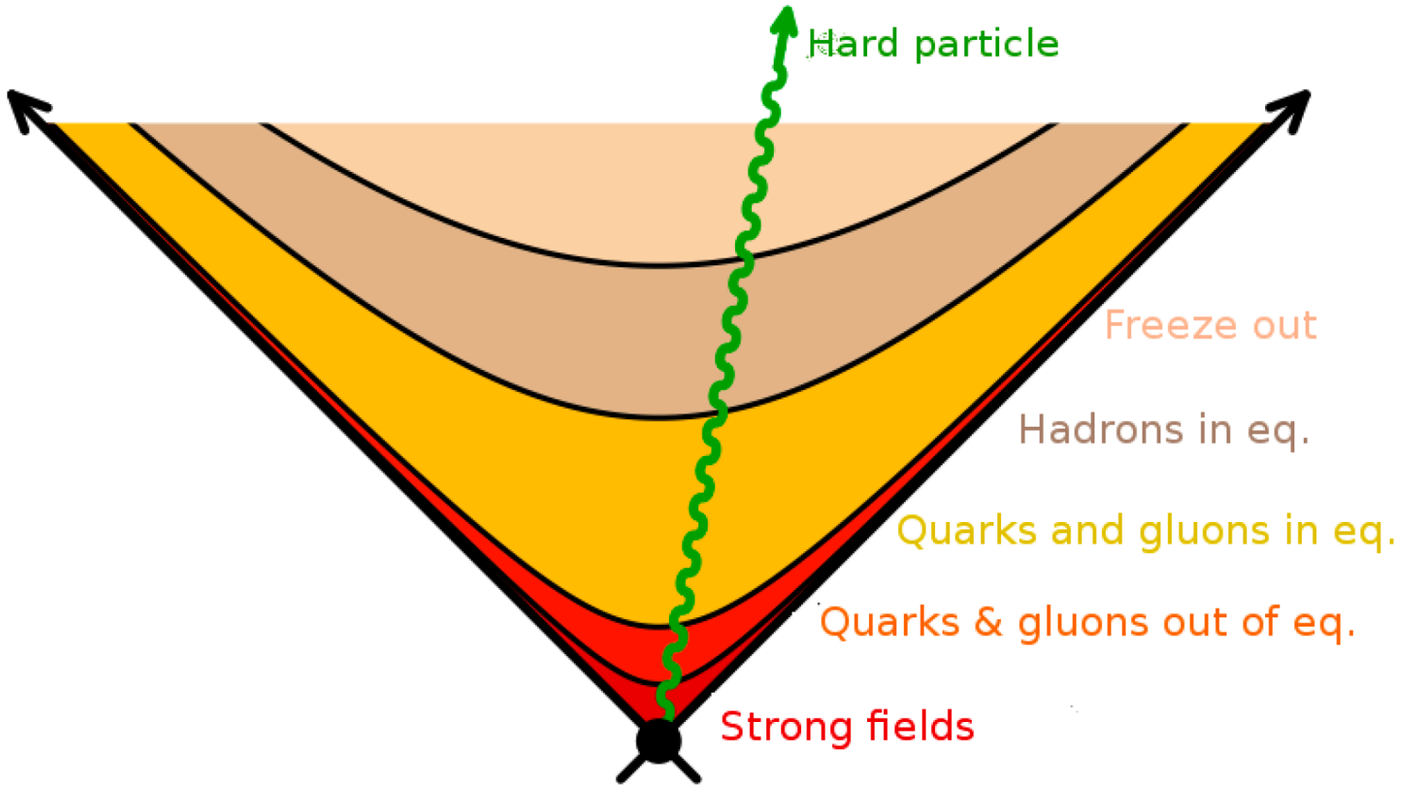
How does it look like?





Quark-gluon pasma

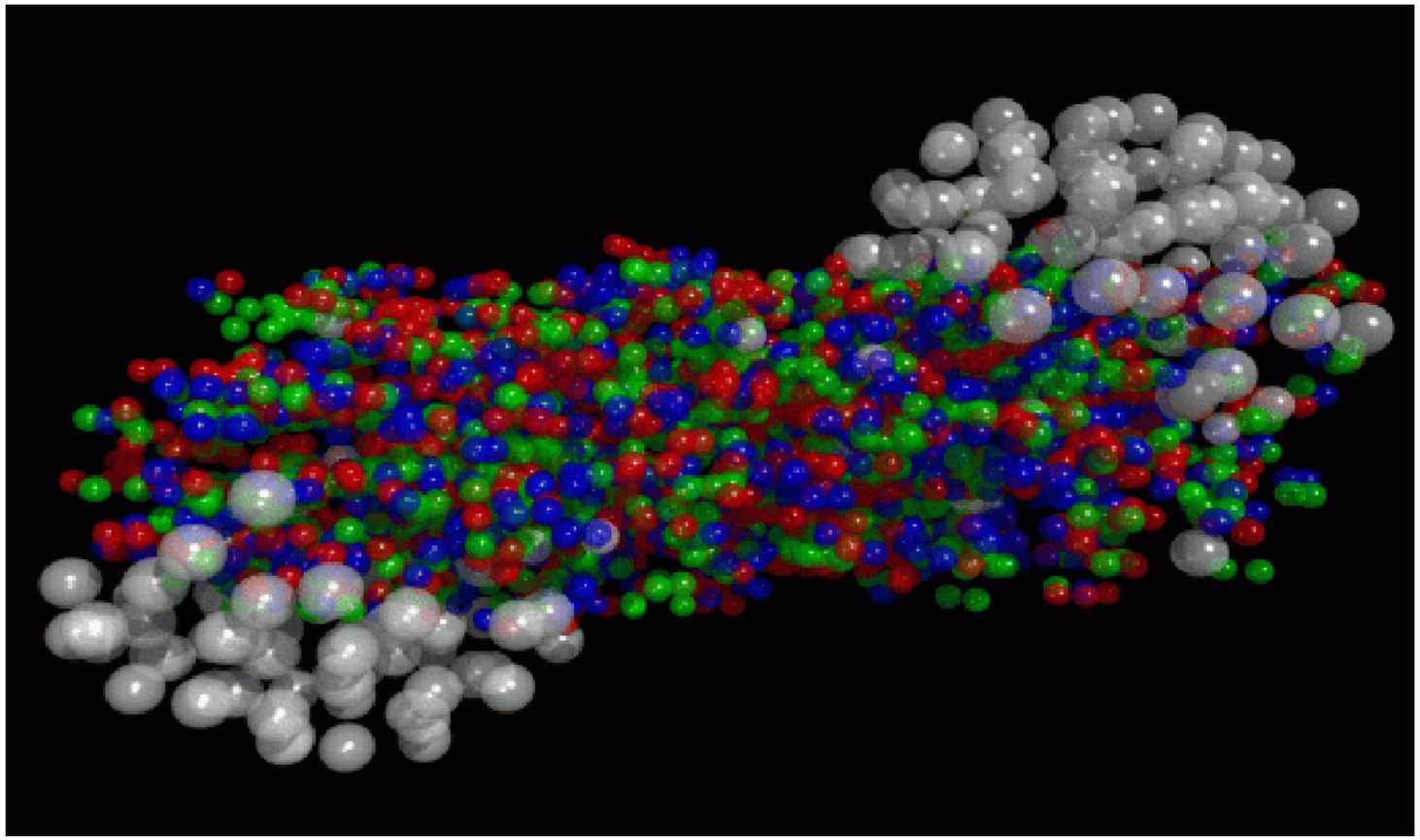
- Several stages before particle can be measured in the detector
- Complicated dynamics at each stage
- Lifetime of QGP is very short

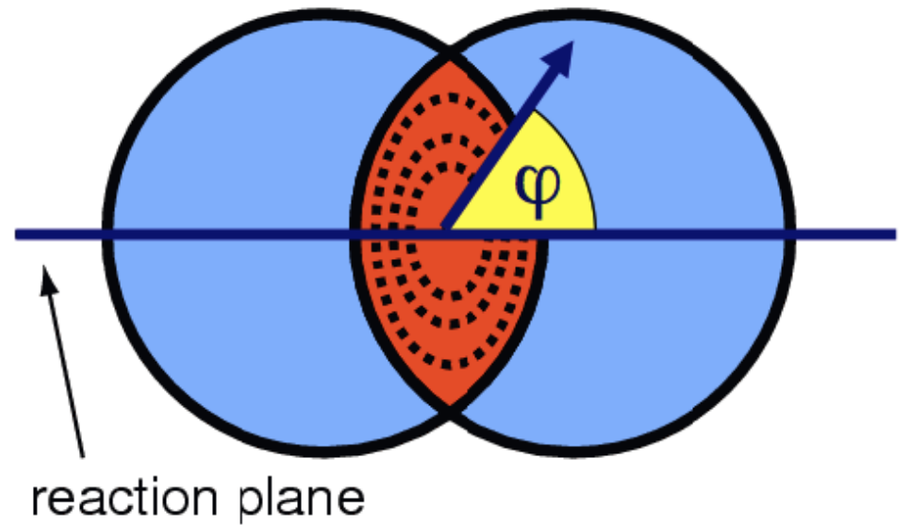


Questions about the QGP

- Does it fully thermalize?
- Is it strongly or weakly coupled?
- Deconfinement?
- What are the local properties of the plasma?
- Are there pseudoparticles?

Hydrodynamics

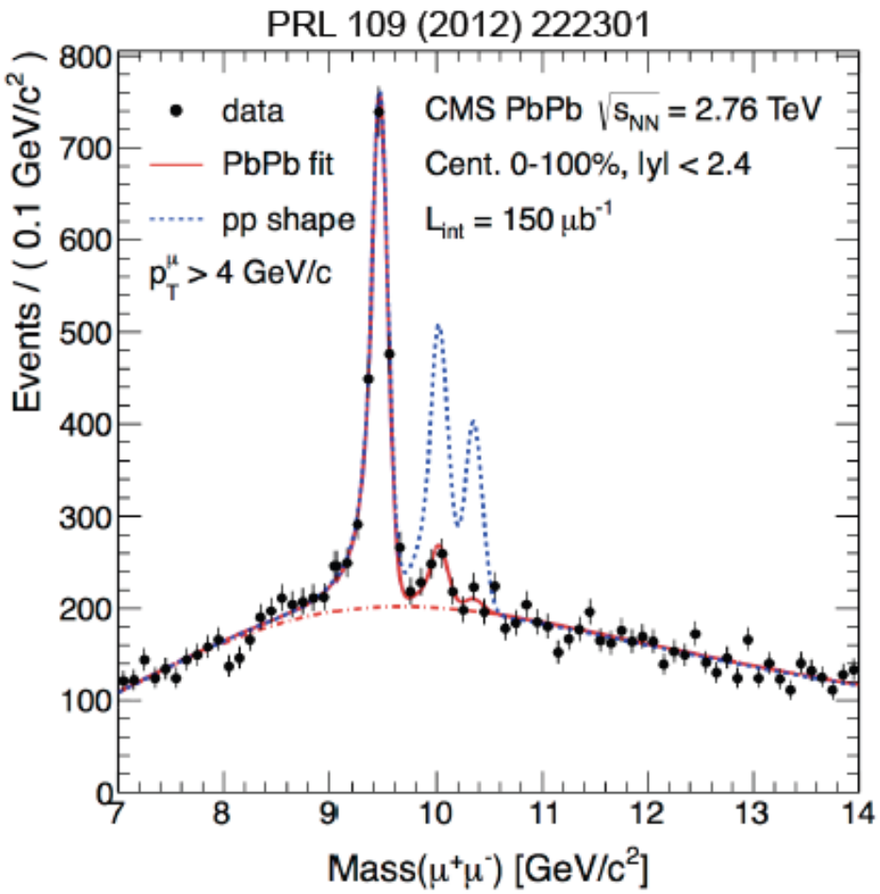




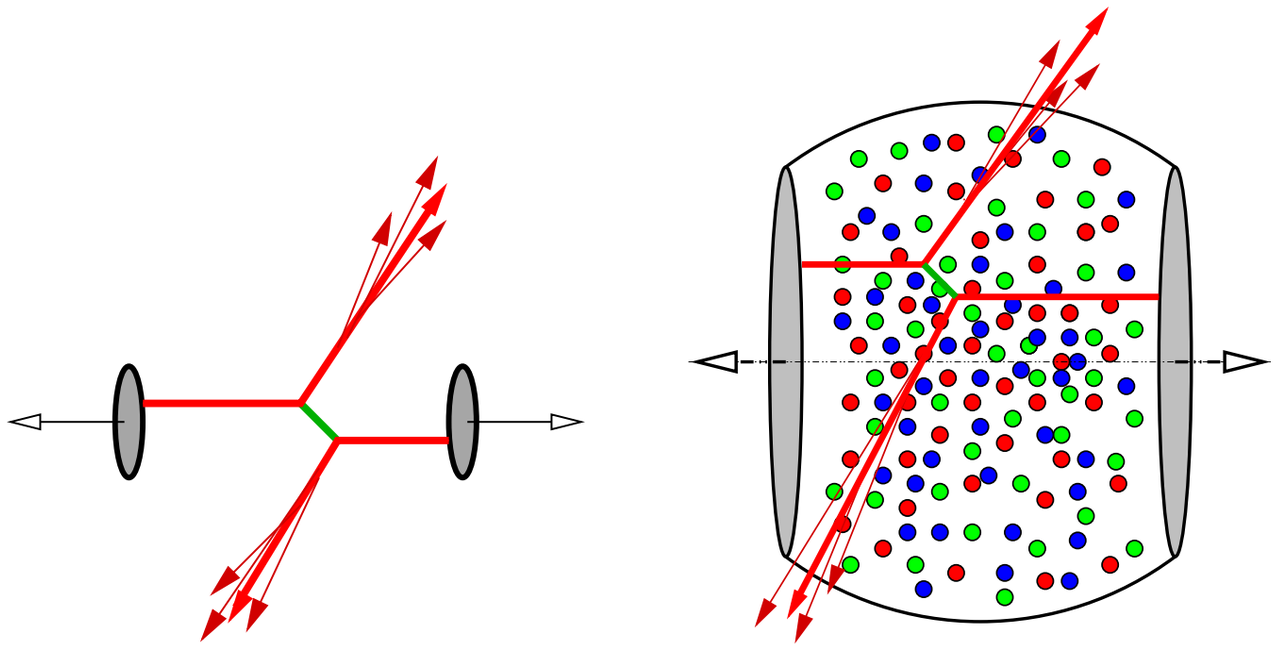
- Initial geometry translates into anisotropies in the n-particle correlation measurements
- Long range rapidity correlations also agree with hydrodynamical predictions
- Measurements consistent with low viscosity

Signatures of deconfinement

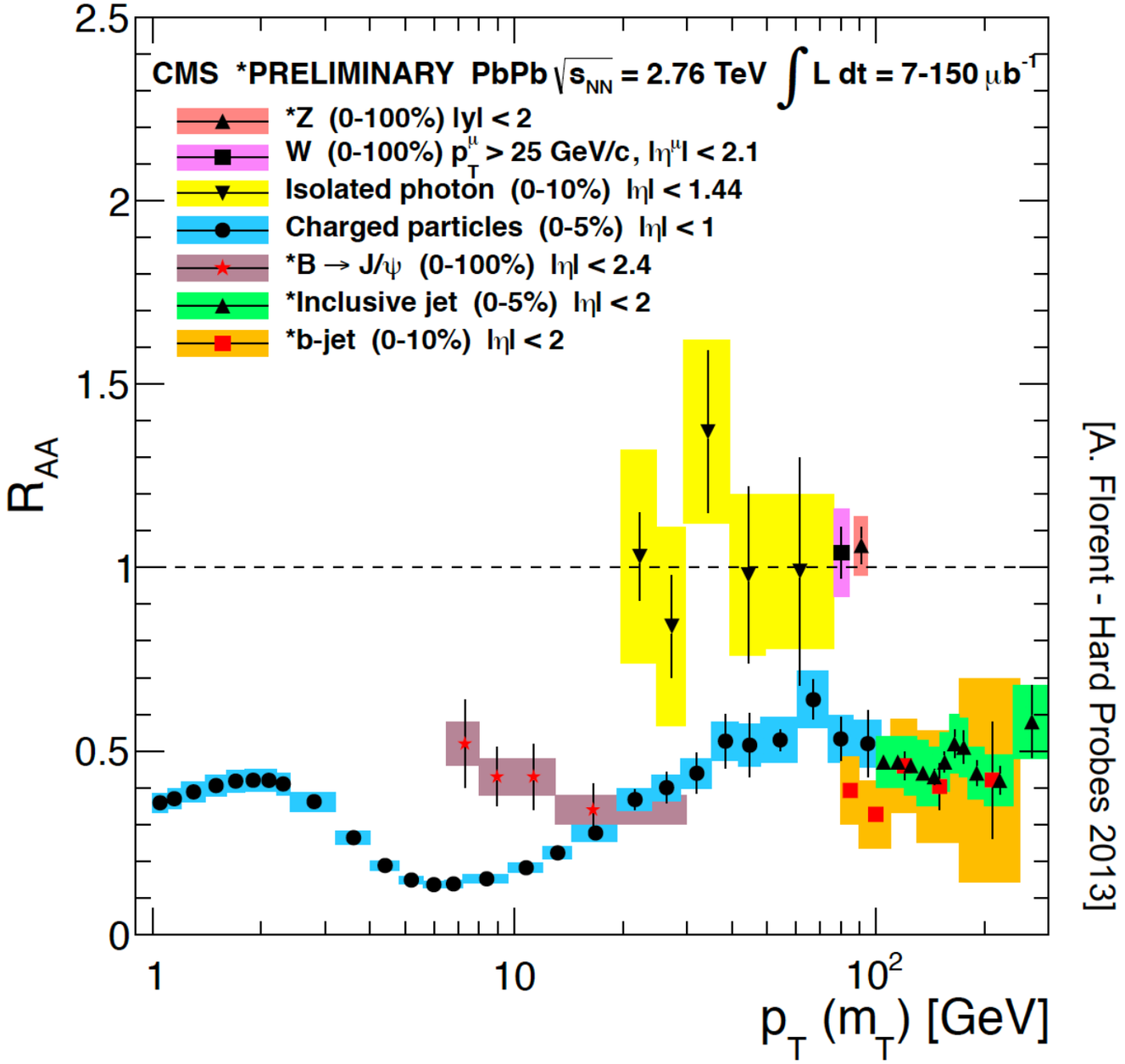
- Suppression of bound states (screening)



- Energy loss of colored particles traversing the plasma



Hard Probes

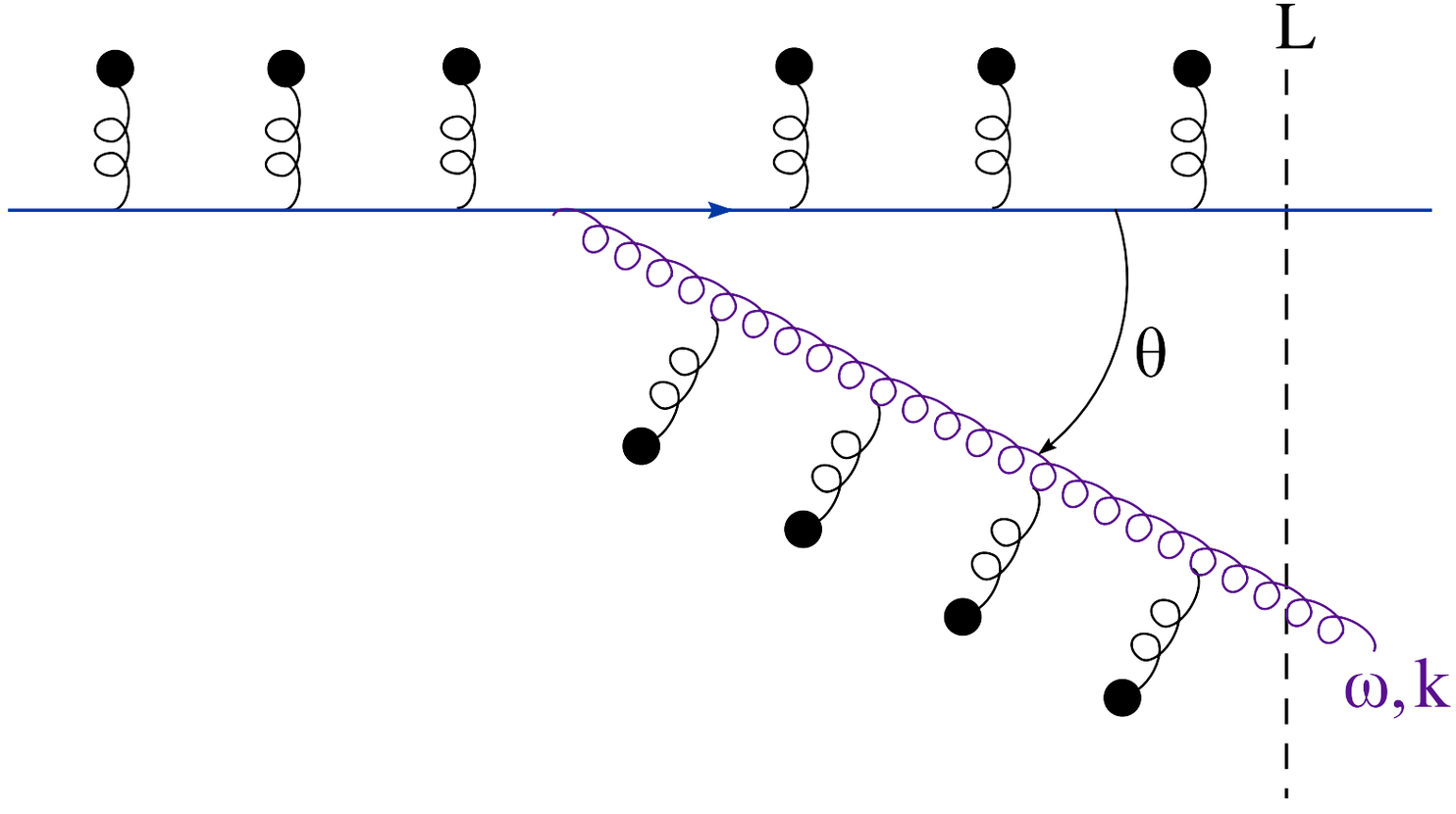


$$R_{AA} = \frac{dN_{AA}/d^2p_T\,dy}{\langle N_{coll}\rangle\, dN_{pp}/d^2p_T\,dy}$$

- Suppression factor is 1 if there are no medium effects
- Colorless probes are not affected
- Hadrons and jets are suppressed

Energy loss

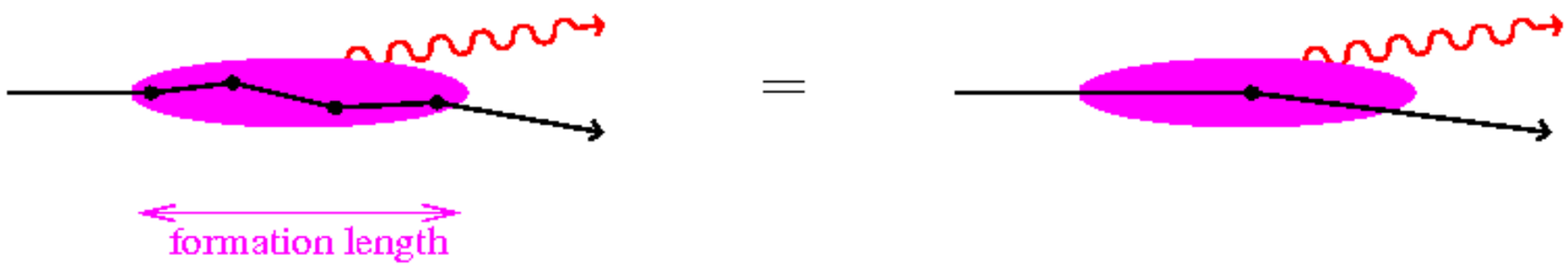
- How does a parton loses energy in a QCD medium?
  - Collisions - Important for heavy particles
  - Radiation - Dominant for light quarks and gluons



In-medium radiation

- QCD radiation is qualitatively different from QED radiation
  - Gluons interact with the medium
  - Color degree of freedom allows for extra radiation
  - Radiation present at very high energies

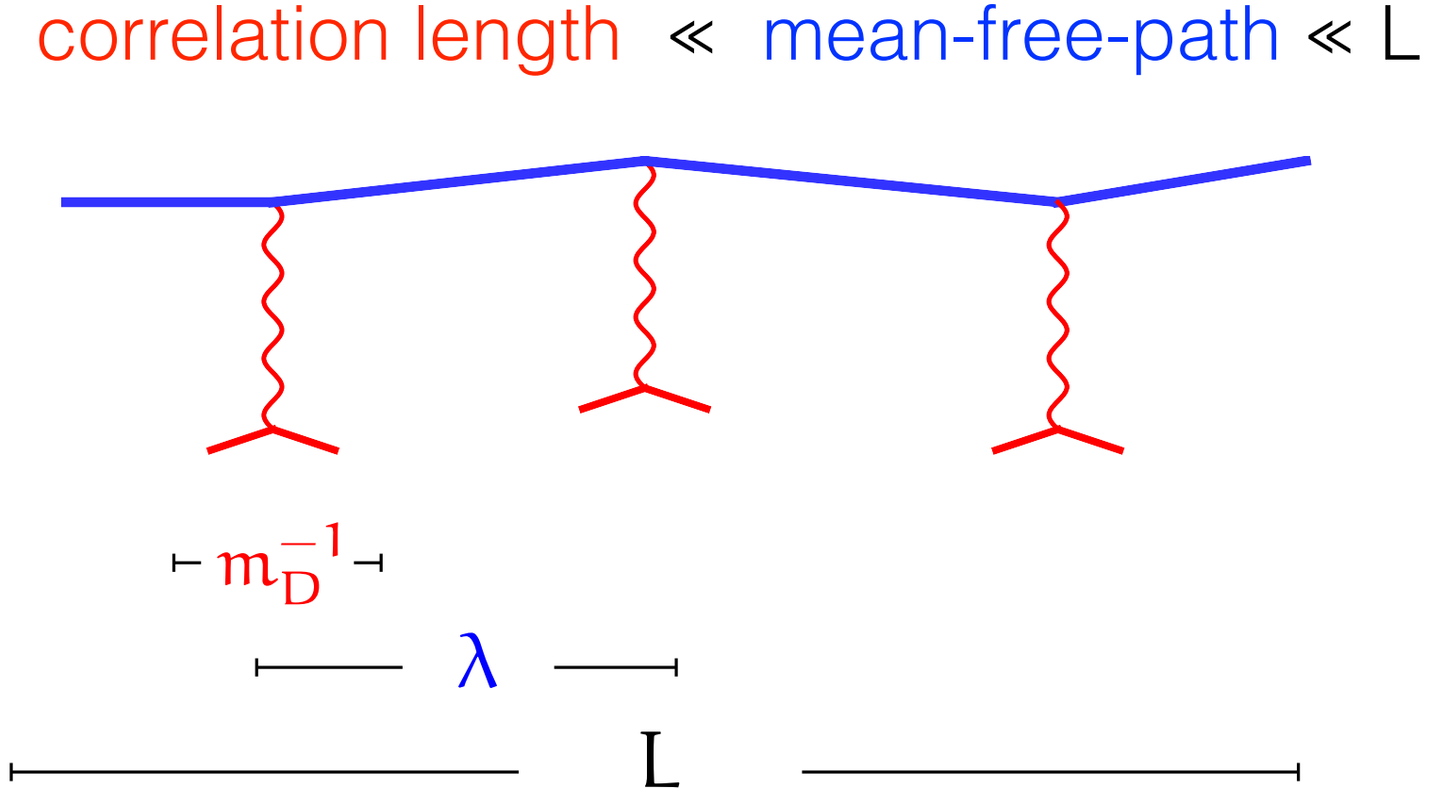
- LPM effect can be important



Medium induced radiation

- Jet quenching parameter quantifies the strength of the interaction between probe and medium

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



Medium induced radiation

- For a single particle propagating through the medium, the gluon emission spectrum can be calculated (BDMPS,HT,GLV, …)

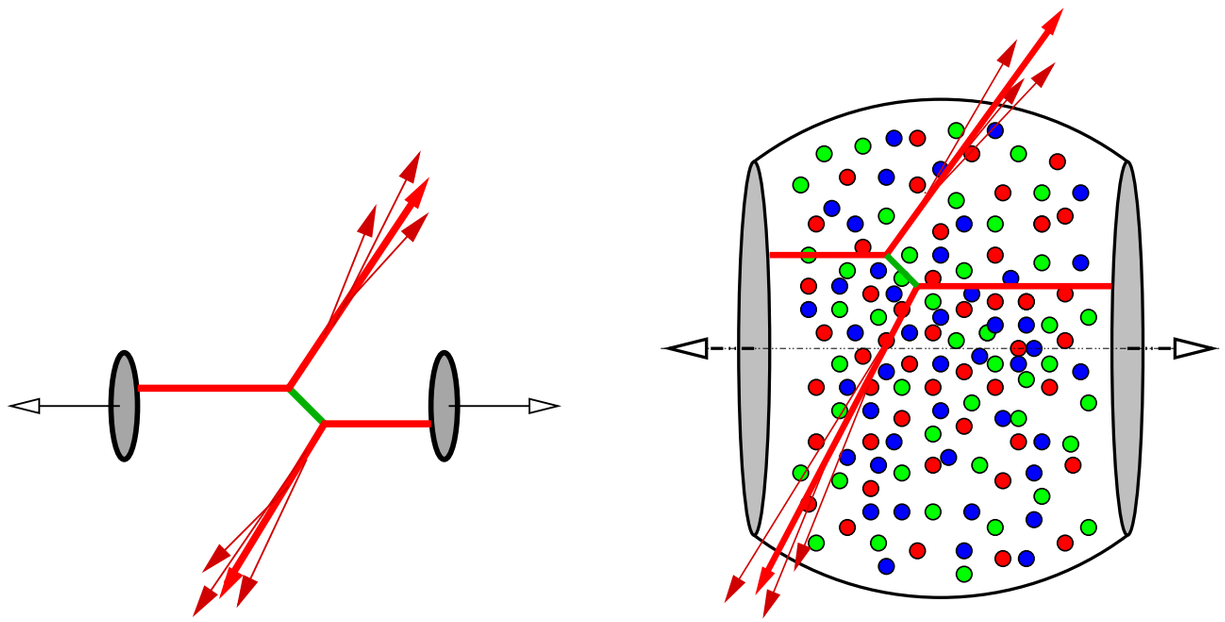
- Relating such calculations to observables requires making additional assumptions:

  - Hadronization

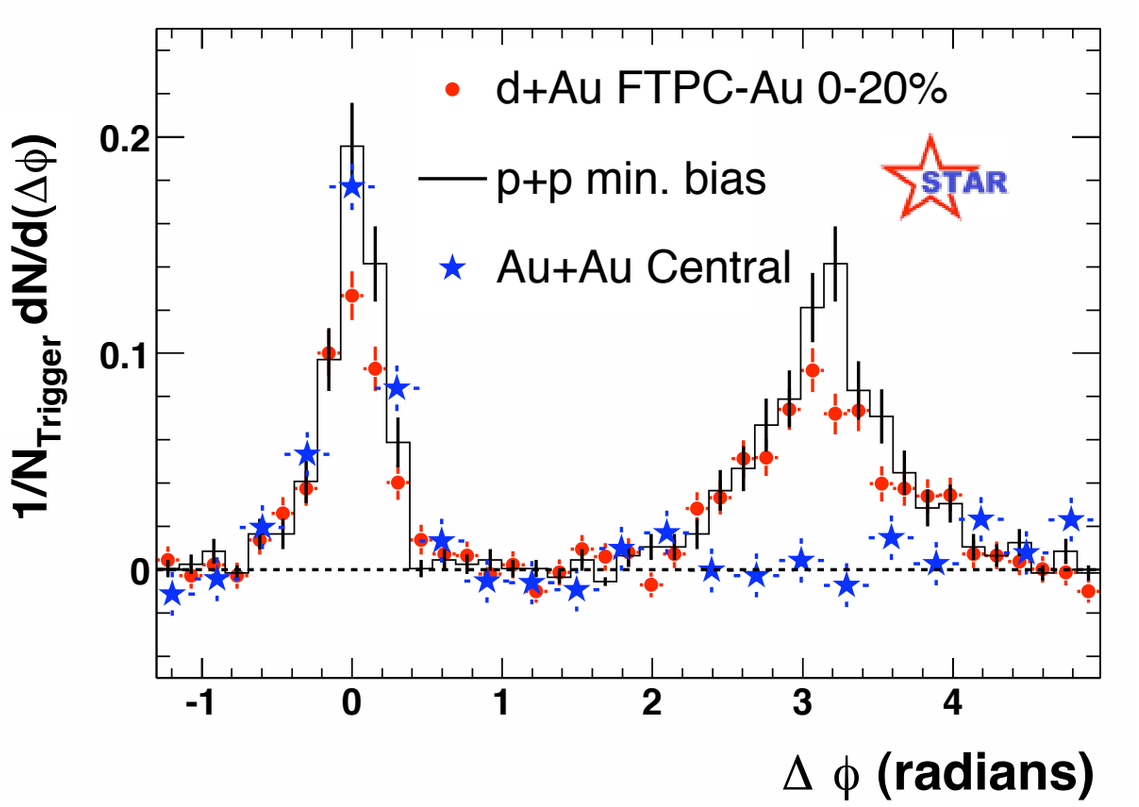
  - Multiple emissions

  - Interplay between medium-induced radiation and vacuum-like radiation

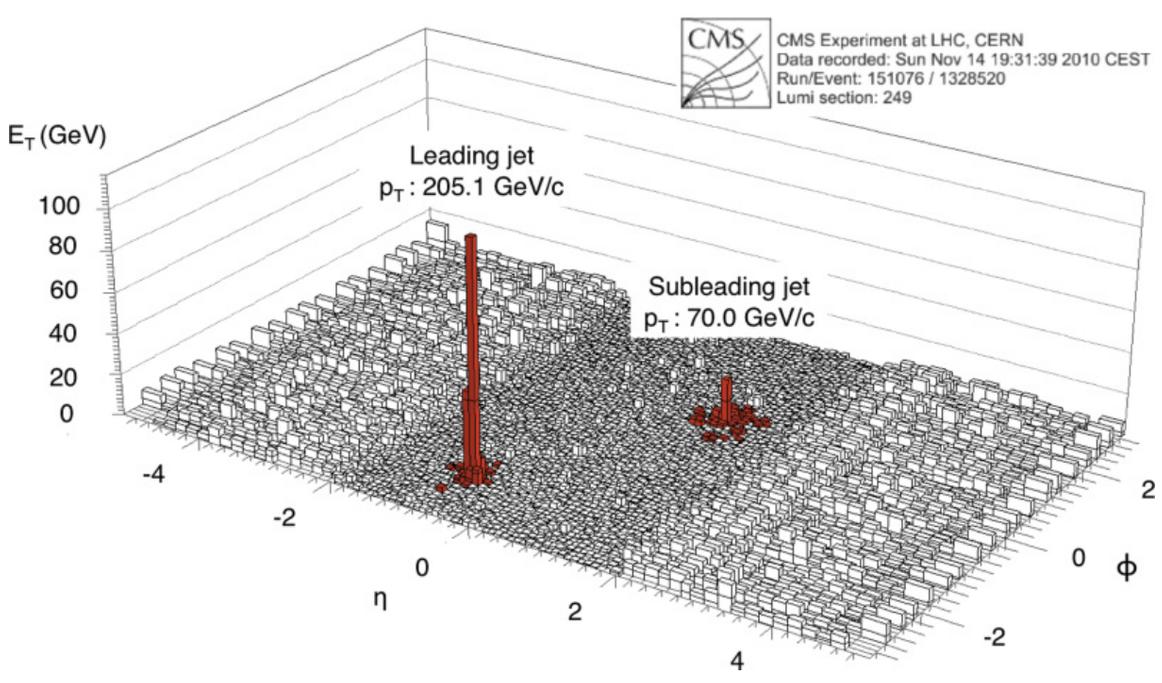
From hadrons to jets



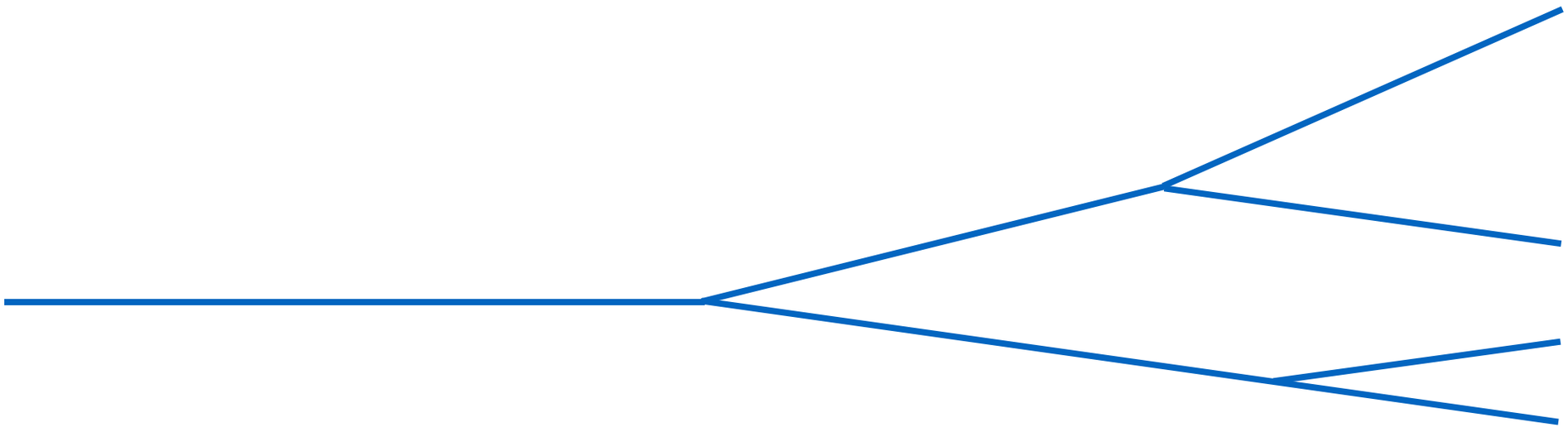
Leading hadrons



Jets



In-medium showers



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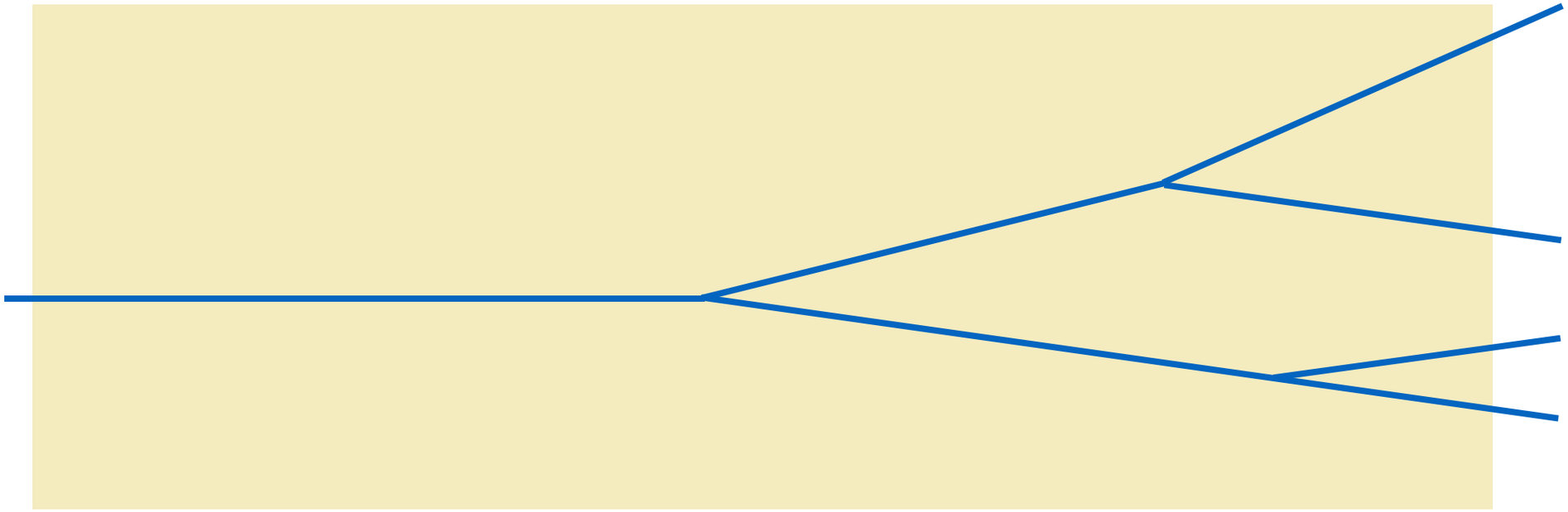

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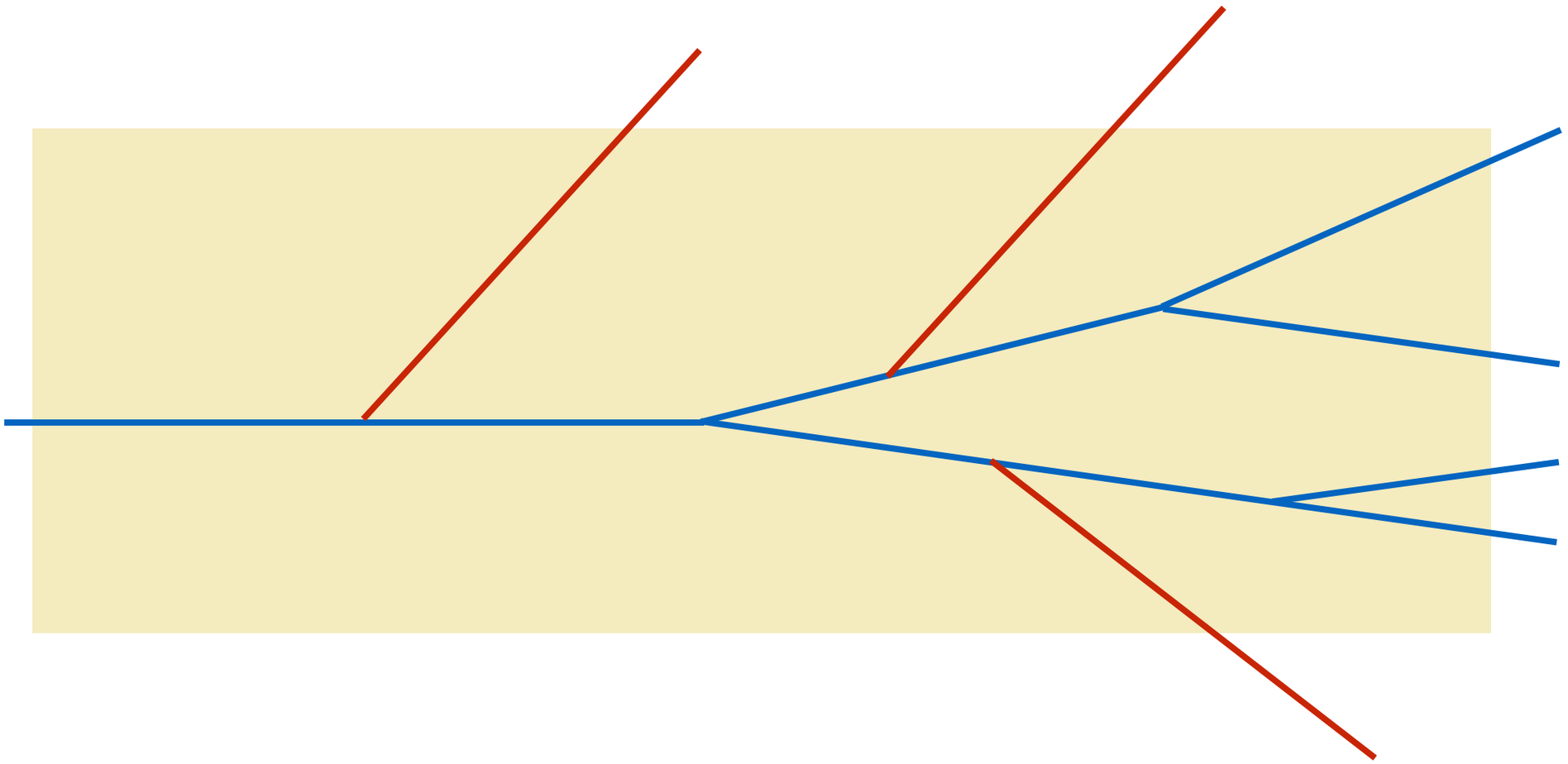
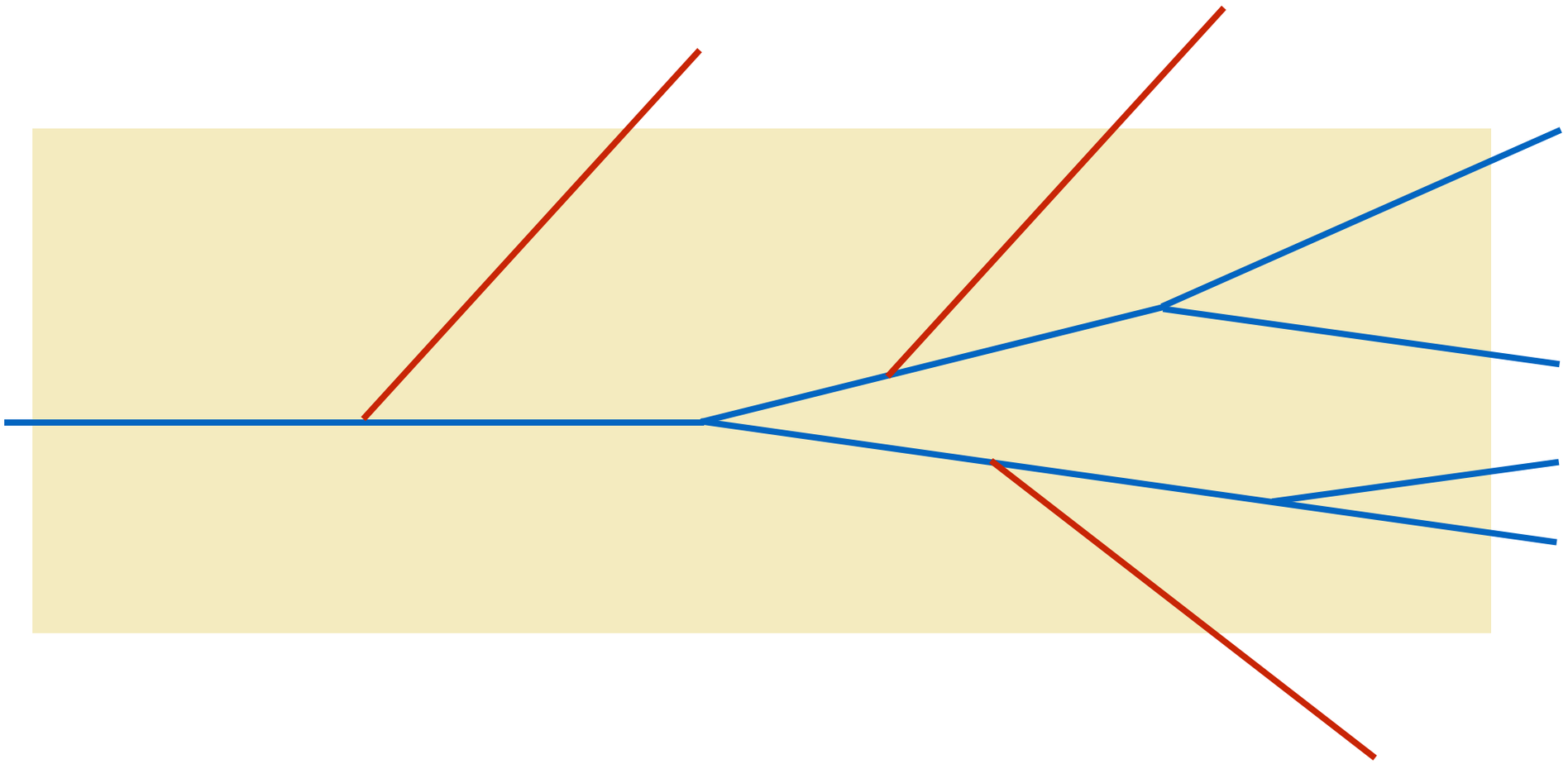


In-medium showers

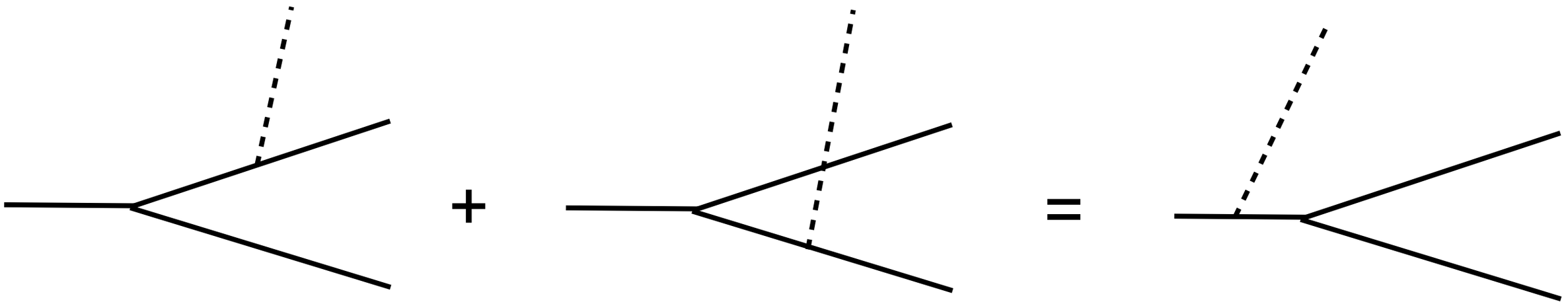


- Different partons in the shower radiate independently?
- Is the shower modified?
- Can medium-induced gluons be distinguished from the shower partons?

Vacuum parton showers

- Probability of gluon emission is soft and collinear divergent
  - Many collimated particles are produced (jets)
  - Resummation is needed
- Color coherence is preserved
  - Large angle emissions are suppressed
  - Angular ordering

Angular ordering



- Large angle emissions can not resolve previous splitting
- They are effectively emitted from the parent parton
- Calculations including only angular ordered diagrams are correct to double and single logarithmic accuracy

Medium modification

- Is the splitting probability modified?

- Are the color coherence and angular order modified?

Medium modification

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Yes, but the modification does not have a collinear divergence…

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You cannot just change the splitting function and keep using DGLAP

- Are the color coherence and angular order modified?

Medium modification

- Is the splitting probability modified?

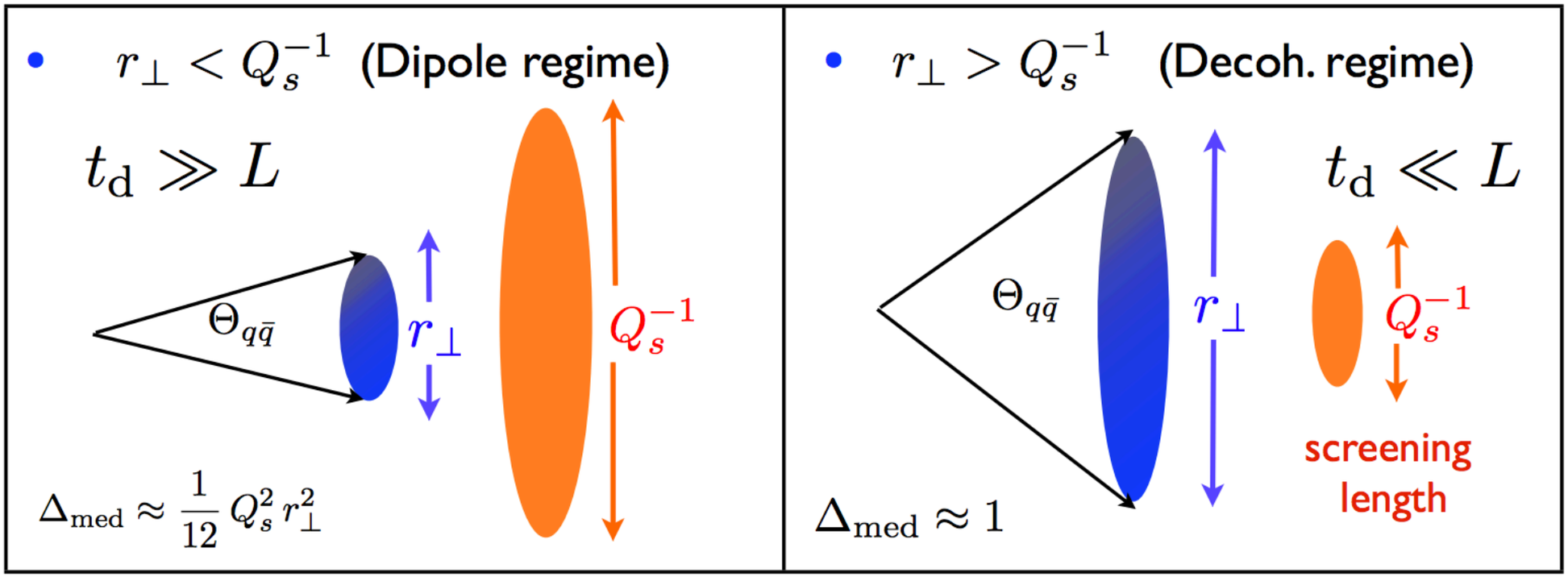
Yes, but the modification does not have a collinear divergence…

You cannot just change the splitting function and keep using DGLAP

- Are the color coherence and angular order modified?

Depends…

Medium resolution



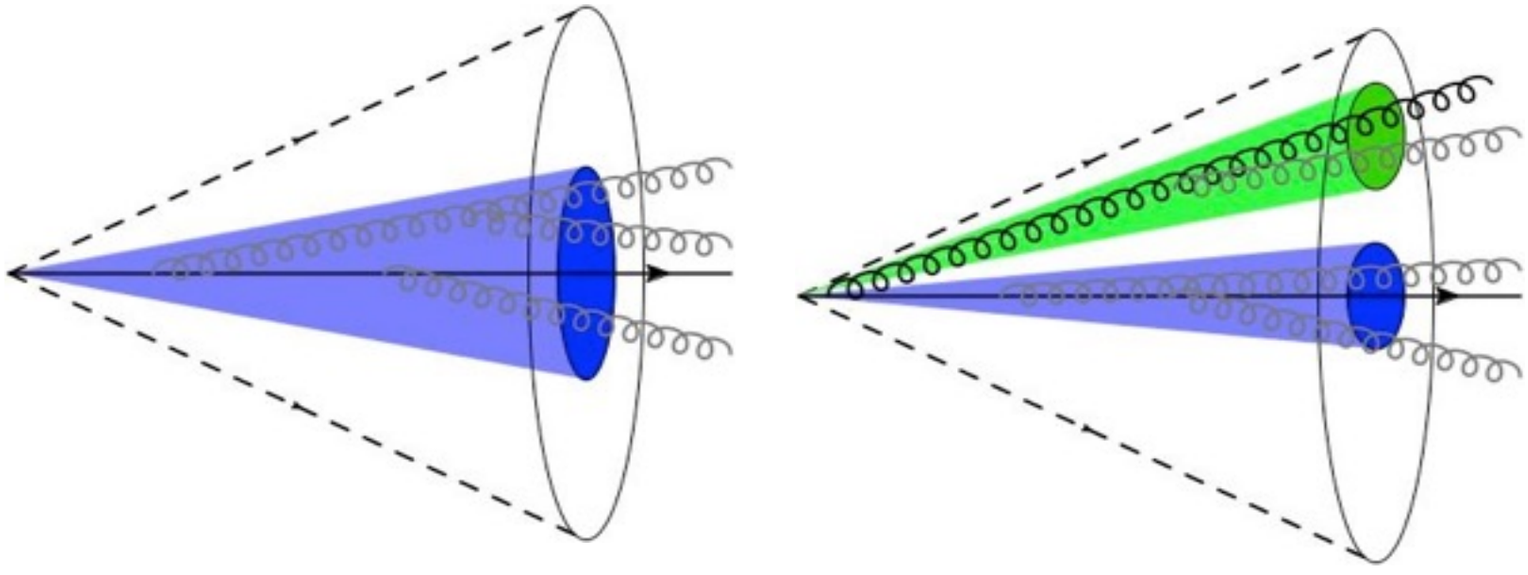
- Medium introduces a transverse resolution scale given by the average transverse momentum transfer

- Emissions at small angles are not resolved by the medium and maintain coherence

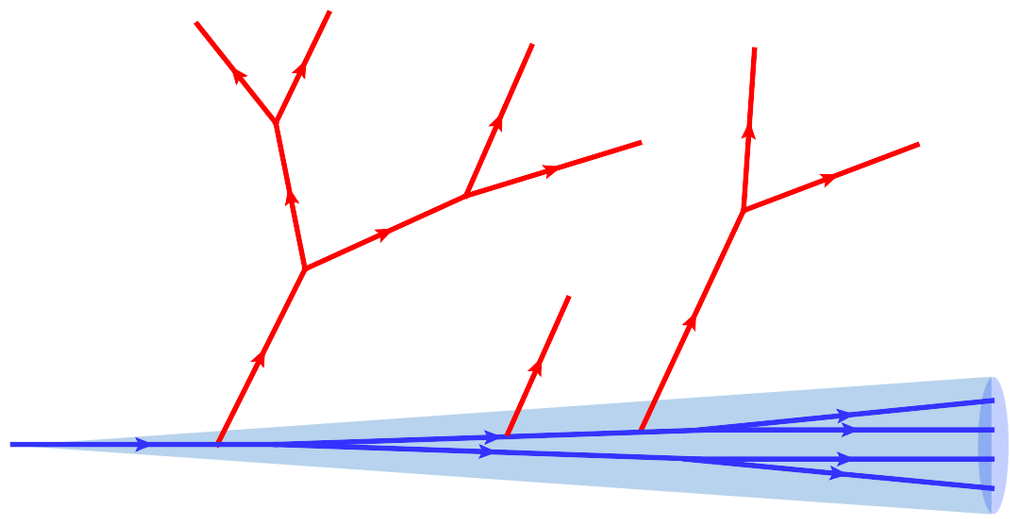
- Emissions at larger angles exchange color with the medium and coherence is destroyed

Mehtar-Tani, Salgado, Tywoniuk
Casalderrey-Solana, Iancu

Coherent energy loss

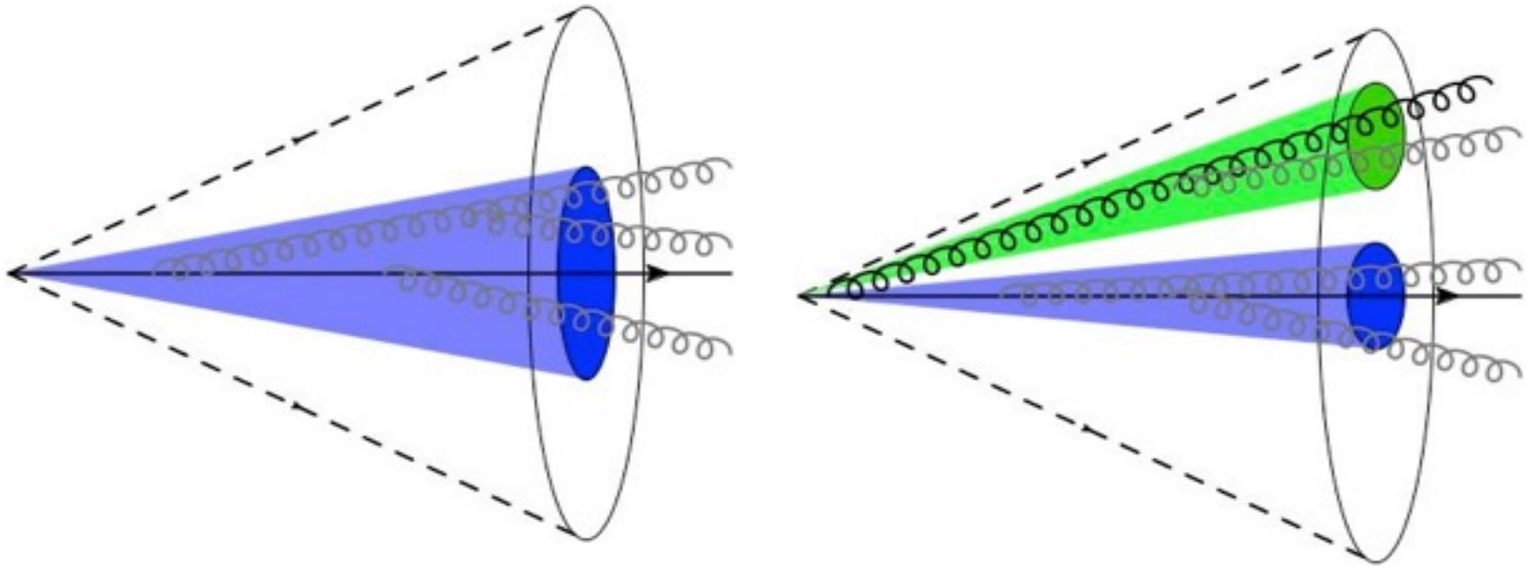


- “Fat jets” lose more energy than “narrow jets”



Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk

Coherent energy loss



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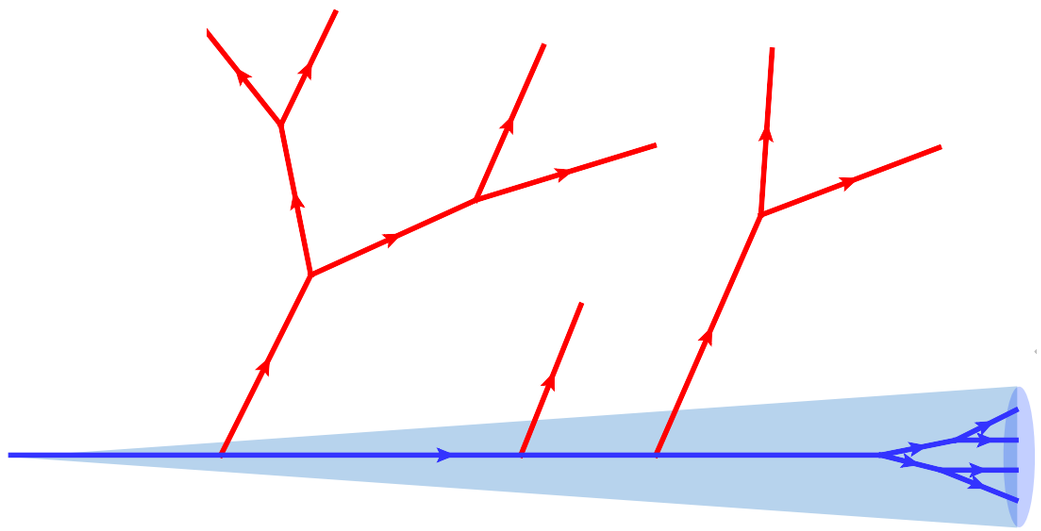


Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk

Difficulties reconciling vacuum showers with medium modification

- Antenna calculation performed only for rigid antennas as sources (external currents), not from previous emissions

- Vacuum showers are easily understood in momentum space, while medium interactions are better understood in coordinate space

- Lack of collinear divergence in medium-induced radiation complicates resummation schemes

Monte Carlo generators?

- Several implementations in the market: JEWEL, JETSCAPE, Q-Pythia, Hybrid, MARTINI…
- All based on Pythia, but with different assumptions on how it is affected by the medium
- Rely on assumptions that don’t have solid theoretical support
- A coherent picture has not emerged from all the different approaches

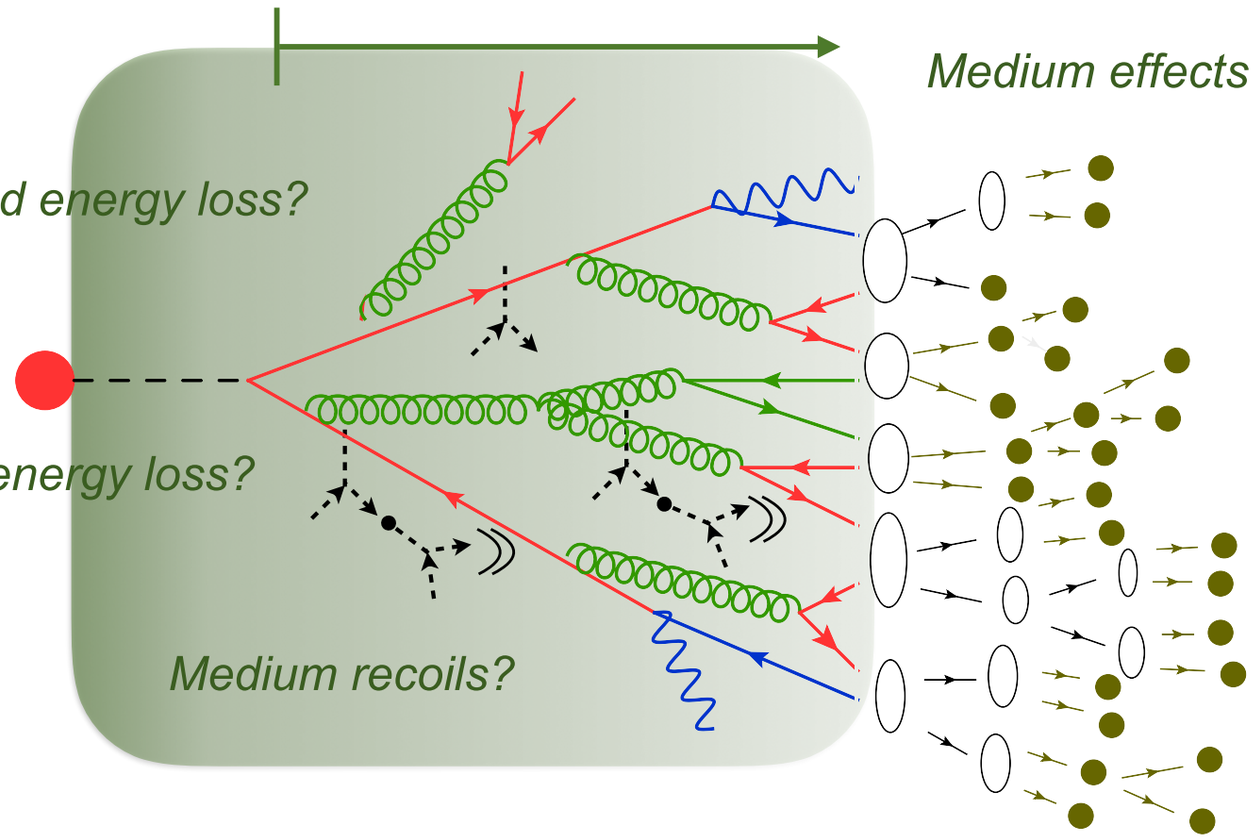
Jet Quenching Monte Carlos

- Why so many?

parton shower: fully in-medium dynamic or afterburn?

Medium effects on Hadronization?

Medium-induced energy loss?



Collisional energy loss?

Medium recoils?

Initialisation: geometry?
1st QGP interaction?

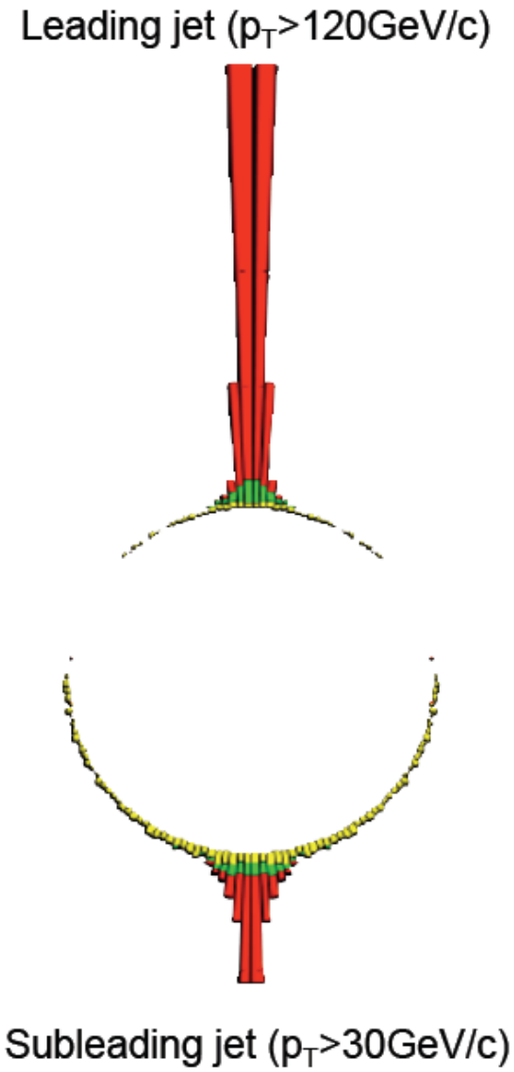
Medium: Bjorken expansion? 3D Hydro? Strong coupled?

What do we know?

- Most of the energy loss is taken away from the jet cone by soft gluons

- The amount of radiated energy seems to be independent of the path length and correlated with fluctuations on jet radius (?)

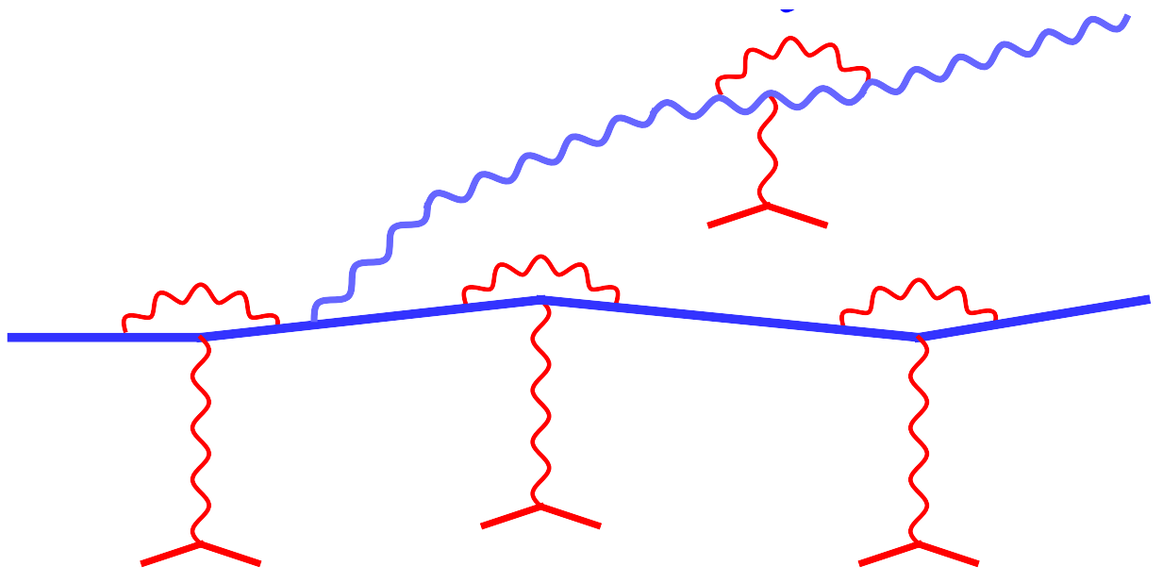
- Color coherence seems to play an important role when substructure observables are considered



Recent developments

- Radiative corrections to the jet quenching parameter
- Two-pronged energy loss
- Dynamical onset of color decoherence
- Jet substructure
- Groomed jets

Radiative corrections

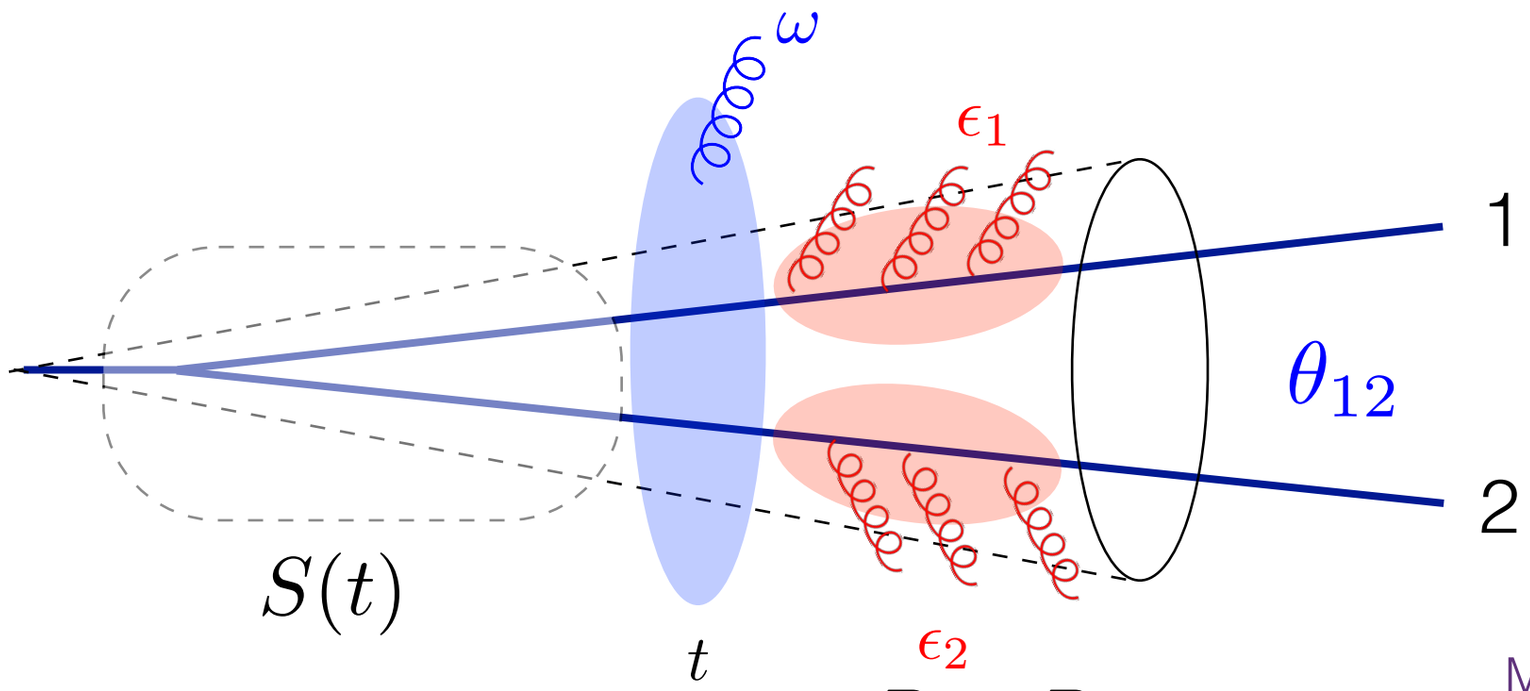


Liou, Mueller, Wu; Blaizot, Dominguez, Iancu, Mehtar-Tani

- Fluctuations due to soft gluon emissions can modify how the probe interacts with the medium

- Double logarithmic enhancement found, leading to a picture similar to the double logarithmic limit of DGLAP, with a different ordering variable

Two-pronged energy loss



Mehtar-Tani, Tywoniuk

decoherence parameter

(single) interference

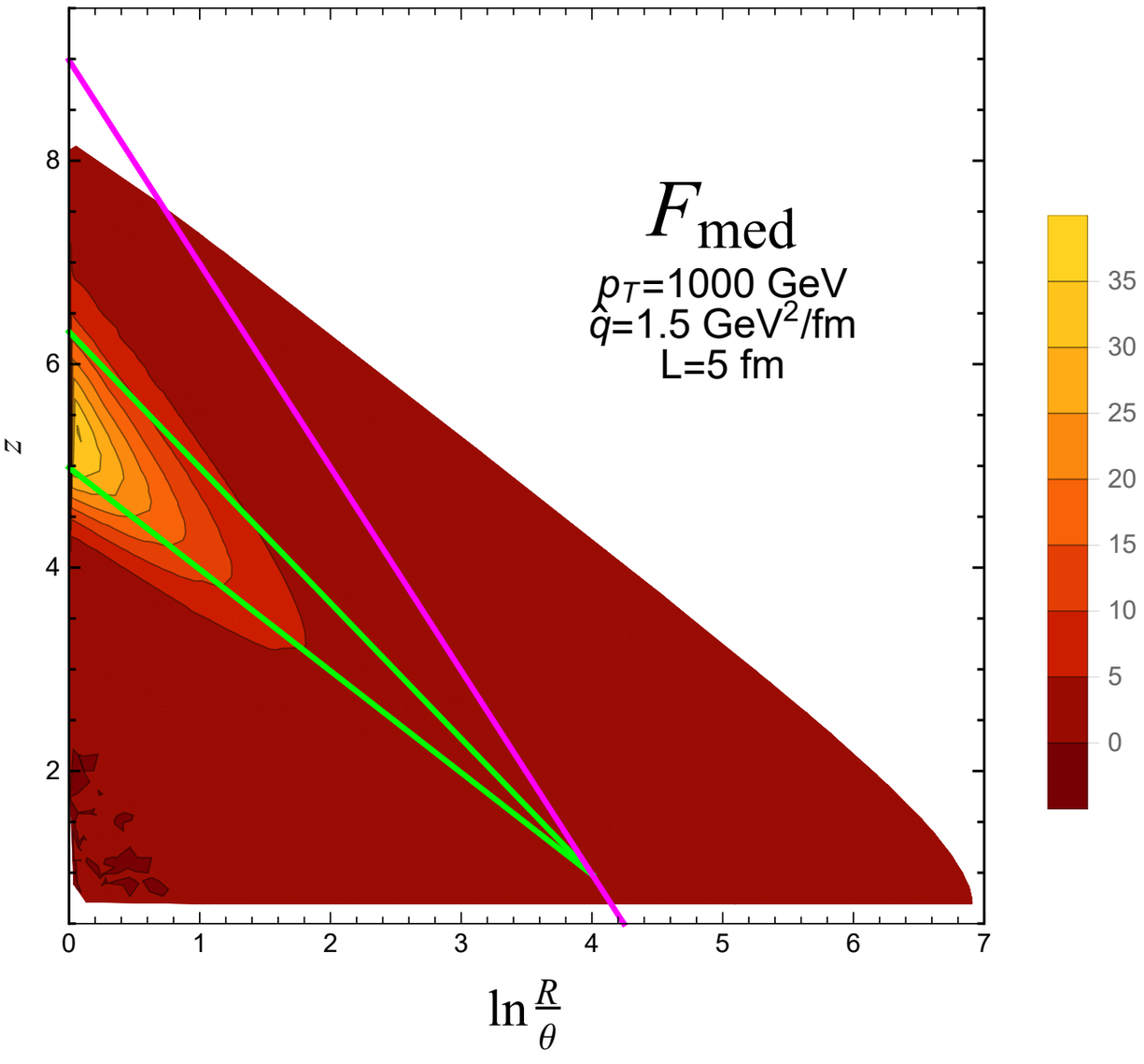
independent energy loss

- Calculate the energy loss of a color correlated set of two particles

- Allows us to go beyond the single particle description of the gluon emission spectrum

Antenna formation

- Consider emission of high energy particles
- We can account for small, finite formation times for the sources
- The probability for production can be plotted in a Lund diagram



Dominguez, Milhano, Salgado, Tywoniuk, Vila

Summary

- Still a lot of work needed before we can claim we really understand the dynamics of jet quenching in heavy ions
- New exciting results and lots of opportunities to learn about collective phenomena in QCD