HP2024 NAGASAKI

Jets and high pT

Yang-Ting Chien
Georgia State University and Jefferson Lab Theory Center

Student Lecture
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U.S. DEPARTMENT OF ENERGY | Office of Science
Georgia State University
Jefferson Lab

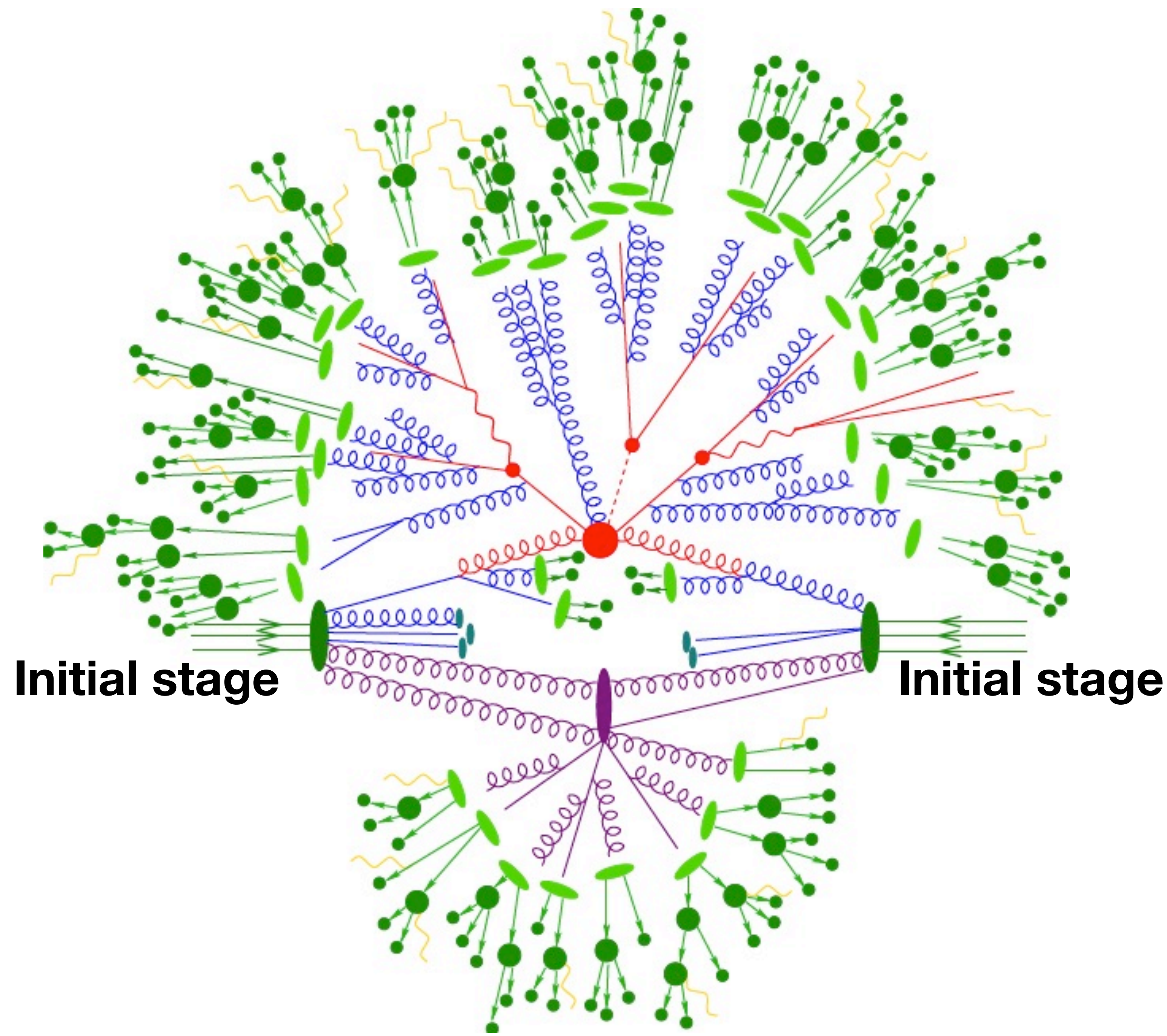
Outline

- Jets and QGP
  - Quenching and energy loss
- Jet substructure
  - Observables and techniques

Heavy flavors and quarkonia are usually part of jets with intrinsic mass scales and bound state dynamics.

(See Zebo Tang's talk)

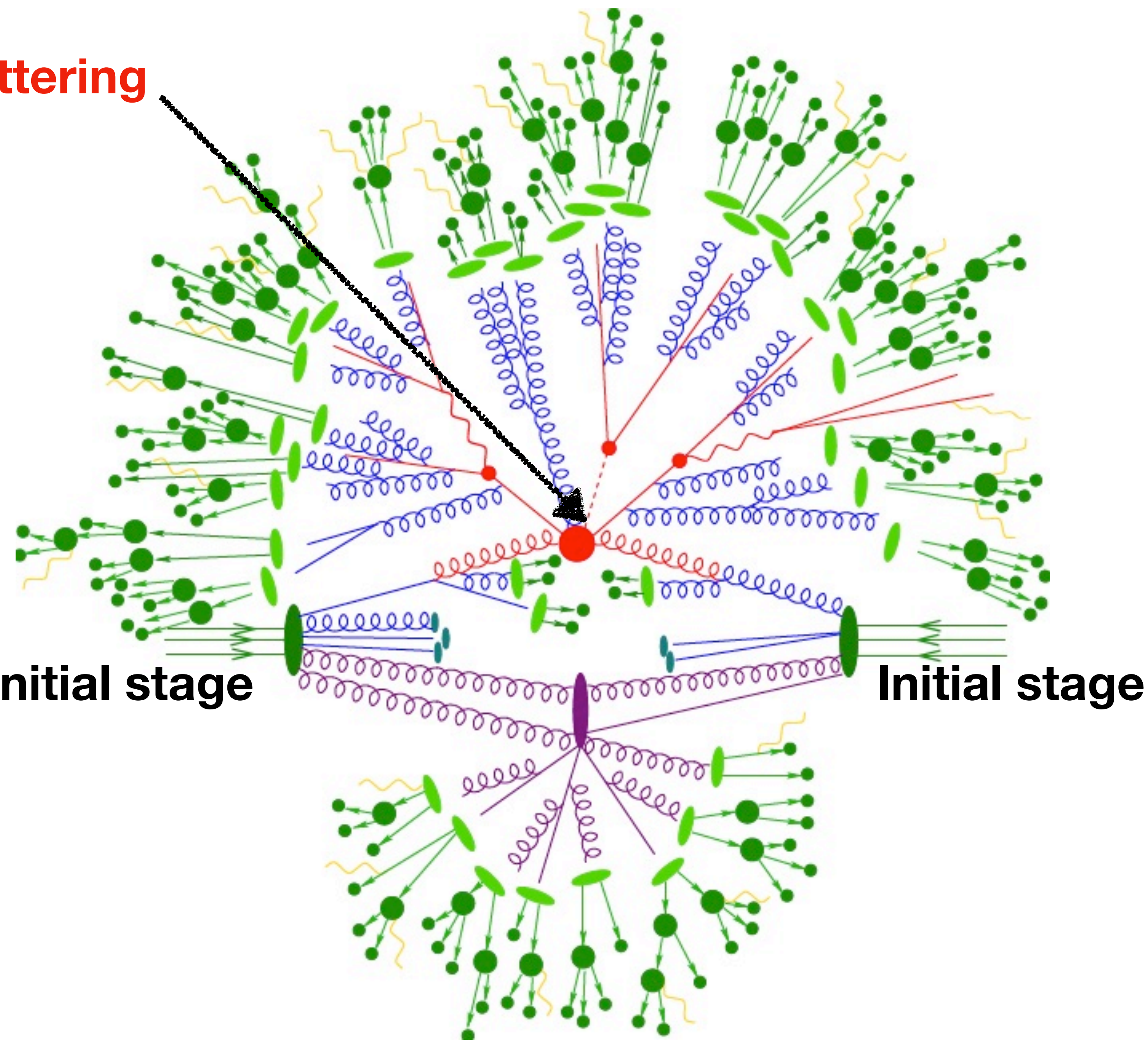
Factorization of high energy hadron collisions



Factorization of high energy hadron collisions

Produces hard probes with various quantum numbers: inclusive jets, Z/γ+jet, c/b jets,…

Short distance
High energy



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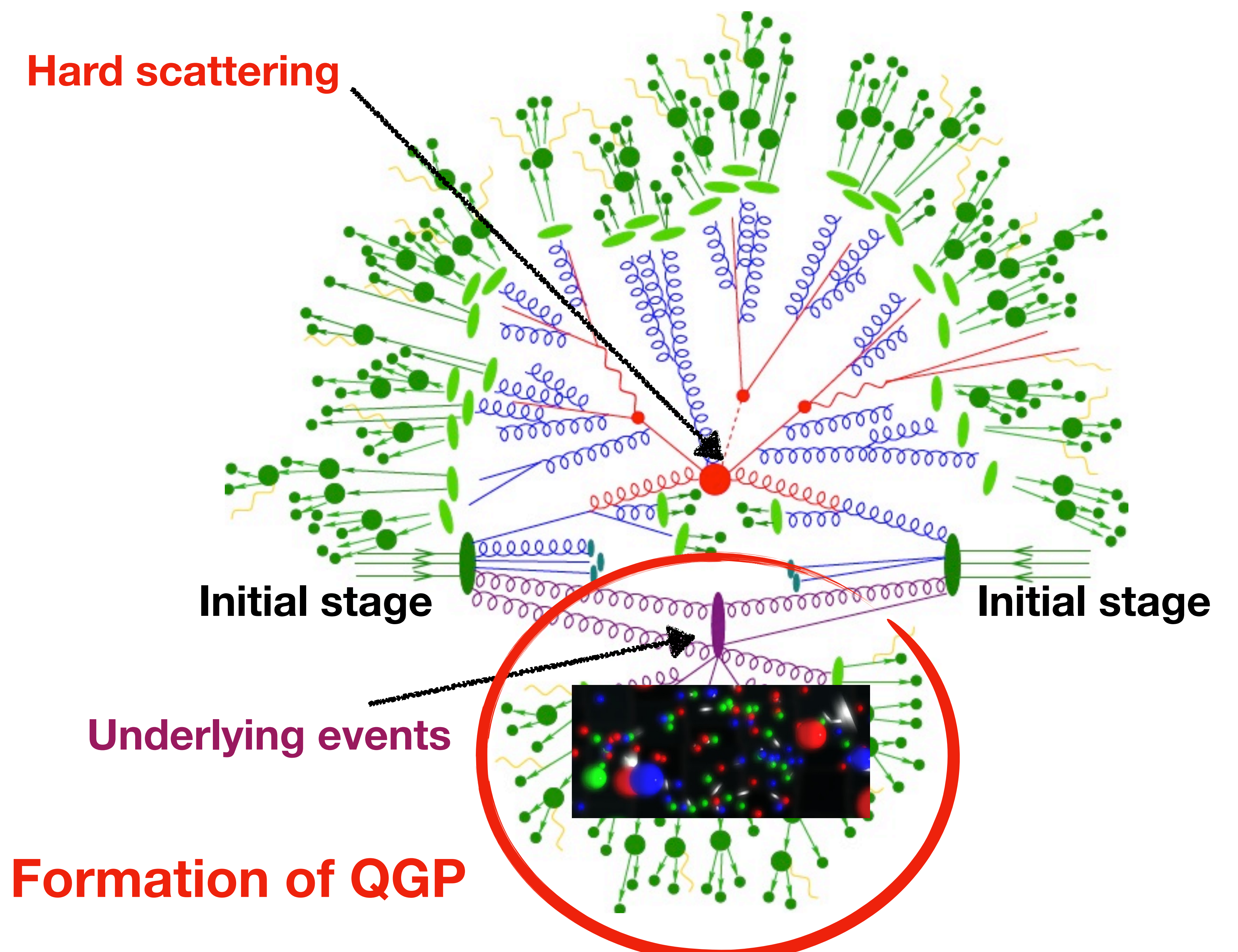
Partonic medium



Factorization of high energy hadron collisions

Produces hard probes with various quantum numbers: inclusive jets, Z/γ+jet, c/b jets,...

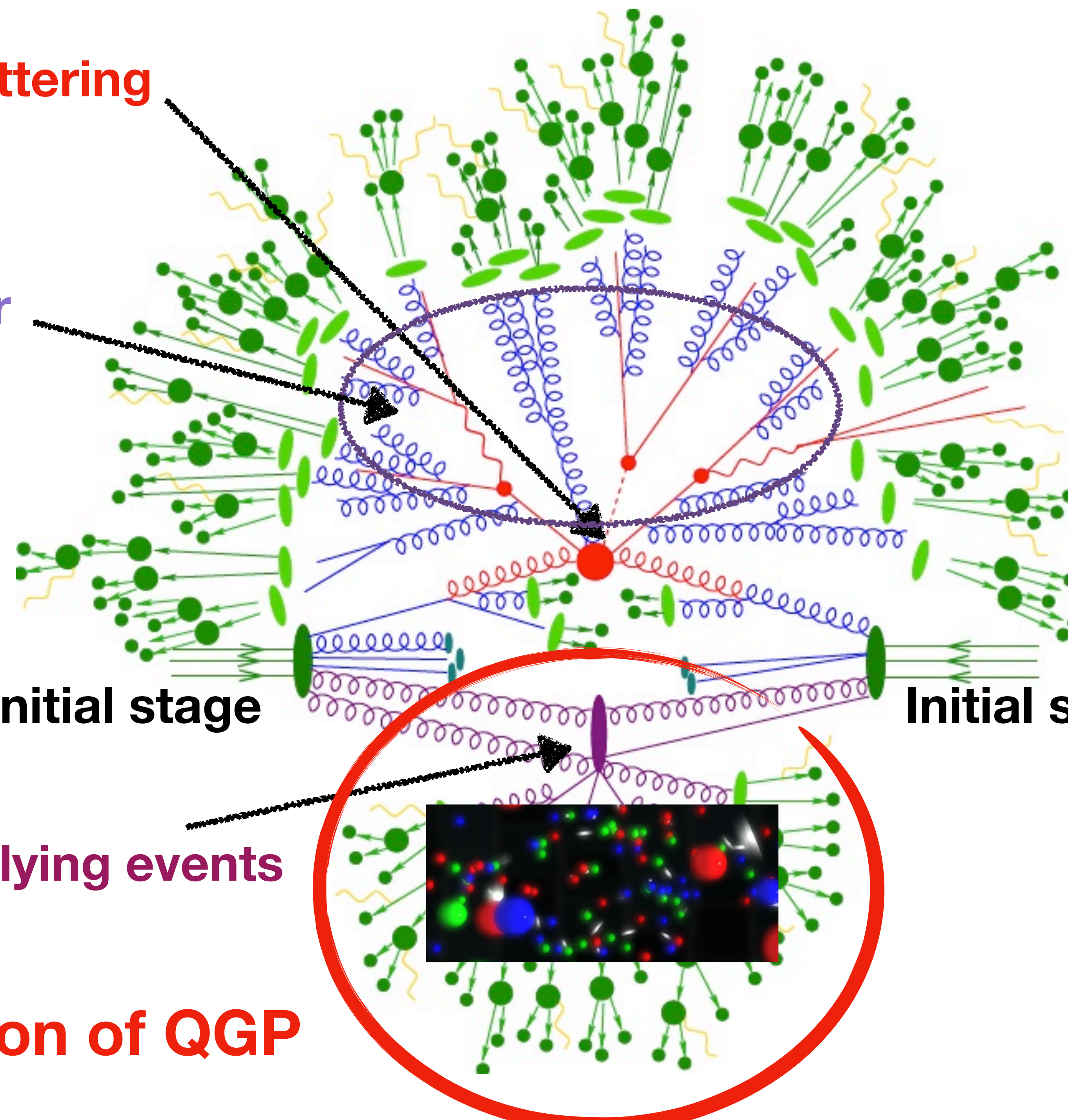
Short distance
High energy

Hard scattering

Parton shower

Sequential emissions of collinear and soft partons

Evolution of jet partonic states



Initial stage

Initial stage

Underlying events

Partonic medium

Formation of QGP

Factorization of high energy hadron collisions

Produces hard probes with various quantum numbers: inclusive jets, Z/γ+jet, c/b jets,…

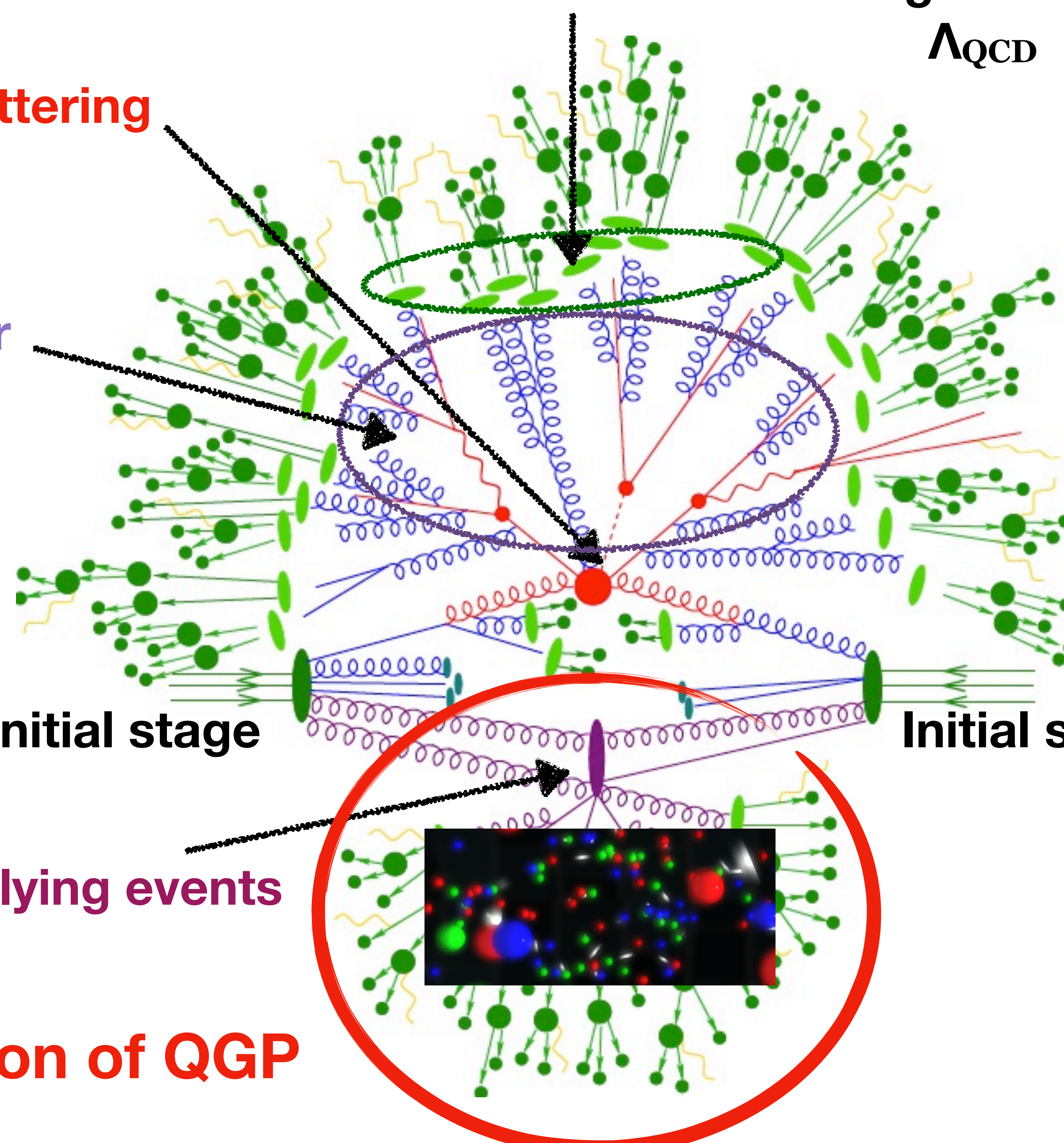
Short distance
High energy

Partons confine into hadrons

Long distance
Λ_{QCD}

Sequential emissions of collinear and soft partons

Evolution of jet partonic states



Partonic medium

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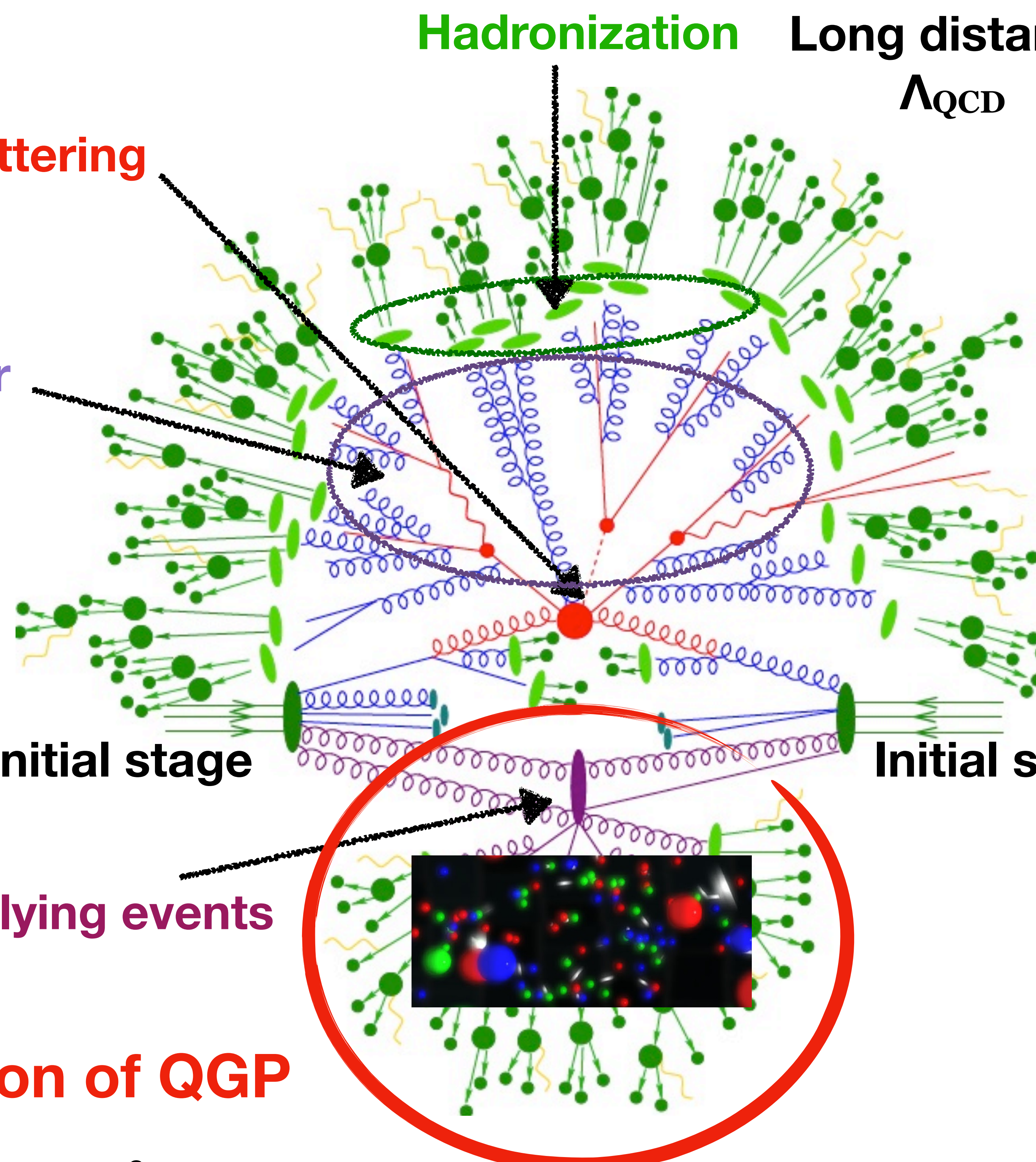

Sequential emissions of collinear and soft partons

Evolution of jet partonic states

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Produces hard probes with various quantum numbers: inclusive jets, Z/γ+jet, c/b jets,…

Short distance
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Hard scattering

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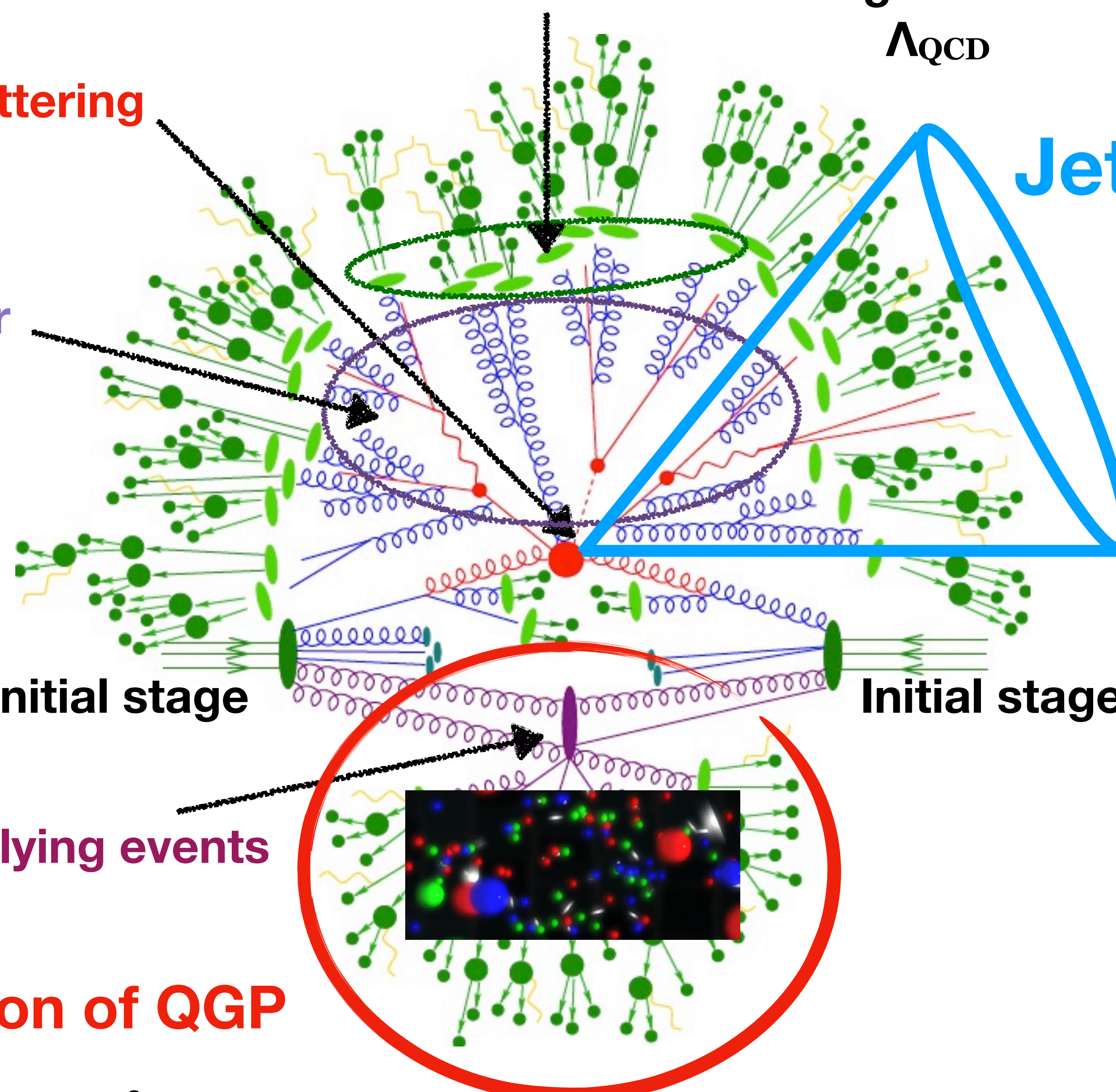
Partonic medium

Hadronization

Partons confine into hadrons

Long distance
Λ_{QCD}



Jet

Initial stage

Initial stage

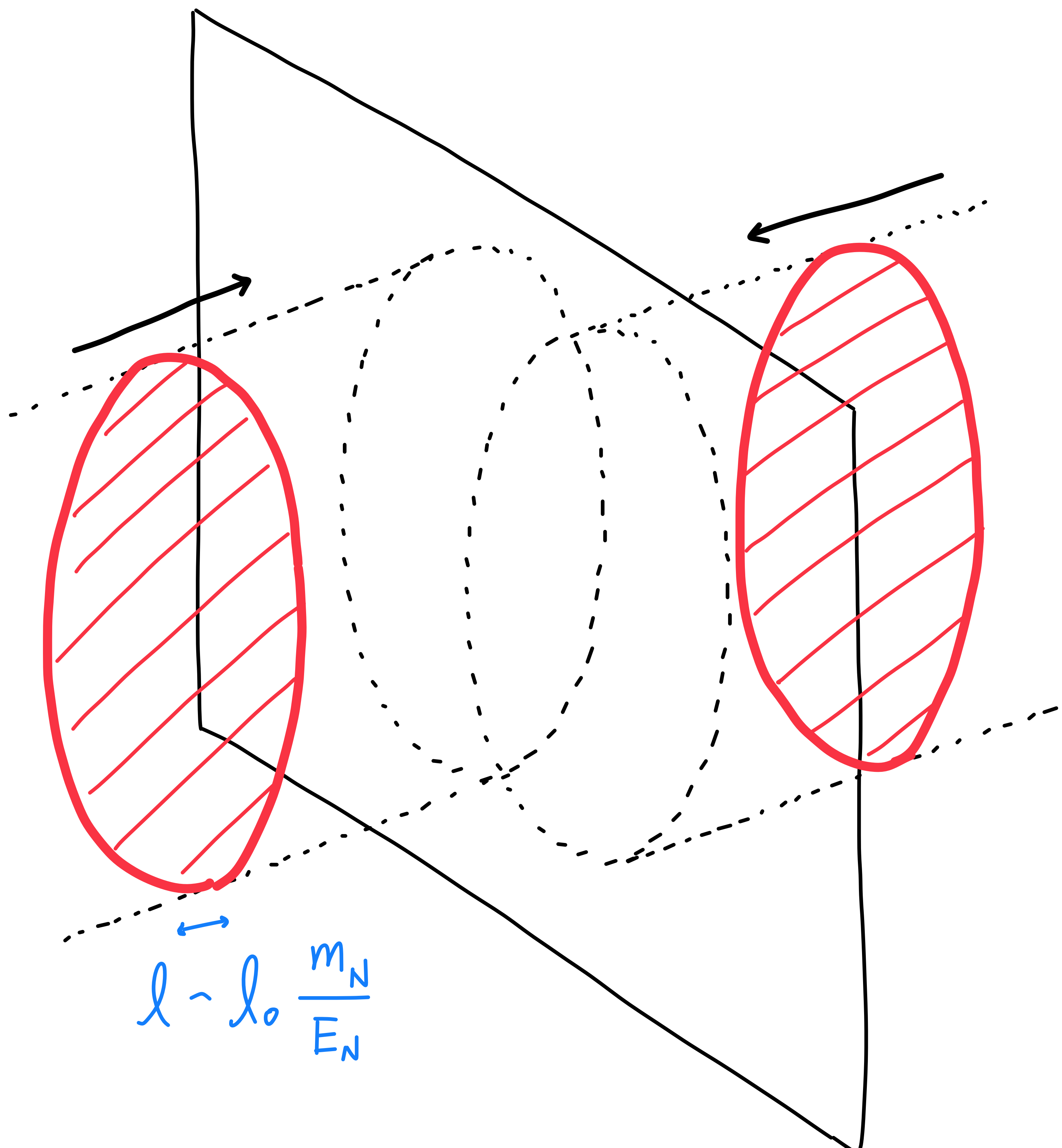
Underlying events

Formation of QGP

A spacetime picture of heavy ion collision with jets

$t<0$

heavy ions are highly Lorentz contracted in the longitudinal direction in the laboratory frame



$$l \sim l_0 \frac{m_N}{E_N}$$

A spacetime picture of heavy ion collision with jets

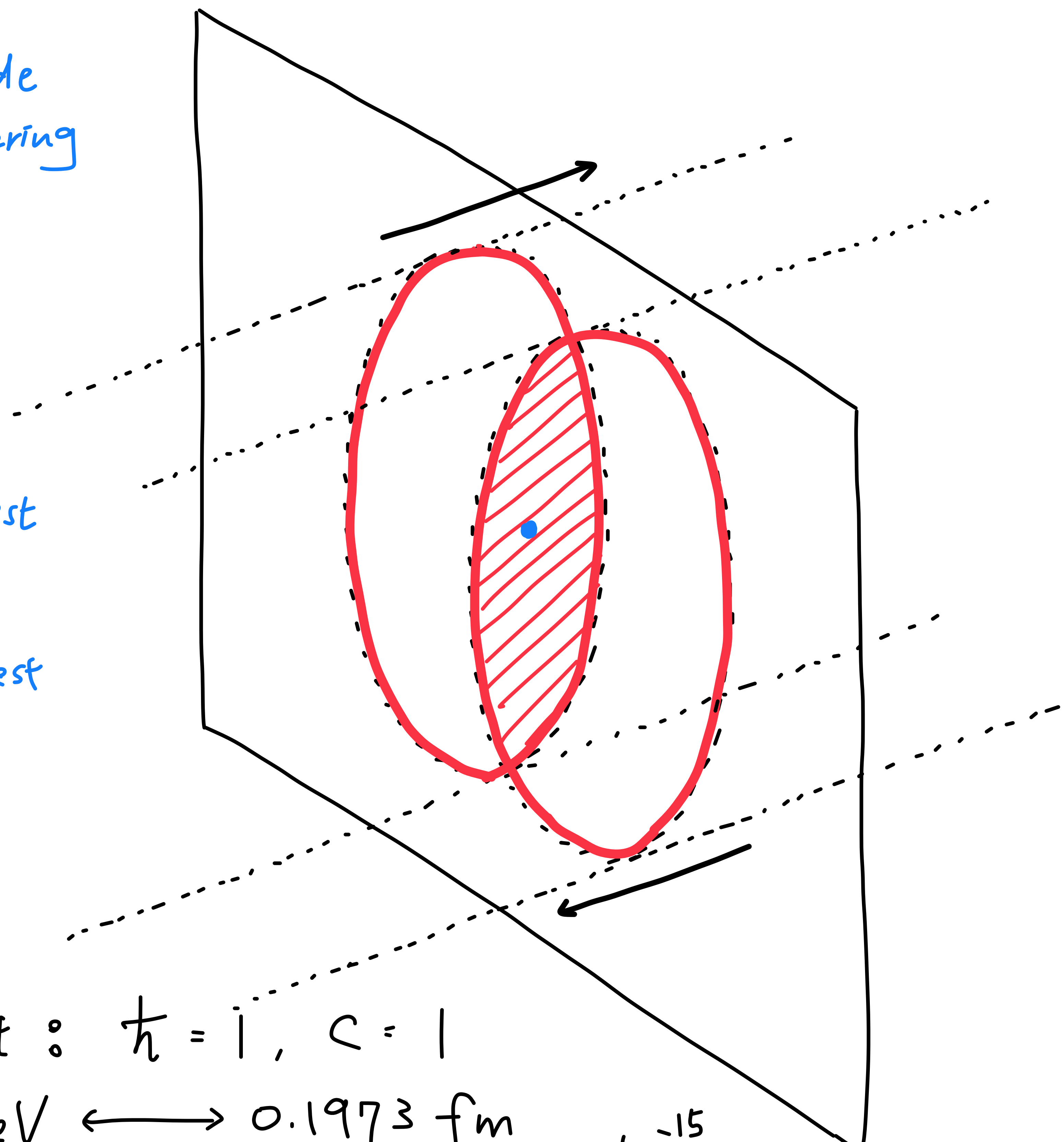
$t \approx 0$

heavy ions collide and hard scattering happens.

Hard scattering energy scale : p_T highest

time scale : $1/p_T$ shortest

$(t \approx 0)$



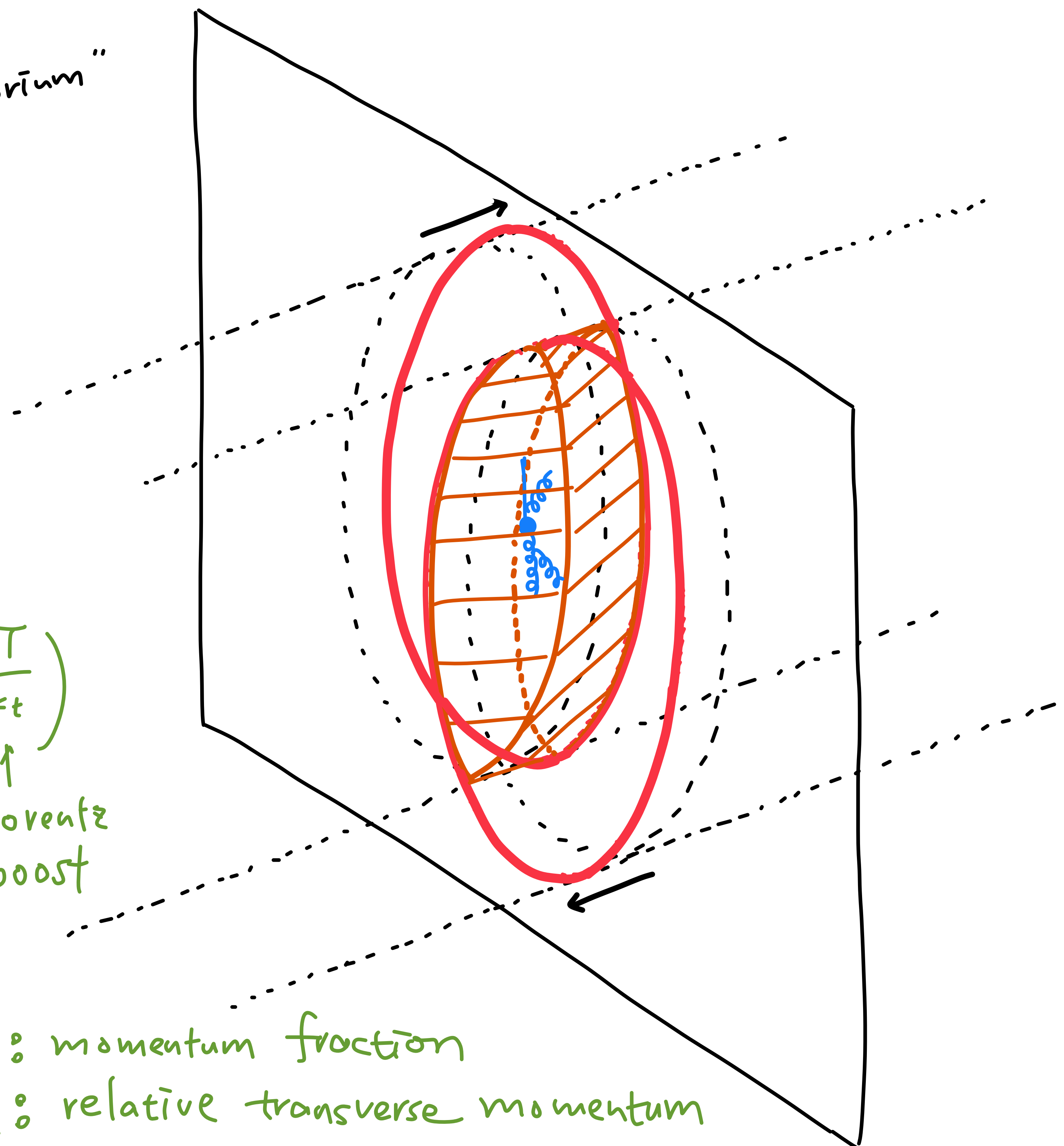
Natural Unit : $\hbar = 1$, $c = 1$

$1 \text{ GeV} \longleftrightarrow 0.1973 \text{ fm}$ → 10^{-15} m

A spacetime picture of heavy ion collision with jets

$t = t_0$

↑ "pre-equilibrium" time

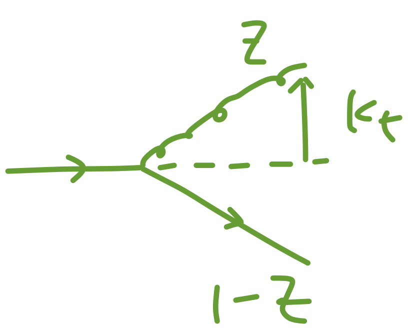


Radiation formation time

: $t_f = \dfrac{z(1-z)p_T}{k_t^2}$

$\sim \left(\dfrac{1}{k_t}\right)\left(\dfrac{p_T}{k_t}\right)$

↑ proper time ↑ Lorentz boost



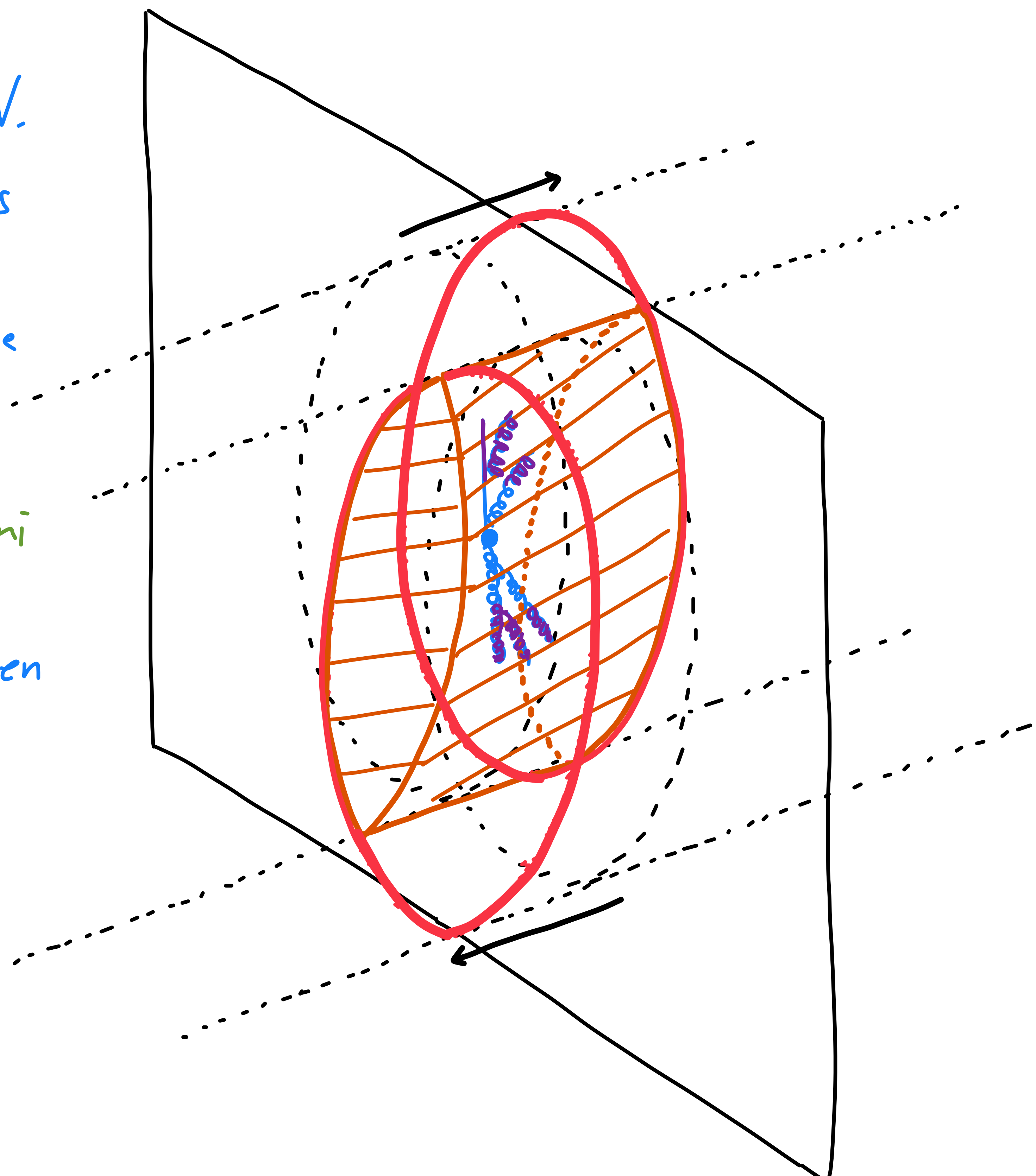
z : momentum fraction

k_t : relative transverse momentum

A spacetime picture of heavy ion collision with jets

For perturbative emissions, $k_t \gtrsim 1$ GeV.

Lorentz boost causes time dilation so t_f can be comparable to nucleus/QGP sizes: a few fermi so that such emissions can happen inside the QGP



A spacetime picture of heavy ion collision with jets

Another important time scale is the QGP lifetime t_c

An estimation from Bjorken expansion

$$t_c = t_0 \left(\frac{T_0}{T_c} \right)^3$$

Say $T_0 \approx 250\,\mathrm{MeV}$

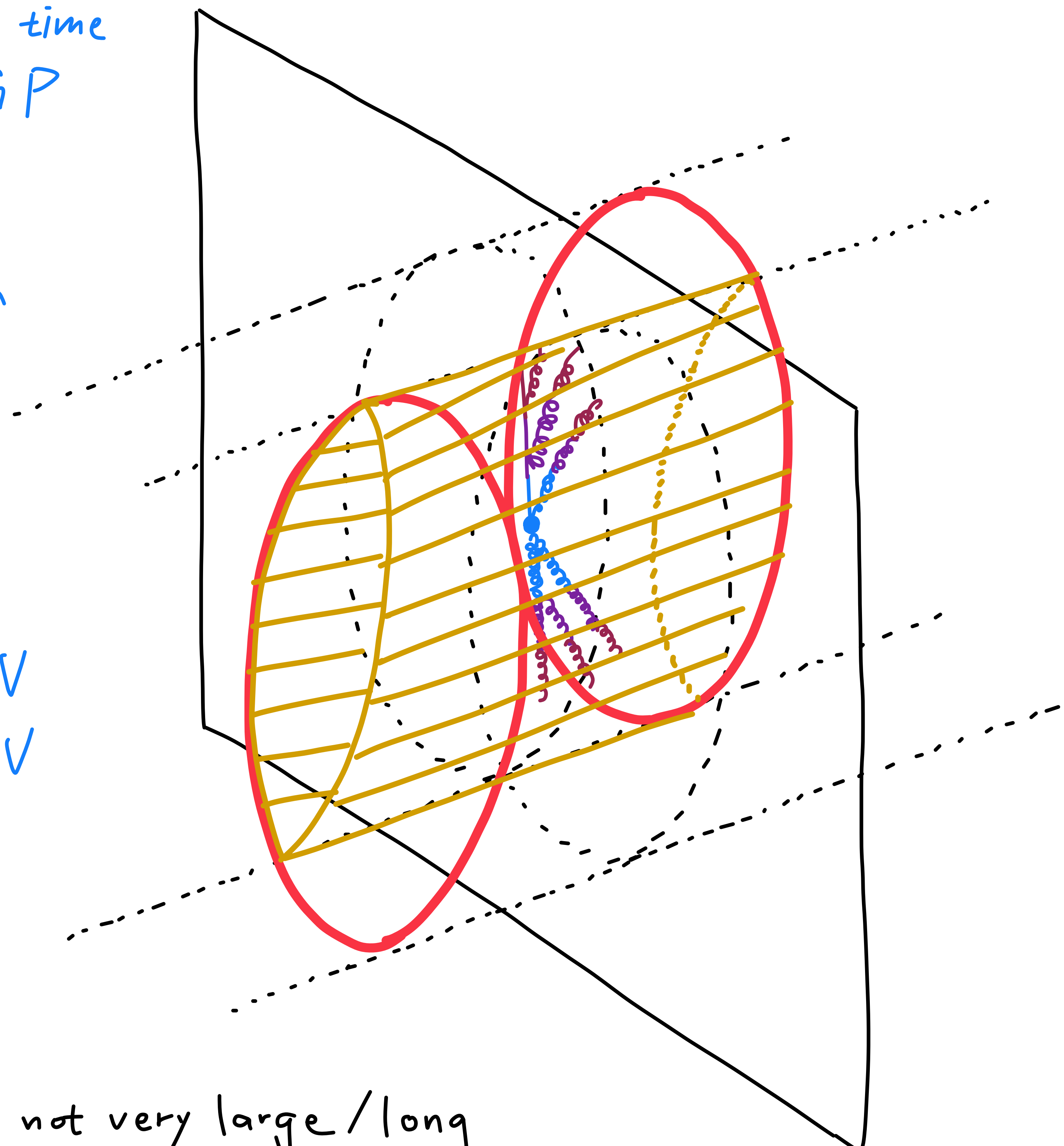
$T_c \approx 170\,\mathrm{MeV}$

$t_0 \lesssim 1\,\mathrm{fm}$

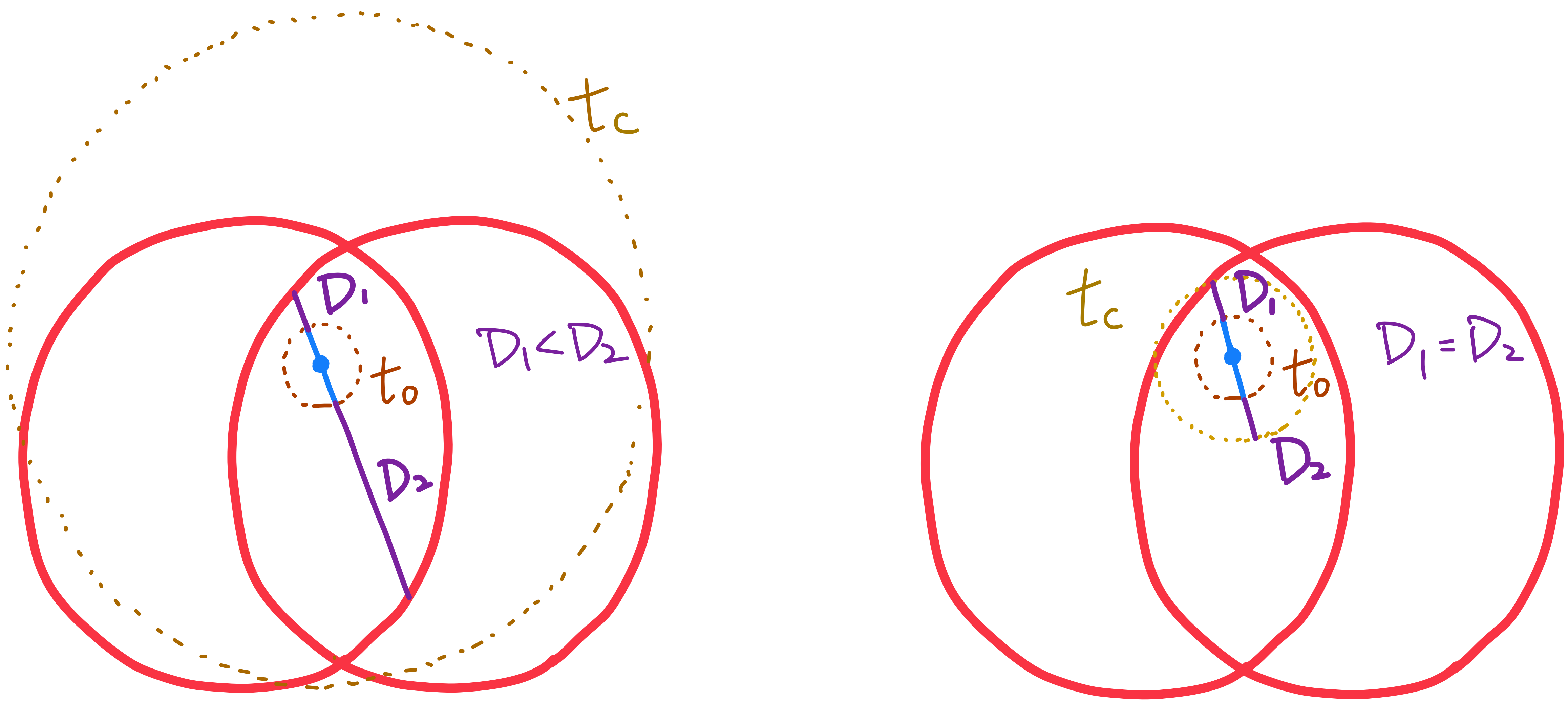
then

$t_c \lesssim \underline{3.2\,\mathrm{fm}}$

actually not very large/long



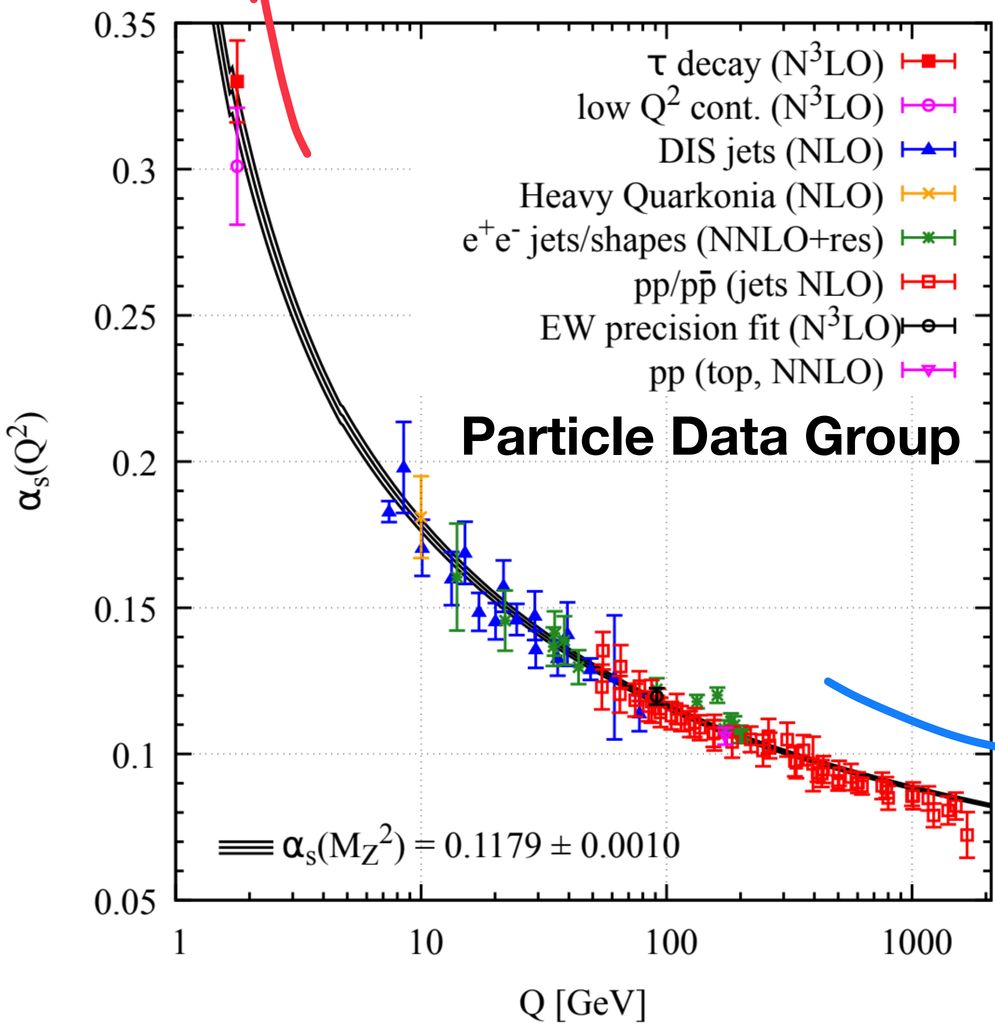
Path-length dependence



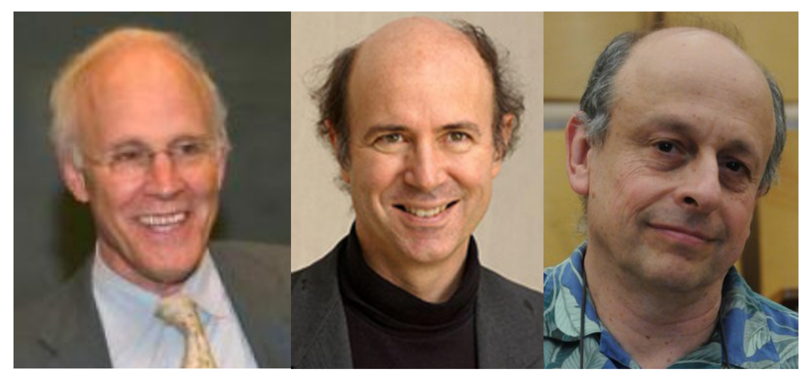
The "path-length" of jets passing through QGP depends on the geometry (hard scattering location, centrality, jet direction, etc) and also the QGP lifetime

Quantum Chromodynamics (QCD)

Color confinement



QCD is formulated using quarks and gluons (partonic degrees of freedom), while hadrons are the observable final states. Thanks to asymptotic freedom, these hidden partons leave clear signature in collider events.

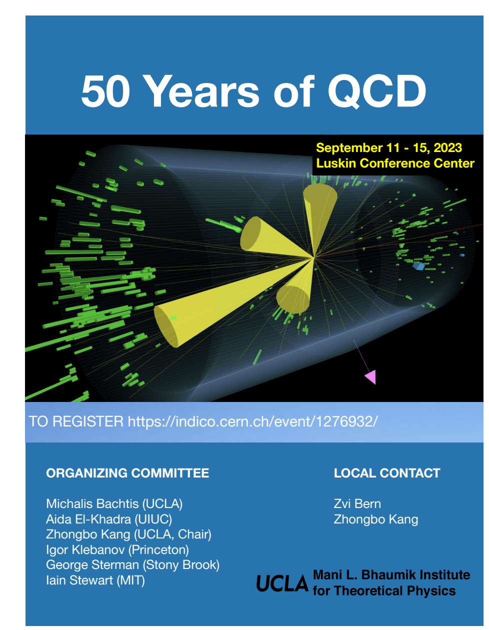


Gross, Wilczek, Politzer
asymptotic freedom (1973)

The coupling is large at low energy and small at high energy

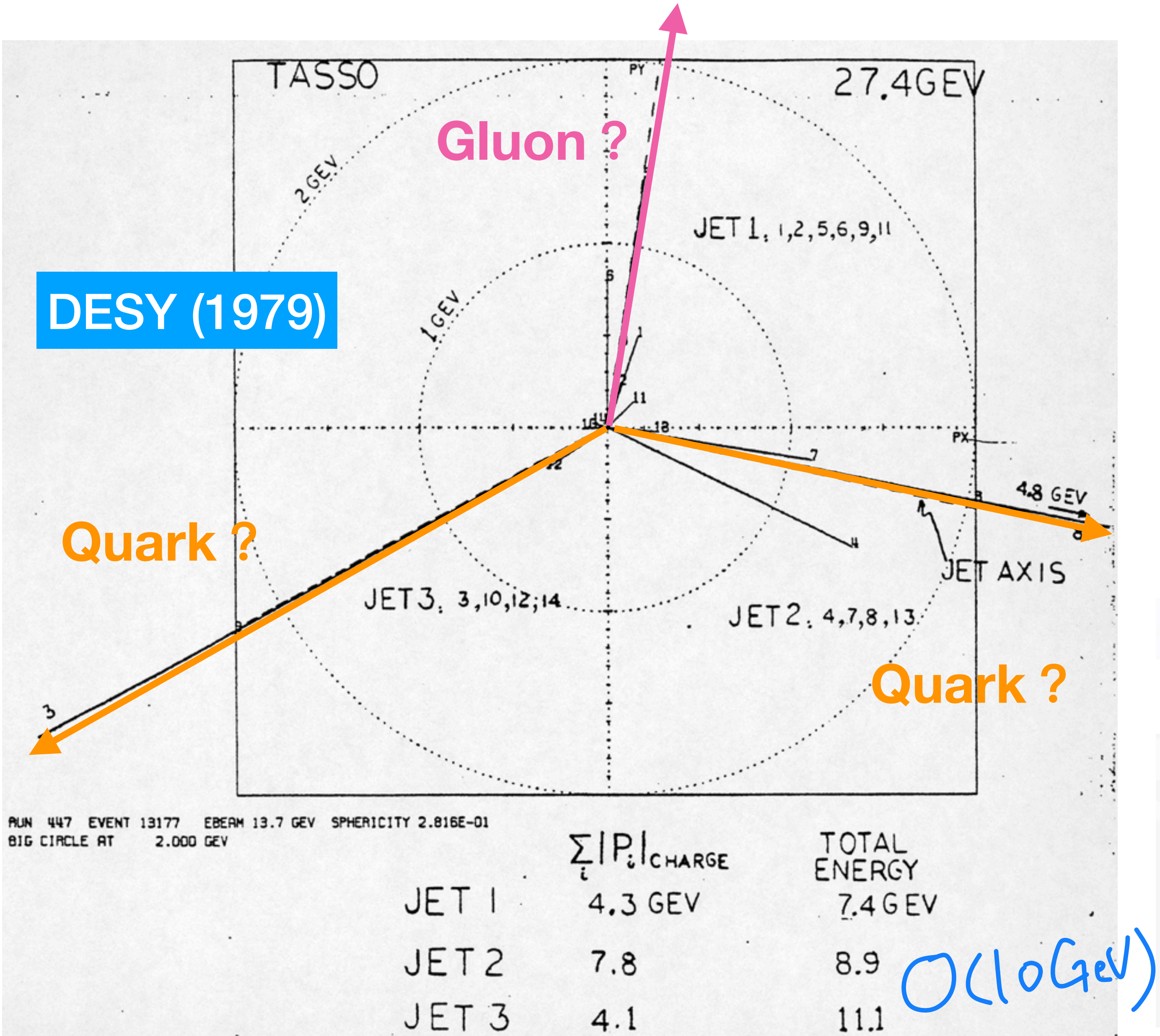
Nonperturbative
Lattice simulation

Perturbative
Series expansion

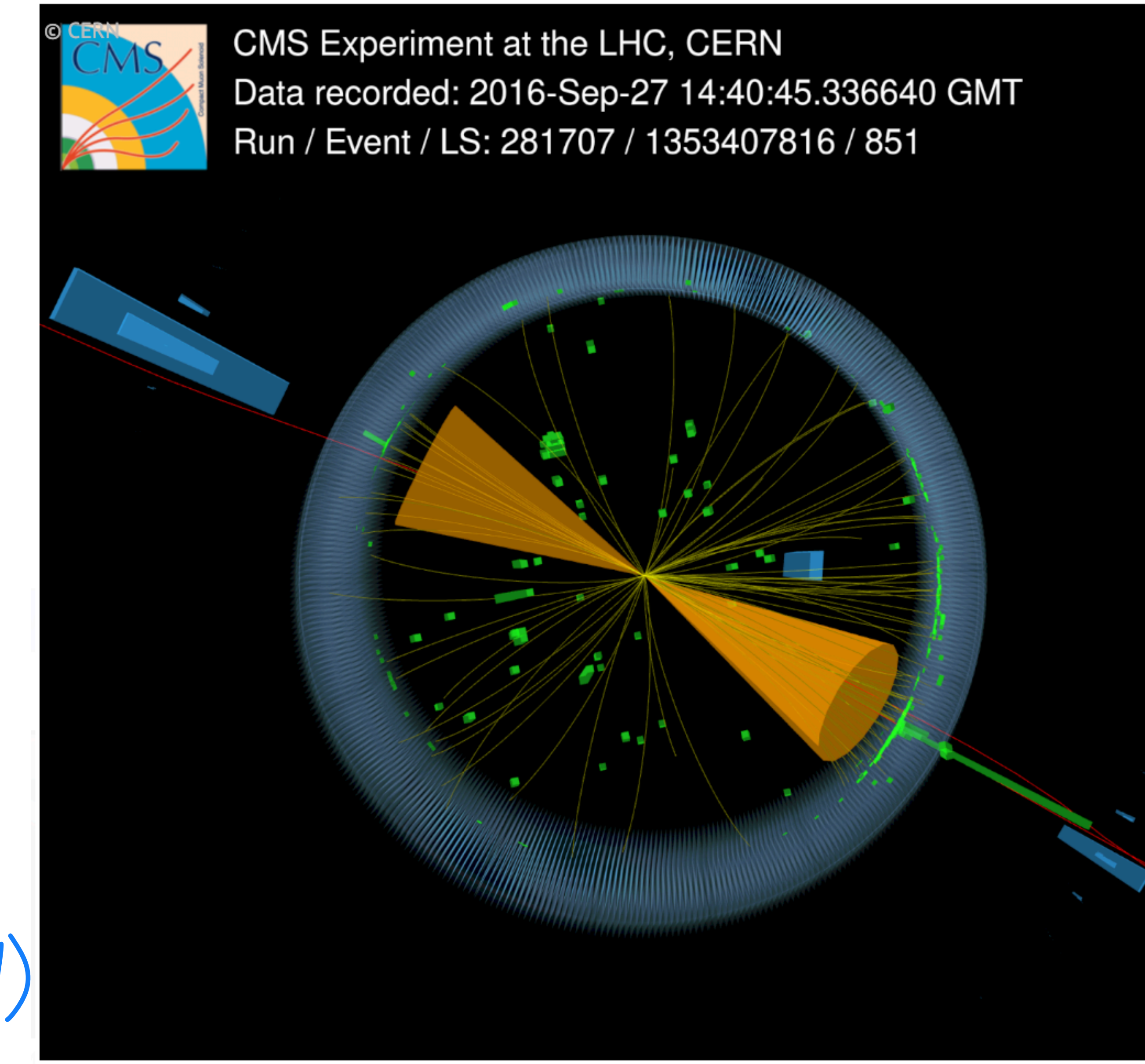


Many excellent talks at “QCD at 50” at UCLA (YouTube link here)

Jets are manifestation of underlying partons

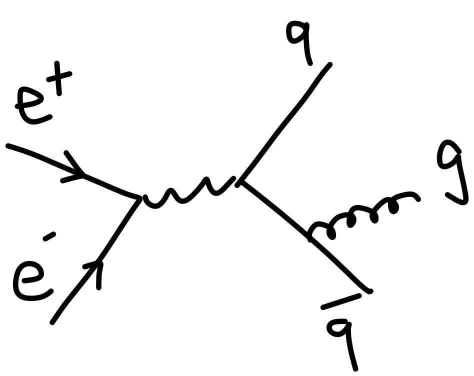


3-jet event confirming the existence of gluon



CMS-PHO-EVENTS-2021-020-1 - Small, Medium, Large, Original

This is an event with two jets (orange cones) with transverse momentum of more than 3 TeV each, produced in proton-proton collisions at a centre-of-mass energy of 13 TeV at the LHC.

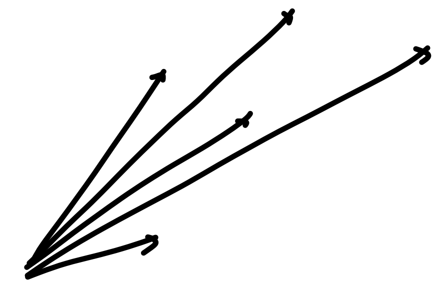


O(1 TeV)

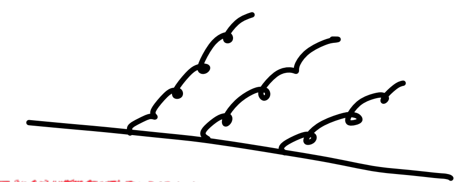
accross 2 orders of magnitude !

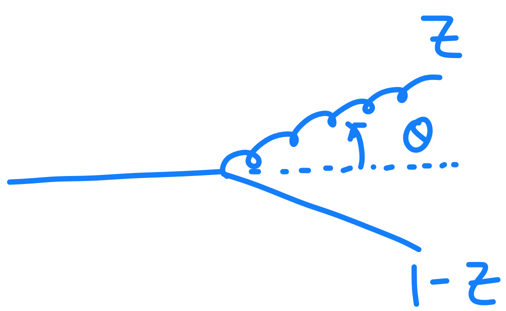
Soft and collinear emissions in jets

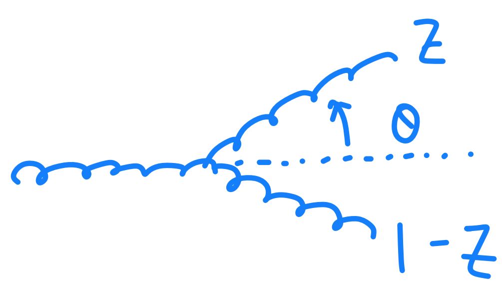
Jets are directional structures produced in high energy collisions: each with a bunch of collimated particles. This is a general feature of gauge theories in 3+1 D.



State of the art: 4 partons in the final state







P(z, θ) becomes large when $z \to 0$ (soft) or $\theta \to 0$ (collinear)

Probability(z, θ) in the collinear limit

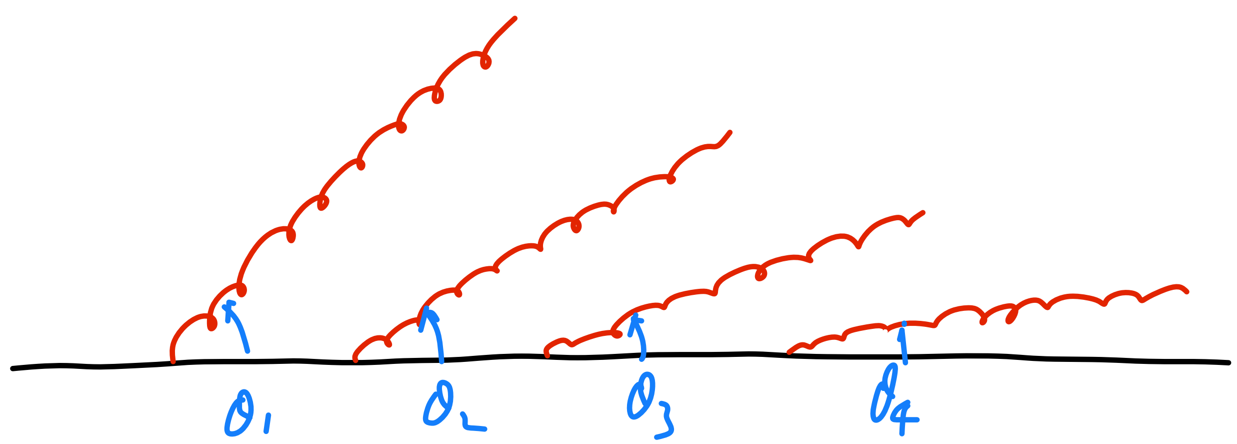
$$\propto \frac{\alpha_s}{2\pi} \cdot C_i \cdot P_{i\to jk}(z) \cdot \frac{1}{\theta}$$

↑ coupling strength
↑ "color charge"
↑ Alteralli-Parisi splitting function $\propto \frac{1}{z}$ in the soft limit

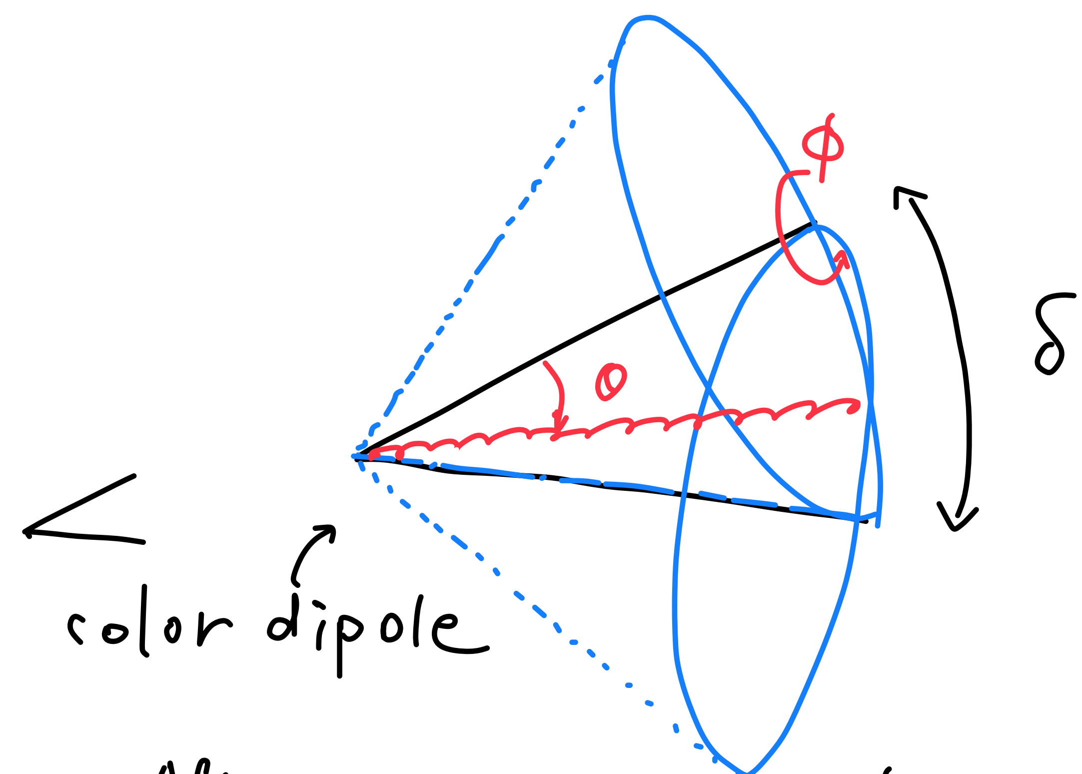
Color coherence

How about multiple, sequential emissions?

Quantum interference results in color coherence, which leads to angular ordering of gluon emissions



$\theta_1 > \theta_2 > \theta_3 > \theta_4 > \cdots$



After averaging over the azimuthal angle ϕ, the emission probability is only nonzero for $\theta < \delta$

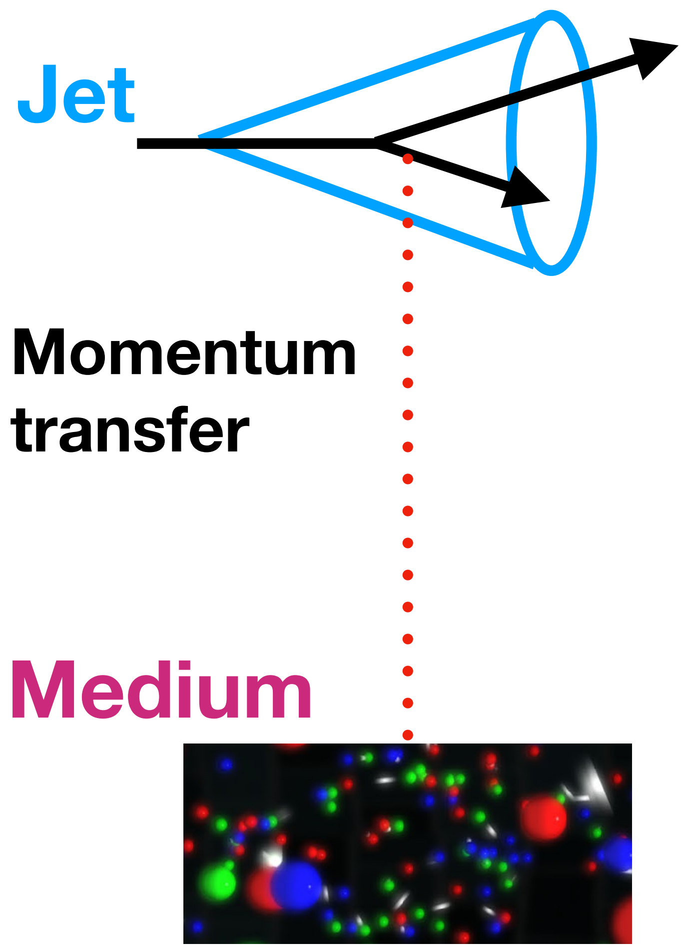
Radiation confined inside the two cones

$t_f \sim \frac{1}{k_t}\frac{1}{\theta}$

$\frac{1}{k_t} > t_f \cdot \delta$

transverse wavelength > dipole separation, then the emitted gluon can not resolve the color dipole

Jet-medium interactions

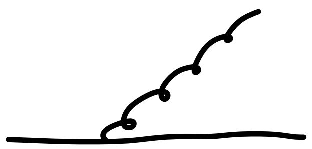


How jets couple to medium depends on the medium "models", which are still challenging to describe from first principle. Some qualitative features about jet-medium interactions have been derived, and we are moving towards more quantitative descriptions.

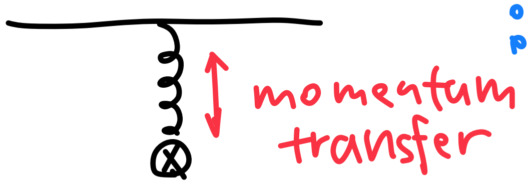
With various regimes of medium density, size, radiation phase spaces

- Color charge distribution — soft-gluon limit, BDMPS-Z, GLV, higher-twist, $SCET_{Glauber}$
- Quasi-particles/recoil — LBT
- Background field — jets as open quatum system
- QCD at finite temperature — thermal field theory, AMY
- Hydrodynamic fluid — EPOS
- Strongly-coupled liquid — AdS/CFT
- Color strings/tubes — Pythia underlying events / Angantyr

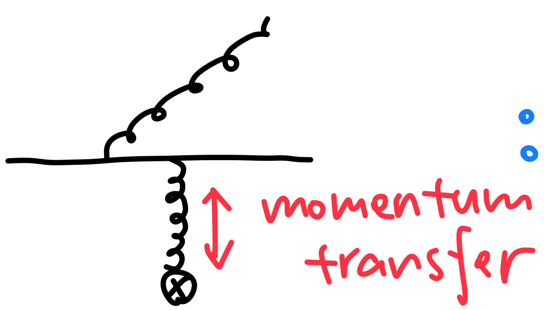
In-medium parton evolution



: Vacuum-like radiation

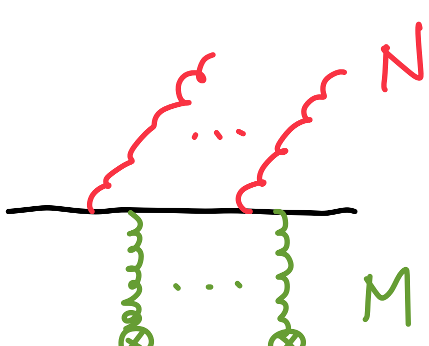


: Collision



: Medium-induced radiation

↓



multiple emissions

multiple scatterings

$\hat{q}$: jet transport parameter

$\hat{q} : \frac{\langle k_t^2 \rangle}{t}$ $\quad k_t$: cummulated transverse momentum after propagating for a time t

$$\left[\frac{GeV^2}{fm}\right] \sim [M^3]$$

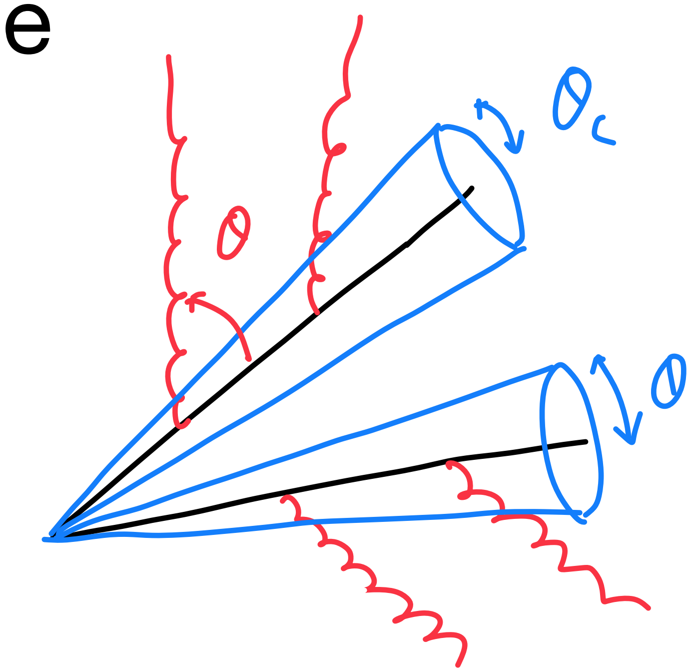
Landau-Pomeranchuk-Migdal (LPM) effect:

During multiple scattering, if the formation time t_f of induced radiation is long compared to mean free path λ, then the radiation can not resolve the nearest scatterings resulting in the suppression of induced radiation

Color decoherence

As we saw, if vacuum radiation by itself can not resolve the color dipole, then color coherence will restrict the radiation to be angular ordered.

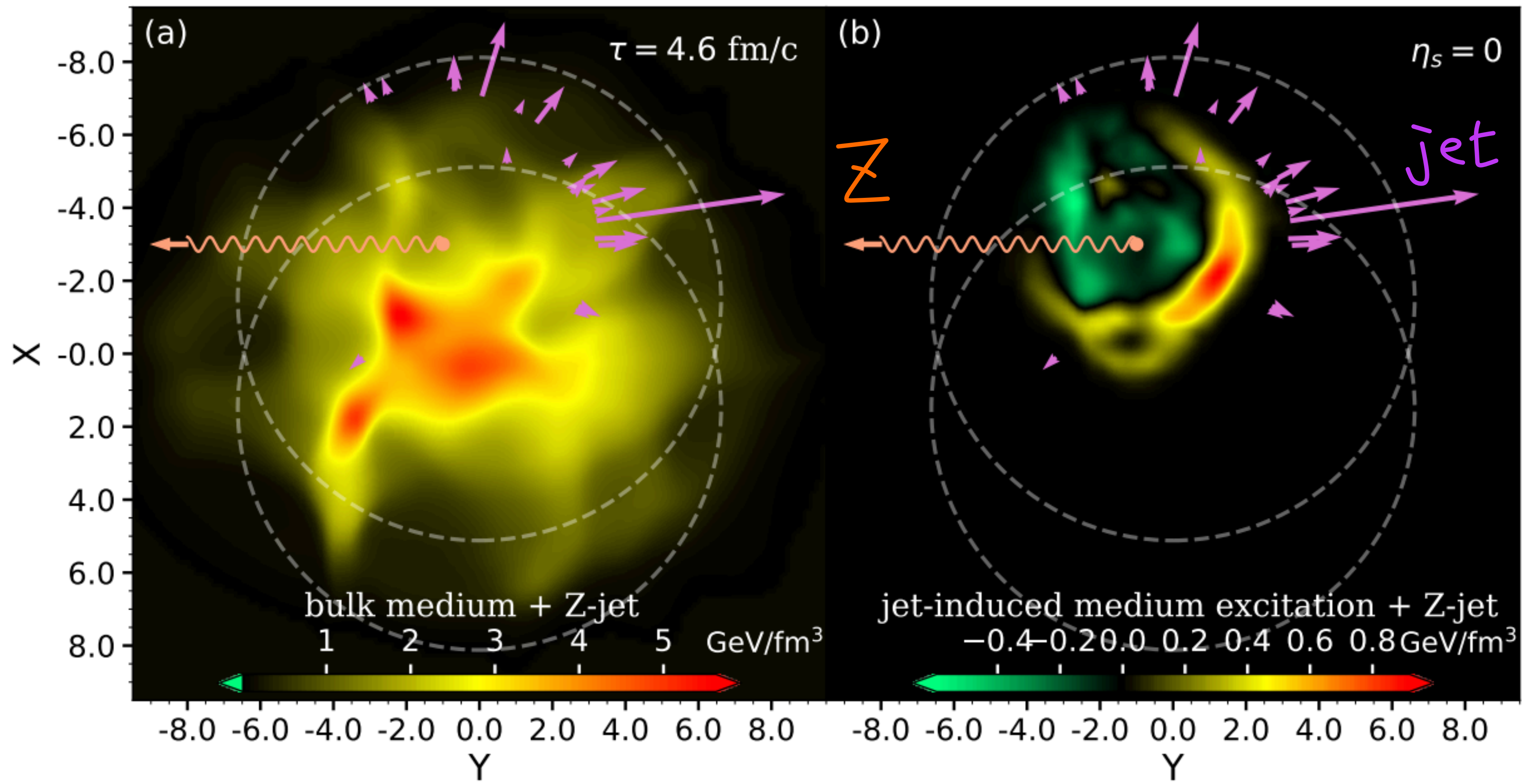
However, with the presence of the medium, the color dipole can be resolved by medium interaction with a resolution angle $\theta_c \sim \frac{1}{\sqrt{\hat{q} \cdot L^3}}$



Wide-angle, soft emission, should be more pronounced

Depending on the jet substructure, the induced radiation may be different: correlation between jet quenching and jet substructure

Medium response and diffusion wake

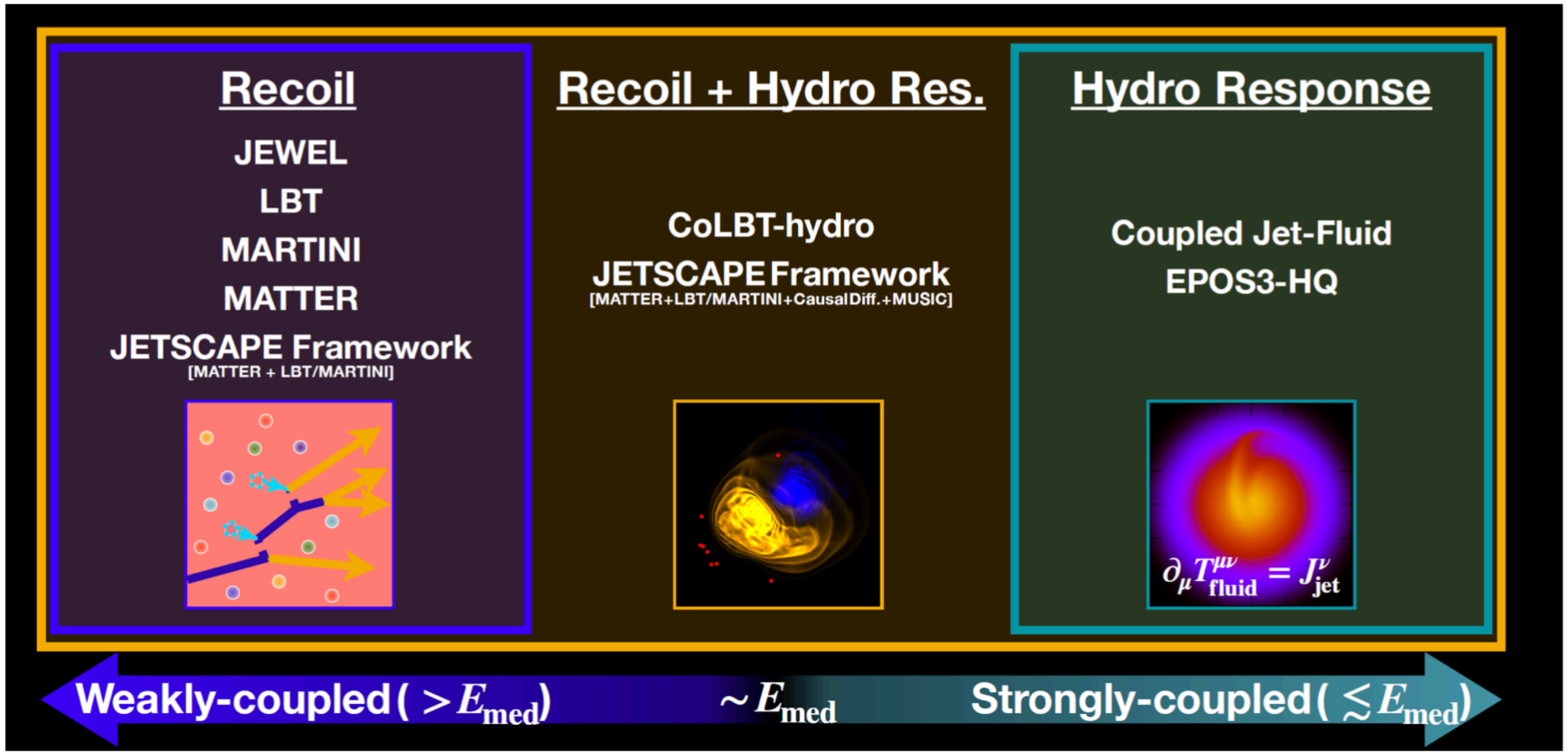


CoLBT-hydro

The back reaction from jets to the medium, in principle, is called medium response.

The study depends on the ability of simulating medium evolution through hydrodynamics or recoil

Monte Carlo implementations



↙ Just to name a few

Picture credit: Y. Tachibana

Other Monte Carlos serving various purposes

: Hybrid (Ads/CFT),

JetMed

Q pythia

Pythia / Angantyr

A full calculation to put together jet and medium evolution require Monte Carlo implementations.

Also, this comprehensive approach is not limited by observables of interest, but require stringent constraints from data through vigorous Bayesian analysis.

Jets are defined by jet algorithms

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Jets from Quantum Chromodynamics

George Sterman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

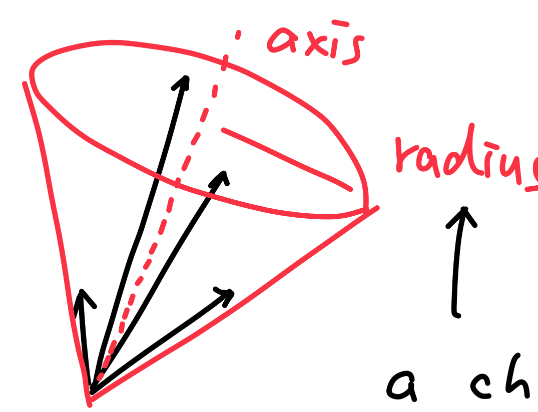
and

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 26 July 1977)

Sterman - Weinberg, 1977

$\hat{n}$ ← dynamically determined



R

↑

a chosen parameter to localize energy flow. It doesn't mean that jets have intrinsic sizes or isolated. Out of jet radiation can be significant

The first Infrared and Collinear (IRC) safe jet definition: a cone-type definition

Therefore jet cross section is finite at any order in perterbative, massless QCD calculations. Insensitive to low, infrared scale such as Λ_{QCD}

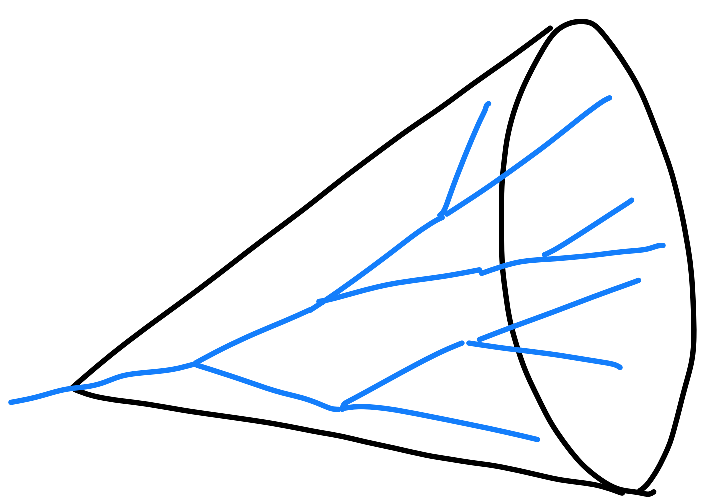
IRC safety is also an important consideration for jet substructure observables for perturbative calculability

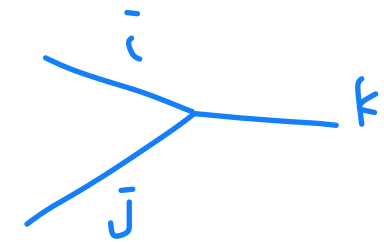
Jets are defined by jet algorithms

A modern standrad is sequential recombination algorithms or clustering algorithms

It is based on sequential, 2 to 1 merging of particles until a cut off set by the chosen jet radius R

In the end of the algorithm, it returns a set of jets, each with a binary tree





The merging is based on a distance metric d_{ij}

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} : k_{ti}^{2p}$$

$$p : \begin{cases} 1, & k_t \\ 0, & \text{Cambridge/Aachen} \\ -1, & \text{anti-}k_t \end{cases}$$

The result from the merging depends on the recombination scheme

recoil sensitive $\quad p_i + p_j = p_k$

recoil free $\quad p_i + p_j \to (|p_i| + |p_j|)\, \hat{p}_{\text{winner}}$

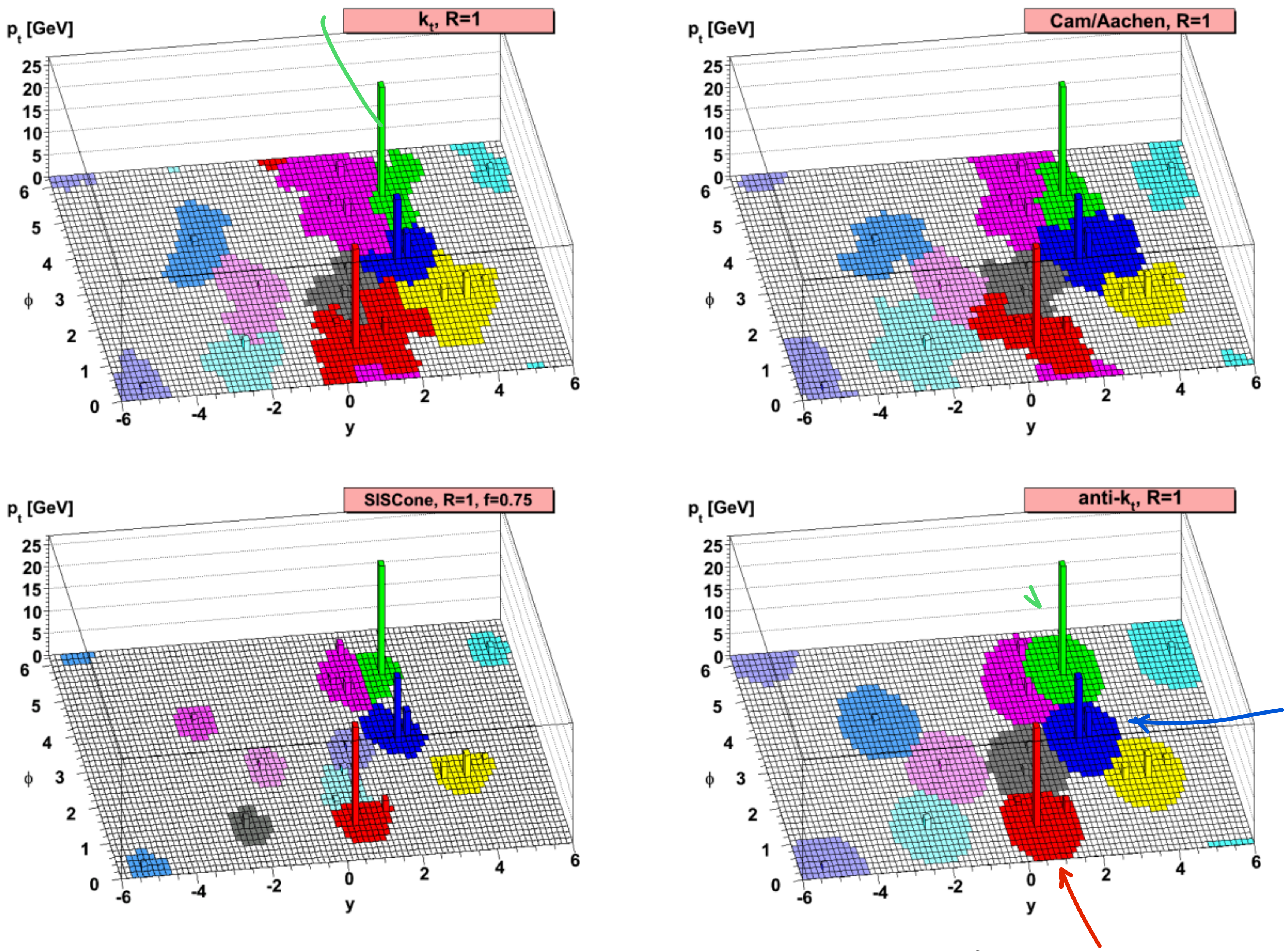
winner-take-all (WTA)

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} : k_{ti}^{2p}$$

Outcome of jet algorithms

p :
- 1, kt — merge soft particles first
- 0, Cambridge/Aachen — merge collinear particles first
- −1, anti-kt — merge hard particles first

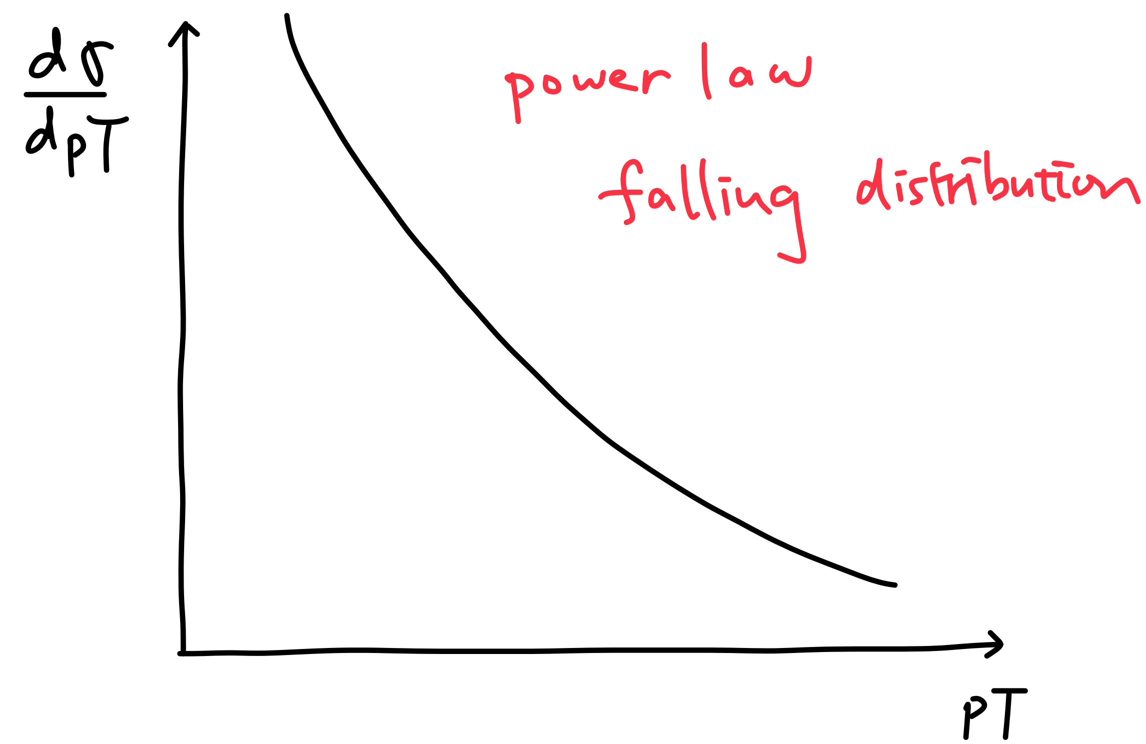


Outcomes of jet algorithms are diffent, but the major energy flows are robust. Differences are around the jet boundaries with soft and wide-angle radiation

Once establishing dominant energy flows, soft particles are clustered into jets essentially according to the angle, giving cone-like jets

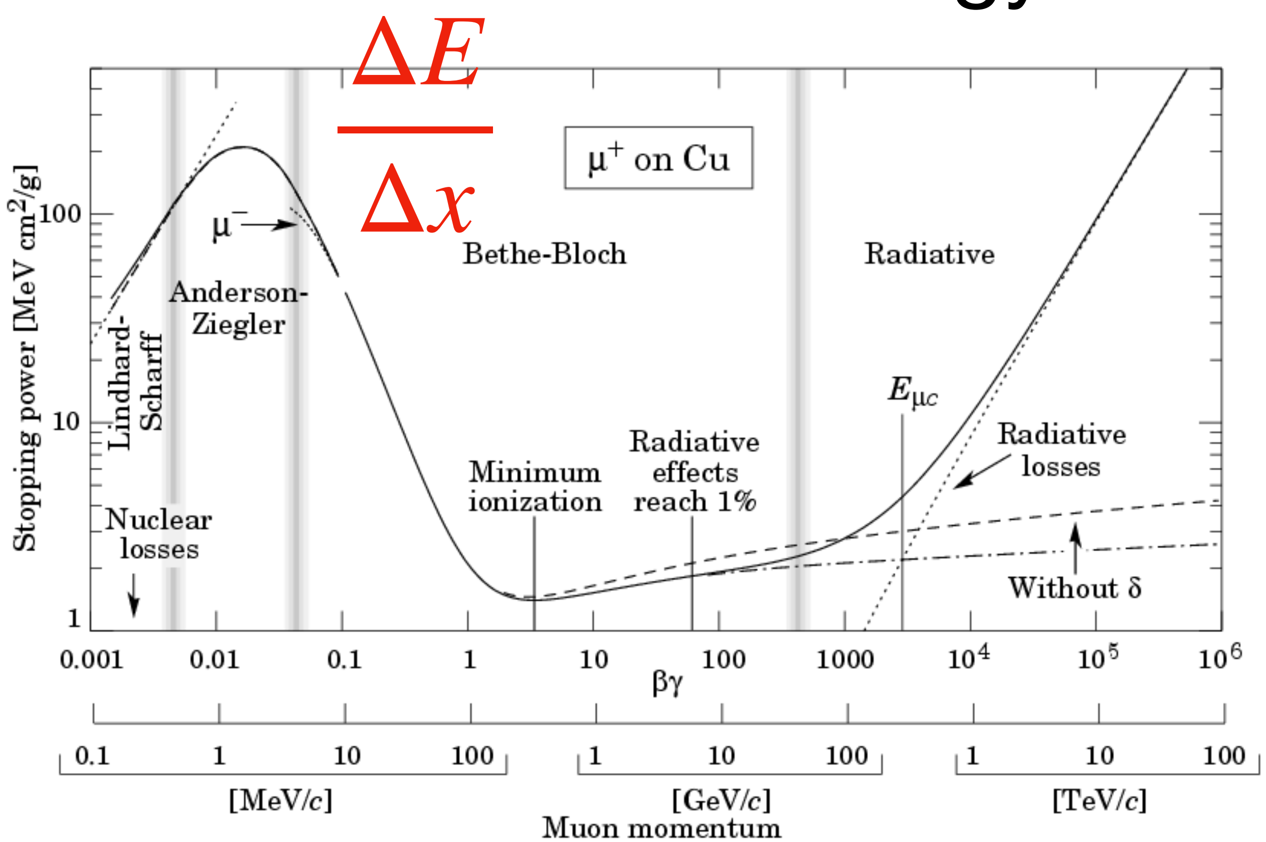
Hadron and jet cross section

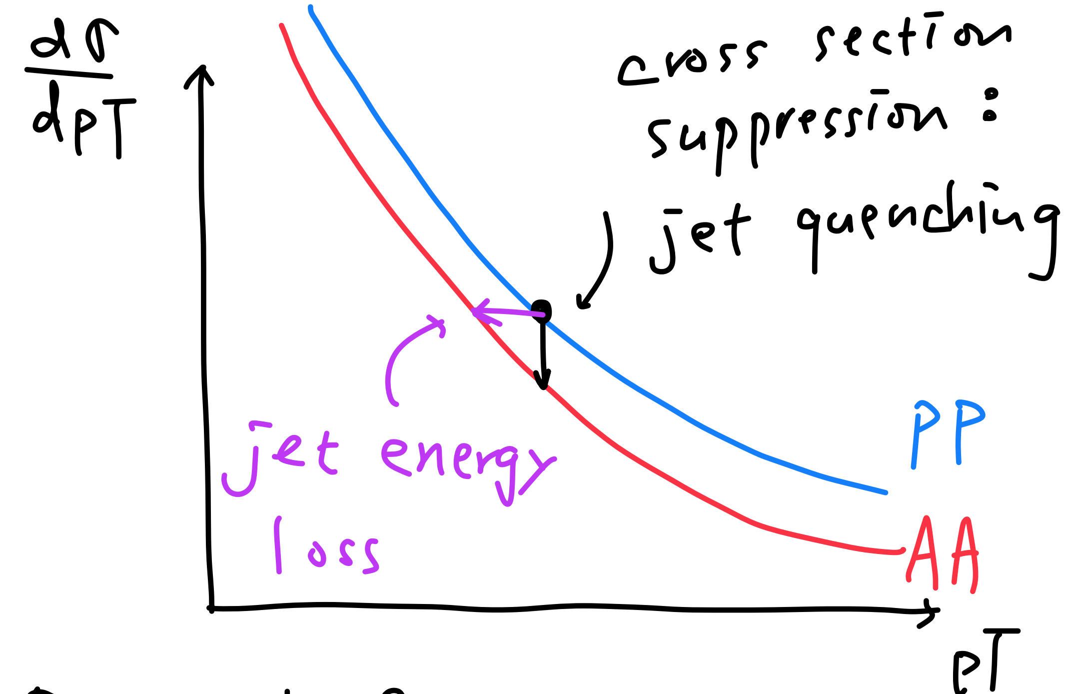
With particle identification (PID) we can study hadron cross sections. Also, with jet reconstruction definition, we can study jet cross sections: counting experiments according to hadron and jet kinematics p_T, η, ϕ. the first few, basic jet observables.



As we saw, jet reconstruction depends on algorithm and jet radius (in fact logarithmically for cross section, slow dependence) and differs in wide-angle, soft radiation, which is capture by a jet function calculabe in pQCD with small hadronization correction. Unlike hadron cross section which depends on nonperturbative fragmentation function.

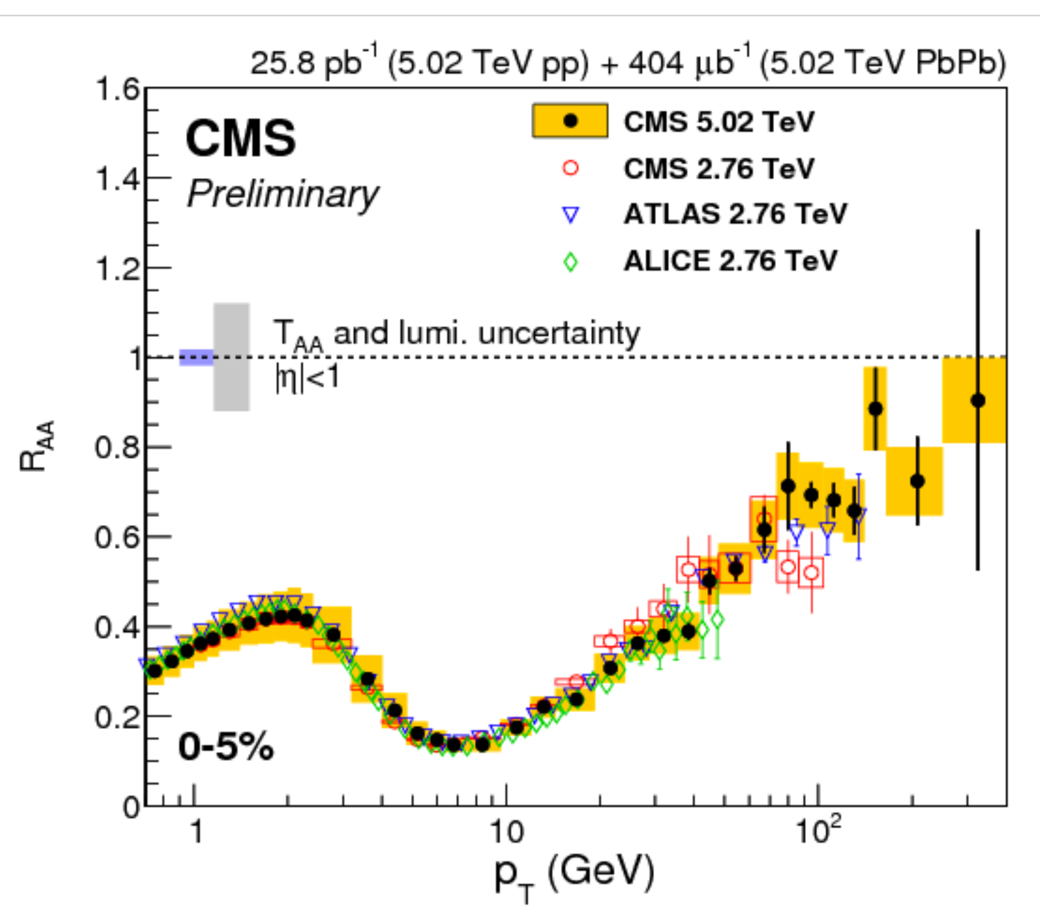
Energy loss and quenching





$\frac{d\sigma}{dp_T}$ steeply falling:
small energy loss → large suppression

Decades-long energy loss paradigm of jet quenching

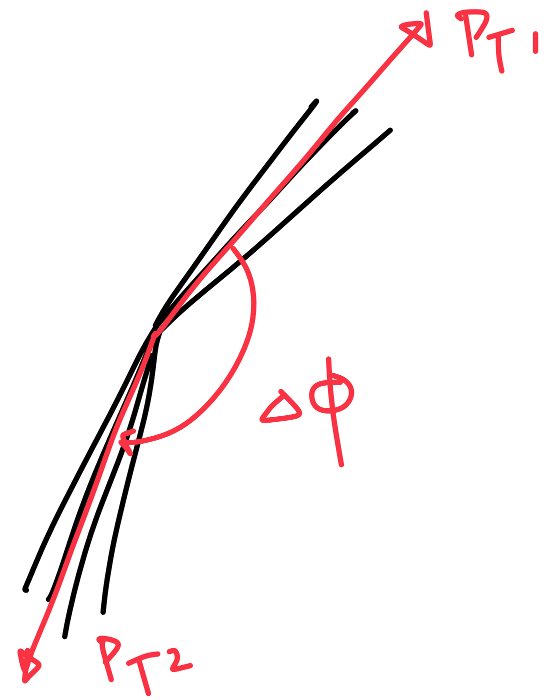


$$R_{AA} = \frac{\text{Cross section in AA}}{T_{AA}\ \text{Cross section in pp}}$$

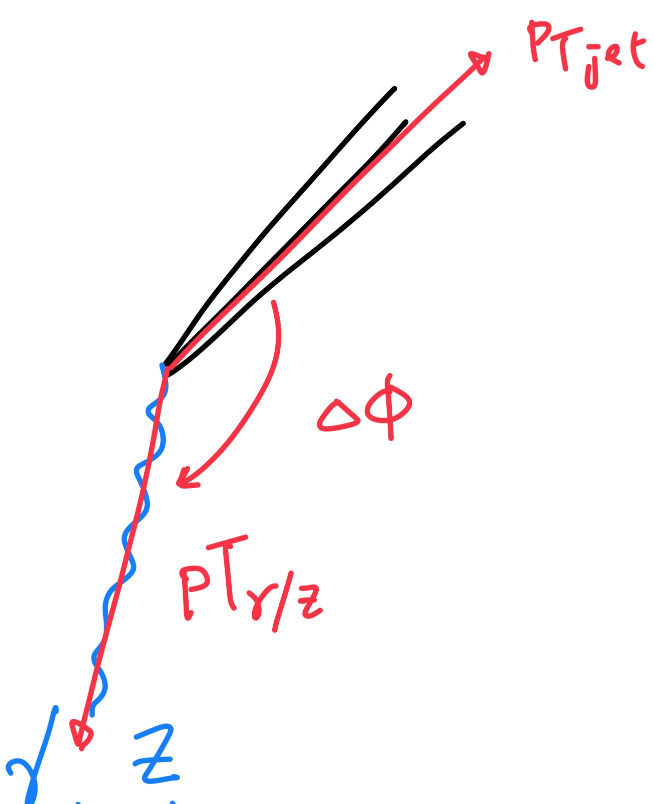
↑ normalization with respect to binary collisions

Dijet and boson+jet

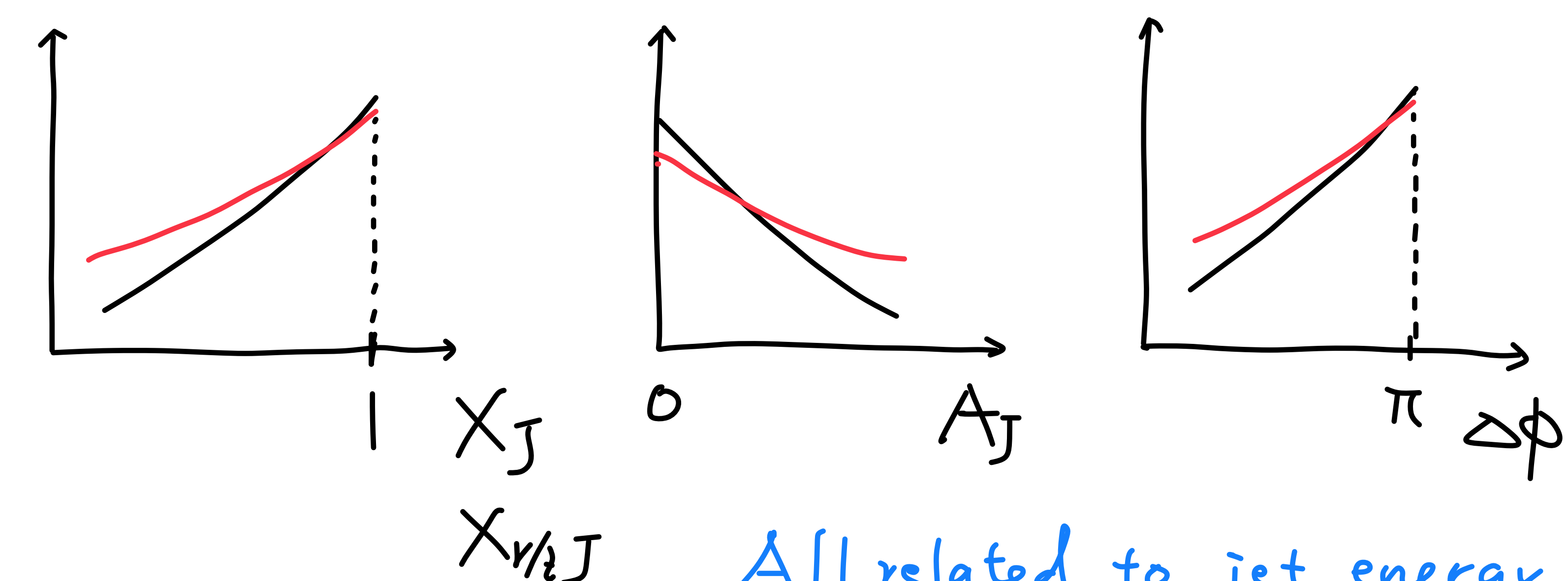
One can also correlate kinematics of two objects dijet or boson-jet



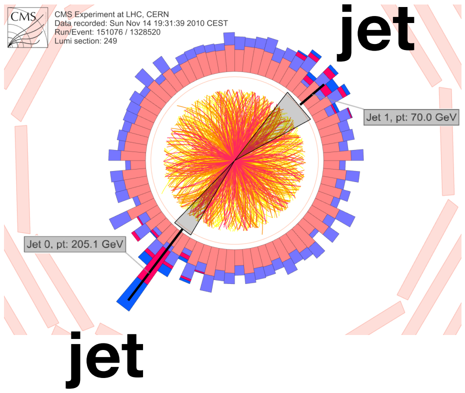
$$\frac{p_{T2}}{p_{T1}} \equiv X_J, \quad \frac{p_{T\,jet}}{p_{T\,\gamma/Z}} \equiv X_{\gamma/Z\,J}, \quad \frac{p_{T2}-p_{T1}}{p_{T2}+p_{T1}} \equiv A_J$$



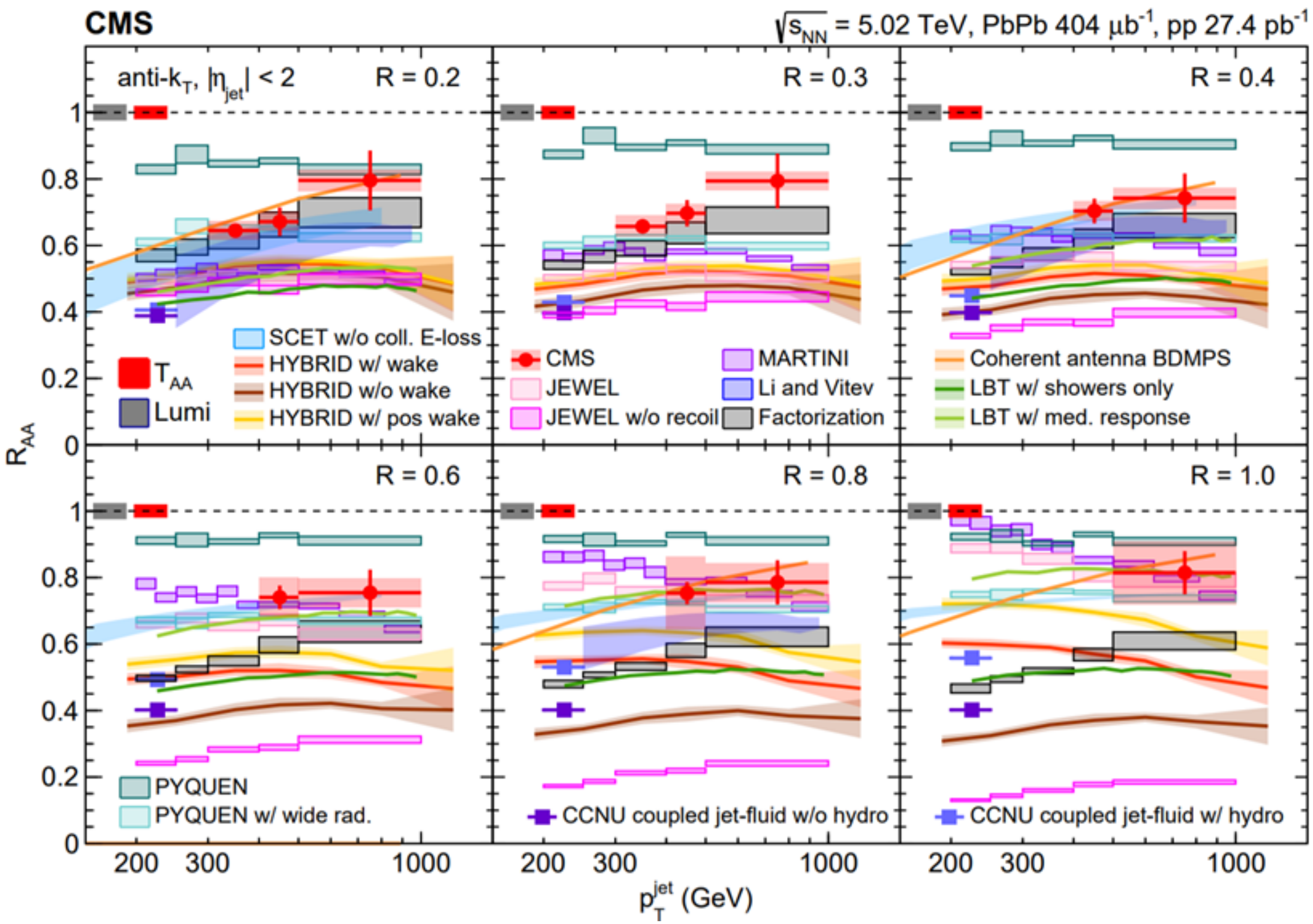
A nice reference unaffected by medium



All related to jet energy loss or deflection

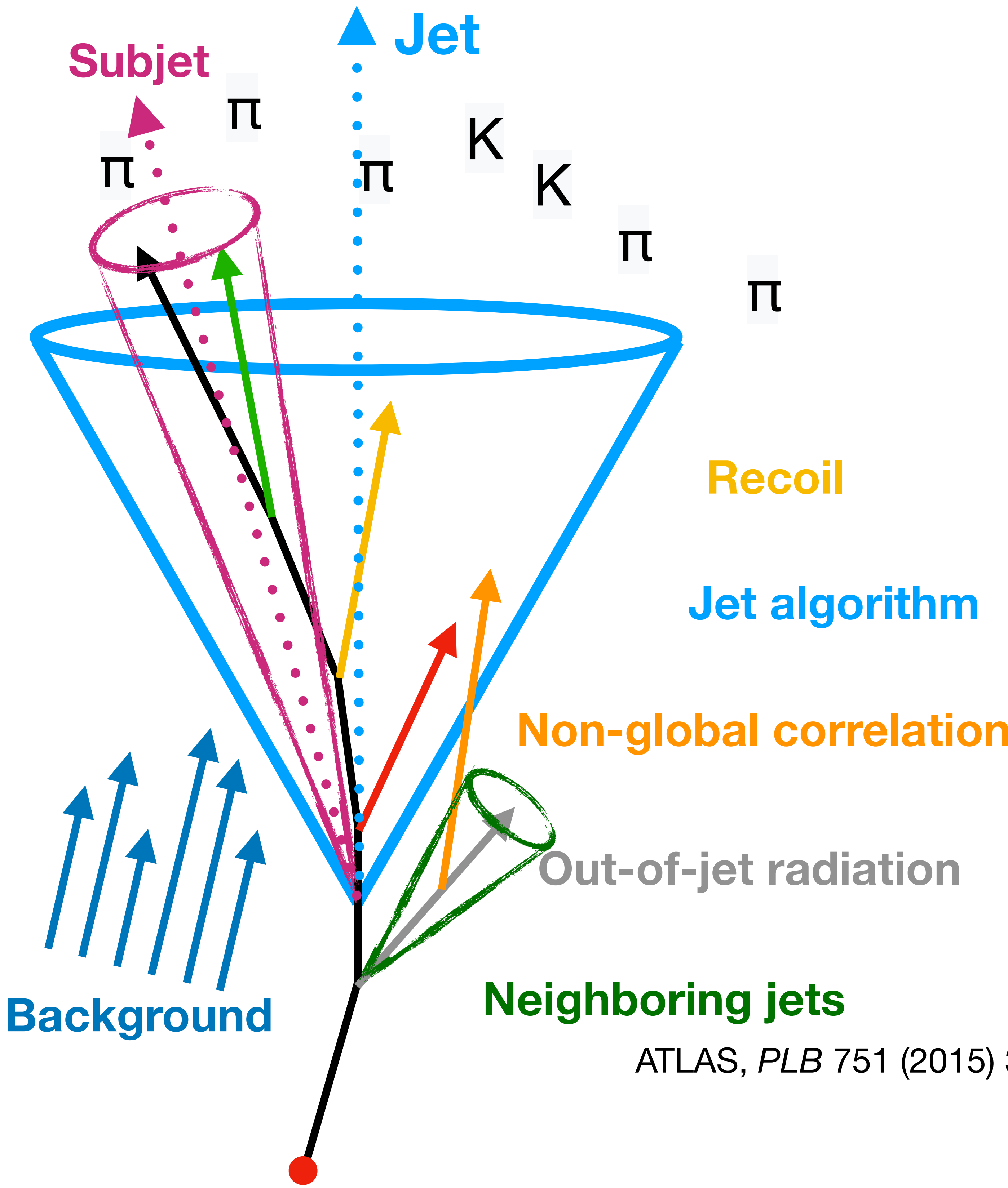


Jet radius dependence of jet quenching



Constrain models with detailed jet (substructure) measurements

Why jet substructure? The devil is in the detail



Jet substructure is everything beyond jet kinematics, to quantify particle distributions around dominant energy flows

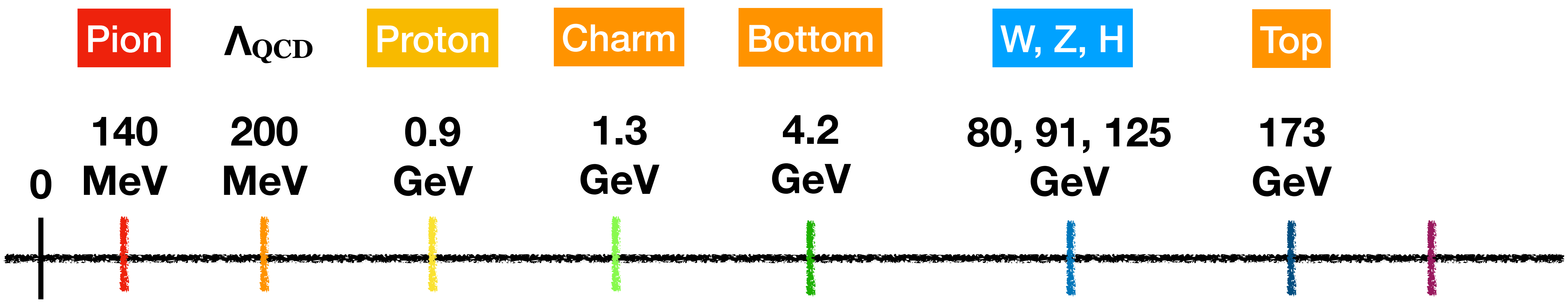
Details of R_{AA}, X_J, $X_{J\gamma}$, A_J depend on jet substructure

Salam et al, *PLB* 512 (2001) 323-330

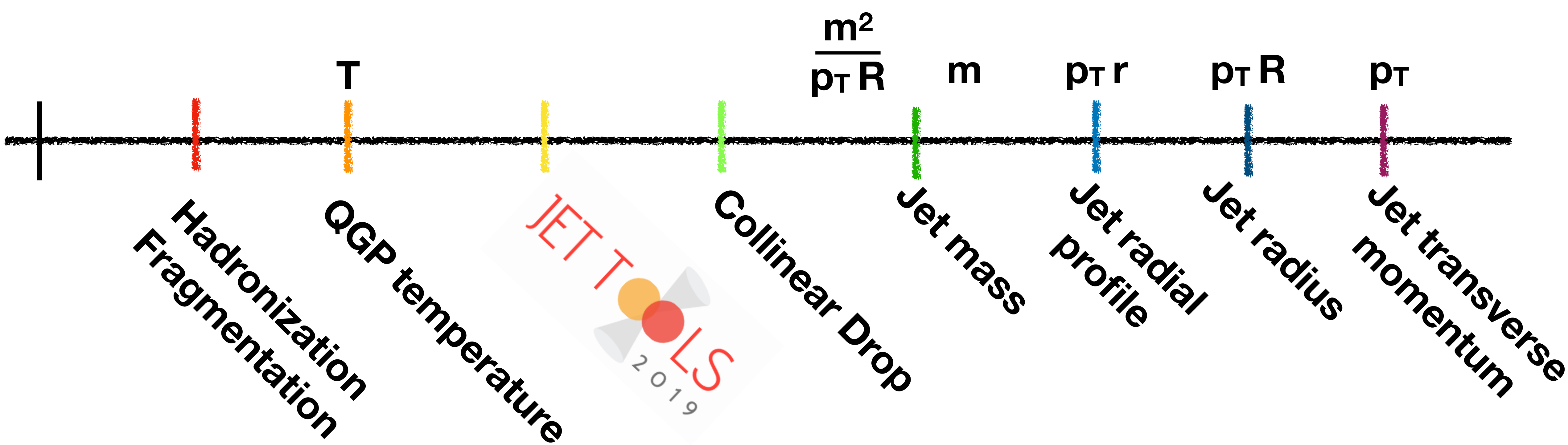
Small-R jet cross section, Out-of-jet energy profile
Salam et al, *JHEP* 04 (2015) 039
Kang et al, *JHEP* 10 (2016) 125

ATLAS, *PLB* 751 (2015) 376-395

Jet substructure are multi-scale probes



Diffent jet substructure observables probes different phase spaces with different characteristic scales



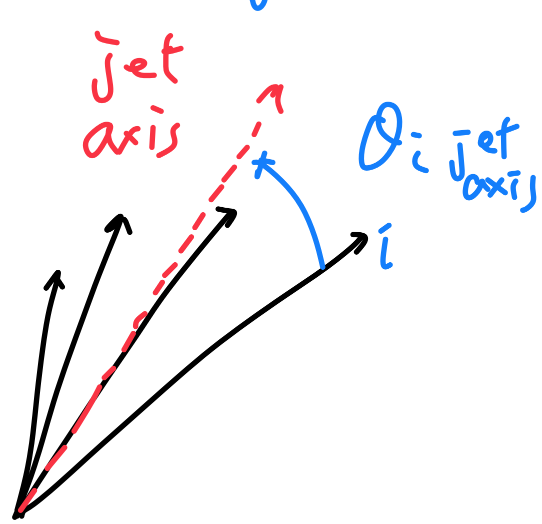
Jet substructure: jet shape

Once we reconstruct jets, which defines a set of particle inside each jet, one can construct all sorts of observables as functions of constituents momenta

For example, generalized jet angularities

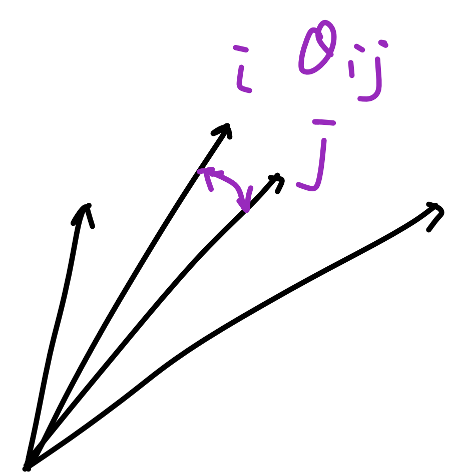
$$\tau_\alpha^\kappa = \sum_{\substack{\text{particles}\\ \text{in}\\ \text{jet}}} {p_t}_i^\kappa \, \theta_{i\,\text{jet axis}}^\alpha$$

$\kappa = 1$ for IRC safety



energy correlation function

$$ECF(2,\alpha) = \sum_{\substack{\text{particle}\\ \text{pairs in}\\ \text{jet}}} {p_t}_i \, {p_t}_j \, \theta_{ij}^\alpha$$



Energy flow polynomial
Energy flow network
⋮
Infinite set of jet substructure observables.

Jet grooming

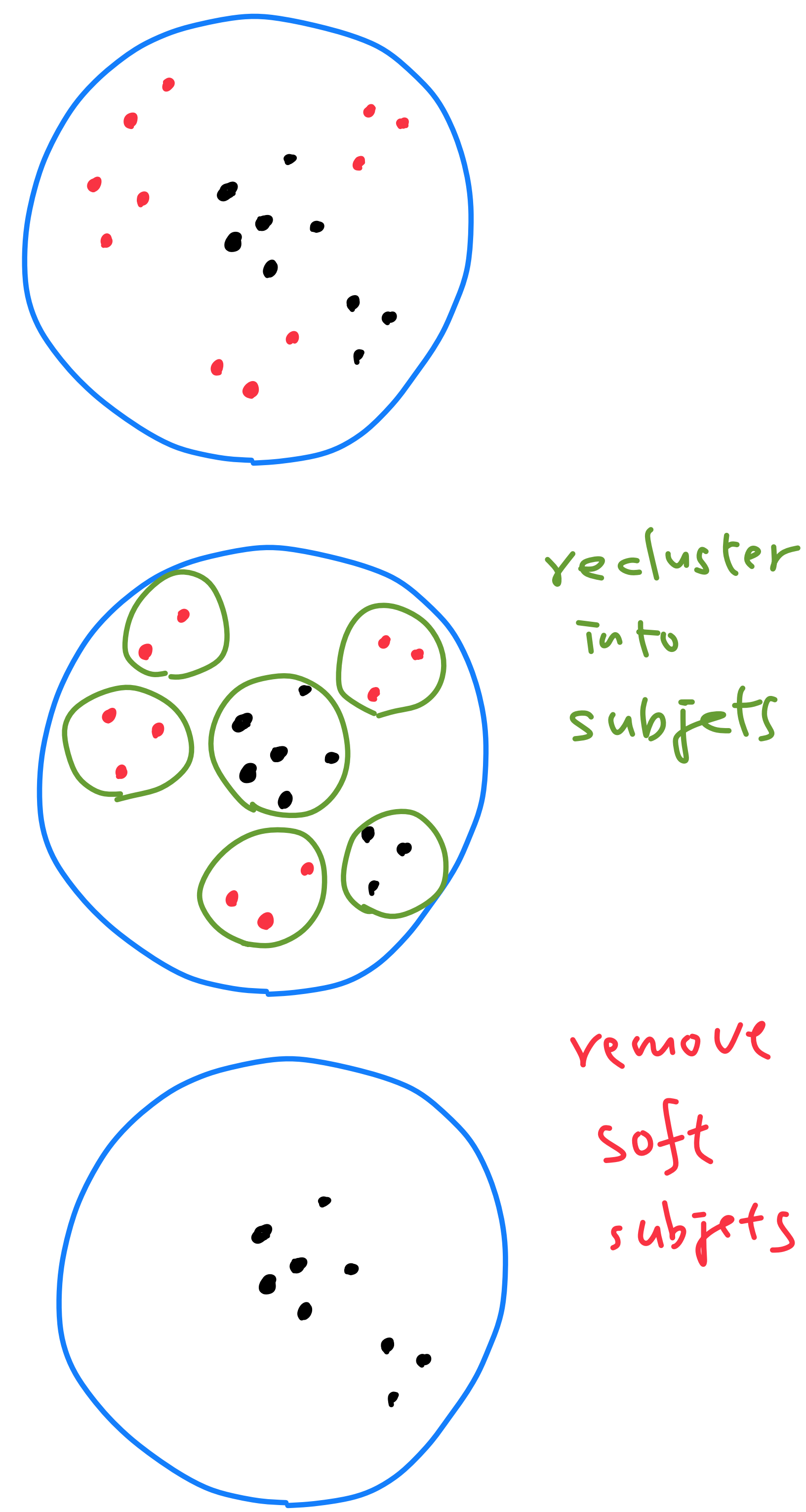
We also have pruning, cleansing, ...

Another way to quantify jet substructure is to make use of structure in jet clustering.

One the other hand, we saw that soft, wide-angle radiation can start to be making jet definition somewhat arbitrary, so we would like to isolate energetic, collinear radiation through a procedure in general called jet grooming

Practically, contamination from pile up and event-wide radiation contamination into jets make jet grooming somewhat essential. Other efforts were made towards background subtractions independent jet substructure

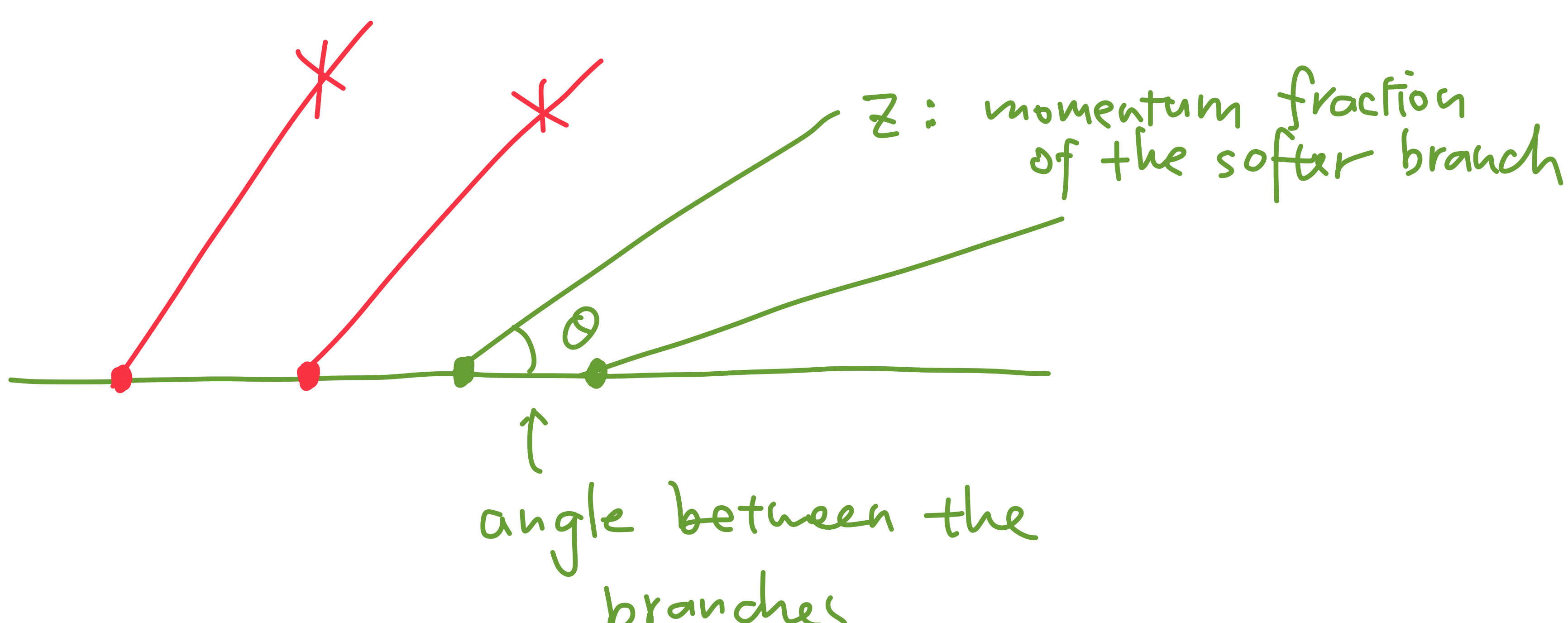
For example, jet trimming



Soft-drop

A noaday widely used and studies method is called soft-drop, which exposed fundamental QCD splitting

Given a reconstructed jet (anti-kt)
Soft-drop starts from reluseering it using Cambridge / Aachen algorithm
producing an angular ordered tree



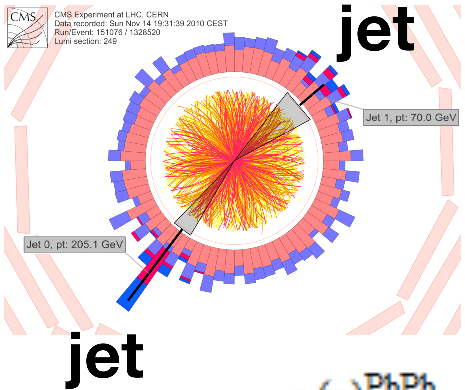
Then one starts from the root of the tree and check the branching kinematics if satisfying the following condition

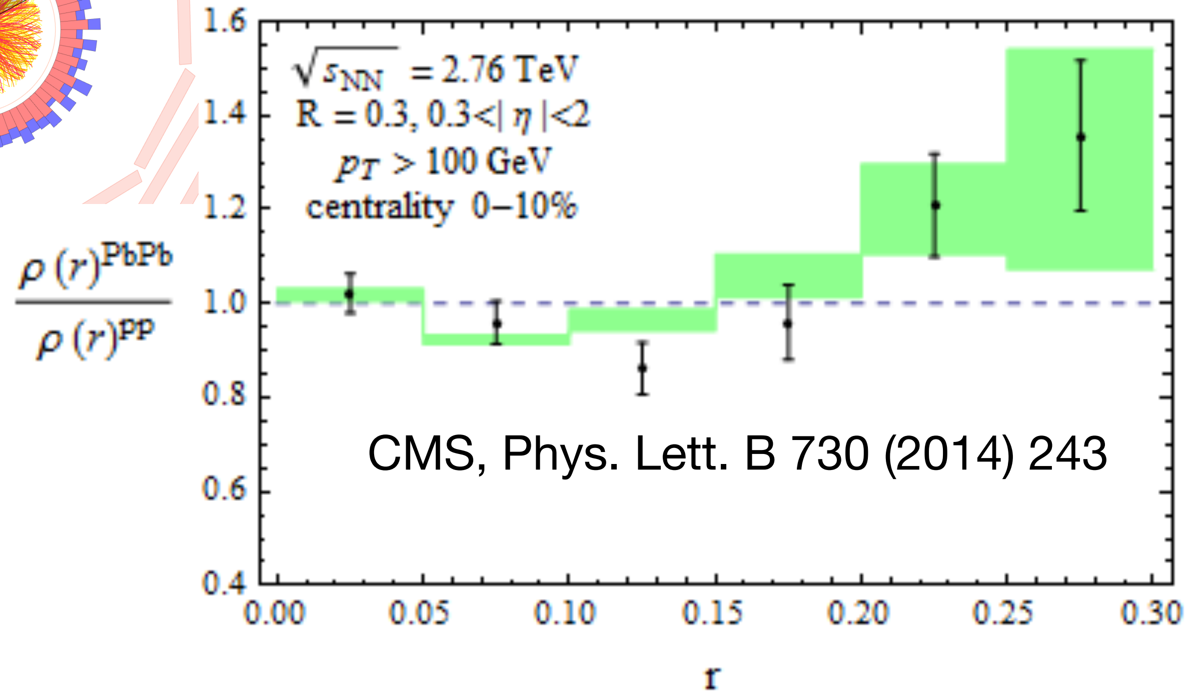
$$z < z_{cut} \left(\frac{\theta}{R} \right)^{\beta}$$

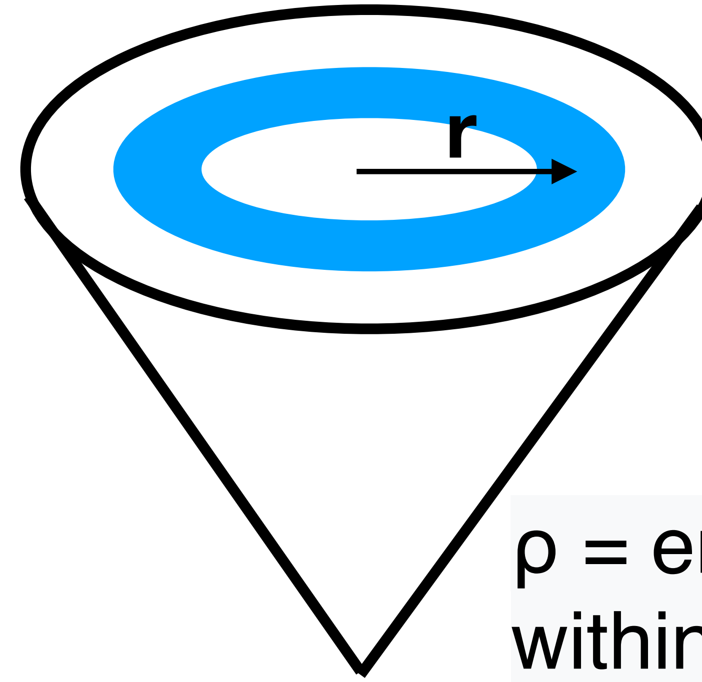
(z_{cut} . β) are parameters.

then remove the soft branch. until reaching a hard splitting. The z and θ then are the z_g and θ_g

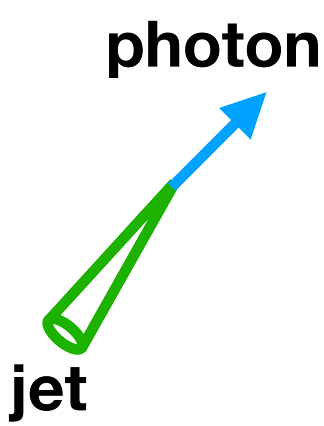
Jet radial energy profile

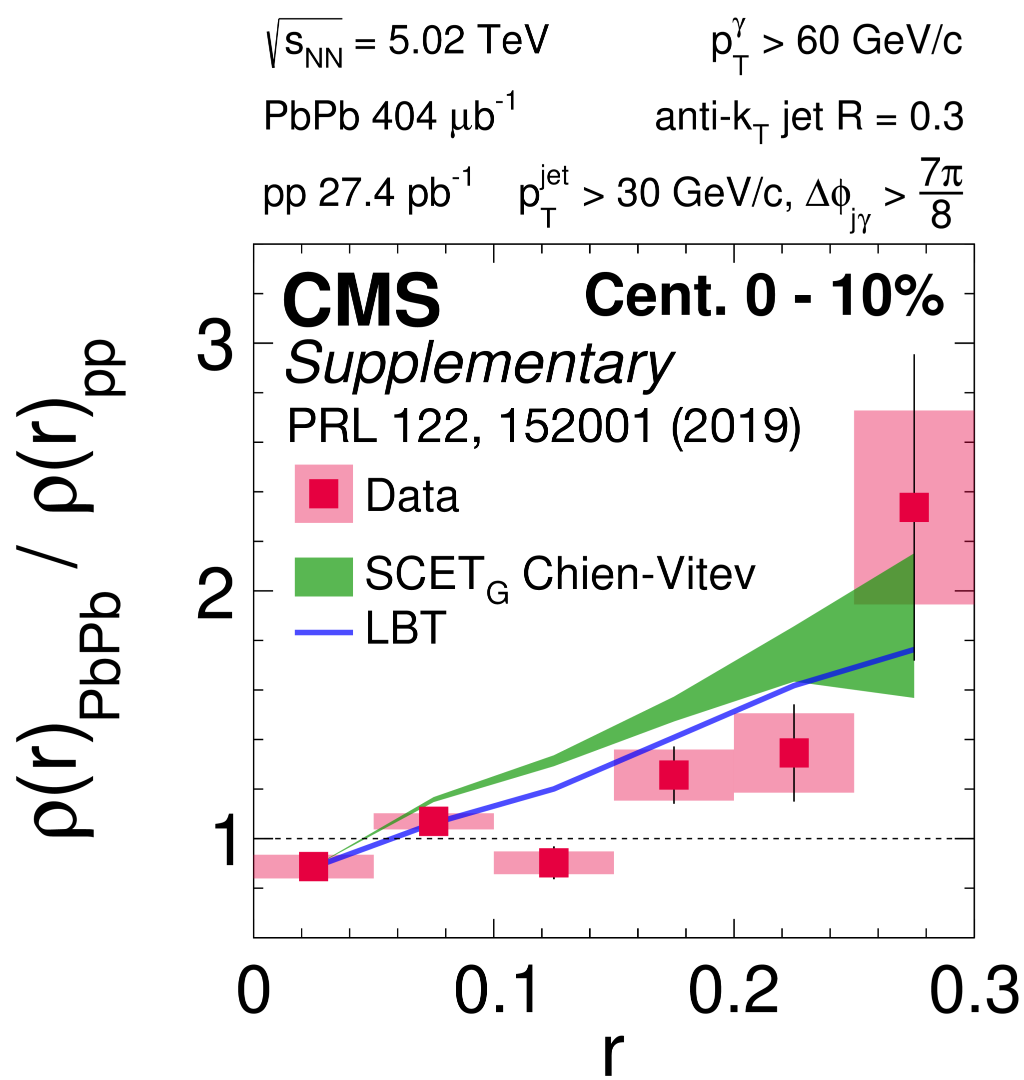


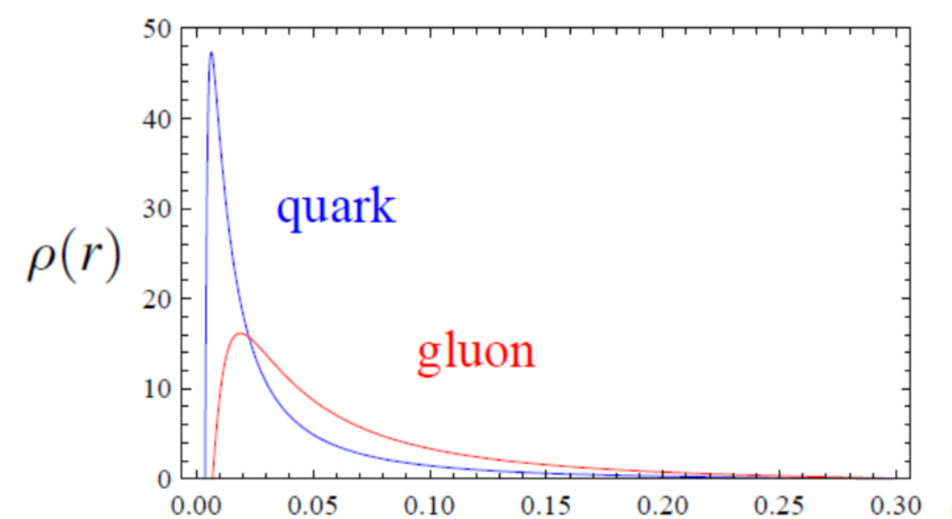




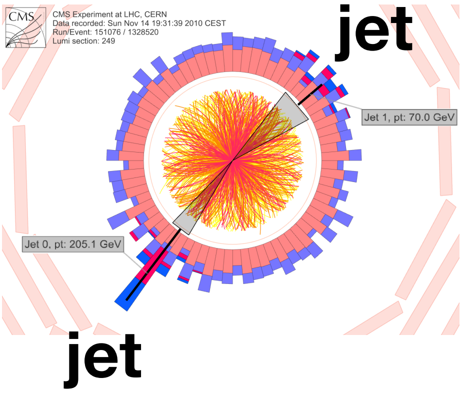
ρ = energy fraction within the ring



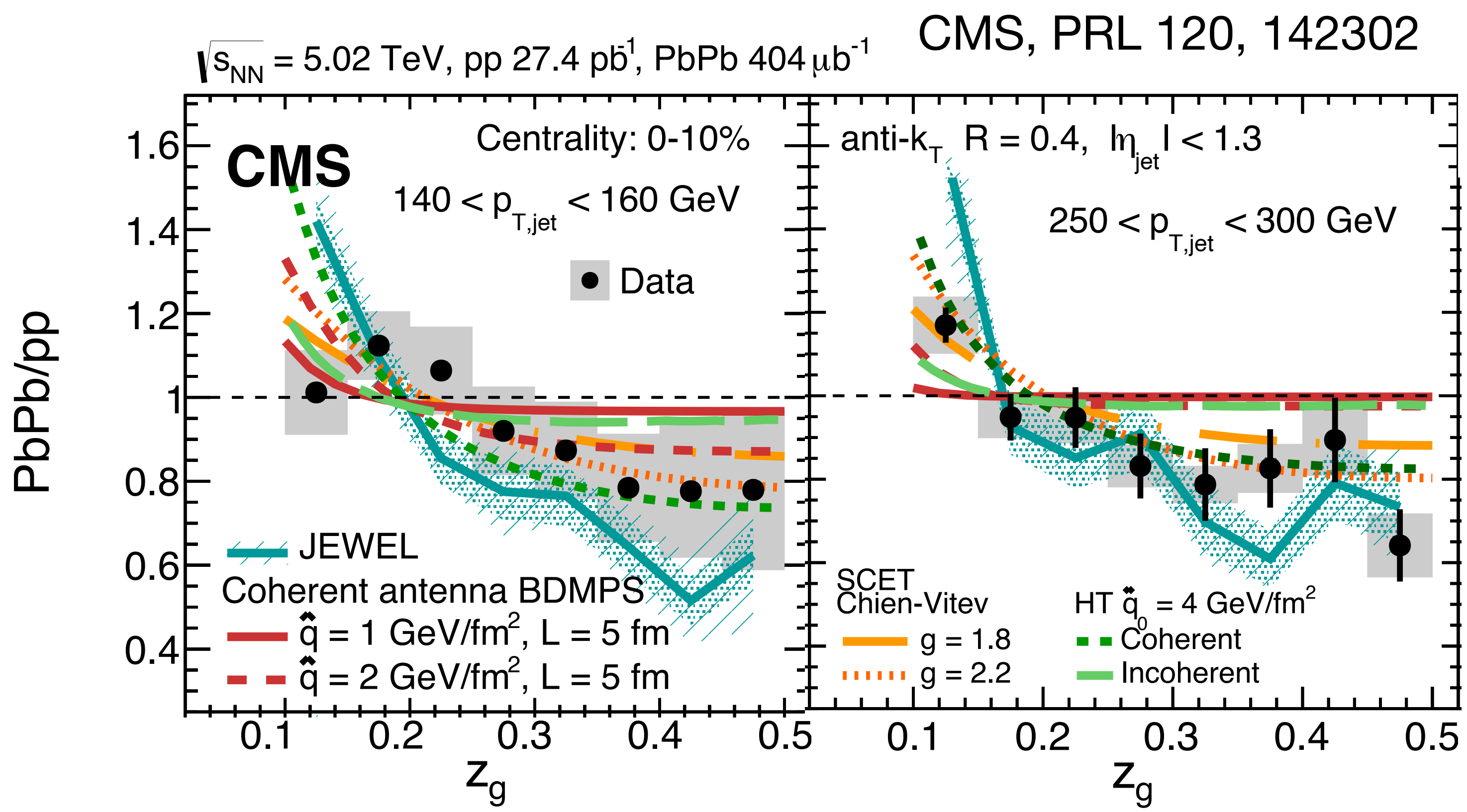


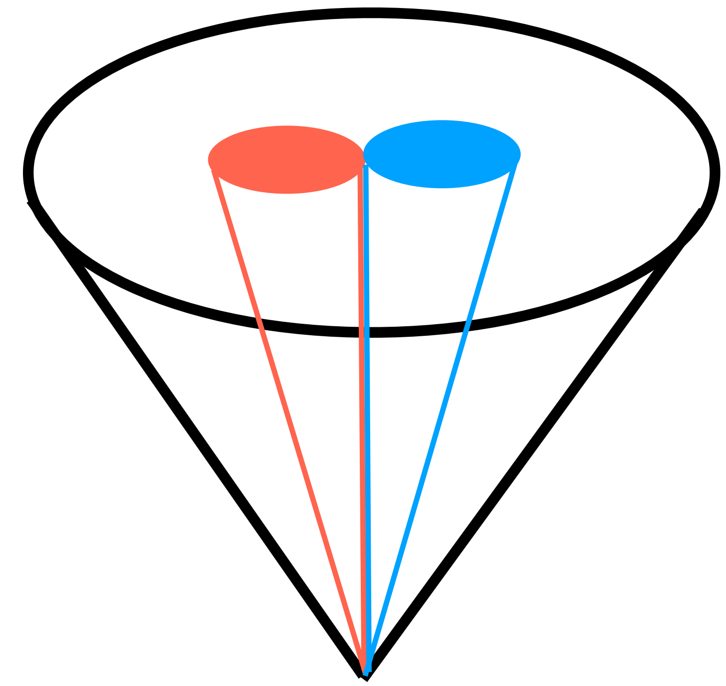


Energy transported away and gluon jet fraction decreases

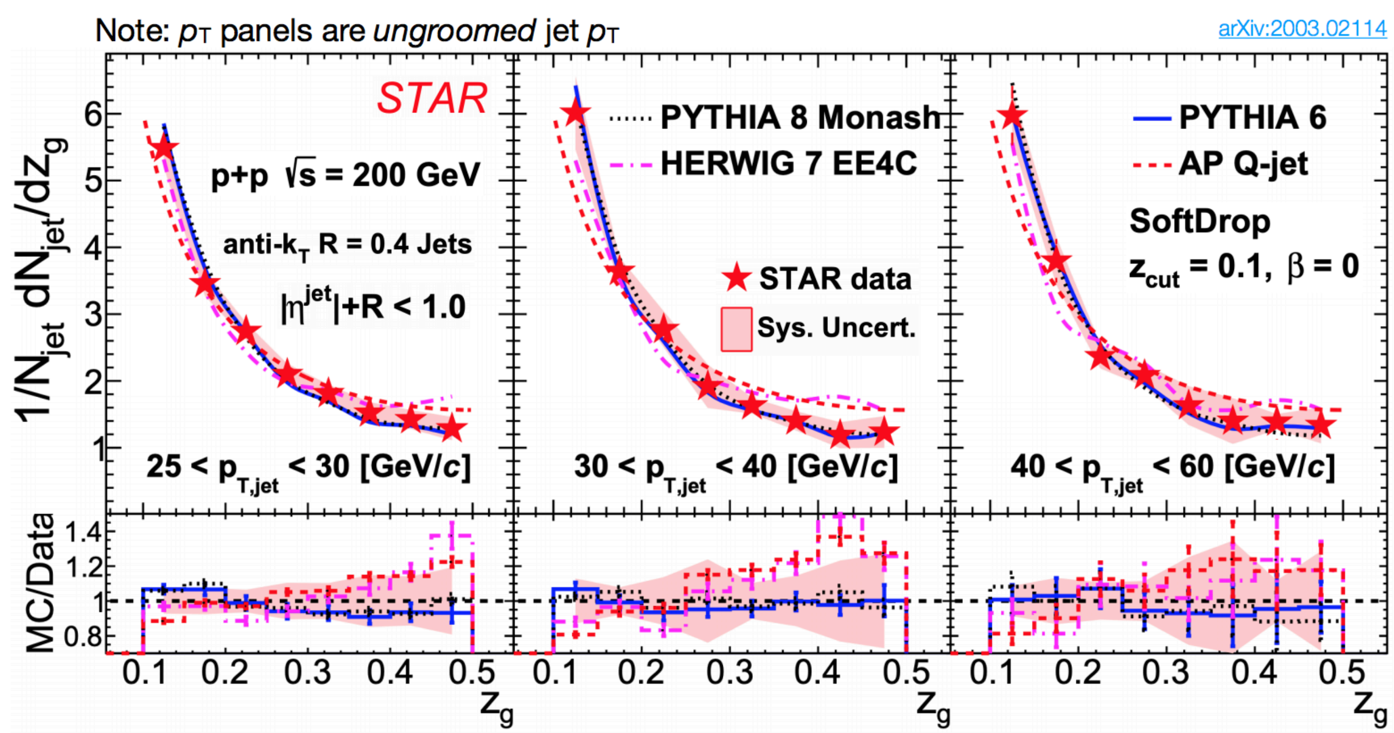


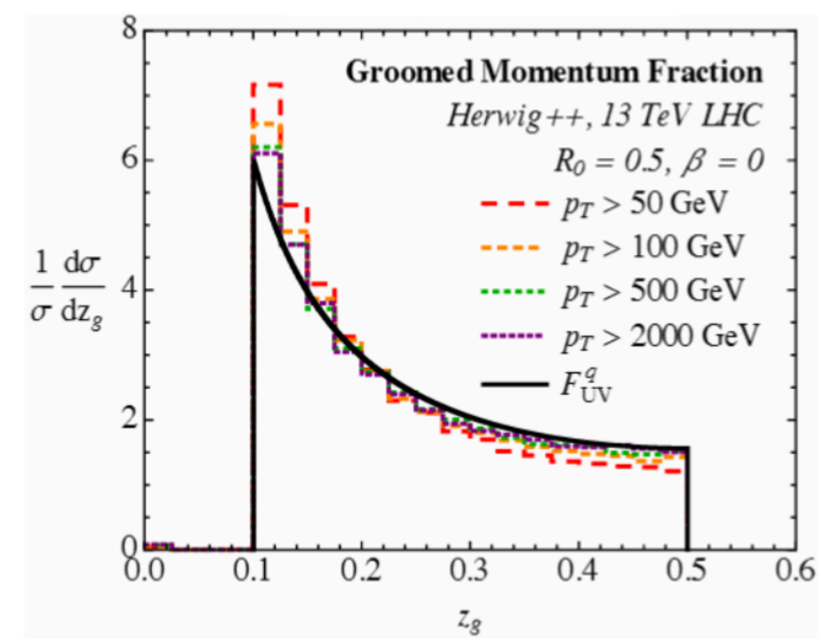
Subjet longitudinal energy profile



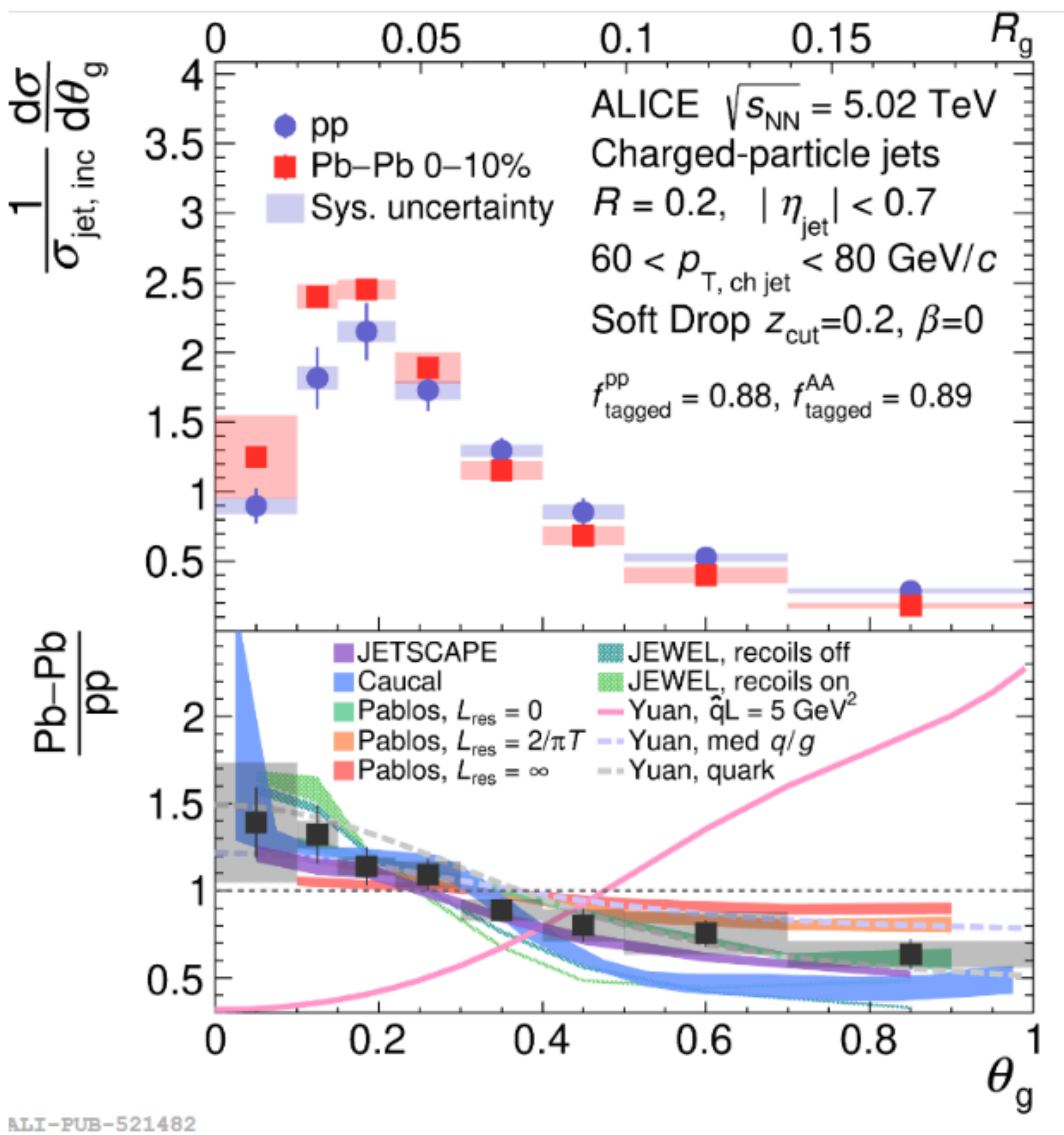


z_g = momentum fraction of soft subjet





Subjet angular distribution



Hint of "jet narrowing" in AA collisions, a phenomenon appearing in jet shape studies, too.

Several reasons may result in this finding: selection bias (comparing different pT jets) flavor dependence of jet substructure (quark vs gluon)

More to clarify in future studies.

Energy-energy correlator

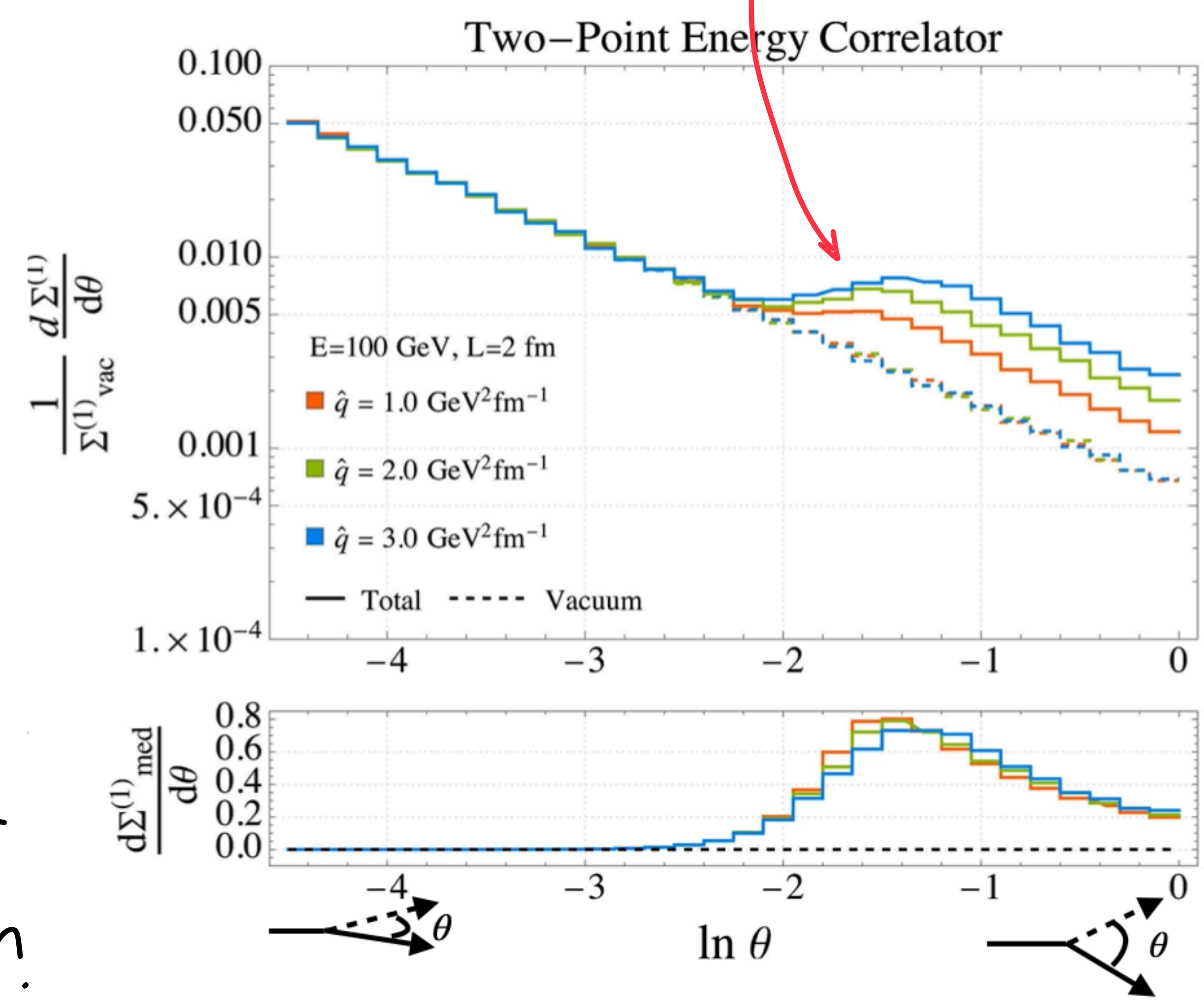
In recent years significant progress is made to understand energy-energy correlators

$$\frac{d\Sigma}{d\chi} = \sum_{i,j} d\sigma \frac{E_i E_j}{E_{jet}^2} \delta(\chi - \chi_{ij})$$

the probability of 2 particles separated by an angle χ weighed by their energy. It is IRC safe and an ensemble average of observable not a jet-by-jet observable distribution.

Because it's weighed by energy, it favors energetic particles and is less sensitive to soft particles.

Interesting feature developes that changes scaling behavior

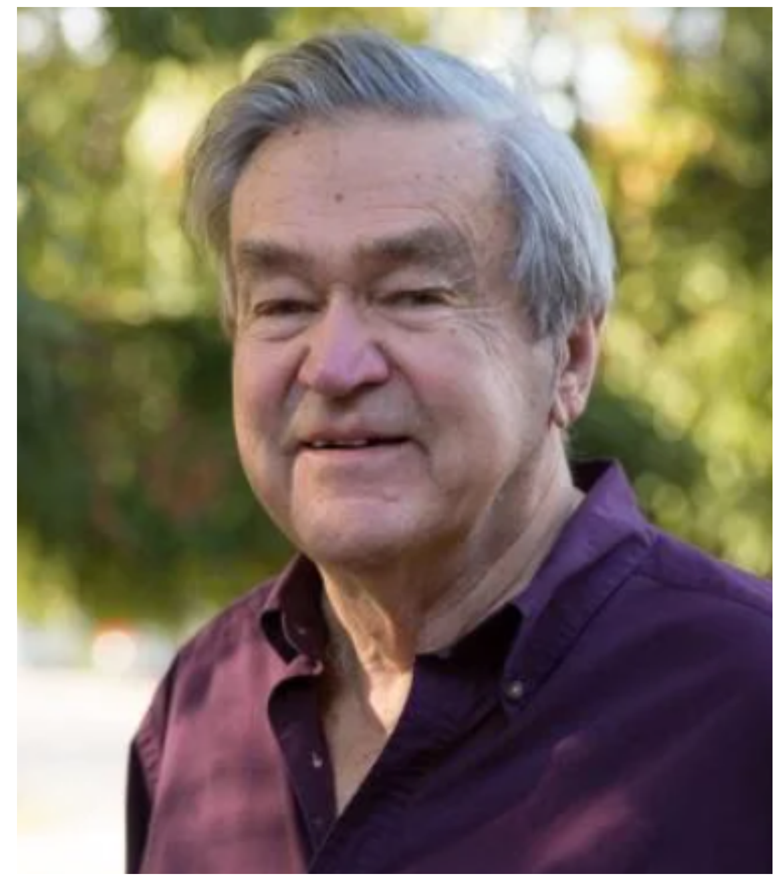


- Jet substructure in heavy ion is a fast developing field
- Sensitivity and precision in theory and experiment are both challenge and opportunity
- Average jet energy distributions (jet shape and fragmentation function) more established
- Explored jet-by-jet substructure fluctuations (zg, rg, mass, etc)
- Energy-energy correlator brings new excitement of probing medium scales
- See the necessity of the synergy between soft and hard probes: “omni-probe”?

Thank you and enjoy new results at HP2024

In memory of two great physicists

Tsung-Dao Lee
1926-2024



James Bjorken
1934-2024