New perspectives in QCD with jet substructure

Gregory Soyez

IPhT, CEA Saclay, CNRS

LightCone 2019, September 16-20 2019

A Model for SU(3) vacuum degeneracy using light cone coordinates

Gregory Soyez (Liege U.)

Jan 2001 - 22 pages

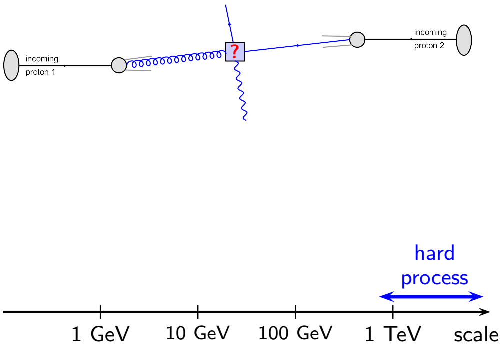
Phys.Rev. D63 (2001) 105012
DOI: 10.1103/PhysRevD.63.105012
e-Print: hep-th/0101072 | PDF

Abstract
Working in light-cone coordinates, we study the zero-modes and the vacuum in a 2+1 dimensional SU(3) gauge model. Considering the fields as independent of the tranverse variables, we dimensionally reduce this model to 1+1 dimensions. After introducing an appropriate su(3) basis and gauge conditions, we extract an adjoint field from the model. Quantization of this adjoint field and field equations lead to two constrained and two dynamical zero-modes. We link the dynamical zero-modes to the vacuum by writing down a Schrodinger equation and prove the non-degeneracy of the SU(3) vacuum provided that we neglect the contribution of constrained zero-modes.

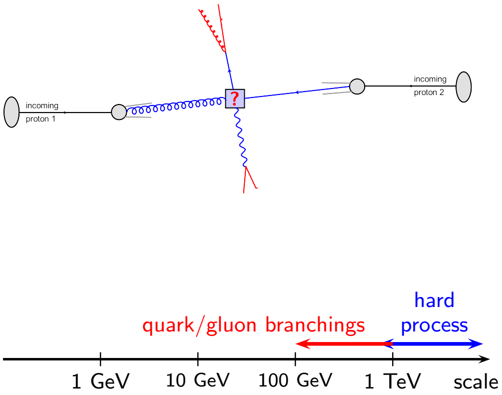
I have departed quite a bit from this topic but let's see if we can find a way to connect...

Anatomy of a high-energy collision

Colliders study fundamental interactions at high energy

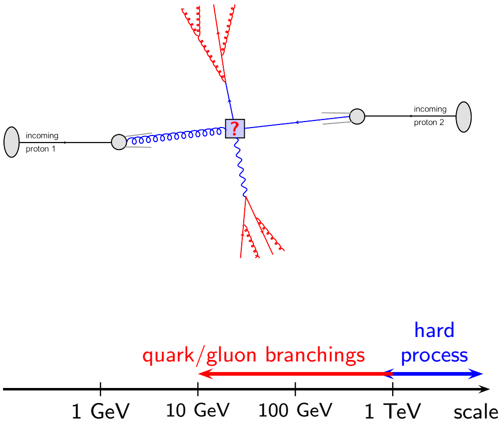


Colliders study fundamental interactions at high energy



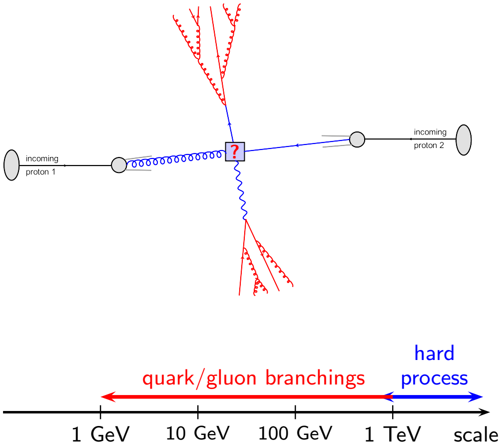
Anatomy of a high-energy collision

Colliders study fundamental interactions at high energy



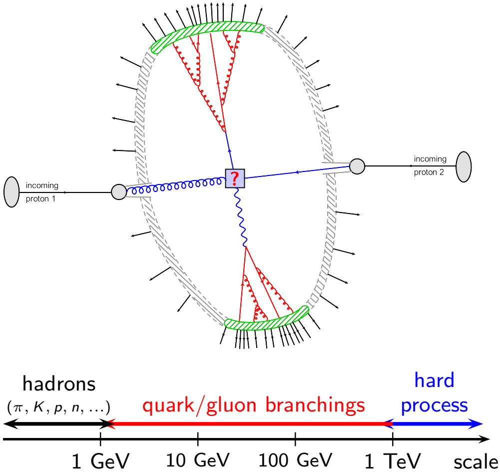
Anatomy of a high-energy collision

Colliders study fundamental interactions at high energy



Anatomy of a high-energy collision

Colliders study fundamental interactions at high energy



Hard + branchings

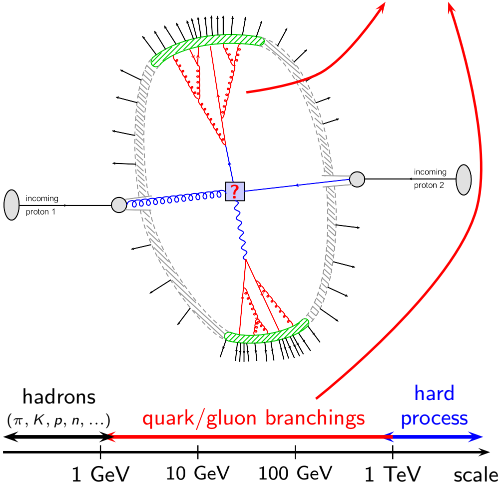
- perturbative QCD
- controlled, solid
- predictive with genuine theory uncertainties

Hadronisation

- NON-perturbative
- needs modelling
- model-dependent

Colliders study fundamental interactions at high energy

topic #1 for this talk



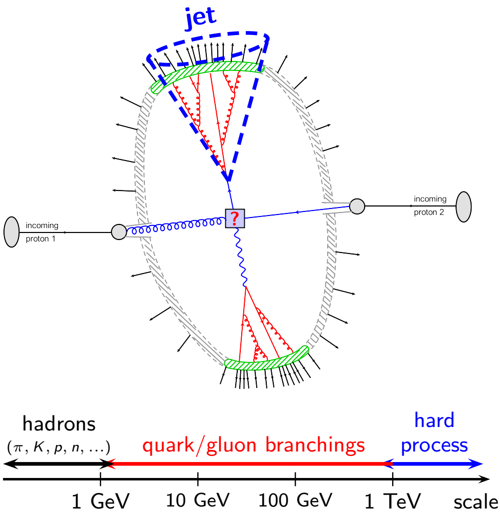
Hard + branchings

- perturbative QCD
- controlled, solid
- predictive with genuine theory uncertainties

Hadronisation

- NON-perturbative
- needs modelling
- model-dependent

Colliders study fundamental interactions at high energy



branchings mostly collinear

$\Downarrow$

"high-energy parton" $\rightarrow$ collimated shower of particles $\equiv$ JET

Jet $\equiv$ proxy to hard parton

our topic #2

Topic #1: parton showers

or "How to connect widely separated scales in pQCD?"

Monte Carlo generators

Generic picture:

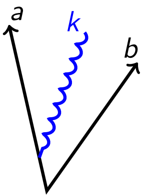
- "all-purpose" (Monte Carlo) Event generators to simulate collisions
- Most used tools in particle physics (Pythia, Herwig, Sherpa, ...)
- Central piece: parton shower (connecting hard to soft perturbative scales)

Monte Carlo generators

Generic picture:

- "all-purpose" (Monte Carlo) Event generators to simulate collisions
- Most used tools in particle physics (Pythia, Herwig, Sherpa, ...)
- Central piece: parton shower (connecting hard to soft perturbative scales)

Main physics idea: gluon radiation from a $q\bar{q}$ dipole has 2 (IR) divergences

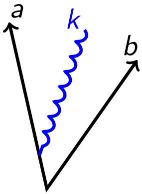


$$\text{soft: } E_k \to 0 \quad \Rightarrow \int_{E_{\min}}^{E_{ab}} \frac{dE_k}{E_k}\alpha_s = \alpha_s \log(E_{ab}/E_{\min})$$

$$\text{collinear: } \theta_{ak} \to 0 \quad \Rightarrow \int_{\theta_{\min}}^{\theta_{ab}} \frac{d\theta_{ak}}{\theta_{ak}}\alpha_s = \alpha_s \log(\theta_{ab}/\theta_{\min})$$

Widely disparate scales $\Rightarrow$ logs resummed to all orders

Towards dipole showers

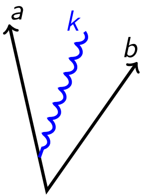


Use Sudakov parametrisation $(Q = (p_a + p_b)^2 = 2p_a.p_b)$:

$$k^\mu = z_a p_a^\mu + z_b p_b^\mu + k_\perp^\mu$$

$$k^2 \ll Q^2 (k^2 \approx 0) \Rightarrow z_{a,b} = \frac{k_\perp}{Q} e^{\pm\eta} \qquad \text{with } \eta = \frac{1}{2} \log \frac{z_a}{z_b}$$

Towards dipole showers



Use Sudakov parametrisation ($Q = (p_a + p_b)^2 = 2p_a.p_b$):

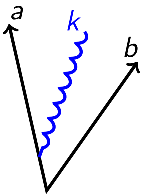
$$k^\mu = z_a p_a^\mu + z_b p_b^\mu + k_\perp^\mu$$

$$k^2 \ll Q^2 (k^2 \approx 0) \Rightarrow z_{a,b} = \frac{k_\perp}{Q} e^{\pm\eta} \qquad \text{with } \eta = \frac{1}{2} \log \frac{z_a}{z_b}$$

Matrix element:

$$[dk]|\mathcal{M}|^2 \approx d\eta \, dk_\perp^2 \frac{d\phi}{2\pi} \frac{\alpha_s(k_\perp) C_F}{4\pi} \frac{z_a P(z_a) \, z_b P(z_b)}{k_\perp^2}$$

Towards dipole showers



Use Sudakov parametrisation ($Q = (p_a + p_b)^2 = 2p_a.p_b$):

$$k^\mu = z_a p_a^\mu + z_b p_b^\mu + k_\perp^\mu$$

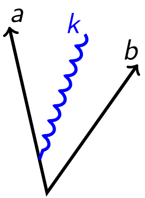
$$k^2 \ll Q^2 (k^2 \approx 0) \Rightarrow z_{a,b} = \frac{k_\perp}{Q} e^{\pm\eta} \qquad \text{with } \eta = \frac{1}{2} \log \frac{z_a}{z_b}$$

Matrix element:

$$[dk]|\mathcal{M}|^2 \approx d\eta \, dk_\perp^2 \frac{d\phi}{2\pi} \frac{\alpha_s(k_\perp) C_F}{4\pi} \frac{z_a P(z_a) \, z_b P(z_b)}{k_\perp^2}$$

- Soft: $k_\perp \ll Q$ ($\eta \approx 0$)
- Collinear: $z_{a,b} \to 0$ (i.e. η departs from ≈ 0)
- Soft&collinear: $k_\perp \ll Q$ and η away from 0

Towards dipole showers



Use Sudakov parametrisation ($Q = (p_a + p_b)^2 = 2p_a.p_b$):

$$k^\mu = z_a p_a^\mu + z_b p_b^\mu + k_\perp^\mu$$

$$k^2 \ll Q^2 (k^2 \approx 0) \Rightarrow z_{a,b} = \frac{k_\perp}{Q} e^{\pm\eta} \qquad \text{with } \eta = \frac{1}{2} \log \frac{z_a}{z_b}$$

Matrix element:

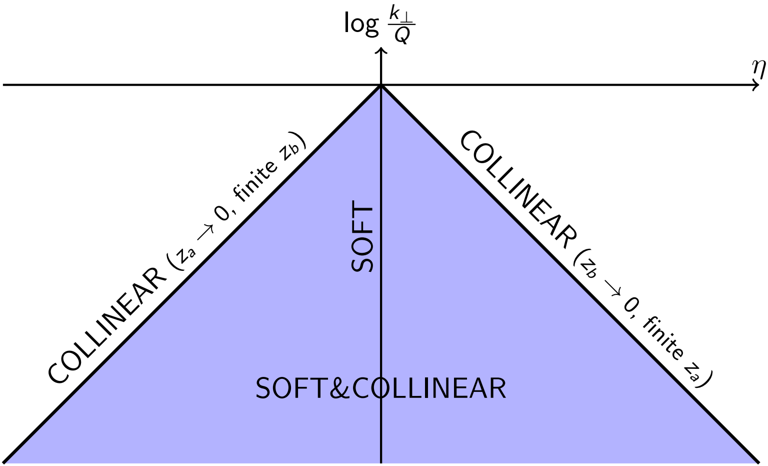
$$[dk]|\mathcal{M}|^2 \approx d\eta\, dk_\perp^2 \frac{d\phi}{2\pi} \frac{\alpha_s(k_\perp) C_F}{4\pi} \frac{z_a P(z_a)\, z_b P(z_b)}{k_\perp^2}$$

- Soft: $k_\perp \ll Q$ ($\eta \approx 0$)
- Collinear: $z_{a,b} \to 0$ (i.e. η departs from ≈ 0)
- Soft&collinear: $k_\perp \ll Q$ and η away from 0

Resummation of (leading) logarithms: $Q \gg k_{\perp 1} \gg k_{\perp 2} \gg \cdots \gg k_{\perp n}$

Towards dipole showers

Convenient representation: the Lund plane



Topic #2: jets, jet substructure

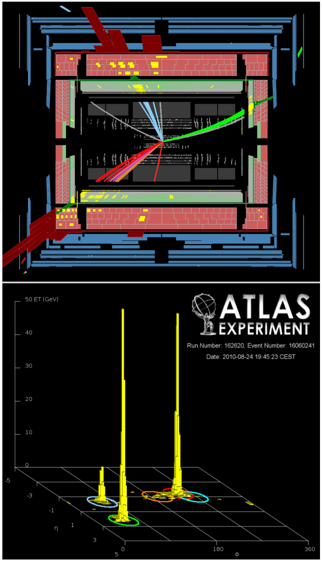
or "opening towards new phenomenology"

40 years of jets for collider phenomenology

Central idea

Jet $\equiv$ proxy for hard parton
$\Rightarrow$ carries info about the hard collision

- Ubiquitous at the LHC
  used in more than 60% of the analyses
- Reconstructions of jets from particles
  using dedicated jet algorithms
- Calculable in perturbative QCD
  (NLO standard, sometimes NNLO)



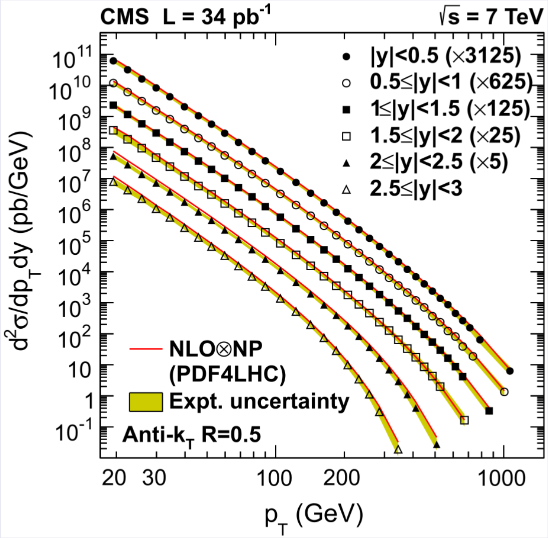
40 years of jets for collider phenomenology

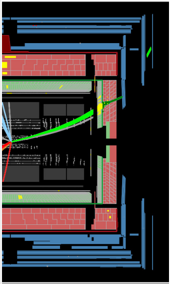
Central idea

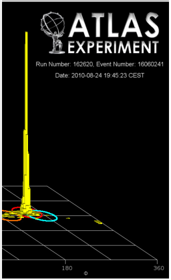
Jet $\equiv$ proxy f
$\Rightarrow$ carries info

- Ubiquitou
  used in m
- Reconstru
  using dedi
- Calculable
  (NLO star

Jet cross-section at the LHC







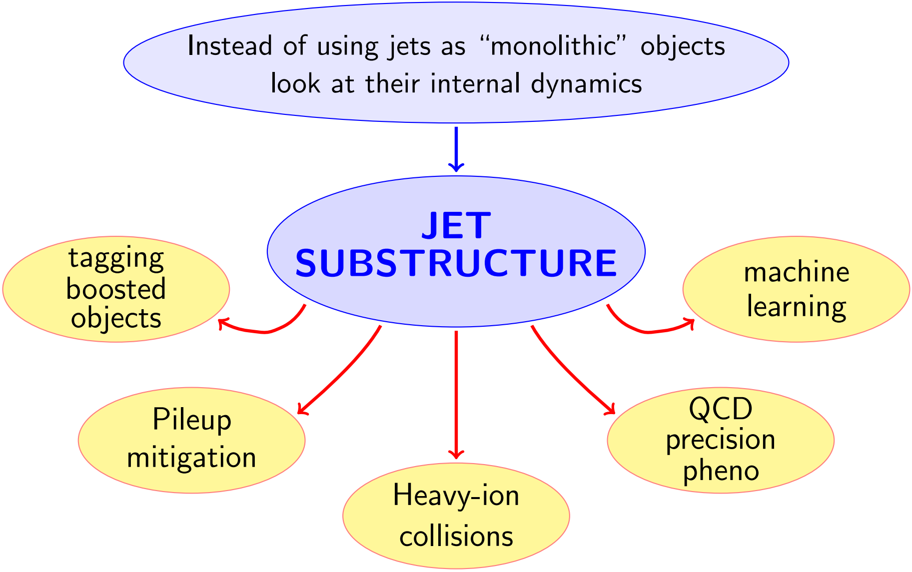
New prospects at the LHC

Instead of using jets as "monolithic" objects
look at their internal dynamics

↓

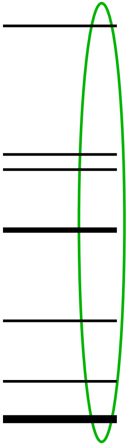
JET SUBSTRUCTURE

New prospects at the LHC



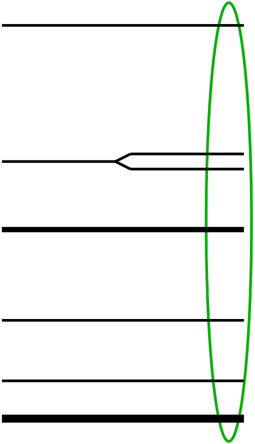
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair

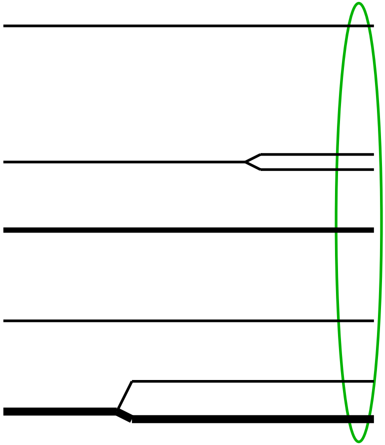


Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair

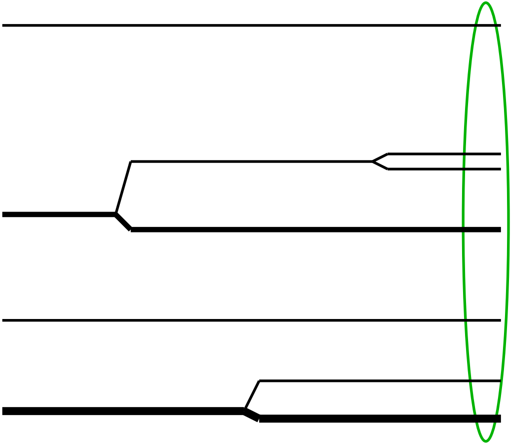


Cambridge/Aachen: iteratively recombine the closest pair



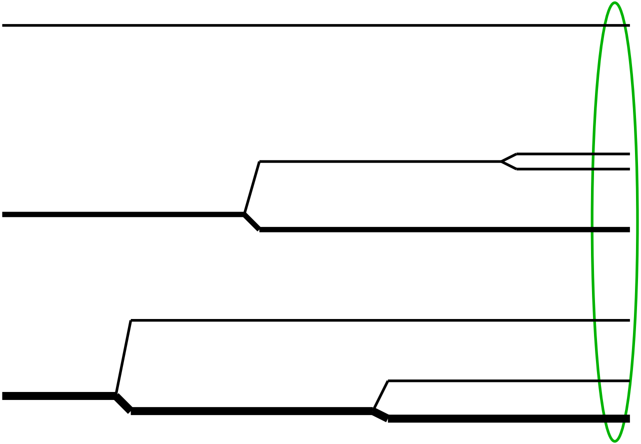
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



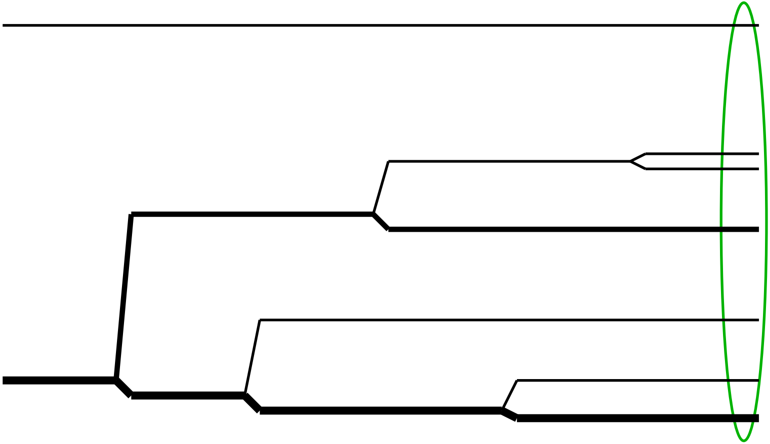
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iterative recombine the closest pair



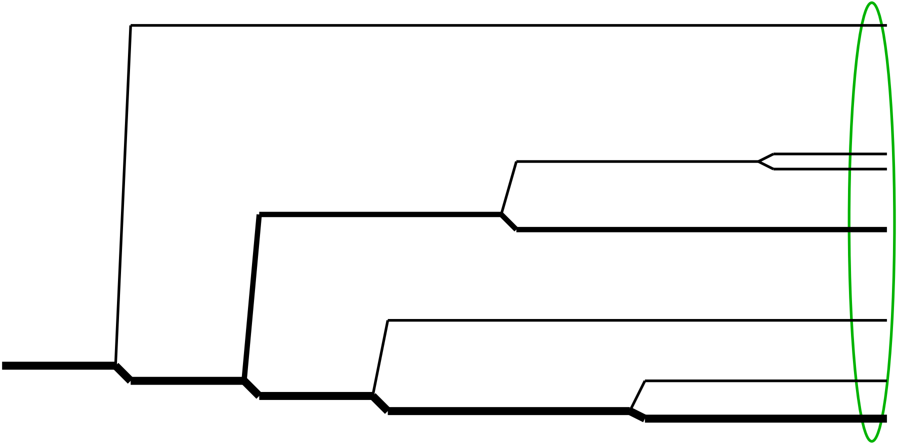
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



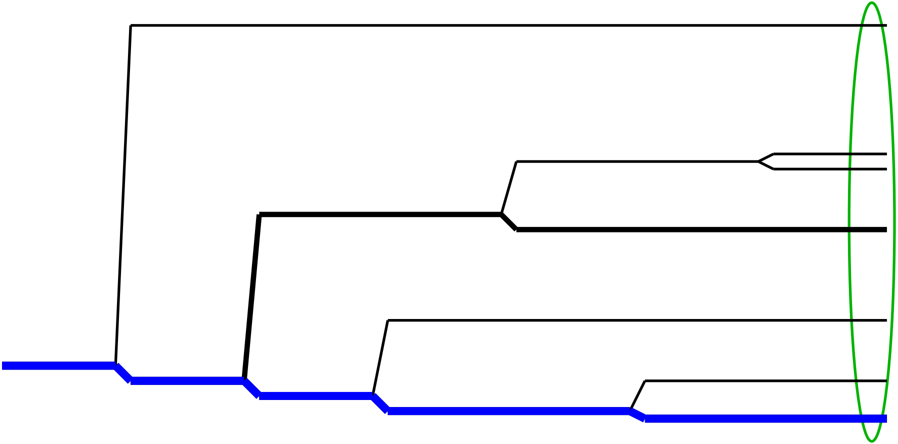
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



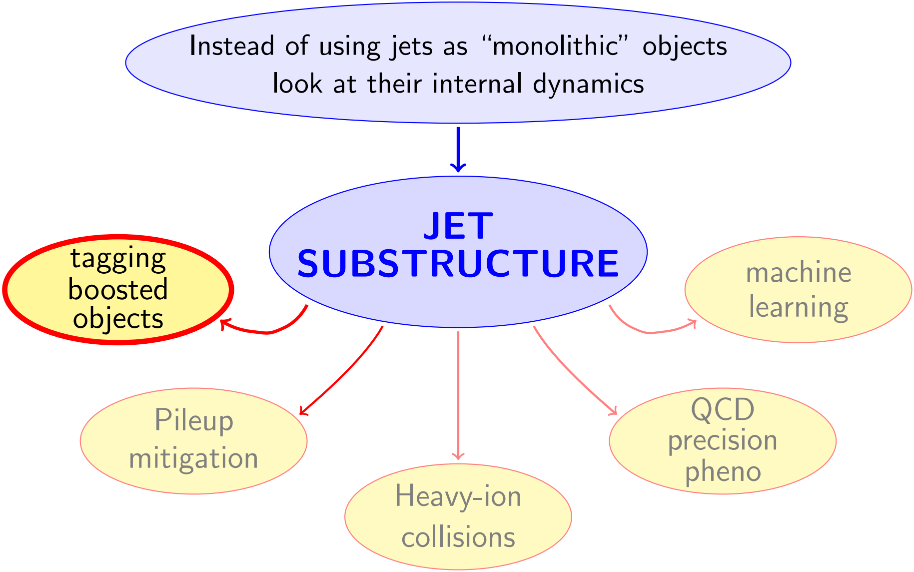
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



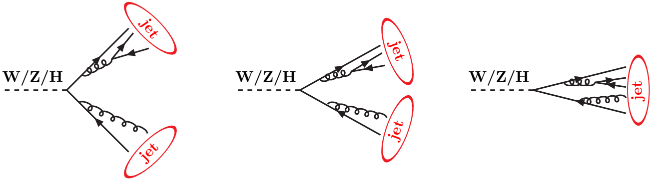
Usage: iteratively undo the clustering to study internal jet dynamics

Typically: follow the hardest branch (largest p_t or z)


Instead of using jets as "monolithic" objects
look at their internal dynamics
JET
SUBSTRUCTURE
tagging
boosted
objects
machine
learning
Pileup
mitigation
Heavy-ion
collisions
QCD
precision
pheno

Boosted objects

$p_t \lesssim m$ $\qquad\qquad$ $p_t \gg m$

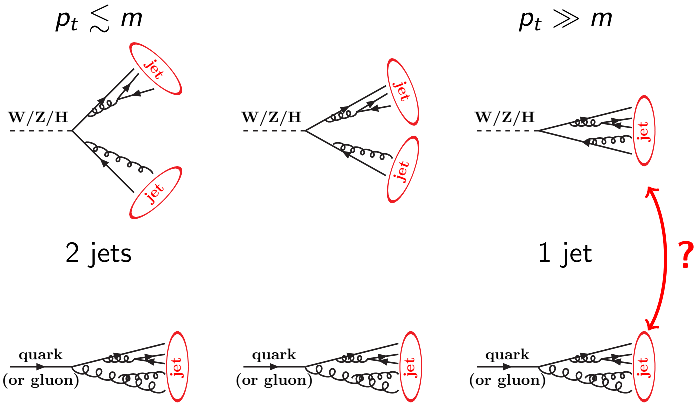


2 jets $\qquad\qquad$ 1 jet

(massive) objects produced boosted (energy $\gg$ mass) are seen as 1 jet:

$$\theta_{q\bar{q}} \sim \frac{m}{p_t}$$

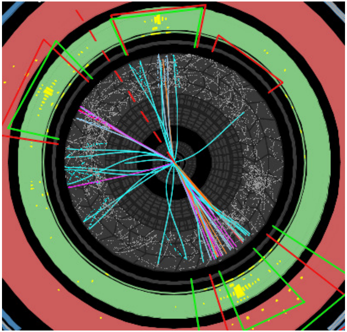
Boosted objects



use substructure to separate from QCD jets

Other examples

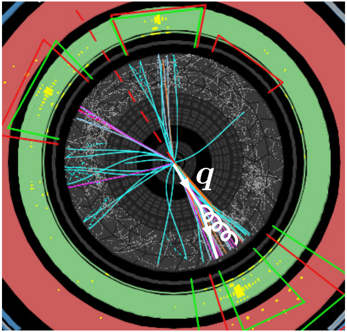
What jet do we have here?



Other examples

What jet do we have here?

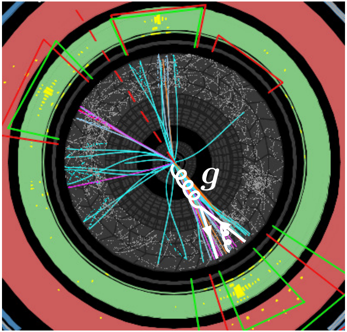
- a quark?



Other examples

What jet do we have here?

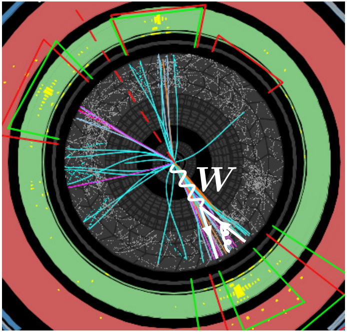
- a quark?
- a gluon?



Other examples

What jet do we have here?

- a quark?
- a gluon?
- a W/Z (or a Higgs)?

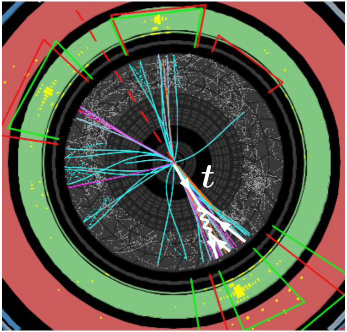


Other examples

What jet do we have here?

- a quark?
- a gluon?
- a W/Z (or a Higgs)?
- a top quark?

Source: ATLAS boosted top candidate

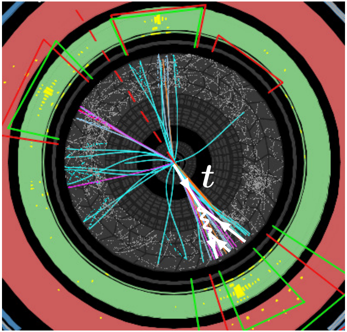


Other examples

What jet do we have here?

- a quark?
- a gluon?
- a W/Z (or a Higgs)?
- a top quark?

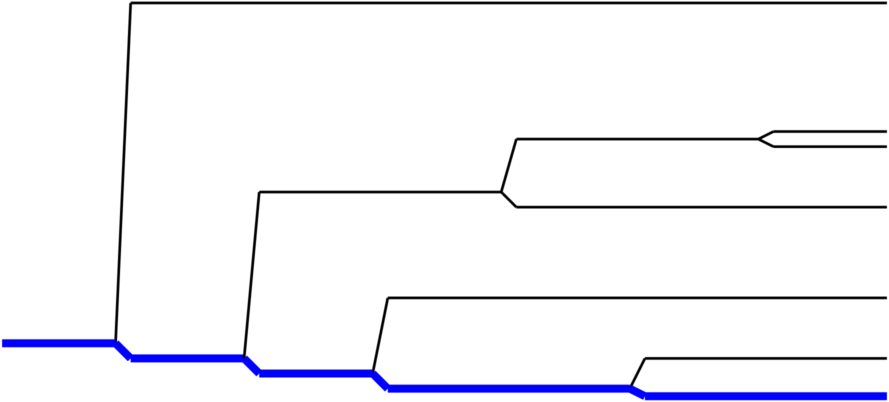
Source: ATLAS boosted top candidate



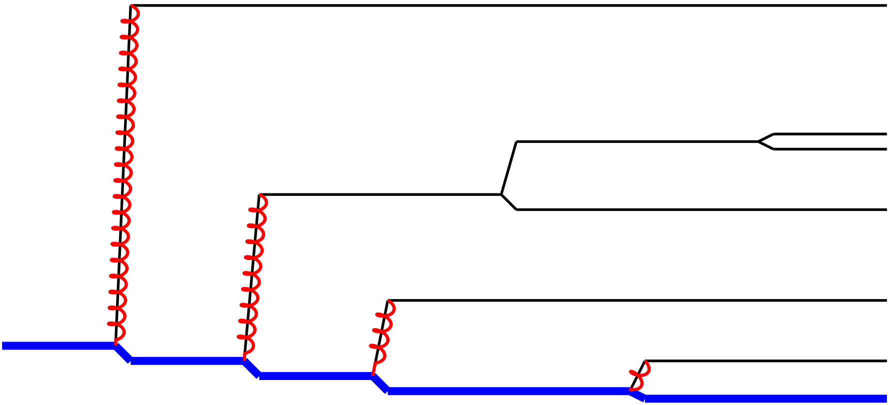
Many applications, e.g. relevant to new physics searches

(modified) Mass-Drop Tagger, Soft-Drop

Idea: look for hard branchings



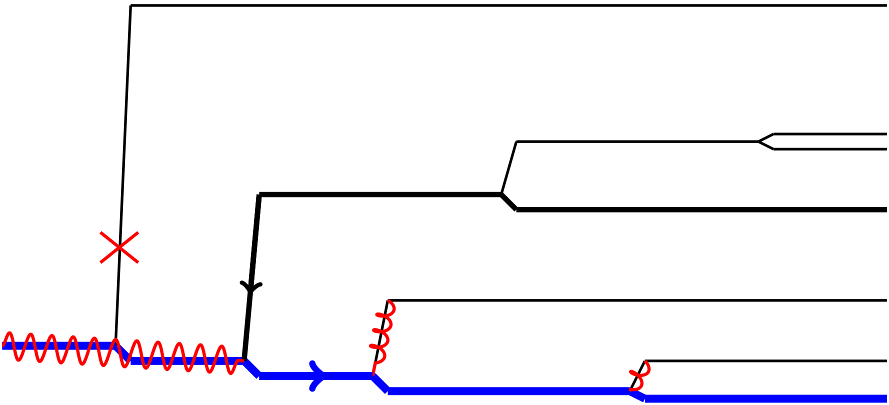
Idea: look for hard branchings



Rare hard branchings for $q/g \to q/g + g$ $(P(z) \sim 1/z)$

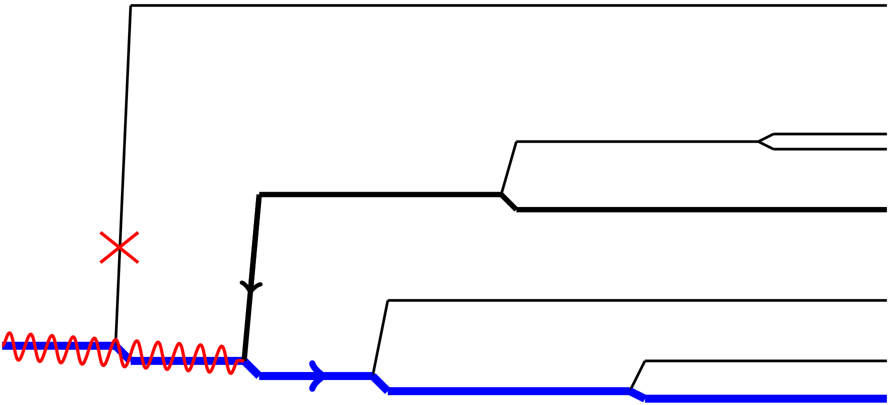
(modified) Mass-Drop Tagger, Soft-Drop

Idea: look for hard branchings

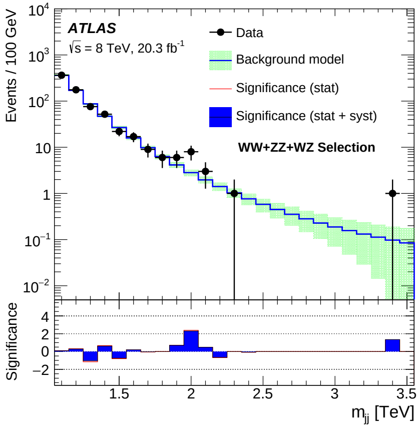


Rare hard branchings for $q/g \to q/g + g$ $(P(z) \sim 1/z)$
Frequent hard branchings for $W/Z/H \to q\bar{q}$ $(P(z) \sim 1)$

Idea: look for hard branchings

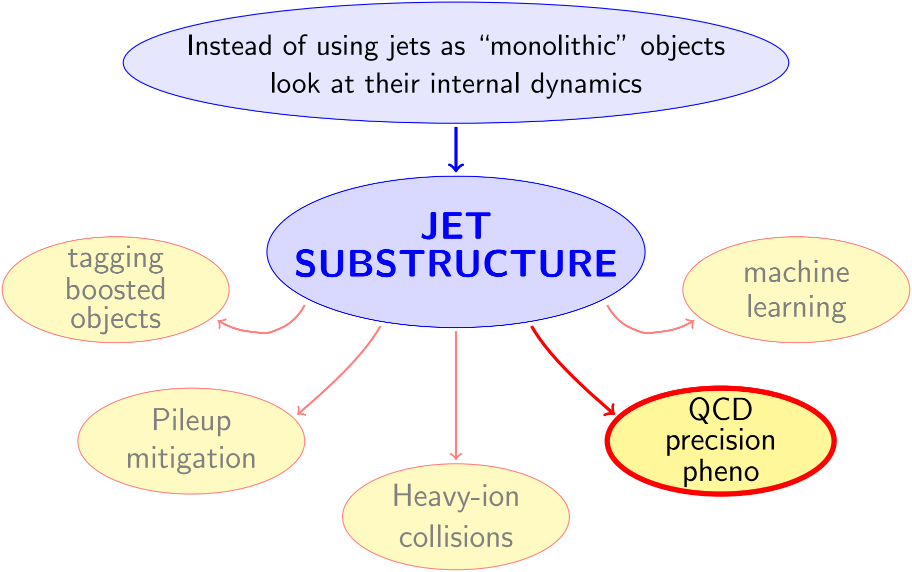


Method: search the first splitting with $z > z_{\text{cut}}$



(now-gone) di-boson excess (end of Run-I)

New prospects at the LHC



Analytic approach to jet substructure

- Main idea:

Boosted jet $\Rightarrow p_t \gg m$

$$\Rightarrow \rho \equiv \frac{m^2}{p_t^2 R^2} \ll 1$$

$\Rightarrow$ expect $\log \rho$ coming with α_s

$\Rightarrow$ need for all-order resummation

Analytic approach to jet substructure

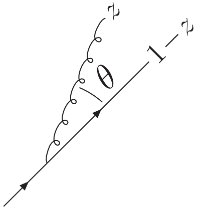
- Main idea:

  Boosted jet $\Rightarrow p_t \gg m$

  $\Rightarrow \rho \equiv \dfrac{m^2}{p_t^2 R^2} \ll 1$

  $\Rightarrow$ expect $\log \rho$ coming with α_s

  $\Rightarrow$ need for all-order resummation



- Example: jet mass with one (soft-and-collinear) gluon emission

$$\text{Prob}_1(>\rho) \simeq \int_0^1 \frac{d\theta^2}{\theta^2}\frac{dz}{z}\frac{\alpha_s C_R}{\pi}\Theta(z\theta^2 > \rho) \simeq \frac{\alpha_s C_R}{2\pi}\log^2(1/\rho)$$

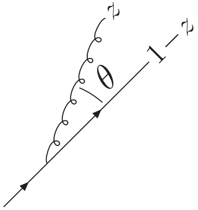
- Main idea:

  Boosted jet $\Rightarrow p_t \gg m$

  $\Rightarrow \rho \equiv \frac{m^2}{p_t^2 R^2} \ll 1$

  $\Rightarrow$ expect $\log \rho$ coming with α_s

  $\Rightarrow$ need for all-order resummation



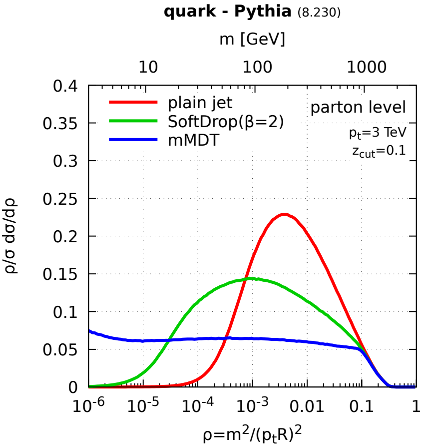
- Example: jet mass with one (soft-and-collinear) gluon emission

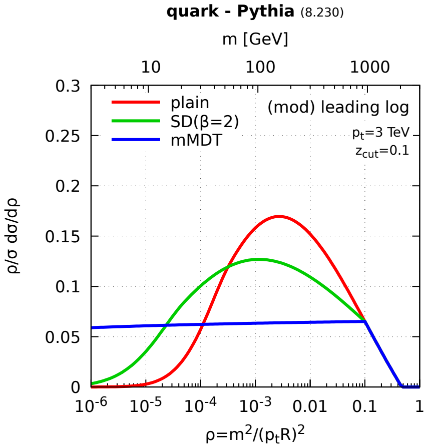
$$\text{Prob}_1(>\rho) \simeq \int_0^1 \frac{d\theta^2}{\theta^2} \frac{dz}{z} \frac{\alpha_s C_R}{\pi} \Theta(z\theta^2 > \rho) \simeq \frac{\alpha_s C_R}{2\pi} \log^2(1/\rho)$$

- Use the same Sudakov parametrisation as for "Monte-Carlo generators" seen earlier, but now treat things analytically

Understanding substructure tools

Breakthrough 5 years ago: jet substructure tools are calculable

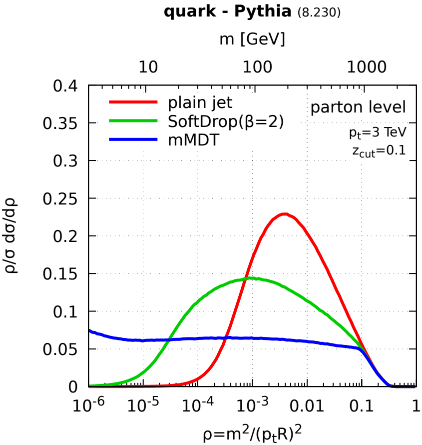


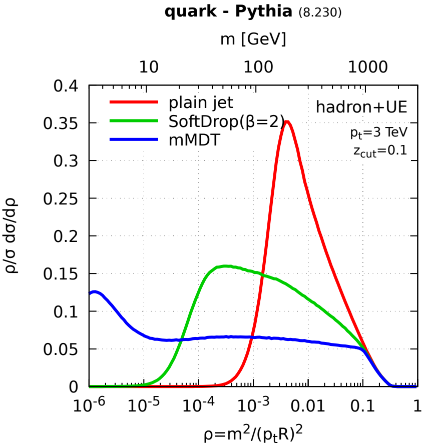


- **qualitative features reproduced and understood**

Understanding substructure tools

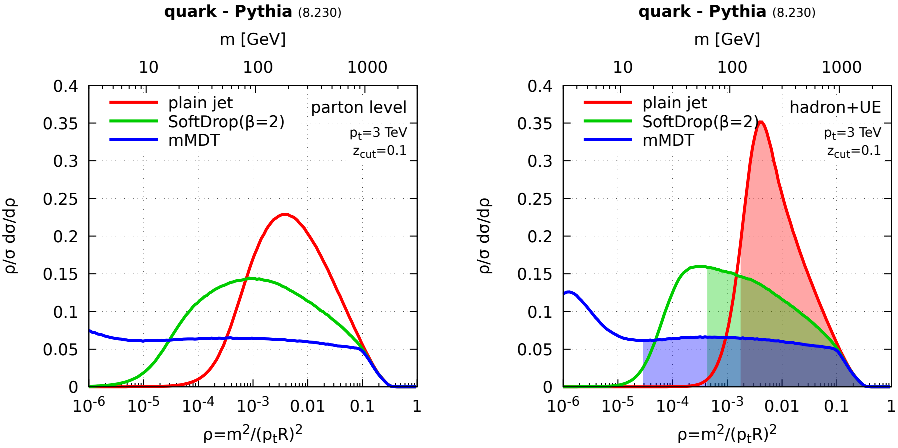
Breakthrough 5 years ago: jet substructure tools are calculable





- **qualitative features reproduced and understood**

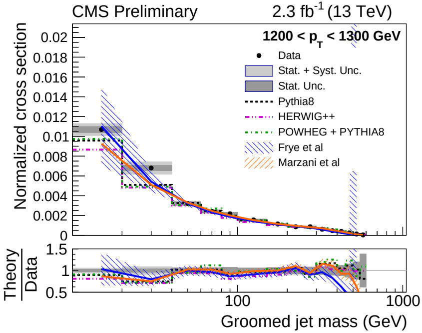
Breakthrough 5 years ago: jet substructure tools are calculable



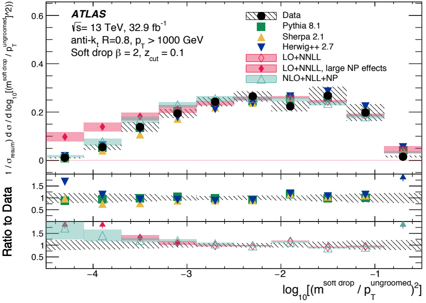
- **qualitative features reproduced and understood**
- **substructure reduces non-perturbative effects**

LHC measurements v. NLL+NLO and NNLL+LO predictions:

CMS-PAS-SMP-16-010



ATLAS(CERN-EP-2017-231)

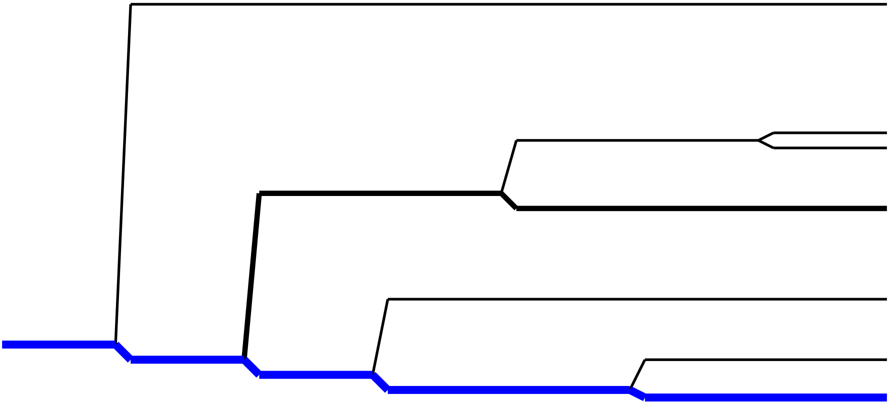


good overall agreement with the data

Precise observable, limited NP effects ⇒ **can we extract α_s?**

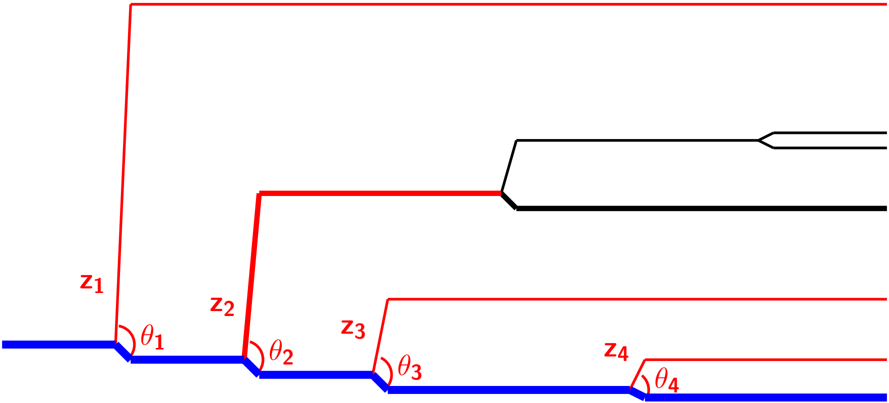
Visualising the sustructure with the Lund plane

[F.Dreyer,G.Salam,GS,18]



Visualising the sustructure with the Lund plane

[F.Dreyer,G.Salam,GS,18]

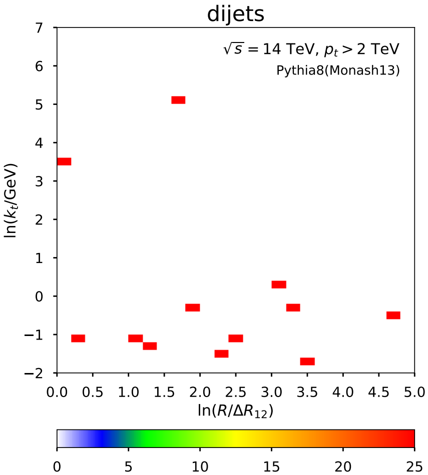


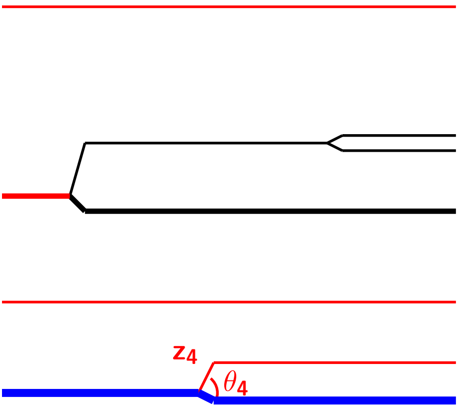
Consider all the emissions from the hardest branch

Visualising the sustructure with the Lund plane

[F.Dreyer,G.Salam,GS,18]

One jet





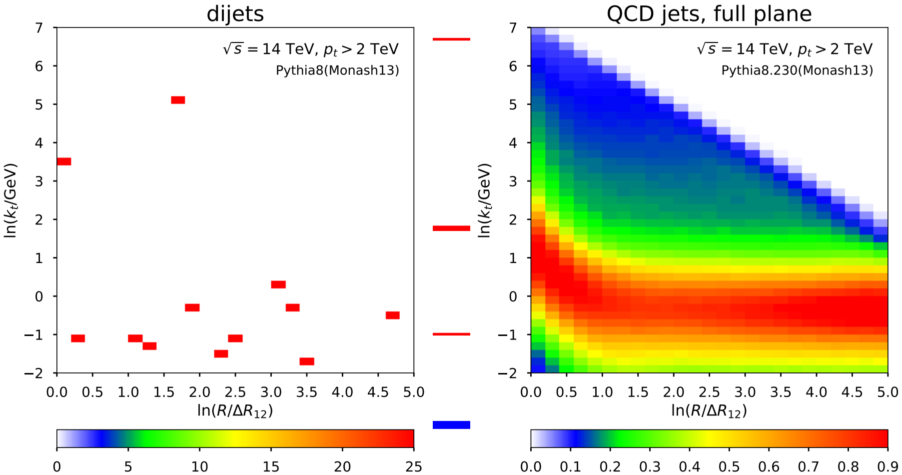
Consider all the emissions from the hardest branch

Put them in the Lund plane

Visualising the sustructure with the Lund plane

[F.Dreyer,G.Salam,GS,18]

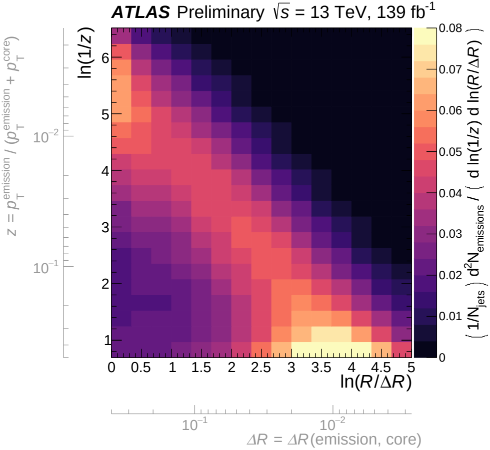
One jet — Average over jets

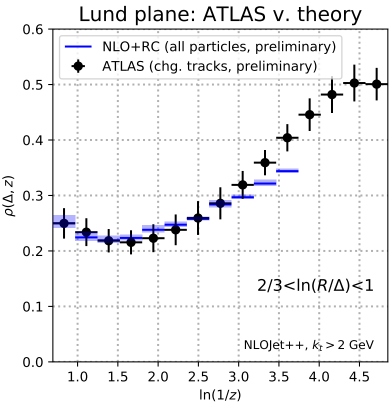


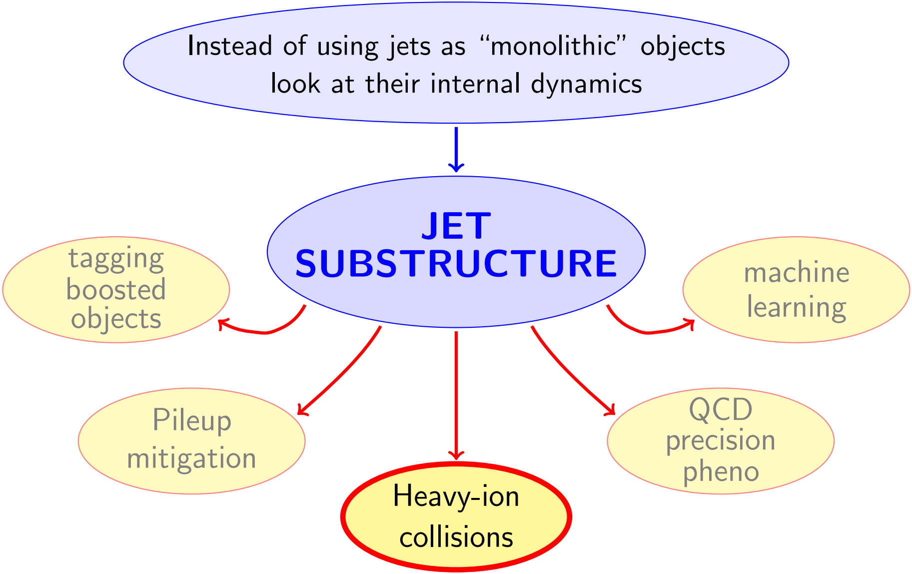
Consider all the emissions from the hardest branch

Put them in the Lund plane

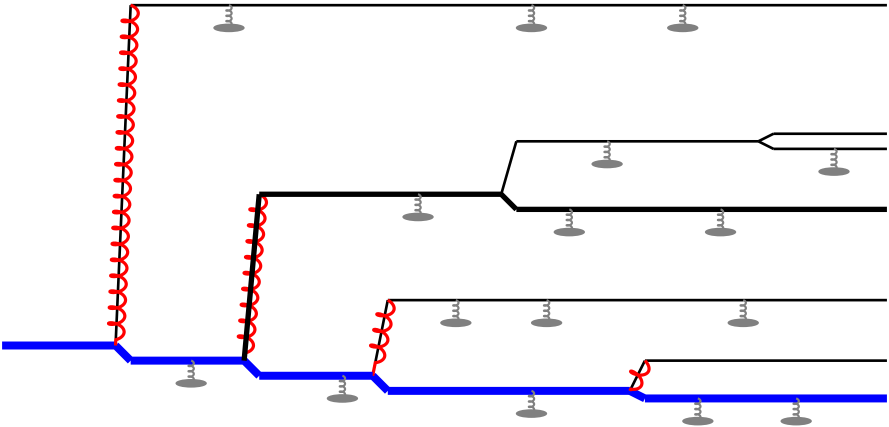
Measured by ATLAS at the LHC






Instead of using jets as "monolithic" objects
look at their internal dynamics
JET
SUBSTRUCTURE
tagging
boosted
objects
machine
learning
Pileup
mitigation
QCD
precision
pheno
Heavy-ion
collisions

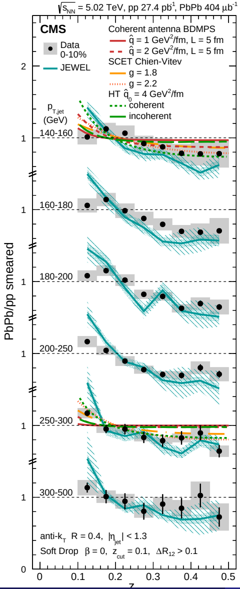
Idea: interaction with the quark-gluon plasma



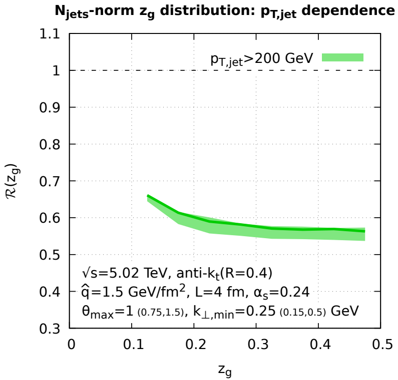
Method: look at the z fraction of the first splitting with $z > z_{\text{cut}}$

Measuring the splitting function

CMS (CMS-HIN-16-006)

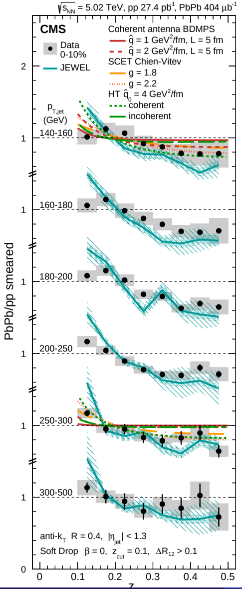


our Monte Carlo

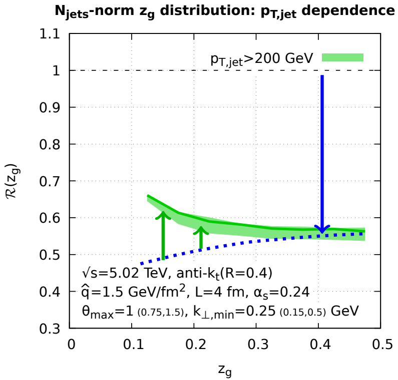


Measuring the splitting function

CMS (CMS-HIN-16-006)



our Monte Carlo



- Reduction from E loss
- Peak from extra emissions

Conclusions

Rich high-energy QCD pheno "close to the light-cone"

- Probe a range of widely-separated scales
- Monte-Carlo Event generators
  - Connect hard process to Λ_{QCD}
  - On-going project: improve parton-shower logarithmic accuracy
- Jets
  - Ubiquitous at colliders
  - Fast and efficient algorithms
- Jet substructure has many applications
  - boosted-object tagging (e.g. for searches)
  - QCD tools and precision physics
  - QGP/jet quenching in heavy-ion collisions
  - pileup mitigation
  - machine learning