New perspectives in QCD with jet substructure

Gregory Soyez

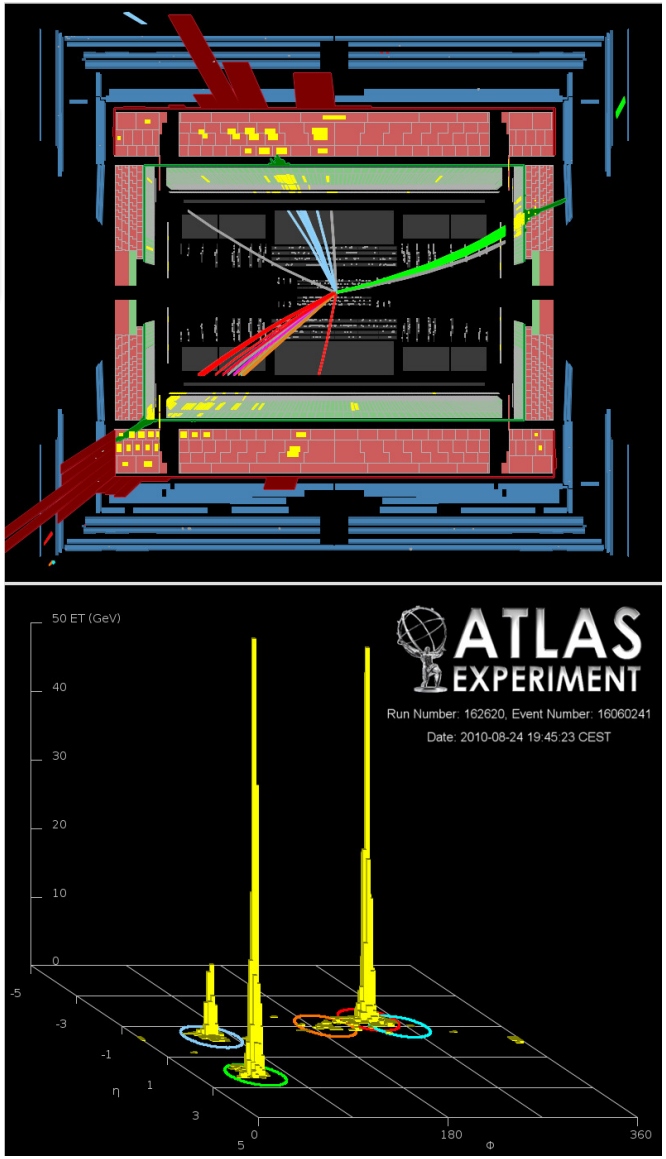
IPhT, CNRS, CEA Saclay

QCD@LHC 2020, August 31-September 3 2020

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

  2 main ways to see jets:

  QCD branchings $\leftrightarrow$ recombination algorithms

  Energy flow $\leftrightarrow$ cone algorithms
- Calculable in perturbative QCD
  (NLO standard, sometimes NNLO)

40 years of jets for collider phenomenology

Central idea

Jet ≡

⇒ carries i

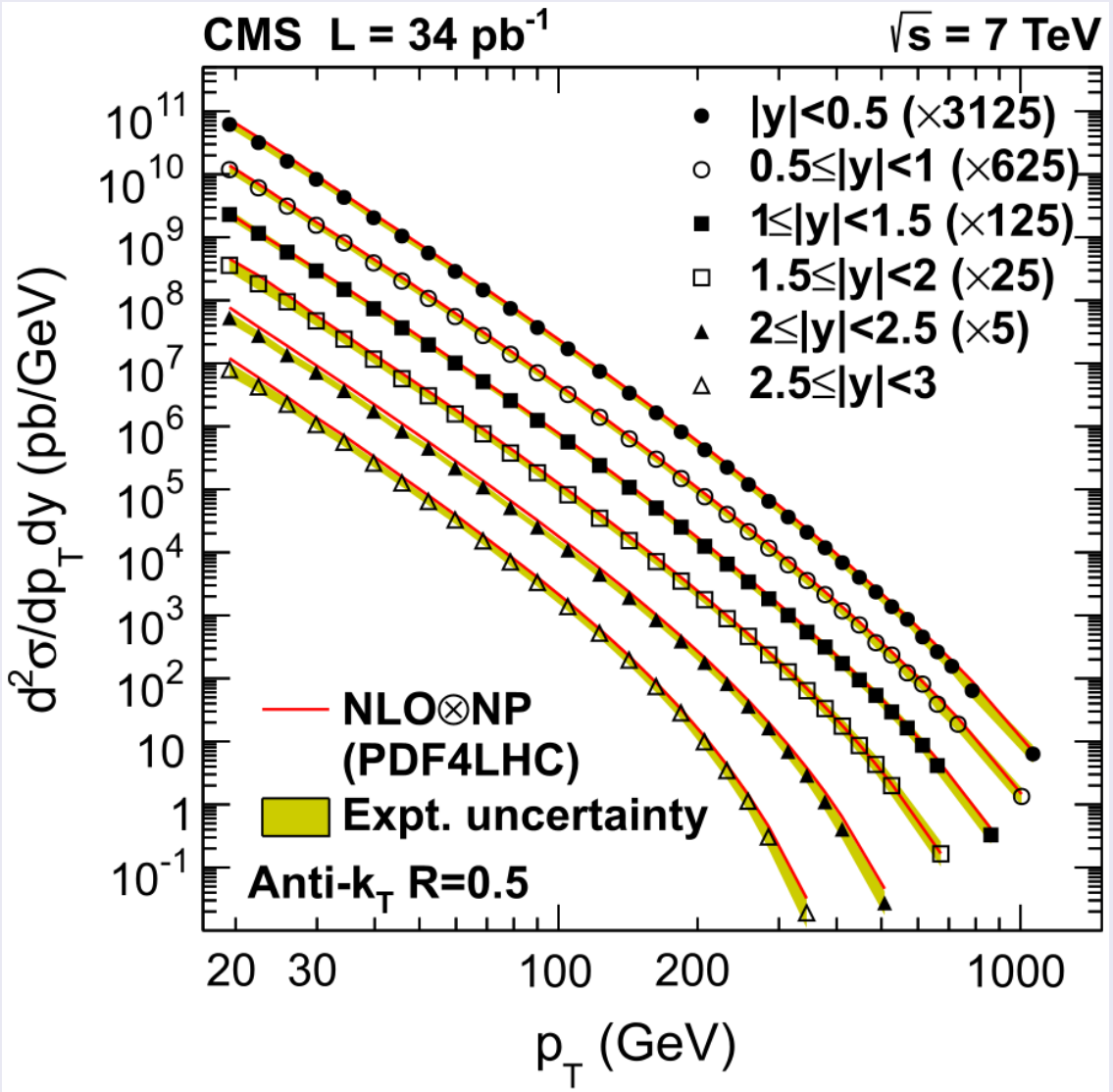
- Ubiquitou
  used in m
- Reconstru
  using dedi

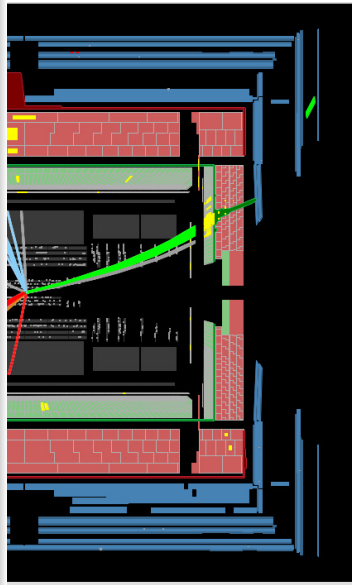
  2 main wa

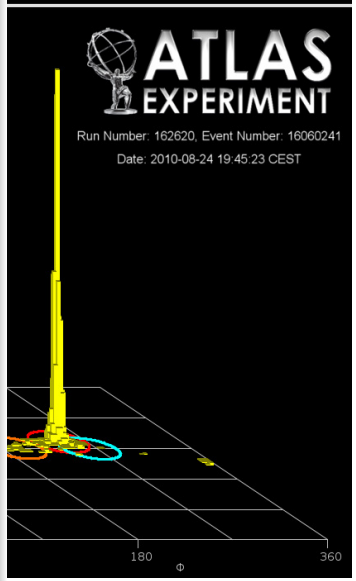
  QCD bra

  Energ
- Calculable
  (NLO star

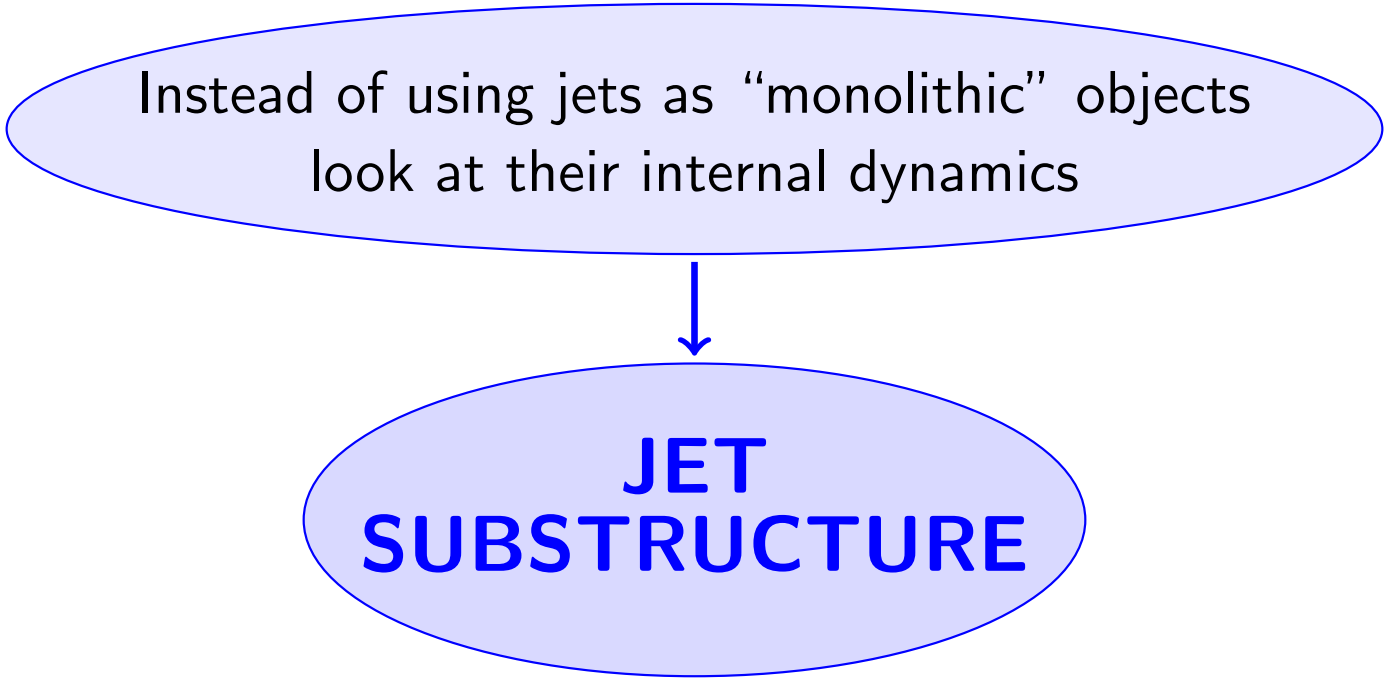
Jet cross-section at the LHC



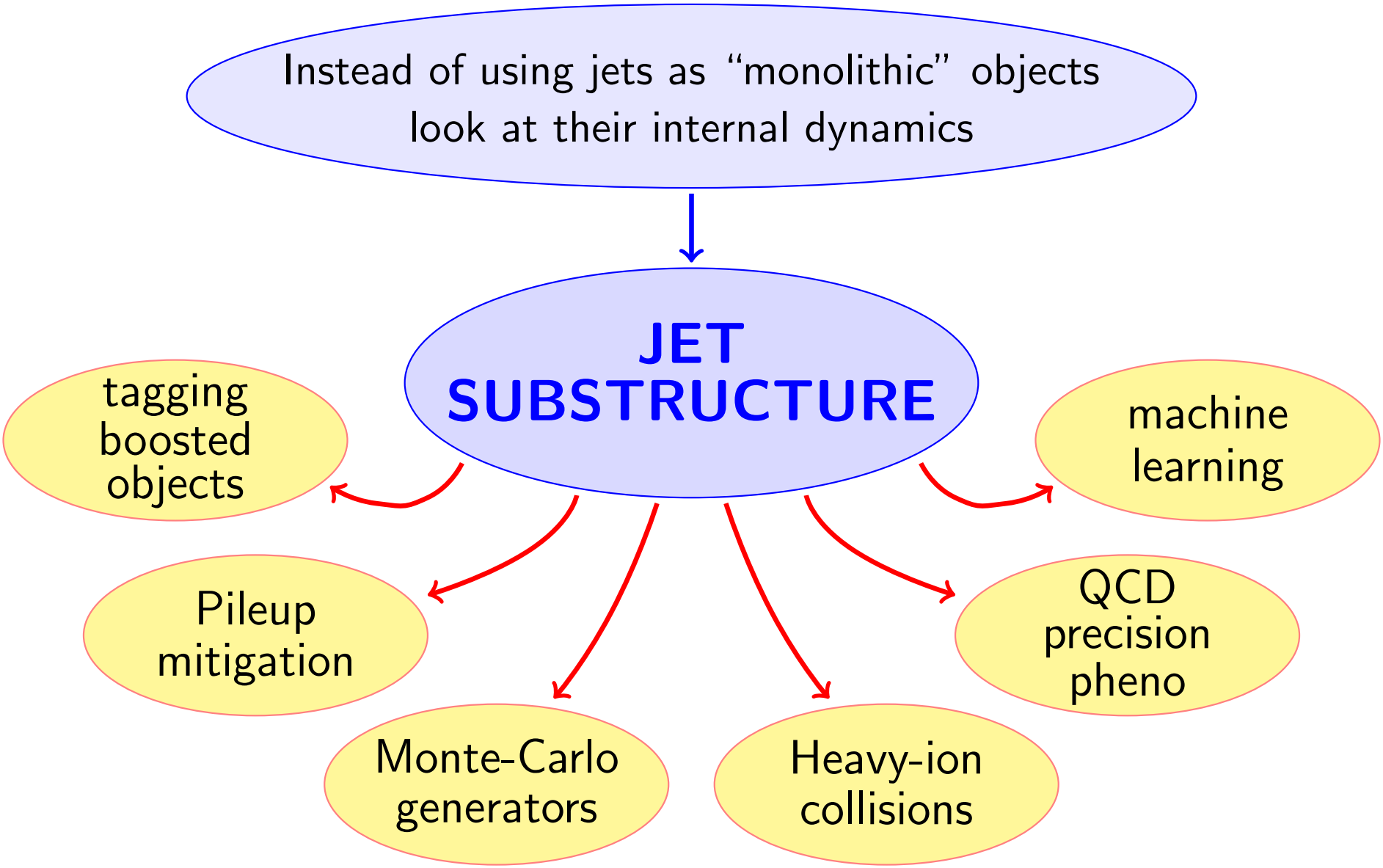




New prospects at the LHC



New prospects at the LHC



A decade of substructure tools

(modified) MassDrop Tagger

(generalised) angularities

(recursive) SoftDrop

N-subjettiness

Trimming

Energy Correlation Functions

Pruning

Shower deconstruct^{n}

Energy flow Polynomials

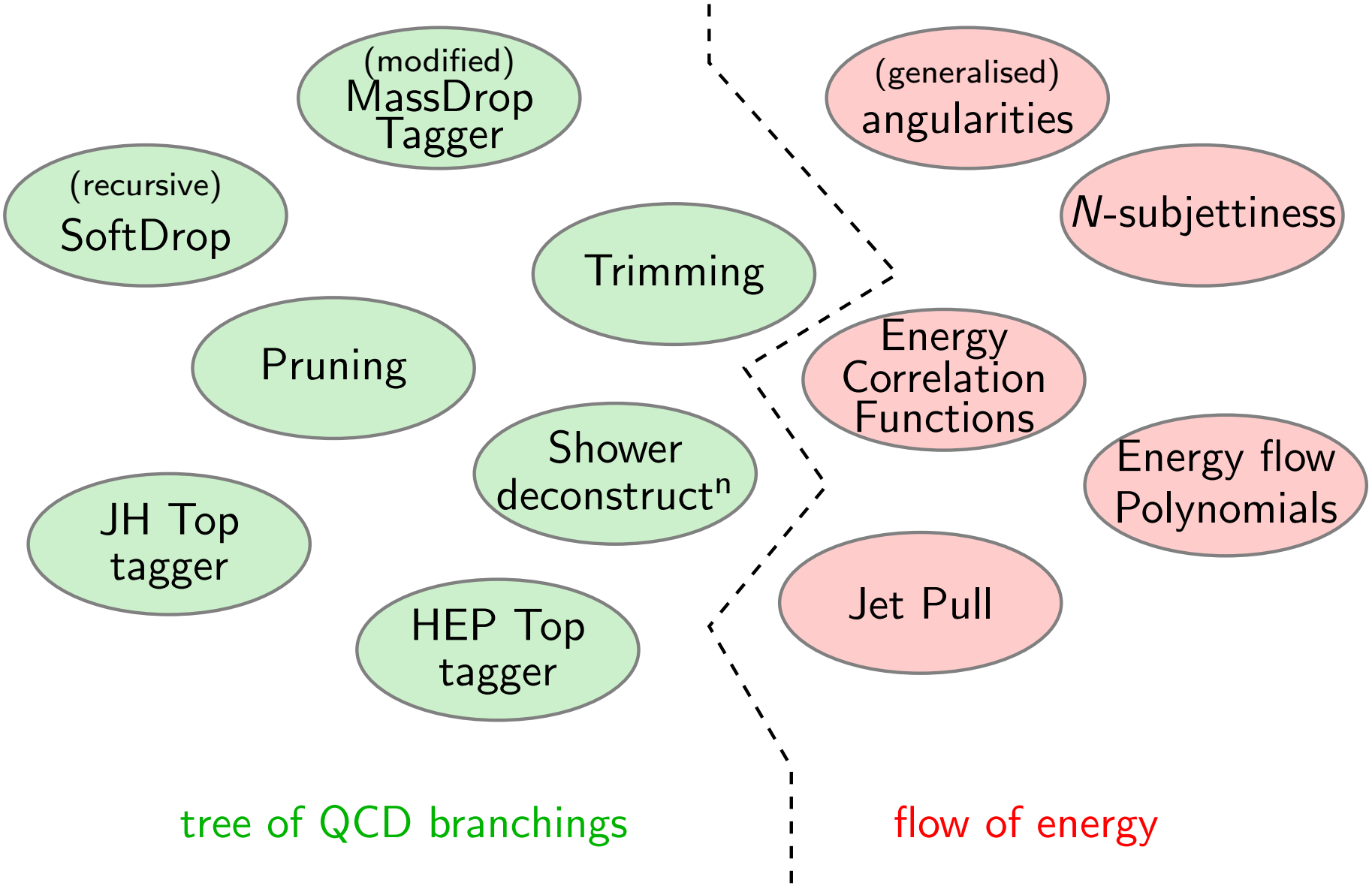
JH Top tagger

Jet Pull

HEP Top tagger

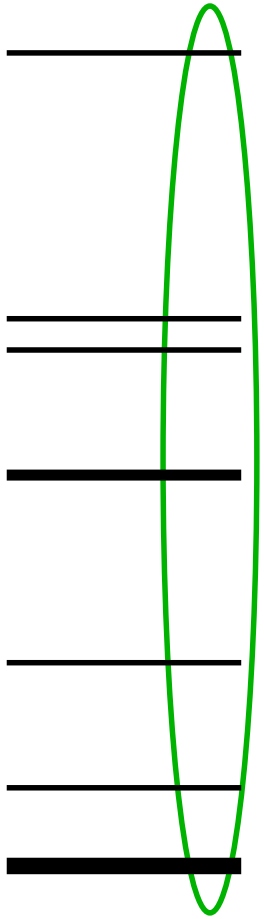
* Non-exhaustive/biased/... list

A decade of substructure tools



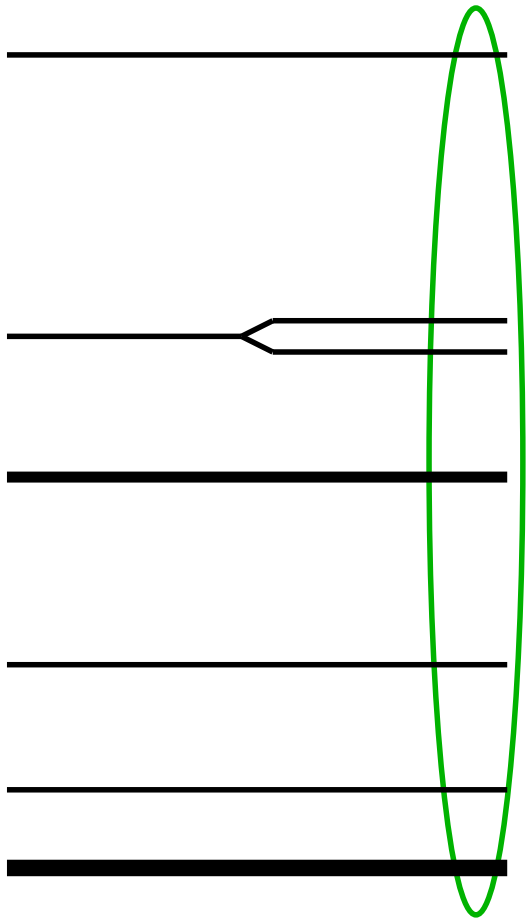
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



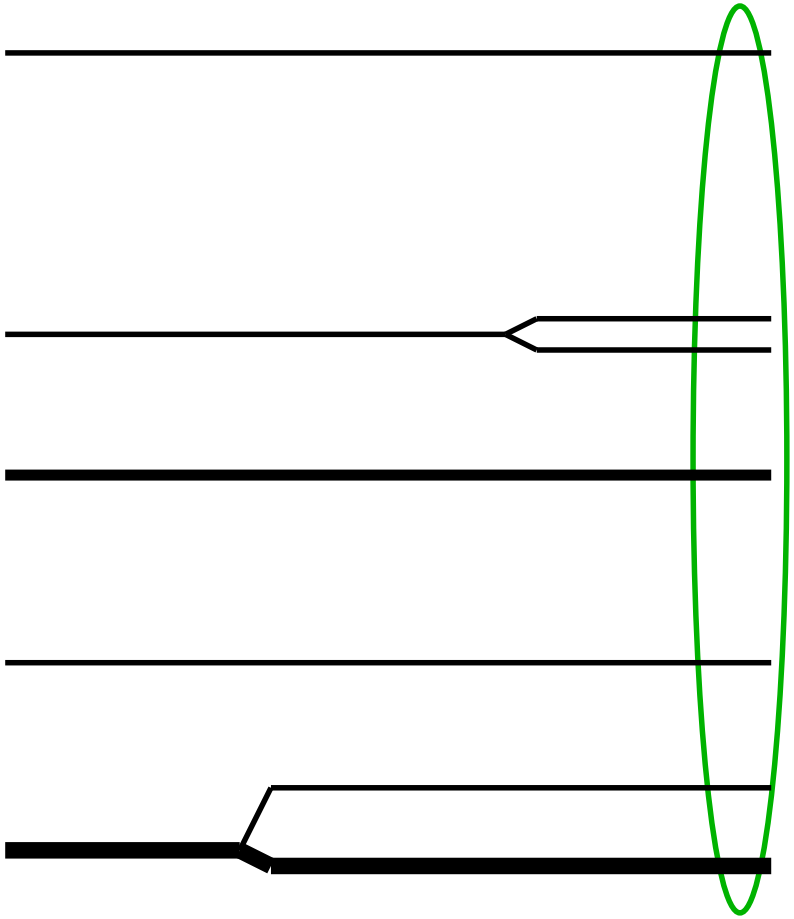
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



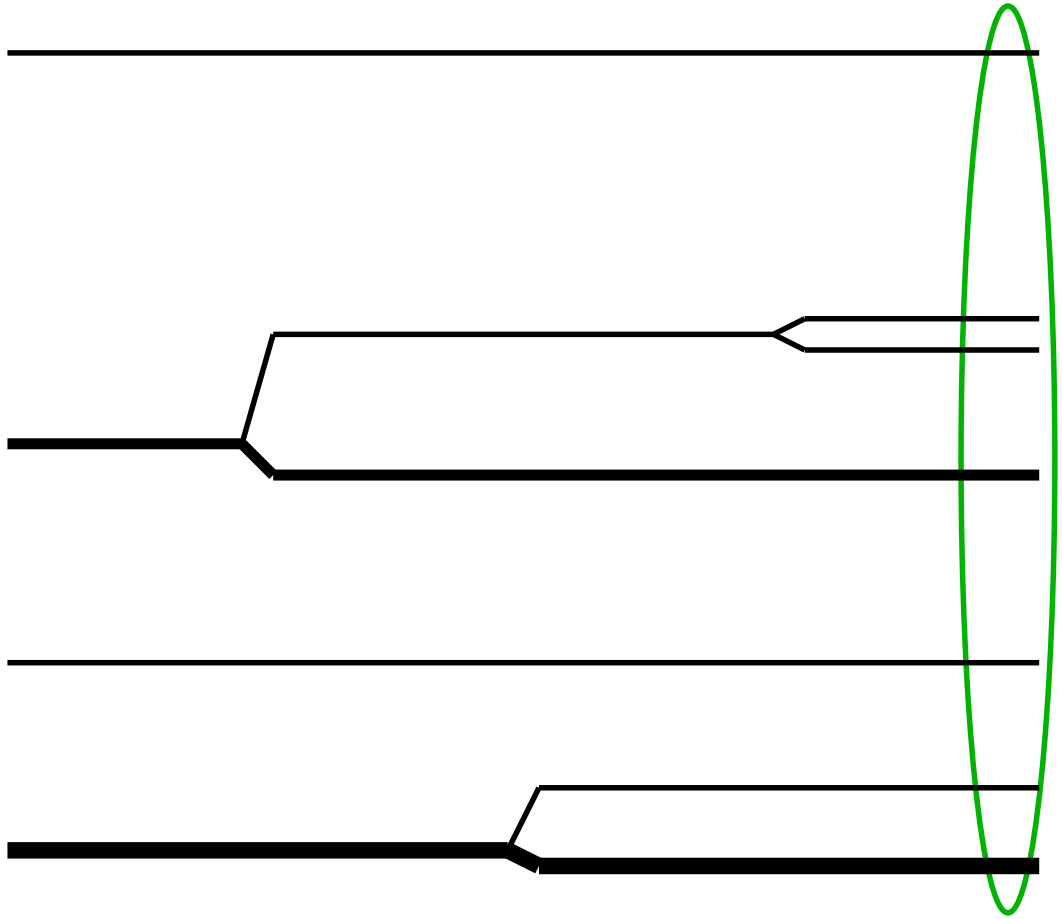
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



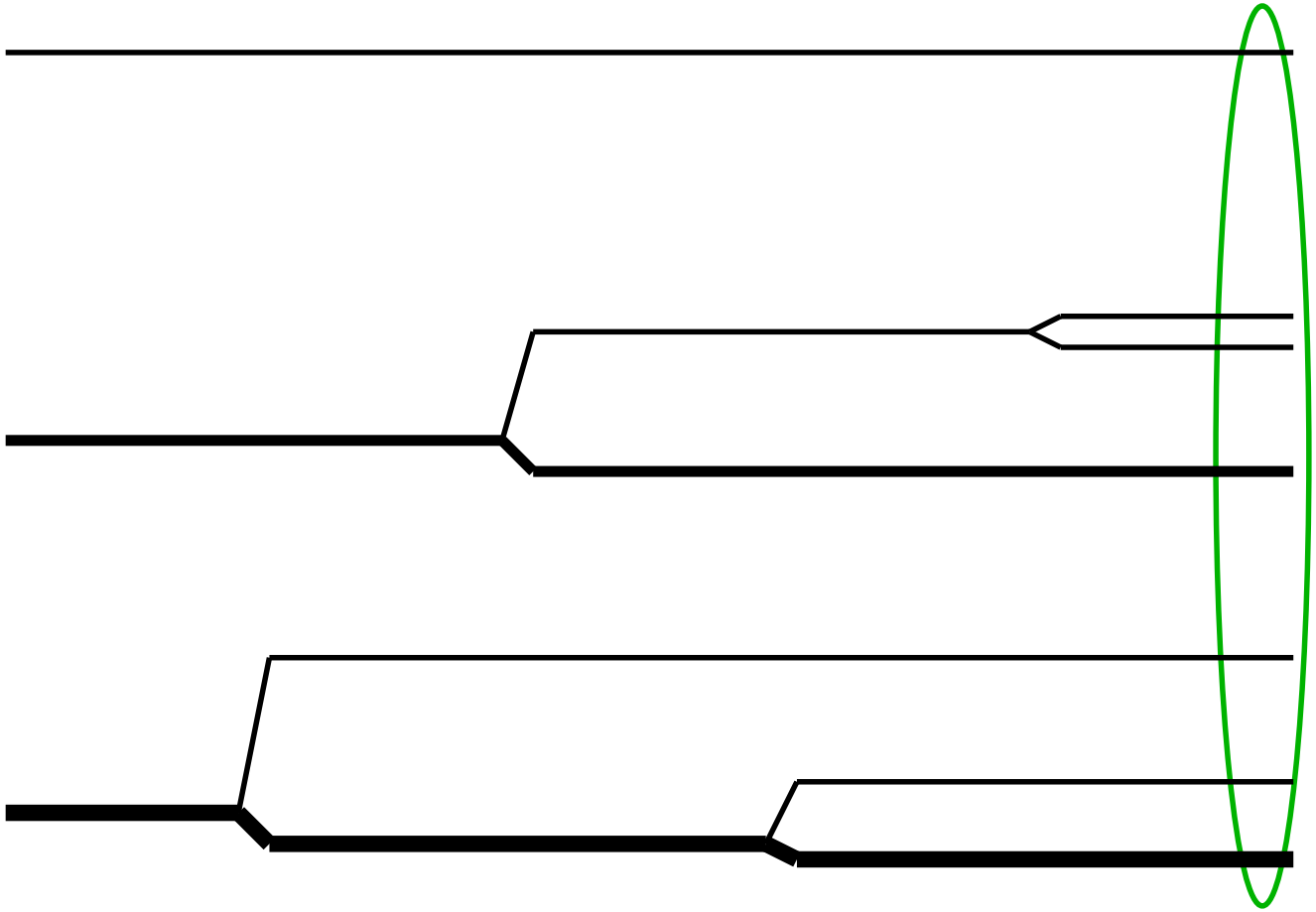
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



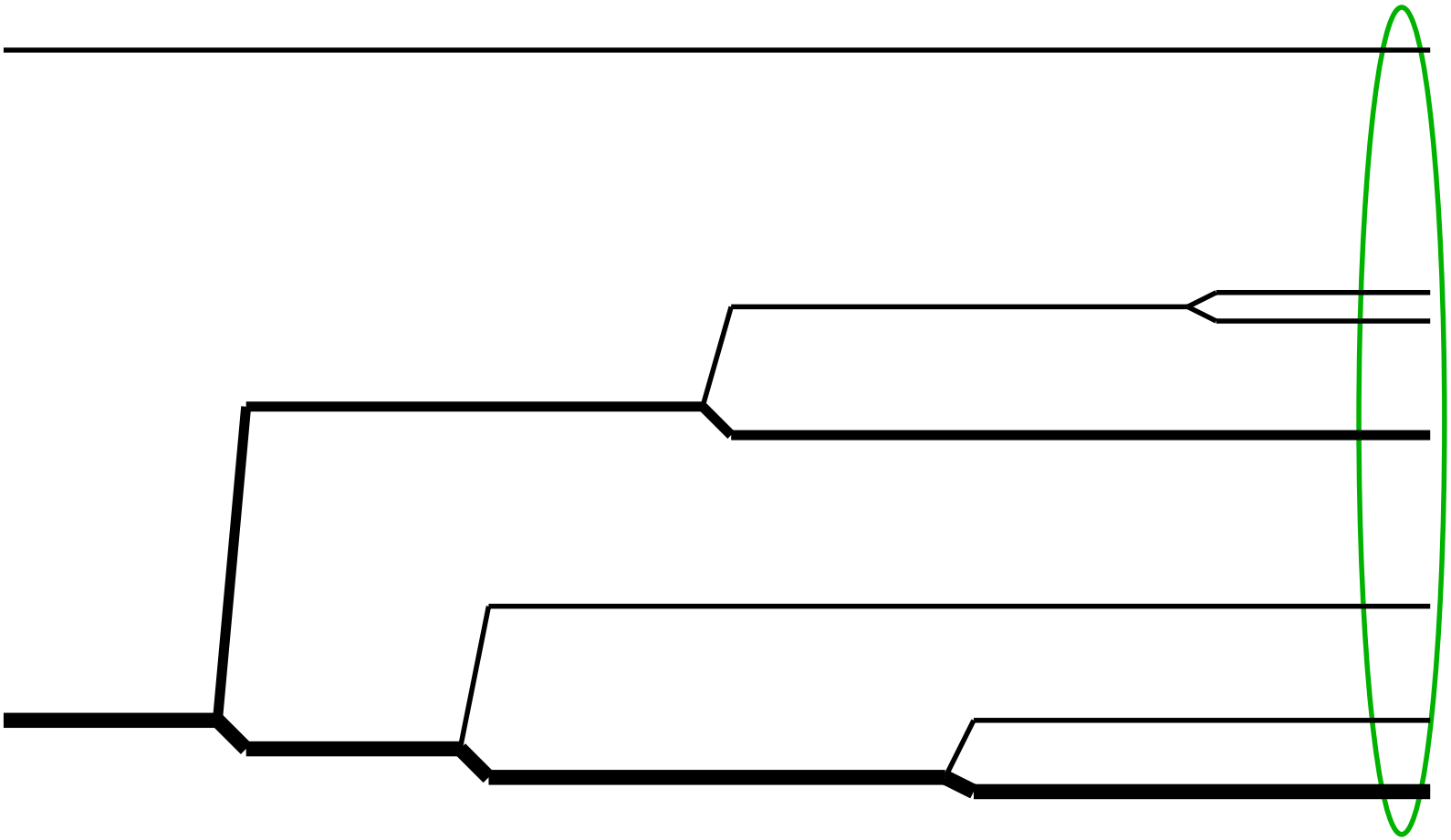
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



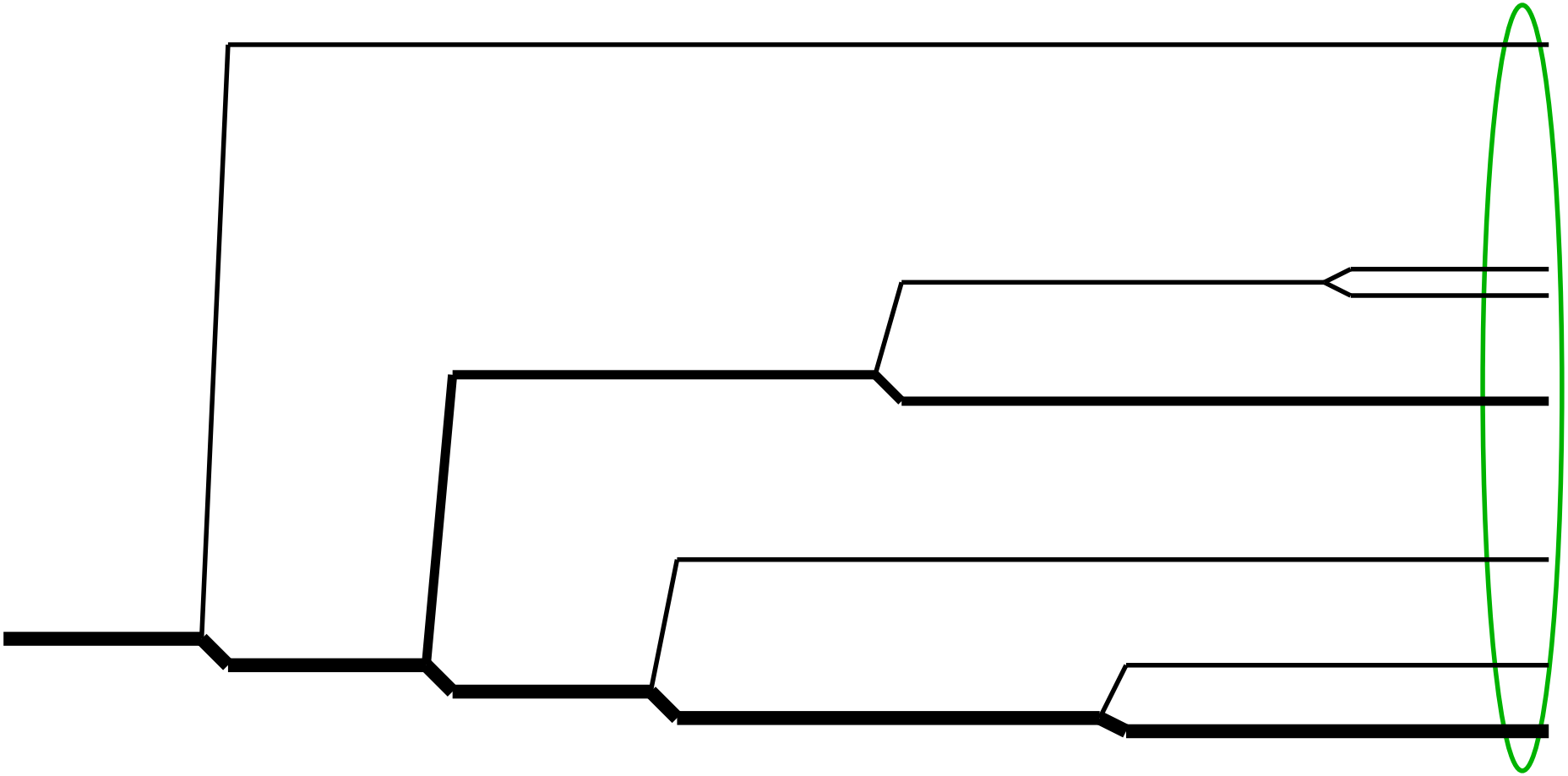
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



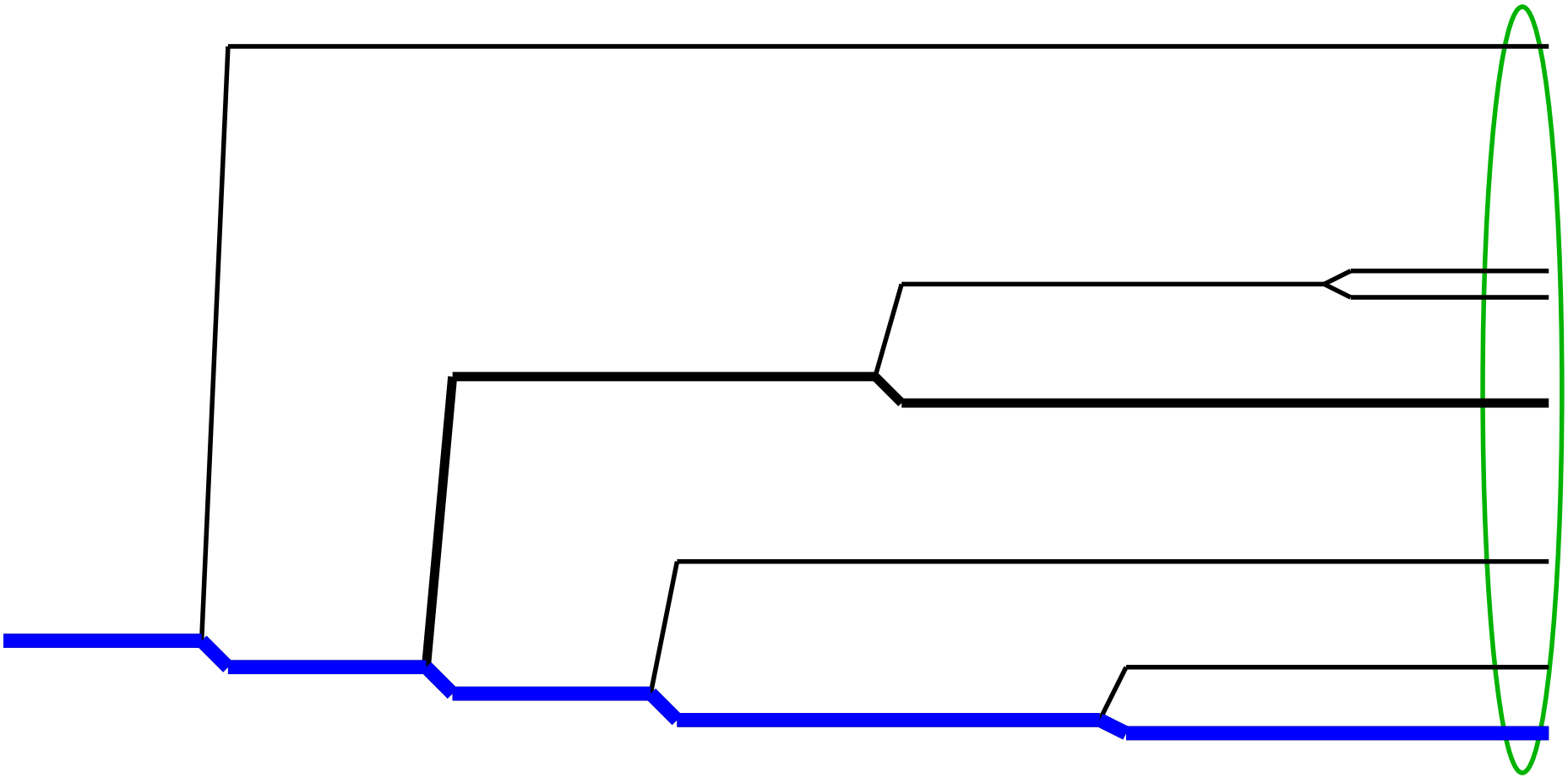
Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



Frequent tool: Cambridge/Aachen (de-)clustering

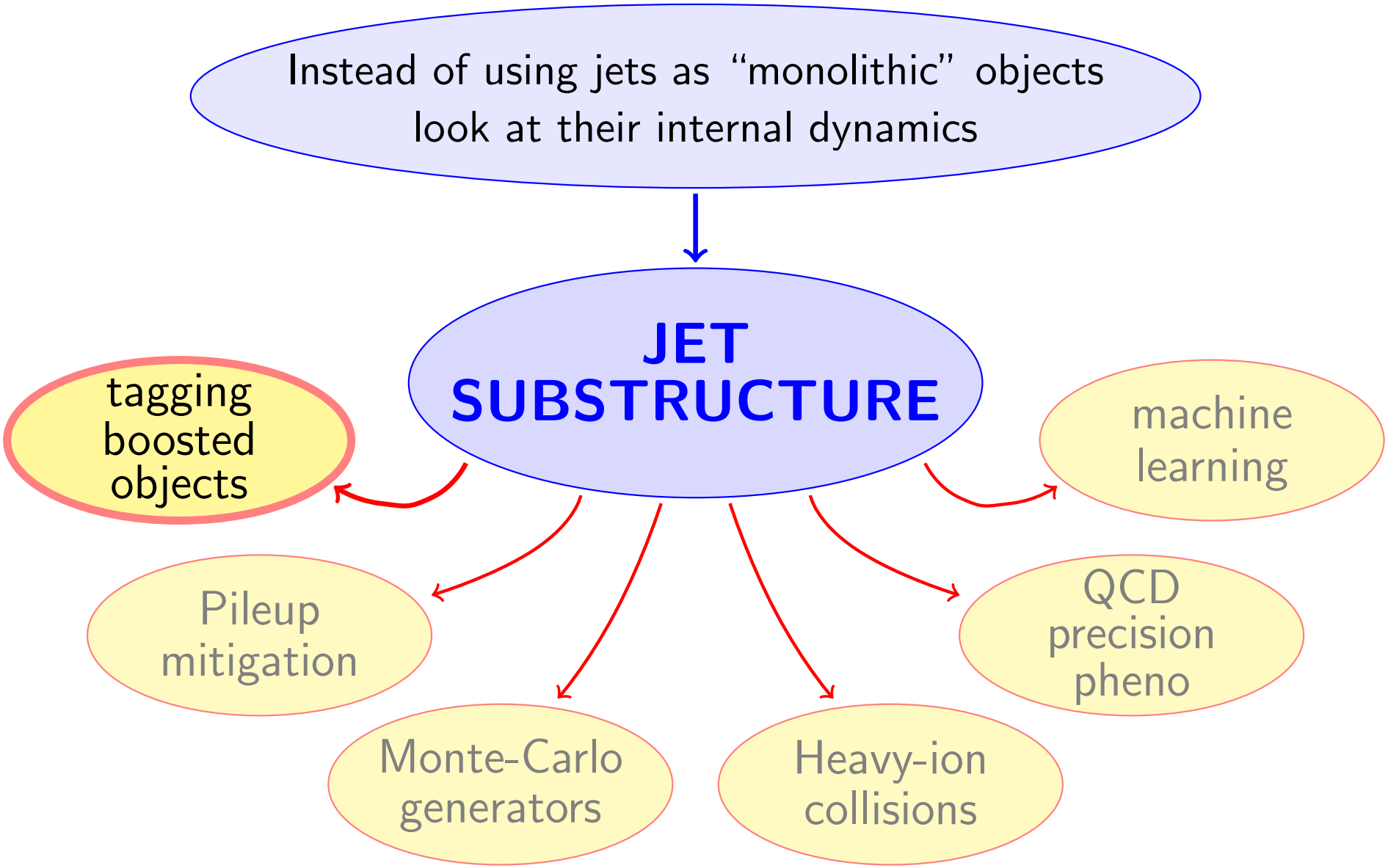
Cambridge/Aachen: iteratively recombine the closest pair



Usage: iteratively undo the clustering to study internal jet dynamics

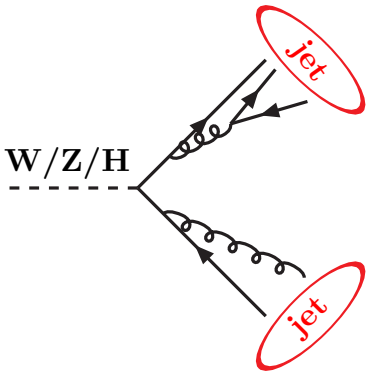
Typically: follow the hardest branch (largest p_t or z)

New prospects at the LHC

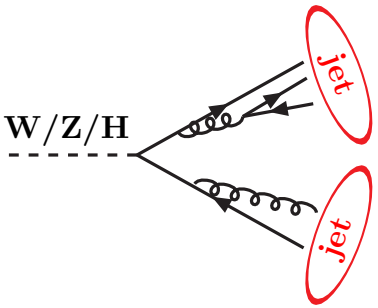


Boosted objects

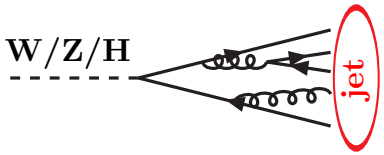
$p_t \lesssim m$



2 jets



$p_t \gg m$

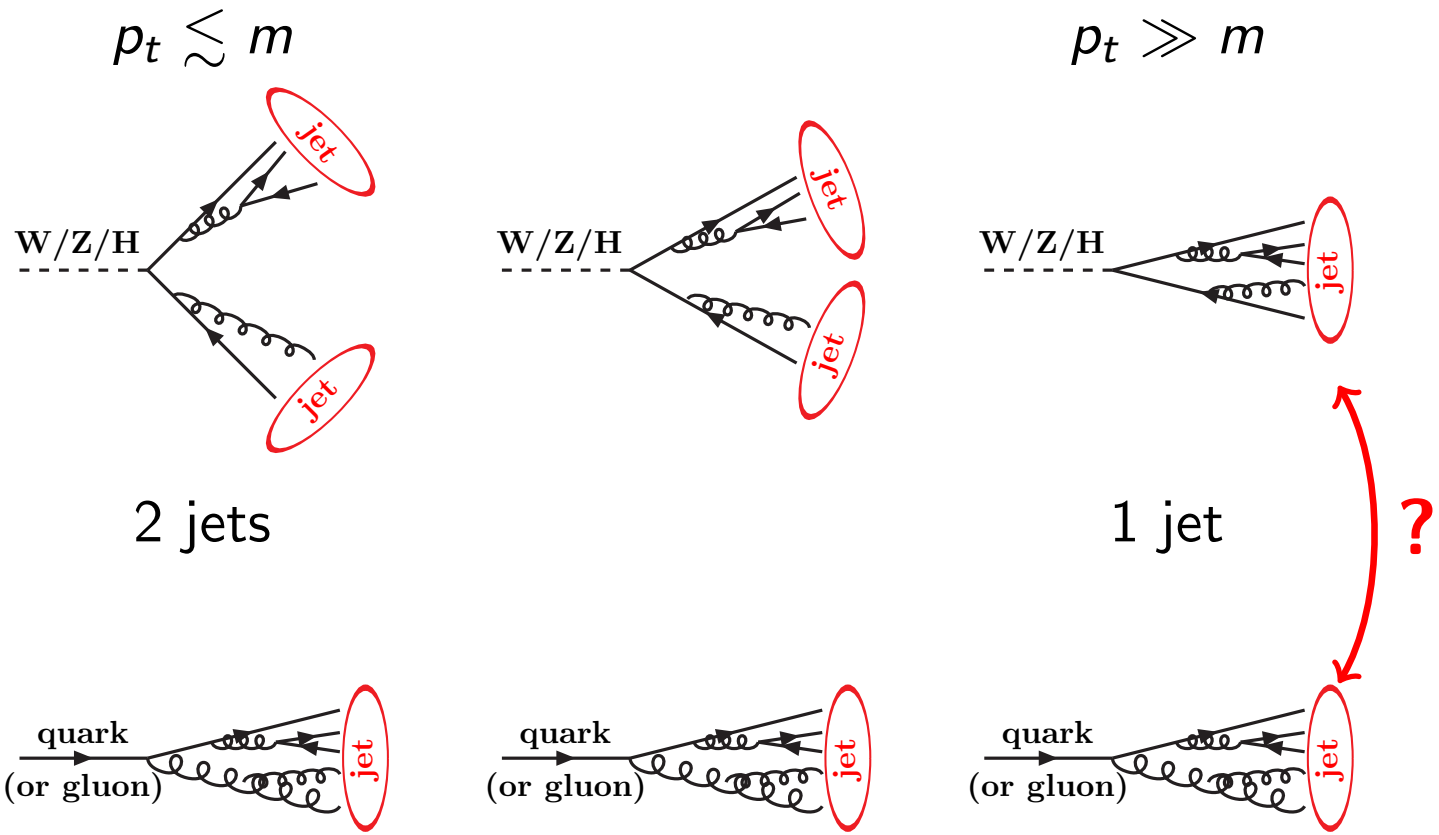


1 jet

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

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

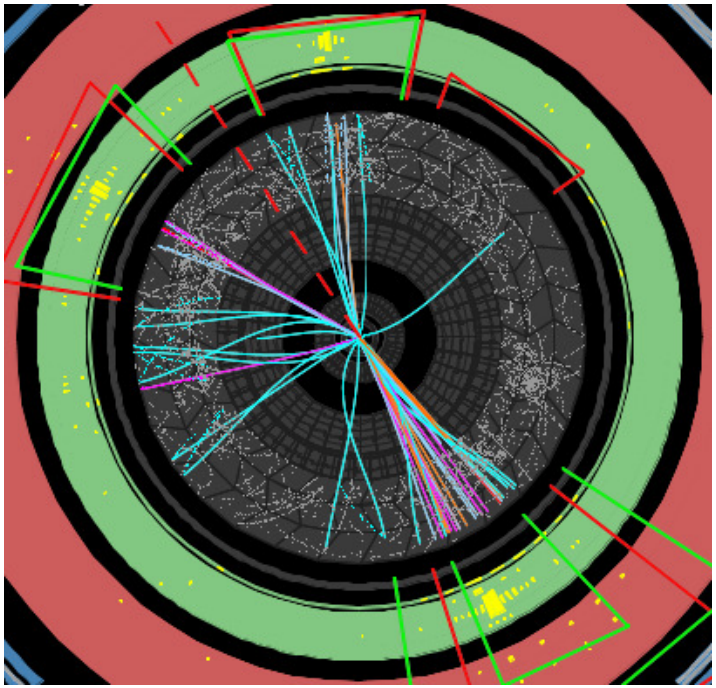
Boosted objects



use substructure to separate from QCD jets

Other examples

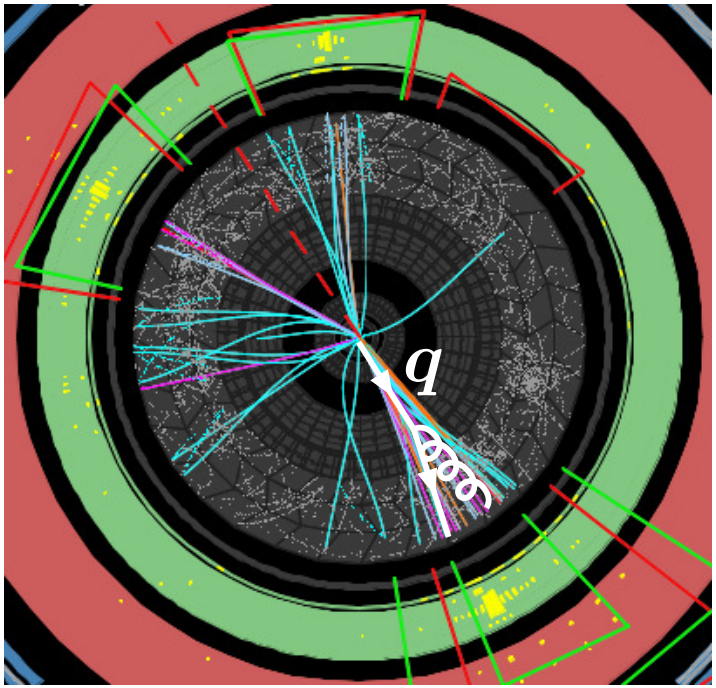
What jet do we have here?



Other examples

What jet do we have here?

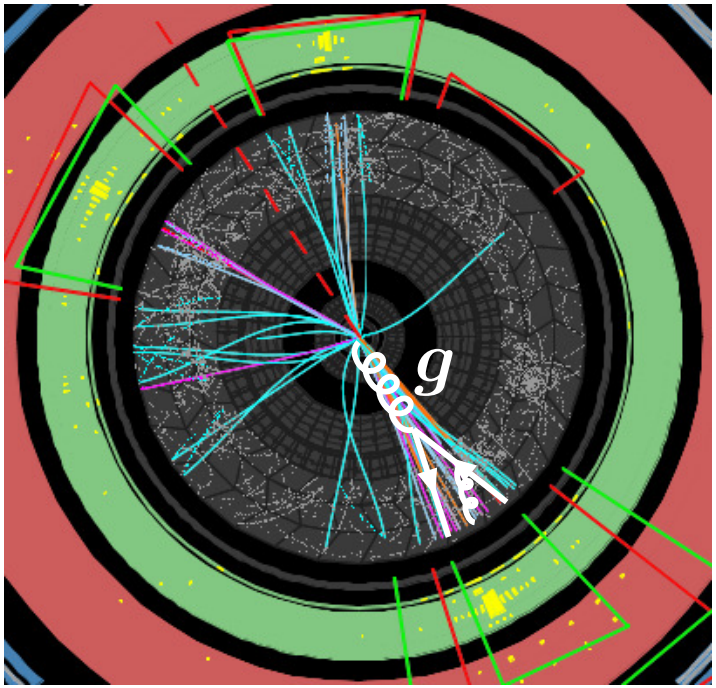
- a quark?



Other examples

What jet do we have here?

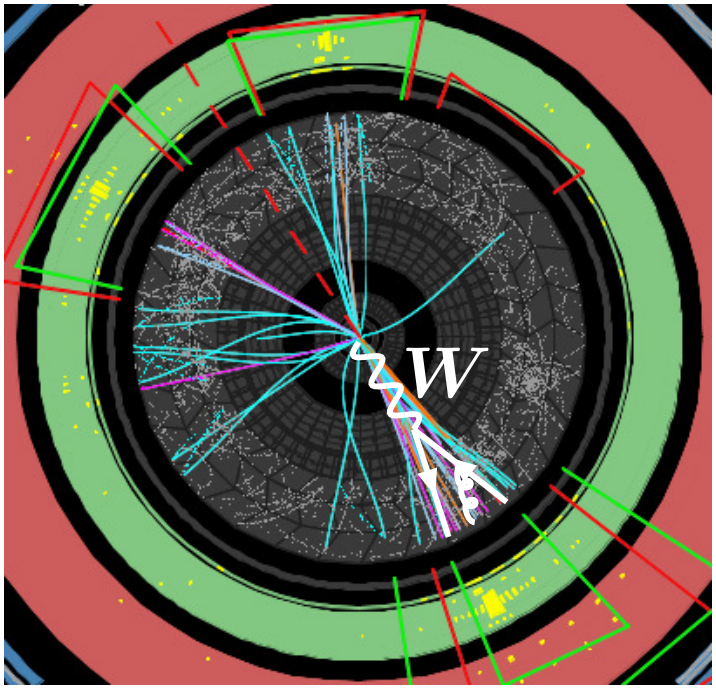
- a quark?
- a gluon?



Other examples

What jet do we have here?

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

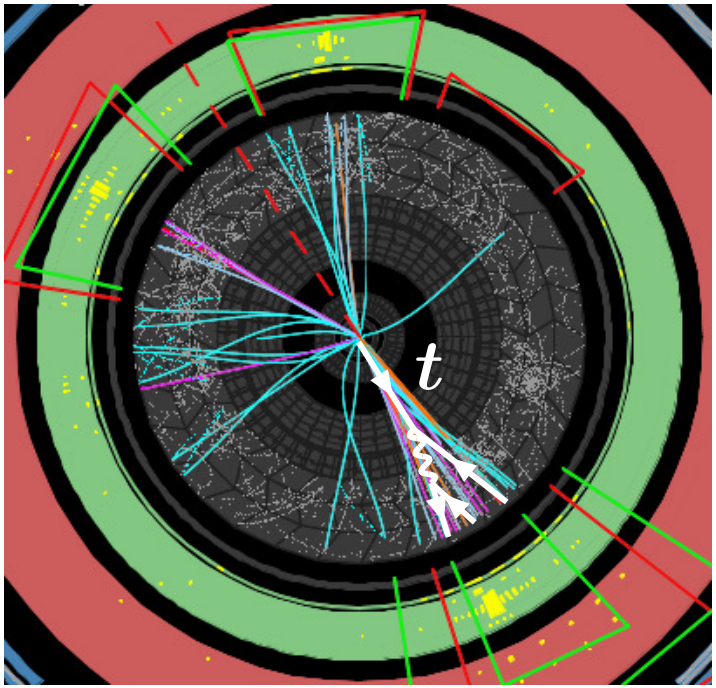


Other examples

What jet do we have here?

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

Source: ATLAS boosted top candidate

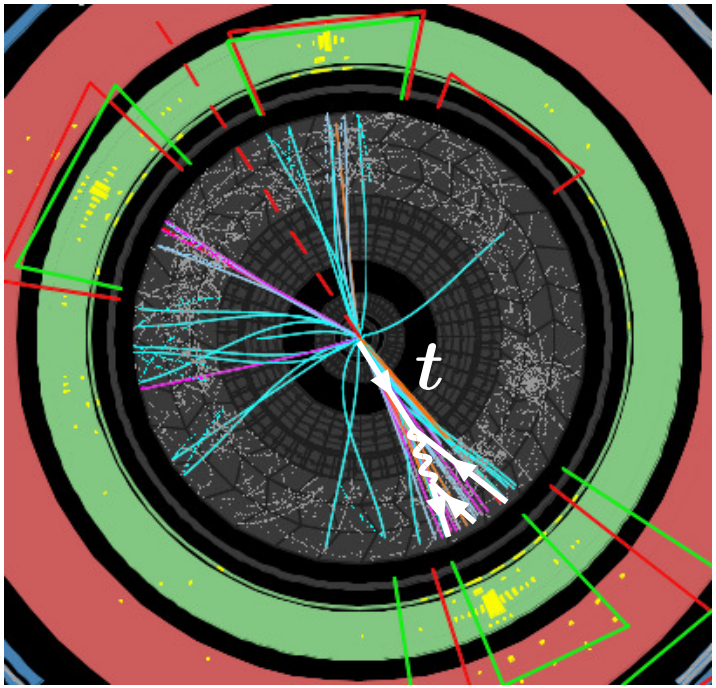


Other examples

What jet do we have here?

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

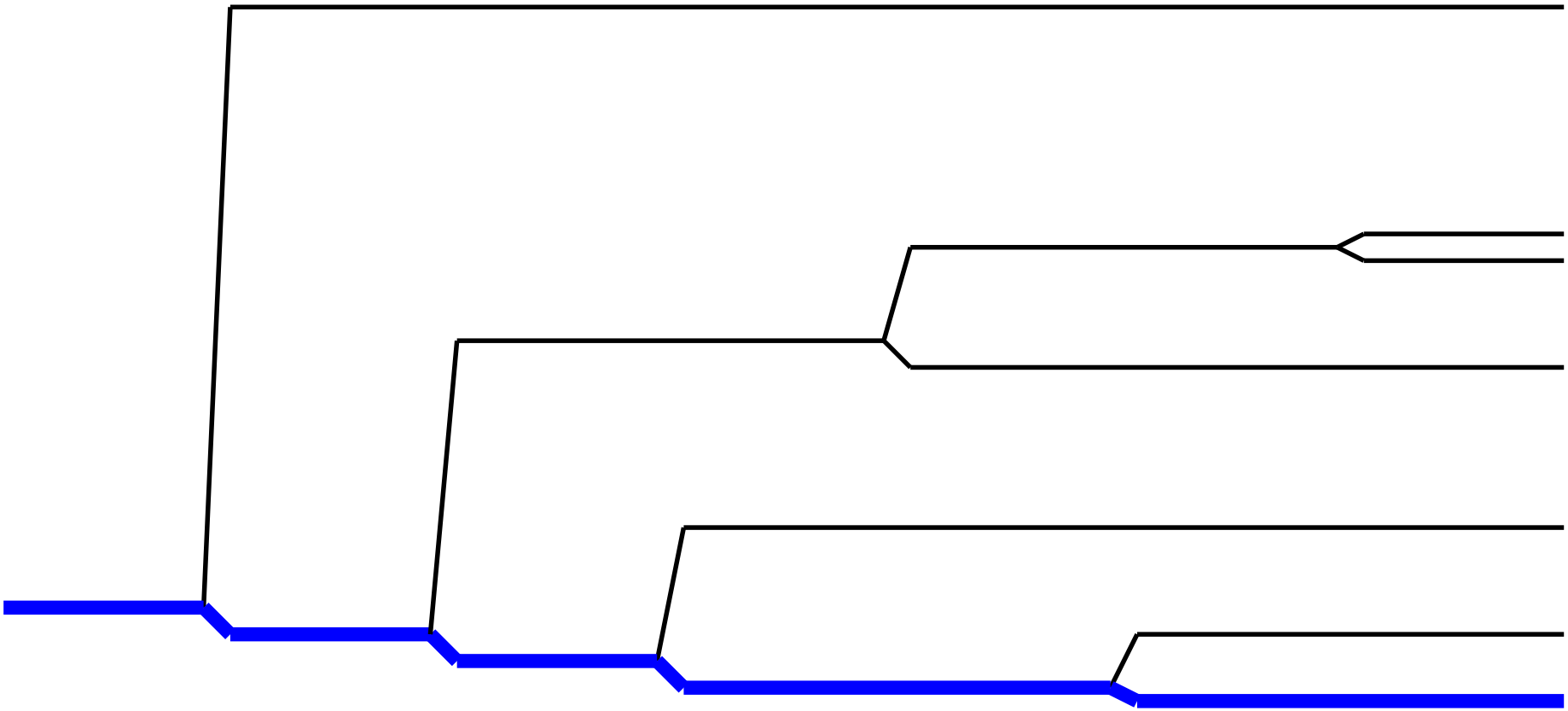
Source: ATLAS boosted top candidate



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

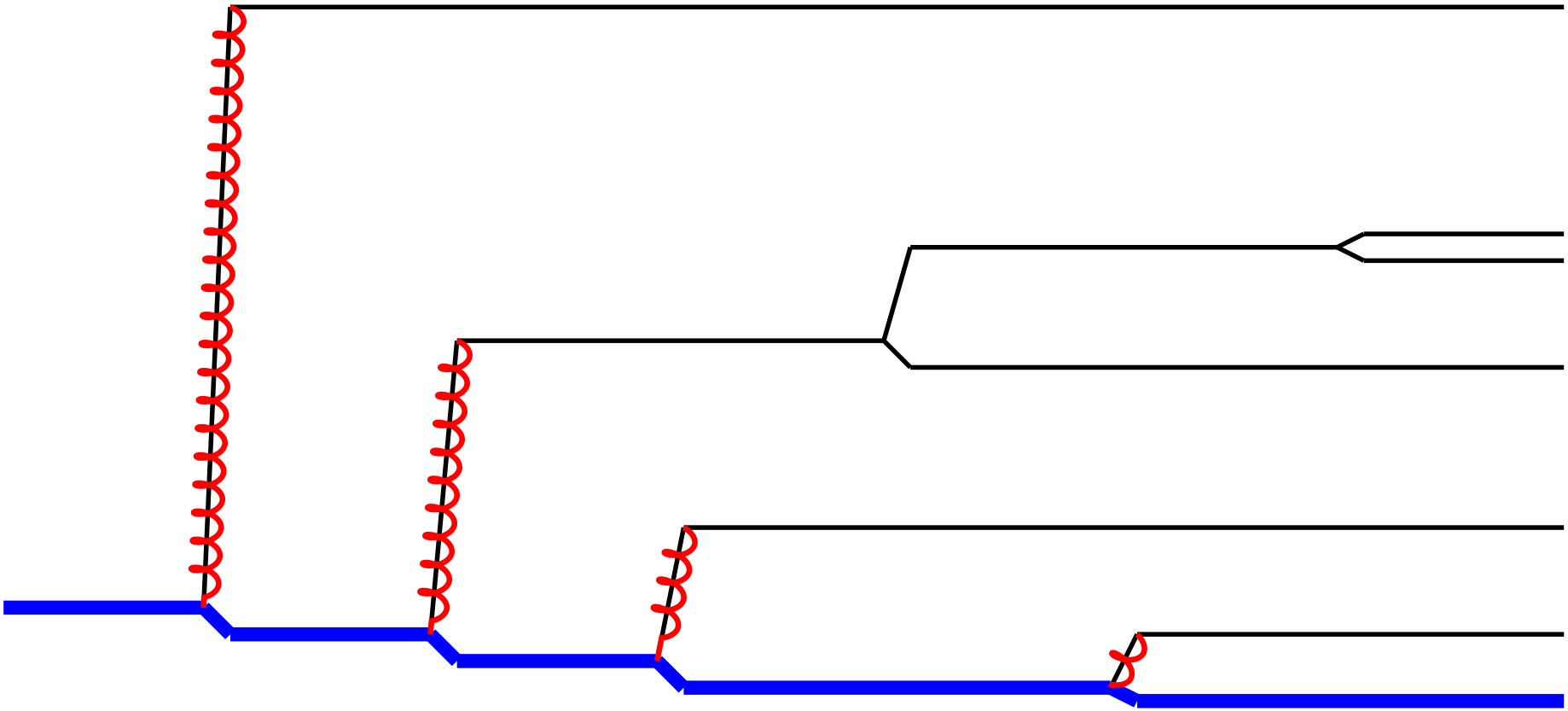
(modified) Mass-Drop Tagger, Soft-Drop

Idea: look for hard branchings



(modified) Mass-Drop Tagger, Soft-Drop

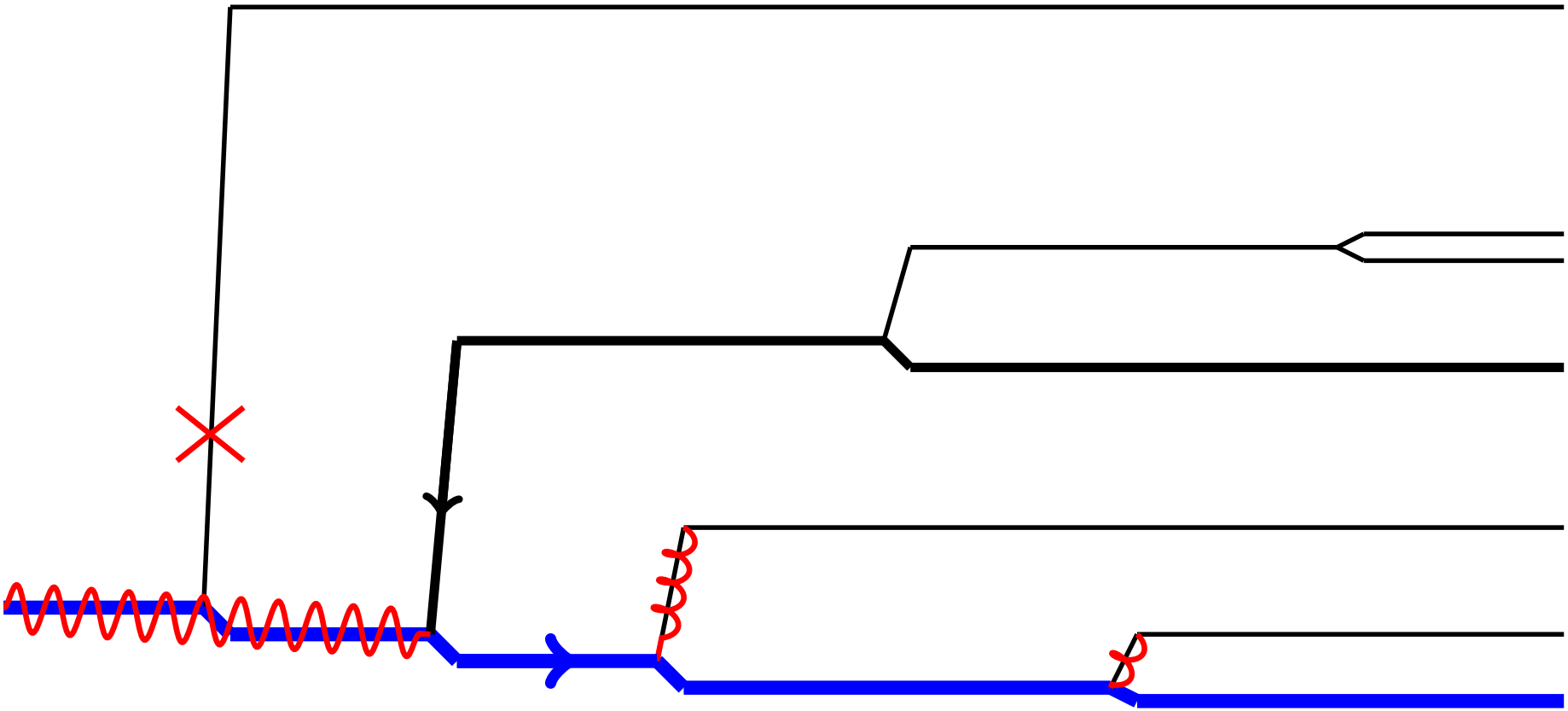
Idea: look for hard branchings



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

(modified) Mass-Drop Tagger, Soft-Drop

Idea: look for hard branchings

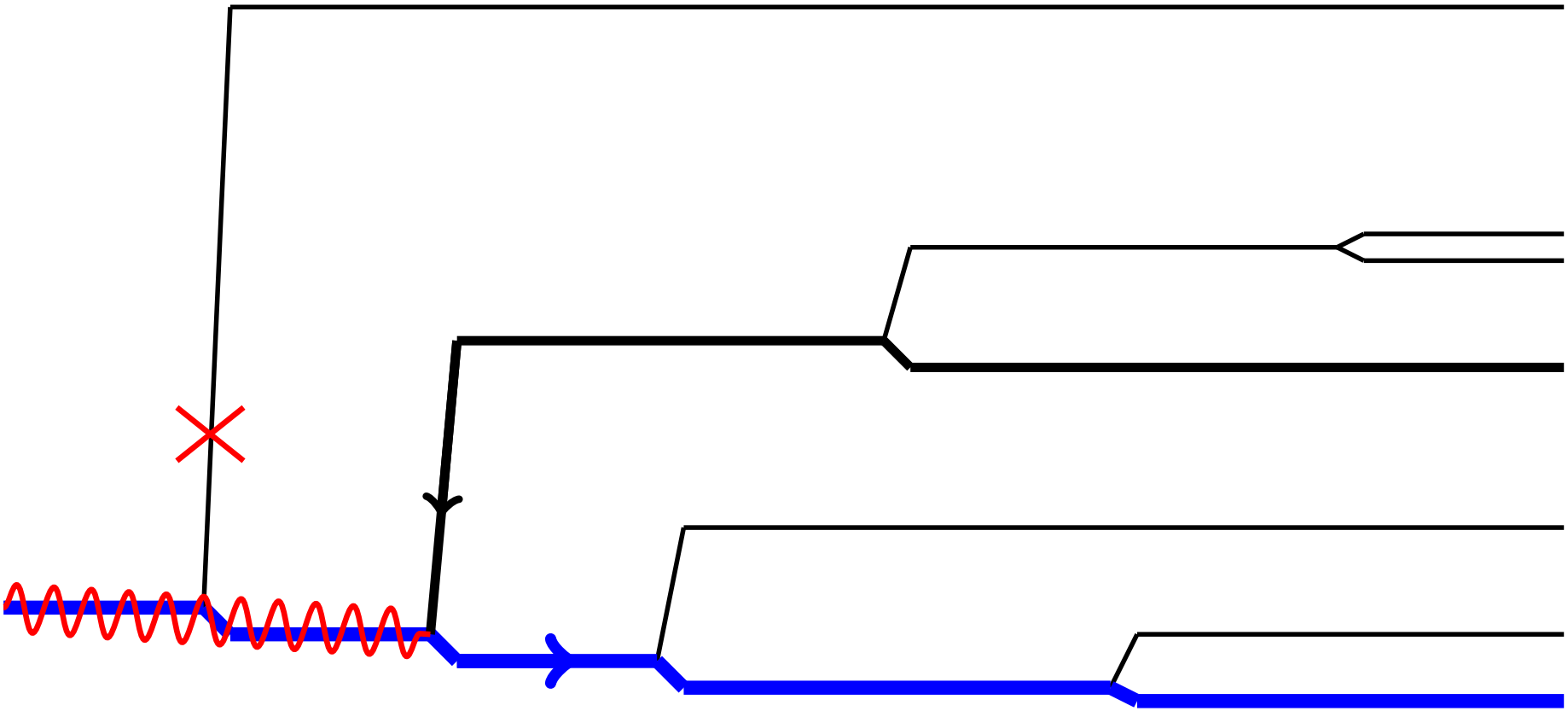


Rare hard branchings for $q/g \to q/g + g$ $(P(z) \sim 1/z)$

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

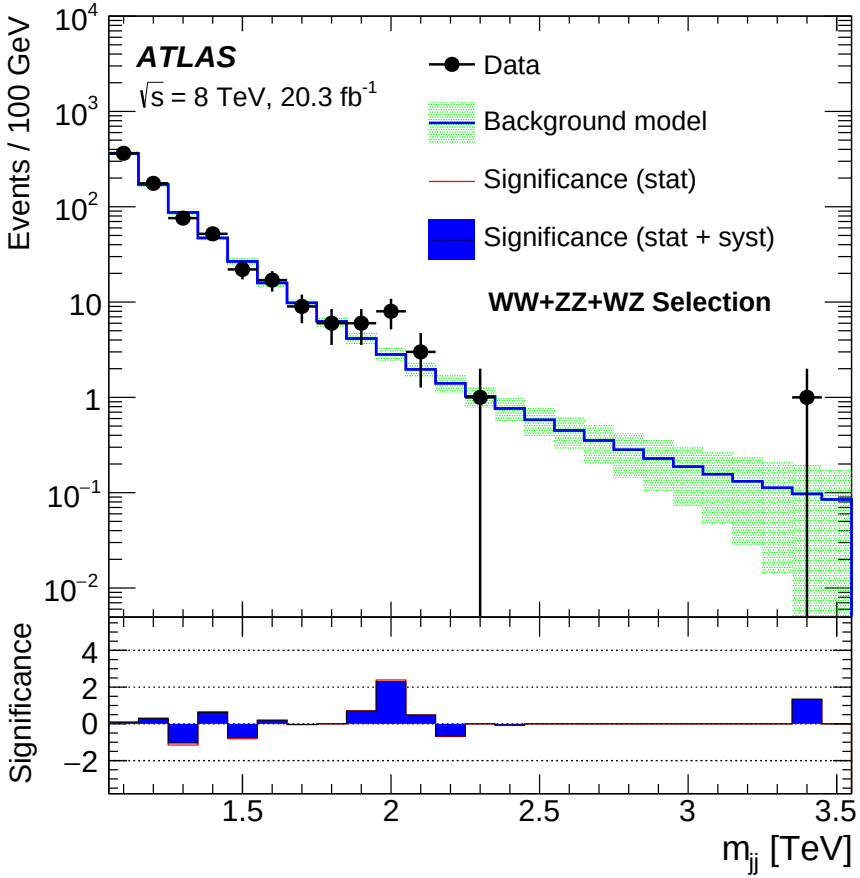
(modified) Mass-Drop Tagger, Soft-Drop

Idea: look for hard branchings



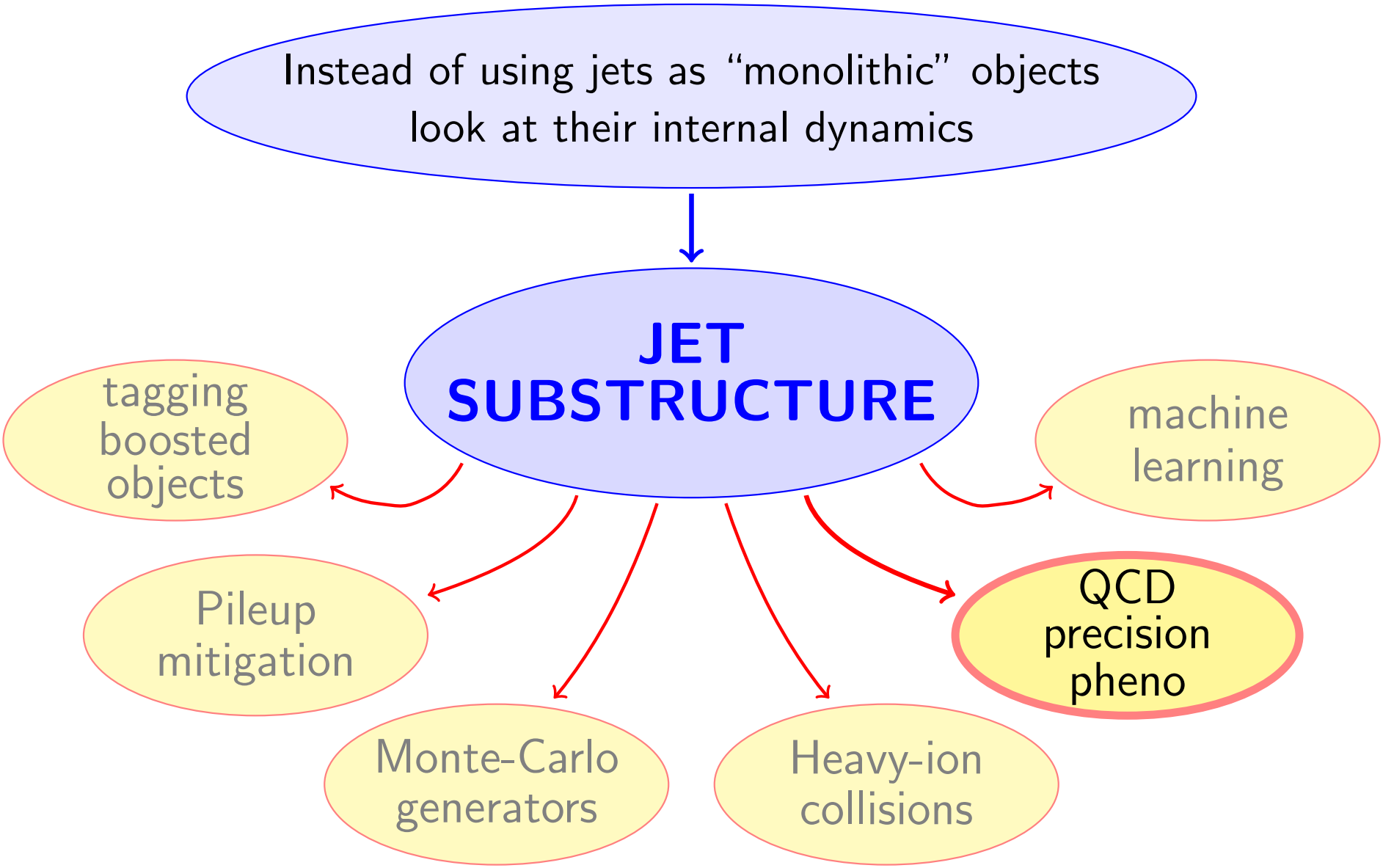
Method: search the first splitting with $z > z_{\text{cut}}$

Searches and measurements



(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

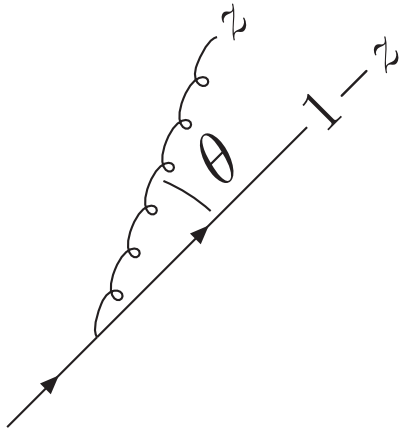
- Main idea:

  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

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

Analytic approach to jet substructure

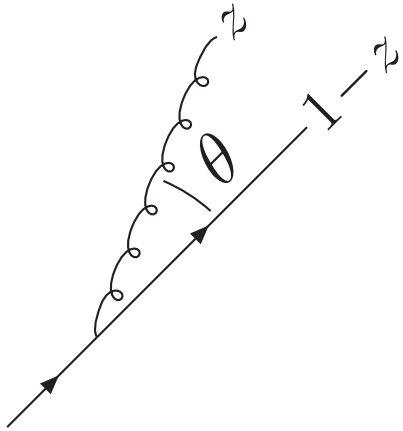
- Main idea:

  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



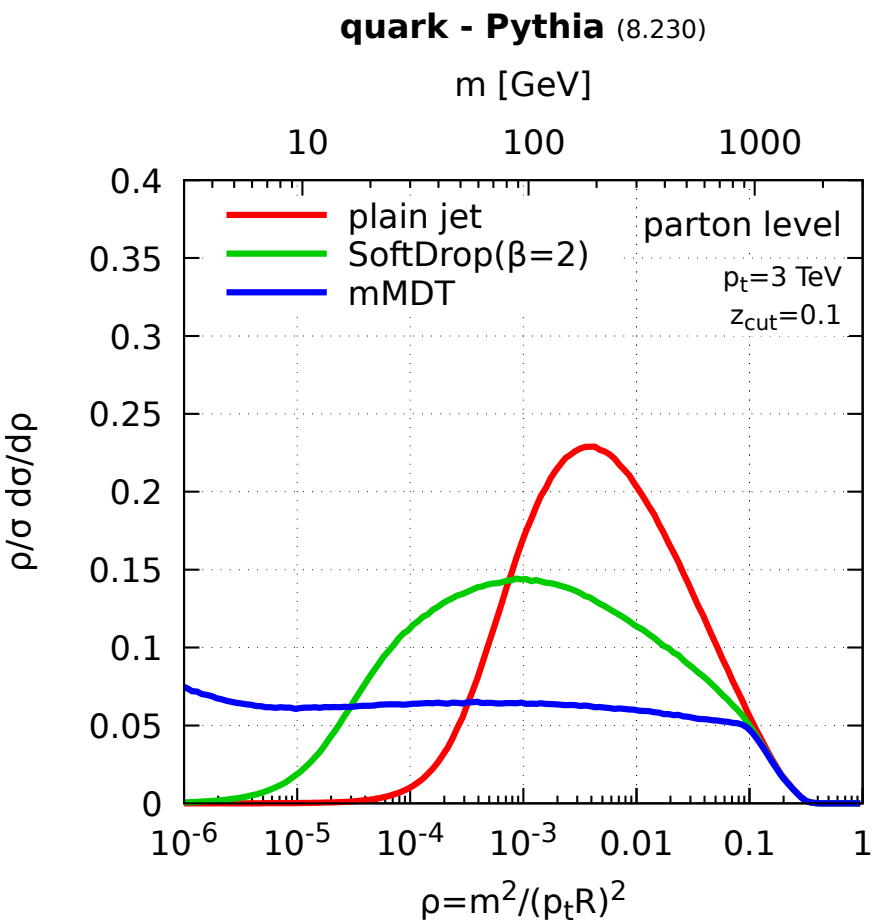
- Example: jet mass with one (soft-and-collinear) gluon emission

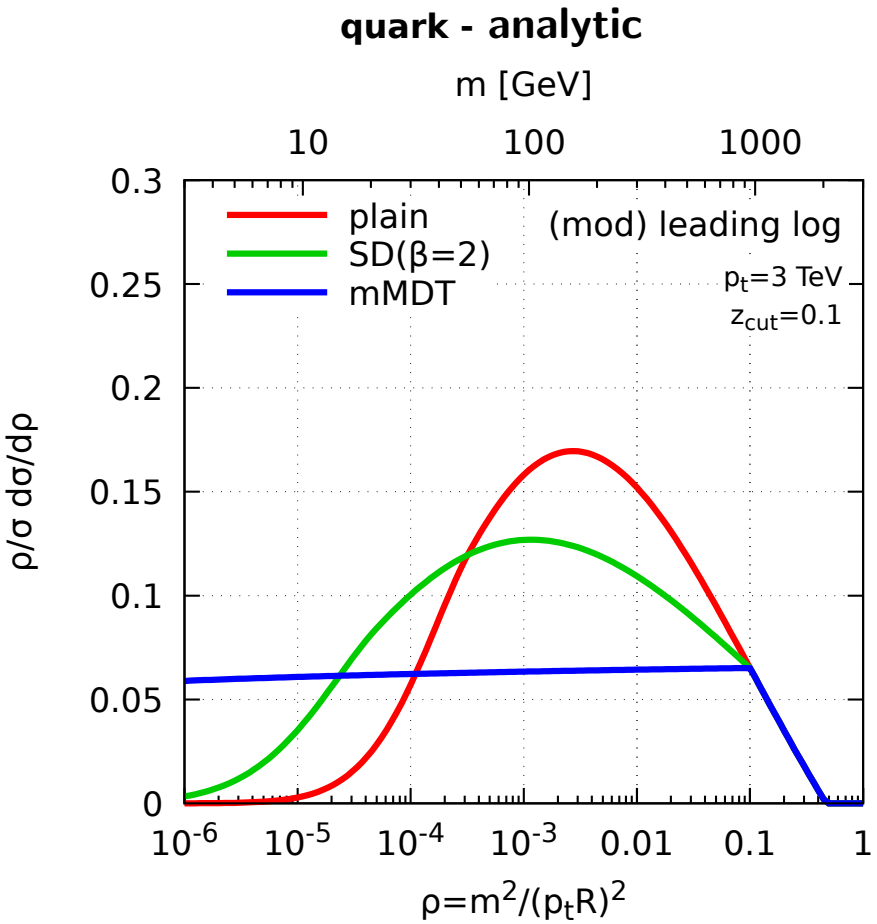
$$\text{Prob}_1(>\rho) \simeq \int_0^1 \frac{d\theta^2}{\theta^2}\frac{dz}{z}\frac{\alpha_s C_R}{\pi}\Theta(z\theta^2 > \rho) \simeq \frac{\alpha_s C_R}{2\pi}\log^2(1/\rho)$$

- All-order resummations including the constraints from the substructure tools

Understanding substructure tools

Breakthrough 5-7 years ago: jet substructure tools are calculable

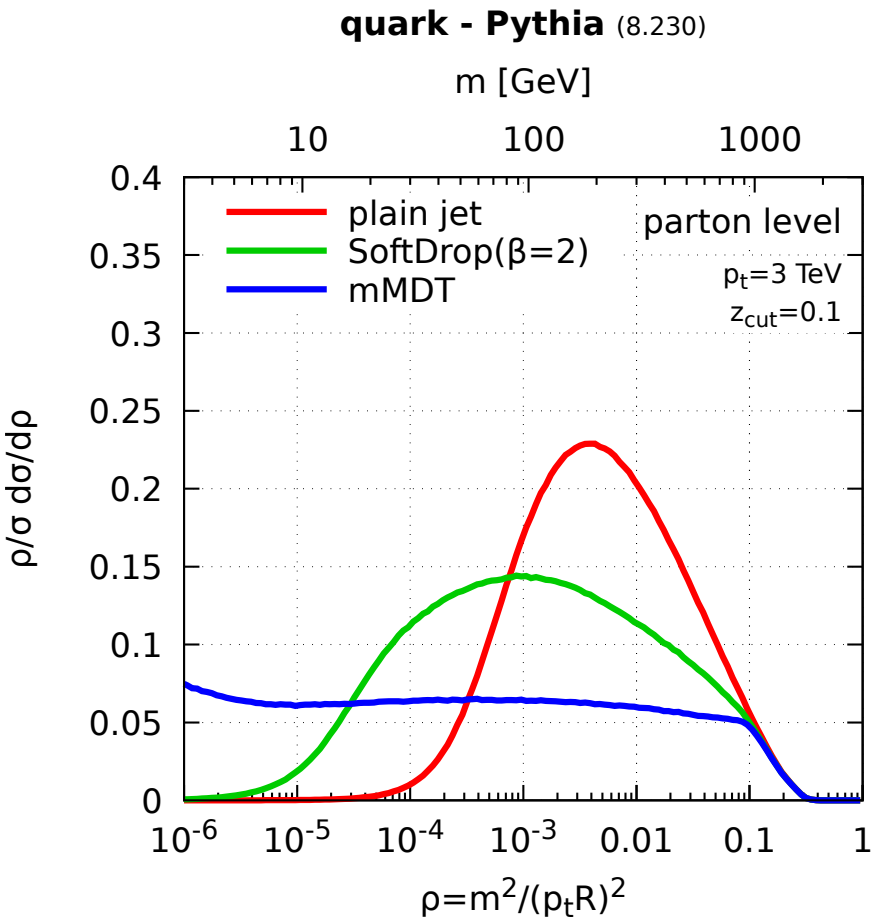


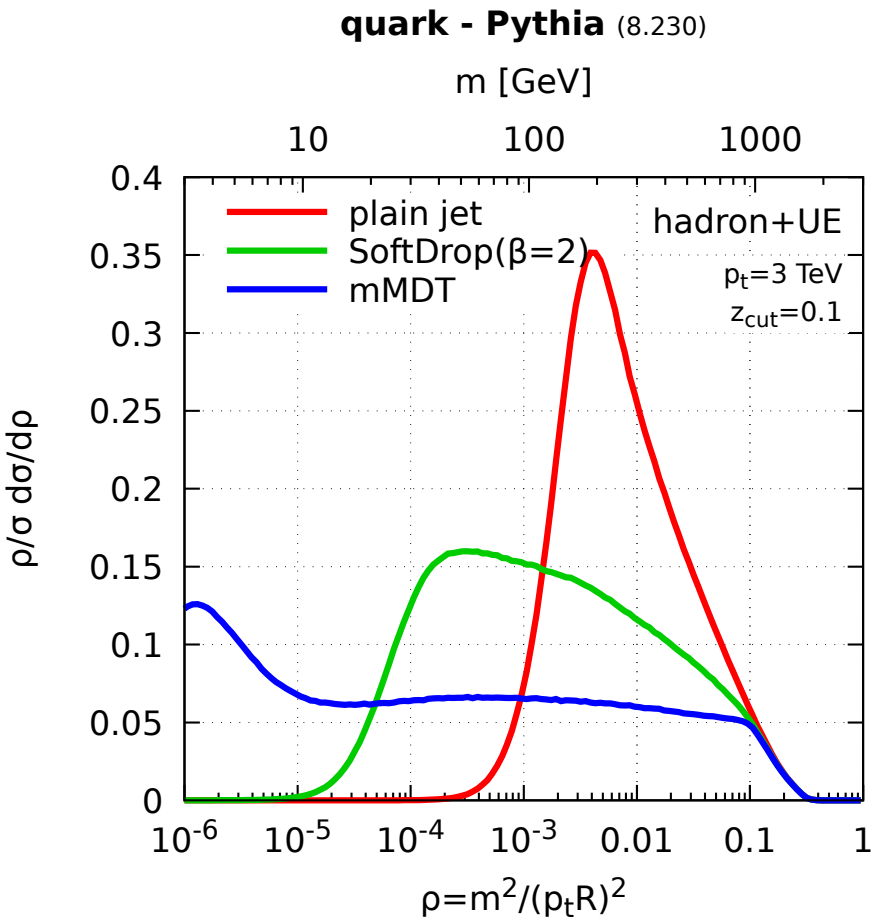


- **qualitative features reproduced and understood**

Understanding substructure tools

Breakthrough 5-7 years ago: jet substructure tools are calculable

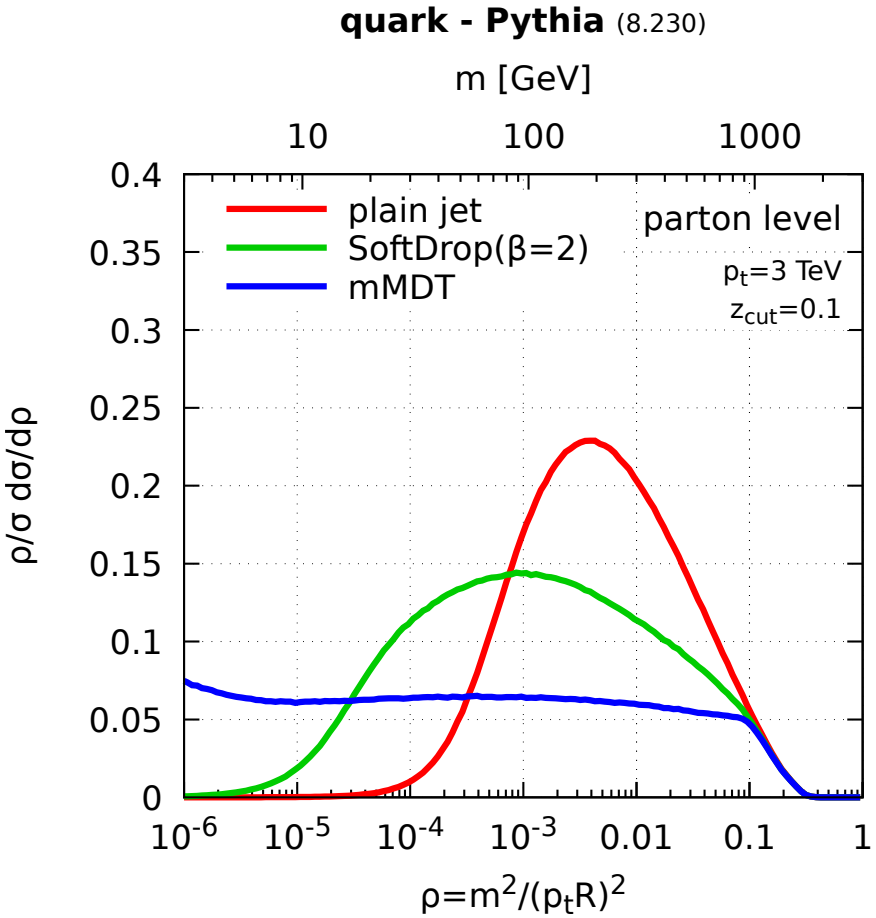


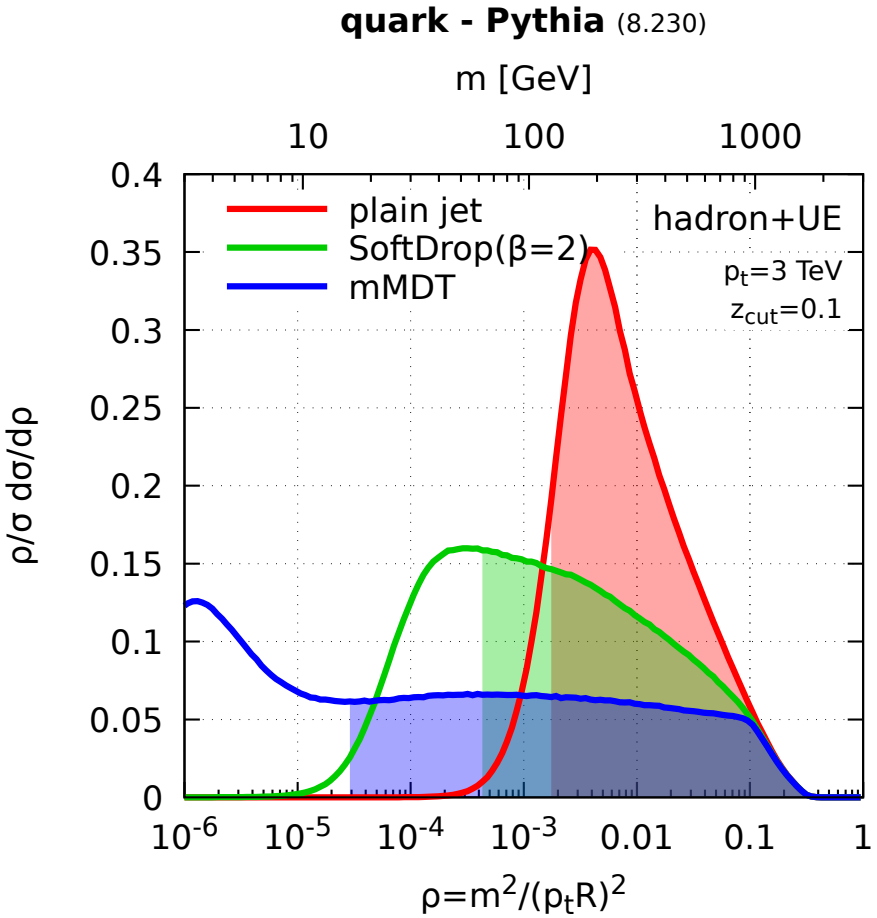


- **qualitative features reproduced and understood**

Understanding substructure tools

Breakthrough 5-7 years ago: jet substructure tools are calculable



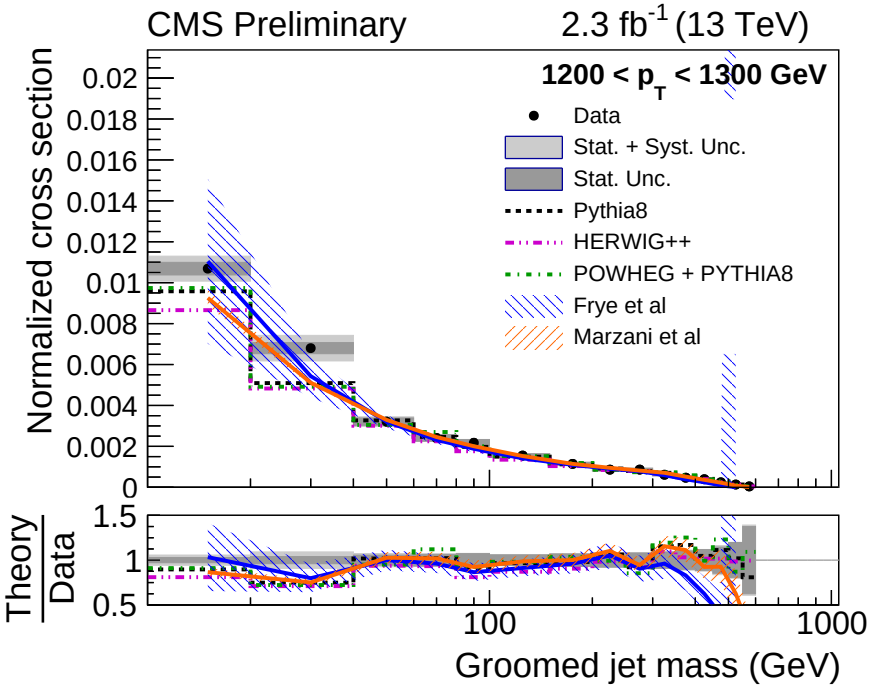


- qualitative features reproduced and understood
- substructure reduces non-perturbative effects

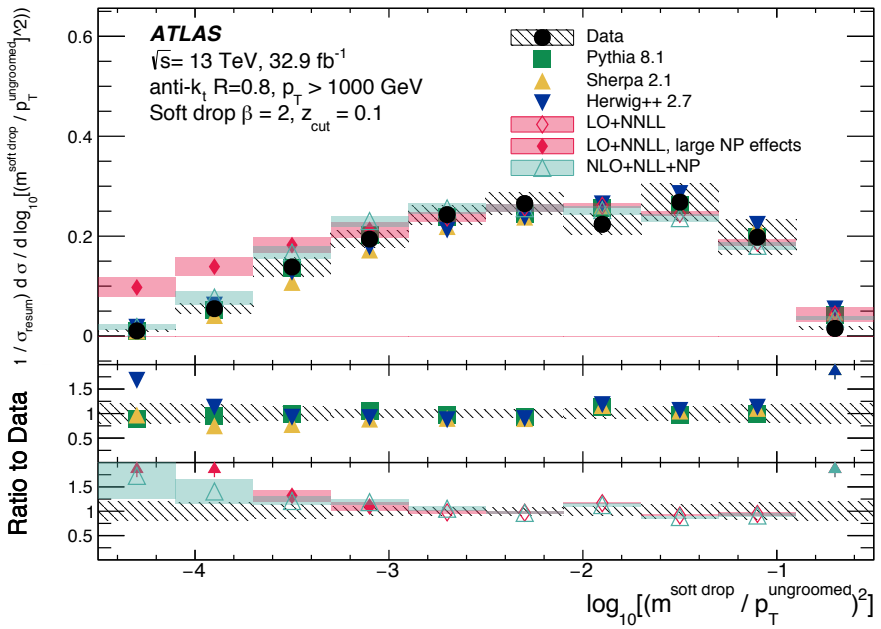
Precision physics

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

CMS-PAS-SMP-16-010



ATLAS(CERN-EP-2017-231)

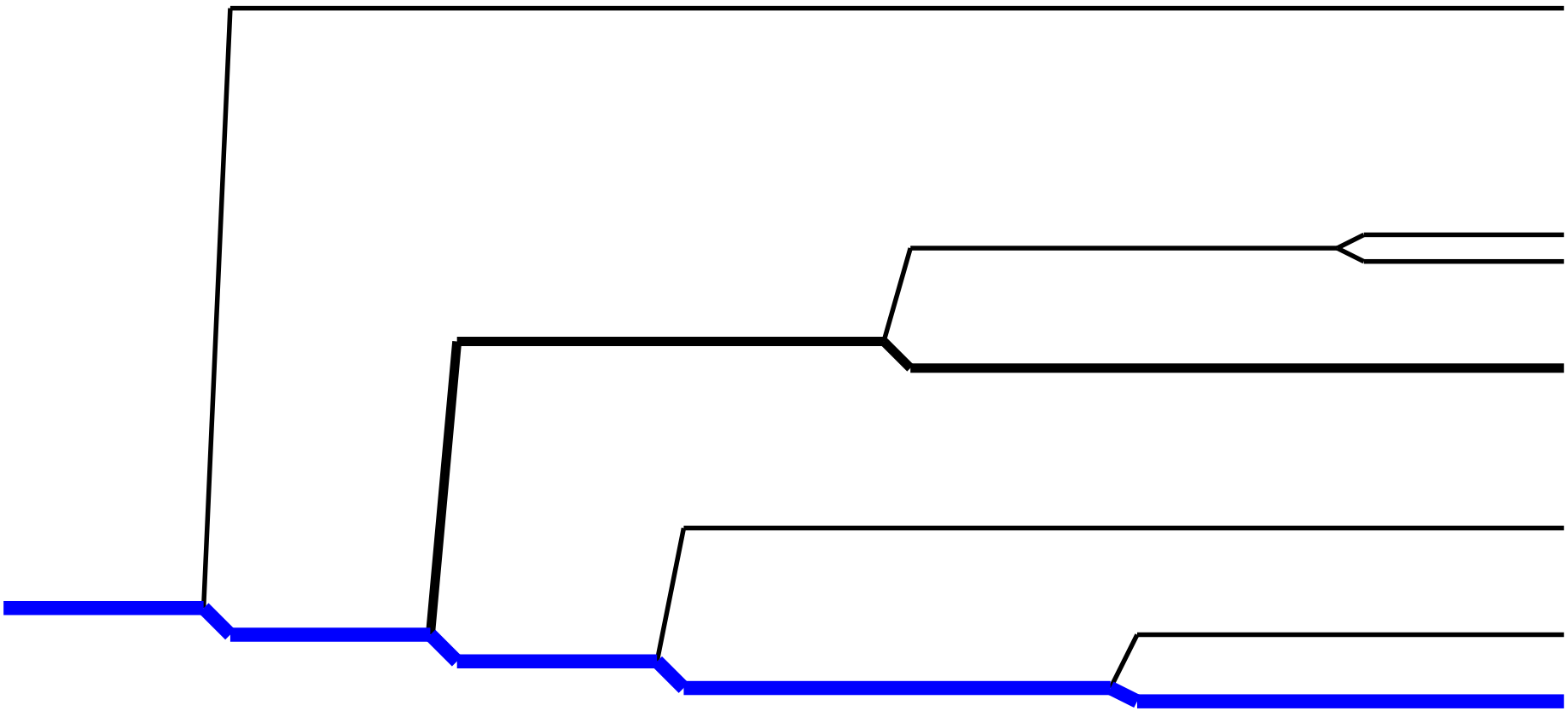


good overall agreement with the data

Precise observable, limited NP effects $\Rightarrow$ **can we extract α_s?**

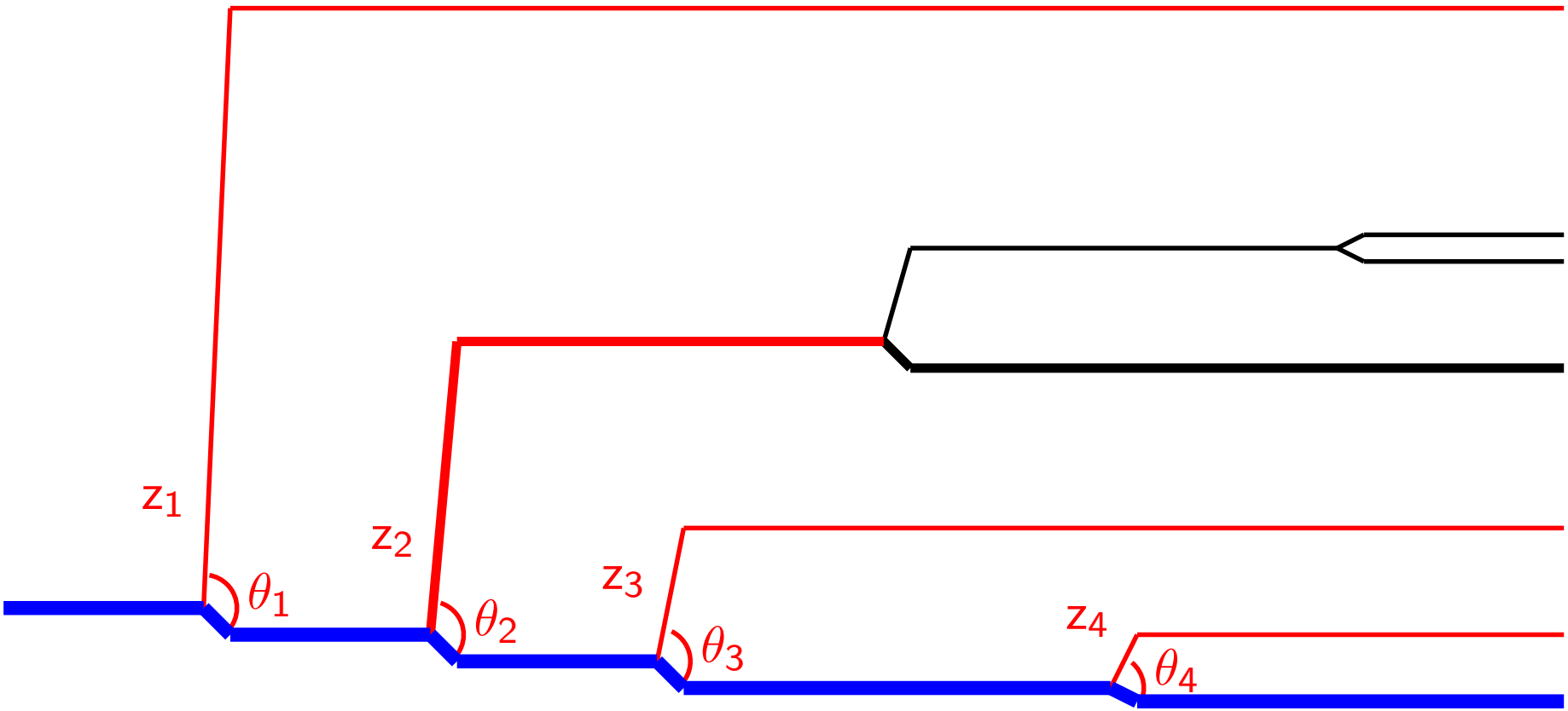
Visualising the sustructure with the Lund plane

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



Visualising the sustructure with the Lund plane

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

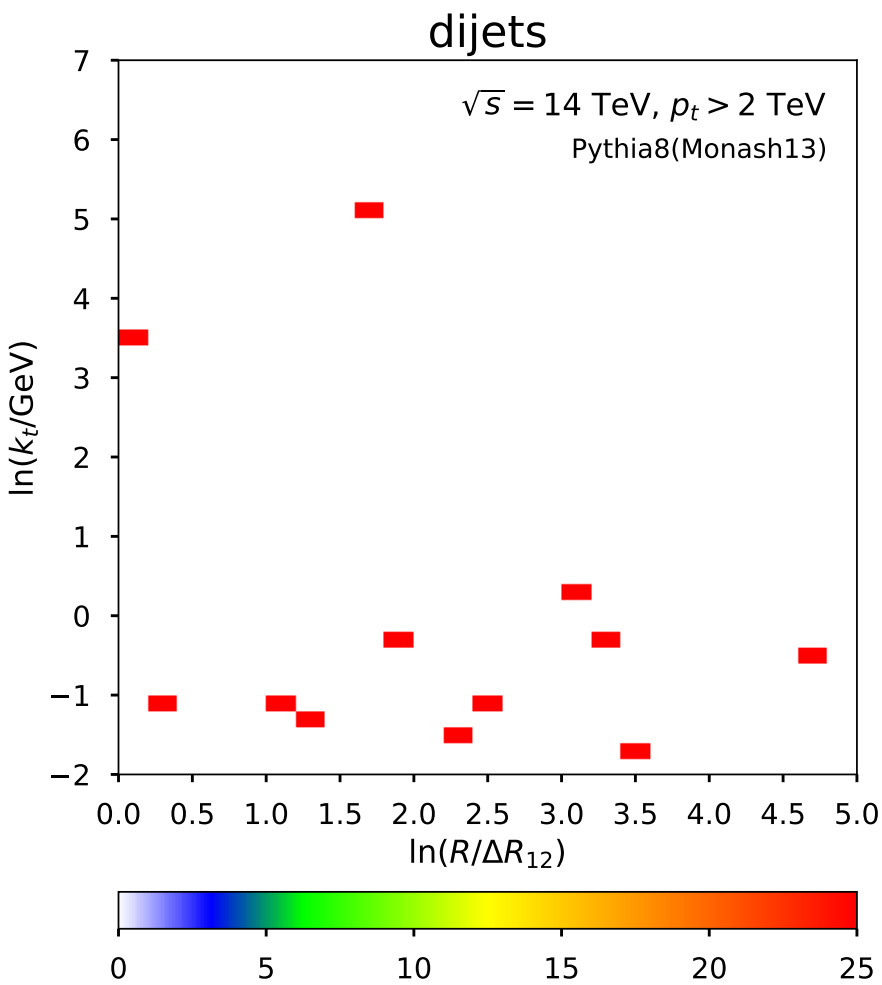


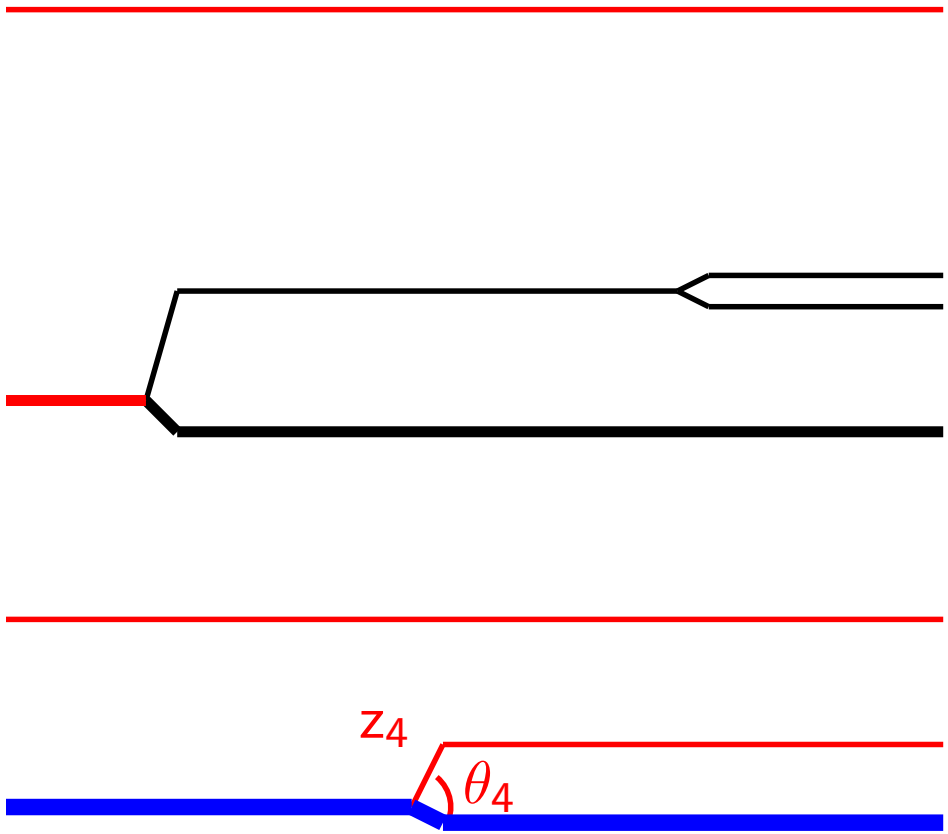
Consider all the emissions from the hardest branch: $\{(z_1, \theta_1), \ldots, (z_n, \theta_n)\}$

Visualising the sustructure with the Lund plane

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

One jet





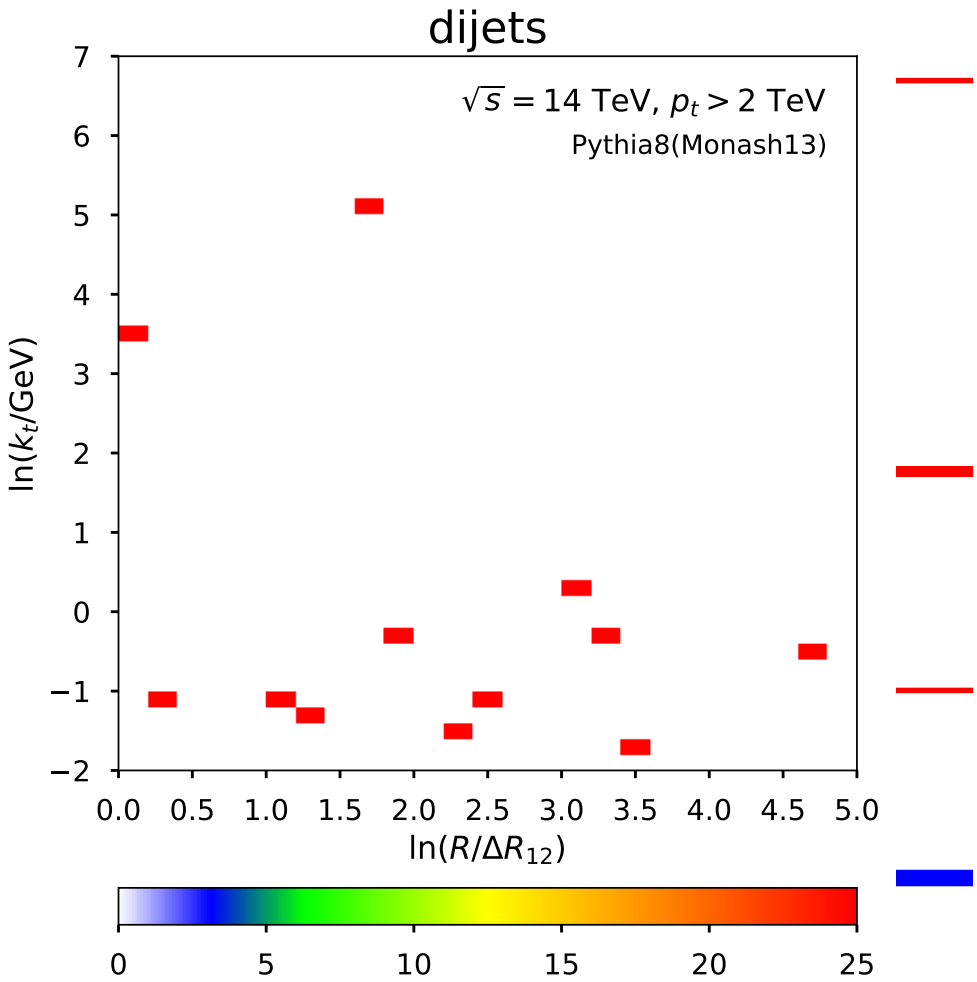
Consider all the emissions from the hardest branch: $\{(z_1, \theta_1), \ldots, (z_n, \theta_n)\}$

Put them in the Lund plane

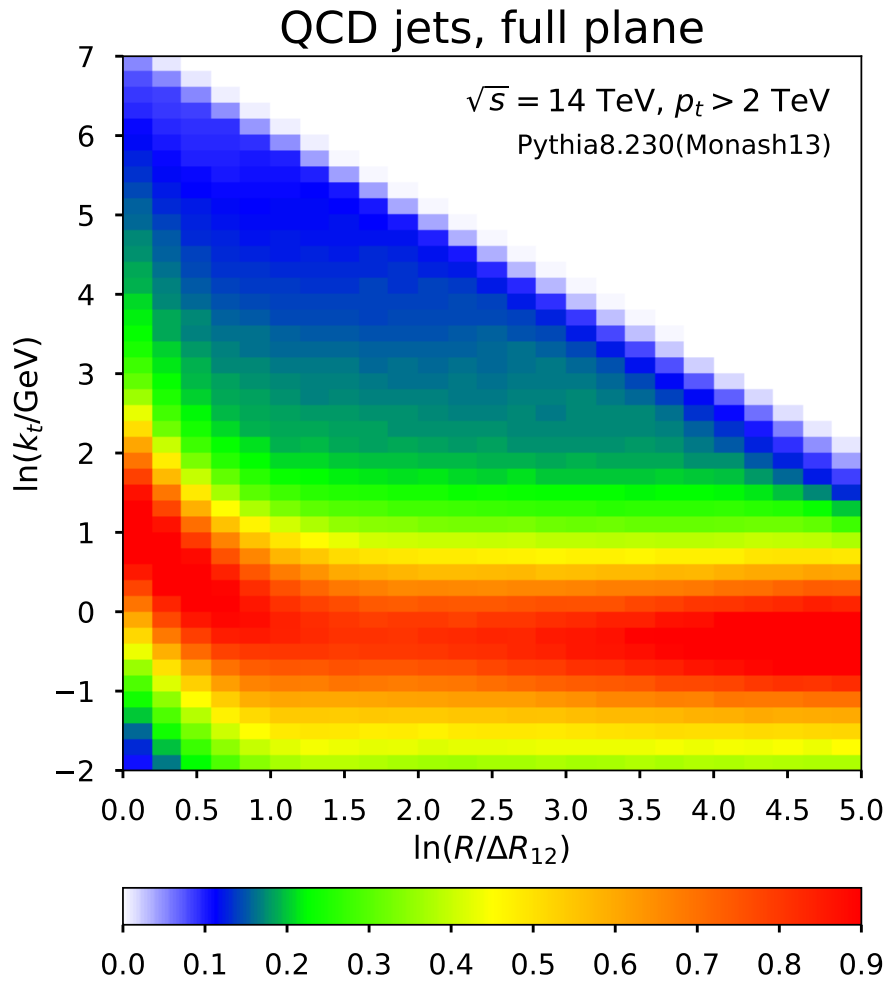
Visualising the sustructure with the Lund plane

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

One jet



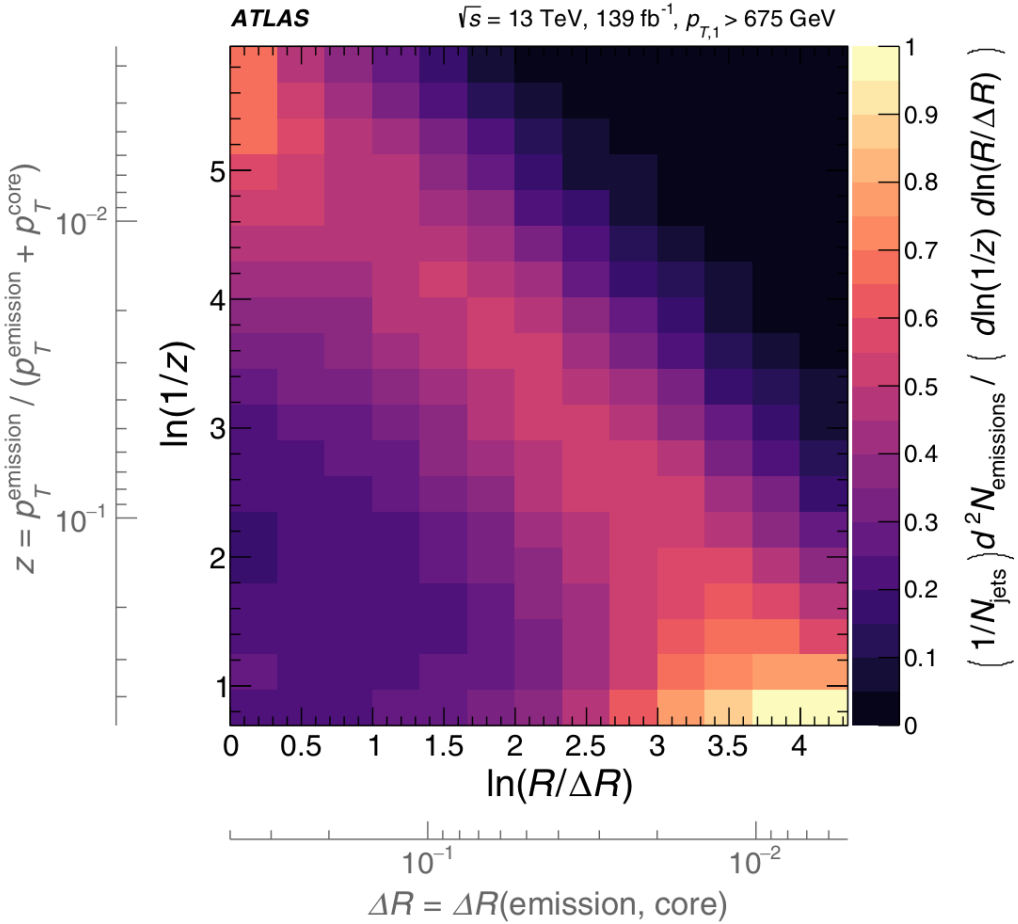
Average over jets



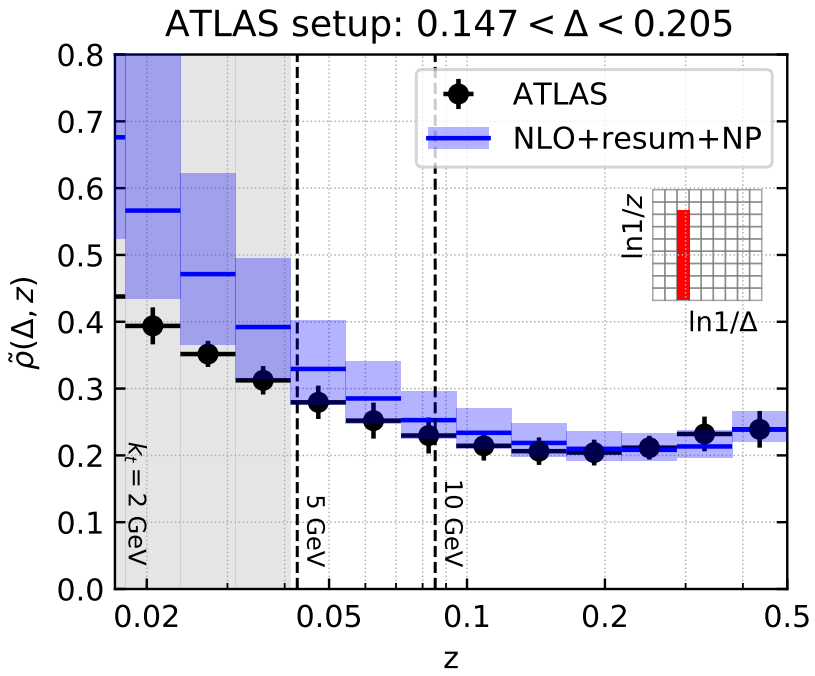
Consider all the emissions from the hardest branch: $\{(z_1, \theta_1), \ldots, (z_n, \theta_n)\}$

Put them in the Lund plane

Measured by ATLAS + compared to QCD analytics



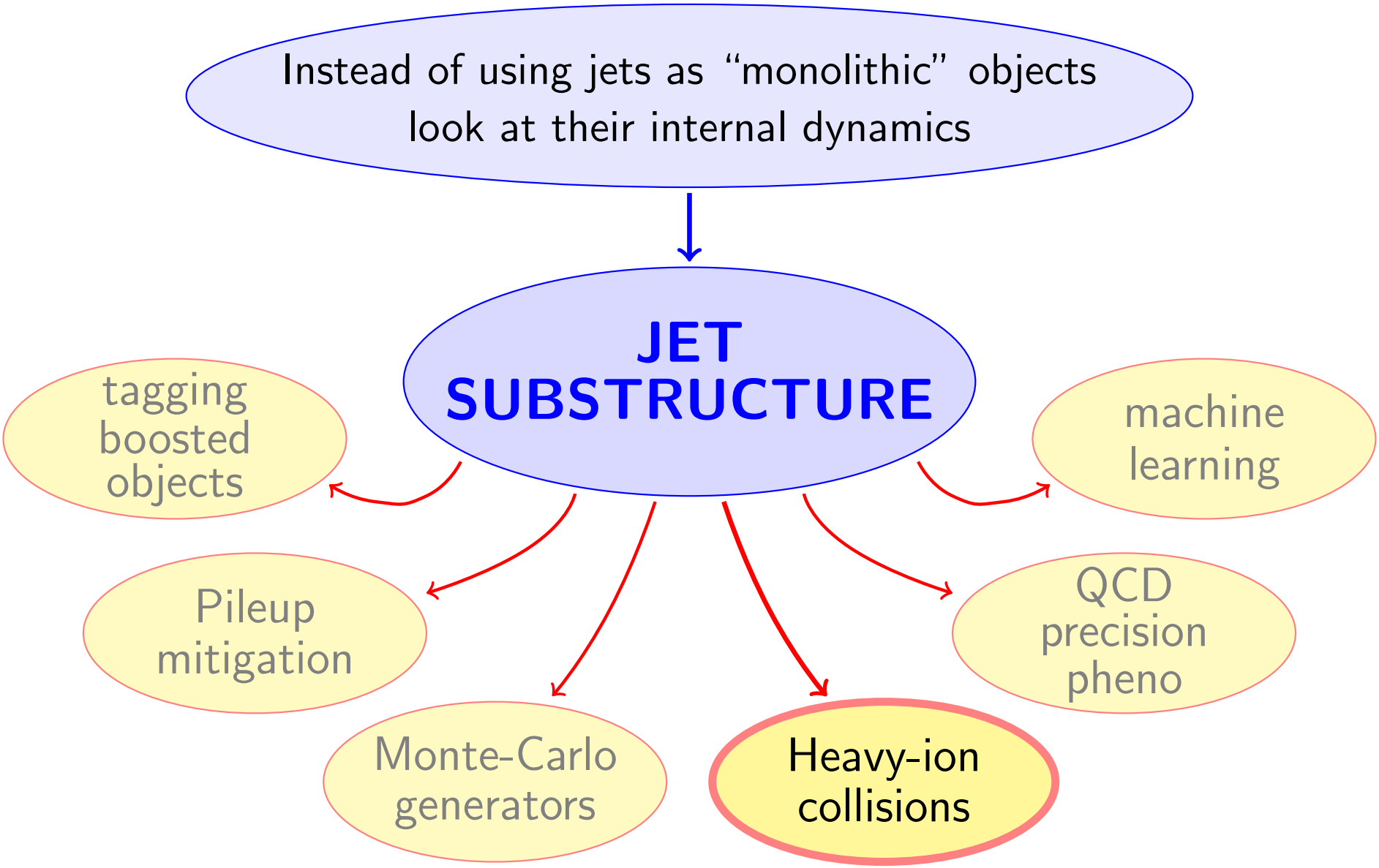
[ATLAS, CERN-EP-2020-030]



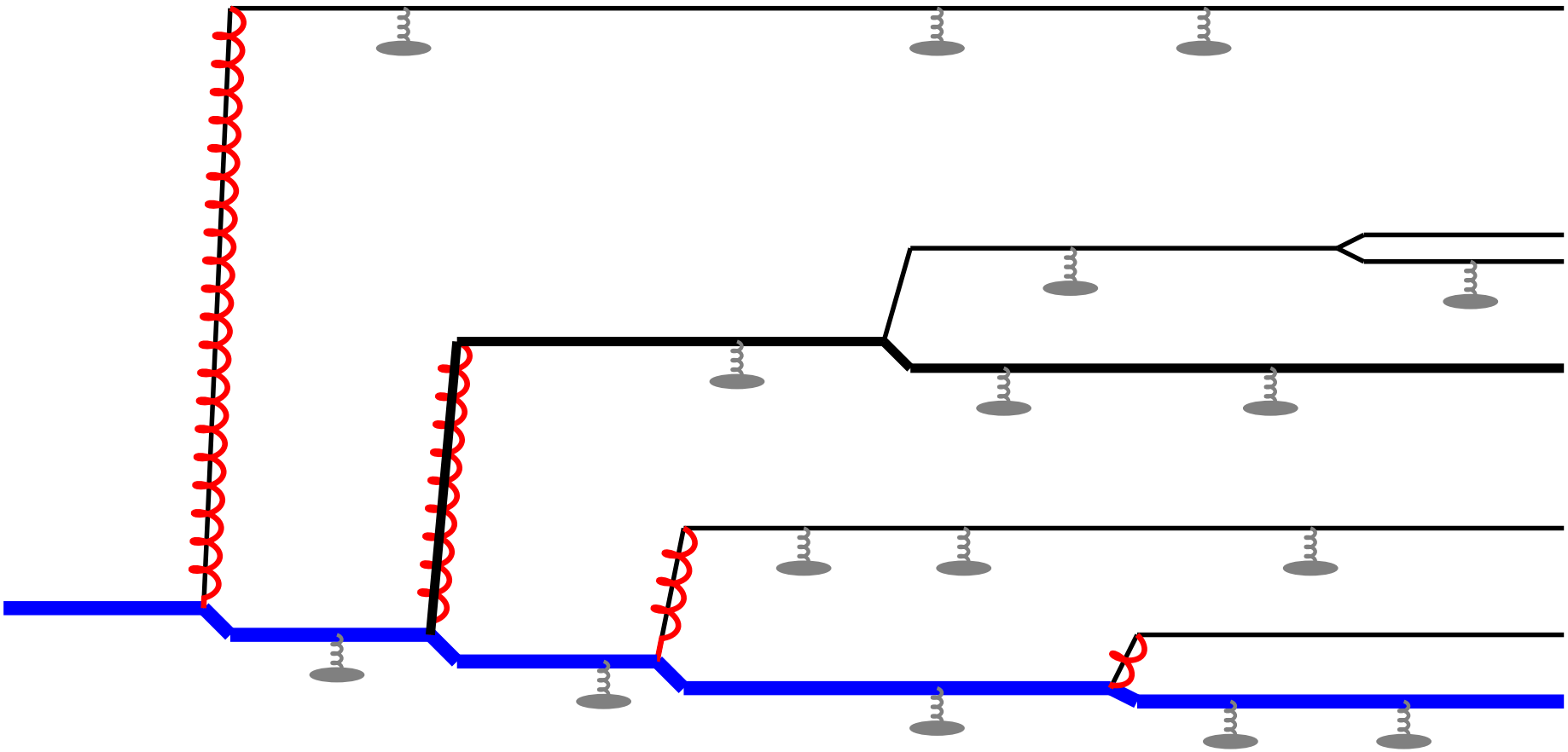
[A.Lifson,G.Salam,GS,07]

see also Phil & Pier's talks

New prospects at the LHC



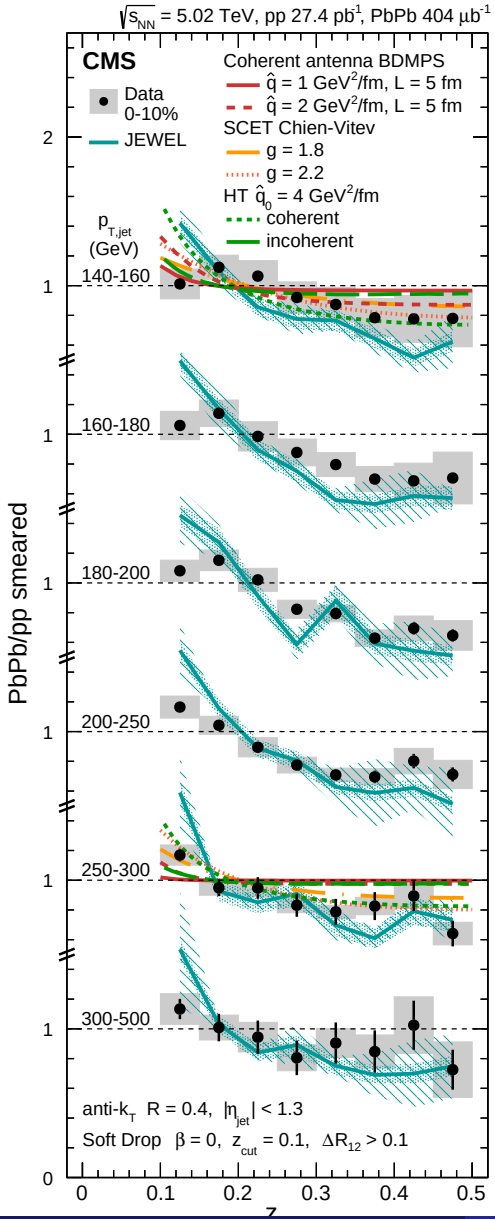
Idea: interaction with the quark-gluon plasma



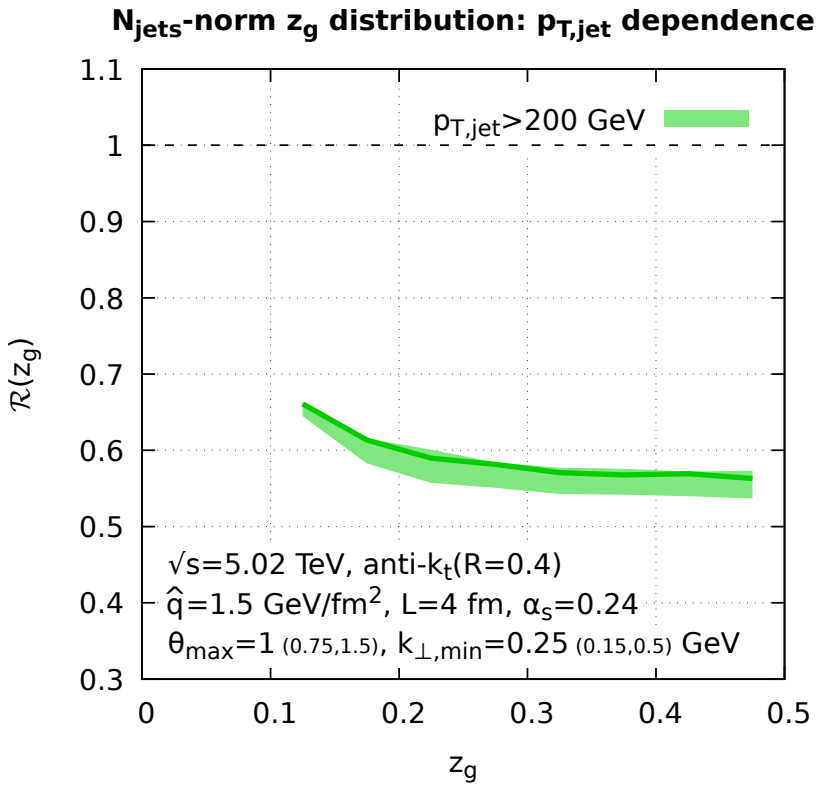
z_g: look at the z fraction of the first splitting with $z > z_{\text{cut}}$

Measuring the splitting function

CMS (CMS-HIN-16-006)



our Monte Carlo



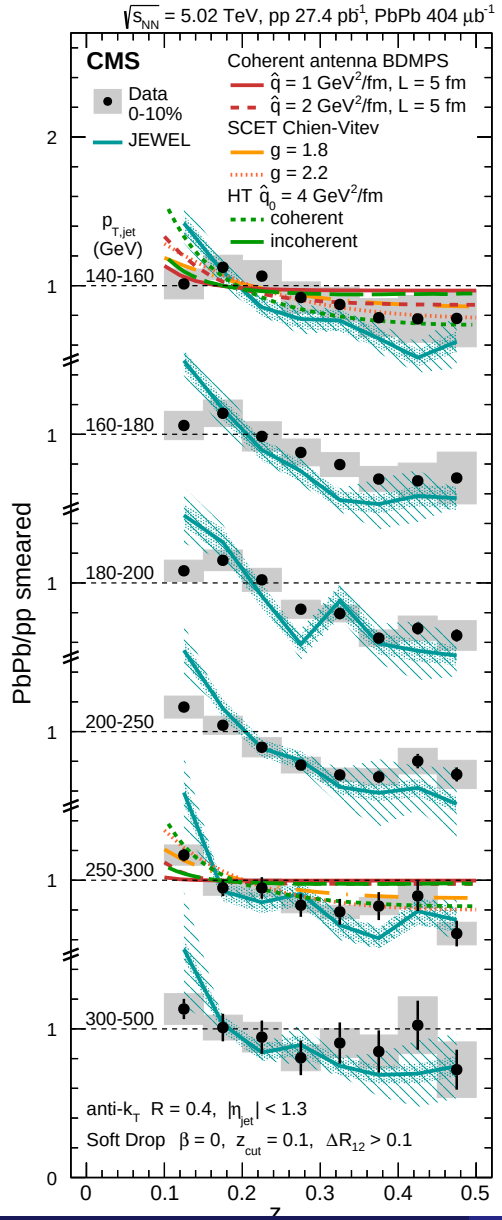
[P.Caucal,E.Iancu,GS,17]

Based on perturbative QCD

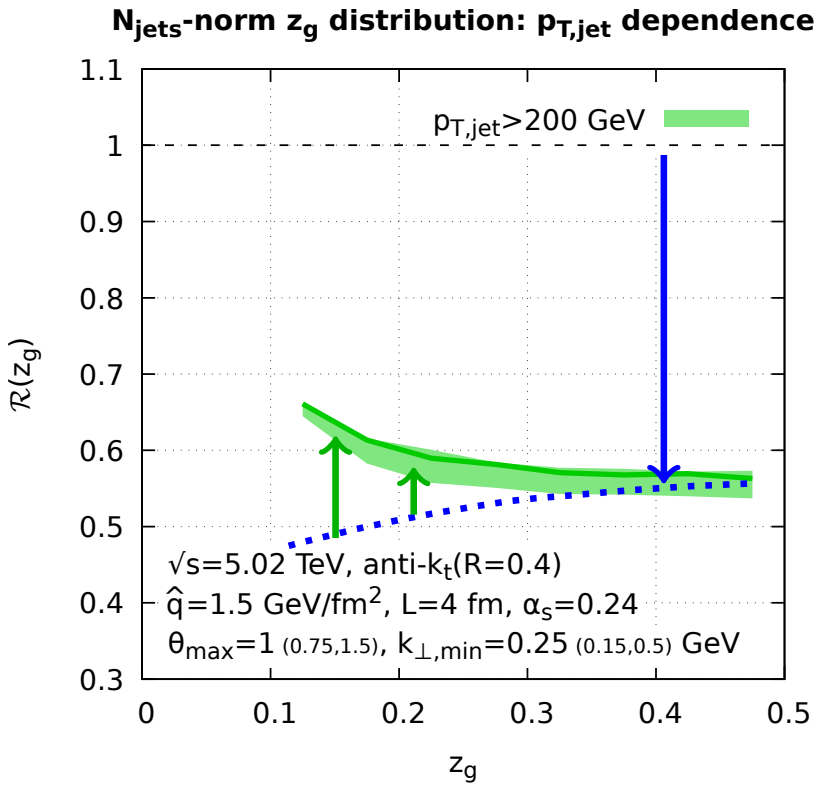
(mostly at double-log accuracy)

Measuring the splitting function

CMS (CMS-HIN-16-006)

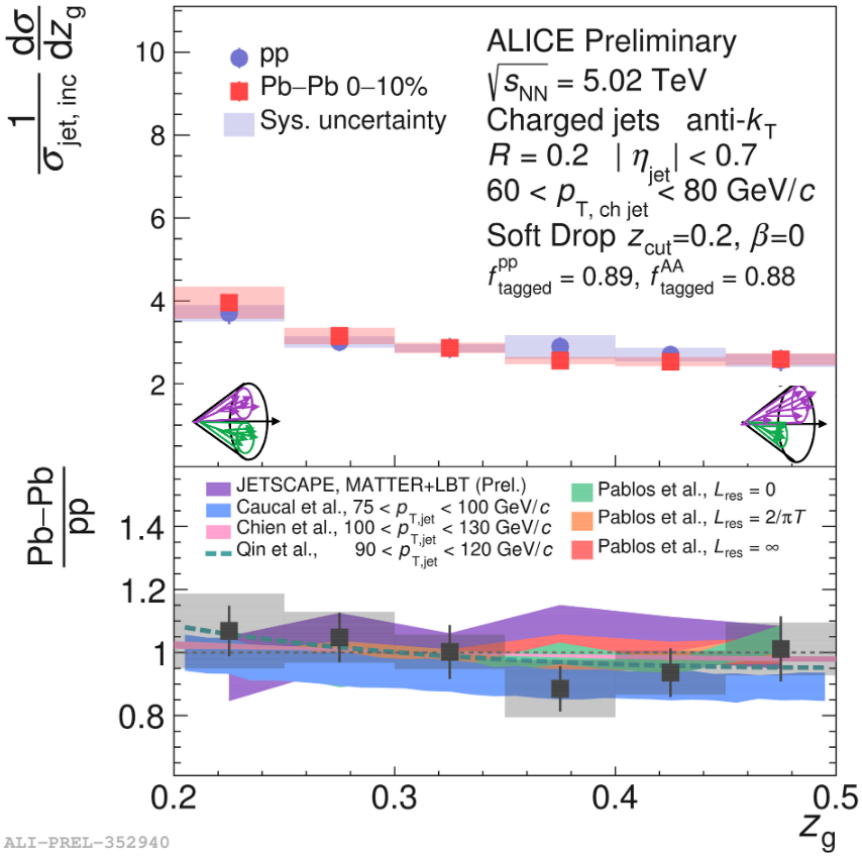


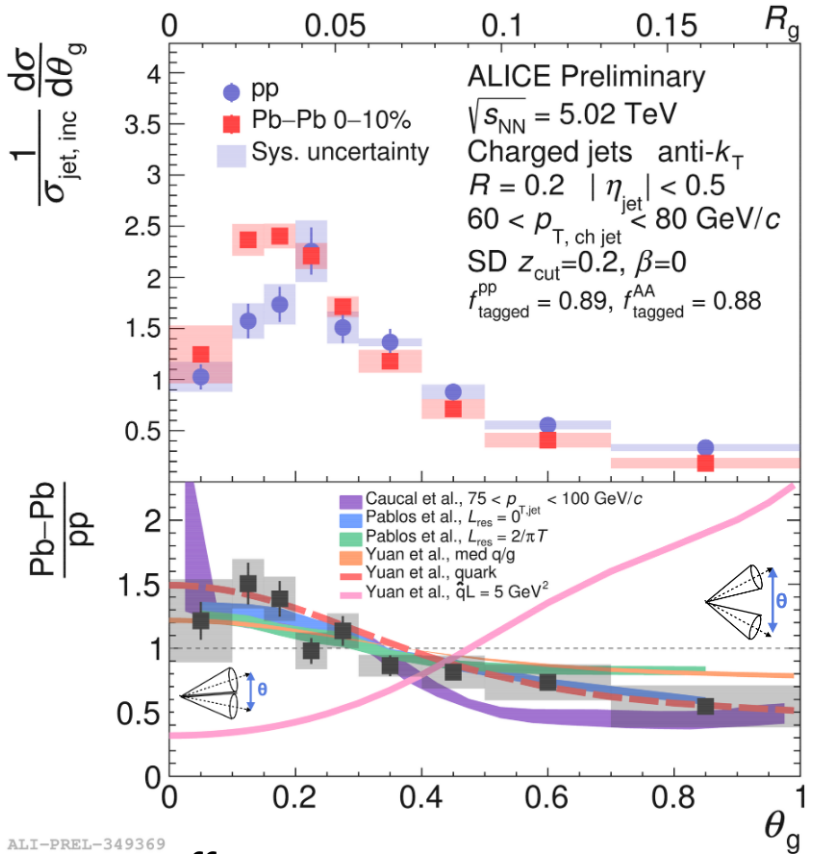
our Monte Carlo



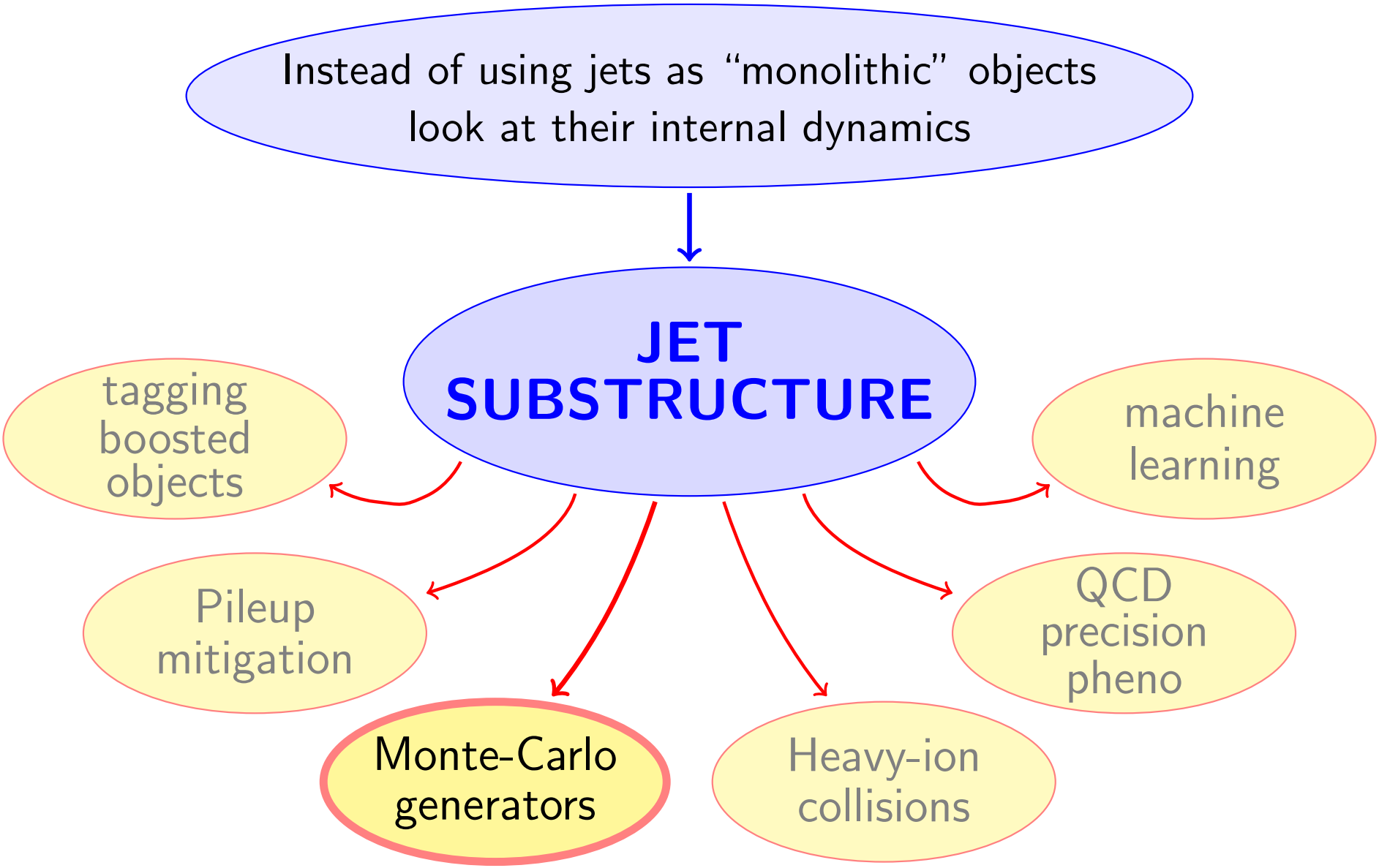
- Reduction from E loss
- Peak from extra emissions

Recent measurement by the Alice collaboration



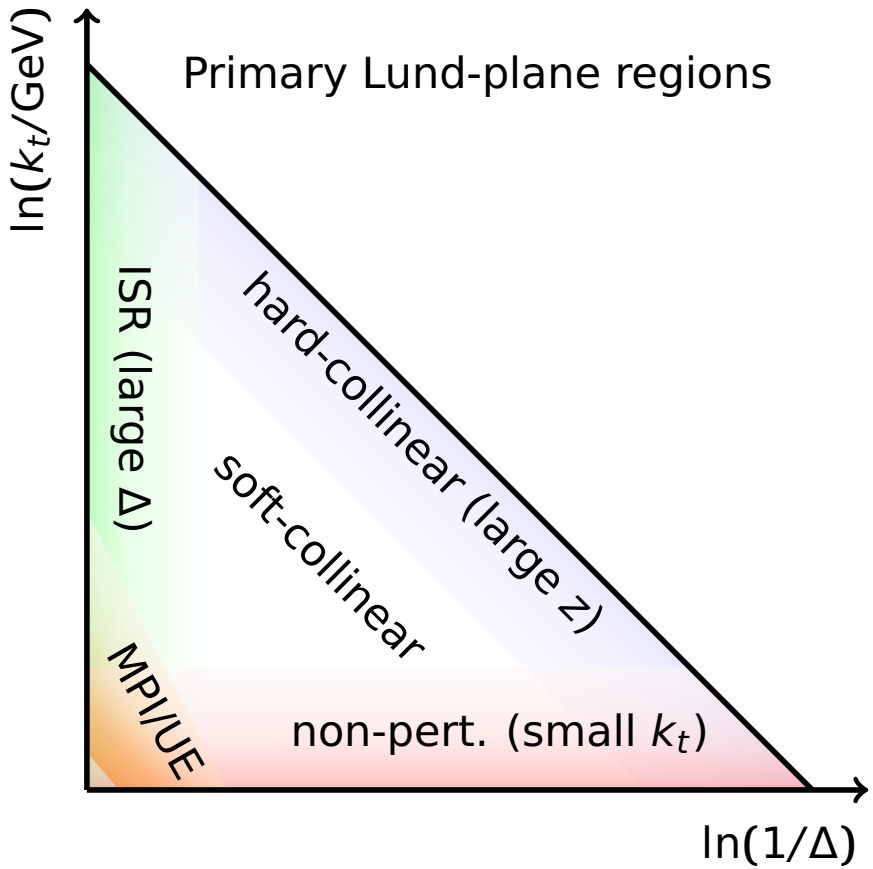


New prospects at the LHC



Substructure for MC development

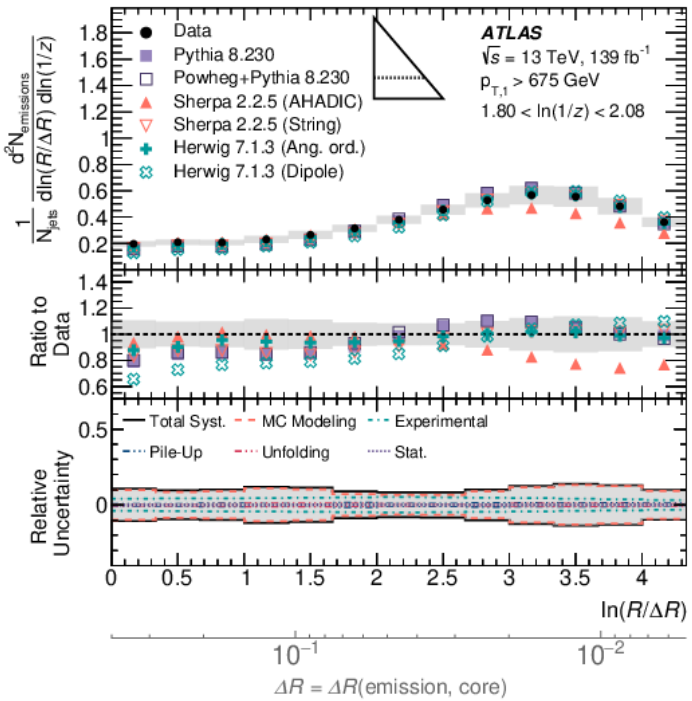
- Already mentioned in Pier's talk on Monday
- Main idea: substructure observables probe QCD dynamics



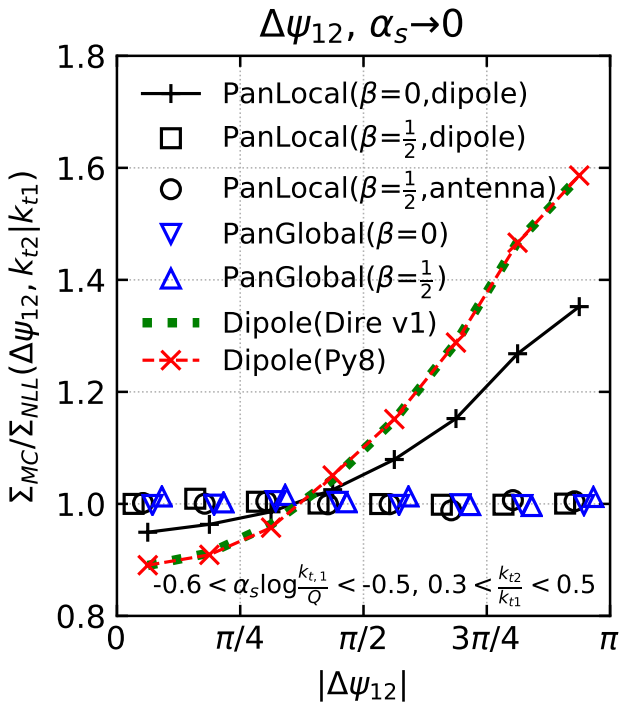
Substructure for MC development

- Already mentioned in Pier's talk on Monday
- Main idea: substructure observables probe QCD dynamics

direct comparison
between data and MC



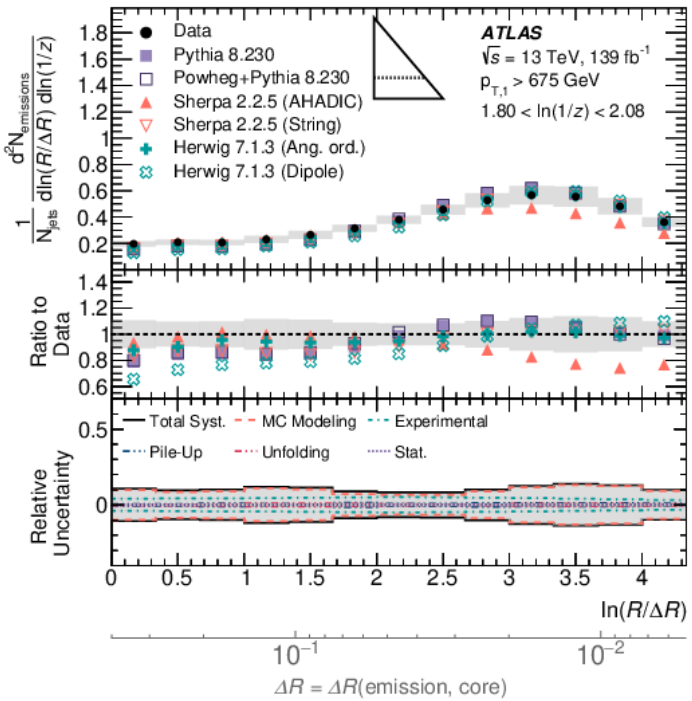
observables for
accuracy tests/developments



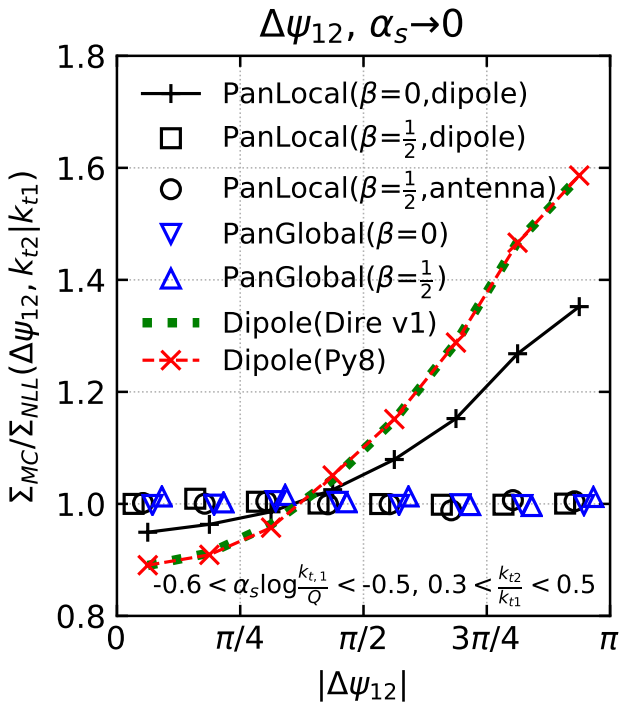
Substructure for MC development

- Already mentioned in Pier's talk on Monday
- Main idea: substructure observables probe QCD dynamics

direct comparison
between data and MC

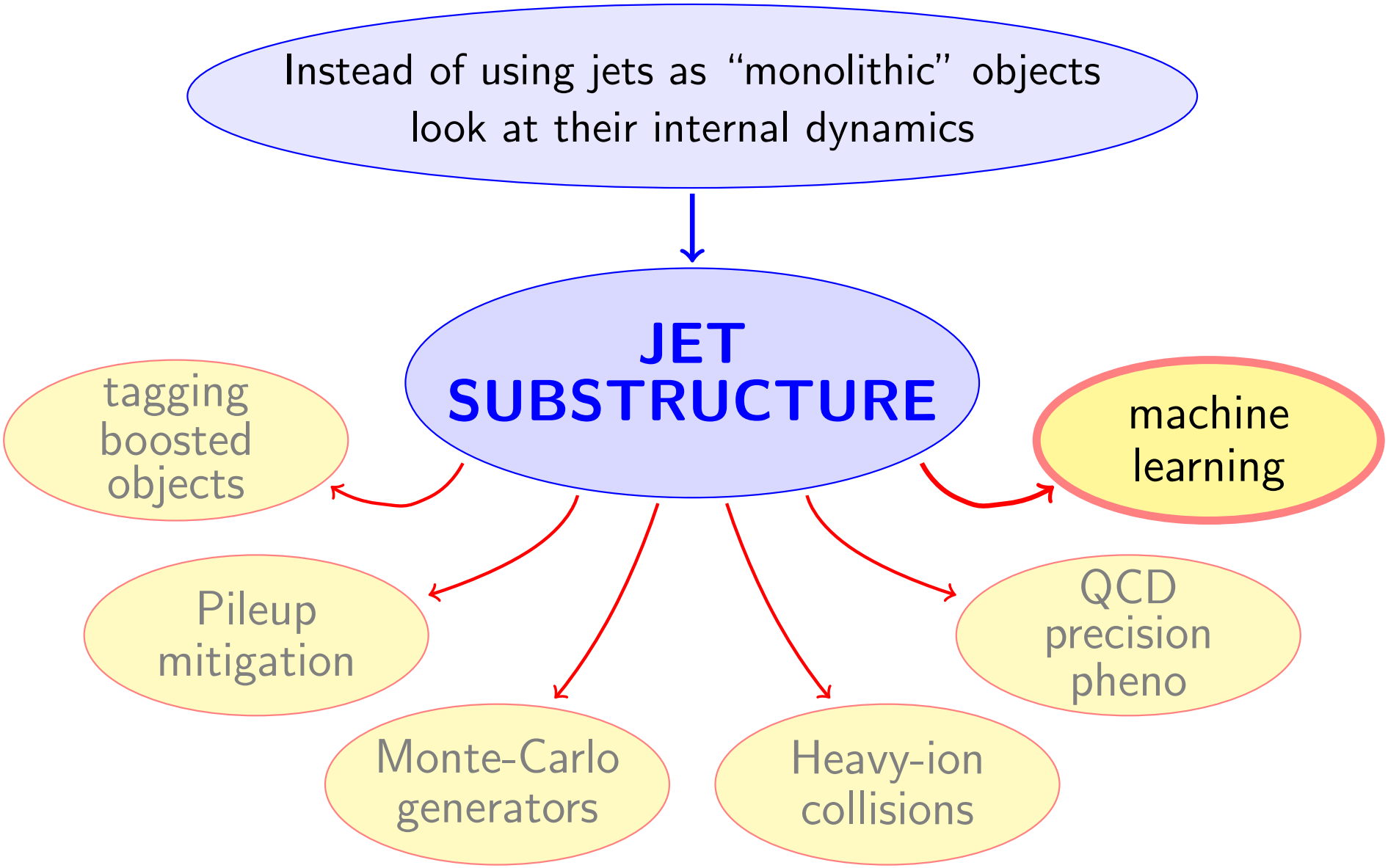


observables for
accuracy tests/developments



Better constraints ⇒ less modelling uncert. ⇒ improved searches

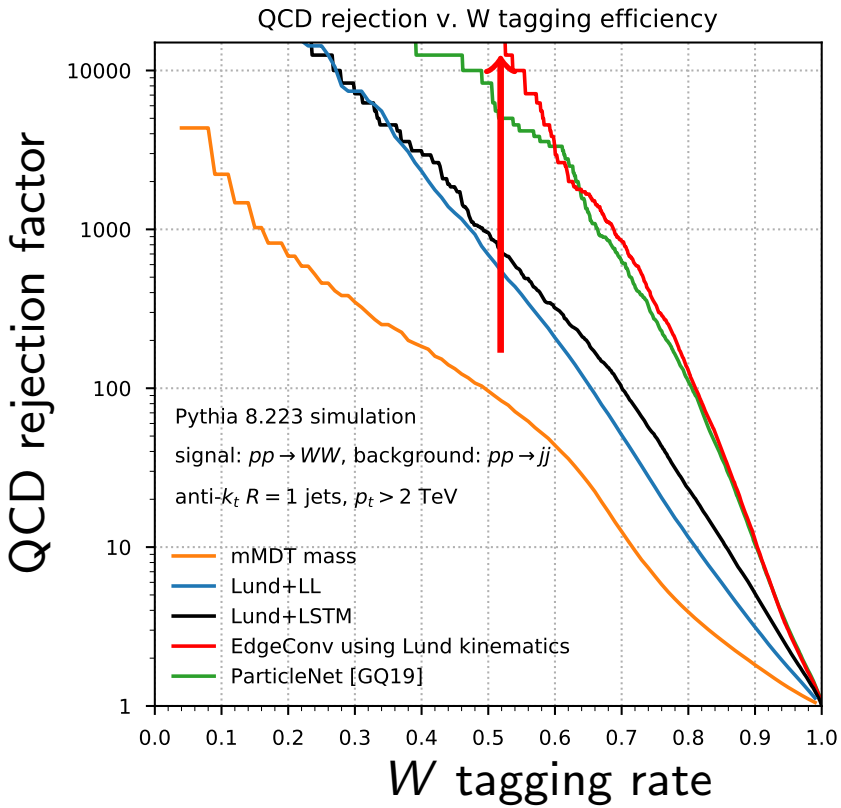
New prospects at the LHC



The Machine-Learning revolution

- substructure went Deep learning 2-3 years ago
- brings large performance gains
- Now a long list of studies
  - different inputs (observables, 4-vectors, images, ...)
  - different architectures
  - initially binary classification, now much more
- some attempts to understand what goes on in the black box

  e.g. assess uncertainties, hints of IRC safety, understand what is learned, analytic insight



[plot from Frederic Dreyer]

Conclusions & perspectives

Take-home messages

- **Substructure is now mainstream and is here to stay**
- **Wide range of applications (Taggers, pQCD, HI, MC, ML)**

More? See these lecture notes (arXiv:1901.10342) and BOOST 2020 talks:

Looking torwards the future

- Jet substructure has often been a playground for new ideas
- Expect more analyses with boosted jets
- Hope for more (unfolded) substructure measerements
- Stay tuned for more deep-learning applications
- **Useful tool to learn about QCD**