New perspectives with jet and their substructure

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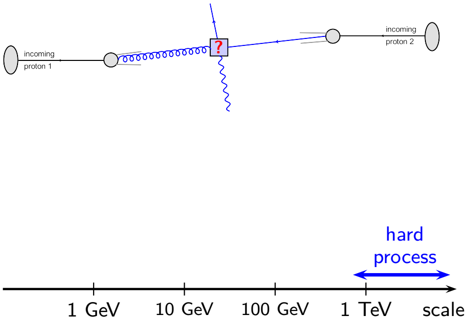
Anatomy of a high-energy collision

Colliders study fundamental interactions at high energy



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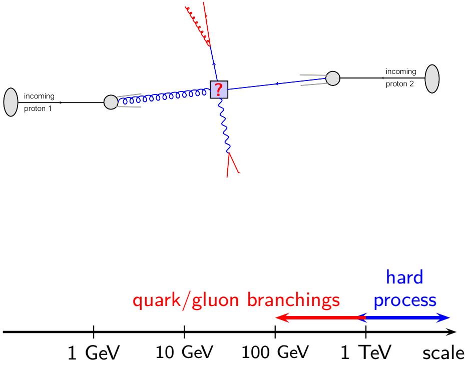

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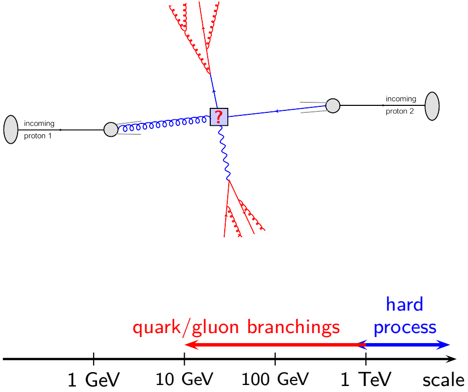

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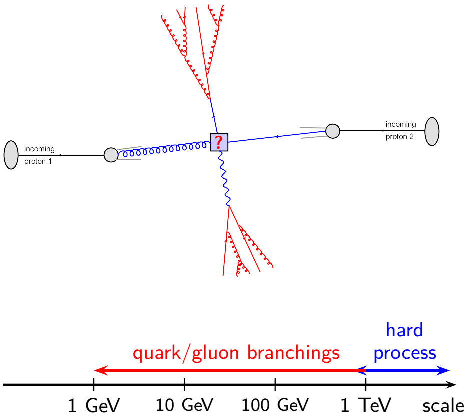

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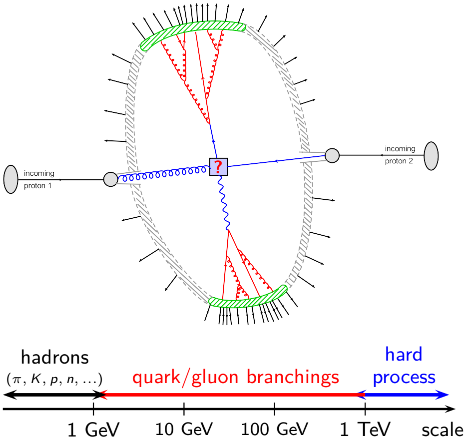


Hard + branchings

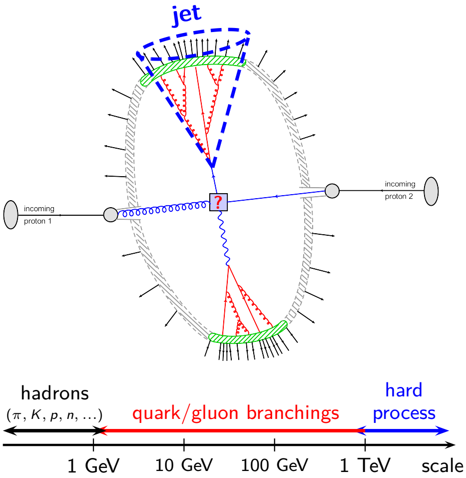
- perturbative QCD
- controlled, solid
- predictive with genuine theory uncertainties

Hadronisation

- NON-perturbative
- needs modelling
- model-dependent

Anatomy of a high-energy collision

Colliders study fundamental interactions at high energy



branchings mostly collinear

(i.e. at small angles)

$\Downarrow$

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

Jet $\equiv$ proxy to hard parton

40 years of jets for collider phenomenology

Central idea

Jet ≡ proxy for hard parton

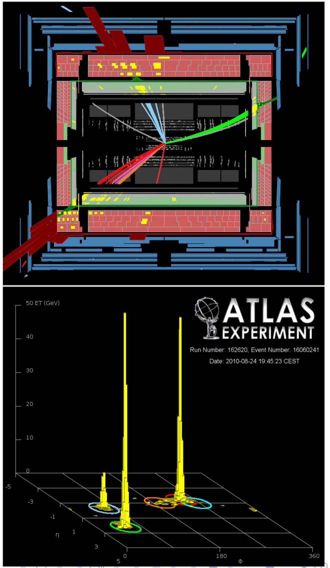
⇒ carries info about the hard collision

- 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 ↔ recombination algorithms

  Energy flow ↔ cone algorithms
- Calculable in perturbative QCD (precision effort)
  Recent progress: NNLO, better PDFs&generators, ...



Central idea

Jet ≡ p

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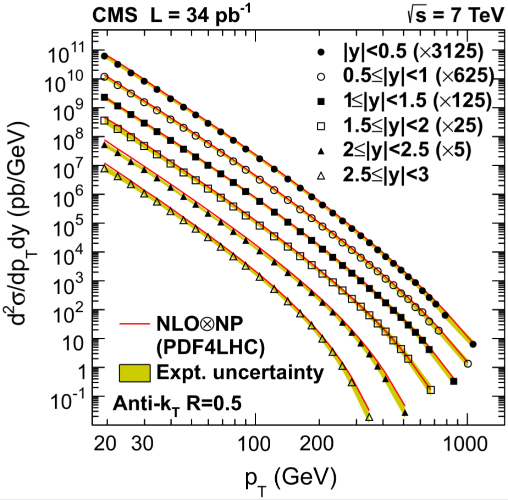
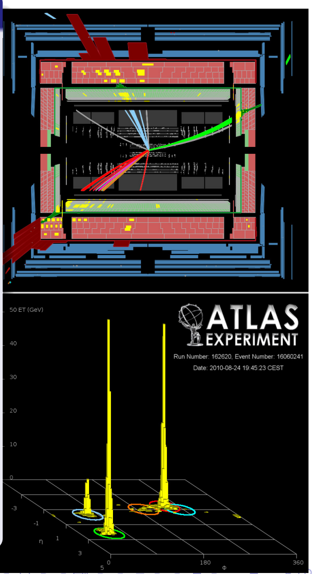
QCD branc

Energy

- Calculable in perturb
  Recent progress: NN

Jet cross-section at the LHC





Plan

Jets are used routinely across the whole LHC physics spectrum

(IMHO) Fun/novelties are related to jet **substructure**

(although this has also become mostly mainstream)

$\Rightarrow$ this talk focuses on jet substructure

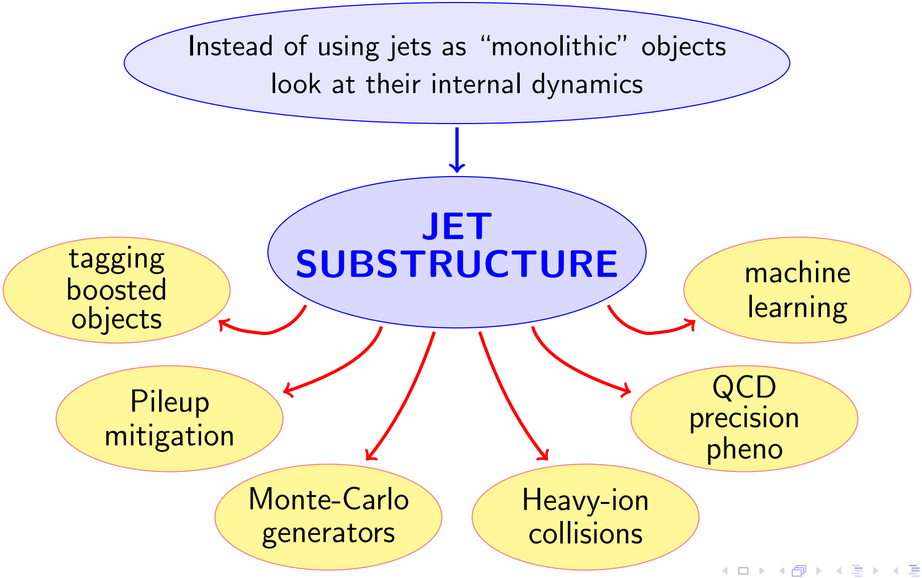
New prospects at the LHC

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

↓

JET SUBSTRUCTURE

New prospects at the LHC



A decade of substructure tools

(modified) MassDrop Tagger

(generalised) angularities

(recursive) SoftDrop

N-subjettiness

Trimming

Pruning

Energy Correlation Functions

Shower deconstruct^{n}

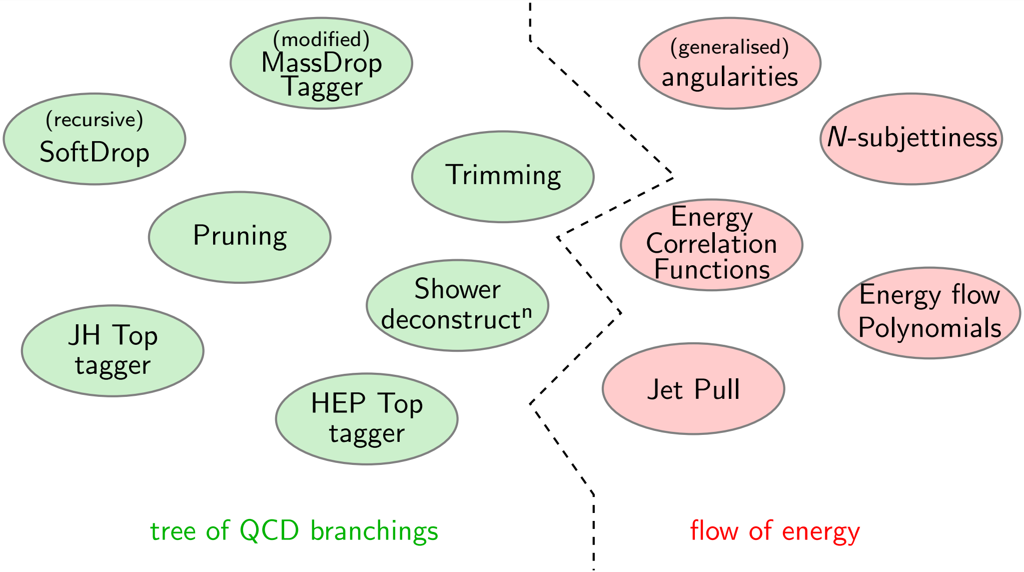
Energy flow Polynomials

JH Top tagger

Jet Pull

HEP Top tagger

* Non-exhaustive/biased/... list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angularities
N-subjettiness
Energy
Correlation
Functions
Energy flow
Polynomials
Jet Pull
tree of QCD branchings
flow of energy

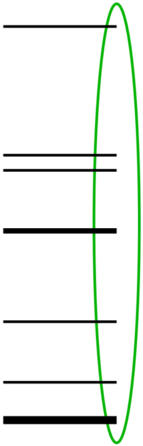
Main idea of the talk:

focus on a single “view” of a jet

use it to show applications in each field

Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



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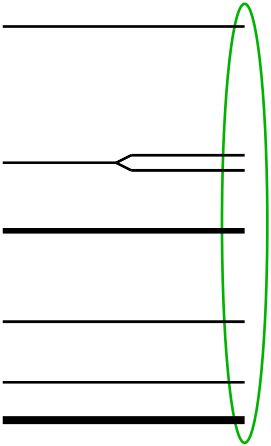

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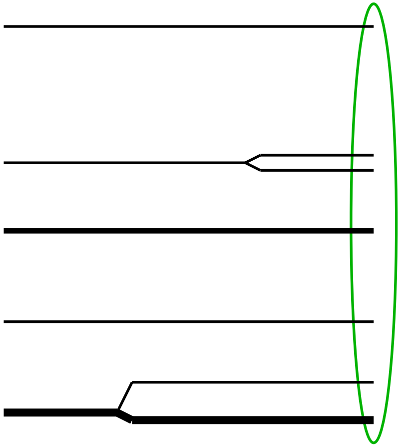

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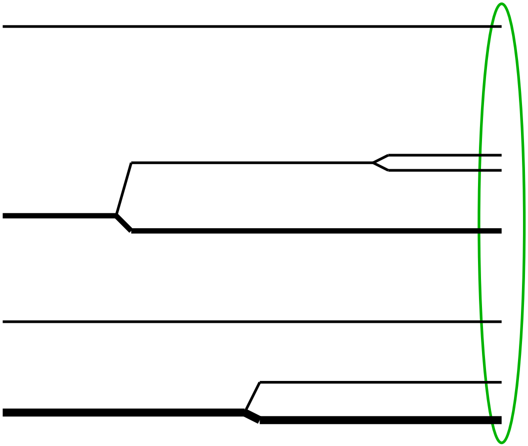

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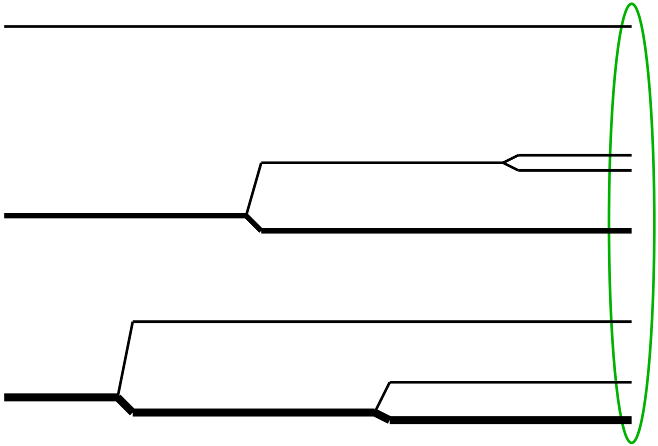

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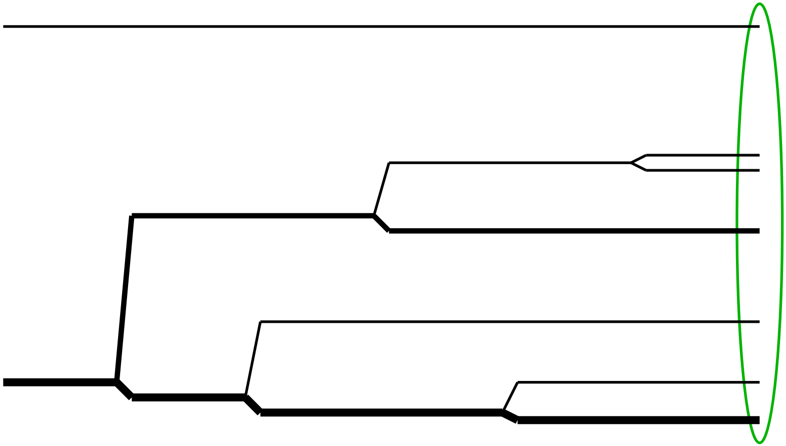

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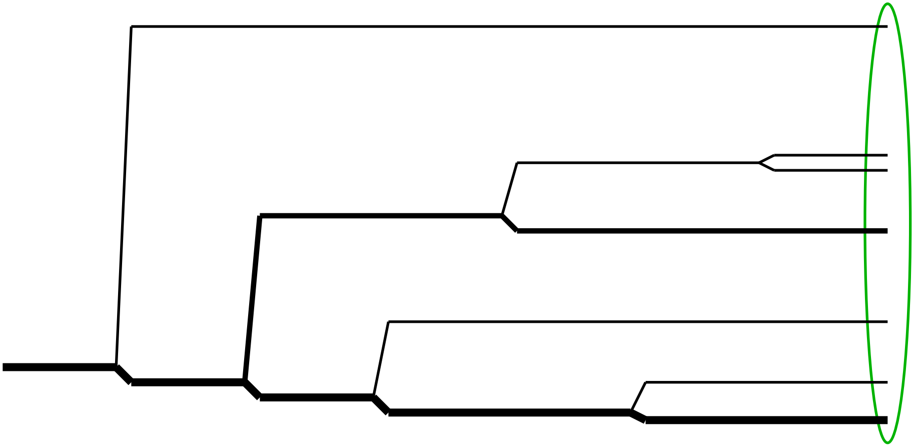

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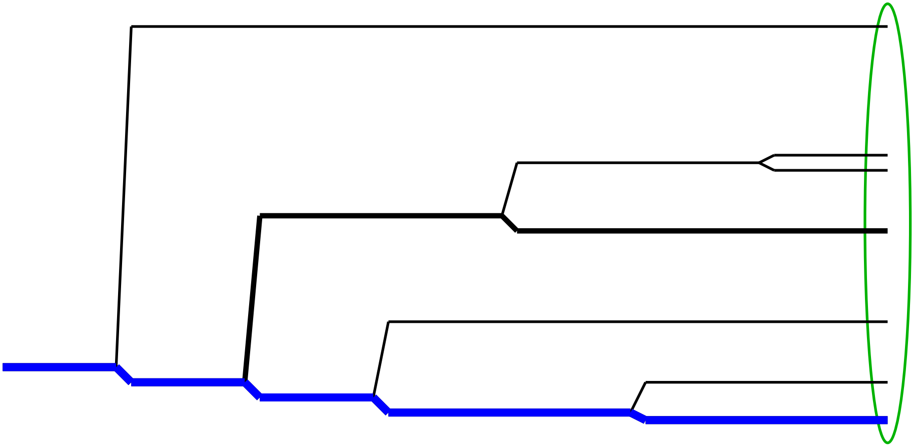
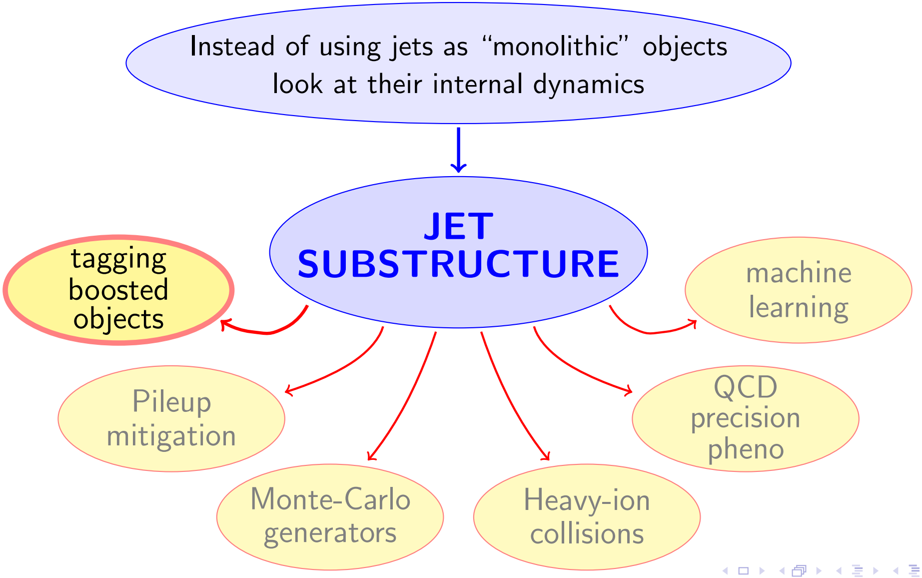


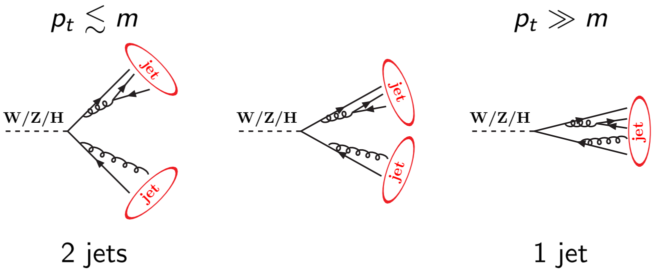
Idea: this tree structure mimics the partonic branching cascade

E.g.: conceptually the largest-energy (p_t or z) branch $\equiv$ emissions from the "leading parton"

New prospects at the LHC



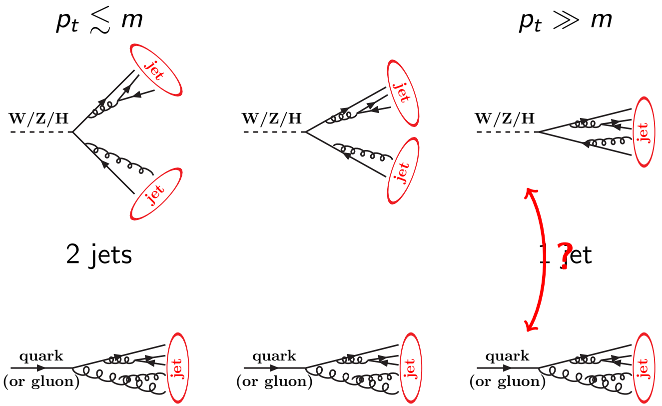
Boosted objects



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

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

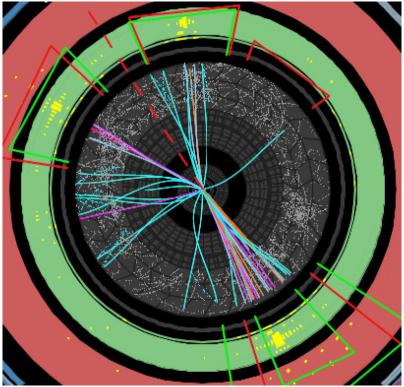
Boosted objects



use substructure to separate from QCD jets

Other examples

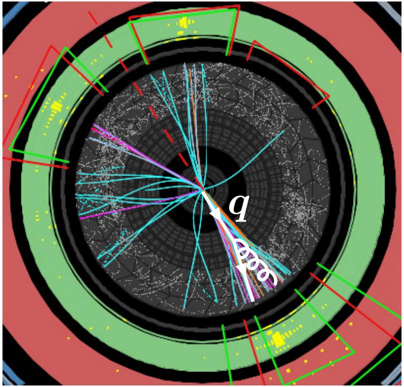
What jet do we have here?



Other examples

What jet do we have here?

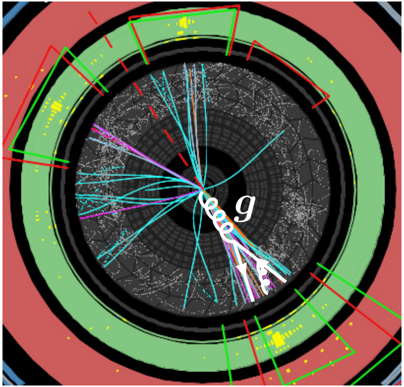
- a quark?



Other examples

What jet do we have here?

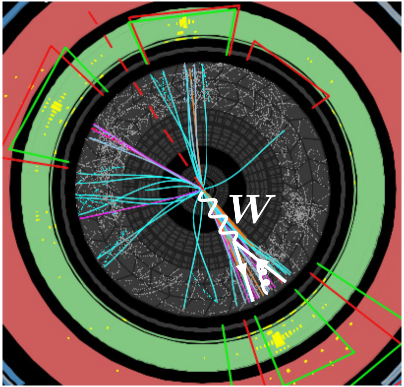
- a quark?
- a gluon?



Other examples

What jet do we have here?

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

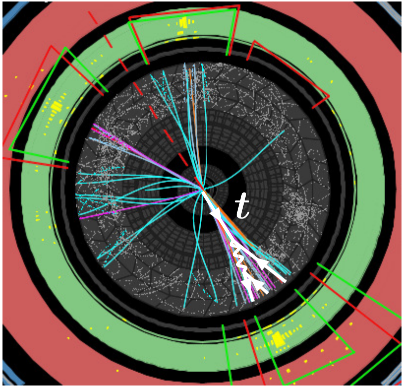


Other examples

What jet do we have here?

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

Source: ATLAS boosted top candidate



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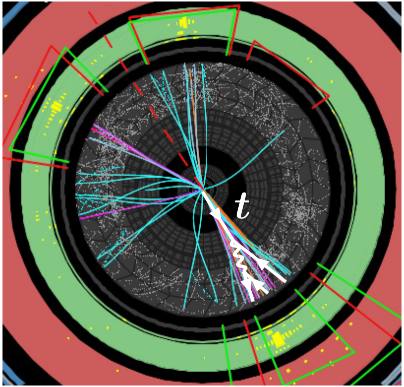
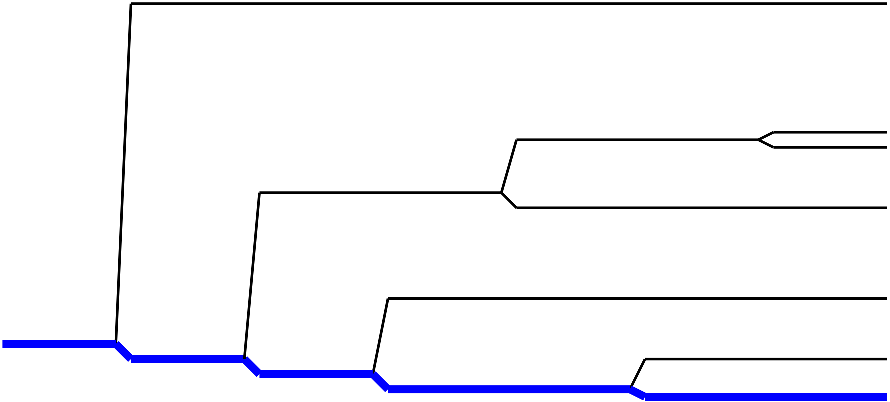


Goal: properly identify the hard process

$\Rightarrow$ Many applications, e.g. relevant to new physics searches

(modified) Mass-Drop Tagger, Soft-Drop

Idea: look for hard branchings



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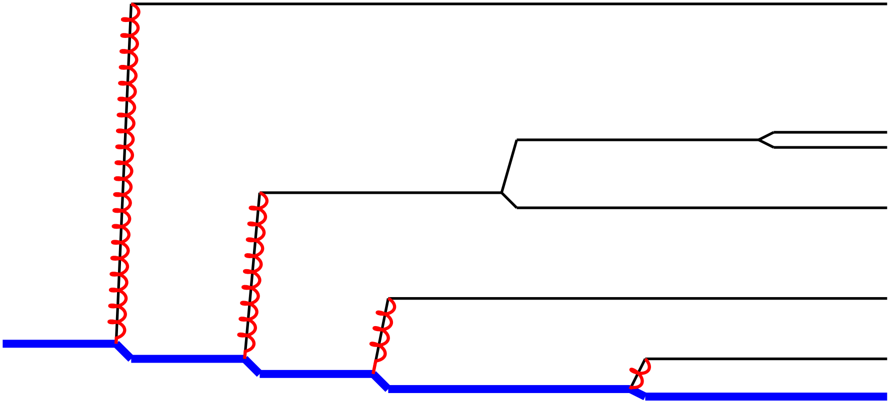

Rare hard branchings for $q/g \to q/g + g$ $(P(z) \sim 1/z)$

(modified) Mass-Drop Tagger, Soft-Drop

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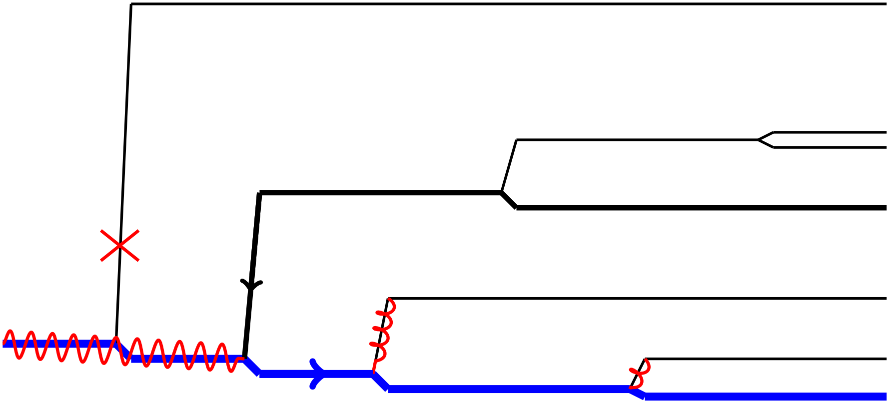
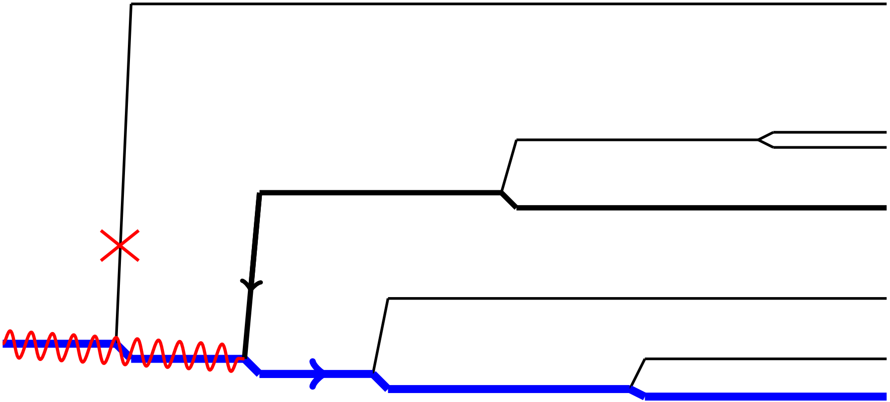


Rare hard branchings for $q/g \to q/g + g$ ($P(z) \sim 1/z$)

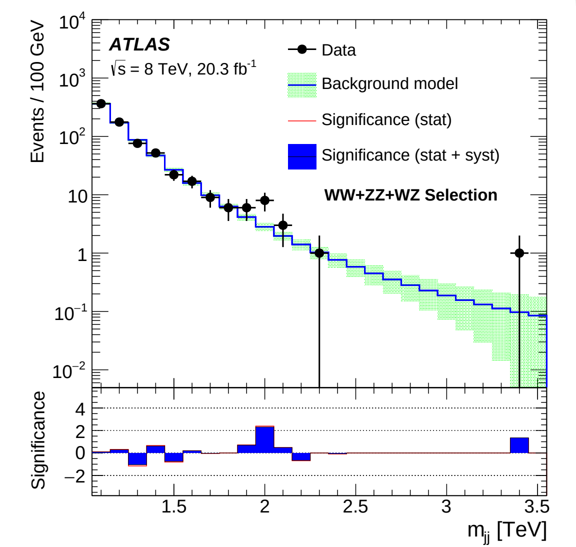
Frequent hard branchings for $W/Z/H \to q\bar{q}$ ($P(z) \sim 1$) + less radiation at large angles

(modified) Mass-Drop Tagger, Soft-Drop

Idea: look for hard branchings

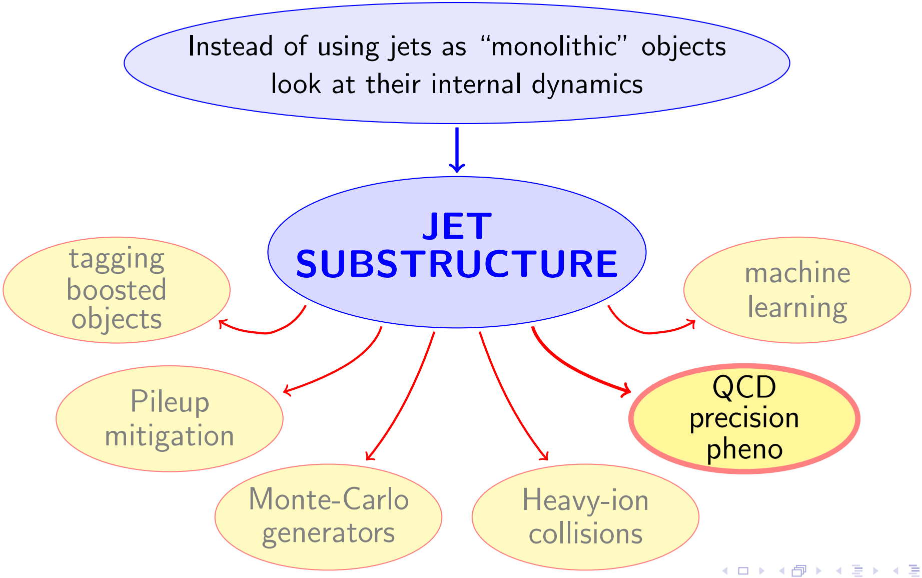


Method: search the first splitting with $z > z_{\text{cut}}$ (+ constrain large-angle radiation)

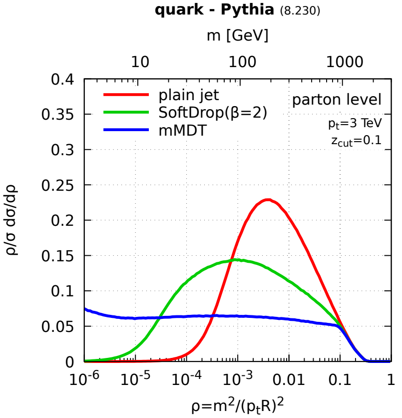


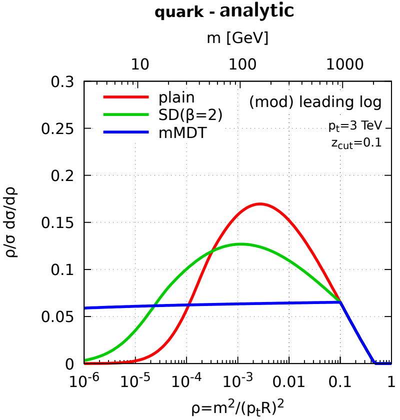
(now-gone) di-boson excess (end of Run-I)

New prospects at the LHC



Breakthrough 7-9 years ago: jet substructure tools are calculable





- qualitative features reproduced and understood

Suited for precision QCD

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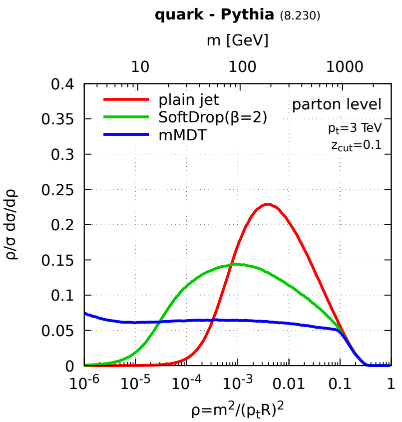

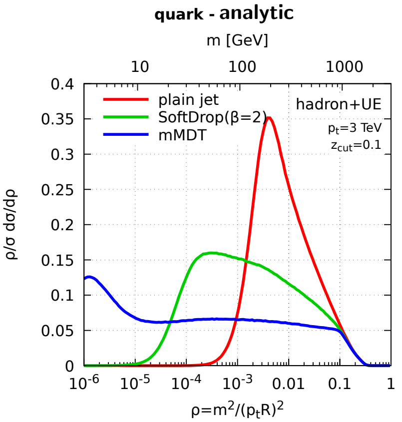

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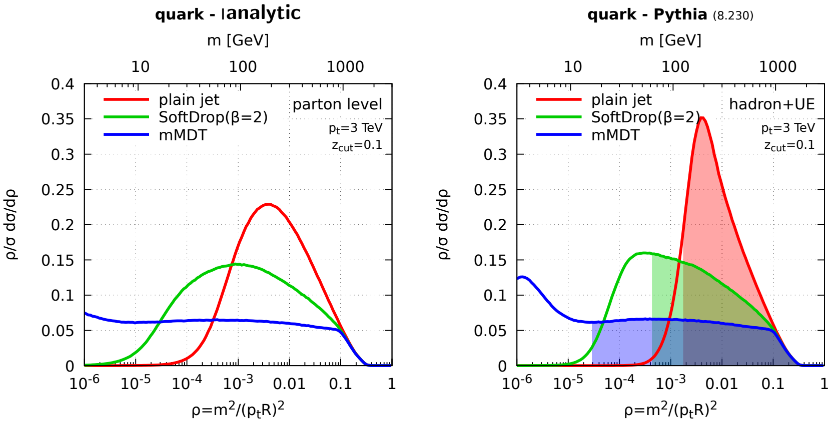

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- **substructure reduces non-perturbative effects**

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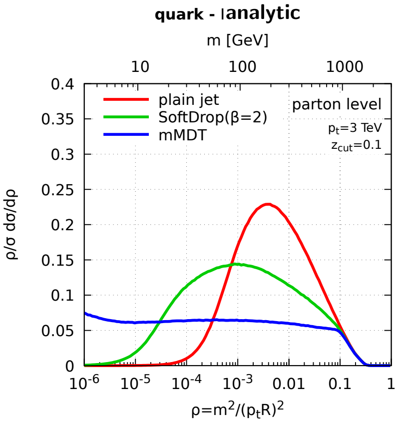
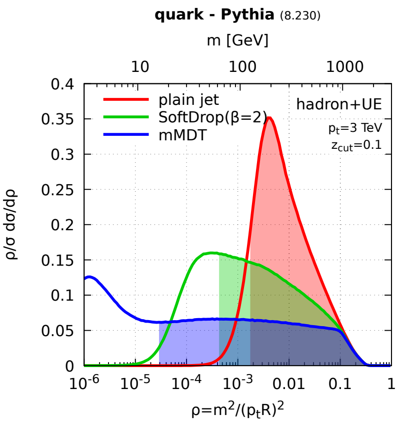




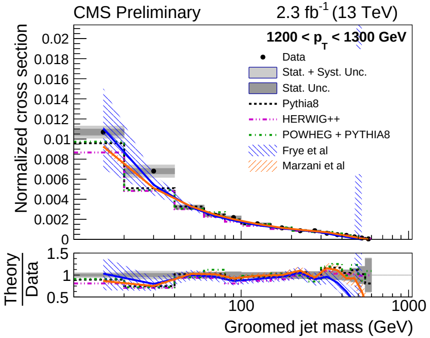
- **qualitative features reproduced and understood**
- **substructure reduces non-perturbative effects**

Suited for precision QCD

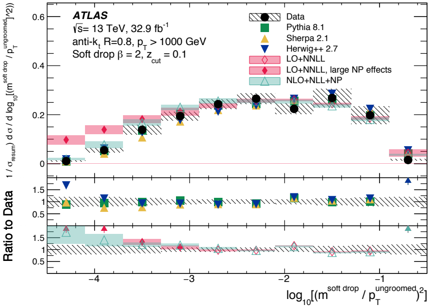
For QCDists: boosted $\Rightarrow$ $p_t \gg m$ $\Rightarrow$ all-orders resummation of $\alpha_s^n \log^n(p_t R/m)$.

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

CMS-PAS-SMP-16-010



ATLAS(CERN-EP-2017-231)

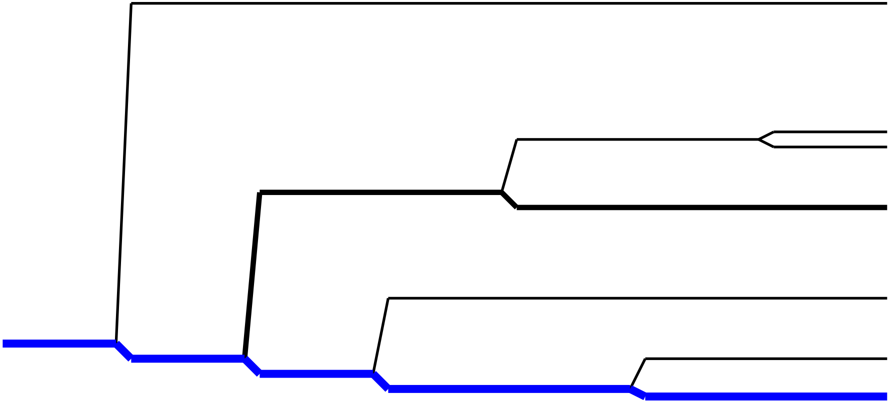


good overall agreement with the data

See also [arXiv:2109.03340] for a recent CMS measurement

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

Visualising the sustructure with the Lund plane



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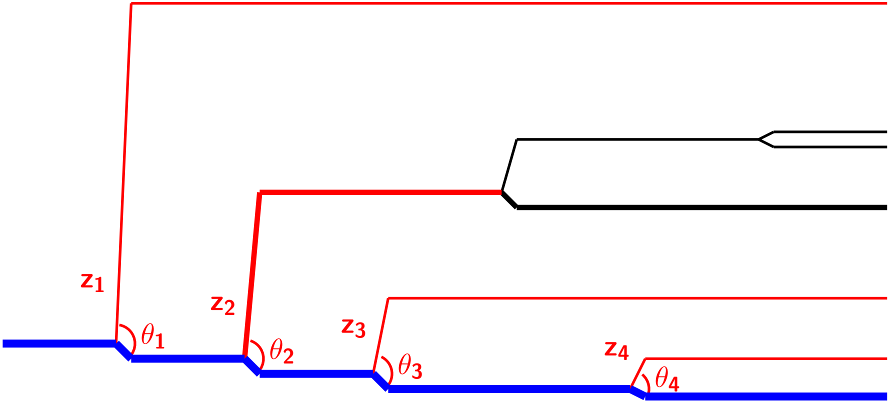
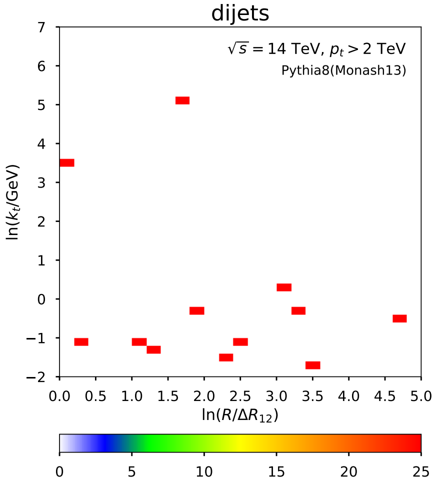
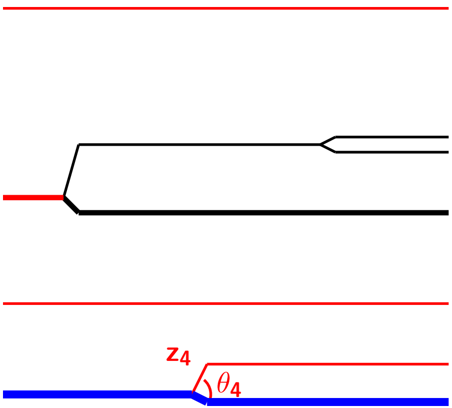


Consider all the emissions from the hardest branch: $\{(z_1, \theta_1), \ldots, (z_n, \theta_n)\}$

Visualising the sustructure with the Lund plane

One jet





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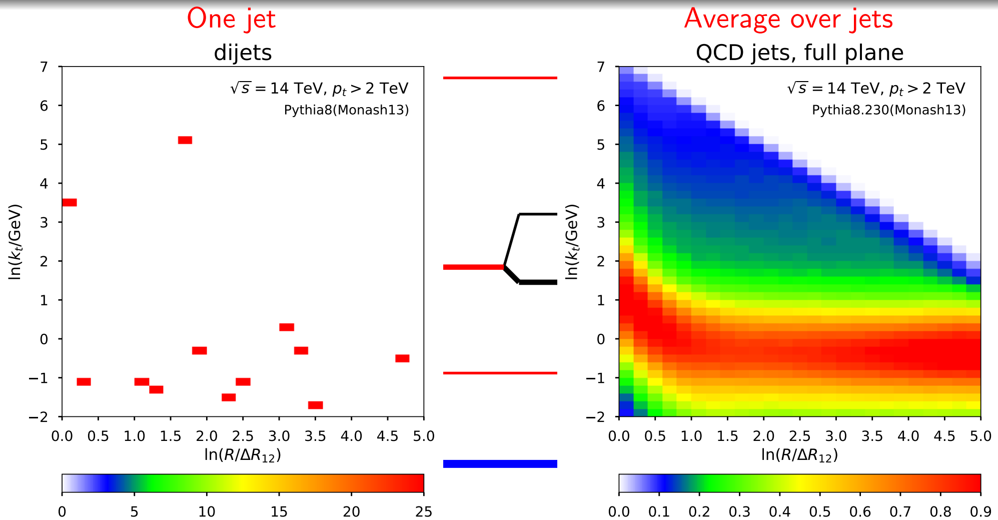
Put them in the Lund plane

Visualising the sustructure with the Lund plane



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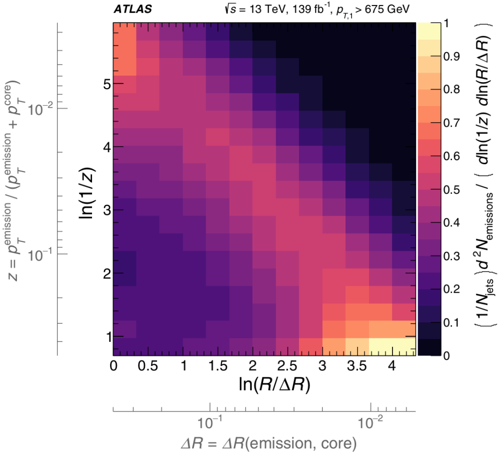
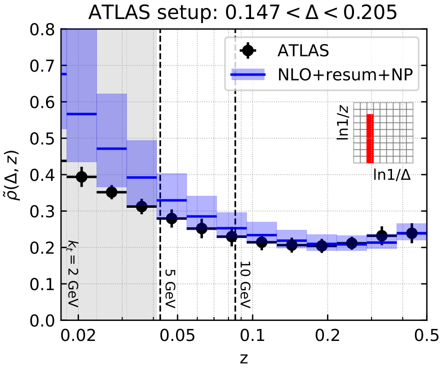
Measured by ATLAS + compared to QCD analytics

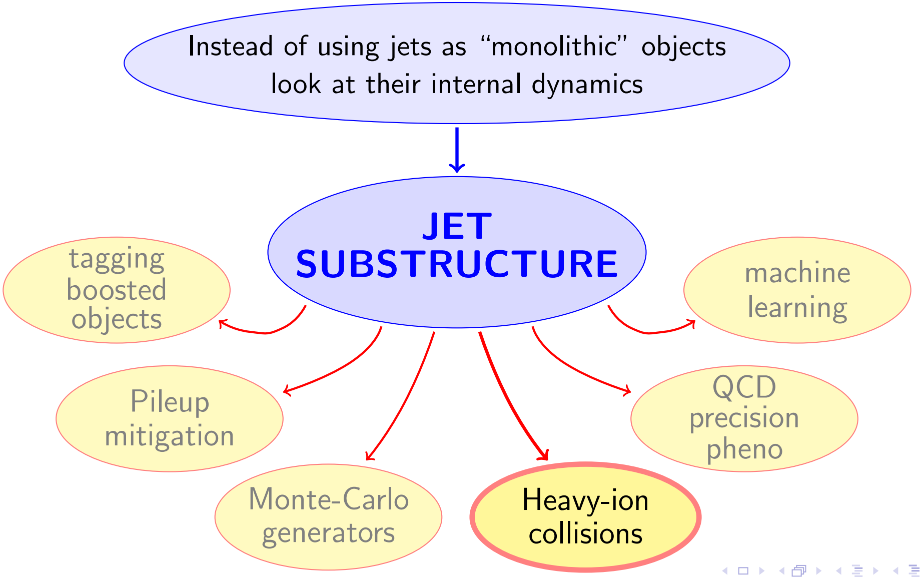


[ATLAS, CERN-EP-2020-030]

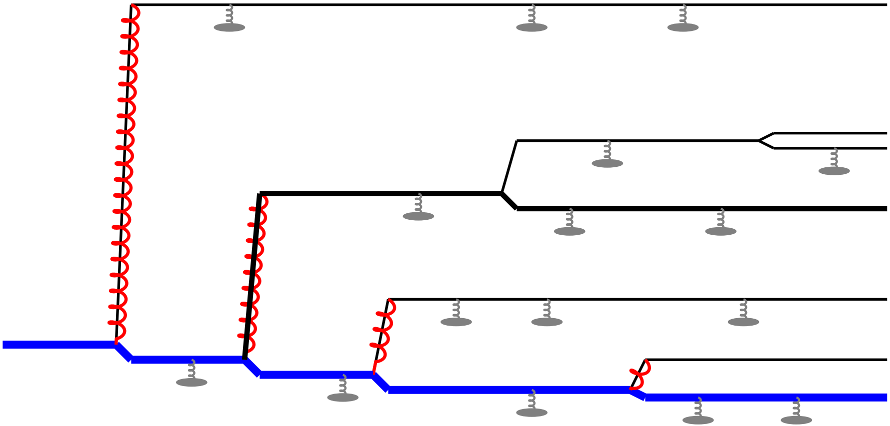


[A.Lifson,G.Salam,GS,07]

New prospects at the LHC



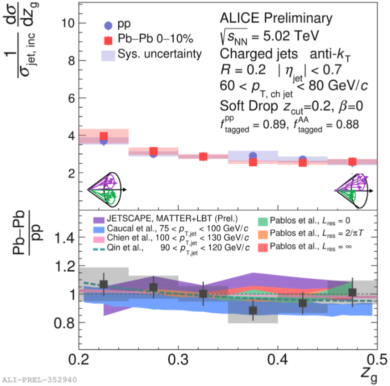
Idea: interaction with the quark-gluon plasma

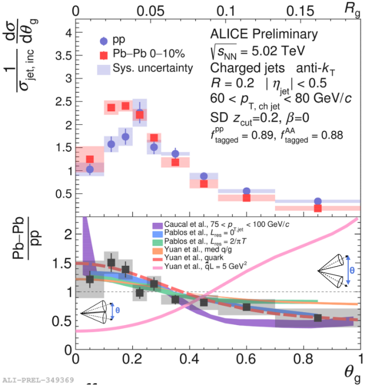


the quark-gluon plasma affects QCD radiation $\Rightarrow$ study through jet substructure

Lots of recent activity (experimentally, theoretically, phenomenologically, ...)

Just one example here: energy fraction and splitting angle of a hard splitting in the jet





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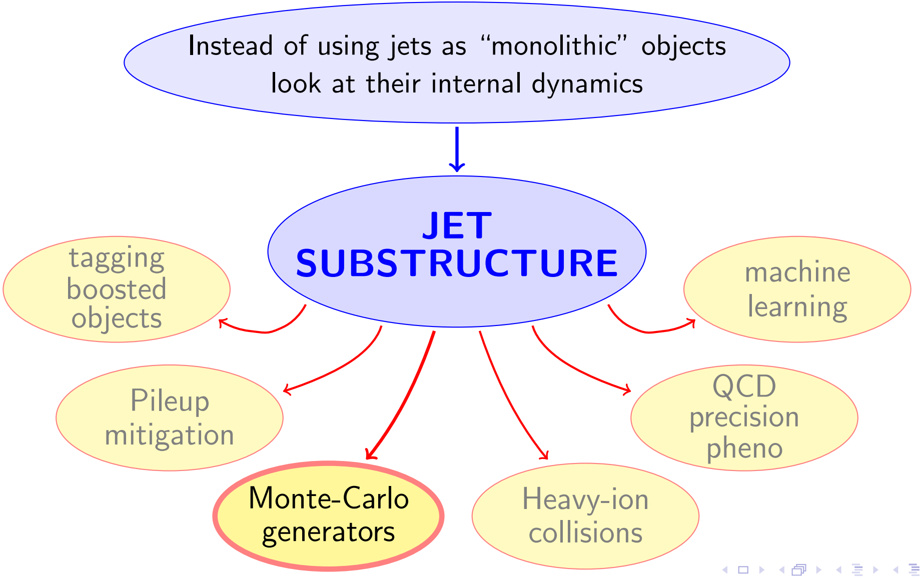
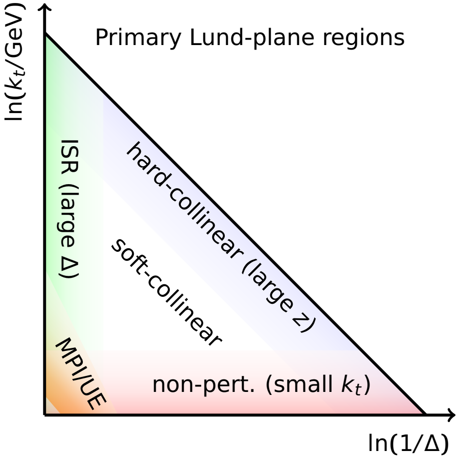


Substructure for MC development

Main idea: MC generators simulate QCD dynamics, substructure probes QCD dynamics



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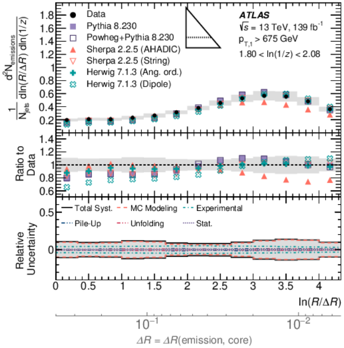
direct comparison
between data and MC



Substructure for MC development

Main idea: MC generators simulate QCD dynamics, substructure probes QCD dynamics

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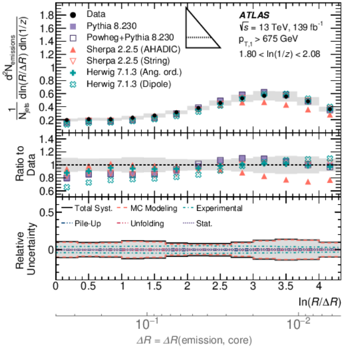
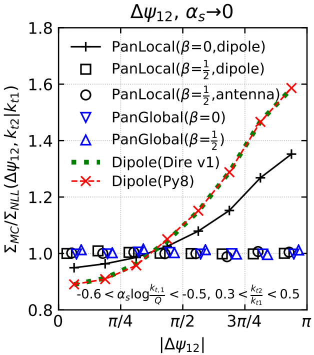


observables for MC accuracy



PanScales NLL showers: e^+e^-,colour,spin,soft spin

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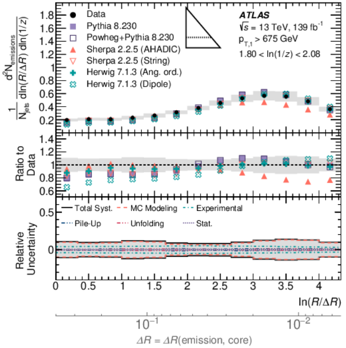

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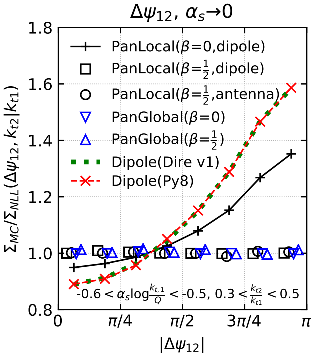

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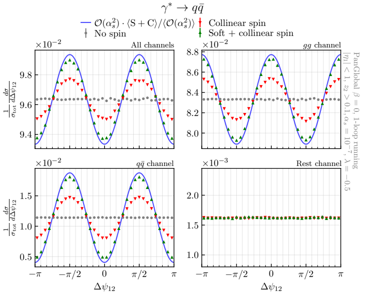
fringe benefits: NLL resum of spin-dependent observables



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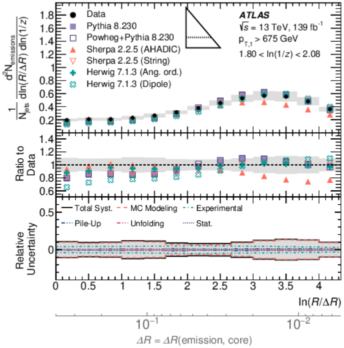

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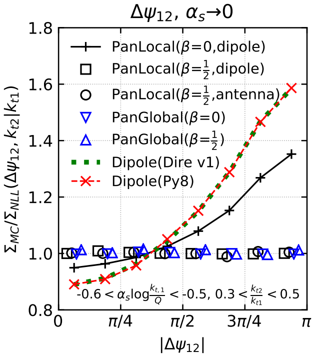

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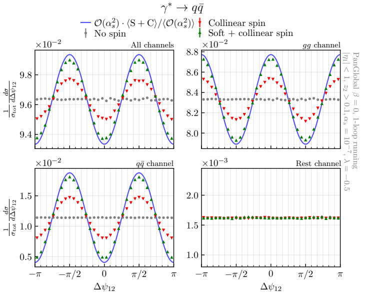
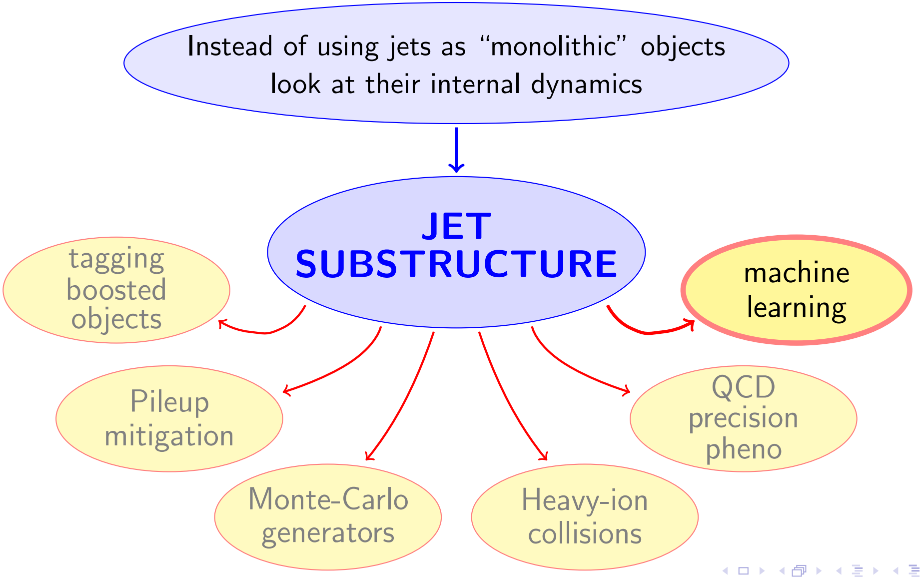


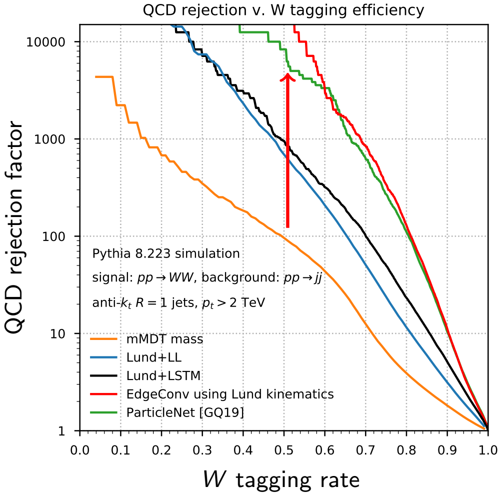
Beyond the "pure QCD interest": better MCs ⇒ less modelling uncert. ⇒ improved searches

New prospects at the LHC



- Deep Learning is now almost everywhere in high-energy physics
- substructure among pioneers ($\gtrsim$5 years ago)
- Most typical example: boosted jet tagging: discriminate "signal" from "background" jets W/Z/H/t v. QCD; q v. g, b tagging, ...

Large gains compared to "standard" techniques



[plot from Frederic Dreyer]

The Machine-Learning revolution

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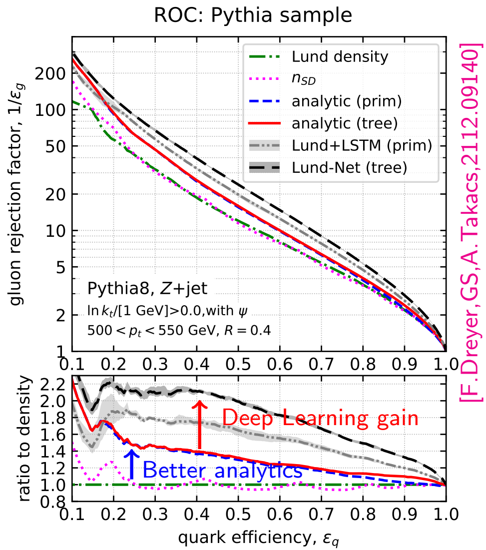

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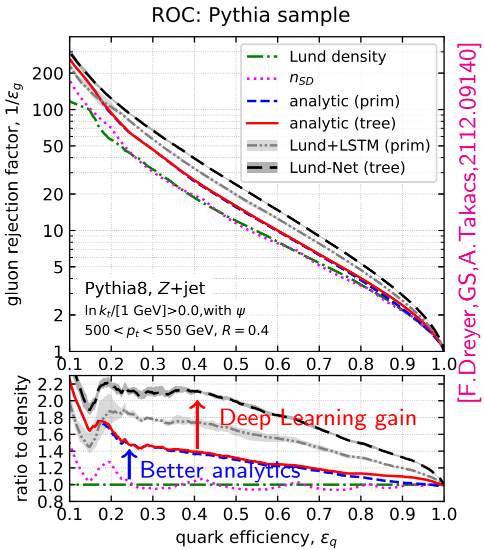

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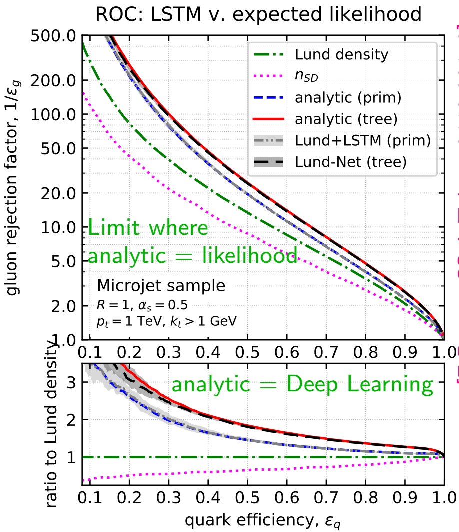
- some attempts to understand what goes on in the black box

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



[F.Dreyer,GS,A.Takacs,2112.09140]

Conclusions & perspectives

Take-home messages

- **Jets are everywhere at colliders (from before LEP to after LHC)**
- **Substructure is now mainstream and is here to stay**
  - **Window on searches for new physics**
  - **Useful tool to learn about QCD**
- **Wide range of applications (Taggers, pQCD, HI, MC, ML)**

Looking towards 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
- More? See these lecture notes (arXiv:1901.10342) and BOOST (2020, 2021) talks