Jet substructure: what else?

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Plan

- Brief introduction to “jets”
- Schematic overview of jet substructure
- Interlude: A helpful representation of emissions in QCD
- Substructure ramifications into:
  - ✓ Searches for new physics
  - ✓ Conceptual understandings of QCD
  - ✓ Precision measurements
  - ✓ Heavy-ion collisions
  - ✓ Machine learning

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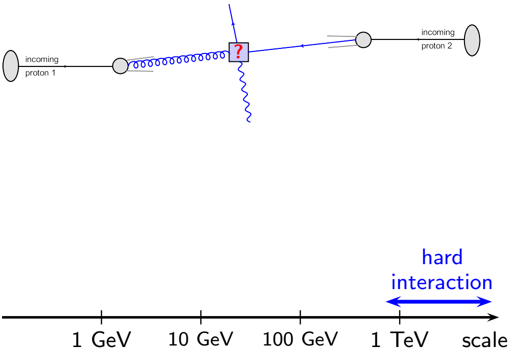
Disclaimer: although this reviews many aspects of the field,
it remains biased towards my own work

See S.Marzani, GS, M.Spannowski, “looking inside jets: an introduction to jet substructure and boosted objects phenomenology”.]

Anatony of a high-energy collision

Colliders study fundamental interactions at high energy



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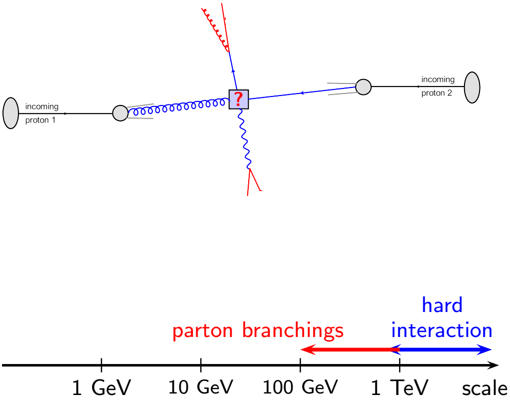

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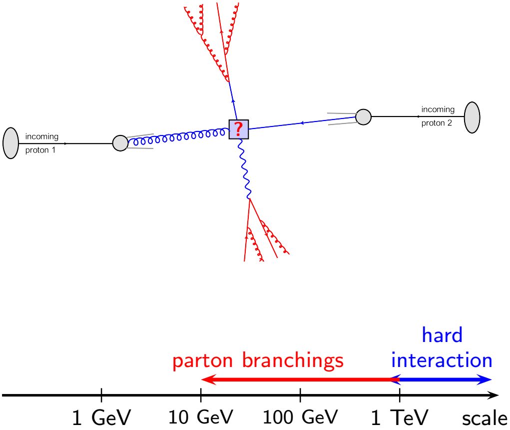

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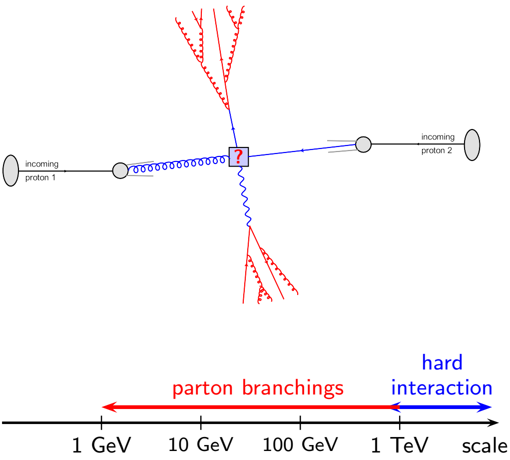

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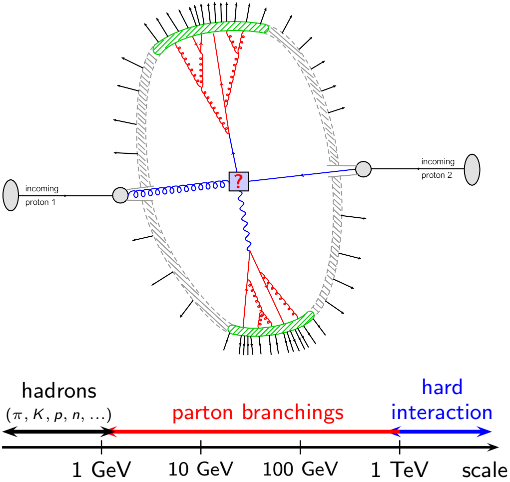

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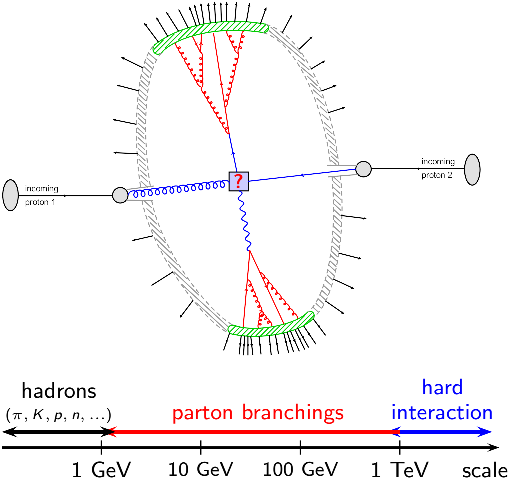

Hard + branchings

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

Hadronisation

- NON-perturbative
- needs modelling
- model-dependent

"Jets"

Basic concepts

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- obtained by running a clustering algorithm
- the LHC uses the anti-k_t algorithm [M.Cacciari, G.Salam, GS, 08]
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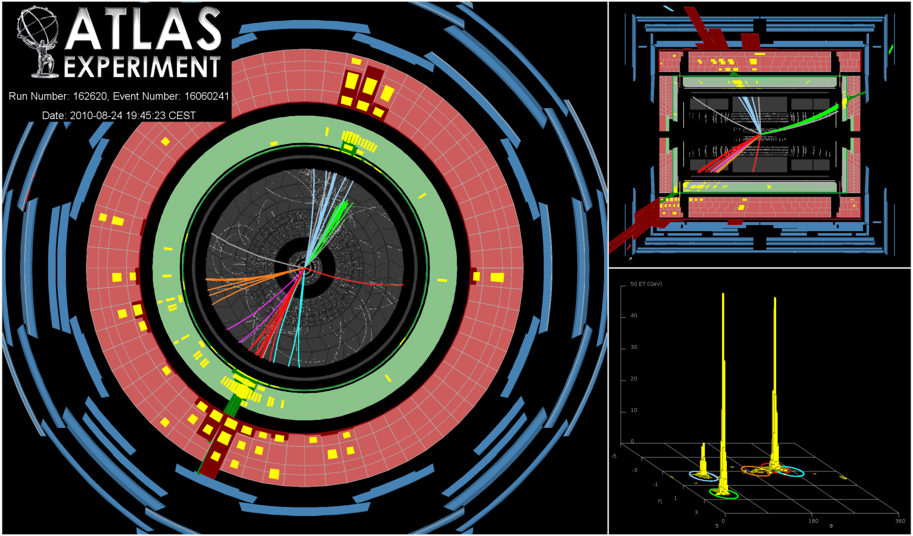
Applications

- ubiquitous in collider physics
- around since 40 years
- used in at least 60% of LHC analyses

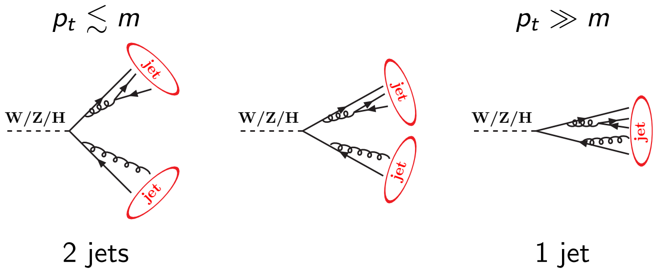
Example of a LHC event



Jet substructure (and boosted objects):

there is more to the picture

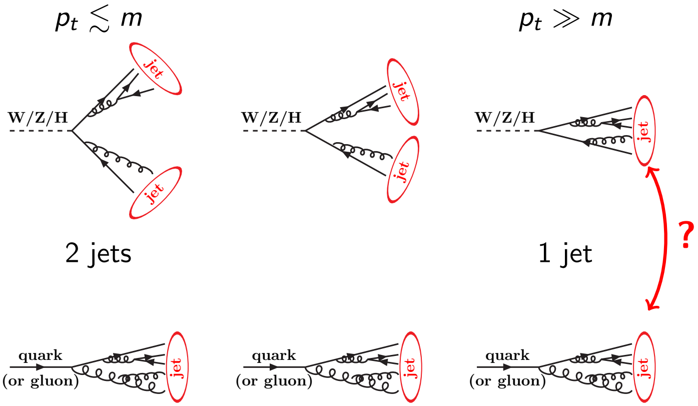
Boosted objects



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

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

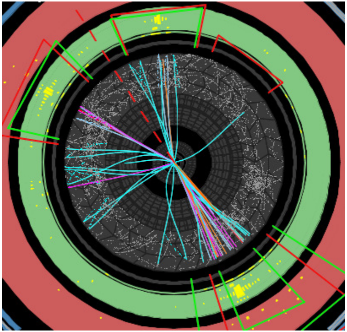
Boosted objects



"Jets" can originate from sth else than a QCD parton (quark/gluon)!
How do we tell?

Other examples

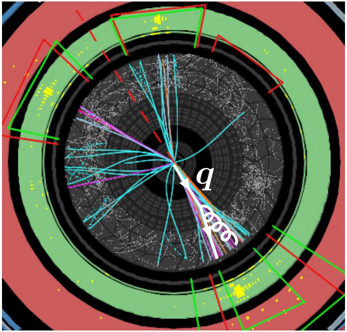
What jet do we have here?



Other examples

What jet do we have here?

- a quark?



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What jet do we have here?

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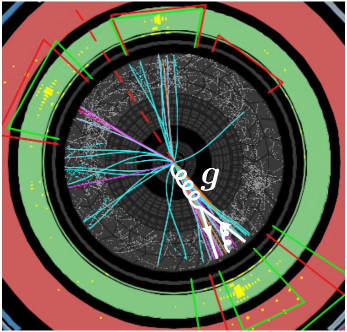
- a gluon?



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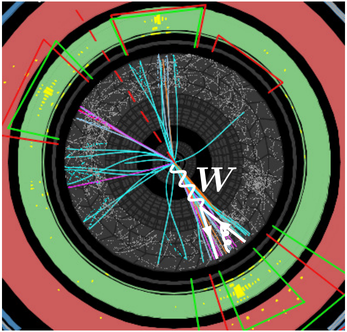

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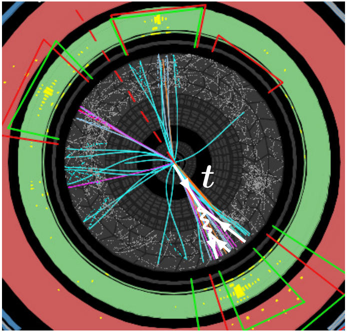

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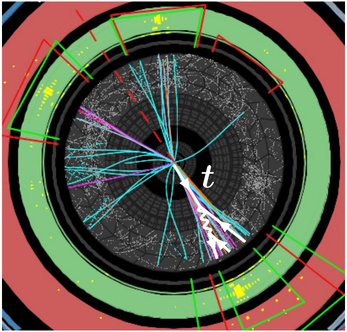
Source: ATLAS boosted top candidate



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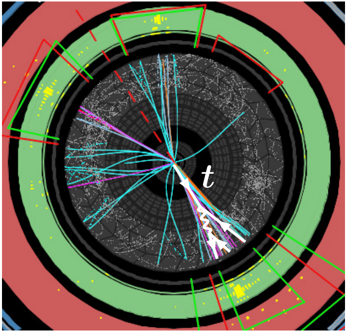

Main idea

look at the internal dynamics of jets i.e. study their **sustructure**
(as opposed to considering jets as monolithic objects)

Main concepts:

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  Clearly beyond the scope of this overview

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- Basic tools are organised around 2(3) major concepts:

  ✓ "peak/prong finders":
  - $W/Z/H/t$ decay into hard partons ⇒ jets with multiple hard cores
  - QCD (q/g) jets dominated by soft radiation ⇒ single cores

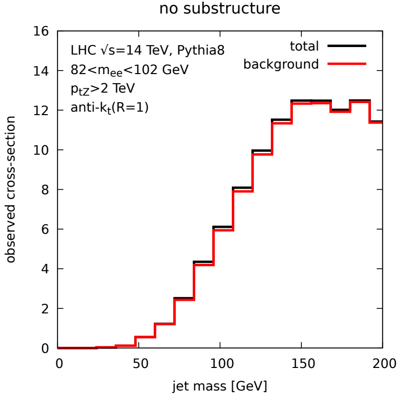
  Tools search for multiple hard cores

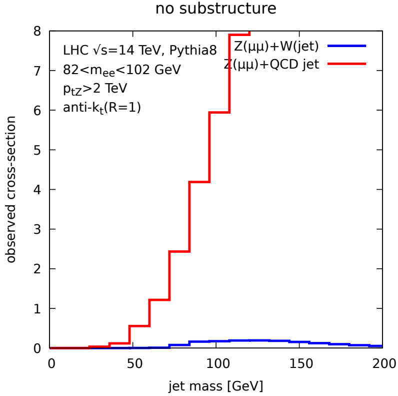
  ✓ Radiation patterns:
  colourless $W/Z/H$ has less radiation than q/g jets
  Tools (jet shapes) to quantify radiation

  ✓ (also grooming to remove soft contamination from fat jets)

A practical example

Boosted W jets: separate boosted $W \to q\bar{q}$ from QCD jets in $Z(\to \mu^+\mu^-)$+jet events





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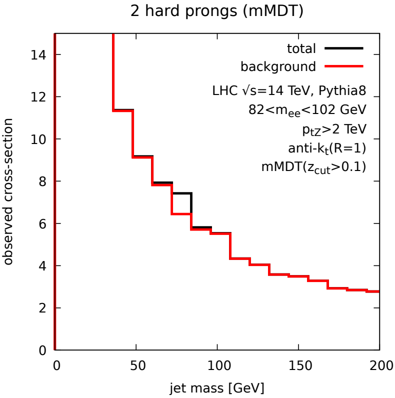

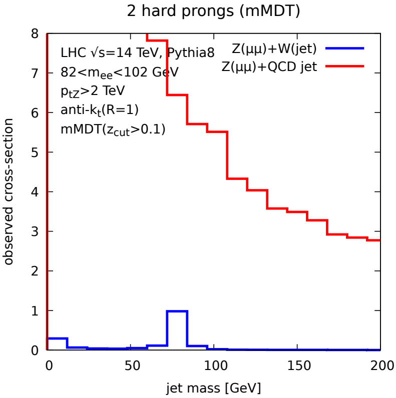

[mMDT/SD: M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13; S.Marzani,GS,J.Thaler,14]

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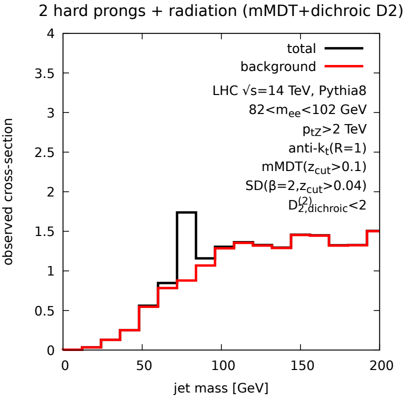
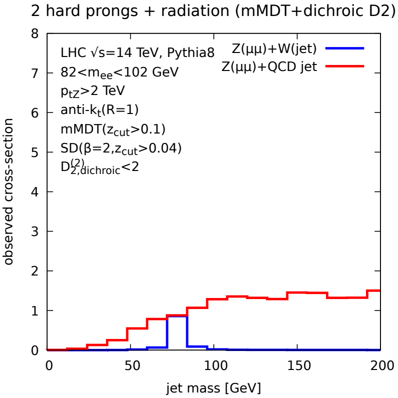


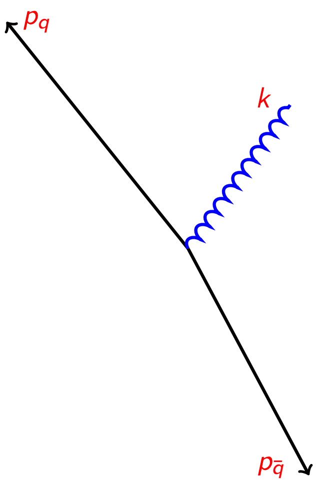


D_2:A.Larkoski,G.Salam,J.Thaler,13;I.Moult,L.Necib,J.Thaler,16; dichroic:G.Salam,L.Schunk,GS,16

Interlude:

A useful representation of radiation in a jet

Take a gluon emission from a $(q\bar{q})$ dipole



Emission:

$$k^\mu \equiv z_q p_q^\mu + z_{\bar{q}} p_{\bar{q}}^\mu + k_\perp^\mu$$

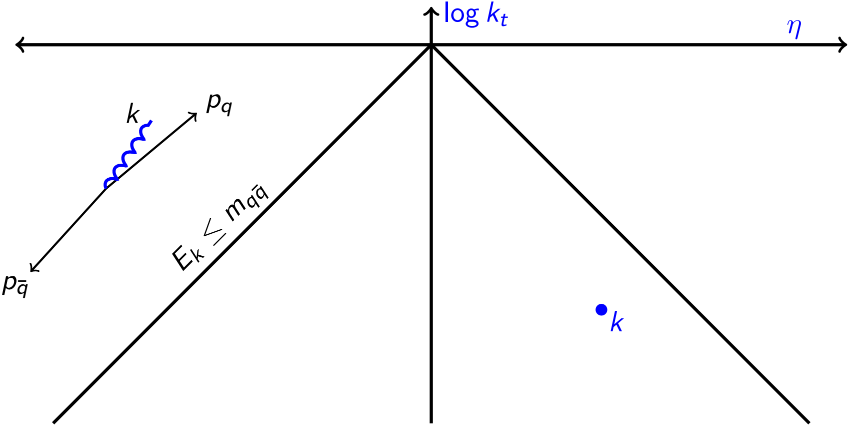
3 degrees of freedom:

- Rapidity: $\eta = \frac{1}{2}\log\frac{z_q}{z_{\bar{q}}}$
- Transverse momentum: $k_\perp$
- Azimuth ϕ

In the soft-collinear approximation

$$d\mathcal{P} = \frac{\alpha_s(k_\perp) C_F}{\pi^2}\, d\eta\, \frac{dk_\perp}{k_\perp}\, d\phi$$

Lund plane: a natural representation uses η and $\log k_\perp$



Basic features of QCD radiations: the Lund plane

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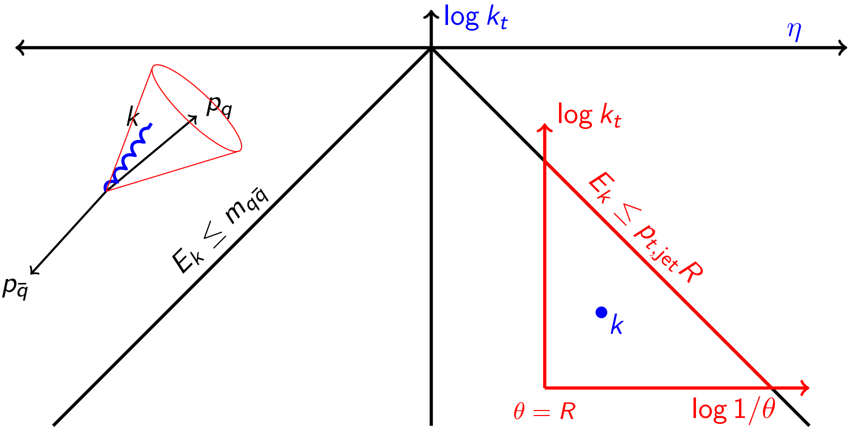
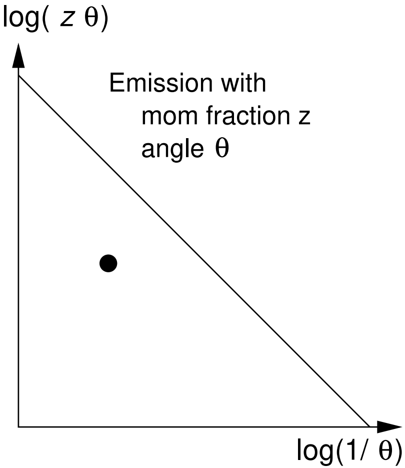
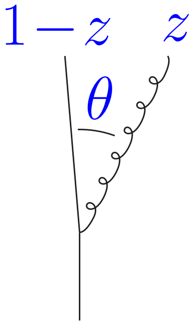


For a jet: $\eta = -\log\tan\theta/2 \approx \log 1/\theta$, $\theta < R$

A look into the Lund plane kinematics





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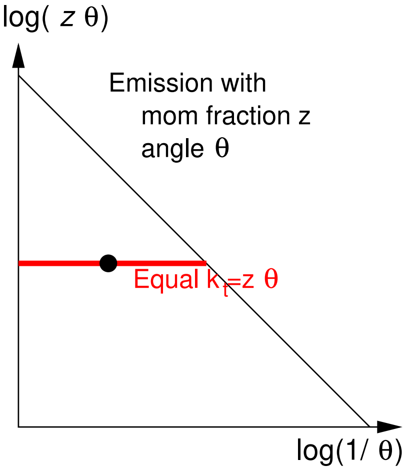

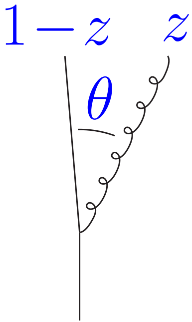

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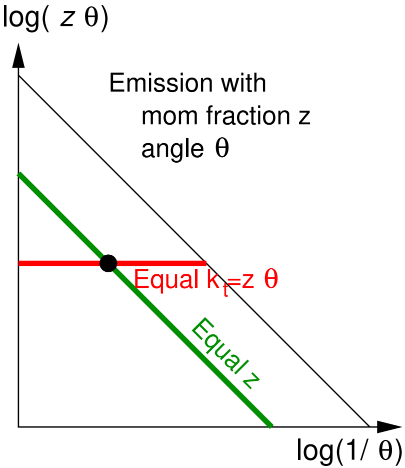

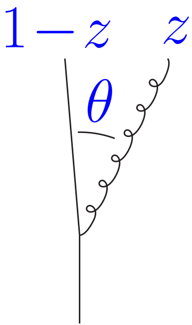

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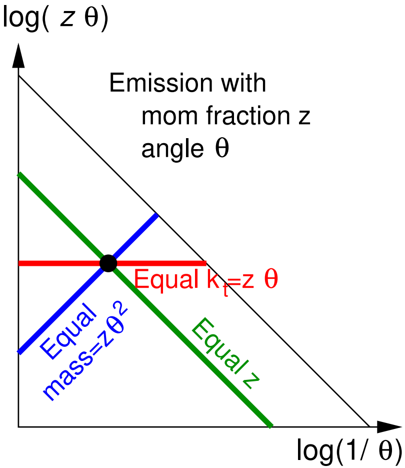

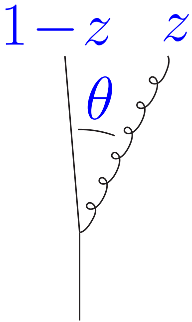

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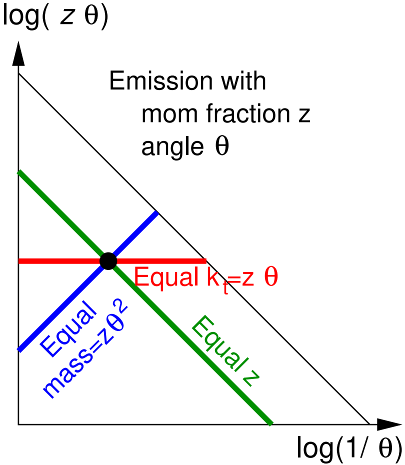
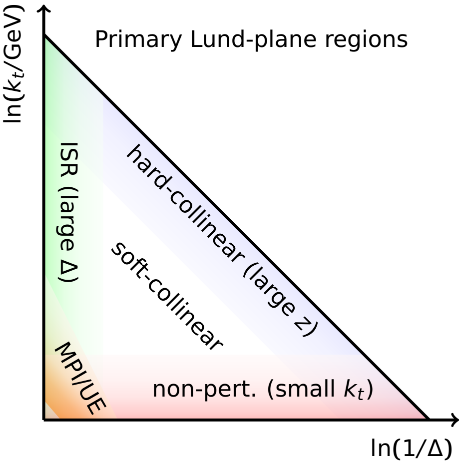


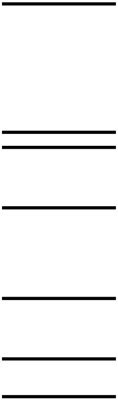


Jet substructure:

A few examples

Frequent tool: Cambridge/Aachen (de-)clustering

Cambridge/Aachen: iteratively recombine the closest pair



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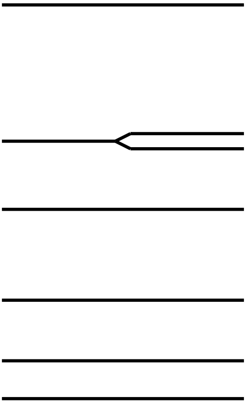

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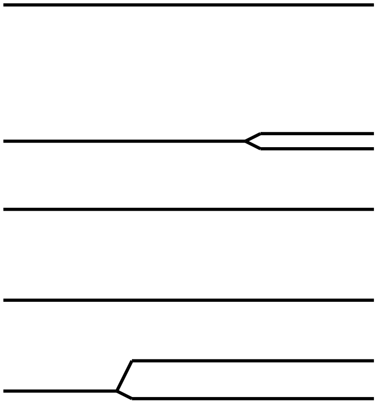

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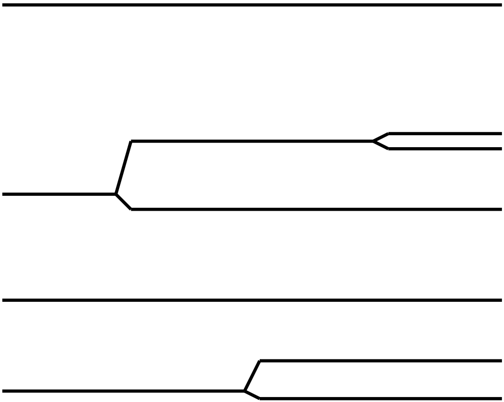

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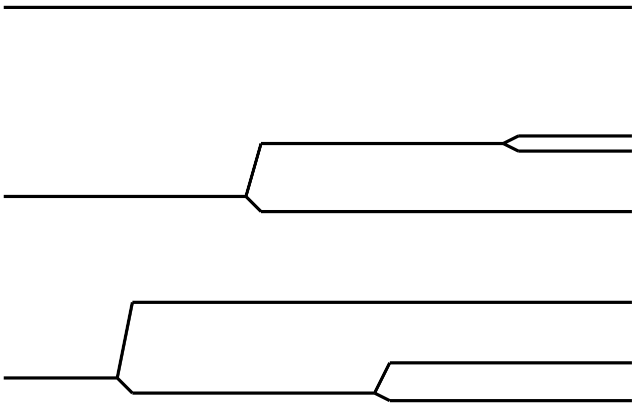

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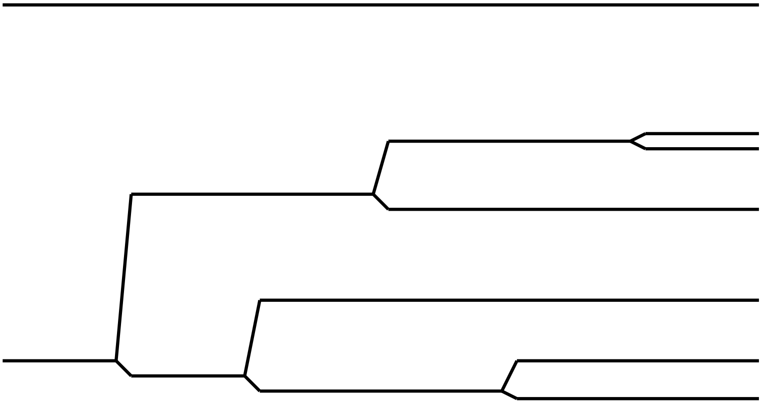

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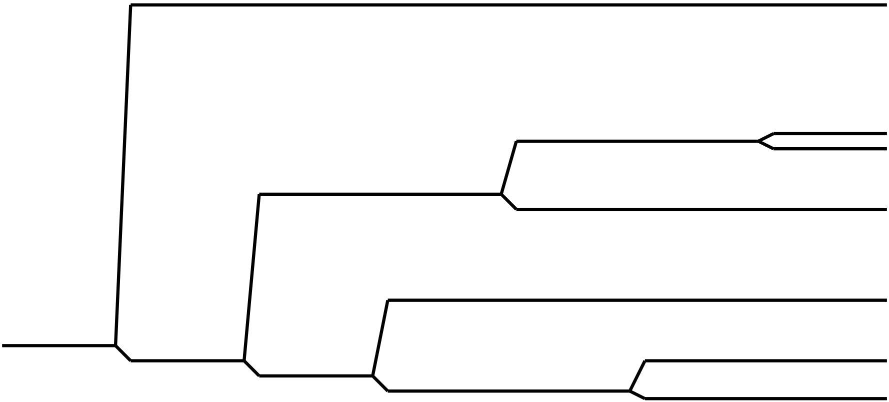

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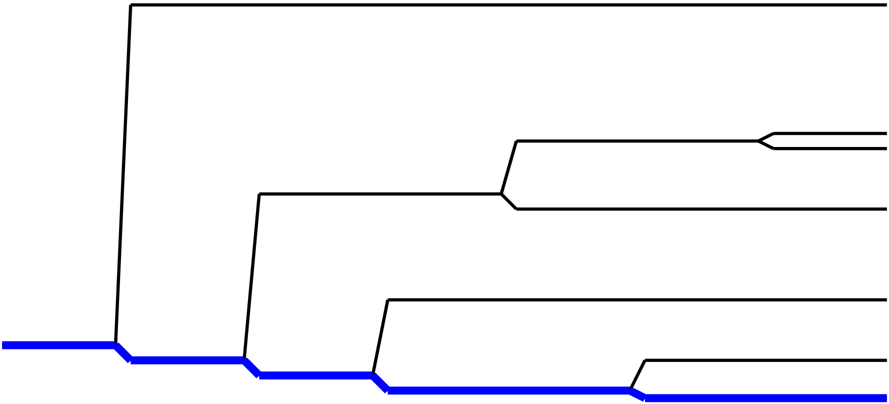
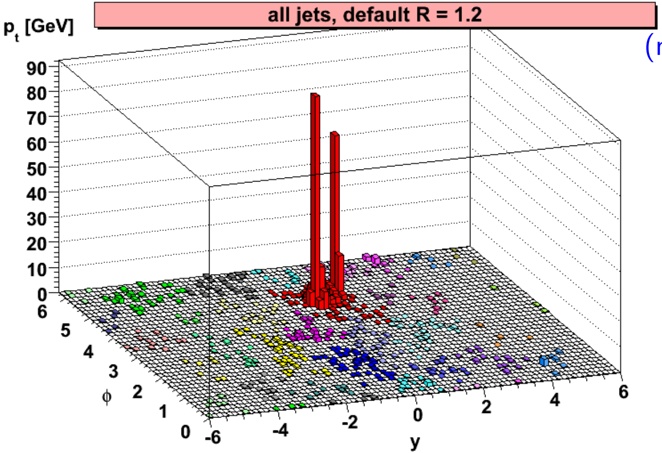


Usage: iteratively undo the clustering to study internal jet dynamics

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

Example: mMDT/SoftDrop prong finder

[J.Butterworth,A.Davison,M.Rubin,G.Salam,08]



(modified)MassDrop

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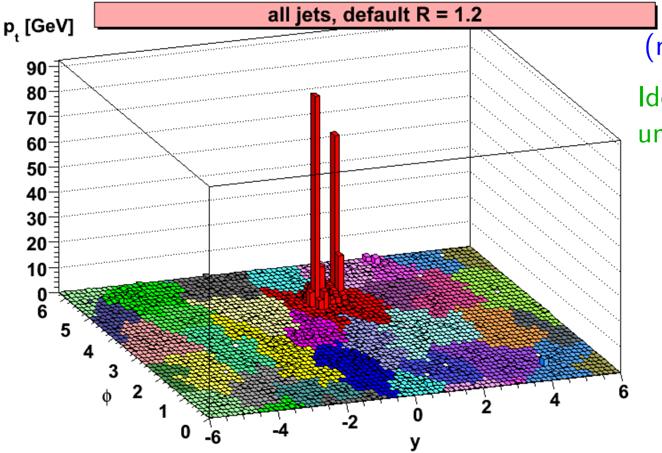

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Idea: undo clustering until $z > z_{\rm cut} \approx 0.1$

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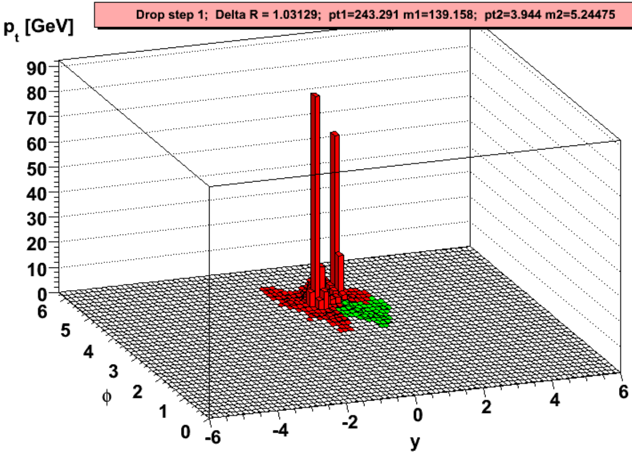

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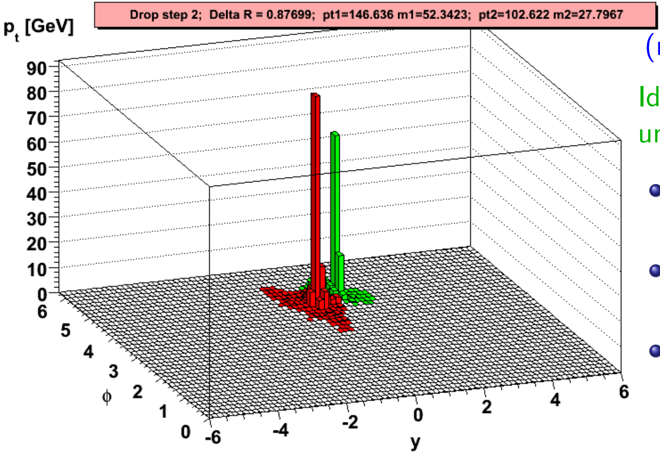

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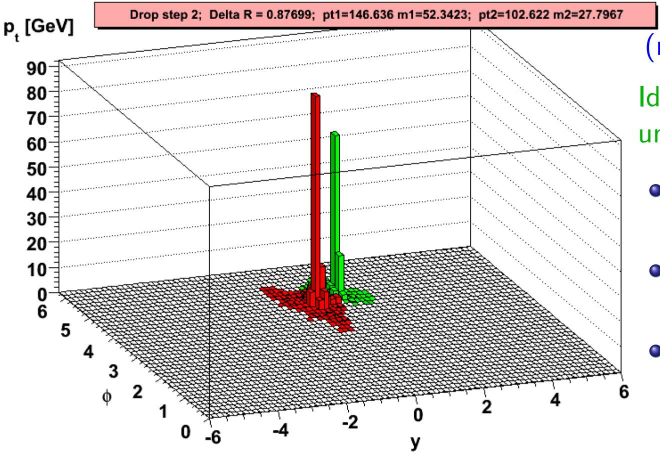

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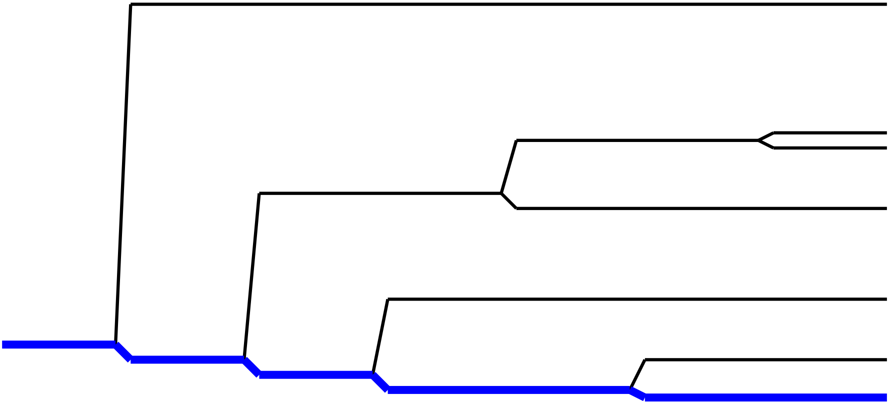
Variant: **SoftDrop**: impose $z > z_{\text{cut}}\theta^{\beta}$ [A.Larkoski,S.Marzani,GS,J.Thaler,14]

Visualising the sustructure with the Lund plane

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



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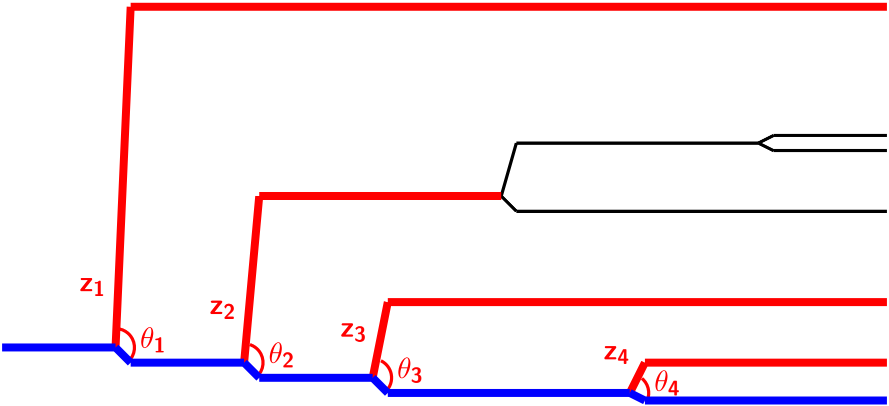

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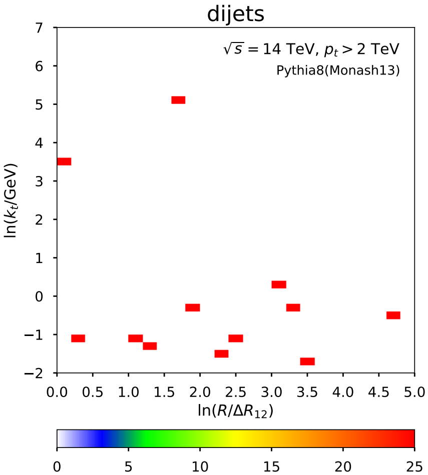
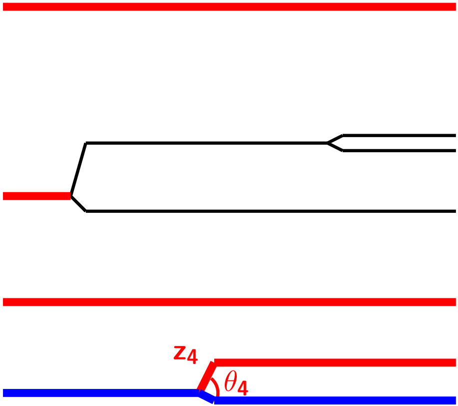
One jet



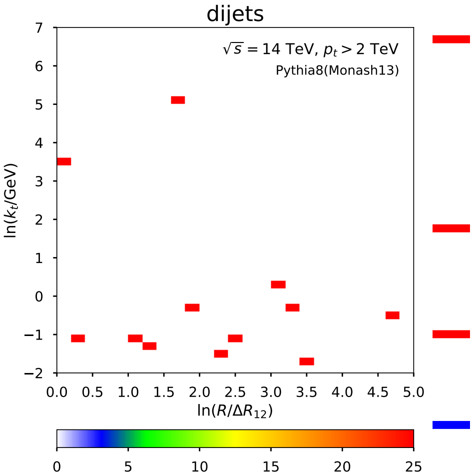


Consider all the emissions from the hardest branch

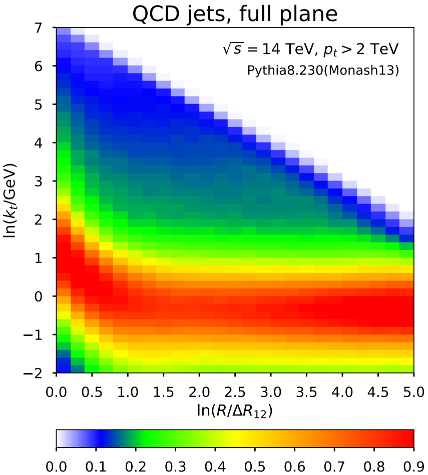
Put them in the Lund plane

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

One jet



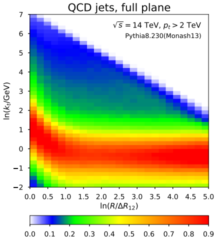
Average over jets

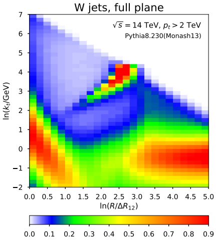


Consider all the emissions from the hardest branch

Put them in the Lund plane

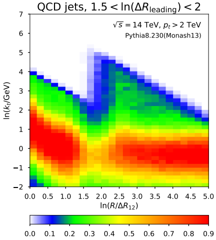
Lund plane and W tagging

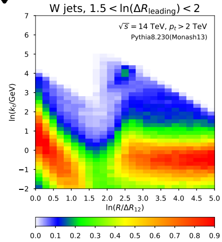




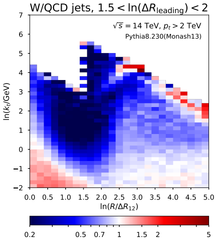
- In practice: split into a "leading" emission and Lund plane for all the others
- Use ratio to build a log-likelihood discriminant

Lund plane after leading removal





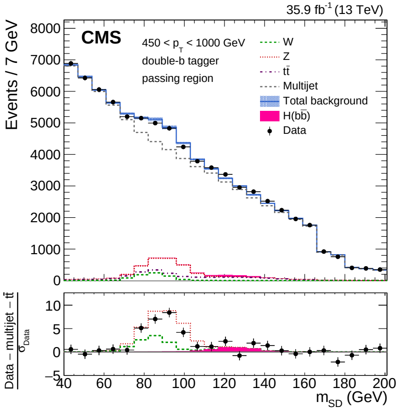
ratio

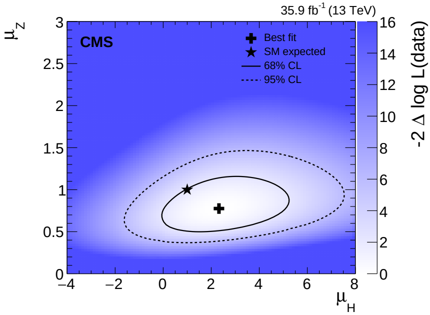


Jet substructure:

Measurements and searches

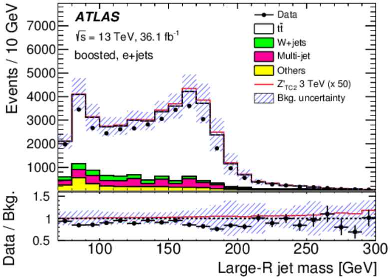
Jet mass after boosted 2-prong tagging: prong finder (mMDT/SD)
+ radiation constraint ($N_2^{(1,DDT)}$)
+ double b tagging

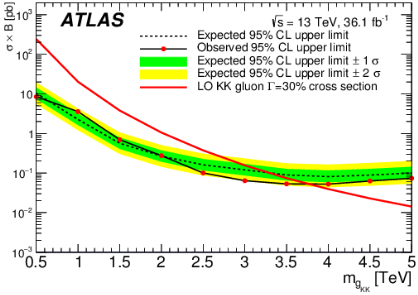




[CMS, 1709.05543]

Boosted top identified via: prong finder (trimming)
+ radiation constraint (τ_{32})





[ATLAS, 1804.10823]

Take home message

- One probes physics at increasingly larger scales
- New physics scales are pushed towards larger scales
- Collision energies could increase

Jet substructure will be increasingly relied upon

Jet substructure:

Analytic understanding in QCD

Analytic understanding of substructure

Idea: boosted $\equiv m \ll p_t \;\Rightarrow\;$ expect $\log p_t/m \;\Rightarrow\;$ resummation

Analytic understanding of substructure

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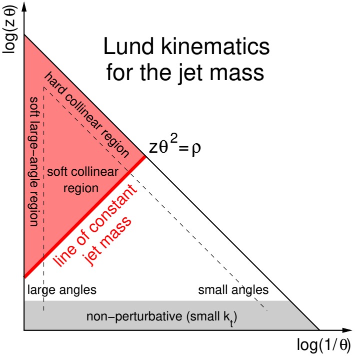
Jet mass: we have

- one emission with $z\theta^2 = \frac{m^2}{p_t^2 R^2}$
  $\longrightarrow$ factor
- no emission at larger $z\theta^2$
  $\longrightarrow$ factor $\exp(-\;)$

Giving $\bar\alpha_s = \frac{\alpha_s C_R}{\pi}$

$$\frac{m}{\sigma}\frac{d\sigma}{dm} = \bar\alpha_s \log\frac{p_t R}{m} \exp\left[-2\bar\alpha_s \log^2\frac{p_t R}{m}\right]$$



Analytic understanding of substructure

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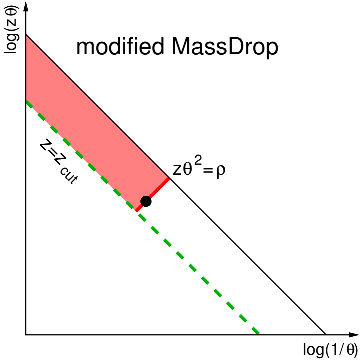
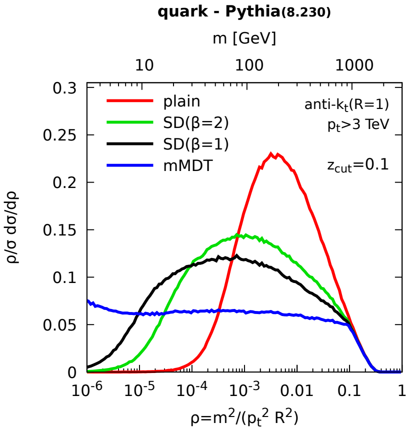
mMDT jet mass: same but $z > z_{\rm cut}$

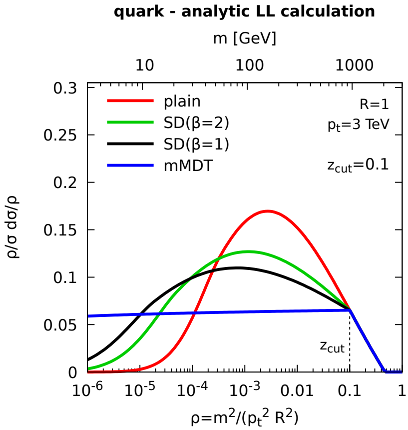
$$\frac{m}{\sigma}\frac{d\sigma}{dm} = \frac{\bar{\alpha}_s}{2} \log\frac{1}{z_{\rm cut}} \exp\left[\bar{\alpha}_s \log\frac{1}{z_{\rm cut}} \log\frac{p_t R}{m}\right]$$



[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

Analytic v. Monte Carlo





The big picture

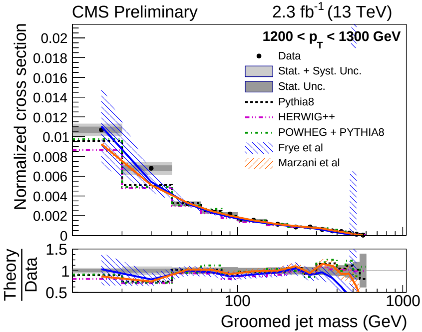
- Now a wide range of tools are "calculable"
  Almost all 2-prong finders, a series of jet shapes, basic 3-prong finders
- brings a better understanding of the details at play
  source of performance, undesirable features, transition points,...
- has allowed for the development of improved tools
  e.g. mMDT, D_2, generalised ECFs, dichroic ratios
- Approached from "standard QCD" or SCET
- has allowed for the development of improved resummation techniques

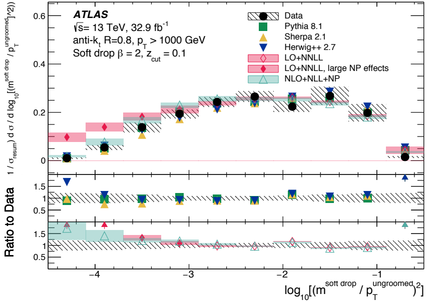
Jet substructure:

Precision measurements

mMDT/SD jet mass

- LHC Measurements (CMS-PAS-SMP-16-010, ATLAS CERN-EP-2017-231)
- NNLL+LO in SCET (Frye,Larkoski,Schwartz,Yan; assumes small z_{cut})
- NLL+NLO in "standard QCD" (Marzani,Schunk,GS; includes (LL) finite z_{cut})

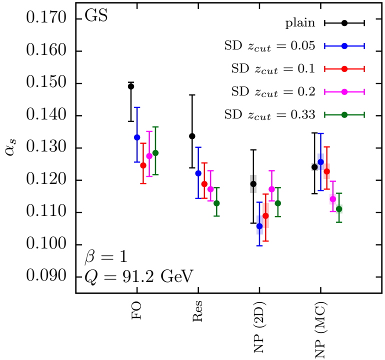


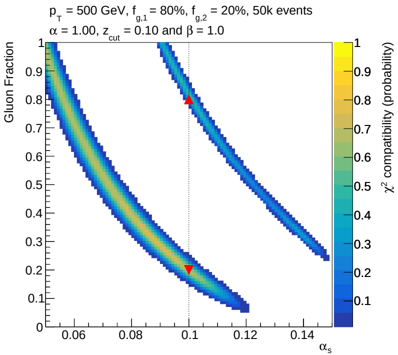


good overall agreement with the data, small non-perturbative effects

Towards measuring α_s

Precise+small NP effects suggests we use it for precision measurements





Already a possible gain at LEP

[S.Marzani,D.Reichelt,S.Schumann,GS, V.Theeuwes, in prep]

Large potential at the LHC

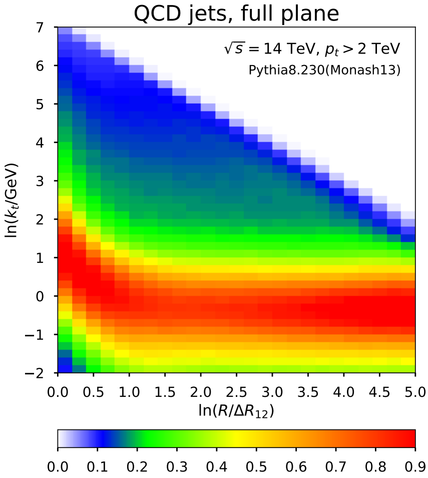
Still key pieces missiing

[Study at Les-Houches 2017]

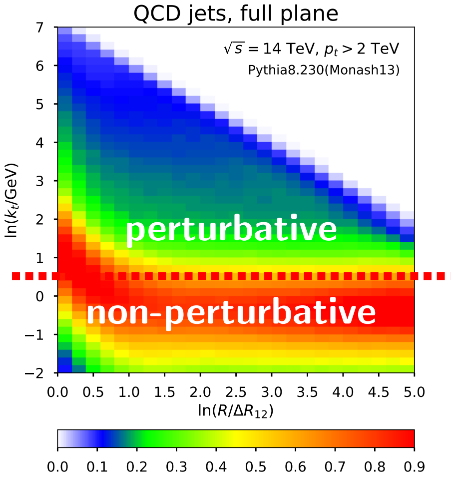
Jet substructure:

Shower constraints

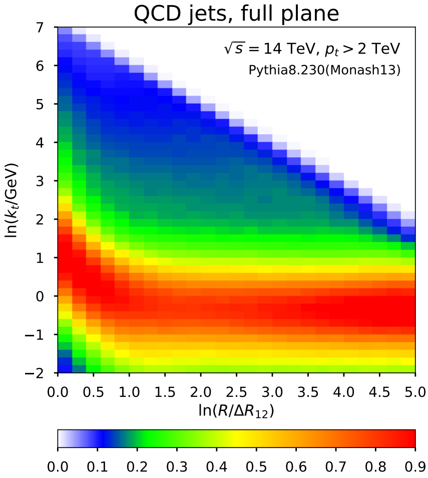
Lund plane and Monte-Carlo generators



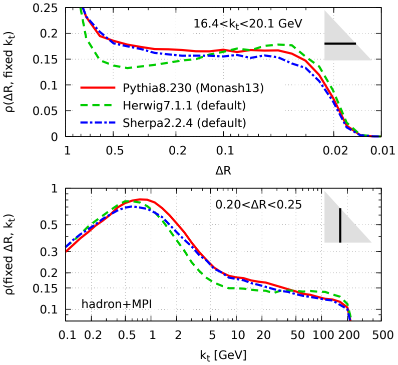
Lund plane and Monte-Carlo generators



Lund plane and Monte-Carlo generators



Slices through the 2D plane



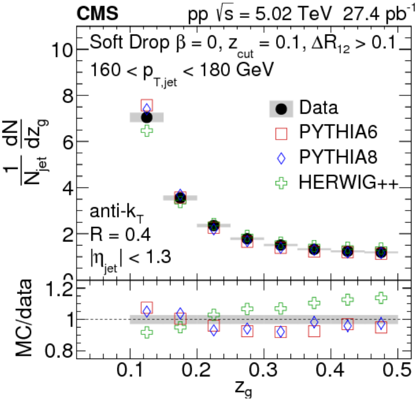
- Flat at small angles (until ISR)
- $\alpha_s(k_t)$ then non-pert bump
- Differences between MCs
- calls for measurement

Jet substructure:

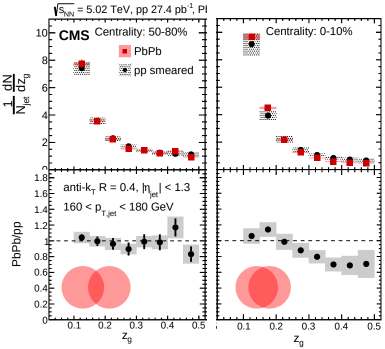
Usage in heavy-ion collisions

The mMDT/SD grooming momentum fraction z_g

Example: $z_g \equiv$ the z fraction that passes the mMDT/SD condition



[CMS,1708.09429]

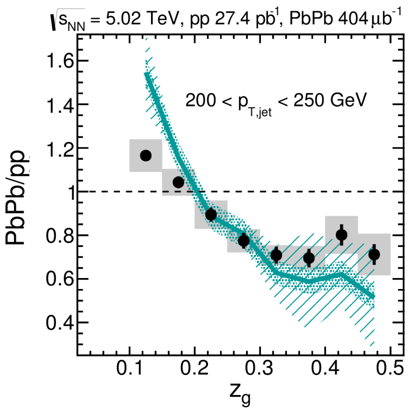


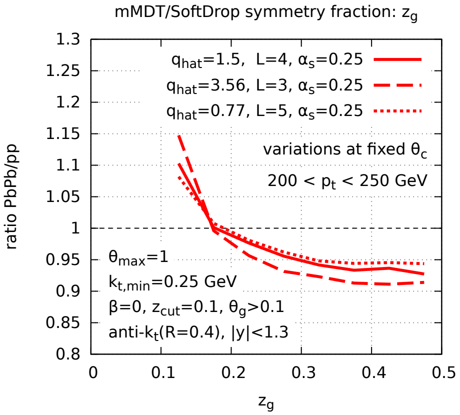
- $\approx$ access to the splitting functions
- Very interesting analytic structure

- Measured in *pp* and *PbPb*
- First use of CMS Open Data

[Larkokski,Marzani,Thaler,Tripathee,Xue,17]

Modifications due to interactions with the quark-gluon plasma





Work in progress to calculate this in QCD

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

Jet substructure:

Machine Learning

THE new trend

Huge effort in using deep learning in the context of jet substructure

Applied to many systems

- Boosted topologies: $W/Z/H$ bosons, top quarks, ...
- b tagging, quark/gluon separation
- pileup mitigation
- fast detector simulation

Several approaches

- Inputs: jet variables, images of jets, jet constituents,
  subjets/clustering trees
- Architectures: CNN, DNN, ANN, LSTM

Lund plane as an example

Example using our "Lund plane" approach:

- "Lund image" fed to a Dense Neural Netword
- "Lund coordinates" fed to a Long Short Term Memeory network

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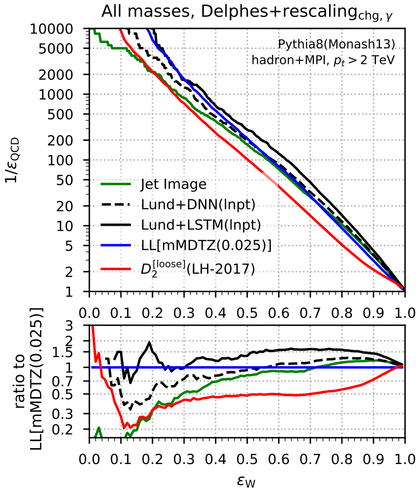

- great performance
- LSTM does even better than Log-Likelihood
- Note: input motivated by QCD
  See also: energy-flow polynomials

[Lund: F.Dreyer,G.Salam,GS,18]
[Jet Image: J.Cogan, M.Kagan, E.Strauss, A.Schwartzman, 14; L.de Oliveira, M.Kagan, L.Mackey, B.Nachman and A.Schwartzman, 15]

Take-home messages

Take-home messages

Jet substructure has gained a lot of importance in the past decade

- Important tool for LHC physics (searches and measurements)
- exciting pQCD phenomenology
  - understanding and development of tools
  - precision pheno at the LHC
  - interesting QCD structure emerging (not covered here)
- Expansion towards new horizons:
  - heavy-ion hard probes
  - machine learning
- Recent work: Lund planes are useful in many aspects