A brief look inside jet substructure

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Getting to grips with QCD, April 4-6 2018

Jets are routine QCD objects

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

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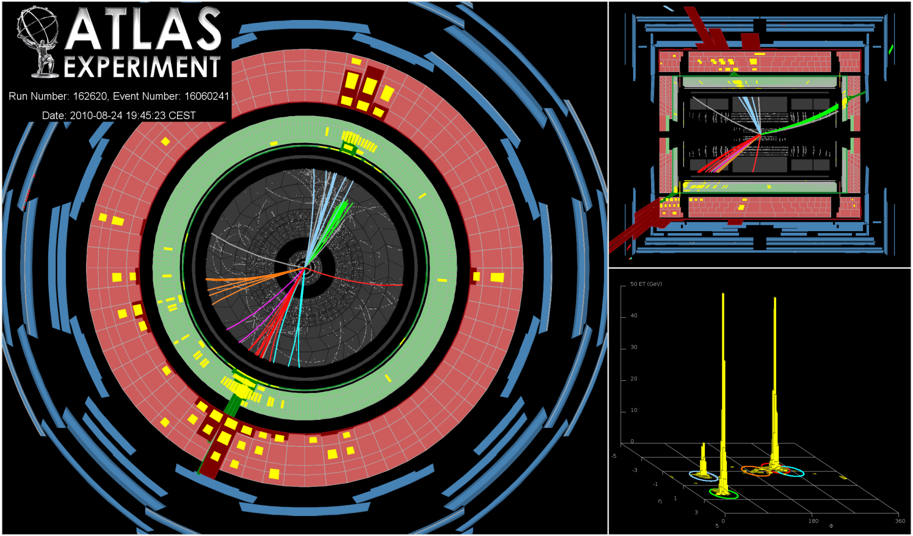
You could live a happy life by just knowing a few things

Concepts:

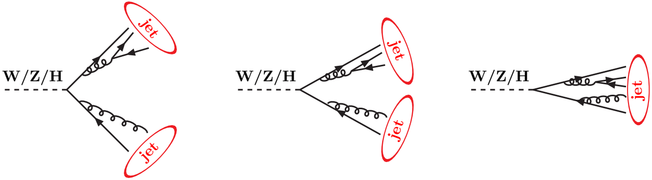
- Jets are proxies to hard partons produced in collisions
- infrared-and-collinear safe
- capture collimated parton cascades from hard scale Q to $\mathcal{O}(1\text{ GeV})$

Practically:

- obtained by running a clustering algorithm
- the LHC uses the anti-k_t algorithm
- FastJet covers covers all your numerical needs for clustering


ATLAS
EXPERIMENT
Run Number: 162620, Event Number: 16060241
Date: 2010-08-24 19:45:23 CEST
50 ET (GeV)
40
30
20
10
0
-5
-3
-1
η
1
3
5
0
180
360
Φ

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



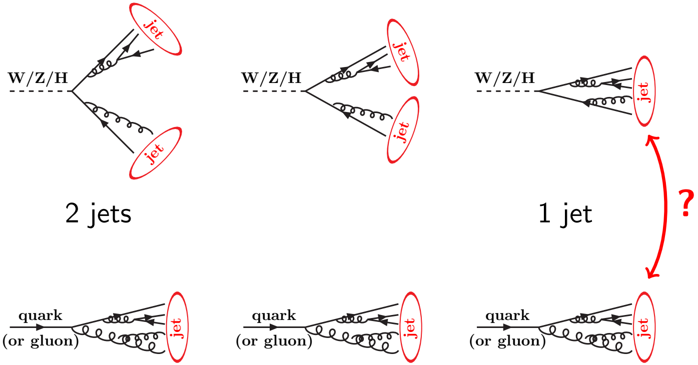
2 jets $\qquad\qquad$ 1 jet

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

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

Boosted objects

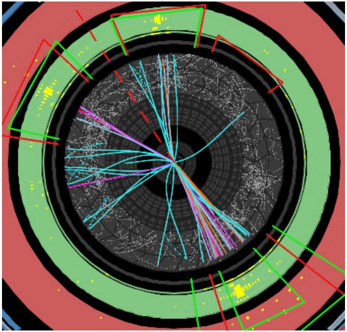
$p_t \lesssim m$ $\qquad\qquad$ $p_t \gg m$



use substructure to separate from QCD jets

Other examples

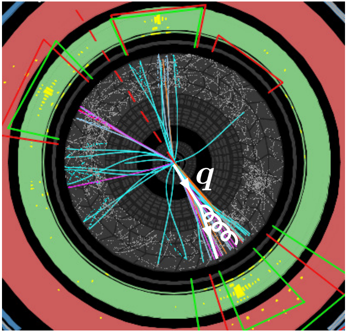
What jet do we have here?



Other examples

What jet do we have here?

- a quark?



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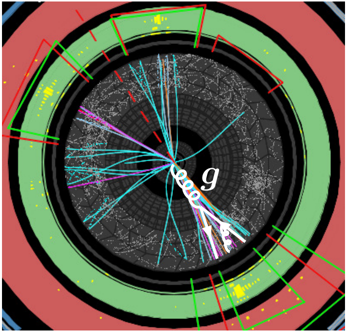

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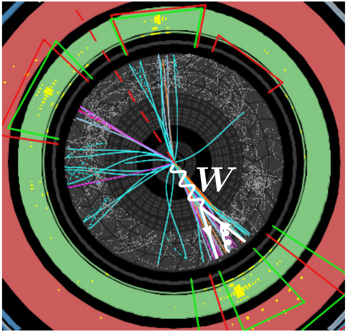
- a quark?
- a gluon?
- a W/Z (or a Higgs)?



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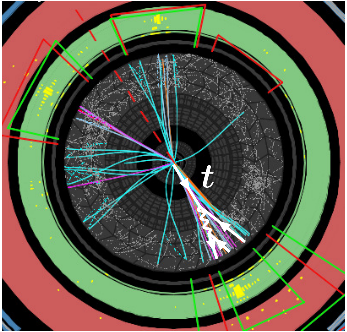

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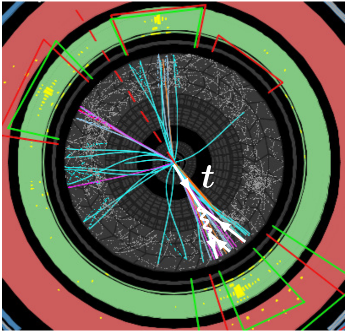
Source: ATLAS boosted top candidate



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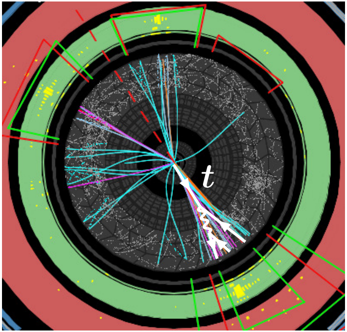

Substructure means looking at the internal dynamics of jets
(as opposed to consider jets as monolithic objects)

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- Basic tools are organised around $2_{(3)}$ major concepts:
  - "peak/prong finders":
    - $W/Z/H/t$ decay into hard partons $\Rightarrow$ jets with multiple hard cores
    - QCD (q/g) jets dominated by soft radiation $\Rightarrow$ 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
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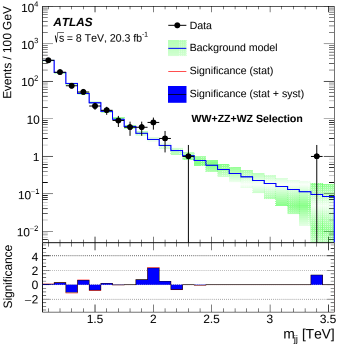
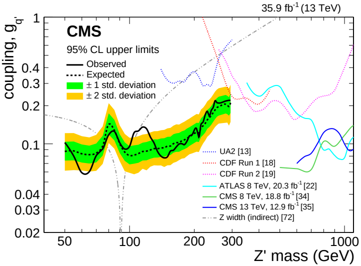
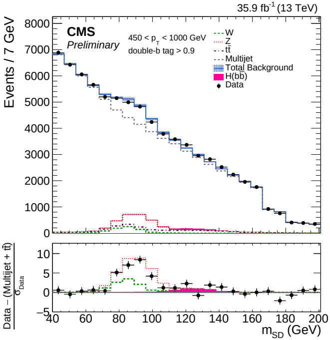
  - (also grooming to remove soft contamination from fat jets)
- Increasing range of applications
  - Searches and measurements at the LHC
  - Precision QCD calculations
  - Measurements in heavy-ion collisions
  - Machine Learning

Searches and measurements







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

↗ Search for $X \to q\bar{q}$
Region inaccessible otherwise

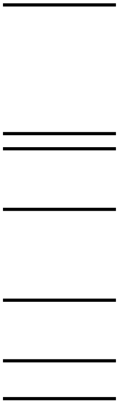
→ Clear Z peak, hint of a H peak

Plan for the talk

Give an overview of these aspects

Articulated around a work in progress
with Frederic Dreyer and Gavin Salam

Cambridge/Aachen: iteratively recombine the closest pair



Pre-requisite number 1: Cambridge/Aachen (de-)clustering

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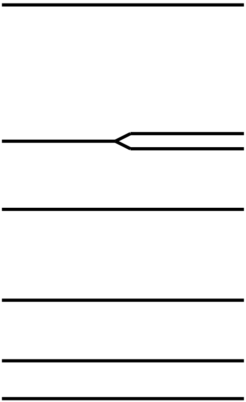

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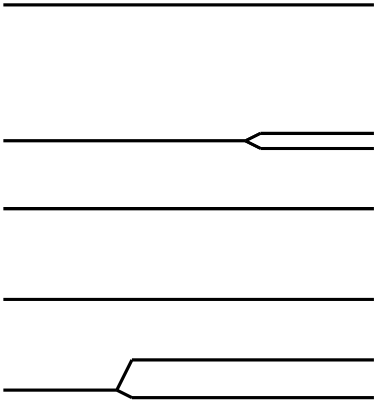

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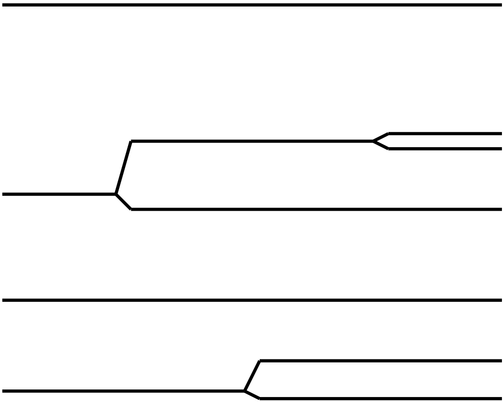

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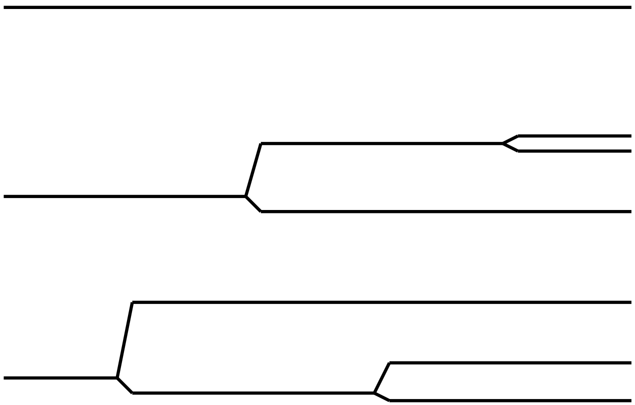

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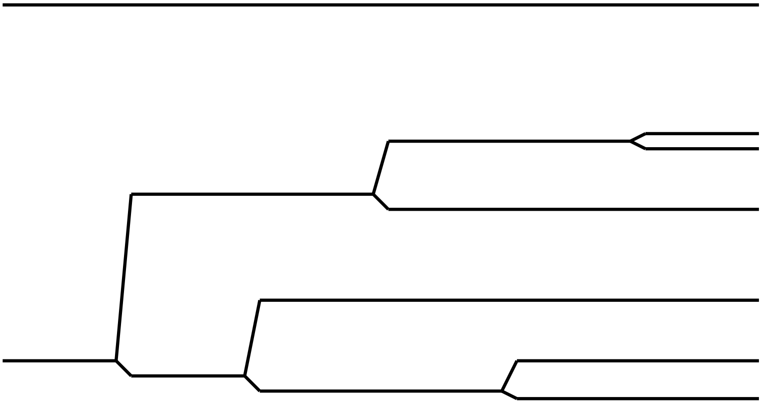

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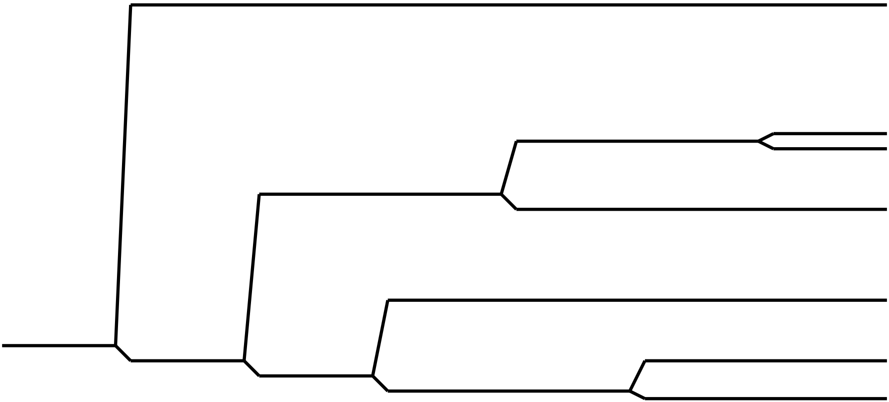

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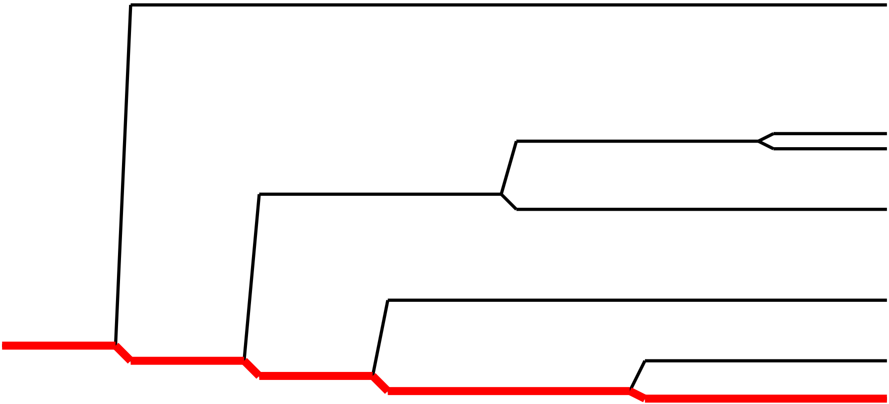
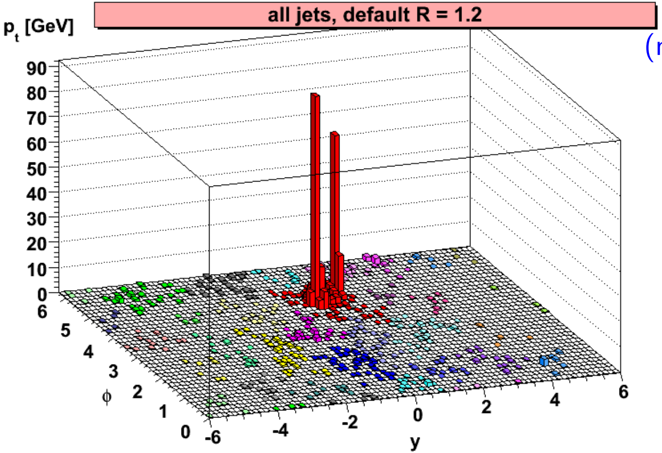


Usage: iteratively undo the clustering to study internal jet dynamics
Typically: follow the hardest branch (largest p_t or z)

Example: mMDT/SD prong finder

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



(modified)MassDrop

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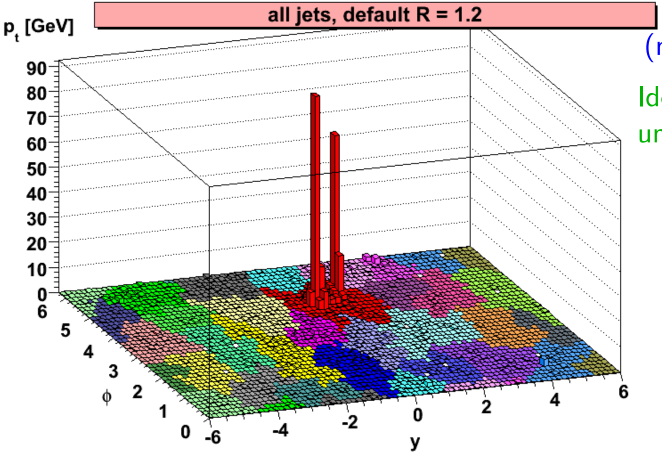

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Idea: undo clustering until $z > z_{\text{cut}} \approx 0.1$

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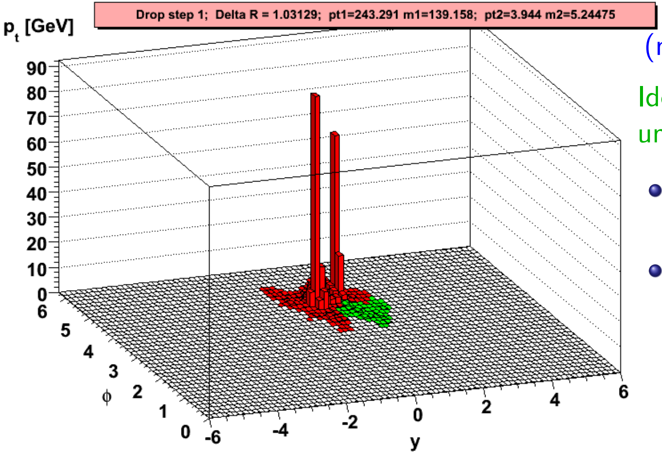

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Idea: undo clustering until $z > z_{\rm cut} \approx 0.1$

- undo the last clustering step
- $z = 0.016 < 0.1$ carry on

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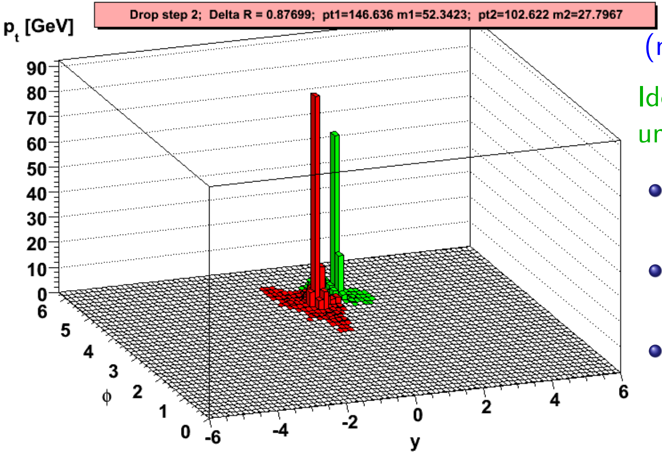

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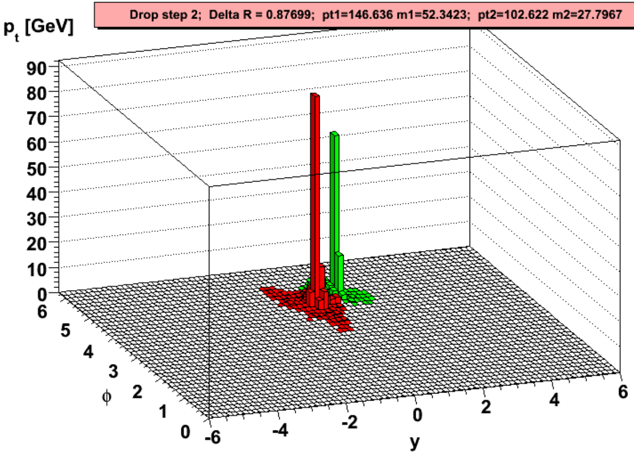

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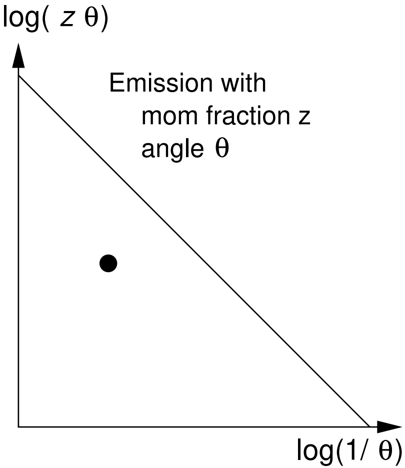
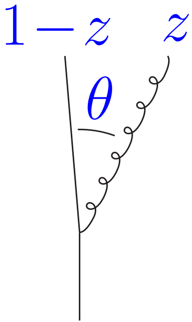
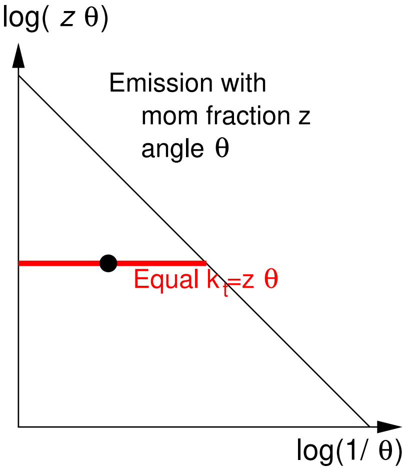
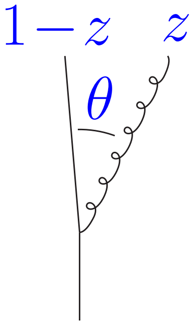
Variant: **SoftDrop**: impose $z > z_{\text{cut}}\theta^{\beta}$ [A.Larkoski,S.Marzani,GS,J.Thaler,14]


log(z θ)
Emission with
mom fraction z
angle θ
log(1/ θ)


1−z
z
θ

Pre-requisite number 2: Lund planes





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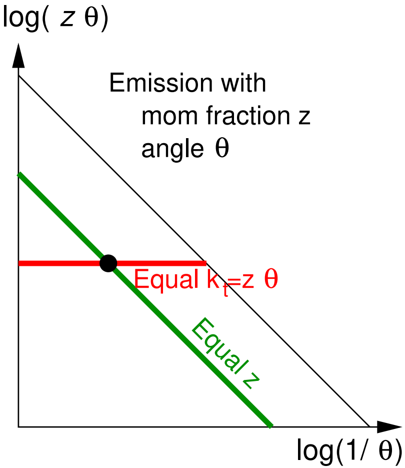

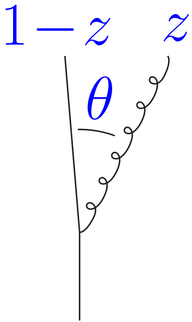

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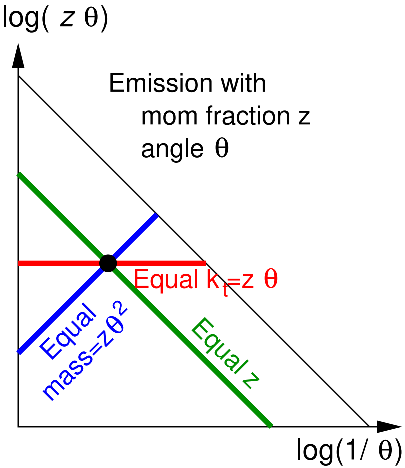

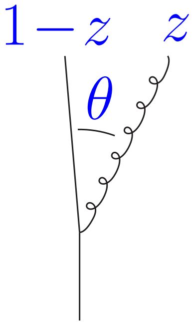

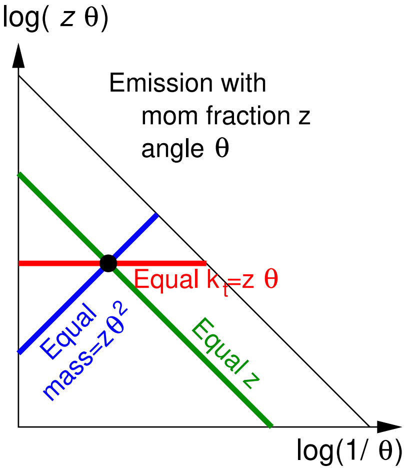

Observables in the boosted limit

Jet "mass": $(z_1\theta_1^2 \gg z_2\theta_2^2 \gg \ldots)$

$$\rho \equiv \frac{m^2}{p_t^2 R^2} = \sum_{i\in\text{jet}} z_i\theta_i^2 \approx z_1\theta_1^2$$

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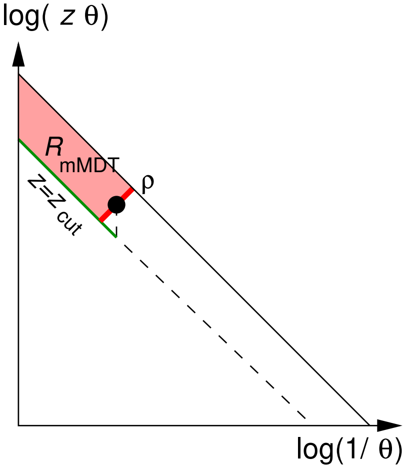

(mMDT) jet mass spectrum at LL

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} = R'_{\text{mMDT}} \exp(-R_{\text{mMDT}})$$

1. emission of given mass

$$R'_{\text{mMDT}} \sim \frac{\alpha_s C_R}{\pi} \log(1/z_{\text{cut}})$$

2. veto on larger-mass (Sudakov)

$$R_{\text{mMDT}} \sim \frac{\alpha_s C_R}{\pi} \log(1/\rho) \log(1/z_{\text{cut}})$$

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

Precision physics at the LHC

- LHC Measurements (CMS-PAS-SMP-16-010, ATLAS CERN-EP-2017-231)
- NNLL+LO in SCET (Frye,Larkoski,Schwartz,Yan; assumes small z_{cut})
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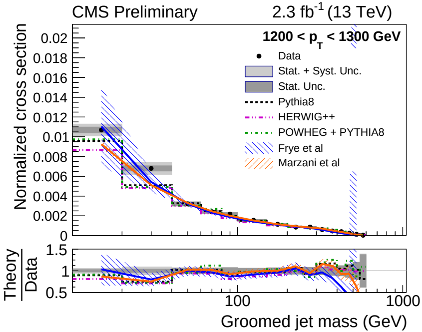

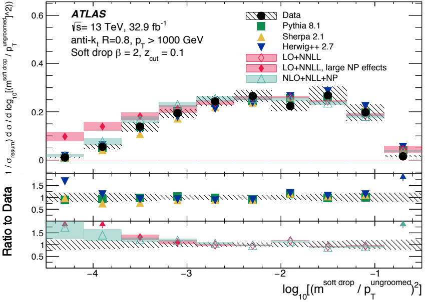

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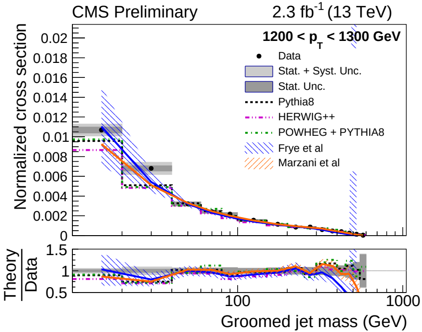

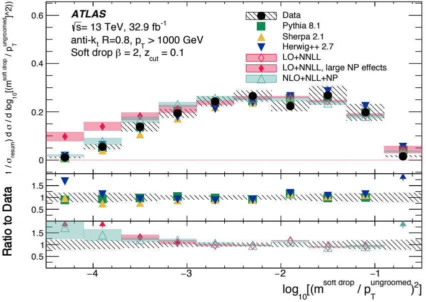

good overall agreement with the data

Precise observable with limited sensitivity to NP effects

$\Rightarrow$ **possibility to extract** α_s (on-going study)

Opening many options

Based on

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2. Lund-plane variables

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We can

- learn about jet dynamics
- constrain Monte-Carlo generators (separately for pQCD and non-pQCD)
- perform analytic studies
- learn about the quark-gluon plasma
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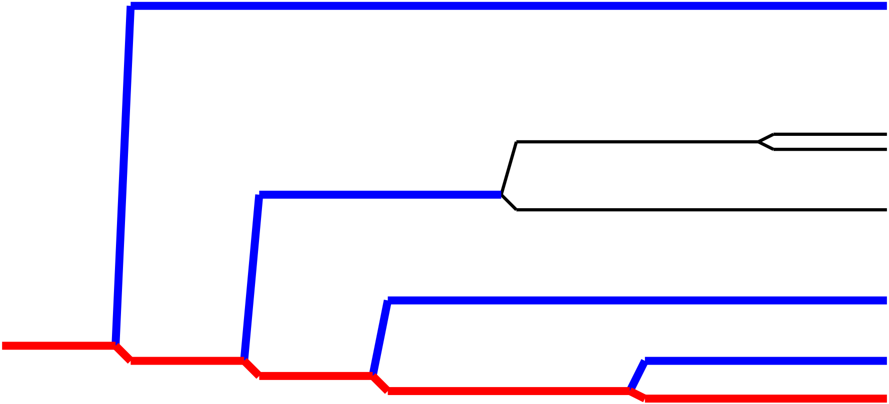
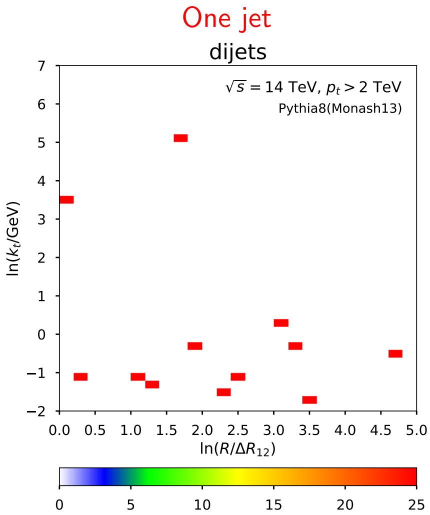
I will illustrate this in the next slides

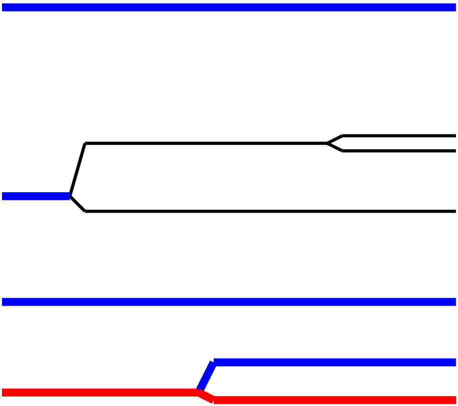
Lund plane density



Consider all the emissions from the hardest branch

Lund plane density





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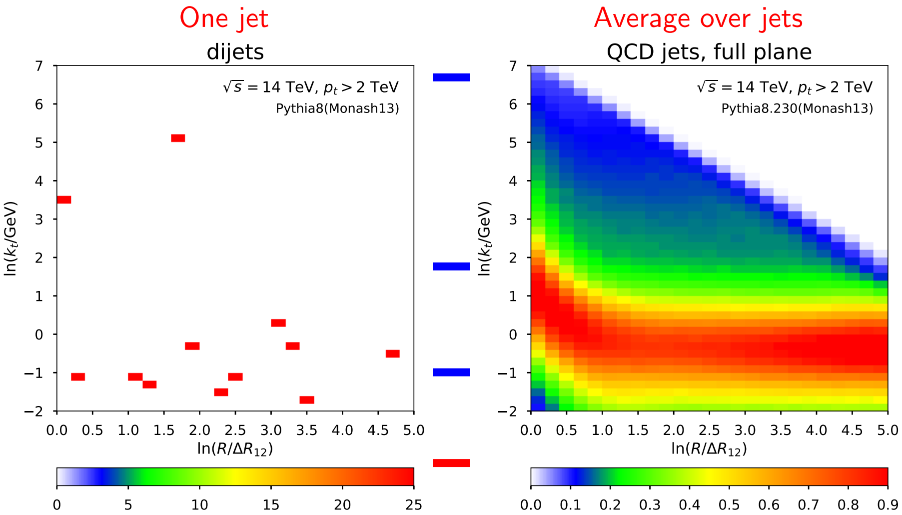

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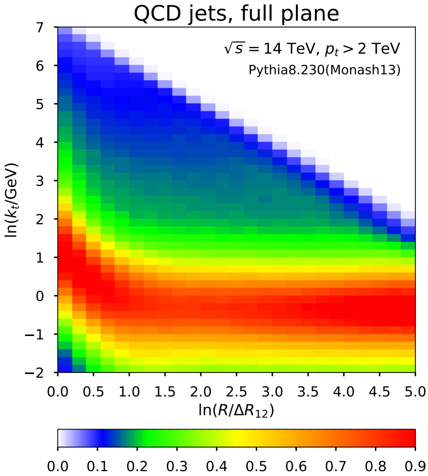
Lund plane and Monte-Carlo generators



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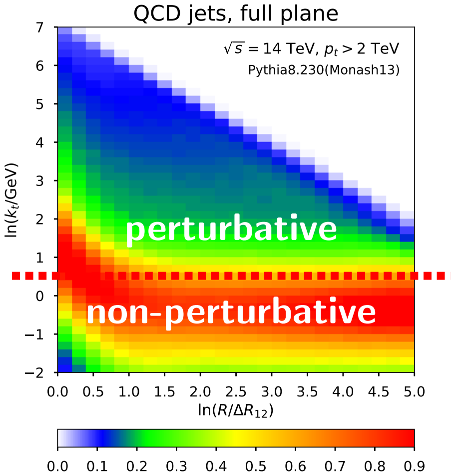

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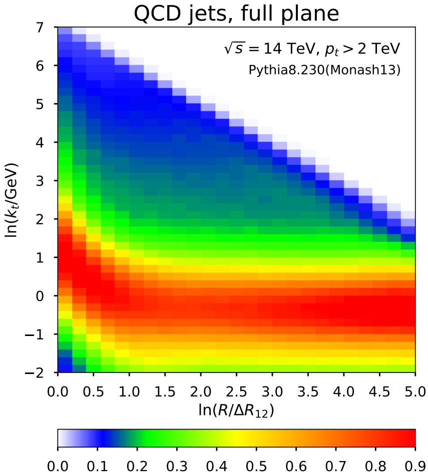
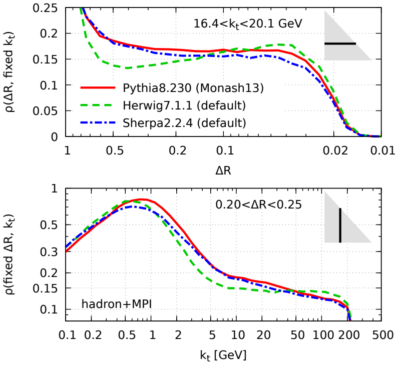


Slices through the 2D plane

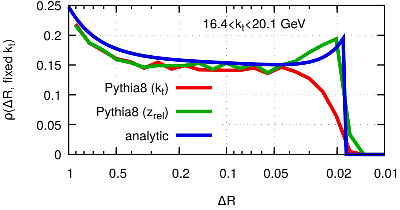


- Flat at small angles (until ISR)
- $\alpha_s(k_t)$ then non-pert bump
- Differences between MCs
- calls for measurement

Lund plane and QCD analytic calculations

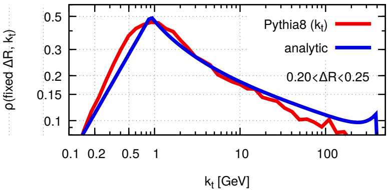
Roughly:

$$\rho(\Delta R, k_t) = \frac{\alpha_s(k_t) C_R}{\pi} z p(z)$$



Additional effects:

- ISR (included here)
- clustering effects
- flavour changes
- energy conservation
- ...

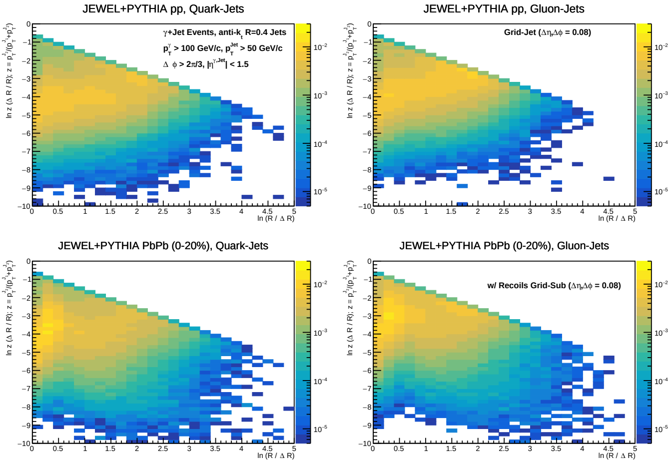


Can be systematically calculated and improved

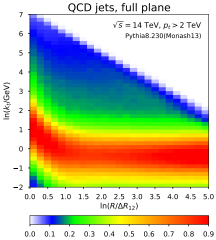
Lund plane and Heavy-ion collisions

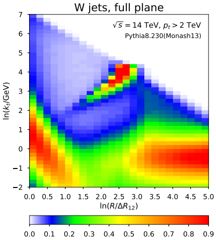
[Y-T. Chien, R. K. Elayavalli]

Quark v. gluon jets in Heavy-ion collisions



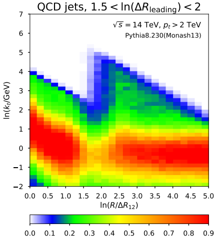
Lund plane and W tagging

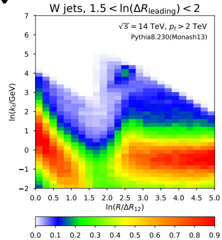




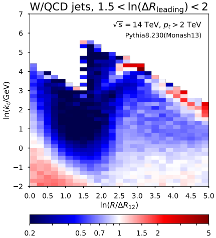
- In practice: split into a “leading” emission and Lund plane for all the others
- Use ratio to build a log-likelihood discriminant

Lund plane
after leading removal

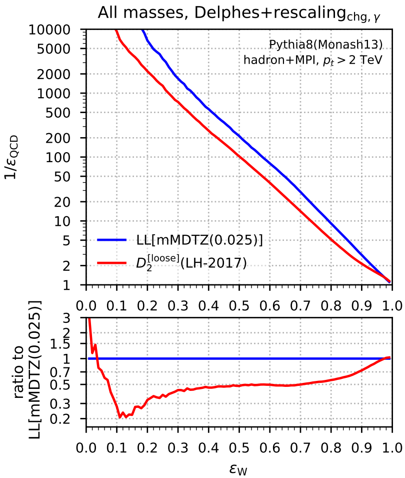




ratio



Lund plane and W tagging



better than "standard" approach
(2-prong tagger + cut on shape)

[D_2^{loose} from Les-Houches PhysTeV 2017]

Lund plane and Machine learning

Previous approach can be used as input to Machine Learning:

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

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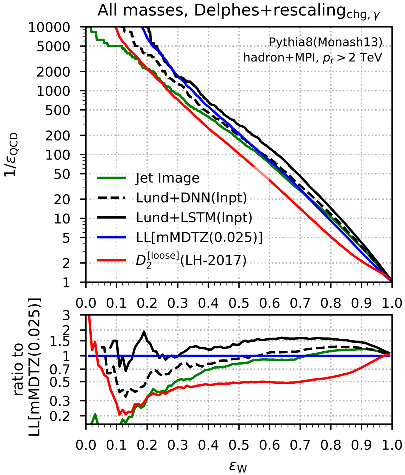

- better than previous ML approaches
- LSTM does even better than Log-Likelihood
- TODO: Log-Likelihood from analytics

[Jet Image: J.Cogan, M.Kagan, E.Strauss, A.Schwartzman, 14; L.de Oliveira, M.Kagan, L.Mackey, B.Nachman and A.Schwartzman, 15]

Conclusions

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

BOOST Annual meeting
around 100 theorists and experimentalists discussing
discussing latest progress in substructure

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July 16-20: BOOST 2018 in Paris
https://indico.cern.ch/e/boost2018