Theoretical aspects of jet substructure

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Karlsruhe, July 6th 2017

Based mainly on work with Gavin Salam, Simone Marzani, Alessandro Fregoso, Andrzej Siodmok, Gregory Soyez, Lais Schunk and Alexander Powling

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Outline

- Introduction to boosted particle searches and jet substructure
- Theoretical issues in substructure studies
- Jet substructure from theory first principles
- Some recent progress and developments
- Conclusions

Boosted object hadronic decays

Boosted regime implies studying particles with $p_T >> M_X$. Important at the LHC with access to TeV scales in p_T.

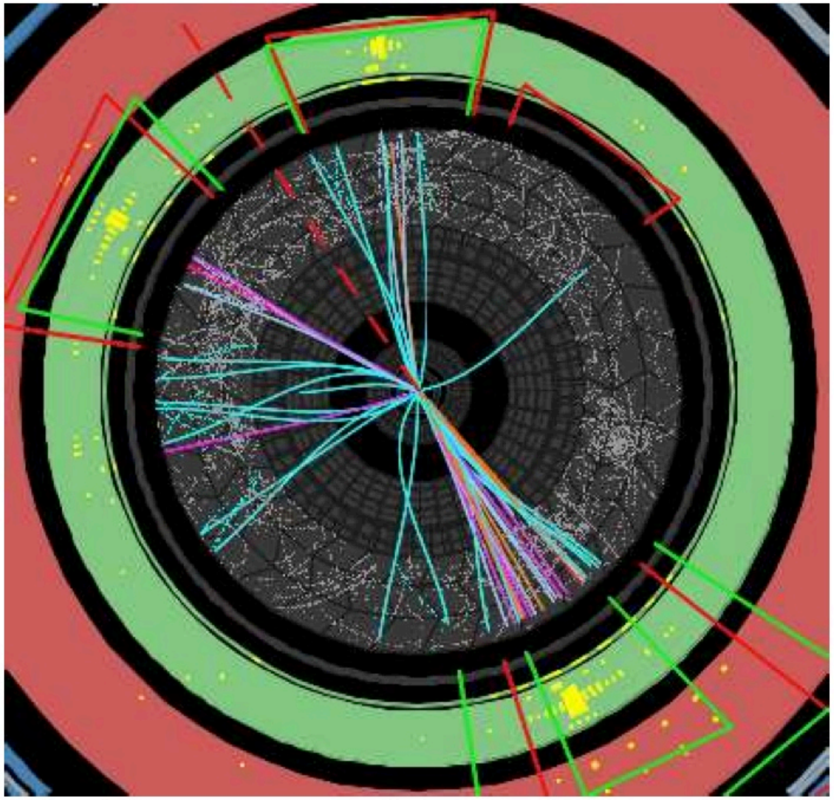
Decay products are collimated.

$$\theta^2 = \frac{M^2}{p_T^2 z(1-z)}$$

Hadronic two-body decays often reconstructed in single jet.

Jets from QCD vs boosted heavy particles

What jet do we have here?



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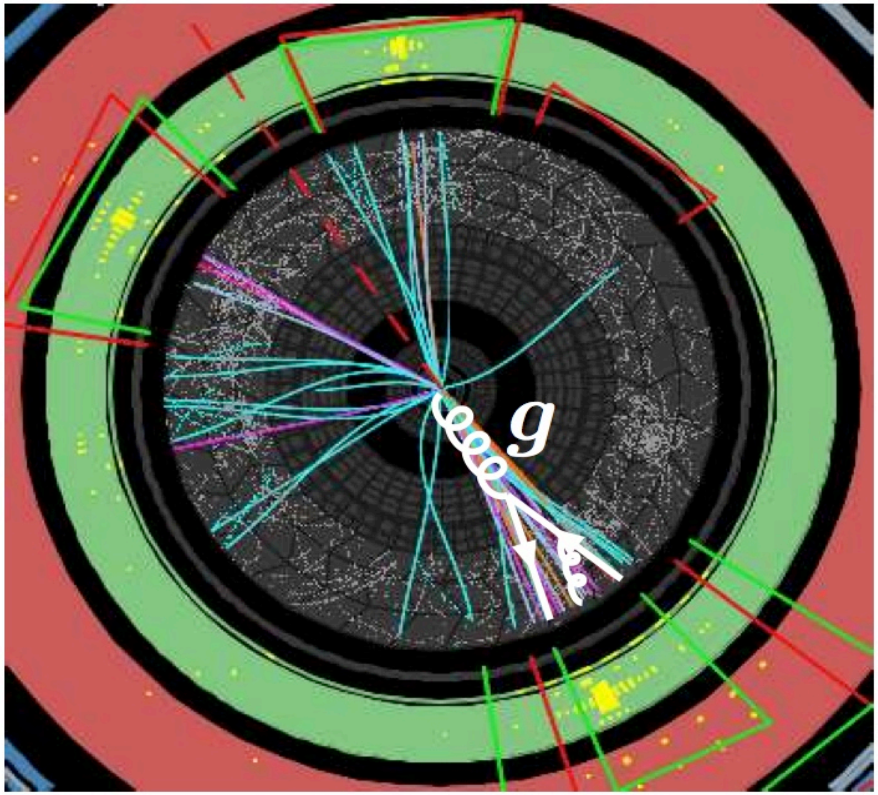
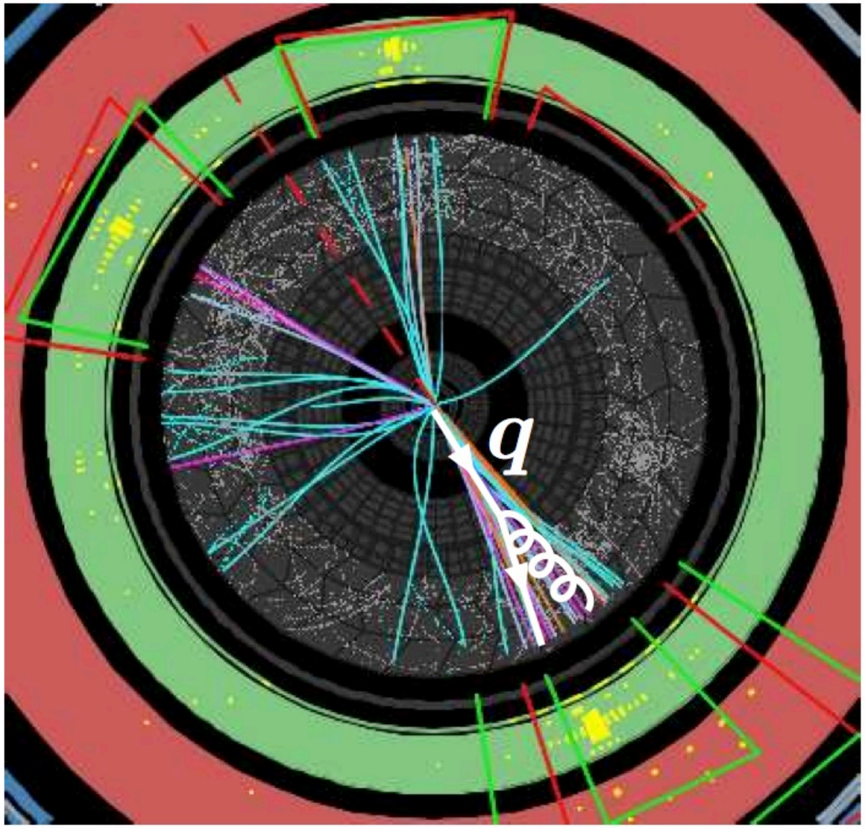
Jets from QCD vs boosted heavy particles

A gluon jet ?



Jets from QCD vs boosted heavy particles

A quark jet ?



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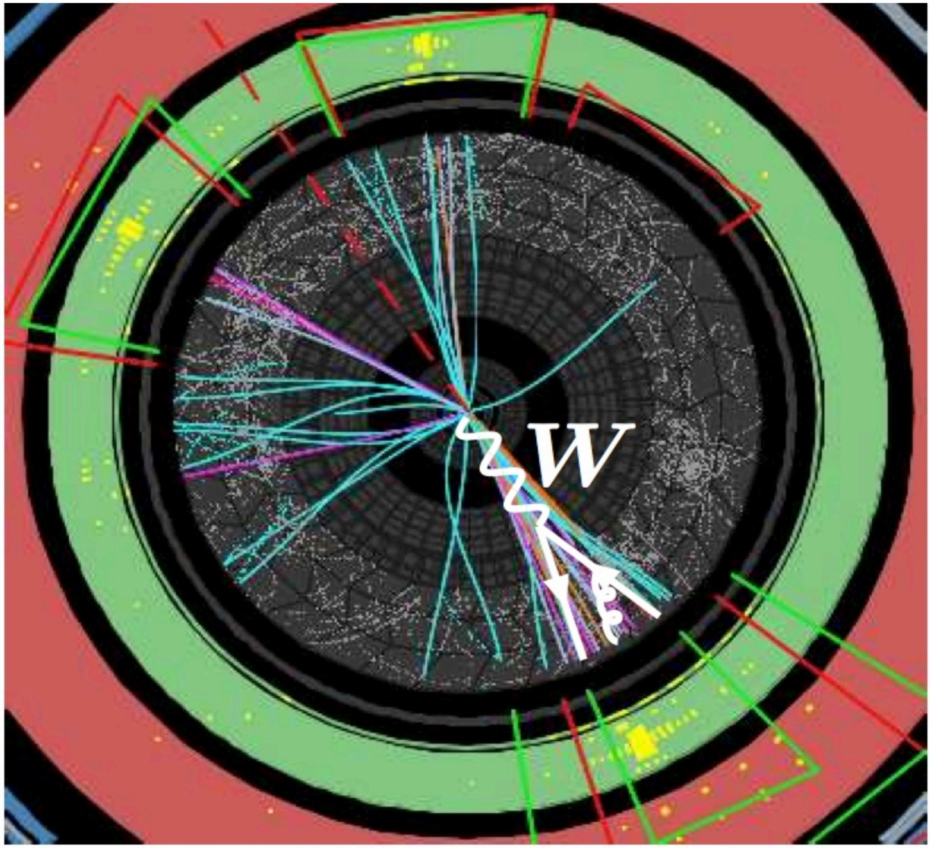
Jets from QCD vs boosted heavy particles

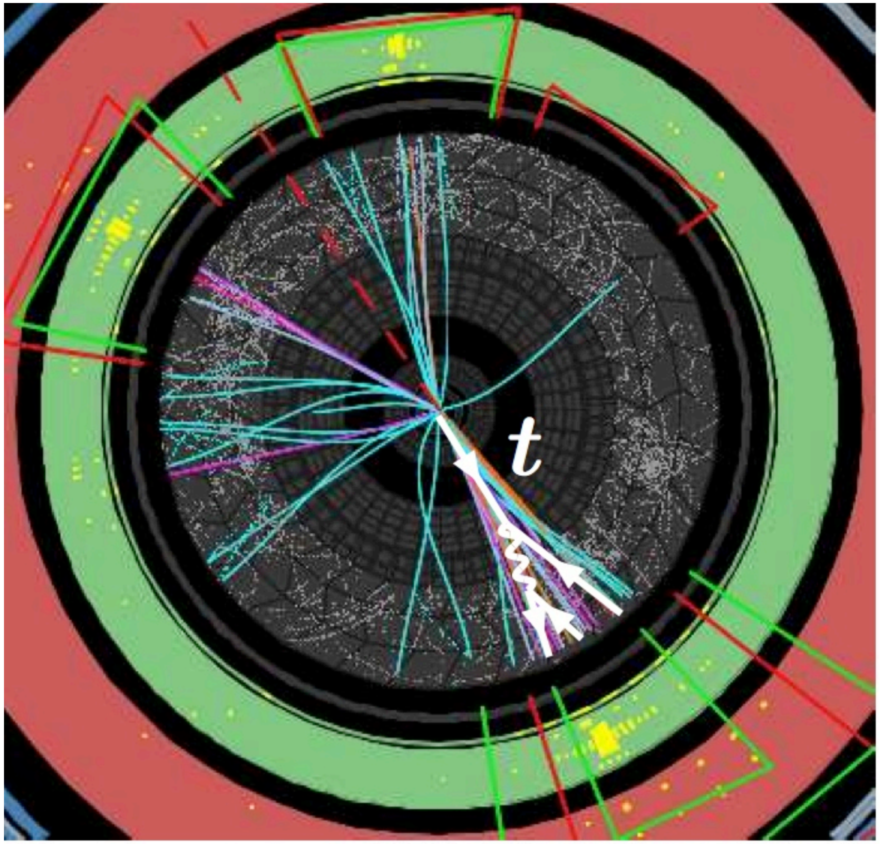
A W/Z/H ?



Jets from QCD vs boosted heavy particles

A top quark?

Source: An ATLAS boosted top candidate



The boosted regime implies a change in paradigm in that jets can be more than quarks and gluons.

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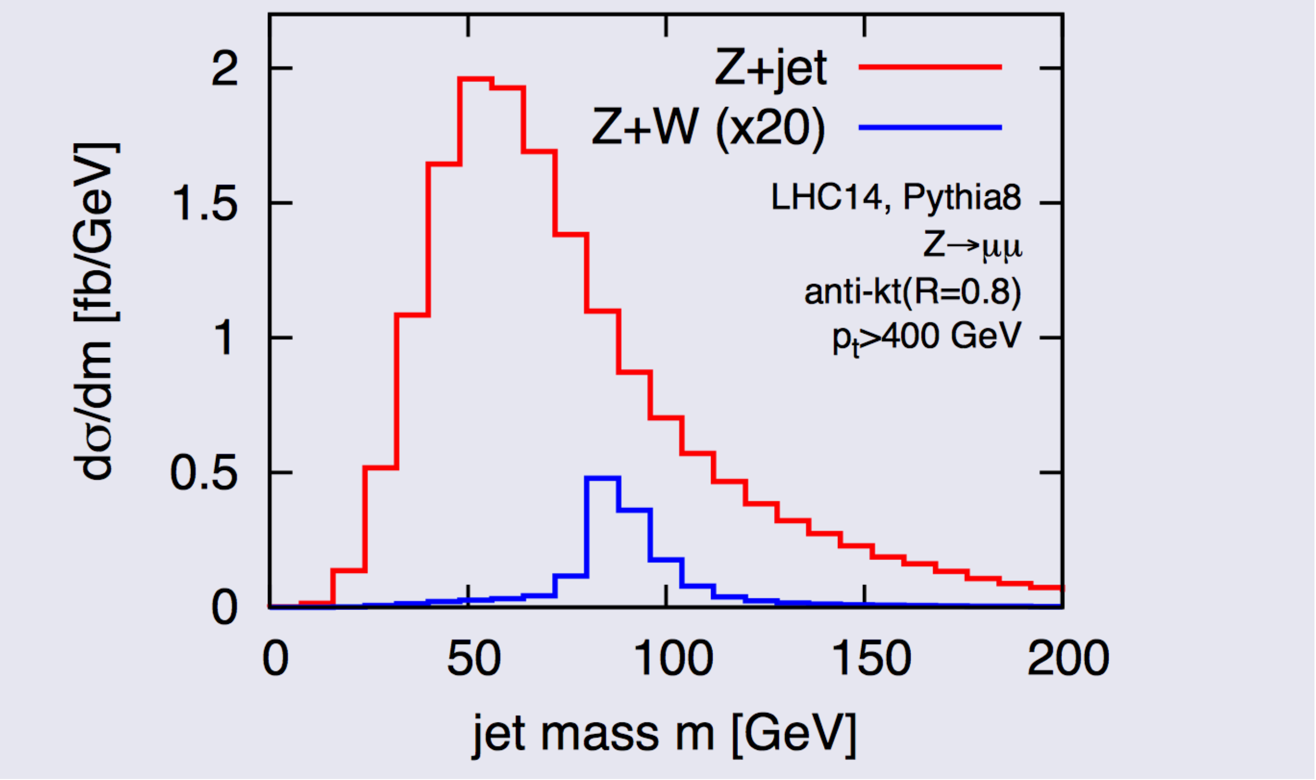
Isn't the jet mass a clue?



Looking at jet mass is not enough!

Jet substructure for LHC searches

Jet substructure as a new Higgs search channel at the LHC

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It is widely considered that, for Higgs boson searches at the Large Hadron Collider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

A key aim of the Large Hadron Collider (LHC) at CERN is to discover the Higgs boson, the particle at the heart of the standard-model (SM) electroweak symmetry breaking mechanism. Current electroweak fits, together with the LEP exclusion limit, favour a light Higgs boson, i.e. one around 120 GeV in mass [1]. This mass region is particularly challenging for the LHC experiments, and any SM Higgs-boson discovery is expected to rely on a combination of several search channels, including gluon fusion $\to H \to \gamma\gamma$, vector boson fusion, and associated production with $t\bar{t}$ pairs [2, 3].

Two significant channels that have generally been considered less promising are those of Higgs-boson production in association with a vector boson, $pp \to WH, ZH$, followed by the dominant light Higgs boson decay, to two b-tagged jets. If there were a way to recover the WH and ZH channels it could have a significant impact on Higgs boson searches at the LHC. Furthermore these two channels also provide unique information on the couplings of a light Higgs boson separately to W and Z bosons.

Reconstructing W or Z associated $H \to b\bar{b}$ production would typically involve identifying a leptonically decaying vector boson, plus two jets tagged as containing b-mesons. Two major difficulties arise in a normal search scenario. The first is related to detector acceptance: leptons and b-jets can be effectively tagged only if they are reasonably central and of sufficiently high transverse momentum. The relatively low mass of the VH (i.e. WH or ZH) system means that in practice it can be produced at rapidities somewhat beyond the acceptance, and it is also not unusual for one or more of the decay products to have too small a transverse momentum. The second issue is the presence of large backgrounds with intrin-responds to only a small fraction of the total VH cross section (about 5% for $p_T > 200$ GeV), but it has several compensating advantages: (i) in terms of acceptance, the larger mass of the VH system causes it to be central, and the transversely boosted kinematics of the V and H ensures that their decay products will have sufficiently large transverse momenta to be tagged; (ii) in terms of backgrounds, it is impossible for example for an event with on-shell top-quarks to produce a high-p_T $b\bar{b}$ system *and* a compensating leptonically decaying W, without there also being significant additional jet activity; (iii) the HZ with $Z \to \nu\bar{\nu}$ channel becomes visible because of the large missing transverse energy.

One of the keys to successfully exploiting the boosted VH channels will lie in the use of jet-finding geared to identifying the characteristic structure of a fast-moving Higgs boson that decays to b and $\bar{b}$ in a common neighbourhood in angle. We will therefore start by describing the method we adopt for this, which builds on previous work on heavy Higgs decays to boosted W's [4], WW scattering at high energies [5] and the analysis of SUSY decay chains [6]. We shall then proceed to discuss event generation, our precise cuts and finally show our results.

When a fast-moving Higgs boson decays, it produces a single fat jet containing two b quarks. A successful identification strategy should flexibly adapt to the fact that the $b\bar{b}$ angular separation will vary significantly with the Higgs p_T and decay orientation, roughly

$$R_{b\bar{b}} \simeq \frac{1}{\sqrt{z(1-z)}}\frac{m_H}{p_T}, \qquad (p_T \gg m_H), \qquad (1)$$

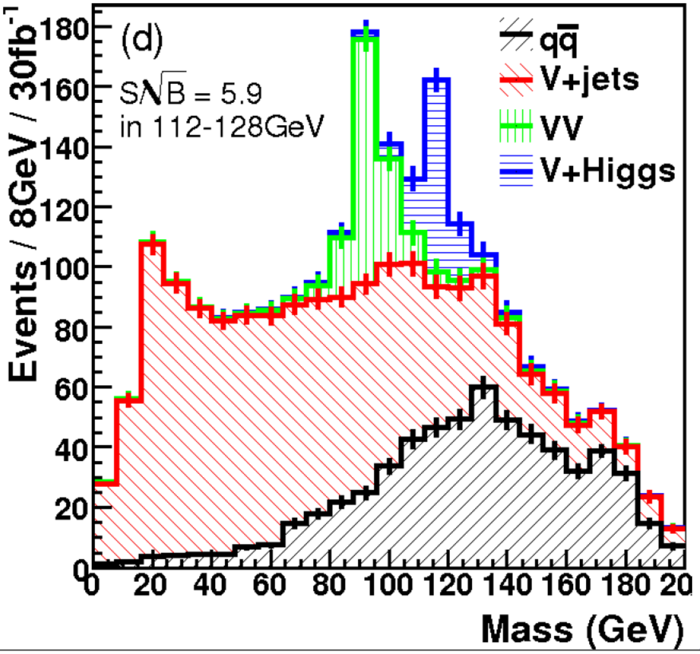
where z, $1-z$ are the momentum fractions of the two quarks. In particular one should capture the $b, \bar{b}$ and any

Since 2008 a vibrant research field emerged based on developing and exploiting jet substructure.

Butterworth, Davison Rubin, Salam 2008. Published in PRL. Builds on work by Seymour 1993.

BDRS paper has over 600 citations. “Jet substructure” title search on arXiv gives > 100 papers post BDRS.

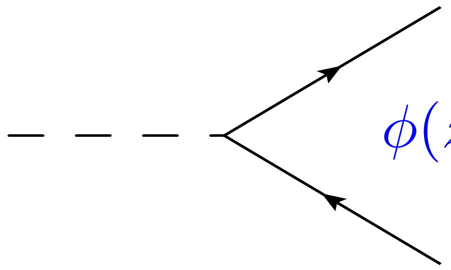
BDRS method results



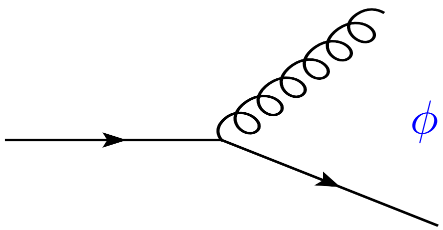
Mass drop method
+ filtering

Signal significance of 4.5σ was demonstrated in MC studies for a Higgs boson of 115 GeV. Turned this unpromising channel into one of the best discovery channels for light Higgs.

Simple physics ideas



$\phi(z) \propto 1$



$\phi(z) \propto \frac{1+z^2}{1-z}$

- Exploit the asymmetric nature of QCD splittings. Produce jets with single hard core or prong versus 2 pronged W/Z/H and 3 pronged t.

- Colour singlet nature of W/Z/H suppressing soft large angle radiation.

Taggers and groomers

Idea 1:
Find $N = 2, 3, \ldots$ hard cores

Works because different splitting

QCD jets: $P(z) \propto 1/z$

$\Rightarrow$ dominated by soft emissions

$\Rightarrow$ "single" hard core

Idea 2:
Constrain radiation patterns

Works because different colours

Radiation pattern is different for

- colourless $W \to q\bar{q}$
- coloured $g \to q\bar{q}$

- Substructure taggers use the above ideas to discriminate signal from background.
- At hadron colliders jet mass can be affected by "uncorrelated" radiation (ISR, UE) and pile up. Leads to loss of signal.

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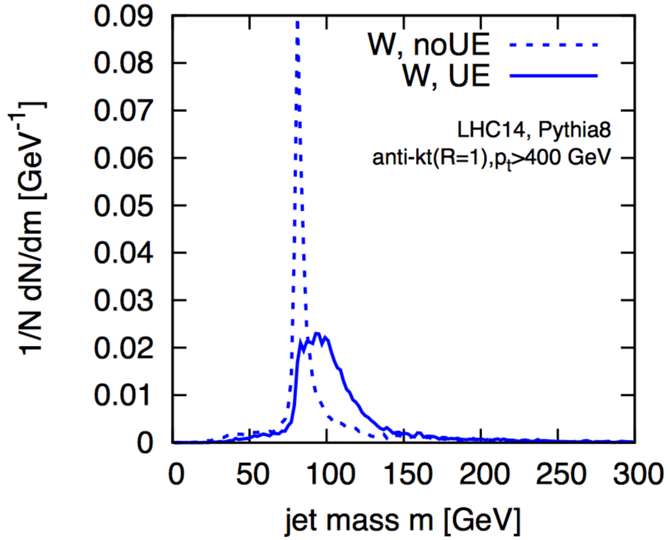
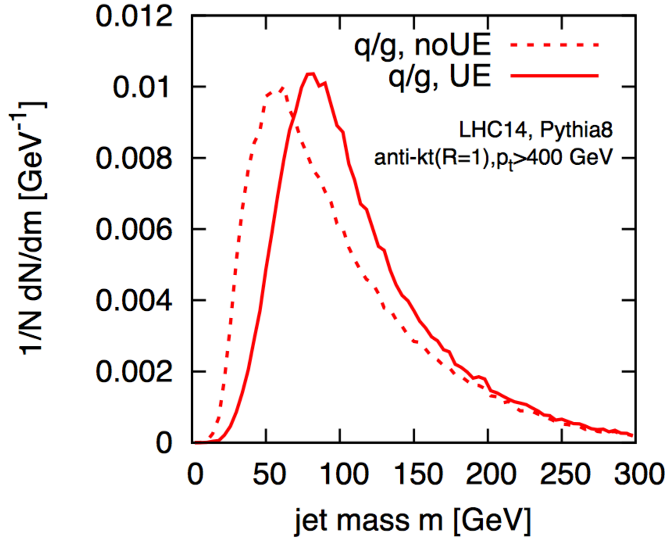
Need for grooming

Fat Jets

One usually work with large-R jets ($R \sim 0.8 - 1.5$)
$\Rightarrow$ large sensitivity to UE (and pileup)





Example of pure groomer is filtering used in BDRS method. Most tools including both tag and groom. We can collectively use the name taggers.

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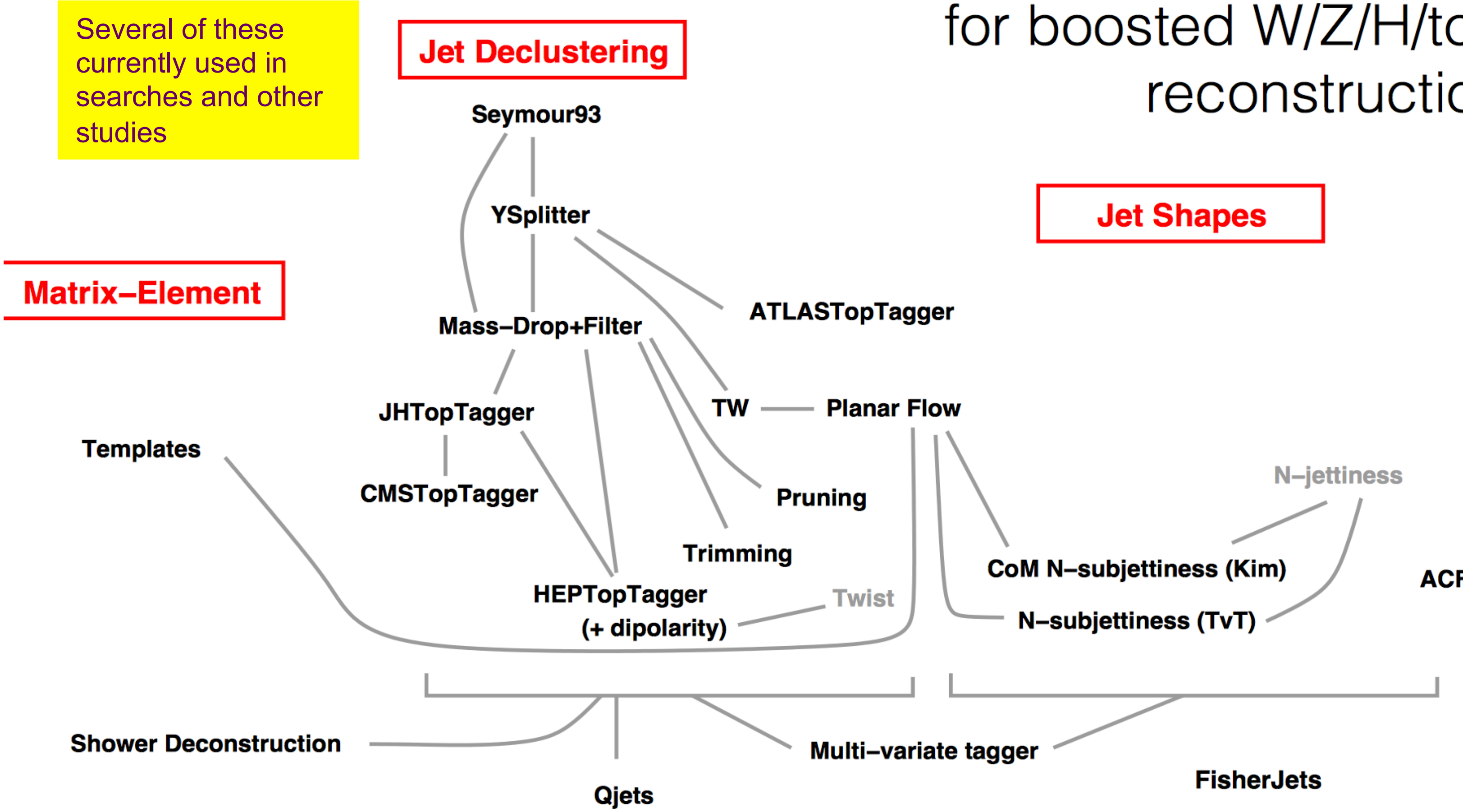
But vast number of tools

Some of the tools developed for boosted W/Z/H/top reconstruction

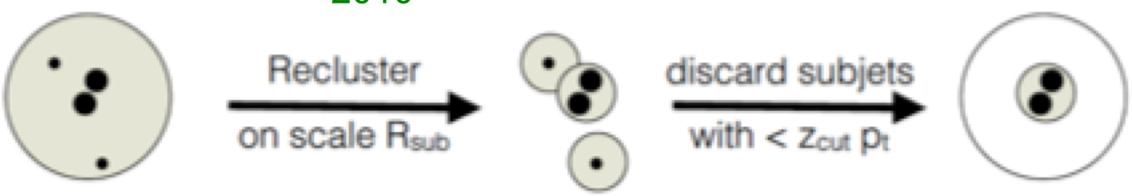
Several of these currently used in searches and other studies



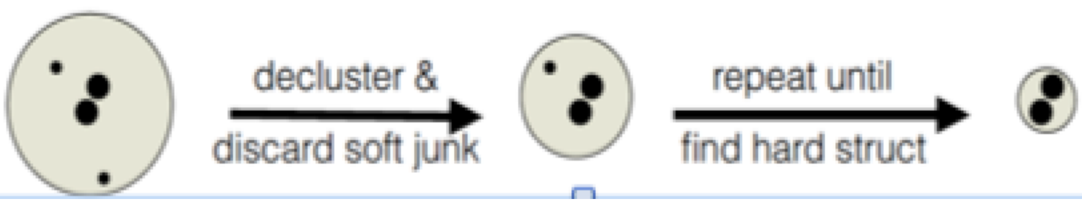
Taken from G.Salam, talk on jet substructure at IFT Madrid 2014. Several more tools developed since then. Extensive use in LHC searches.

Some common methods

Trimming Krohn, Thaler, Wang 2010



Modified mass drop tagger (mMDT) MD, Fregoso, Marzani, Salam 2013



$$\frac{\min\left(p_{ti}, p_{tj}\right)}{p_{ti} + p_{tj}} > z_{\text{cut}}$$

SoftDrop same as mMDT but uses $\frac{\min\left(p_{ti}, p_{tj}\right)}{p_{ti} + p_{tj}} > z_{\text{cut}}\theta^{\beta}$ Larkoski, Marzani, Soyez, Thaler 2014

$\beta = 0$ **most commonly used which is the same as mMDT**

Open questions

- Why so many methods? Danger of duplication/redundancy.
- Questions about "robustness" of methods.

- Which combinations are meaningful and optimal? Understanding correlations important.

- Do we have good theoretical control over the results?

Shift focus to understanding tools. But what aspects of QCD are involved?

QCD theory issues

Theoretical issues and progress

We focus on two main issues here :

- Large logarithms that emerge in the boosted regime.

$$\frac{1}{\sigma}\frac{d\sigma}{dm_j^2} \sim \frac{1}{m_j^2}\frac{C_i\alpha_s}{\pi}\ln\left(\frac{R^2p_t^2}{m_j^2}\right)$$

- They need to be resummed but accurate **resummation at hadron colliders is complicated**

- Non-perturbative effects due to hadronisation and underlying event. Further complications from pile-up.

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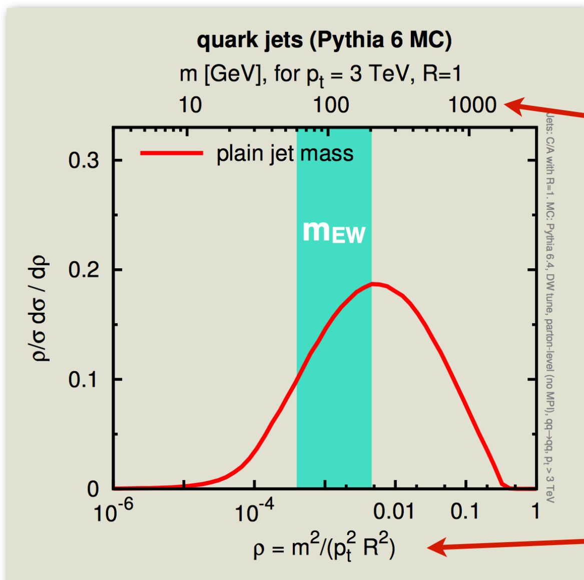
Relevance of large logarithms



Physical mass for 3 TeV, R=1 jets

ρ ~ Rescaled mass^2
(i.e. the QCD variable)

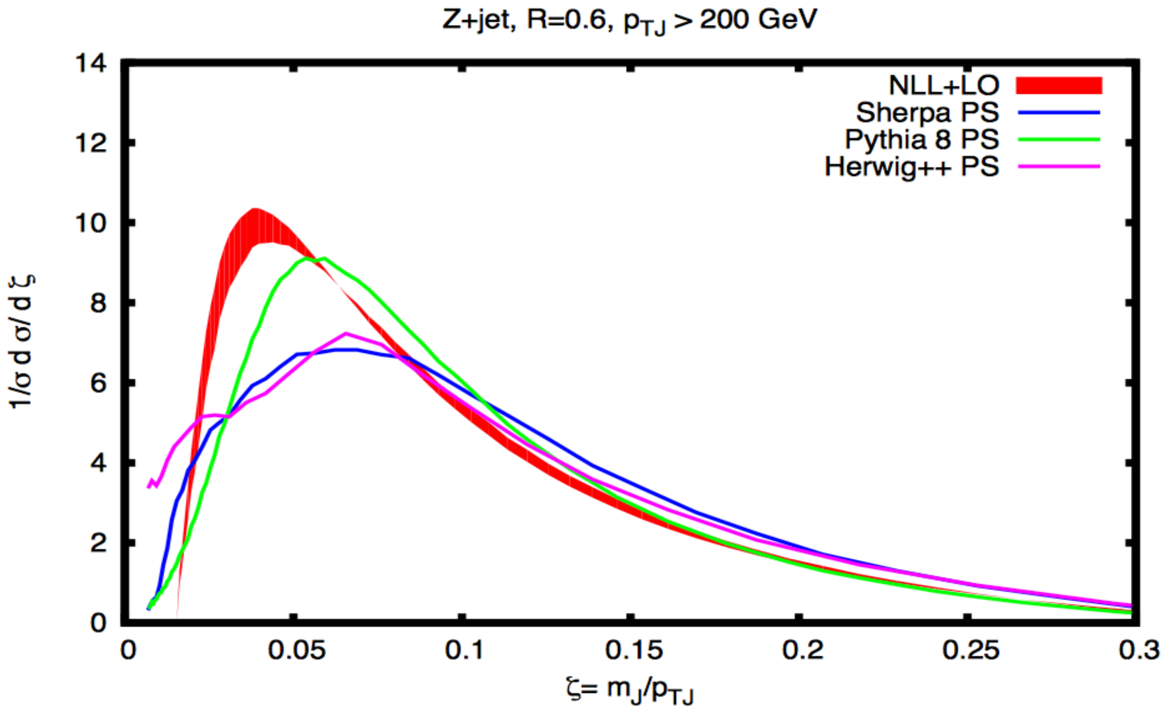
$$\rho = \frac{m_j^2}{R^2 p_T^2}$$

Do we need to worry about large logs for jet masses ~ 100 GeV?

Yes, certainly for jet p_t in the TeV region!

The standard general tools for looking at such observables are parton showers in MC event generators.

Why not just use showers?



Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky 2012

Large differences between showers at parton level. Showers only achieve a resummation of leading logarithms. Beyond this level showers can and often do differ.

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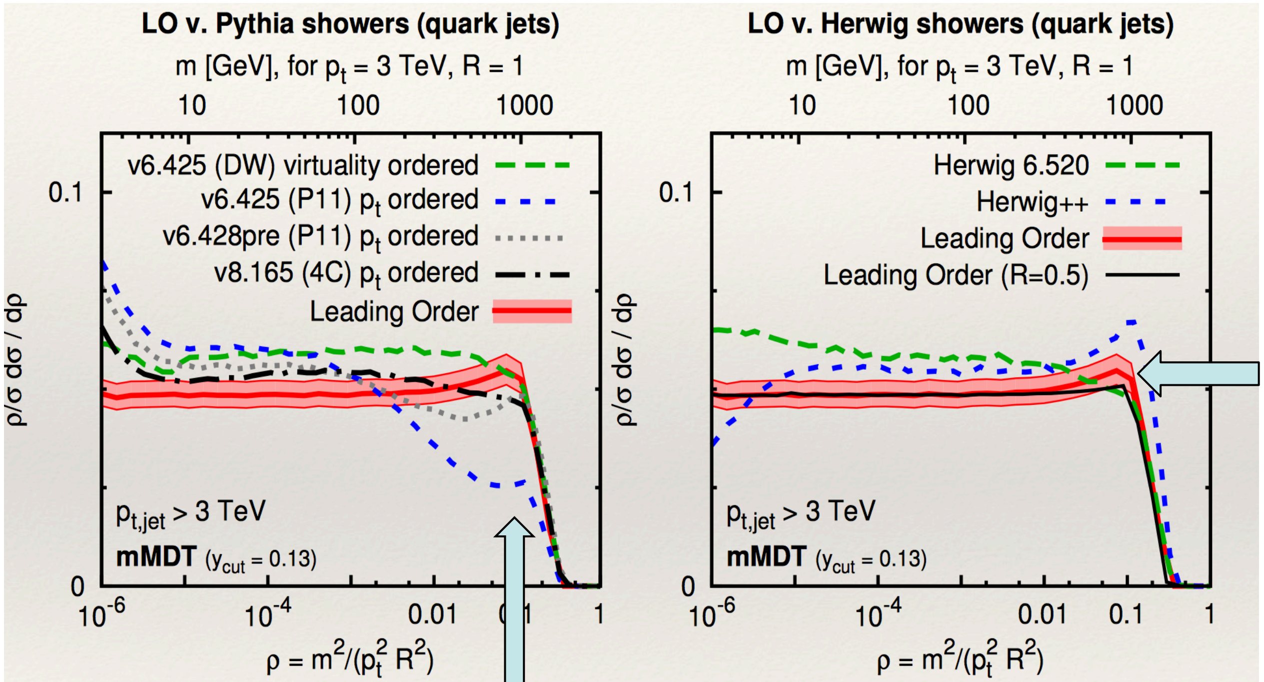
Limitations of showers



Bump at larger masses not in most showers

Pythia 6 p_t ordered

Jet masses with "mass drop" tagger

Different MC showers don't always agree.

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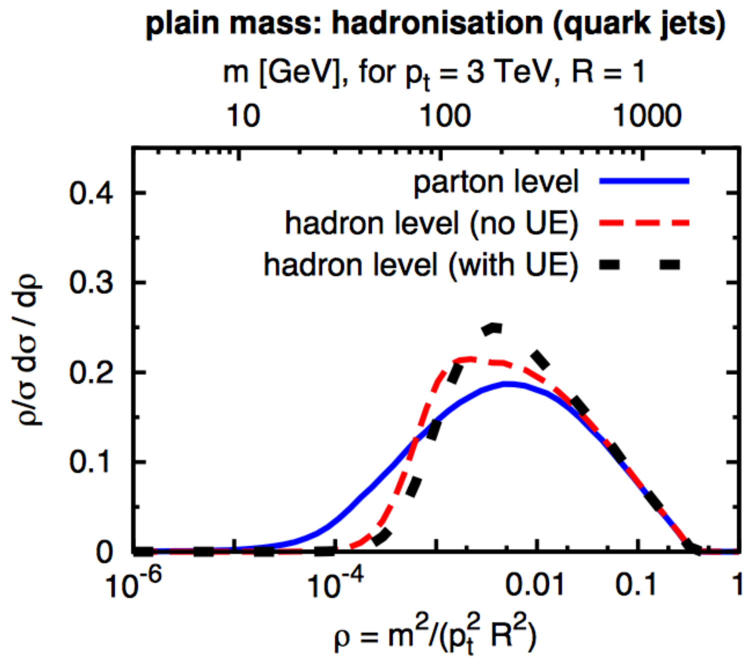
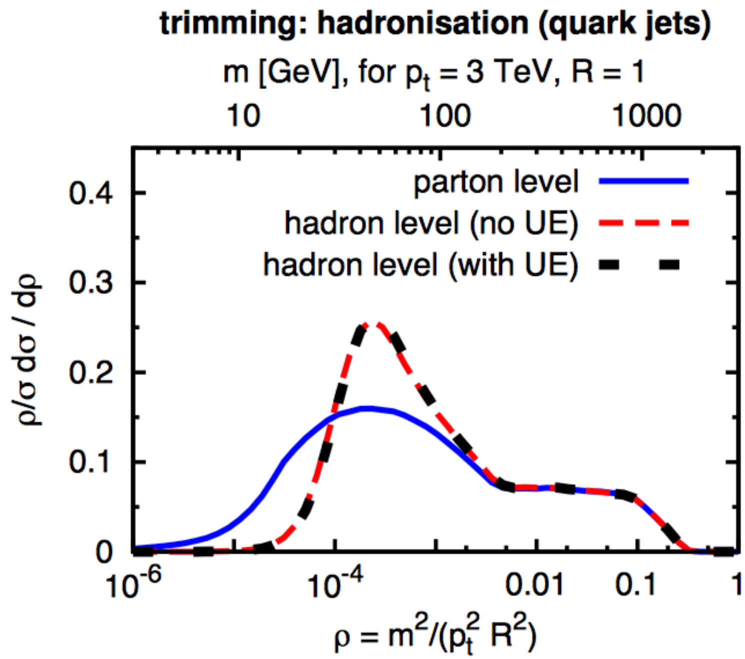
Non-perturbative effects



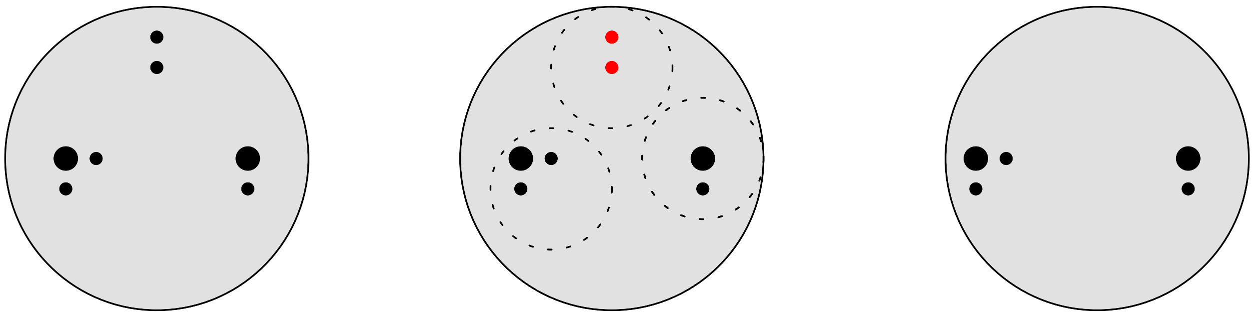


Are these important in the TeV region? Consider that a 1 GeV gluon inside an R=1 3 TeV jet can produce a jet mass of 55 GeV.

$$m_j^2 \sim \Lambda p_T R^2$$

NP bumps visible but where NP = Non-Perturbative!

Large logs for groomed jets?



- Trimming reclusters jet and discards soft subjets. mMDT declusters jet and removes soft emissions.

- No need to worry about large logs?

"*Soft gluons are evil, but with ….. method we don't have to worry about them since it eliminates soft gluons entirely*"
[Theorist at 2009 Manchester meeting on "Soft gluons and new physics at the LHC"]

Recent progress

Analytical approach

Can we get some direct insight from first principles of QCD rather than relying on shower models?

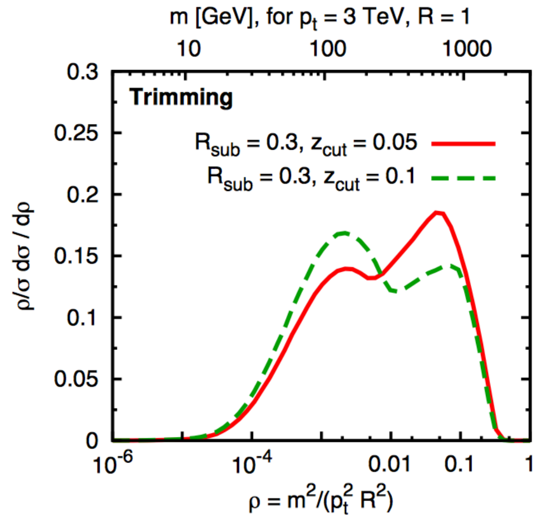
Well-developed analytical methods to resum large logarithms in pQCD and SCET.

$$\frac{1}{n!}\prod_i \frac{C_F \alpha_s\left(z_i \theta_i p_t^{\text{jet}}\right)}{\pi}\frac{dz_i}{z_i}\frac{d\theta_i^2}{\theta_i^2}$$

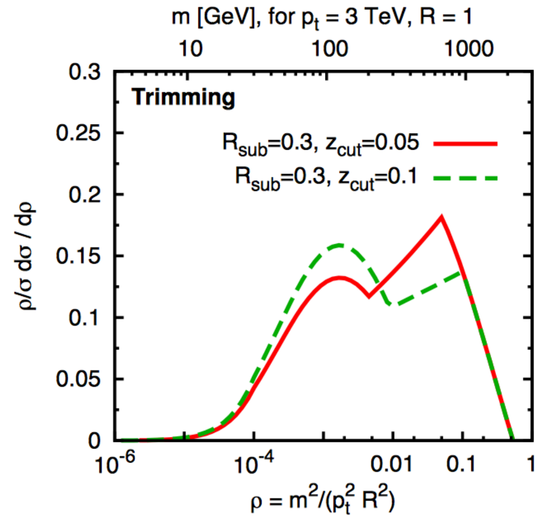
- Factorisation of multiple soft-collinear emissions.
- Virtual corrections incorporated via unitarity.
- Understanding behaviour of substructure observables to all-orders in certain limits.

Analytical understanding of jet substructure

Monte Carlo



Analytic



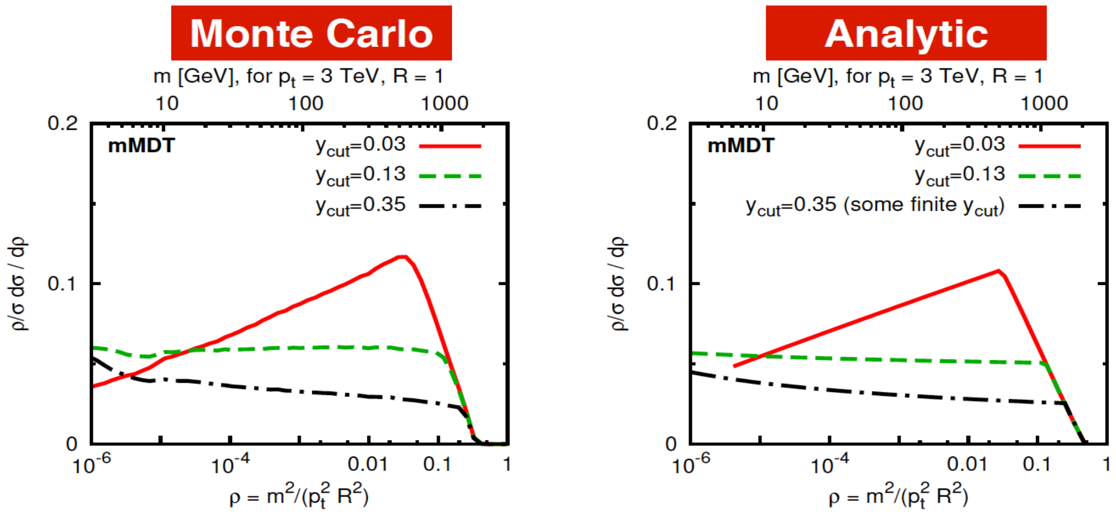
Bumps and kinks for QCD background. Only found after analytics

MD, Fregoso, Marzani, Salam 2013

Jet masses with trimming

- Many tools are now understood from first principles analytic resummed calculations. Shower model independent.
- Analytics revealed features such as kinks and bumps in background.

Analytics for substructure



Jet mass with mMDT

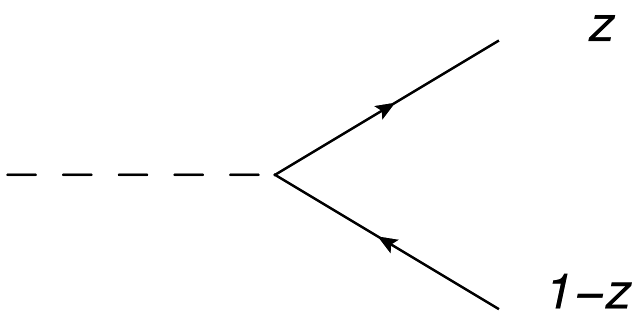
Redundancy of μ parameter of mass-drop found with analytics

- mMDT is a unique jet observable. Free from complex soft gluon effects affecting most observables. Can be computed to high precision.
- SoftDrop generalisation of mMDT also shares this property.

Dasgupta, Fregoso, Marzani and Salam 2013

What about signal jets?

- Substructure tools give rich variety of behaviour on background jets.

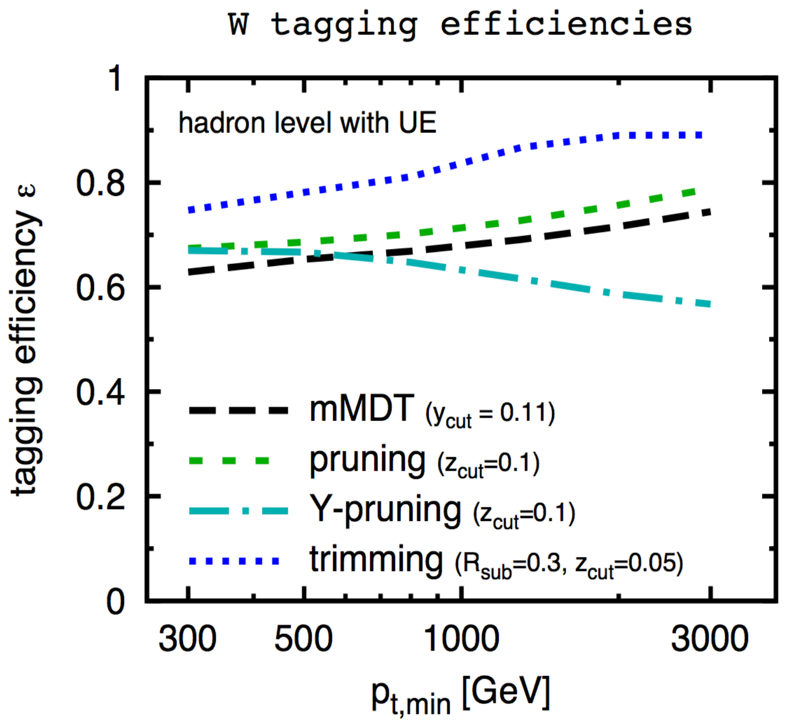


- For signal jets most tools are rather similar.

$$\epsilon_s = \int_{y_{\rm cut}}^{1-y_{\rm cut}} dz = 1 - 2y_{\rm cut}$$

Generic result for any two-body tagger that imposes a prong symmetry condition. Predicts 80% signal efficiency for y_{cut} = 0.1

Signal jets



Tree level is a good approximation with small effects from ISR and FSR.

MD, Siodmok and Powling 2015.

In majority of cases performance of tools driven by impact on background.

Applications

OR WHAT DOES THIS BUY US?

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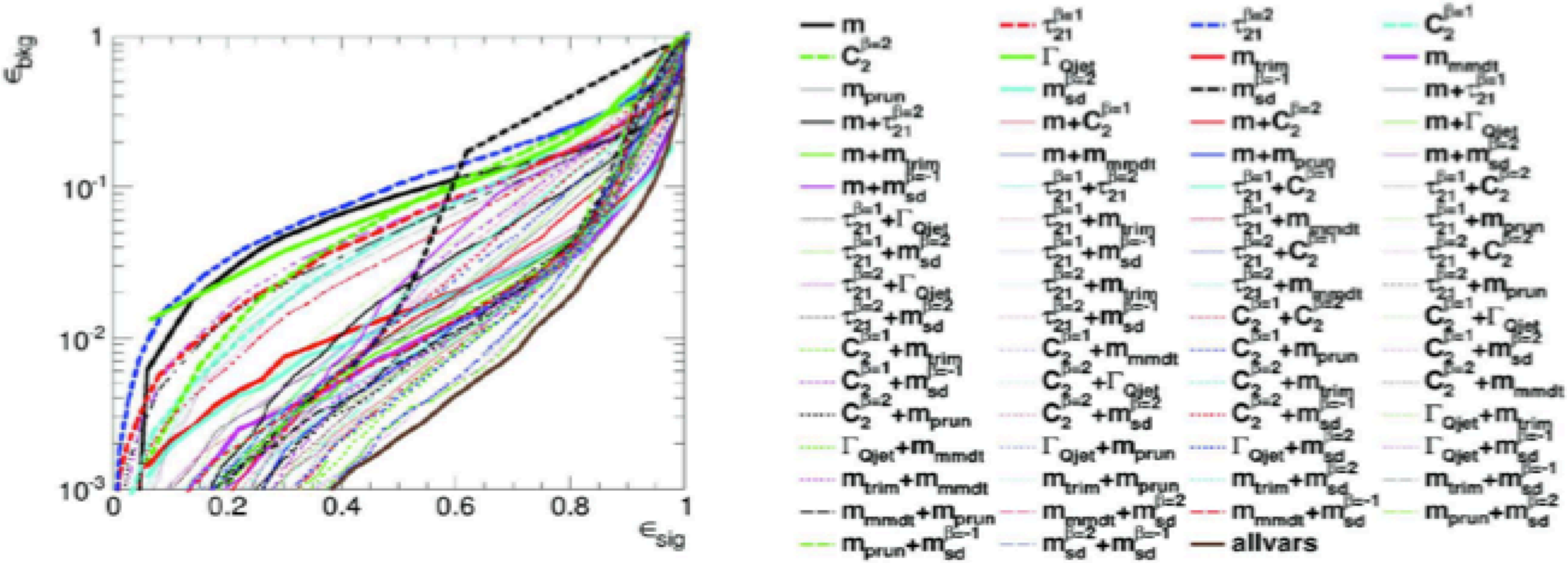
Systematic understanding



Until 2013 there was no real physics understanding of tools and a hit and trial approach to performance.

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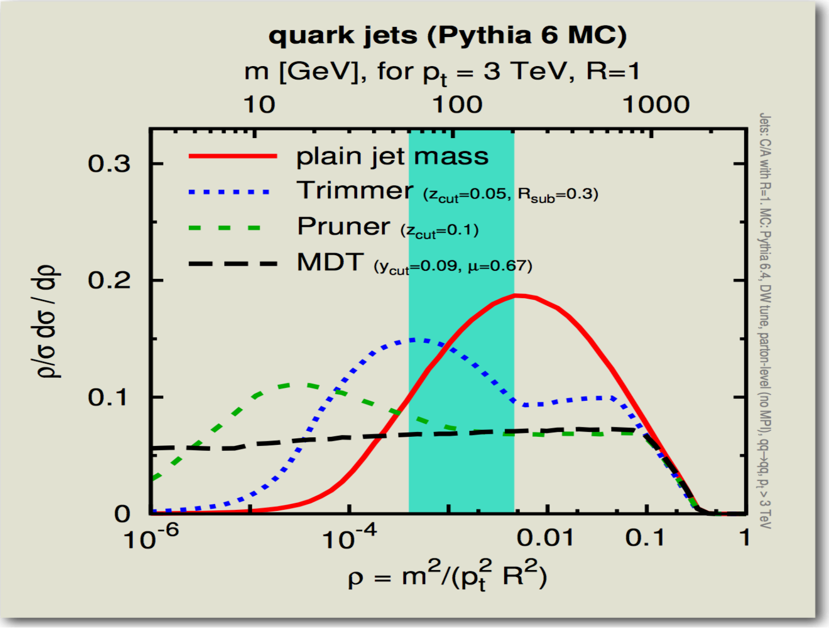
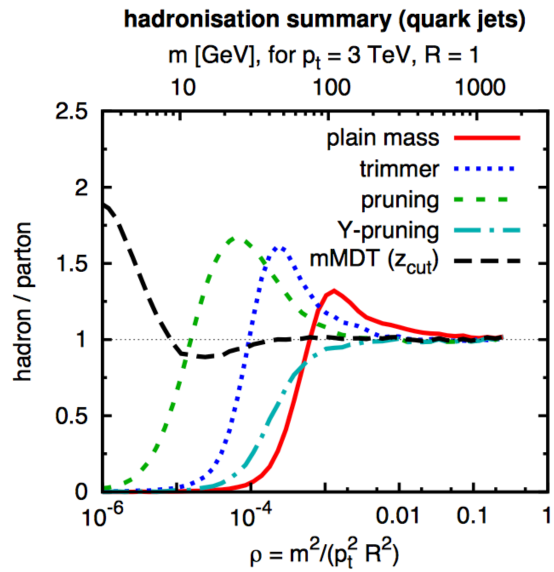
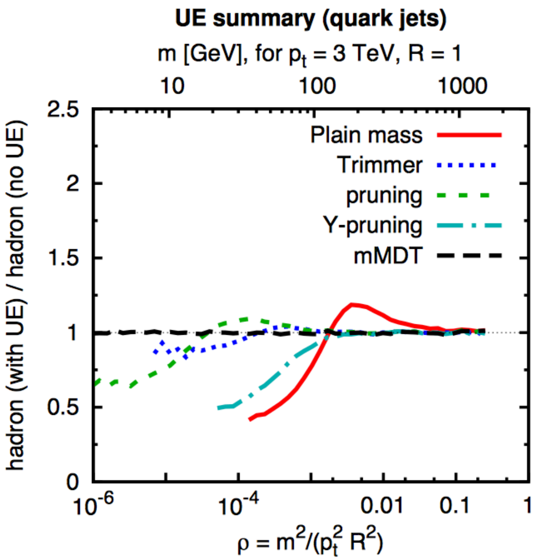
Systematic understanding



Can easily do “the right” MC studies to meaningfully compare tools and bring out their main features.

Reduced non-perturbative effects

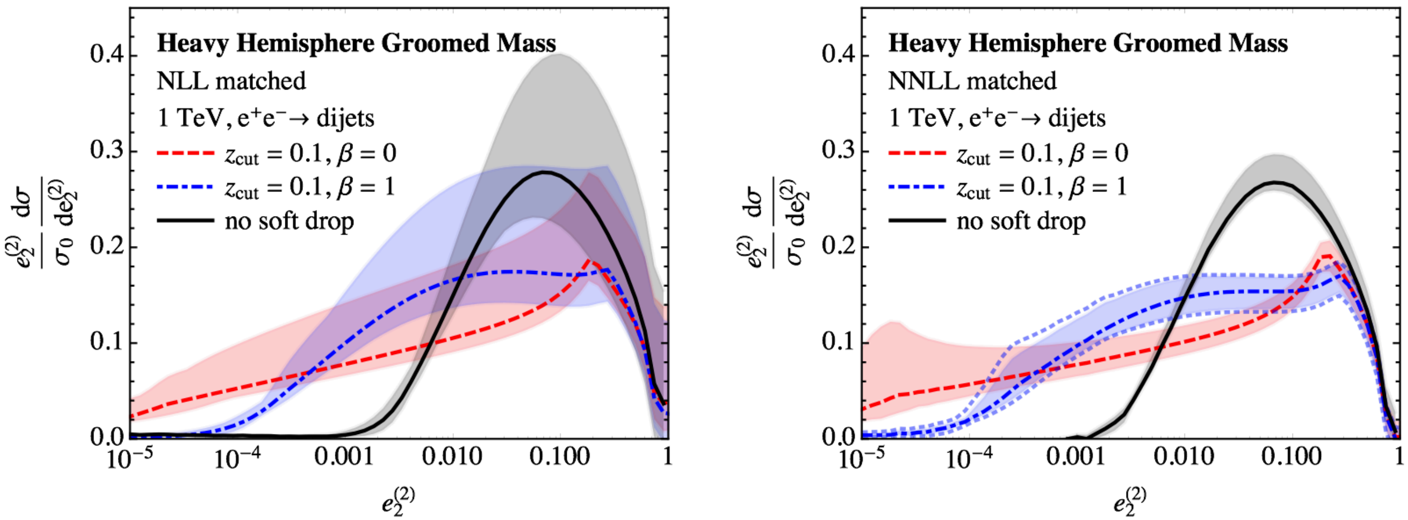




Tools designed which are more robust against NP effects : mMDT and SoftDrop.

Opens the door to precision phenomenology for jet substructure at the LHC i.e. comparison of accurate theory to more precise measurements.

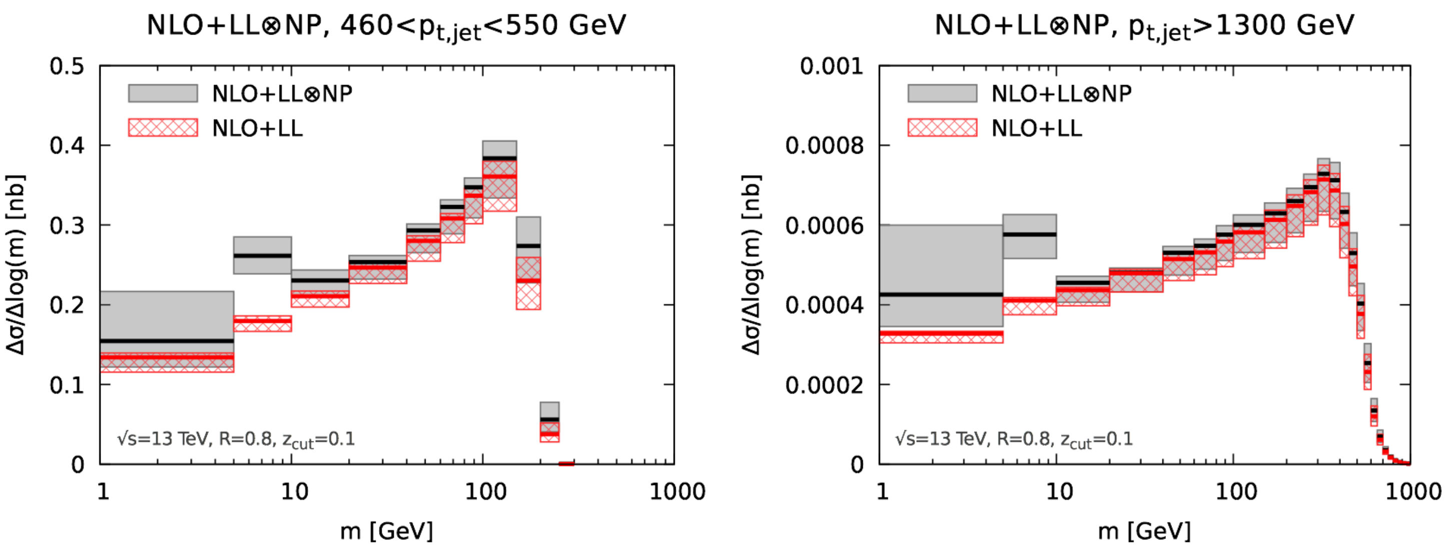
Precise calculations for substructure



Higher log accuracy calculations for mMDT and SoftDrop. Not currently achieved for plain jet mass at hadron colliders.

Frye, Larkoski, Schwartz, Yan 2016

Phenomenology for substructure



- Resummed calculations matched to NLO with non-pert. effects for mMDT. Can be directly compared to LHC data.

- This is a novelty in the context of substructure tools at hadron colliders. Marzani, Schunk, Soyez 2017

Performance

Can we design tools based on analytical insight that outperform old methods?

One idea is to exploit the Sudakov suppression of QCD background jets.

$$\rho \frac{d\sigma}{d\rho} \sim \frac{C_R \alpha_s}{\pi} \ln \frac{1}{\rho}\, e^{-\frac{C_R \alpha_s}{2\pi} \ln^2 \frac{1}{\rho}}$$

$$\rho = \frac{m^2}{R^2 p_T^2}$$

Prefactor

Sudakov exponential suppression

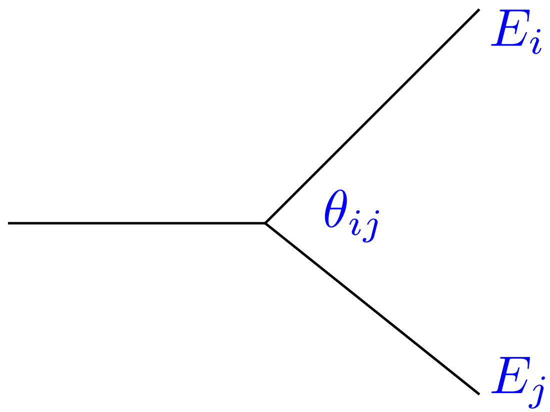
Plain mass vs mMDT

$$\left(\rho\frac{d\sigma}{d\rho}\right)^{\text{plain}} \approx \frac{C_F\alpha_s}{\pi}\ln\frac{1}{\rho}\exp\left[-\frac{C_F\alpha_s}{2\pi}\ln^2\frac{1}{\rho}\right]$$

$$\left(\rho\frac{d\sigma}{d\rho}\right)^{\text{mMDT}} \approx \frac{C_F\alpha_s}{\pi}\ln\frac{1}{y}\exp\left[-\frac{C_F\alpha_s}{\pi}\ln\frac{1}{y}\ln\frac{1}{\rho}\right]$$

Prefactor is different which helps to reduce background. However Sudakov suppression is not as large. Can we benefit from both?

Y-splitter method



Butterworth, Cox, Forshaw, 2002

Proposed long ago but discarded in favour of new tools

- Decluster a jet into 2 subjets using the kt distance measure
- Ask for a cut forcing prongs to be more "symmetric" i.e. a Y configuration

$$\frac{\min(E_i, E_j)}{E_i + E_j} > y$$

Tag jet if passes cut or discard. Doesn't recurse like mMDT.

Y-splitter structure

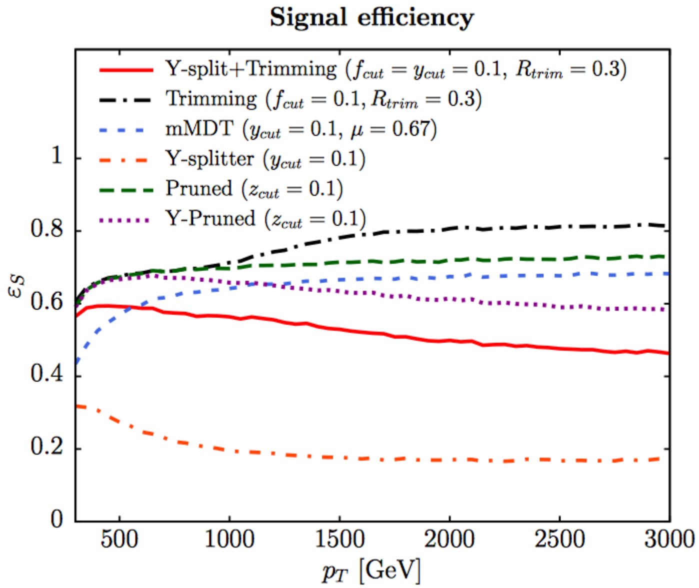
Analytical calculations for Y-splitter tell an interesting story.

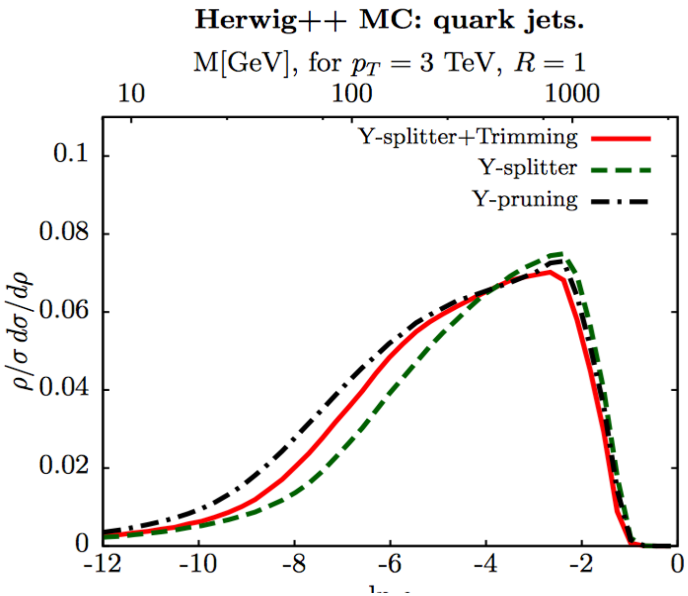
$$\left(\rho \frac{d\sigma}{d\rho}\right)^{\mathrm{Y-splitter}} \approx \frac{C_F \alpha_s}{\pi} \ln \frac{1}{y} \exp\left[-\frac{C_F \alpha_s}{2\pi} \ln^2 \frac{1}{\rho}\right]$$

The result is a hybrid of mMDT prefactor and plain mass Sudakov. Results in excellent background suppression.

MD, Powling, Soyez, Schunk 2016

Y-splitter plus grooming

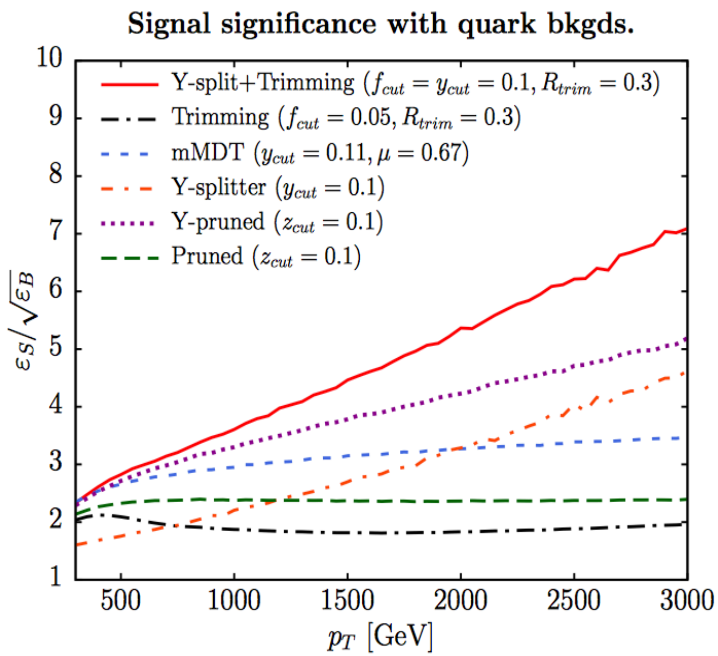


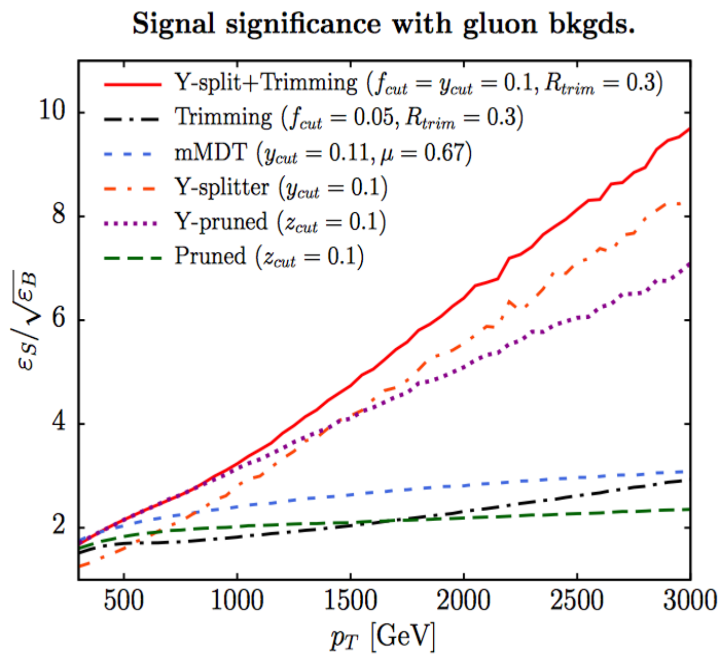


- Y-splitter has not seen extensive use. Loss of signal due to ISR and NP effects.
- Y-splitter is a tagger rather than groomer. Combine Y-splitter with grooming? Rescues signal leaving background as before

→ Illustrates what can be gained by combining complementary tools.

Performance





Pretty decent for such an ancient tool albeit supplemented with grooming! Performance similar with mMDT grooming but trimming works best. MD, Powling, Siodmok 2015

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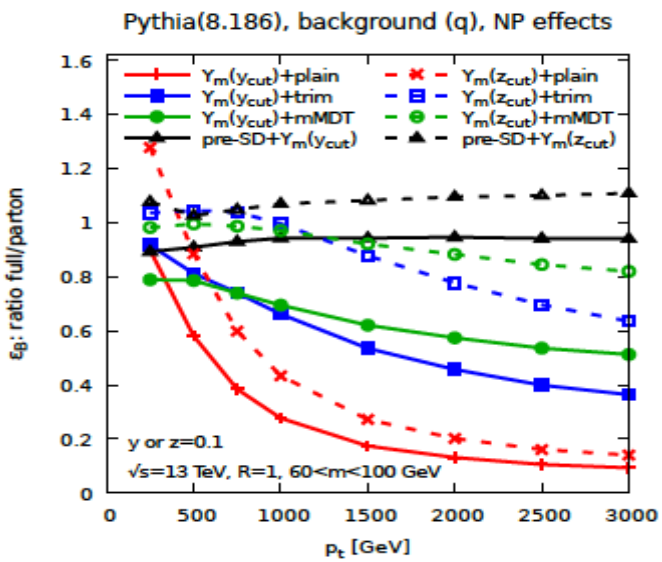
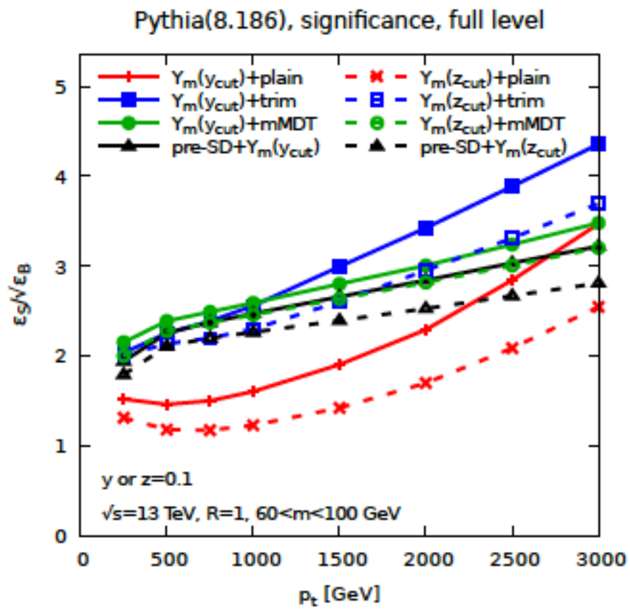
Non-perturbative effects

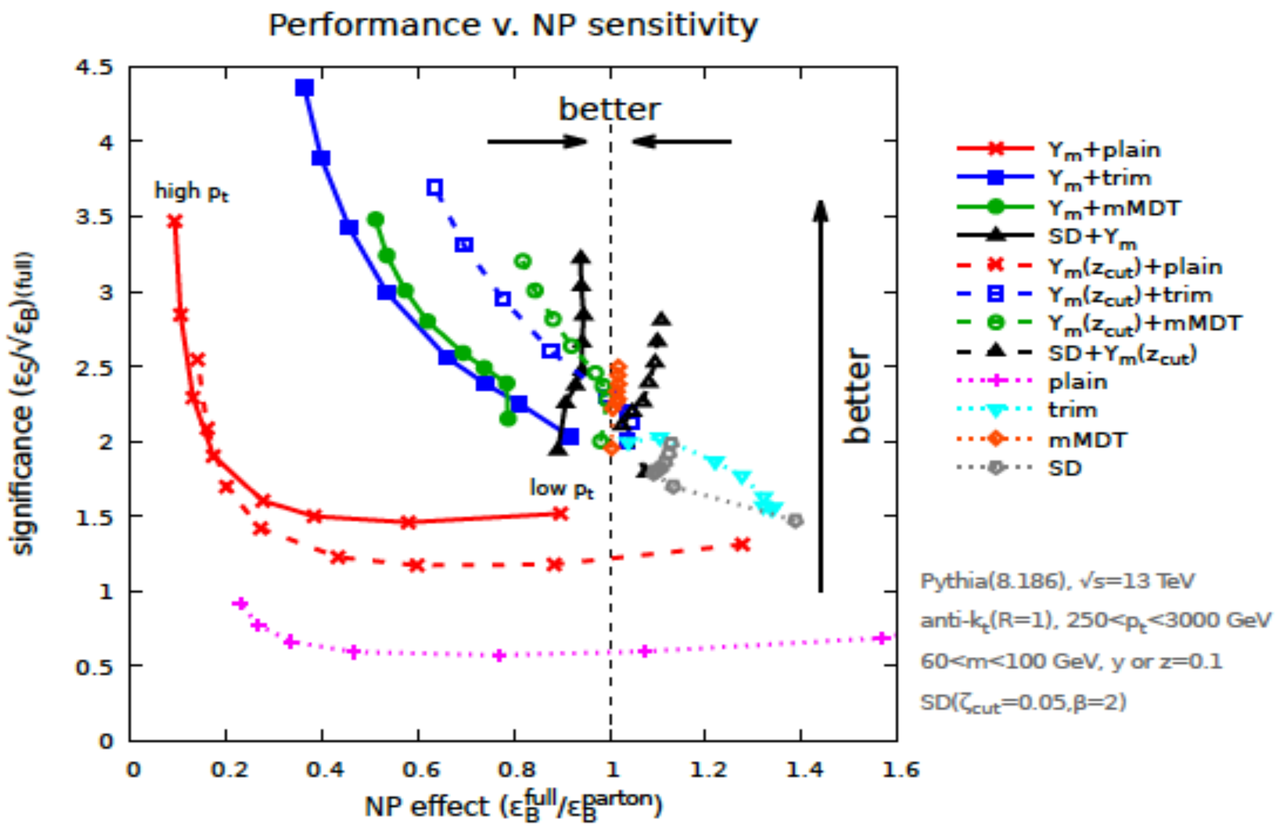




- Y-splitter with grooming appears a high performance tool for boosted object studies.

- The role of non-pert. effects provides a sobering note. Illustrates a general feature seen for other observables too such as jet shapes. Up to 60% effects for YS+trimming.

Performance vs robustness



Trade-off between sheer performance and non-pert. effects.

To what extent should TeV scale searches rely on our knowledge of physics at 1 GeV?

Summary and conclusions

- Significant progress in jet substructure studies over last decade.
- Many tools developed and implemented in LHC searches and studies.
- Understanding jet substructure theoretically is harder but substantial progress made.
- Among remaining challenges balancing performance and reliability stands out.