Jet substructure and infrared QCD dynamics

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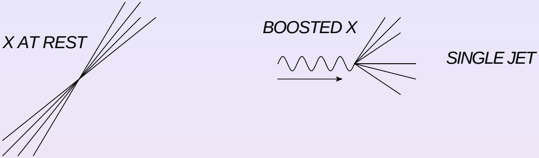
In collaboration with Gavin Salam, Simone Marzani, Alessandro Fregoso, Alex Powling

Overview

- Boosted object LHC searches and jet substructure
- Substructure techniques and recent advances
- Infrared QCD dynamics and understanding jet substructure
  - Resummed calculations for jet substructure observables
  - Comparisons to event generator tools
  - Designing modified tools
- Outlook

LHC searches in the highly boosted regime



Exploits situations where $p_T \gg M_X$. Decay products encompassed in a single fat jet.

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

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- New heavy particles decay to lighter (boosted) EW scale particles
- Look at high p_T regime of say Higgs production

Initial idea goes back to Seymour 1993

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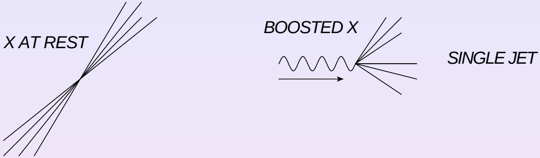

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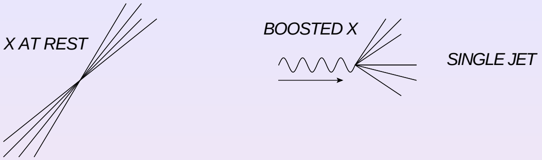

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Jet substructure methods – basic ideas

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

Jet substructure methods become powerful discovery tools. Main ideas are

- Use knowledge about QCD radiation to discriminate against background and tag signal. Cut on z to discriminate against bckgd.
- Use grooming techniques to clean signal of contamination from ISR, UE/pile-up. Typically Smaller angular scale involved.

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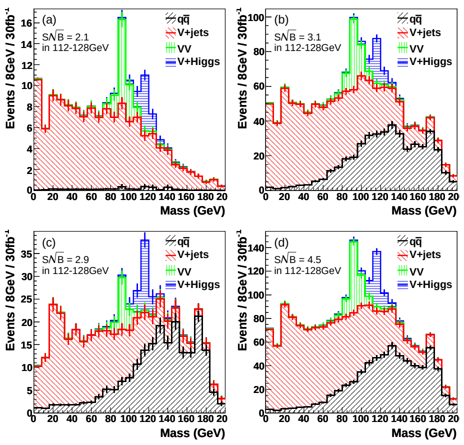
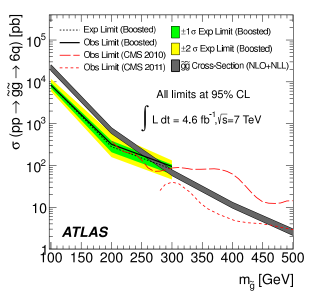


Rescued an unpromising channel. Associated Higgs production $V + H$ with Higgs decays to $b\bar{b}$. Uses the mass-drop+filtering substructure method of BDRS.

Butterworth, Davison, Rubin and Salam 2008.

Jet substructure methods

- A plethora of different methods exist by now
  YSplitter, Mass-drop + filtering, pruning, trimming, ATLAS top tagger, JH top tagger, CMS top tagger, Planar Flow, N subjettiness, Q jets, Templates etc.
- Many methods are being implemented in searches



ATLAS collaboration, 2012

A list of open questions

- Do we really need so many different taggers?
- In what ways are they similar and where are the differences?
- Are some methods better than others?
- How do results obtained depend on the many parameters of the taggers?
- How to make the best choice of a tagger for a given search?

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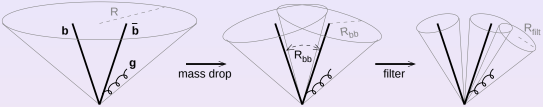
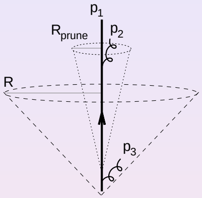
Current taggers – mass drop



Definition

- Break the jet j into two subjets by undoing its last stage of clustering. Label the two subjets j_1, j_2 such that $m_{j_1} > m_{j_2}$.
- If there was a significant mass drop, $m_{j_1} < \mu m_j$, and the splitting is not too asymmetric, $y = \min(p_{tj_1}^2, p_{tj_2}^2)\Delta R_{j_1 j_2}^2 / m_j^2 > y_{\text{cut}}$, then deem j to be the tagged jet
- Otherwise redefine j to be equal to j_1 and go back to step 1 (unless j consists of just a single particle, in which case the original jet is deemed untagged).

Definition changed to follow more energetic branch rather than heavier branch - modified Mass Drop Tagger.



Definition

Pruning [7,8] takes an initial jet, and from its mass deduces a pruning radius $R_{\text{prune}} = R_{\text{fact}} \cdot \frac{2m}{p_t}$, where R_{fact} is a parameter of the tagger. It then reclusters the jet and for every clustering step, involving objects a and b, it checks whether $\Delta_{ab} > R_{\text{prune}}$ and $\min(p_{ta}, p_{tb}) < z_{\text{cut}} p_{t,(a+b)}$, where z_{cut} is a second parameter of the tagger.If so, then the softer of the a and b is discarded. Otherwise a and b are recombined as usual. Clustering then proceeds with the remaining objects, applying the pruning check at each stage.

Need for insight

Several techniques around. Natural to compare them.

> *The [Monte Carlo] findings discussed above indicate that while [pruning, trimming and filtering] have qualitatively similar effects, there are important differences. For our choice of parameters, pruning acts most aggressively on the signal and background followed by trimming and filtering.*

Boost 2010 proceedings

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- No idea of how these findings depend on tagger parameters or jet masses or p_t.

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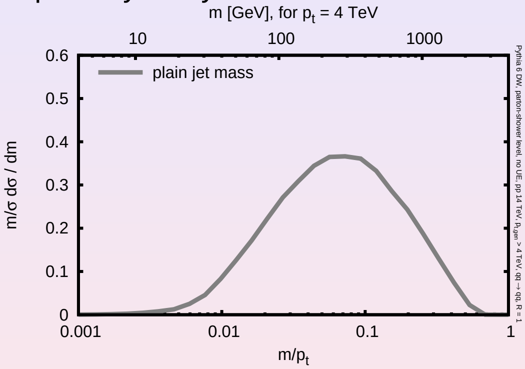
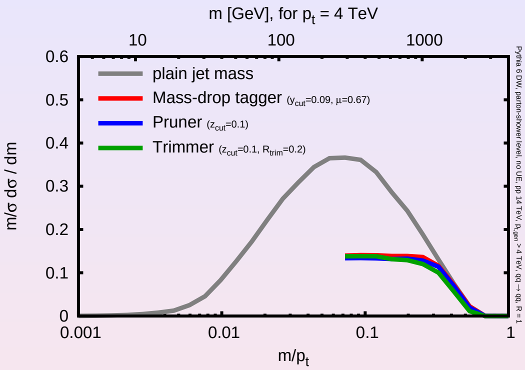
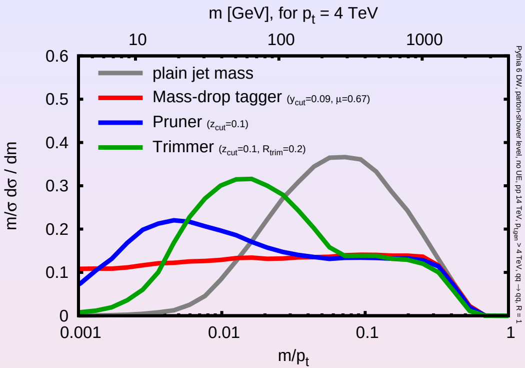
The right MC study can already be instructive. But is often inspired by analytics!



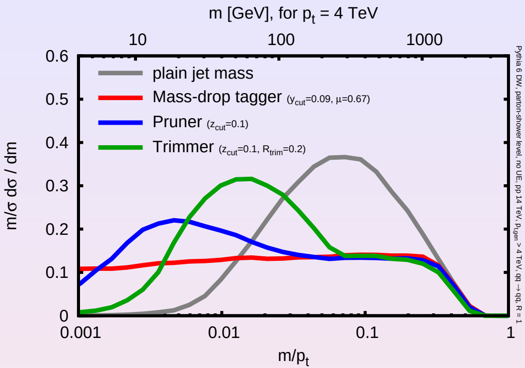


Taggers look similar



But only for a limited mass range How do we understand what we are seeing? Why do pruning and trimming have kinks? Can we compute the positions?

Needs analysis and calculation



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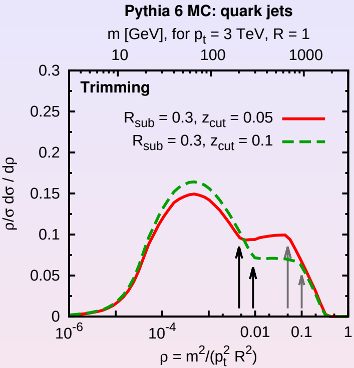
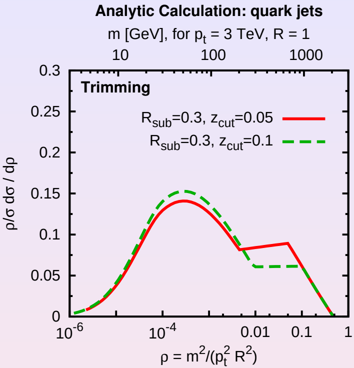
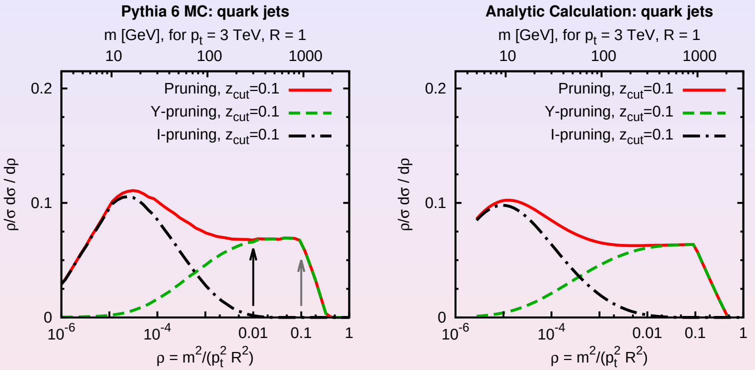
Analytic calculations v MC simulation–trimming





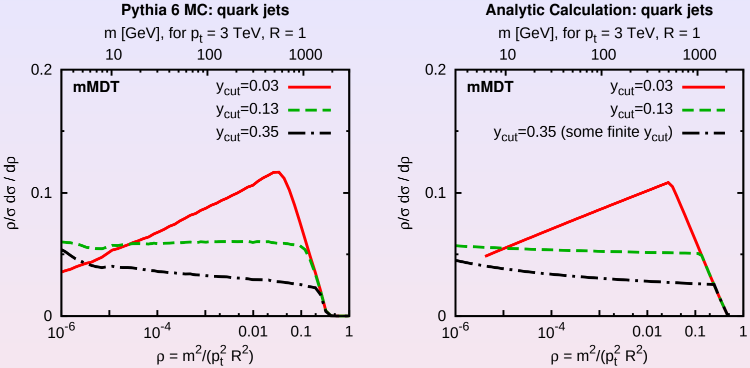
$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} \simeq \rho \frac{d}{d\rho} \exp\left[-\frac{\alpha_s C_F}{2\pi}\left(-\frac{3}{2}\ln\frac{1}{\rho} + \Theta(\rho - z)\ln^2\frac{1}{\rho} + \right.\right.$$
$$\left.\left. +\Theta(z-\rho)\left(\ln^2\frac{1}{z} + 2\ln\frac{z}{\rho}\ln\frac{1}{z}\right) + \Theta(zr^2-\rho)\ln^2\frac{zr^2}{\rho}\right)\right].$$

Analytic calculations v MC simulation –pruning



Pruning result comprises 2 distinct components, Sane or Y pruning is better behaved.

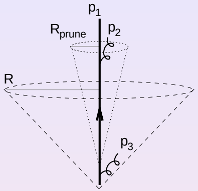
Analytic calculations v MC simulation –mMDT

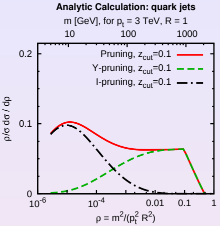


$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} \sim \rho \frac{d}{d\rho} \exp\left[-\frac{C_F \alpha_s}{\pi}\left(\ln\frac{1}{y_{\rm cut}}\ln\frac{1}{\rho} - \frac{3}{4}\ln\frac{1}{\rho}\right)\right]$$

Note flatness for particular $y_{\rm cut}$. Unique single-log structure. Tagged distribution can be possibly described by NLO calculations!

Improving pruning –the Y pruning modification





Pruning has a flaw which leads to anomalous behaviour. Situation when dominant emission is pruned away leaving core of jet i.e single prong – I-pruning. Define sane or Y-pruning as pruning with condition that at least one emission is tested for and passes cuts. Implies desirable two-pronged structure. Also removes undesirable double logs from pruning:

$$\frac{\rho}{\sigma}\frac{d\sigma^{\text{Y-prune}}}{d\rho} \sim \frac{C_F\alpha_s}{\pi}\left(\ln\frac{1}{z_{\text{cut}}}\right)\exp\left(-\frac{C_F\alpha_s}{2\pi}\ln^2\rho\right)$$

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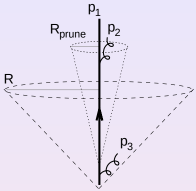

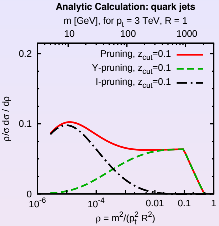

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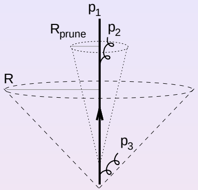

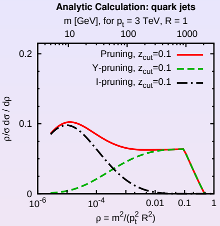

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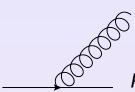
Non-perturbative effects



Taggers performance also critically depends on sensitivity to hadronisation UE and pile-up. Estimate hadronisation sensitivity by taking soft emission with $k_t = \mu_I$ with $\mu_I \sim 1\,\mathrm{GeV}$. Then

$$m^2 = \omega p_T \theta^2 = \mu_I p_T \theta \sim \mu_I p_T$$

For $p_T = 3\,\mathrm{TeV}$ gives $m \sim 55\,\mathrm{GeV}$!
Compare mMDT for fixed $k_t = \mu_I$

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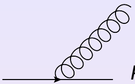
Gives $m \sim 3\,\mathrm{GeV}$. mMDT much more robust against hadronisation. Pruning and trimming are like plain jet mass.



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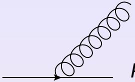

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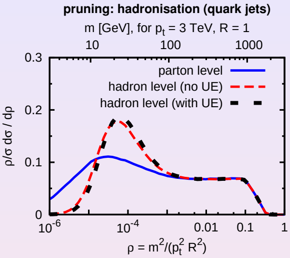

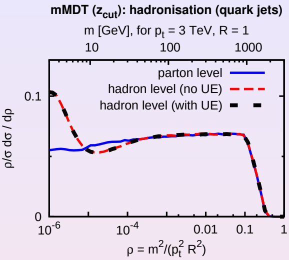

Monte Carlo studies reveal pruning and trimming indeed v. affected by hadronisation even around EW scale. mMDT is relatively safe.

UE effects are much more modest for all methods.

Y pruning less affected than pruning by hadronisation but more by UE.

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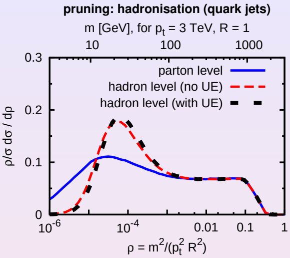

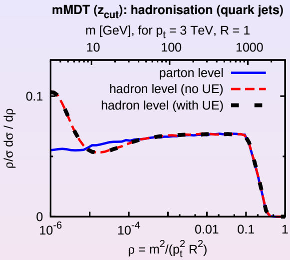

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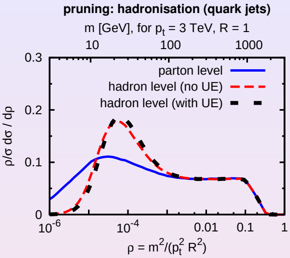

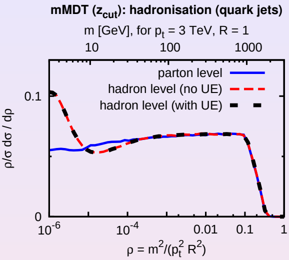

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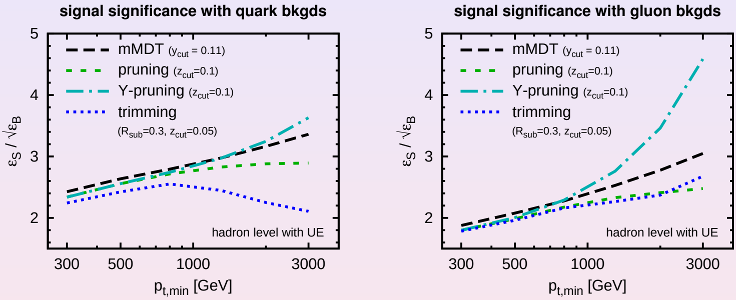
In the final analysis....

It is performance that counts ! We now understand what features of the taggers drive the signal efficiencies.



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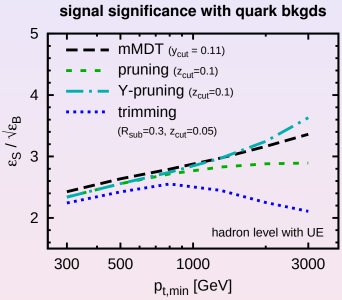

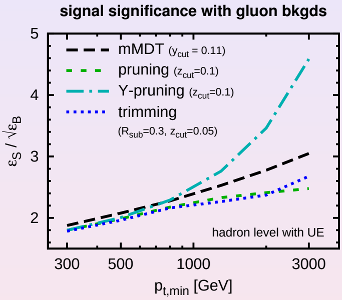

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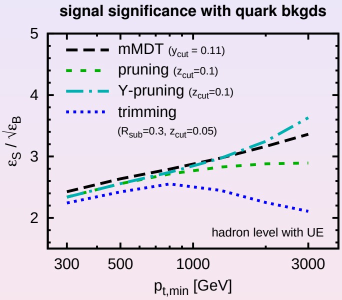

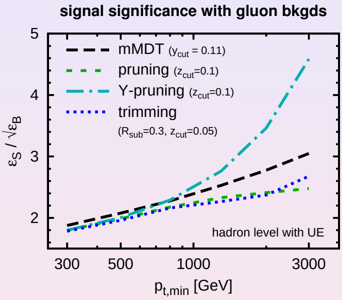

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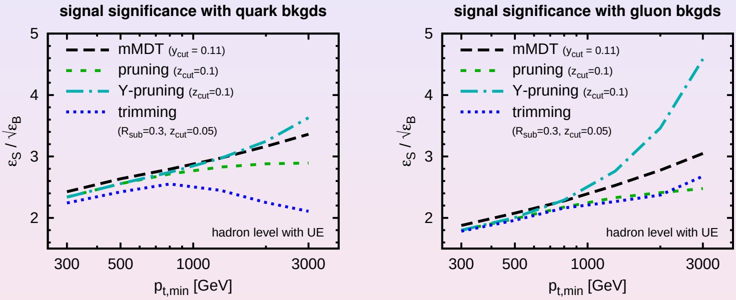

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Outlook

- A partial analytical insight into jet substructure tools has recently been obtained.
- We can extend this understanding : analytical calculations for signal processes, higher log accuracy for the taggers, calculations for a wider range and combinations of taggers
- We should put this understanding to use in developing better more robust tools.