Jet substructure with 100 fb^{-1} : a theory perspective

Mrinal Dasgupta
University of Manchester

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Outline

- Introduction and basics
- Some key theory issues
- Selective review of recent developments
- Lessons and future directions

Basic ideas

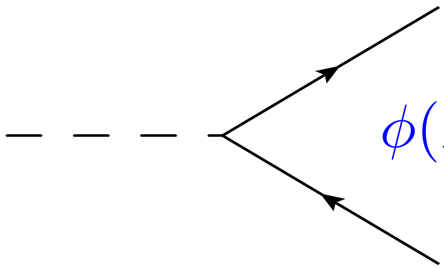
Key idea : for tagging a particle with mass M exploit boosted regime i.e. $P_T >> M$.

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

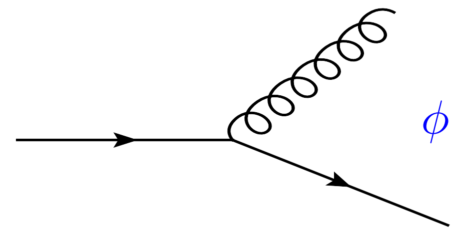
Either from going to high p_T or from decay of heavy new particle

Hadronic decays reconstructed in single “fat” jet. Use our knowledge of QCD jets to distinguish this from background.

Basic ideas



$$\phi(z) \propto 1$$



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

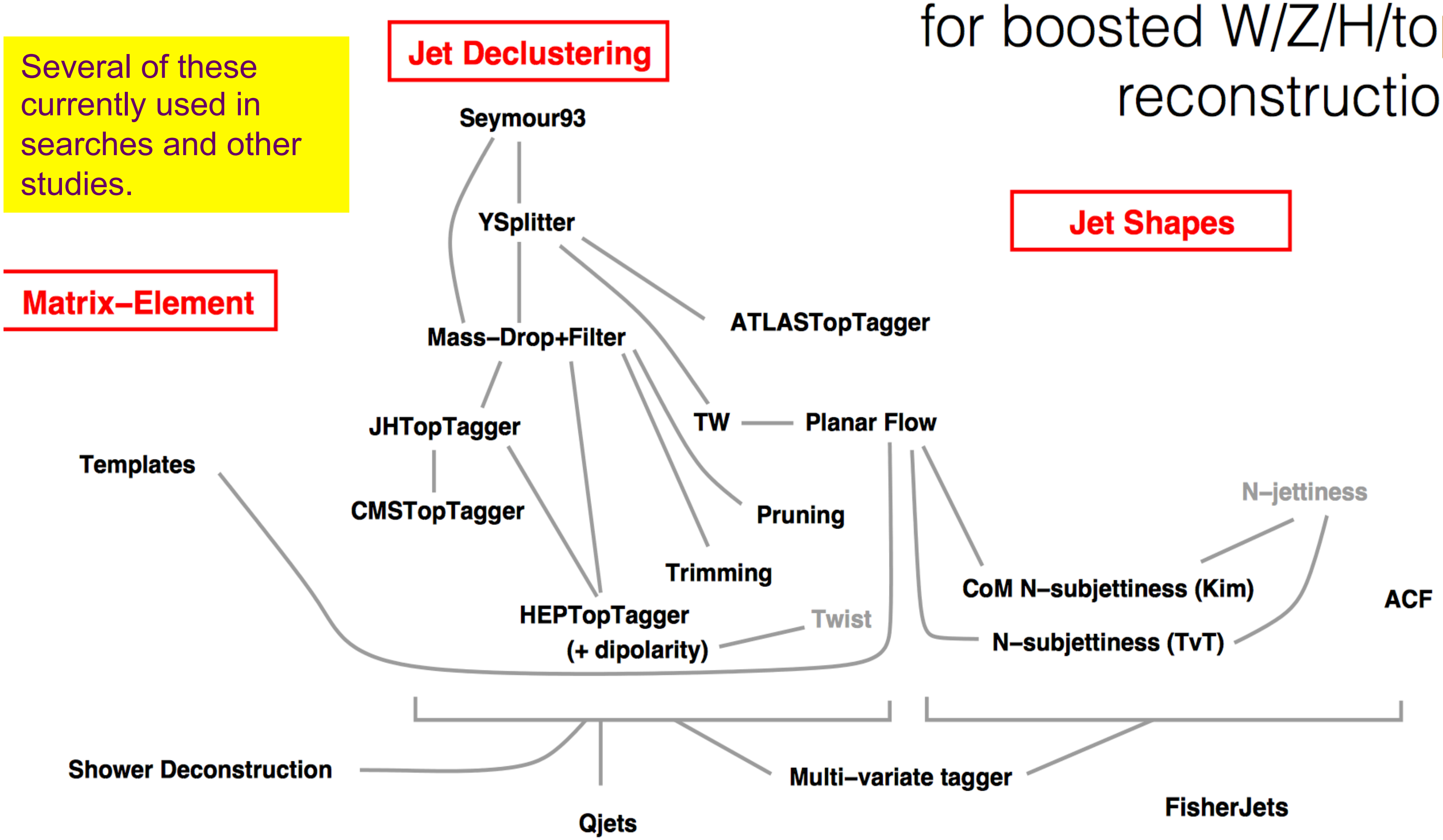
- Exploit the asymmetric nature of QCD splittings. Produce jets with single hard core or prong versus 2 pronged W/Z/H and 3 pronged t.

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

Lots of tools

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

Several of these currently used in searches and other studies.



Open Questions

- Why so many tools to exploit limited physics principles?
- Do we understand physics behind tools? What factors drive performance?
- How robust are tools? E.g. does performance change with kinematics and parameters?

How to decide which tools to use in searches and for data/ theory comparisons?

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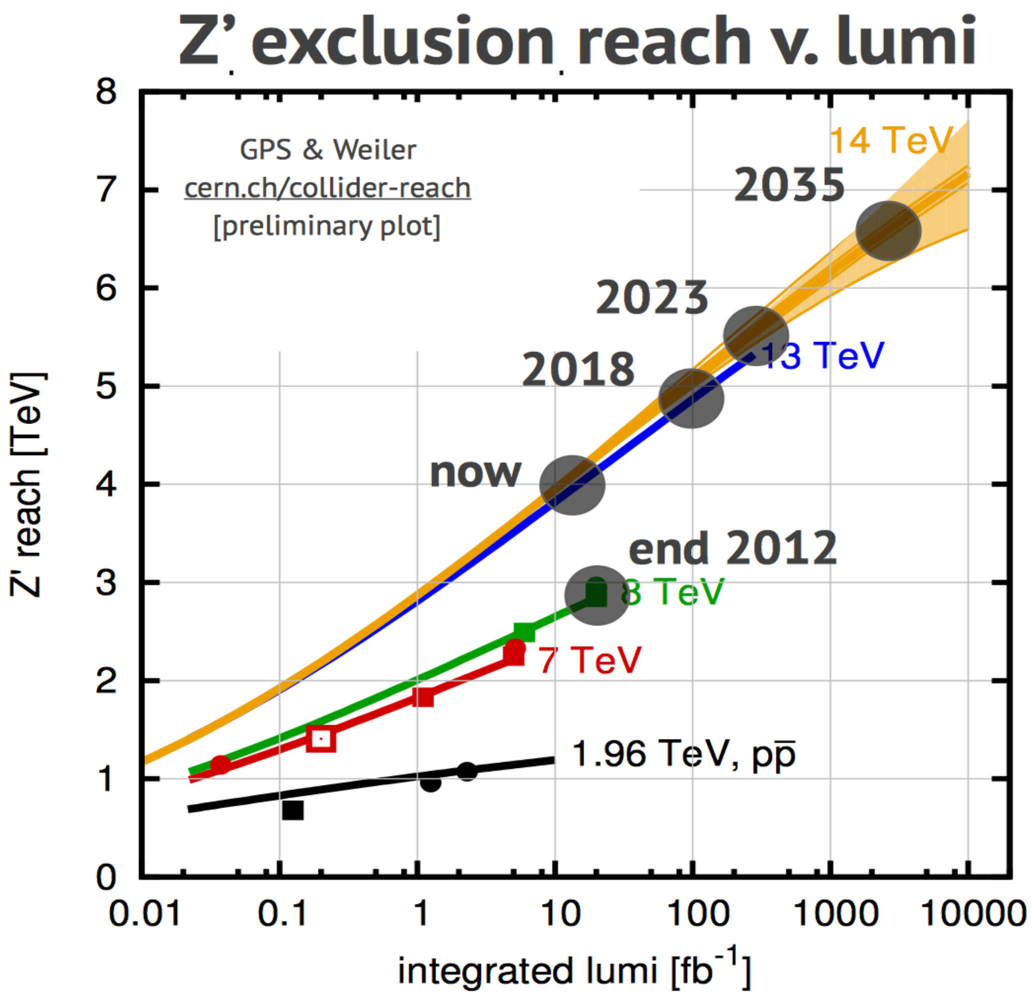
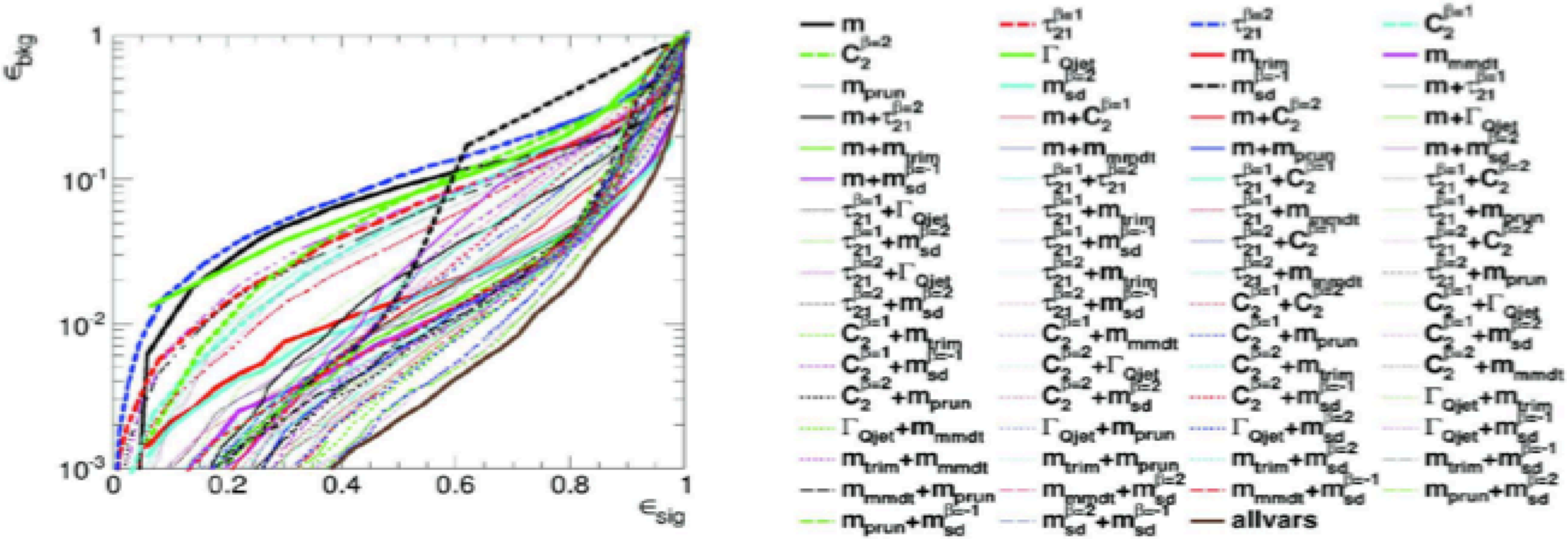
Shift focus to understanding tools



Plot taken from a talk by G. Salam

Increased center of mass energy and increase of collider reach implies shift from moderate to large boosts. How do tools hold up?

MC studies of tools



Until 2013 tools analysed using purely Monte Carlo methods over limited phase space regions. Does not give enough insight into physics. No way to assess theoretical control.

Is this the best we can do after 4 decades of QCD studies?

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Theory issues

OR WHY ITS NOT EASY TO GO BEYOND MC AND THEIR LIMITATIONS

Large logarithms

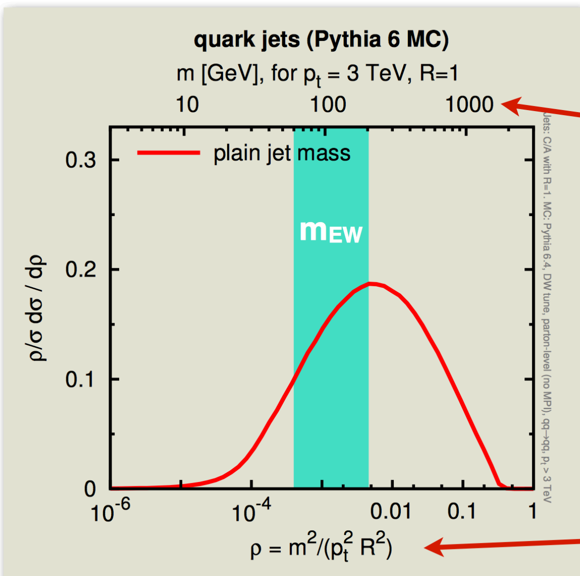
$$\frac{1}{\sigma}\frac{d\sigma}{dm_j^2} \sim \frac{1}{m_j^2}\frac{C_i\alpha_s}{\pi}\ln\left(\frac{R^2p_t^2}{m_j^2}\right)$$

$p_t >> m_j$

- Large logarithms in boosted regime mean fixed-order QCD has limited use.

- Resummed calculations are complicated and not generally possible to high accuracy. Partially included in parton showers.

Large logarithms and resummation



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!

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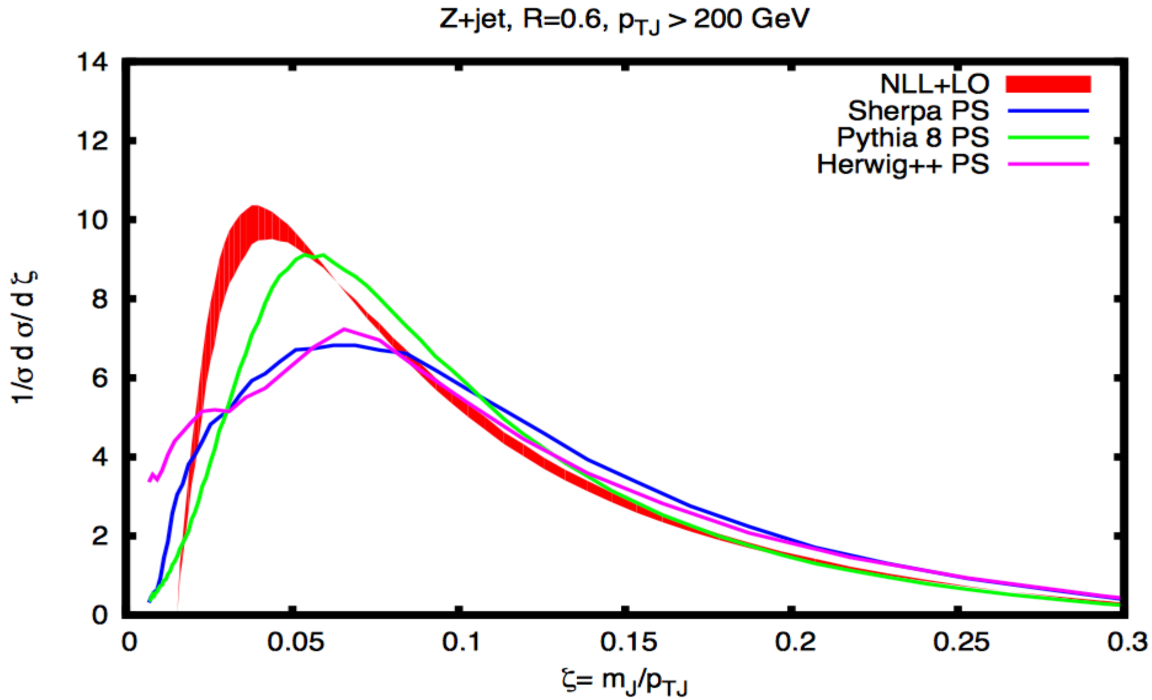
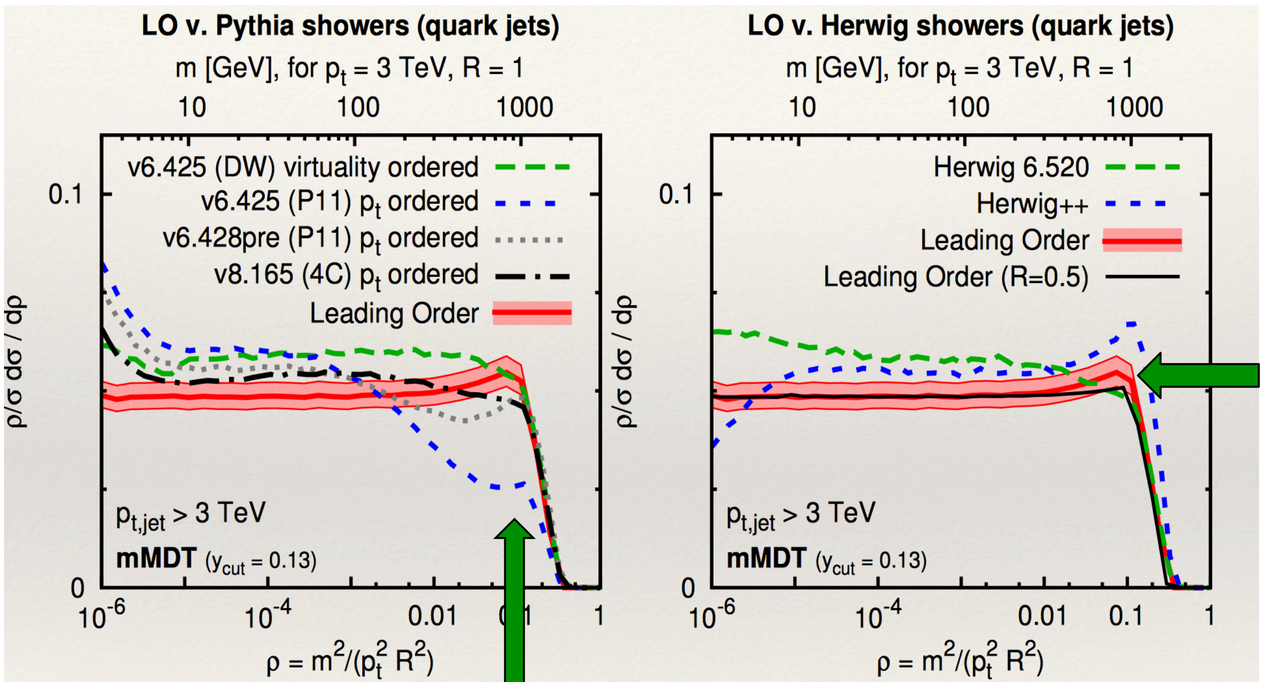
Why not just use showers?



Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky 2012

Large differences between showers at parton level. Keep in mind for q/g studies later.

Limitations of showers



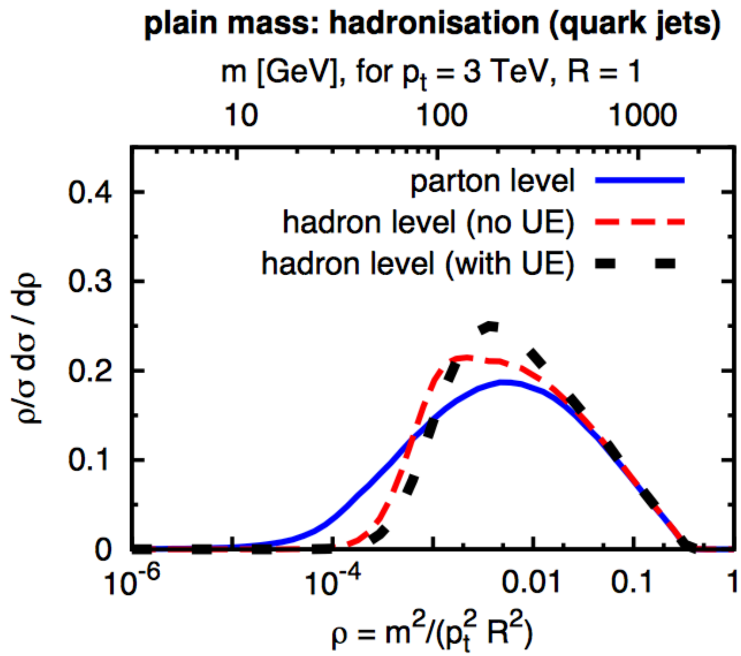
Bump at larger masses not in most showers

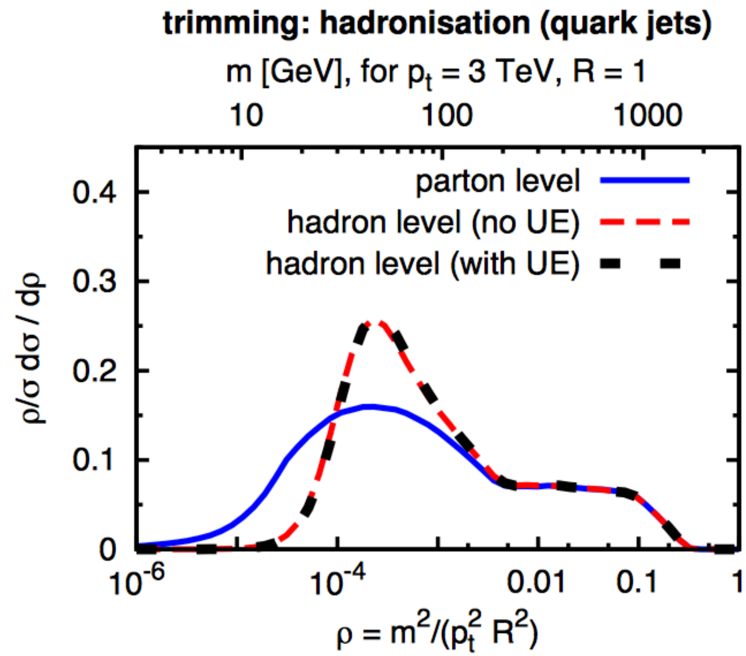
Pythia 6 p_t ordered fails

Jet masses with "mass drop" tagger

Different MC showers don't always agree.

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.

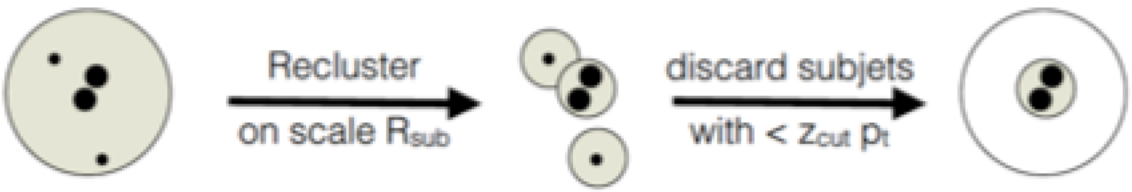
$$m_j^2 \sim \Lambda p_T R^2$$

NP bumps visible but where NP = Non-Perturbative!

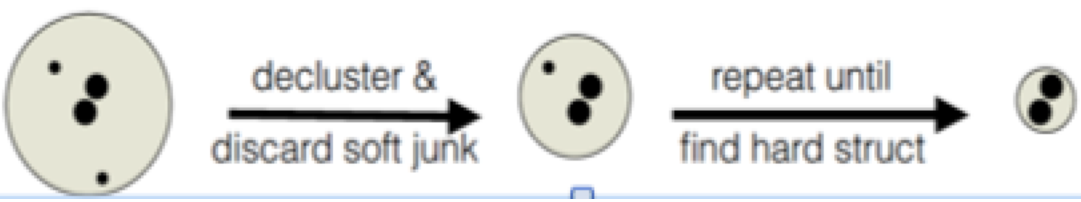
Recent progress

Progress in understanding tools

Trimming Krohn, Thaler, Wang 2010



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



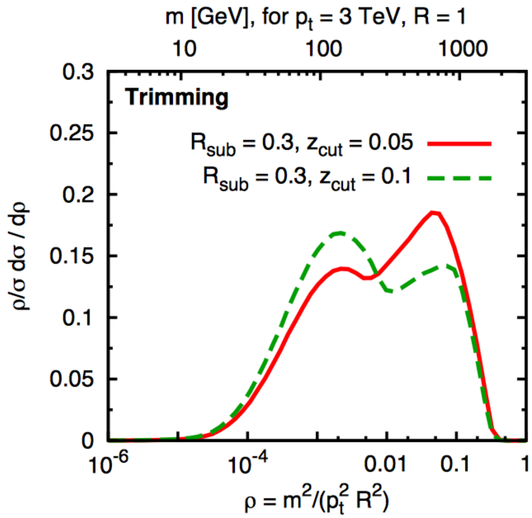
$$\frac{\min(p_{ti}, p_{tj})}{p_{ti} + p_{tj}} > z_{\mathrm{cut}}$$

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

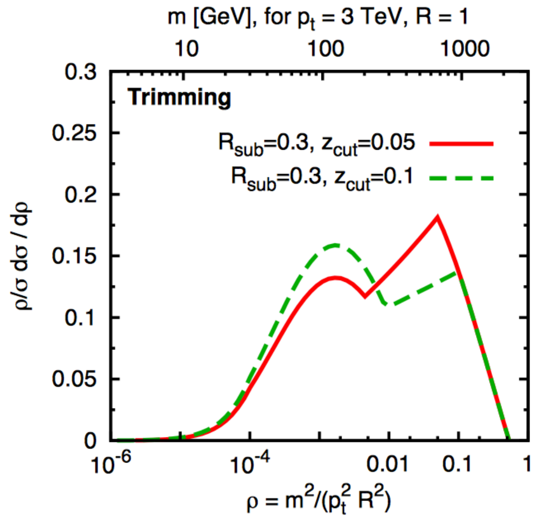
$\beta = 0$ **most commonly used which is the same as mMDT**

Analytical understanding of jet substructure

Monte Carlo



Analytic



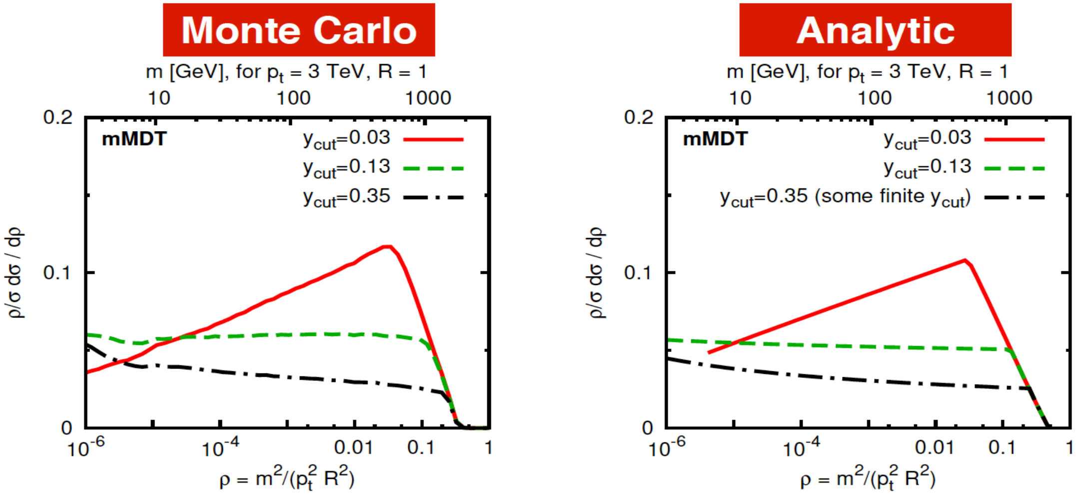
Jet masses with trimming

Bumps and kinks for QCD background. Only found after analytics

MD, Fregoso, Marzani, Salam 2013

Many tools are now understood from first principles analytic resummed calculations. Shower model independent. Clearly shows up flaws and reveals features.

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.
- SoftDrop generalisation of mMDT also shares this property.

Dasgupta, Fregoso, Marzani and Salam 2013

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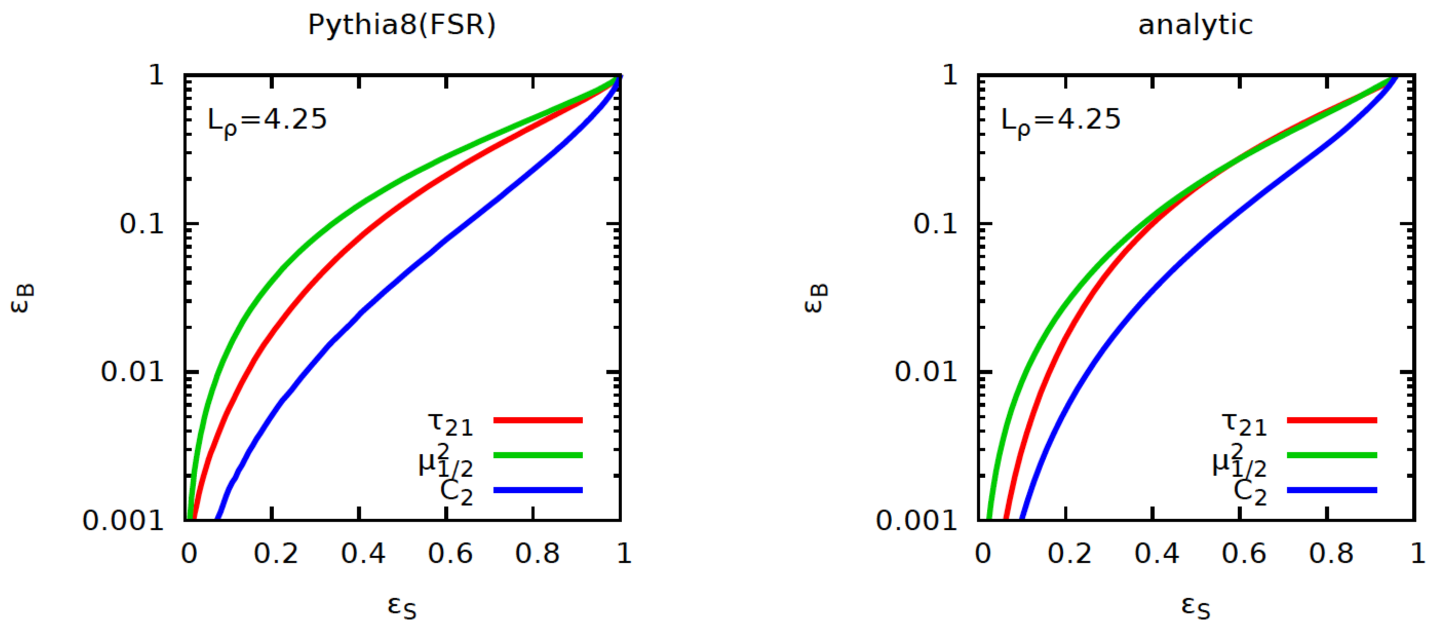
Monte Carlo v Analytic

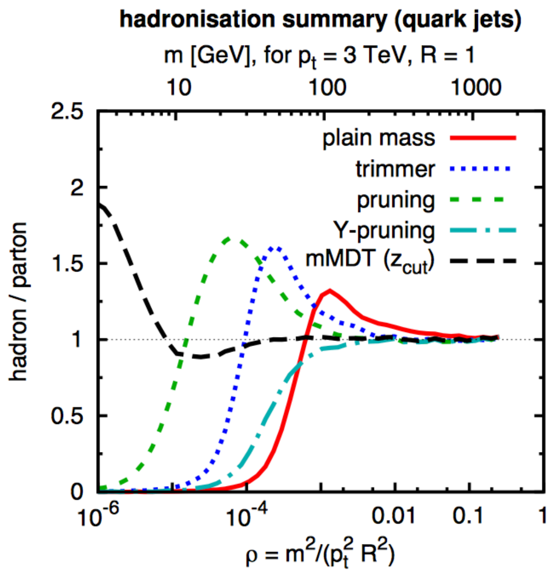
First understanding for jet shapes:

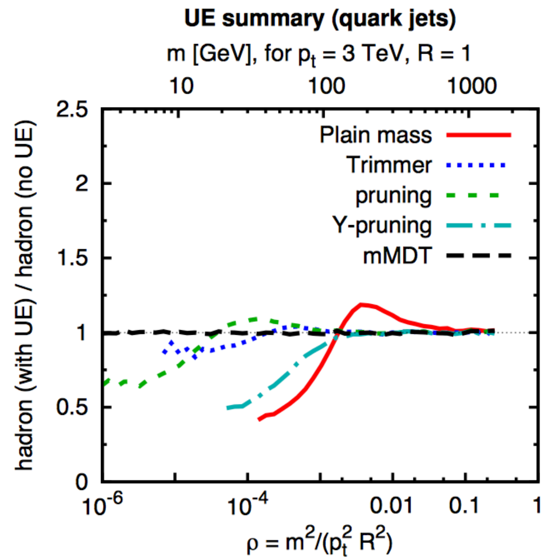


Analytic understanding for radiation constraining jet shapes

Dasgupta, Soyez and Schunk 2015. See also Larkoski, Moult and Neill 2015 for dedicated calculation of C_2.

Reduced non-perturbative effects

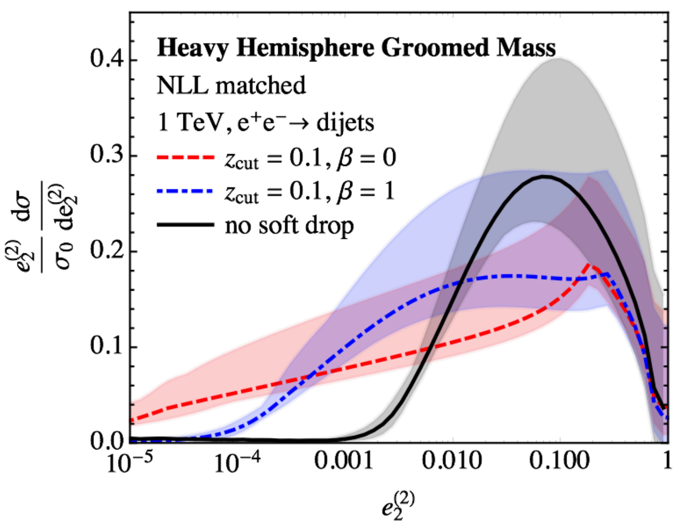


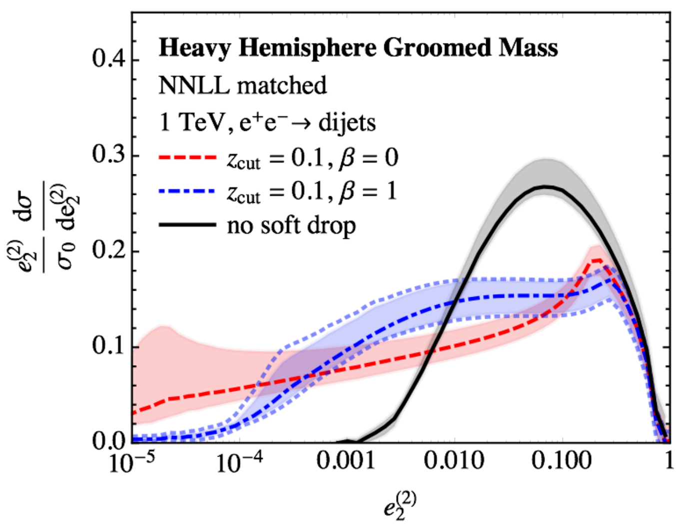


Tools designed which are more robust against NP effects : mMDT and SoftDrop.

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

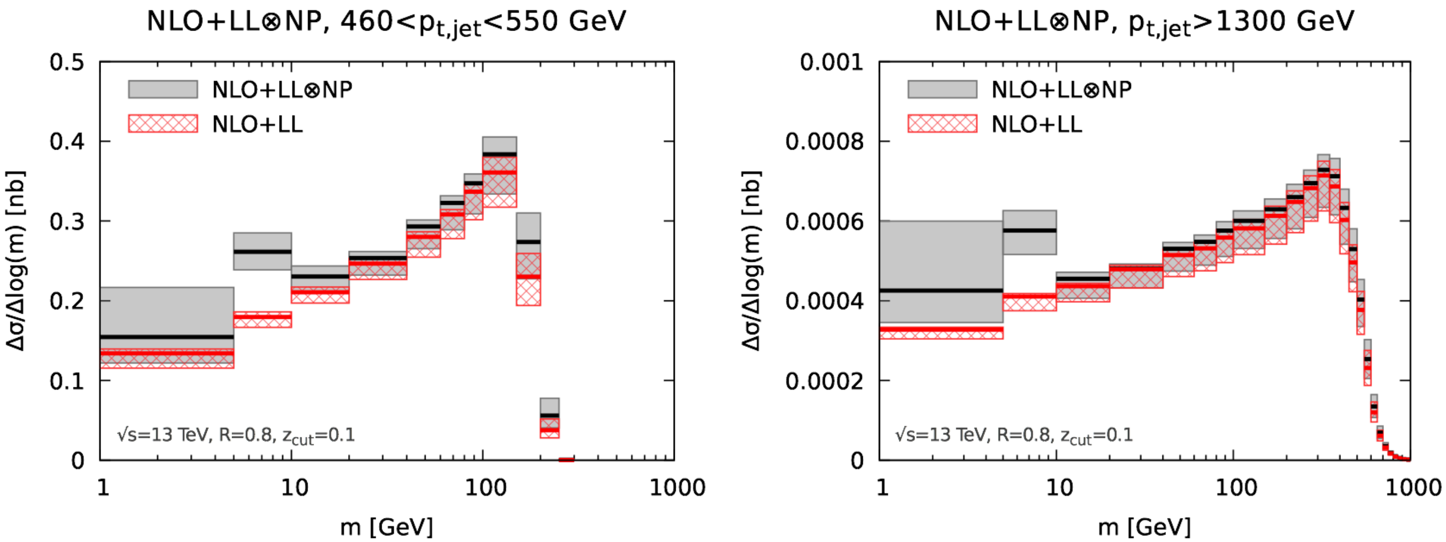




Higher log accuracy calculations for mMDT and SoftDrop.

Frye, Larkoski, Schwartz, Yan 2016

Phenomenology for substructure

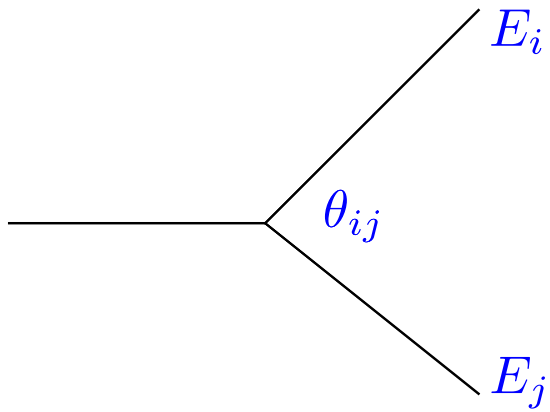


Matched resummed calculations with NP effects for mMDT.
Should be directly compared to LHC data.

Marzani, Schunk, Soyez 2017

Designing new high performance tools

Y splitter



Butterworth, Cox, Forshaw, 2002

Not a new tool in itself

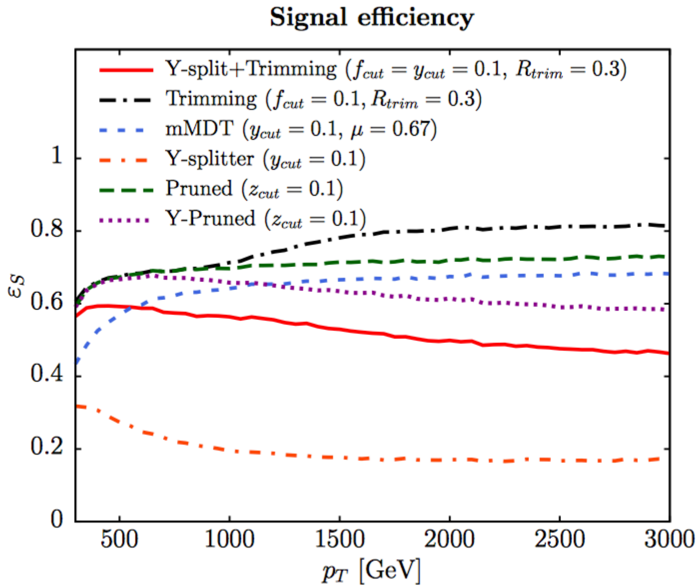
- Decluster a jet into 2 subjets using the kt distance measure

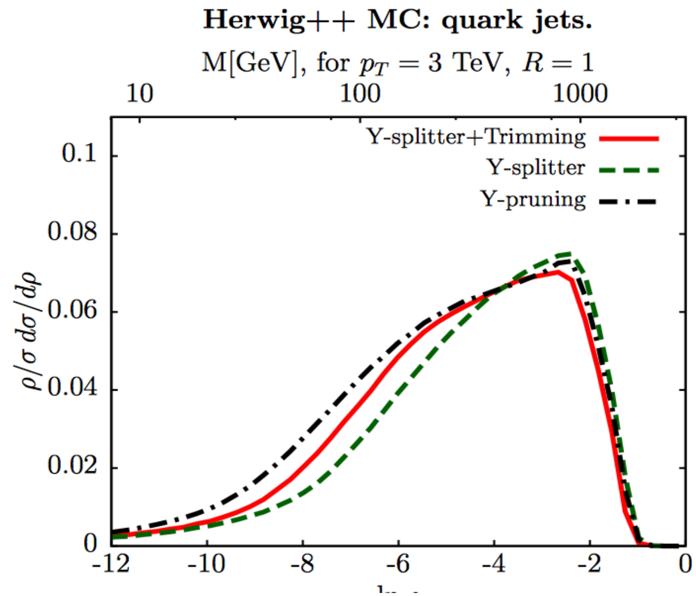
- Ask for a cut forcing prongs to be more "symmetric" i.e. a Y configuration

$$\frac{k_{t,ij}^2}{m_j^2} \approx \frac{\min(E_i, E_j)}{\max(E_i, E_j)} > y_{\rm cut} \quad \text{OR} \quad \frac{\min(E_i, E_j)}{E_i + E_j} > z_{\rm cut}$$

Tag jet if passes cut or discard

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.

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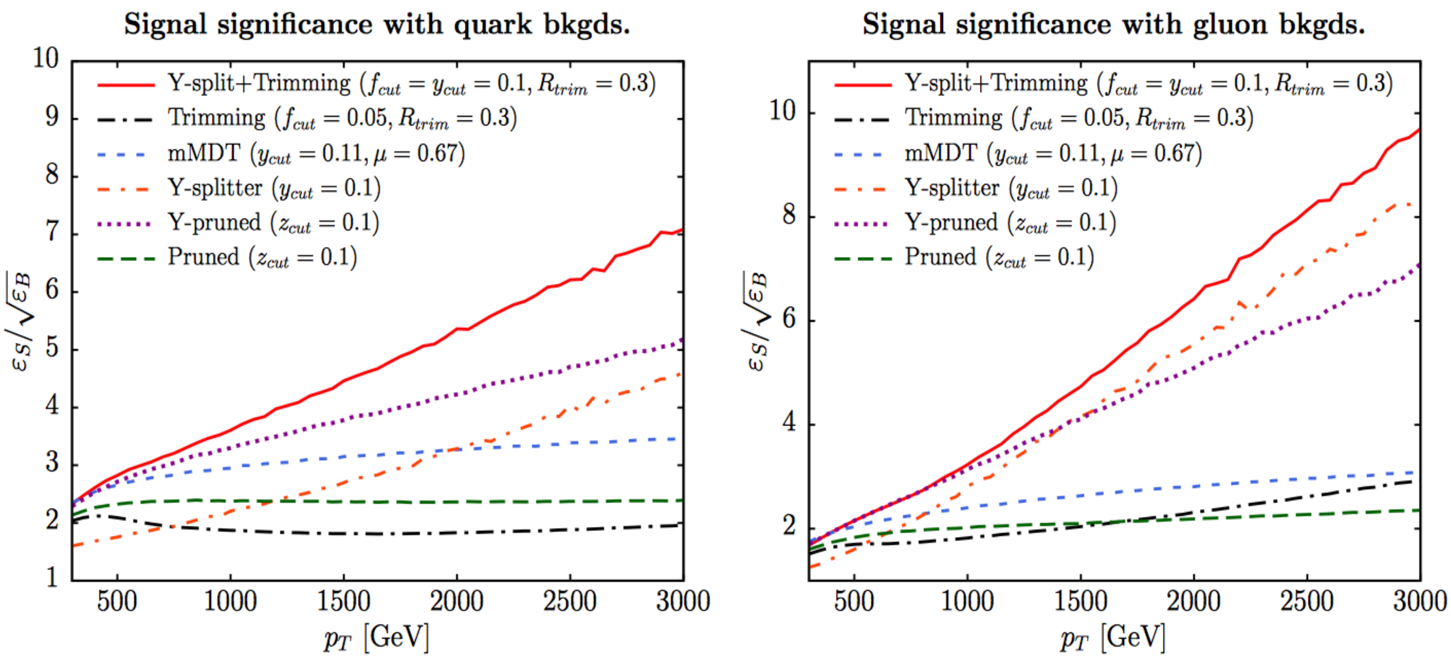
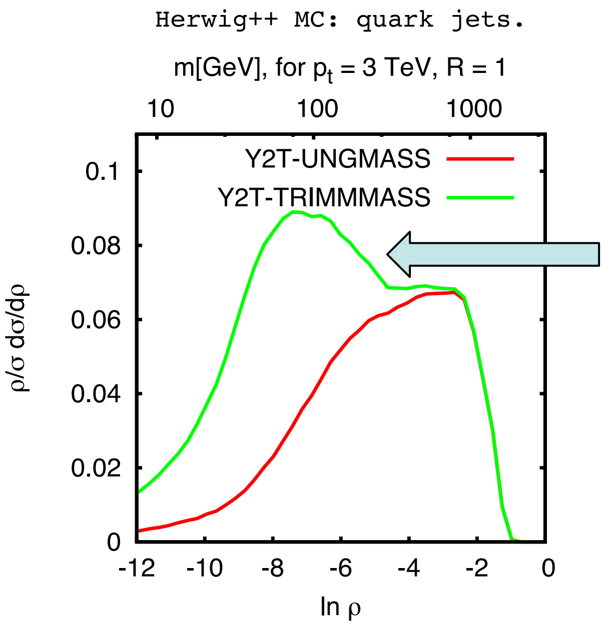
Performance for searches

MD, Powling and Siodmok, 2015 MD, Powling, Schunk. Soyez, 2016



Pretty decent for such an ancient tool albeit supplemented with grooming! Performance similar with grooming using mMDT but trimming works best

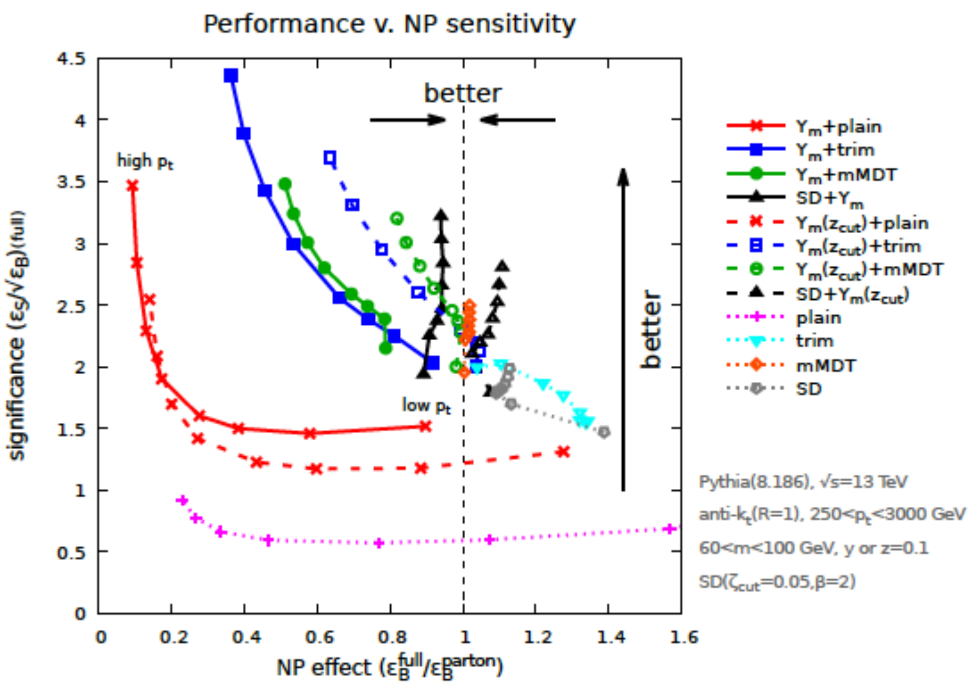
Grooming + Y-splitter



Result looks like trimming. Poor performance

Does not work in reverse order. Order in which tools are used matters. Also understood from analytics.

Performance v NP sensitivity



Trade off between sheer performance and robustness. An important feature seen in taggers, jet shapes and q/g discrimination.

Summary

Several jet substructure tools have been developed rapidly over the last few years.

The field is now more mature and one needs to work on theoretical control over results.

One of the key questions to address is how to approach the sensitivity to NP effects.

To what extent should methods and results for exploring the TeV scale depend on our knowledge of QCD at 1 GeV?

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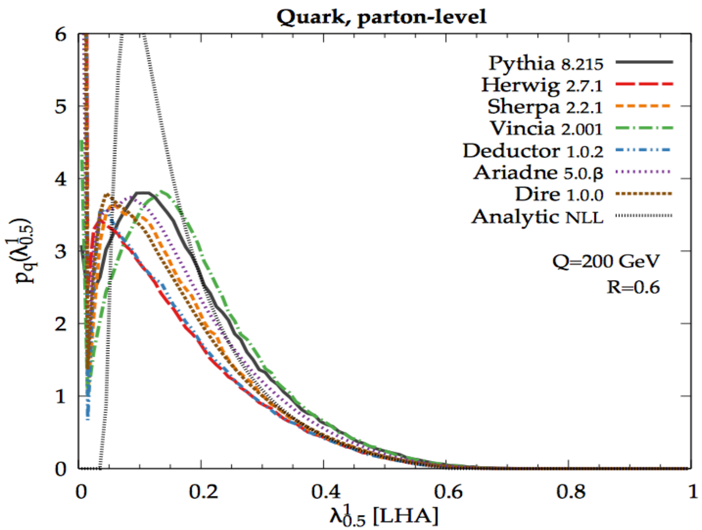
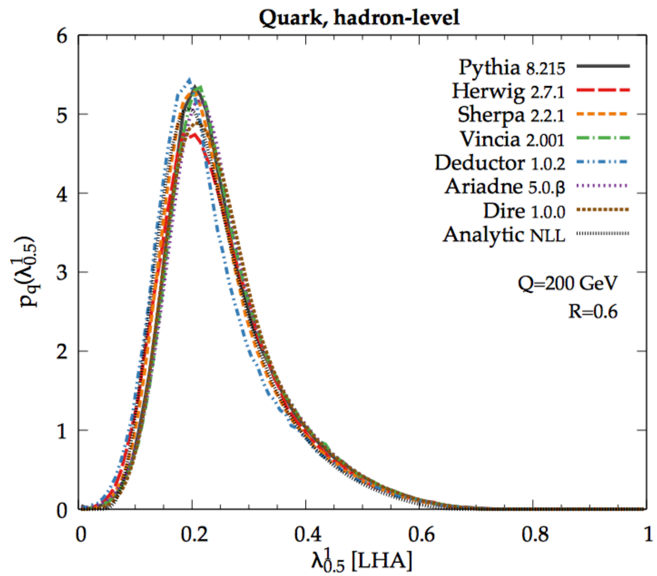
Quark/Gluon discrimination





Use generalised angularities

$$\lambda^\kappa_\beta = \sum_{i \in \mathrm{jet}} z_i^\kappa \theta_i^\beta,$$

$\kappa = 1$ are IRC safe . More robust but not necessarily better discriminators. Focus on LHA with $\beta = 0.5$

A problem at the interface of PT and NP

Soyez, Thaler et.al 2017

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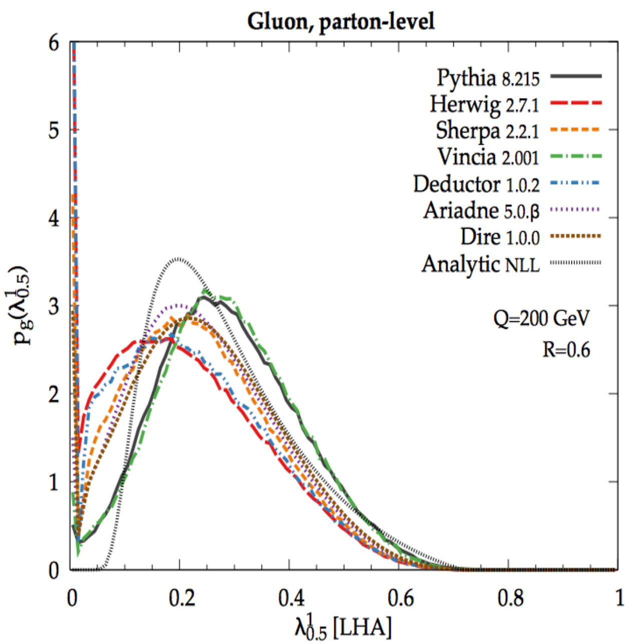
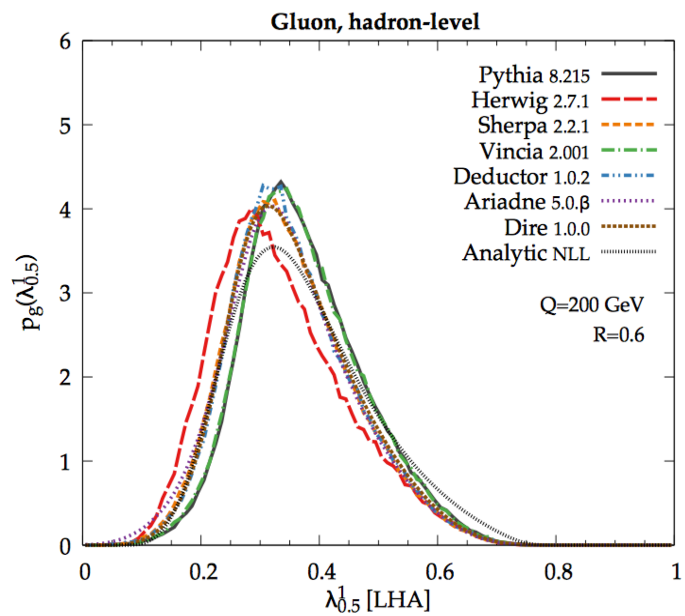
Quark/Gluon discrimination

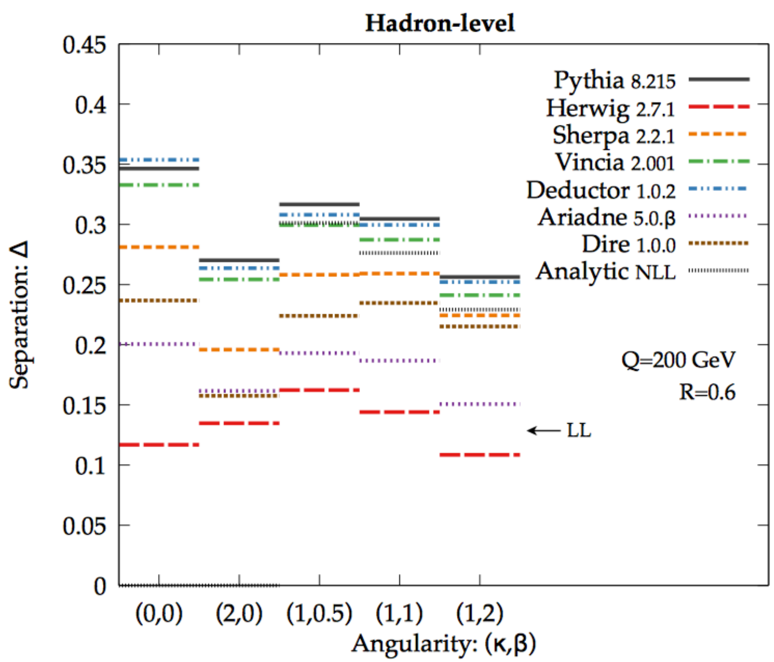




Differences between generators persist at hadron level for gluon jets. For quark jets LEP tunes clearly help but more work is needed on gluon jets.

Soyez, Thaler et.al 2017

q/g Separation Power



$$\Delta = \frac{1}{2}\int d\lambda\, \frac{\left(p_q(\lambda) - p_g(\lambda)\right)^2}{p_q(\lambda) + p_g(\lambda)} = 1 - 2\int d\lambda\, \frac{p_q(\lambda)\, p_g(\lambda)}{p_q(\lambda) + p_g(\lambda)}$$

Significant differences between event generators.

β dependence in these studies is opposite to that of previous ATLAS studies.

Need for precise LHC measurements of angularities to tune event generators and constrain gluon jets better.

Soyez, Thaler et. al 2017