MANCHESTER 1824

The University of Manchester

Jet substructure on the back of an envelope

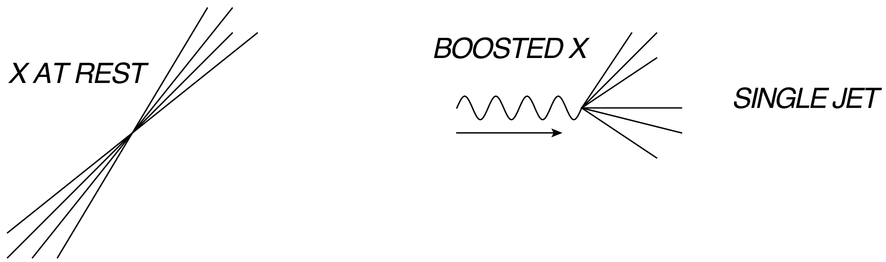
Mrinal Dasgupta

Muenster workshop on Parton Showers, Event Generators and Resummation, June 10-12, 2014

Based on published work with Gavin Salam, Simone Marzani, Alessandro Fregoso and Alex Powling and work in progress with Andrzej Siodmok and Alex Powling.

The University of Manchester

Jet substructure at the LHC



Since 2008 a vibrant field has emerged based on using jet substructure to discover highly boosted new particles at the LHC. Exploits a situation when $p_T >> M_X$.

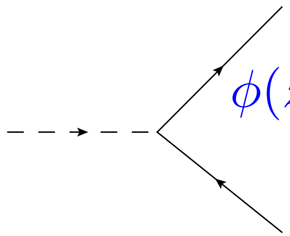
Seymour 1993, Butterworth, Davison, Rubin and Salam 2008

Well over 100 papers in the last 5 years and its own dedicated conference.

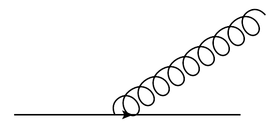
Note: Registration is now open for BOOST 2014 at UCL

http://www.hep.ucl.ac.uk/boost2014/

Jet substructure for signal vs background



$\phi(z) \propto 1$



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

2 main handles to play with

- Backgrounds favour asymmetric splittings while signals do not. QCD radiation is enhanced in soft and collinear regions.
- For colour singlet signals soft large-angle radiation is cut off due to angular ordering. This suggests cutting on wide-angle emissions will beat down backgrounds without affecting signal.

Numerous ways to achieve these goals. 10-20 methods have been invented and tested against MC results.

Substructure methods

- Commonly studied methods include : mass-drop, pruning and trimming techniques, N subjettiness, template overlap, energy correlation functions, shower deconstruction, planar flow and several others.

For a review see : BOOST 2012 proceedings arXiv:1311.2708 and references therein.

- Introduce several new parameters (energy/angular cuts) in addition to those already inherent in jet finding. Appear at first sight to be complex sophisticated tools.

Questions that arise can include:

- Potential duplication and redundance?
- Issues of robustness ,dependence of results on parameters, jet algorithms, kinematics etc ?
- Calculability, IRC safety etc ?
- Performance – is there a “best” tagger? How do we compare tools meaningfully?

MC vs analytic studies

- The easiest way to test statements on taggers is via Monte Carlo.
- These studies do not always bring the required insight. Hard to run for all parameter combinations across huge range of kinematics from few hundred Gev to multi-Tev and R=0.4 to R ~ 1.

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 report

Analytical approach?

- Can we describe action of taggers with pQCD calculations?
- If not should we be using them?

  Don't want to rely on 1 GeV physics to make discoveries at TeV scale.
- If yes do we need fixed-order or parton-showers/resummation?
- Can we resum logs for such complicated observables?

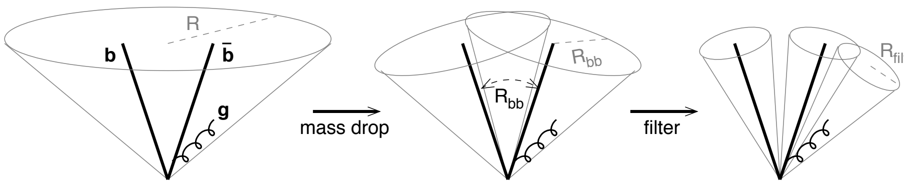
Schwartz, Boost 2012

Precision QCD

MANCHESTER 1824

The University of Manchester

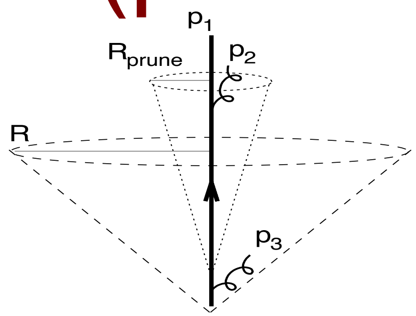
Definitions (MDT)



- Break the jet j into subjets j_1 and j_2 such that $m_{j1} >$ mj2
- If there is a mass-drop $m_{j1} < \mu m_j$ and not too asymmetric splitting $y = \min(p_{tj_1}^2, p_{tj_2}^2)\Delta R_{j_1 j_2}^2/m_j^2 > y_{\rm cut}$ tag the jet j else recurse to j_1
- Note that we modified the tagger to follow higher p_t branch - more amenable to resummation. Modified mass-drop tagger.

Butterworth, Davison, Rubin, Salam 2008
Dasgupta, Fregoso, Marzani, Salam, 2013

Definitions (pruning, trimming)



Pruning sets a radius R_{prune} ~ m/p_t and reclusters the jet such that if 2 objects are separated by angles larger than this and $\min(p_{ta}, p_{tb}) < z_{\mathrm{cut}} p_{t,(a+b)}$ then the softer object is discarded.

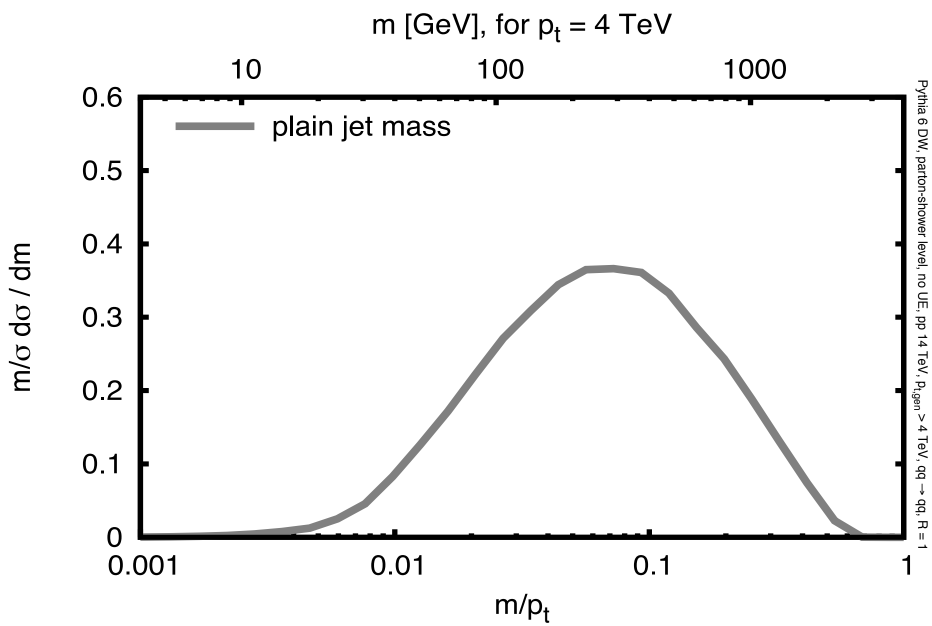
Trimming uses a fixed radius $R_{trim.}$

Current understanding

- Analytical studies have paved the way for a sophisticated understanding of this sub-field.

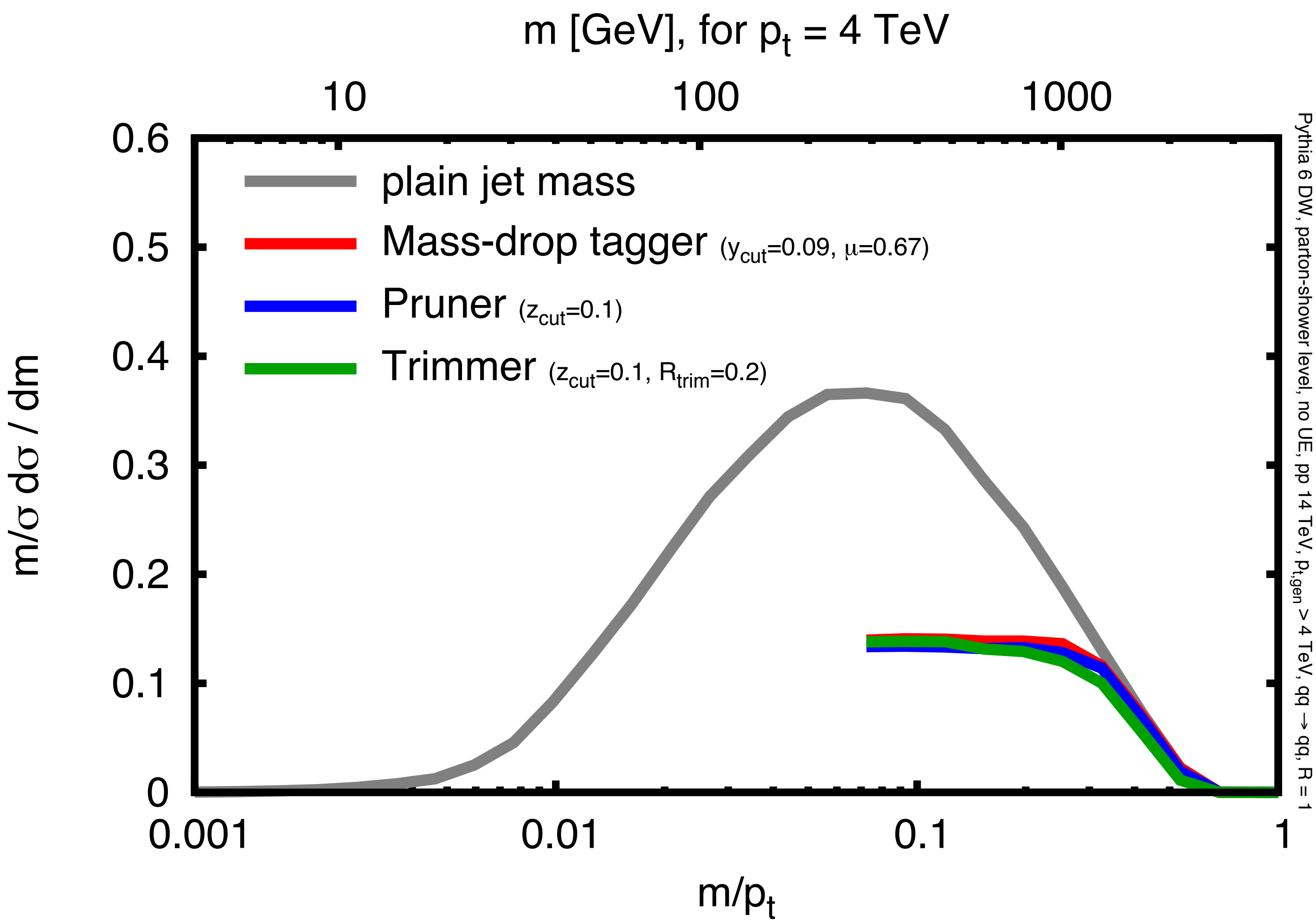
MD, Fregoso, Marzani, Salam, Powling, 2013

- Post analytics we can do the “right” MC studies too.

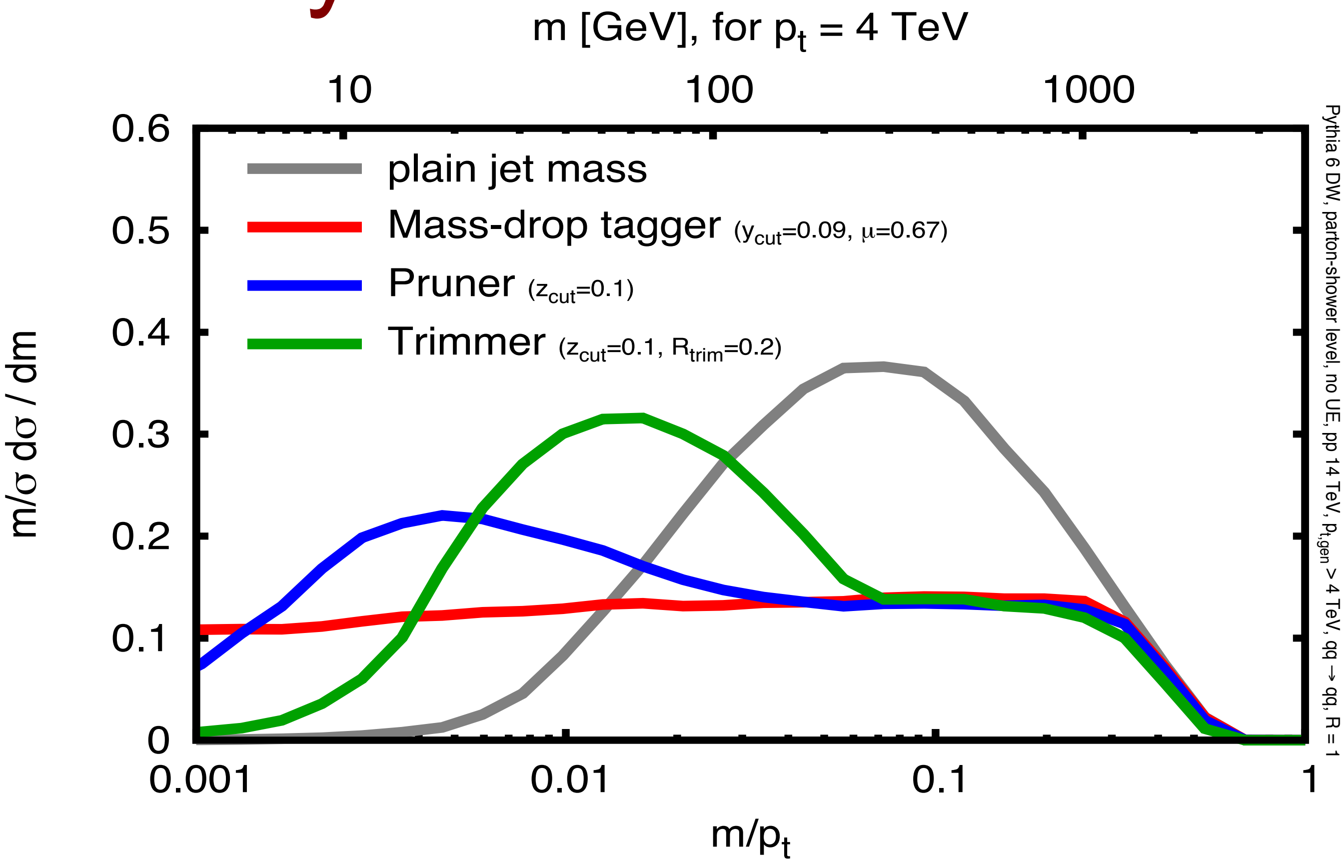


The University of Manchester

Taggers look similar



But only over limited mass range

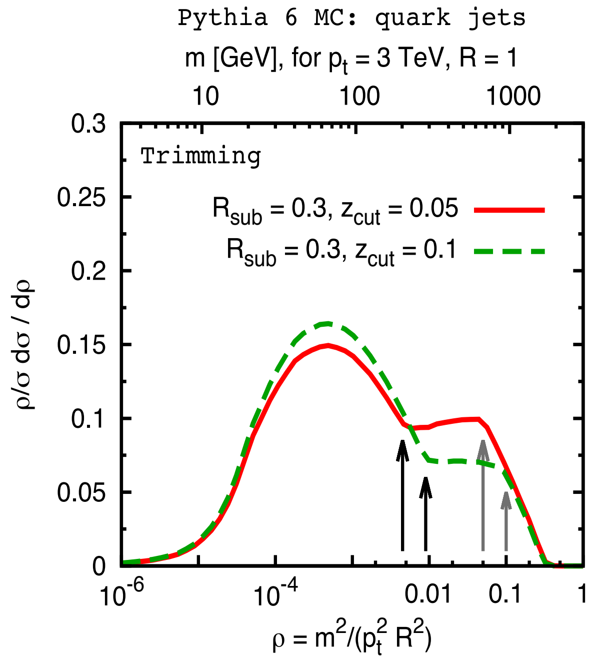


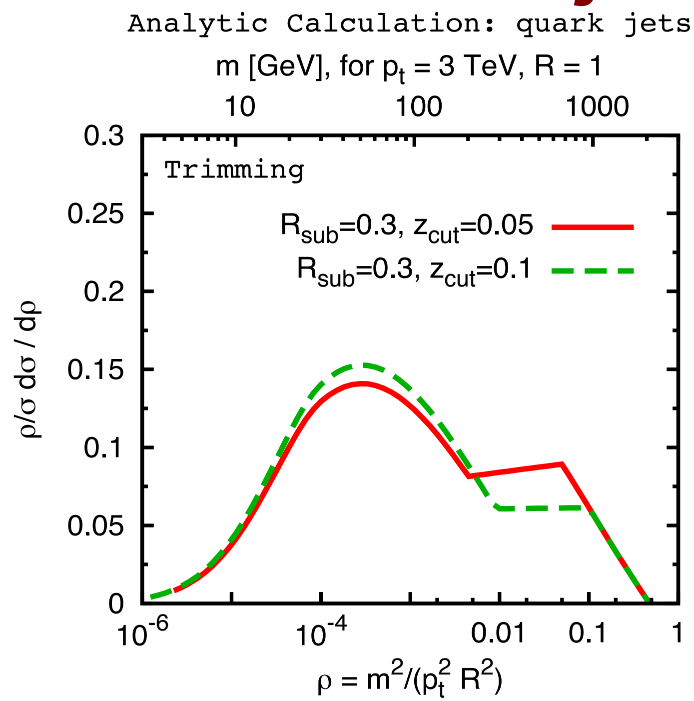
How do we understand these shapes? Position of kinks, peaks etc? Needs analysis and calculation.

The University of Manchester

MANCHESTER 1824

Analytical Results for QCD jets



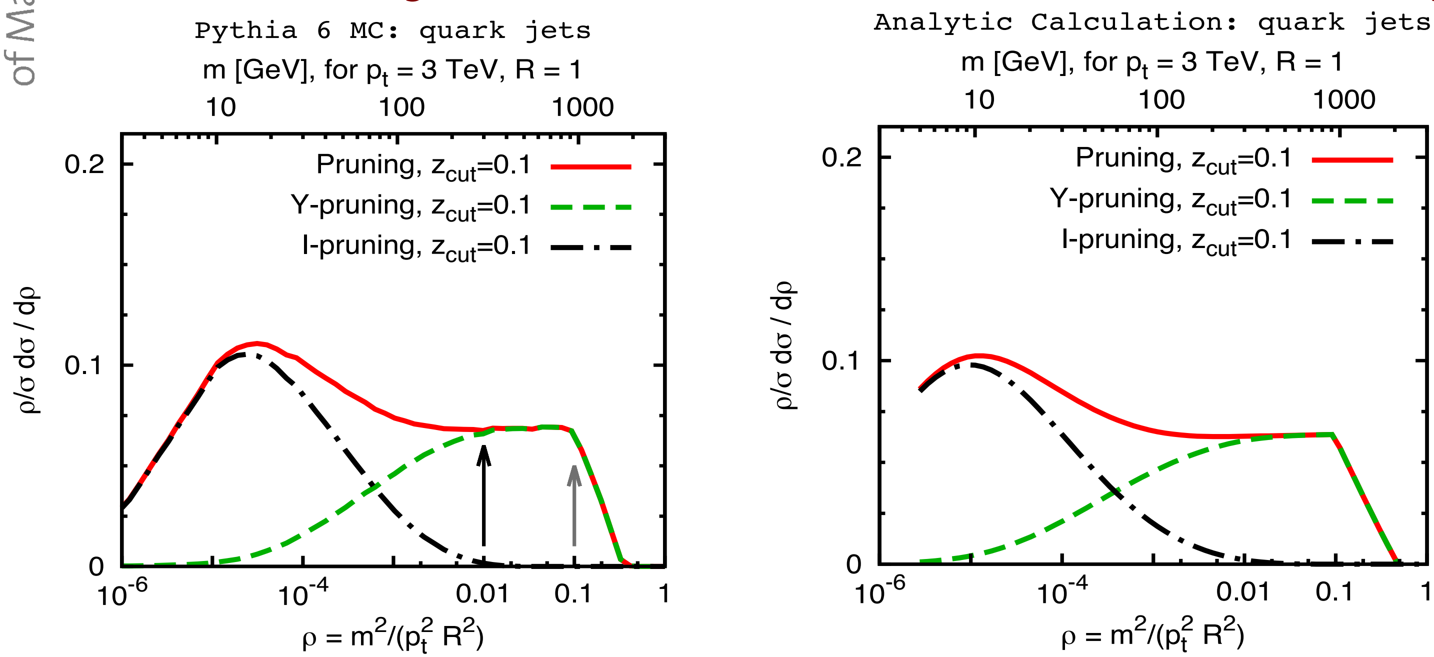


$$\rho\frac{\partial}{\partial\rho}\exp\left[-C_F\frac{\alpha_s}{2\pi}\left(-\frac{3}{2}\ln\frac{1}{\rho}+\Theta\left(\rho-z\right)\ln^2\frac{1}{\rho}+\Theta\left(z-\rho\right)2\ln\frac{z}{\rho}\ln\frac{1}{z}+\Theta\left(zr^2-\rho\right)\ln^2\frac{zr^2}{\rho}\right)\right]$$

Trimming MC vs analytical

Dasgupta, Fergoso, Marzani, Salam 2013

Analytical results for QCD jets

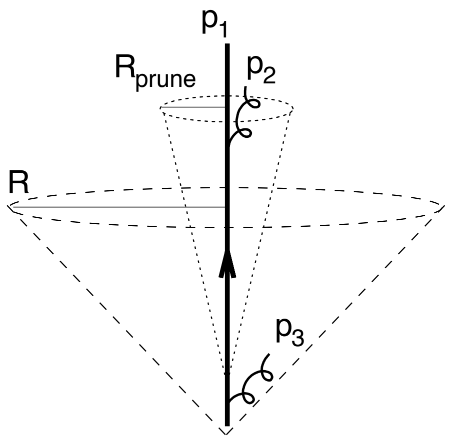


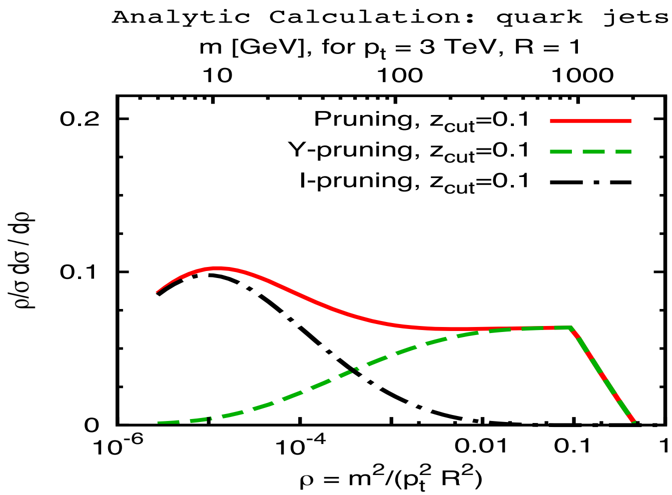
Pruning has a more complicated/interesting structure. LO result is single logarithmic

$$\rho \frac{d\sigma}{d\rho} \sim \alpha_s \ln \frac{1}{z_{\mathrm{cut}}}$$ LO (First term of Y pruning)

$$\rho \frac{d\sigma}{d\rho} \sim \alpha_s^2 \ln^3 \frac{1}{\rho}$$ NLO (First term of I pruning)

I pruning vs Y pruning



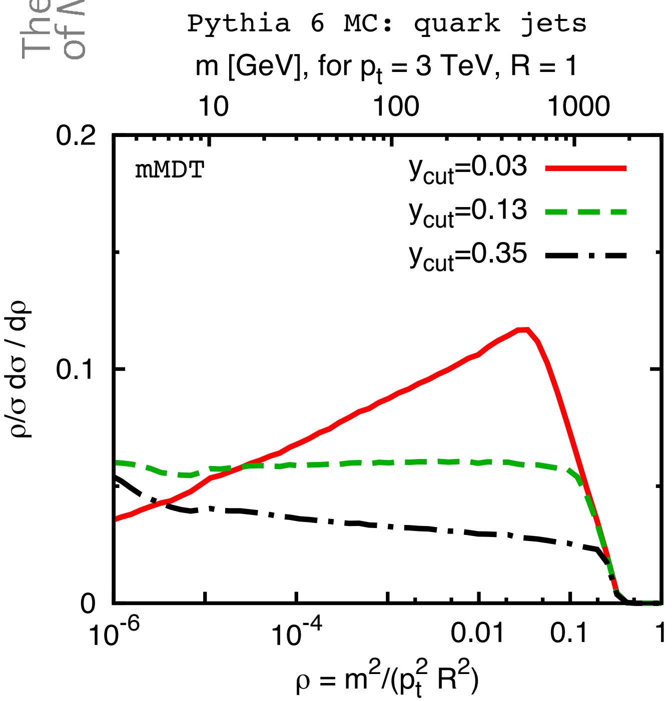


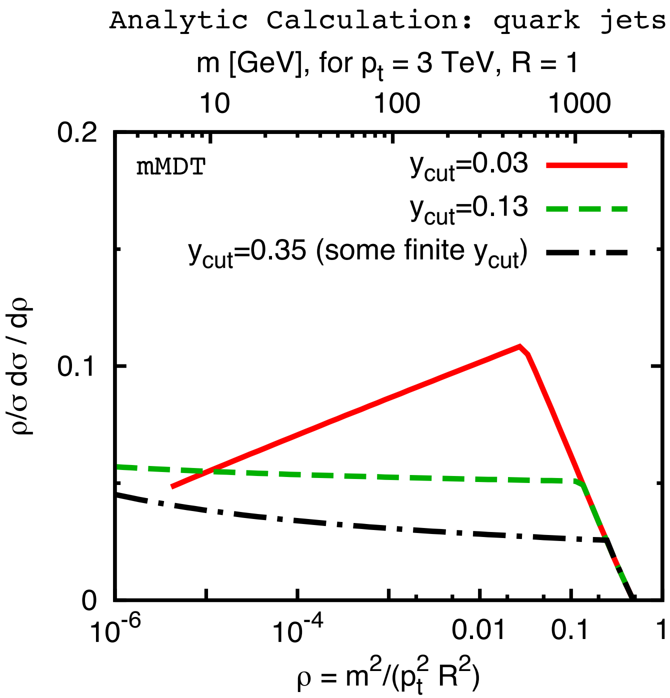
$$\frac{\rho}{\sigma}\frac{d\sigma^{\mathrm{Y-prune}}}{d\rho} \sim \frac{C_F\alpha_s}{\pi}\left(\ln\frac{1}{z_{\mathrm{cut}}}\right)\exp\left(-\frac{C_F\alpha_s}{2\pi}\ln^2\rho\right)$$

I pruning eliminated by demanding that at least one emission is tested and passes the pruning cut. Y pruning has one log less but benefits from a double log suppression.

MD, Fregoso, Marzani and Salam 2013

Analytical results for QCD jets





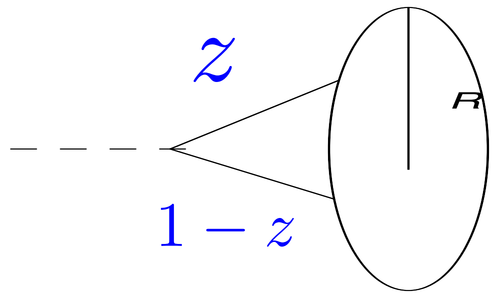
$$\rho \frac{\partial}{\partial \rho} \exp\left[-C_F \frac{\alpha_s}{\pi}\left(\ln\frac{1}{y_{\mathrm{cut}}}\ln\frac{1}{\rho} - \frac{3}{4}\ln\frac{1}{\rho}\right)\right]\ ,\ \rho < y$$

mMDT has a unique single log structure. Can produce a flat background. No non-global logs. May even be a good variable for strong coupling extraction!

The mass drop tagger seems not to depend on mass drop !

MD, Fregoso, Salam, Marzani 2013

What about signal processes?



$$\theta_{bb}^2 \sim \frac{m_H^2}{p_T^2 z(1-z)}$$

Let us take $H \to b\bar{b}$ in V+H production as an example and work in the narrow width limit.

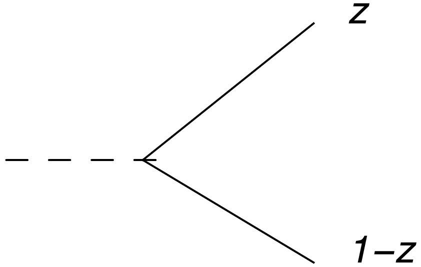
- Taggers exhibit similarities and differences already at tree level in cases.
- Then one has to analyse the response to ISR and FSR
- Shall impose a mass window $|M_j^2 - M_H^2| < 2M_H \delta M$

Signal processes tree level

We shall initially work in the formal limit

$$1 \gg R^2 \gg \Delta = \frac{m_H^2}{p_T^2}$$

but shall extrapolate our results to R ~ 1.



For plain mass

$$\epsilon_s = \int_0^1 dz\, \Theta\left(R^2 - \frac{m_H^2}{p_T^2 z(1-z)}\right) \sim 1 - \mathcal{O}\left(\Delta/R^2\right)$$

MANCHESTER 1824

The University of Manchester

Signal processes tree level

Mass drop and pruning

$$\epsilon_s = \int_y^{1-y} dz = 1 - 2y, \;\; y \gtrapprox \frac{\Delta}{R^2}$$

Trimming

$$\epsilon_s = \; (1-2y)\Theta\left(1-2y\right) + \sqrt{1-\frac{4\Delta}{r_{\rm trim}^2}}\Theta\left(\frac{1}{4}-\frac{\Delta}{r_{\rm trim^2}}\right)\Theta\left(y-\frac{1}{2}\right) +$$
$$\left(2y-1+\sqrt{1-\frac{4\Delta}{r_{\rm trim}^2}}\right)\Theta\left(\frac{1}{4}-\frac{\Delta}{r_{\rm trim^2}}\right)\Theta\left(\frac{1}{2}-y\right)\Theta\left(y-\frac{1}{2}\sqrt{1-\frac{4\Delta}{r_{\rm trim}^2}}\right)$$

Can we adjust parameters so as to lower background while maintaining signal? Also need to study radiative corrections from ISR and FSR.

MANCHESTER 1824

The University of Manchester

ISR effects for plain jet mass

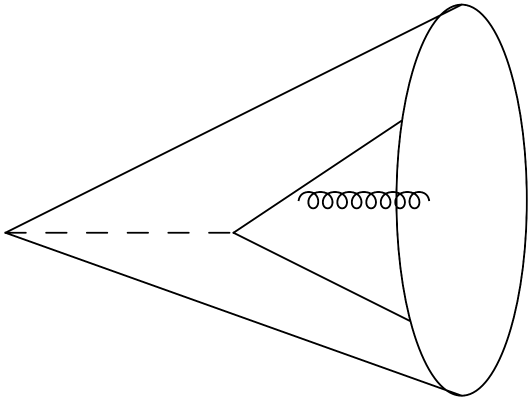
Compute the probability of staying within the mass window constraint $|M_j^2 - M_H^2| < 2M_H\delta M$

ISR contribution can be resummed with neglect of non-global logarithms for Cambridge Aachen R ~ 1.
Delenda, Appleby, Banfi, Dasgupta, 2006

$$\epsilon_s = \epsilon_0 \exp\left[-\frac{C_F\alpha_s}{\pi} R^2 \ln\left(\frac{p_T^2 R^2}{2M_H\delta M}\right)\right]$$

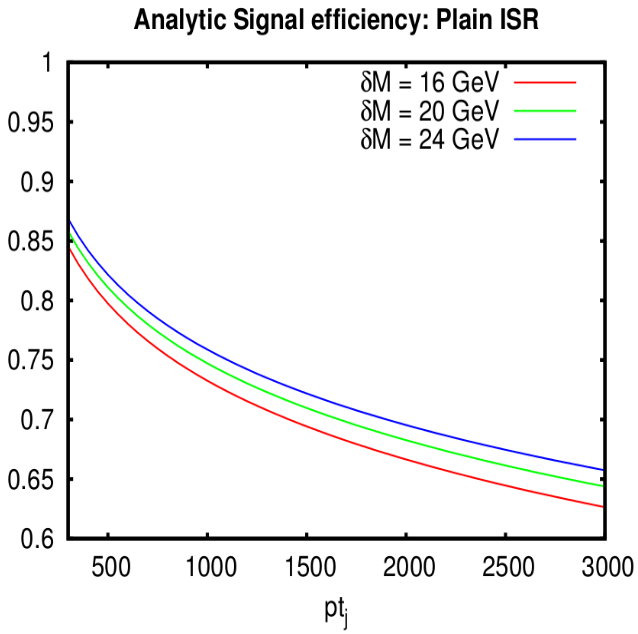
(fixed-coupling approximation)

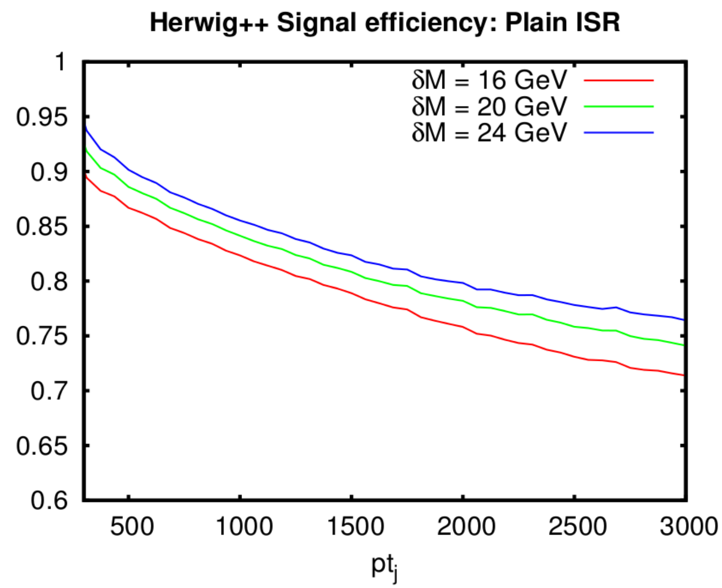
Plain jet mass



We can also do corresponding calculation for FSR. For $m/p_t << R$, angular ordering property suppresses radiation at large angles. Negligible contribution.

Plain mass results





Agreement with MC at the expected level. FSR minimal as expected. UE is dominant for R=1.

ISR for taggers

mMDT

$$\epsilon_S^{\mathrm{ISR}} \approx -C_F \frac{\alpha_s}{\pi} \int_0^1 \frac{dx}{x} d\theta^2 \Theta\left(x - \max\left(y_{\mathrm{cut}}, \frac{\Delta}{\theta^2+\Delta}\frac{1-\mu^2}{\mu^2}, \frac{2M_H \Delta M}{p_T^2\left(\theta^2+\Delta\right)}\right)\right)$$

At high p_T result goes as

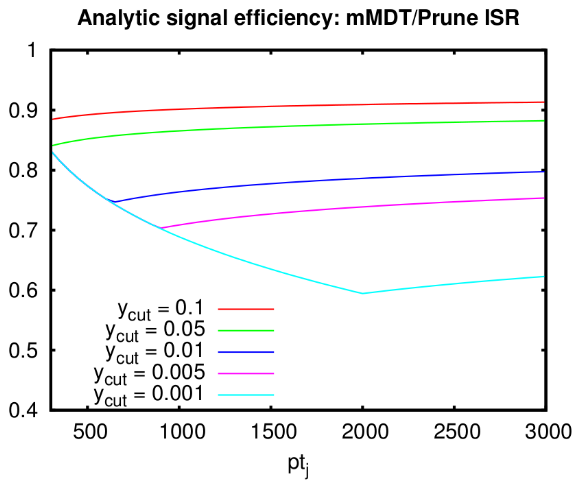
$$-C_F \frac{\alpha_s}{\pi} \ln \frac{1}{y_{\mathrm{cut}}}$$

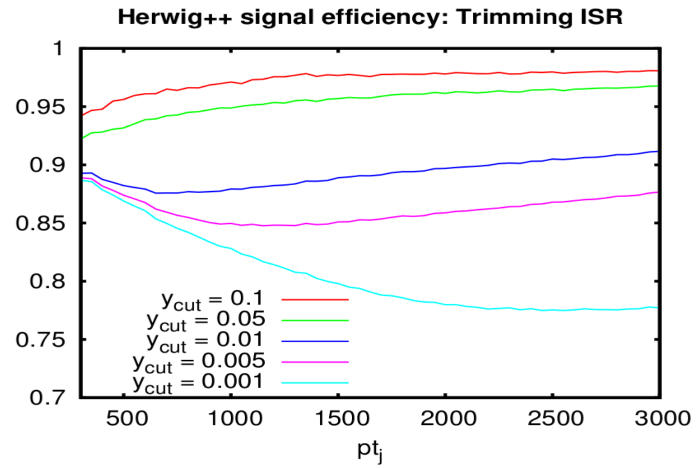
At lower p_T there will be a transition to the plain mass or a dependence on the mass drop parameter. One may also resum logs of $y_{cut.}$

The University of Manchester

MANCHESTER 1824

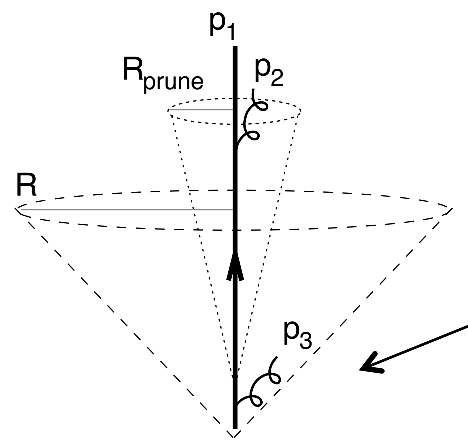
Other taggers





Pruning and trimming produce a very similar result for ISR. In reasonable agreement with MC.

Y pruning



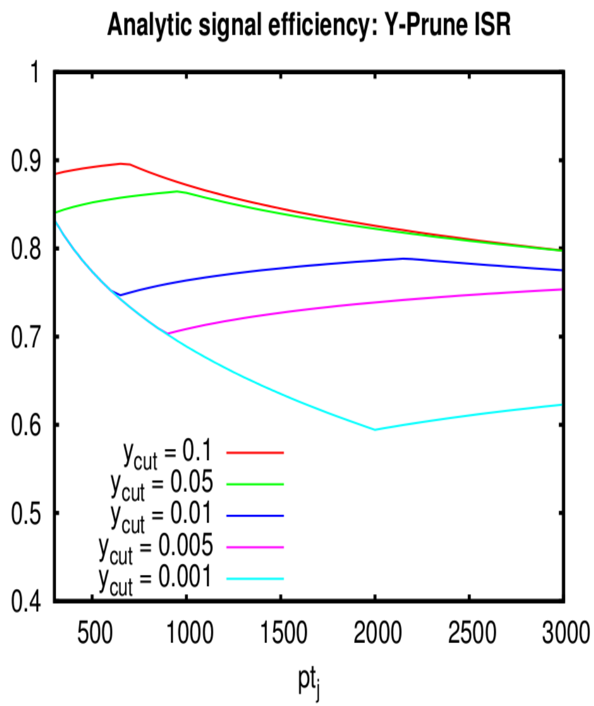
ISR gluon can set R_{prune} and change Y pruned to I pruned

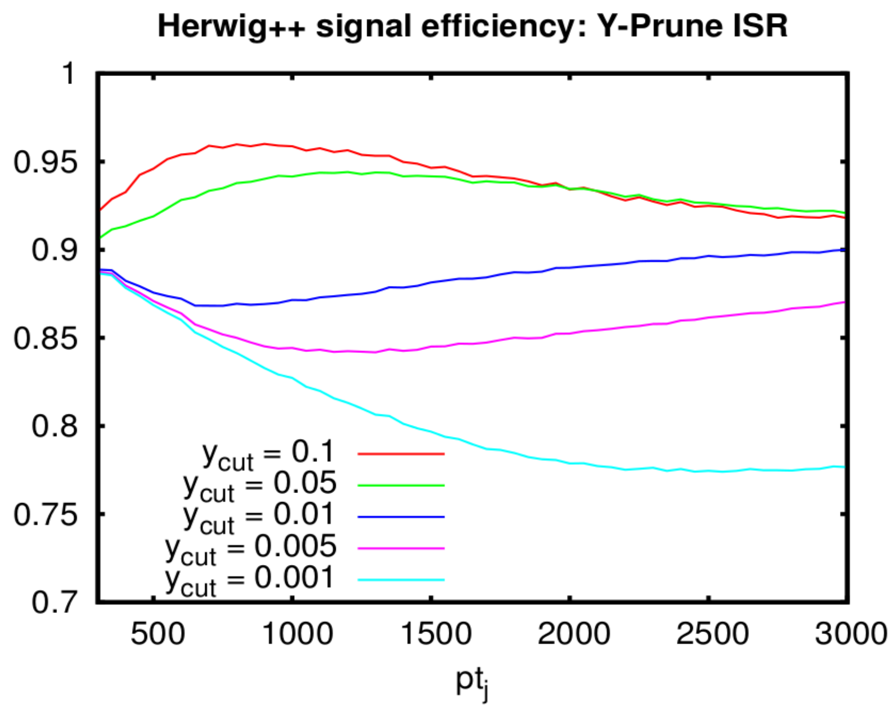
$$-C_F \frac{\alpha_s}{\pi} R^2 \ln \frac{y_{\rm cut}}{\Delta} \Theta\left(\beta - 3\right) \left[\sqrt{1 - \frac{4}{1+\beta}} \Theta\left(\frac{1}{1+\beta} - y_{\rm cut}\left(1 - y_{\rm cut}\right)\right) + \left(1 - 2y_{\rm cut}\right) \Theta\left(y_{\rm cut}\left(1 - y_{\rm cut}\right) - \frac{1}{1+\beta}\right) \right].$$

$$\Delta = \frac{m_H^2}{p_T^2} \qquad \beta = \frac{R^2 y_{\rm cut}}{\Delta}$$

Predicts loss of signal at high p_T

Y pruning



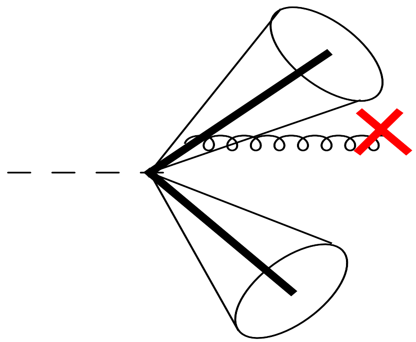


Again this feature agrees with HERWIG++

The University of Manchester

MANCHESTER 1824

Final state radiation



Contributes when emissions are removed by the taggers. Emissions are softer than y_{cut} p_T , emitted outside some angular region around the hard partons.

$\theta^2 > r^2_{\rm trim}$ for trimming

$\theta^2 > \frac{m_H^2}{p_T^2} = z(1-z)\theta^2_{b\bar{b}}$ for pruning

$\theta^2 > \theta^2_{b\bar{b}}$ for mMDT

The latter 2 are genuine soft large-angle corrections not described by angular ordering approximation

MANCHESTER 1824

The University of Manchester

FSR results

mMDT, pruning and Y pruning all take the form

$$\epsilon_S^{\mathrm{FSR}} = -\mathcal{A} C_F \frac{\alpha_s}{\pi} \ln \frac{y_{\mathrm{cut}}}{\epsilon}, \; y_{\mathrm{cut}} > \epsilon \qquad \epsilon = \frac{\delta M}{M_H}$$

with $\mathcal{A}$ arising from from angular and z integrals. For mMDT $\mathcal{A}$ ~ 0.6 with a small p_T dependence.

For pruning and Y pruning $\mathcal{A} \sim \frac{2\pi}{\sqrt{3}}$.
For trimming the angular integral produces a $\ln \frac{1}{r_{\mathrm{trim}}^2}$ collinear enhancement.

MANCHESTER 1824

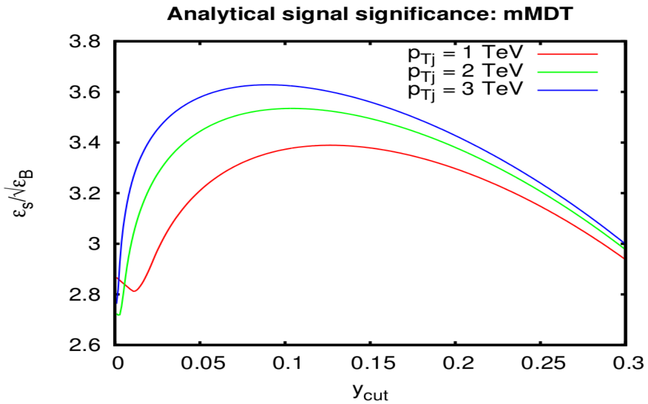
The University of Manchester

Optimal values

- How to use all this information? We have seen effects that push as in different directions e.g. minimising ISR shifts us to larger y_{cut} but this increases the FSR loss.
- In general want to achieve a large $\frac{\epsilon_s}{\sqrt{\epsilon_B}}$
- Can use analytical formulae to dervive optimal parameter values.

Work in progress with A.Siodmok and A.Powling

Some preliminary work for mMDT



As a first approximation switch off radiative corrections in signal and work with tree level result.

$$\frac{\epsilon_s}{\sqrt{\epsilon_B}} = \frac{1-2y_{\mathrm{cut}}}{\sqrt{\Sigma\left(\rho_H+\epsilon\right)-\Sigma\left(\rho_H-\epsilon\right)}} \qquad \rho_H = \frac{m_H^2}{p_T^2}$$

Maximising this gives $\displaystyle \frac{-4y_{\mathrm{cut}}}{1-2y_{\mathrm{cut}}} = C_F\frac{\alpha_s}{\pi}\ln\frac{y_{\mathrm{cut}}}{\rho} + \frac{4}{3+4\ln y_{\mathrm{cut}}}$

One can deduce the optimal y_{cut} for various p_T

Summary and outlook

- Task for theorists is to really understand taggers which has begun.
- For the taggers we studied here signals relatively stable against radiative corrections (modest effects unless one makes extreme parameter choices).
- Optimal values probably dictated significantly by background. But for other taggers e.g. N subjettiness this is no longer the case.
- Good understanding of signal also important for taggers that perform similarly on background (Ysplitter, Ypruning)
- Ongoing task is to use all this to design the best taggers. In this context tagger combinations appear promising.