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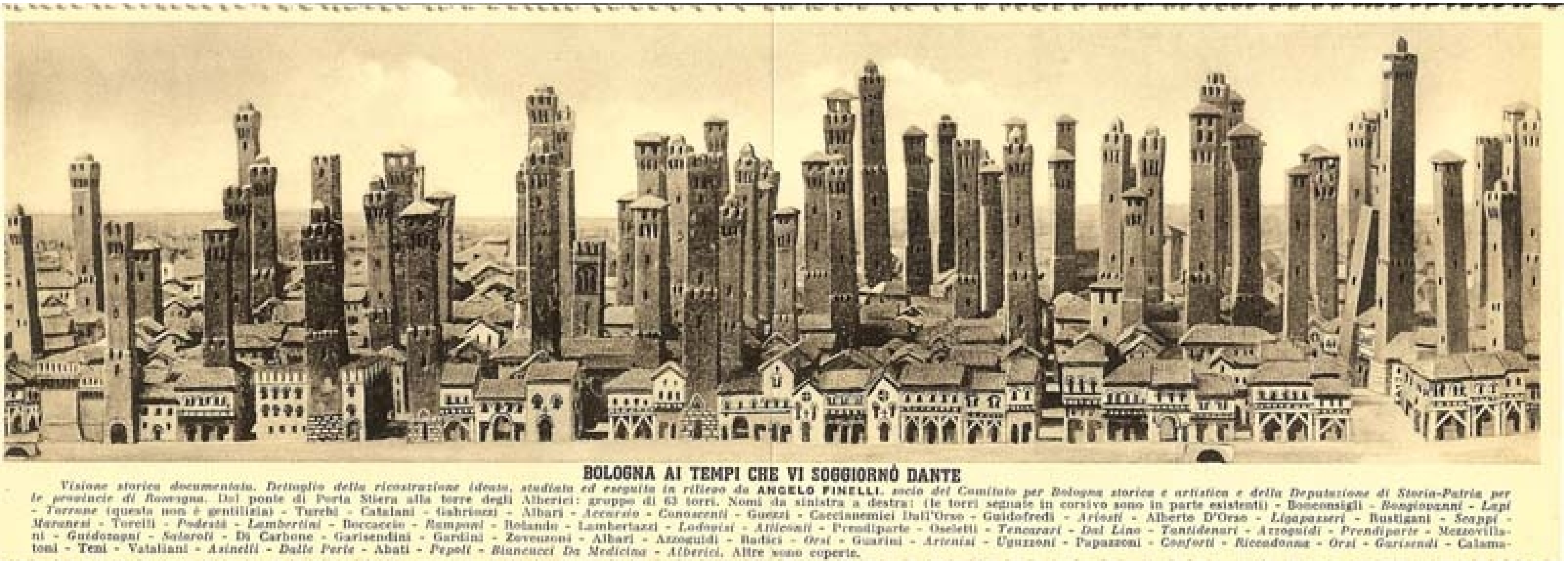
QCD understanding of jet substructure and comparison to MC predictions

Andrzej Siódmok



A Postcard of Bologna at the time of Dante

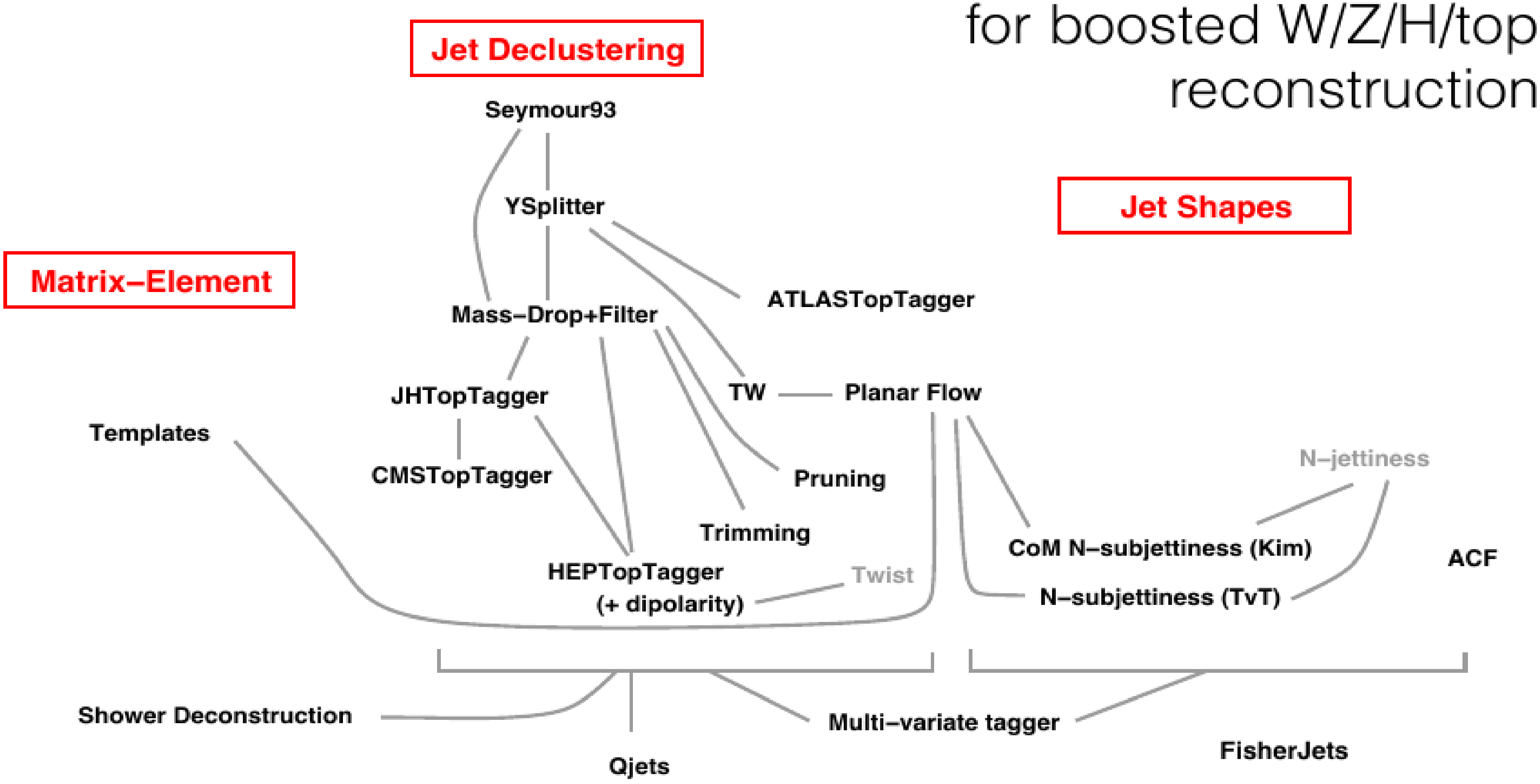
ISMD – 12 September 2014 - Bologna

Motivation

- Boosted techniques are very useful ⇒ it is very active research field.
- Well over 100 papers in the last 5 years and its own dedicated conference.
- Many techniques available with several parameters (energy/angular cuts ect) in addition to those already inherent in jet finding [see talk by M. Spannowsky]

Motivation

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



Taken from G. Salam

apologies for omitted taggers, arguable links, etc.

- Appear at first sight to be complex sophisticated tools.

Motivation

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?

Answers can be obtain from:

- Monte Carlo generators which are very powerful, however the MC 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 for different R=0.4 to R = 1.

Boost 2010 proceedings:
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.

Can we get some guidance from analytical calculation?

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Can we get some guidance from analytical calculation? Yes, we can!

Jet substructure for background

[M. Dasgupta, A. Fregoso, S Marziani G. P. Salam arXiv:1307.0007]

For phenomenology

Jet mass: *m*

[as compared to W/Z/H or top mass]

For QCD calculations

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

[R is jet opening angle – or radius]

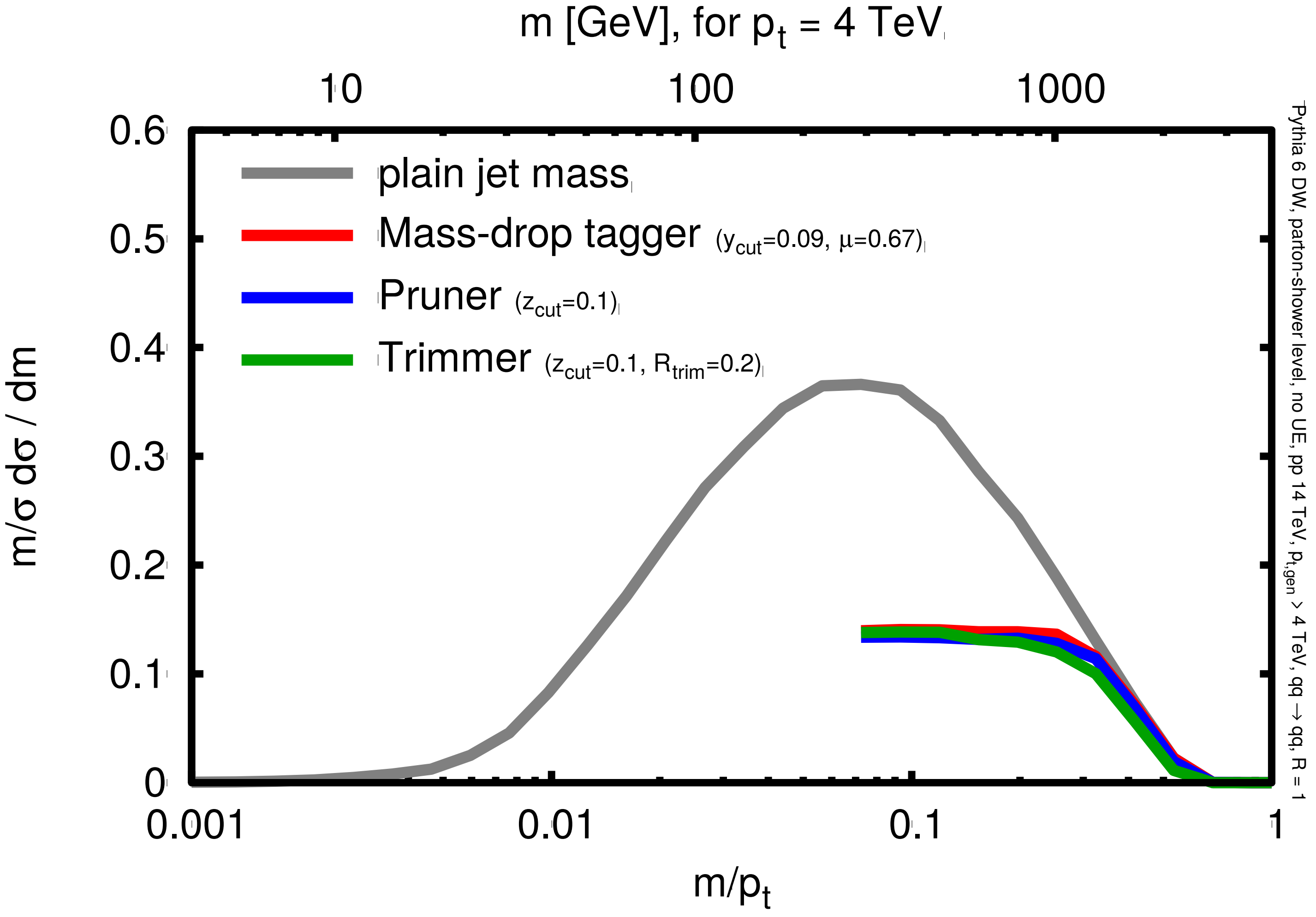
Because ρ is invariant under boosts along jet direction

Analytical results simplest when expressed in terms of rho.

Jet substructure for background (MC Studies – Pythia 6)

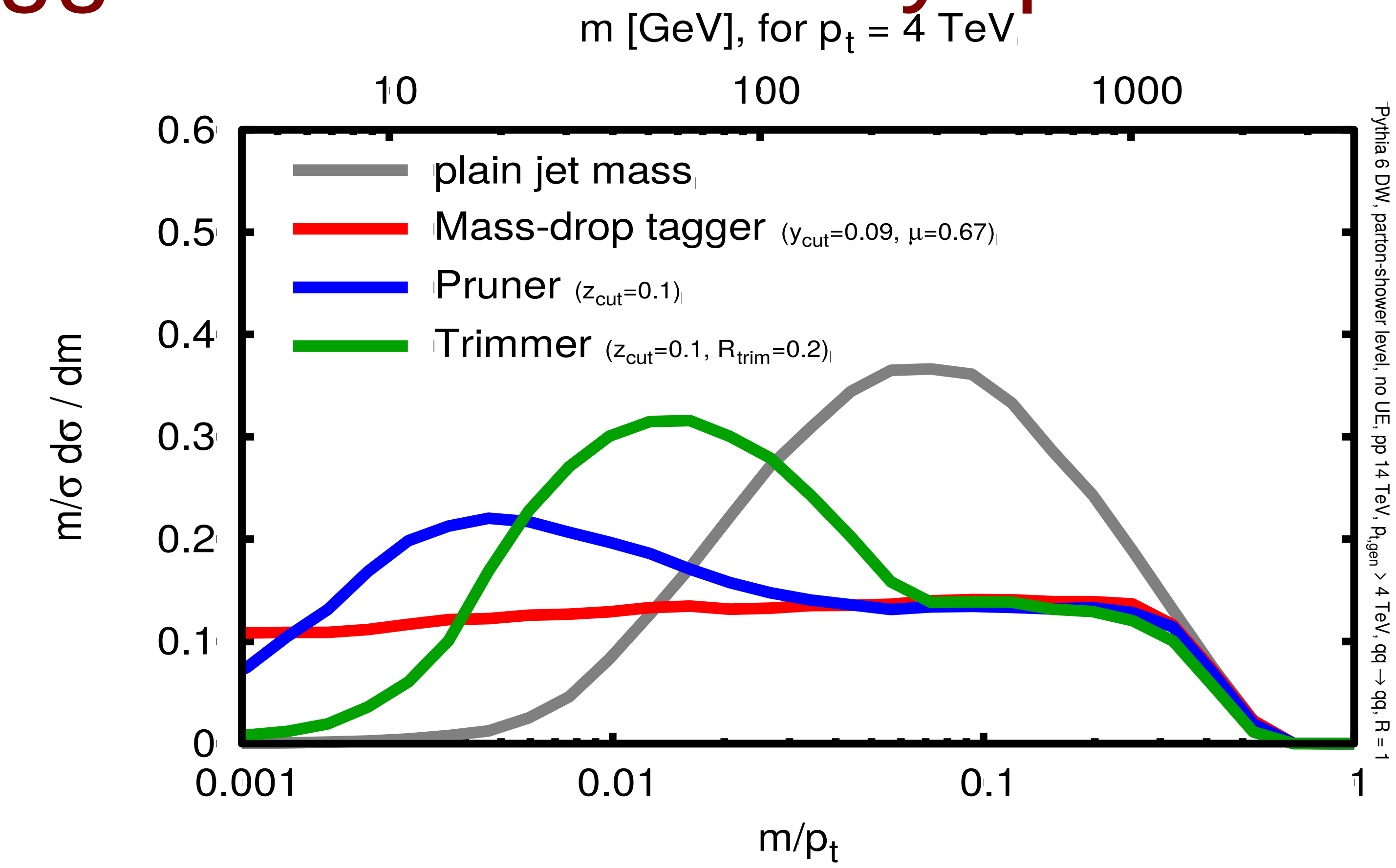
[M. Dasgupta, A. Fregoso, S Marziani G. P. Salam arXiv:1307.0007]

Taggers can look similar



Jet substructure for background (MC Studies – Pythia 6)

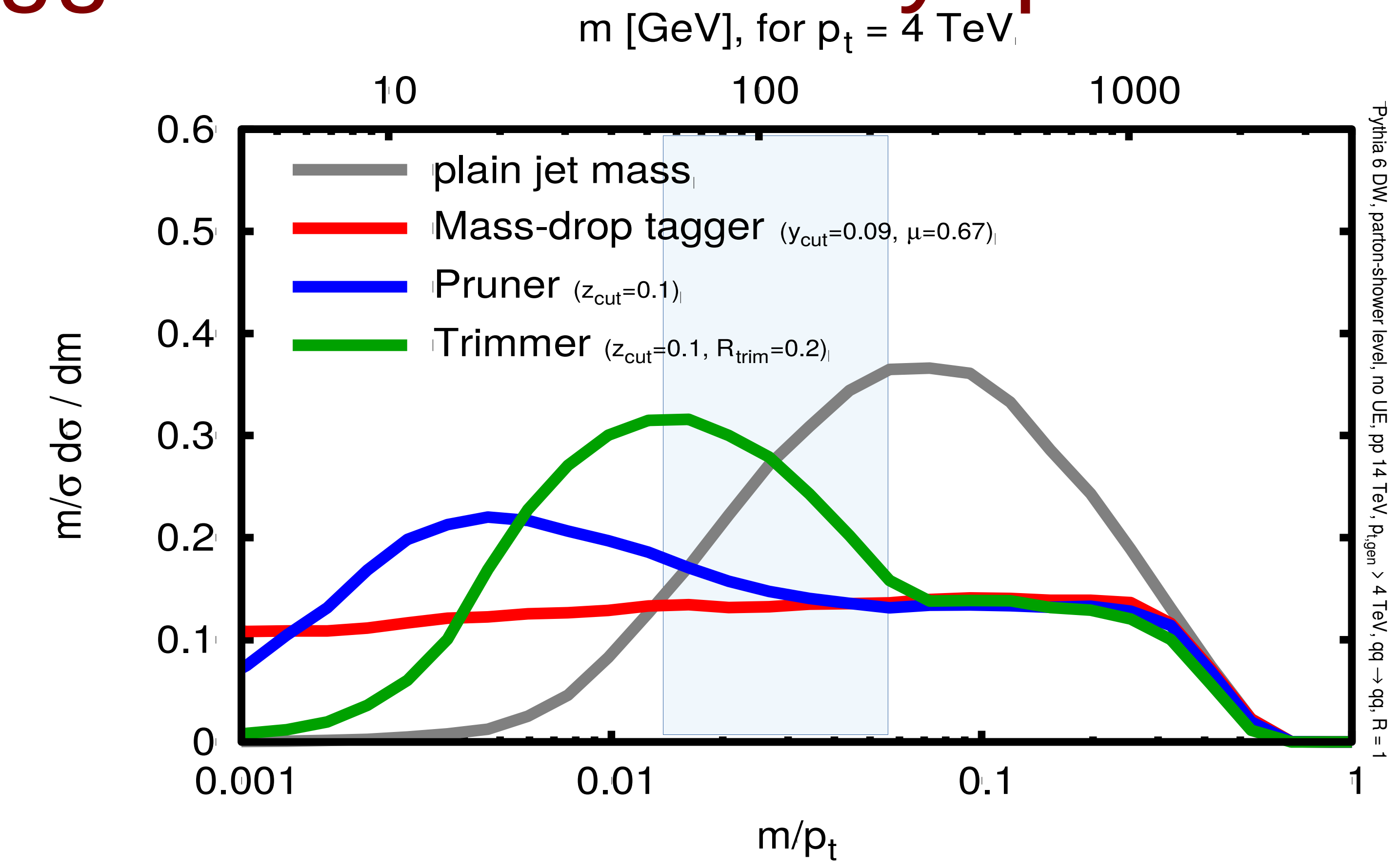
Taggers can look really quite different



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

Jet substructure for background (MC Studies – Pythia 6)

Taggers can look really quite different



Kinks are especially dangerous for data-driver backgrounds.

Jet substructure for background - mMDT

For a jet clustered with C/A:

1. undo last clustering step to break jet (mass *m*) into two subjets with $m_1 > m_2$
2. If significant mass-drop ($m_1 < \mu m$) and subjet energy-sharing not too asymmetric
$$\min(p_{t1}^2, p_{t2}^2)\Delta R_{12}^2 < y_{\rm cut} m^2$$
jet is **tagged**.
3. Otherwise discard subjet 2, and go to step 1 with jet → subjet 1.

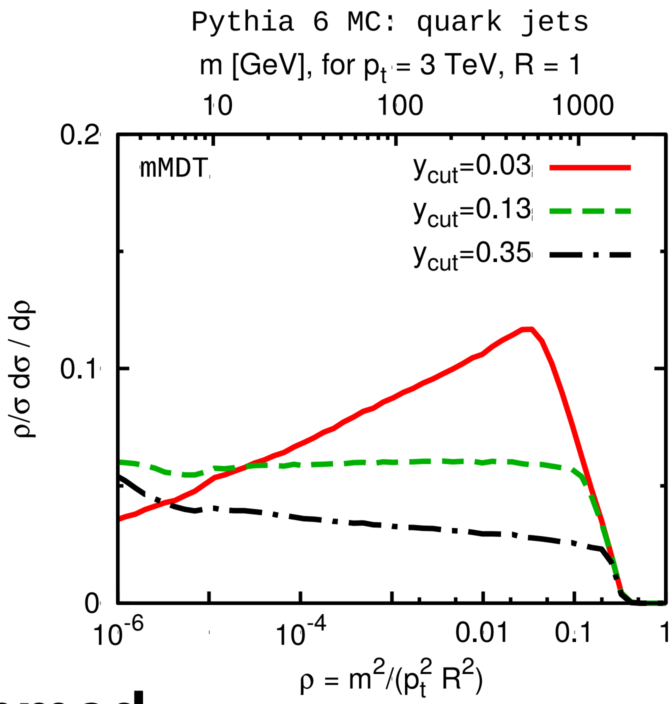
Mass-Drop Tagger

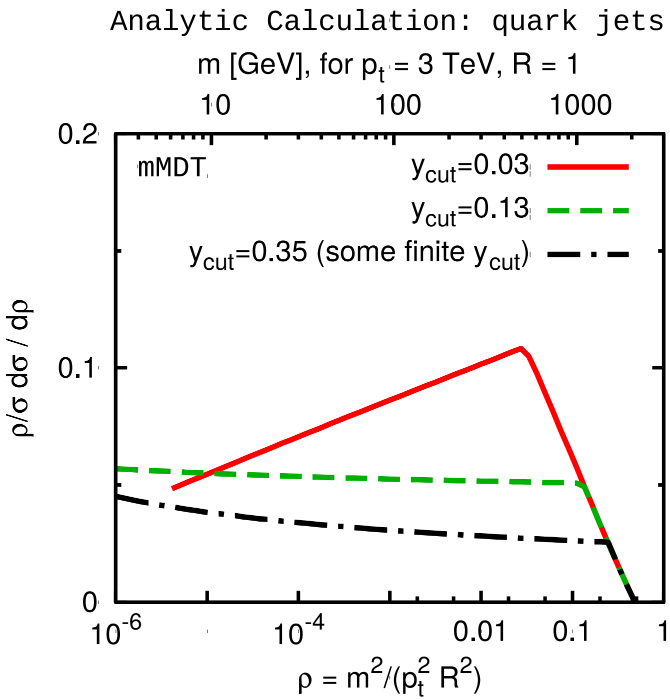
two parameters:
μ and $y_{\rm cut}$ ($\sim z_{\rm cut}$)

Jet substructure for background - mMDT

LO:

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}^{(\text{MDT, LO})} = \frac{\alpha_s C_F}{\pi}\left[\Theta(\rho - y_{\text{cut}})\ln\frac{1}{\rho} + \Theta(y_{\text{cut}} - \rho)\ln\frac{1}{y_{\text{cut}}} - \frac{3}{4}\right]$$





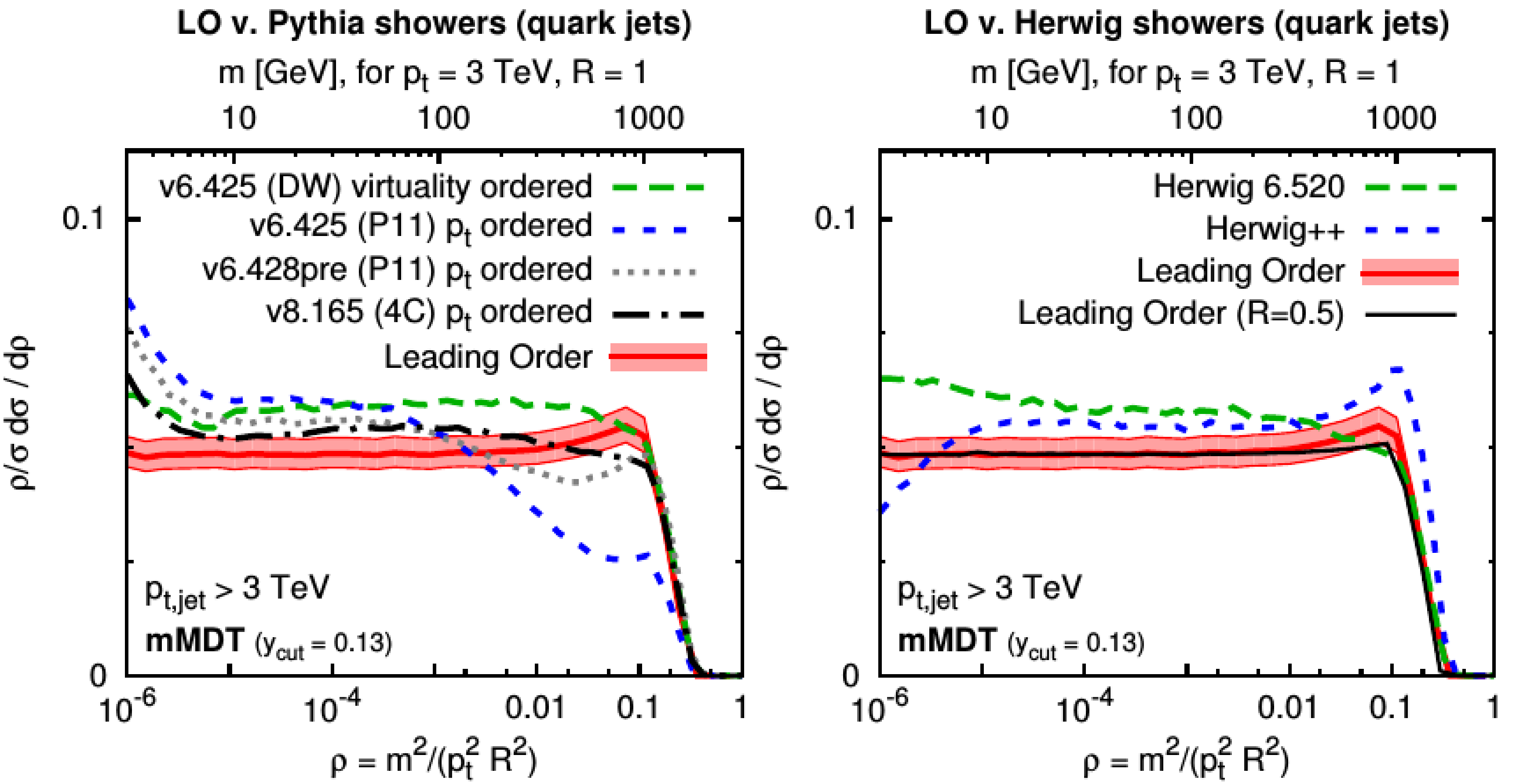
Resummed:

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

mMDT has a unique single log structure. Can produce a flat background. No non-global logs. The mass drop tagger seems not to depend on mass drop!

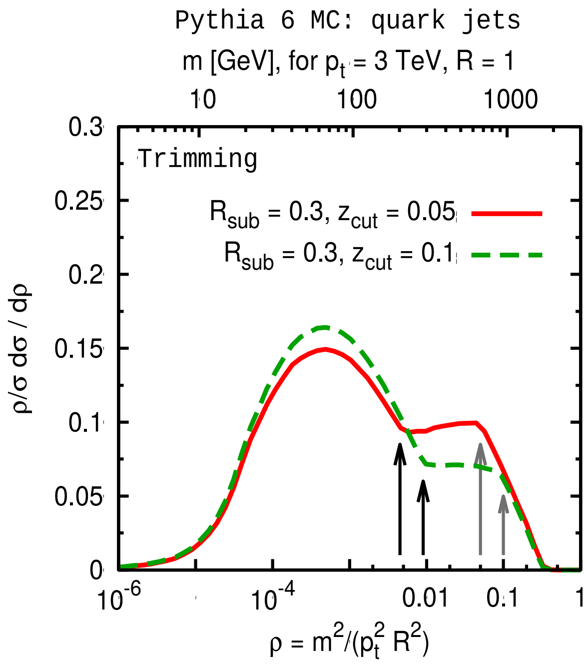
Dasgupta, Fregoso, Salam, Marzani 2013

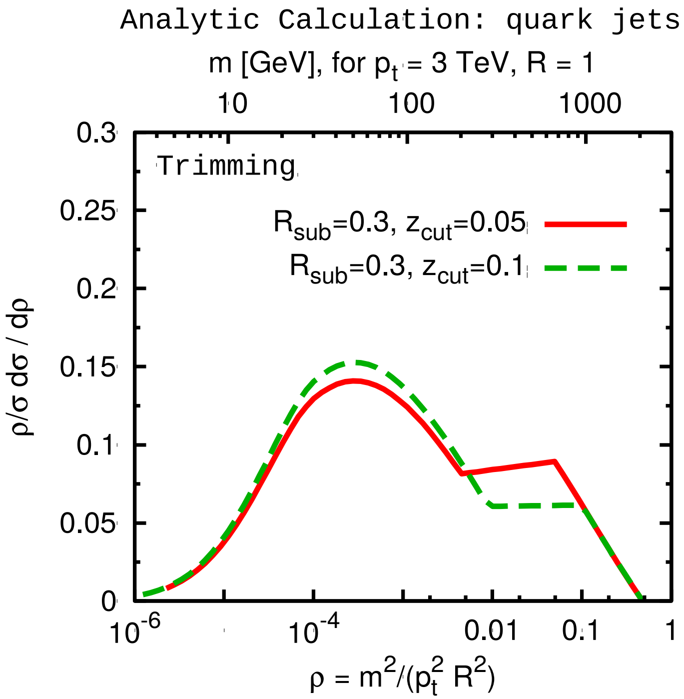
Jet substructure for background - mMDT



Issue found in Pythia 6 pt-ordered shower → promptly identified and fixed by Pythia authors!

Jet substructure for background - trimming





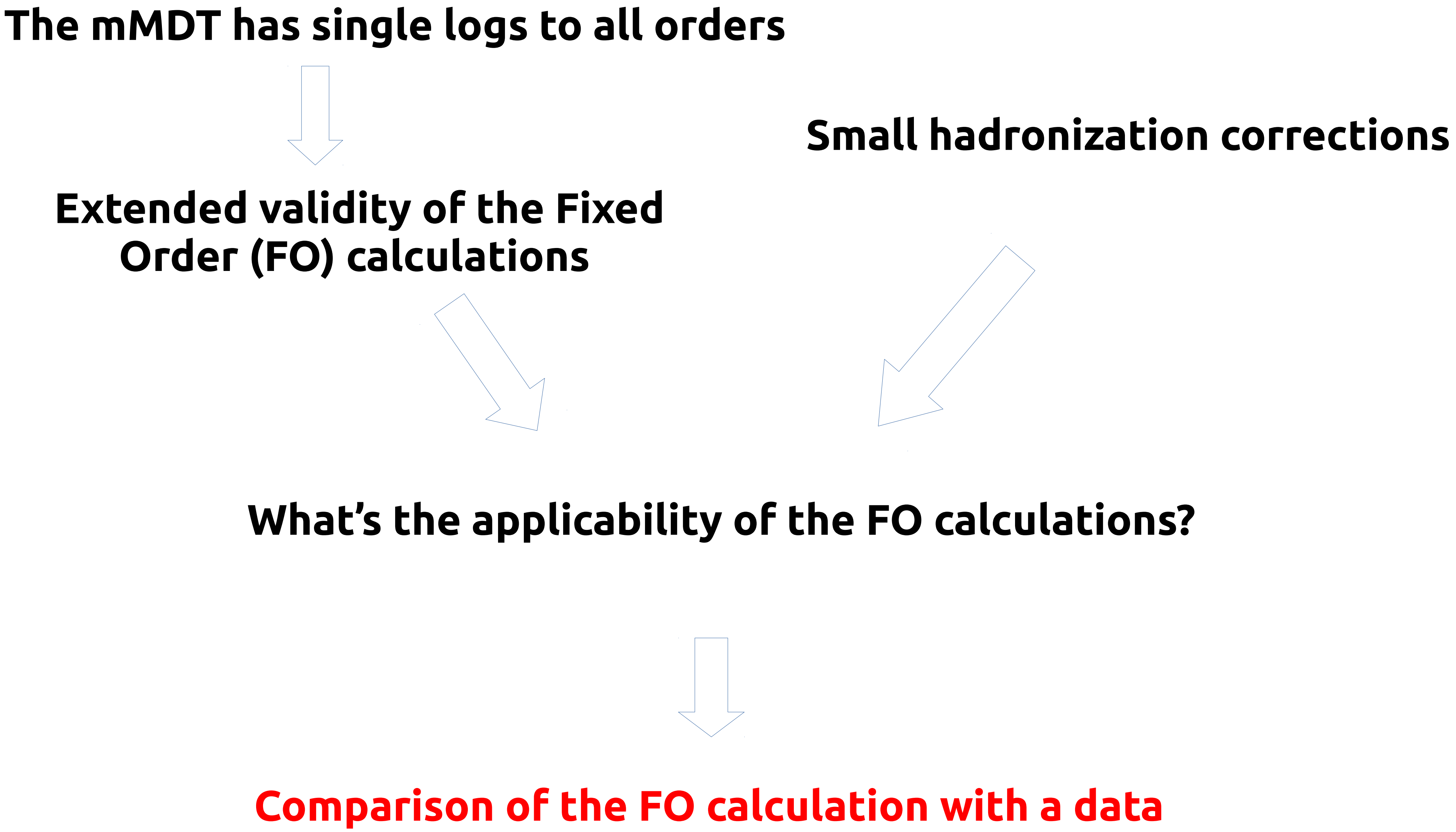
$$\rho\frac{\partial}{\partial\rho}\exp\left[-C_F\frac{\alpha_s}{2\pi}\left(-\frac{3}{2}\ln\frac{1}{\rho}+\Theta\left(\rho-z\right)\ln^2\frac{1}{\rho}+\Theta\left(z-\rho\right)2\ln\frac{z}{\rho}\ln\frac{1}{z}+\Theta\left(zr^2-\rho\right)\ln^2\frac{zr^2}{\rho}\right)\right]$$

Non-trivial agreement!
(also for dependence on parameters)

[M. Dasgupta, A. Fregoso, S Marziani G. P. Salam arXiv:1307.0007]

mMDT phenomenology

M. Dasgupta, A.S and A.Powling



The mMDT has single logs to all orders

Extended validity of the Fixed Order (FO) calculations

Small hadronization corrections

What’s the applicability of the FO calculations?

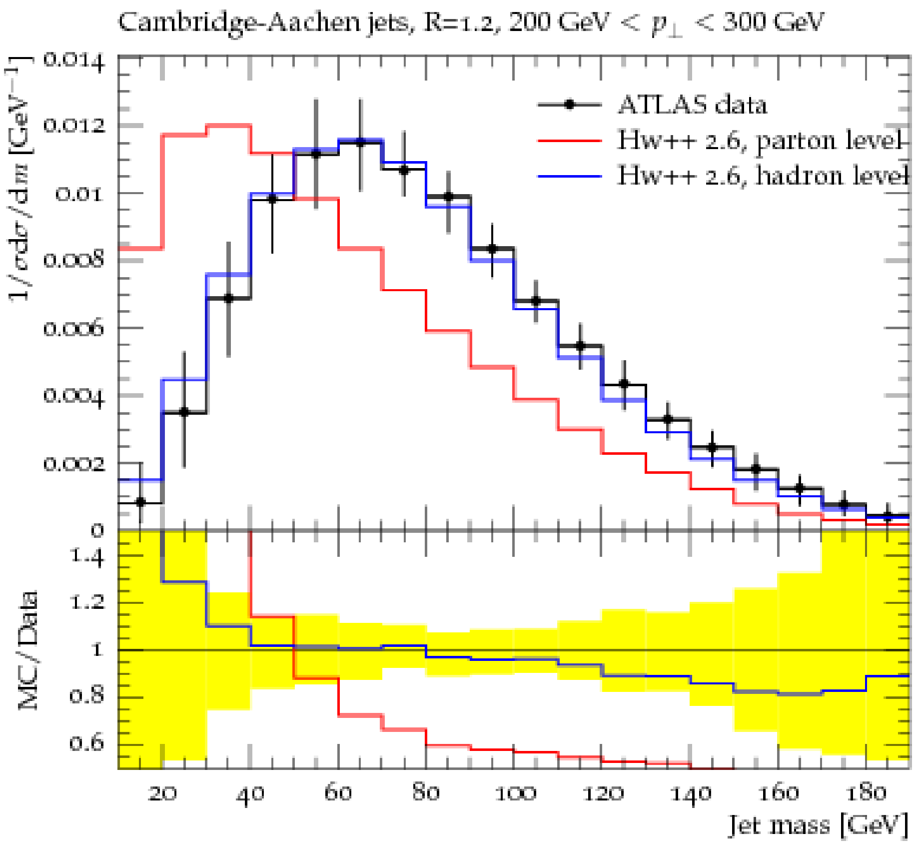
Comparison of the FO calculation with a data

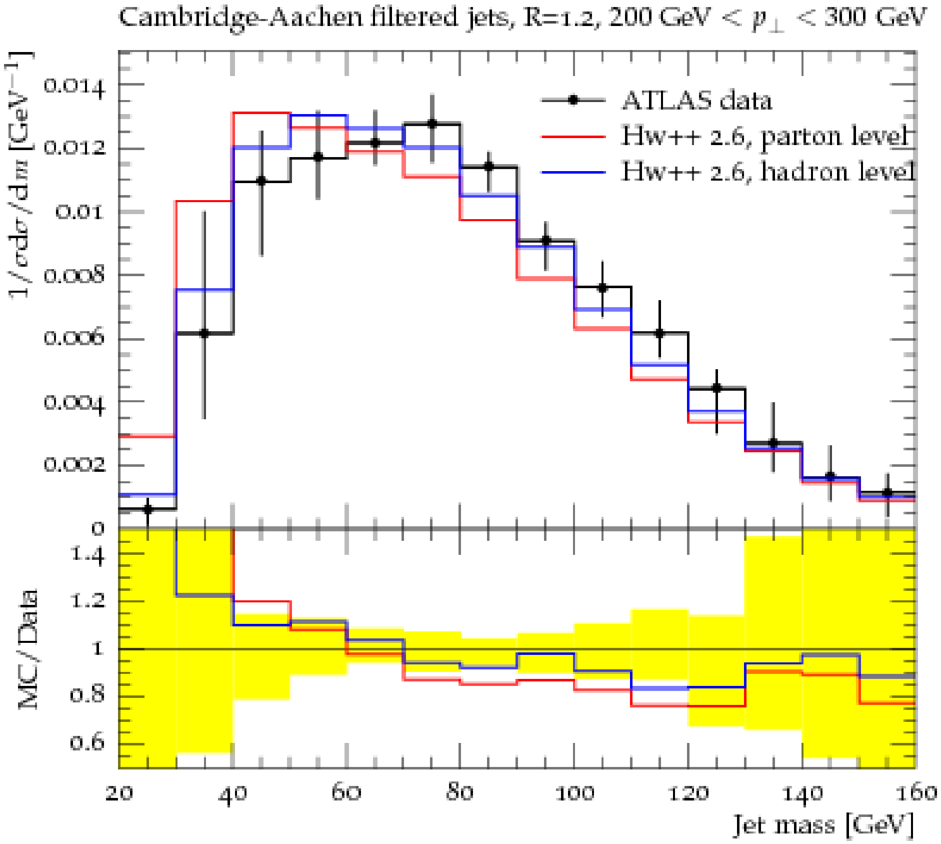
mMDT phenomenology
ATLAS measurment of the jet mass with MDT [JHEP 1205 (2012)]

Hadronization + MPI effects

Plain Mass

ATLAS MDT





significant effcts

visible effcts (small m)

red line – parton level
blue line – hadron level

mMDT – not very sensitive to hadronization!

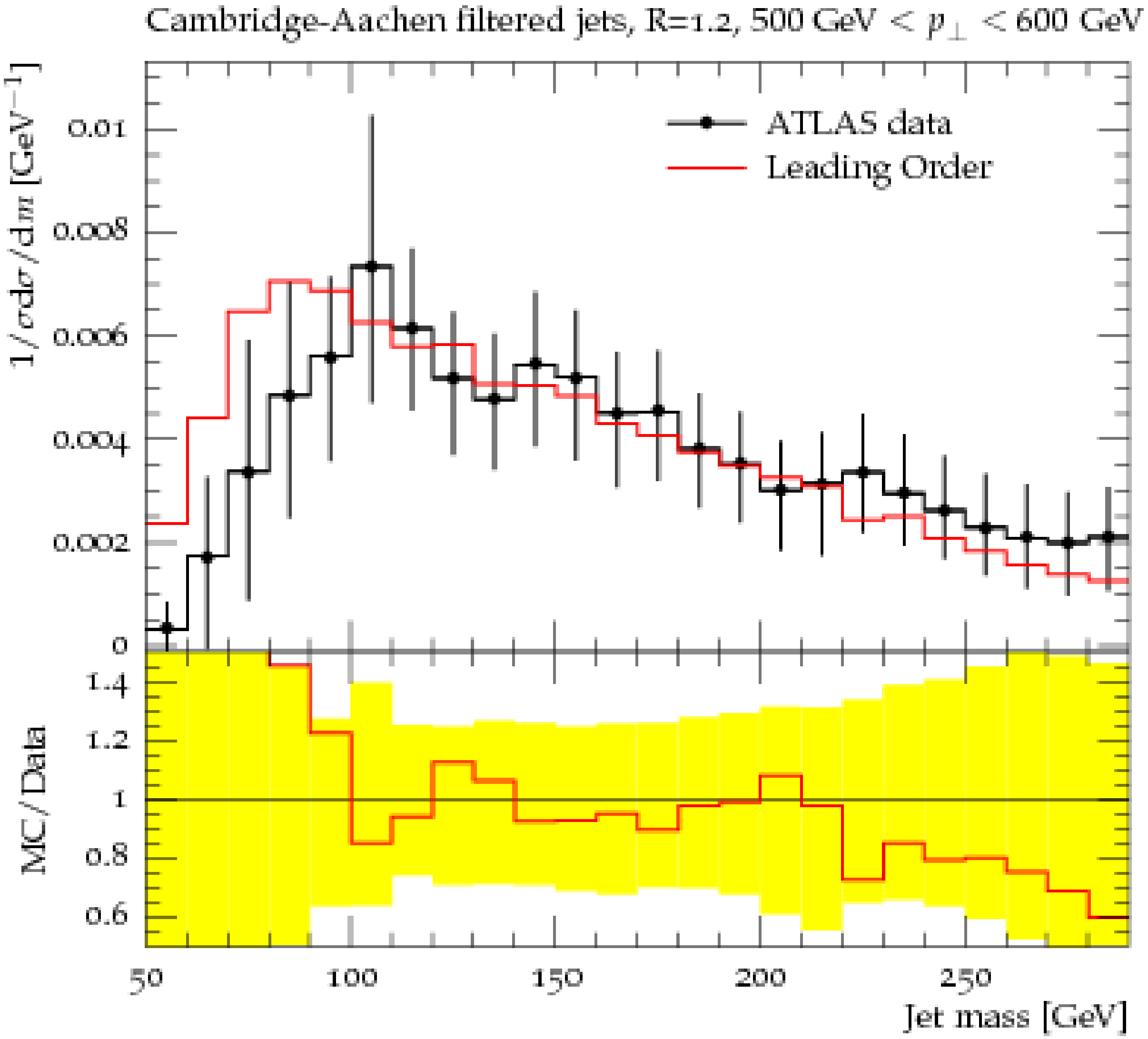
mMDT phenomenology

ATLAS measurment of the jet mass with MDT [JHEP 1205 (2012)]

LO results (njet+Sherpa)

ATLAS MDT 500< pT < 600 GeV

M. Dasgupta, A.S and A.Powling



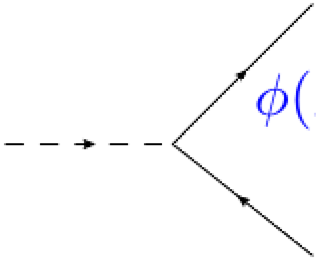
Good agreement!

Jet substructure for signal vs background

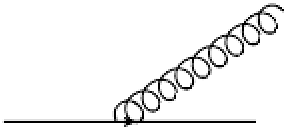
- To fully use “Boost” you want to study all possible signal (W/Z/H/top/...) and QCD jets

$$\frac{\epsilon_s}{\sqrt{\epsilon_B}}$$

- Two main handles to play with:



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



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

- Backgrounds favor asymmetric splittings while signals do not.

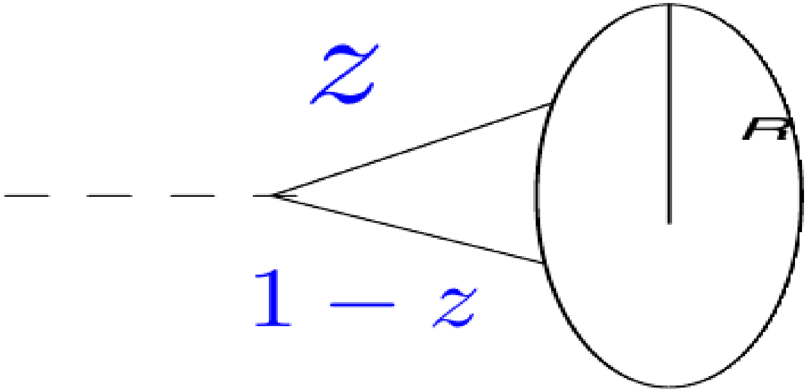
- QCD radiation is enhanced in soft and collinear regions.

- 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.

What about signal processes?

M. Dasgupta, A.S and A.Powling

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



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

- 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

$$M_H - \delta M < M_j < M_H + \delta M \quad \Rightarrow \quad |M_j^2 - M_H^2| < 2 M_H \delta M$$

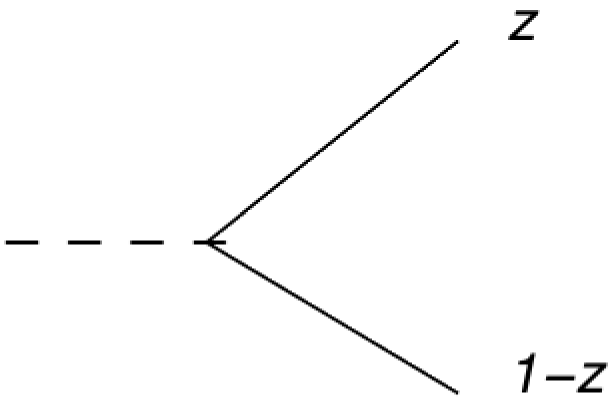
Signal processes H -> b bar

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



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

Signal process: tree level

Mass drop and pruning

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

Trimming

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

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

ISR effects for plain jet mass

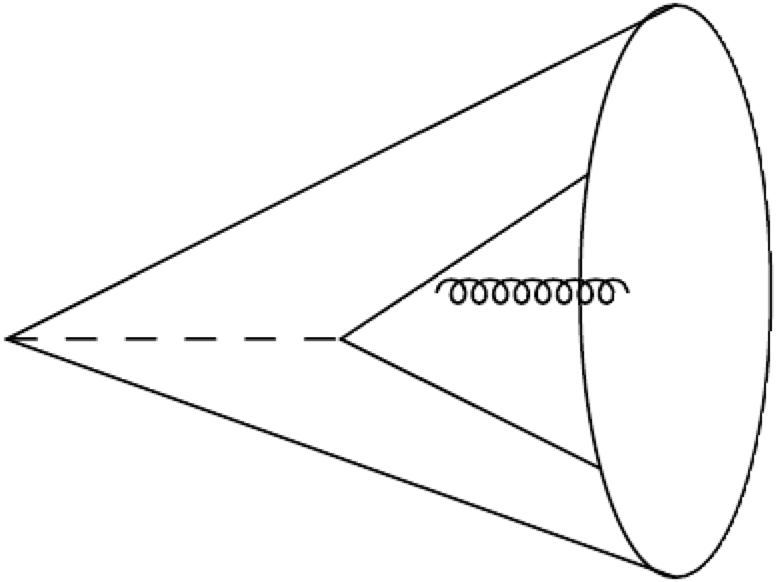
Compute the probability of staying within the mass window constraint

$$|M_j^2 - M_H^2| < 2M_H \delta M$$

for the case of fixed-coupling (it is easy to extend this for running)

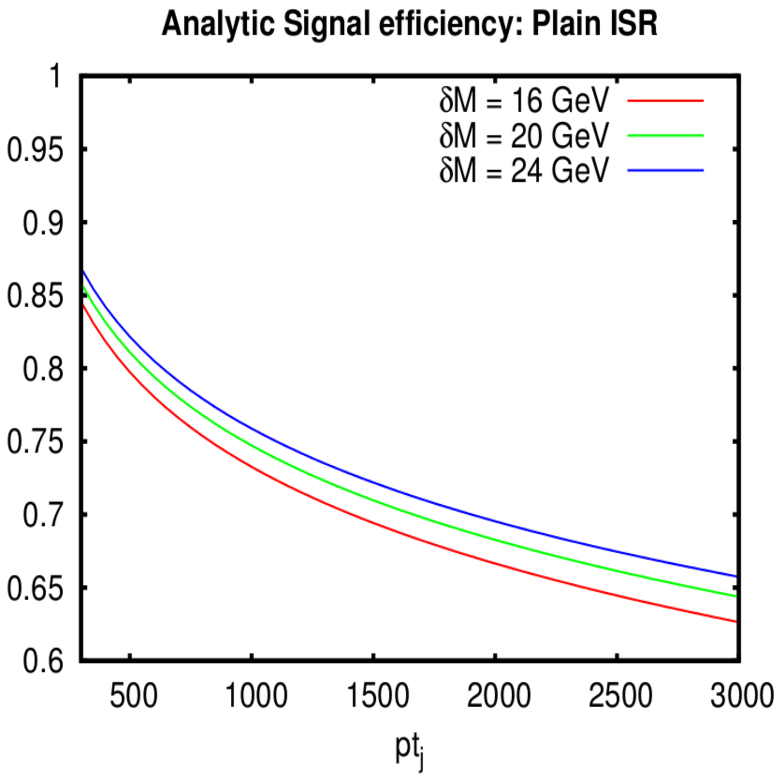
$$\epsilon_s \approx 1 - \frac{C_F \alpha_s}{\pi} R^2 \ln\left(\frac{p_T^2 R^2}{2M\delta M}\right)$$

Plain jet mass

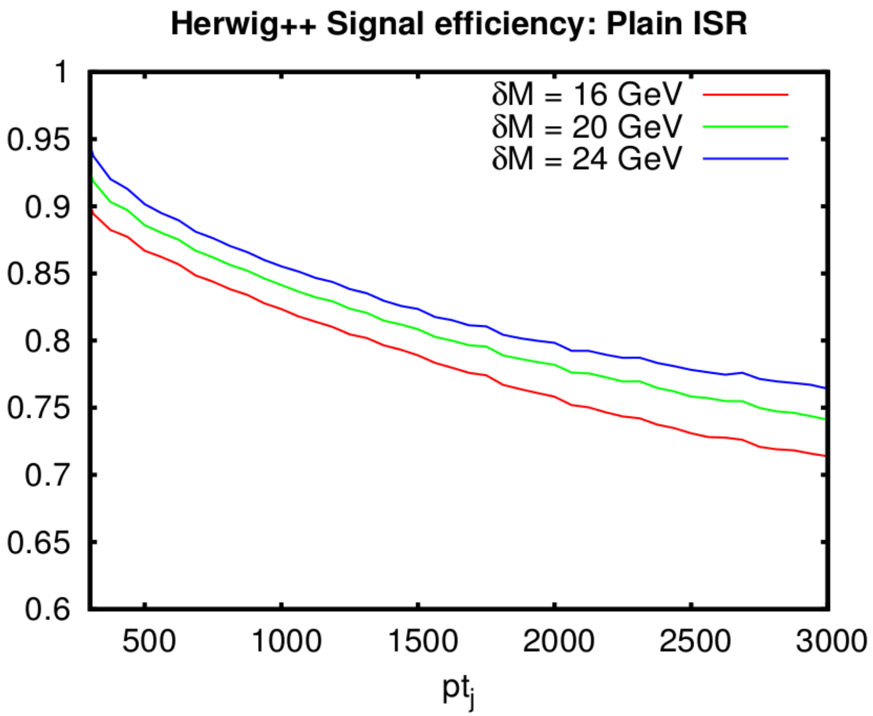


We can also do corresponding calculation for FSR. For m/p_t << R, angular ordering property suppresses radiation at large angles. Negligible contribution.

Plain mass results



Analytic Signal efficiency: Plain ISR



Herwig++ Signal efficiency: Plain ISR

- Agreement with MC (Herwig++) at the expected level.
- FSR minimal as expected.
- UE is dominant for R=1.

ISR – other taggers

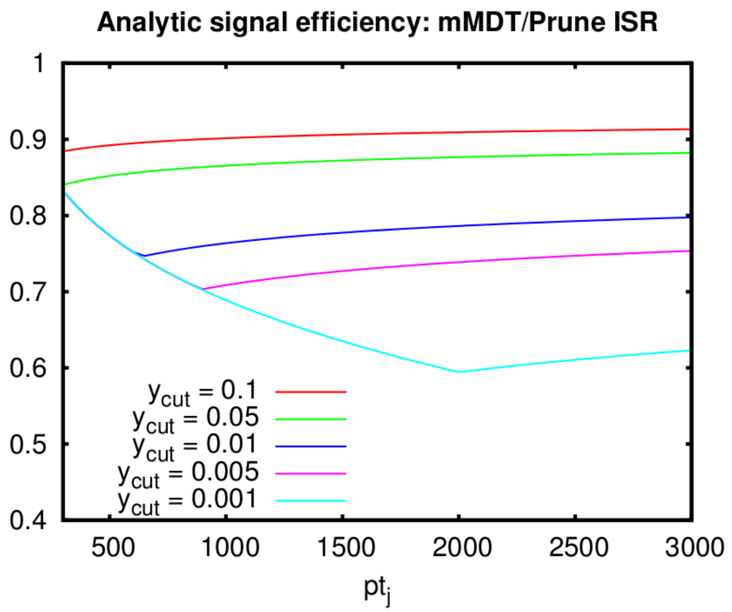
mMDT

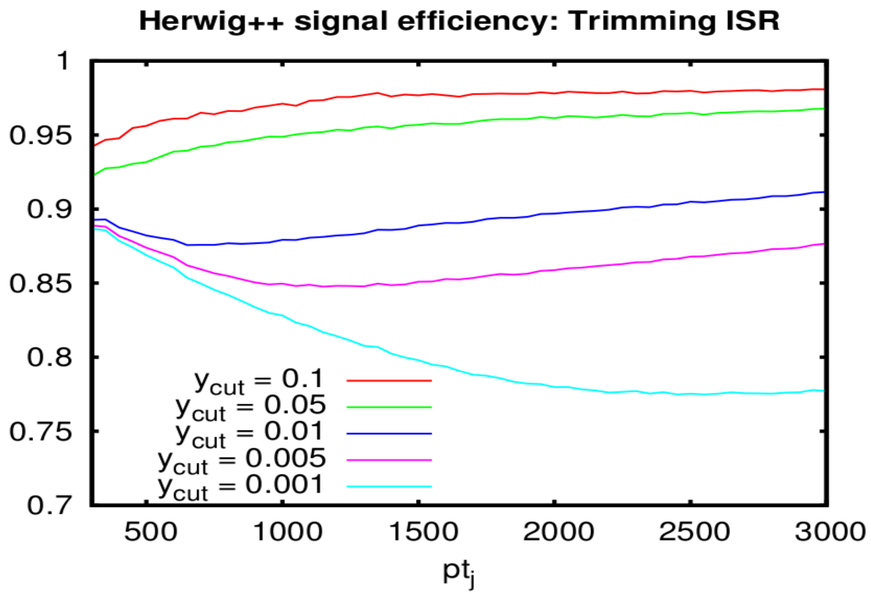
$$\epsilon_S^{\mathrm{ISR}} \approx -C_F \frac{\alpha_s}{\pi} \int_0^1 \frac{dx}{x} d\theta^2 \Theta\left(x - \max\left(y_{\mathrm{cut}}, \frac{\Delta}{\theta^2+\Delta}\frac{1-\mu^2}{\mu^2}, \frac{2M_H \Delta M}{p_T^2\left(\theta^2+\Delta\right)}\right)\right)$$

At high pT result goes as

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

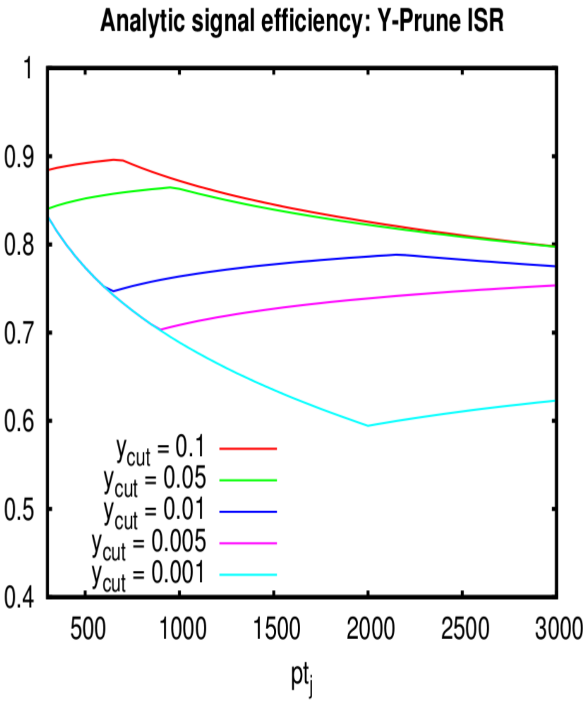
ISR – other taggers

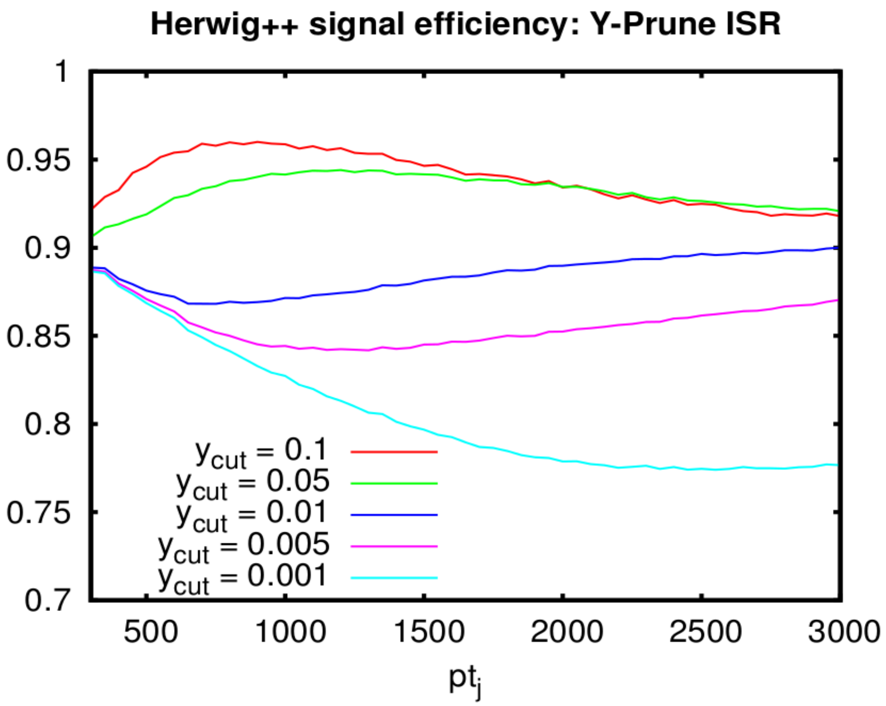




Pruning and trimming produce a very similar result for ISR.
In reasonable agreement with Herwig++.

ISR – Y pruning


Analytic signal efficiency: Y-Prune ISR


Herwig++ signal efficiency: Y-Prune ISR

Predicts loss of signal at high p_T

Again this feature agrees with Herwig++

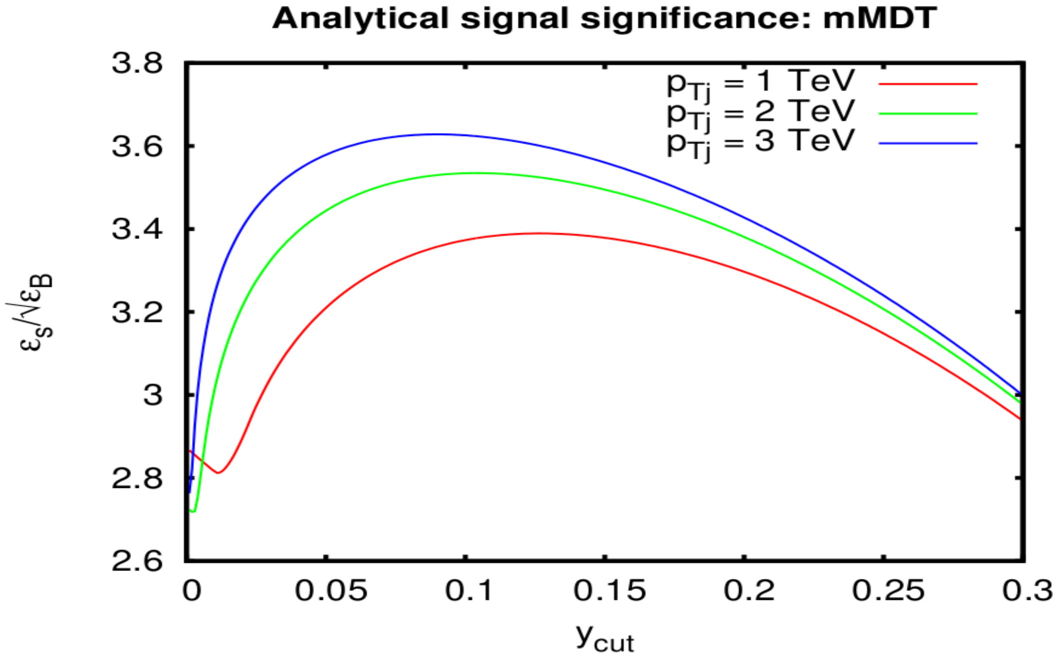
Optimal values

Work in progress M. Dasgupta, A.S and A.Powling

- 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 (FSR calculations for all taggers in progress).
- In general want to achieve a large $\frac{\epsilon_s}{\sqrt{\epsilon_B}}$
- Can use analytical formulae to derive optimal parameter values.

Optimal values- preliminary work for mMDT

Work in progress M. Dasgupta, A.S and A.Powling



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

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

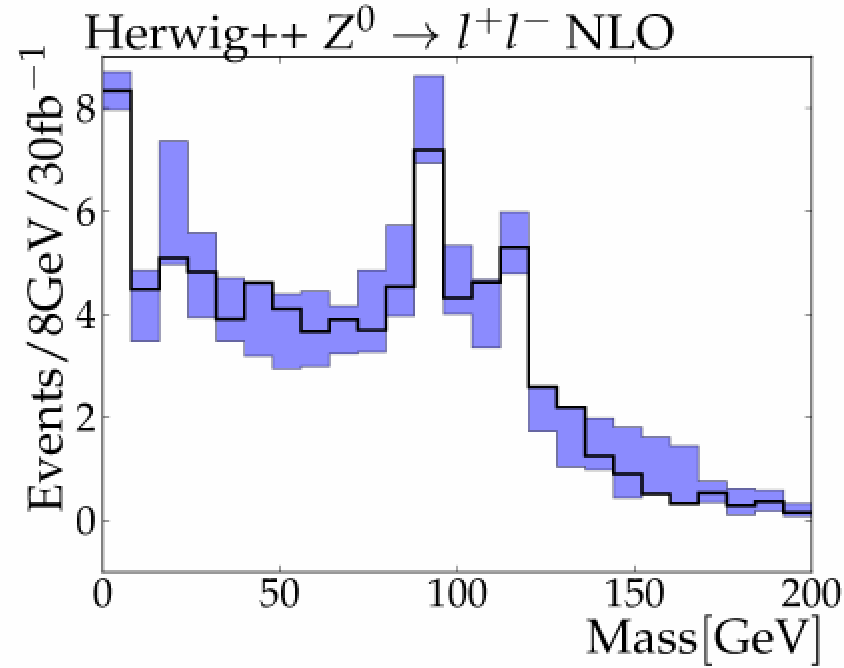
One can deduce the optimal $y_{\text{cut for various pT}}$

$$\frac{-4y_{\text{cut}}}{1-2y_{\text{cut}}} = C_F\frac{\alpha_s}{\pi}\ln\frac{y_{\text{cut}}}{\rho} + \frac{4}{3+4\ln y_{\text{cut}}}$$

MDT: Tuning Uncertainties

Eur. Phys. J. C72 (2012) P. Richardson, D. Winn

Reconstructed Higgs boson mass distribution: based on MDT analysis
J. Butterworth, A. Davison, M. Rubin, Ga Salam Phys.Rev.Lett.100:242001



Dependence of searches for boosted Higgs bosons using jet substructure on the perturbative and non-perturbative parameters of the Herwig++ Monte Carlo event generator.

Values are presented for a new tune of the parameters of the event generator, together with the an estimate of the uncertainties based on varying the parameters around the best-fit values.

Summary

- Task for theorists is to really understand taggers.

- 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.

- Good understanding of signal also important for taggers that perform similarly on background (Ysplitter, Ypruning).

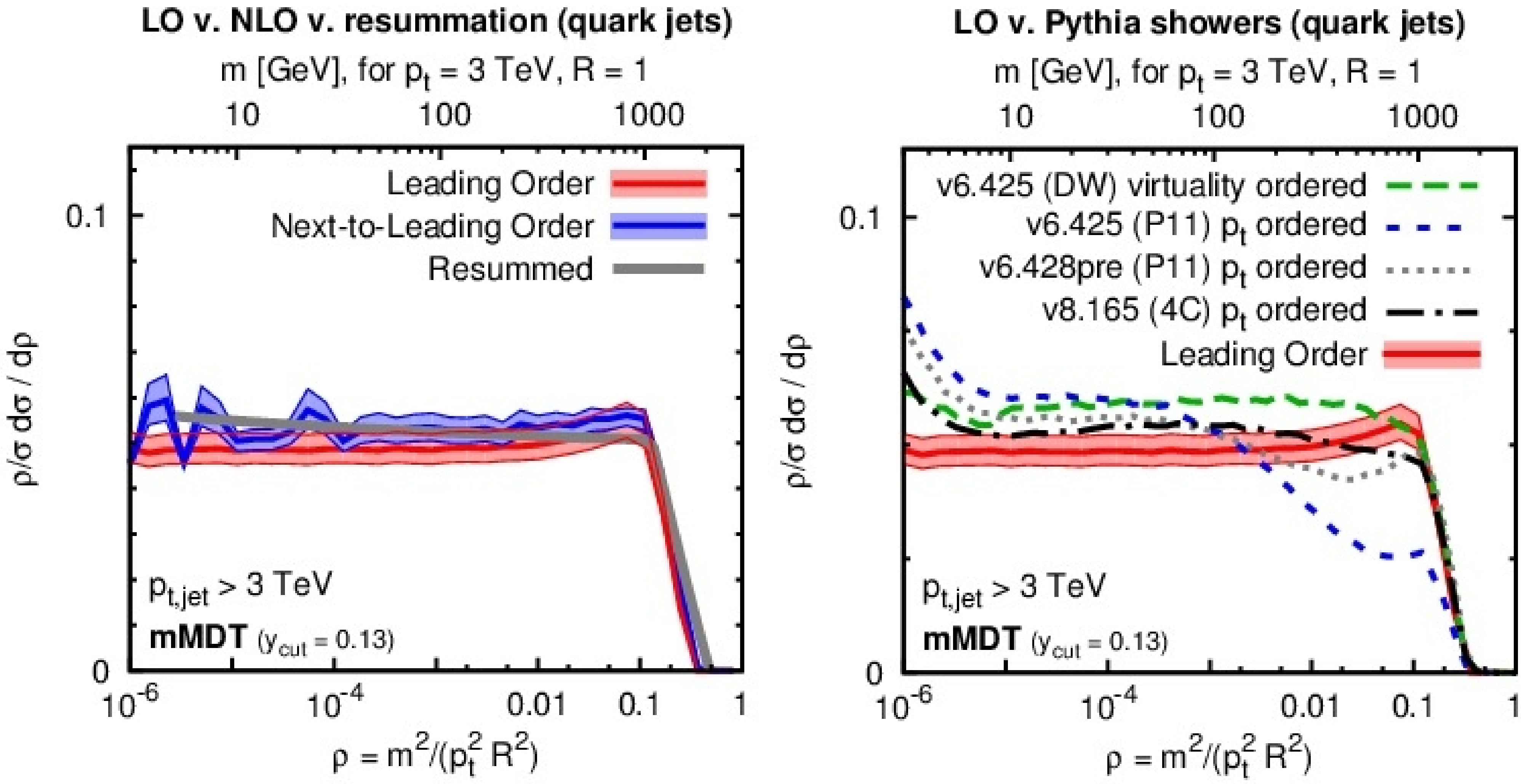
- Ongoing task is to use all this to design the best taggers. In this context tagger combinations appear promising.
- Better understanding of taggers leads to meaningful MC studies

Thank you very much for your attention

Backup

mMDT phenomenology

[M. Dasgupta, A. Fregoso, S Marziani G. P. Salam and A. Powling arXiv:1307.0007]

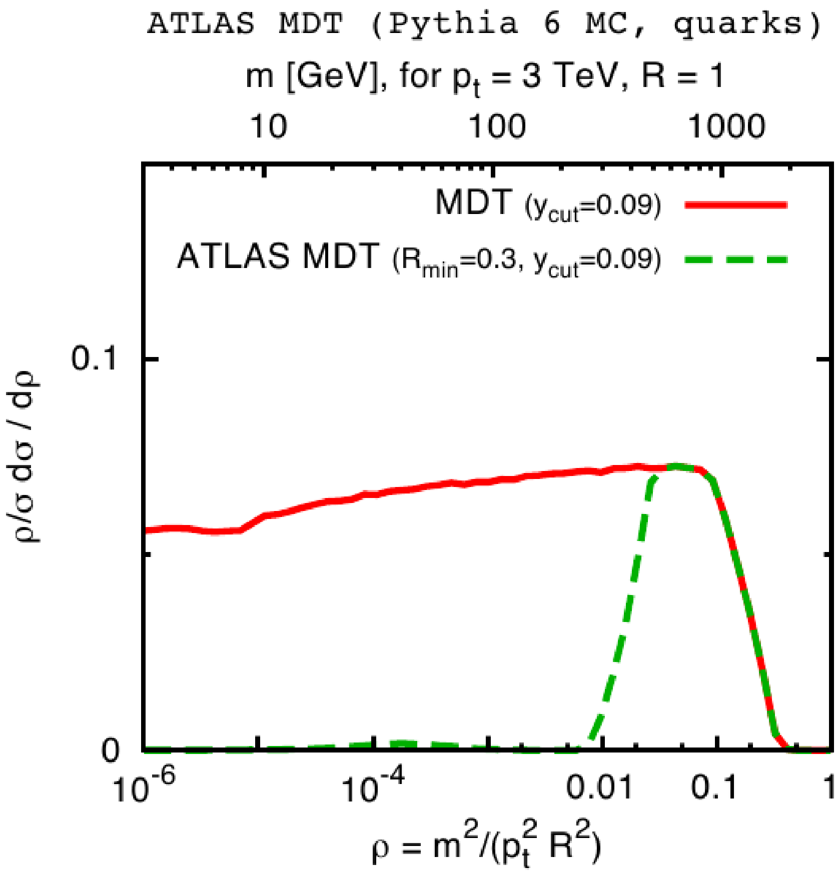


Remarkable agreement of MC! Useful for a validation (see above).

mMDT phenomenology

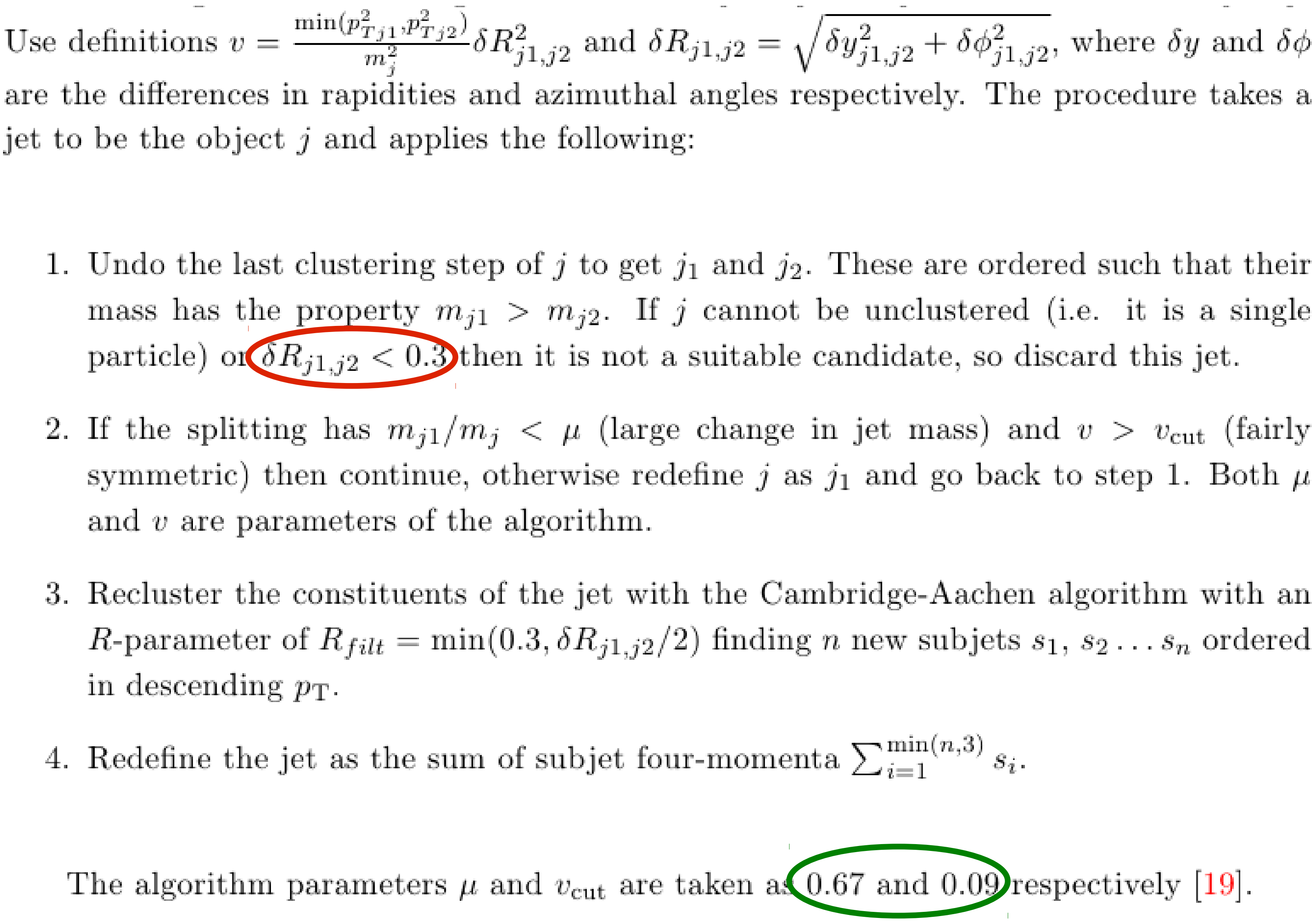
ATLAS measurment of the jet mass with MDT [JHEP 1205 (2012)]

- ATLAS measured the jet mass with MDM
- But different version of the tagger with Rmin=0.3 between the prongs
- This cut significantly changes the tagger's behaviour: mass minimum
- The single-log region is reduced (can even disappear)
- Let's use LO calculation to compare with the data



mMDT phenomenology

ATLAS measurment of the jet mass with MDT [JHEP 1205 (2012)]



Use definitions $v = \frac{\min(p_{Tj1}^2, p_{Tj2}^2)}{m_j^2} \delta R_{j1,j2}^2$ and $\delta R_{j1,j2} = \sqrt{\delta y_{j1,j2}^2 + \delta\phi_{j1,j2}^2}$, where δy and $\delta\phi$ are the differences in rapidities and azimuthal angles respectively. The procedure takes a jet to be the object j and applies the following:

1. Undo the last clustering step of j to get j_1 and j_2. These are ordered such that their mass has the property $m_{j1} > m_{j2}$. If j cannot be unclustered (i.e. it is a single particle) or $\delta R_{j1,j2} < 0.3$ then it is not a suitable candidate, so discard this jet.
2. If the splitting has $m_{j1}/m_j < \mu$ (large change in jet mass) and $v > v_{\text{cut}}$ (fairly symmetric) then continue, otherwise redefine j as j_1 and go back to step 1. Both μ and v are parameters of the algorithm.
3. Recluster the constituents of the jet with the Cambridge-Aachen algorithm with an R-parameter of $R_{filt} = \min(0.3, \delta R_{j1,j2}/2)$ finding n new subjets s_1, $s_2 \ldots s_n$ ordered in descending p_{T}.
4. Redefine the jet as the sum of subjet four-momenta $\sum_{i=1}^{\min(n,3)} s_i$.

The algorithm parameters μ and v_{cut} are taken as 0.67 and 0.09 respectively [19].

Trimming

Krohn, Thaler & Wang ’09

Take all particles in a jet of radius **R** and recluster them into subjets with a jet definition with radius

$$\mathbf{R_{sub}} < R$$

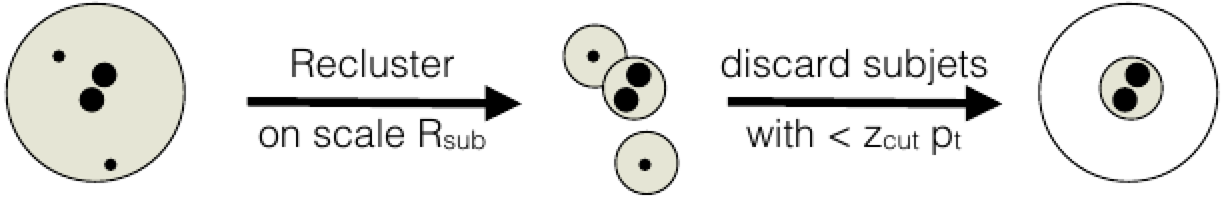
The subjets that satisfy the condition

$$p_t^{(subjet)} > \mathbf{z_{cut}}\, p_t^{(jet)}$$

are kept and merged to form the trimmed jet.

two parameters: R_{sub} and z_{cut}

Use z_{cut} because signals (bkgds) tend to have large (small) z_{cut}



Pruning

Ellis, Vermillion & Walsh '09

Take a jet and define

$$R_{\mathrm{prune}} = m / p_t$$

Recluster with k_t or C/A alg.
At each i+j clustering step, if

$$p_{ti} \text{ or } p_{tj} < z_{\mathrm{cut}}\, p_{t(i+j)\mathrm{asdf}}$$

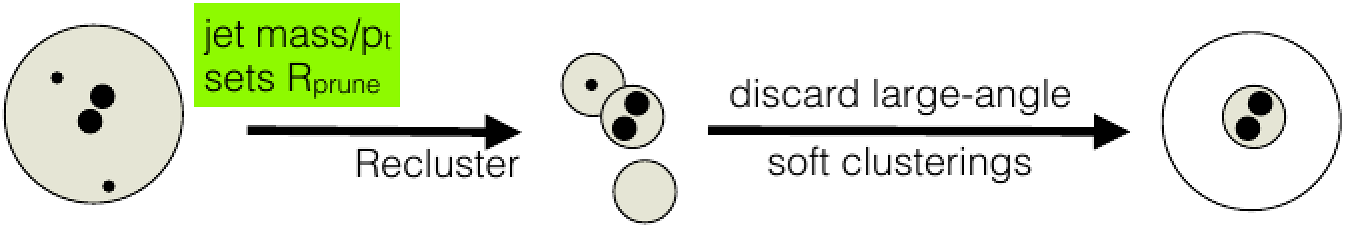
$$\Delta R_{ij} > R_{\mathrm{prune}}$$

discard softer prong.

Acts similarly to filtering, but with **dynamic subjet radius**

one (main) parameter: z_{cut}

we'll study variant with C/A reclustering



jet mass/p_t sets R_{prune}

Recluster

discard large-angle soft clusterings