On jet substructure methods for signal jets

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[arxiv: 1503.01088, JHEP]

BOOST2015 Chicago

10 - 14 August 2015

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We might hope BSM signal to be as prominent as Chicago Spire...

We might hope BSM signal to be as prominent as Chicago Spire...
but I had a look around and I haven't seen Chicago Spire...

Therefore, more likely BSM signal will be of that size...

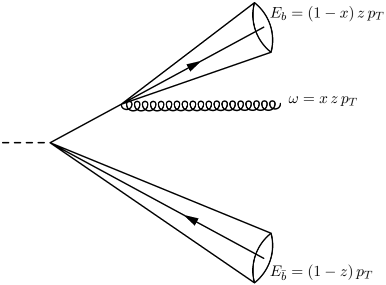
You need to understand your tools to enhance the signal and get good perspective...

Motivation to study jet substructure for signal jets.

- M. Dasgupta, A. Fregoso, S. Marzani, G. Salam
  "Towards an understanding of jet substructure" JHEP 1309 (2013) 029:
  "...We look forward to continued future work on this subject. This may include the extension of our analysis to signal processes, ..."
- Understanding jet substructure methods for signal jets is especially important when taggers perform similarly on QCD jets
  (I will show such an example - Y-pruning and Y-splitter).
- Having good understanding of jet substructure methods can be used to significantly improve them
  (for example: mMDT or Y-pruning, it will be also the case this time: Y-splitter + trimming)
- Having analytical results for signal and QCD jets we can make analytical estimates for optimal values and compare with MC results.

Fixing notation (LO Plain Jet Mass results)

$pp \to W/Z, H$ with Higgs decay to a $b\bar{b}$ and work in a narrow width approx.



- Highly boosted regime: $\Delta = \frac{M_H^2}{p_T^2} \ll R^2$
- Small-angle approximation: $\theta_{b\bar{b}}^2 \approx \frac{\Delta}{z(1-z)}$
- decay products in fat jet $\theta_{b\bar{b}}^2 < R^2$: $z(1-z) > \frac{\Delta}{R^2}$
- discard terms which are power suppressed in Δ

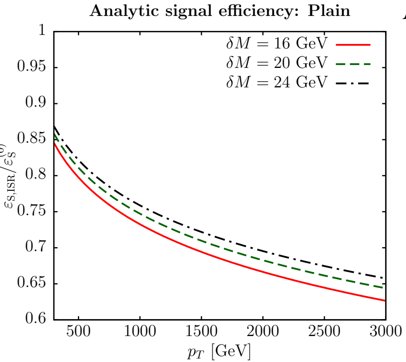
Plain mass Lowest-Order (LO) results for the signal efficiency :

$$\varepsilon_S^{(0)} = \int_0^1 dz\, \Theta\left(R^2 - \frac{\Delta}{z(1-z)}\right) = \sqrt{1 - \frac{4\Delta}{R^2}}\,\Theta\left(R^2 - 4\Delta\right) \approx 1 - \frac{2\Delta}{R^2} + \mathcal{O}\left(\frac{\Delta}{R^2}\right)^2$$

- trivially in good agreement with corresponding MC results
- as one can easily anticipate with increasing boosts, i.e. smaller Δ, the efficiency of reconstruction inside a single jet increases.
- at LO of δM since the jet mass $M_j = M_H$

Plain Jet Mass - Initial State Radiation

- We consider $pp \to ZH$ with soft gluons radiated by the incoming $q\bar{q}$ pair
- ISR soft gluon with energy: $\omega \ll p_T \Rightarrow$ eikonal approximation.

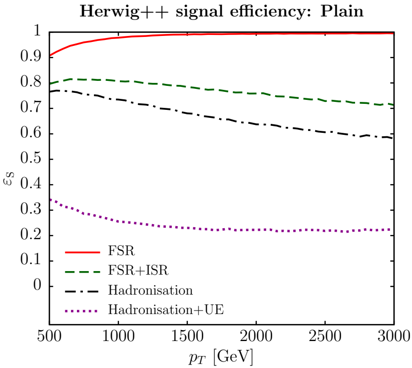


Analytics:

- jet in a mass window:
  $M_H - \delta M < M_j < M_H + \delta M$
- the leading logarithmic result (fixed α_s):
  $\frac{\varepsilon_{\mathrm{S,ISR}}}{\varepsilon_{\mathrm{S}}^{(0)}} \simeq 1 - \frac{C_F \alpha_s}{\pi} R^2 \ln\left(\frac{p_T^2 R^2}{2 M_H \delta M}\right).$
- resum the leading logs (far from easy - non-global, clustering logs), instead working estimate by exponentiating the order α_s result.
- $\varepsilon_{\mathrm{S,ISR}}$ decreases with p_T
- larger $\delta M \Rightarrow$ larger efficiency

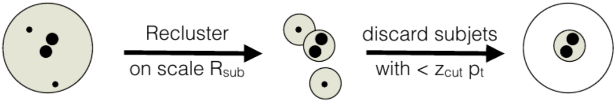
Plain Jet Mass - Final State Radiation and NP effects

- Due to angular ordering most of FSR radiation from b quarks is emitted at angles smaller than $\theta^2_{b\bar{b}}$ (FSR is always recombined inside the fat jet)

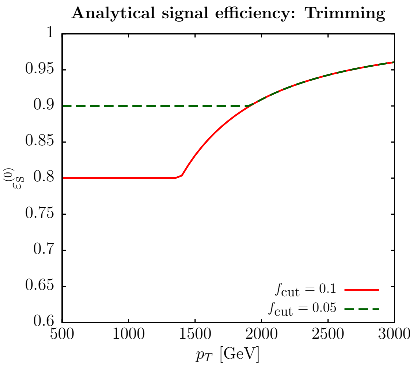


- We tag the signal jet as the highest p_T Cambridge/Aachen jet with $R = 1$ (unless stated otherwise).
- hadronisation has moderate effect on ε_S, which increases $\sim \sqrt{p_T}$, see [M. Dasgupta, L. Magnea, G. P. Salam, JHEP **0802** (2008) 055]
- the dominant contribution comes from underlying event $\Rightarrow$ one needs to consider removal of the UE for efficient tagging.

Trimming



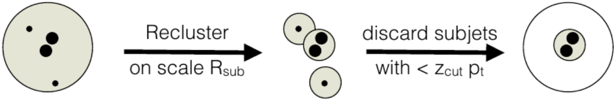
LO results



Analytics:

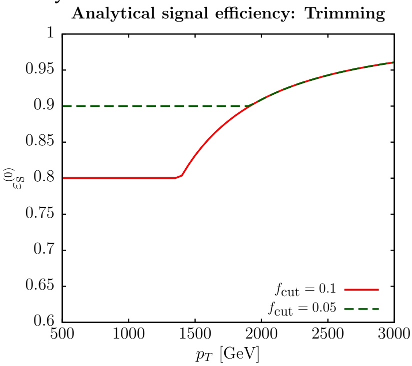
- transition point at $p_T^{trans.} = M_H/(\sqrt{f_{\rm cut}}R_{\rm trim})$
- below $p_T^{trans.}$ $\varepsilon_S^{(0)} = 1 - 2f_{\rm cut}$
- above it $\varepsilon_S^{(0)} = \sqrt{1 - \frac{4\Delta}{R_{\rm trim}^2}}$

Trimming

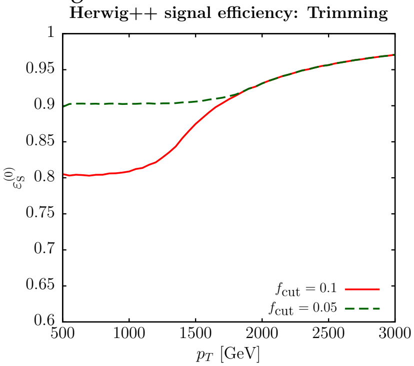


LO results:

Analytical



Herwig++ 2.7.1

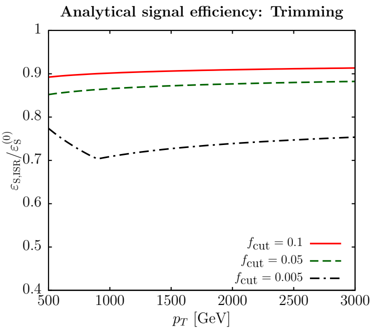


Trimming - Initial State Radiation

- The result obtained has two distinct regimes. For $f_{\text{cut}} > \frac{2M_H \delta M}{R^2 p_T^2}$:

$$\frac{\varepsilon_{\text{S,ISR}}}{\varepsilon_{\text{S}}^{(0)}} \approx 1 - C_F \frac{\alpha_s}{\pi} \left(R^2 \ln \frac{1}{f_{\text{cut}}} + R_{\text{trim}}^2 \ln \left(\frac{f_{\text{cut}} p_T^2 R_{\text{trim}}^2}{2M_H \delta M} \right) \Theta \left(f_{\text{cut}} - \frac{2M_H \delta M}{p_T^2 R_{\text{trim}}^2} \right) \right),$$

while for $f_{\text{cut}} < \frac{2M_H \delta M}{R^2 p_T^2}$: $\frac{\varepsilon_{\text{S,ISR}}}{\varepsilon_{\text{S}}^{(0)}} \approx 1 - C_F \frac{\alpha_s}{\pi} R^2 \ln \frac{R^2 p_T^2}{2M_H \delta M}$.



- for large $f_{\text{cut}} > \frac{2M_H \delta M}{R^2 p_T^2}$ log from plain jet mass replaced by $\ln 1/f_{\text{cut}}$
- for small f_{cut} transition to plain jet log dependence
- Term with R_{trim} vanishes as $R_{\text{trim}} \to 0 \Rightarrow$ small R_{trim} less ISR contamination. However FSR...
- resummation of $\ln 1/f_{\text{cut}}$ highly involved and phenomenologically not relevant.

Trimming - Initial State Radiation

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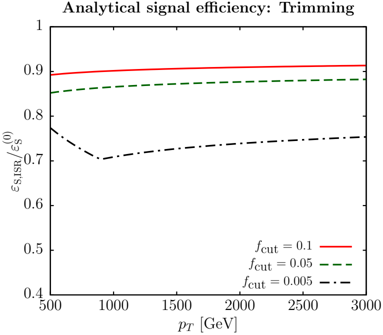
Analytical



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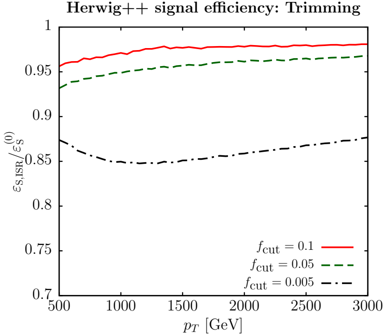


Trimming - Final State Radiation

- FSR when not recombined into the fat jet, results in a shift in mass.
- hard FSR gluon can make b falling below the asymmetry cuts.
- 3 distinct regimes:
  - $R_{\text{trim}} \ll \theta_{b\bar{b}} \Rightarrow$ collinear enhancement with log in R_{trim} and soft log from δM constraint (most singular contribution)
  - $R_{\text{trim}} \sim \theta_{b\bar{b}}$ no collinear enhancement $\Rightarrow$ pure soft single logarithm (similar to pruning and the mMDT)
  - $R_{\text{trim}} \gg \theta_{b\bar{b}}$ becomes more like the plain jet where large angle corrections are strongly suppressed.

Trimming - Final State Radiation

Most singular contribution ($R_{\text{trim}} \ll \theta_{b\bar{b}}$)

$$\varepsilon^{(1)}_{\text{S,FSR}} = -2C_F \frac{\alpha_s}{\pi} \ln \frac{\Delta}{R^2_{\text{trim}}} \left[C_1 \left(f_{\text{cut}}, \epsilon\right) \Theta \left(f_{\text{cut}} - \frac{\epsilon}{1+\epsilon} \right) + C_2 \left(f_{\text{cut}}, \epsilon\right) \Theta \left(\frac{\epsilon}{1+\epsilon} - f_{\text{cut}} \right) \right]$$

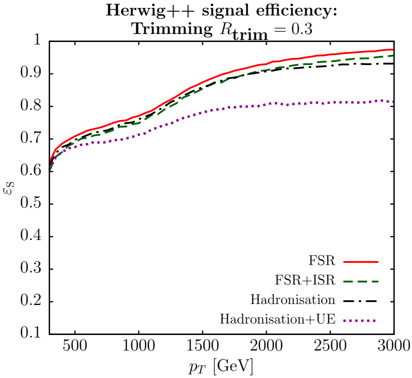
$$C_1 = (1-2f_{\text{cut}}) + (1-2f_{\text{cut}}) \ln \frac{f_{\text{cut}}}{\epsilon} + f_{\text{cut}} \ln f_{\text{cut}} - (1-f_{\text{cut}}) \ln(1-f_{\text{cut}}) \,,$$

$$C_2 = \frac{f_{\text{cut}}}{\epsilon} - f_{\text{cut}} - f_{\text{cut}} \ln \frac{1}{\epsilon}, \quad \epsilon = \frac{2\delta M}{M_H}$$

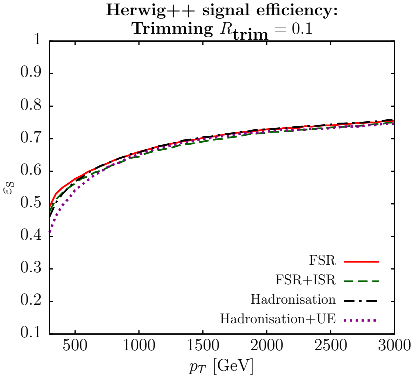
- for $\epsilon \ll f_{\text{cut}}$ the $\varepsilon_{\text{S,FSR}}$ will be dominated by a $\ln \frac{f_{\text{cut}}}{\epsilon}$ and f_{cut} constraint means that in practice such logs are negligible for a wide range of δM.
- for $p_T = 300$ GeV, $f_{\text{cut}} = 0.1$: $\varepsilon^{(0)}_{\text{S}} = 1 - 2f_{\text{cut}} = 0.8$.
  $R_{\text{trim}} = 0.1 \Rightarrow \ln\left(\Delta/R^2_{\text{trim}}\right) \sim \ln 17$ significant radiative corrections.
  $R_{\text{trim}} = 0.3$ reduces $\ln \Delta/R^2_{\text{trim}}$ to $\sim \ln 2$ does not require resummation.
- for $p_T = 3$ TeV, $R_{\text{trim}} = 0.1$ would ensure small FSR and ISR and UE corr.
- Expressed as a percentage of $\varepsilon^{(0)}_{\text{S}}$, the FSR corr., is roughly 2%-10% for δM between 2 GeV to 10 GeV when $R^2_{\text{trim}} \simeq \Delta/2$.
- Implication: full fixed-order calculations (or matched with parton shower) would give a better description of the $\varepsilon_{\text{S,FSR}}$

Trimming - Non-perturbative effects

$f_{\text{cut}} = 0.1, R_{\text{trim}} = 0.3$

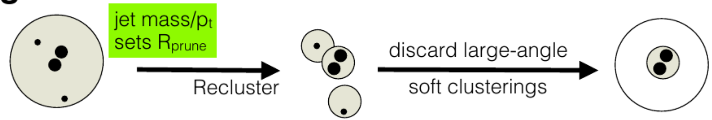


$f_{\text{cut}} = 0.1, R_{\text{trim}} = 0.1$



- Hadronization has little effect - action of trimming on contributions which are soft and wide angle in the jet.
- UE has a larger impact due to soft contamination which is not checked for energy asymmetry. (inside the R_{trim} the algorithm is inactive)
- UE contribution could thus be substantially reduced by choosing a smaller R_{trim} (contribute to a change in the jet mass squared $\sim R^4_{\text{trim}}$)

Pruning



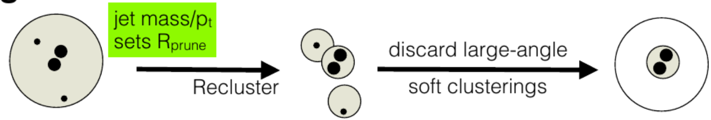
Discard large angle soft clusterings:
if both $\Delta R_{ij} > R_{\rm prune}$ and the splitting is p_T asym. $\min(p_{T_i}, p_{T_j}) < z_{\rm cut} p_{T_{(i+j)}}$ are true, discard the softer of i and j, else i, j are combined as usual.

At zeroth order the two signal prongs are always at an angle larger than $R_{\rm prune}$ and so the result is simply $1 - 2z_{\rm cut}$.

ISR pruning is similar to trimming with $R^2_{\rm trim}$ replaced by $R^2_{\rm prune} \approx \Delta + x\theta^2$.

- for sufficiently soft emissions: $x \to 0$, responsible for logarithmic corrections, one can just replace $R^2_{\rm prune}$ by Δ.
- The result is $\ln \frac{1}{z_{\rm cut}}$, dependence with a transition to the plain mass behaviour visible for smaller $z_{\rm cut}$ values as for trimming.
- We verified it with MC (plot later).

Pruning

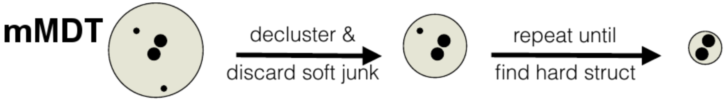


FSR

- For the case of pruning there is no collinear enhancement since radiation that is lost is emitted at an angle (wrt both hard prongs) larger than $R^2_{\text{prune}} \sim \Delta = z(1-z)\theta^2_{b\bar{b}}$ i.e. essentially of order $\theta^2_{b\bar{b}}$.
- thus have only a single log, that results from the loss of soft radiation at relative large angles, comparable to $b\bar{b}$ dipole size.

$$\varepsilon^{(1)}_{\text{S,FSR}} = -C_F \frac{\alpha_s}{\pi} \frac{2\pi}{\sqrt{3}} \ln \frac{z_{\text{cut}}}{\epsilon}, \; z_{\text{cut}} > \epsilon, \; \epsilon = \frac{2\delta M}{M_H}. \tag{1}$$

- However even for $\delta M = 2$ GeV and $z_{\text{cut}} = 0.1$ we get modest $\sim \ln 3$, implying that soft enhanced effects can be neglected.
- Therefore to assess FSR corrections in more detail, as we found for trimming, it is necessary to go beyond the soft approximation and study hard corrections.



Difference with MDT:
1) asym. conditions not satisfied: follow the harder branch rather than the more massive
2) notted that mass drop condition had a negligible impact (we ingnore it)

At zeroth order we obtain a signal efficiency $\varepsilon_S^{(0)} = 1 - 2y_{\mathrm{cut}}$ coming from the asymmetry cut, which is the same result as for pruning.

ISR General behaviour will be similar to pruning and trimming

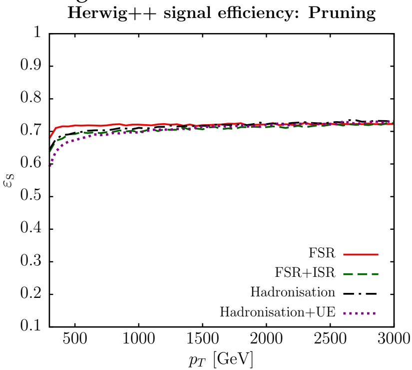
- The result is $\ln \frac{1}{y_{\mathrm{cut}}}$, dependence with a transition to the plain mass behaviour visible for smaller y_{cut} values as for trimming.
- Slightly different position of the transition to the plain mass behaviour

$$x > \frac{y_{\mathrm{cut}}}{2}\left(1 + \sqrt{1 + \frac{4\Delta}{y_{\mathrm{cut}} R^2}}\right),$$

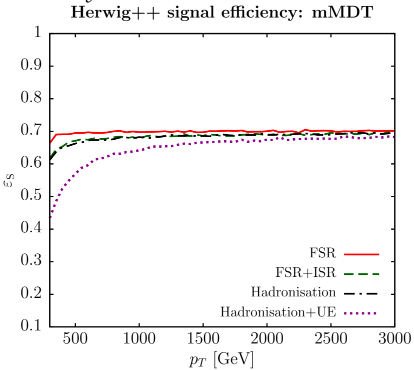
  which for $y_{\mathrm{cut}} \gg \Delta/R^2$ reduces to the same constraint as for the case of pruning and trimming i.e. $x > y_{\mathrm{cut}}$.
- For reasonable values of $y_{\mathrm{cut}} \sim 0.1$, mMDT behaves essentially identical to pruning and trimming.

For **FSR** corrections in the soft approximation, we do not observe any significant differences between mMDT and pruning.

Pruning $z_{\mathrm{cut}} = 0.1$



mMDT $y_{\mathrm{cut}} = 0.1$



- remarkable similarity for entire p_T at parton level and after hadr.
- At lower p_T UE contamination more pronounced for mMDT: larger effective radius $\theta_{b\bar{b}} = \frac{M_H}{p_T\sqrt{z(1-z)}}$ as compared to $R_{\mathrm{prune}} \approx M_H/p_T$ and different def. of the asymmetry parameters y_{cut} vs z_{cut} (use mMDT with filtering as suggested in original paper)
- Keep in mind that for QCD background jets much more pronounced non-perturbative effects were observed for pruning than for mMDT.

Y-pruning is a modification of pruning where one requires that at least one clustering is explicitly checked for and passes the pruning criteria else one discards the jet.

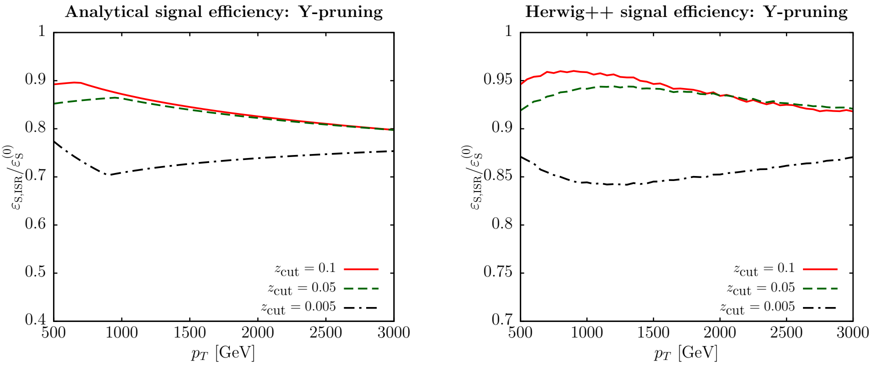
ISR: This modification produces extra contribution compared to Pruning:

$$\Delta\varepsilon_S \approx -C_F \frac{\alpha_s}{\pi} R^2 \ln \frac{z_{\text{cut}} R^2}{\Delta} \Theta\left(\beta - 3\right) \left[\sqrt{1 - \frac{4}{1+\beta}} \Theta\left(\frac{1}{1+\beta} - z_{\text{cut}}\left(1 - z_{\text{cut}}\right) \right) + (1 - 2z_{\text{cut}}) \Theta\left(z_{\text{cut}}(1 - z_{\text{cut}}) - \frac{1}{1+\beta} \right) \right],$$

where we defined $\beta = \frac{z_{\text{cut}} R^2}{\Delta}$.

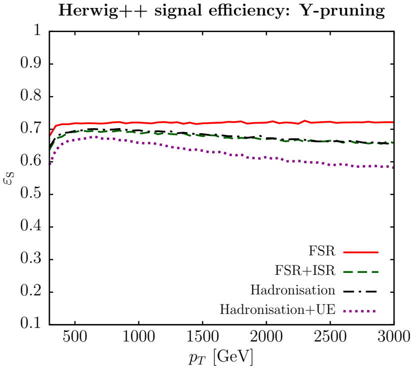
- At high p_T $\Delta\varepsilon_S$ dominates log dependence of pruning on z_{cut}.
- We can distinguish Y-pruning from other taggers by looking at the response to ISR in the high p_T limit.

FSR: there is no significant difference between Y-pruning and pruning. The soft large-angle contributions we saw for ISR are strongly suppressed for the case of FSR, due to the colour singlet Higgs and angular ordering.



- p_T dependence of Y-pruning is significantly different from that of pruning for the same $z_{cut} = 0.1$.
- as expected the ε_S first increases with p_T as for pruning, then decreases beyond a certain point which we expect to be the onset of the logarithmic behaviour $\Delta\varepsilon_S$

Y-Pruning- NP effects



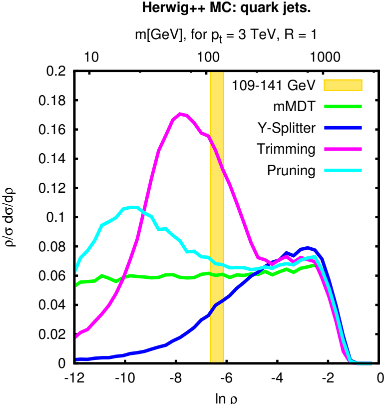
- as expected there is some significant loss of signal due to UE contributions as also observed for QCD jets.
- Due to its strong suppression of QCD jets Y-pruning produced a signal significance that was at least comparable and at high p_T exceeded that from the other taggers studied (mMDT, pruning and trimming).

Takes a fat jet constructed with the k_t algorithm and undoes the last step of the clustering. The k_t distance d_{ij} is given, at small opening angles

$$d_{ij} = \min(z, 1-z)^2 p_T^2 \theta_{ij}^2$$

Cut on d_{ij} to be $\sim M_W^2$ (M_H^2 in our case) or cut on the ratio of d_{ij} to the jet invariant mass M_j^2: $\frac{d_{ij}}{M_j^2} = \frac{\min(z,1-z)}{\max(z,1-z)} > y_{\rm cut}$ (we use this option)

Why Y-splitter is interesting?



Action of Y-splitter on QCD background

- Leading order the result:
  $$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}^{\text{(Y-splitter,LO)}} \simeq C_F \frac{\alpha_s}{\pi}\left(\ln\frac{1}{y_{\rm cut}} - \frac{3}{4}\right), \quad \rho < y_{\rm cut}$$
  (like mass drop)
- however at higher orders there is a double log suppression

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}^{\text{(Y-splitter)}} \simeq C_F \frac{\alpha_s}{\pi}\left(\ln\frac{1}{y_{\rm cut}} - \frac{3}{4}\right)\exp\left[-\frac{C_F\alpha_s}{2\pi}\ln^2\frac{1}{\rho}\right]$$

$\Rightarrow$ much more effective at killing background than mMDT pruning and trimming

Zeroth order the result is similar to that for mMDT and pruning: $\varepsilon_{\mathrm{S}}^{(0)} = 1 - 2y_{\mathrm{cut}}$, which is as usual a consequence of the uniform z distribution and the asymmetry cuts on z.

ISR

- ISR gluon contaminates the jet and gives a result that is essentially like the plain jet mass.

FSR

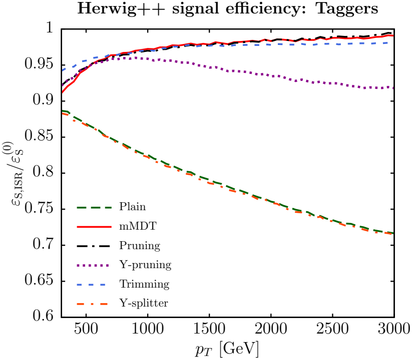
- In contrast to ISR a soft FSR gluon will nearly always be clustered with the hard emitting partons, as a consequence of its softness and angular ordering, ends up as part of the fat jet, thus not contributing to a loss in mass.

NP effects

- MC studies for Y-splitter with hadronisation and UE shows that effects are comparable in size to the plain jet mass.

Taggers - ISR comparison

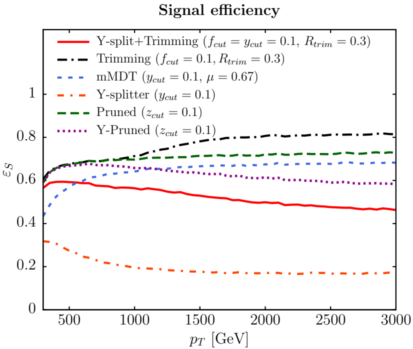
ISR: $f_{\text{cut}} = y_{\text{cut}} = 0.1$ and $R_{\text{trim}} = 0.3$



- Y-splitter and the plain jet mass are essentially identical.
- mMDT, trimming and pruning - similar behaviour to one another as we expected from our analytical estimates.
- Y-pruning suffers at high p_T ($\Delta\varepsilon_S$) as already observed, while still remaining far better than Y-splitter..

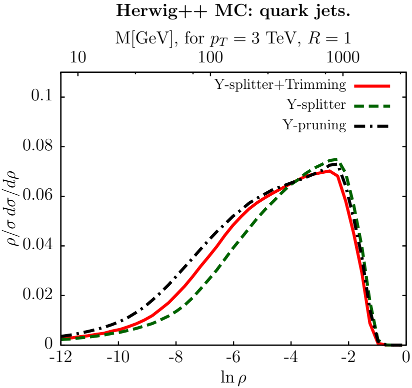
Y-splitter with trimming

Problem: lack of any effective grooming element in Y-splitter
Solution: Y-splitter with trimming[1,2]



- use of trimming substantially stops the loss of signal we saw with Y-splitter.
- Y-splitter with trimming bears a qualitative similarity to Y-pruning.
- Y-splitter with trimming still does not reach the signal efficiency of some other methods
- it is worth examining the signal significances ($\varepsilon_S/\sqrt{\varepsilon_B}$)

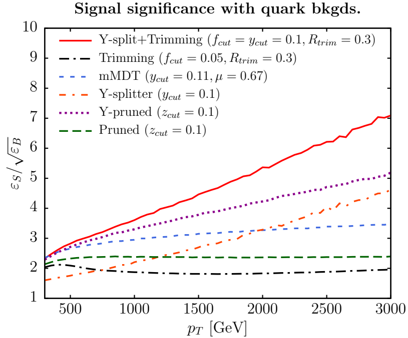
[1]not necessary trimming, possible combination with mMDT or soft drop...
[2]Remark: [Y-splitter, trimming]$\neq 0$

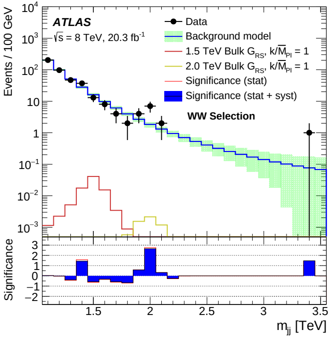


Action of Y-splitter with trimming on QCD background

- Y-splitter is very similar to Y-pruning (subleading terms ensure that Y-splitter suppresses the background more.)
- this makes Y-splitter action on signal worth exploring further
- Trimming does not change much when used after Y-spliter
- At all orders the result for Y-splitter will be done in a forthcoming paper.

Hadronic W jets with quark (left panel)





- Y-splitter with trimming[3] outperforms the other taggers discussed over a range of p_T. (For H similar results particularly at high p_T)
- A detailed study of optimal parameters for Y-splitter+trimming will be presented in forthcoming work.

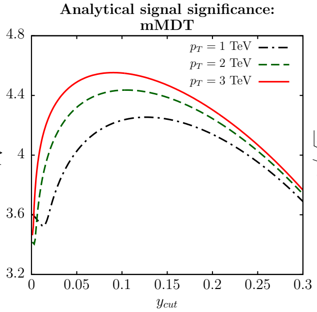
[3] Preliminary studies for Y-splitter+mMDT/pruning/soft drop give a similar qualitative effect.

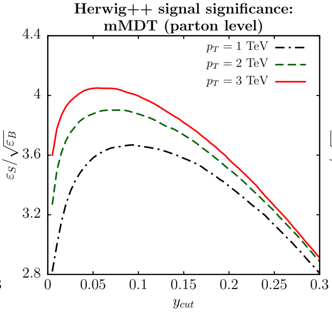
Optimal values

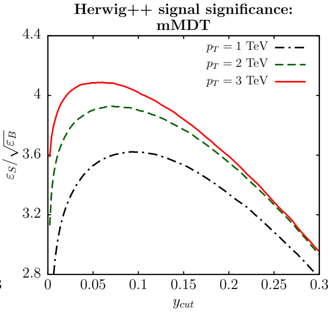
- We use analytical expressions[4] to derive values of parameters that maximise the signal significance $\frac{\varepsilon_S}{\sqrt{\varepsilon_B}}$ for the different taggers.
- We do not expect the values so derived to really be optimal in the sense that they will not take into account non-perturbative effects.
- We examine to what extent general trends in analytics, such as the dependence of optimal parameters on p_T, are replicated in full MC studies.
- Tests of the robustness - methods should be independent of our detailed knowledge about non-perturbative corrections.

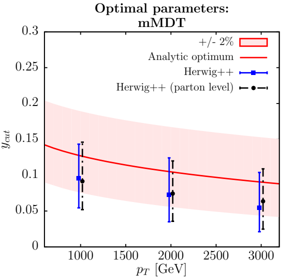
[4] lowest order results for the signal (except trimming) and resummed calculations for QCD background.

Optimal values - mMDT







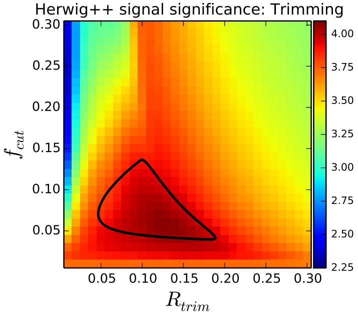


- Herwig parton level agrees with analytics (both the peak positions and the evolution of opt. y_{cut} with p_T).
- hadronisation and UE do not change the picture significantly
- peaks are broad $\Rightarrow$ slightly non-optimal y_{cut} is still ok.
- good degree of overlap within tolerance band between full MC and analytical estimates.

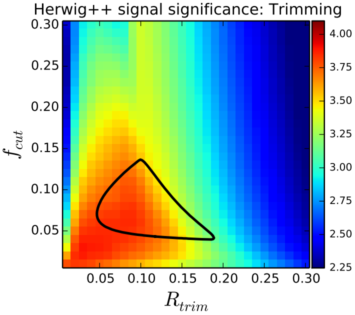
Optimal values - Trimming

- In contrast to mMDT and (Y-)pruning, we include FSR radiative corrections to the signal efficiency which are crucial for optimisation. (LO result suggests optimal $R_{\text{trim}} \to 0$. FSR: large logs when $R_{\text{trim}} \to 0$).

Parton level (3 TeV)



Hadron level (3 TeV)



- Analytics (black contour $\pm 2\%$) in agreement with parton level results.
- non-perturbative corrections increase with R_{trim}.

Summary

- We saw analytical and MC results investigating the impact of taggers on signal jets ($H \to b\bar{b}$).
- We carried out analytical calculation to assess the impact of ISR and FSR, as well as dependence on various taggers parameters and kinematic cuts.
- MC studies were used for comparison and to examine non-perturbative effects.
- We find that tagger performance is more robust for the case of signal jets than was apparent for QCD background.
  Exception: Y-splitter (ISR and UE $\Rightarrow$ signal loss $\sim$ plain mass).

Summary

- This is because we observe absence of genuine log enhancements in the signal efficiency for sensibly chosen tagger parameter values:

Tagger	ISR	FSR
Plain	$R^2 \ln \frac{R^2}{\epsilon\Delta}$	$\Delta \ln \Delta$
Trimming	$R^2 \ln \frac{1}{f_{\text{cut}}}$	$2 \ln \frac{\Delta}{R^2_{\text{trim}}} C_2(f_{\text{cut}}, \epsilon)$
Pruning	$R^2 \ln \frac{1}{z_{\text{cut}}}$	$\frac{2\pi}{\sqrt{3}} \ln \frac{z_{\text{cut}}}{\epsilon}$
Y-pruning	$R^2 \ln \frac{z_{\text{cut}} R^2}{\Delta}$	$\frac{2\pi}{\sqrt{3}} \ln \frac{z_{\text{cut}}}{\epsilon}$
mMDT	$R^2 \ln \frac{1}{y_{\text{cut}}}$	$0.646 \ln \frac{y_{\text{cut}}}{\epsilon}$
Y-splitter	$R^2 \ln \frac{R^2}{\epsilon\Delta}$	$\mathcal{O}\left(y_{\text{cut}}\right)$

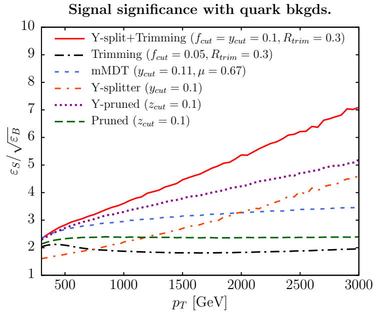
- interesting question: about the potential role for fixed-order (FO) calculations in the context of jet substructure studies
- however we check that we can adjust parameters such as δM to obtain good agreement between FO and Parton Shower.

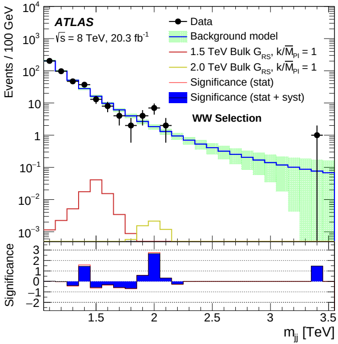
Summary - Optimal values

- We have carried out an analytical study of optimal parameter values for various taggers.
- Based on lowest order results for the signal and resummed calculations for QCD background, generally provide a good indicator of the dependence of signal significance on the tagger parameters.
- The analytical formulae which also do not include non-perturbative effects give rise to optimal values that are fairly compatible with those produced by full MC studies.
- This is encouraging from the point of view of robustness of the various methods!

Summary

- Introduction of a combination of Y-splitter with trimming in an attempt to improve the response of Y-splitter to ISR/UE contamination (Motivation was observation that Y-splitter is very effective in suppressing QCD bkg).
- The combination gives very good results and might be useful for the recent boosted "bump" studies.





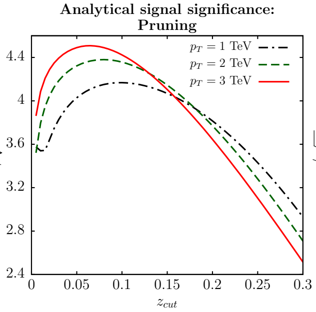
- our forthcoming analytical calculations for the case of Y-splitter with trimming will shed further light on this and ...

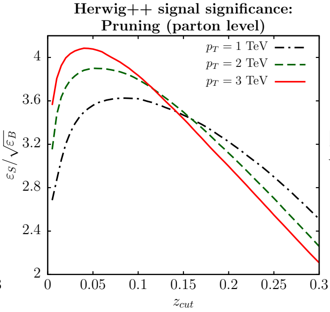
... to get a good perspective

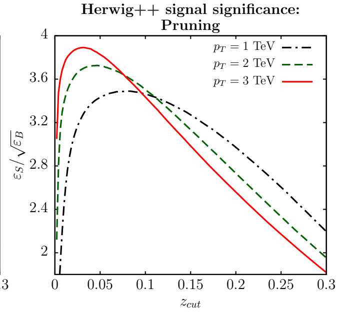
Thank you for the attention!

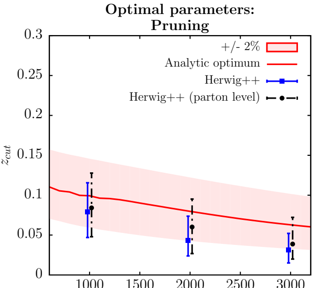
Backup slides

Optimal values - Pruning



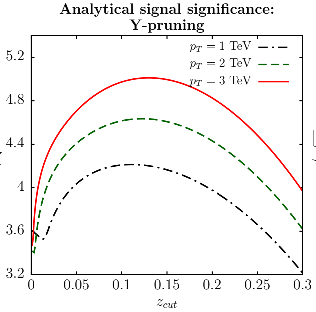


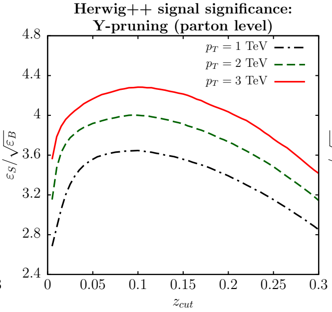


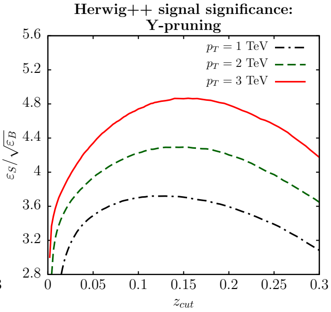


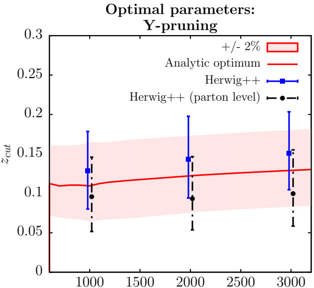
- Herwig parton and hadron level agrees with analytics (both the peak positions and the evolution of opt. y_{cut} with p_T).
- at higher p_T narrower peaks then mMDT $\Rightarrow$ more precise about the choice of z_{cut}.
- Pruning authors: optimal value $z_{\text{cut}} = 0.1$ at moderate transverse momenta ($100 - 500$ GeV for W bosons) our results are consistent as we approach this region.
- for larger boosts, optimal value slightly smaller ($z_{\text{cut}} \sim 0.075$).

Optimal values - Y-pruning









- Analytics again broadly in agreement with MC results.
- Peaks are quite broad
- peaks are broad ⇒ slightly non-optimal y_{cut} is still ok.
- the optimal z_{cut} does not depend strongly on p_T

Fixed-order results vs parton showers for FSR

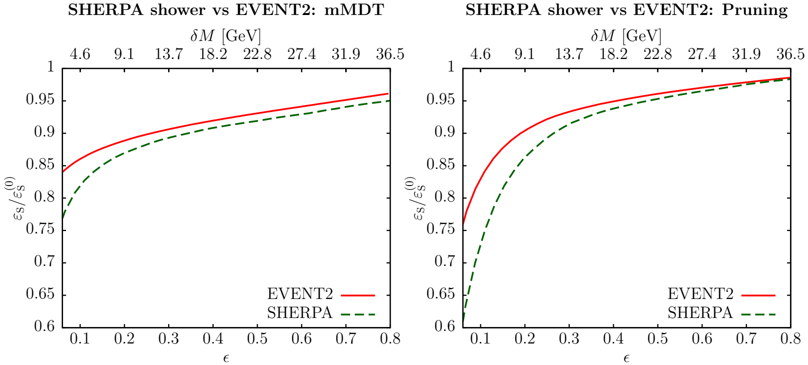


Figure : Ratio for signal efficiency normalised to lowest-order result, with EVENT2 and Sherpa 2.0.0, for e^+e^- annihilation with virtual Z production and hadronic decay, where we consider a Z boson with a transverse boost to $p_T = 3$ TeV.

Fixed-order results vs parton showers for FSR

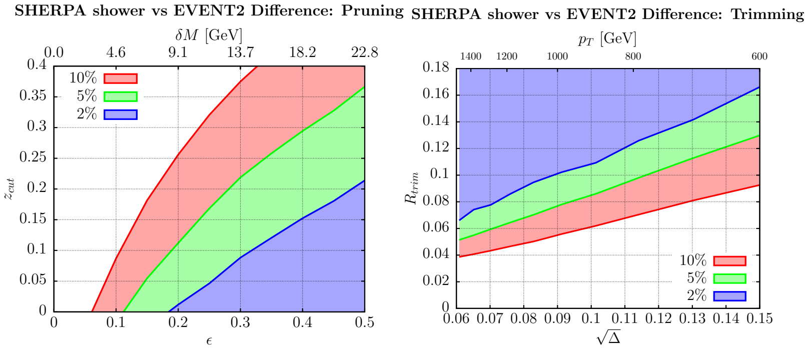
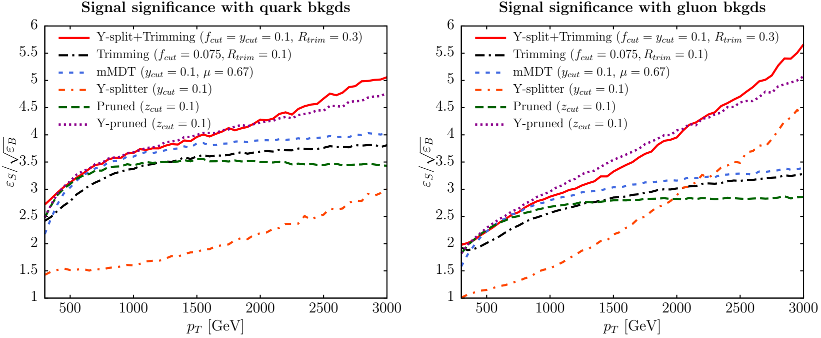


Figure : Contour plot showing the maximum percentage difference in signal efficiency between EVENT2 at order α_s and Sherpa 2.0.0 final state shower both normalised to the lowest order result. In the left hand panel we apply pruning with different values for ϵ and z_{cut} with $p_T = 3$ TeV. In the right hand panel we apply trimming with different values for $\sqrt{\Delta}$ and R_{trim} with $f_{\text{cut}} = 0.1$.

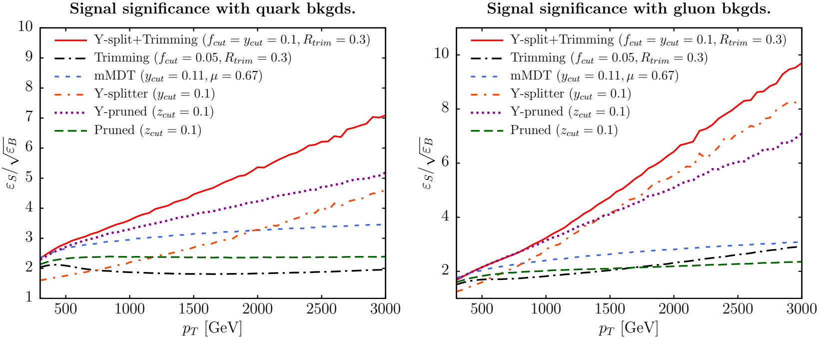
Hadronic H jets with quark (left panel) and gluon (right panel)
Herwig++ (full simulation) results[5]



- One observes that the Y-splitter with trimming method outperforms the taggers discussed here, particularly at high p_T.
- A detailed study of optimal parameters for Y-splitter+trimming will be presented in forthcoming work.

[5] We obtained similar results with Pythia 6.

Hadronic W jets with quark (left panel) and gluon (right panel)



- Y-splitter with trimming[6] outperforms the other taggers discussed over a range of p_T. (For H similar results particularly at high p_T)
- A detailed study of optimal parameters for Y-splitter+trimming will be presented in forthcoming work.

[6]Preliminary studies for Y-splitter+mMDT/pruning/soft drop give a similar qualitative effect.

At all orders the result for Y-splitter can. Since the derivation of this result takes us away from our current focus on signals, we shall not provide it here, but shall do so in a forthcoming paper. The basic fixed coupling result, for small ρ can be expressed in the form:

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}^{\text{(Y-splitter)}} \simeq C_F \frac{\alpha_s}{\pi}\left(\ln\frac{1}{y_{\text{cut}}} - \frac{3}{4}\right)\exp\left[-\frac{C_F\alpha_s}{2\pi}\ln^2\frac{1}{\rho}\right],$$

which represents a Sudakov suppression of the leading order result. The form of this result is identical to that derived for Y-pruning in the region $\rho < z_{\text{cut}}^2$ and when $\alpha_s \ln\frac{1}{z_{\text{cut}}}\ln\frac{1}{\rho} \ll 1$, though subleading logarithmic terms will differ. One can verify this similarity of Y-splitter to Y-pruning, for the case of QCD jets, by examining the results produced by MC and we shall do so in the next subsection.