Y-splitter with grooming as an effective boosted object tagger

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Work currently being finalized with Mrinal Dasgupta, Alexander Powling and Gregory Soyez.

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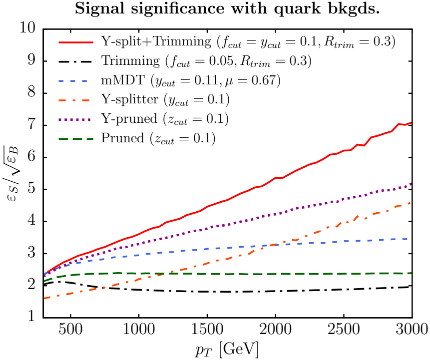
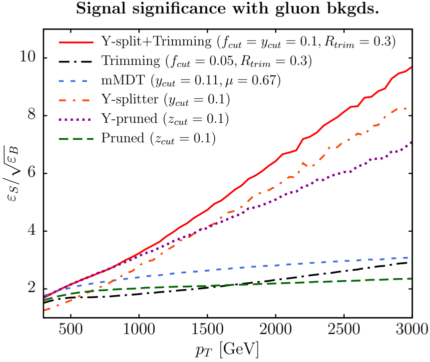
Y-splitter

- Proposed as WW tagger; [Butterworth, Cox and Forshaw (2002)]
- Used in ATLAS top tagger; [Broojimans et. al]
- Undo last step of k_T clustering, i.e. using the distance $d_{ij} = \min\left(p_{Ti}^2, p_{Tj}^2\right)\theta_{ij}^2$
- Impose the condition $d_{ij}/m_{jet}^2 > y$.
- Retains symmetric 2-pronged structures (keeps signal while eliminating QCD background).

Motivation

- Monte Carlo studies show a good performance for the combination Y-splitter and trimming.
  Dasgupta, Powling, Siodmok (2015)

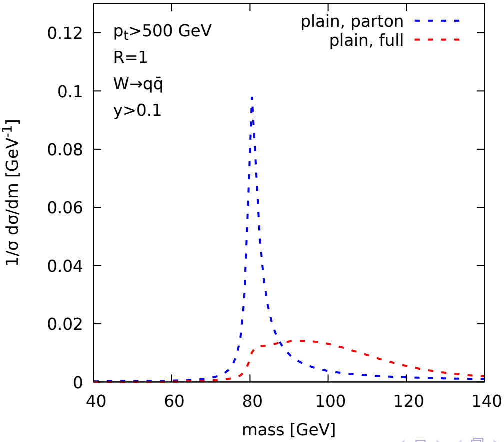




Motivation

Y-splitter + plain jets:

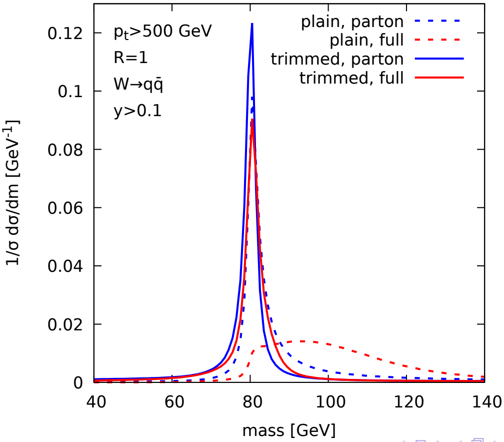
- NP effects cause a strong smearing of mass distribution peak.



Motivation

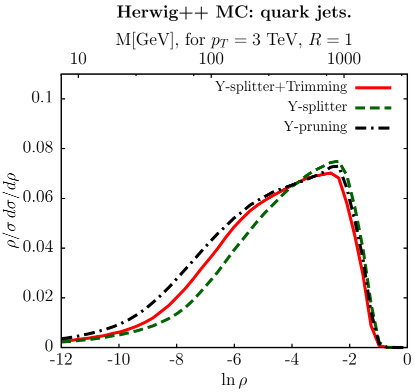
Y-splitter + trimmed jets:

- NP effects in mass distribution peak are smaller;
- At parton level, trimming does not cause a significant change.



Motivation

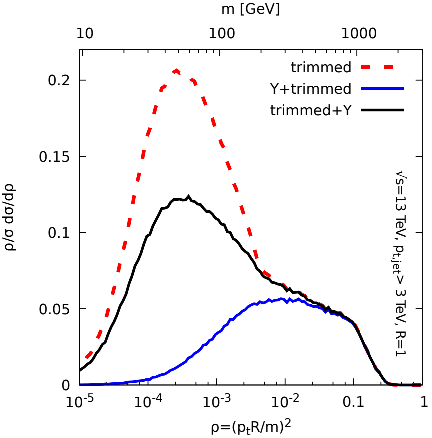
- Trimming does not change significantly Y-splitter background.



Dasgupta, Powling, Siodmok (2015)

Trimming before Y-splitter

- Doing trimming before Y-splitter → lose this property;



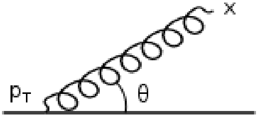
Our work

- Study Y-splitter and Y-splitter with grooming;
- Compute analytically $\frac{m}{\sigma}\frac{d\sigma}{dm}$ with a cut y;
- Focus on QCD background;
- Compare with Monte Carlo, study impact of NP effects;
- Consider the parameters $f_{trim} = y_{mMDT} = y$;
- Study variants and improvements.

Plain Y-splitter

Leading Order

- Define $\rho = m^2/(p_T^2 R^2) \ll 1$, boosted jets;
- One gluon emission in soft-collinear limit;



- The energy fraction of the gluon x, angle of emission θ;
- Y-splitter condition is $(x\theta)^2/(x\theta^2) = x > y$;

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{y_{cut}}^{\text{LO,soft-coll.}} = \frac{C_F\alpha_s}{\pi}\left(\log\frac{1}{y}\Theta\left(y-\rho\right)+\log\frac{1}{\rho}\Theta\left(\rho-y\right)\right).$$

- For small ρ : $\log(1/\rho) \to \log(1/y)$, reduction of QCD background.

Next-to-Leading Order

- Two gluon emissions, can be real or virtual;

- Y-splitter condition is $\max(x_1^2\theta_1^2, x_2^2\theta_2^2)/\max(x_1\theta_1^2, x_2\theta_2^2) > y$;
- We find

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{y_{cut}}^{\text{NLO, LL}} \overset{\rho<y}{=} \frac{C_F\alpha_s}{\pi}\log\frac{1}{y} \times \left[\frac{C_F\alpha_s}{2\pi}\log^2\frac{1}{\rho} + \text{sub-leading}\right].$$

Resummation (all orders)

- For $\rho < y$, we can resum $\log(1/\rho)$ (leading-log)

$$\left.\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\right|_{y_{cut}}^{LL} = \frac{C_F\alpha_s}{\pi}\log\frac{1}{y} \times \exp\left[-\frac{C_F\alpha_s}{2\pi}\log^2\frac{1}{\rho}\right]$$

- Compared with plain mass distribution (without cut)

$$\left.\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\right|_{plain}^{LL} = \frac{C_F\alpha_s}{\pi}\log\frac{1}{\rho} \times \exp\left[-\frac{C_F\alpha_s}{2\pi}\log^2\frac{1}{\rho}\right]$$

- Same Sudakov suppression, different pre-factors;
  Small pre-factor+large exponent=good performance (Soyez's talk)

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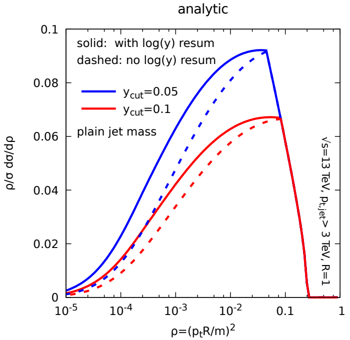
- Same Sudakov suppression, different pre-factors;
  Small pre-factor+large exponent=good performance (Soyez's talk)
- Similar structure to Y-pruning; Dasgupta, Fregoso, Marzani and Salam (2013)
- It is possible resum $\log(1/y)$ effects, expression more complicated.

Comparison with Monte Carlo

- Mass distribution, analytic vs. Monte Carlo simulation.



- Adding the $\log(1/y)$ resummation changes the curve, but not fundamentally.

Y-splitter with Grooming

1 - Apply Y-splitter cut
2 - Apply Grooming

Trimming at Fixed Order

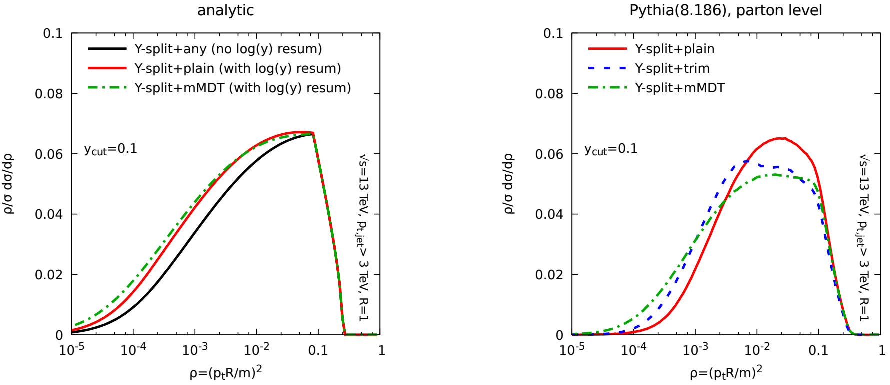
- LO (1 gluon): same results as Y-splitter.
- NLO (2 gluons): multiple regions depending on y and $r = R_{trim}/R$;
- We can write :

$$\frac{1}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{trim}^{\mathrm{NLO}} = \frac{1}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{y_{cut}}^{\mathrm{NLO}} + \mathcal{F}^{\mathrm{trim}}.$$

- When $\rho \to 0$, trimming correction to Y-splitter vanishes , background mostly untouched (LL $\log(1/\rho)$);
- For other regions, correction is always sub-dominant in $\log(1/\rho)$.

Comparison to Monte Carlo

- Both mMDT and trimming are the same at LL $\log(1/\rho)$;
- mMDT has less transition points;
- Resummation of $\log(1/y)$ is possible (mMDT done in paper).



Variants

Mass declustering

- Replaced kt declustering by gen-kt with $p = 1/2$ (mass-like ordering);
- Removes regime "dominant mass" $\neq$ "dominant k_T";
- Small improvement in performance;
- Same Sudakov exponent as previously (LL).

z cut Condition

- Condition replaced by $\min(p_{t1}, p_{t2})/(p_{t1} + p_{t2}) > z_{cut}$;
- Easier to resum higher orders;
- Small loss in performance, less NP effects;
- Same Sudakov exponent (LL).

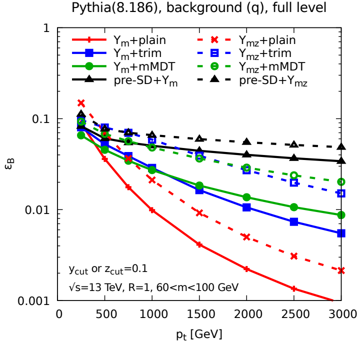
Pre-grooming (Soft Drop)

- Groom jet before Y-splitter cut;
- Smaller Sudakov suppression (region $z < z_{cut}\theta^{\beta}$ no longer vetoed);
- Loss in performance, less NP effects.

MC study and NP effects

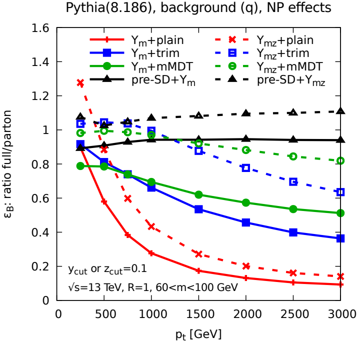
MC simulations and NP effects

Efficiency (ε_B)



Smaller is better.

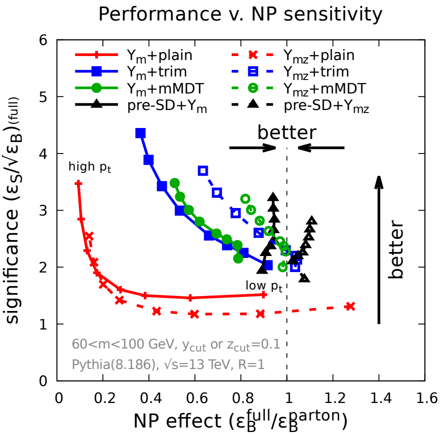
Sensitivity to NP effects($\varepsilon_B^{full}/\varepsilon_B^{parton}$)



Closer to 1 is better.

- Trade-off between performance and insensitivity to NP effects.

Observations



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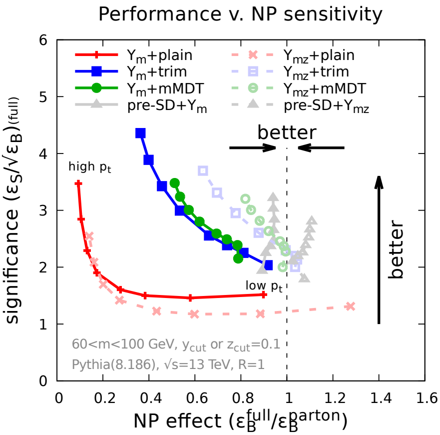
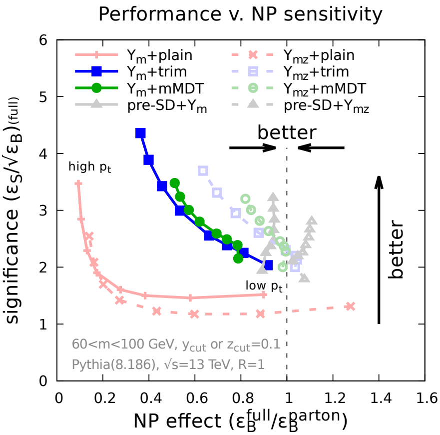


- Adding grooming to Y-splitter increases performance and decreases NP effects;

Observations



- Adding grooming to Y-splitter increases performance and decreases NP effects;
- mMDT slightly less NP effects than trimming, but less discriminant;

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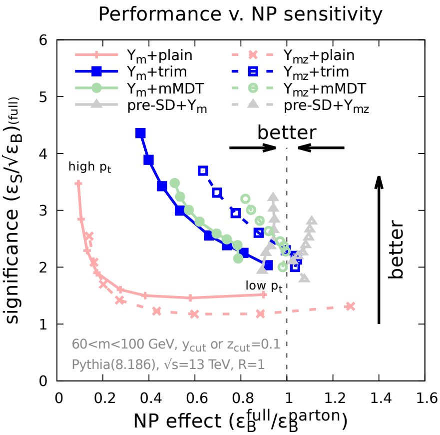

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- Using z_{cut} decreases performance and reduces NP effects;

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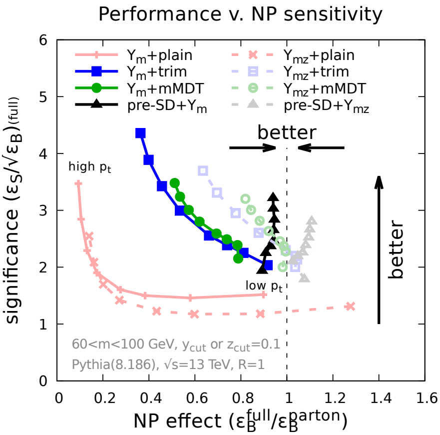
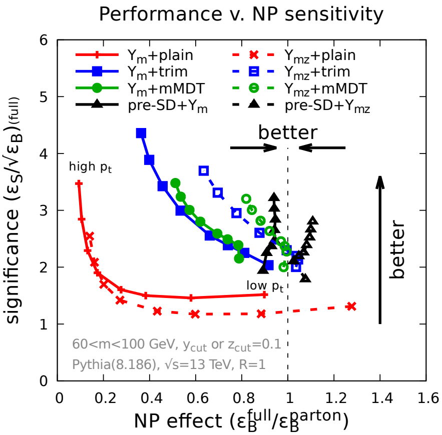


- Adding grooming to Y-splitter increases performance and decreases NP effects;
- mMDT slightly less NP effects than trimming, but less discriminant.
- Using z_{cut} decreases performance and reduces NP effects;
- Pre-grooming decreases performance and reduces NP effects.

Conclusion

- Analytic results for Y-splitter (with or without grooming);
- Suggested variations with various advantages;
- Trade off between performance and insensitivity to NP effects;
- Future: for NP insensitive cases, do an optimization based on parton level results.

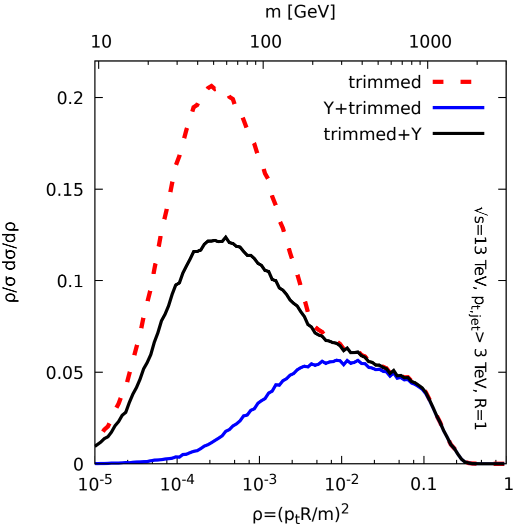


Backup slides

Triming and mMDT

- **Trimming** :
  Krohn, Thaler, Wang (2009)
  1. Recluster jets using $R_{trim} < R$;
  2. Retain only subjets $p_T^{sub} > f_{trim} p_T^{jet}$.
- **(modified) Mass Drop Tagger**:
  Butterworth, Davison, Rubin and Salam, (2008)
  Dasgupta, Fregoso, Marzani and Salam, (2013)
  Apply recursion:
  1. Split jet in two $j \to j_1 + j_2$;
  2. Stop if splitting satisfies $\min\left(p_{Ti}^2, p_{Tj}^2\right) \theta_{ij}^2 / m_{jet}^2 > y_{mMDT}$;
  3. Otherwise, eliminate subjet with smaller p_T.

Trimming before Y-splitter



Trimming at Fixed Order

- We note p_1 the particle with a dominant mass, region a is $k_{T1} > k_{T2}$ and region b is $k_{T1} < k_{T2}$;

$$\frac{1}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{\text{trim}}^{\text{NLO}} = \frac{1}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{\text{y}_{\text{cut}}}^{\text{NLO}} + \mathcal{F}^{\text{trim,a}} + \mathcal{F}^{\text{trim,b}}.$$

- In the region $\underline{\rho < y^2 r^2}$:

$$\mathcal{F}^{\text{trim,a}} = \frac{1}{\rho}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \frac{1}{2}\ln\frac{1}{r^2}\ln^2 y,$$

$$\mathcal{F}^{\text{trim,b}} = -\frac{1}{\rho}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \frac{1}{2}\ln\frac{1}{r^2}\ln^2 y.$$

- $\underline{y^2 r^2 < \rho < y r^2}$: $\mathcal{F}^{\text{trim,b}}$ remains the same,

$$\mathcal{F}^{\text{trim,a}} = \frac{1}{\rho}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \left(\frac{1}{2}\ln^2\frac{1}{y}\ln\frac{1}{r^2} - \frac{1}{6}\ln^3\frac{\rho}{y^2 r^2}\right).$$

Trimming at Fixed Order

- $\underline{y^2 > \rho > yr^2}$

$$\mathcal{F}^{\text{trim,a}} = \frac{1}{\rho}\left(\frac{C_F\alpha_s}{\pi}\right)^2\left(\frac{1}{2}\ln\frac{y}{\rho}\ln^2\frac{1}{y} - \frac{1}{6}\ln^3\frac{1}{y}\right),$$
$$\mathcal{F}^{\text{trim,b}} = -\frac{1}{\rho}\left(\frac{C_F\alpha_s}{\pi}\right)^2\frac{1}{2}\ln\frac{y}{\rho}\ln^2\frac{1}{y}.$$

- $\underline{y > \rho > y^2}$: $\mathcal{F}^{\text{trim,b}}$ remains the same,

$$\mathcal{F}^{\text{trim,a}} = \frac{1}{\rho}\left(\frac{C_F\alpha_s}{\pi}\right)^2\left(\frac{1}{3}\ln^3\frac{y}{\rho} + \frac{1}{2}\ln^2\frac{y}{\rho}\ln\frac{\rho}{y^2}\right).$$

- $\underline{\rho > y}$: no Y-splitter effects.

mMDT at Fixed Order

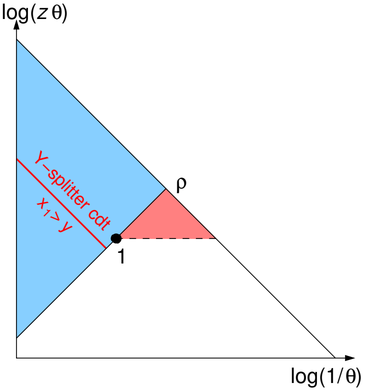
- For $\rho < y^2$:

$$\mathcal{F}^{\mathrm{mMDT}} = \frac{-1}{6} \ln^3 \frac{1}{y}.$$

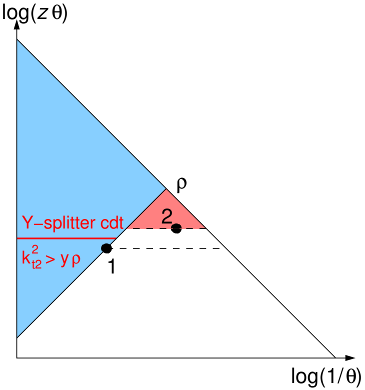
- For $y > \rho > y^2$: sum of contributions a and b of trimming in same region.

Lund diagram Y-splitter

Emission that dominates the jet mass also has the largest k_t.



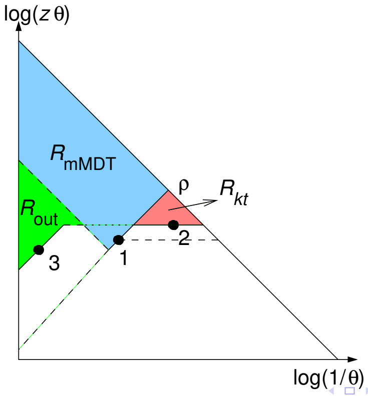
Emission with larger k_t than the k_t of the emission that dominates the mass.



Resummation for Y-splitter with mMDT

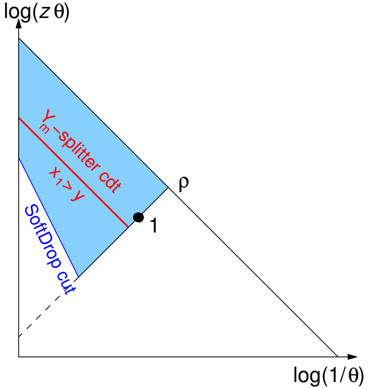
$$\frac{\sigma}{\rho}\frac{d\sigma}{d\rho}\bigg|_{\mathrm{mMDT}}^{\mathrm{resum}} = \int_y^1 dx_1\, P(x_1)\frac{\alpha_s(\rho x_1)}{2\pi} e^{-R_{\mathrm{mMDT}(\rho)}}$$

$$\left[e^{-R_{k_t}(k_{t1};\rho)-R_{\mathrm{out}}(k_{t1}^2/y)} + \int_{k_{t1}}^{\sqrt{\rho}} \frac{dk_{t2}}{k_{t2}} R'_{k_t}(k_{t2};\rho) e^{-R_{k_t}(k_{t2};\rho)-R_{\mathrm{out}}(k_{t2}^2/y)}\right]$$



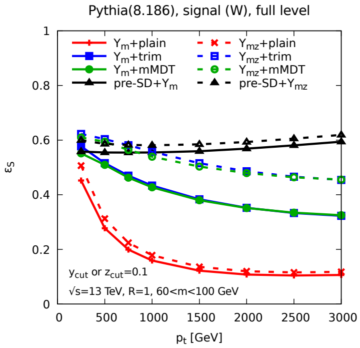
Y-splitter with pre-grooming

- Y-splitter applied on a pre-groomed jet with SoftDrop.
- Shadowed area : vetoed by SoftDrop and entering into the Sudakov factor.
- Dashed (red) line: Y-splitter (z_m) condition.

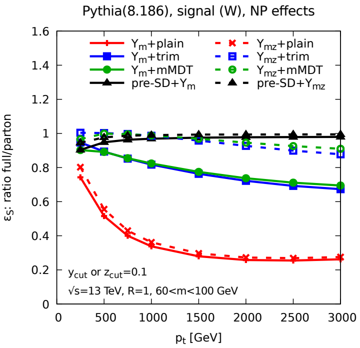


Efficiency and NP effects (signal)

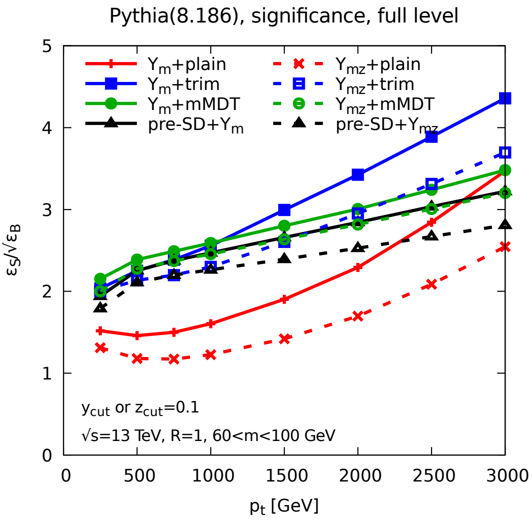
Efficiency (ε_B)



Sensitivity to NP effects($\varepsilon_B^{full}/\varepsilon_B^{parton}$)



Significance



Observations - k_T vs. gen-$k_T^{(p=1/2)}$