Safely Eating Junk:
Pileup and **I**nfrared **R**adiation **A**n**N**i**H**il**A**tion
(PIRANHA)

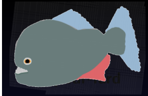
Samuel Alipour-fard

in collaboration with Patrick Komiske, Eric Metodiev, and Jesse Thaler

MIT

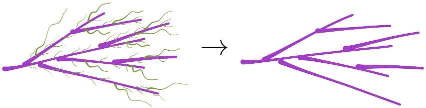
samuelaf@mit.edu

Jet Physics: From RHIC/LHC to EIC Jul 1, 2022

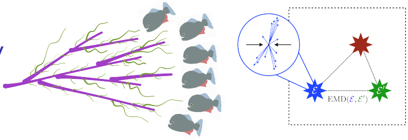


Overview

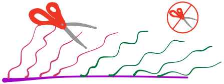
Motivation



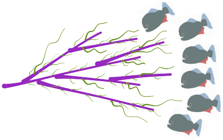
PIRANHAs from Geometry

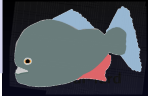


Performance of PIRANHA



vs.

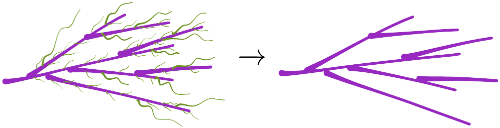




Motivation

Grooming:

A systematic procedure for removing contaminating soft radiation from particle collision data.

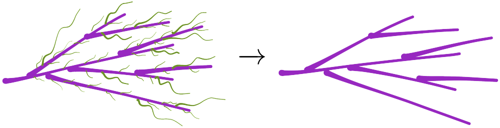


- Grooming, pileup mitigation, and similar strategies extract high energy information from jets
- Grooming helps us understand the *high energy* interactions of the microscopic universe
  (hard process/leading vertex)

Motivation

Grooming:

A systematic procedure for removing contaminating soft radiation from particle collision data.



This definition groups techniques traditionally separated into

Grooming (see e.g. [1901.10342])

Filtering:[0802.2470], Pruning:[0912.0033], Trimming:[0912.1342]
mMDT/Soft Drop:[1307.0007],[1402.2657]; Dynamical:[1911.00375]

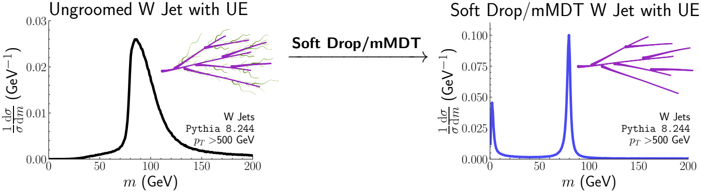
Pile-up Mitigation (see e.g. [1801.09721])

Areas: [0707.1378],[0802.1188],[1111.6097], Charged Hadron Subtraction
Cleansing [1309.4777], SoftKiller [1407.0408], PUPPI [1407.6013], PUMML [1707.08600]

Motivation

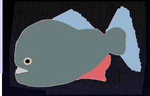
- **Experiment**: Groomed information is resilient to detector effects, pileup, initial state radiation
  ATLAS:[1711.08341], CMS:[1807.05974]

- **Theory**: Grooming can facilitate precision calculations of jet substructure observables
  Frye-Larkoski-Schwartz-Yan:[1603.09338]
  Larkoski-Marzani-Soyez-Thaler:[1402.2657]



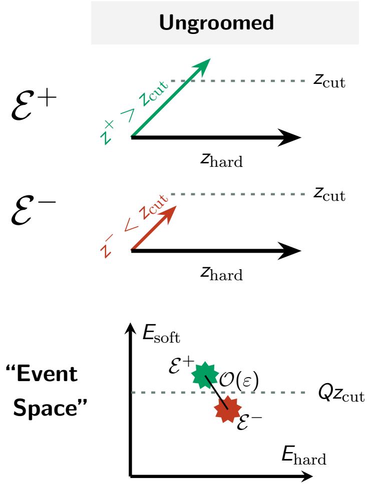
mMDT: Dasgupta-Fregoso-Marzani-Salam:[1307.0007]
Soft Drop: Larkoski-Marzani-Soyez-Thaler:[1402.2657]

- In this motivating discussion, we will limit ourselves to mMDT, or Soft Drop with $\beta_{\rm SD} = 0$.



Motivation: IRC Sensitivity

Grooming techniques such as Soft Drop/mMDT implement hard cutoffs ($z_{\rm cut}$), leading to **discontinuous behavior**:



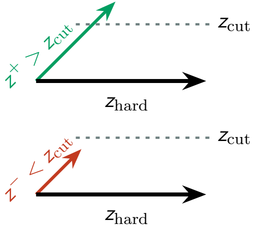
Motivation: IRC Sensitivity

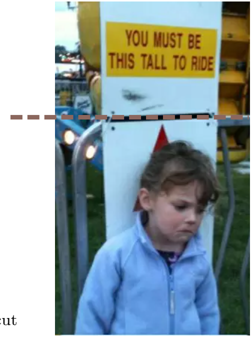
Grooming techniques such as Soft Drop/mMDT implement hard cutoffs (z_{cut}), leading to **discontinuous behavior**:

Ungroomed	**SD/mMDT**

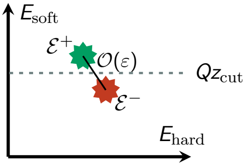
$\mathcal{E}^+$

$\mathcal{E}^-$



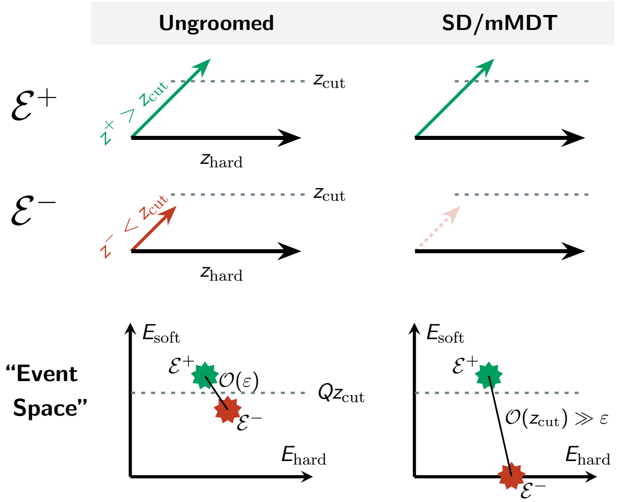


"Event Space"



Motivation: IRC Sensitivity

Grooming techniques such as Soft Drop/mMDT implement hard cutoffs ($z_{\rm cut}$), leading to **discontinuous behavior**:

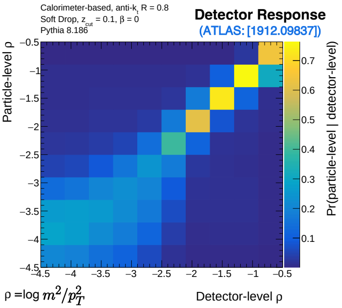


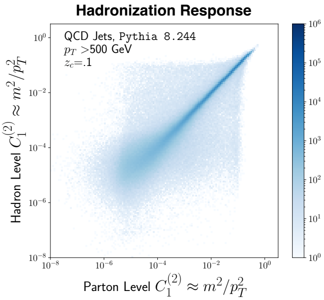
Motivation: IRC Sensitivity

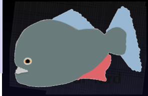
Grooming techniques such as Soft Drop/mMDT implement hard cutoffs ($z_{\rm cut}$), leading to **discontinuous behavior**.

Consequences:

- Sensitivity to detector effects ATLAS:[PHYS-PUB-2019-027, 1912.09837]
- Theoretical complications Hoang-Mantry-Pathak-Stewart:[1906.11843]



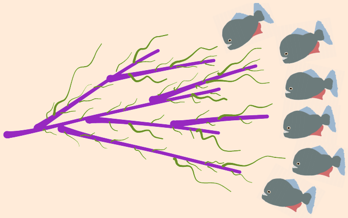


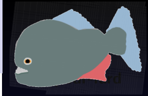


Introducing: PIRANHA Grooming

Grooming: Remove contaminating soft radiation.

PIRANHA: *Continuously* remove contaminating soft radiation (no hard cutoffs)

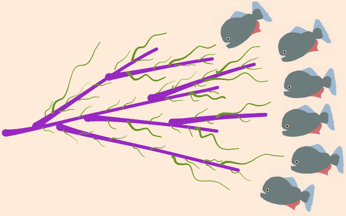


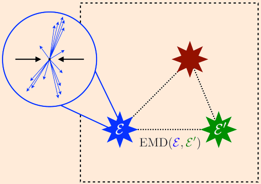


Introducing: PIRANHA Grooming

Grooming: Remove contaminating soft radiation.

PIRANHA: *Continuously* remove contaminating soft radiation (no hard cutoffs) **using geometry**.





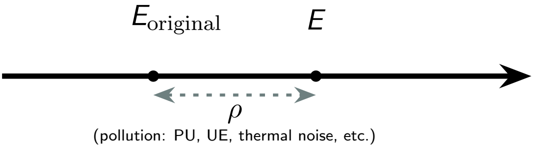
Detail: EMD Definition

Komiske-Metodiev-Thaler:[1902.02346],[2004.04159], Cesarotti-Thaler:[2004.06125]
Cai-Cheng-Craig-Craig:[2008.08604]

Introducing: PIRANHA Grooming

Subtraction through geometry:

- **Simple example**: Grooming real numbers

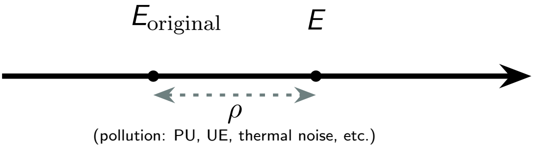


How can we remove pollution with only the metric?

Introducing: PIRANHA Grooming

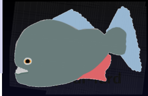
Subtraction through geometry:

- **Simple example**: Grooming real numbers



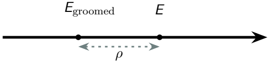
How can we remove pollution with only the metric?

$$E_{\text{groomed}} = \text{argmin}_{E'} \; ||E, E' + \rho|| \\ = E - \rho \\ = E_{\text{original}}$$



Subtraction through geometry:

- **Simple example**: Real line

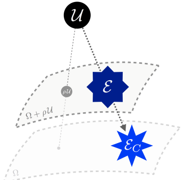


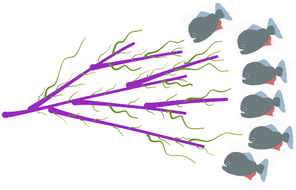
$$E_{\text{groomed}} = \text{argmin}_{E'} \; ||E, E' + \rho||$$

- **PIRANHA**: Grooming jet events

$$\mathcal{E}_{\text{groomed}} = \mathcal{E}_{\text{C}} = \text{argmin}_{\mathcal{E}'} \text{EMD}\left(\mathcal{E}, \mathcal{E}' + \rho\mathcal{U}\right)$$

where $\rho\mathcal{U}$ is a "uniform event": underlying event, pileup, etc.





Komiske-Metodiev-Thaler:[2004.04159]

Introducing: PIRANHA Grooming

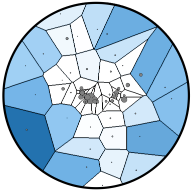
$$\mathcal{E}_{\text{groomed}} = \mathcal{E}_{\text{C}} = \text{argmin}_{\mathcal{E}'} \text{EMD}\left(\mathcal{E}, \mathcal{E}' + \rho\,\mathcal{U}\right)$$

Optimal transport theory $\rightarrow$ **Apollonius Subtraction**!

$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Apoll.}}$$

Komiske-Metodiev-Thaler:[2004.04159]

Similar to area subtraction pileup mitigation techniques like **Voronoi Area Subtraction**. Detail: More PIRANHA for PU



$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Voronoi}}$$

[2004.04159] Cacciari-Salam:[0707.1378]; +Soyez:[0802.1188], [1111.6097]

Introducing: PIRANHA Grooming

$$\mathcal{E}_{\text{groomed}} = \mathcal{E}_{\text{C}} = \text{argmin}_{\mathcal{E}'} \text{EMD}\left(\mathcal{E}, \mathcal{E}' + \rho\,\mathcal{U}\right)$$

Optimal transport theory → **Apollonius Subtraction**!

$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Apoll.}}$$

Komiske-Metodiev-Thaler:[2004.04159]

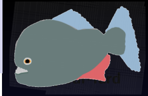
Weaknesses of Apollonius Subtraction:

- Computationally expensive;
- Not amenable to resummed theoretical calculation.

Motivation for **Recursive Subtraction (P-RS)**:

- Efficient, tree-based, amenable to calculation.

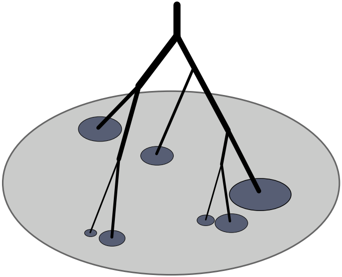
  Detail: Runtime Comparison
- Similar to grooming techniques like mMDT/Soft Drop



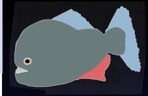
Introducing: Recursive Safe Subtraction

Motivation for **Recursive Subtraction (P-RS)**.
Tree-based, efficient, similar to **mMDT/Soft Drop**:

- Begin with a jet with an angular-ordered tree of emissions (e.g. reclustered with Cambridge-Aachen)
- Loop through the tree of emissions, widest emission first



- Energy fraction of an emission: $z_{\mathrm{s,h}} = E_{\mathrm{soft,hard}}/E_{\mathrm{total}}$
- Both use a grooming parameter z_{cut}
- SD uses a parameter β_{SD} ($\beta_{\mathrm{SD}} = 0$ produces mMDT)

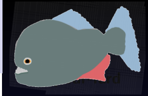


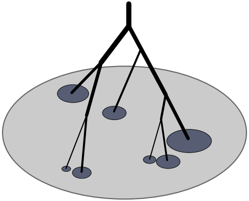
Introducing: Recursive Safe Subtraction

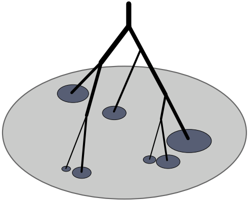
Soft Drop

- **Check** $z_s > z_{\mathrm{cut}}\theta^{\beta_{\mathrm{SD}}}$.
- **Passed:** Keep remaining jet.
- **Failed:** Groom softer branch.

P-RS



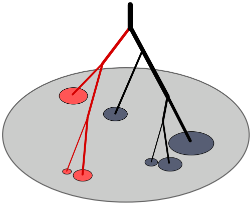




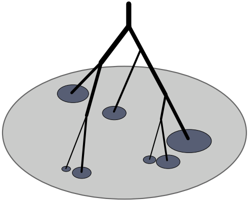
Introducing: Recursive Safe Subtraction

Soft Drop

- **Check** $z_s > z_{\text{cut}}\theta^{\beta_{\text{SD}}}$.
- **Passed:** Keep remaining jet.
- **Failed:** Groom softer branch.



P-RS

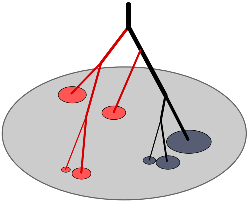


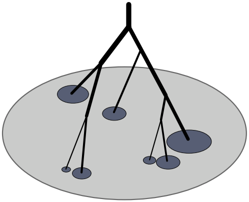
Introducing: Recursive Safe Subtraction

Soft Drop

- **Check** $z_s > z_{\mathrm{cut}}\theta^{\beta_{\mathrm{SD}}}$.
- **Passed:** Keep remaining jet.
- **Failed:** Groom softer branch.

P-RS





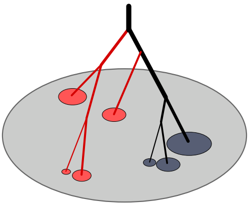
Introducing: Recursive Safe Subtraction

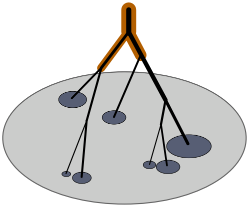
Soft Drop

- **Check** $z_s > z_{cut}\theta^{\beta_{SD}}$.
- **Passed:** Keep remaining jet.
- **Failed:** Groom softer branch.

P-RS

- **Check** $z_s > z_{cut}^{(n)}/2$. ($z_{cut}^{(0)} = z_{cut}$)
- **Passed:** Subtract from (send piranhas) each branch, $z_{s,h} \to z_{s,h} - z_{cut}^{(n)}/2$.





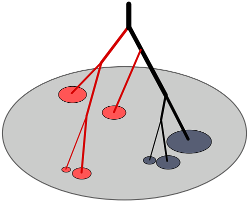
Introducing: Recursive Safe Subtraction

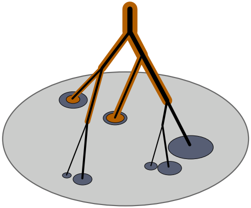
Soft Drop

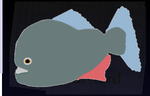
- **Check** $z_s > z_{\rm cut}\theta^{\beta_{\rm SD}}$.
- **Passed:** Keep remaining jet.
- **Failed:** Groom softer branch.

P-RS

- **Check** $z_s > z_{\rm cut}^{(n)}/2$. ($z_{\rm cut}^{(0)} = z_{\rm cut}$)
- **Passed:** Subtract from (send piranhas) each branch, $z_{\rm s,h} \to z_{\rm s,h} - z_{\rm cut}^{(n)}/2$.







Introducing: Recursive Safe Subtraction

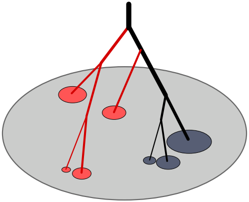
Soft Drop

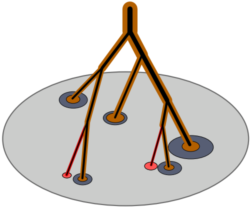
- **Check** $z_s > z_{cut}\theta^{\beta_{SD}}$.
- **Passed:** Keep remaining jet.
- **Failed:** Groom softer branch.

P-RS

- **Check** $z_s > z^{(n)}_{cut}/2$.
  ($z^{(0)}_{cut} = z_{cut}$)
- **Passed:** Subtract from (send piranhas) each branch, $z_{s,h} \to z_{s,h} - z^{(n)}_{cut}/2$.
- **Failed:** Groom softer, set $z^{(n+1)}_{cut} = z^{(n)}_{cut} - z_s$.

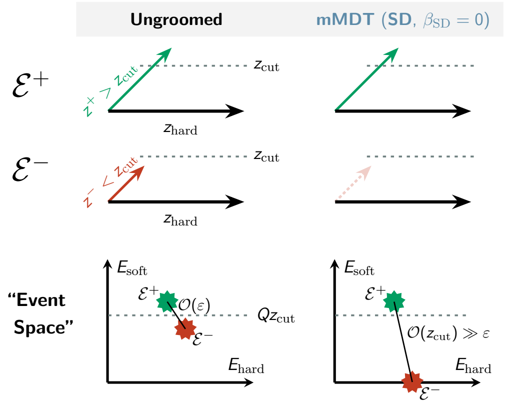
Detail: soft≠hard, or $f \neq 1/2$





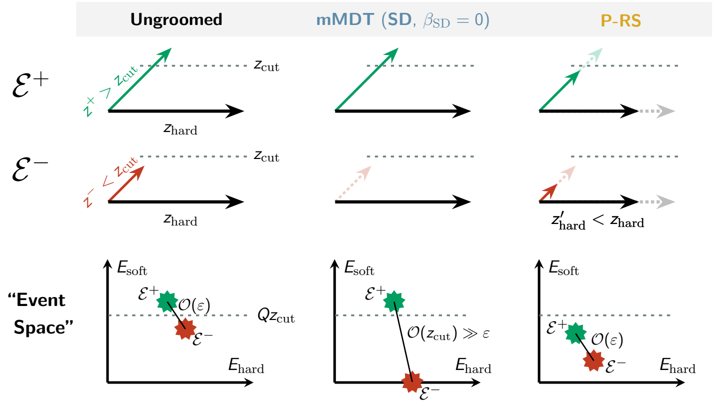
PIRANHA Grooming: Eating up the competition

Let's compare the continuity of **P-RS** grooming to the discontinuity of **Soft Drop/mMDT**:



PIRANHA Grooming: Eating up the competition

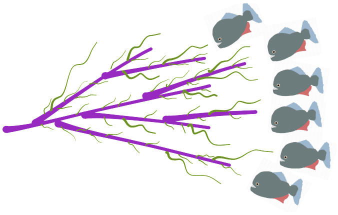
Let's compare the continuity of **P-RS** grooming to the discontinuity of **Soft Drop/mMDT**:



PIRANHA Performance

PIRANHA groomers (like P-RS) **are continuous!**

⏩ Clustering Discontinuity



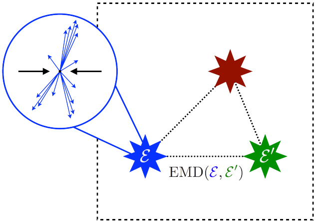
Let's study some phenomenological implications in `Pythia`:

- Study responses of P-RS and Soft Drop, with $z_{\text{cut}} = .1$;
- **Soft Distortions:** Hadronization, exclusion of neutral particles (proxy for smearing);
- **Additive Contamination**: Pileup (minimum-bias events over dijets). `Soyez:[1801.09721]` ⏩ Also: Underlying Event

PIRANHA Performance: **EMD as a Tool**

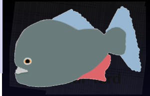
Useful tool: **E**nergy **M**over's **D**istance (**EMD**):

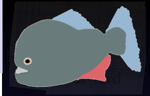
- Observable independent "distance" between jets;
- EMD bounds changes of a broad class of observables.



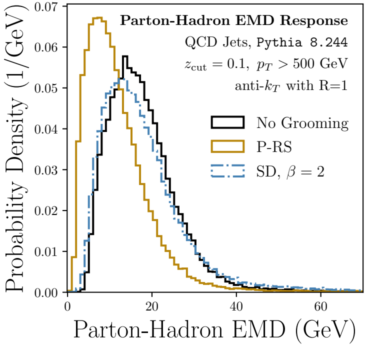
Komiske-Metodiev-Thaler:[1902.02346]

EMD helps us answer the question:
"How robust is grooming against low-energy pollution?"



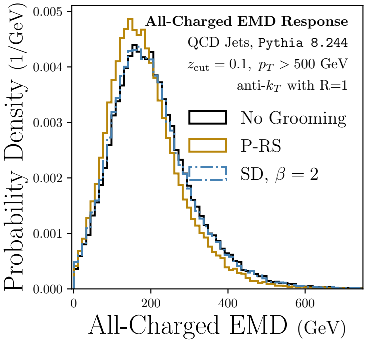


How robust is grooming against soft distortions from hadronization?



- **P-RS:** Small hadronization tweaks → smaller changes
- **Soft Drop ($\beta_{\text{SD}} = 2$):** Small tweaks → larger changes

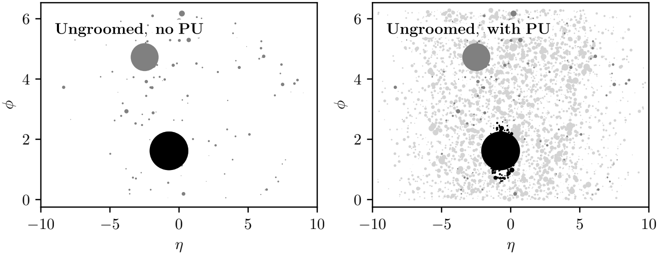
How robust is grooming against exclusion of neutral particles ("smearing")?



- **P-RS:** Exclude neutral particles → smaller changes
- **Soft Drop:** Exclude neutral particles → larger changes

PIRANHA Performance: **Pileup** Soyez:[1801.09721]

- Dijets layered with min. bias (light grey), study **leading jet (black)** (subleading jet in **dark grey**):

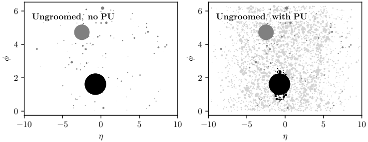


- Grid median bkg. estimation of PU energy density ρ
- Remove energy: $z_{\mathrm{cut}} p_T = \rho A_{\mathrm{jet}} \approx (p_T)_{\mathrm{PU\ in\ jet}}$

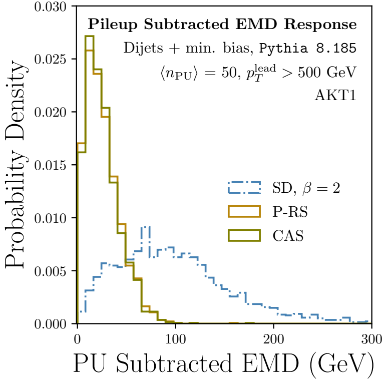
- Compare to **Constituent Area Subtraction (CAS)**, a pileup mitigation algorithm which influenced PIRANHA

Berta-Spousta-Miller-Leitner:[1403.3108], Komiske-Metodiev-Thaler:[2004.04159]

PIRANHA Performance: **Pileup** Soyez:[1801.09721]

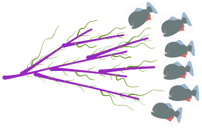


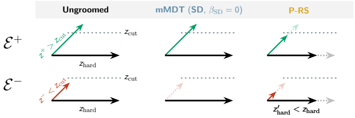
How well can grooming remove pileup?



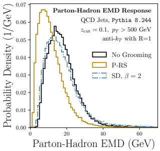
Punchlines!

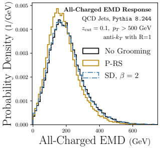
- Grooming is an important tool, and traditional groomers have discontinuities which lead to infrared sensitivity.
- PIRANHA grooming is a continuous strategy for grooming based on geometry and optimal transport.

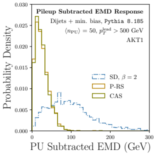




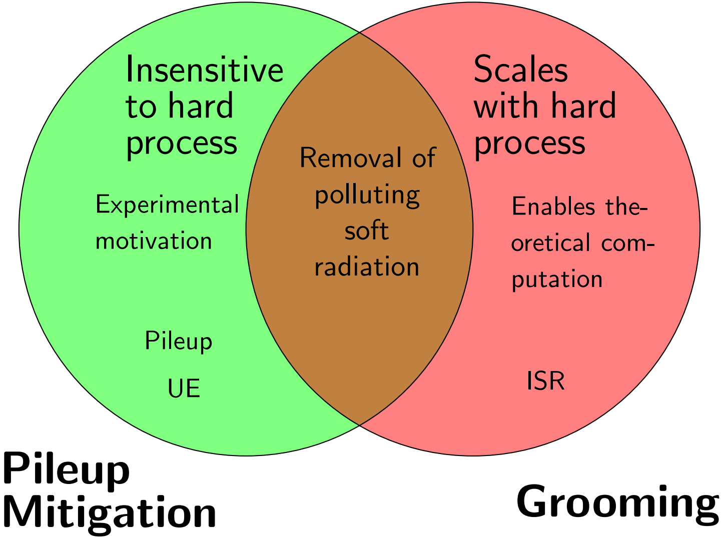
- Recursive Subtraction (P-RS) is a robust technique for the removal of soft radiation.



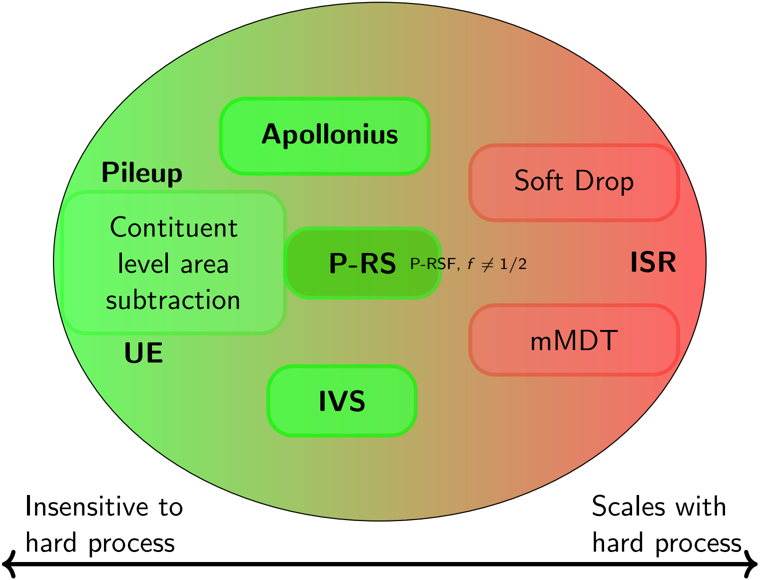




Grooming vs. Pileup Mitigation

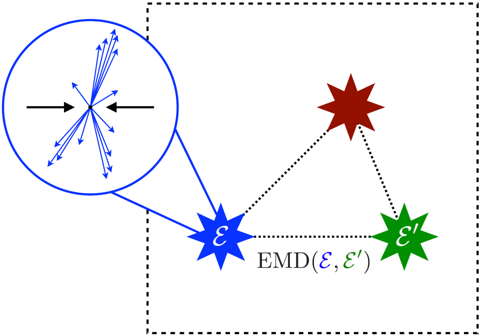


Grooming vs. Pileup Mitigation



Energy Mover's Distance ("work" to move $\mathcal{E}$ into $\mathcal{E}'$)

$\Rightarrow$ **Geometry** in event space: Main presentation



$$\mathrm{EMD}(\mathcal{E},\mathcal{E}') = \min_f \sum_{i\in\mathcal{E},\ j\in\mathcal{E}'} f_{ij}\theta_{ij} + |E(\mathcal{E}) - E(\mathcal{E}')|$$

$$f_{ij} \geq 0, \quad \sum_{i\in\mathcal{E}} f_{ij} \leq E_j, \quad \sum_{j\in\mathcal{E}'} f_{ij} \leq E_i, \quad \sum_{i\in\mathcal{E},\ j\in\mathcal{E}'} f_{ij} = \min\left(E(\mathcal{E}), E(\mathcal{E}')\right)$$

Komiske-Metodiev-Thaler:[1902.02346]

Introducing: Energy Mover's Distance (EMD)

Common choices for angular metric ("ground metric"):

$$\theta_{ij} = \sqrt{-(n_i - n_j)^2} \quad (1)$$

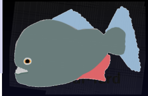
where n_i^μ is a four vector describing the motion of particle i.

$$n^\mu_{i,\ e^+e^-} = \frac{p_i^\mu}{E_i} = (1, \mathbf{v}_i)^\mu,$$

$$n^\mu_{i,\ \text{hadronic}} = \frac{p_i^\mu}{E_{T\ i}} = (\cosh(y_i), \mathbf{v}_{T\ i}, \sinh(y_i))^\mu.$$

Komiske-Metodiev-Thaler:[2004.04159]

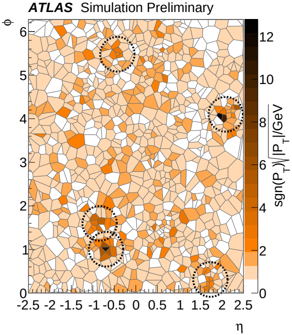
Introducing: PIRANHA Grooming



Apollonius Subtraction (AS):

$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Apoll.}}$$

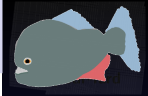
Similar to pileup mitigation techniques like **Voronoi Area Subtraction**



$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Voronoi}}$$

[ATLAS-CONF-2017-065] Cacciari-Salam:[0707.1378]; +Soyez:[0802.1188],[1111.6097]

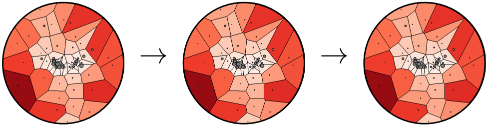
PIRANHA Grooming: The Cast of Characters



- **Apollonius grooming**: Closest to optimal transport

$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Apoll.}}$$

- **Iterated Voronoi Subtraction**: Efficient variant



$$p_{T,i,\ \mathrm{n^{th}step}}^{\text{groomed}} = p_{T,i,\ \mathrm{n^{th}step}} - \rho A_{i,\ \mathrm{n^{th}step}}^{\text{Voronoi}}$$

- **Recursive Safe Subtraction**: Closest to traditional grooming methods

Main presentation

PIRANHA Performance: Overview

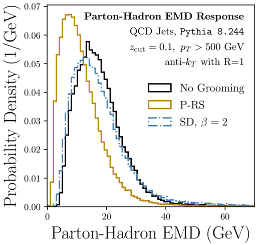
Tweaks to Energy Flow:

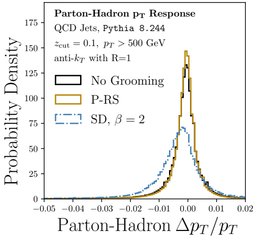
- **Hadronization:** RSS is more robust to the effects of hadronization than Soft Drop/mMDT.
- **Detector effects:** With a rough analysis, RSS seems more robust to detector effects than Soft Drop/mMDT.
- Robust for a range of z_{cut} values. $z_{\text{cut}} \neq .1$

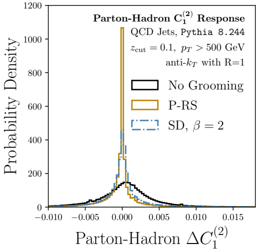
Additive Contamination:

- **Pileup:** RSS mitigates PU more accurately than Soft Drop and some existing methods. $\langle n_{\text{PU}} \rangle \neq 50$
- **UE:** Initial analysis suggests P-RS better at removing UE from ungroomed events, but less robust against UE
- **UE and Mass Resolution:** RSS leads to slightly worse mass resolution, but comparable acceptance (slightly greater for a simplified tagging scheme). Top Jets

PIRANHA Performance: **Hadronization**



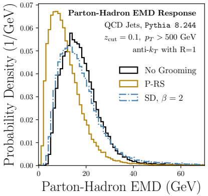


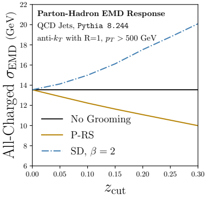


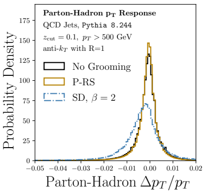
- **P-RS:** Small hadronization tweaks $\rightarrow$ smaller changes
- **Soft Drop:** Small tweaks $\rightarrow$ larger changes

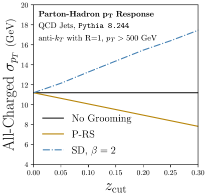
P-RS Parton-Hadron Response

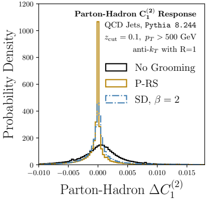
▸▸ Overview

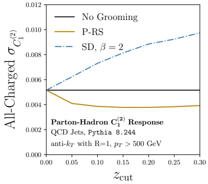






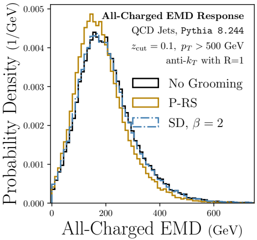


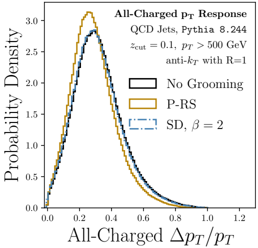


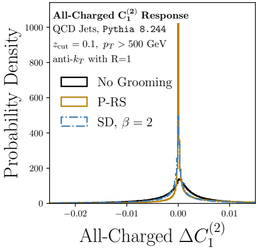


PIRANHA Performance: **Detector Proxy**

Main Presentation

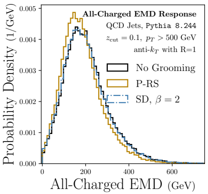


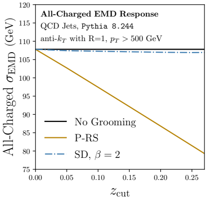


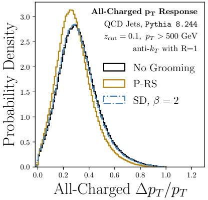


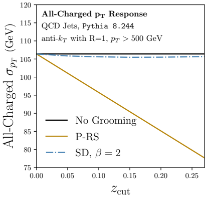
- **P-RS:** Exclude neutral particles $\rightarrow$ smaller changes
- **Soft Drop:** Exclude neutral particles $\rightarrow$ larger changes

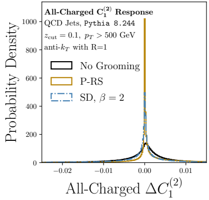
P-RS All-Charged Response

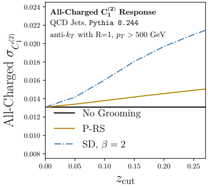




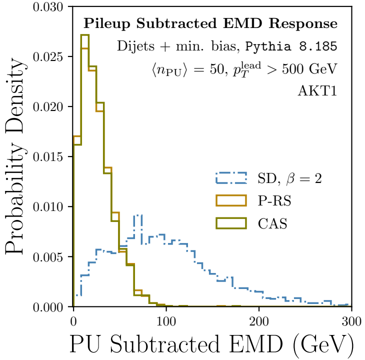






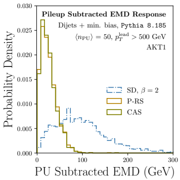


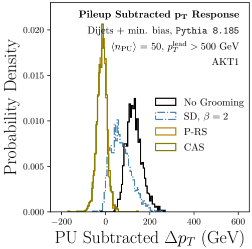
PIRANHA Performance: **Pileup** Soyez:[1801.09721]

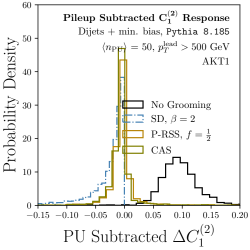


- **P-RS:** Subtract pileup $\rightarrow$ smaller changes
- **SD**, **CAS**: Subtract pileup $\rightarrow$ larger changes
- **Preliminary:** requires additional tuning; would like $\langle \Delta p_T \rangle_{\mathrm{CAS}} = 0$. However, still expect wider variance for CAS, as above. Haven't tested against more popular pileup mitigation algorithms.

PIRANHA Performance: **Pileup** Soyez:[1801.09721]



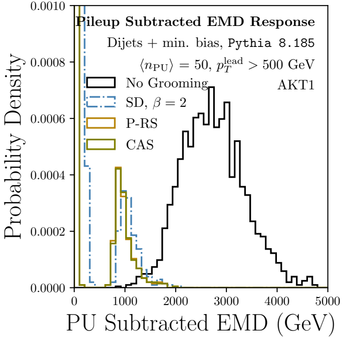


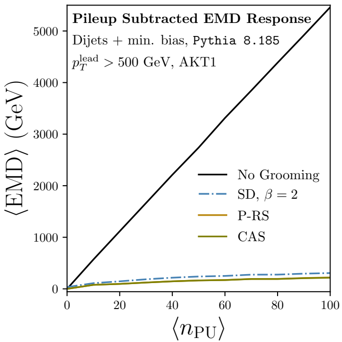


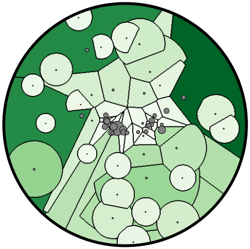
- **P-RS:** Subtract pileup $\rightarrow$ smaller changes
- **SD**, **CAS**: Subtract pileup $\rightarrow$ larger changes
- **Preliminary:** requires additional tuning; would like $\langle \Delta p_T \rangle_{\rm CAS} = 0$. However, still expect wider variance for CAS, as above. Haven't tested against more popular pileup mitigation algorithms.

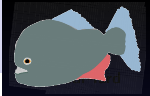
RSS Pileup Response

▸▸ Overview



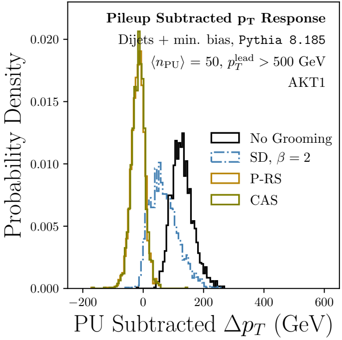


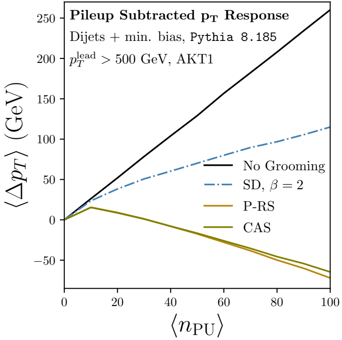




RSS Pileup Response

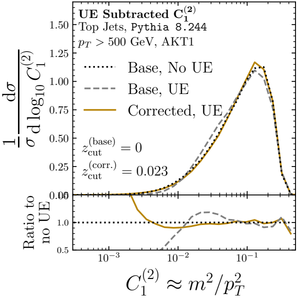
▶▶ Overview



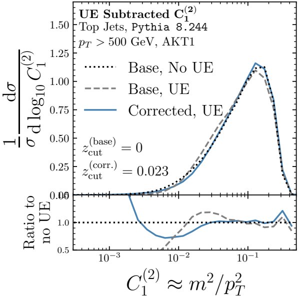


PIRANHA Performance: **UE**

- Underlying event (UE) of secondary parton interactions an important source of additive contamination
- “`multiple parton interactions = on`” in `Pythia`)
- Harder to compare event-by-event; compare distributions instead, tune to remove effects of UE

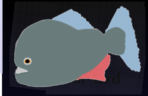


P-RS

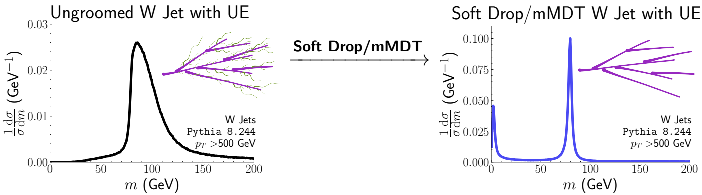


Soft Drop

PIRANHA Performance: **UE Mass Resolution**



- Grooming often used for mass resolution and boosted object tagging
- Underlying event (UE) an important source of contamination in these contexts

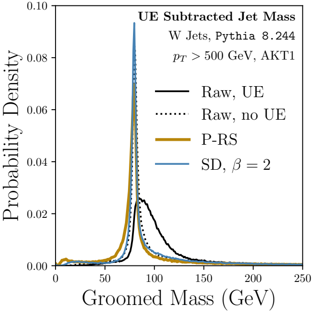


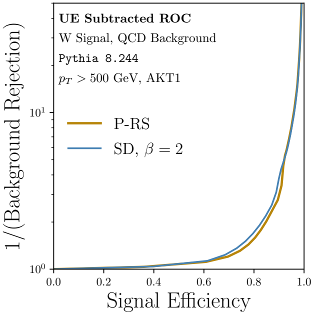
PIRANHA Performance: **UE Mass Resolution**

- Grooming often used for mass resolution and boosted object tagging
- Underlying event (UE) an important source of contamination in these contexts
- Simulate UE with multi-parton interaction in `Pythia`

Can P-RS Compete?

- Tune z_{cut} for **P-RS** and **Soft Drop** to produce a sharply peaked mass distribution (left)
- Reject QCD background (right): restrict to mass windows $(m_W - \delta m, m_W + \delta m)$

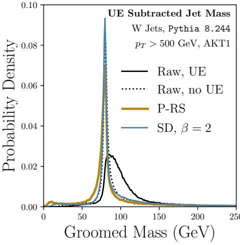


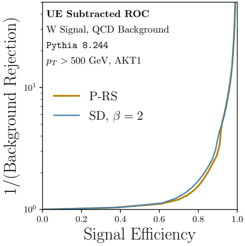


P-RS Mass Resolution

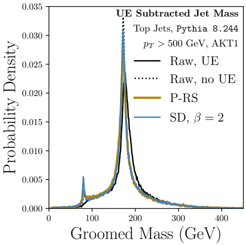
⏩ Overview

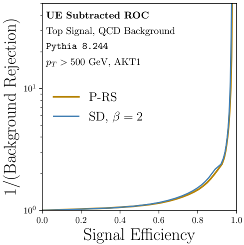
W Jets with UE:





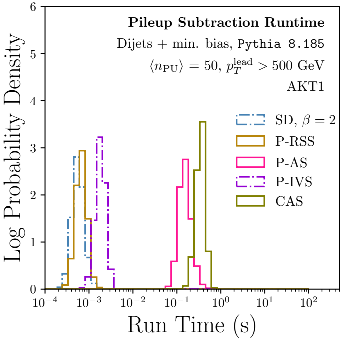
Top Jets with UE:

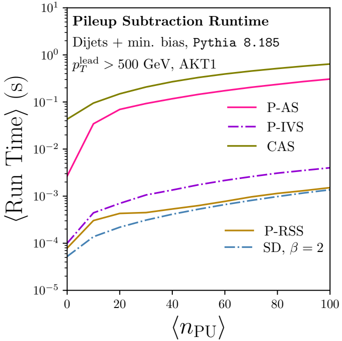




Grooming Runtime

Main presentation





Non-Global Effects

Non-Global Logarithms:

Jet substructure with analytical methods [1307.0013]

Mrinal Dasgupta,[1] Alessandro Fregoso,[2] Simone Marzani[3] and Alexander Powling[2]

[3]Since non-global logarithms arise away from the collinear region, in this calculation we shall not make a collinear approximation and hence use the distance measure $\Delta_\alpha^2 = 2(1 - \cos\alpha)$.

Clustering Logarithms:

Soft Drop [1402.2657]

Andrew J. Larkoski,[a] Simone Marzani,[b] Gregory Soyez,[c] and Jesse Thaler[a]

[5]Because the original jet is defined with the anti-k_t algorithm, we are not sensitive to clustering logarithms first described in Ref. [118].

Generations of Groomers

c. 2008

1st Generation (Mass Drop): **IRC safety**

↓

c. 2015

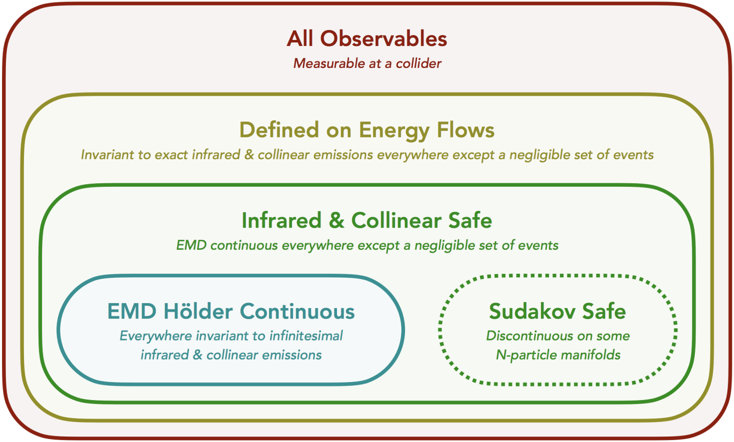
2nd Generation (mMDT, Soft Drop): **Calculability**

↓

c. 2022

PIRANHA (Apollonius, IVS, P-RS): **Continuity**

Generalizations of IRC Safety



Komiske-Metodiev-Thaler:[2004.04159]

Some Interesting Quantities for Groomed Jets

- Dropped energy

$$\Delta_E = E(\mathcal{E}) - E(\mathcal{E}_{\text{groomed}})$$

- Generalized jet energy correlation functions (GECFs)

$$C_1^{(\beta)} = \sum_{i,j \in \text{jet}} z_i z_j \theta^\beta,$$

$$(C_1^{(2)} \sim m^2/p_T^2)$$

Recursive Subtraction with a Fraction (RSF)

SD/mMDT

- **Check** $z > z_{\mathrm{cut}}\theta^{\beta}$.

RSF

- **Check** $z > f z_{\mathrm{cut}}^{(n)}$.

  $(z_{\mathrm{cut}}^{(0)} = z_{\mathrm{cut}})$

Here, f is the fraction of the total grooming energy assigned to the softer branch.

Main presentation

Recursive Subtraction with a Fraction (RSF)

SD/mMDT

- **Check** $z > z_{\text{cut}}\theta^{\beta}$.
- **Failed:** Groom softer branch and continue

RSF

- **Check** $z > f z_{\text{cut}}^{(n)}$.

  ($z_{\text{cut}}^{(0)} = z_{\text{cut}}$)
- **Failed:** Groom energy from both branches (softer branch completely), set $z_{\text{cut}}^{(n+1)} = z_{\text{cut}}^{(n)} - z/f$, and continue

Here, f is the fraction of the total grooming energy assigned to the softer branch.

Main presentation

Recursive Subtraction with a Fraction (RSF)

SD/mMDT

- **Check** $z > z_{\text{cut}}\theta^{\beta}$.
- **Failed:** Groom softer branch and continue
- **Passed:** Keep remaining jet

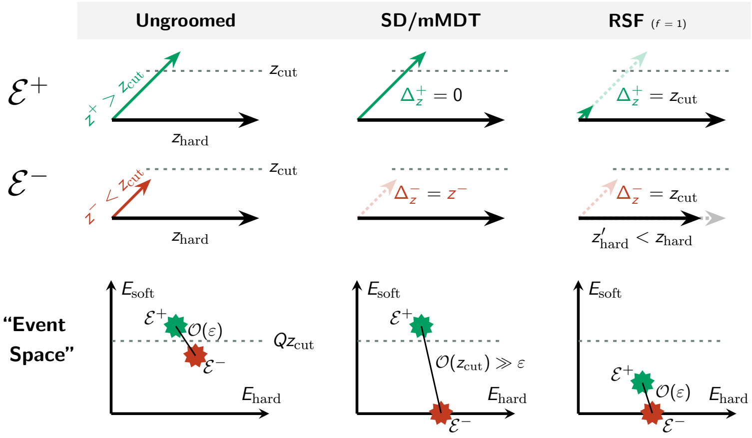
RSF

- **Check** $z > f z_{\text{cut}}^{(n)}$.
  $(z_{\text{cut}}^{(0)} = z_{\text{cut}})$
- **Failed:** Groom energy from both branches (softer branch completely), set $z_{\text{cut}}^{(n+1)} = z_{\text{cut}}^{(n)} - z/f$, and continue
- **Passed:** Groom energy from both branches, $z \to z - f z_{\text{cut}}^{(n)}$, and keep remaining jet.

Here, f is the fraction of the total grooming energy assigned to the softer branch.

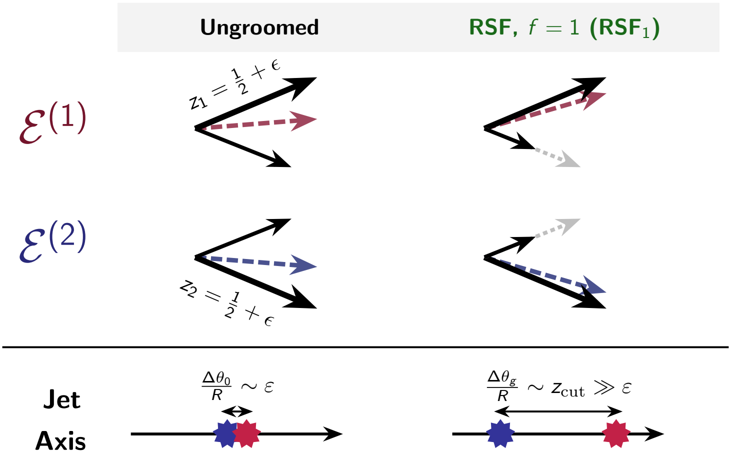
Main presentation

Recursive Subtraction with a Fraction: Example



Recursive Subtraction with a Fraction

Recursive Subtraction with a Fraction $f \neq 1/2$ has suppressed **soft discontinuous** behavior:
(*discontinuous to small changes in energy*)

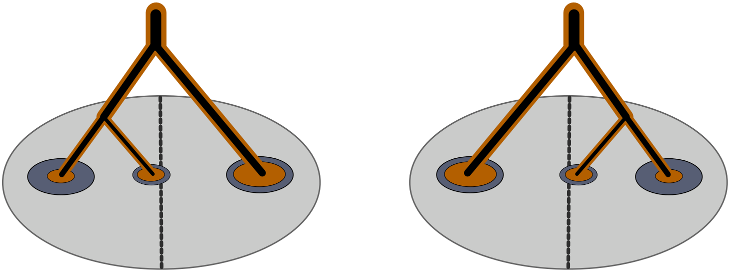


Clustering Discontinuity

Tree-based groomers inherit discontinuity from clustering.

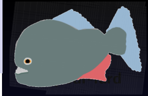
Angular-ordered C/A clustering (as in Soft Drop, RSF)
$\implies$ **angularly discontinuous** behavior.
(*discontinuous to small changes in angles of constituents*)

Example in P-RS (P-RSF, $f = 1/2$):

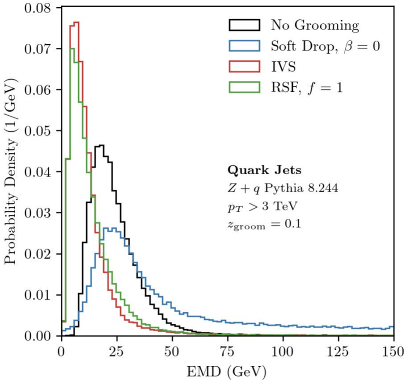


Main presentation

RSF Performance: Hadronization



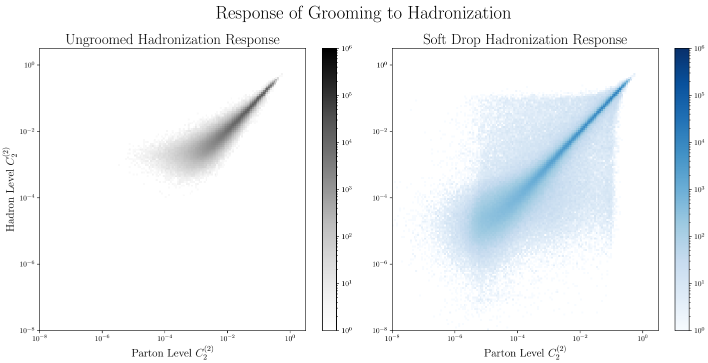
Hadronization tweaks energy; susceptible to discontinuity!



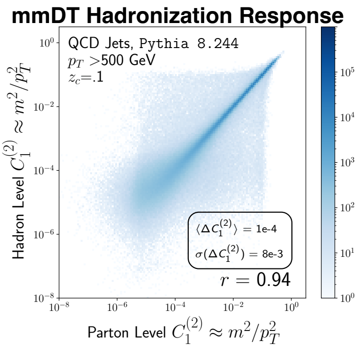
- **mMDT/Soft Drop:** Small tweaks → large changes.
- **PIRANHA** (**IVS**), **RSF**$_1$: Tweaks → small changes!
- EMD bounds changes of a broad class of observables.

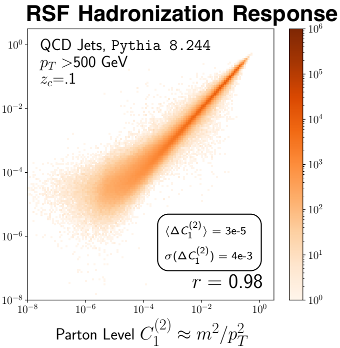
Komiske-Metodiev-Thaler:[1902.02346] Eqn (2) and Figure 2.

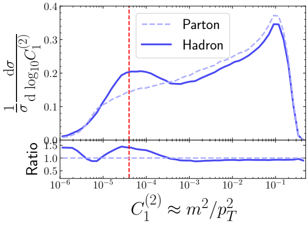
RSF Performance: Hadronization

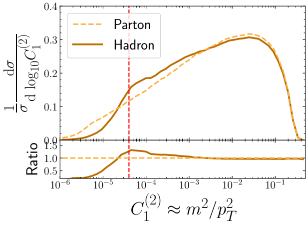


RSF Performance: Hadronization

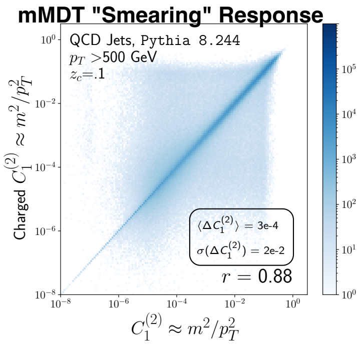


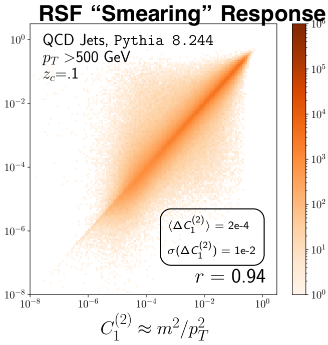


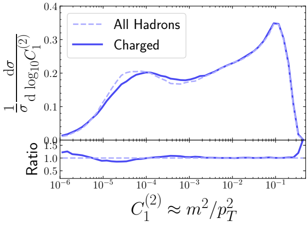


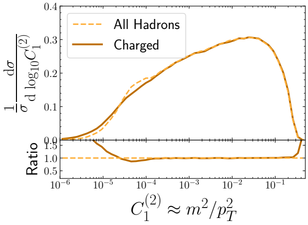


RSF Performance: Detector Proxy



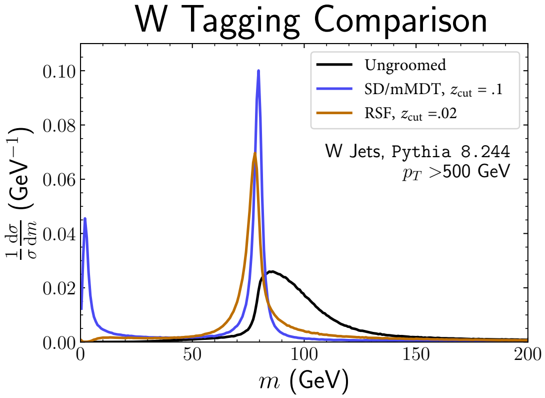




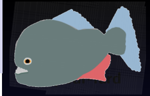


RSF Performance: Underlying Event

W Jets: P-RS leads to shifted mass determinations and slightly worse mass resolution:

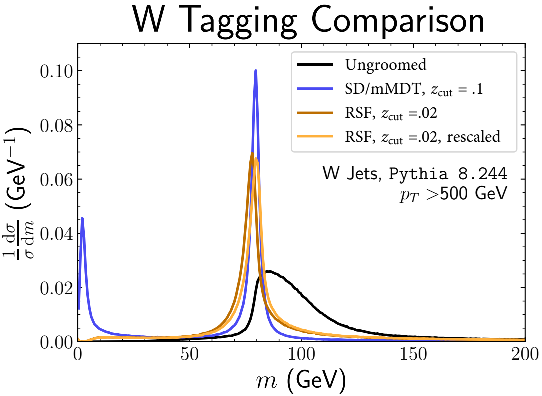


- Tune $z_{\rm cut}$ to remove radiation from the UE.
- Mass shifted by $\sim$2%.



RSF Performance: Mass Resolution

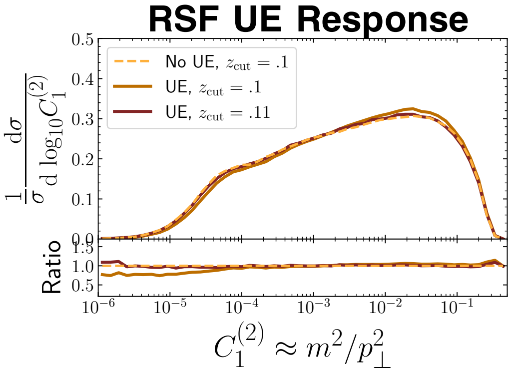
W Tagging: P-RS leads to shifted mass determinations and worse mass resolution:



- Tune $z_{\rm cut}$ to remove radiation from the UE.
- Mass shifted by $\sim$2%.

RSF Performance: Underlying Event

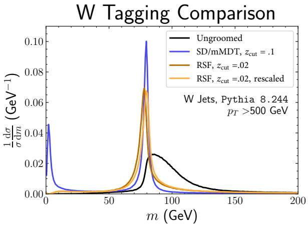
- Increase $z_{\rm cut}$ to remove additional radiation/corrections from the UE:

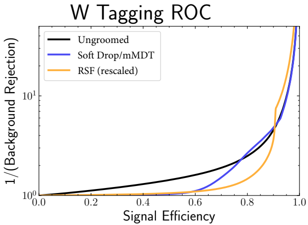


- UE, $z_{\rm cut} = .1$: Max is 106% the max of no UE
- UE, $z_{\rm cut} = .11$: Max is 101% the max of no UE

RSF: W Mass Resolution

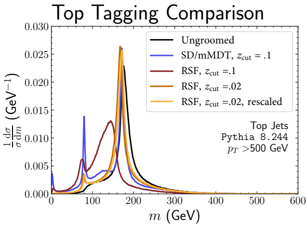
Recursive Subtraction with a Fraction (RSF) gives worse W mass resolution than **mMDT/Soft Drop**, potentially greater acceptance:

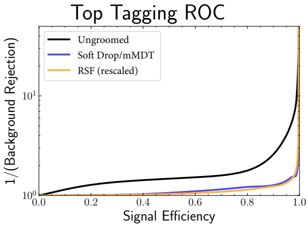




RSF: Top Mass Resolution

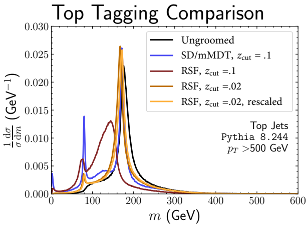
Recursive Subtraction with a Fraction (RSF) gives worse Top mass resolution than **mMDT/Soft Drop**, potentially greater acceptance:

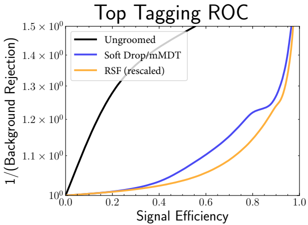




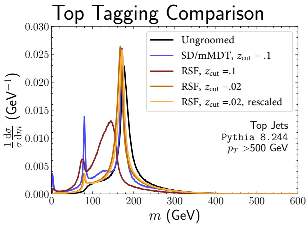
RSF: Top Mass Resolution

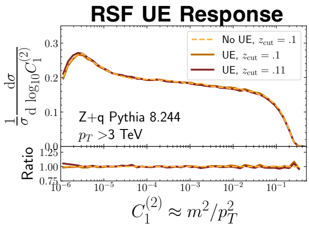
Recursive Subtraction with a Fraction (RSF) gives worse mass resolution than **mMDT/Soft Drop**, potentially greater acceptance:





If z-cut is adjusted for measuring the W-mass (or to account for underlying event in a particular case), is it possible to use this same z-cut elsewhere with RSF?





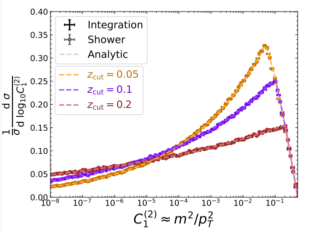
- Groomed energy scales with energy of hard process/leading vertex.
- Expect similar behavior in, say, UE reduction from similar $z_{\rm cut}$ values at the same energy scales, but not as the energy scale is changed.

Towards Resummed Calculation

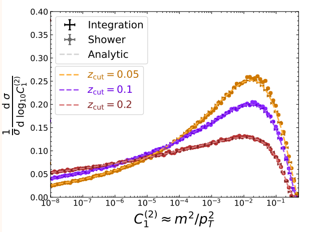
Re-summation for the first surviving emission, RSF, $f = 1$.

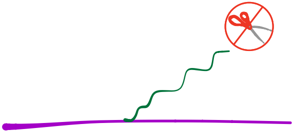
Fixed coupling, **one emission** calculations:

Soft Drop/mMDT

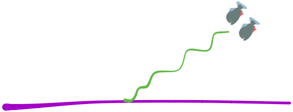


RSF, $f = 1$ (RSF$_1$)





Sharp cutoff $\rightarrow$ kink



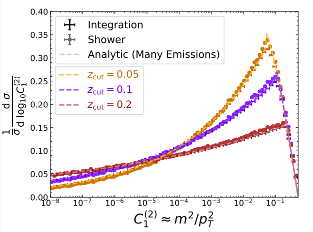
No sharp cutoff $\rightarrow$ smooth

Towards Resummed Calculation

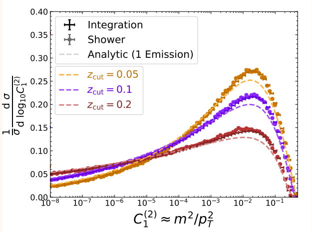
Re-summation for the first surviving emission, RSF, $f = 1$.

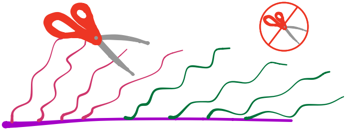
Fixed coupling, **multiple emission** calculations:

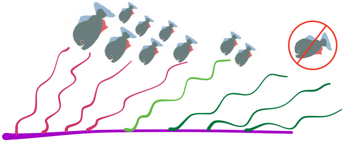
Soft Drop/mMDT



RSF, $f = 1$ (RSF$_1$)





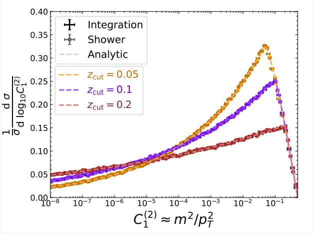


Sharp cutoff → kink

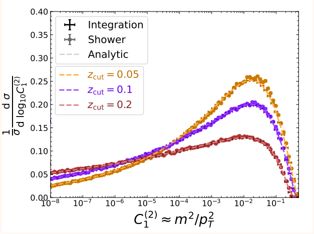
No sharp cutoff → smooth

Single emission:

Soft Drop/mMDT



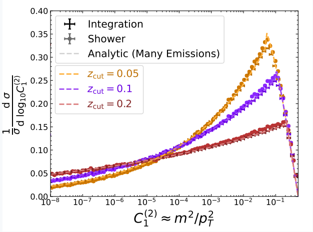
RSF, $f = 1$ (RSF$_1$)



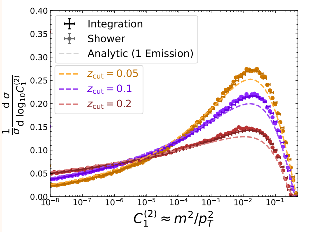
- **Soft Drop** has single logarithmic structure below $z_{\rm cut}$ and double logarithmic structure above (piece-wise).
- **RSF** ($f = 1$) has a single logarithmic structure (not piece-wise). Does not exponentiate, but expansions and approximations reveal single logarithmic structure.

Multiple emissions:

Soft Drop/mMDT



RSF, $f = 1$ (RSF$_1$)

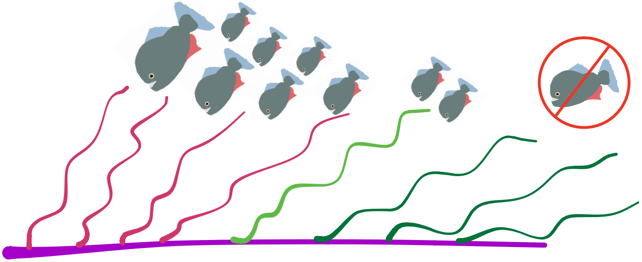


- **Soft Drop** is amenable to simpler methods/calculations in the case of multiple emissions.
- **RSF** ($f = 1$) has an intricate structure of correlations between emissions, and is addressed here only numerically (i.e. no "CAESAR formula"!).

Emissions of RSF Groomed Jets

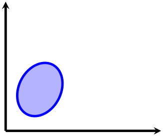
RSF where at every branch, only the softer branch is groomed ($f = 1$). There will be three types of emissions:

- **Pre-critical emissions**: completely groomed away, using up some of the grooming parameter
- One **critical emission**: the first emission to survive the grooming process
- **Subsequent emissions**: emissions after the critical emission, completely ungroomed



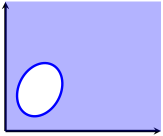
Lund Diagrammar

$$\iint_{\bigcirc} \mathrm{d}\log\theta \; z \; \mathrm{d}\log z \; \frac{\alpha_s}{\pi} \; [\bar{p}(z)]_{+}^{(1/2)} \triangleq$$

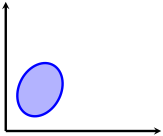


, (2)

$= 0,$

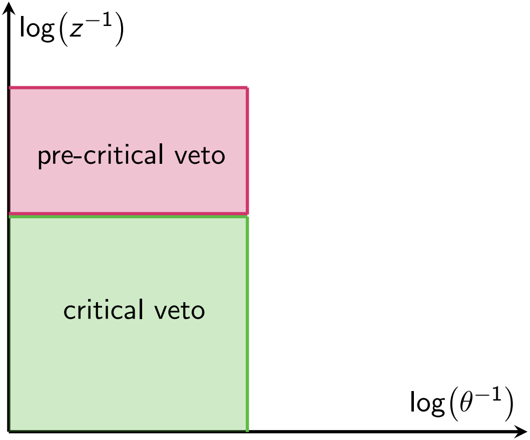


$= -$



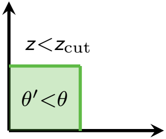
. (3)

Lund Diagrammar



Lund Diagrammar: Critical Emissions

$$\Sigma_{\rm crit}(\theta) \approx \exp\Bigg[\; - $$

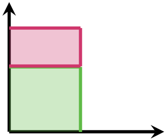


$$\Bigg]$$

$$= \exp\left[-\frac{\alpha_s}{\pi}\int_\theta^1 \frac{\mathrm{d}\theta'}{\theta'}\int_{z_{\rm cut}}^{1/2} \bar{p}(z)\right]$$

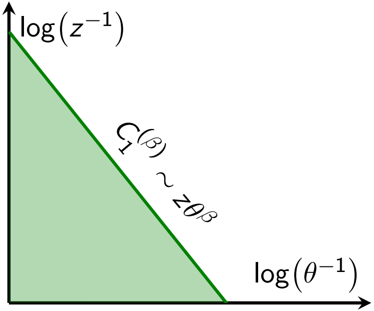
Lund Diagrammar: Pre-critical Emissions

$$\Sigma_{\mathrm{pre}}(z_{\mathrm{pre}}|\theta_{\mathrm{crit}})\Sigma_{\mathrm{crit}}(\theta_{\mathrm{crit}}) = \exp\left[- \right.$$

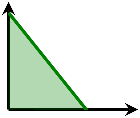


$$\left. \right]$$

Lund Diagrammar: Subsequent Emissions



$$\Sigma_{\text{sub}}(C_1^{(\beta)}) \approx \exp\left[- \right.$$



$$\left. \right]$$