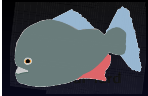
Safely Eating Junk: **P**ileup and **I**nfrared **R**adiation **AnNiHilA**tion

(PIRANHA)



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

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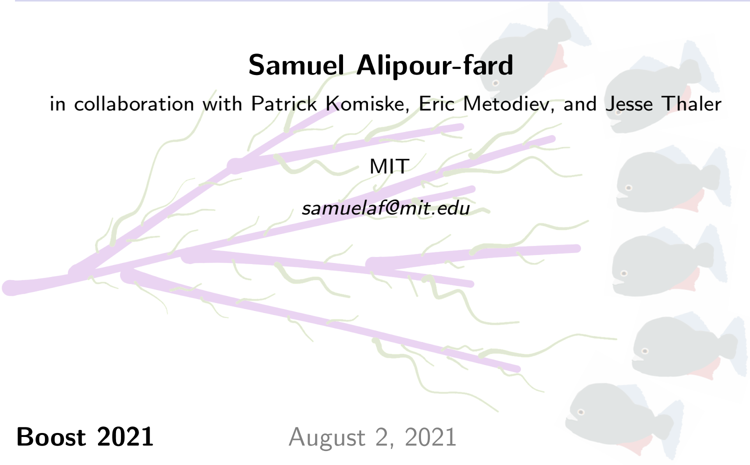
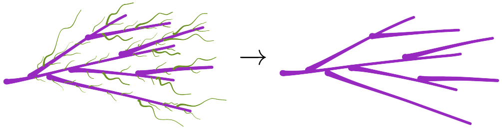


Boost 2021 August 2, 2021

Motivation

Grooming:

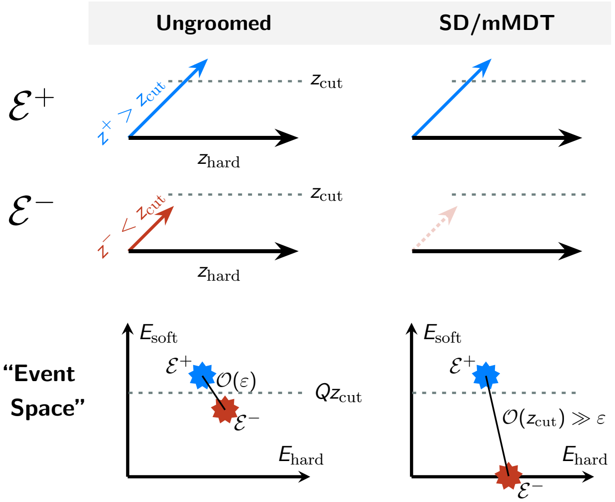
A systematic procedure for removing contaminating soft radiation from particle collision data.



- **Experiment**: Groomed information is resilient to detector effects, pileup, initial state radiation
  CMS:[1807.05974], ATLAS:[1711.08341]
- **Theory**: Grooming can facilitate precision calculations of jet substructure observables
  Frye-Larkoski-Schwartz-Yan:[1603.09338]
  Marzani-Schunk-Soyez:[1712.05105]
- Focus on **mMDT** Dasgupta-Fregoso-Marzani-Salam:[1307.0007]
  (AKA **Soft Drop** with $\beta = 0$: Larkoski-Marzani-Soyez-Thaler:[1402.2657])

Motivation

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

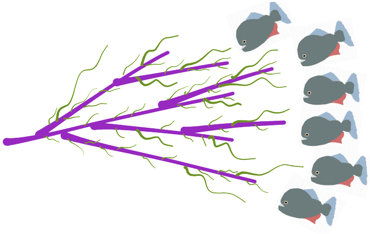


Introducing: PIRANHA Grooming

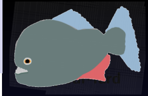
PIRANHA:

A systematic procedure for *continuously* removing contaminating soft radiation (no hard cutoffs).

- Intuitively described as the optimal transport of piranhas hungry for soft radiation.



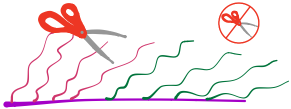
- **Recursive safe subtraction** is a tree-based PIRANHA grooming procedure analogous to procedures like Soft Drop/mMDT.

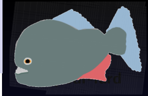


Introducing: Recursive Safe Subtraction (RSS)

Soft Drop/mMDT

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





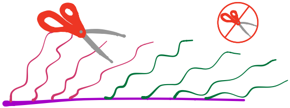
Introducing: Recursive Safe Subtraction (RSS)

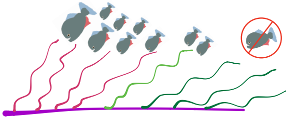
Soft Drop/mMDT

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

PIRANHA-RSS

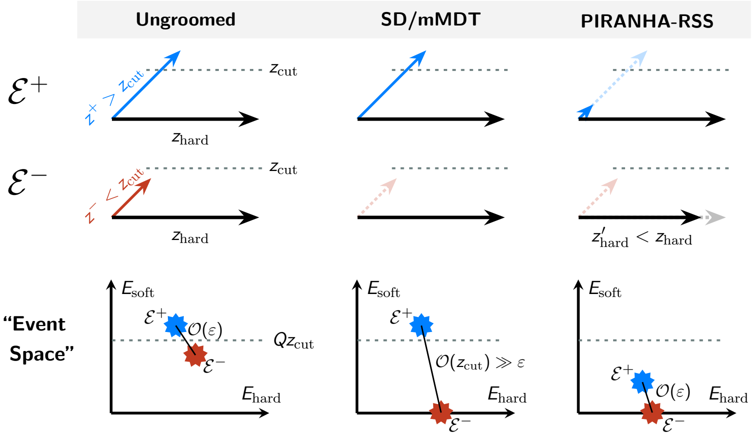
- **Check** $z > z_{\mathrm{cut}}^{(n)}$.
  $(z_{\mathrm{cut}}^{(0)} = z_{\mathrm{cut}})$
- **Failed:** Groom softer branch, set $z_{\mathrm{cut}}^{(n+1)} = z_{\mathrm{cut}}^{(n)} - z$, and continue.
- **Passed:** Remove energy from the softer branch, $z \to z - z_{\mathrm{cut}}^{(n)}$, and keep remaining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





PIRANHA Grooming: Eating up the competition

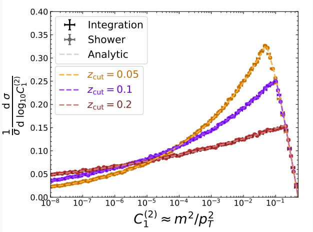
Let's compare the continuity of PIRANHA-RSS grooming to that of Soft Drop/mMDT:



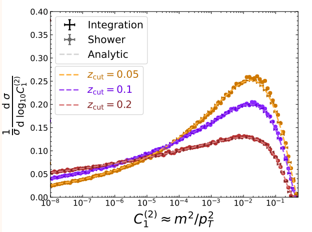
PIRANHA groomers are continuous!

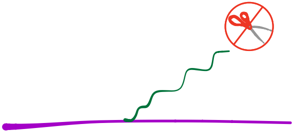
Fixed coupling, **one emission** calculations:

Soft Drop/mMDT

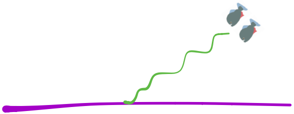


PIRANHA-RSS





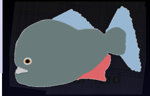
Sharp cutoff $\rightarrow$ kink



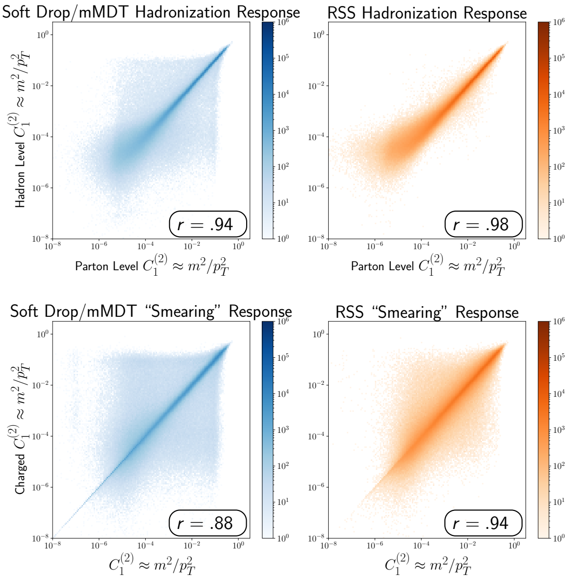
No sharp cutoff $\rightarrow$ smooth

Motivation
PIRANHAs from Geometry
Strengths of PIRANHA Grooming

Strengths of PIRANHA Grooming



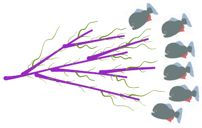
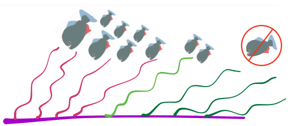
PIRANHA in `Pythia 8.244`, QCD jets, $P_T \geq 500$ GeV:



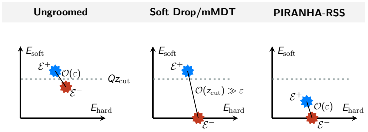
Punchlines!

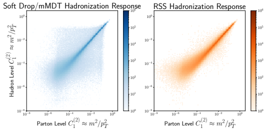
- Grooming is an important tool in the study of high energy microscopic physics.

- PIRANHA grooming is a continuous strategy for grooming based on geometry and optimal transport.

- PIRANHA grooming methods overcome discontinuities of previous methods.





Motivation

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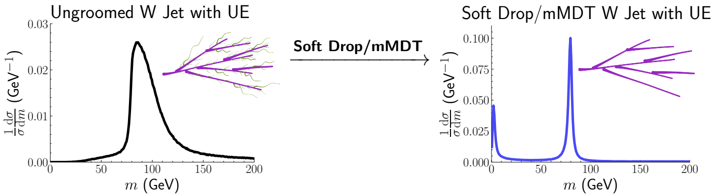


mMDT: Dasgupta-Fregoso-Marzani-Salam:[1307.0007]
Soft Drop: Larkoski-Marzani-Soyez-Thaler:[1402.2657]

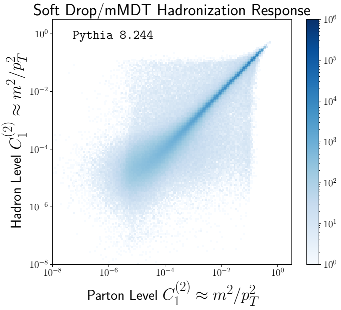
- To simplify conclusions for the rest of the talk, we will limit ourselves to mMDT, or Soft Drop with $\beta = 0$.

Motivation

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

Consequences:

- Increased sensitivity to detector effects
- Theoretical complications Hoang-Mantry-Pathak-Stewart:[1906.11843]

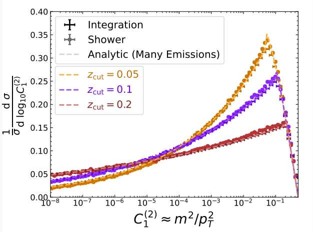


Strengths of PIRANHA Grooming

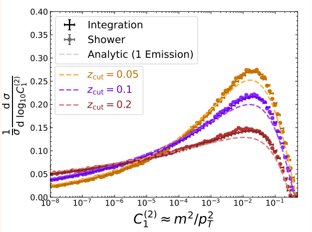
PIRANHA groomers are continuous!

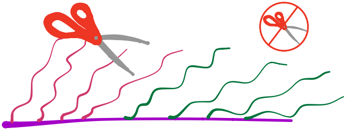
Fixed coupling, **multiple emission** calculations:

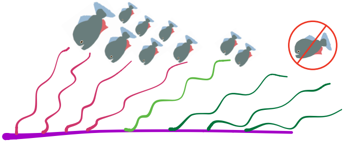
Soft Drop/mMDT



PIRANHA-RSS $(f = 1)$



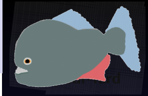




Sharp cutoff $\rightarrow$ kink

No sharp cutoff $\rightarrow$ smooth

Robustness of PIRANHA



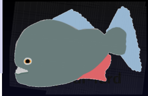
PIRANHA groomers are continuous!

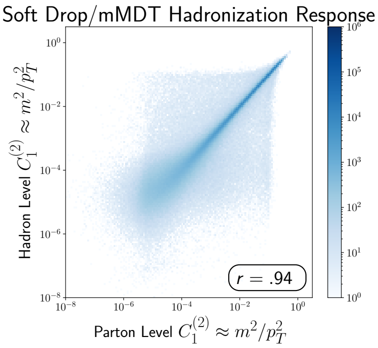
Let's examine the implications of the continuity of PIRANHA in `Pythia 8.244` on QCD jets, with $P_T \geq 500$ GeV:

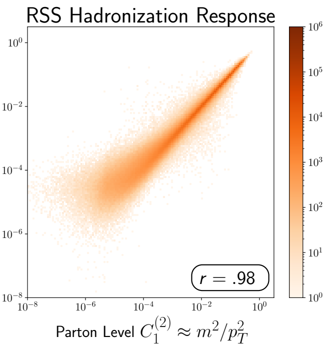
- Hadronization (parton level vs. hadron level)
- Detector effects (**Proxy:** all vs. charged)
- Underlying event (UE: multi-parton interactions on vs. off)

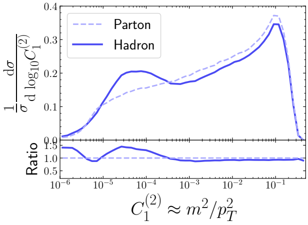
- Comparing **Soft Drop/mMDT** and **PIRANHA-RSS**, both with $z_{\text{cut}} = .1$.

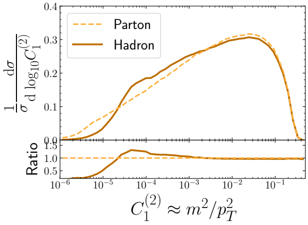
Robustness of PIRANHA: Hadronization



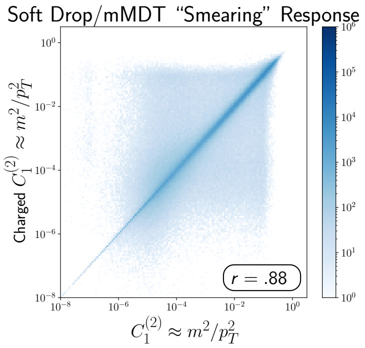


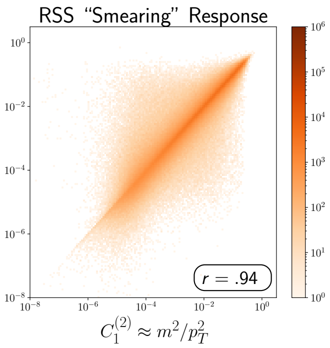


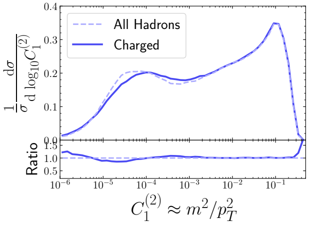


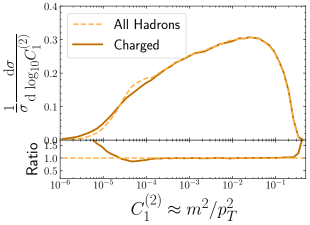


Robustness of PIRANHA: Detector Proxy



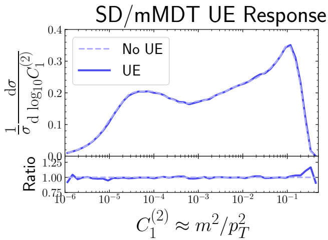


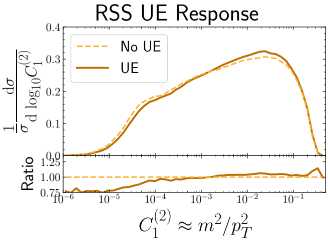




Subtleties of PIRANHA: Underlying Event

UE modeled by multi-parton interactions in `Pythia`:

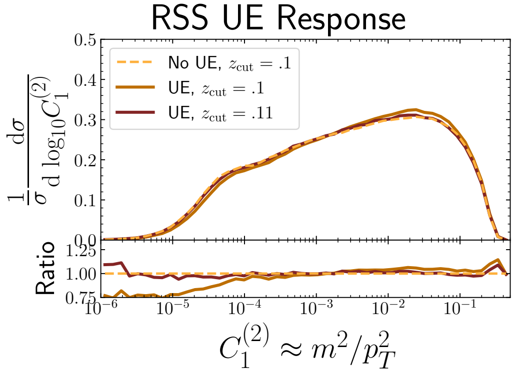




- Unlike Soft Drop/mMDT, RSS can remove only a limited amount of energy, leading to slight responses to the underlying event.

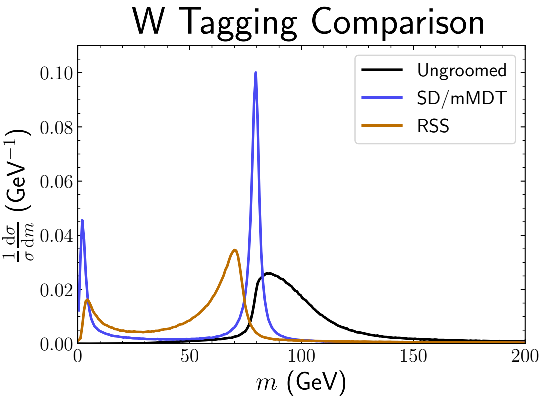
Subtleties of PIRANHA: Underlying Event

- For RSS, we can *increase* z_{cut} to remove additional radiation/corrections due to the underlying event:



Subtleties of PIRANHA: W Tagging

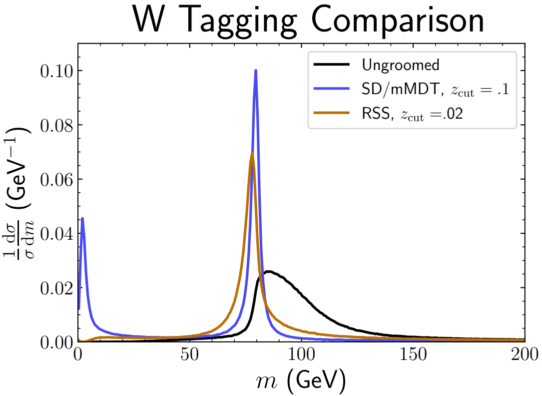
W Tagging: RSS leads to shifted mass determinations and worse mass resolution:



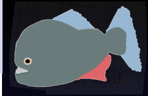
- $z_{\text{cut}} = .1$ grooms too much!
- Mass shifted by $\sim$12%

Subtleties of PIRANHA: W Tagging

W Tagging: RSS leads to shifted mass determinations and worse mass resolution:

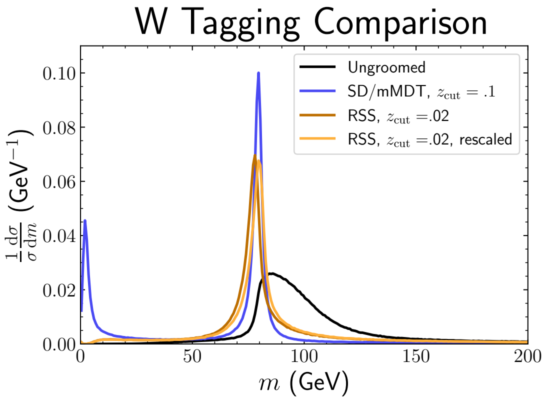


- This time, *decrease* $z_{\rm cut}$ to remove less radiation.
- Mass shifted by $\sim$2%.



Subtleties of PIRANHA: W Tagging

W Tagging: RSS leads to shifted mass determinations and worse mass resolution:



- This time, *decrease* $z_{\rm cut}$ to remove less radiation.
- Mass shifted by $\sim$2%.

Summary

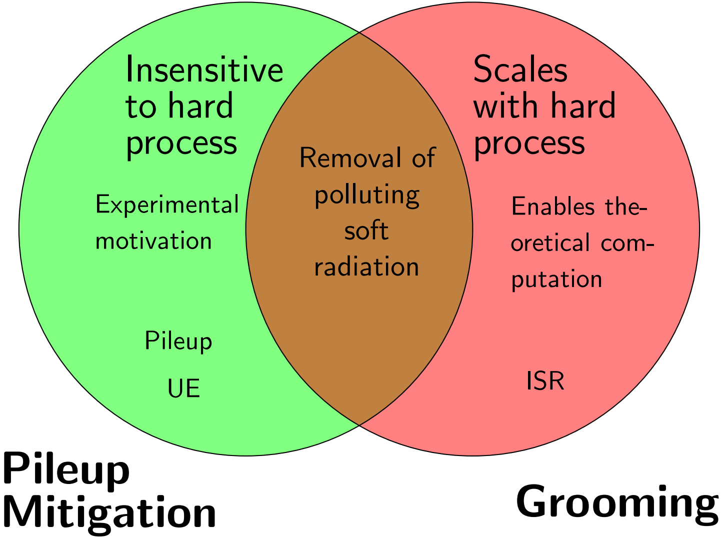
Strengths:

- **Hadronization:** RSS is more robust to the effects of hadronization than Soft Drop/mMDT.
- **Detector effects:** Using simple models of smearing, RSS appears to be more robust to detector effects than Soft Drop/mMDT.

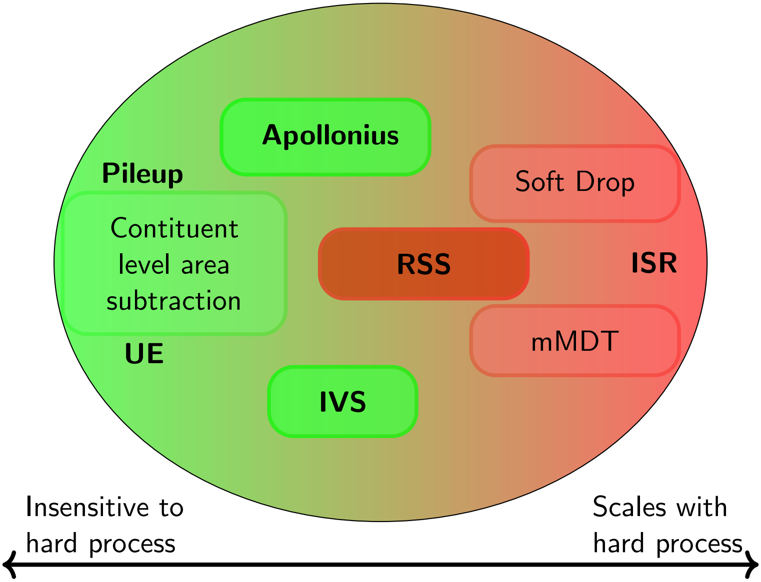
Subtleties:

- **Underlying event:** Distributions of observables in RSS jets are robust against UE, especially if we shift z_{cut} to account for UE.
- **W Tagging:** RSS leads to shifted mass determinations and worse mass resolution, but potentially greater acceptance.

Grooming vs. Pileup Mitigation



Grooming vs. Pileup Mitigation



Generations of Groomers

c. 2008

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

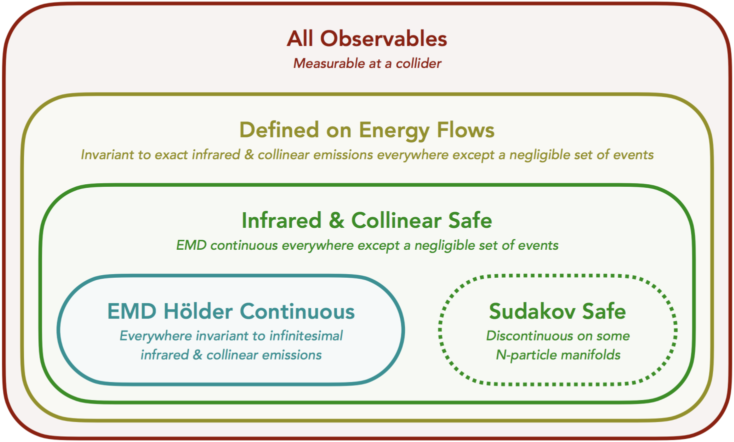
↓ c. 2015

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

↓ c. 2021

PIRANHA (Apollonius, IVS, RSS): **Continuity**

Generalizations of IRC Safety

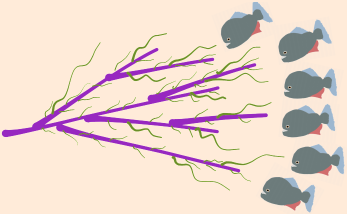


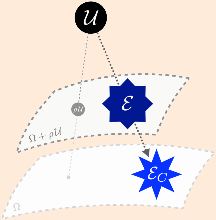
Komiske-Metodiev-Thaler: [2004.04159]

PIRANHA Grooming

Grooming: Remove contaminating soft radiation.

PIRANHA: *Continuously* subtract off contaminating soft radiation *using geometry*.





Komiske-Metodiev-Thaler:[2004.04159]

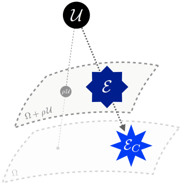
First Solution:

$$\mathcal{E}_{\text{groomed}} = \mathcal{E}_{\text{C}} = \text{argmin}_{\mathcal{E}'} \text{EMD}\left(\mathcal{E}, \mathcal{E}' + \rho\mathcal{U}\right) \qquad (1)$$

PIRANHA Grooming

Solution:

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



PIRANHA Grooming

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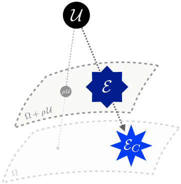
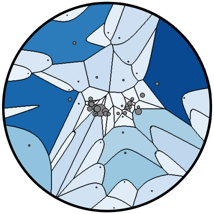
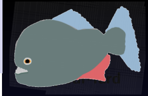


Well studied in optimal transport $\rightarrow$ **Apollonius grooming**!



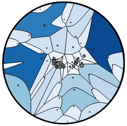
$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Apoll.}}$$

Komiske-Metodiev-Thaler:[2004.04159]



PIRANHA Grooming: The Cast of Characters

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

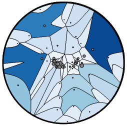


$$p_{T,i}^{\text{groomed}} = p_{T,i} - \rho A_i^{\text{Apoll.}}$$

- Weakness: computationally expensive
- Would like to develop models of the geometric grooming procedure
- Keep IRC safety/continuity in event space while improving computational power

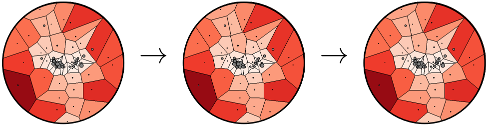
PIRANHA Grooming: The Cast of Characters

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



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

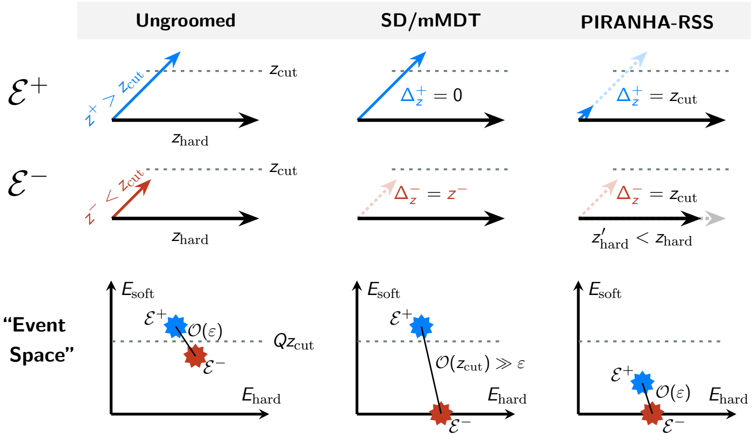
- **Iterated Voronoi Subtraction**: Efficient variant



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

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

PIRANHA Grooming: Eating up the competition



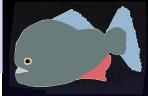
Introducing: Recursive Safe Subtraction

SD/mMDT

PIRANHA-RSS

In RSS, f is the fraction of energy removed from the softer branch.

Introducing: Recursive Safe Subtraction



SD/mMDT

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

PIRANHA-RSS

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

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

In RSS, f is the fraction of energy removed from the softer branch.

Introducing: Recursive Safe Subtraction

SD/mMDT

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

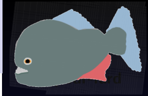
PIRANHA-RSS

- **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

In RSS, f is the fraction of energy removed from the softer branch.

Introducing: Recursive Safe Subtraction



SD/mMDT

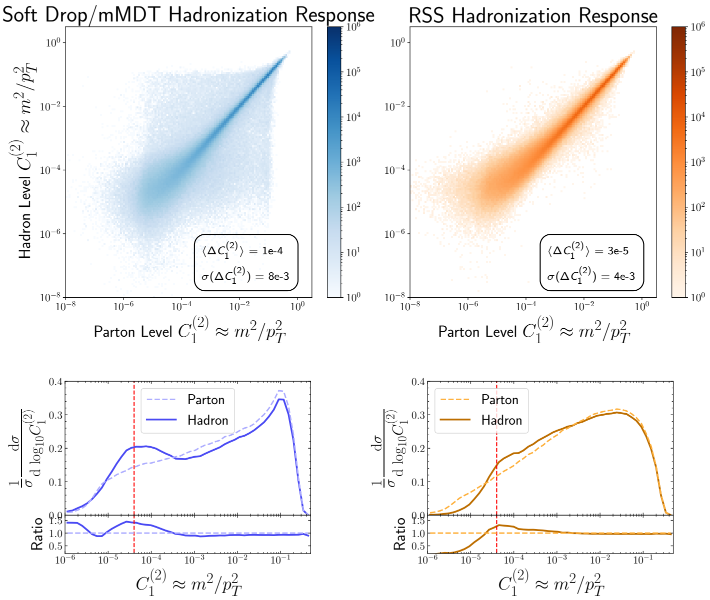
- **Check** $z > z_{\text{cut}}\theta^{\beta}$.
- **Failed:** Groom softer branch and continue
- **Passed:** Keep remaining jet

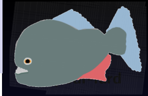
PIRANHA-RSS

- **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.

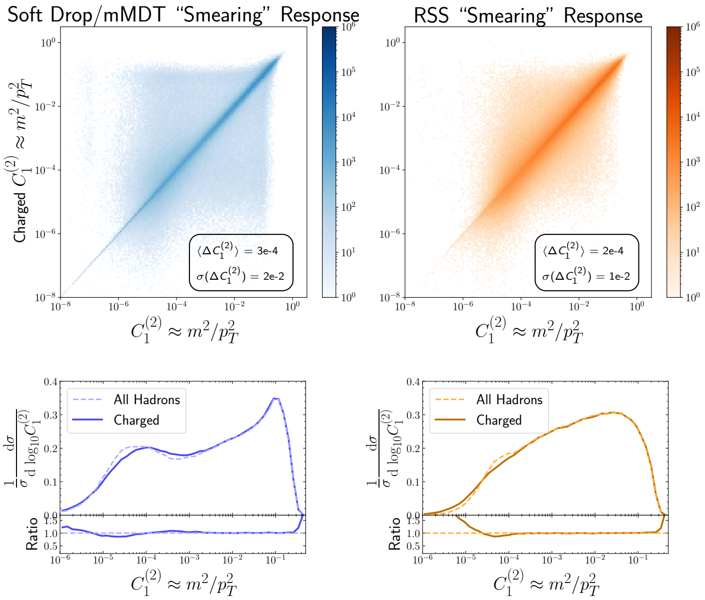
In RSS, f is the fraction of energy removed from the softer branch.

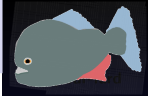
Robustness of PIRANHA: Hadronization





Robustness of PIRANHA: Detector Proxy





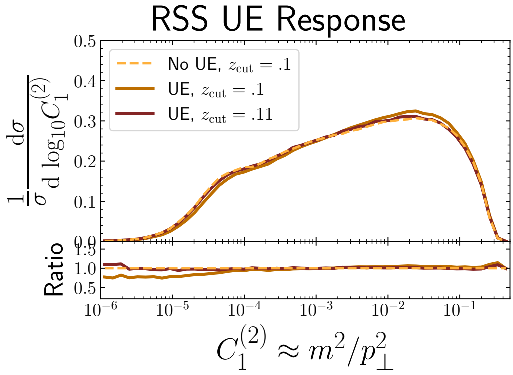
Motivation

PIRANHAs from Geometry

Strengths of PIRANHA Grooming

Subtleties of PIRANHA: Underlying Event

- In RSS, we may increase $z_{\rm cut}$ to remove additional radiation/corrections due to the underlying event:



- 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

Some Interesting Quantities for Groomed Jets

- Dropped energy

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

- Generalized jet energy correlation functions (GECFs)

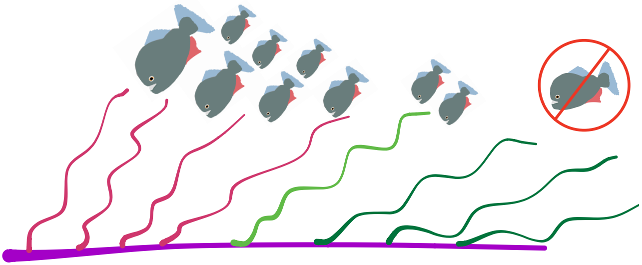
$$C_1^{(\beta)} = \sum_{i,j \in \mathrm{jet}} z_i z_j \theta^{\beta},$$

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

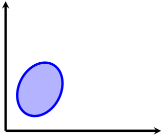
Emissions of RSS Groomed Jets

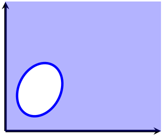
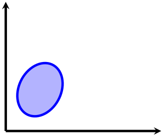
RSS where at every branch, only the softer branch is groomed ($f = 1$). There will be three types of emissions:

- **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

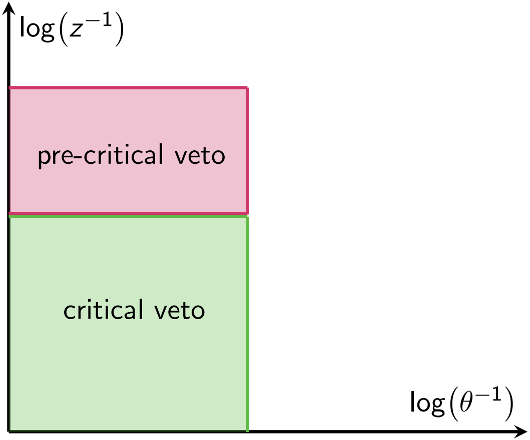


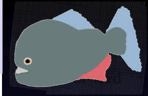
Lund Diagrammar

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

 $= 0,$  $= \; -$  . (3)

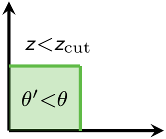
Lund Diagrammar





Lund Diagrammar: Critical Emissions

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

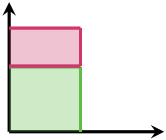


$$\Bigg]$$

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

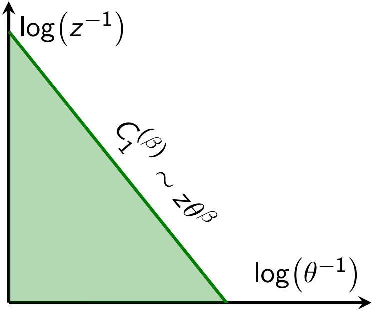
Lund Diagrammar: Pre-critical Emissions

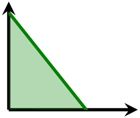
$$\Sigma_{\text{pre}}(z_{\text{pre}}|\theta_{\text{crit}})\Sigma_{\text{crit}}(\theta_{\text{crit}}) = \exp\left[- \right.$$



$$\left. \right]$$

Lund Diagrammar: Subsequent Emissions



$\Sigma_{\text{sub}}(C_1^{(\beta)}) \approx \exp\Bigg[-$  $\Bigg]$