The XCone Jet Algorithm

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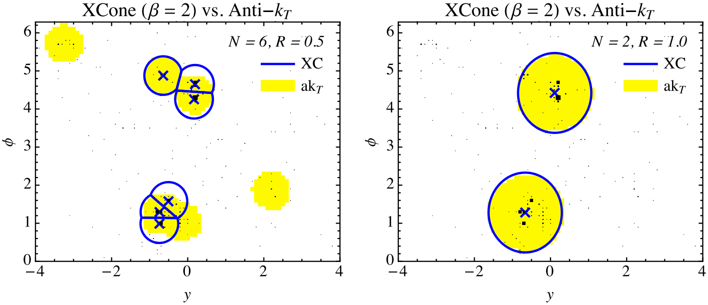
August 12, 2015 — Boost 2015, Chicago

Work with Iain Stewart, Frank Tackmann, Jesse Thaler, Chris Vermilion
arXiv:1508.01516 [Algorithm] and 1508.01518 [Case Studies]
Code available in NSUBJETTINESS v2.2 in FASTJET CONTRIB

XCone: An eXclusive Cone Jet Algorithm

Boosted $t\bar{t} \to$ hadrons from BOOST 2010 sample



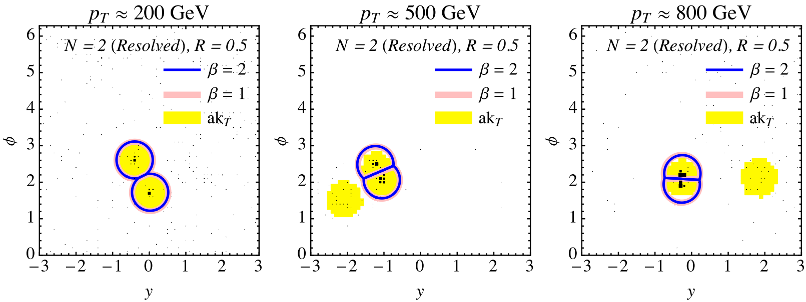
Exclusive cone algorithm based on minimizing N-jettiness

Returns fixed number of (approximately) conical jets

Well-suited for searches with known number of jets

Advantages of Substructure-Based Algorithm

Higgs $\to b\bar{b}$ with increasing p_T



Exclusivity allows axes to be found regardless of proximity

Cones give consistent jet area and dynamic split-merge

$\Rightarrow$ Nearly uniform reconstruction across different kinematic ranges!

Outline

N-jettiness Review and Measure Choice

How N-jettiness defines locations and shapes of jet regions

Overview of Algorithm Structure

Finding jet regions through minimization from IRC-safe seed axes

Applications to Important LHC Search Channels

Reconstructing heavy particles across kinematic regimes

- Heavy Resonance (N $=$ 2)
- Boosted Higgs (N $=$ 2)
- Boosted Top (N $=$ 6)

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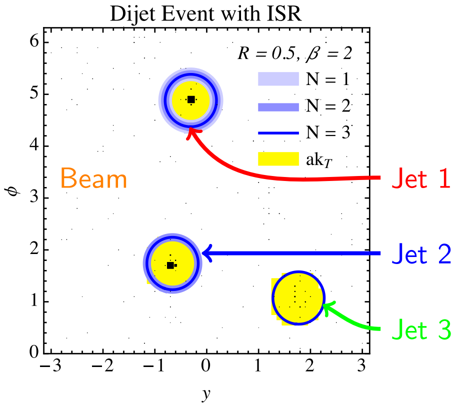
Basics of N-jettiness

General definition of N-jettiness:
[Stewart, Tackmann, Waalewijn, 1004.2489]; see also [Brandt, Dahmen, 1979]

$$\widetilde{\mathcal{T}}_N = \sum_i \min\left\{\rho_{\text{jet}}(p_i, n_1), \ldots, \rho_{\text{jet}}(p_i, n_N), \rho_{\text{beam}}(p_i)\right\}$$

$$\mathcal{T}_N = \min_{n_1, n_2, \ldots, n_N} \widetilde{\mathcal{T}}_N$$



- $\mathcal{T}_N$ partitioning: N jets + beam (unclustered) region
- Quality measure of particle alignment along N axes
- Minimization of $\mathcal{T}_N$ defines exclusive jet algorithm

Different Measure Choices

- Useful: **Conical Measure**

$$\rho_{\text{jet}}(p_i, n_A) = p_{Ti} \left(\frac{R_{iA}}{R} \right)^{\beta}$$

$$\rho_{\text{beam}}(p_i) = p_{Ti}$$

  - Not optimized for calculations

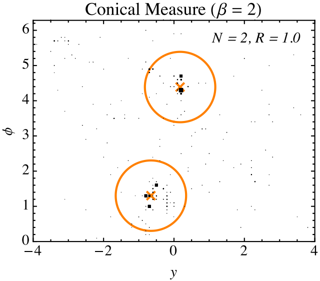
- "Natural": **Geometric Measure**

$$\rho_{\text{jet}}(p_i, n_A) = \frac{n_A \cdot p_i}{\rho_0}$$

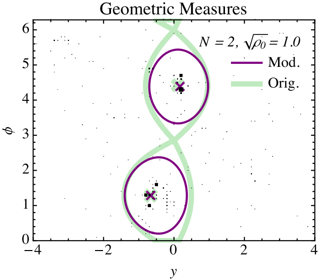
$$\rho_{\text{beam}}(p_i) = \min\{n_a \cdot p_i,\ n_b \cdot p_i\}$$

  - Yields football jets with y-dependence

- **Want calculability without sacrificing conical performance**



[Thaler, Van Tilburg, 1108.2701]



[Jouttenus, Stewart, Tackmann, Waalewijn, 1302.0846]

Conical Geometric Measure

- Simplest solution (XCone Default, $\beta = 2$):

$\approx p_{Ti} R_{iA}^2$ (Conical Measure!)

Minimizes unclustered p_T

$$\rho_{\text{jet}}(p_i, n_A) = \frac{2(\cosh y_A)\, n_A \cdot p_i}{R^2}, \quad \rho_{\text{beam}}(p_i) = p_{Ti}$$

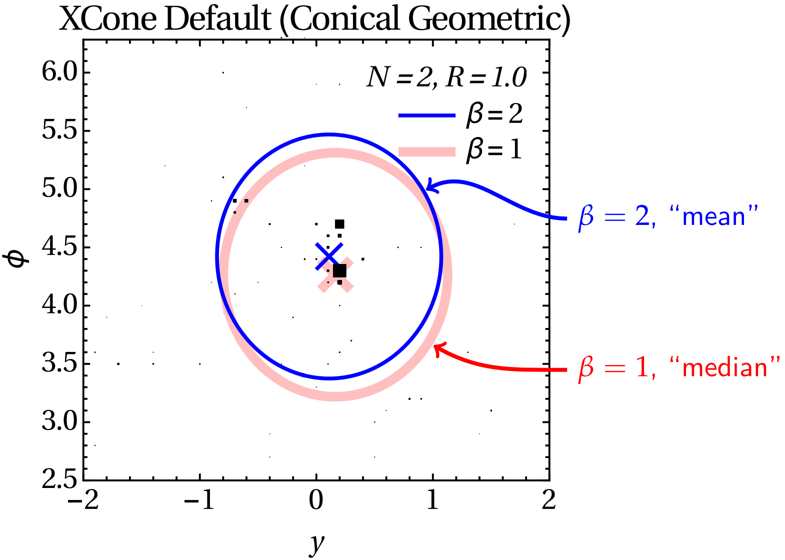
- Generalizes to:

Adjusts axis behavior

$$\rho_{\text{jet}}(p_i, n_A) = p_{Ti} \left(\frac{2 n_A \cdot p_i}{n_{TA}\, p_{Ti}} \frac{1}{R^2} \right)^{\beta/2}, \quad \rho_{\text{beam}}(p_i) = p_{Ti}$$

$\beta = 1$ corresponds to recoil-free measure

Visual Comparison between $\beta = 1$ and $\beta = 2$



- Difference is negligible with no substructure

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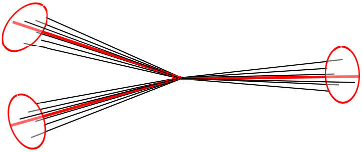
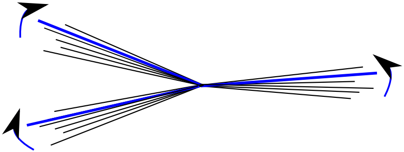
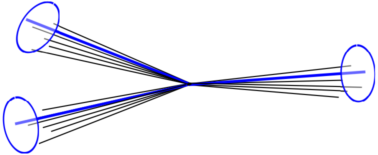
Minimization Steps

Step 1: Find IRC-safe seed axes and partition event





Step 2: Minimize axes
within each jet region



Step 3: Re-partition event

Repeat 2. and 3. until convergence.

Choice of Seed Axes

- Smart choice of seed axes is necessary for good performance
- Exclusive Genk_T, GenE_T axes approximate $\mathcal{T}_N$ minima

$$\text{Gen}k_T : d_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right)\frac{R_{ij}^2}{R^2}, \qquad d_{iB} = p_{Ti}^{2p}$$

$$\text{Gen}E_T : \phi_r = \frac{p_{Ti}^{\delta}\phi_i + p_{Tj}^{\delta}\phi_j}{p_{Ti}^{\delta} + p_{Tj}^{\delta}}, \qquad \eta_r = \frac{p_{Ti}^{\delta}\eta_i + p_{Tj}^{\delta}\eta_j}{p_{Ti}^{\delta} + p_{Tj}^{\delta}}$$

- $k_T\,(p=1)$, $C/A\,(p=0)$, anti$-k_T\,(p=-1)$
- E_T-scheme $(\delta = 1)$, WTA-scheme $(\delta \to \infty)$

Define a set of seed axes in (p, δ) parameter space

(Good) Choice of Seed Axes

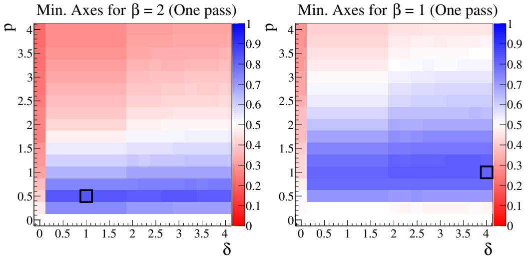
- For good seed axes, mimic N-jettiness, e.g. :

$$\sqrt{d_{ij}} \simeq p_{Ti}^{p} \left(\frac{R_{ij}}{R} \right) \quad \leftrightarrow \quad \mathcal{T}_i \simeq p_{Ti} \left(\frac{R_{iA}}{R} \right)^{\beta}$$

- Recommended parameters are (for $0 < \beta \leq 2$):

$$p \simeq \frac{1}{\beta} \quad , \quad \delta \simeq \frac{1}{\beta - 1}$$

- Fraction of overlap with global minima ($\Delta R < 0.1$):



- Important: Include R in definition of seed axes!

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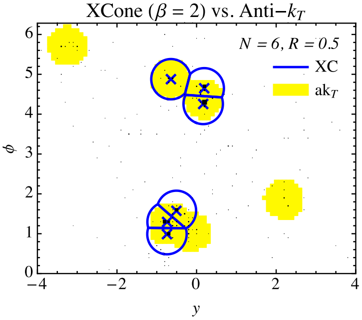
Comparison to Anti-k_T: General Considerations



Anti-k_T:

- Conical, subject to "nibbling"
- Variable # of jets (inclusive)
- Merges adjacent jets

XCone:

- Conical, except for overlapping
- Fixed # of jets (exclusive)
- Splits adjacent jets

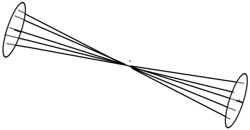
For well-separated jets, 2 hardest anti-k_T $\approx$ XCone $N = 2$

Comparison to Anti-k_T in $Z' \to$ dijets

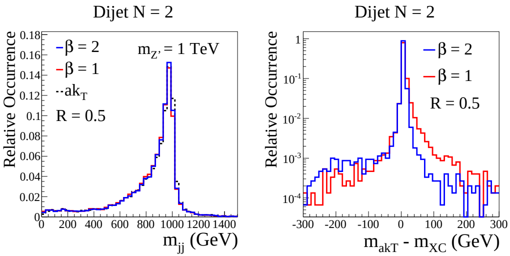
$$Z' \to q\bar{q}\ (u, d, s)$$

(Pythia 8, $\sqrt{s} = 14$ TeV)

$\Longrightarrow$



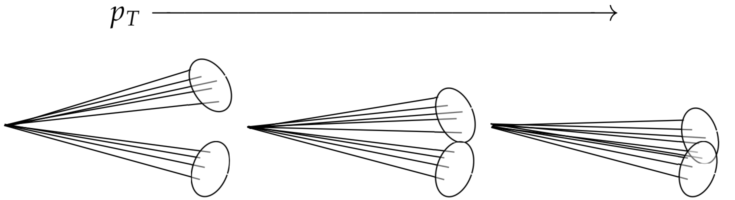
Signal: 2 (hard) back-to-back jets

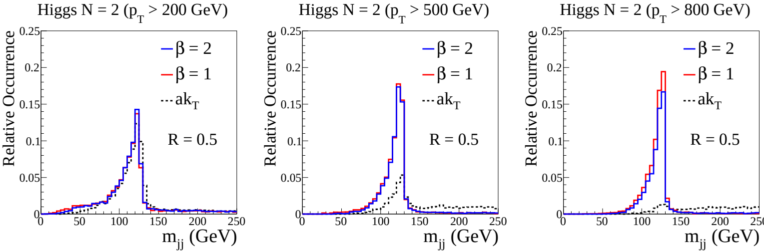


- Over 90% of XCone $\beta = 2$ jets are within $R/2$ of two hardest anti-k_T jets (and over 85% for $\beta = 1$)
- Similarity even extends to $N = 3$ (except for FSR)

Boosted Higgs Mass Resolution

Key difference when subjets are boosted, e.g. $pp \to HZ \to b\bar{b}\nu\bar{\nu}$.

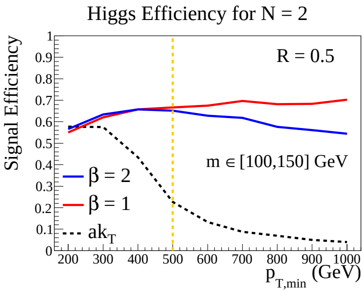




Good resolution even past merging point of $p_T \simeq \frac{2m_H}{R} \simeq 500$ GeV

Boosted Higgs Reconstruction Efficiency

For boosted jets, difference between $\beta = 1$ and $\beta = 2$ is visible:



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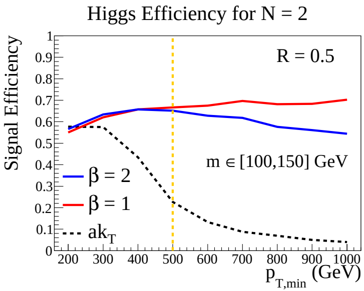
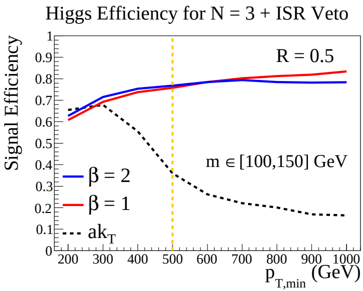


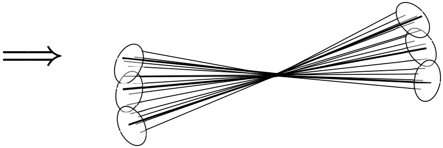


Improve efficiency with $N = 3$ to identify and veto potential ISR

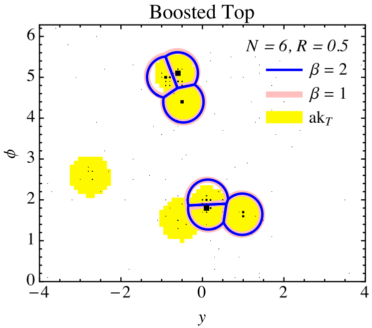
Boosted Top Reconstruction

Classic example of jet substructure

$$pp \to \bar{t}\ t \;\curvearrowright bW \;\curvearrowright q\bar{q}'$$



Most Obvious: $N = 6$ + kinematic grouping



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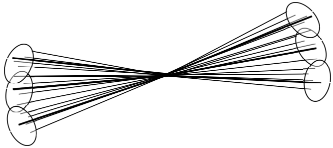
Classic example of jet substructure

$$pp \to \bar{t}\ t$$

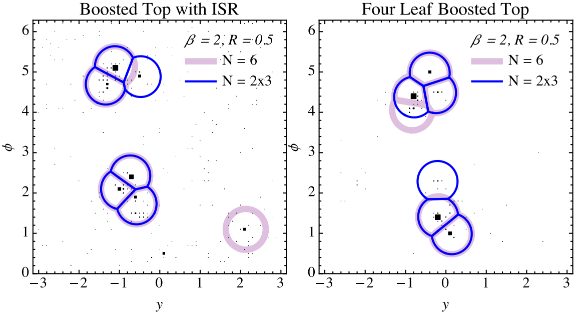
$$\hookrightarrow bW$$

$$\hookrightarrow q\bar{q}'$$

$\Longrightarrow$

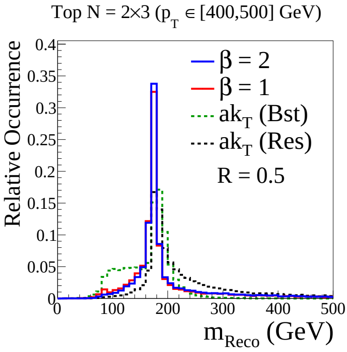


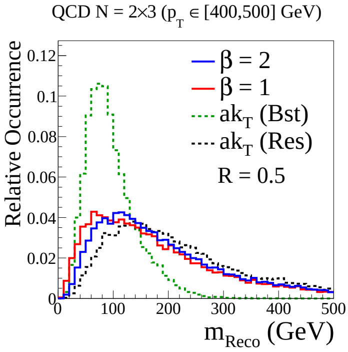
More Intuitively: $N = 2 \times 3$ $(R_2 \to \infty, R_3 = 0.5)$



Boosted Top Reconstruction with $N = 2 \times 3$

BOOST 2010 Samples (Herwig, $\sqrt{s} = 7$ TeV)





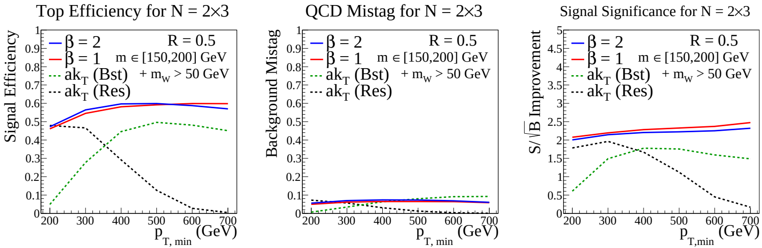
Compare:

- Boosted: 2 anti-k_T jets ($R = 1.0$) with 3 k_T subjets
- Resolved: 2 k_T jets ($R \to \infty$) with 3 anti-k_T subjets

XCone reduces W shoulder and high mass tail by identifying all subjets while also removing contamination

Boosted Top Reconstruction Efficiency

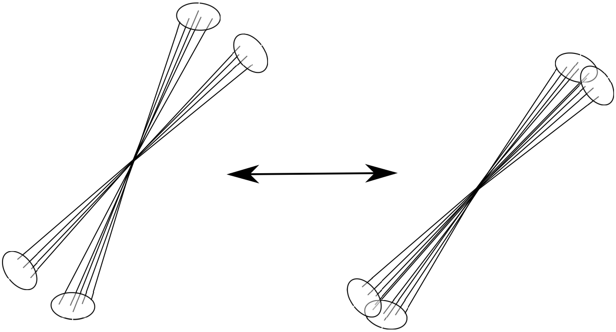
Cutting tight on mass gives strong signal efficiency and significance



- Higher significance than traditional strategies across all p_T!
- Further gains possible with additional discrimination methods

Further Potential Applications

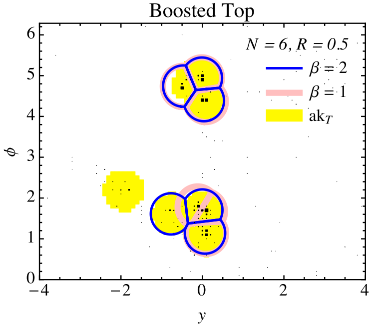
- Di-Higgs with $N = 2 \times 2$:



[See Michael Kagan's talk on Monday, Andreas Hinzmann's talk on Tuesday]

- Boosted W/Z for Diboson resonances with $N = 2 \times 2$
- $t\bar{t}H$ with $N = 3 \times 2, 3$
- RPV SUSY with $N =$ many (?)

Conclusion

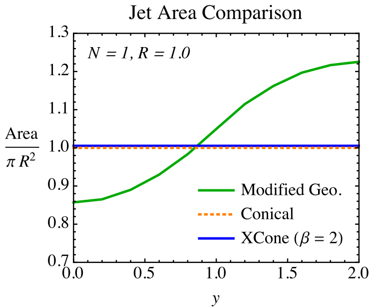


- XCone: a new exclusive cone algorithm with high reconstruction efficiency across kinematic regimes
- Well-suited for many LHC search channels with flexible usage
- Future studies will explore wide array of options to better fight backgrounds and account for ISR/FSR

Looking forward to potential applications in Run 2!

Thank you!

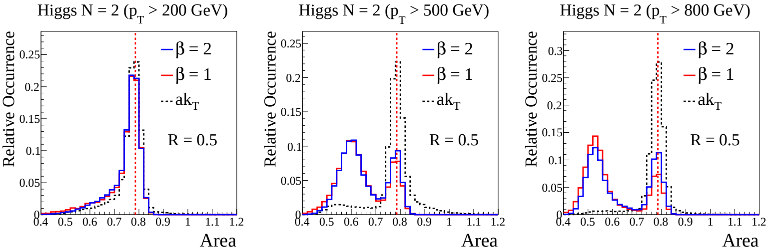
Jet Areas



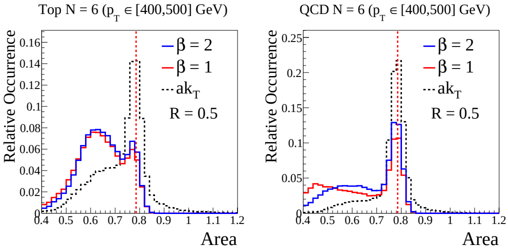
- Geometric measures have closed-form integral area expression
- For small jets, conical geometric within 1% of conical area

Area Distributions

Boosted Higgs:



Boosted Top:



N-jettiness Minimization

- Minimization inspired by stable cone finding, but with slight offset due to n_A dependence
- Starting from seed axes, iteratively calculate new axes as:

$$\rho_{\text{jet}}(n_A, p_i) = n_A \cdot p_i \, g(p_i, n_A),$$

$$n_A^{\text{new}} = \left\{1, \frac{\vec{q}_A}{|\vec{q}_A|}\right\} \qquad \text{with} \qquad \vec{q}_A = \sum_{i \in A} \vec{p}_i \, g(p_i, n_A^{\text{old}}).$$

- For $g = 1$, minimum is $n_A = \left\{1, \frac{\vec{p}_A}{|\vec{p}_A|}\right\}$ (i.e. stable cones)

More General Conical Geometric Measure

$$\rho_{\text{jet}}(p_i, n_A) = \frac{p_{Ti}}{(2\cosh y_i)^{\gamma-1}} \left(\frac{2 n_A \cdot p_i}{n_{TA}\, p_{Ti}} \frac{1}{R^2} \right)^{\beta/2},$$

$$\rho_{\text{beam}}(p_i) = \frac{p_{Ti}}{(2\cosh y_i)^{\gamma-1}}$$

$\cosh y_i$ adjusts rapidity dependence, favors central jets for $\gamma > 1$

Identical factors in jet/beam measure maintain constant jet shape

Default is $\gamma = 1$ to maintain similar behavior to conical measure

δ Heuristic

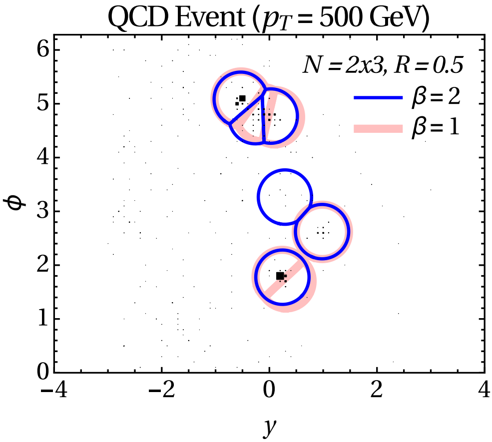
Optimum value of δ comes from:

$$\mathcal{T}_N \sim p_{T1}|\phi_1 - \phi_A|^\beta + p_{T2}|\phi_2 - \phi_A|^\beta$$

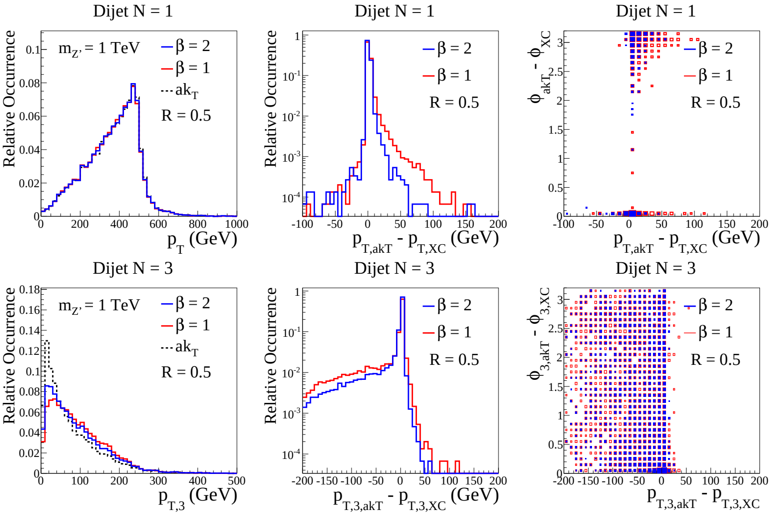
Solving $\mathrm{d}\mathcal{T}_N/\mathrm{d}\phi_A = 0$ to find minimum:

$$\phi_A = \frac{p_{T1}^\delta \phi_1 + p_{T2}^\delta \phi_2}{p_{T1}^\delta + p_{T2}^\delta}, \qquad \delta = \frac{1}{\beta - 1}$$

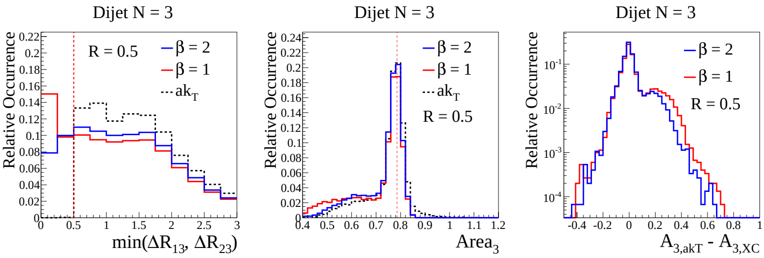
QCD Background Display



Dijet Similarity in $N = 1, 3$

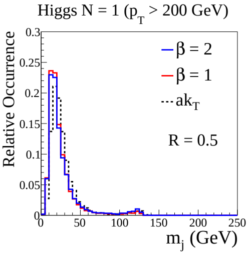


Dijet ISR vs. FSR

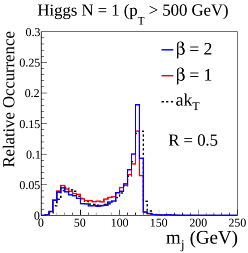


- XCone $N = 3$ jets can abut with one of $N = 2$ jets, whereas the 3^{rd} anti-k_T jet is repelled to $\Delta R_3 = R$
- Allows XCone to find FSR easier than anti-k_T if it is $< R$
- XCone and anti-k_T find similar results for ISR jets

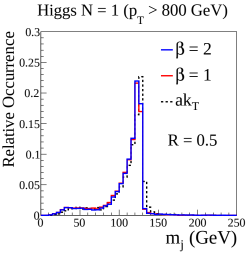
Higgs $N = 1$



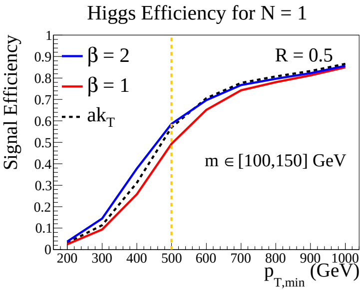
Higgs N = 1 (p_T > 200 GeV)
Relative Occurrence
β = 2
β = 1
ak_T
R = 0.5
m_j (GeV)



Higgs N = 1 (p_T > 500 GeV)
Relative Occurrence
β = 2
β = 1
ak_T
R = 0.5
m_j (GeV)

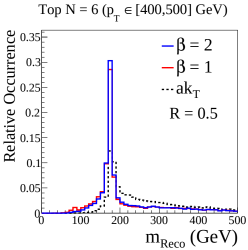


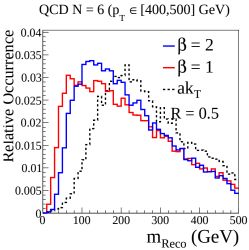
Higgs N = 1 (p_T > 800 GeV)
Relative Occurrence
β = 2
β = 1
ak_T
R = 0.5
m_j (GeV)

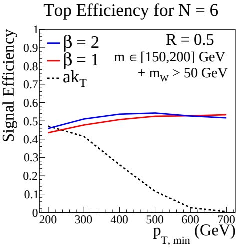


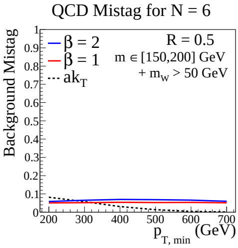
Higgs Efficiency for N = 1
Signal Efficiency
β = 2
β = 1
ak_T
R = 0.5
m ∈ [100,150] GeV
p_T,min (GeV)

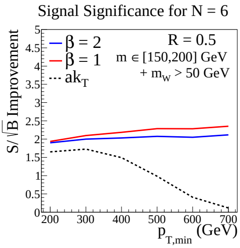
Boosted Top Reconstruction with $N = 6$



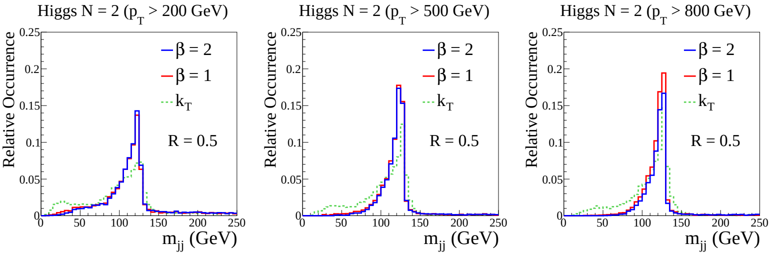


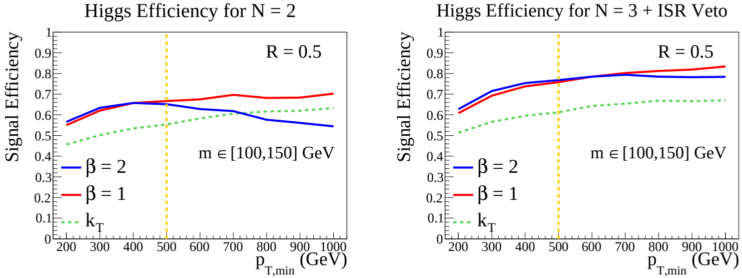






Comparison to Exclusive k_T in Boosted Higgs





Comparison to Exclusive k_T in Boosted Tops