XCone
N-jettiness as an Exclusive Cone Jet Algorithm

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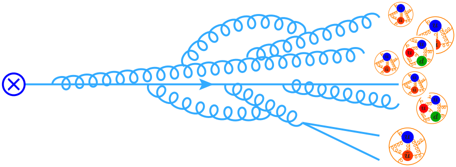
based on
Stewart, FT, Thaler, Vermilion, Wilkason (arXiv:1508.01516)
Thaler, Wilkason (arXiv:1508.01518)

Introduction.

Why Jets?

QCD doesn't let us observe quarks and gluons directly, only jets of hadrons



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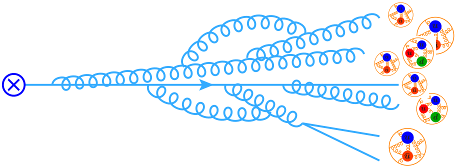
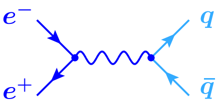
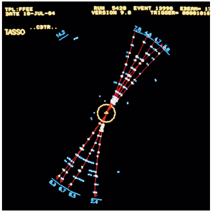
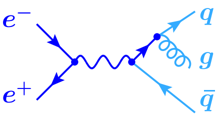


Jets tell us the QCD final state of the hard interaction process

- 36 years ago:





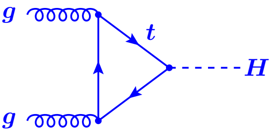


- Today: Essentially the same (just a bit more complicated ...)

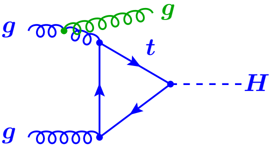
Executive Summary of Higgs Production.

$\sim 2/3$ of Higgs bosons are produced at low p_T

0 jets

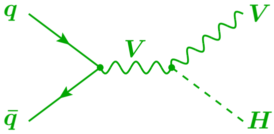


0-1 jets

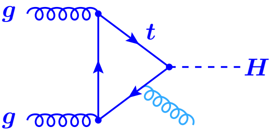


$\sim 1/3$ of Higgs bosons have sizeable p_T

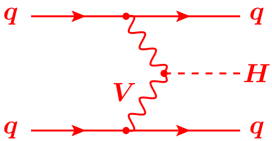
0 (normal) jets



1 jet



2 (quark) jets



- Kinematics and number of jets distinguishes different Higgs processes
- Discriminates against different backgrounds (e.g. in $H \to WW, \tau\tau, b\bar{b}$)

Why Else Jets?

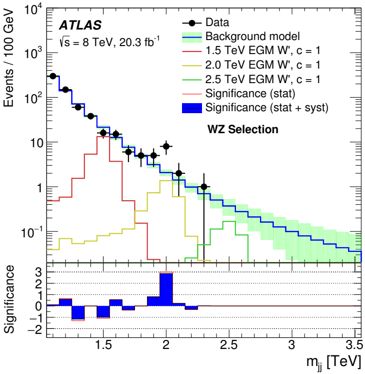
Jets are essential also in EW final states

Recall $\mathrm{BR}(W \to q\bar{q}') = 67\%$

$\mathrm{BR}(Z \to q\bar{q}) = 70\%$

- Diboson excess is in dijet mass spectrum of two *filtered W/Z-tagged jets*

  [ATLAS 1506.00962]



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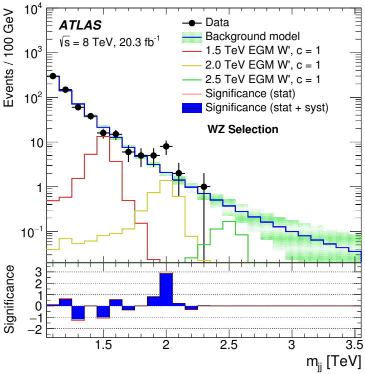
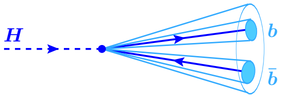
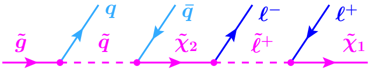


Search strategies increasingly rely on exploiting jet substructure

- Boosted decays: top-jets, W/Z-jets, Higgs-jets

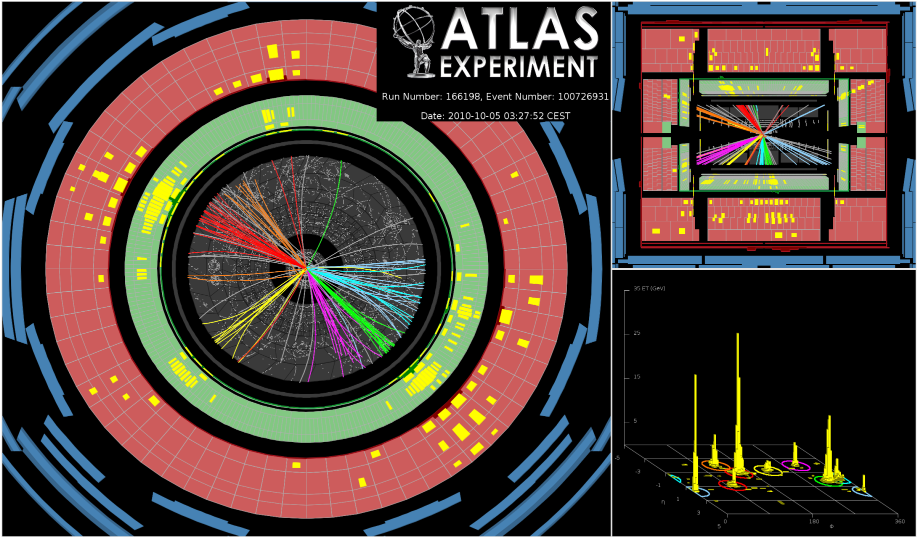


- Distinguish quark jets (from BSM cascades) from gluon jets (QCD backgrounds)



- Jet mass, shape, charge, tracks, ...

Jets Are Ubiquitous.



- How many jets are there? ⇒ What is a jet and what is not a jet?

What is a Jet?

This is a jet

What is a Jet?

This is a jet

This is not a jet

What is a Jet?

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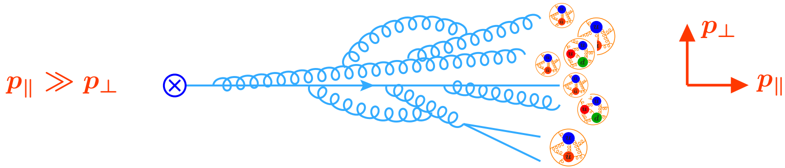
What is a Jet?

This is a jet	This is not a jet

$p_{\parallel} \gg p_{\perp}$ $\qquad$ $p_{\parallel} \sim p_{\perp}$

$p_{\parallel}$: total momentum along direction of flight
$p_{\perp}$: intrinsic transverse momentum

Jet Algorithms



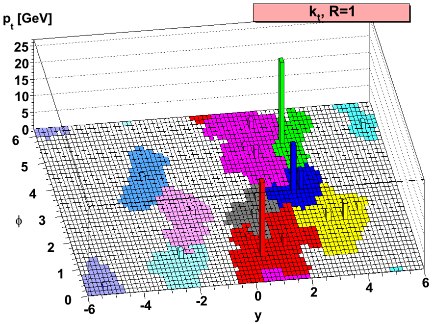
Basically want to combine all energetic particles with $p_{\parallel} \gg p_{\perp}$

- Jets should correspond to initiating hard partons
- It is inevitable to scoop up soft radiation
- Should be IR safe (better: insensitive to nonperturbative corrections)
- Transverse/angular size is a key parameter: jet radius R

Development of jet algorithms has a long history (that I won't discuss)

- Jade, fixed cone, iterative cone, MidPoint, k$_T$, CA, anti-k$_T$, ...
- Standard choice today: anti-k$_T$ [Cacciari, Salam, Soyez]

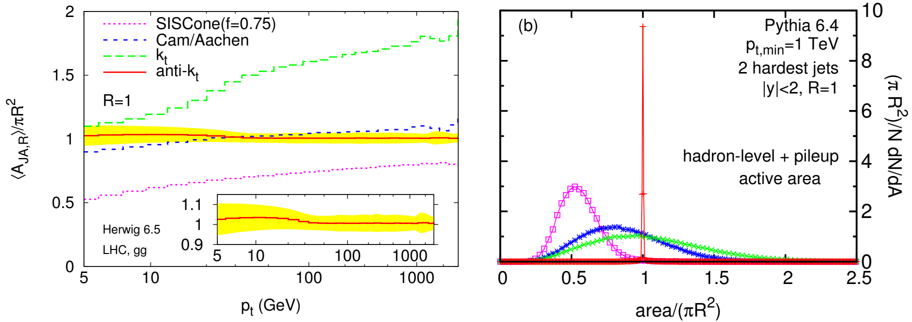
Key Features of Anti-k_T



Sequential combination where hard particles are combined first

- Jet boundary is insensitive to soft radiation
  - Important for theory, factorization properties
- Jets are conical with uniform and constant area $\approx \pi R^2$
  (except when clipped by a harder jet)
  - Important for experimental calibration, pile-up removal, ...

$\Rightarrow$ These important properties of anti-k_T are maintained by XCone



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Why a New Jet Algorithm?

What's wrong with anti-k$_T$?

- Nothing per se, it answers the question:

  "How many jets has this event and what are they?"

- It is not very good at identifying overlapping jets or jet substructure
  (It's not designed for that, and this is why many dedicated substructure techniques have been developed.)

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XCone is an *exclusive* jet algorithm

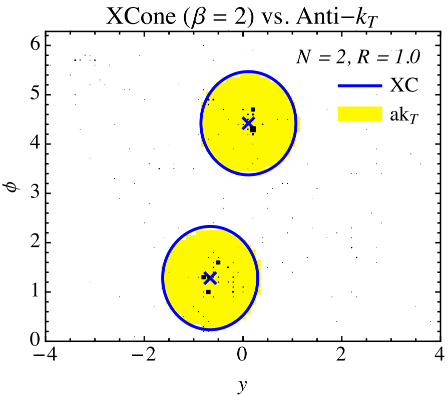
- It answers a different question, for a given fixed N:

  "What is the best way to interpret this event as an N-jet event?"

- This is the relevant question if one already knows the signal topology one is looking for
- It always returns "the best" N jets
- Provides smooth transition between resolved and boosted regimes

XCone vs. Anti-k_T

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



Well-separated jets

- XCone jets practically the same as leading anti-k_T jets

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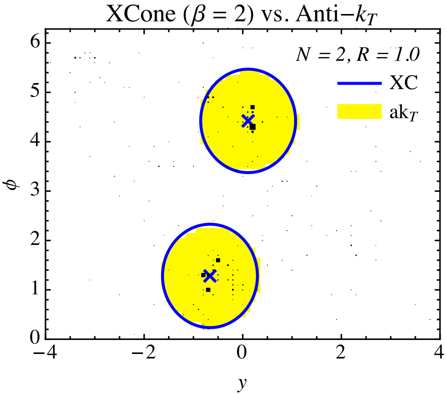

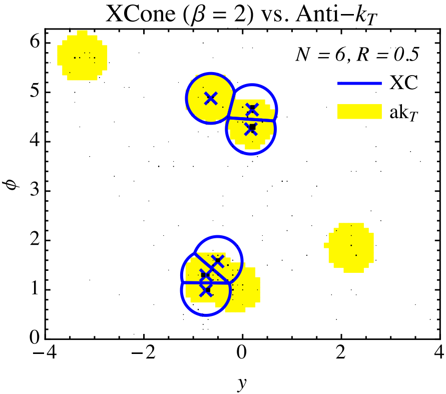

Well-separated jets

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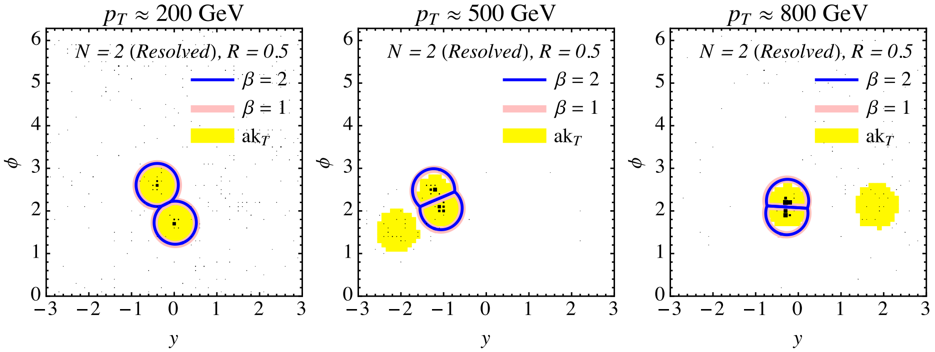
Adjacent/overlapping jets

- anti-k_T merges signal jets, picks up ISR, FSR jets
- XCone still finds signal jets, split by nearest-neighbor

Substructure Without Substructure.

Boosted $H \to b\bar{b}$ with increasing p_T



Key advantage of XCone

- Exclusivity allows signal jets to be found regardless of proximity
- Automatically resolves overlapping jets

⇒ Provides stable performance and smooth transition from resolved (well-separated) regime to boosted (substructure) regime

Overview of Algorithm.

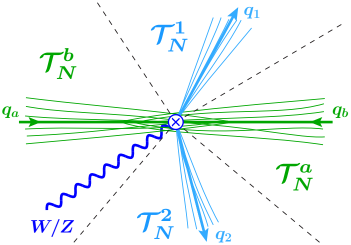
Jet partitioning

- Start from standard N-jettiness [Stewart, FT, Waalewijn]

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

$$= \widetilde{\mathcal{T}}_N^a + \widetilde{\mathcal{T}}_N^b + \widetilde{\mathcal{T}}_N^1 + \cdots \widetilde{\mathcal{T}}_N^N$$

  - Given N jet axes $\{n_k = (1, \vec{n}_k)\}$, partitions particles into N jet regions and beam region
  - Shape and size of jet regions depend on $\rho_{\rm jet}$ and $\rho_{\rm beam}$ measures



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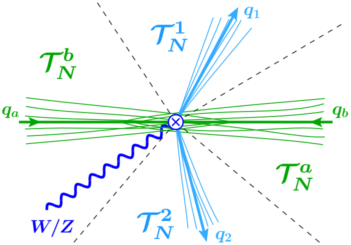


Axis finding

- Minimize over all jet axes

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

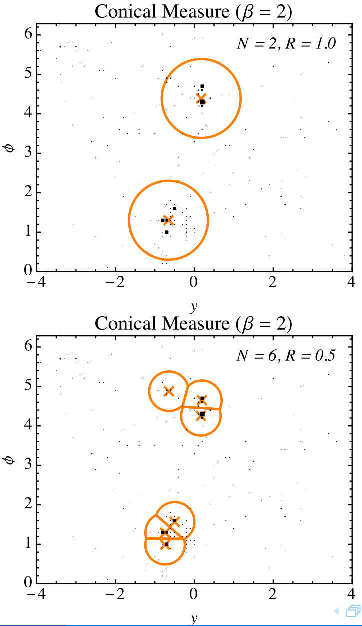
  - Finding exact global minimum is computationally expensive (prohibitive)
  - Finding approximate (local) minimum is sufficient and inexpensive (Procedure just needs to be IR safe and is part of the algorithm definition)

Conical Measure.

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

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

- First used in context of N-subjettiness [Thaler, van Tilburg]
- Angular exponent β controls jet axis behaviour
  - $\beta = 2$: Axis along total jet momentum
  - $\beta = 1$: Axis along hardest cluster in a jet
- Pro: Yields exact cones of radius R for non-overlapping jets
- Con: Nonlinear dependence on axis and particle momenta, which is not ideal for axis finding and calculations



Geometric Measure.

[Jouttenus, Stewart, Tackmann, Waalewijn]

$$\rho_{\rm jet}(p_i, n_A) = \frac{n_A \cdot p_i}{\rho_0} \approx \frac{p_{Ti}}{2\cosh y_A} \frac{R_{iA}^2}{\rho_0}$$

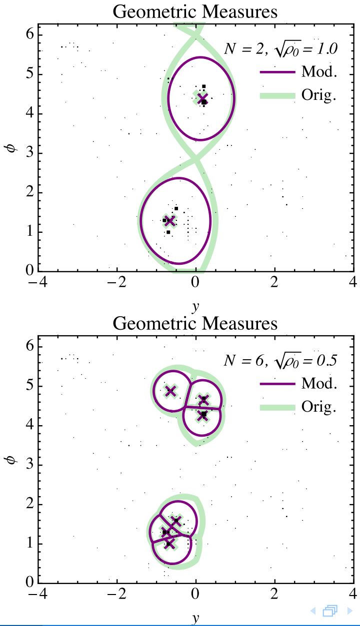
original:

$$\rho_{\rm beam}(p_i) = \min\{n_a \cdot p_i, n_b \cdot p_i\} = m_{Ti} e^{-|y_i|}$$

modified:

$$\rho_{\rm beam}(p_i) = \frac{m_{Ti}}{2\cosh y_i}$$

- Pro: Linear in both n_A and p_i
  - Most natural/easiest for calculations
  - Resummation known to NNLL for any number of jets
- Con: Non-conical football jets
  - $\rho_0 \simeq R^2$, but area is y-dependent



Conical Geometric Measure.

XCone default ($\beta = 2$)

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

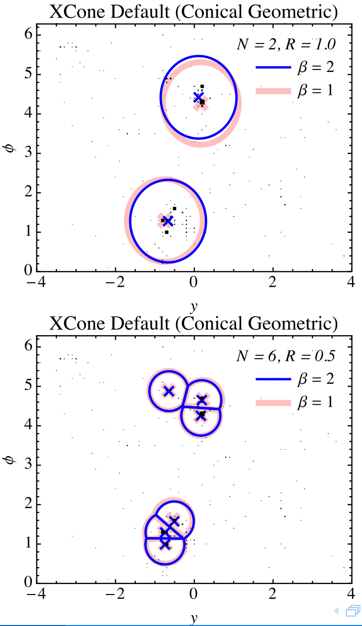
$$\rho_{\text{beam}}(p_i) = p_{Ti}$$

- ✓ Linear in p_i
- ✓ Almost conical
- ✓ Beam measure minimizes unassigned p_T, which means one typically finds N highest-p_T jets

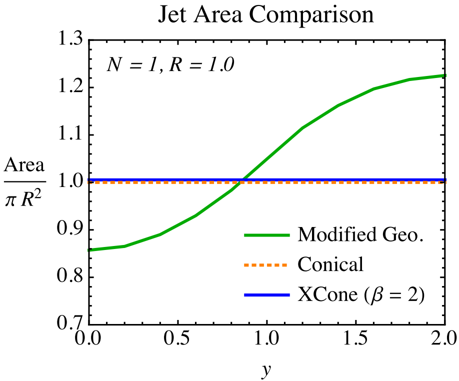
Generalizes to

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

- β controls axis behaviour as for conical



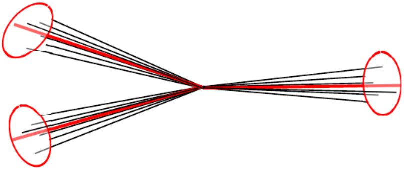
Jet Area.

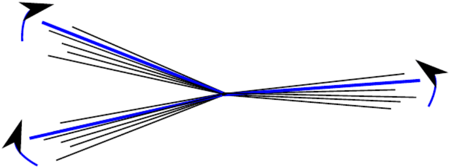


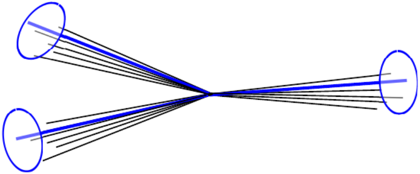
- Jet area for geometric measures has a closed-form integral expression
  - explicitly depends on y
  - Can be corrected for by taking $\rho_0 \to \rho(y_A, R)$ ("Geometric-R measure")
- Conical measure has exact $A = \pi R^2$
- XCone default is within 1% of exact conical area

Axis Minimization.

Step 1: Find a set of IR safe seed axes $\{n_A\}$ and partition event







Step 2: Update axes by minimizing $\mathcal{T}_N^i$ in each region

Step 3: Re-partition event

Repeat steps 2 and 3 until axes have converged

Choice of Seed Axis.

For IR safety avoid any stochastic elements $\rightarrow$ One-pass minimization

- Finding good set of seed axis is important to find good (local) minimum
- Run generalized exclusive k_T clustering
  - Pick metric and recombination scheme that mimic N-jettiness
  - Important to use the same R
  - Use direction of N jets as seed axis

Nontrivial test sample: Boosted tops in presence of ISR (Boost 2010 top sample)

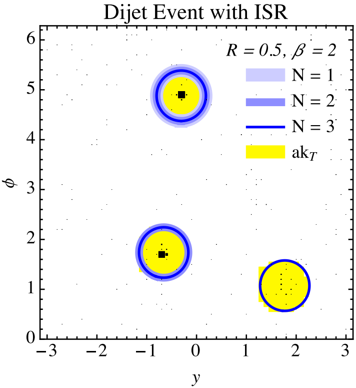
- XCone jets ($\beta = 2$) that are aligned with those of the global $\mathcal{T}_N$ minimum (found by brute force)

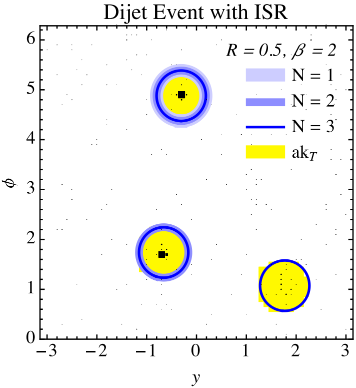
	Seed axes	One-pass min
Fraction of aligned jets	0.95	0.96
Fraction of events with $\geq$ 4 aligned jets	0.99	0.99
Fraction of events with $\geq$ 5 aligned jets	0.92	0.93
Fraction of events with $\geq$ 6 aligned jets	0.78	0.81

Case Studies.

Heavy Dijet Resonance.

Heavy $Z' \to q\bar{q}$ $\to$ Signal: 2 hard back-to-back jets $\to$ Pick N $= 2$





In resolved regime, XCone has practically the same performance as anti-k$_T$

- N $=$ 1,2,3 XCone jets typically match N highest-p_T anti-k$_T$ jets
- Over 90% of XCone jets are within $R/2$ of two hardest anti-k$_T$ jets

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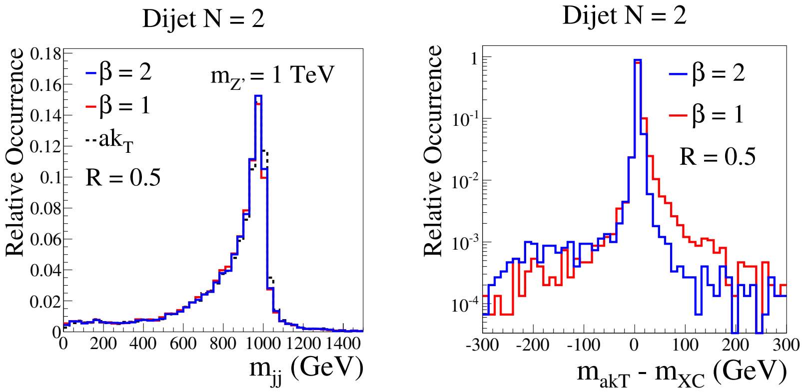

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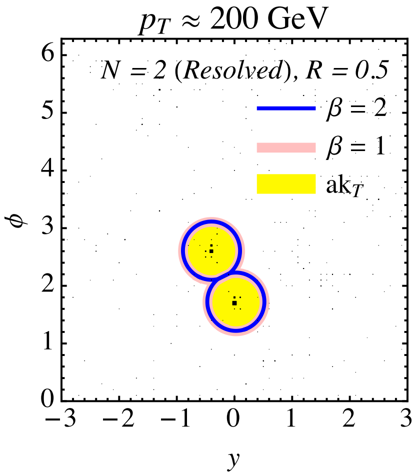
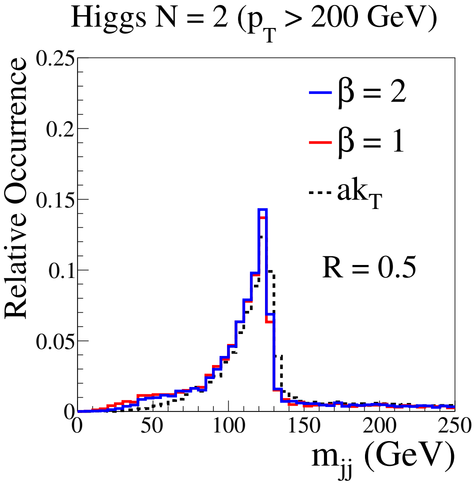
Boosted Higgs Reconstruction.

$pp \to VH(\to b\bar{b})$ $\to$ Signal: 2 close-by (b-)jets $\to$ Pick $N = 2$





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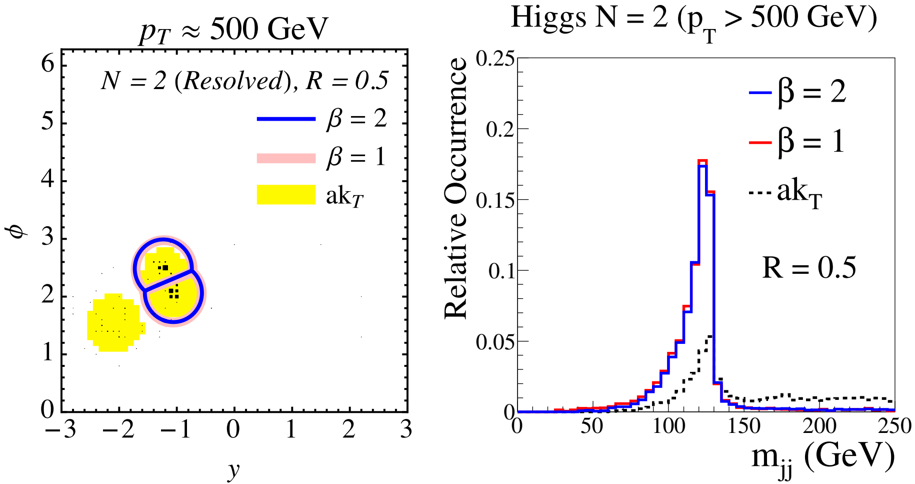

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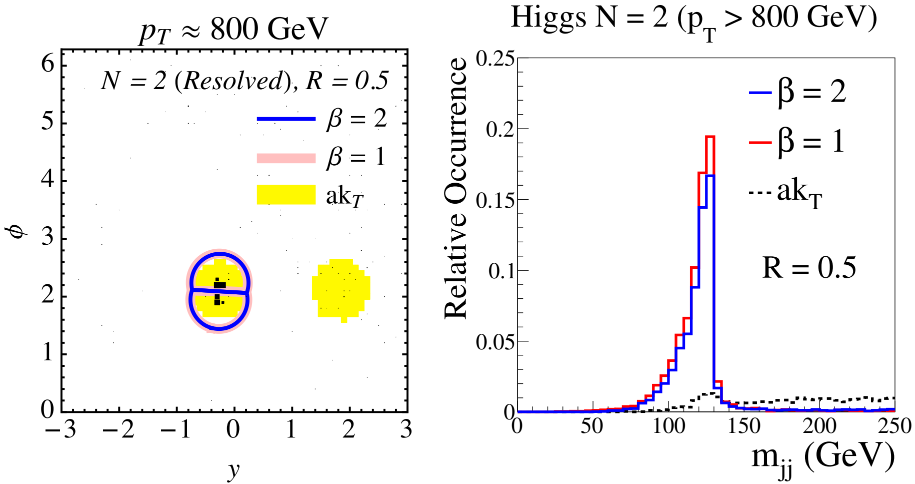

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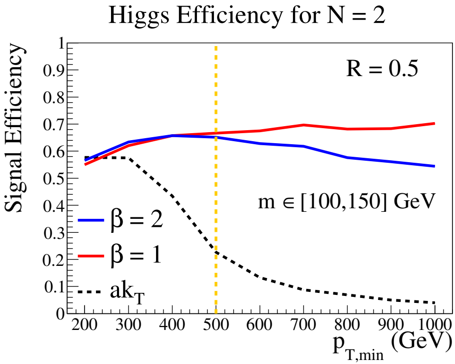
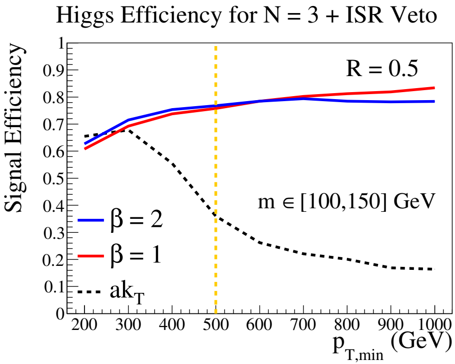
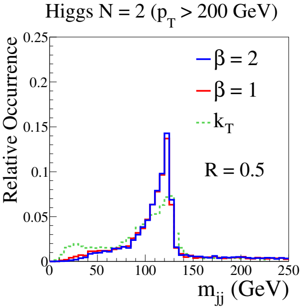


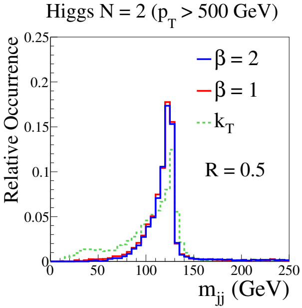


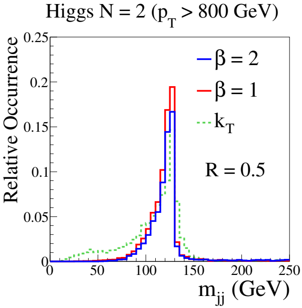
XCone allows standard resolved analysis to be smoothly extended into boosted regime without loss of performance

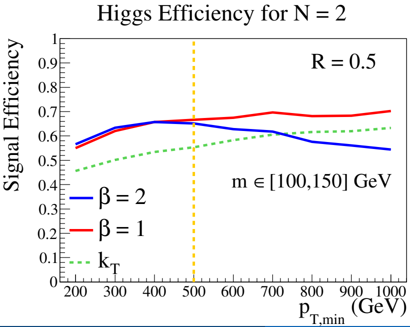
- Merging point: $p_T \simeq 2m_H/R \simeq 500\,\mathrm{GeV}$
- Effectively provides automatic transition from 2-jettiness to 2-subjettiness
- Further improvements possible, e.g. with $N = 3$ and explicit ISR veto

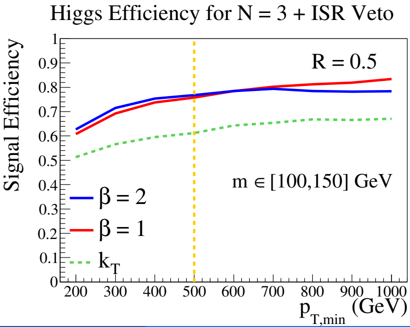
Comparison to Exclusive k_T in Boosted Higgs.









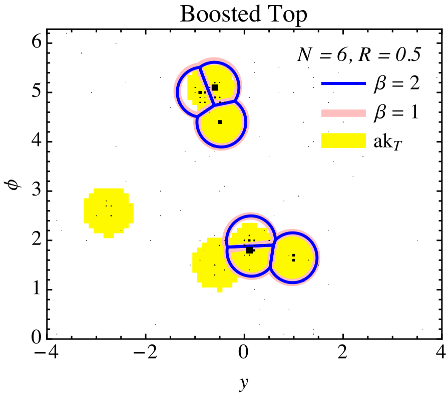


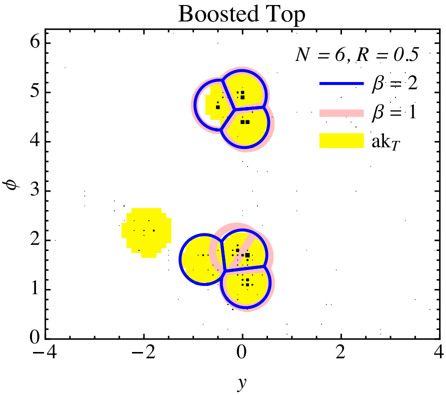
Reconstructing Boosted Hadronic Top.

Classic example of jet substructure

$pp \to t\bar{t} \to WWb\bar{b} \to q\bar{q}q\bar{q}b\bar{b}$ $\to$ Signal: 2 groups of 3 jets

$\to$ Most obvious: Pick N = 6 with kinematic grouping of 3 nearby jets



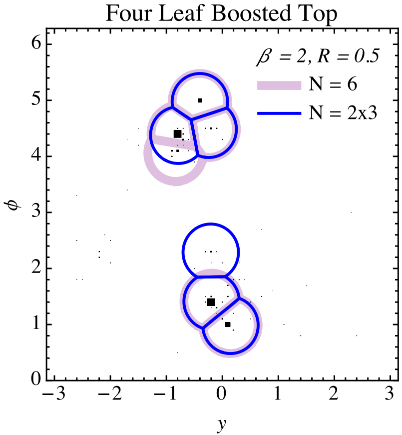


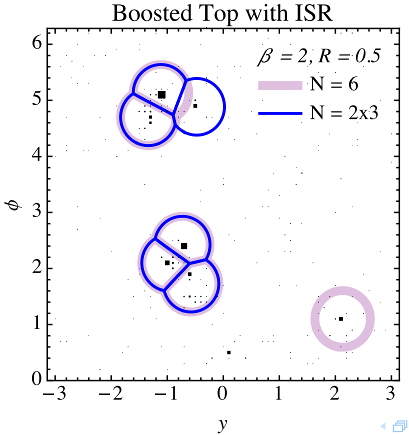
Reconstructing Boosted Hadronic Top.

Classic example of jet substructure

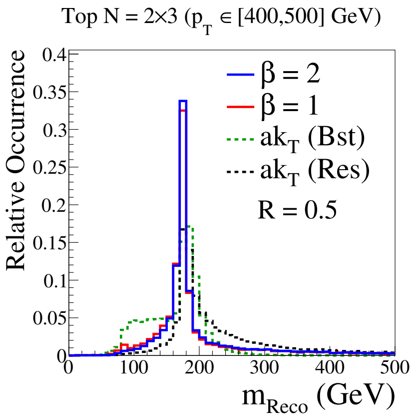
$pp \to t\bar{t} \to WWb\bar{b} \to q\bar{q}q\bar{q}b\bar{b}$ $\rightarrow$ Signal: 2 groups of 3 jets

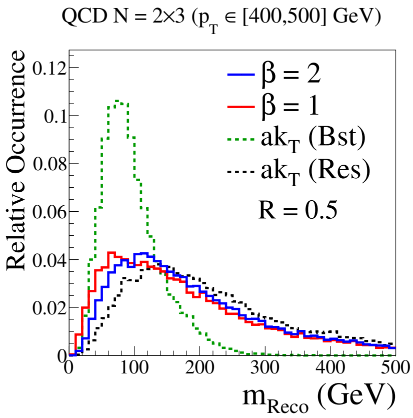
$\rightarrow$ Better: Pick $\mathrm{N} = 2\times 3$ (with $R_2 \to \infty$, $R_3 = 0.5$)





Boosted Top Reconstruction ($N = 2\times3$).

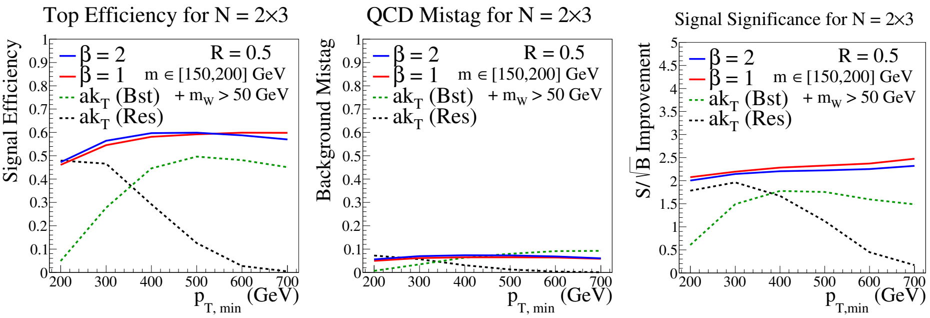




Compare XCone with $N = 2\times3$ to

- "Resolved": 2 k$_T$ jets ($R \gg 1$) with 3 anti-k$_T$ subjets
- "Boosted": 2 anti-k$_T$ jets ($R = 1.0$) with 3 k$_T$ subjets

Boosted Top Reconstruction ($N = 2\times3$).



Compare XCone with $N = 2\times3$ to

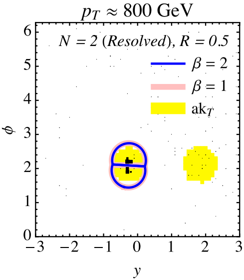
- "Resolved": 2 k_T jets ($R \gg 1$) with 3 anti-k_T subjets
- "Boosted": 2 anti-k_T jets ($R = 1.0$) with 3 k_T subjets

⇒ Higher significance than traditional strategies across all p_T

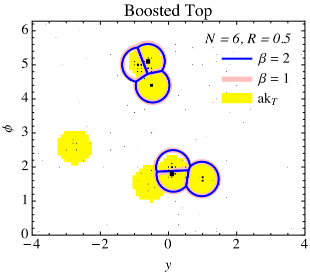
⇒ Further improvement possible with additional discrimination methods

Summary.

Jets are our window onto the hard interaction



XCONE



An exclusive jet algorithm that works across kinematic regimes

- Well-suited for many LHC applications, particularly in intermediate “quasi-boosted” regimes
- Inherits good theory properties of underlying N-jettiness

$\Rightarrow$ Opens a wide array of possibilities to explore

$\Rightarrow$ Code is available in NSUBJETTINESS v2.2 in FASTJET CONTRIB