50 Years of Jet Physics: A Brief, But Biased History of Jets and Jet Substructure

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Steve Ellis
Page 229 – “Then Ellis took the stage. His lecture style was half comedian and half television sports announcer.”
At a meeting in St. Vincent (the Aosta valley below Mont Blanc) during 2/25 – 3/1/1985 when the first SUSY discovery was NOT confirmed.
In the “Dark Ages” (late 1960’s) there was only QED

- At Caltech, where I was a grad student, Dick Feynman taught a ONE(!) quarter course in QED (there was little understanding of renormalization at that time) and that was all the Quantum Field Theory (QFT) offered.

- The argument was that QFT was not relevant for either the Weak or Strong interactions and QED was a solved(!) problem!! (Wrong on all points!)
  Still in the 1 hour per week that Murray Gell-Mann taught (a course I called “what Murray did last night”) it was clear that QFT was the language used by the “Grand Old Men”.

- ASIDE: Eventually I led a student revolt of Particle Theory Students demanding that QFT be formally taught, and so Steven Frautschi was enlisted to teach it.

- In summary: theoretically no Standard Model (just the S-matrix and Regge poles), and experimentally no colliders, no jets!!! Just low energy fixed-target hadron collisions yielding resonances and soft pions.

Also: no email, no arXiv, no cellphones, no Facebook and computers communicated thru punched cards.
But importantly in the late 1960’s-

• Theory: Feynman was already at work interpreting the resonances and soft pions as indicating that hadrons are bound states of what he called partons, including (importantly) soft or “wee” (dE/E) partons. These partons were treated as “dynamical objects”, and not necessarily Gell-Mann’s quarks, which were “algebraic objects”.

• The (James) Bjorken (bj) scaling observed in electron-proton scattering at SLAC during this period suggested that the electrically charged partons are fermions and essentially free at short distances.

Deeply Inelastic electron-proton scattering:

\[ p^\nu = (m, \vec{0}), \quad k^\mu = (E, \vec{k}) = (E, 0, 0, k), \]
\[ k'^\mu = (E', \vec{k'}), \quad q^\mu = k'^\mu - k^\mu, \quad \left| q^2 \right| = Q^2, \quad \nu = \frac{p \cdot q}{m} = (E - E') \]
\[ x_{bj} \equiv \frac{Q^2}{2mv} = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2m(E - E')}, \quad y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E} \]
Details -

• Deeply Inelastic electron-proton scattering (DIS):

\[ p' = (m, 0), \ k'^\mu = (E, \tilde{k}) = (E, 0, 0, k), \]

\[ k'^\mu = (E', \tilde{k'}) = (E', k' \sin \theta, 0, k' \cos \theta), \]

\[ q^\mu = k^\mu - k'^\mu, \ |q^2| = Q^2, \nu = \frac{p \cdot q}{m} = (E - E') \]

\[ x_{bj} \equiv \frac{Q^2}{2 p \cdot q} = \frac{Q^2}{2 m \nu} = \frac{Q^2}{2 m (E - E')}, \ y = \frac{q \cdot p}{k \cdot p} = \frac{1 - E'}{E} \]

"Observed"  Spin-Flip  Spin-NonFlip

\[ \frac{Q^4}{s} \frac{d\sigma}{dx dy} = 4\pi \alpha^2 \left[ x y^2 F_1 \left( x, Q^2 \right) + (1 - y) F_2 \left( x, Q^2 \right) \right] \]

\[ \frac{Q \nu \rightarrow \infty}{x, y \text{ fixed}} \rightarrow 4\pi \alpha^2 \left[ x y^2 F_1 \left( x \right) + (1 - y) F_2 \left( x \right) \right] \text{[Scaling]} \]

Charged partons are pointlike (free?) fermions with nonzero probability to carry finite fraction, \( x_F = x_{bj} \) of proton’s momentum (at least approximately)
Seemed like Gell-Mann’s quarks? But ~ free??

- ASIDE: This stimulated an industry to look for “free” fractionally charged particles, for example, produced by cosmic rays and trapped in the shells of mollusks. A big player was George Zweig (of Aces, fame), also then at Caltech. No luck finding quarks, but George went on to very successfully study the physics of ears!

- Still, as already suggested by Feynman, such partons could be pair-wise produced in electron-positron annihilation and generate “jetty” final states, which were eventually observed experimentally.
So Parton Picture (~1970):

- Confining interactions soft (~ 100 MeV) and slow (time dilated in CM frame)

- Hard interactions rare but fast

- Partons are always confined in hadrons at long distance (compared to a fermi) but act nearly freely at short times/distances

- Describe hadrons in terms of (approximately scale invariant) parton distributions (pdf’s) describing the sharing of longitudinal momentum with limited transverse momentum – measured in DIS

- Outgoing isolated partons fragment into hadrons described by (approximately) collinear sharing of momentum – Fragmentation functions, jetty structure built in.

- No QFT basis!!
Early 1970’s

• THEORY: Idea of jets of hadrons from rare (large angle) scattered partons more clearly spelled out:
  Berman, Bjorken and Kogut (1971); Ellis and Kislinger (1974)
Still no real underlying theory or jet definitions!

• First proton collider – the ISR (Intersecting Storage Ring) at CERN, 23.5 < √s/GeV < 62.4. Detectors were repurposed single-arm versions from the fixed target world.

  Primarily observe: \( p + p \rightarrow \pi^0, \pm + X \) (inclusive pion production)

  Exciting early CCOR collaboration result (1973, reported but not published)

\[
S^2 \frac{d\sigma}{d^3 p/E|_{\pi^0 + X}} \approx F\left(\frac{2p_T}{\sqrt{s}} \equiv x_T\right) \quad [\text{Scaling again!}]
\]
Early 1970’s: ISR and the parton model

- Primarily observe: \( p + p \rightarrow \pi^{0,\pm} + X \) (inclusive pion production)

Exciting early CCOR collaboration result (1973)

\[
\frac{d\sigma}{dp_T^2} \sim \iint F(x_1) F(x_2) \frac{d\hat{\sigma}}{dp_T^2} \left( p_T, \frac{s}{p_T^2}, x_1, x_2, z \right) D(z) \\
\times \left\{ 1 + \mathcal{O} \left( \frac{m^2}{p_T^2} \right) \right\} \\
\Rightarrow \frac{d\sigma}{dp_T^2} \propto p_T^{-4} \left[ pp \rightarrow \pi^0 X \right]
\]

\[
\Rightarrow s^2 \frac{d\sigma}{d^3 p/E} \bigg|_{pp\rightarrow\pi^0 + X} \approx F \left( \frac{2p_T}{\sqrt{s}} \equiv x_T \right) \quad \text{[Scaling again!]} \\
\frac{s^{4.12} d\sigma}{d^3 p/E} \bigg|_{pp\rightarrow\pi^0 + X} \approx G(x_T) \quad \text{[non-Scaling!]} 
\]

Alas, correct for detector aging
Rest of 1970’s

• THEORY: QCD “discovered” – non-Abelian SU(3) theory found to have desired properties, Gross, Politzer and Wilczek: QCD running coupling $\alpha_s(\mu)$ [2004 Nobel Prize]

$$\mu \frac{d\alpha_s(\mu)}{d\mu} - \frac{\beta_0}{2\pi} \alpha_s(\mu) \Rightarrow \alpha_s(\mu) = \frac{2\pi}{\beta_0 \ln\left(\mu/\Lambda_{QCD}\right)}, \quad \beta_0 = 11 - \frac{2}{3} n_f, \quad \Lambda_{QCD} = \mu_0 e^{-2\pi/\alpha_s(\mu_0)} \quad \Lambda_{QCD} \approx 200 \text{ MeV}$$

$\mu \rightarrow 0$ Asymptotic Freedom

$\mu \rightarrow \Lambda_{QCD}$ Infrared Slavery

Immortalized in an early (2012) episode of the Big Bang Theory!

This is UV (short distance) behavior, QCD also has soft and collinear divergences in the infrared (massless quarks and gluons).

• Perturbative QCD was enthusiastically tested via the calculation of infrared safe “event shape” measures in $e^+e^-$ annihilation at PETRA at DESY (and then LEP at CERN) – Thrust, Jet Broadening, Energy-Energy Correlations.

While not using the exclusive jet definitions common today, the PETRA discussion did use the language of jets (or clusters), see e.g., Sterman and Weinberg, “Jets from QCD” (1977).
**1980’s**

THEORY: QCD improved parton model – same basic structure as original parton model but now “understood” asymptotic freedom (small short-distance coupling) and infrared slavery (confinement). Plus

- Partons are quarks AND gluons (vector bosons) → “confirmed” by “3-jet events” at PETRA (1979) - found in distributions of (total) event shapes (not jet algorithms).

- QCD is NOT scale invariant (bj scaling was only approximate), but coupling and pdf’s vary *slowly* with resolution (momentum) scale, as expected for an interacting theory where charges and momentum are shared – But this behavior is PREDICTABLE in QCD (the anomalous dimensions are calculable)! And agrees with data.

- The soft and collinear singularities in a theory with massless gluons can (must) be factored into the (measurable) pdf’s and fragmentation functions and make them run with resolution scale $\mu \sim Q$.

  But play no role for appropriately defined *Infrared Safe* quantities (insensitive to soft or collinear partons)!
1980’s EXPERIMENT: “Real” jet identifying algorithms appear for e^+e^- annihilation events in the form of “recombination” algorithms – think of recombining the showers from the originally produced quarks (and gluons). Start with a list of observed hadrons (or QCD partons), end with a list of jets. All hadrons are in a jet, since all come from the hard scattering! (Unlike pp events)

• JADE at PETRA (1986): Define a pairwise distance measure:

\[ y_{kl} \equiv 2(1 - \cos \theta_{kl}) \frac{E_k E_l}{E_{\text{vis}}^2} \frac{M_{kl}^2}{s} \quad \text{[ignoring particle masses]} \]

Identify pair with smallest \( y_{kl} \) and replace pair in list with cluster with \( p_{\text{cl}} = p_k + p_l \) yielding a new list.

Repeat until all \( y_{kl} > y_{\text{cut}} \) (the IR cutoff)

The remaining clusters in the list are then the jets.

• By 1990 it was recognized (at a meeting in Durham) that higher orders in the theory were better behaved for the Durham (also kT) algorithm with distance measure

\[ y_{kl}(k_T) = 2(1 - \cos \theta_{kl}) \frac{\min(E_k^2, E_l^2)}{E_{\text{vis}}^2} \quad \text{[cluster soft parton with closest other parton]} \]

The application to the lists is just as above.
1980’s into 1990’s

EXPERIMENT: pp collisions became important. The experiences at the SpbarpS at CERN in the mid 1980’s (with nearly 4π detectors) indicated that jets would be important also in hadron-hadron collisions. The jets at UA1 and UA2 were rudimentary (and detector dependent) but useful in finding the W and Z (but not SUSY – see the book “Nobel Dreams” by Taubes). However, the mindset was that jets represented a single parton; color conservation guarantees that cannot be true in detail.

- Learned pp collision (unlike ee) events are cylindrical (not spherical).
  Appropriate kinematic variables are $E, P_T, \phi$ (azimuth around beam) and rapidity $y = 0.5 \ln[(E+p_z)/(E-p_z)]$ or pseudorapidity $\eta = \ln[\cot(\theta/2)] \approx y$, instead of $\theta$.
  The appropriate angular separation variable is $\Delta R^2 = \Delta y^2 + \Delta \phi^2$ (instead of $\Delta \theta$).

- The partons not participating in the large angle scatter interact (softly) and generate a largely uncorrelated “underlying” event along with the jets. This underlying event is much like a typical minimum bias (low $p_T$) event (just at lower total energy) with a fairly uniform (in $\phi$ and $y$) distribution of soft hadrons (recall the “wee” partons).

- Learned to use LEGO plots – energy on the surface of the $(y,\phi)$ cylinder.
1980’s into 1990’s

• THEORY: QCD improved parton model -

QCD is a predictive (and testable) theory - a big change from the dark ages!
Jet cross section is a convolution

\[
\frac{d\sigma}{dp_T dy} = \sum_a \int dx_a F_{a/A}(x_a, \mu) \sum_b \int dx_b F_{b/B}(x_b, \mu) \frac{d\hat{\sigma}(x_a, x_b, \mu; p_T, y)}{dp_T dy}
\]

Measure, “run” with resolution scale \(\mu\)

Parton cross section:
Calculate in pQCD, depends on jet definition, sums over Fragmentation D

• But there remains an inherent ambiguity for QCD jets. They are initiated by a colored parton at short distance, but necessarily composed of colorless hadrons at large distances. So we know there is a soft interaction to conserve color, which is not uniquely defined, until given the details of the jet algorithm. There is no single, correct result!!
1980’s into 1990’s

• EXPERIMENT:
  An idealized UA1 style jet looked like – (but QM)

Since most of the particles in the event are not in the jets, felt the need for a different (non-recombination) style jet algorithm.

1990 – the Snowmass Accord – Iterative Cone Algorithm: Agreed to by Theorists and Experimenters to be used at the Tevatron (CDF and D0). Actually was not full – 4-vector definition until Run II. Worked OK for 10% agreement, but ….

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CONE center - \((y^C, \varphi^C)\)

\[ \Delta R^i \equiv \sqrt{(y^i - y^C)^2 + (\varphi^i - \varphi^C)^2} \leq R \]

CONE \(i \in C \) iff \( P_{\mu}^C = \sum_{i \in C} p_{\mu}^i \)

4-vector direction \( \bar{y}^C = 0.5 \ln \left[ \frac{p_0^C + p_z^C}{p_0^C - p_z^C} \right] ; \bar{\varphi}^C = \arctan \left[ \frac{P_y^C}{P_x^C} \right] \)

Jet = stable cone \( (\bar{y}^C, \bar{\varphi}^C) = (y^C, \varphi^C) \)

Find by iteration, \( i.e., \) put next trial cone at \( (\bar{y}^C, \bar{\varphi}^C) \)

Ellis, Kunszt and Soper, pQCD NLO, 1989-92
Coded in Fortran!!
Cone Issues arose as things became more detailed

1) Stable Cones can and do Overlap: need rules for merging and splitting, but NOT the same for D0 and CDF

2) Seeds – experiments only look for jets around active regions (save computer time, which was an issue then)

⇒ problem for theory, IR sensitive (Unsafe?) at NNLO

This is a BIG deal philosophically – but not a big deal numerically (in data)
⇒ Could use SEEDLESS version (SISCone) at the LHC

3) Splash-out from smearing of energetic parton at edge of cone – can be quantitatively relevant (the $R_{\text{sep}}$ thing)

4) Dark towers – secondary showers may not be clustered in any jet

By the mid-1990’s the Recombination Algorithm had been adapted to pp collisions: Ellis and Soper (1993), Catani, et al. (1993)
Recombination Algorithms – unlike ee focus on on large $p_T$, some particles not in a jet

Merge jet constituents pairwise based on “distance” defined by minimum value of $d_{ij}$, i.e. make list of metric values (rapidity $y$ and azimuth $\phi$, $p_T$ transverse to beam) [Inclusive Mode]

$$\text{Pair } ij : d_{ij} \equiv \text{Min} \left[ \left( p_{T,i} \right)^\alpha, \left( p_{T,j} \right)^\alpha \right] \frac{\sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}}{R} \equiv \text{Min} \left[ \left( p_{T,i} \right)^\alpha, \left( p_{T,j} \right)^\alpha \right] \frac{\Delta R_{ij}}{R},$$

$$\text{Single } i : d_i = \left( p_{T,i} \right)^\alpha \quad [\text{New}]$$

If $d_{ij}$ is the minimum, merge pair (add 4-vectors), replace pair with sum in list and redo list;

If $d_i$ is the minimum $\rightarrow i$ is a jet! (no more merging for $i$, it is isolated by $R$),

Continue until only “jets” left, ignore small $p_T$ jets (in the “beam” jet).

1 angular size parameter $R$, plus

$\alpha = 1$, ordinary $k_T$ (kT), recombine soft stuff first

$\alpha = 0$, Cambridge/Aachen (C/A), controlled by angles only

$\alpha = -1$, Anti-$k_T$ (AkT) just recombine stuff around hard guys – cone-like (with seeds), Salam, et al. (2008)
Recombination Algorithm – in action, here C/A algorithm on QCD jet

Think of starting with calorimeter cells, recombine “closest” pair at each step leading to larger $p_T$

For CA close in quantity

$$\Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

$(0.05 \times 0.05)$ Cells with $E > 1$ GeV
Note: the details of the substructure (at each step) depend on the algorithm (important for using substructure).
Recombination Lessons:

👍 Jet identification is unique – no merge/split stage as with cone

👍 “Everything (interesting) in a jet”, no Dark Towers (soft particles in “beam jet”)

👎 Resulting jets are more amorphous for $\alpha \geq 0$, energy calibration more difficult
(subtraction for Underlying Event + PileUp?)

👎 But for $\alpha < 0$, Anti-kT (Carriari, Salam & Soyez), jet area seems stable and
geometrically regular * - the “real” cone algorithm (but large pT jets take a bite out of
small pT one)

→ Use Anti-kT at the LHC!

But note, while the Anti-kT algorithm is useful for identifying jets, unlike kT and C/A it
does NOT usefully describe the jet substructure, i.e., it does not capture the physics of
the underlying QCD showering.
Jet Areas – from Salam & Cacciari, Salam & Soyez

Anti-kT very regular leading jets, But bites others

Amorphous edges

S/M effect
Jet Issues for the LHC (~2005):

- ATLAS and CMS to primarily use Anti-kT with various, but different(!) R values (As of summer 2016 there are results for one shared R value, R=0.4)

- Realized that familiar particles (W, Z, Top) can be boosted enough at the LHC that hadronic decays may be observed as single jet. Want to ID this jets! → TAGGERS

- Finding the Higgs – Are decays into photons and leptons enough? It turns out the answer is yes, but we looked for other ways, like tagged hadronic decays.

- Understood that all jet algorithms include “Uncorrelated” contributions from the underlying event, a situation that grows worse as the luminosity is increased.

- Recognized the need to deal with the underlying event (UE) contributions to jets and the also the worse problem of Pile-Up (PU) events at the eventual large luminosity – we needed GROOMERS

The era of Jet Substructure begins!
Review:

• JETS: The shower of QCD radiation emitted by colored particles produced (initially) in isolation in momentum space – the dominant feature of hadronic final states at colliders

• JETS: Defined in detail by the specific jet algorithm, i.e., QCD jets have LITTLE INTRINSIC substructure – “everything is a smooth distribution”; plus for QCD jets there is an essential ambiguity – partons are colored while jets are not

• At the LHC “formerly” heavy objects can be boosted sufficiently to be detected as single jets with INTRINSIC substructure, which drove the development of new jet tools

• Jet Substructure Tools:
  GROOMERS – remove “UN-associated” hadrons from jet (including Underlying event and Pile-Up)

  TAGGERS – ID the “primary source” of jet, Q vs G, W, Z, H, top, sparticles (?)

• But details tied to specific jet algorithm – relax that connection ⇒ Qjets
History: Early Jet Substructure

- In the Cone Jet days (1992) Ellis, Kunszt and Soper looked at the distribution of energy within the cone ($r < R$) at NLO (2 partons in the jet).

- The predicted distribution had more energy near the edge of the cone than the data, illustrating the merge/split issues already mentioned. “Fixed” at the time with a new (and unwanted) parameter $R_{\text{sep}}$ (don’t include 2 partons further than $R_{\text{sep}}$ apart). Consider fraction $F$ of jet $E_T$ inside $r$. Too much energy near $R$ without $R_{\text{sep}}$ fix.

- In 1997 Seymour wrote a prescient paper suggesting the usefulness of studying the internal structure of jets.
QCD Jets - What was once a signal is now a Bkg!

- Apply algorithm to elements in the detector (tracks, calorimeter cells) and obtain jets as list of such constituents (just partons for the theory case)

- Kinematic details shaped by details of the algorithm

- Mass \( m_{jet}^2 = p_{jet,\mu}^T p_{jet,\mu}, \quad p_{jet}^T = \sum_{\text{jet constituents } k} p_k^T \)

  Irony: jets around for \(~45\) years, but jet masses only looked at seriously for last 7 years, since BOOST 2009 – see BOOST proceedings for detailed explanations

- Groomed Mass, as above after grooming (removing some constituents)

- Simple related tagger – cut on groomed mass, e.g., jets in mass bin around \( M_W \)

- Here focus on example of pruning and pruned mass
Jet Masses in NLO QCD: A Brief Review

- In NLO PertThy (EKS)

\[ \sqrt{p_{J,\mu} p_{J}^\mu} \Rightarrow \sqrt{\langle M^2 \rangle_{NLO}} = f \left( \frac{p_J}{\sqrt{s}} \right) \sqrt{\alpha_s} \left( \frac{p_J}{p_T} \right) p_J R \]

Phasespace from PDFs, 
\( f \sim 1 \) and const

Jet Size, \( R \sim \Delta \theta \), determined by jet algorithm

- Peaked at low mass due to soft, collinear emission (log(m)/m behavior)

- "Shoulder" where mass arises from hard, large angle emission

- Cuts off for \((M/P)^2 > 0.25 \sim R^2/4\)
  \((M/P > 0.5)\) large mass can’t fit in fixed size jet, QCD suppressed for \(M/P > 0.3 \sim \gamma < 3\)

Useful QCD "Rule-of-Thumb"

\[ \Rightarrow \sqrt{\langle M^2 \rangle_{NLO}} \sim 0.2 \ p_J \ R \ (1 \pm 0.25) \]
More realistic add shower to all orders  (radiation from colored partons)

• Probability of no extra emissions and zero mass goes to zero
  \((\text{Sudakov} \sim \exp[-(\alpha_s/2\pi)C_{A/F} \ln^2(m^2/pT^2)])\).

• Low mass peak moves away from origin.

• Shoulder region only slightly changed.

• Low mass peak order \(\sim 1\), shoulder order \(\alpha_s\) (factor \(\sim 1/10\))
  – can use log on y-axis to resolve both.
Jet Mass in PYTHIA (showered & matched set)
R = 1, 500 GeV/c < pT < 700 GeV/c

Algorithm matters

Turns over, goes to zero at 0
At least qualitatively the expected shape – masses slightly larger than MC – need the true hard emissions (as in matched sets)

Large mass tail grows, as expected, with jet size parameter in the algorithm - You find what you look for!
Sample Groomers – (figures from ATLAS 1306.4945)

Pruning

\[ \frac{p_T^{j_1}}{p_T^{j_2}} > \frac{z_{cut}}{\Delta R_{j_1,j_2} < R_{cut}} \]

Based on properties at \(2 \rightarrow 1\) mergings

Trimming

\[ k_r R = R_{sub} \]

Based on properties of subjets

Mass Drop, Filtering

Also Modified Mass Drop (mMDT)

\[ \frac{m_{j_1}}{m_{j_2}} < \mu_{cut} \text{ and } y > y_{cut} \]

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The Idea of a groomer at work (idealized, early animation)
Sample Taggers -

- Simplest – Groom and cut on mass

- More elaborate – HEP TopTagger

look for specific number of subjets
A Brief Review of Pruning (Ellis, Vermilion and Walsh, 2009)

• Like other groomers, given a jet (identified by some generic jet algorithm like AkT, kT or C/A) pruning attempts to remove from the jets those constituents that are unlikely to be "associated" with the jet or at least carry no significant/useful information.

• In particular, we expect the mass of the resulting pruned jet to be small if we start with an every-day QCD jet, and near the particle mass if we start with a jet containing the decay products of a heavy particle. Thus can use in a TAGGER.

• Pruning will can remove much of the uncorrelated contributions from UE and PU that make significant contributions to the jet mass.
Basic Idea of Pruning -

• Prune (remove) those constituents of the original jet that are:
  soft
  large angle

• These soft, large angle constituents are (statistically) less likely to be correlated with the energetic constituents in the jet and yet can still make measurable contributions to the mass

• Soft, small angle constituents can also be uncorrelated (UE, PU), but make a small contribution to the mass

• Most configurations that arise from actual heavy particle decay will not tend to be pruned (not all, but most).
Pruning in Action -

• Given the list of constituents in a jet, remerge using the kT or C/A algorithm

• At each potential merging step, \( j+k \rightarrow l \), check for soft - \( p_k/p_l < z_{\text{cut}} \) (\( p_k < p_j \))

  large angle - \( \Delta R_{jk} > R_{\text{cut}} \cdot (2m_{\text{jet}}/p_{\text{jet}}) \), where \( 2m_{\text{jet}}/p_{\text{jet}} \) is angular scale set by jet itself

• If both cuts are satisfied, prune (remove) constituent \( k \) and proceed

• Larger \( z_{\text{cut}} \) and smaller \( R_{\text{cut}} \) values correspond to more aggressive pruning

• The level of pruning tends to be determined by the LESS aggressive of the two parameters (since we must satisfy both cuts)
Default Parameters

• The original studies (0912.0033) suggested

\[ R_{\text{cut}} = 0.5 \ (kT \ & \ C/A) \Rightarrow \Delta R > m_{\text{jet}}/p_{\text{jet}} \]

\[ z_{\text{cut}} = 0.1 \ (C/A) \]

\[ z_{\text{cut}} = 0.15 \ (kT, \ since \ nearby \ soft \ constituents \ are \ merged \ early \ and \ are \ no \ longer \ as \ soft) \]

• Also, to ensure that decay products of “signal” particle “fit” in jet (size \( R \)) and are rarely pruned,

require \( m_{\text{particle}}/p_{\text{jet}}/R \) be less than 0.5
Groomed (Pruned) Fixed Order (NLO) Result (dashed):
Pruning removes, soft, wide angle constituents

Prune “small” masses to zero mass (soft, wide angle emission is pruned), only one parton remains in jet

“Large” mass shoulder unchanged (hard, symmetric splitting is not pruned)
Pruning in Action

Pruning of a QCD jet near the top mass with the CA algorithm

Red is higher $p_T$
Blue is lower $p_T$
Green X is a pruning

Start with cells with energy $> 1$ GeV

$p_T$: $600 \to 590$ GeV
mass: $170 \to 160$ GeV
Pruning in Action

Pruning of a QCD jet near the top mass with the CA algorithm

Red is higher $p_T$
Blue is lower $p_T$
Green X is a pruning

Start with cells with energy $> 1$ GeV

$p_T$: $600 \rightarrow 550$ GeV
mass: $180 \rightarrow 30$ GeV

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Impact of Pruning on Simulated data—qualitatively just what we want!

⇒ The mass resolution of pruned top jets is narrower ⇒ Pruned QCD jets have lower mass, sometimes much lower

500 < \( p_T \) < 700 GeV

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Underlying Event Rejection with Pruning

The mass resolution of *pruned* jets is (essentially) unchanged with or without the underlying event.

**top study**

- **CA**
- **$k_T$**

$500 < p_T < 700$ GeV

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Underlying Event Rejection with Pruning

The jet mass distribution for QCD jets is significantly suppressed for pruned jets (essentially) independent of the underlying event.

QCD study

- no pruning
- pruning

500 < \( p_T \) < 700 GeV

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Pruning at CMS, e.g., 1303.4811

- Prune with C/A using parameters
  \( z_{\text{cut}} = 0.1 \) (default)
  \( R_{\text{cut}} = 0.25, \Delta R > 0.5 \ m_{\text{jet}}/p_{\text{jet}} \) (aggressive)

- Conclude that Pruning is most aggressive groomer studied -
Pruning at ATLAS – Comments/Explanations (a cautionary tale)

A dramatic contrast (to my thoroughly biased eye) between the CMS and ATLAS jet grooming/tagging analyses as reported at BOOST 2013 and the Boosted Boson Workshop (CERN, 3/25/14) –

⇒ CMS analyses finds jet pruning is **very** effective
⇒ ATLAS finds pruning is **not** very effective!

😁😁😁😁 at UW!!!!!

The following comments attempt to explain this difference between the two collaborations.

Pruning Refs: 0912.0033, 0903.5081
Compare - Pruning at ATLAS – 1306.4945

• Prune with kT using parameters

\[ z_{\text{cut}} = 0.1, 0.05 \text{ (less aggressive than default = 0.15)} \]

\[ R_{\text{cut}} = 0.1, 0.2, 0.3, \Delta R > R_{\text{cut}} \left( \frac{2m_{\text{jet}}}{p_{\text{jet}}} \right) \text{ (more aggressive than default)} \]

• Conclude pruning is NOT very effective groomer – AS EXPECTED due to parameter choices

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Comments:

• Pruning is observed to be performant at ATLAS when appropriate parameter values are chosen, i.e., consistent with CMS

• Analysis of lowest pT bin needs to be clarified (boost too small for small R?)

• ATLAS study had kinematic variable correlation information, but was difficult to interpret due to multiple “knobs” being turned at once (e.g., vary algorithm AND R values)

• Experimental folks should talk to their Theory friends often!!
Qjets & Volatility ($\Gamma$) (Ellis, Hornig, Krohn, Roy and Schwartz, 2012)

- Qjet idea is that there is no “correct” algorithm for pruning (or grooming in general);
- So prune several times with a defined but “random” set of algorithms;
- Generates a mass DISTRIBUTION for each jet;
- The width of this distribution is the volatility $\Gamma$;
- A jet containing a real decay will exhibit small volatility, while QCD jets exhibit larger volatility;
Volatility – a sophisticated Qjet variable

For jet sample make plot of Volatility values (distribution)

As expected Volatility distribution is BROADER for QCD than boosted W

\[ \Gamma \equiv \sqrt{\left\langle m_j^2 \right\rangle - \left\langle m_j \right\rangle^2} / \left\langle m_j \right\rangle \]

From ATLAS-CONF-2013-087

(a) Truth Jets
(b) Reconstructed Jets

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Qjets details (from ATLAS-CONF-2013-87)

1. Start with a jet found by any jet algorithm and collect the constituents into a list.

2. Compute a set of weights $\omega_{ij}$, which reflect how likely a pair of four-vectors is to be merged, for all pairs of four-vectors. Here, the weights are chosen to be defined as:

   \[ \omega_{ij}^{(\alpha)} = \exp \left\{ -\alpha \frac{d_{ij} - d_{\min}}{d_{\min}} \right\} \]  

   where $\alpha$ is the *rigidity* which controls the sensitivity of the pair selection to the random number generation, $d_{ij} \equiv \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta \phi_{ij}^2$ the distance measure for the $(i, j)$ pair and $d_{\min}$ the minimum of the distance between all pairs. Then the probability $\Omega_{ij} = \omega_{ij}/N$ is defined, where $N = \sum \omega_{ij}$.

3. Instead of finding the single minimum $d_{ij}$ as in Equation 1, generate a random number, using Equation 3 as a probability density function, and choose a pair of four-vectors as above according to the probabilities $\Omega_{ij}$.

4. Consider this pair for merging, and veto (as in normal pruning) if they fail the cuts in Equation 2.

5. Continue until all pairs are merged: the result is one Q-jet. The algorithm can be repeated multiple times to generate a distribution of Q-jets for every jet.

\[ d_{ij} = \min \left( \frac{\Delta R_{ij}^2}{R^2} \right) \] 

\[ d_{iB} = p_{Ti}^2 \]

\[ z_{ij} = \frac{\min(p_{T,i}, p_{T,j})}{|p_{T,i} + p_{T,j}|} < z_{\text{cut}} \text{ and } \Delta R_{ij} > d_{\text{cut}}. \]
Cut on $\Gamma$ as tagger – from same ATLAS analysis (“ROC” curves)

Good basic Tagger! Even with just 25 iterations per jet

From ATLAS-CONF-2013-087
Conclusions (2017):

• Jets are an ubiquitous and extremely useful feature of the final states in high energy hadronic collisions.

• QCD and modern calculational techniques allow us to understand, with good precision, the production rates of jets as defined by modern jet algorithms and their substructure.

• Progress in the last 10 years, both theoretical and experimental, provide us with techniques to TAG jets resulting from the production of heavy particles (vs those from light partons).

• Likewise we have techniques to GROOM and to control the impact of uncorrelated contributions from Pile Up.

• JETS ARE GREAT!!

    Learn how to use them!