The (Recent) History of Boosted Physics Workshops

Steve Ellis

Big Picture:

The LHC is intended to find new “stuff” (BSM physics)

At the LHC new and old heavy particles will often be boosted → 1 jet

It will be a challenge to find the new stuff!

☞ Experimenters and Theorists will need to work together!!!
E.g., this week!

Borrowed results from many sources – thanks!

Department of Physics
University of Washington

Oxford University 22.06.10

University of Oxford

Precursor - Boost 2009:

BOOST 2009

GIVING NEW PHYSICS A BOOST

SLAC NATIONAL ACCELERATOR LABORATORY

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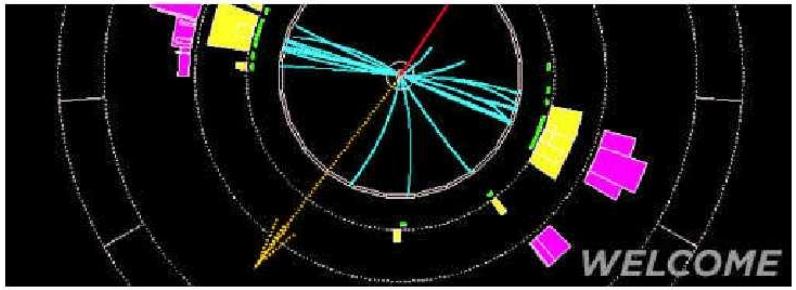


Giving New Physics a Boost

Thursday and Friday, July 9-10, 2009 from 8:00 am to 5:00 pm.
Kavli Auditorium
SLAC National Accelerator Laboratory
Menlo Park, California

Many signatures of new physics that could be discovered at the Tevatron or LHC involve highly boosted objects, which can confuse standard event reconstruction techniques due to the overlapping nature of their decay products in the detector. SLAC is hosting a two-day workshop to bring together the leading theorists and experimentalists in order to better understand the physics behind these novel signatures and how to detect them. The list of topics includes "lepton jets", boosted top jets ("t-tagging"), boosted Higgs ("fat-bottom") jets, di-tau jets, displaced-vertex jets, and light-gluino jets. We look forward to presentations and lively discussions.

REGISTRATION

This meeting is free to registered participants. Registration is necessary to participate in the workshop.

» Register

ACCOMMODATIONS

Please reserve your room early at Stanford Guest House.

» More Information

SLAC National Accelerator Laboratory, Menlo Park, CA
Operated by Stanford University for the U.S. Dept. of Energy

http://www-conf.slac.stanford.edu/Boost2009/default.asp

As in 2010, there were 2 Primary Topics & Working Groups in 2009 -

Boosted Hadronic Final States

- *Jet Algorithms*
- *Subjet observables*
- *Discrimination from ordinary jets*
- *Comparison between Theory & Data*

Boosted Leptonic Final States

- *Classification of Models & Signals*
- *State of MC Generators*

Working Groups: Physics topics

Hadronic Final States

- *Boosted tops (test case and new physics tag)*
- *Boosted Higgs (search target)*
- *RPV Susy (search target)*

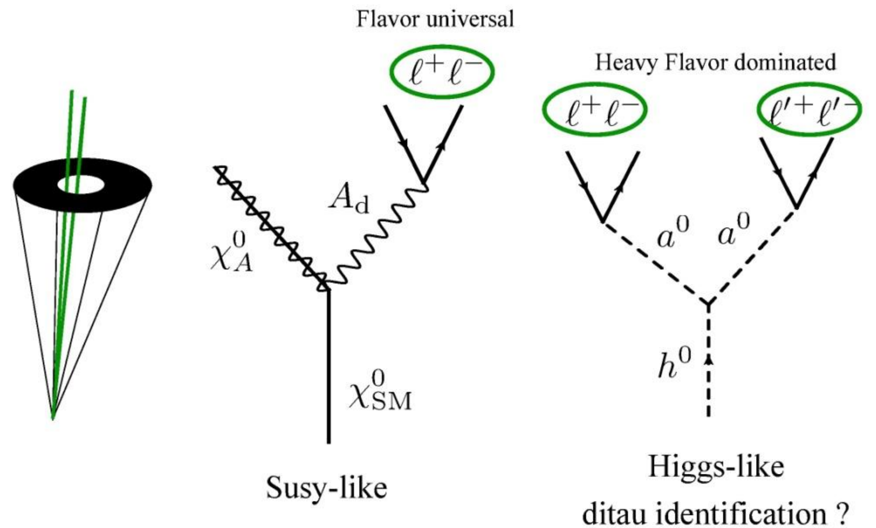
Leptonic Final States

- *Lepton jets*
- *Light vectors/PGBs*

Report from Lepton Jets -

Summary:

- Still making operative definitions of lepton Jets
- New signals + tools appearing
- Important searches to be done at Tevatron
- Early searches possible at LHC
- B-Physics & Fixed Targets Experiments



Report from Hadron Jets -

Short term plan Forward:

- Compare various jet tagging/grooming strategies on a set of interesting processes (assigned HW):
  - Z + Higgs (120 GeV), Z pairs, Z + jet
  - Jet pairs, top pairs
  - Common set of generator choices (or even better, event samples).
- Try to understand what each strategy does at each step, comparing as
  - possible between different strategies.
  - Results binned (somewhat widely) in pT
  - Study jet mass reconstruction and other interesting variables.

(Still needs to be done systematically – but there is progress, see talks this week)

Hadronic Jets II - Questions

- Can we get early and clean samples (from LHC) to use to calibrate our simulations? (boosted top σ ~ fraction of a pb at 7 TeV, tuff now, but will happen)

- Can we calibrate using tops without fitting away the new physics?

- Can we develop a more general toolkit for dealing with jet substructure that is less tuned to look for W/Z/Higgs-like topologies (two body decays) or top-like topologies (two two body decays)?

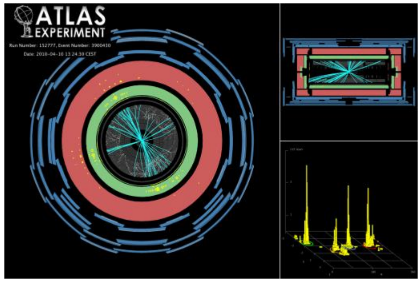
- Does a “jet mass” trigger make sense (perhaps for an upgrade) and would we gain anything by including one?

Seattle Workshop on Jet Substructure – Boost 2009.5

WiKi at (may be useful this week)

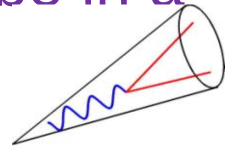
http://librarian.phys.washington.edu/lhc-jets/index.php/Main_Page

Background for Workshop:



- Hadronic "stuff" is be organized into jets

- At 14 (7) TeV many interesting particles (t, W, Z, Higgs, Susy, ..) will be boosted enough to be in a single jet



☞ Want to reconstruct objects from multiple jets (as at Tevatron), but also

☞ Want to use single jets in SEARCH for BSM physics

☞ Want to distinguish jets with decays from QCD jets

☞ Want to use jet substructure for this purpose

See the following Review talks by Gustaaf, Jay and Gavin

Goals for Discussion in Seattle –

– Experimental challenges for jet substructure

– Comparison of jet substructure techniques

– Development of software tools

– Development of theoretical tools (QCD & SCET)

Working Groups in Seattle –

1) Develop, compare and (learn how to) certify jet substructure tools
(Brock provided some sample data sets http://tev4.phys.washington.edu/TeraScale/)

- **Tagging specific states, e.g., top quarks, Higgs**

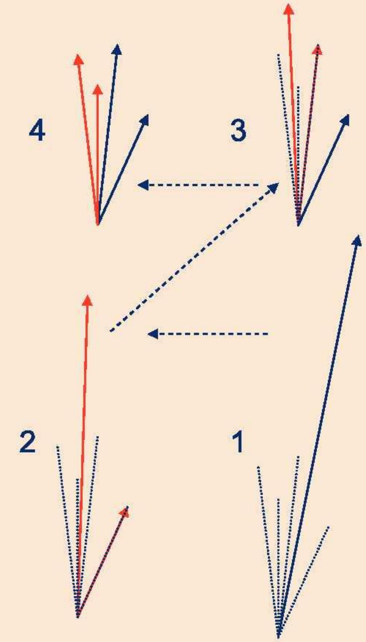
- **Generic grooming of jets for searches, e.g., pruning, trimming**

2) Utilize and compare SCET and standard QCD theory tools and results

Here review a few highlights -

Top Tagging : Kaplan et al

- Cluster jets with C-A
  - R : Function of sum pT of event
- Reverse cluster sequence
  - Throw out soft clusters
    - Fraction of hard jet pt < δp
- Repeat on clusters until one of:
  - Both subjets are harder than δp (PASS)
  - Both subjets are softer than δp (FAIL)
  - Subjets are too close (FAIL)
    - $|\delta\eta| + |\delta\varphi| < \delta r$
  - There is only one cell left (FAIL)
- Apply cuts:
  - Total mass consistent with m_{top}
  - 2 subjets consistent with m_W
  - W helicity consistent with top decay



U of Washington Jet Workshop

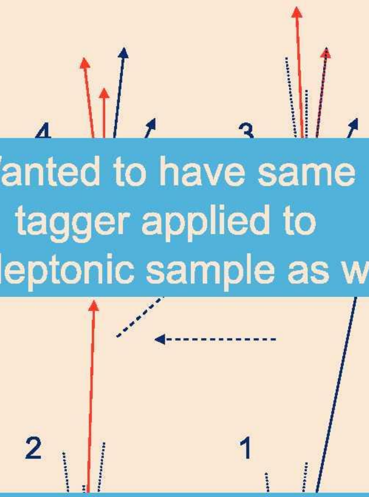
Sal Rappoccio

Top-tagger designed to identify hard subjets in CA jet substructure, identify tops from these subjets

CMS study on top-tagging (from Johns Hopkins group) highlights substructure issues - and successes in implementing jet substructure techniques

Top Tagging : CMS

- Cluster jets with C-A
  - R : ~~Function of sum pT of event~~
- Reverse cluster sequence
  - Throw out soft clusters
    - Fraction of hard jet pt < δp
- Repeat on clusters until one of:
  - Both subjets are harder than δp (PASS)
  - Both subjets are softer than δp (FAIL)
  - ~~Subjets are too close (FAIL)~~
    - ~~$|\delta\eta| + |\delta\varphi| < \delta r$~~
  - There is only one cell left (FAIL)
- Apply cuts:
  - Total mass consistent with m_{top}
  - ~~2 subjets consistent with m_W~~
  - ~~W helicity consistent with top decay~~
  - Minimum mass pairing of subjets consis with W



Wanted to have same tagger applied to semileptonic sample as well

Found di-subjet min mass pairing more experimentally accessible (consulting with Brock)

Sal Rappoccio

U of Washington Jet Workshop

Procedure augmented by CMS for use - but key elements still retained

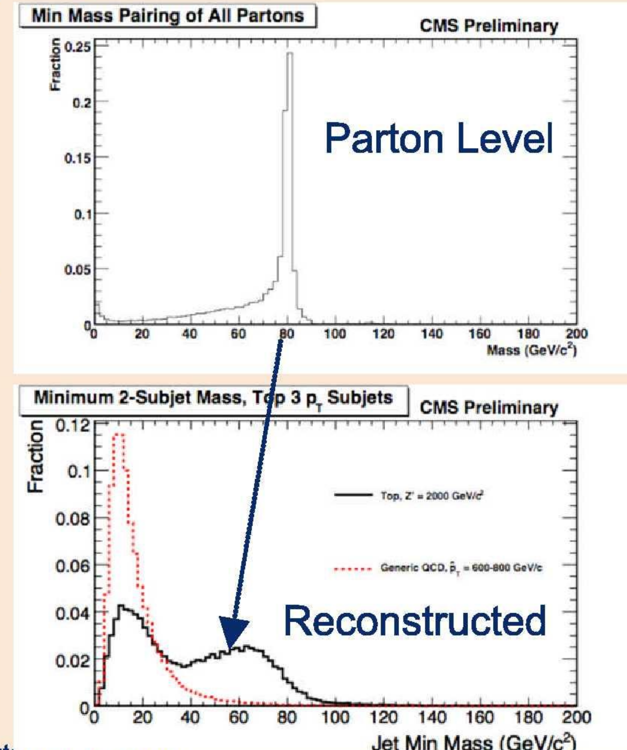
Expect to happen for all substructure methods - important to communicate between theory and experiment!

CMS study on top-tagging (from Johns Hopkins group) highlights substructure issues - and successes in implementing jet substructure techniques

Top Tagging : CMS

- Discriminate **top jets** against **non-top jets**
  - Top mass
  - **W mass ~ min di-subjet mass**

bq → j1+j2
bq' → j1+j3
qq' → j1+j3



Sal Rappoccio

U of Washington Jet Workshop

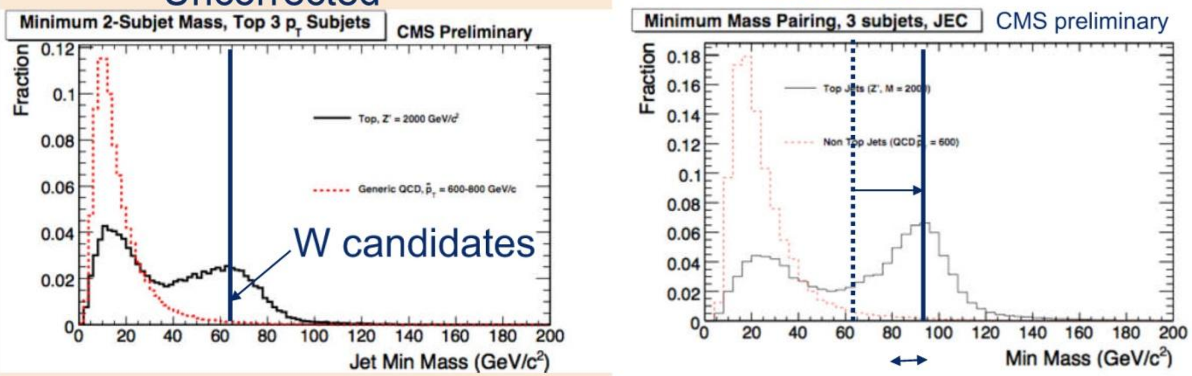
Top reconstruction efficiency does not suffer from decreased resolution! - cuts and background rejection changes, but tag rate robust

Parton level kinematics very different from detector level - worry that correlations in the substructure can be lost

Experimental Challenges for Subjets

How can we calibrate subjets?

Uncorrected Corrected



Significant over-correction

Sal Rappoccio

U of Washington Jet Workshop

Can calibration through standard candle channels work? e.g., EW+jet; can also add in heavy flavor tags to jets

Hear more this week!

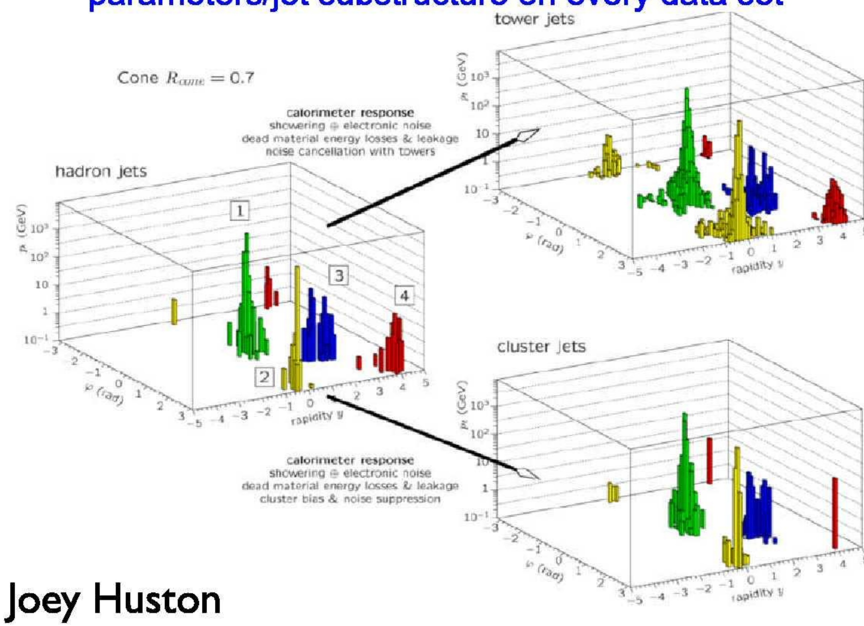
Jet energy scale correction does not apply to subjets - e.g., soft physics has been removed, smaller area

Possible that improved theory calculations can help here?

ATLAS jet reconstruction (These are not your Daddy's jets)

- Using calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/ parameters/jet substructure on every data set

Hear more this week!



blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level

rather than jet itself being corrected

similar to running at hadron level in Monte Carlos

Joey Huston

These "dynamic" techniques with calibrated topo-clusters could be tested with calibrated jets at known energies - Z decays or γ+jet

Joey Huston emphasizes that using topo-clusters can offer a local calibration to study different algorithms and substructure methods on data sets

Issues surrounding UE and pile-up effects on jets

Both UE and pile-up will affect the jet finding, reconstruction, calibration and hence **jet substructure analyses**, the extent to which we can only begin to asses. Here are several of the issues we will talk about today:

- **Jet energy scale (JES) and mass distortions**
  - UE will augment (raise) the parton-level JES
  - Pile-up will augment (raise) the particle-level JES
  - Detector signal shaping for pile-up in ATLAS can also reduce the JES
- **Angular smearing**
  - Angular resolution is degraded by the presence of additional soft radiation
  - Uncorrelated pile-up affects also particle-level pointing resolution
  - "Back-reaction" occurs when this smearing is sever enough to add or subtract particles that otherwise would not have contributed
- **Diffuse and point-like contributions**
  - Diffuse background radiation will also flatten structure like planar flow
  - Point-like component of min. bias (MB) will hinder the diffuse approximation
- **Spurious jets**
  - Pure MB jets will affect jet multiplicity and isolation criteria
  - Close-by jets will increase, limiting JES precision even for sub-jets

David Miller

What we think we know about pile-up and substructure

...and what we'd like to know

So far...

- Pile-up will be an issue for substructure analyses, but will it be dominant?
- At the luminosities for $H \rightarrow bb$: **yes**. Next year? No, but there will be enough to start testing tools
- Tracks provide a huge tool-box for finding, augmenting, and improving calorimeter jets, even without the need for 1-1 track-particle correlations

For the future

Can pruning help? More this week?

- Demonstrate–in data–the correlations and efficacy of track-based corrections
- Measure the level of correlation between pruning scales (z_{cut}, D_{cut}) and track based quantities
- Evaluate the scale(s) at which pile-up induces relevant sub-structures. Are they reducible?
- Can we use tracks to identify which jets and then prune?
- Can we use *JVF* to tune z_{cut}?

Comparing Pruning and Trimming

- Both techniques democratic regarding channel
- Comparison gives insight into how algorithms really operate on jet substructure
  - Both methods based on well motivated theory principles - but their action on real jets is complex
  - Identifying benefits and deficits can lead to better understanding of jet substructure
  - Experimentally implemented jet substructure tools likely to be some mix of techniques, adapted to the detector and analysis
- FastJet plugins exist - easy to construct comparative analyses
  - Driven improvements in analysis tools

Trimming

Krohn, Thaler, Wang
hep-ph/0912.1342

- Run a jet algorithm (kT) on a found jet, with angular scale R_{sub} smaller than the R value used for the initial jet
- Discard all subjets with $pT < f_{cut} \Lambda_{hard}$
    - f_{cut} is a dimensionless parameter, Λ_{hard} a hard scale
- The remaining subjets form the new (trimmed) jet
- Filtering: same procedure as trimming, but keep the N hardest subjets (instead of a pT cut on subjets)

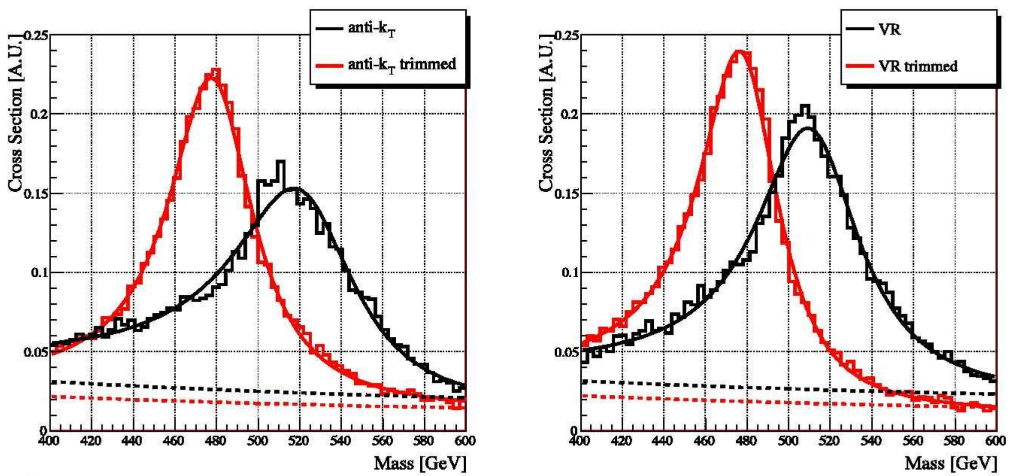
Trimming designed for use on QCD jets
e.g., heavy particle decay (with low boost) to 2 jets

Trimming

	Improvement	$f_{\rm cut}$, $N_{\rm cut}$	$R_{\rm sub}$	R_0, ρ	Γ [GeV]	M [GeV]
anti-k_T	-	-	-	1.0*	71	522
anti-k_T (N)	40%	5*	0.2*	1.5*	62	499
anti-k_T (f, p_T)	59%	$3\times10^{-2*}$	0.2	1.5	52	475
anti-k_T (f, H)	61%	$1\times10^{-2*}$	0.2	1.5	50	478
VR	30%	-	-	200* GeV	62	511
VR (N)	53%	5	0.2	275* GeV	53	498
VR (f, p_T)	68%	3×10^{-2}	0.2	300* GeV	49	475
VR (f, H)	73%	1×10^{-2}	0.2	300* GeV	47	478
Filtering	27%	2	$R_0/2$	1.3*	61	515

$$S(m) = \alpha\left[\frac{1+\beta(m-M)}{(m^2-M^2)^2+\Gamma^2M^2}\right],$$
$$B(m) = \delta + \gamma/m,$$

$$\Delta \equiv S(M) = \frac{\alpha}{\Gamma^2M^2},$$

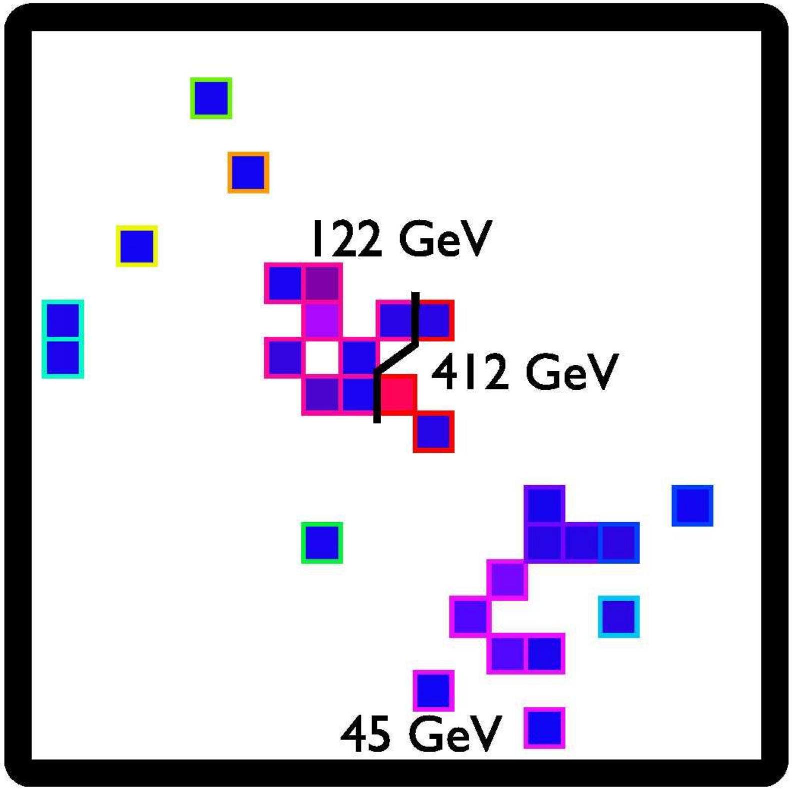


Trimming paper

Color octet scalar
$\phi\rightarrow gg$: 2j final state

Trimming yields improvements in pulling S from B

Trimming Example: QCD Jet



0.1x0.1 cells (y, ϕ)

Trimming designed to remove soft, isolated subjets through "pre-clustering"

11 subjets found
3 remain after pT cut:
$p_{T\,subjet} > 0.03\, p_{T\,jet} = 18$ GeV

pT of subjets removed:
7, 6, 4, 4, 1, 1, 1, 1 GeV

Pruning

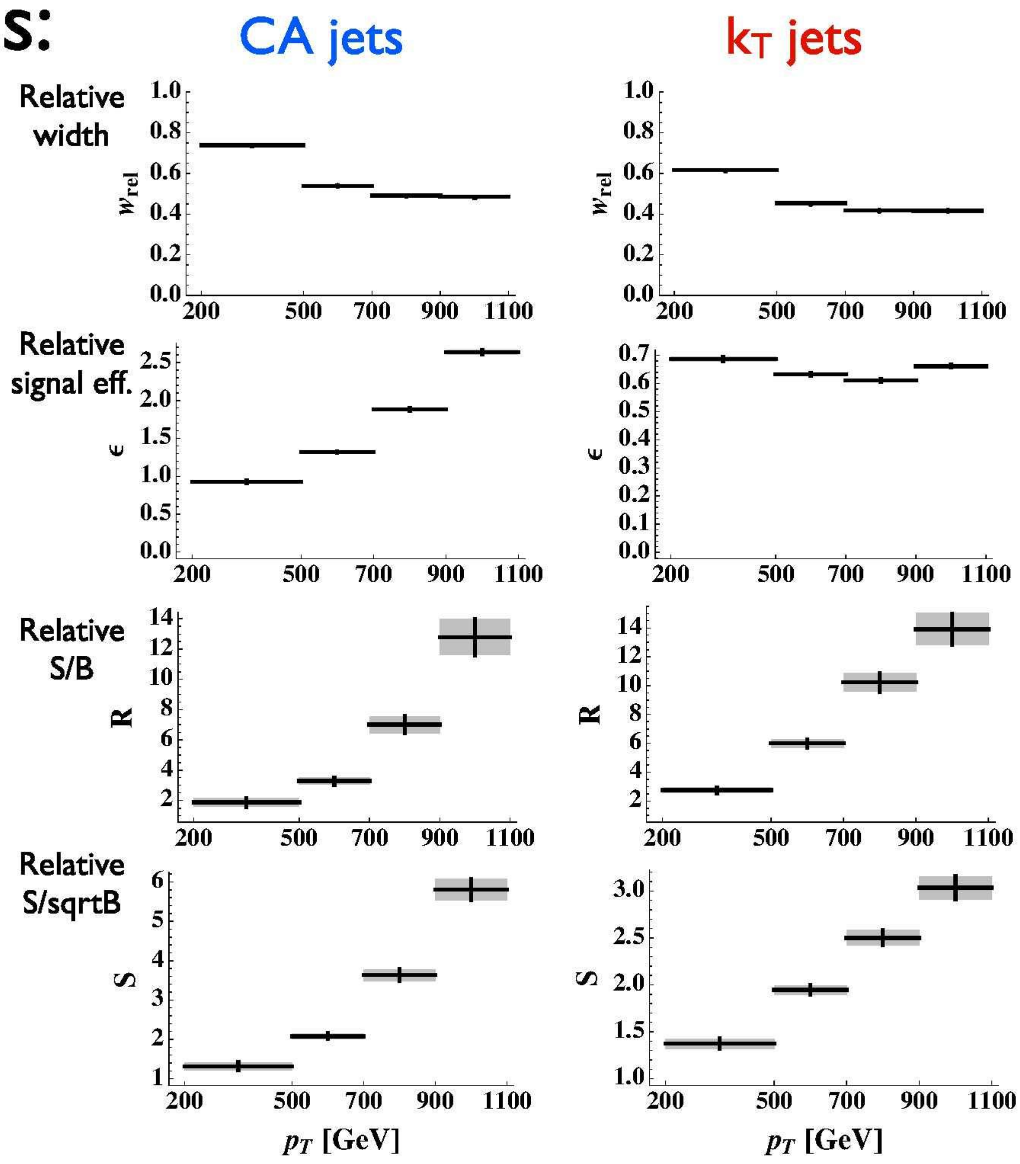
Ellis, Vermilion, JW
hep-ph/0903.5081
hep-ph/0912.0033

- Run CA or kT algorithm on the found jet, and at each recombination test if:
    - $z < z_{cut}$ and $\Delta R > D_{cut}$
        - $z_{cut} = 0.10$ for CA, 0.15 for kT; $D_{cut} = m_J/pT_J$
- If so, veto on the recombination - discard the lower pT daughter and continue
- The resulting jet is the new (pruned) jet

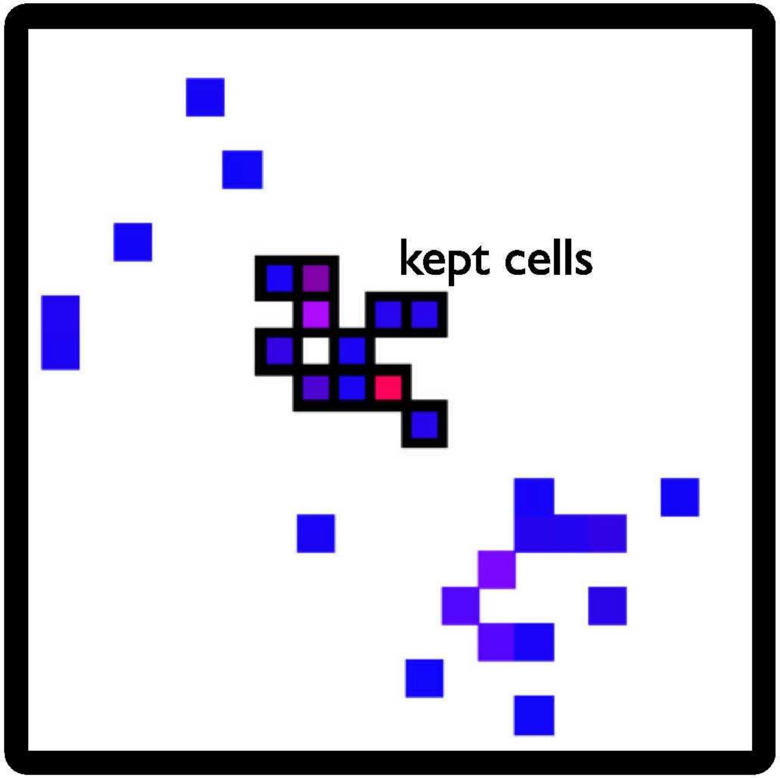
Pruning designed to identify jets from boosted heavy particles
i.e., heavy particle decay (with large boost) to 1 jet

Pruning on tops:

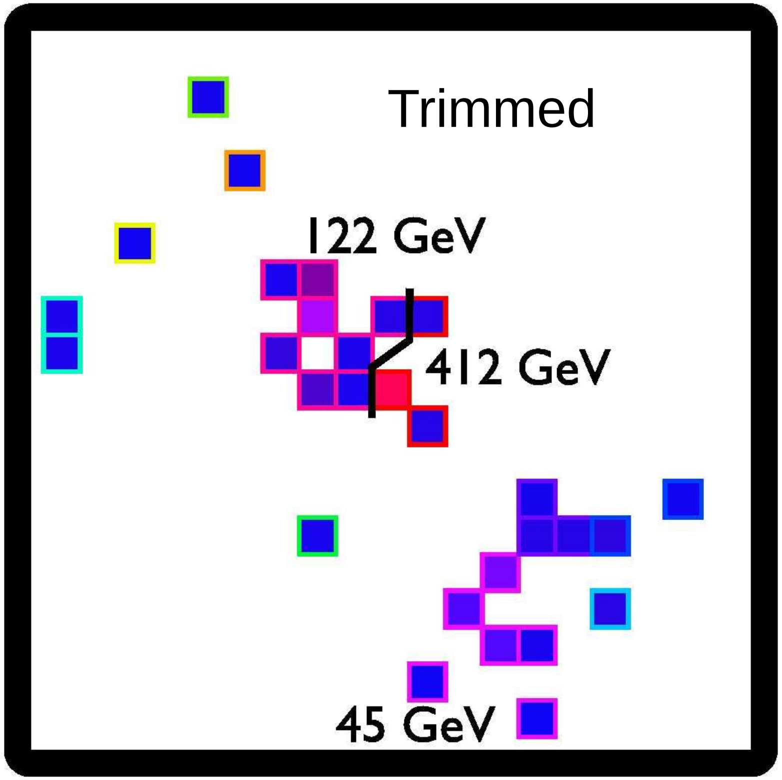
- Plot relative width, efficiency, S/B, S/sqrt(B) using a constant D = 1.0
- Variables are relative: improvements for pruning over not pruning
- Relative width is the improvement in mass resolution - at high p_T, pruned top mass width is 40% of unpruned
- Pruning shows consistent improvements, dramatically increasing at high p_T
- Statistical error bars shown



Pruning Example: QCD Jet

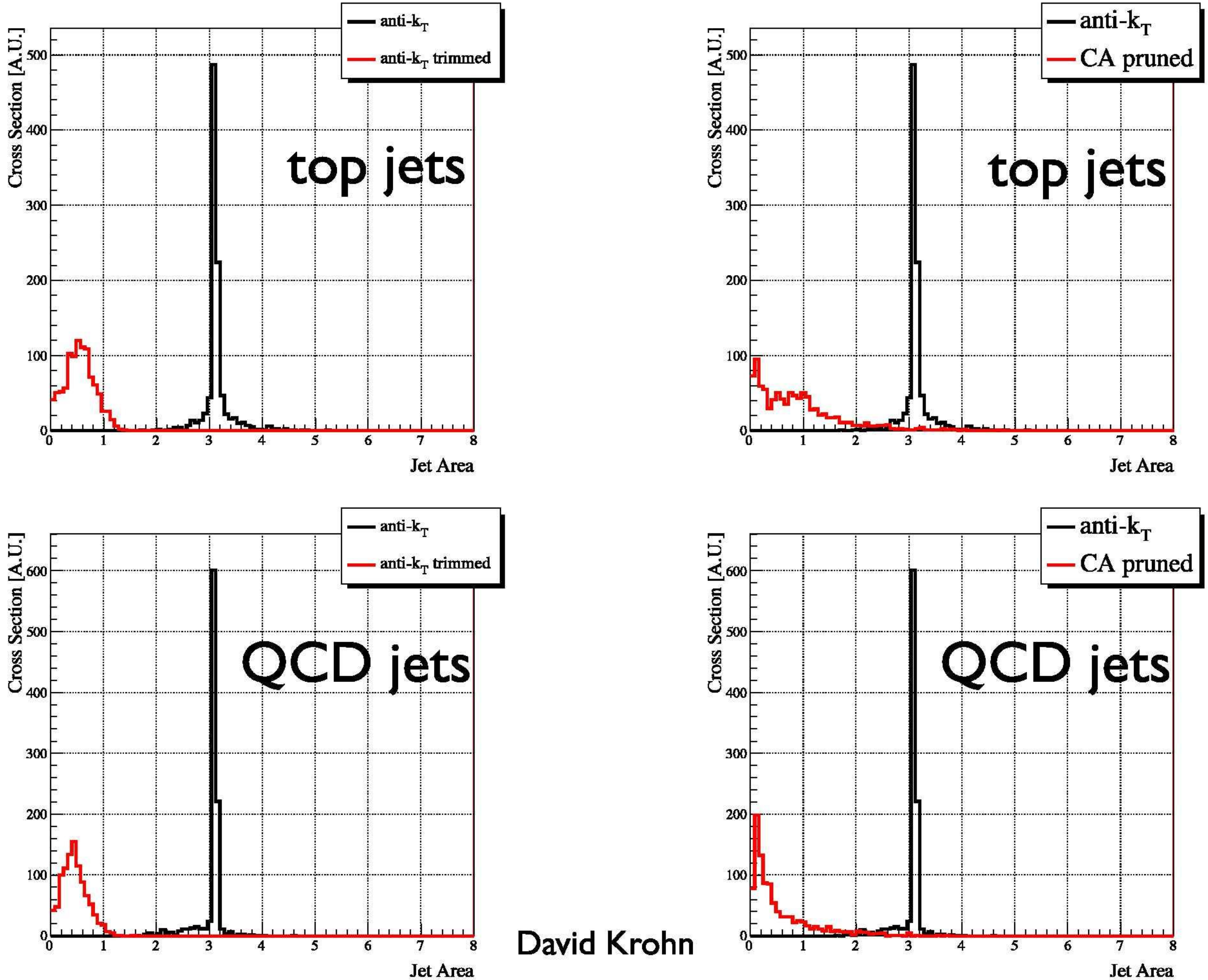


0.1x0.1 cells (y, ϕ)



0.1x0.1 cells (y, ϕ)

Jet areas: sensitivity to UE/pileup



David Krohn

Comparison conclusions

- Trimming corrects back to the FSR-only shape better
- Pruning over-corrects somewhat
  - Larger jet areas indicate it is not so simple - pruning is not removing "more" of the substructure than trimming, it is removing different parts
- Trimming is a local operation - objects clustered into subjets and trimmed or kept - similar to operations with topological clusters
- Pruning operates over the whole jet, and uses the algorithm to determine what to keep - seems better for reconstructing decays
- Can parameters of the algorithms be tuned to give similar behavior? Or merged into an algorithm good for both types of uses?
  - Current comparison work by groups at Princeton, UW, Oregon

See talk by M. Spannowsky

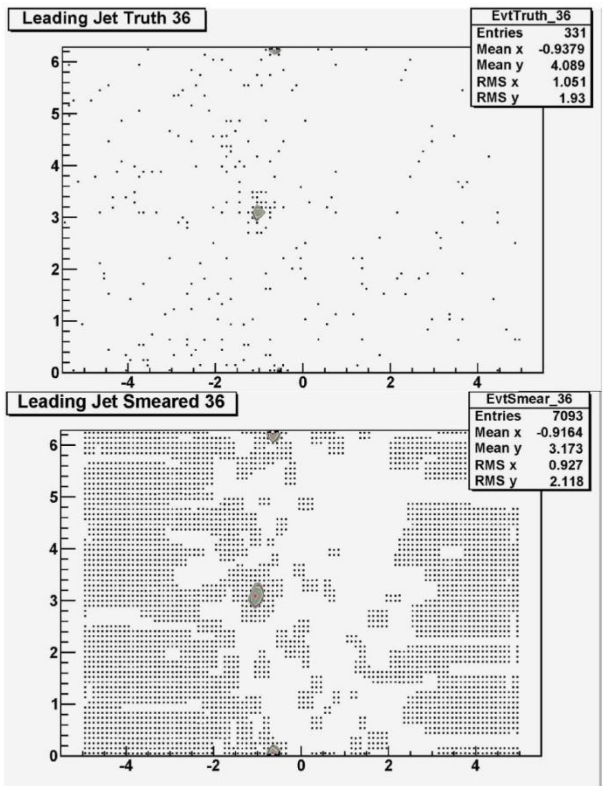
Software Development

- Pruning/Trimming comparison a good context for development of better jet analysis software
  - FastJet plugins exist for both algorithms - easy to make jets - but how to compare?
  - SpartyJet framework discussed, used extensively at workshop
    - Works as a wrapper for FastJet, allows user to run jet-related analysis
- Jet substructure classes being developed in SpartyJet
  - Can work with different versions - original, pruned, trimmed - of a jet
  - Access to a wide variety of substructure observables without writing the framework yourself
  - At UW, pruning and trimming comparison being done with SpartyJet

See presentation by C. Vermilion

Advanced theorist's detector - from Peter Loch

Only relies on a FastJet header file and STL! Simple, portable



Simple radial energy distribution in tower grids

- Ignore longitudinal development
  - Particle energy distributed transverse to direction of flight of particle in a plane through the particle impact point into the calorimeter
  - Shape of distribution from experiment/full simulation
- Integrated energy in profile is the same as particle energy
  - No calibration/acceptance/smearing of energy
- Distributed energies projected into regular eta/phi grid within modeled detector acceptance
  - Fakes calorimeter tower signal definition, including high eta losses
  - Different grid and eta acceptance for EM particles

Detector defaults

- EM acceptance -2.5 < eta < 2.5
  - Photons/electrons outside are mapped onto HAD towers
- HAD acceptance -5.0 < eta < 5.0
  - Particles outside are ignored completely
- Cylindrical calorimeter
  - R = 1200 mm, -2500 mm < z < 2500 mm
- High granularity
  - 0.025 x 0.025 (EM)
  - 0.1 x 0.1 (HAD)

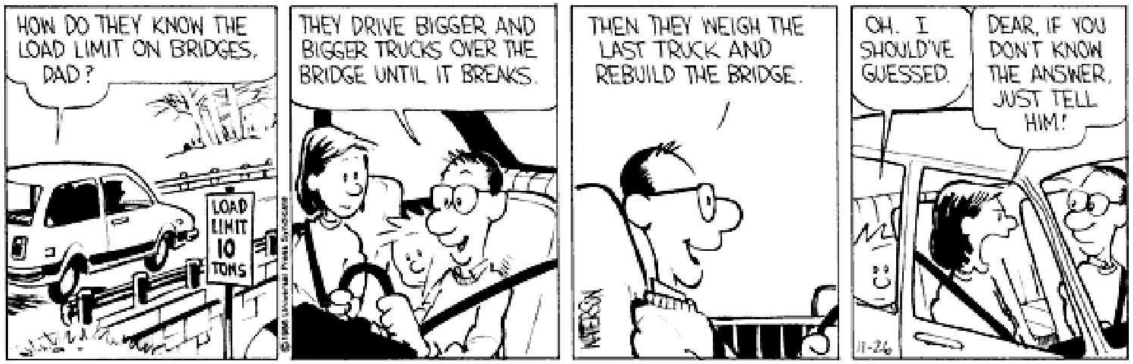
Shower shapes

- Presently Gaussian within cylinder
  - Lateral extend /cylinder radius 80 mm for EM particles (also in HAD grid!)
  - 160 mm for all others
  - Gaussian showers are too wide, this is just a simplification!
- Energy distributed in small "spots"

Peter Loch

Dangers of Jet Substructure from Monte Carlo

- Words of caution from Steve Mrenna:
  - Jet substructure will depend on physics that the MC doesn't get right (subleading effects)
  - Different MCs can give widely different results
  - Not well understood what physics details substructure techniques depend on
- Parton shower development can be fueled by theory calculations and more detailed substructure studies



Has the bridge already broken? It's hard to tell...

Check current MC status this week!

Seeing in color: Matt Schwartz

Jet Superstructure:

- Combines radiation pattern inside jets with global event structure to distinguish between processes
- Defines observables to tag jets as color connected to the beams or another central jet
- QCD radiation occurs inside color dipoles

Boosted color singlet decays are largely color-disconnected from the rest of the event

QCD background events are more color-connected

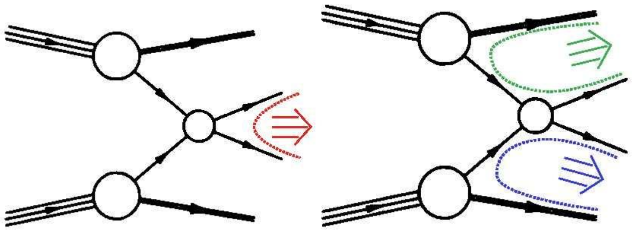
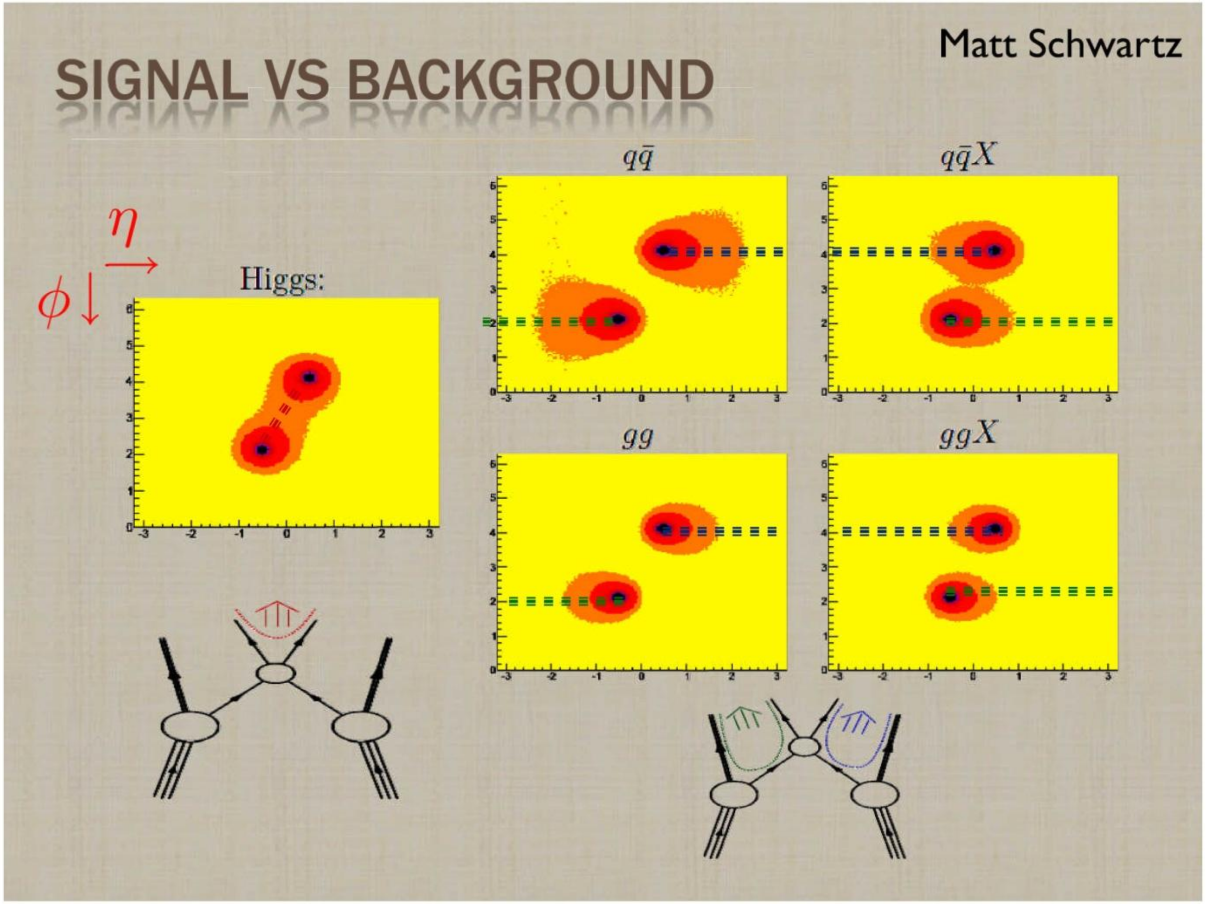


FIG. 1: Possible color connections for signal ($pp \to H \to b\bar{b}$) and for background ($pp \to b\bar{b}$).

Matthew Schwartz and Jason Gallicchio (arXiv:1001.5027)

Study color connections using Monte Carlo

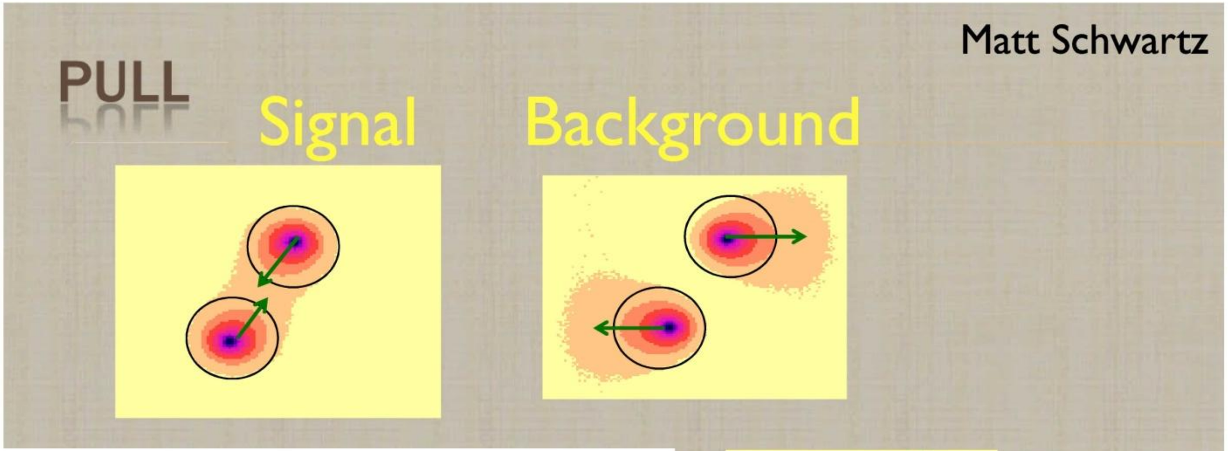
Parton shower single parton configurations millions of times, map radiation pattern



Signal (Higgs) events have most of their radiation between the central jets, background (dijet) events have radiation towards the beam (higher rapidity)

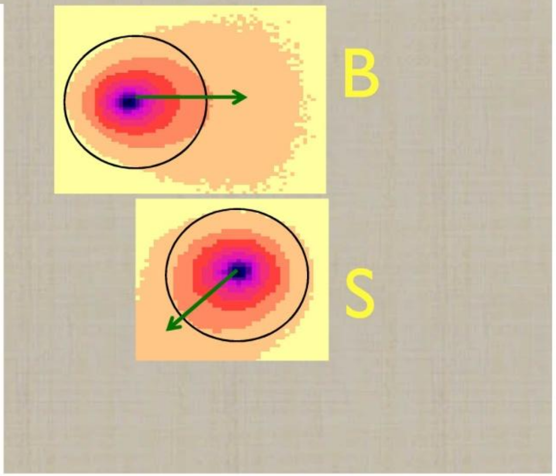
Quantify with Observables: Pull

Pull is a pT-weighted vector describing the direction of radiation in a jet wrt the jet centroid (~axis)



$$\vec{p} = \sum_{i \in J} \frac{p_T^i |r_i|}{p_T^J} \vec{r}_i$$

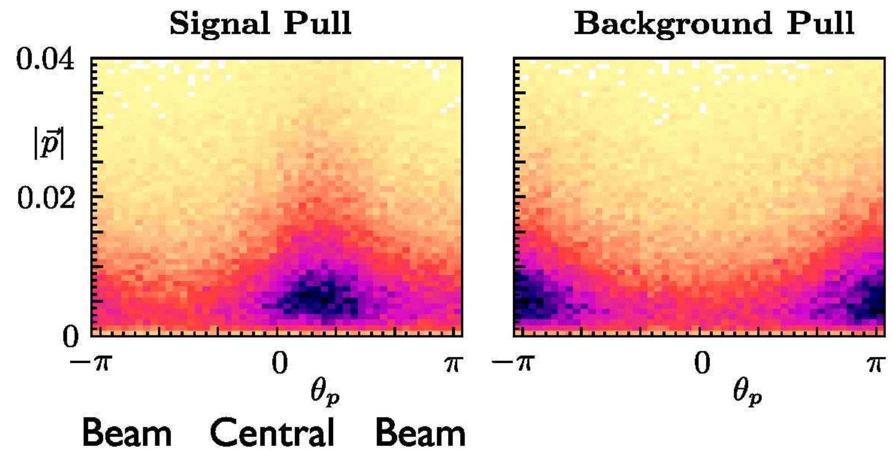
$$\vec{r}_i = (y_i, \phi_i) - (y_J, \phi_J)$$



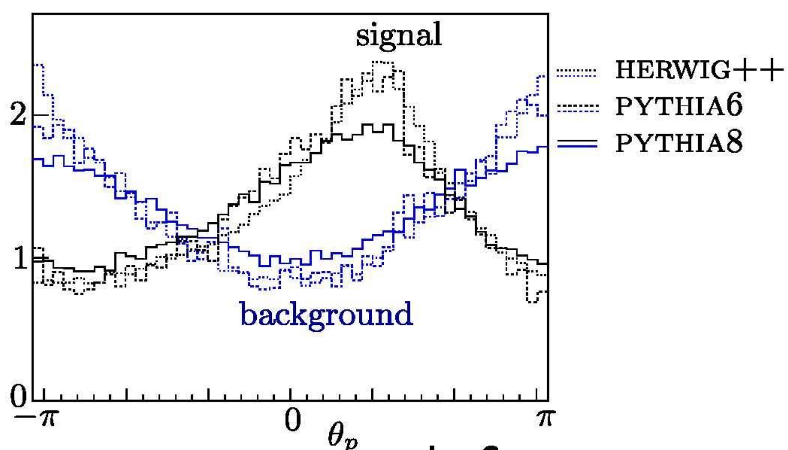
Jets color-connected to the beam have pulls towards large rapidity
Centrally color-connected jets have "central" pulls

Pull Angle

The magnitude of pull is not very informative - but the angle is



pull angle distribution for fixed parton configuration



Jet Superstructure paper

$$\vec{p} = \sum_{i \in J} \frac{p_T^i |r_i|}{p_T^J} \vec{r}_i$$

$$\vec{r}_i = (y_i, \phi_i) - (y_J, \phi_J)$$

Advantages of Jet Superstructure

- Largely orthogonal to other observables
  - Uses inter-jet measures for discrimination
  - Could be combined with fat-jet substructure (e.g., the Higgs filter) to identify color singlet decays
- Very straightforward application in clean events
  - Easy to calibrate from Z production
  - Would learn something about shower reconstruction in a detector in applying to real events
- The "pull" observable may be calculable for simple event topologies
  - Calculable in SCET? - the technology is developing rapidly

HW (expectations) for Boost 2010 :

- Better understanding of tools to tag and/or groom jets using jet substructure – both absolutely and comparatively –

  to find old/new physics

  to reduce specific algorithm dependence

  to reduce impact of UE and Pile Up

- Better understanding of how well experiments can utilize and calibrate these tools given specific detector strengths and weaknesses

HW (expectations) for Boost 2010 :

- Better understanding of what measurements need to be made this year and how to communicate the results to the larger community $\Rightarrow$ practice discussing physics with theorists!

- Better software tools – e.g.,

  FastJet plugins

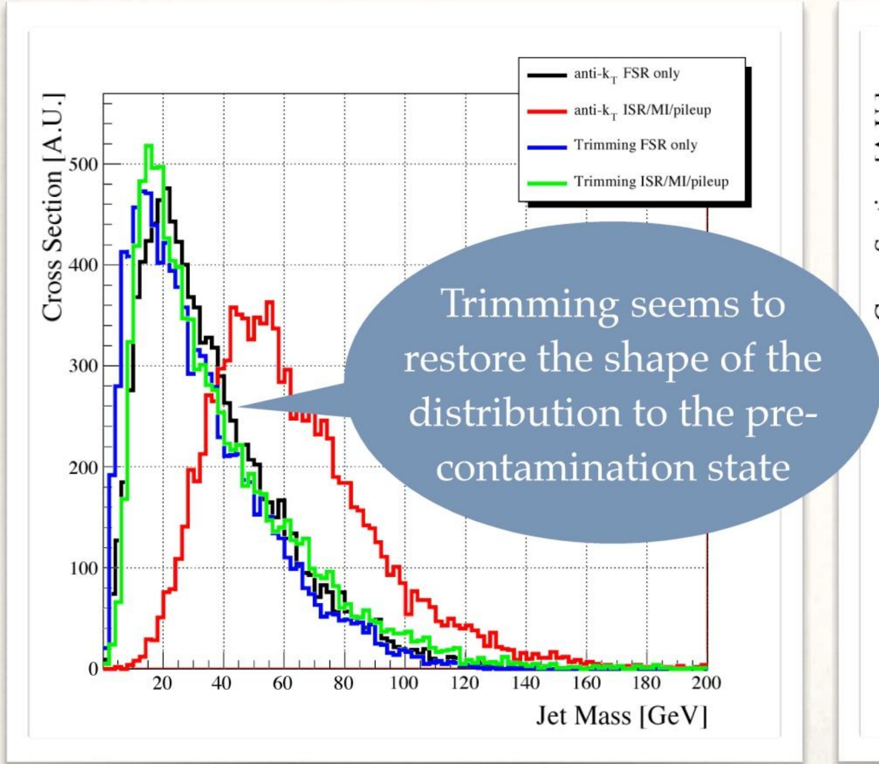
  Useful analysis interfaces like SpartyJet, e.g., to simplify the comparison of various analysis techniques

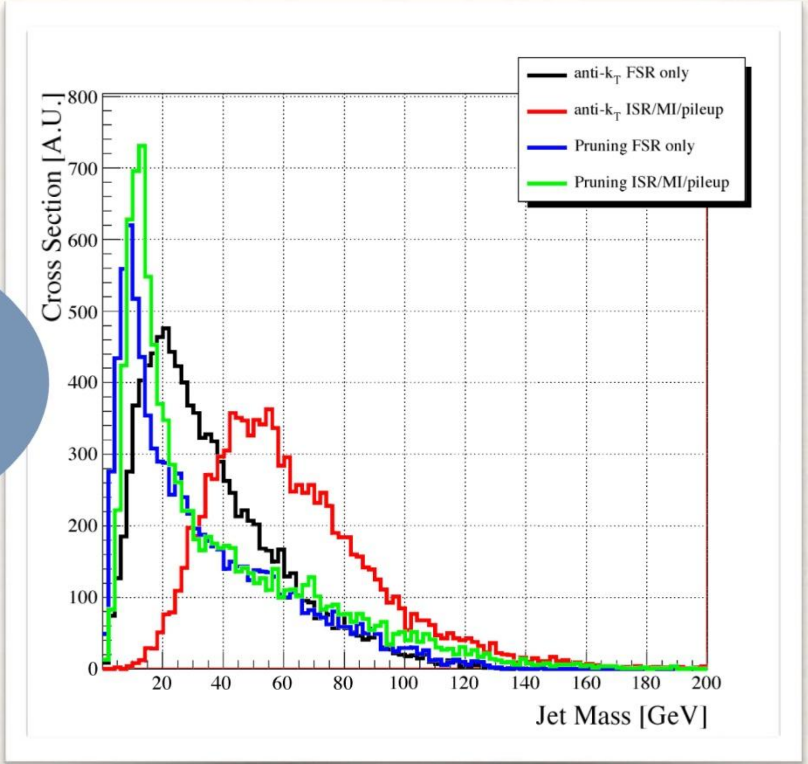
  Fast but realistic detector simulations for studies inside AND outside of the experimental collaborations

Extra Detail Slides

Jet Mass

Trimming is a smaller correction to the underlying FSR

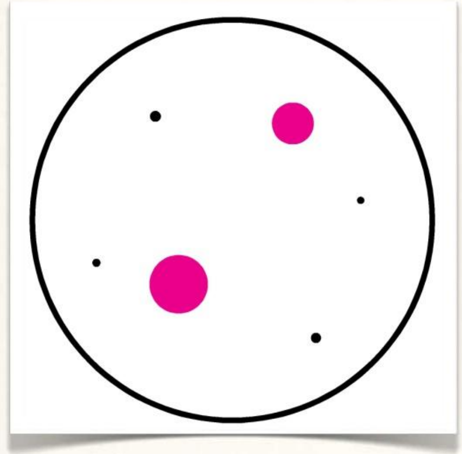




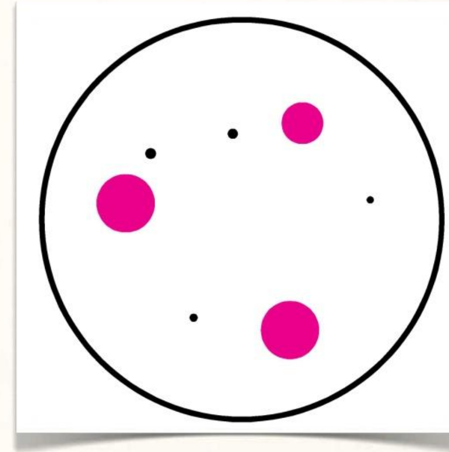
David Krohn

$\Delta R = 1.0$

Planar Flow



Pf ≈ 0



Pf ≈ 1

- Planar flow is another jet shape designed to measure how plane / pencil like a jet is.

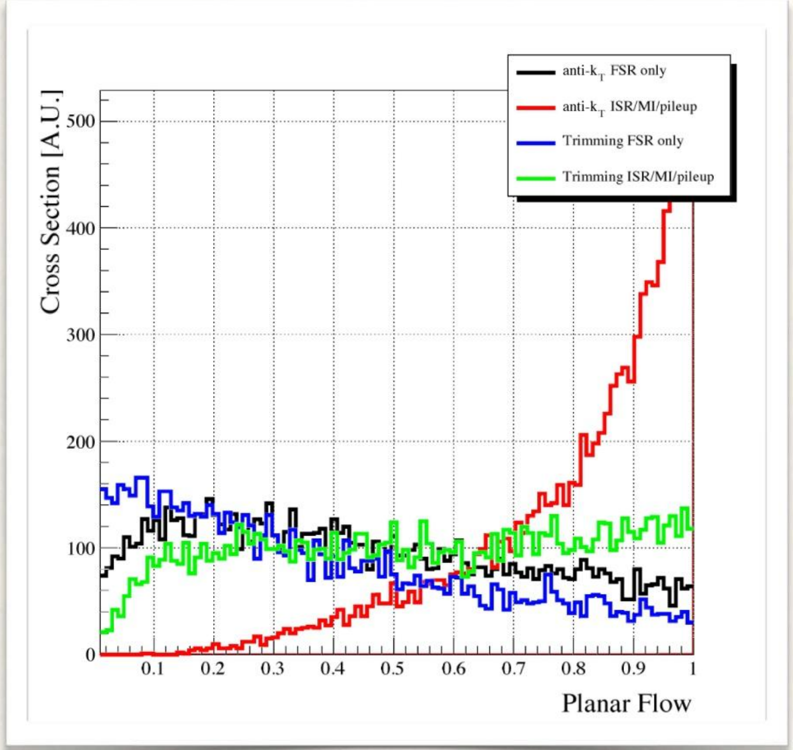
- Defined as normalized product of two jet moments:

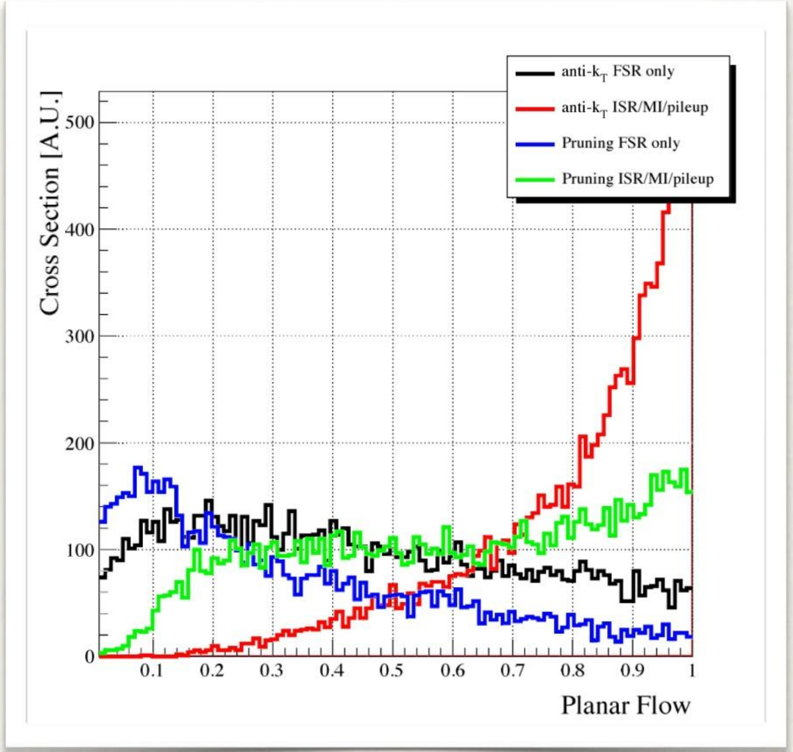
$$\mathrm{Pf} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2} \qquad I_w^{kl} = \sum_i E_i \frac{p_{i,k}}{E_i}\frac{p_{i,l}}{E_i}$$

▸L. G. Almeida et al., *Substructure of high-pT Jets at the LHC*, Phys. Rev. D79 (2009) 074017, [0807.0234].
▸J. Thaler and L.-T. Wang, *Strategies to Identify Boosted Tops*, JHEP 07 (2008) 092, [0806.0023]

David Krohn

Planar flow: more sensitive to jet substructure details non-FSR skews PF to high values - most cut back

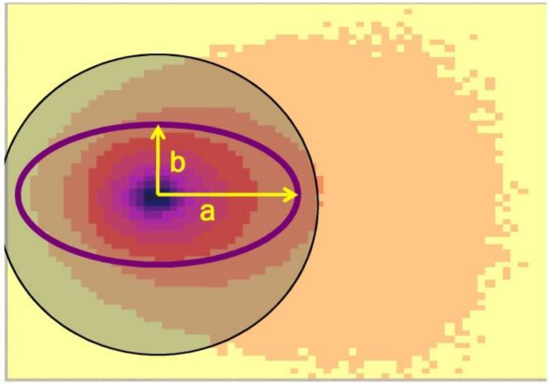




Not as good at restoring the distribution (compared to jet mass), but still progress

David Krohn

Higher Moment Observables



Matt Schwartz

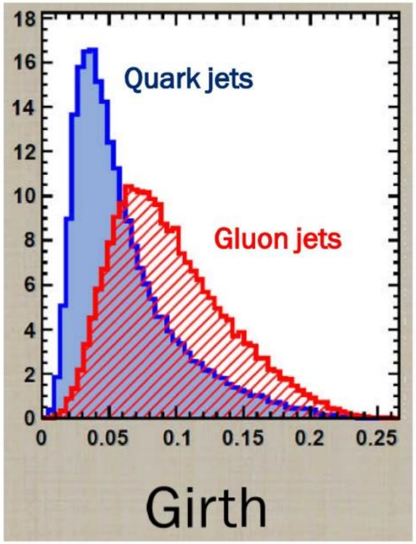
The radiation pattern will depend on the color charge of the jet and the event topology
- observables can sort this out

$$I = \sum_i \frac{p_T^i}{p_T^J} |r_i| \begin{pmatrix} \Delta\phi_i^2 & -\Delta\phi_i \Delta y_i \\ -\Delta\phi_i \Delta y_i & \Delta\eta_i^2 \end{pmatrix}$$

$\longrightarrow$ yields eigenvalues a, b

girth: $\sqrt{a^2 + b^2}$ - size of jet

eccentricity: $\sqrt{1 - \frac{b^2}{a^2}}$ - no clear use



Use girth for quark vs. gluon jet separation

Soft Collinear Effective Theory (SCET) (Recent but Incomplete List)

- Jets and Jet Substructure in e+e-
  SDE, Hornig, Lee, Vermilion and Walsh (UC/UW)
  0912.0262, 1001.0014

  Cheung, Luke and Zuberi (Toronto) 0910.2479

  Jouttenus (MIT) 0912.5509

- Jets and Jet Substructure in pp
  Stewart, Tackmann and Waalewijn (MIT) 1004.2489
  (and previous)

- Also Banfi, Dasgupta, Khelifa-Kerfa, Marzani (Zurich/Oxford)
  1004.3483

More Information:

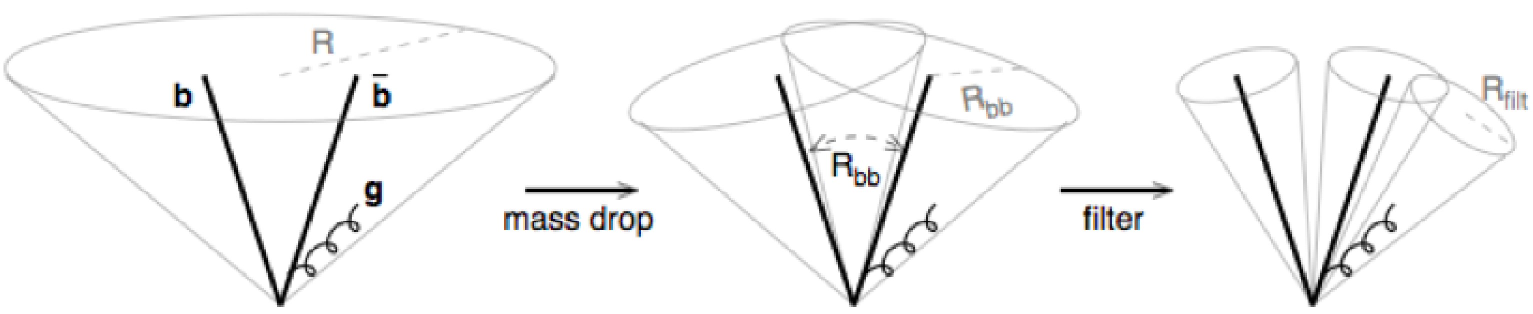
- software at tinyurl.com/jetpruning

- See comparisons from Jet Substructure Workshop in Seattle in January 2010 (HW for Boost 2010)
  WiKi at
  http://librarian.phys.washington.edu/lhc-jets/index.php/Main_Page

- Jet tools available e.g.,

  http://librarian.phys.washington.edu/lhc-jets/index.php/SpartyJet

- “Boosted Higgs” (arXiv:0802.2470; Butterworth, Davison, Rubin, Salam)
  1. Starting with found jet, traverse merging history along heavier branch, looking for mass drop and a splitting that is not too asymmetric:
     $m_{daughter}/m_{branch} < \mu_{cut}(= 0.67)$,
     $y \equiv \frac{\min(p_{Ti}^2, p_{Tj}^2)}{m_{branch}^2} \Delta R_{ij}^2 > y_{cut}(= 0.09)$.
     This branching must have two b-tags.
  2. Uncluster below this branching down to
     $\Delta R = R_{cut}(= \min(0.3, R_{b\bar{b}}/2))$.
  3. Take 3 hardest subjets — capturing hardest radiation, but eliminating soft UE.



- "Top Tagging" (arXiv:0806.0848; Kaplan, Rehermann, Schwartz, Tweedie)
  1. Starting with found jet, traverse merging history along harder branch, looking for splitting with

$$z_i \equiv p_T^i / p_T^{jet} > z_{cut},$$
$$\Delta R > R_{cut}.$$

     This is the top-level splitting.
     - Throw out branches with $z_i < z_{cut}$ and continue. If both z_i fail, this is an irreducible branching.
     - If $\Delta R < R_{cut}$, stop. This is an "irreducible" splitting.
  2. Repeat on the two daughters of the found branch.
  3. Result is 1-4 subjets. Require 3 or 4.
  4. Additional cuts can be made on the subjet kinematics. . .

Compare to other "Jet Grooming" – CA jets

- PSJ (Kaplan, et al., for tops) – find primary subjets and build "groomed" jet from these (3 or 4 of them)

1. Define $\delta_p = \frac{\min\left(p_{T1}, p_{T2}\right)}{p_{T,J}}$, $\delta_{p,\mathrm{MIN}} = 0.1\ \left(p_T < 800\ \mathrm{GeV/c}\right), 0.05\ \left(p_T > 800\ \mathrm{GeV/c}\right)$

   $\delta_R = \left|\Delta\eta_{12}\right| + \left|\Delta\phi_{12}\right|$, $\delta_{R,\mathrm{MIN}} = 0.19$
2. Start of top of branch (the jet) and follow hardest daughter at each branching (discarding softer daughters) until reach first branching where $\delta_p > \delta_{p,\mathrm{MIN}}, \delta_R > \delta_{R,\mathrm{MIN}}$. If does not exist, discard jet.
3. If such a branching exists, start again with each daughter of this branching as top branch as in 2. Again follow along the hardest daughter (discarding softer daughters) until a branching where $\delta_p > \delta_{p,\mathrm{MIN}}, \delta_R > \delta_{R,\mathrm{MIN}}$. If present, the daughters of this (2^{nd}) hard branching are primary subjets. If not present, the original daughter is primary subjet. This can yield 2, 3 or 4 primary subjets.
4. Keep only 3 and 4 subjet cases and recombine the subjets with CA algorithm.

Compare to other "Jet Grooming" – CA jets

- MDF (Butterworth, et al., for Higgs) – find primary subjets and build "groomed" jet from these (2 or 3 of them)

1. For each p $\rightarrow$ 1,2 branching define $a_1 = \frac{\max(m_1, m_2)}{m_p}$, $\mu = 0.67$

   $$y = \frac{\min\left[p_{T,1}^2, p_{T,2}^2\right]}{m_J^2}\Delta R_{12}^2, \quad y_{\mathrm{cut}} = 0.09$$

2. Start of top of branch (the jet) and follow hardest daughter at each branching (discarding softer daughters) until reach first branching where $a_1 < \mu, y > y_{\mathrm{cut}}$. If does not exist, discard jet.
3. If such a branching exists, define $\Delta R_{bb} = \Delta R_{12}, D_{\mathrm{filt}} = \min(0.3, \Delta R_{bb}/2)$ and start again with each daughter of this branching as top branch as in 2. Again follow along the hardest daughter (discarding softer daughters) until a branching where $\Delta R < D_{\mathrm{filt}}$, (but $\Delta R > D_{\mathrm{filt}}$ for early branchings). If present, the daughters of this (2nd) hard branching are primary subjets. If not present, the original daughter is primary subjet. This can yield 2, 3 or 4 primary subjets.
4. Keep the 3 hardest subjets (discard 1 subjet case but keep if only 2). Recombine the (2 or) 3 subjets with CA algorithm.