Theory Overview of Jet-substructure

Tuhin S. Roy

University of Washington

A little bit of History

LU TP 93-8

Mike Seymore

Z. Phys. C62 (1994) 127

Searches for New Particles Using Cone and Cluster Jet Algorithms: A Comparative Study

Michael H. Seymour
Department of Theoretical Physics, University of Lund,
Sölvegatan 14A, S-22362 Lund, Sweden

Butterworth, Cox, Forshaw (hep-ph/021098)

Butterworth, Ellis, Raklev (hep-ph/0702150)

ATLAS Y-splitter (ATL-PHYS-CONF-2008-008)

Butterworth, Davison, Rubin, Salam (0802.2470)

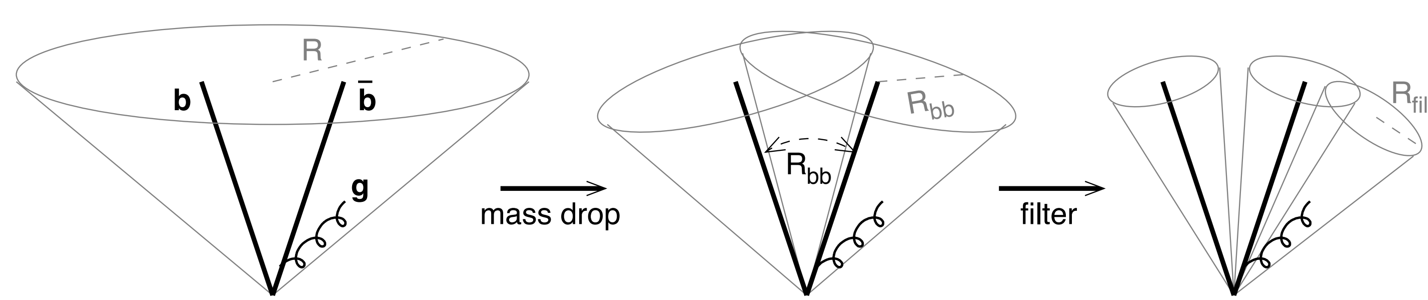


FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region one then further reduces the radius to $R_{\rm filt}$ and takes the three hardest subjets, so as to filter away UE contamination while retaining hard perturbative radiation from the Higgs decay products.

[Johns Hopkins] Top Tagging

(Kaplan, Rehermann, Schwartz, Tweedie; 0806.0848)

New jet shapes

(Almeida, et al.; 0807.0234, 0810.0934)

3-body kinematic variables

(Thaler, Wang; 0806.0023)

Pruning

(Ellis, Vermilion, Walsh; 0903.5081)

CMS Top Tagging

(0909.4894)

HEP Top Tagger

(Plehn, Salam, Spannowsky; 0910.5472)

Jet Trimming

(Krohn, Thaler, Wang; 0912.1342)

More jet shapes

(Chekanov, Proudfoot, Levy, Yoshida; 1002.3982, 1009.2749)

HEP Top Tagger++

(Plehn, Spannowsky, Takeuchi, Zerwas; 1006.2833...)

Jet Pull

(Gallicchio, Schwartz; 1001.5027)

New physics multi-tagging

(Kribs, Martin, Roy, Spannowsky; 0912.4731, 1006.1656)

Template overlap

(Almeida et al.; 1006.2035)

ISR tagging

(Krohn, Randall, Wang 1101.0810)

N-Subjettiness

(Thaler, Van Tilburg 1011.2268; Kim 1011.1493)

“Jet substructure without trees”

(Jankowiak, Larkoski; 1104.1646)

Shower deconstruction

(Spannowsky, Soper 1102.3480)

Dipolarity

(Hook, Jankowiak, Wacker; 1102.1012)

Multivariate quark/gluon discrimination

(Gallicchio, Schwartz; 1106.3076)

too much creativity to fit in one page

Too much creativity to be reviewed in a 20 minutes talk

I will concentrate on a few of my favorite topics

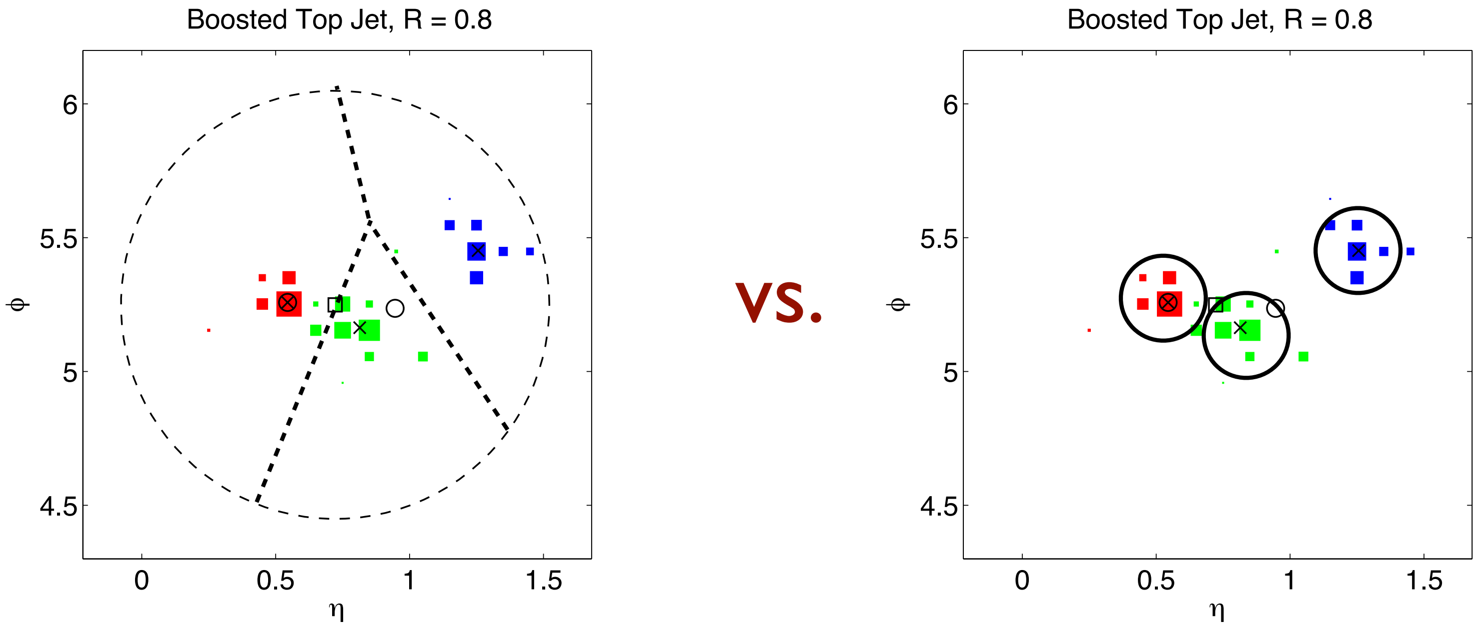
Borrowed results from many sources – thanks!

A bit of Organization

Jet Grooming	Filtering	Butterworth, Davison, Rubin, Salam (0802.2470)
	Pruning	Ellis, Vermilion, Walsh (0903.5081)
	Trimming	Krohn, Thaler, Wang (0912.1342)
2-pronged resonances	Mass-drop/Filtering	Butterworth, Davison, Rubin, Salam (0802.2470)
	and variations	Plehn, Salam, Spannowsky (0910.5472)
		Kribs, Martin, TSR, Spannowsky; (0912.4731, 1006.1656)
3-pronged resonances	Y-splitter	Butterworth, Cox, Forshaw (hep-ph/021098)
	Johns Hopkins tagger	Kaplan, Rehermann, Schwartz, Tweedie (0806.0848)
	HEP tagger	Plehn, Spannowsky, Takeuchi, Zerwas (1006.2833)
	tree-less approach	Jankowiak, Larkoski (1104.1646)
General procedures	Template method	Almeida et al. (1006.2035)
	N-subjettiness	Thaler, Van Tilburg (1011.2268); Kim (1011.1493)
	Multi-variate approach	Gallicchio, Schwartz (1106.3076)
	Shower deconstruction	Spannowsky, Soper 1102.3480)
	Qjets	Ellis, Hornig, Krohn, TSR, Schwartz (1201.1914)

Jet Grooming

Start with a large jet (capturing all decay products)



loss of mass resolution from out-of-cone effects

A grooming procedure removes radiation which is more likely to be contamination from the Underlying events and Pile-up

Improved mass resolution expected.

Mass drop/Filtering

Butterworth, Davison, Rubin, Salam
0802.2470

Start with high-p_t jet C/A, R=1.2

1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]

dimensionless rejection of asymmetric QCD branching

Filter the jet

- Reconsider region of interest at smaller $R_{\text{filt}} = \min[0.3, \frac{\Delta R_{j_1, j_2}}{2}]$
- Take **3** hardest subjets

Pruning

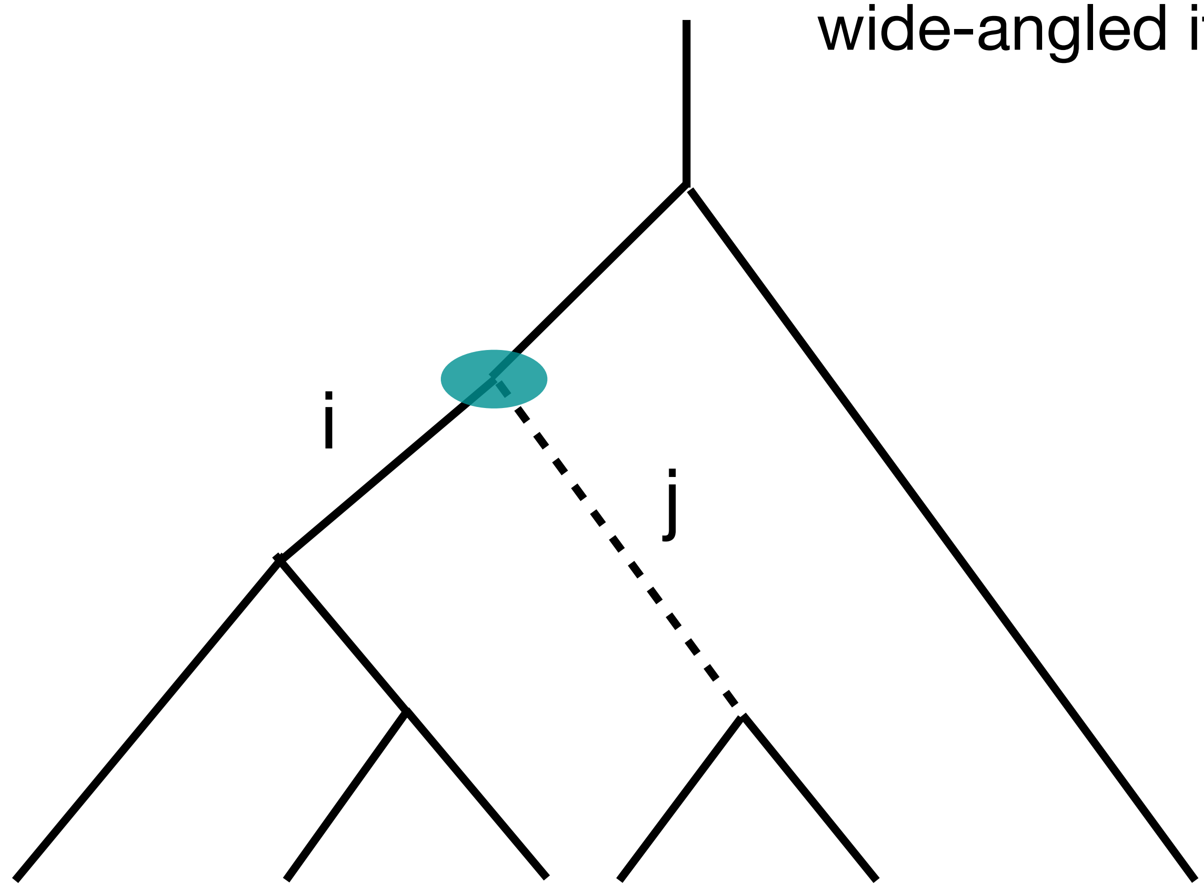
Ellis, Vermilion, Walsh
0903.5081, 0912.0033

At every step of clustering check whether the branch to be added is soft **and** wide angled.

- if yes discard the softer four-vector.

soft if: $$\frac{\min\left(p_{T_i}, p_{T_j}\right)}{|\vec{p_{T_i}} + \vec{p_{T_j}}|} < z_{\rm cut}$$

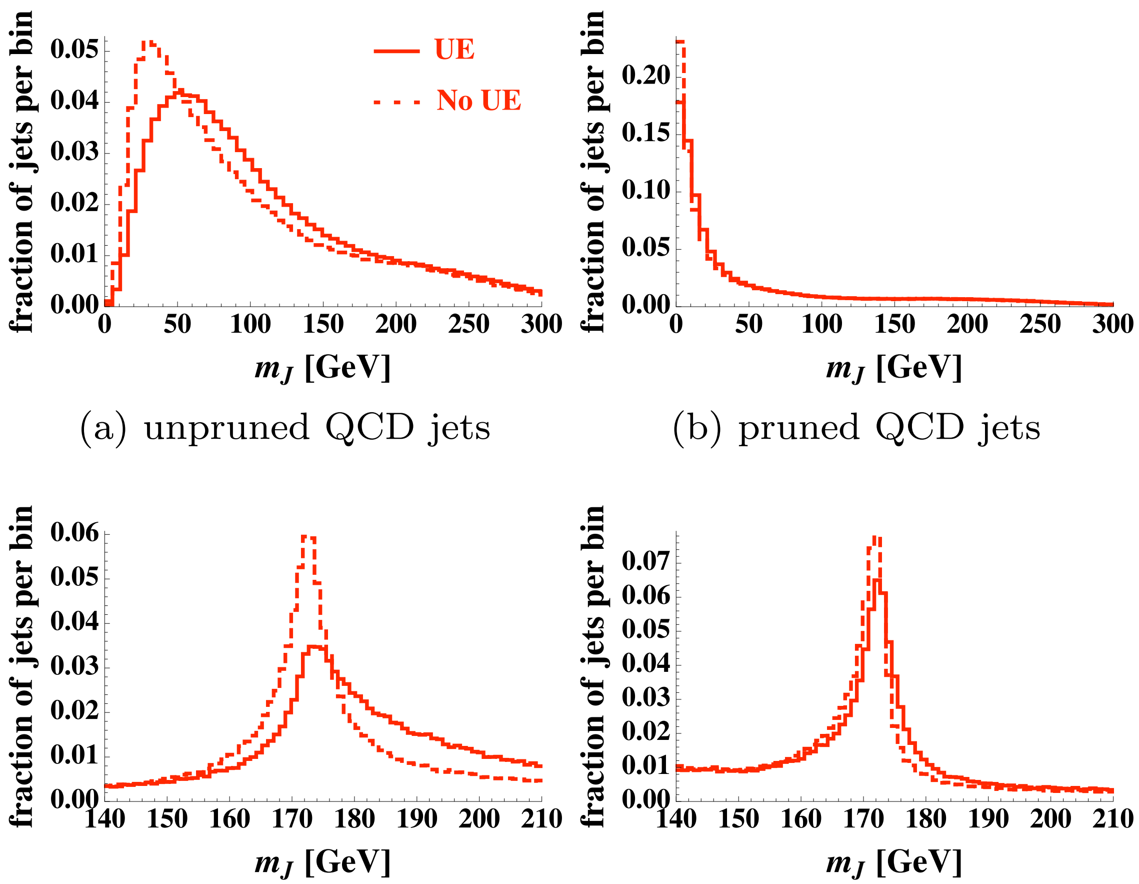
wide-angled if: $$\Delta R_{ij} > D_{\rm cut}$$



$$D_{\rm cut} = \frac{m_J}{p_{T_J}}$$

Pruning

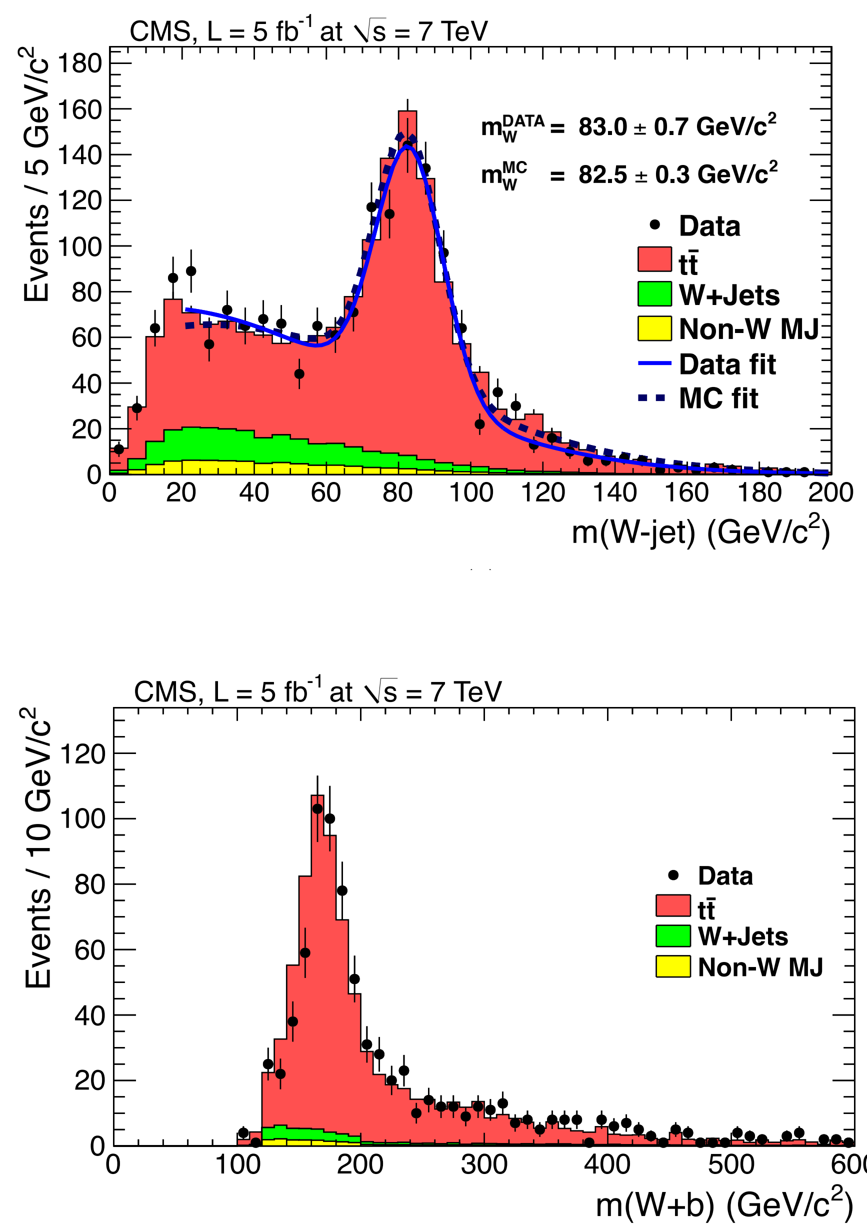
Ellis, Vermilion, Walsh
0903.5081



(a) unpruned QCD jets (b) pruned QCD jets

(c) unpruned top jets (d) pruned top jets

arXiv:0912.0033v1



arXiv:1204.2488v1

Trimming

Krohn, Thaler, Wang

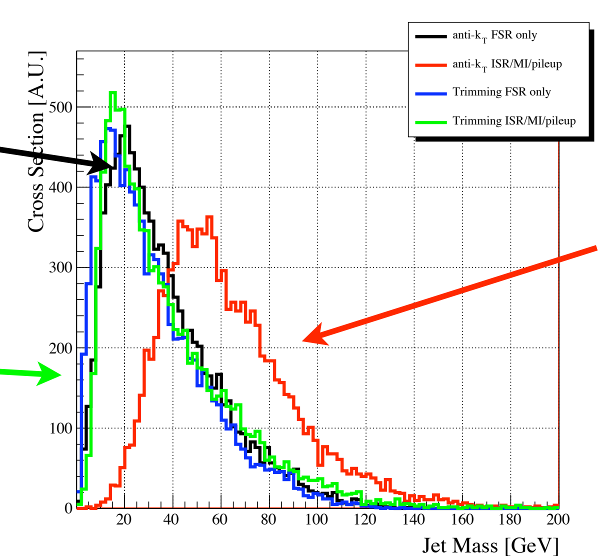
0912.1342

- Introducing a "cut" on soft radiation.
  - Discard "stuff" below the cut after jet clustering.
- Our implementation.
  - Cluster all calorimeter data using any algorithm
  - Take the constituents of each jet and recluster with smaller radius Rsub (Rsub = 0.2 seems to work well).
  - Discard the subjet i if $p_{Ti} < f_{\rm cut} \cdot \Lambda_{\rm hard}$ ⟵ ISR argument.
- Best choice of the hard scattering scale and fcut.
  - Process dependent.
  - Can be optimized experimentally.

Without contamination

With contamination

With "trimming"



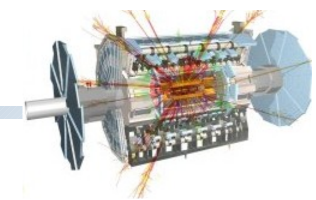
Lian-Tao Wang

Higgs @ Tevatron and LHC, Seattle,

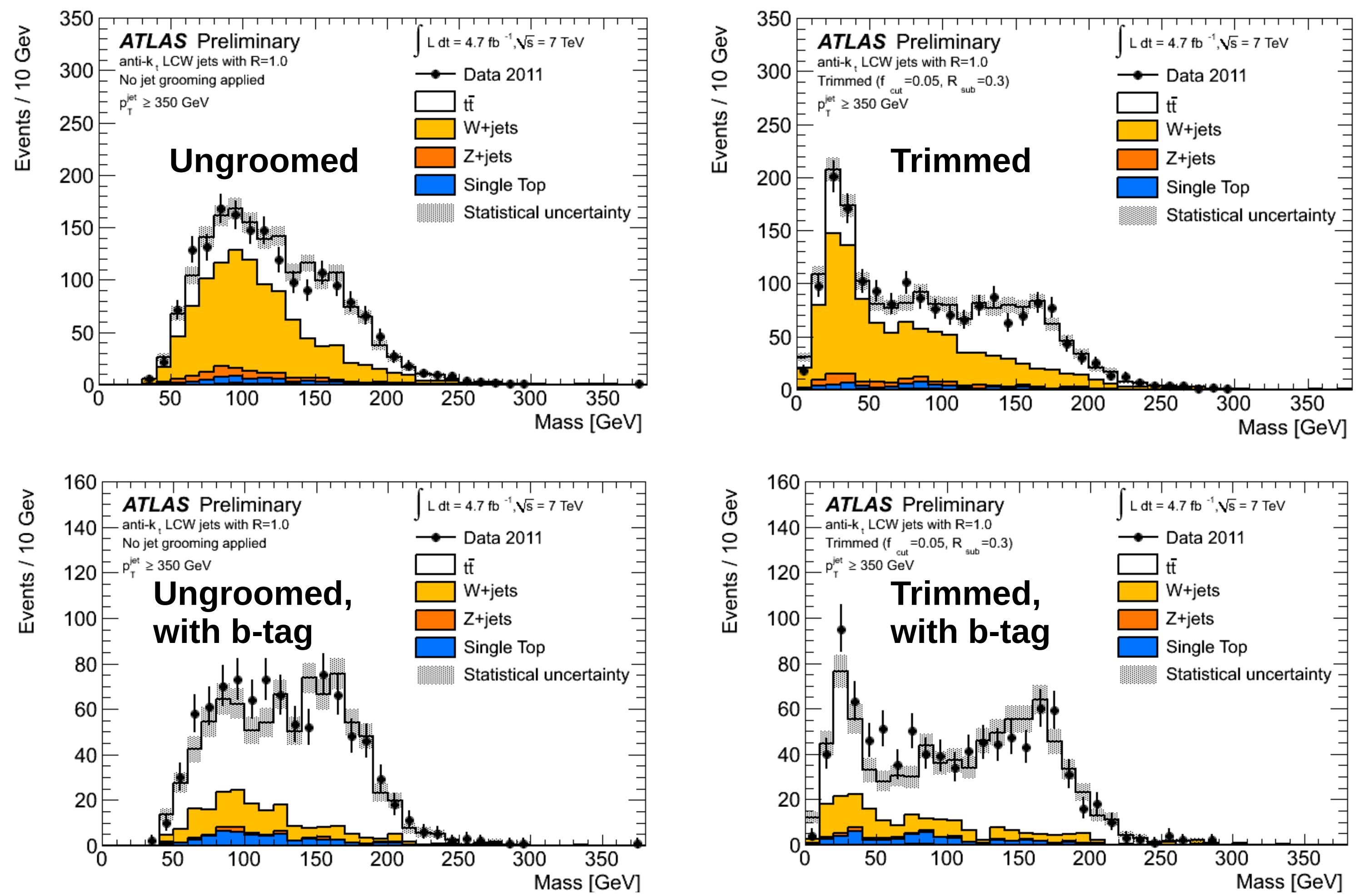
Trimming

Krohn, Thaler, Wang
0912.1342

SM ttbar events in data



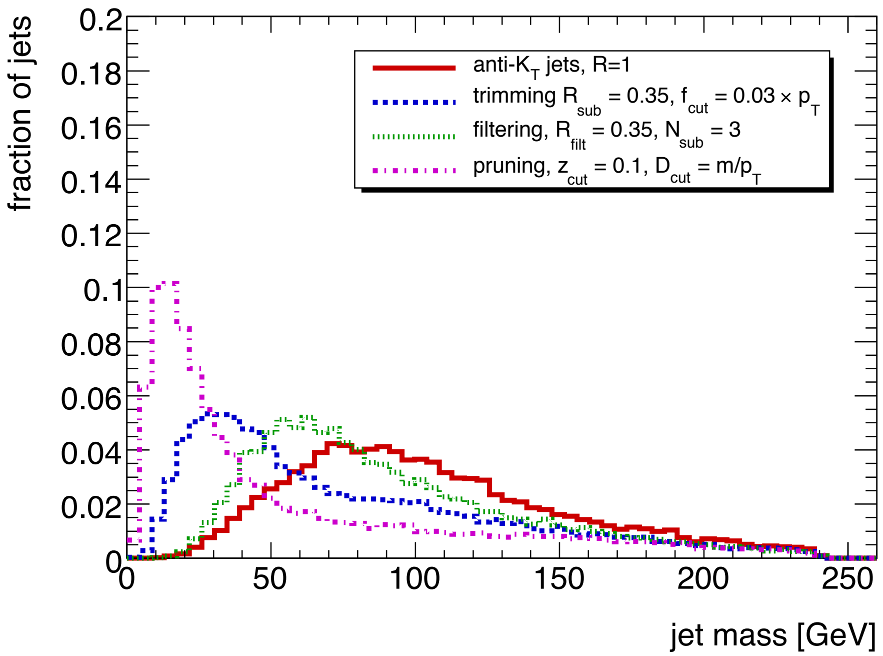
- **Jet Mass** (leading p_T anti-kt R=1.0 jet, p_T > 350 GeV)



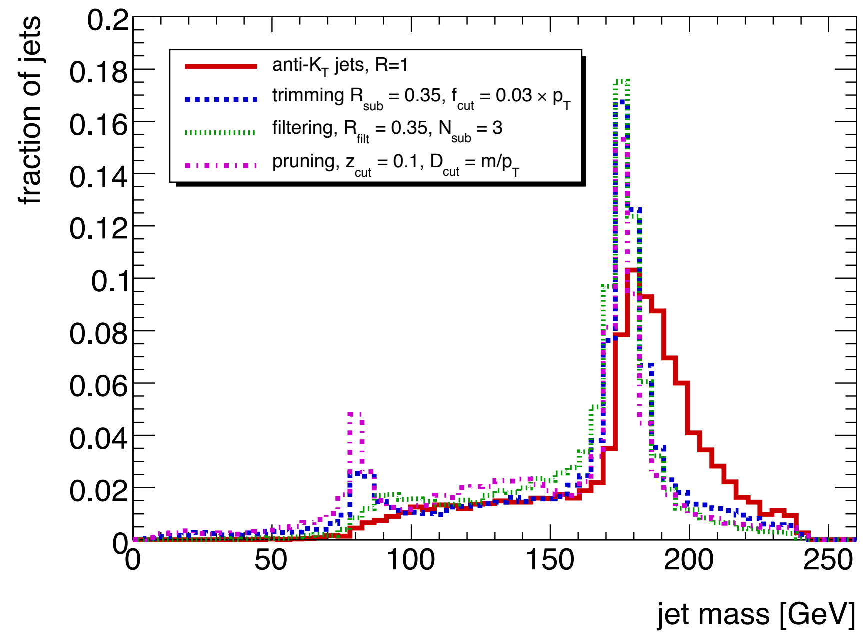
Emily Thompson – *Columbia University*
on behalf of the ATLAS Collaboration

Boost 2012

Filtering vs. Trimming vs. Pruning



(a) dijets, 500–600 GeV



(b) $t\bar{t}$, 500–600 GeV

Christopher Vermilion

Boost 2010

The relevant kinematic pattern

small p_T

all taggers perform reasonably well

business

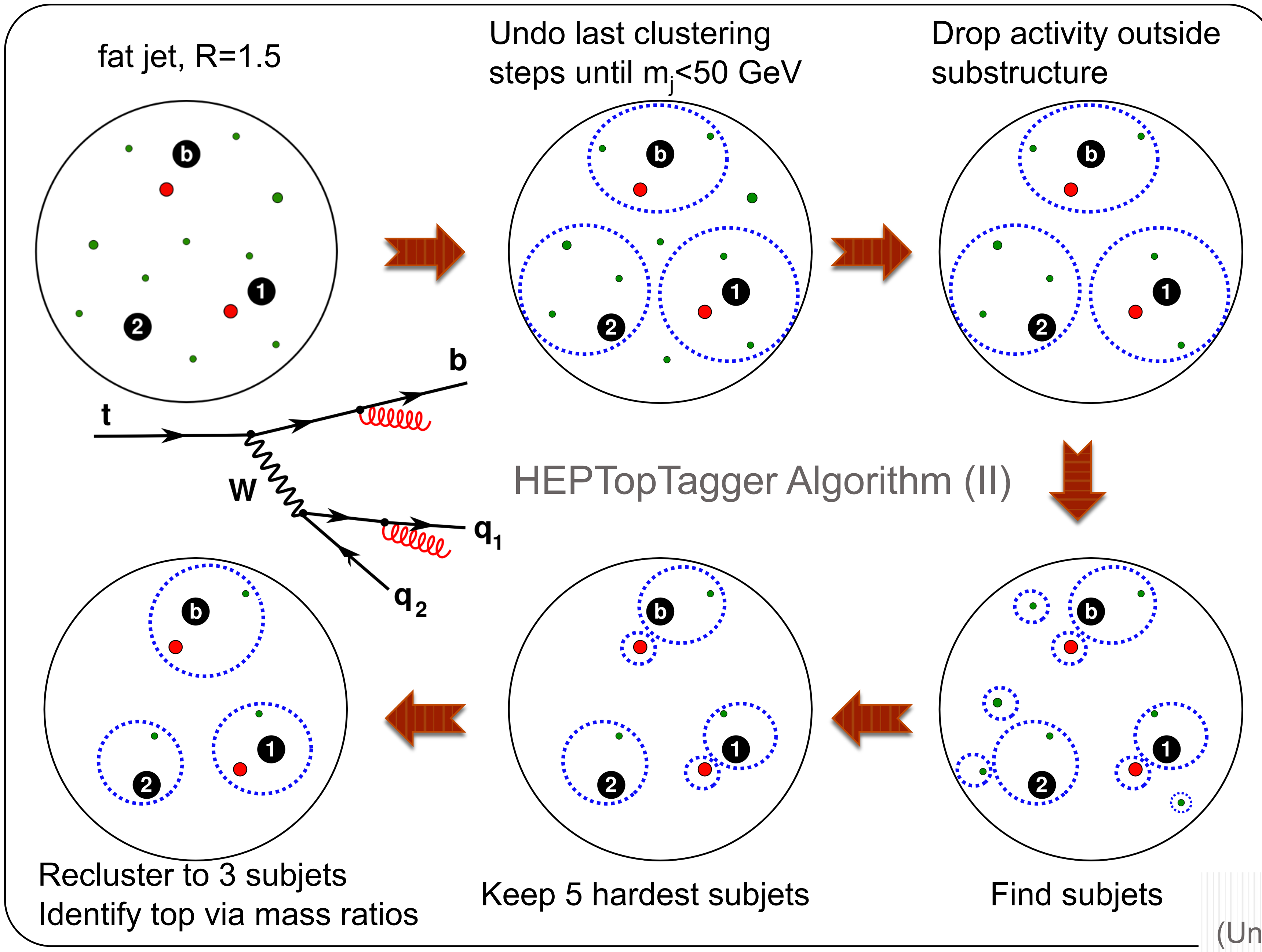
	large p_T, non busy final state e.g. Z’ -> tt	small p_T, non busy final state e.g. pp -> h Z
	large p_T, busy final state e.g. SUSY cascade	small p_T, busy final state e.g. pp -> tth

hardest scenario
HEP tagger is useful

HEP top tagger

Plehn, Spannowsky, Takeuchi, Zerwas
1006.2833

$p_T > 200$GeV



stay tuned for ATLAS results

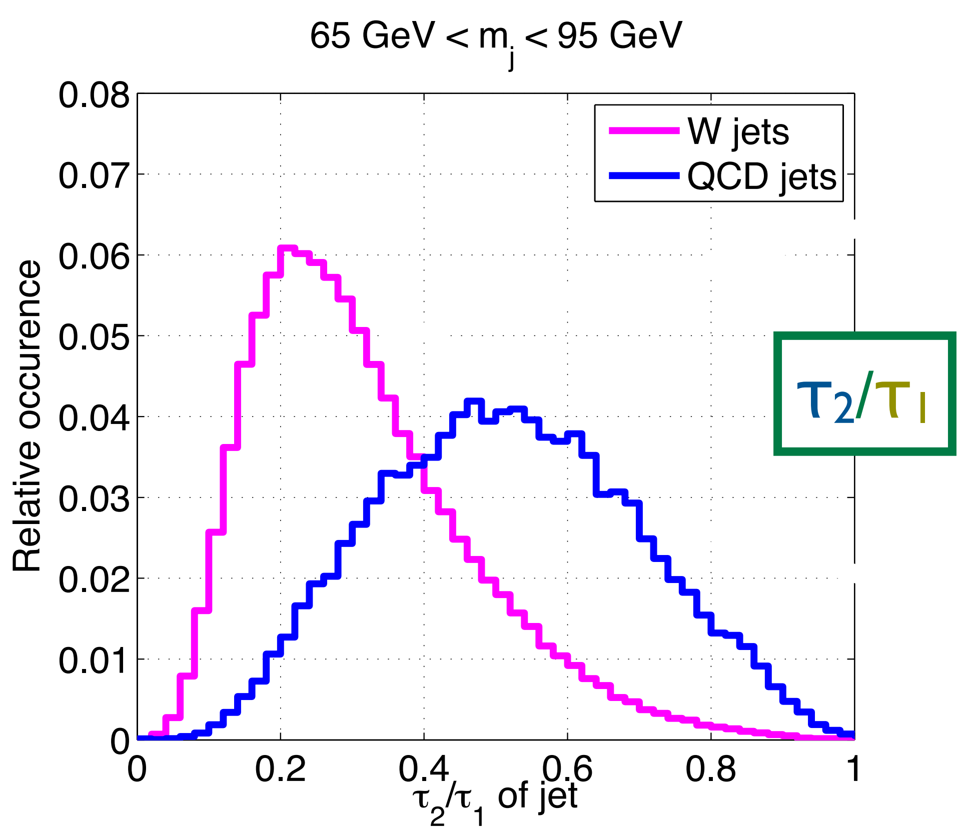
Gregor Kasieczka
(Universität Heidelberg, Germany)
for the ATLAS Collaboration,
Boost2012 Valencia, Spain

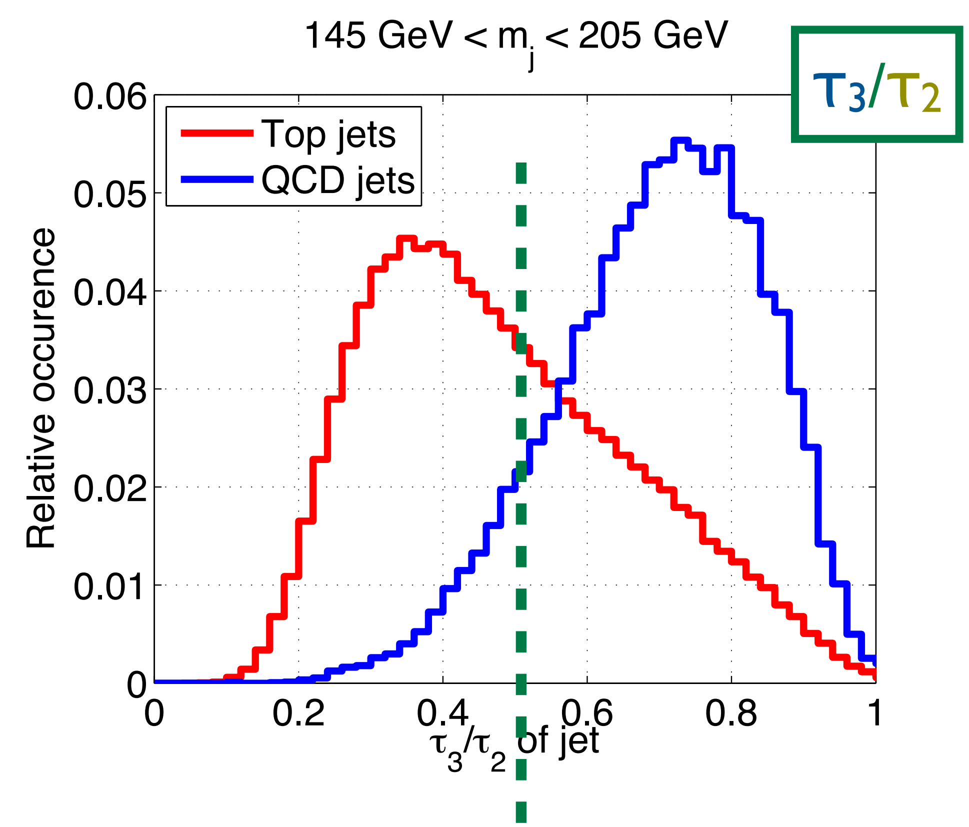
N-subjettiness

Thaler, Tilburg
1011.2268, 1108.2701

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}$$

Tagging with τ_N/τ_{N-1}





N-subjettiness

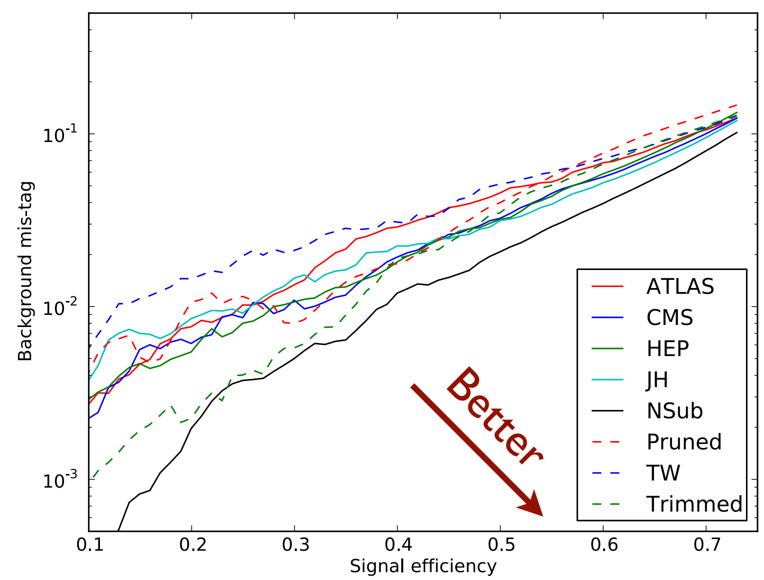
Thaler, Tilburg
1011.2268, 1108.2701

Top Tagging c. 2012

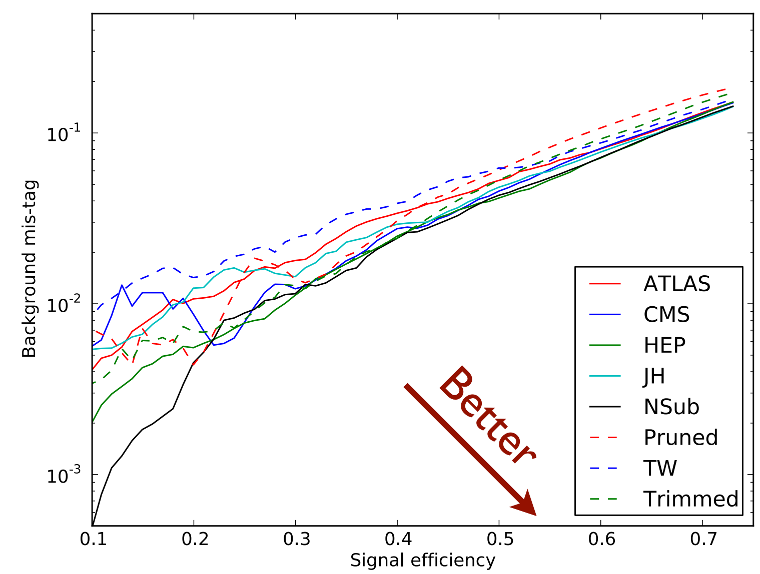
Boost2011 Top Benchmark

500 GeV < p_T < 600 GeV

Herwig 6.5



Herwig++



Pythia 6.4 more optimistic, Sherpa more pessimistic.
Detector effects also important.

Ideally: Calibrate in Data & Validate with Calculations

Multivariate approach

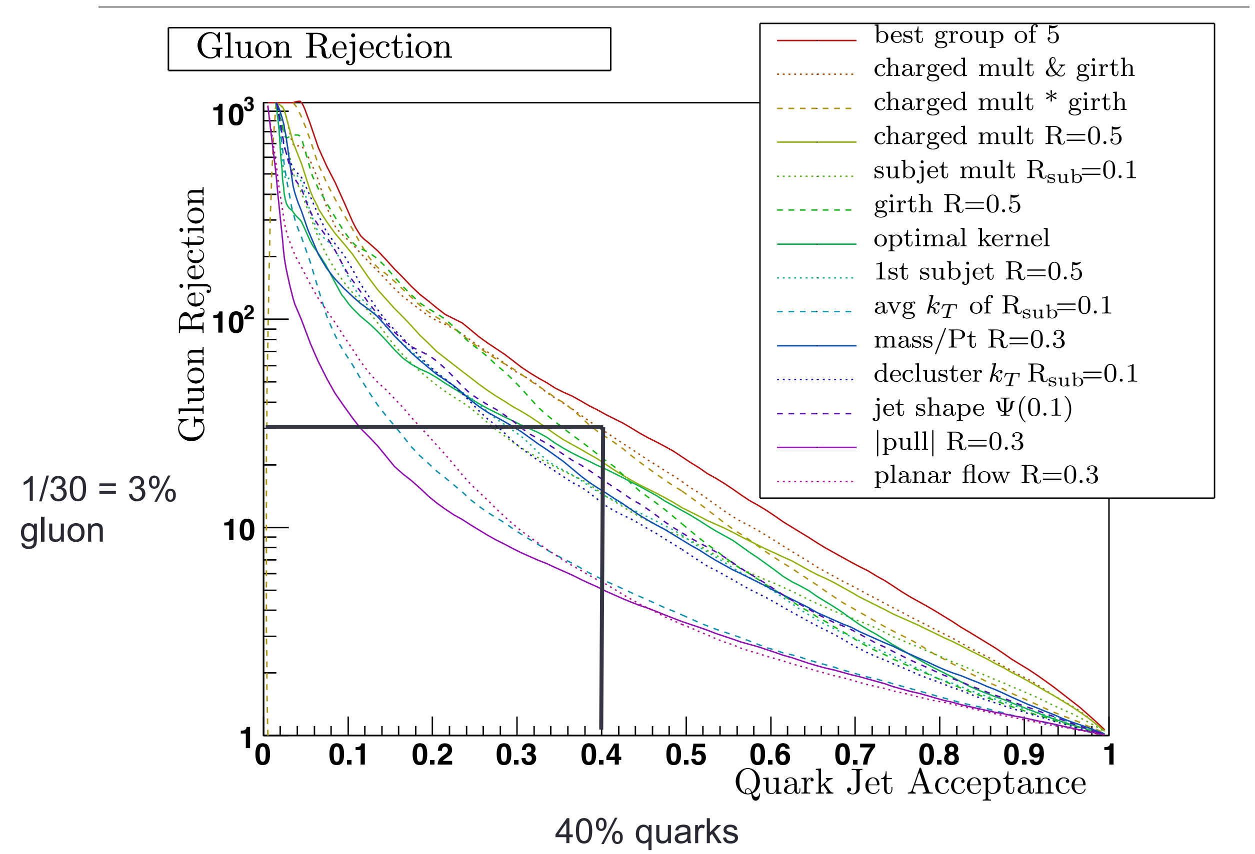
Gallicchio, Schwartz
1104.1175, 1106.3076

Quark versus Gluon jets

We looked at 10,000 variables

The menu, including varying jet size

- Distinguishable particles/tracks/subjets
  - multiplicity, $\langle p_T \rangle$, σ_{p_T}, $\langle k_T \rangle$,
  - charge-weighted p_T sum
- Moments
  - mass, girth, jet broadening
  - angularities
  - optimal kernel
  - 2D: pull, planar flow
- Subjet properties
  - Multiplicity for different algorithms and $R_{\rm sub}$
  - First subjet's p_T, 2nd's p_T, etc.
  - Ratios of subjet p_T's.
  - k_T splitting scale



Show http://jets.physics.harvard.edu/qvg

Matthew Schwartz

Santa Fe 2012

Multivariate approach

Ellis, TSR, Scholtz
1210.1855 ,1210.3657

Photon vs. QCD-jets vs. Photon-jets

Jet substructure in photon physics

substructure variables

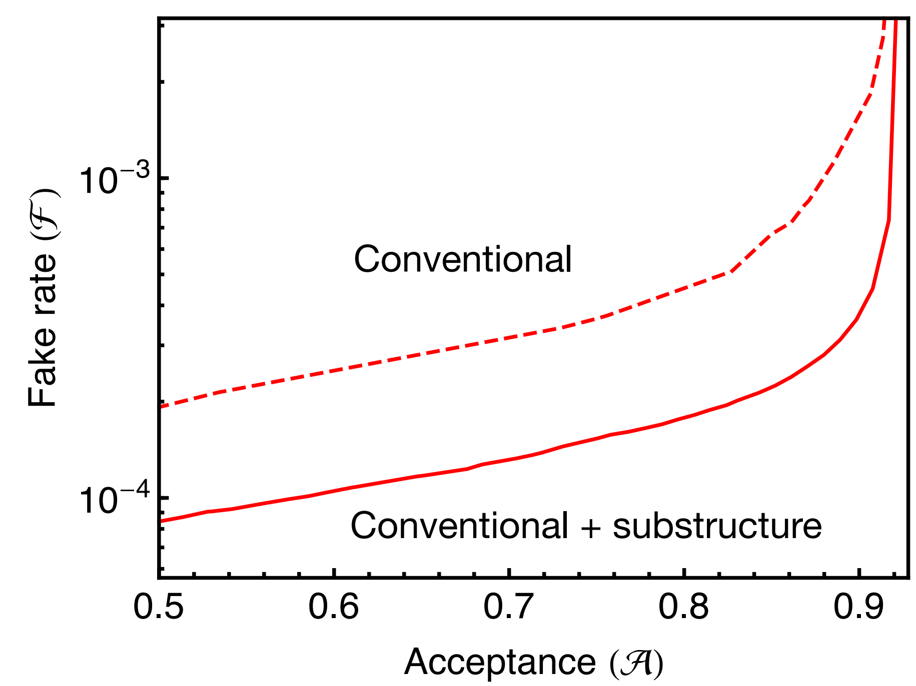
N-Subjettiness $$\tau_N = \frac{\sum_k p_{T_k} \times \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}}{\sum_k p_{T_k} \times R}$$

Leading Subjet $$\lambda_J = \log\left(1 - \frac{p_{T_L}}{p_{T_J}}\right)$$

Energy-Energy Correlation $$\epsilon_J = \frac{1}{E_J^2} \sum_{(i>j)\in N_{\text{hard}}} E_i E_j$$

Subjet Spread $$\rho_J = \frac{1}{R} \sum_{(i>j)\in N_{\text{hard}}} \Delta R_{i,j}$$

Subjet Area of the Jet $$\delta_J = \frac{1}{A_J} \sum_{i\in N_{\text{hard}}} A_i$$



Photons vs. QCD-jets

Multivariate approach

Ellis, TSR, Scholtz
1210.1855 ,1210.3657

Photon vs. QCD-jets vs. Photon-jets

substructure variables

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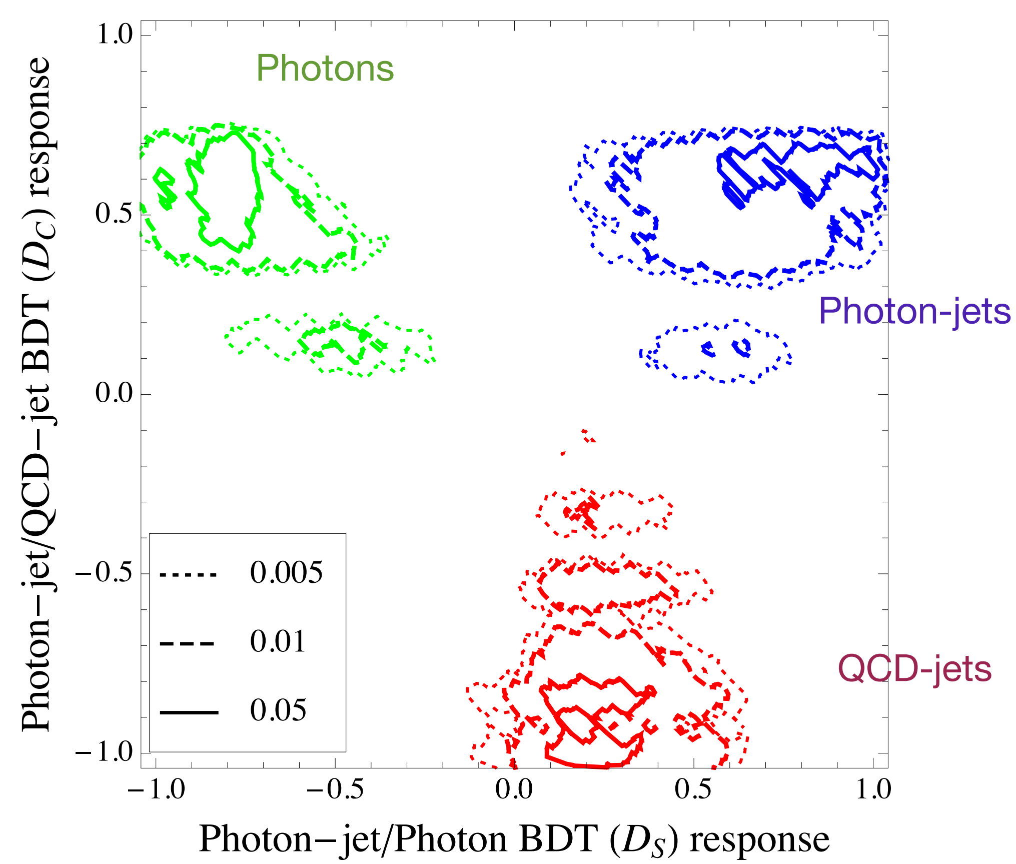
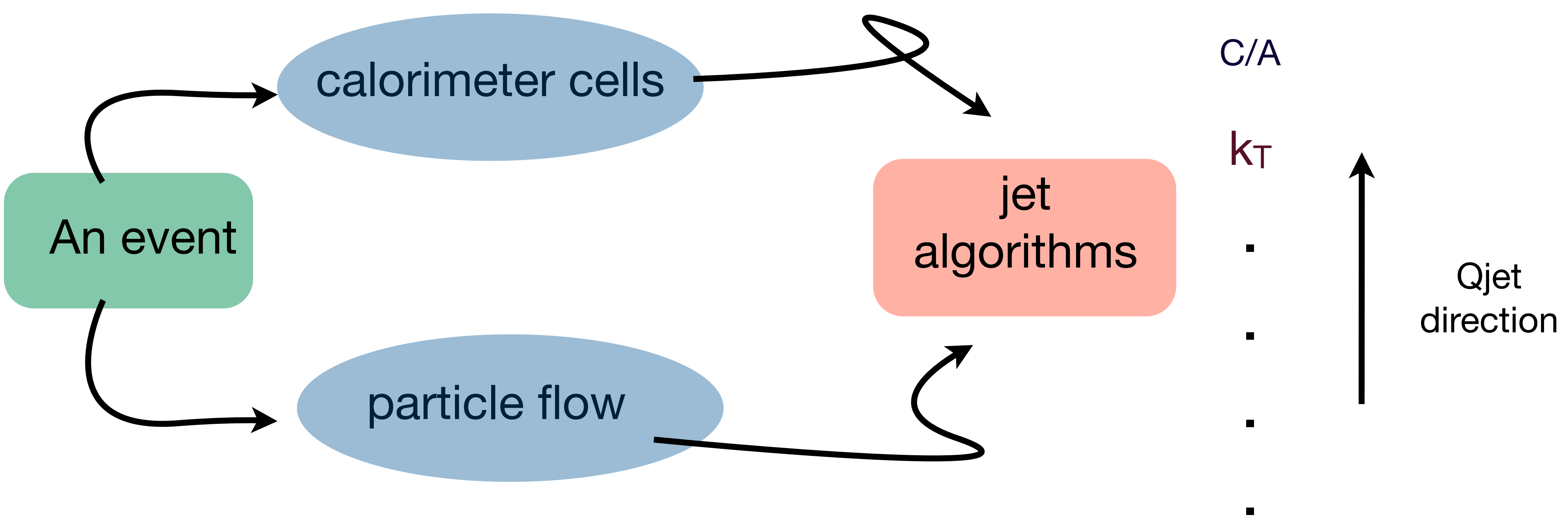


QJets

Ellis, Hornig, Krohn, TSR, Schwartz

1201.1914

Qjets is an idea that explores the dimension of clustering history



it is a challenging task

QJets

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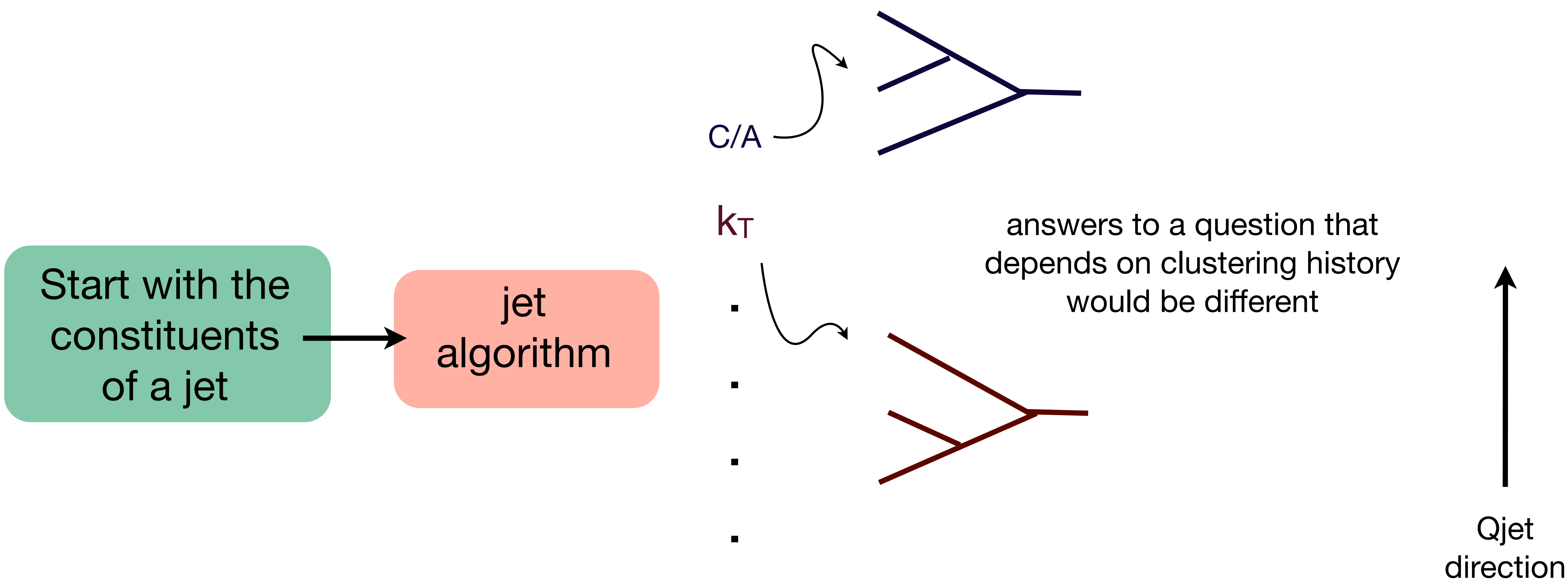


it is a challenging task -- let us start with something simpler

QJets

Ellis, Hornig, Krohn, TSR, Schwartz

1201.1914

As in a sequential recombination algorithm, assign every pair of four-vectors a distance measure d_{ij}.

However, unlike a normal sequential algorithm (where the pair with the smallest measure is clustered), here a given pair is randomly selected for merging with probability

$$\Omega_{ij} = \frac{1}{N} \exp\left(-\alpha \; \frac{d_{ij}}{d_{\min}}\right)$$

rigidity parameter

Repeat many (~100-1000) times, till the distribution (of the observable) stabilizes.

QJets

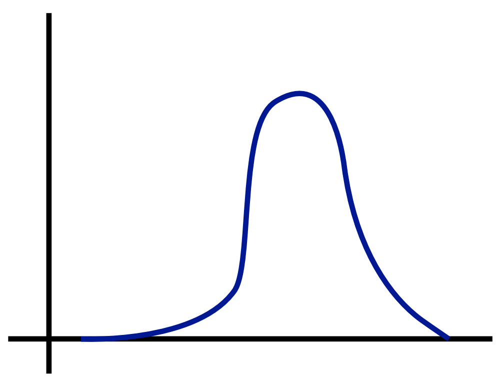
Ellis, Hornig, Krohn, TSR, Schwartz

1201.1914

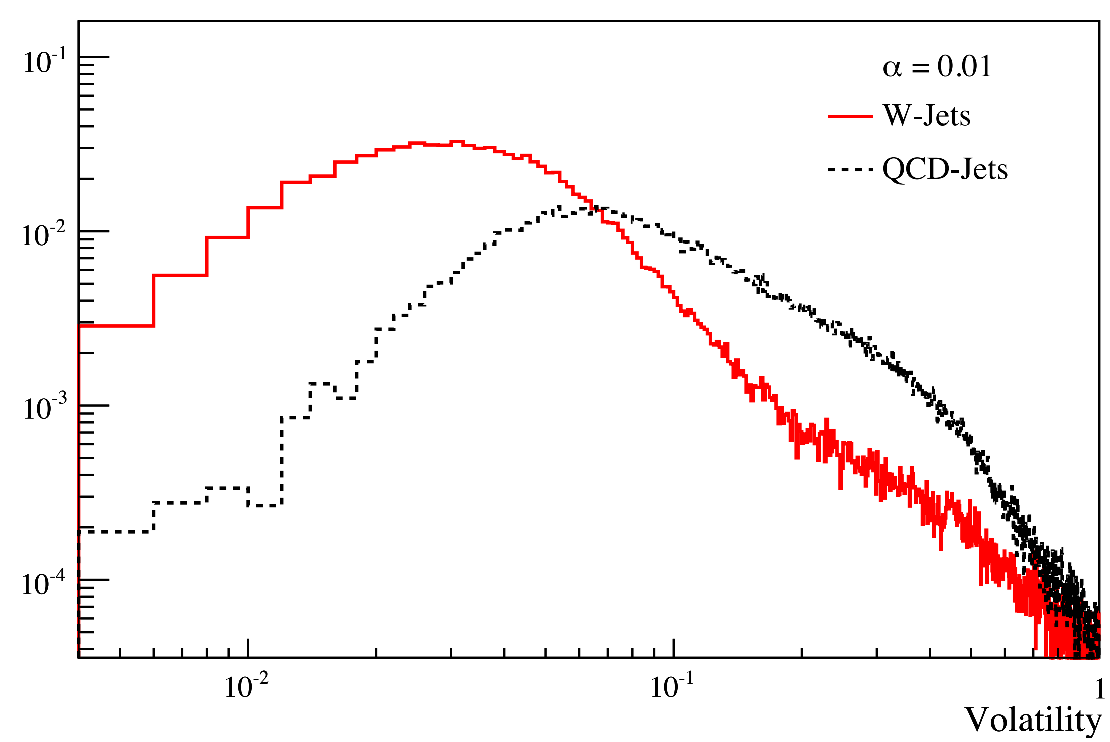
Take a sample jet

cluster it many times using QJets clustering algorithm

prune it every time it is being clustered



QJet pruned jetmass distribution for a single jet



volatility of a jet $\mathcal{V} = \dfrac{\omega_p}{m_p}$

ω_p = width of jetmass distribution

m_p = averaged pruned jetmass

QJets

Ellis, Hornig, Krohn, TSR, Schwartz

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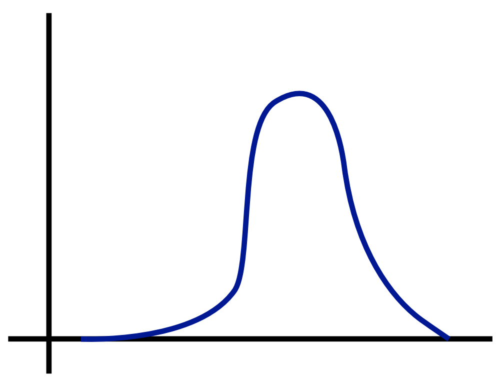

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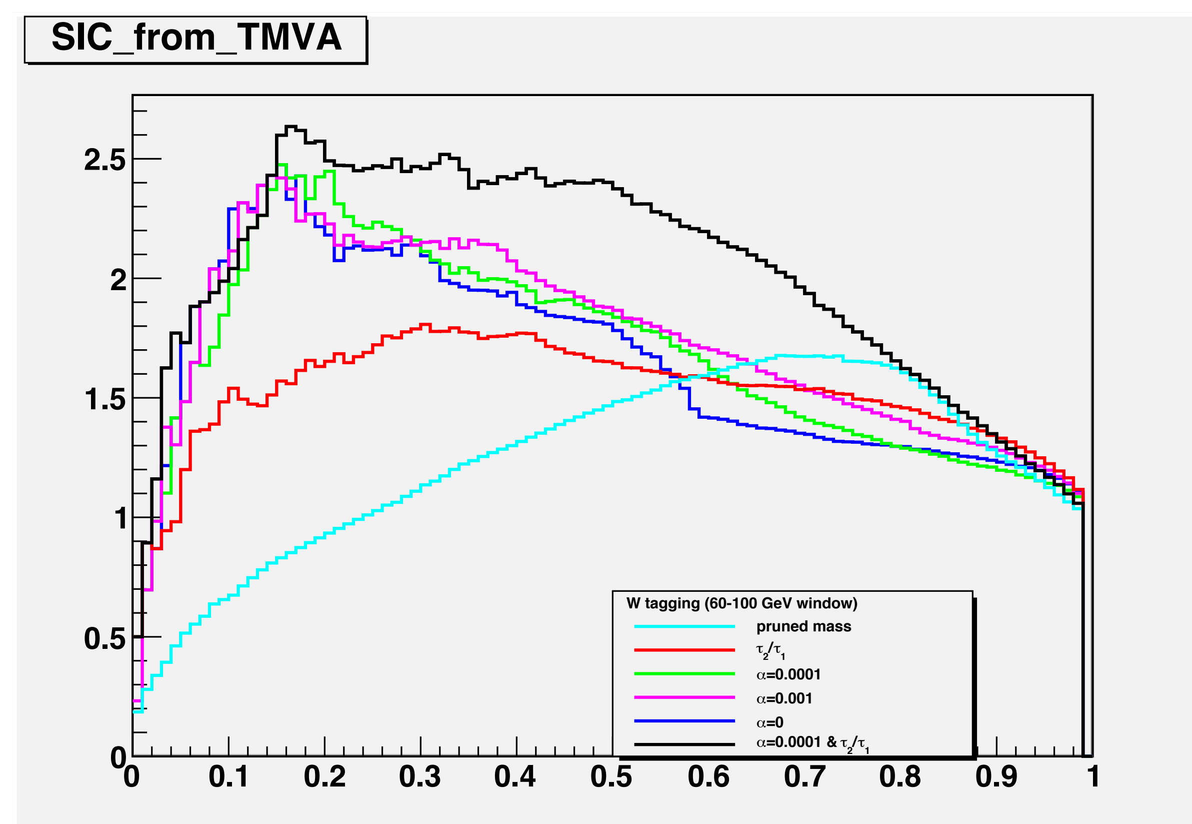


Outlook

Progress we've made, theoretical and experimental, was not imaginable a few years ago, when the discussion about jets used to be confined to "cone" v. "k_t"

Today we have basic subjet tools + many advances (shapes, Qjets, deconstruction, BDT taggers, ...)

Successful adoption by the experiments!

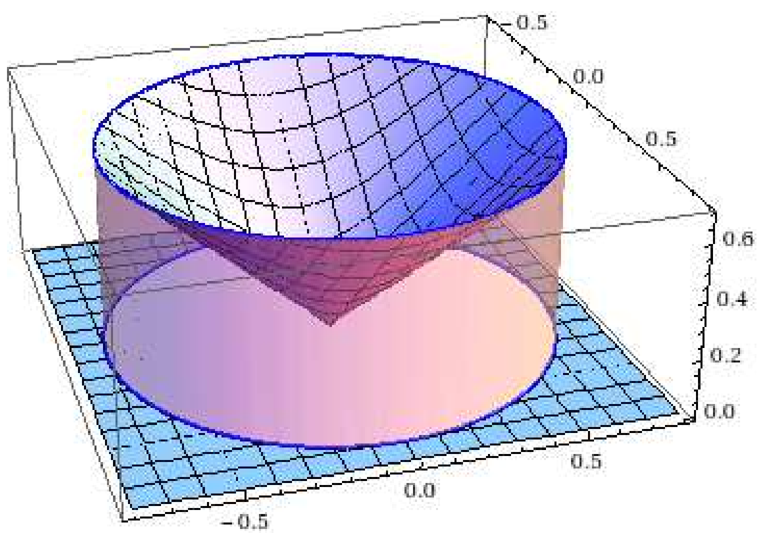
Job for theorists now:
Really understand the taggers?
Understand intermediate p_t regions?
More searches?

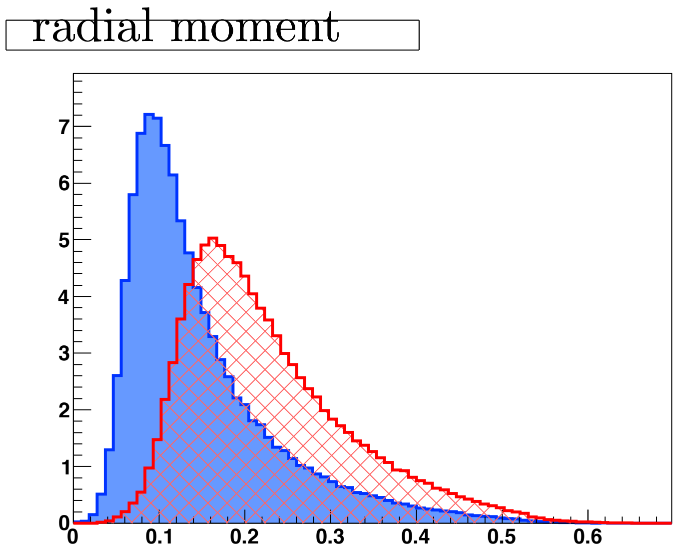
back-up

Girth

Weight p_T deposits by distance from jet center

Radial Moment, or Girth : $$g = \frac{1}{p_T^{jet}} \sum_{i \in \text{jet}} p_T^i |r_i|$$





Planar flow

Defined in
L. Almeida, S. Lee, G. Perez,
G. Sterman, I. Sung, J Virzi, arXiv:0807.0234