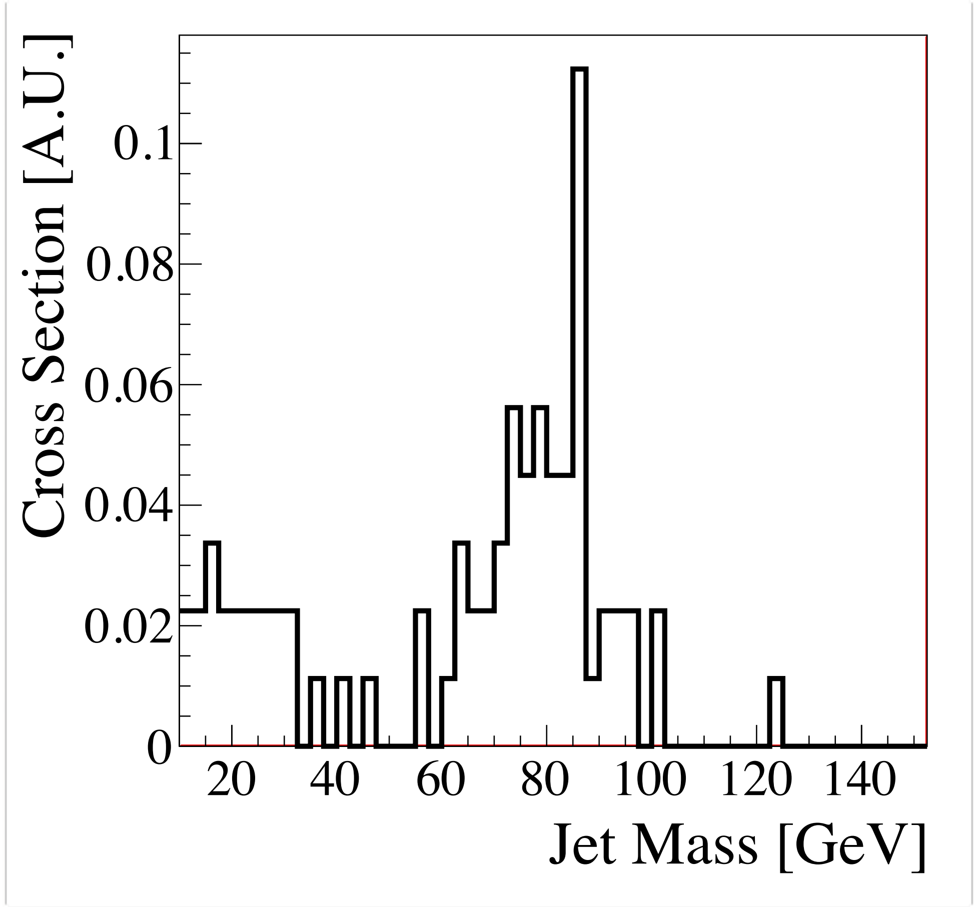
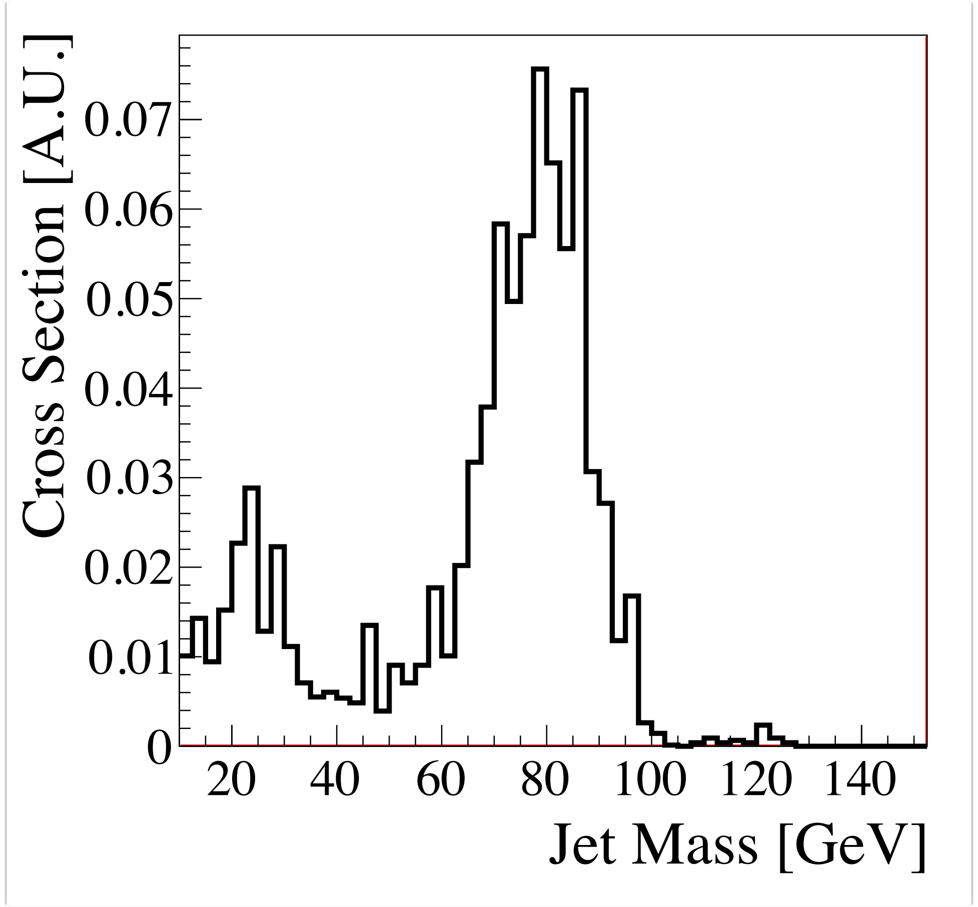




New Jet Tools

David Krohn (Harvard)

Chicago 2012 Workshop On LHC Physics, 5/2/12

Outline

- New Measurements of Particle/Event Properties
- Improved Taggers
- General Techniques
- Formal Developments

- *Note: I won't really discuss analyses tailored to a specific new physics signal (e.g. boosted stops) - lots of interesting work here, but not enough time.*

Takeaway

- The first iteration of substructure tools has been experimentally checked and the results are very encouraging.

1. Techniques have are/have developed to measure new properties of light parton jets (color charge, color connections, electric charge)

2. Lots of general techniques exist to improve/simplify the search for boosted heavy particles

3. Progress in more formal analytic calculation has been made

Introduction

Recent History

- Jet substructure was first proposed in the 90’s by Mike Seymour.
- Butterworth et. al. applied substructure techniques in ’02 to the study of WW scattering.
- There’s was a significant burst of activity in jet substructure in ‘08
  - Butterworth et. al.’s search for boosted Higgs
  - Thaler/Wang, Johns Hopkins, Stony Brook top taggers
- Jet grooming techniques ’08 and ’09 (Filtering/Pruning/Trimming)

- Experimental studies of the '08 and '09 theory papers have been coming out over the past year. The results are encouraging! (see talks by Miller and Rappoccio)
  - The procedures work as advertised and backgrounds seem to be well modeled by Pythia/Herwig.

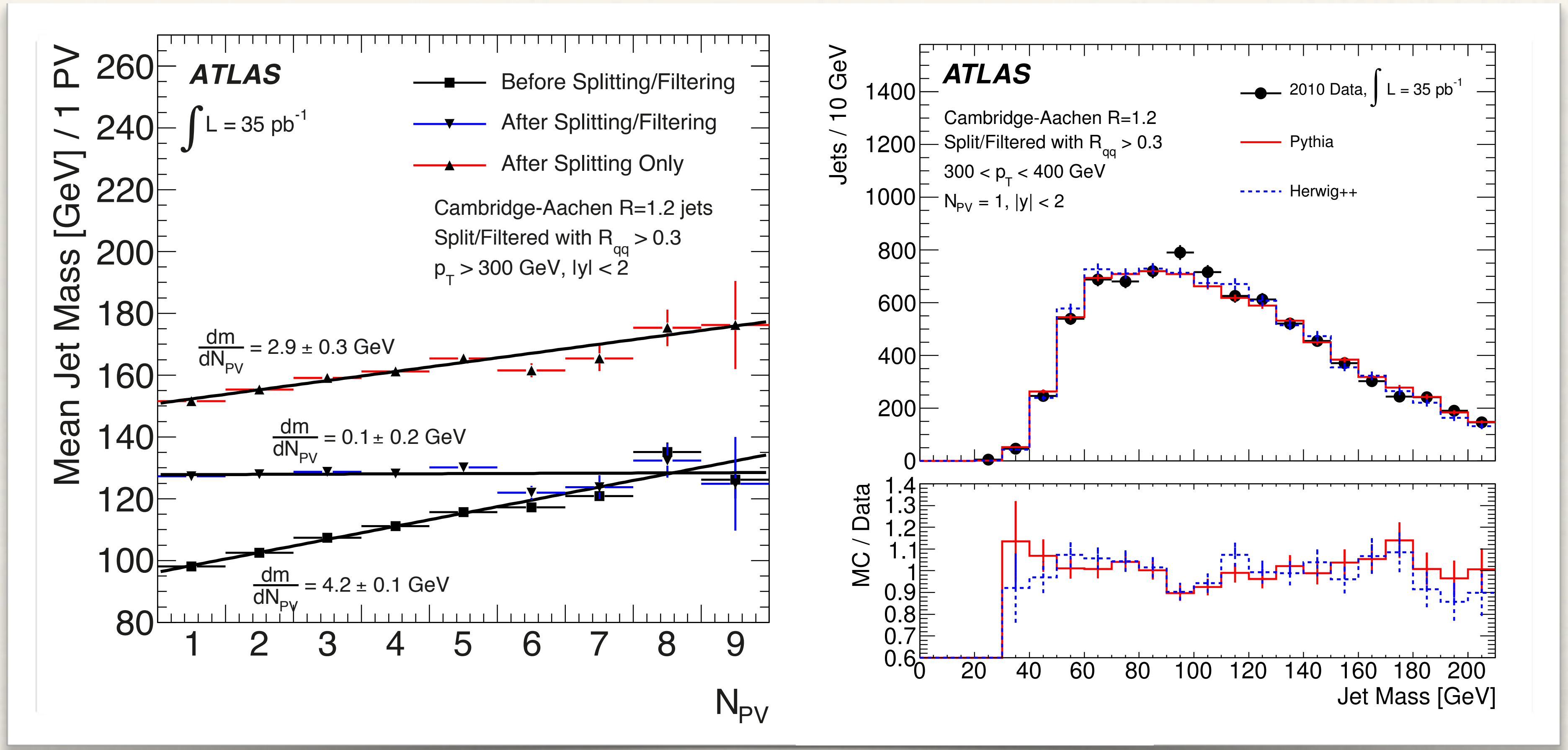


Figure source: 1203.4606

- Theorists have therefore been encouraged to develop more sophisticated techniques to extract more information.
    - No rest for our experimental friends.

- For a review of recent activity, see the ’10 and ’11 boost proceedings, [1012.5412,1201.0008] as well as an overview of top tagging techniques in [1112.4441]

Measuring New Event Properties

Quarks vs. Gluons

- Because they have different "color charges", a jet from a gluon will shower differently than a quark.
- Jet mass gets at this information, but there are other observables sensitive to the difference.
- *Quark and gluon tagging at the LHC* [1106.3076] introduces some of these observables and discusses calibration regions.

$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} |r_i|$$

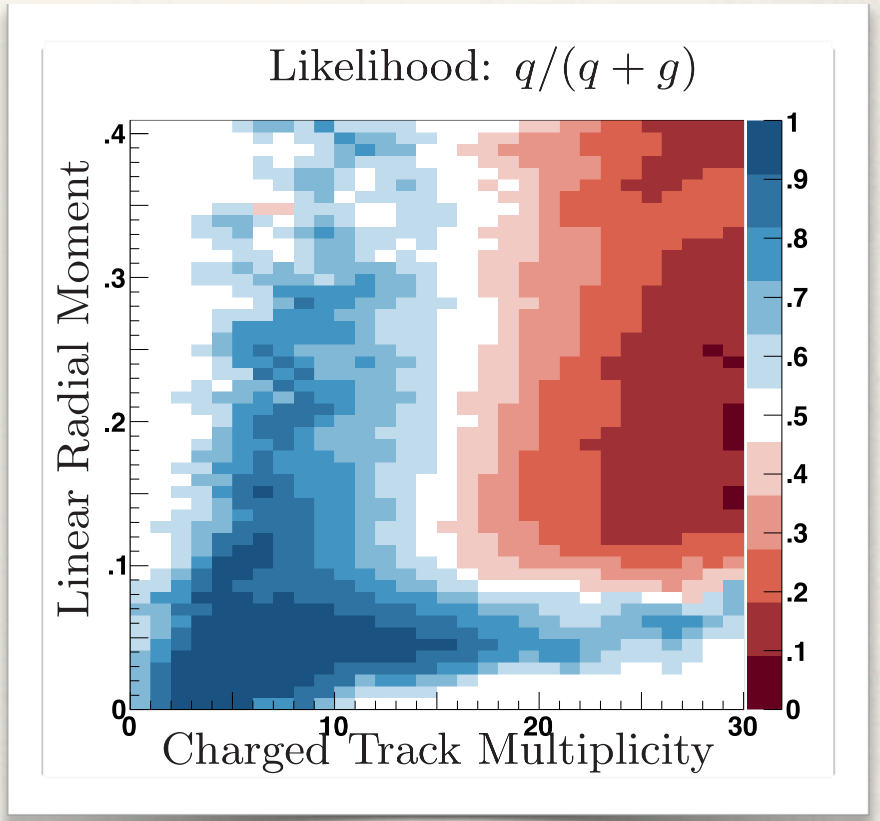
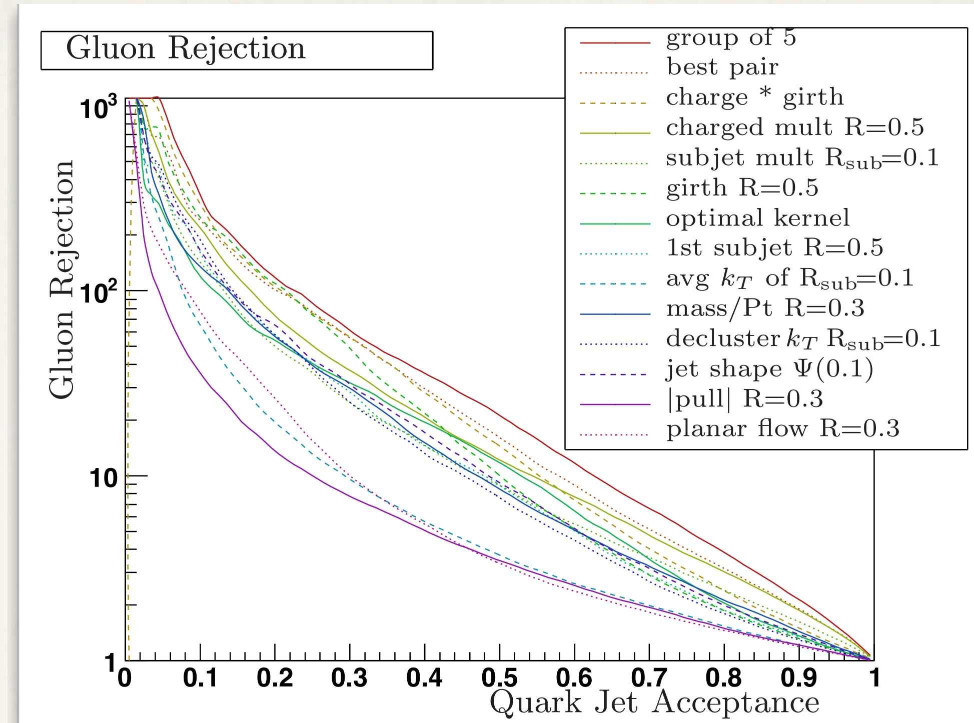


Figure source: 1106.3076

- Apply BDT - can keep 50% of quark jets, discard 95% of gluon jets.

- In a related paper [1104.1175] they define regions of high q/g concentration - will allow for calibration.



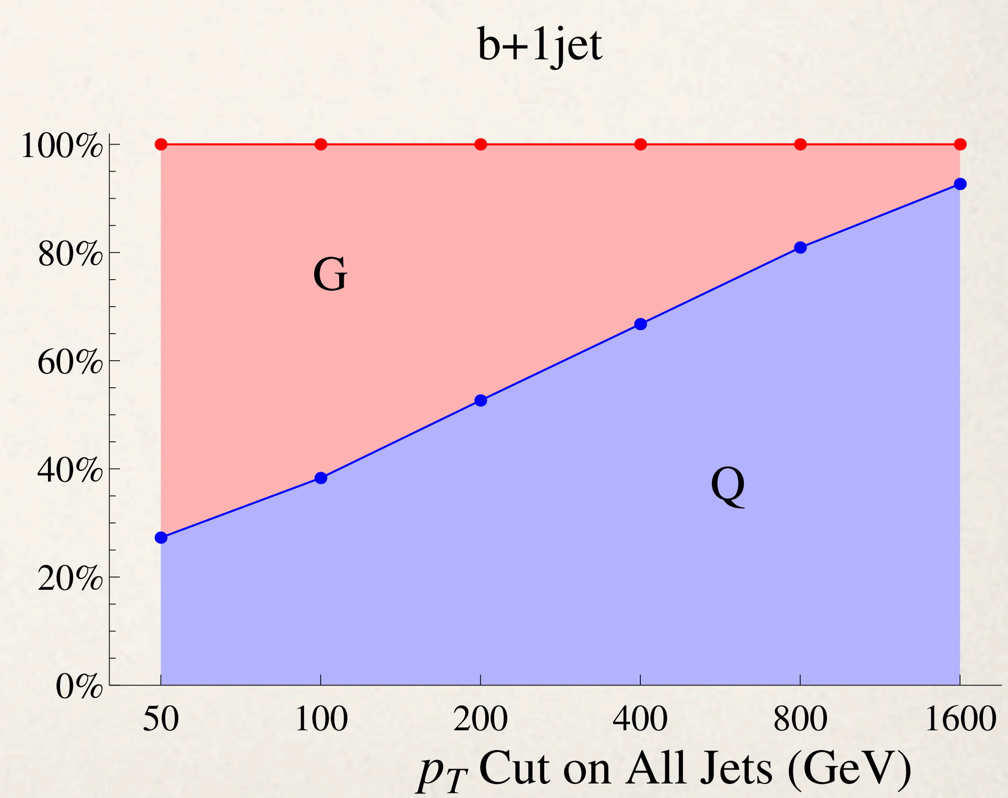
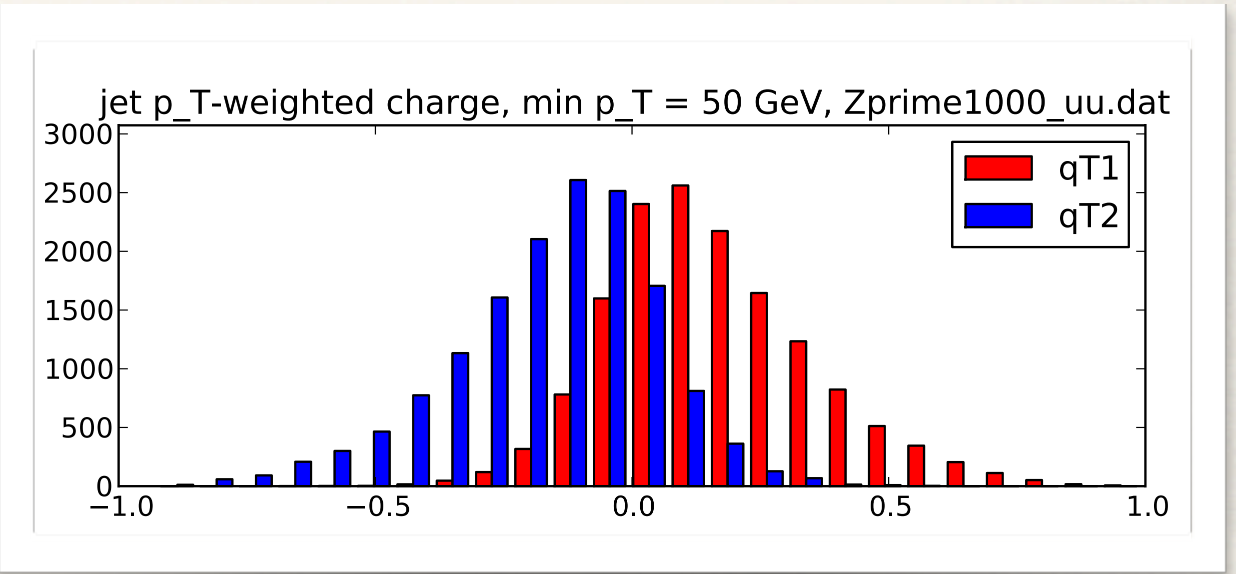


Figure sources: 1106.3076, 1104.1175

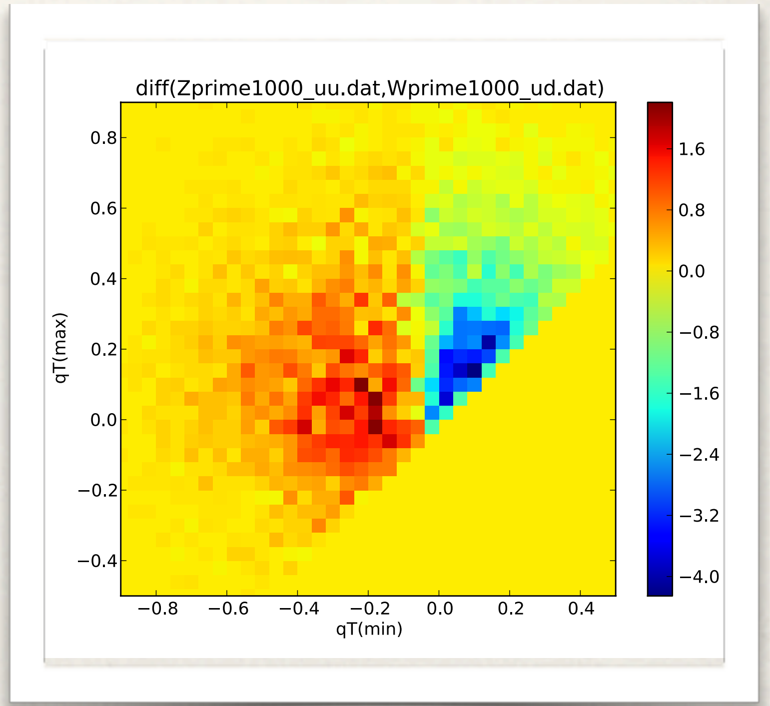
Jet Charge (u vs. d vs. g)



- Similarly, the partons which initiate jets give rise to a cloud of hadrons which retain some of the charge information.

- Hard to see, but the LHC is an exquisite machine - possible.

$$\frac{\sum_i Q_i p_{T,i}}{\sum_i p_{T,i}}$$



Based on work in progress with T. Lin, M. Schwartz, W. Waalewijn

- Develop methods to calibrate and evolve to different scales.
  - Will reduce theory uncertainties from fragmentation functions

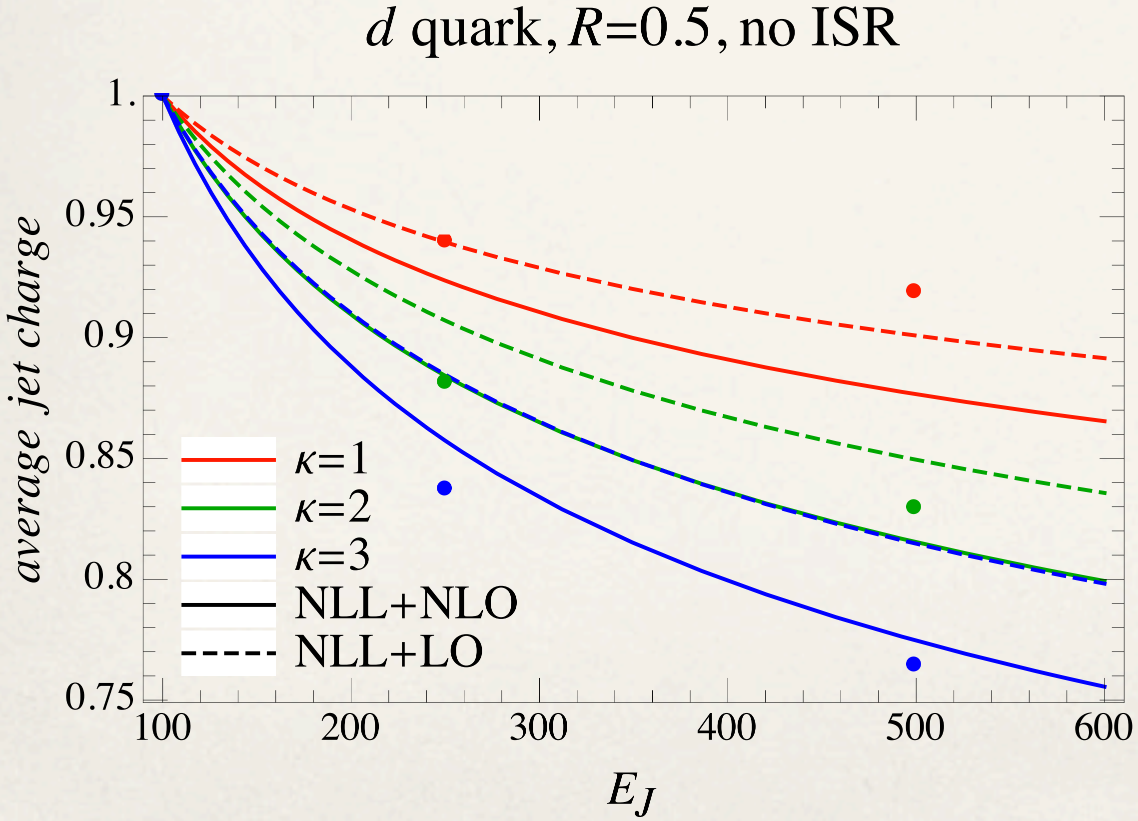
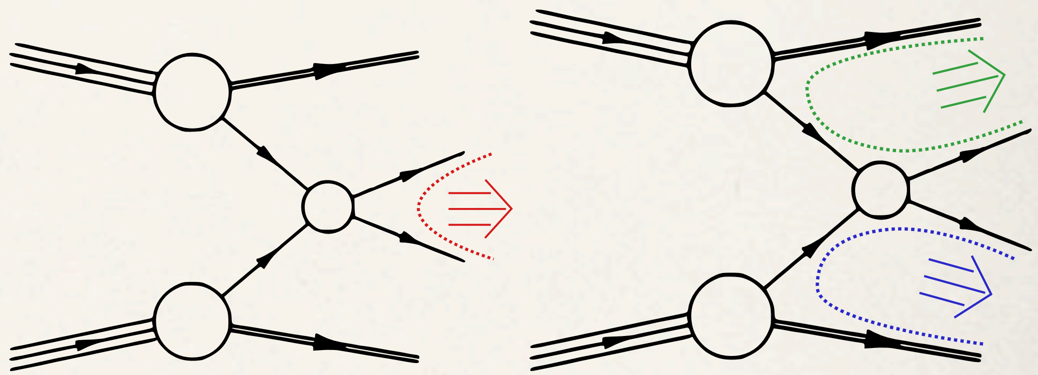


Figure source: Wouter Waalewijn

- Could help improve BSM searches
  - W′ vs Z′, VBF, RPV SUSY
  - With pure signal , can distinguish W′ from Z′ with ~20 events.
- Also measurements of the SM (e.g. top pol. / correlation)

Color Structure

- The leading color lines for, say, h->qq are different than, g->qq
- These can lead to different radiation patterns in the event
  - Measurable by looking at where the radiation "points" [1001.5027]
- Helpful for many channels, both SM (e.g. Higgs) and BSM [1006.1650]



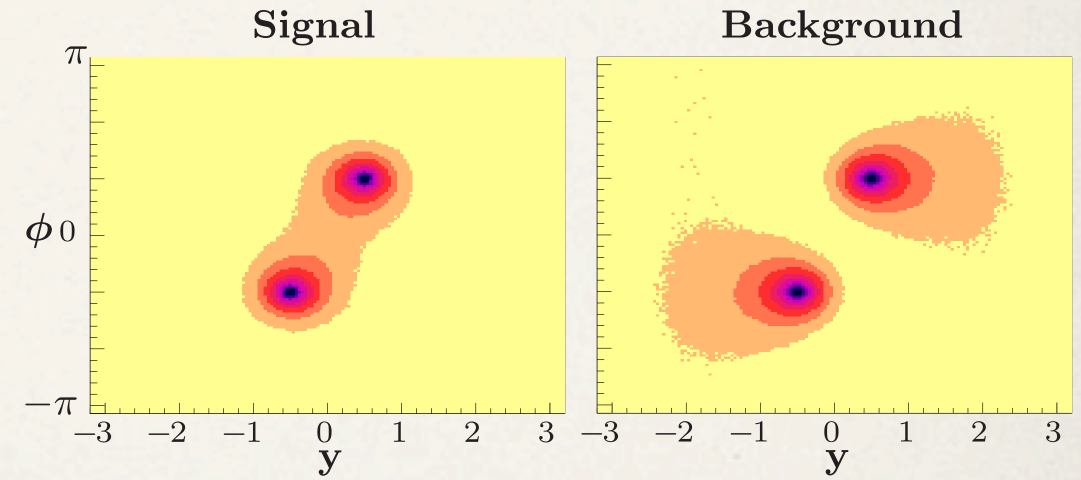
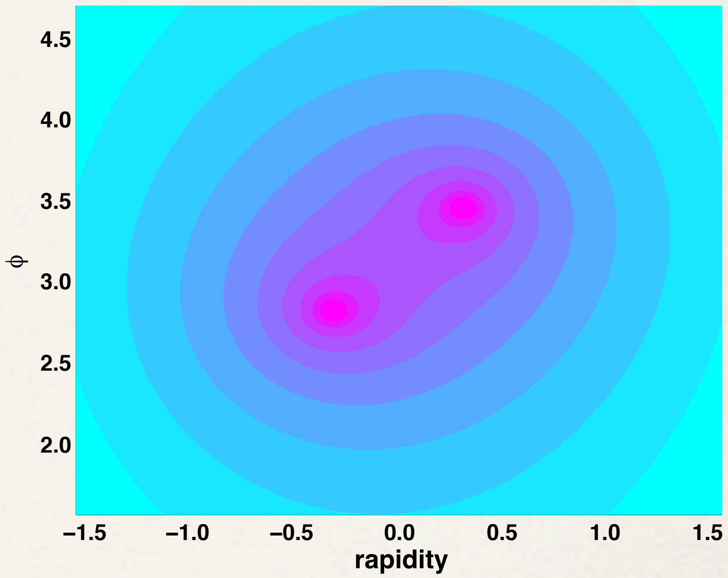


Figure source: 1001.5027

Improved Taggers

Turbo Taggers

- Since the original set of top taggers (Thaler/Wang, JHU, Stony Brook), much work has gone into refining the algorithms and incorporating new information
  - e.g. *Jet Dipolarity: Top Tagging with Color Flow* [1102.1012]
  - e.g. adding tracking information [1112.3378]



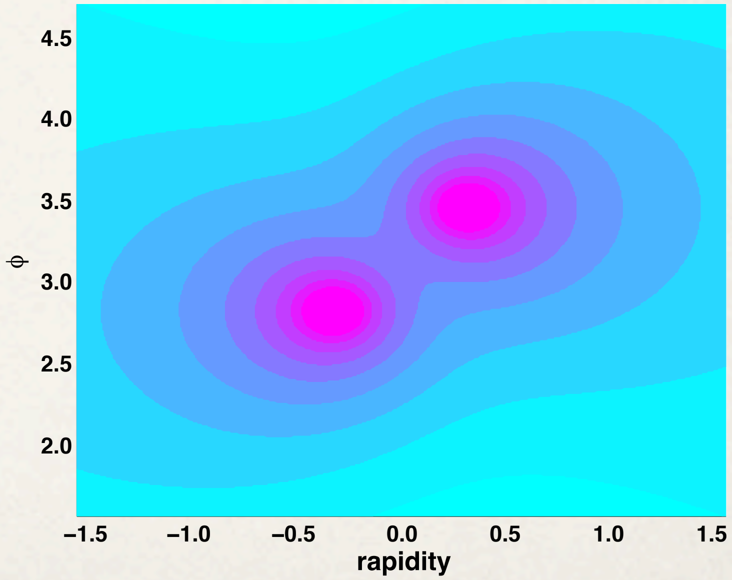


Figure source: 1102.1012

- BDT "kitchen sink" applied to W-tagging [1012.2077]
  - Employ jet shapes, grooming sensitivities, etc.
  - Find ~2x improvement in S/r(B)

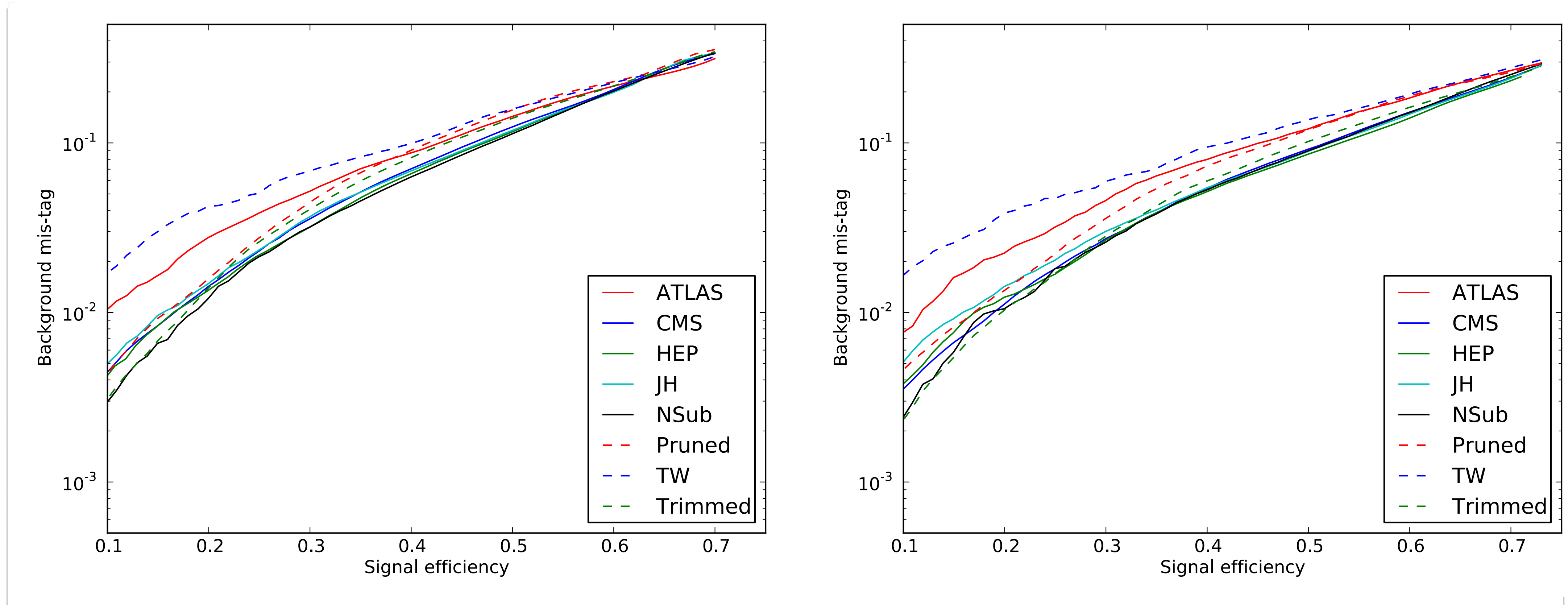
p_T (GeV)		200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000
filt	μ	.49	.4	.66	.66	.68	.69	.71	.71	.73	.72	.74	.72	.76	.74	.74	.76	.8
	y_{cut}	.13	.17	.15	.14	.12	.1	.09	.09	.08	.08	.07	.07	.06	.06	.06	.05	.04
	ε_S	.61	.52	.57	.58	.61	.64	.66	.65	.66	.64	.64	.61	.61	.6	.58	.58	.59
	ε_B	.13	.082	.084	.079	.083	.088	.089	.085	.086	.081	.08	.075	.076	.073	.072	.077	.084
	sig	1.7	1.8	2	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.2	2.2	2.2	2.2	2.2	2.1	2
trim	R_{sub}	.17	.22	.22	.21	.17	.17	.16	.15	.15	.15	.15	.16	.16	.15	.16	.15	.17
	f_{cut}	.08	.1	.11	.1	.09	.08	.08	.07	.07	.06	.05	.05	.05	.05	.04	.04	.03
	ε_S	.58	.61	.6	.62	.64	.67	.67	.69	.7	.72	.74	.74	.74	.74	.74	.71	.7
	ε_B	.1	.11	.1	.1	.1	.11	.11	.11	.11	.12	.12	.13	.13	.13	.14	.14	.15
	sig	1.8	1.8	1.9	1.9	2	2	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2	1.9	1.8
prun	R_{cut}^{factor}	.48	.54	.56	.53	.55	.52	.52	.52	.49	.32	.33	.35	.37	.39	.29	.17	.16
	z_{cut}	.17	.15	.13	.12	.1	.09	.08	.07	.07	.06	.06	.05	.05	.04	.04	.04	.03
	ε_S	.55	.57	.6	.62	.66	.68	.69	.71	.72	.73	.72	.73	.72	.73	.72	.7	.67
	ε_B	.1	.098	.099	.097	.1	.1	.11	.11	.11	.11	.11	.11	.11	.12	.12	.12	.12
	sig	1.7	1.8	1.9	2	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.1	2.1	2	1.9

} Part of the kitchen sink

Figure source: 1012.2077

- See also [1111.5034,1110.2214]

- At least for top tagging, after experimental resolution is taken into account, it looks like we're close to maxing out:



(a) all p_T, optimised

(b) p_T 500–600 GeV, optimised

Figure source: 1201.0008

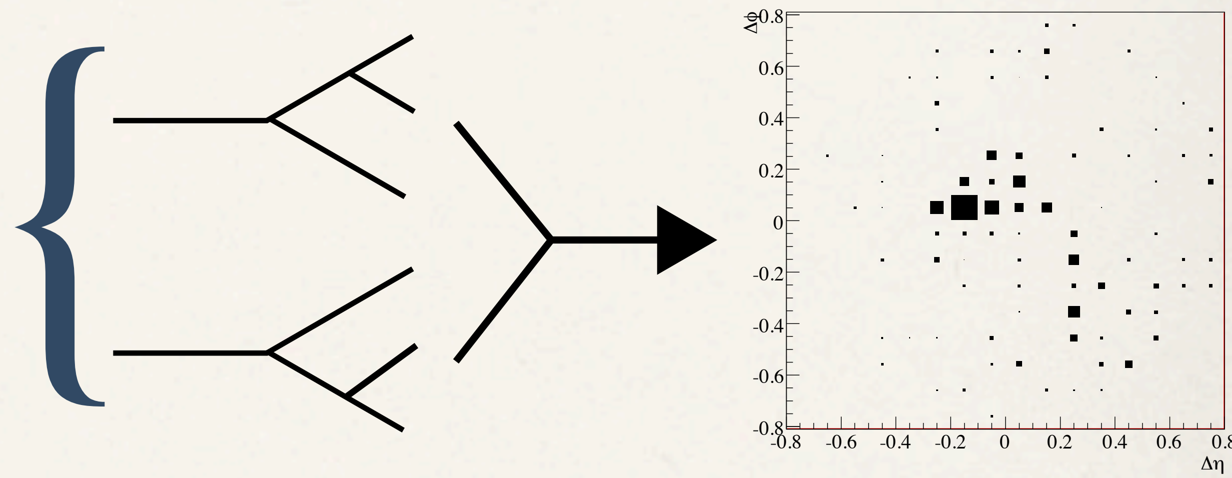
General Purpose Tools

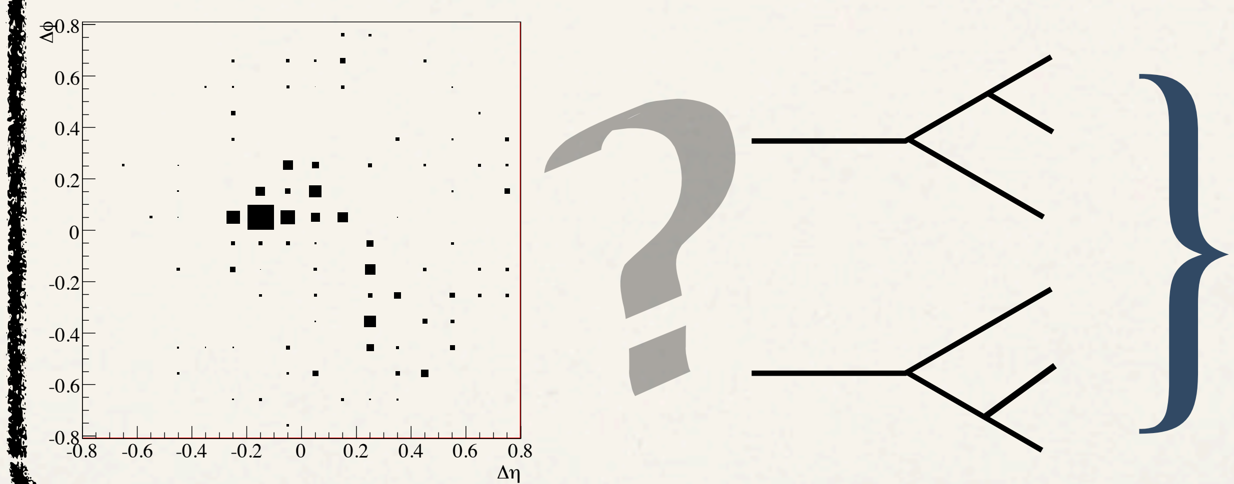
Better Statistics (QJets)

- Lots of algorithms make an semi-arbitrary choice and stick with it

- e.g., using CA over kT unwind a clustering history

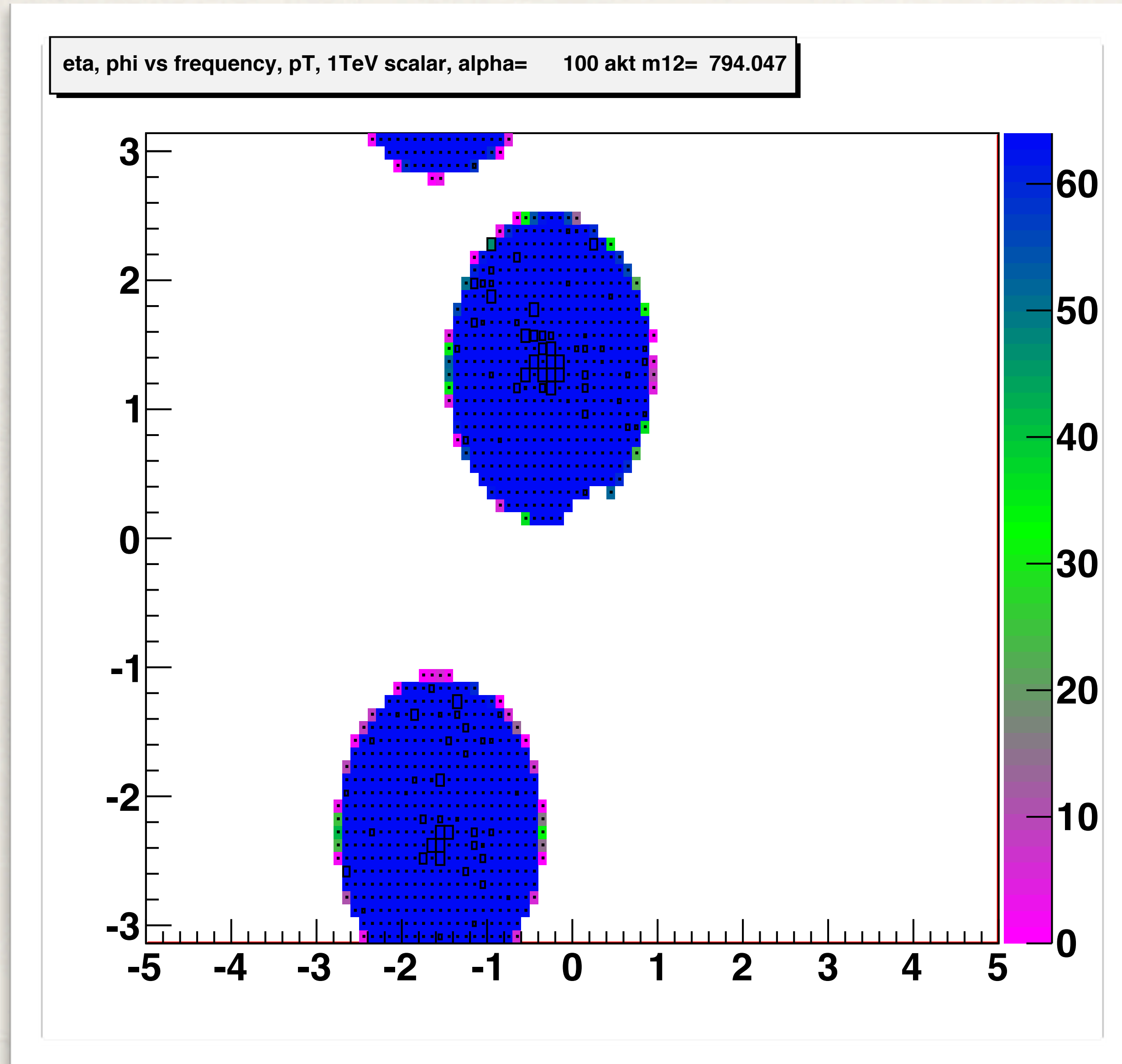
The energy distribution for a particular tree is unambiguous



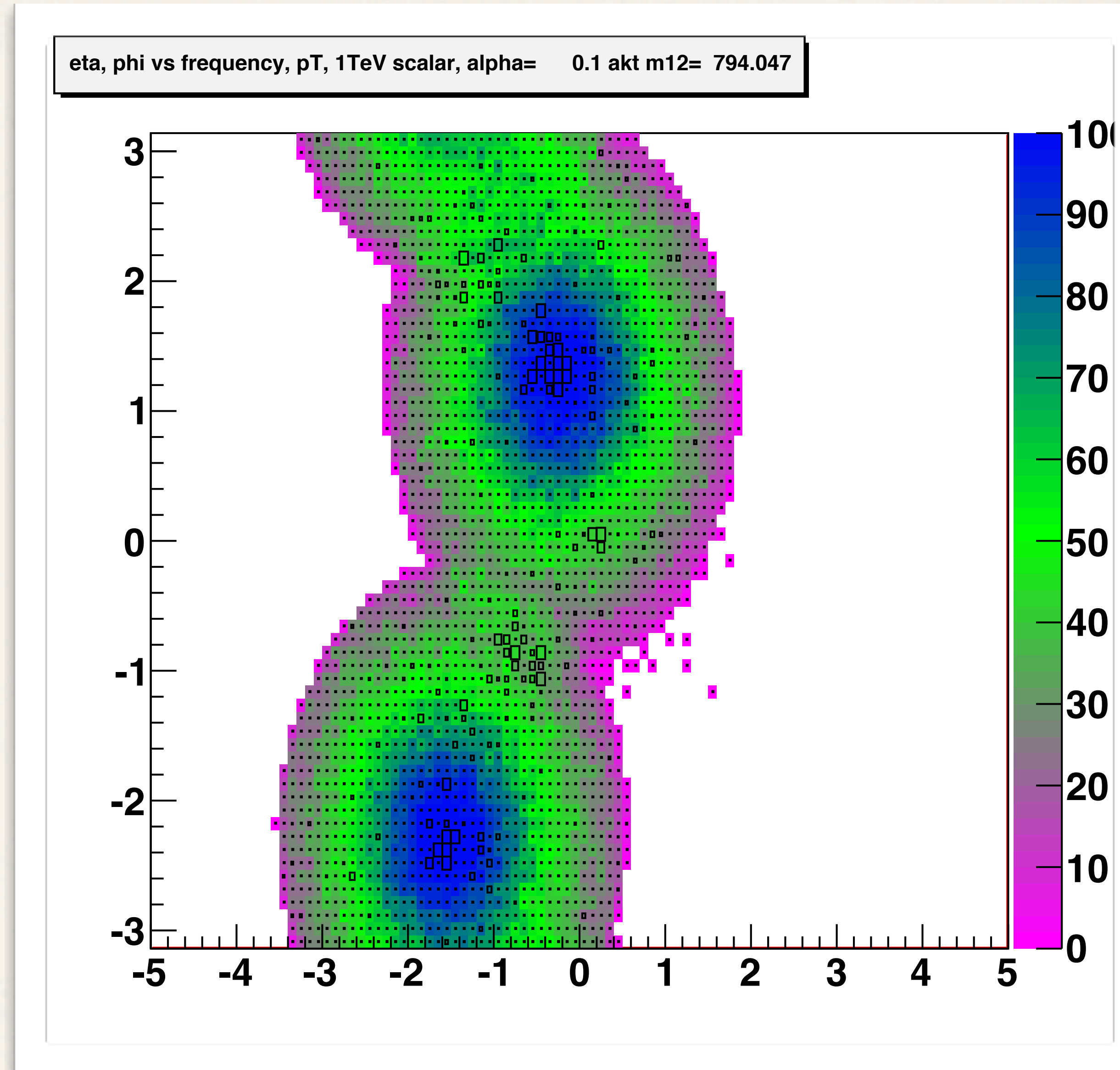


But, more than one tree can correspond to the same energy

- By averaging over these arbitrary procedures unwanted statistical fluctuations decrease [1201.1914] anti-kT



Qjets



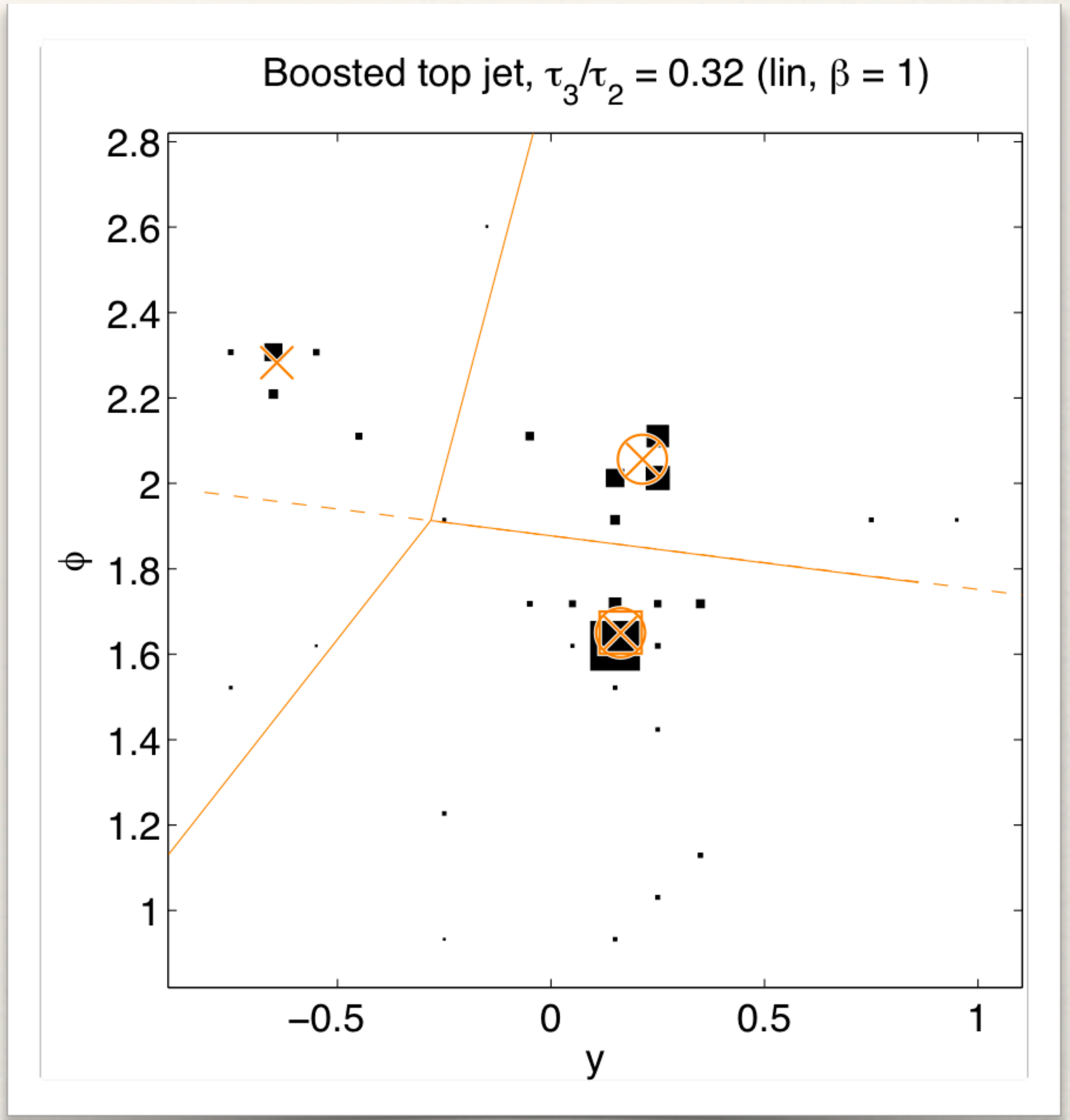
- Original paper focused on substructure - new work will study use as a general get algorithm: **Qanti-kT**
- When you cluster with Qjets, a calocell isn't either in a jet or not in it - it's in it some fraction of the time.

More General Substructure

- N-subjettiness: generalize thrust to substructure, so one can ask how "N-prong" like does a jet appear [1011.2268]

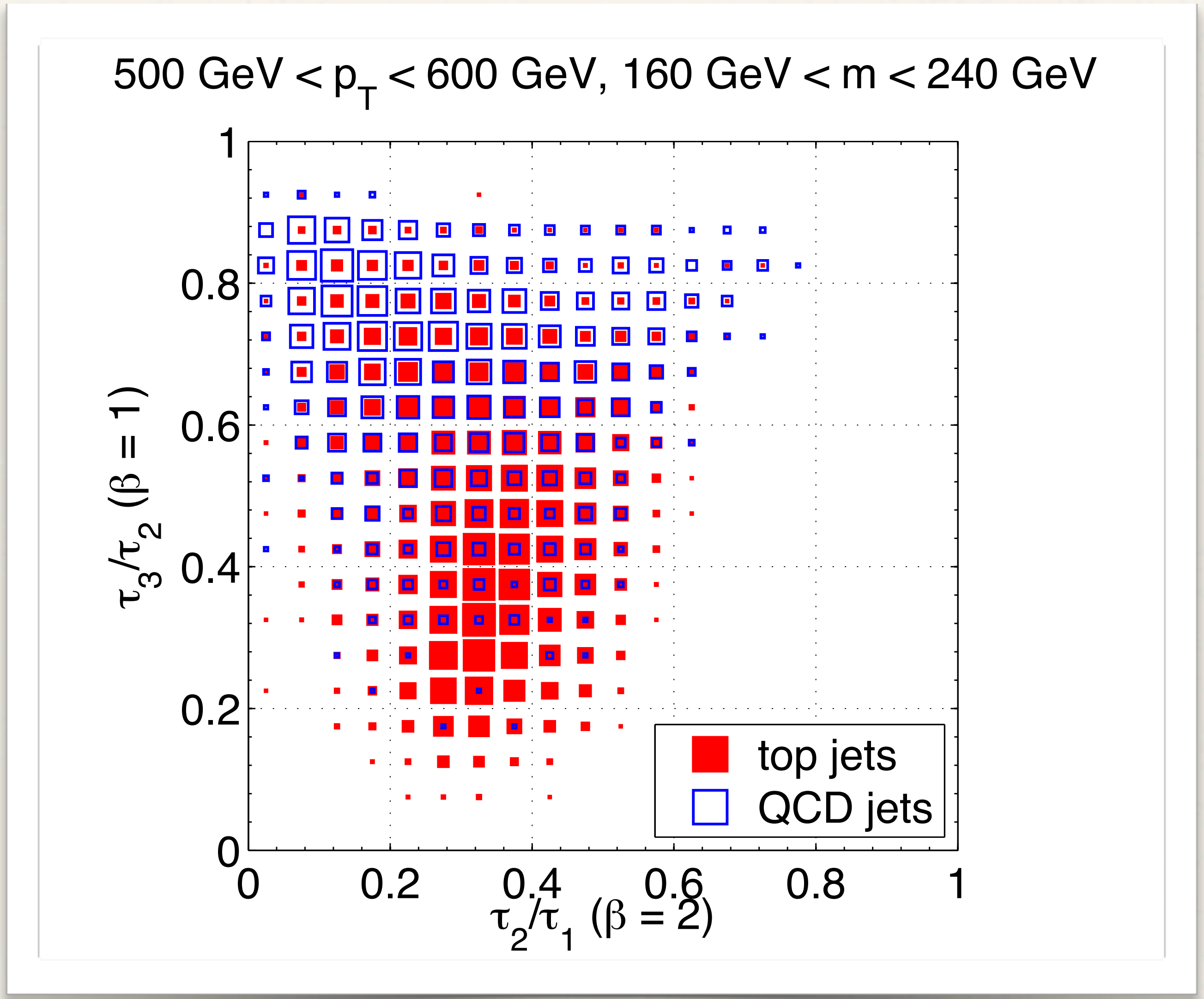
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \times \min(\delta R_{1,k}, \delta R_{2,k}, \ldots, \delta R_{N,k})$$

$$d_0 = \sum_k p_{T,k} R,$$



Source: http://www.jthaler.net/jets/NsubPicture.png

- Very competitive (leading?) top tagger [1108.2701]

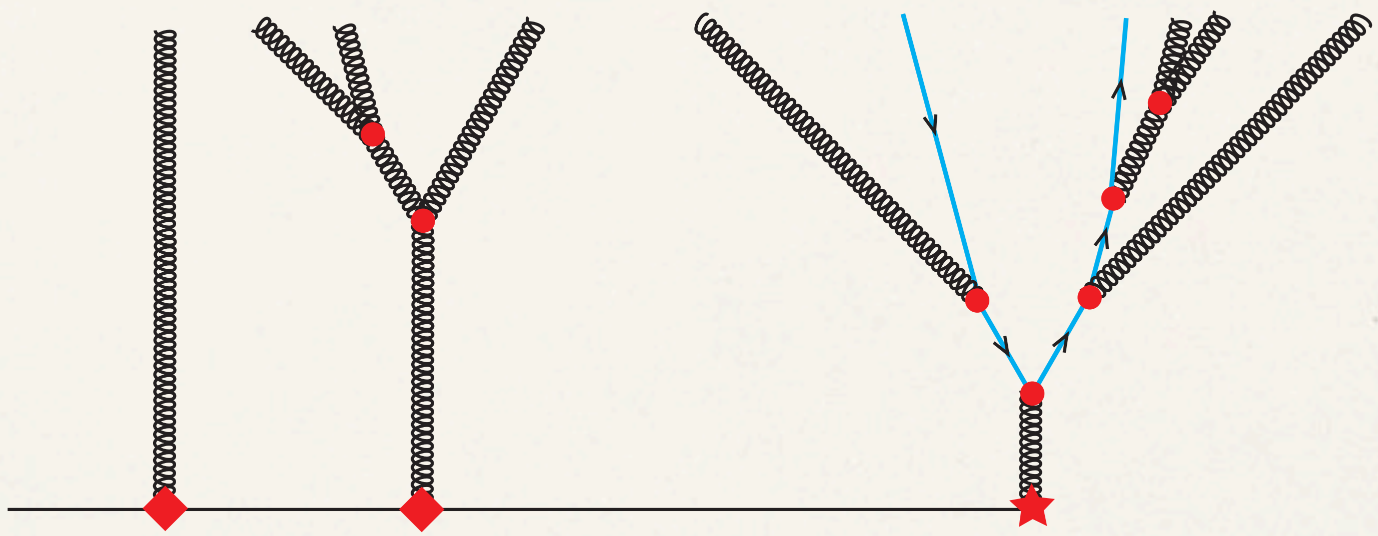


- Amenable to analytic treatment
    - Not based on algorithmic procedure

Figure source: 1108.2701

Other Cool Techniques

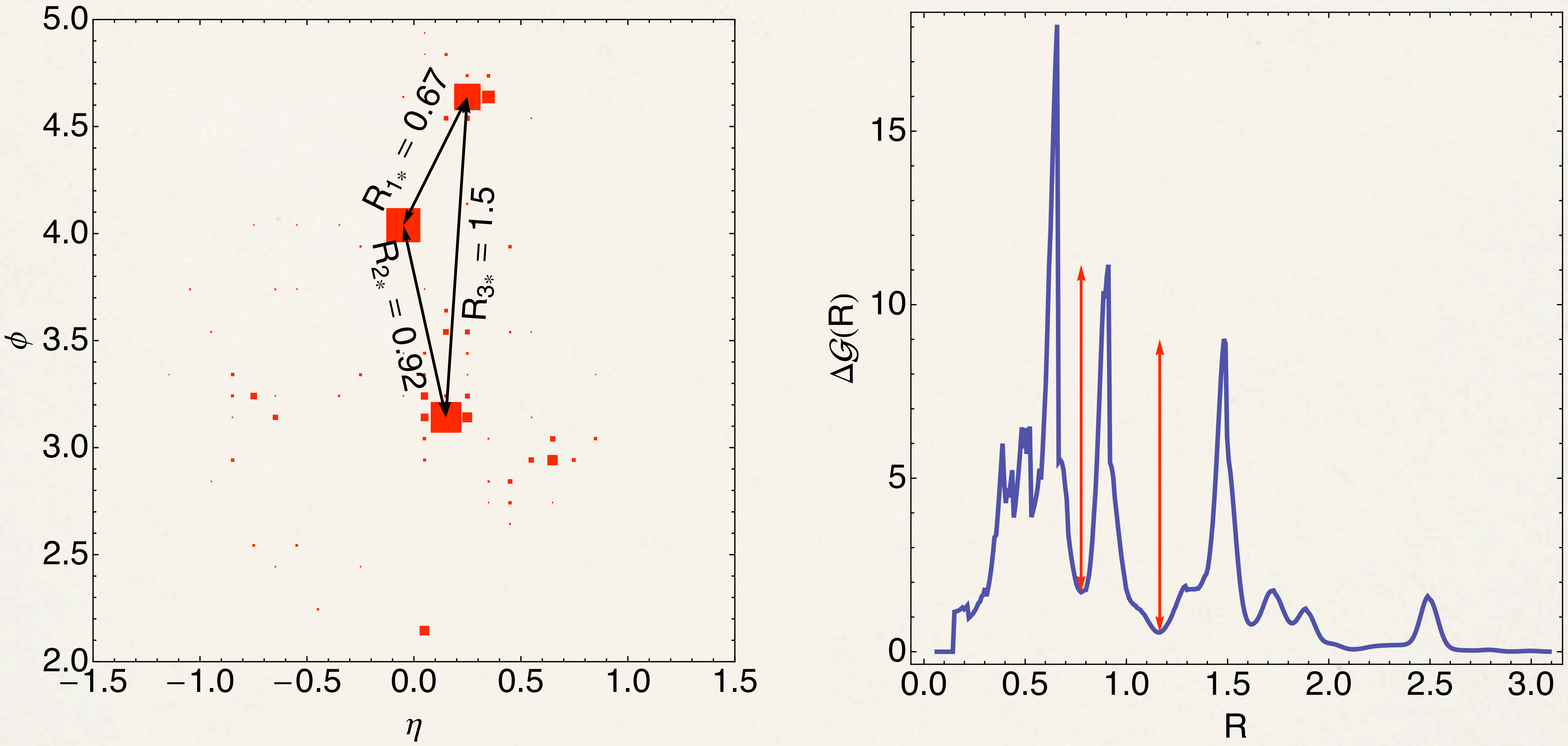
- Shower deconstruction: Apply full knowledge of showering+ISR+MI to determine event weight [1102.3480]



- Template overlap: Define overlap function of radiation with radiation expected from, say, top or Higgs decays [1006.2035,1112.1957]

Figure source: 1102.3480

- *Jet Substructure Without Trees* [1104.1646]
  - Use angular correlation functions



- *High Multiplicity Searches at the LHC Using Jet Masses* [1202.0558]
  - Look for a few massive jets rather than many skinny ones
  - Might be able to simplify the analysis

Figure source: 1104.1646

Formal Developments

Analytic Calculations

- Most jet tools are designed based on a qualitative understanding of QCD and later optimized using a MC.
- Recently, progress has been made in analytic calculations:
  - M. Rubin studied filtering parameters in [1002.4557]
  - [1204.3898] studied 2-subjettiness in boosted Z->qq using SCET

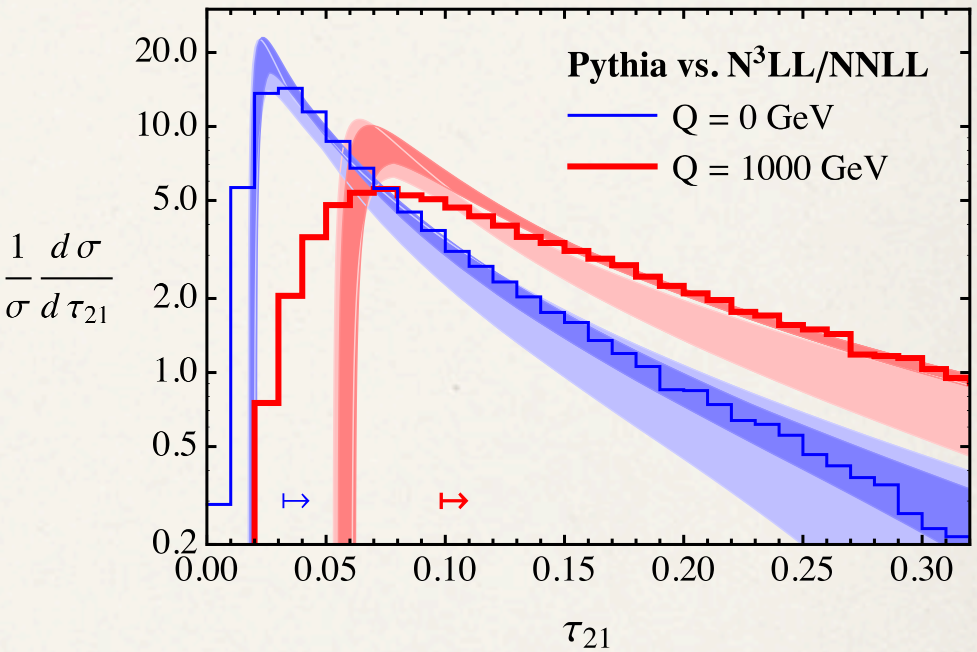


Figure source [1204.3898]

Factorization

- Walsh and Zuberi studied the properties of different jet grooming procedures [1110.5333]
  - Mass drop + filtering, pruning, trimming, N-subjettiness
  - Generic declustering+filtering doesn't factorize, but can be made to allow factorization to work

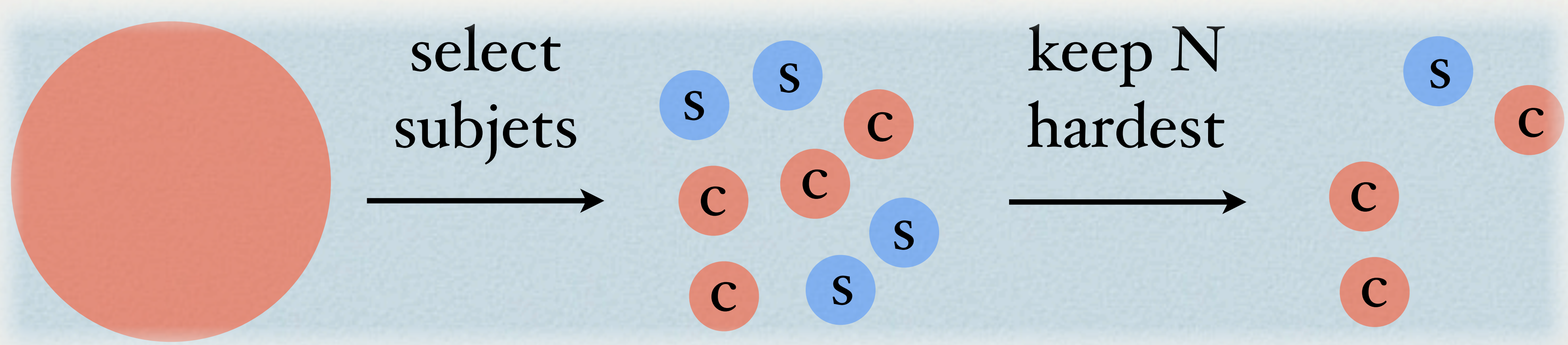


Figure source: http://indico.cern.ch/getFile.py/access?contribId=20&resId=0&materialId=slides&confId=113980

Targeted Analyses (only a sample)

- Boosted SUSY
  - *Stop Reconstruction with Tagged Tops* [1006.2833]
  - *Heavy Squarks at the LHC* [1102.0302]
- Higgses
  - *Discovering the Higgs Boson in New Physics Events using Jet Substructure* [0912.4731]
  - *Higgs Discovery through Top-Partners using Jet Substructure* [1012.2866]
  - *Ditau-Jet Tagging and Boosted Higgses from a Multi-TeV Resonance* [1011.4523]
  - Ditau jets in Higgs searches [1106.4545]
- Exotica
  - *Composite Octet Searches with Jet Substructure* [1107.3563]
  - *Uncovering the Charming Higgs at the LHC* [1203.5174]
  - *Diboson-Jets and the Search for Resonant Zh Production* [1204.0525]

Conclusions

- Tools have been developed to look at the detailed structure of the hard partons in an event: (1) q vs. g, (2) u or d, (3) color connections
- Top/W/Z/Higgs taggers have been improved. Probably reaching their limits.
- Fun new general purpose tools: smarter statistical treatment of jets, more general substructure characterization, many more...
- Analytic calculations have been made, important formal progress.