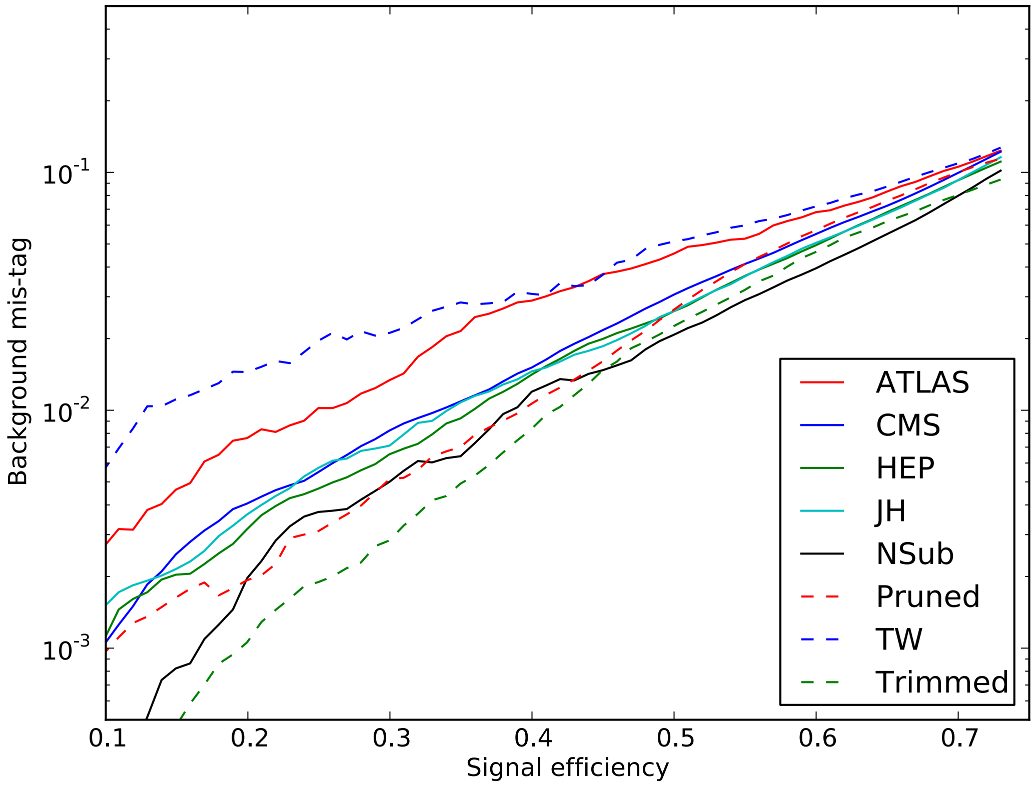
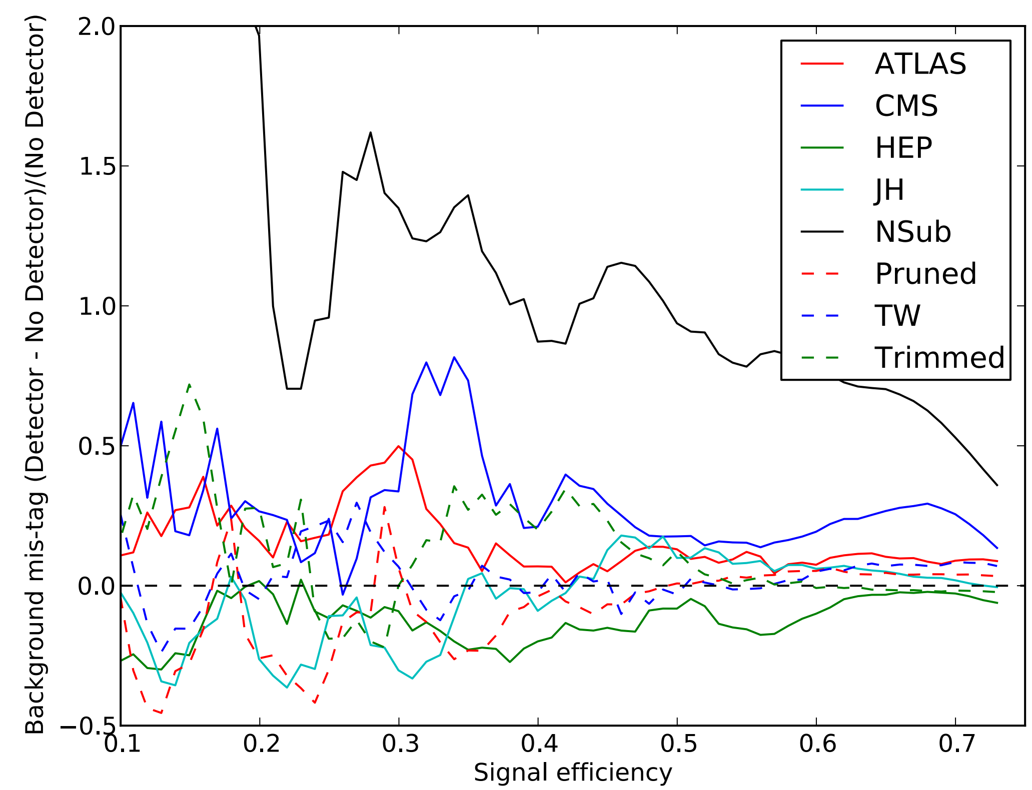
Top tagger comparisons from BOOST 2011



http://boost2011.org



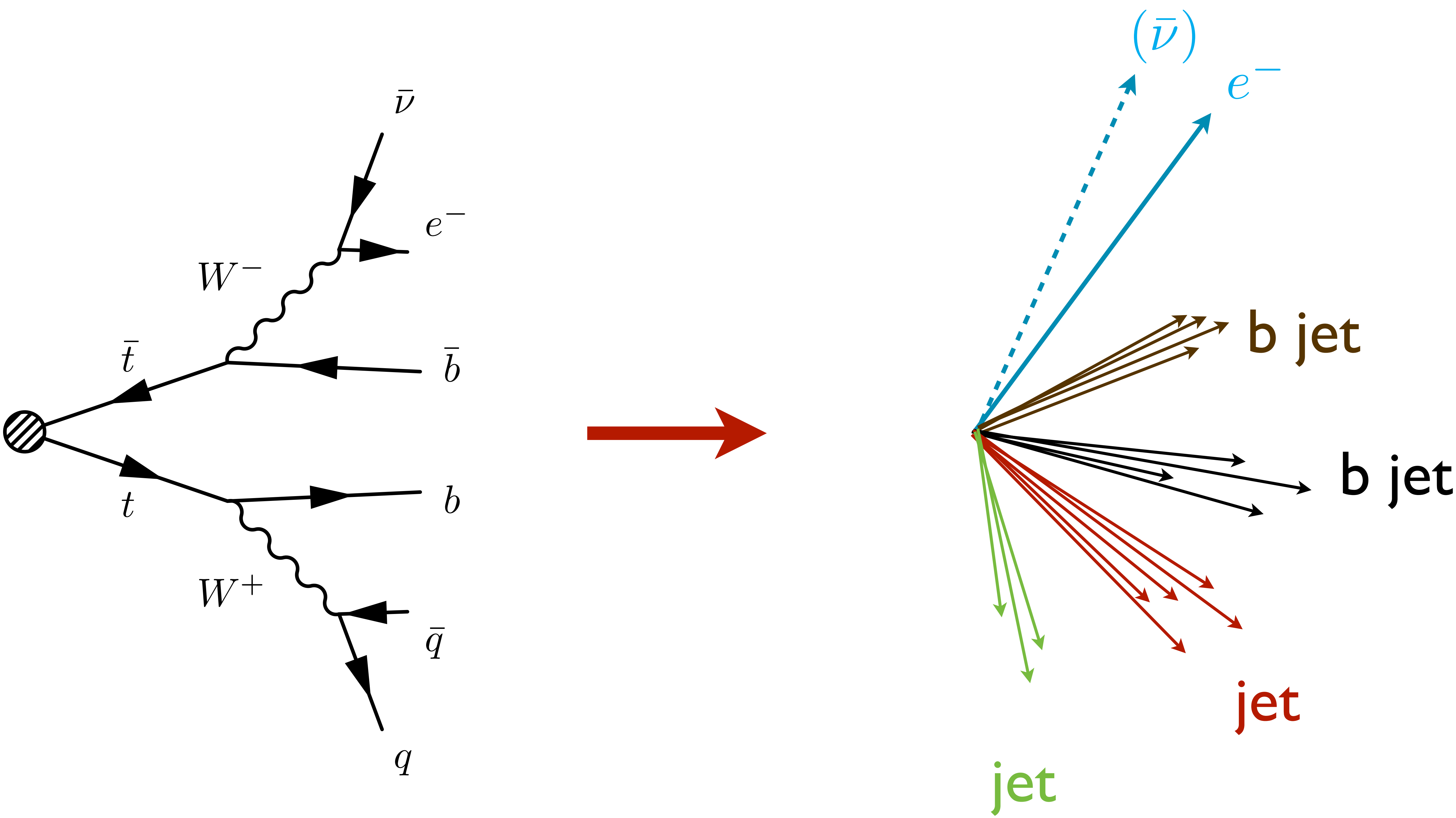
Christopher Vermilion

Top Physics Workshop

CERN

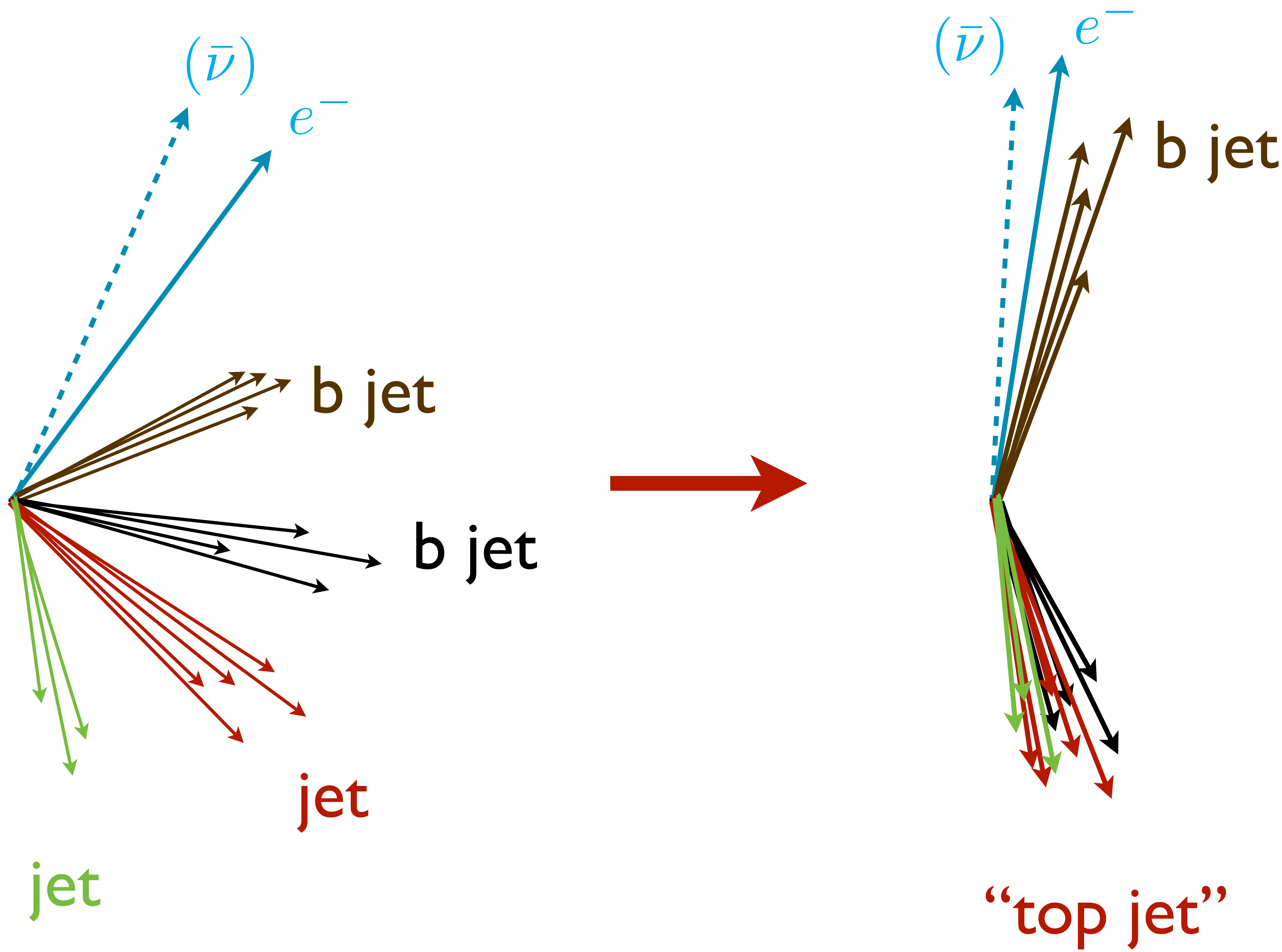
3/5/12

Lots of reasons to study tops...

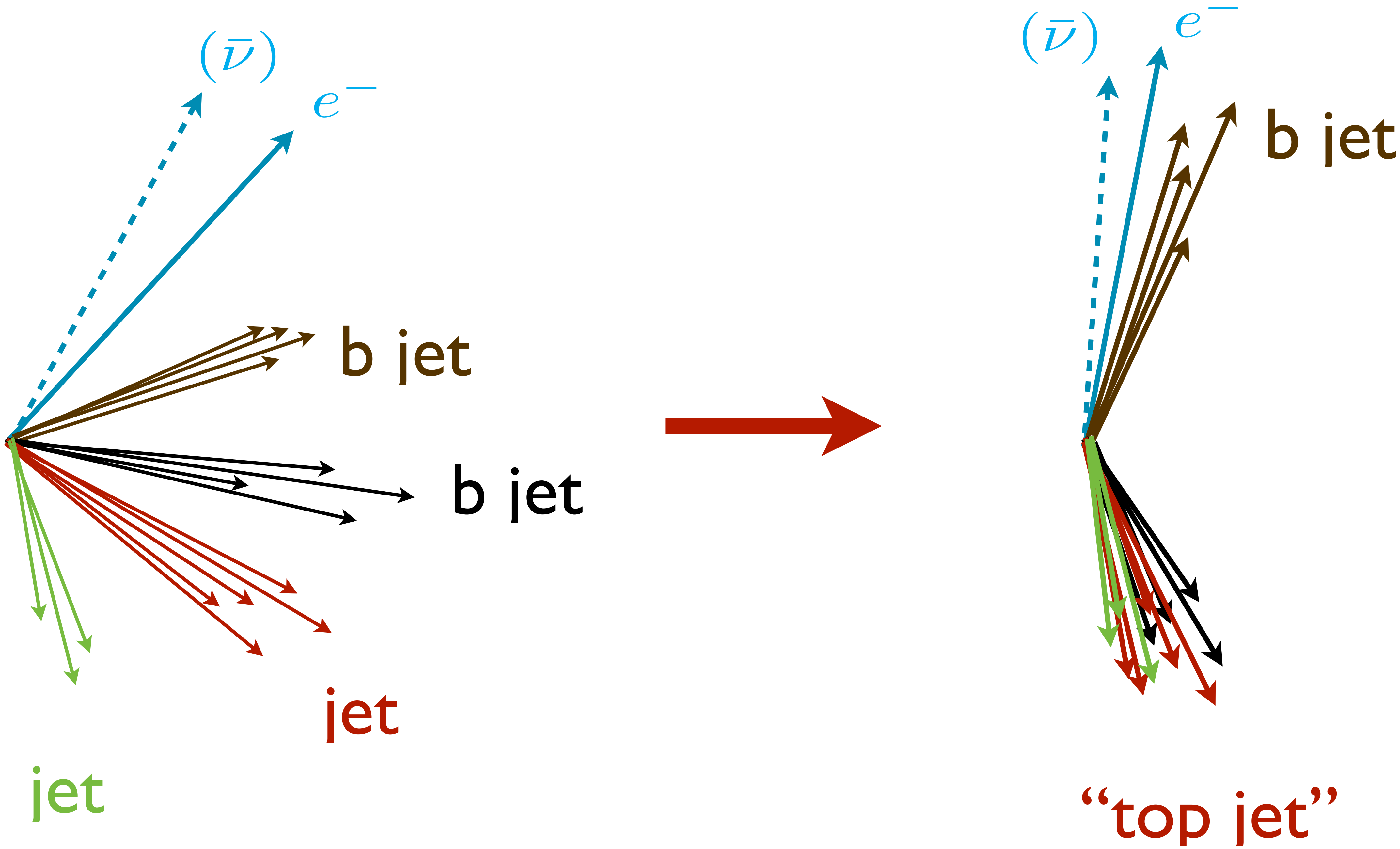


Almost always worth it to study hadronic decays:
BR(dilepton) ~ 4%; BR(at least one jet) ~ 80%

High-p_T: tops in single jets

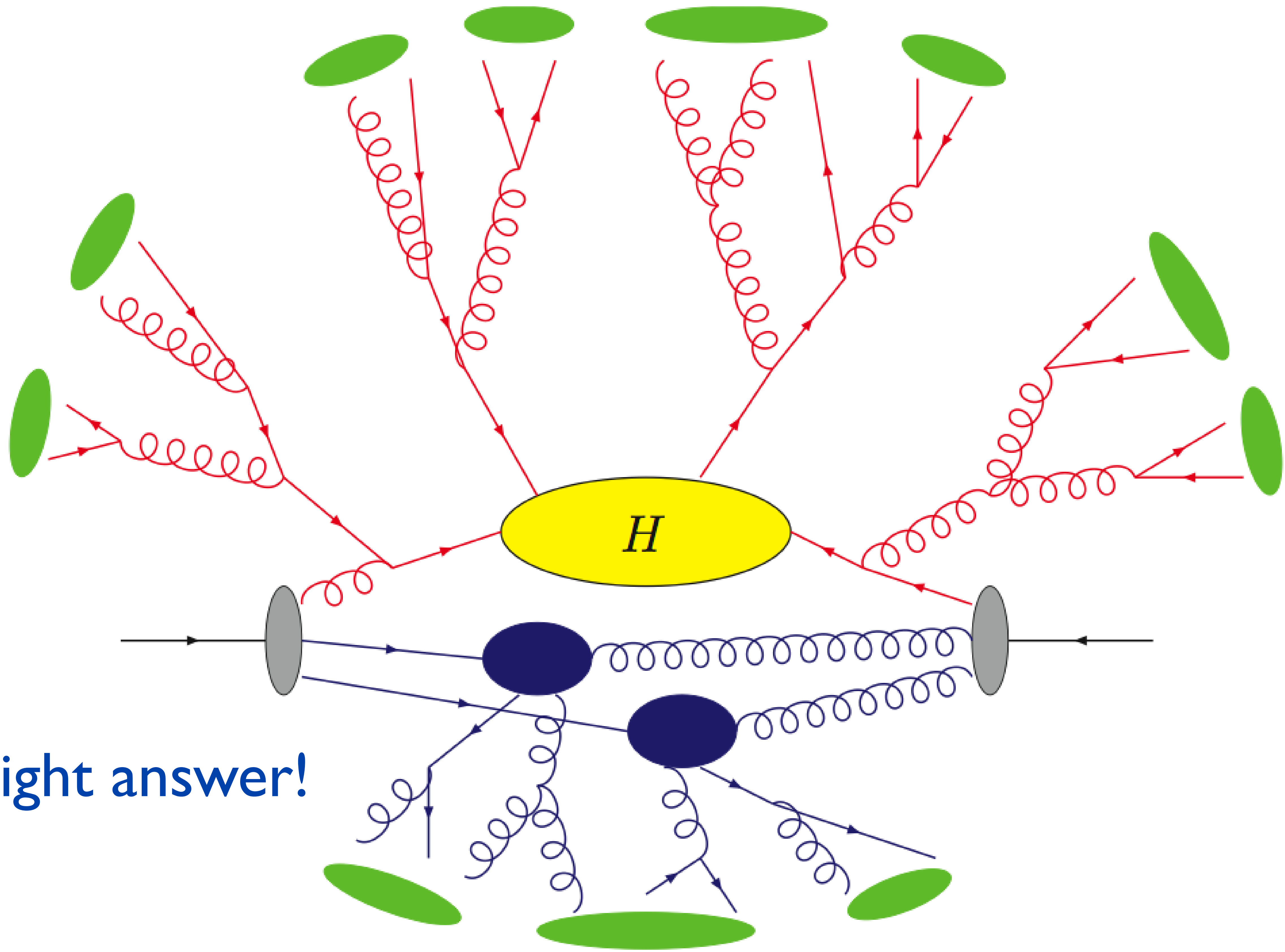


High-p_T: heavy particles in single jets



Interesting problem: can you interpolate
between top = 3 jets, top = 1 jet??

But jets are a mess -- need to *construct* jets with some algorithm!

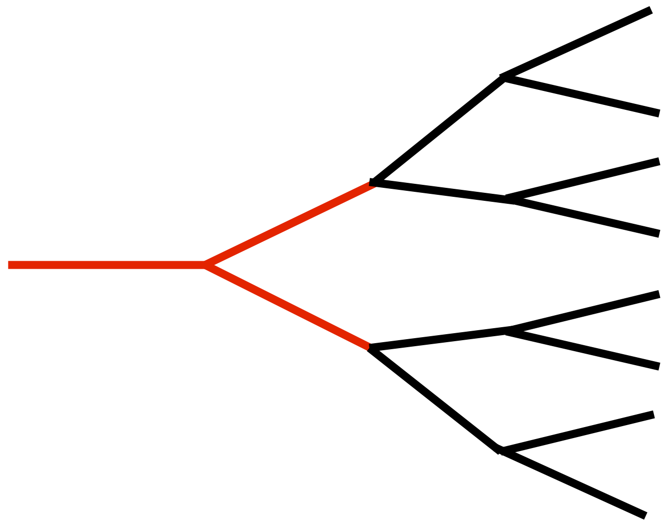


No right answer!

Building Jets: Recombination Algorithms

- Build jets from "protojets" with repeated 2→1 mergings
  - Typically the inputs are calorimeter cells
- A distance metric ρ_{ij} determines how "close" two protojets are
- Some other metric tells you when to stop
- Left with a tree-like merging history

Can we use substructure
to distinguish different types of jets?



Goal: distinguish heavy particle jets from QCD

- Jet mass
  - Heavy particles: $m_{jet} \sim m_X$
  - QCD: $m_{jet} \sim \# \, p_T$
- Subjet kinematics
  - Heavy particle: roughly symmetric subjets
  - QCD: typically hard core with diffuse radiation; asymmetric subjets
- Color flow
  - Heavy particle: if color singlet, decay products are color connected
  - QCD: often contains color connections to rest of event

Also: spin, charge

All jet substructure methods use some combination of these properties!

Problem 1: algorithm biases

- Jet algorithm shapes substructure, distorts kinematics you might expect from a decay
  - Plus -- lose information by doing {particles} ➔ {jet}
- One solution: don't use subjets!

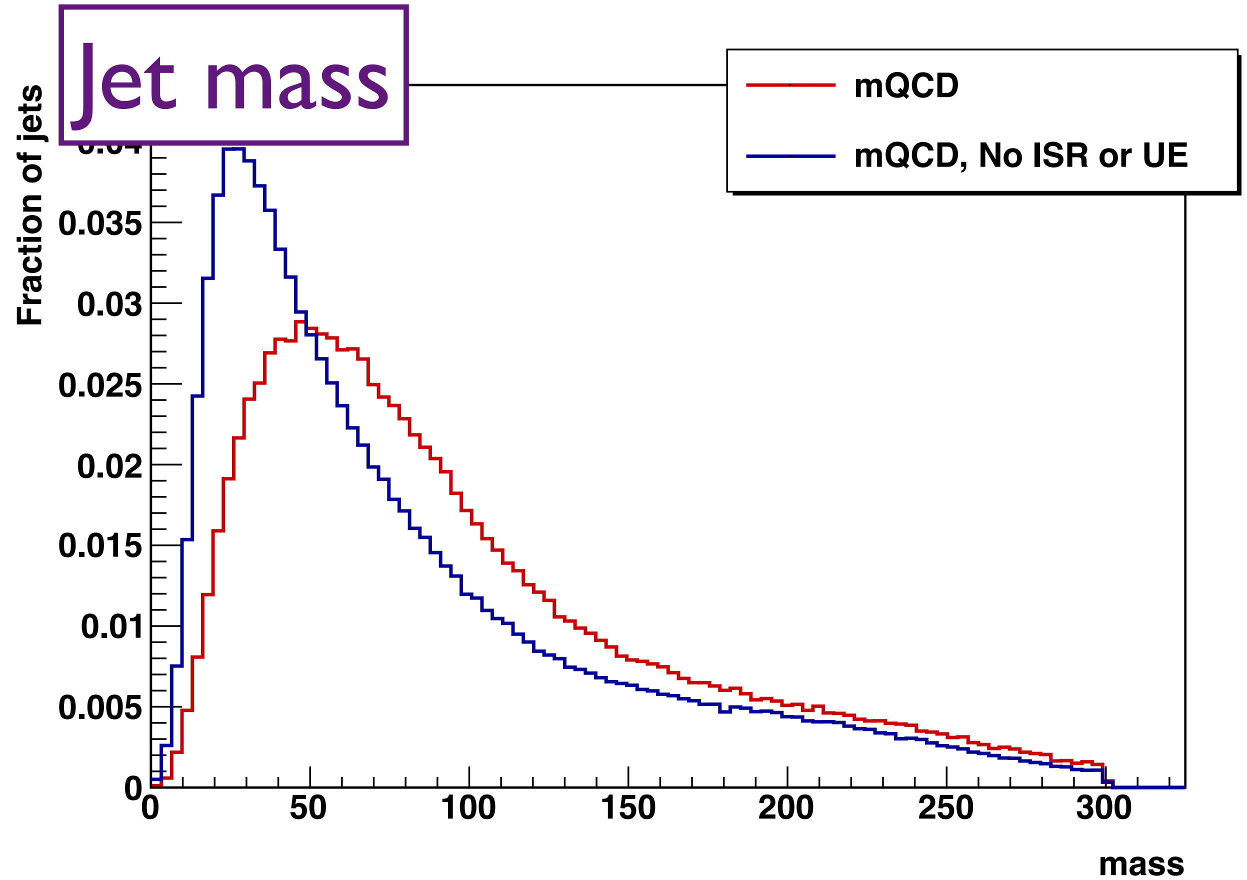
➔ Jet shapes

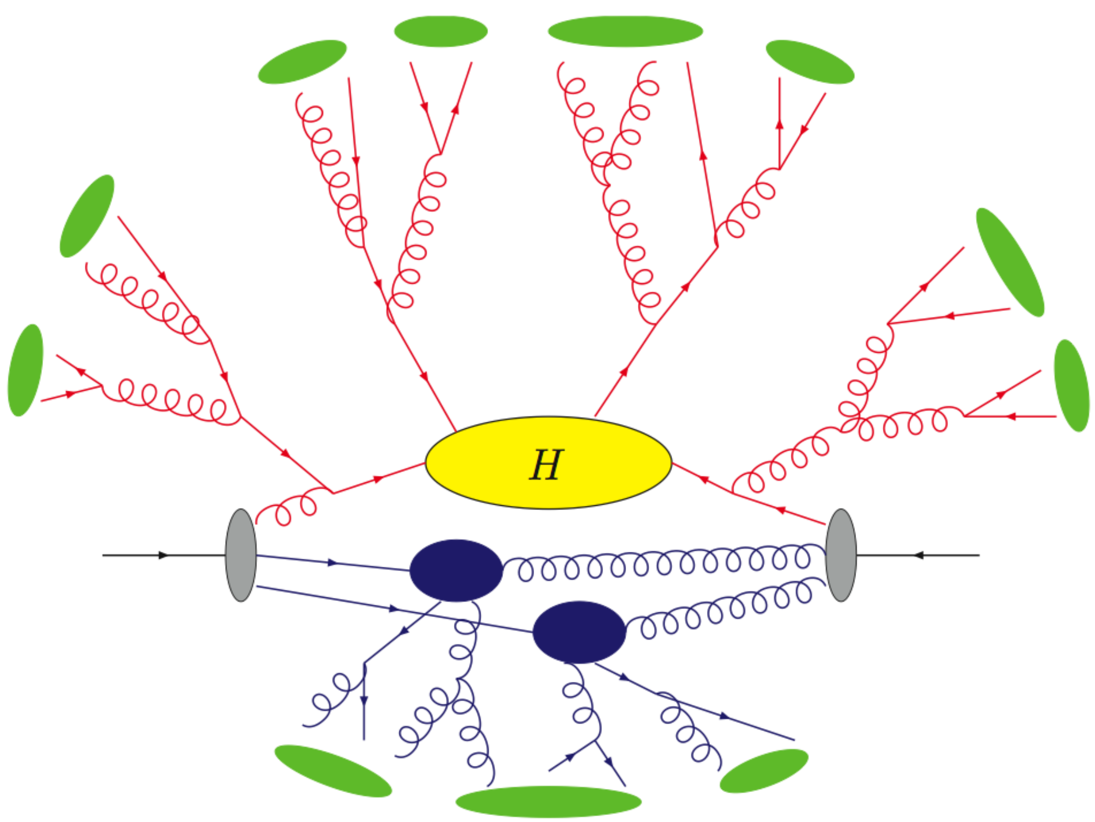
- Other solution: .....?

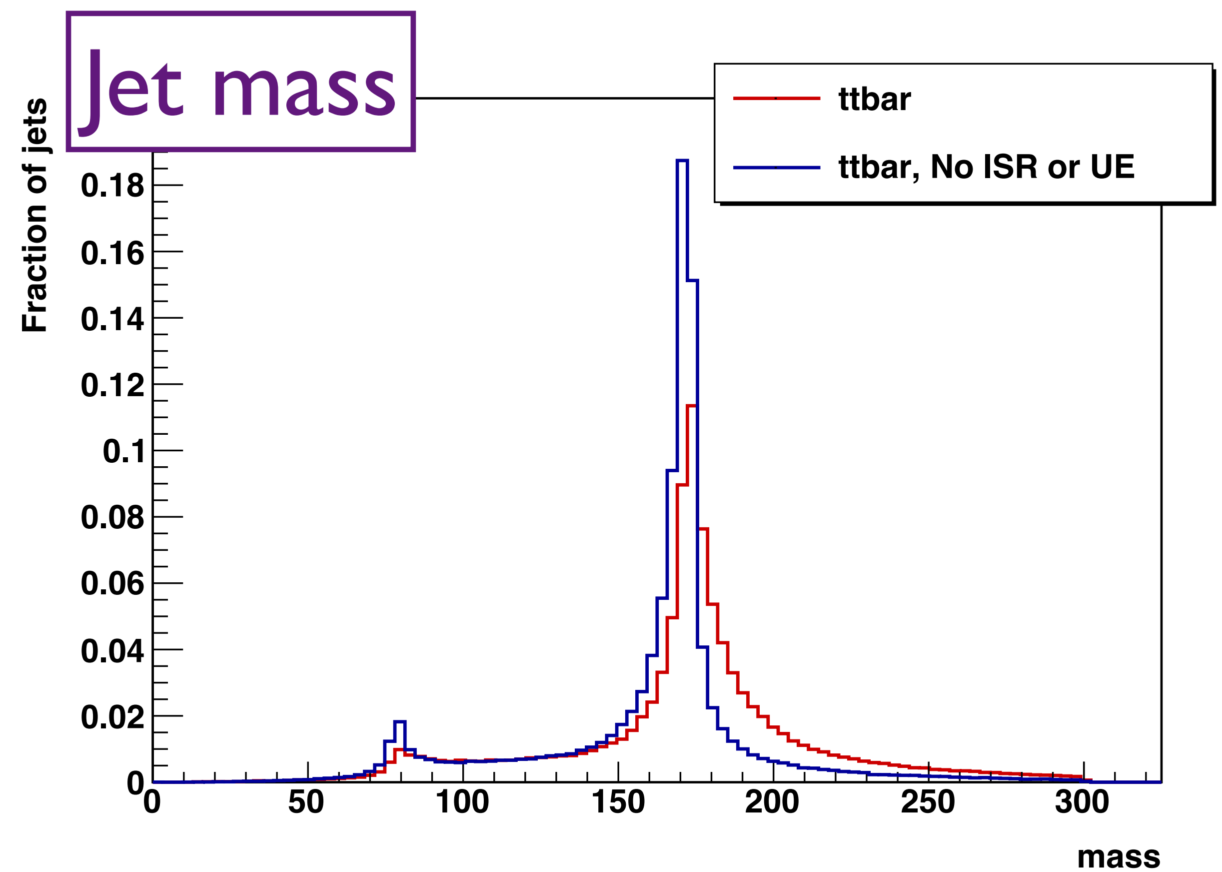
Problem 2: splash-in distorts masses (and everything else)

pp collisions:
extra radiation from ISR, UE, PU

Shifts mass distributions
upward, broadens peaks!







Lots of ideas to use jet substructure and address these challenges...

(see backup slides for overview and cites)

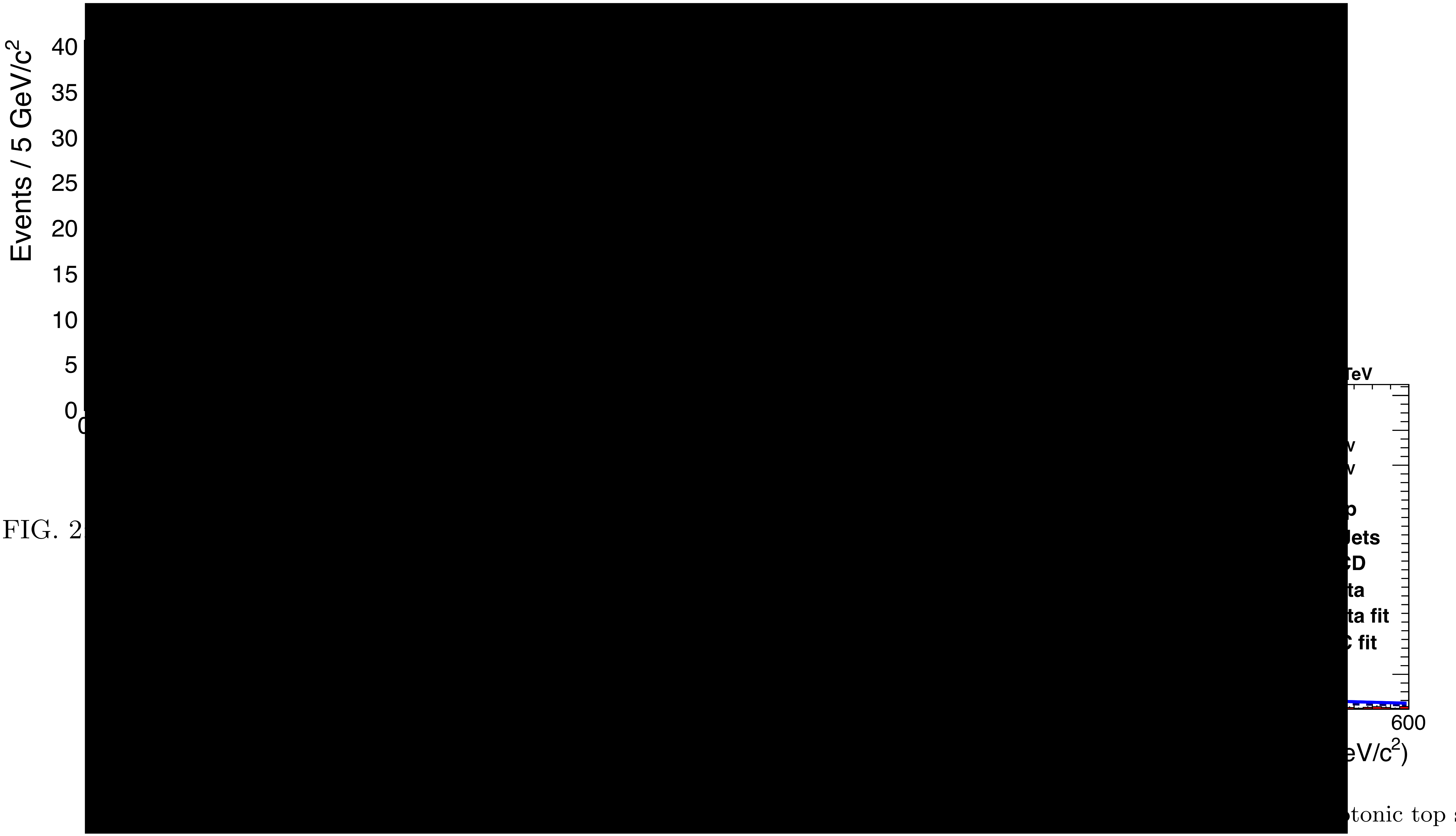
Application: top quark jet ID

(Green = included in Boost comparisons)

- Substructure kinematics, using kT/CA clustering
  - Subjet mass, energy sharing z, k_T splitting scales
  - "ATLAS", "Thaler/Wang" taggers from Boost fall into this category
- "Grooming" techniques: remove distortions from soft radiation
  - Typically groom, then measure jet, subjet masses
  - Filtering, pruning, trimming
- Hybrid taggers
  - Typically groom away part of jet looking for structure, then examine kinematics
  - BDRS "mass-drop filter" (boosted Higgs), Johns Hopkins top tagger, CMS top tagger, HEP top tagger
- Jet shapes
  - Avoid subjet finding/clustering altogether and measure energy distribution within jet
  - N-subjettiness, angular correlations, template overlap, planar flow

So far, results suggest that hybrid taggers and jet shapes are most powerful

Experimental status



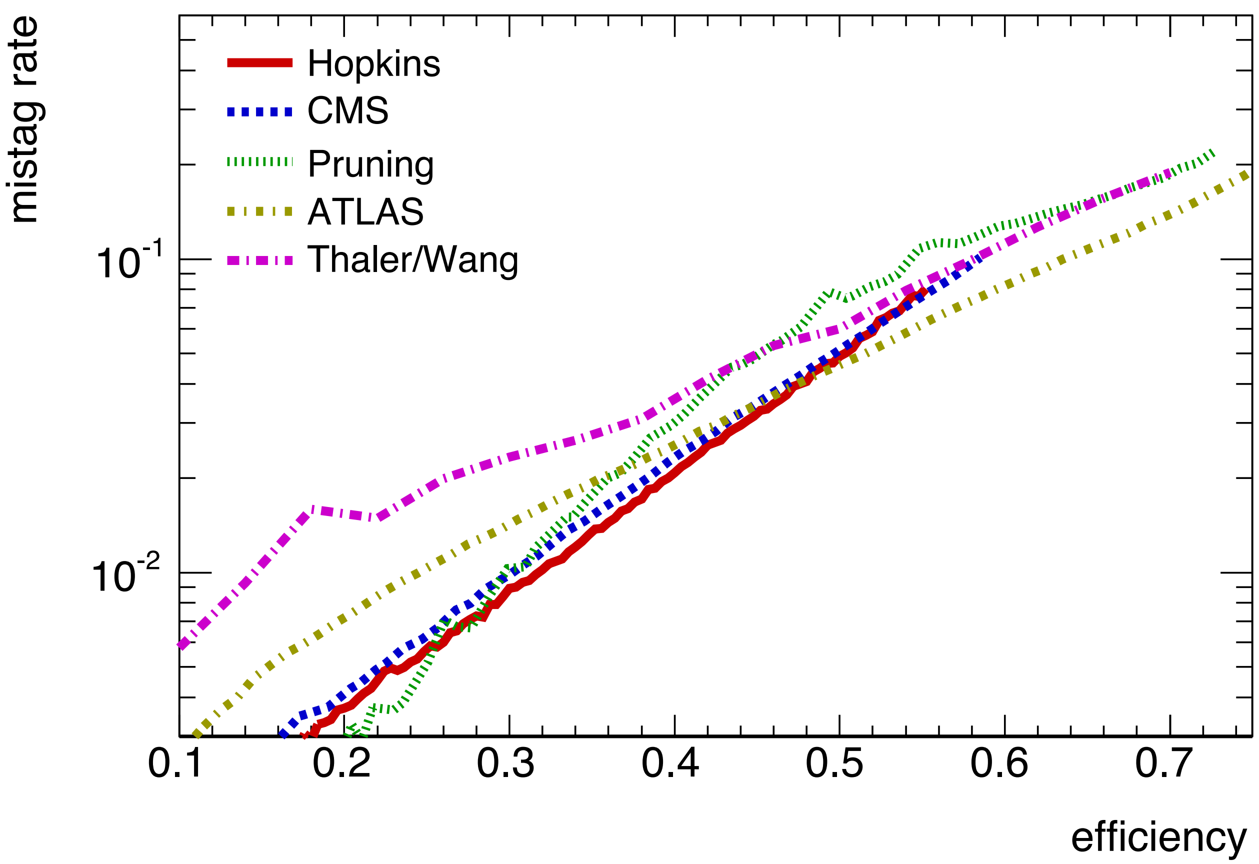
Tune in tomorrow morning! (plus Adam's talk)

BOOST

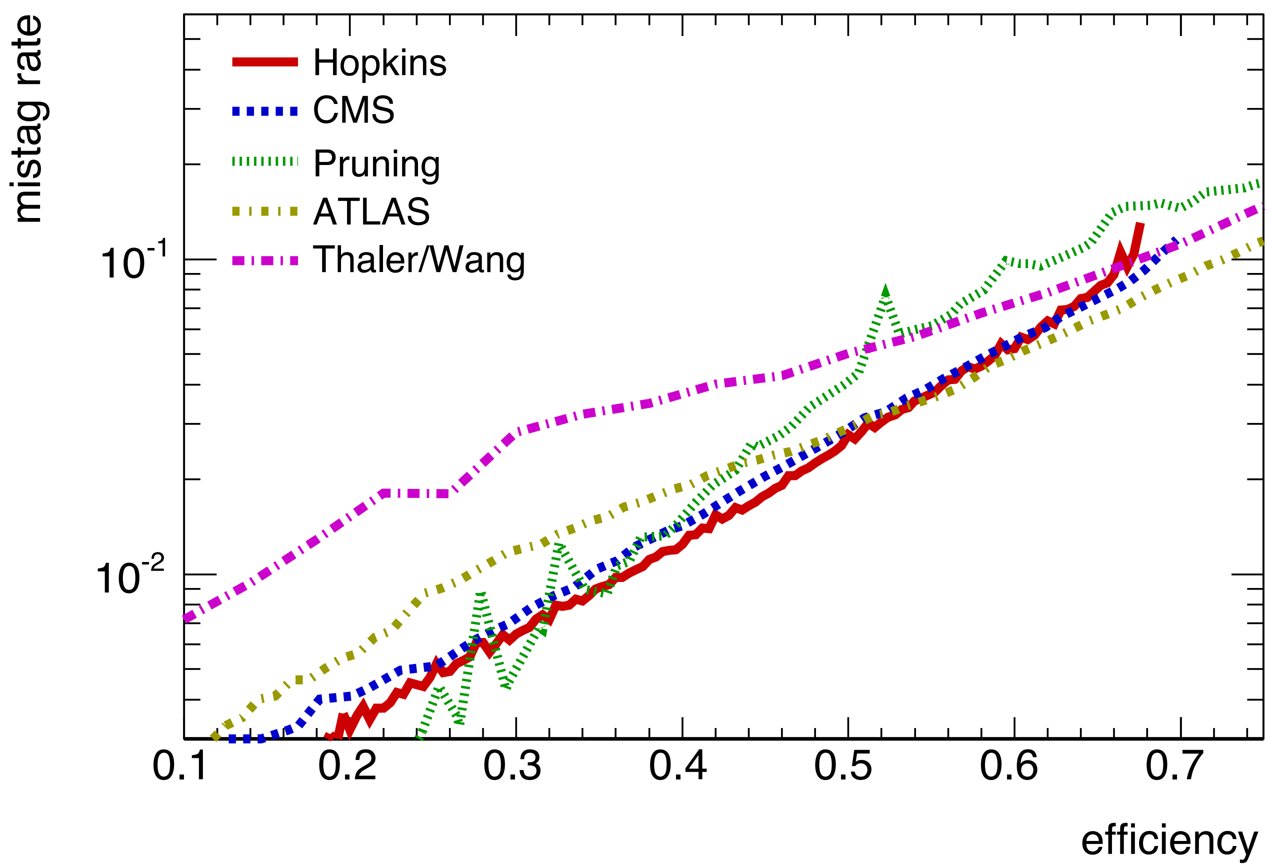
- An ongoing series of workshops bringing together theorists and experimentalists working on boosted objects
    - 7/2009 at SLAC, 6/2010 at Oxford, 5/2011 at Princeton, 7/2012 at Valencia
- Workshops followed by *reports*:
    - 1012.5412, 1201.0008
    - Summarize theory and experiment progress
    - Build consensus on priorities for new measurements, calculations
    - Benchmark tools and comparisons

Boost 2010: Comparing five top tagging methods

arXiv:1012.5412



(b) all p_T samples



(d) 500–600 GeV

Boost 2011 comparisons

- Stick to tops vs. QCD for simplicity, time

- Expand set of taggers
  - Add HEP, N-subjettiness, trimming
- Expand set of samples (incl. matching)
  - Added Herwig++, Sherpa to last year's Herwig 6.5
- Consider (some) detector effects

- Publish software to implement all methods discussed
  - Comparisons are a *benchmark*

http://boost2011.org :

Boost: The Home Game

Boost 2011 results

For more, see arXiv:1201.0008

Jet Substructure at the Tevatron and LHC: New results, new tools, new benchmarks*

A Altheimer[1], S Arora[2], L Asquith[3], G Brooijmans[1], J Butterworth[4], M Campanelli[4], B Chapleau[5], A E Cholakian[1,6], J P Chou[7], M Dasgupta[8], A Davison[4], J Dolen[9], S D Ellis[10], R Essig[11,12,13], J J Fan[14], R Field[15], A Fregoso[8], J Gallicchio[6], Y Gershtein[2], A Gomes[16], A Haas[11], E Halkiadakis[2], V Halyo[14], S Hoeche[11], A Hook[11,17], A Hornig[10], P Huang[18], E Izaguirre[11,17], M Jankowiak[11,17], G Kribs[19,20], D Krohn[6], A J Larkoski[11], A Lath[2], C Lee[21], S J Lee[22], P Loch[23], P Maksimovic[24], M Martinez[25], D W Miller[11,17], T Plehn[26], K Prokofiev[27], R Rahmat[28], S Rappoccio[24], A Safonov[29], G P Salam[30,14,31], S Schumann[32], M D Schwartz[6], A Schwartzman[11], M Seymour[8], J Shao[33], P Sinervo[34], M Son[35], D E Soper[20], M Spannowsky[36], I W Stewart[21], M Strassler[2], E Strauss[11], M Takeuchi[26], J Thaler[21], S Thomas[2], B Tweedie[37], R Vasquez Sierra[9], C K Vermilion[38,39], M Villaplana[40], M Vos[40], J Wacker[11], D Walker[6], J R Walsh[38,41], L-T Wang[14], S Wilbur[42], I Yavin[27], and W Zhu[14]

[1] Columbia University, Nevis Laboratory, 136 S Broadway, Irvington, NY 10533, USA

[2] Rutgers University, Department of Physics and Astronomy, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

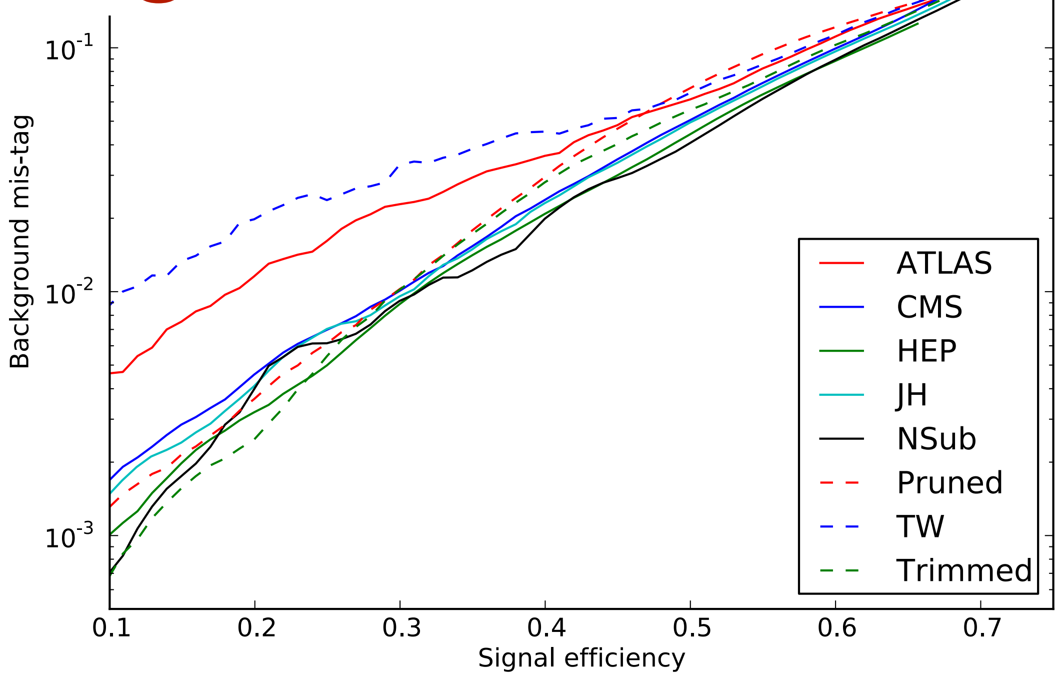
[3] Argonne National Laboratory, 9700 S. Cass Avenue Argonne, IL 60439, USA

[4] Department of Physics and Astronomy, University College London, WC1E 6BT, UK

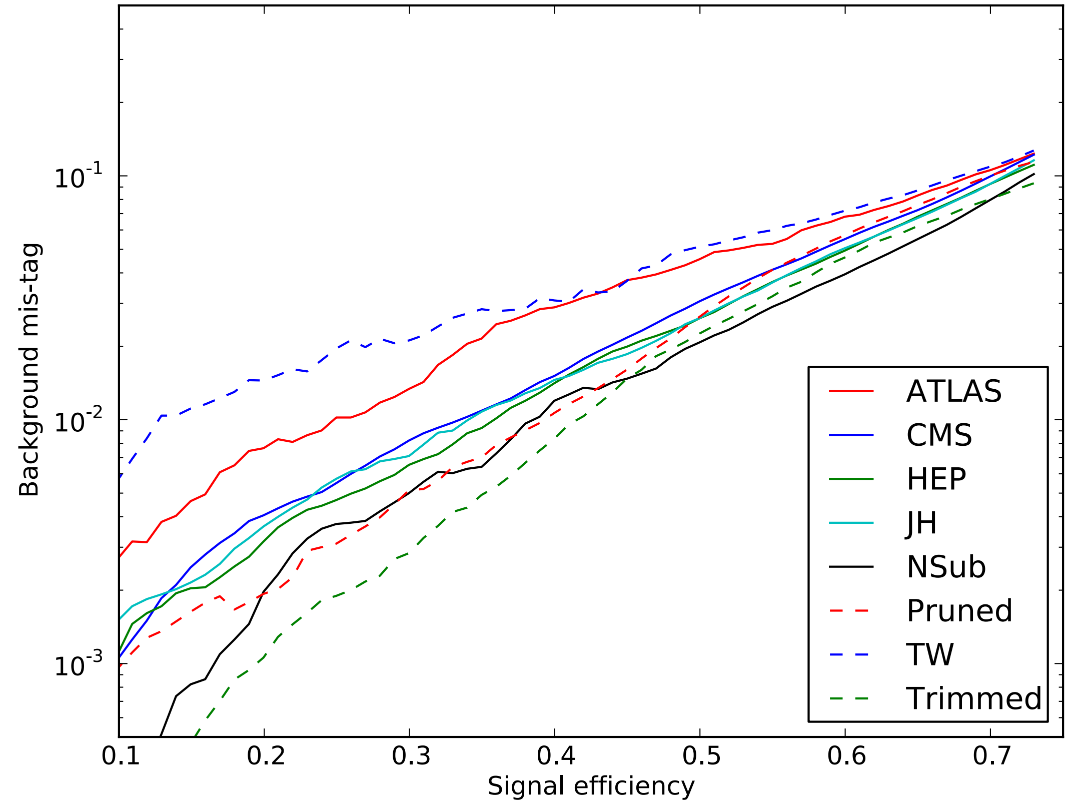
[5] McGill University, High Energy Physics Group, 3600 University Street, Montréal, Québec H3A 2T8, Canada

[6] Department of Physics, Harvard University, Cambridge, MA 02138, USA

Herwig 6.5 events



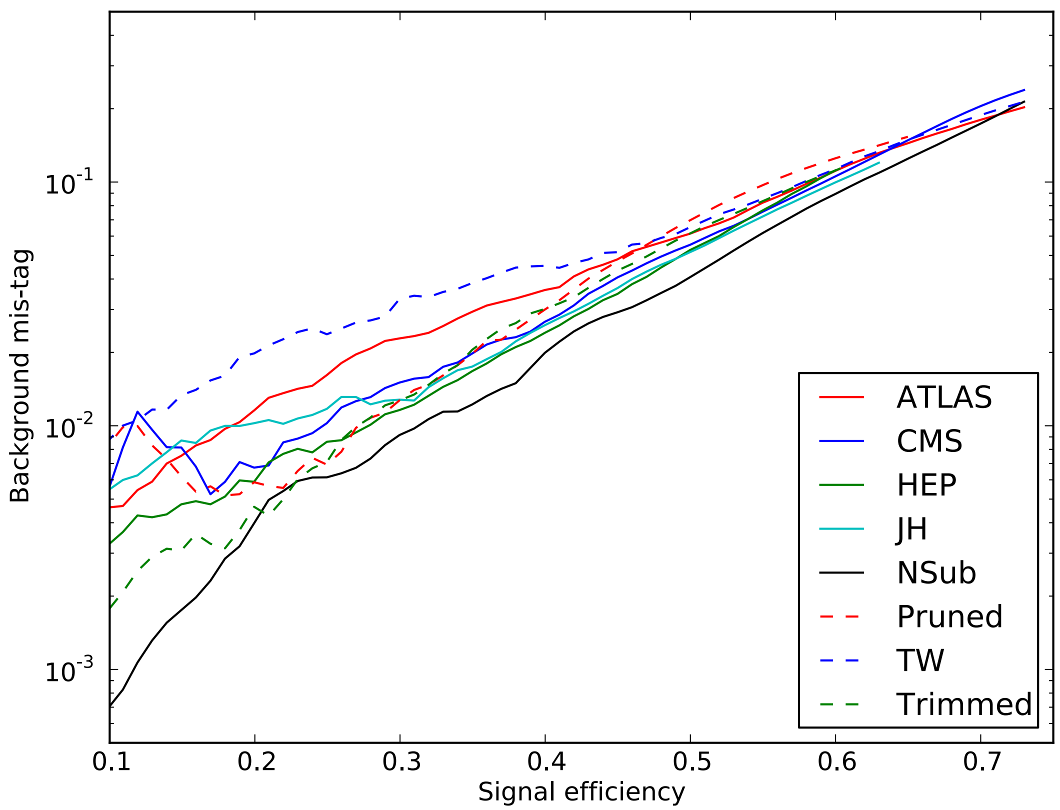
(a) all p_T, optimised



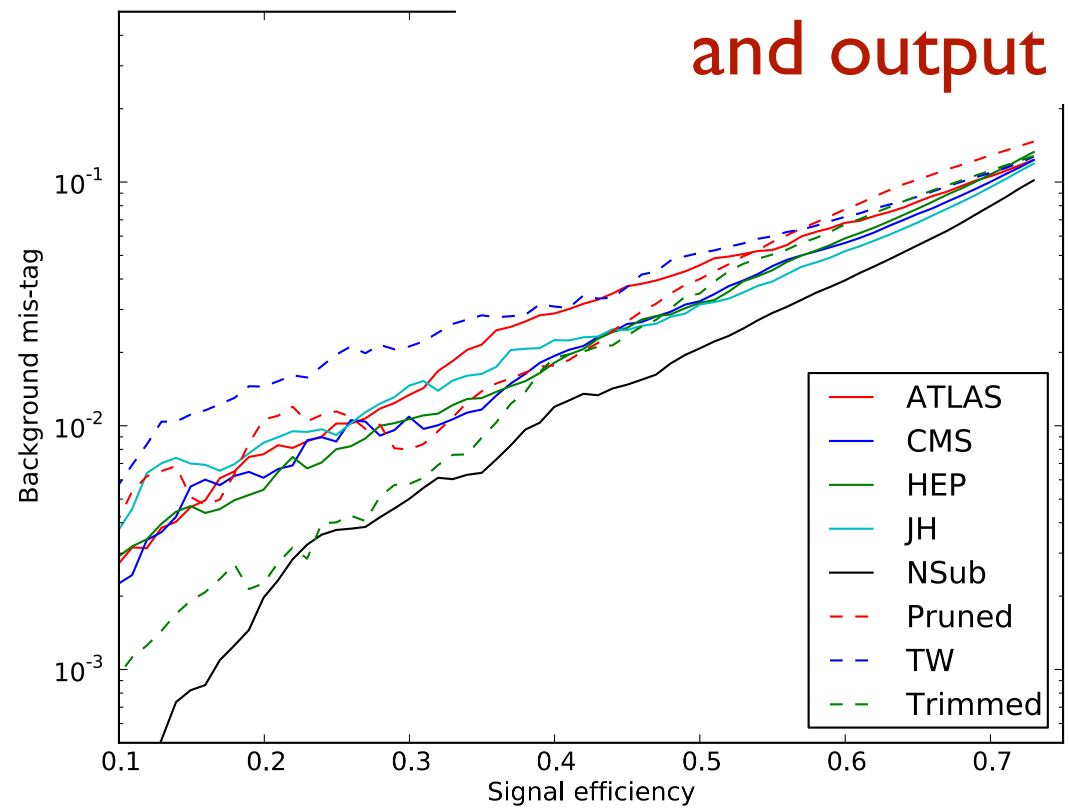
(b) p_T 500–600 GeV, optimised

(200--800 GeV, flat)

(over input parameters and output cuts)

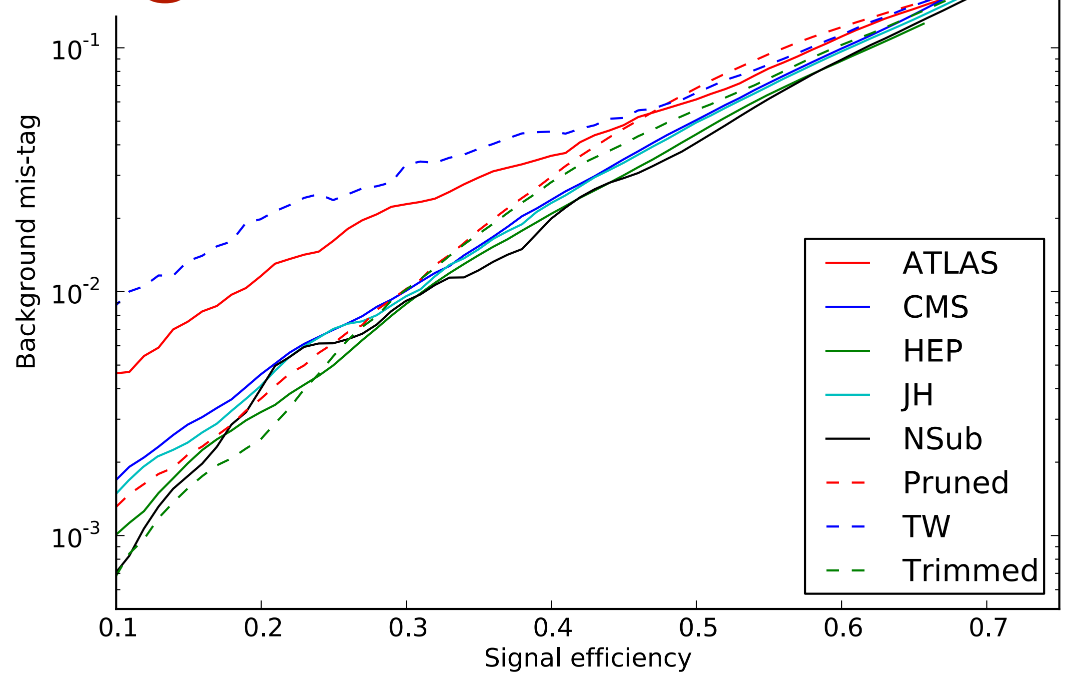


(c) all p_T

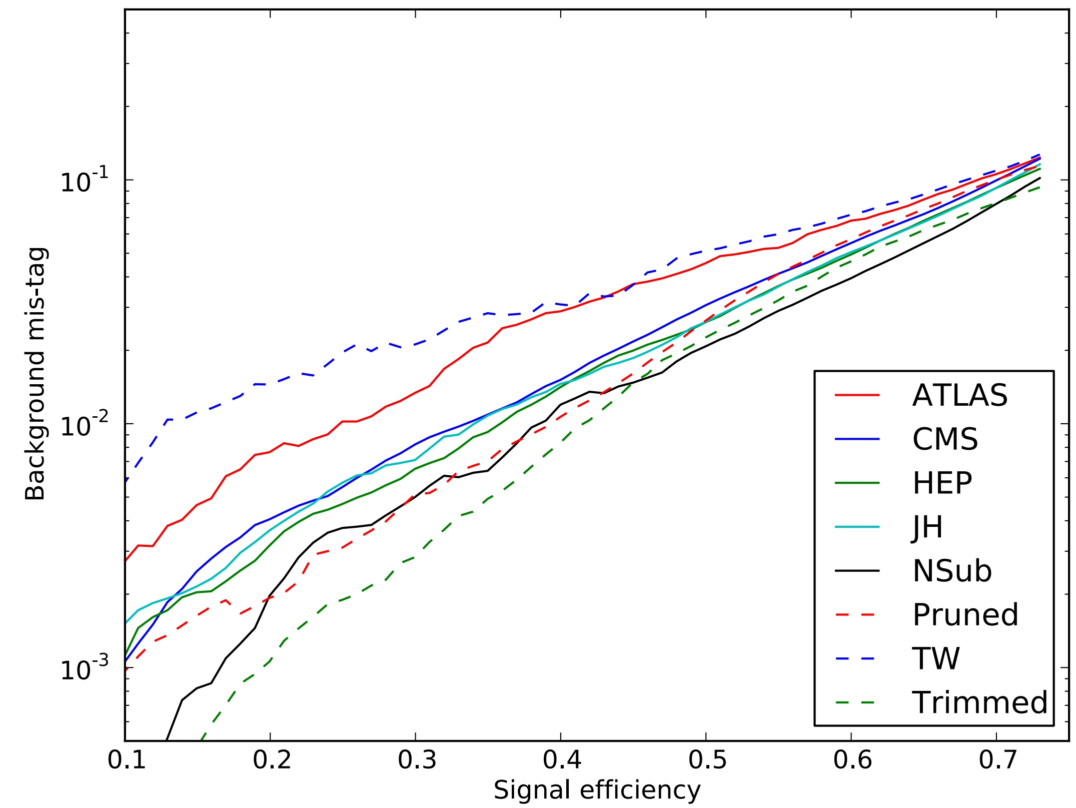


(d) p_T 500–600 GeV

Herwig 6.5 events



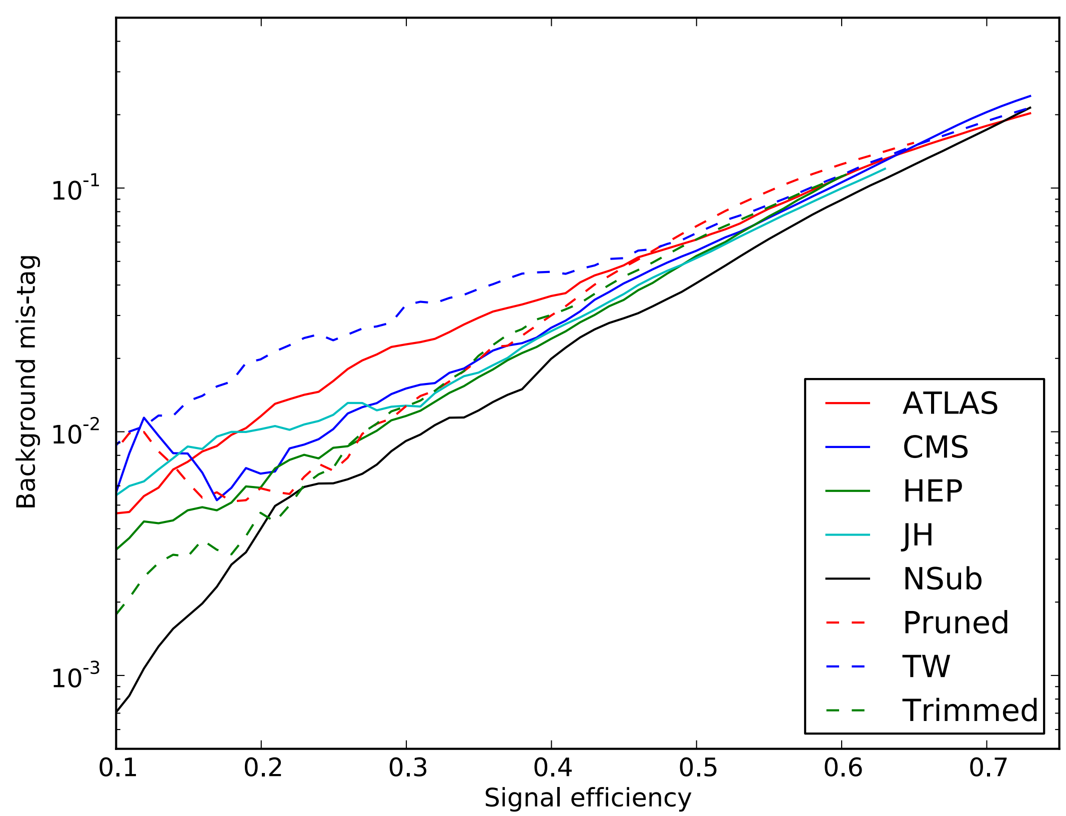
(a) all p_T, optimised



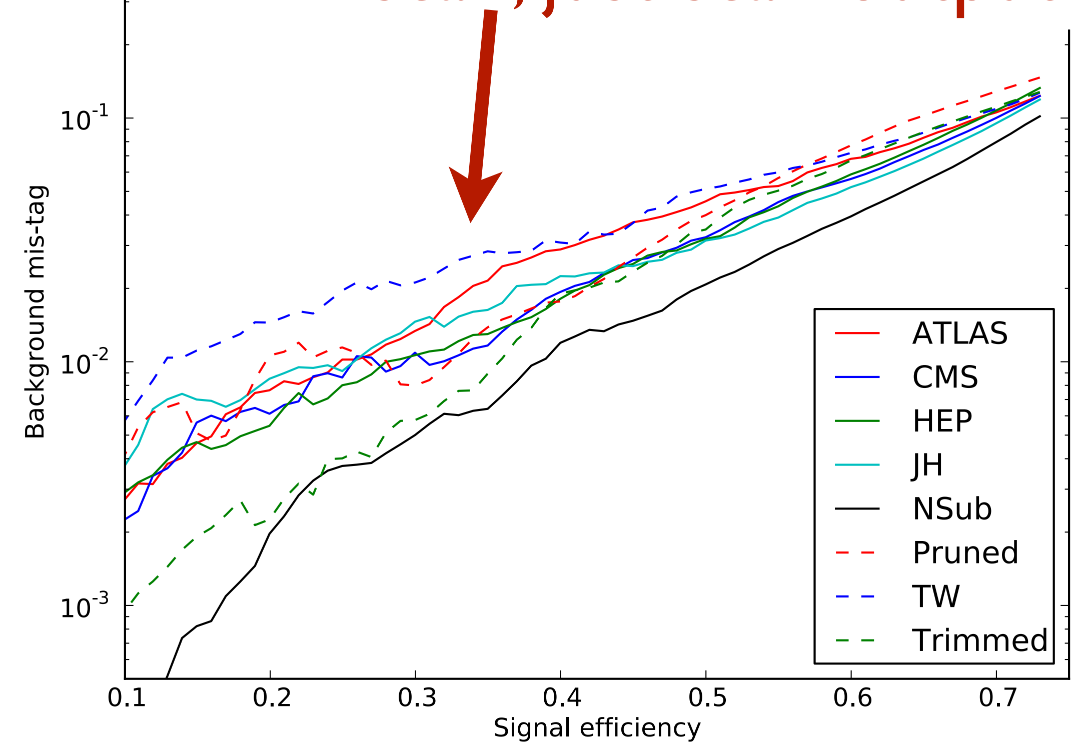
(b) p_T 500–600 GeV, optimised

(200--800 GeV, flat)

Take 35% eff. point from input scan; just scan output cuts



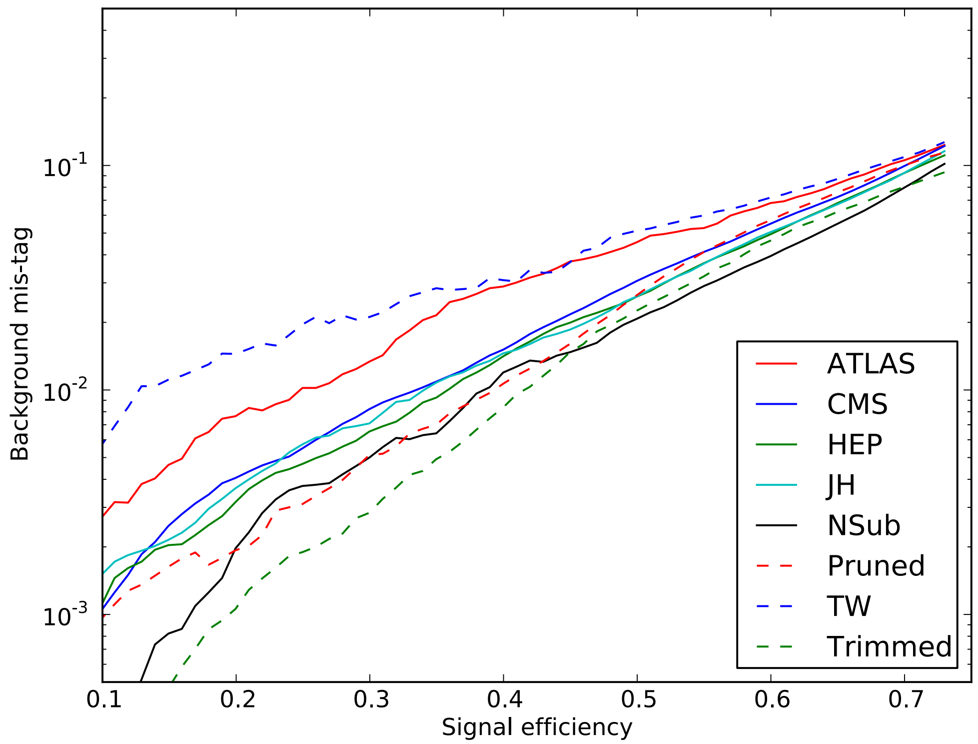
(c) all p_T



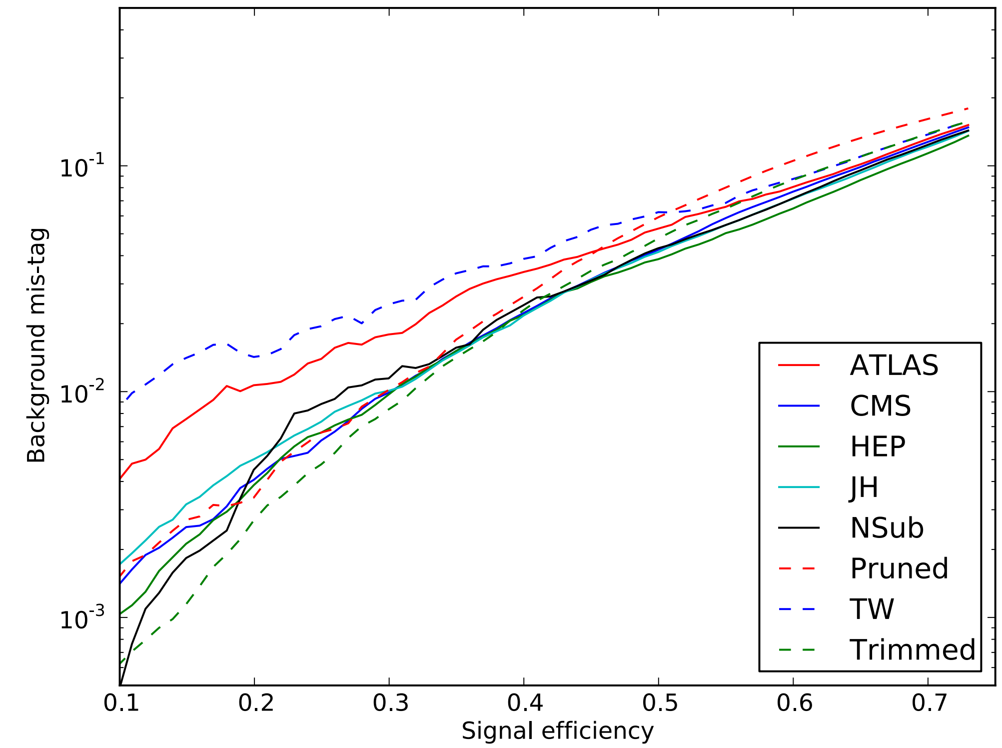
(d) p_T 500–600 GeV

Herwig 6.5

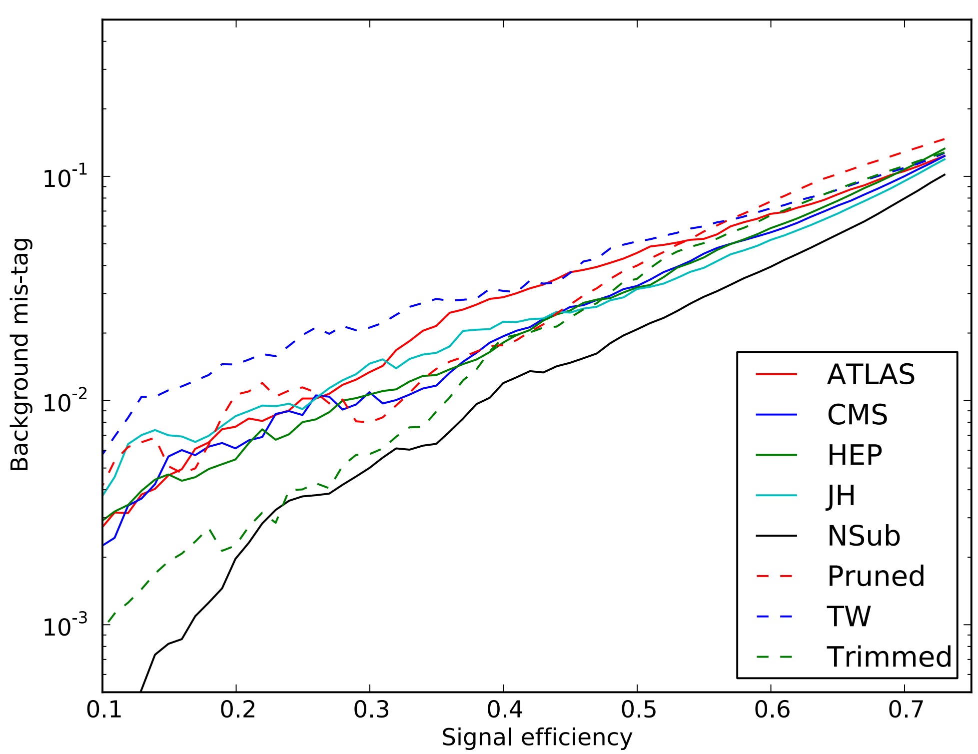
Herwig++



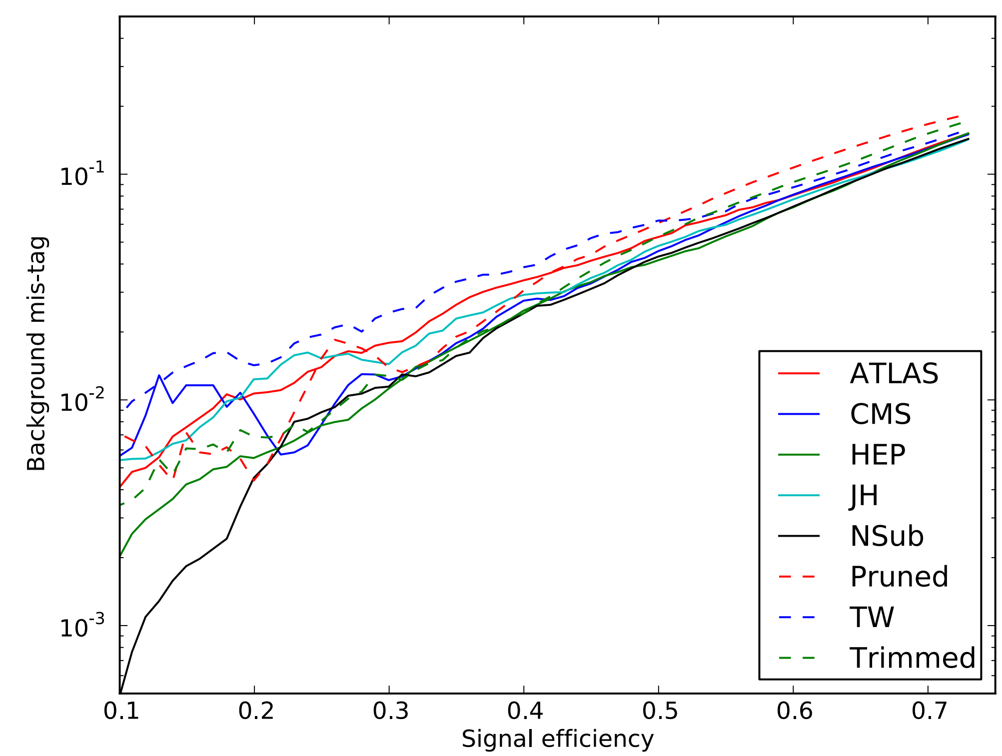
(b) p_T 500–600 GeV, optimised



(b) p_T 500–600 GeV, optimised

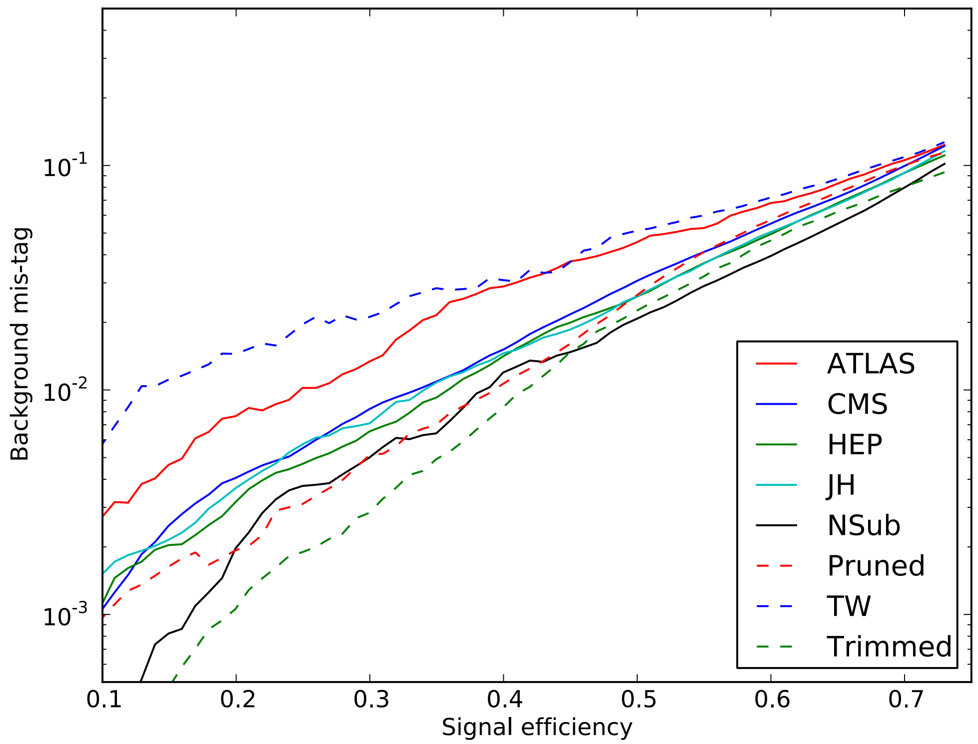


(d) p_T 500–600 GeV

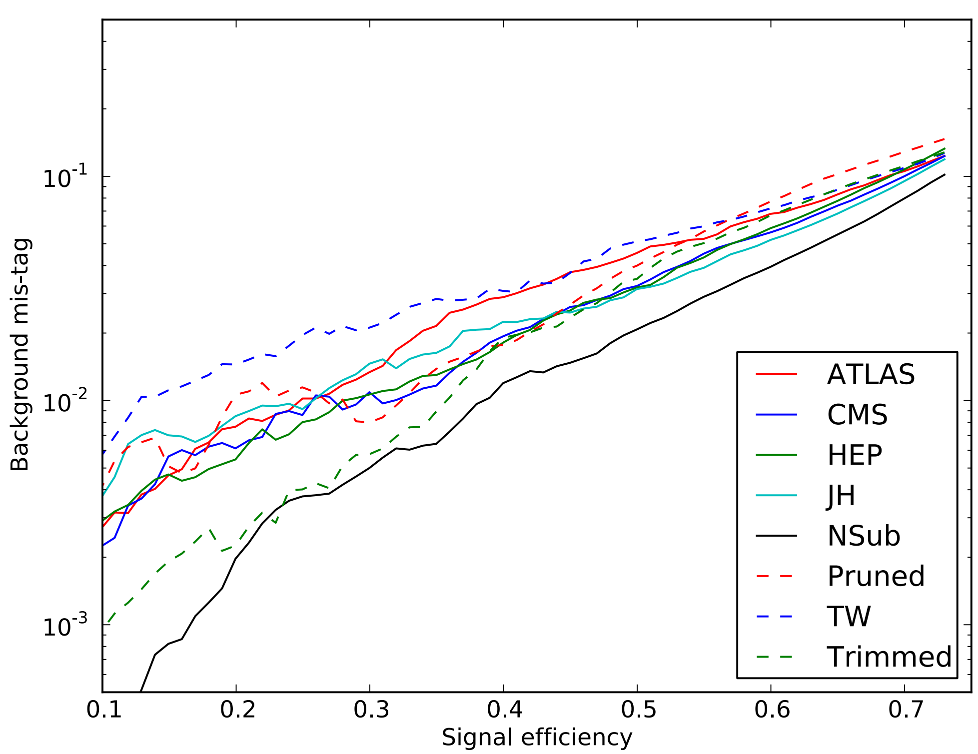


(d) p_T 500–600 GeV

Herwig 6.5

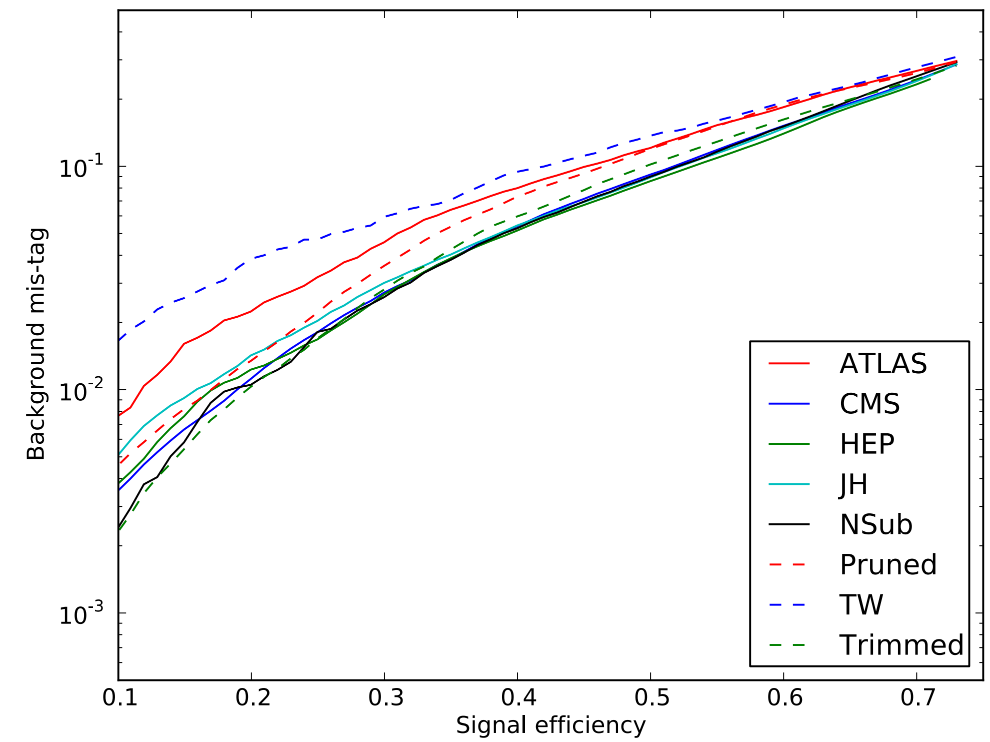


(b) p_T 500–600 GeV, optimised

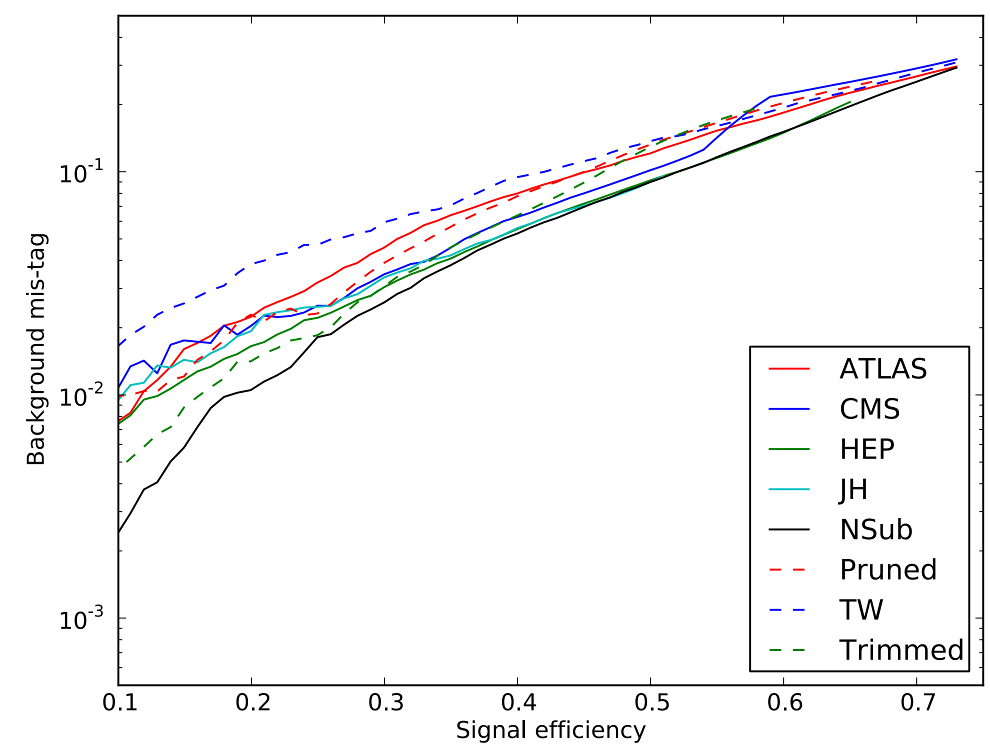


(d) p_T 500–600 GeV

Sherpa

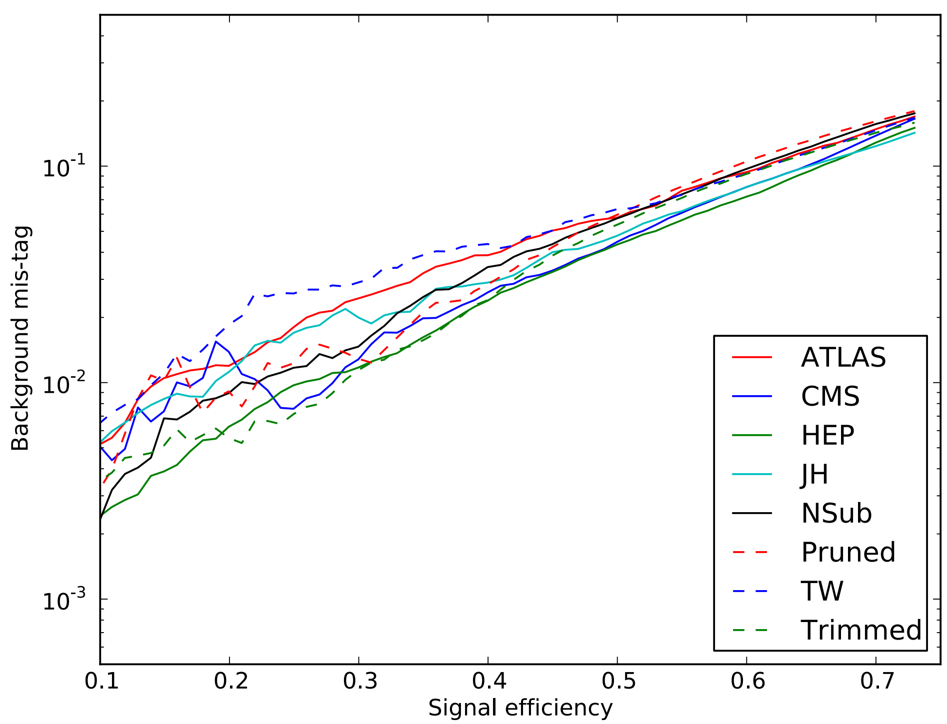


(b) p_T 500–600 GeV, optimised

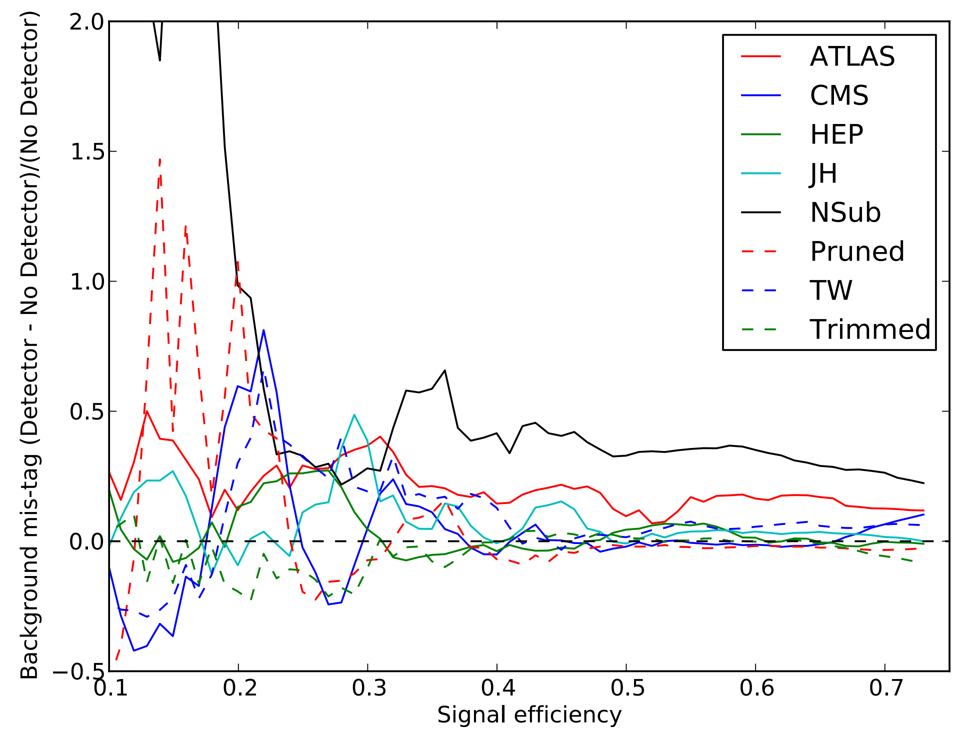


(d) p_T 500–600 GeV

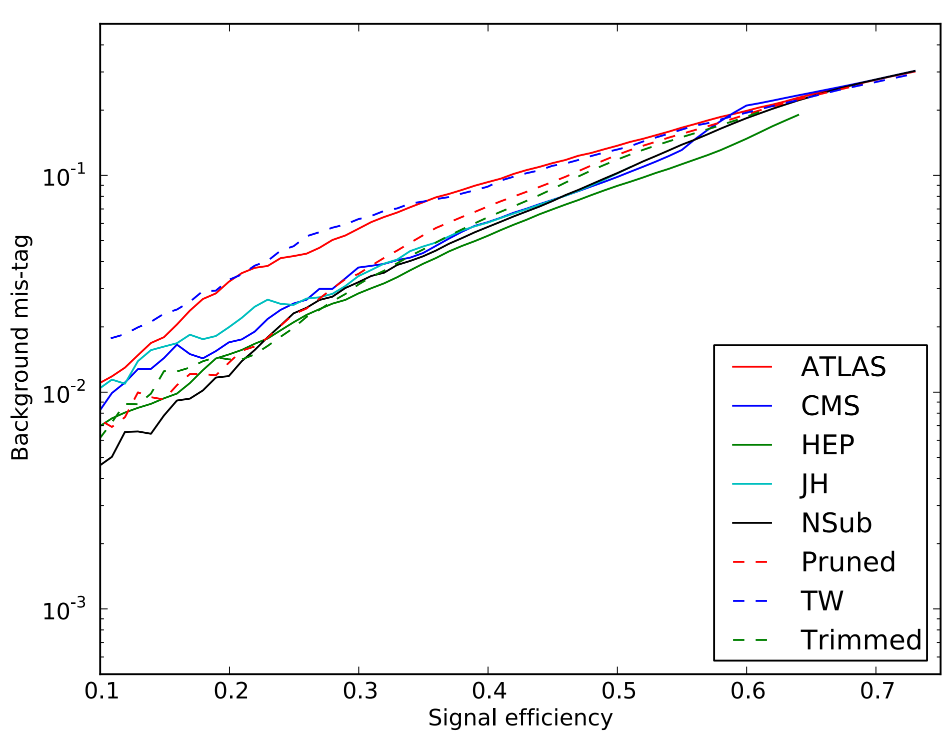
Detector effects with “LochSim”



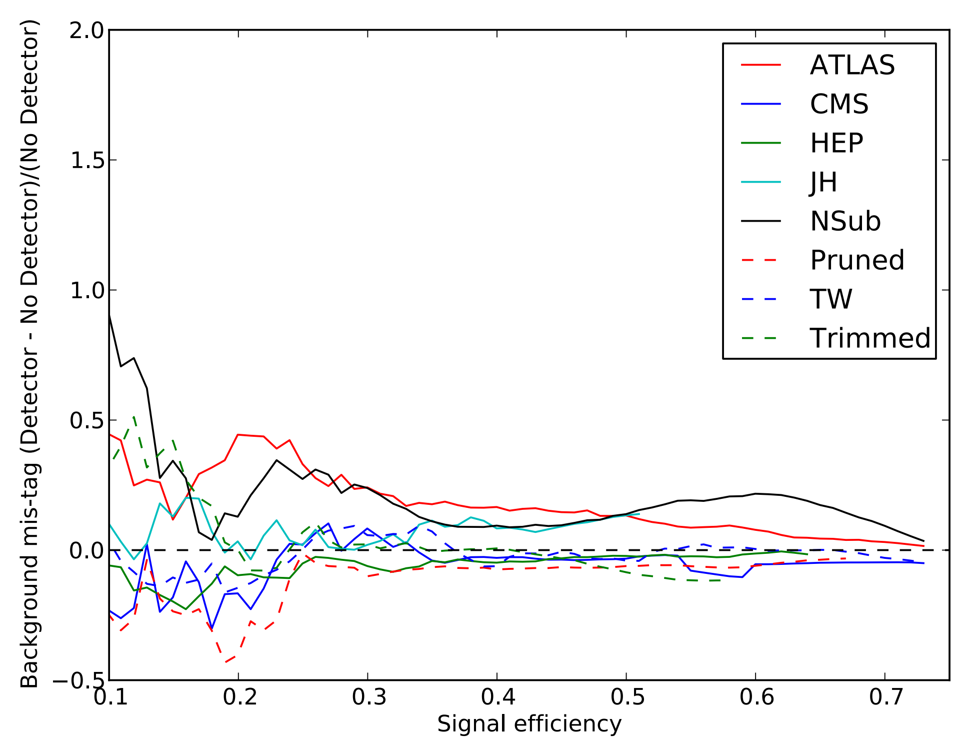
(c) HERWIG++



(d) HERWIG++, fractional difference

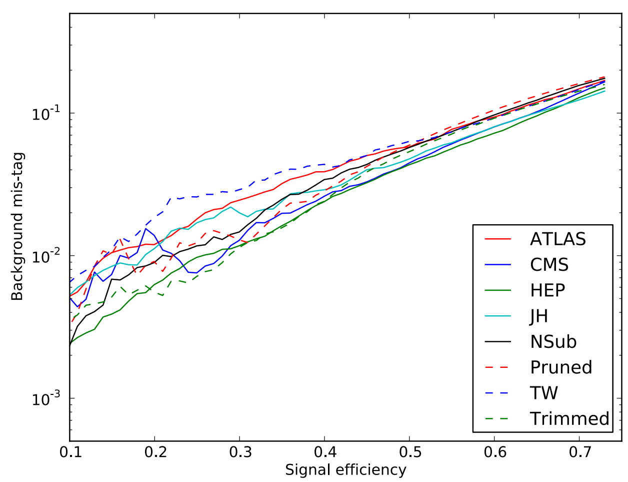


(e) SHERPA

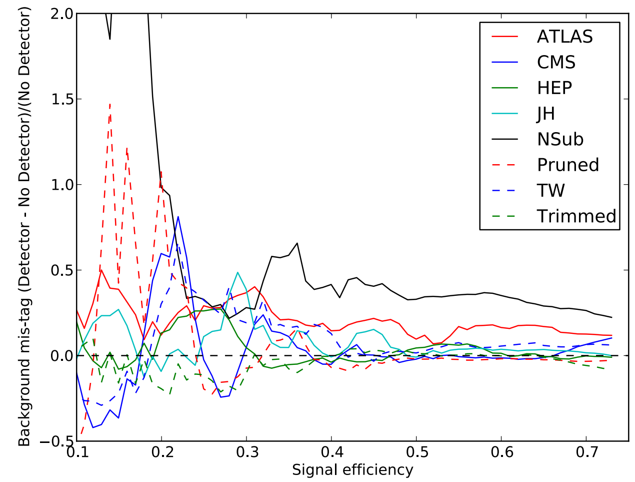


(f) SHERPA, fractional difference

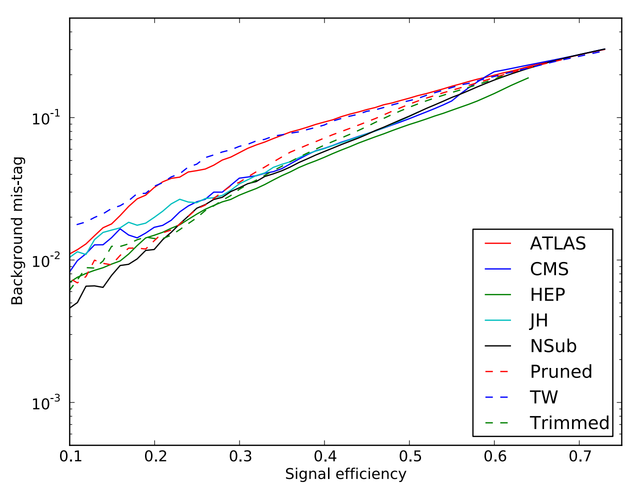
Detector effects with “LochSim”



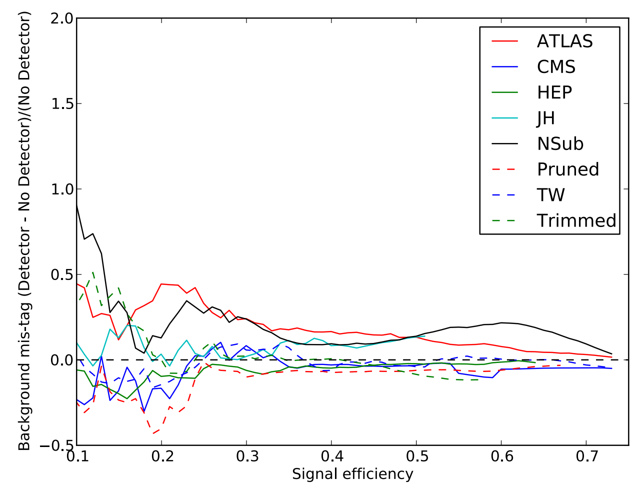
(c) HERWIG++



(d) HERWIG++, fractional difference



(e) SHERPA



(f) SHERPA, fractional difference

Simulation code available at
http://atlas.physics.arizona.edu/~loch
(or in SpartyJet!)

Do we trust this simulation?

Not really...

This is a test case and first trial of Peter’s simulation: expect some bugs!

With some testing and validation, this could be a really useful tool in jet studies.

“BOOST: The Home Game” (http://boost2011.org)

- Links to samples used in last two reports
- FastJet code for all taggers explored
- SpartyJet scripts to run taggers, scan parameters and cuts
- Even the Python/matplotlib script I used to make the plots
- Thorough and lucid instructions

Basically, everything you need to completely reproduce and examine every result in the report is linked from one webpage!

Behind the scenes: software tools for jet studies

- FastJet 3
  - Began as catalog of efficient jet algorithms
  - Now a really nice suite of jet algorithms, measurements, and manipulations
- SpartyJet: extending FastJet
  - Has evolved alongside FastJet (so some aspects now superseded by FJ)
  - Simple, easy-to-use Python interface (including full set of FJ 3 features)
  - Built-in, no-fuss input handling for all standard event formats (and many non-standard)
  - Nice framework for building up chains of jet tools (find, filter, cluster, cut...)
  - Graphical output browser, now including a large set of on-the-fly, tunable analyses

http://fastjet.fr, http://projects.hepforge.org/spartyjet

My favorite thing about FJ 3:

Providing a way to standardize jet tools

Jet measurement: `FunctionOfPseudoJet<T>`
Jet modification: `Transformer`
Jet cut: `Selector`

Expect to see future tools written this way!
(and old tools gradually re-written -- see trimming, pruning, filtering in FJ 3)

This kind of standardization is what enables shotgun-style comparisons like the Boost report.

Conclusions

- Lots of proposed techniques to search for top jets.
- BOOST 2011 report compares all *for which software is available*.
    - Hybrid, jet shape taggers looking good; N-subjettiness looks especially promising.
    - Differences aren't that big, especially compared to MC spread!
- Beyond the report: we've provided all the tools needed to extend these comparisons for any application you're interested in.
    - Go forth and multiply (our results)!

Thank you!

Bonus slides

Jet substructure: "the early days"

- Seymour (Z. Phys. **C62** (1994) 127): boosted Ws
  - jet mass, subjet separation angle, filtering, jet areas, variable R
  - interesting but ahead of its time!
- Butterworth, et al. (hep-ph/0201098, hep-ph/0702150): boosted Ws
  - y_{cut} -- subjet separation in k_T
- Butterworth, Davison, Rubin, Salam (0802.2470): boosted Higgs
  - **Mass drop**: $m_{subjet} < \mu\, m_{jet}$ (if not, discard soft subjet and repeat)
  - **Filtering**: recluster with smaller R, keep 3 hardest subjets
  - Related: 0906.0728 (neutralinos)

Extension to 2-step decays (tops)

- Brooijmans (ATL-PHYS-CONF-2008-008): "**Y-Splitter**"
    - k_T measures for last three mergings in k_T jets
- Kaplan, Rehermann, Schwartz, Tweedie (0806.0848): "**Top tagging**"
    - Identify hard splittings by discarding soft, wide-angle branchings
    - Find W in subjets, then cut on top, W masses
    - CMS variant: 0909.4894
- Thaler, Wang (0806.0023)
    - Several substructure variables, mostly energy sharing (z)

Generic methods: "Jet grooming"

- Ellis, CV, Walsh (0903.5081, 0912.0033): "**Pruning**"
  - Similar to first step in top-tagging, but bottom up
  - Remove soft, large angle mergings as you go
  - No attempt to find a specific number of subjets
- Krohn, Thaler, Wang (0912.1342): "**Trimming**"
  - Adaptive filtering
  - Recluster with small R, keep subjets with $p_T^i > f\, p_T^{jet}$

(Filtering can also be put in this category)

Jet shapes -- more general than subjets

Generically, jet shape = f($\{p_T{}^i\}$)

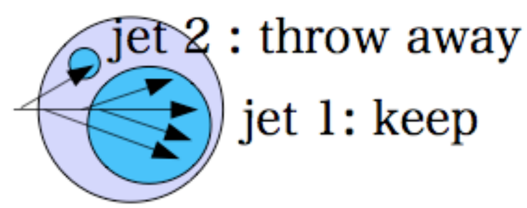
- Almeida, et al. (0807.0234, 0810.0934)
    - Several jet shapes for QCD, top jets
    - Mass, "**planar flow**"
- Chekanov, Proudfoot (+Levy, Yoshida) (1002.3982, 1009.2749)
    - Eccentricity and related geometrical measures
- Almeida, et al. (1006.2035): "**Template Overlap**"
    - Find some set of variables that characterizes signal (tops)
- Kim (1011.1493); Thaler, Van Tilburg (1011.2268): "**N-Subjettiness**"
    - Smooth interpolation between N subjets

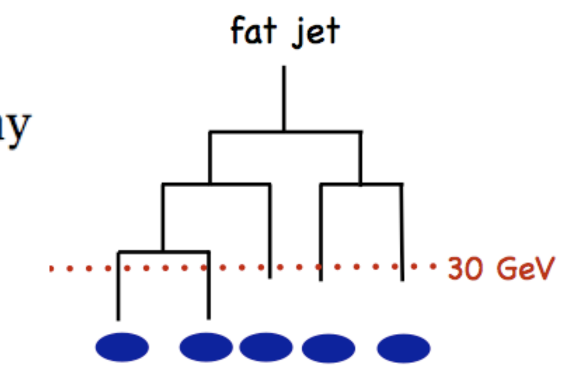
HEPTopTagger

[JHEP 1010:078,2010. arXiv:1006.2833 [hep-ph] T. Plehn, M. Spannowsky, D. Zerwas, MT]

1. **fat jets** – C/A($R = 1.5$), $p_T^{\text{fatjet}} > 200$ GeV
2. **mass drop criterion**

– find hard proto-jets $m_j < 30$ GeV, $m_{j1} < 0.8 m_j$ to keep j_1 and j_2



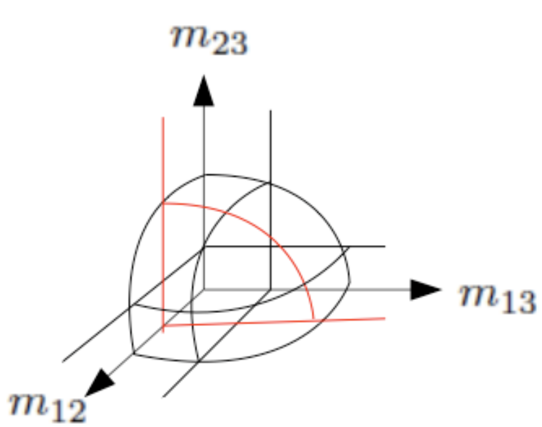


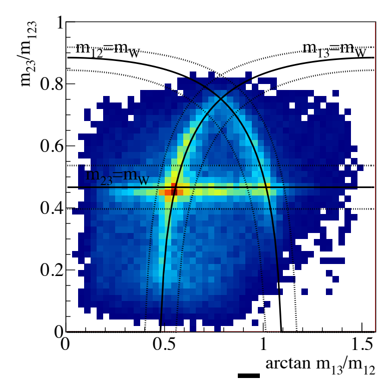
3. **choose 3 hard proto-jets with best filtered mass**

– $|m_{jjj}^{\text{filt}} - m_t| < 25$ GeV and $p_T^{\text{rec}} > 200$ GeV $\rightarrow$ top candidate

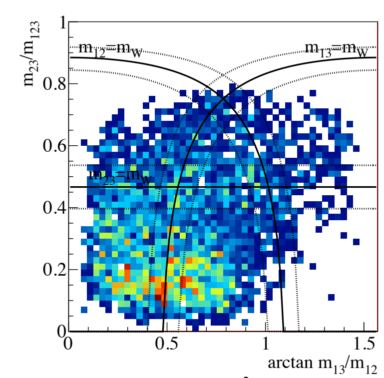
4. **check mass ratios**

– m_t condition: $m_t^2 = m_{123}^2 = m_{12}^2 + m_{13}^2 + m_{23}^2$ $\rightarrow$ spherical surface: 2D mass ratios

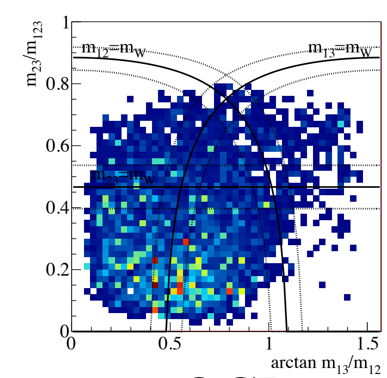




$t\bar{t}$



W+jets



QCD

– W mass condition, soft-collinear cut $\rightarrow$ tagged top

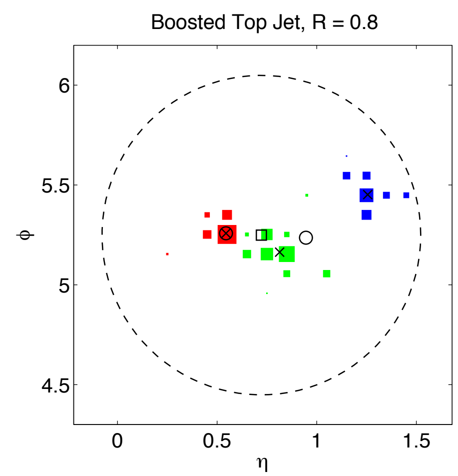
N-subjettiness

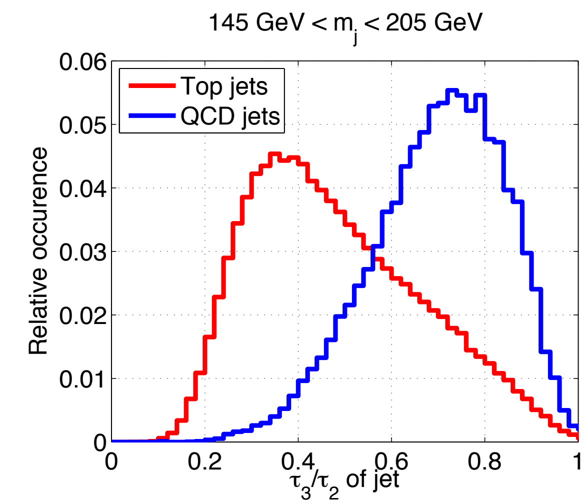
A New Substructure Measure

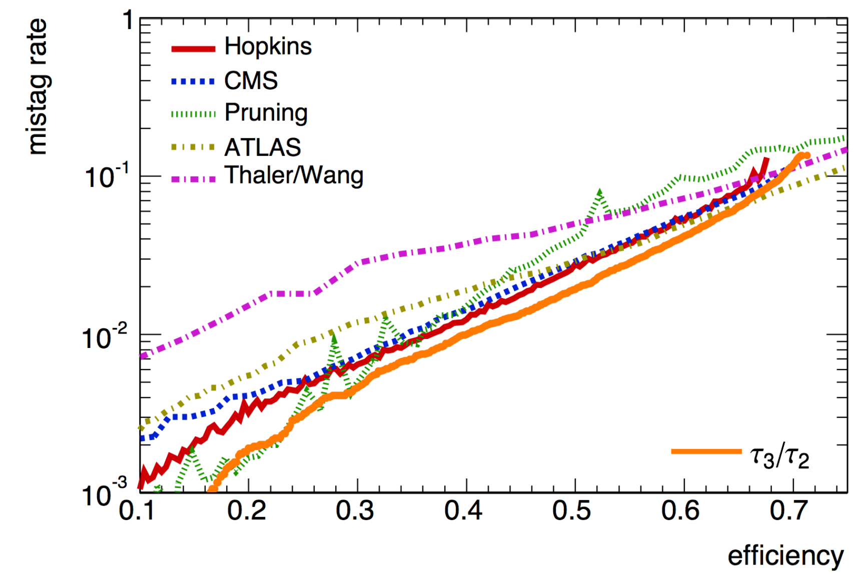
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min_A \{\Delta R_{A,k}\}$$

Top Tagging with τ_3/τ_2

(W/Z/H Tagging with τ_2/τ_1)







[Thaler, Van Tilburg: 1011.2268; See also J.-H. Kim: 1011.1493]

("Substructure without trees": Jankowiak, Larkoski; 1104.1646)

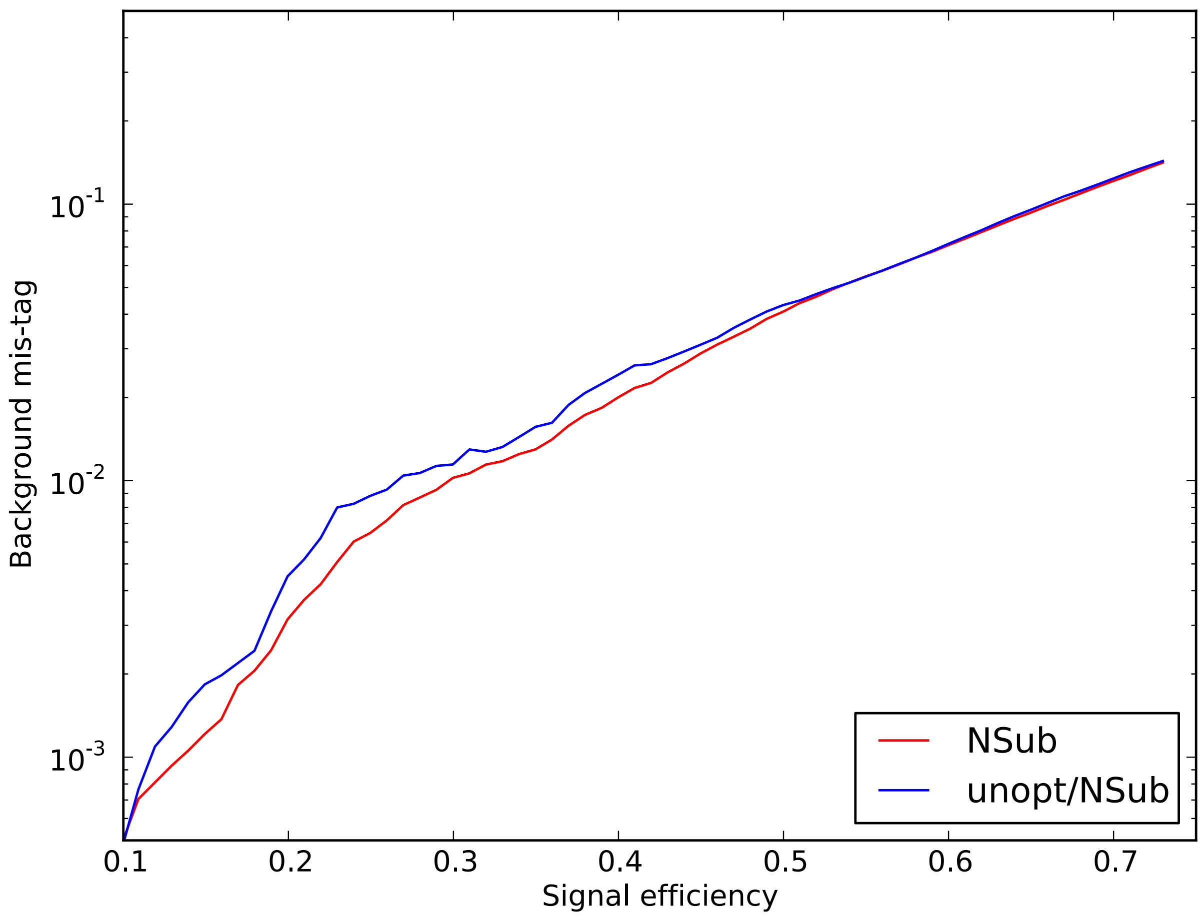
Angular Correlations

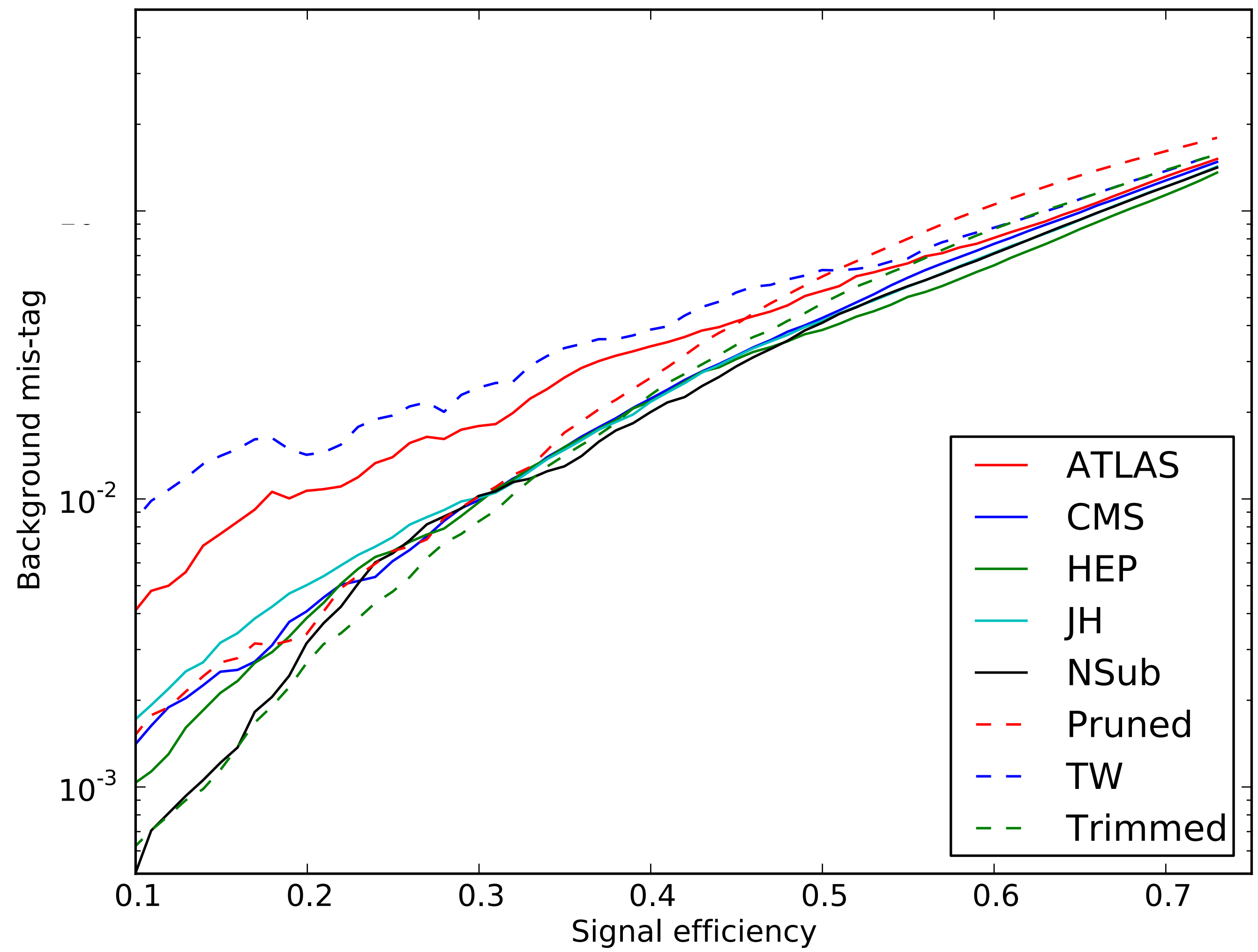
- For any IRC safe set of particles {*i*}:

$$\mathcal{G}(R) \equiv \frac{\sum_{i \neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2 \Theta(R - \Delta R_{ij})}{\sum_{i \neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2} \approx \frac{\sum_{i \neq j} p_i \cdot p_j \Theta(R - \Delta R_{ij})}{\sum_{i \neq j} p_i \cdot p_j}$$

- *R* is **not** measured wrt jet center
  - Distinct from angular profile
- Quantifies jet scaling in an IRC safe way

N-subjettiness with optimized β





Herwig++, 500-600

Why FastJet v3?

To make it easier and safer for users
to do advanced things with jets

Incorporating lessons we've learned while writing taggers,
mimicking real analyses (particle ID's, acceptances, etc.)
& performing background subtraction
[as well as some frequent requests]

v3.0.2 and doc: http://fastjet.fr

(next few slides from FJ website)

Jets are self-aware

Jets from a cluster sequence know about properties deriving from the clustering itself

```
ClusterSequence cs(input_particles, jet_def);
vector<PseudoJet> jets = cs.inclusive_jets();
// extract the constituents of a jet
vector<PseudoJet> constituents = jets[0].constituents();


ClusterSequenceArea csa(input_particles, jet_def, area_def);
vector<PseudoJet> jets = csa.inclusive_jets();
// get the scalar area of a jet
double area = jets[0].area();
```

Composite jets

Jets can be joined

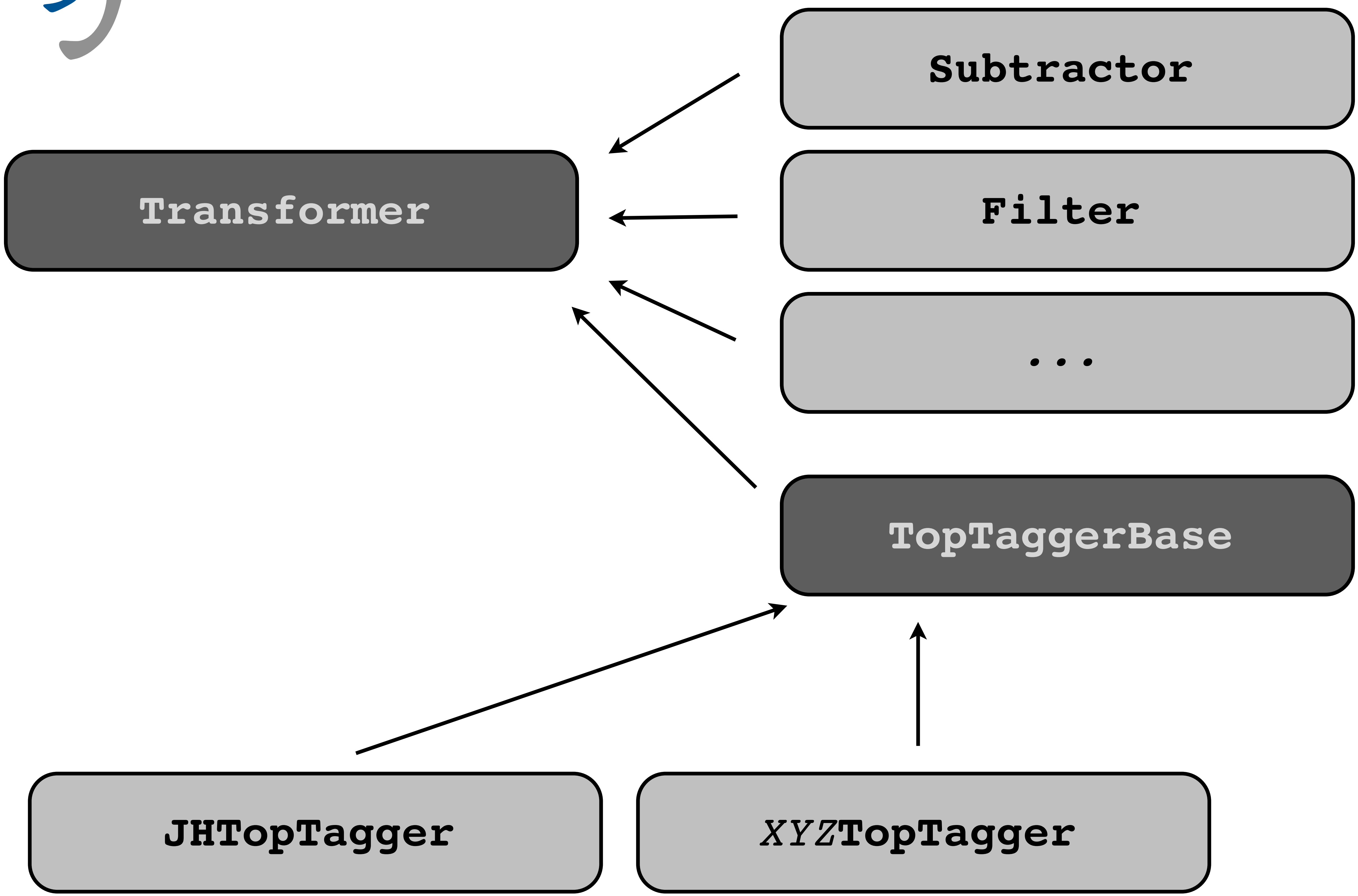
```
// subjets of a top candidate
PseudoJet W1;
PseudoJet W2;
PseudoJet b;

// build the top
PseudoJet W = join(W1,W2); // result is a 'sensible' PseudoJet,
PseudoJet top = join(W,b); // with additions (see pieces() below)

// top constituents: all the initial particles in the jet
vector<PseudoJet> constituents = top.constituents();

// top pieces: the b and the W
vector<PseudoJet> pieces = top.pieces();
```

Transformers



Taggers

Example of a boosted top tagger

```
#include "fastjet/tools/JHTopTagger.hh"

double delta_pt=0.1, delta_r=0.19;
JHTopTagger = top_tagger(delta_pt,delta_r);
top_tagger.set_top_selector(SelectorMassRange(150,200));
top_tagger.set_W_selector(SelectorMassRange(65,95));

PseudoJet tagged_jet = top_tagger(jet);    // top candidate

// extract structure
if (tagged_jet != 0) {
 PseudoJet W = tagged_jet.structure_of<JHTopTagger>().W();
 PseudoJet nonW = tagged_jet.structure_of<JHTopTagger>().non_W();
}
```