Boosted Topologies and Algorithms

Brock Tweedie
PITT PACC, University of Pittsburgh
@ Next Steps in the Energy Frontier - Hadron Colliders
Fermilab
26 August 2014

"Heavy" ➜ "Light"

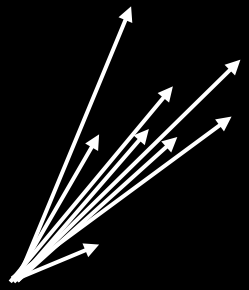
$$\frac{m(\text{top})}{100\ \text{TeV}} \sim \frac{m(\text{bottom})}{E(\text{Tevatron})}$$

$$\frac{m(\text{W-boson})}{100\ \text{TeV}} \sim \frac{m(\text{tau})}{E(\text{Tevatron})}$$

Main novelty: $m >> \Lambda_{QCD}$

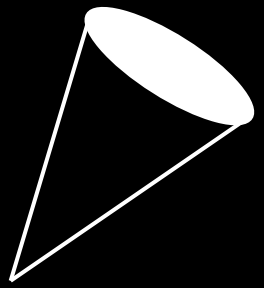
Jet Substructure

energetic spray of hadrons

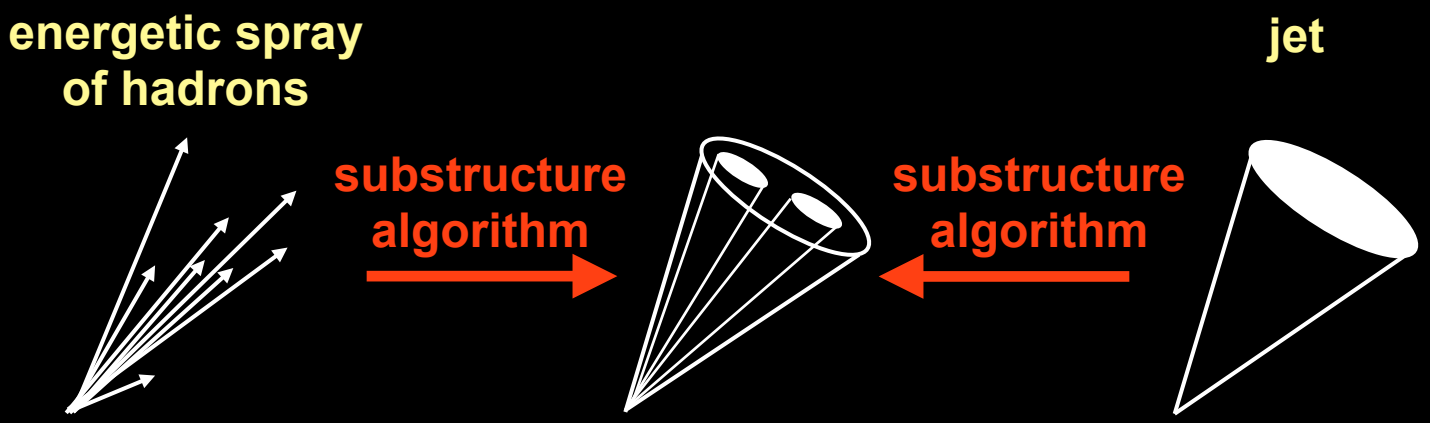


jet algorithm

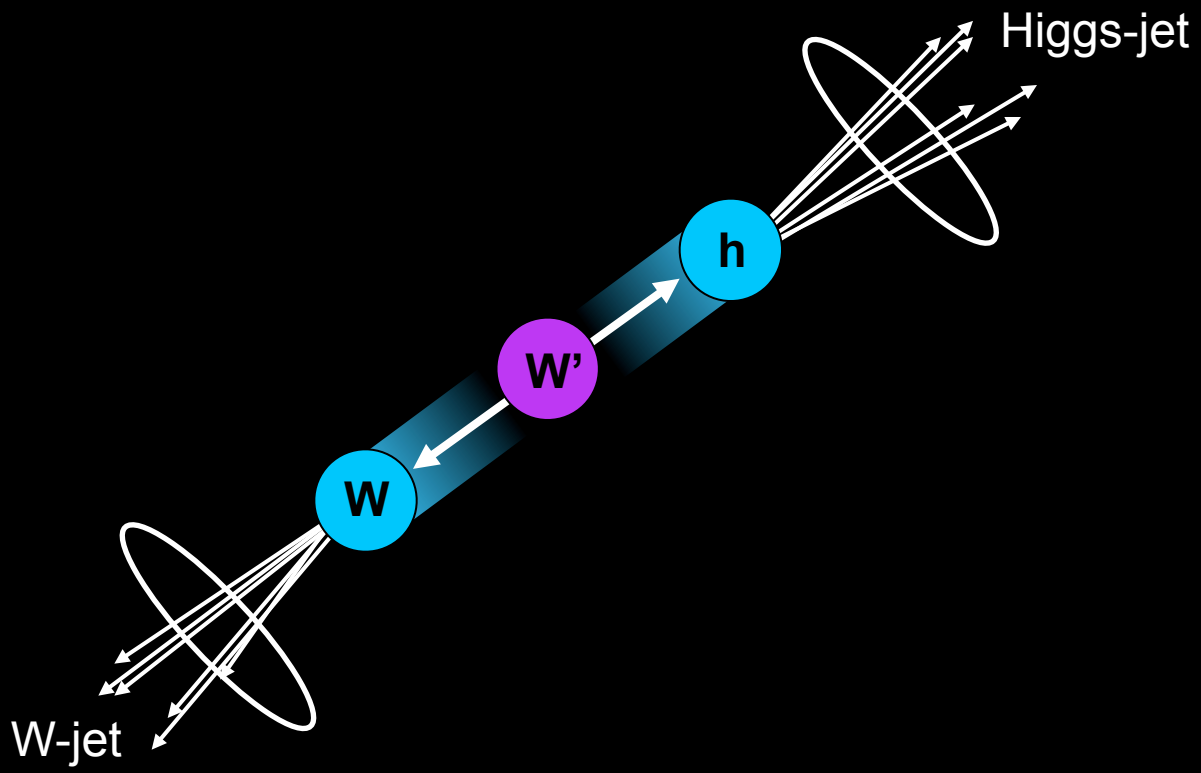
jet



Jet Substructure



New Physics Applications



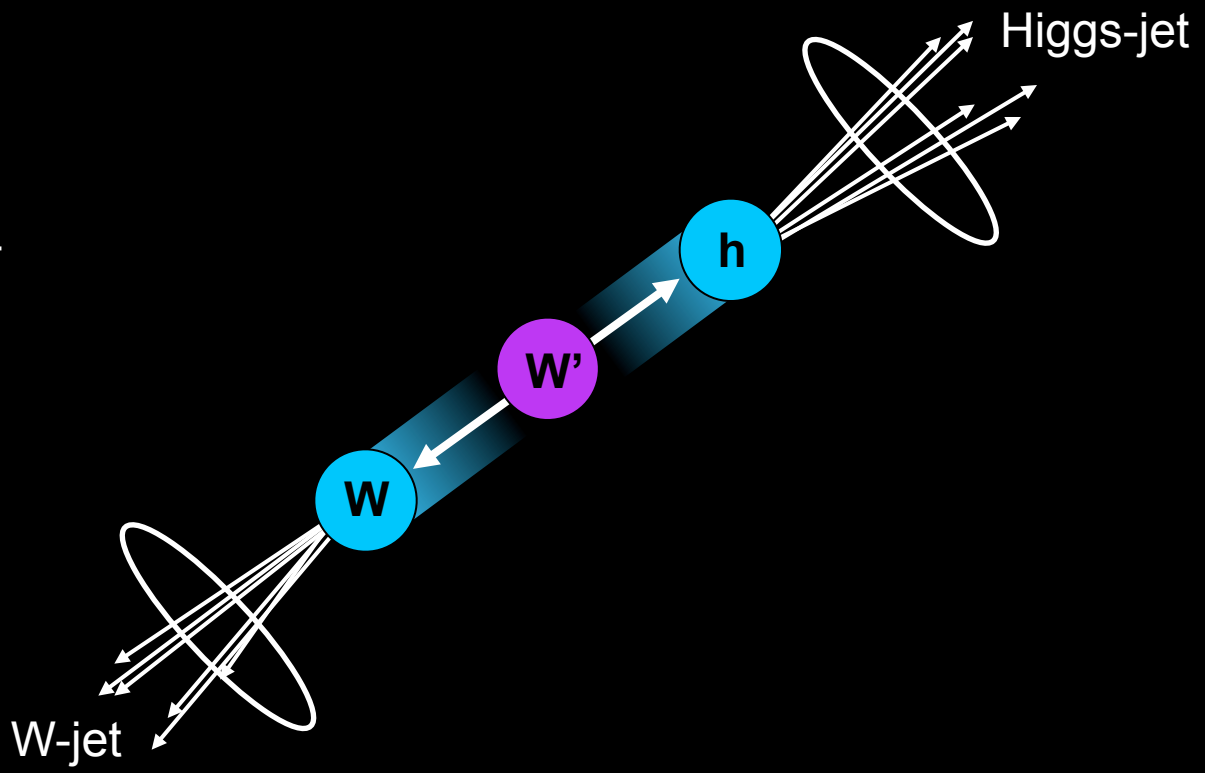
TeV-scale resonance: X → W / Z / Higgs / top

("primed" gauge bosons, capital H, KK graviton, excited quark)

BR(W→jets) = 67%, BR(Z→jets) = 70%, BR(h→jets) = 80%, BR(t→jets) = 67%

New Physics Applications

$$\Delta R \sim \frac{2m}{p_T} \sim \frac{2(100)}{(1000/2)} \sim 0.4$$



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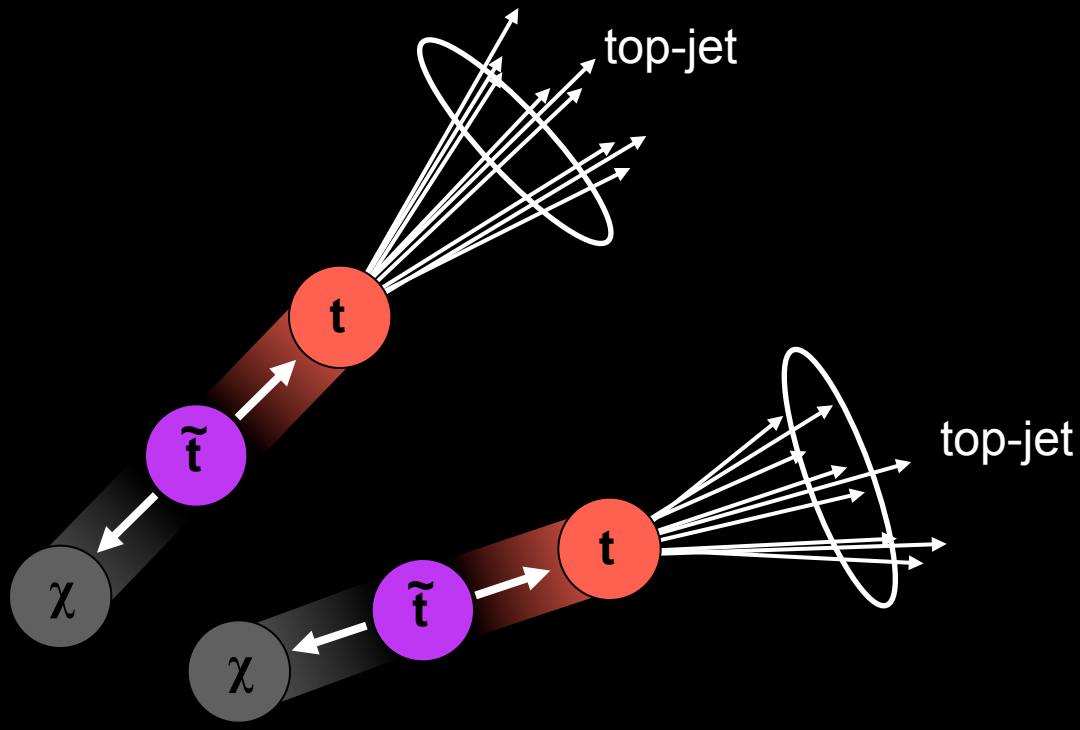
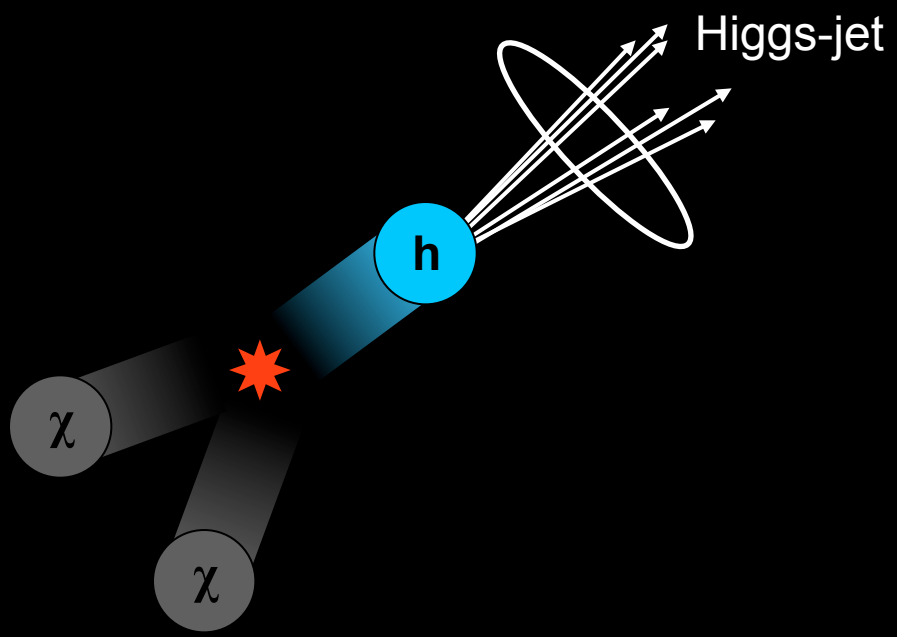
New Physics Applications



TeV-scale pair-produced
(stop, gluino, vector-like top/bottom)

BR(W→jets) = 67%, BR(Z→jets) = 70%, BR(h→jets) = 80%, BR(t→jets) = 67%

New Physics Applications

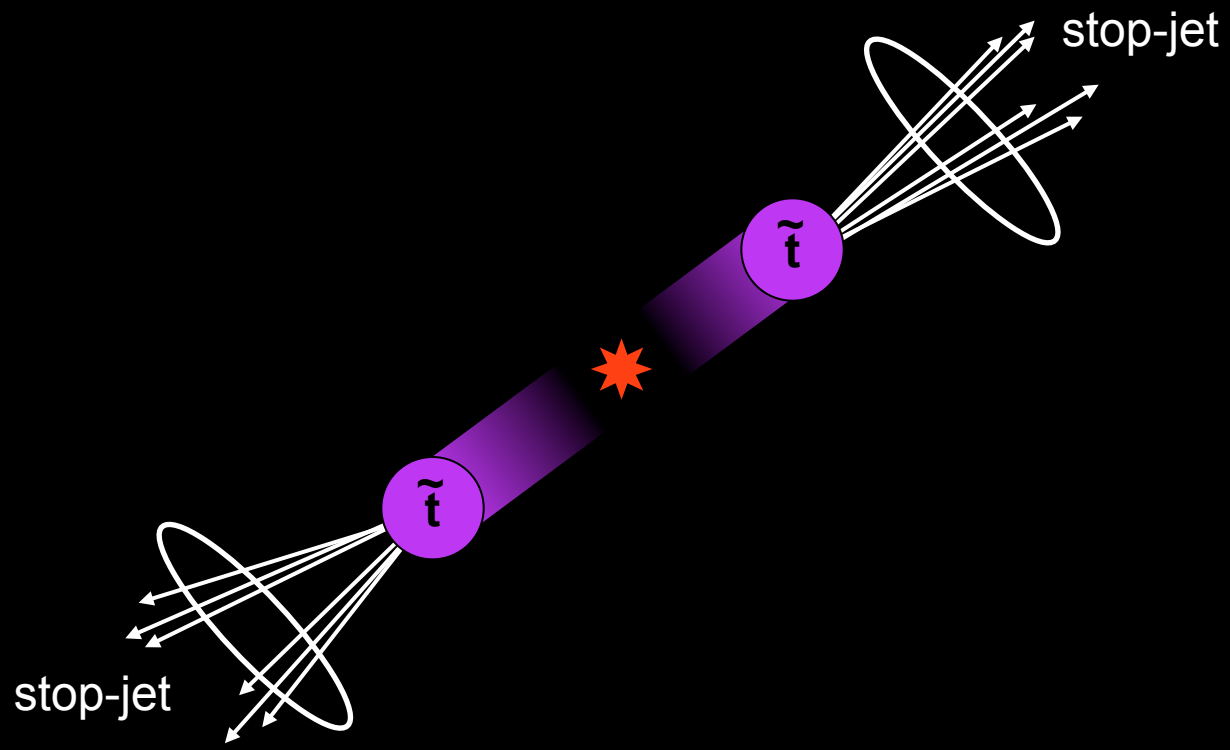


SM + dark matter

(contact operators + EW brem)

BR(W→jets) = 67%, BR(Z→jets) = 70%, BR(h→jets) = 80%, BR(t→jets) = 67%

New Physics Applications

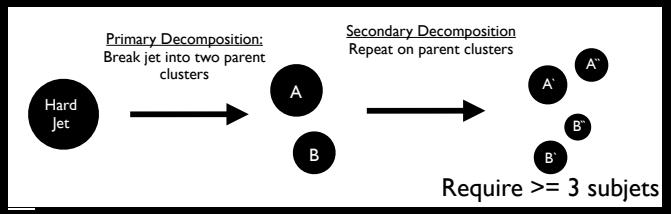


Pair-produced X → quarks/gluons at high-p_T
(RPV SUSY)

BR(X→jets) = 100% ??

Substructure Tactics

Declustering



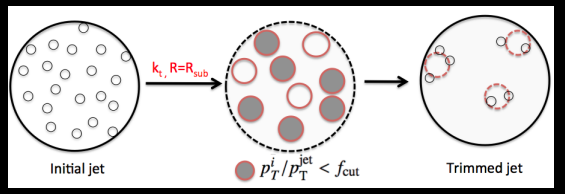
Shape Observables

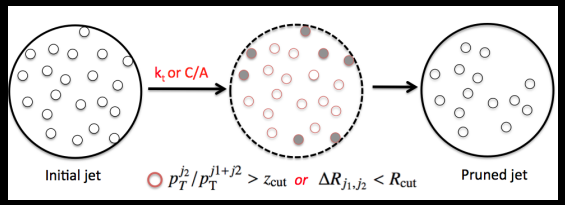
$$OV_3 = \max_{\{\tau_n\}} \exp\left[-\sum_{i=1}^{3} \frac{1}{2\sigma_i^2}\left(E_i - \sum_{\substack{\Delta R(\text{topo},i) \\ <0.2}} E_{\text{topo}}\right)^2\right]$$

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

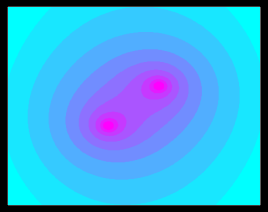
$$C_2^\beta = \frac{\sum_{i,j,k} p_{Ti} p_{Tj} p_{Tk} (R_{ij} R_{ik} R_{jk})^\beta \sum_i p_{Ti}}{(\sum_{i,j} p_{Ti} p_{Tj} (R_{ij})^\beta)^2}$$

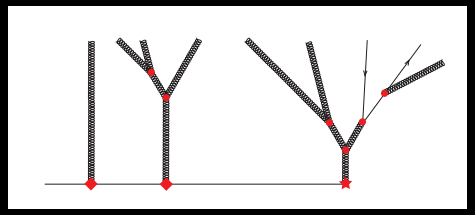
Grooming



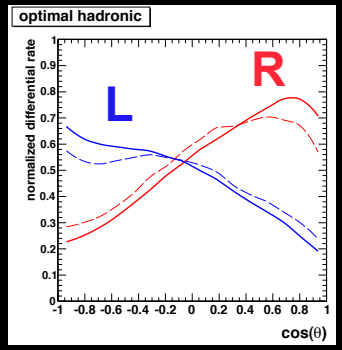


Color-flow / Radiation pattern



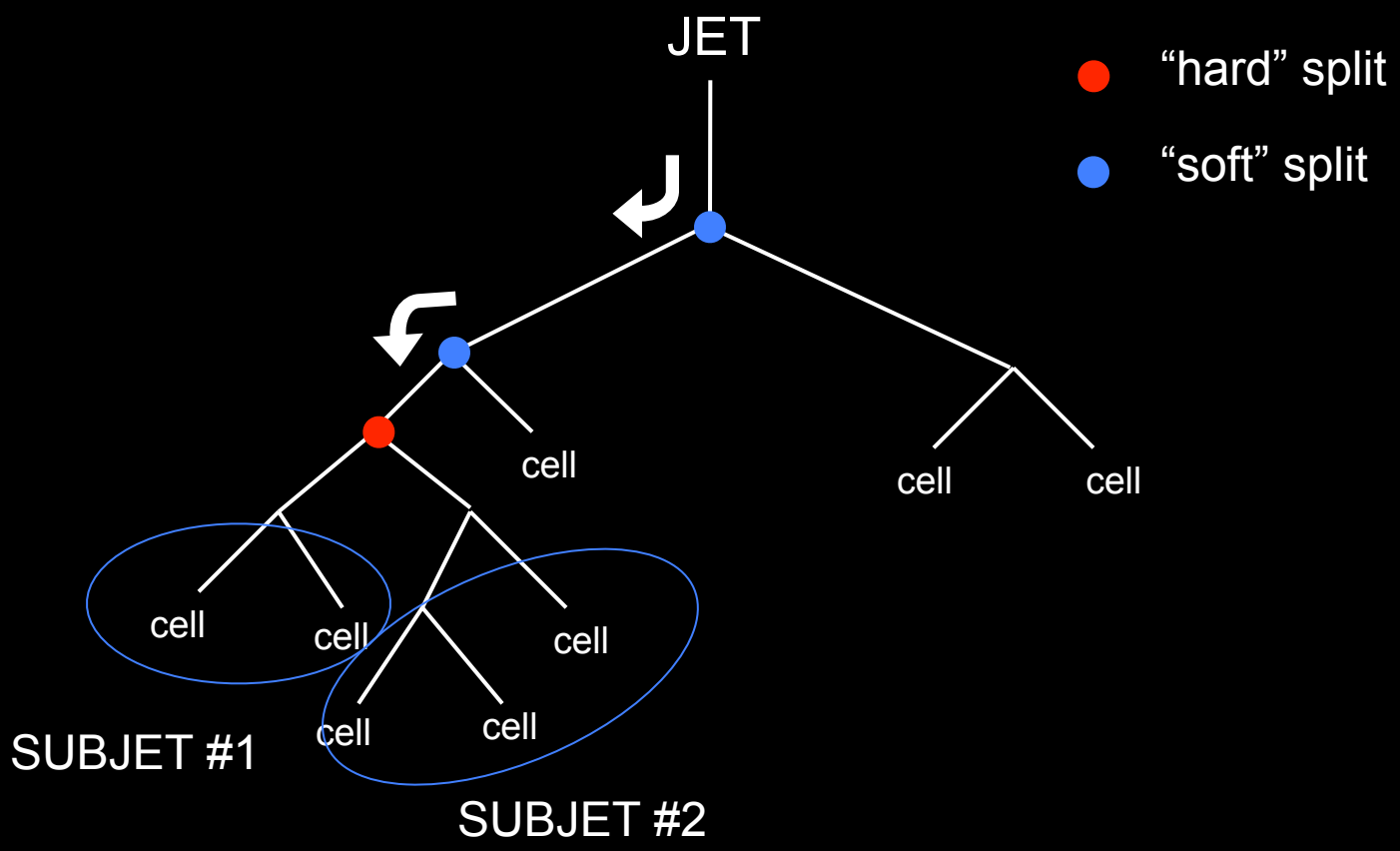


Polarization



* Many available as internal/external classes and contribs for FastJet

Substructure via Declustering



Seymour (1994)
Butterworth, Cox, Forshaw (2002)
Butterworth, Davison, Rubin, Salam (2008)

HEPTopTagger

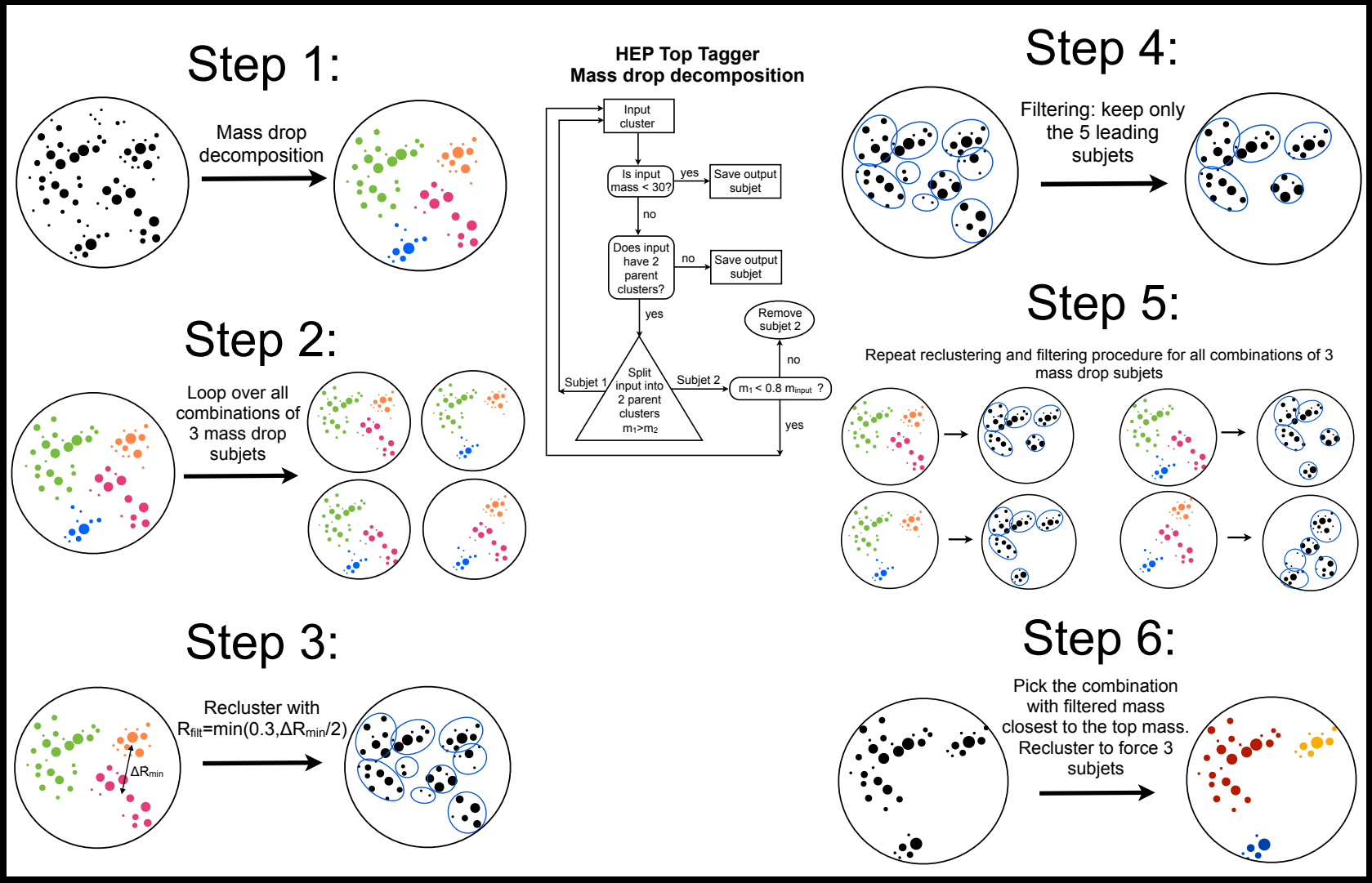


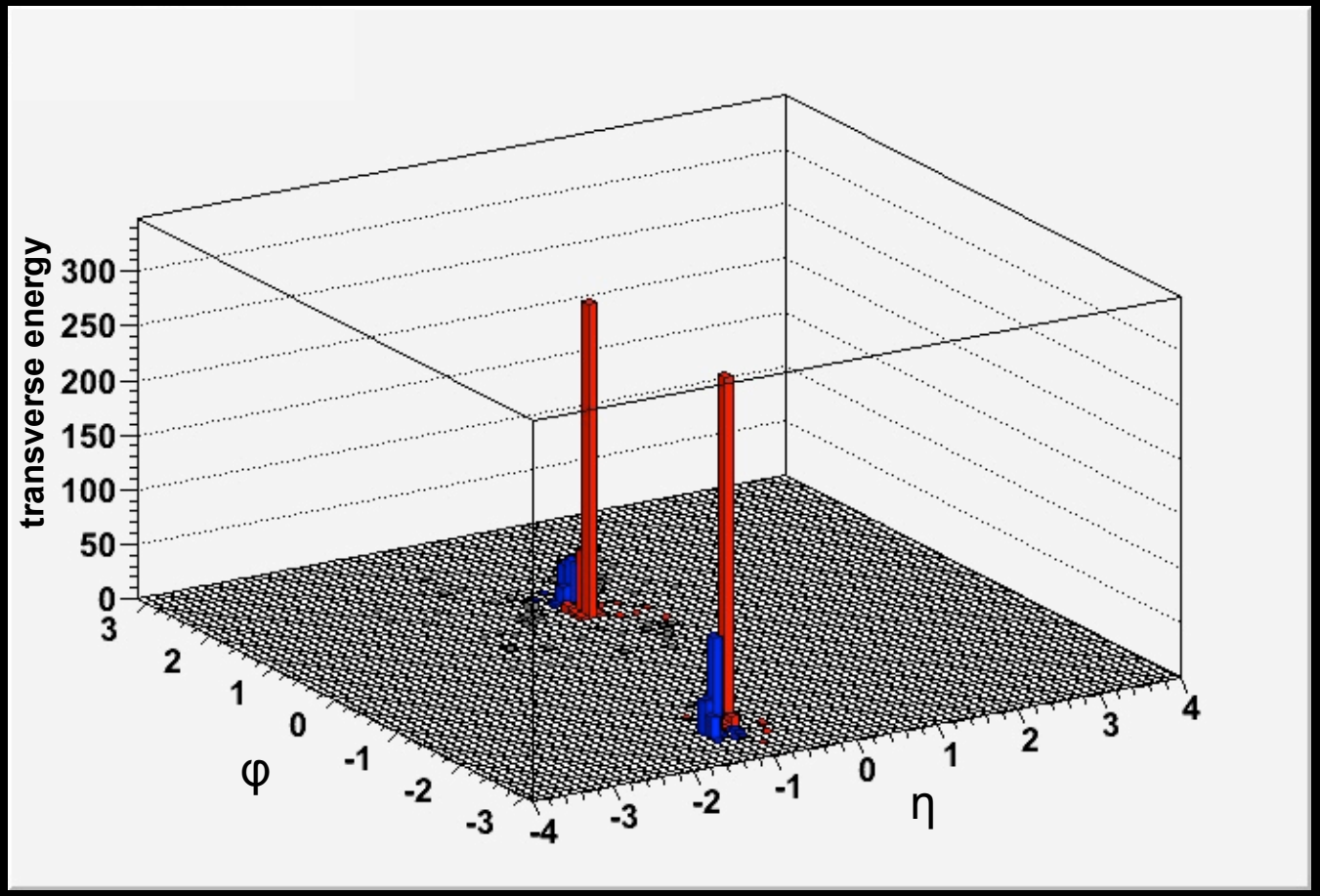
Figure by CMS, based on **Plehn, Spannowsky, Takeuchi, Zerwas (2010)**

N-Subjettiness

$$\tau_N = \min_{\hat{n}_1,\hat{n}_2,\ldots,\hat{n}_N} \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{1,k}, R_{2,k}, \cdots, R_{N,k}\right\}$$

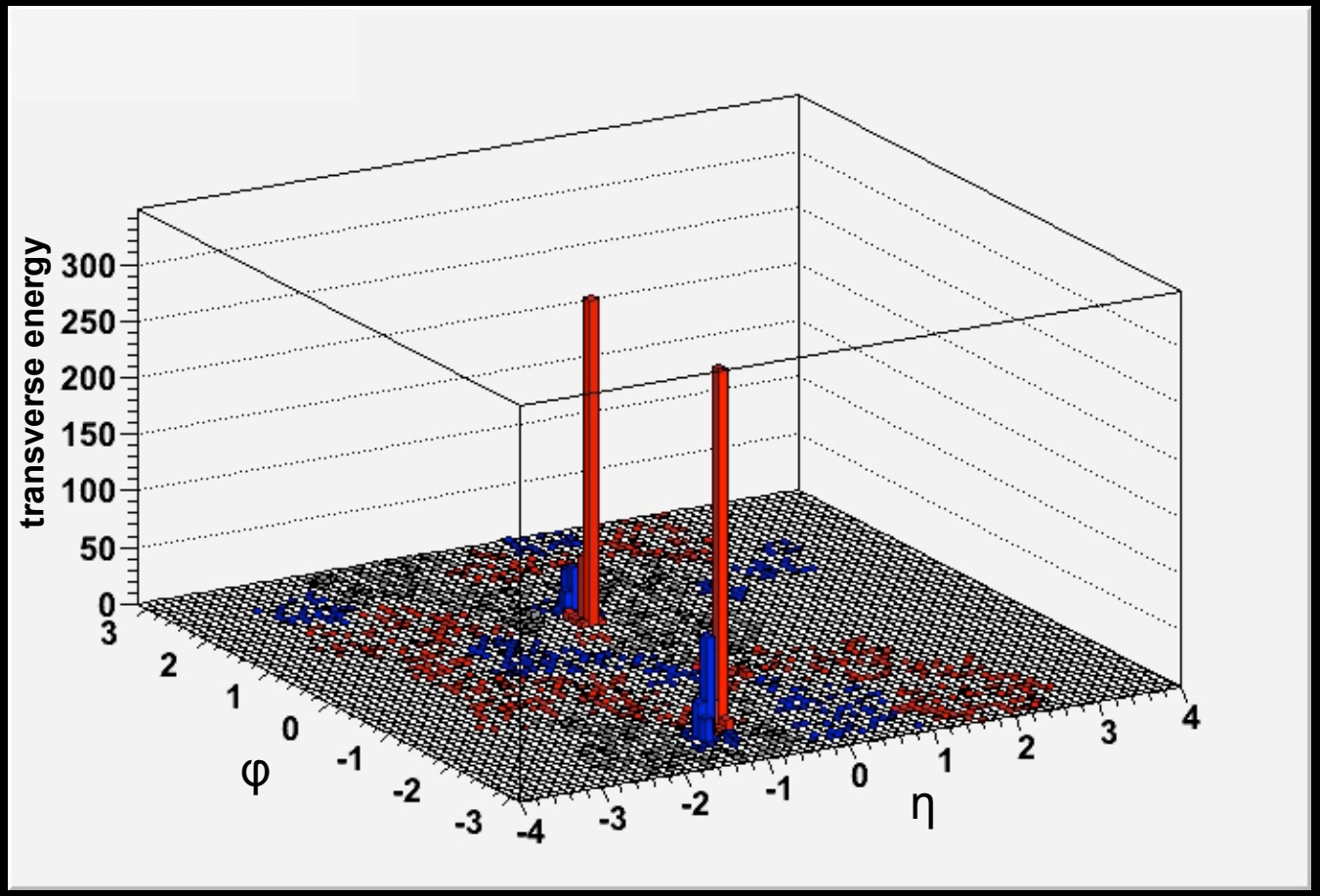
Thaler & Van Tilburg (2010)

Trimming Example



Krohn, Thaler, Wang (2009)

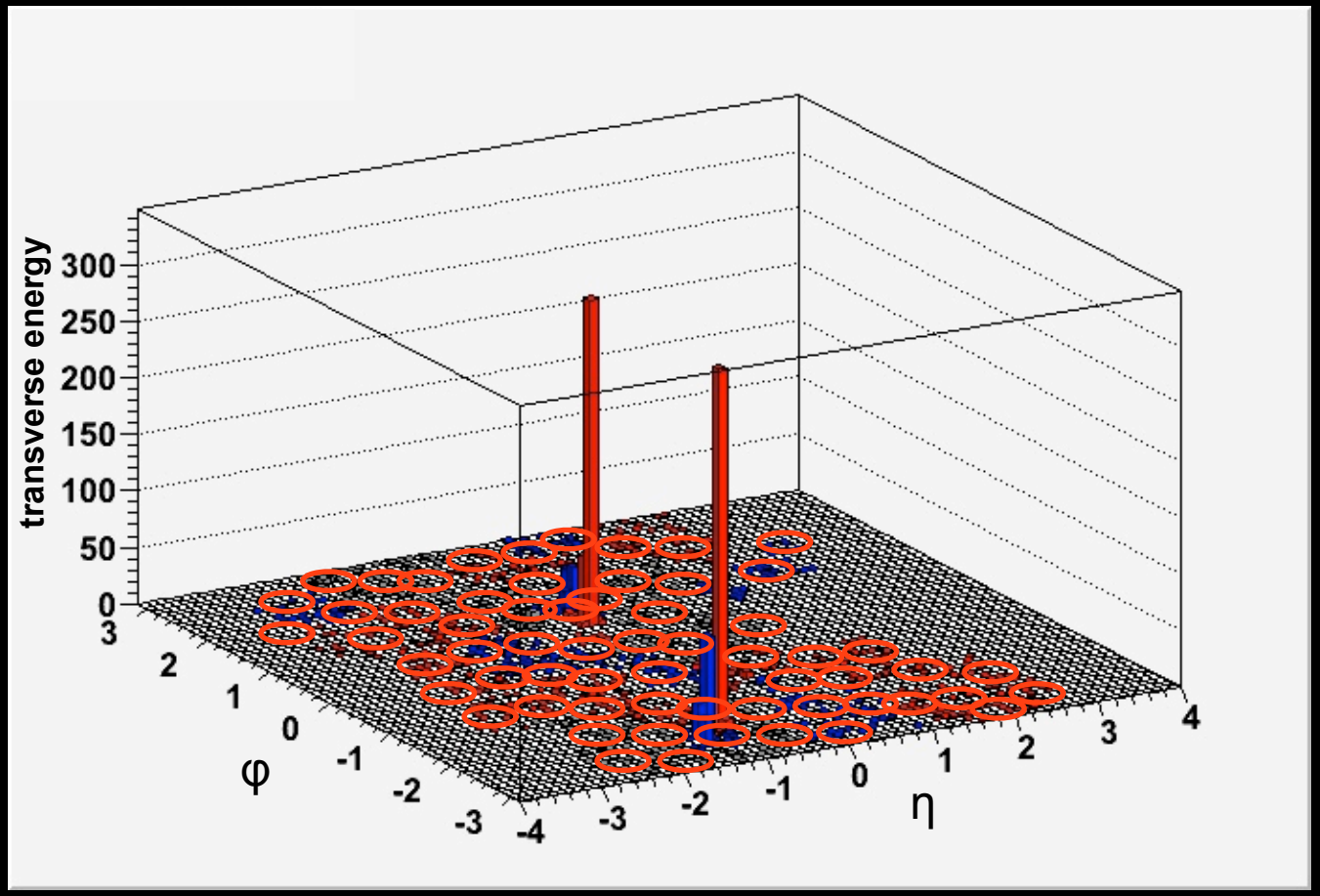
Trimming Example



+ pileup
(μ=20, charged included)

Krohn, Thaler, Wang (2009)

Trimming Example



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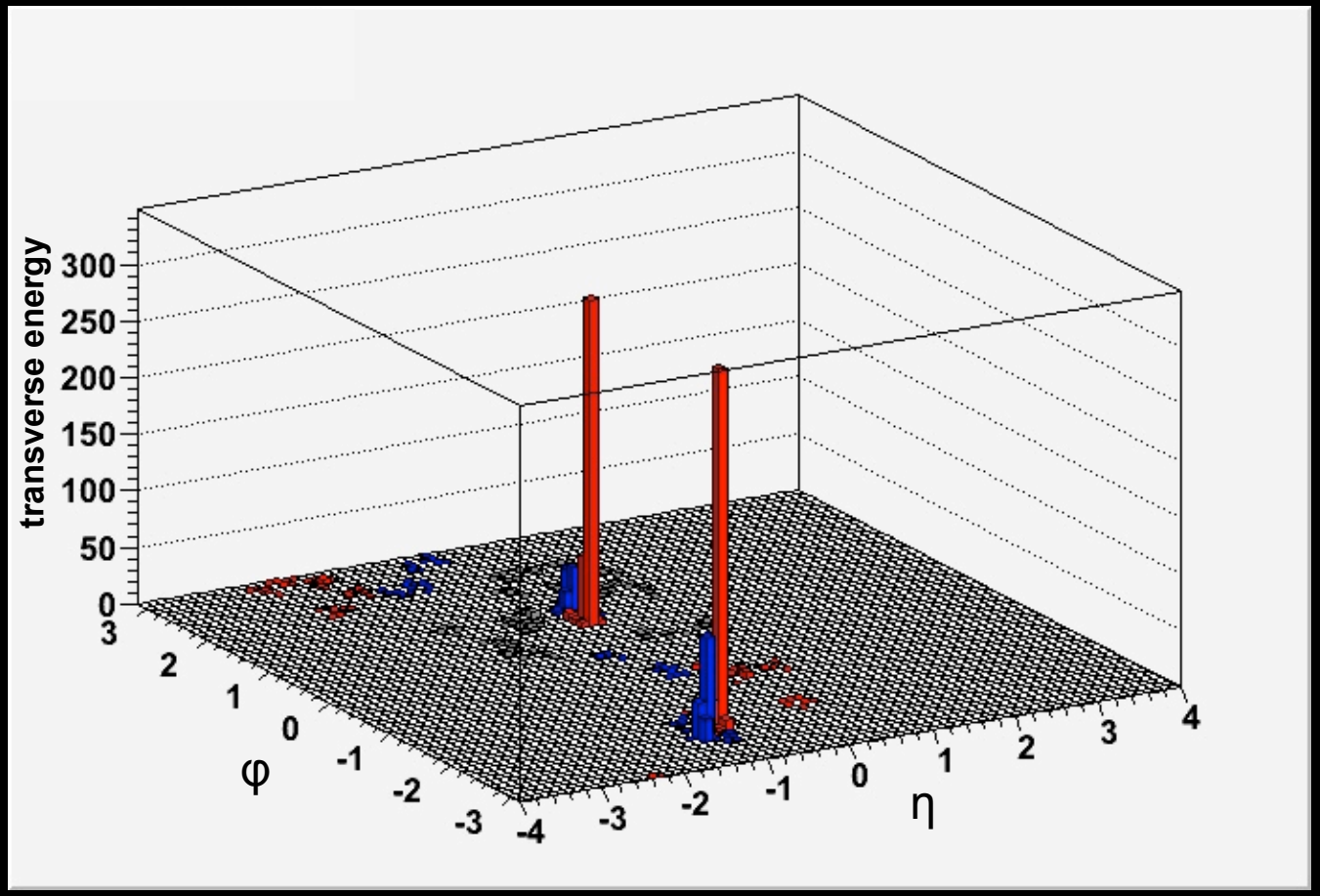
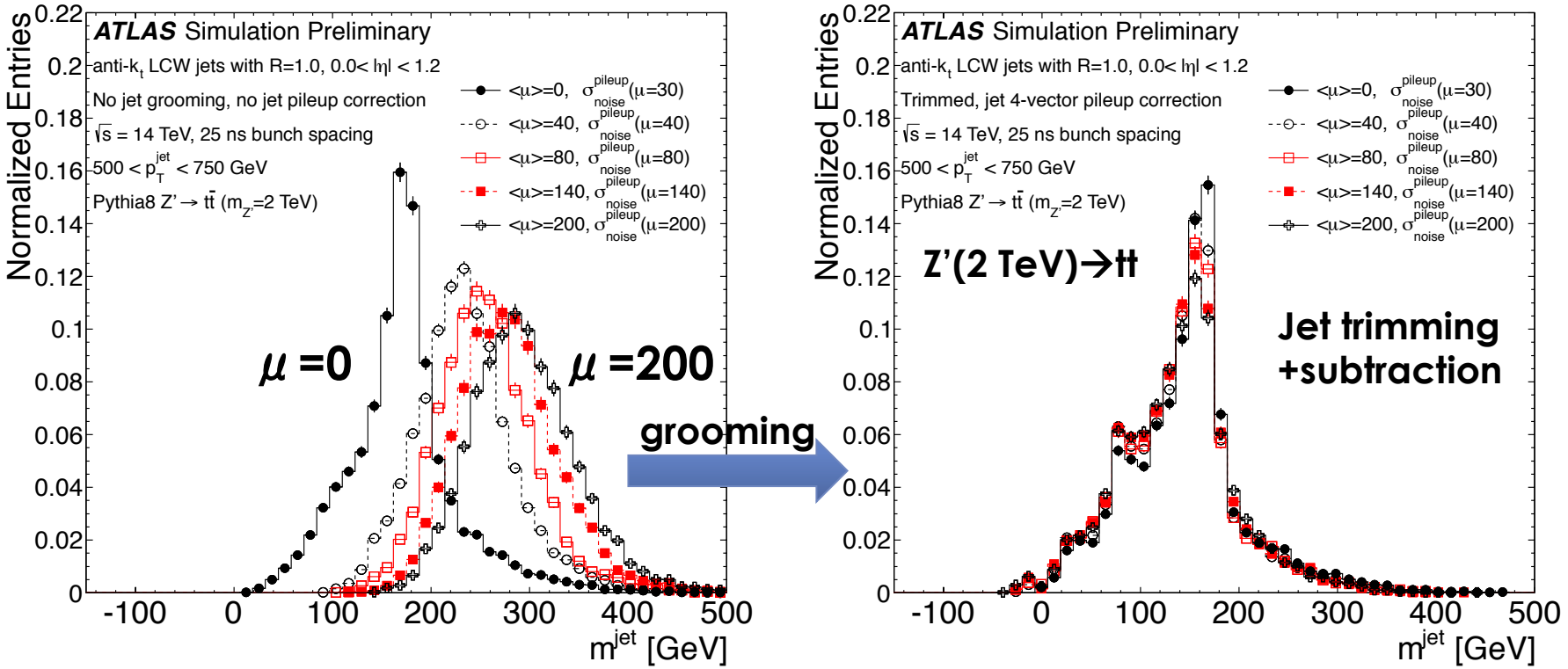


+ trimming

Krohn, Thaler, Wang (2009)

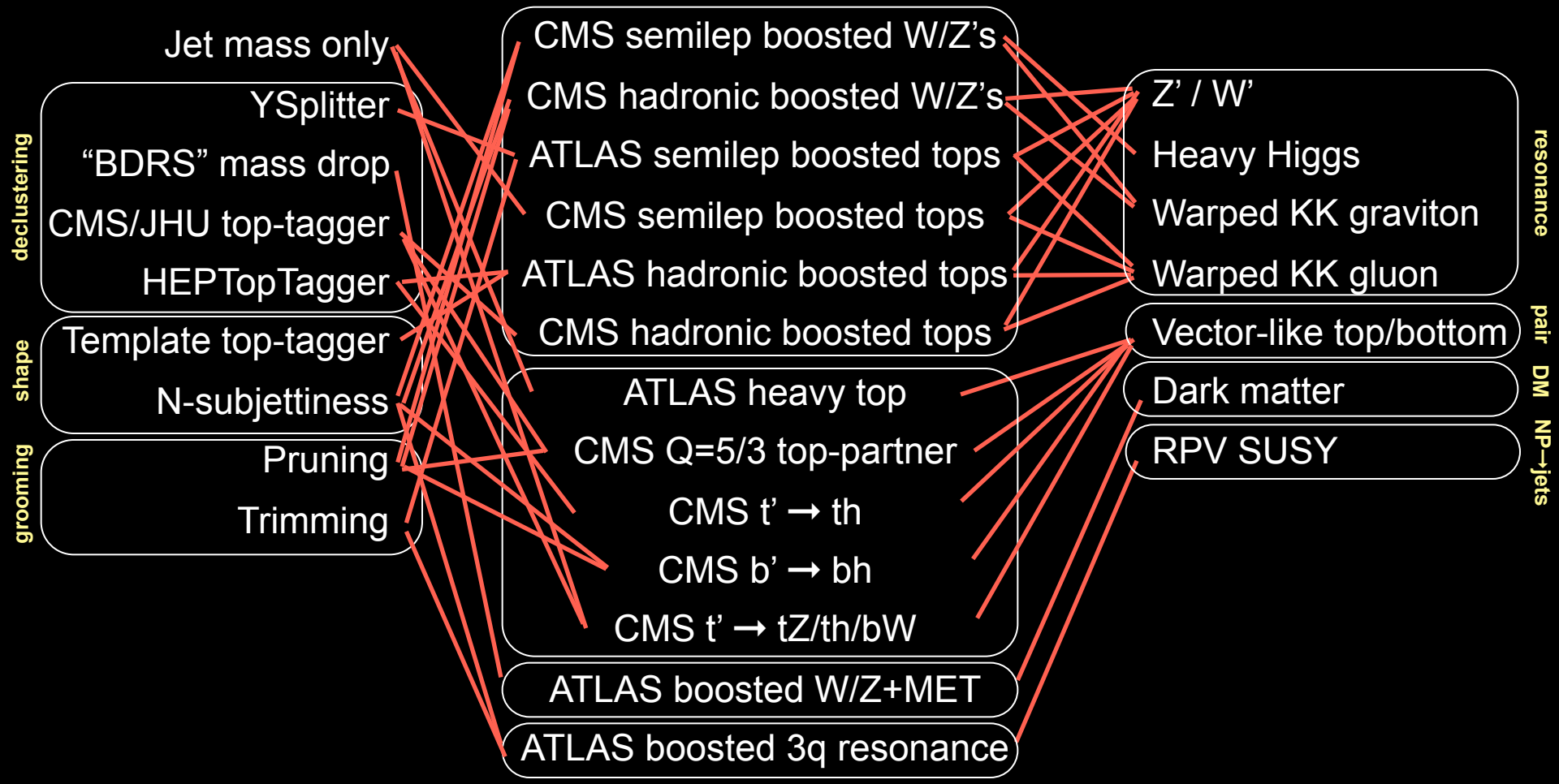
Trimming Top-Jets



here combined with jet area-based 4-vector subtraction

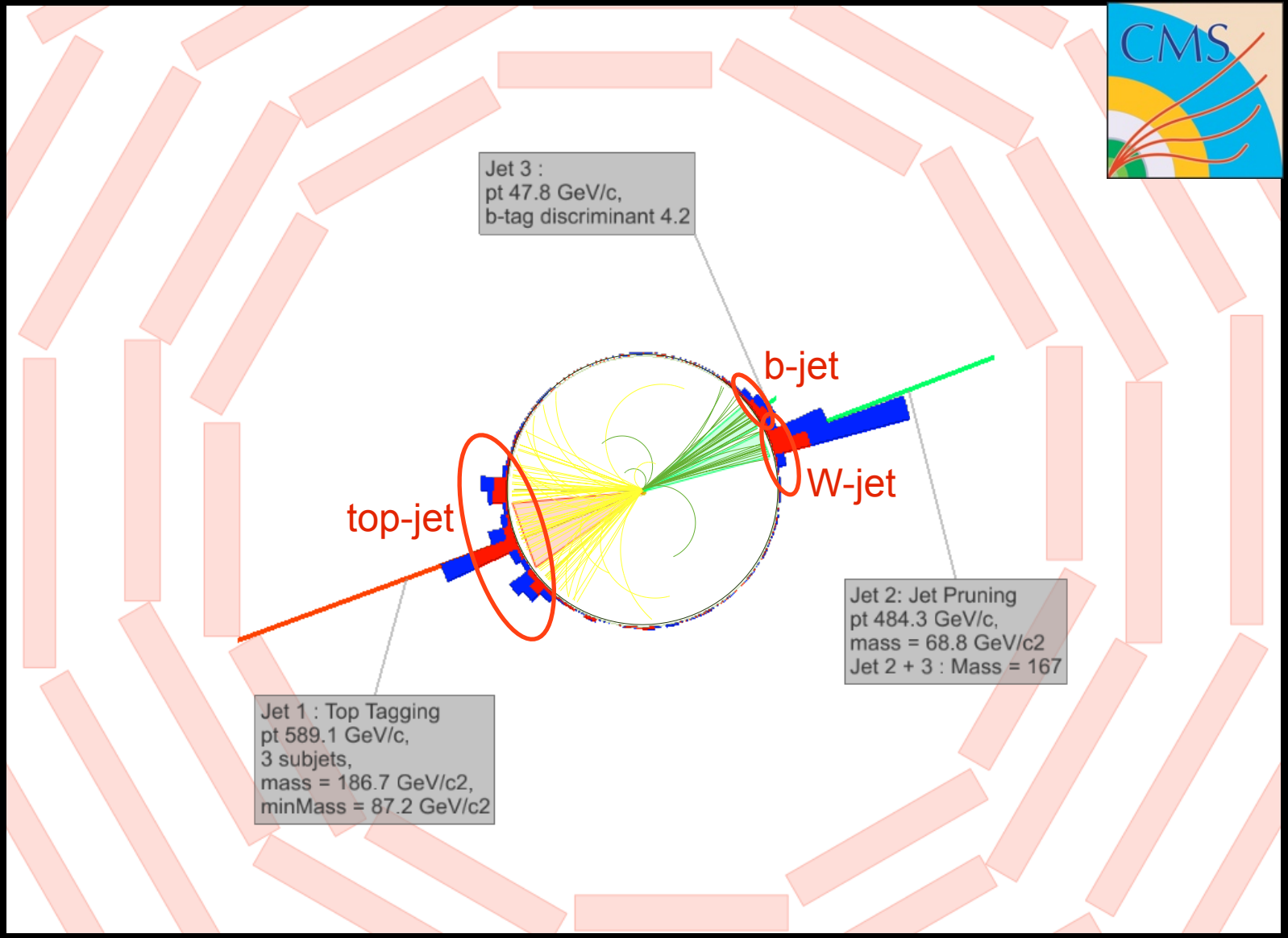
*** With trimming alone, the peak shifts by ~10 GeV, but there are now many other methods that should play well with substructure: Jet Cleansing, Constituent Subtractor, SoftKiller, PUPPI, ...**

Tools ↔ Searches ↔ Models



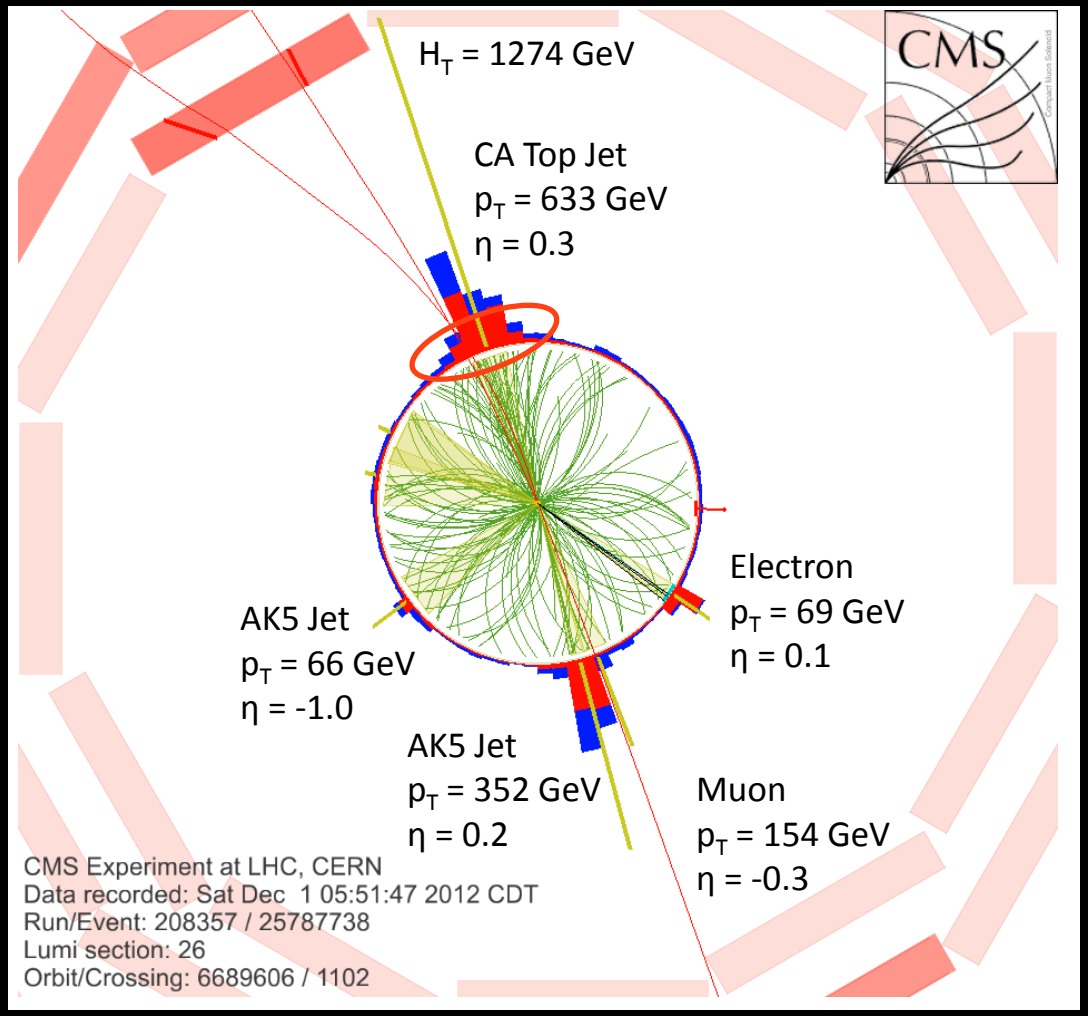
And quickly growing...

CMS "Triple-Tagged" Event



KK gluon Limit: M > 1.8 TeV standalone (2.5 TeV combined w/ l+jets) 1309.2030

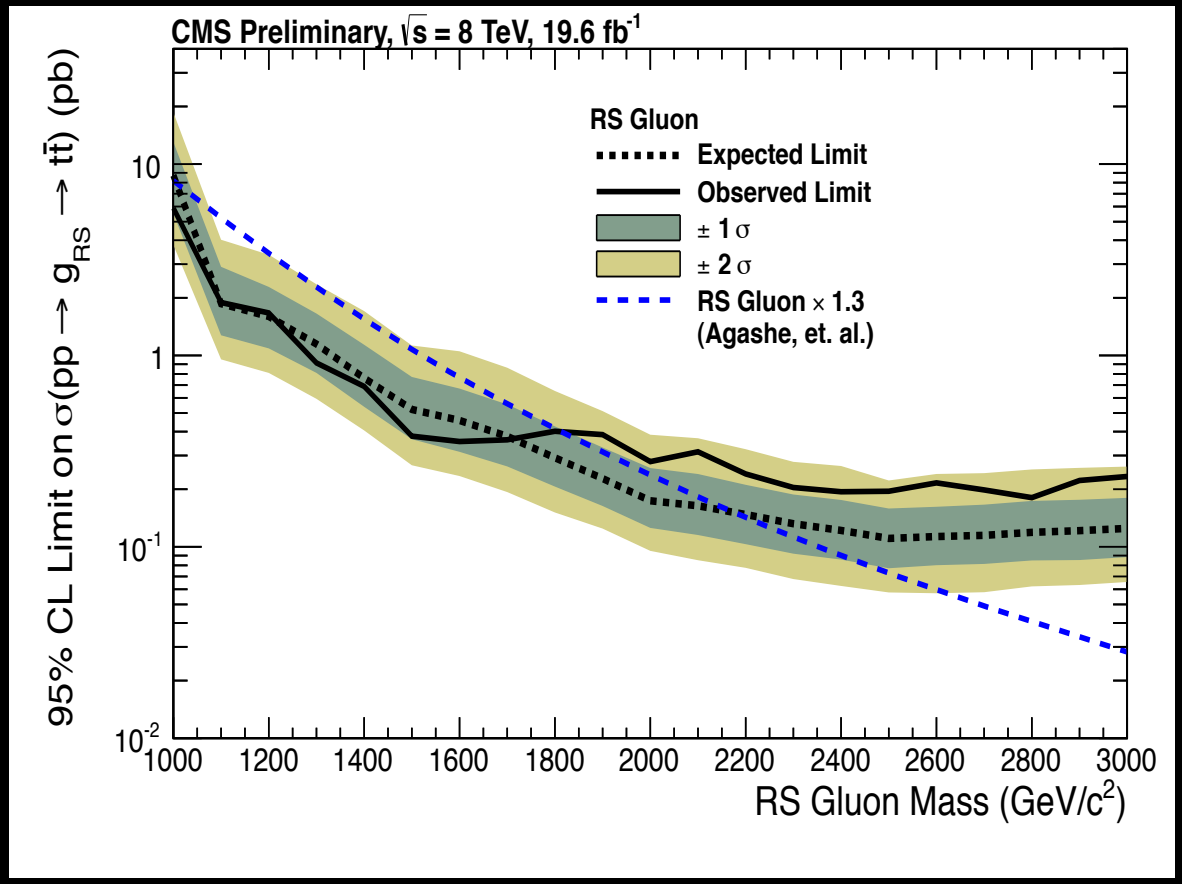
Heavy Q=+5/3 Top Partner



SSDL + top/W-jets Limit: M > 770 GeV

1312.2391

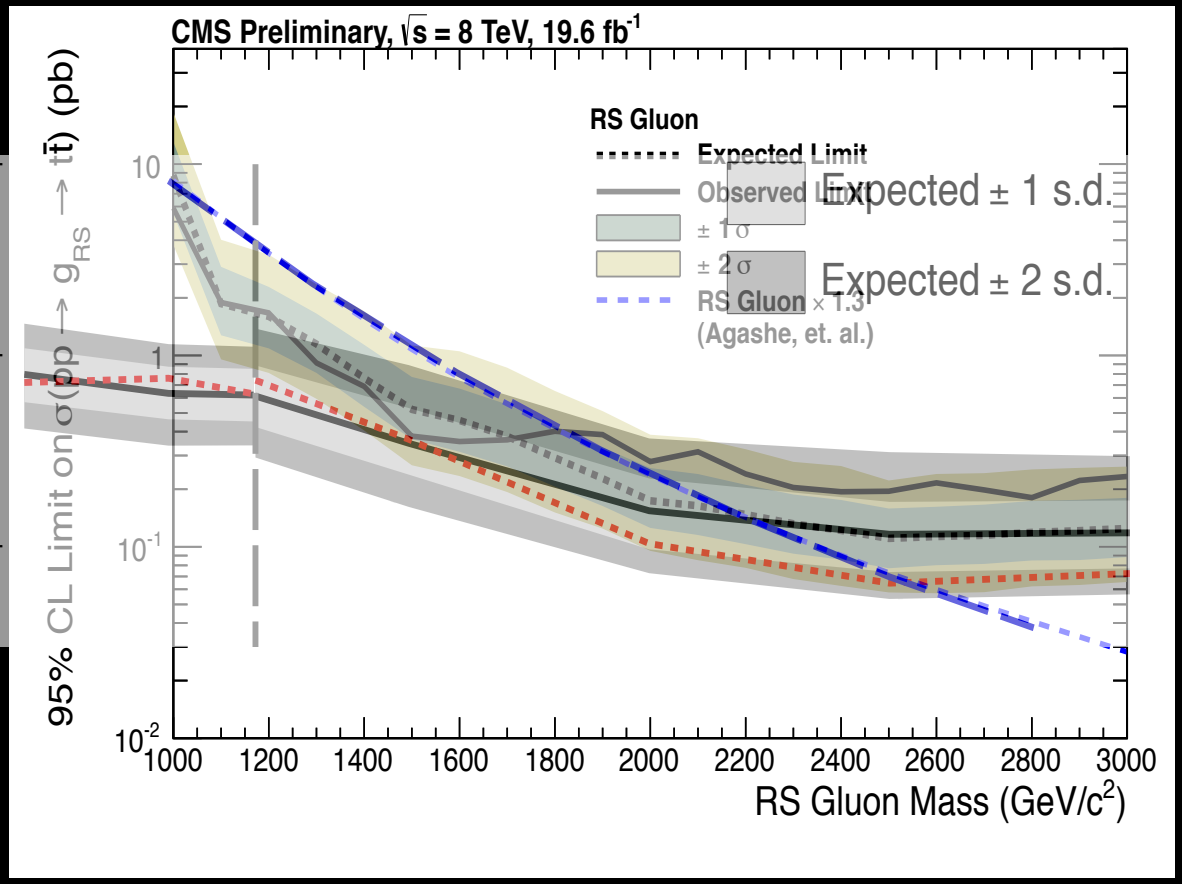
tt Resonance Comparison



CMS all-hadronic

CMS PAS B2G-12-005

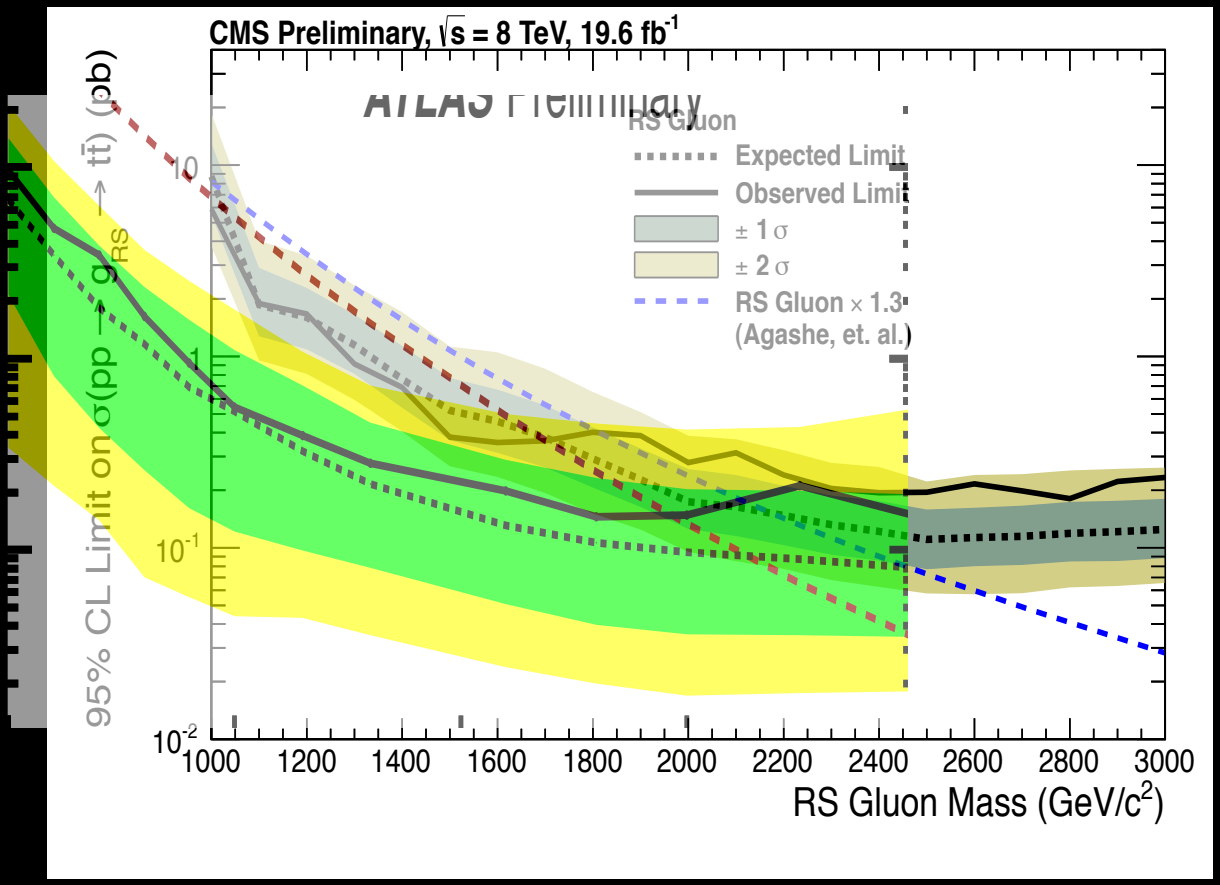
tt Resonance Comparison



+ CMS l+jets

CMS PAS B2G-12-006

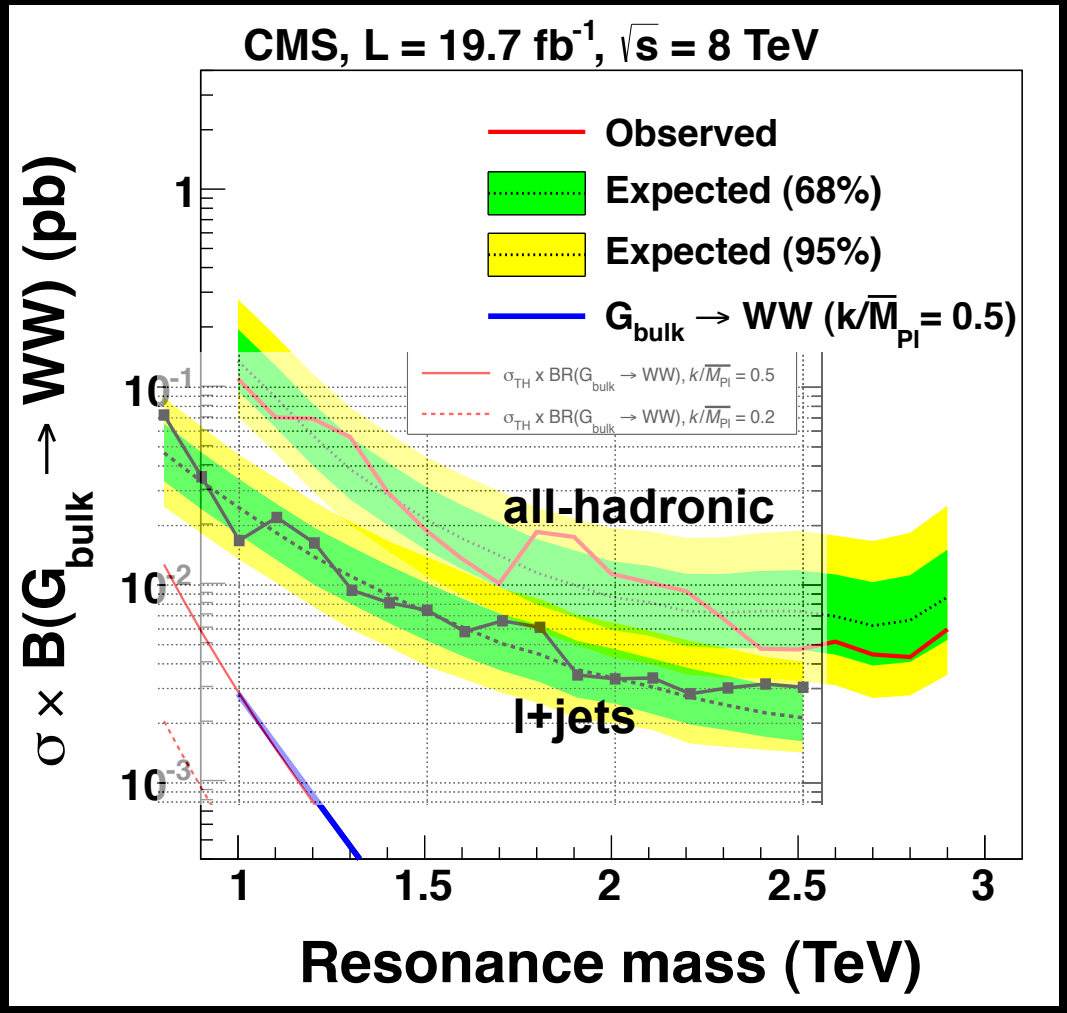
tt Resonance Comparison



+ ATLAS l+jets

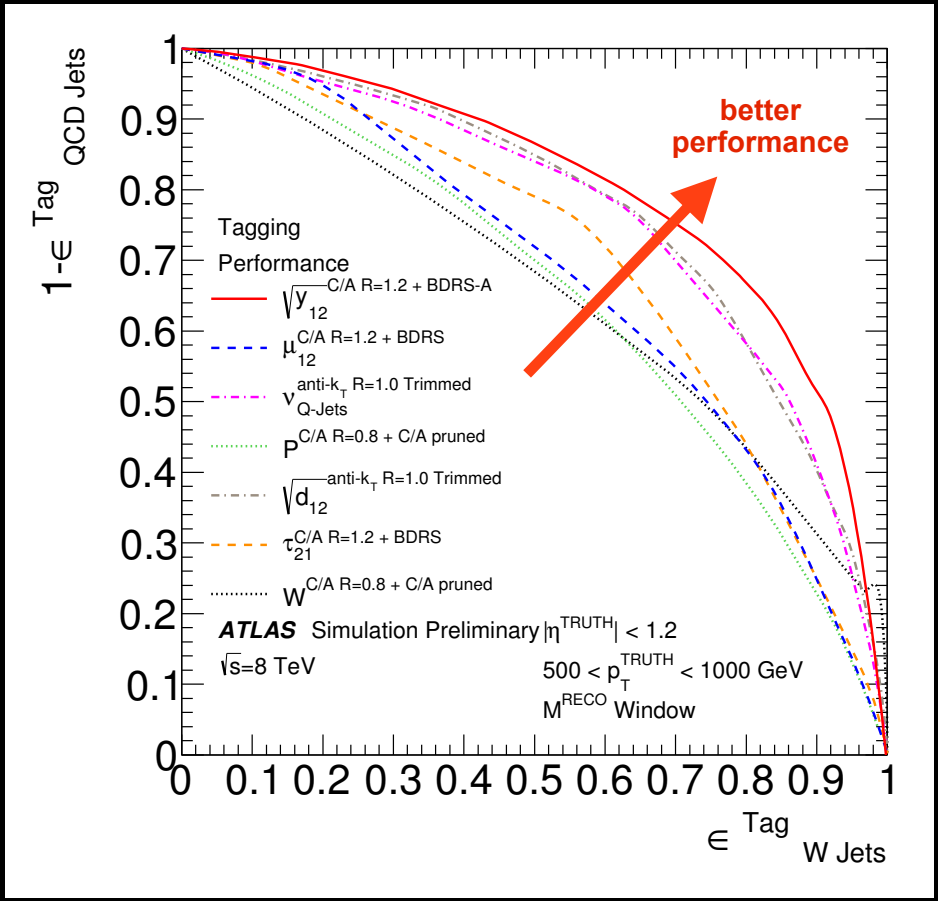
ATLAS-CONF-2013-052

WW Resonance Comparison



1405.1994, 1405.3477

ATLAS W-Tagger Studies

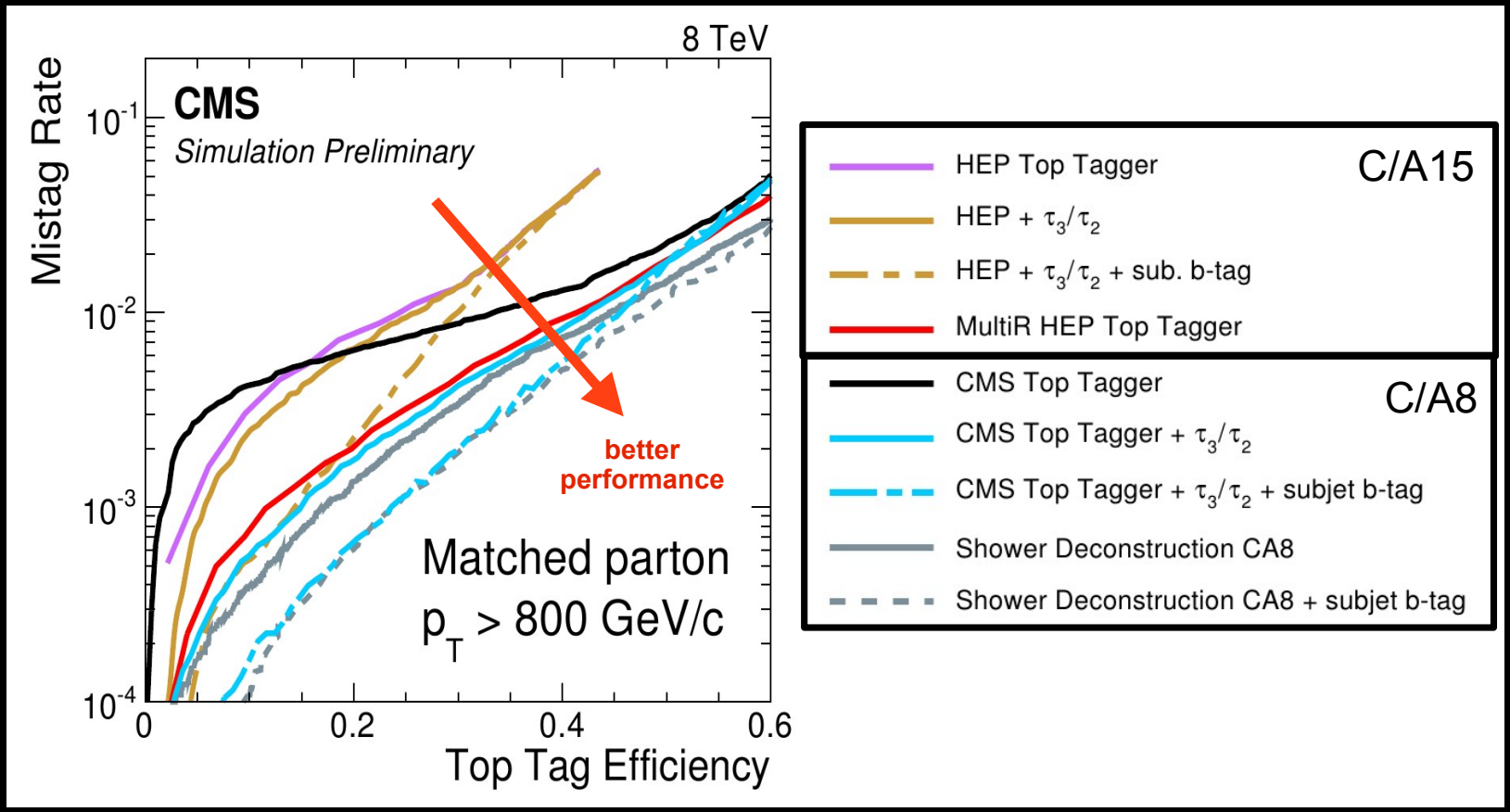


starting with groomed mass window
ε(W) ≡ 68%, ε(QCD) ~ 0.1

ATL-PHYS-PUB-2014-004

* See also CMS PAS JME-13-006

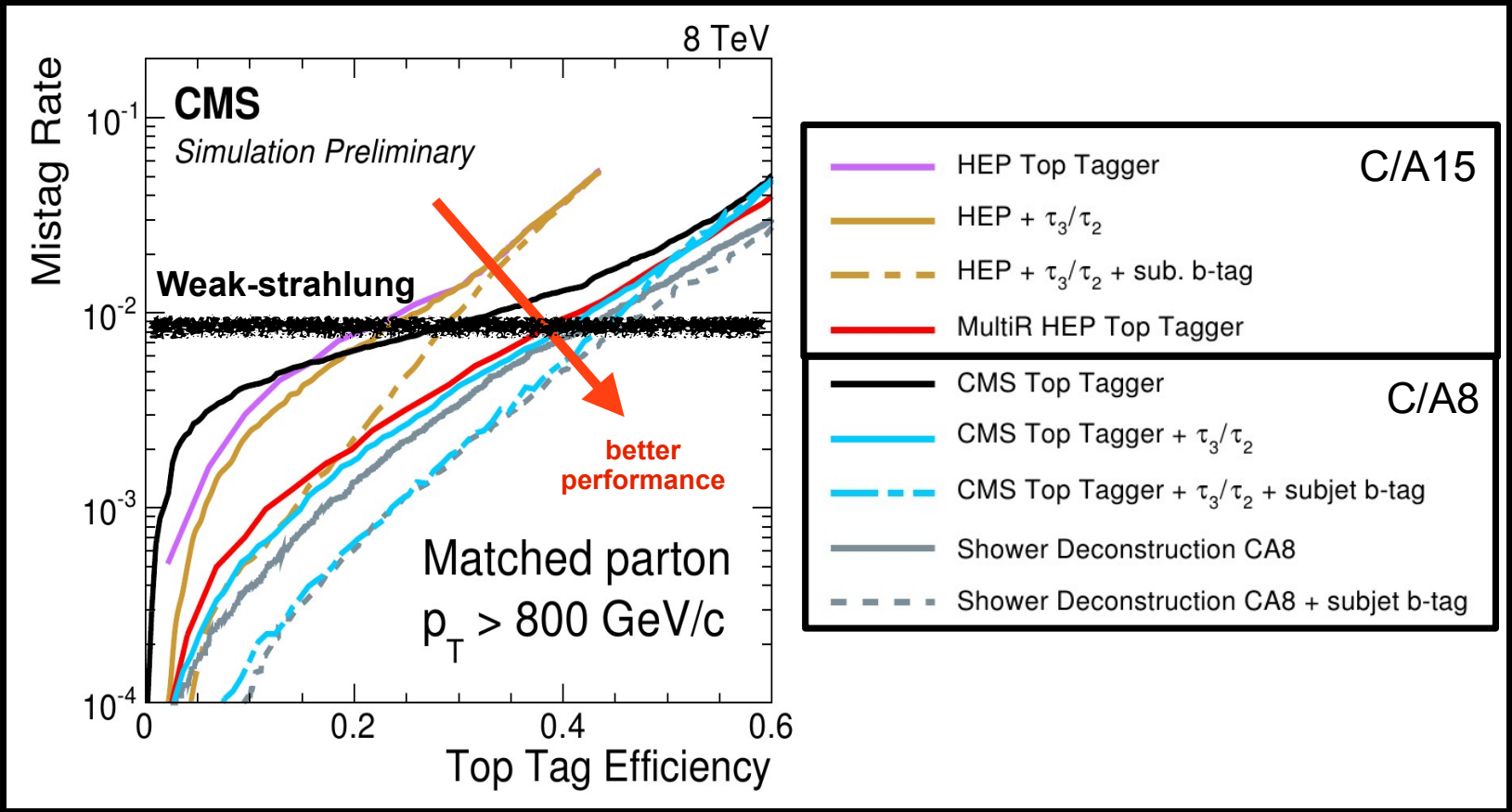
CMS Top-Tagger Studies



CMS PAS JME-13-007

* See also ATLAS-CONF-2013-084, 2014-003

CMS Top-Tagger Studies

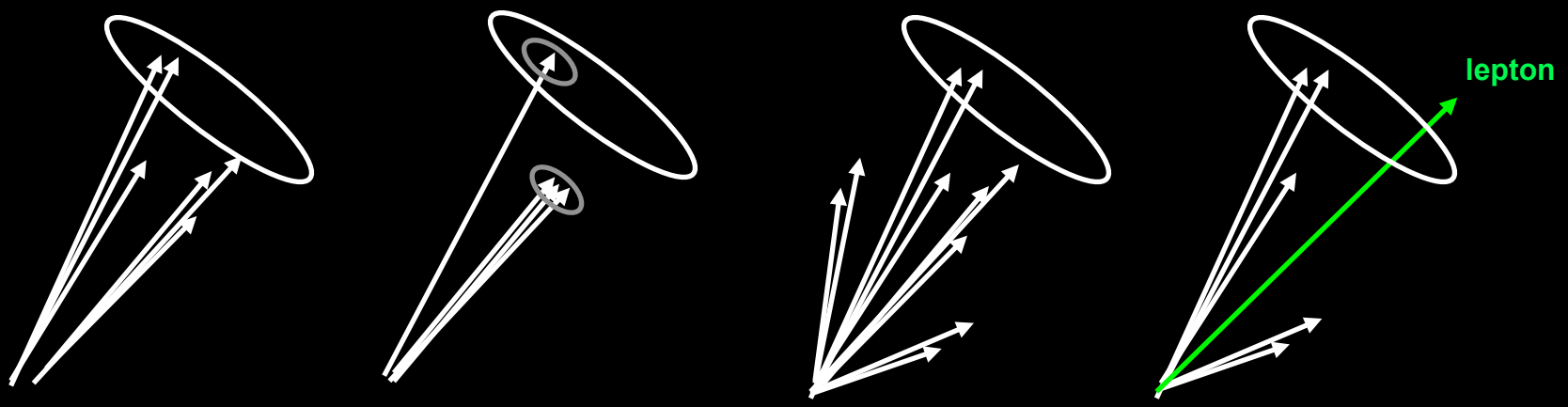


CMS PAS JME-13-007

* See also ATLAS-CONF-2013-084, 2014-003

Higgs-Jets for NP Searches

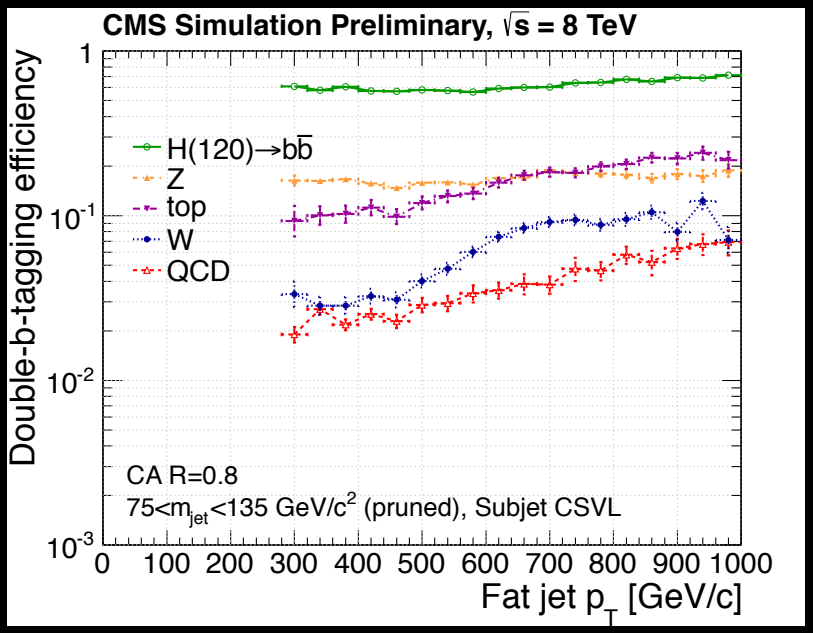
bb (60%) $\tau^+\tau^-$ (6%) Hadronic *VV** (11%) Semi-lep *WW** (7%)



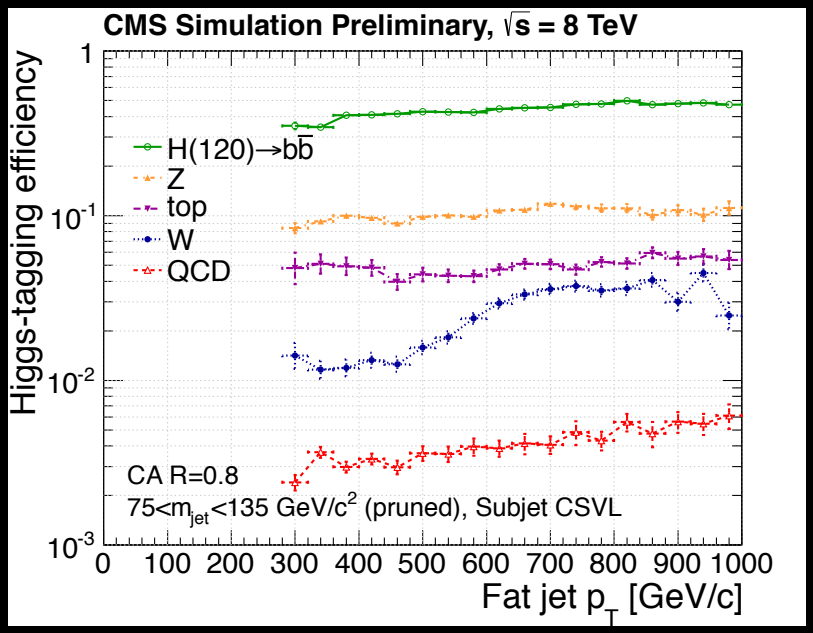
+ diphoton-jet, lepton-jets

bb-jets now in use by CMS for t' → th and b' → bh searches
(limits ~800 GeV for 100% BR)

(h→bb)-Jet Tagging



double-b-tag rate for jets in mass window



total Higgs-tag rate

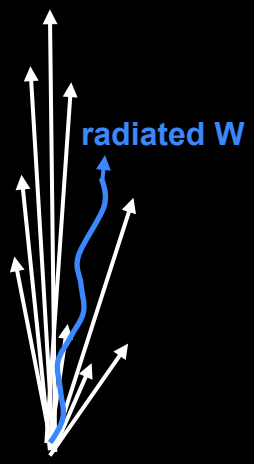
CMS PAS BTV-13-001

Novelties at p_T >> TeV

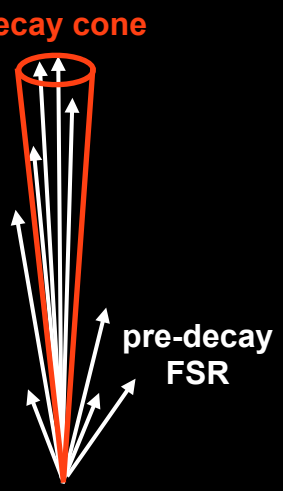
- Many algorithms become independent of momentum/ angle scales anyway (or easily adapted)
- However, tops radiate at $\Delta R >> m_t/p_T$ before they decay, whereas weak bosons radiate very little at $\Delta R >> m_W/p_T$
  - active tagging cone should shrink for tops ($R \sim 4m_t/p_T$)
  - W/Z/h should incorporate analog of tau “isolation annulus”, becomes progressively more powerful at higher p_T
- Background-jets can contain weak radiation
  - naive double-log scaling reduces to single-log with shrinking jet cone, but still potentially ~1% nuisance for hadronic top-jets
  - main background for semilep top-jets
- And then there are the detectors...

Jets at the Energy Frontier

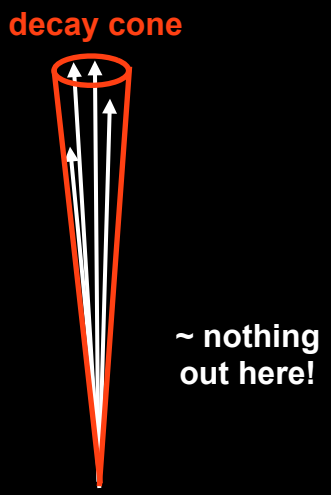
Multi-TeV QCD-jet



Multi-TeV top-jet



Multi-TeV W/Z/h-jet



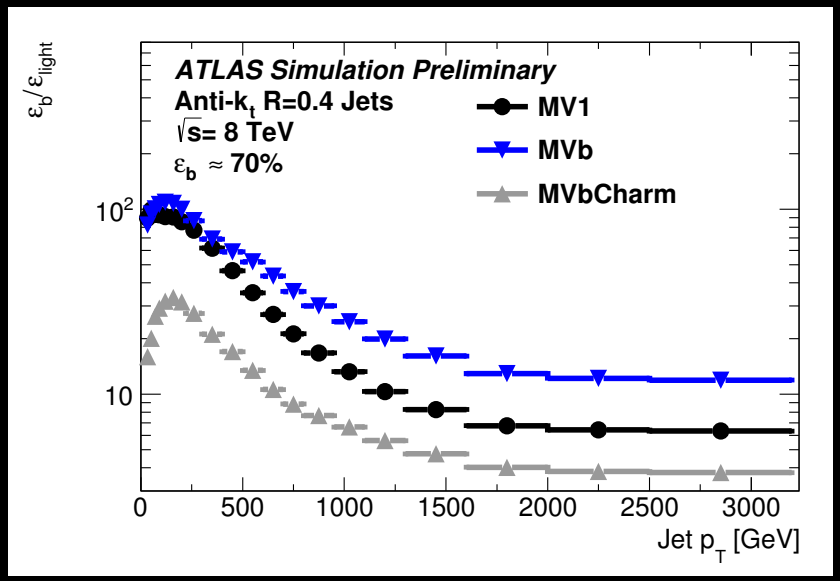
★ also g→tt splittings

Detector Questions

- When does the intrinsic size of detector elements become a major problem?
  - LHC: HCAL cells (~0.1) → ECAL cells (~0.02) → tracks (~10^{-3})
  - will/should future detector angular resolution scale with 1/E?
  - is high-p_T substructure a hardware or software problem?
- When does b-tagging break?
  - minimal boost-invariant b/c tag: muon-in-jet (~20% b-tag, ~3% light-jet mistag from HF splittings)
  - improvements in tracking crucial to beat this
- How reliable is lepton ID inside of semileptonic top- and Higgs-jets?
  - muons should be doable with mini-isolation, etc
  - are electrons lost?

Software Improvements

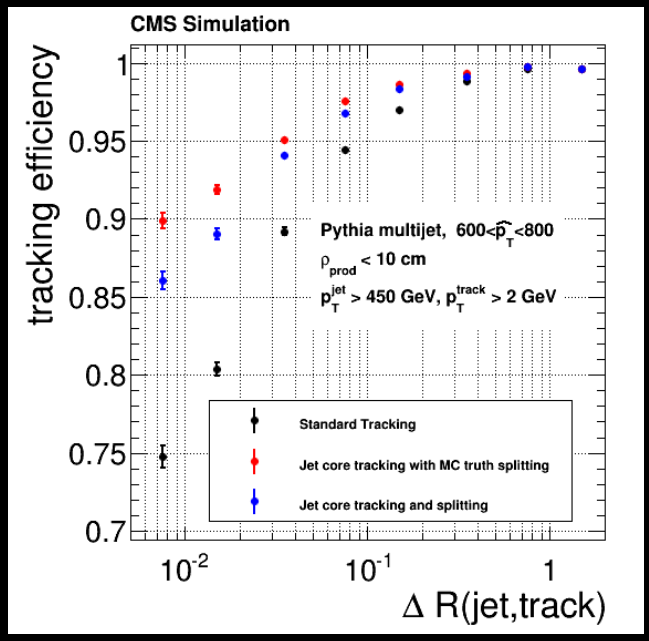
b-tagging



Dominik Duda talk @ BOOST 2014

+ Improvements using small-R jets, track-jets, b-subjets

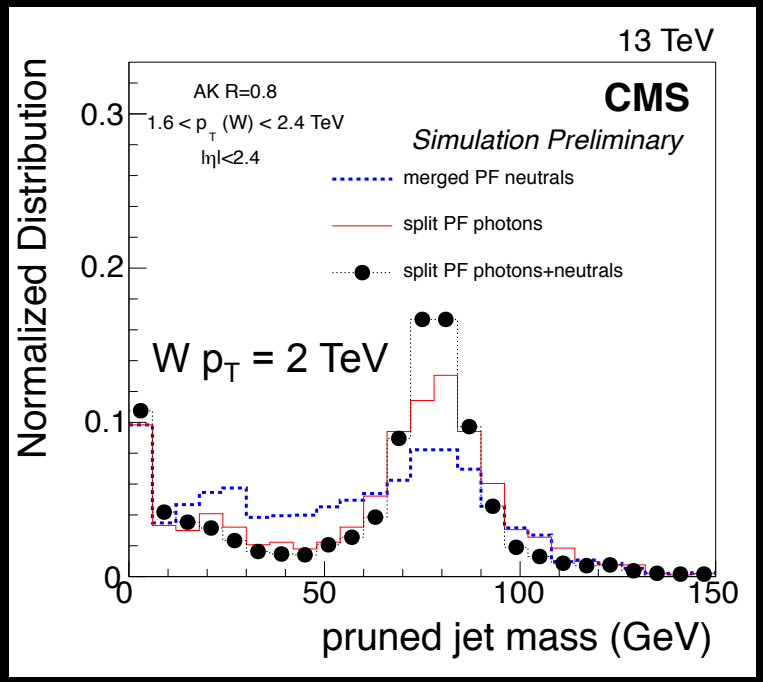
tracking

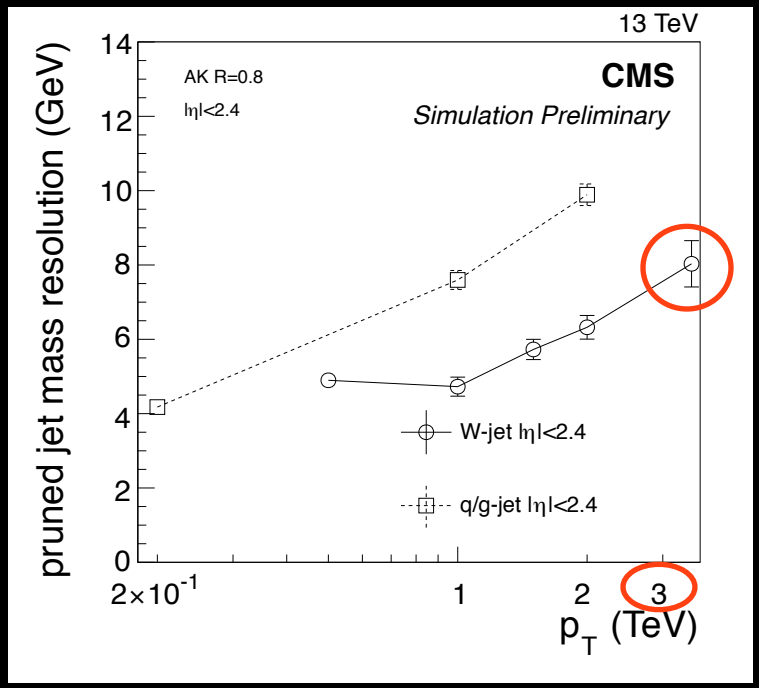


Andreas Hinzmann talk @ BOOST 2014

Software Improvements

Particle flow fully exploiting ECAL spatial resolution



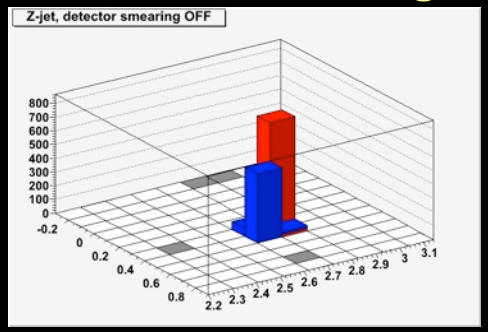


Andreas Hinzmann talk @ BOOST 2014

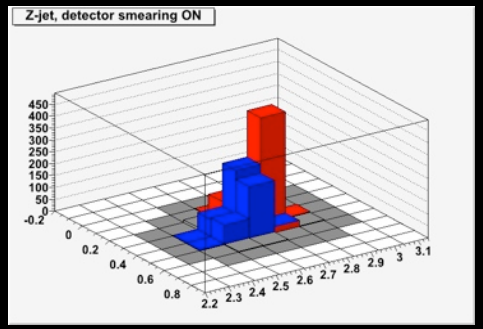
CMS PAS JME-14-002 (to appear)

A Toy Calorimeter Model for High-p_T Substructure

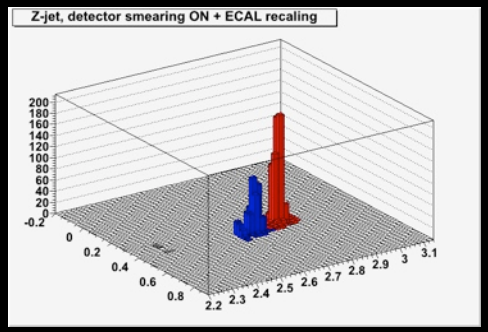
1.5 TeV Z-jet
0.1x0.1 "theorist" grid



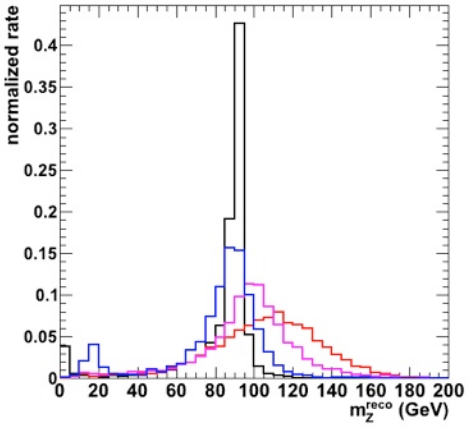
+ parametrized material showers



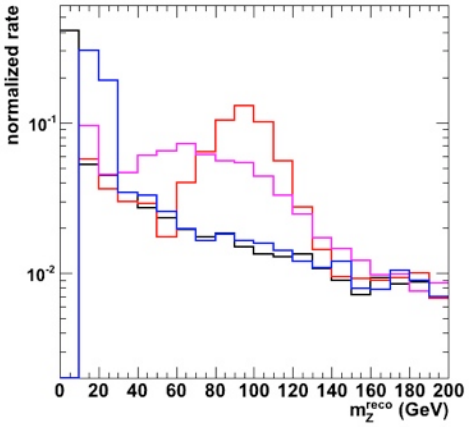
+ ECAL Energy-flow



1.5 TeV Z-jets



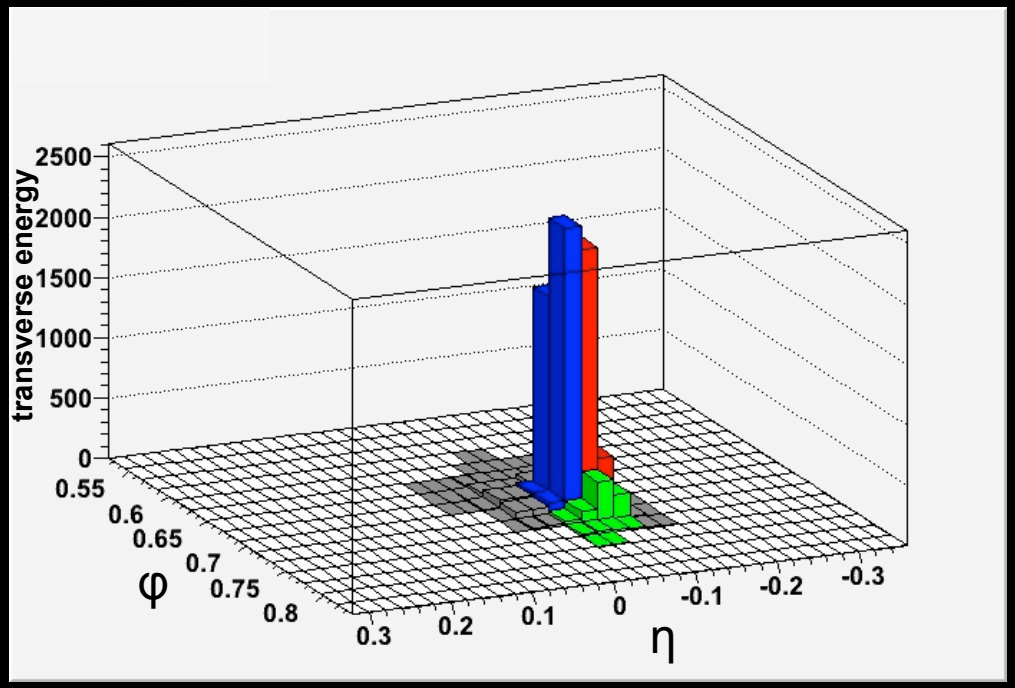
1.5 TeV quark-jets



Particle-level
Theorist grid
Simple ECAL E-flow
Minijet ECAL E-flow

Son, Spethmann, Tweedie (2012)

9.4 TeV Top-Jet

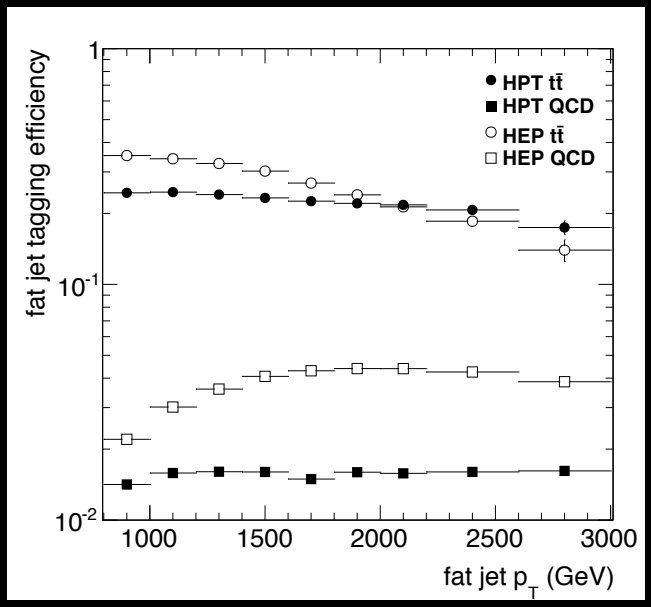


Using “fat” jet radius < 0.1
CMS-like detector
(FCC detector may be 2x better)

* Work in progress with Zhenyu Han & Minho Son

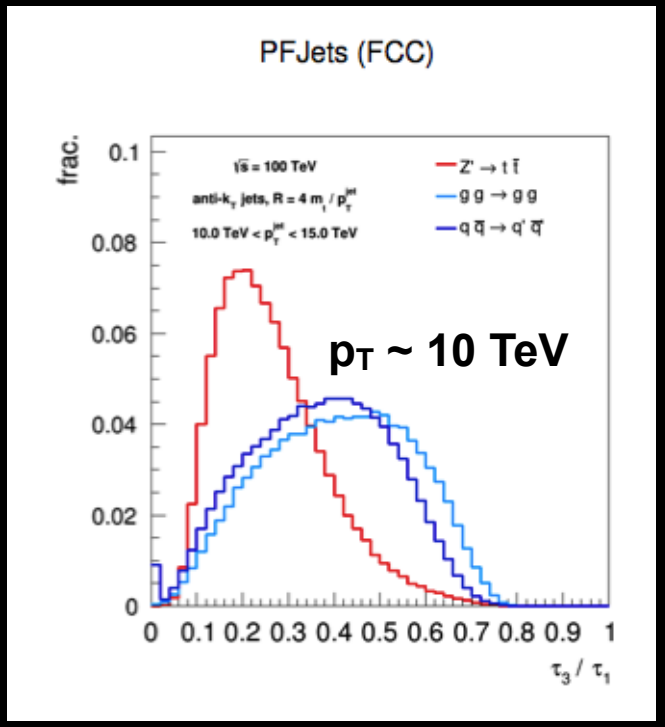
Exploiting Tracks at p_T >> TeV

HPTTopTagger



Schätzel & Spannowsky (2013)

Track-jet observables



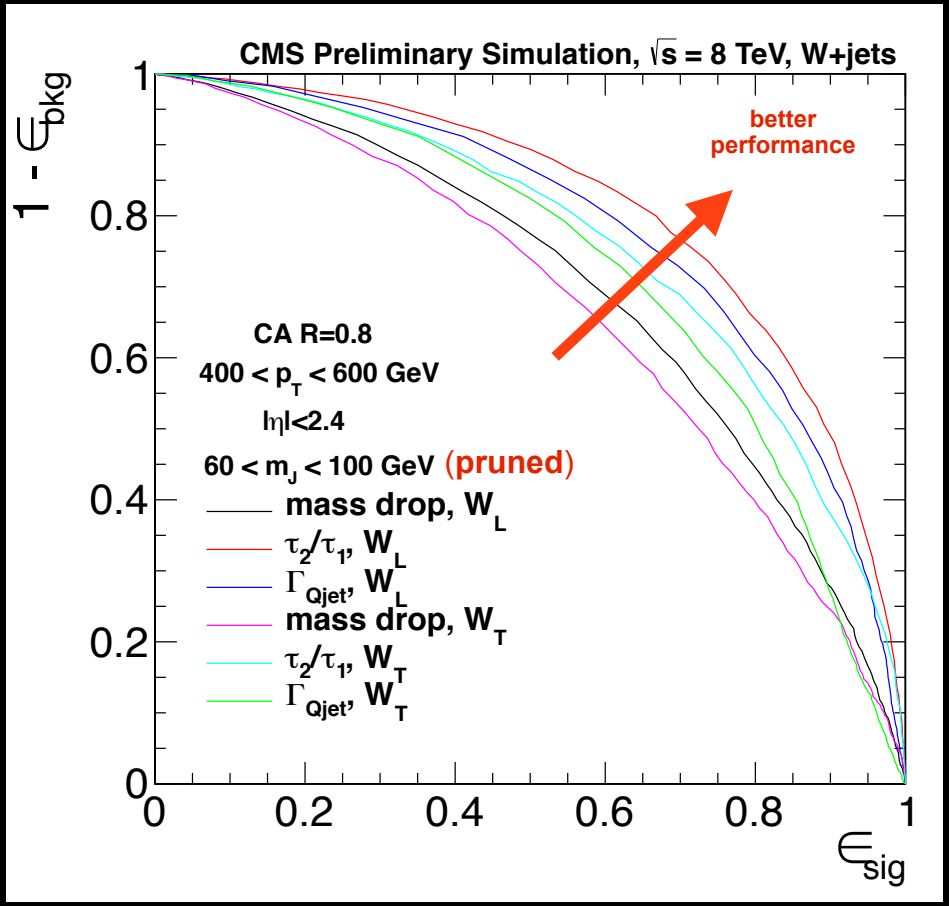
Larkoski, Maltoni, Selvaggi (work in progress)

Summary

- 8 TeV LHC has been a proving ground for substructure-based NP searches
  - largest efforts so far on resonances (VV, tt), with t'/b' searches coming up fast, and many others on their way
  - many substructure approaches, can be powerful in combination
  - already probing multi-TeV territory!
- 13 TeV LHC substructure looks healthy
  - lots of good ideas for pileup subtraction
  - detector+algorithms can potentially handle $p_T > 3$ TeV
- Requirements / capabilities of future detectors under active investigation
  - what do we need to see $p_T \sim 10$ TeV boosted objects?
  - learning valuable lessons from pushing LHC to its limits
- Applications are already exploding, lots more to do at the Energy Frontier!

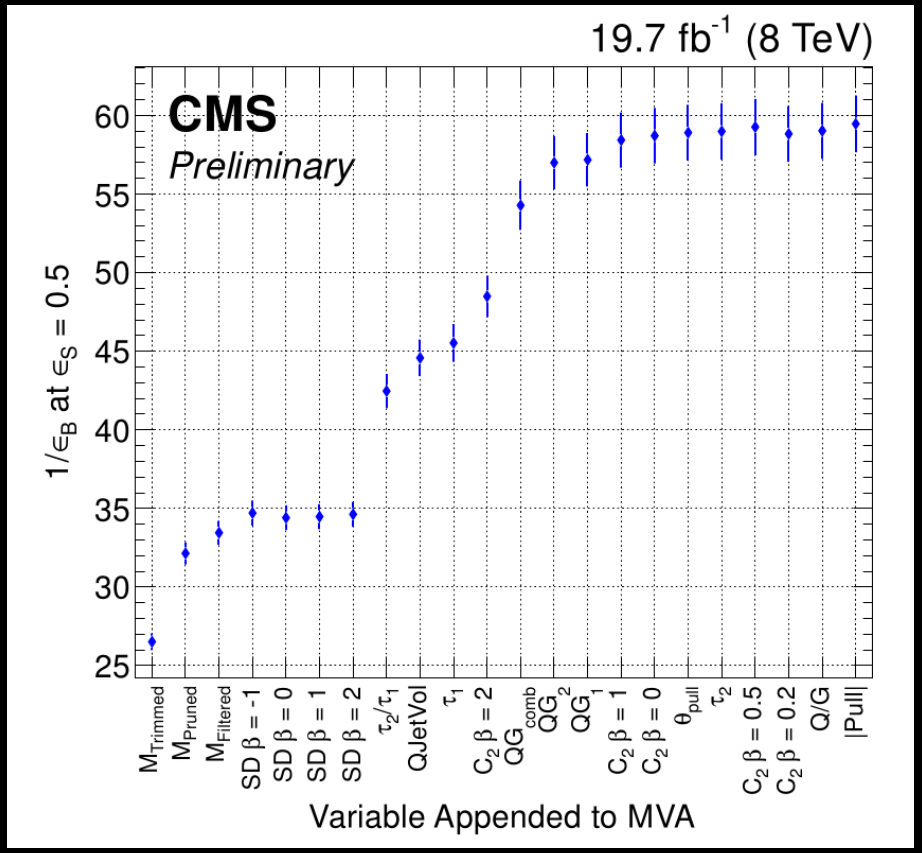
More…

CMS W-Taggers



CMS PAS JME-13-006

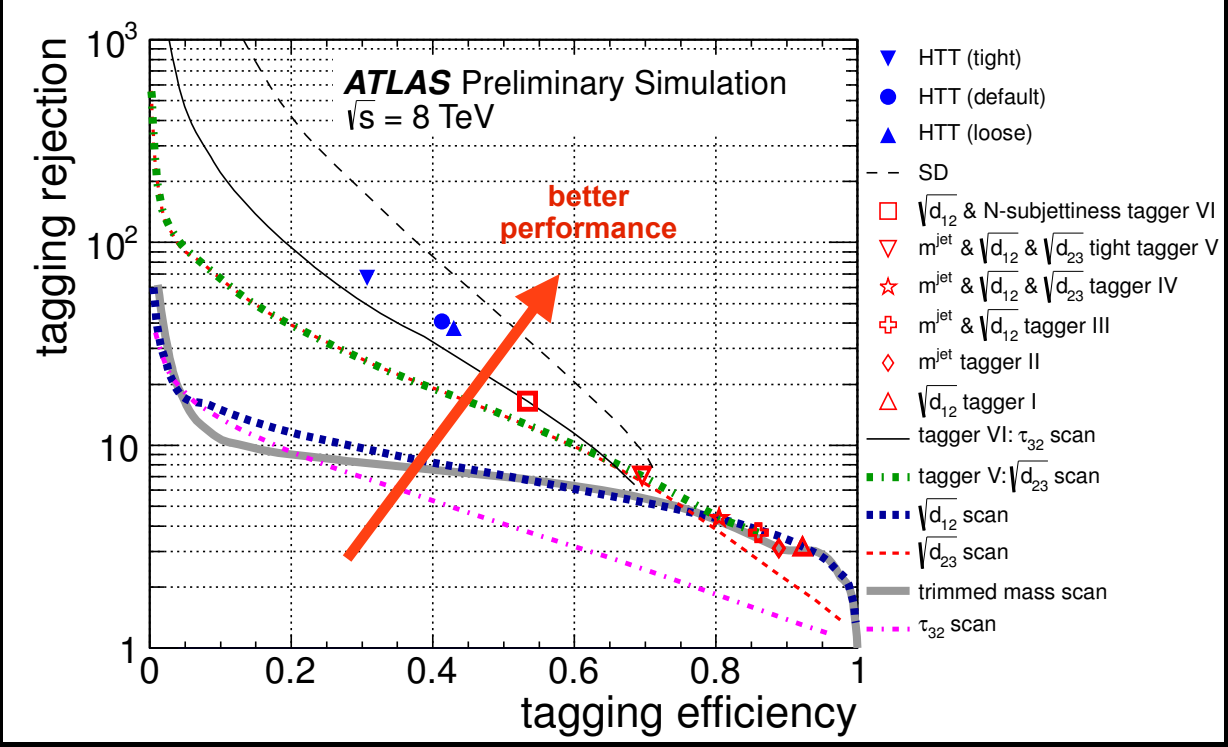
CMS Multivariate W-Tagging



"Tag & Probe" study, p_T > 250

Tobias Lapsien talk @ BOOST 2014

ATLAS Top-Taggers



1.75 TeV Z' decays

ATLAS-CONF-2013-084
ATLAS-CONF-2014-003