Top Tagging

Tilman Plehn

Universität Heidelberg

Wien 08/2014

Fat jets

Boosted particles at the LHC

1994 boosted $W \to 2$ jets from heavy Higgs [Seymour]

1994 boosted $t \to 3$ jets [Seymour]

2002 boosted $W \to 2$ jets from strongly interacting WW [YSplitter: Butterworth, Cox, Forshaw]

2006 boosted $t \to 3$ jets from resonances [Agashe, Belyaev, Krupovnickas, Perez, Virzi]

2008 boosted $H \to b\bar{b}$ [BDRS Higgs tagger: Butterworth, Davison, Rubin, Salam]

2008 boosted $t \to 3$ jets from resonances [JH/CMS tagger: Kaplan, Rehermann, Schwartz, Tweedie]

2009 boosted $t \to 3$ jets in Higgs production [HEPTopTagger: TP, Salam, Spannowsky]

2009 boosted $t \to 3$ jets from resonances [Template Tagger: Almeida, Lee, Perez, Sterman, Sung, Virzi]

. . .

2010 first meta analysis review [BOOST proceedings, Ed: Karagoz, Spannowsky, Vos]

. . .

2011 N-Subjettiness [Thaler, van Tilburg]

2011 Shower Deconstruction [Soper, Spannowsky]

2011 pedagogical review (partly basis for this talk) [TP, Spannowsky]

. . .

2014 BDRS tagger with 427 citations, BOOST 2009-2014 [2016 at CMS place]

Jet Algorithms

Definition of jets

- jet–parton duality $\Leftrightarrow$ what are partons in detector?
- need algorithm to reconstruct what was one parton [IR save recombination algos]
- crucial for any LHC analysis
- extension to b and t perturbative QCD problem

Different measures [FASTJET: Cacciari, Salam, Soyez]

- define jet–jet and jet–beam distance [and resolution y_{cut}]

$$
\begin{array}{lll}
k_T & y_{ij} = \dfrac{\Delta R_{ij}}{D} \min\left(p_{T,i}, p_{T,j}\right) & y_{iB} = p_{T,i} \\
\text{C/A} & y_{ij} = \dfrac{\Delta R_{ij}}{D} & y_{iB} = 1 \\
\text{anti-}k_T & y_{ij} = \dfrac{\Delta R_{ij}}{D} \min\left(p_{T,i}^{-1}, p_{T,j}^{-1}\right) & y_{iB} = p_{T,i}^{-1} \; .
\end{array}
$$

- (1) find minimum $y_{\text{min}} = \min_{kl}(y_{kl}, y_{kB})$
  (2a) if $y_{\text{min}} = y_{kl} < y_{\text{cut}}$ combine k and l, go to (1)
  (2b) if $y_{\text{min}} = y_{kB} < y_{\text{cut}}$ remove k, go to (1)
  (2c) if $y_{\text{min}} > y_{\text{cut}}$, done
- theoretical and experimental trade-off decisions
- fat jets: use clustering history

Analysis: $Z' \to t\bar{t}$

LHC target $m_{Z'} \gtrsim 1.5$ TeV

- purely leptonic decays rate limited
- semi-leptonic approximate reconstruction of neutrino 4-vector:

  massless neutrino
  2D missing energy vector
  top or W mass constraints
- purely hadronic decays deemed not useful

Many taggers [Hopkins/CMS tagger, HEPTopTagger, template tagger, shower deconstruction]

- top jets new concept at LHC
- hadronic top identification and reconstruction
- jet separation challenging for heavy Z'
- combination of calo and tracker great

Analysis: $Z' \to t\bar{t}$

LHC target $m_{Z'} \gtrsim 1.5$ TeV

- purely leptonic decays rate limited
- semi-leptonic approximate reconstruction of neutrino 4-vector:

  massless neutrino
  2D missing energy vector
  top or W mass constraints
- purely hadronic decays deemed not useful

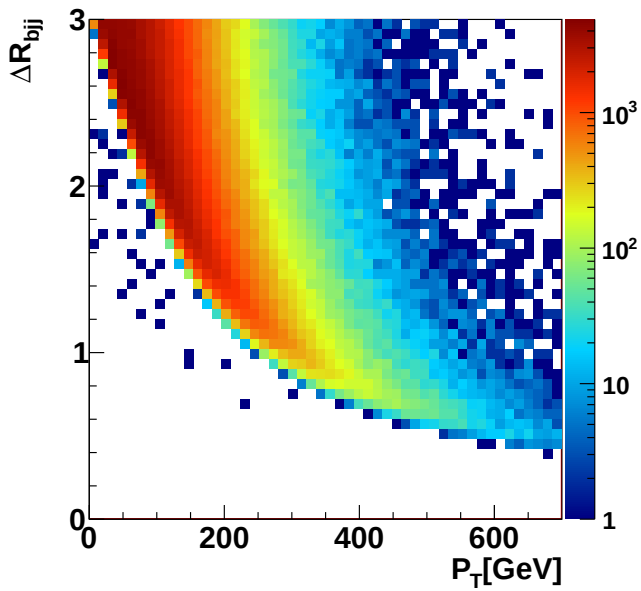
Many taggers [Hopkins/CMS tagger, HEPTopTagger, template tagger, shower deconstruction]

- top jets new concept at LHC
- hadronic top identification and reconstruction
- jet separation challenging for heavy Z'
- combination of calo and tracker great

Validation and systematics

- tagging easier for higher boost, $p_{T,t} > 600$ GeV
- Standard Model events at lower $p_{T,t} < 400$ GeV

$\Rightarrow$ p_T range main challenge



Analysis: $Z' \to t\bar{t}$

LHC target $m_{Z'} \gtrsim 1.5$ TeV

- purely leptonic decays rate limited
- semi-leptonic approximate reconstruction of neutrino 4-vector:

  massless neutrino
  2D missing energy vector
  top or W mass constraints
- purely hadronic decays deemed not useful

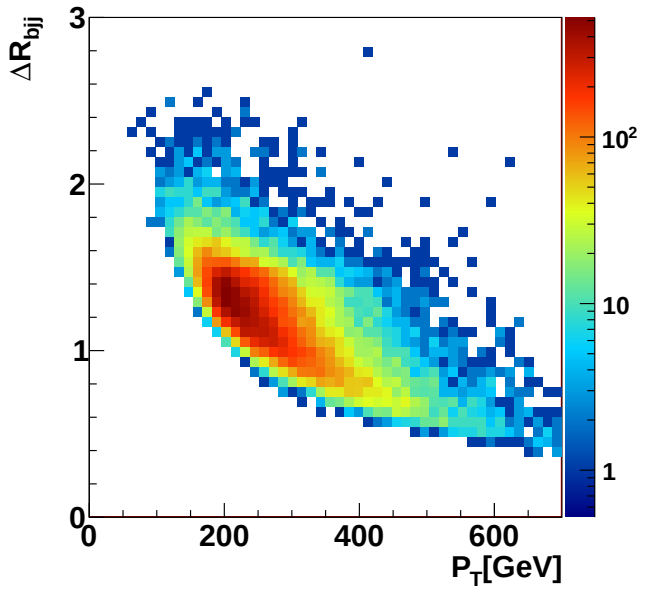
Many taggers [Hopkins/CMS tagger, HEPTopTagger, template tagger, shower deconstruction]

- top jets new concept at LHC
- hadronic top identification and reconstruction
- jet separation challenging for heavy Z'
- combination of calo and tracker great

Validation and systematics

- tagging easier for higher boost, $p_{T,t} > 600$ GeV
- Standard Model events at lower $p_{T,t} < 400$ GeV

$\Rightarrow$ p_T range main challenge



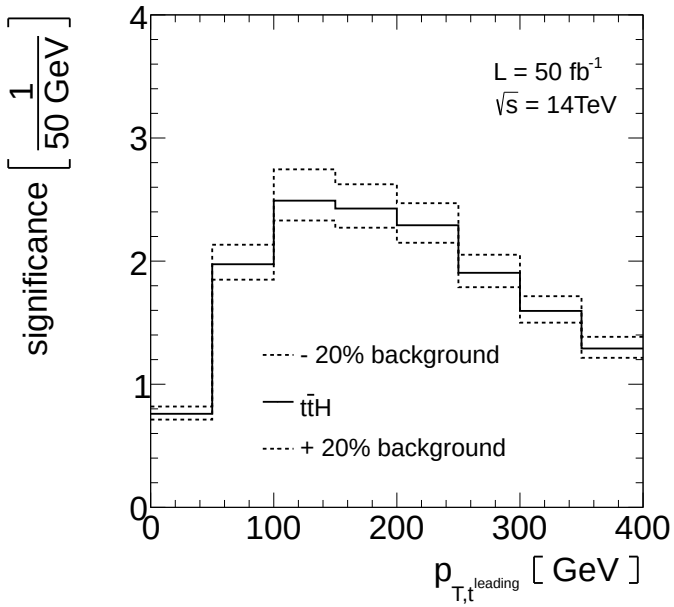
Analysis: $t\bar{t}H, H \to b\bar{b}$

Sad story of $t\bar{t}H, H \to b\bar{b}$ [CMS-TDR]

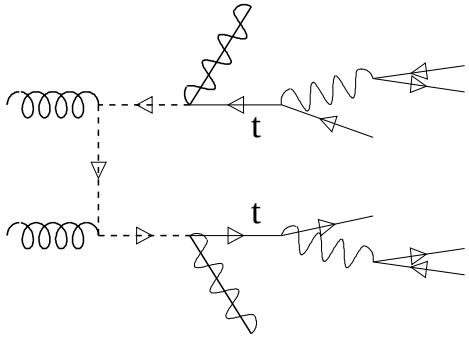
- trigger: $t \to bW^+ \to b\ell^+\nu$
  reconstruction and rate: $\bar{t} \to \bar{b}W^- \to \bar{b}jj$
- continuum background $t\bar{t}b\bar{b}, t\bar{t}jj$ [weighted by b-tag]
- 1– combinatorics: m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$
  2– kinematics: peak-on-peak
  3– systematics: $S/B \sim \mathcal{O}(0.1)$

Tagger [TP, Salam, Spannowsky]

- S/B: Higgs and tops decays products boosted [solves 1]
- boosted regime different for S and B [solves 2]
- watch S/B... [to solve 3]
- fun: fat Higgs jet + fat top jet [similarly $HH \to b\bar{b}b\bar{b}$]



Analysis: top partners

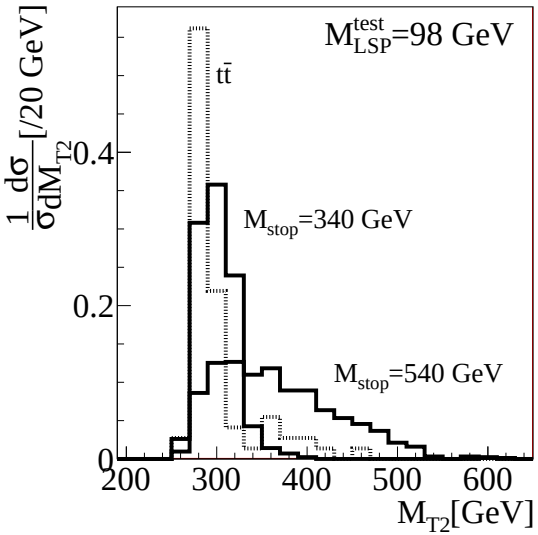


Stop pairs including reconstruction [TP, Spannowsky, Takeuchi, Zerwas]

- stop crucial for hierarchy problem
  comparison to other top partners [Meade & Reece]
- hadronic: $\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0\ \bar{t}\tilde{\chi}_1^0$
- stop mass from m_{T2} endpoint [like sleptons or sbottoms]

$$m_{T2}(\hat{m}_\chi) = \min_{\not{p}_T = q_1 + q_2} \left[\max_j \ m_{T,j}(q_j; \hat{m}_\chi) \right] \overset{!}{<} m_{\tilde{t}}$$

$\Rightarrow$ hadronic search as easy as $b\bar{b} + \not{E}_T$



N-Subjettiness

N-Jettiness to count subjets inside fat jet [Thaler, van Tilburg]

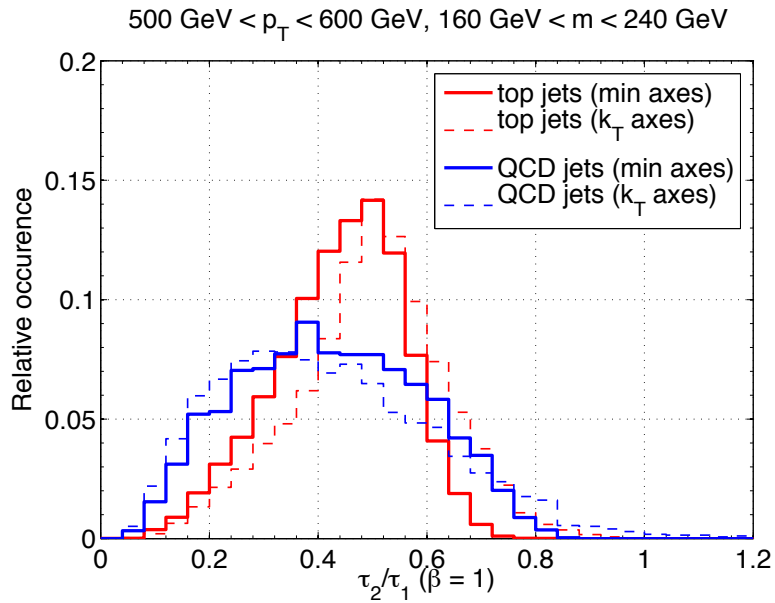
- how many subjets do the calo entries correspond to?
- event shape using N subjet directions $\hat{n}_j$ $[\beta > 0]$

$$\tau_N = \frac{1}{\sum_{\alpha \in \text{jet}} p_{T,\alpha} R_0^\beta} \sum_{\alpha \in \text{jet}} p_{T,\alpha} \min_{k=1,\ldots,N} (\Delta R_{k,\alpha})^\beta$$

- choice of reference axes

  1- from subjet algorithm
  2- from minimization of τ_N

- $\tau_N \to 1$ means many calo entries away from N axes
  $\tau_N \to 0$ means perfect matching
- systematics cancelled in ratios
  τ_{N+1}/τ_N with dip for $N+1$ subjets



N-Subjettiness

N-Jettiness to count subjets inside fat jet [Thaler, van Tilburg]

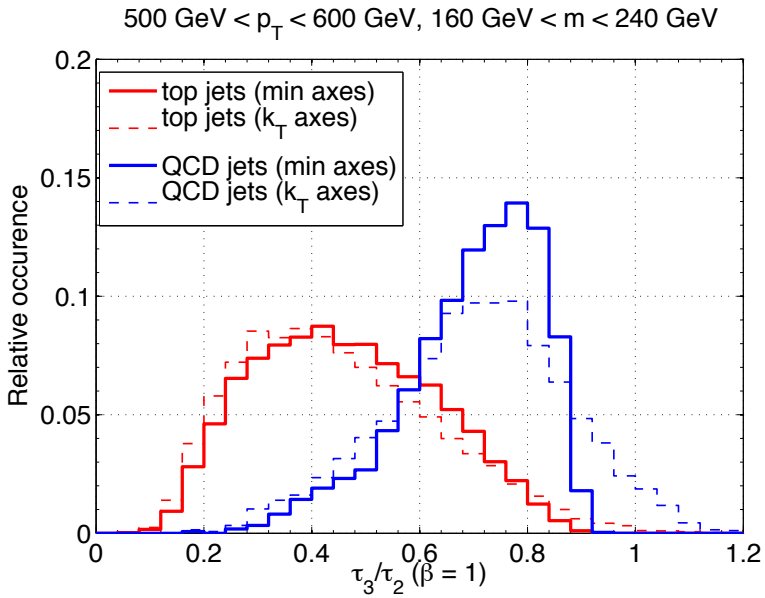
- how many subjets do the calo entries correspond to?
- event shape using N subjet directions $\hat{n}_j$ $[\beta > 0]$

$$\tau_N = \frac{1}{\sum_{\alpha \in \text{jet}} p_{T,\alpha} R_0^\beta} \sum_{\alpha \in \text{jet}} p_{T,\alpha} \min_{k=1,\ldots,N} (\Delta R_{k,\alpha})^\beta$$

- choice of reference axes

  1- from subjet algorithm
  2- from minimization of τ_N

- $\tau_N \to 1$ means many calo entries away from N axes
  $\tau_N \to 0$ means perfect matching
- systematics cancelled in ratios
  τ_{N+1}/τ_N with dip for $N+1$ subjets



N-Subjettiness

N-Jettiness to count subjets inside fat jet [Thaler, van Tilburg]

- how many subjets do the calo entries correspond to?
- event shape using N subjet directions $\hat{n}_j$ $[\beta > 0]$

$$\tau_N = \frac{1}{\sum_{\alpha \in \text{jet}} p_{T,\alpha} R_0^\beta} \sum_{\alpha \in \text{jet}} p_{T,\alpha} \min_{k=1,\ldots,N} (\Delta R_{k,\alpha})^\beta$$

- choice of reference axes

  1- from subjet algorithm
  2- from minimization of τ_N

- $\tau_N \to 1$ means many calo entries away from N axes
  $\tau_N \to 0$ means perfect matching
- systematics cancelled in ratios
  τ_{N+1}/τ_N with dip for $N+1$ subjets

Tagger

- simple selection

$$m_{\text{fat jet}} = 160\ldots240 \;\; \text{GeV} \qquad \frac{\tau_3}{\tau_2} < 0.6$$

- multi-variate in N and β with some improvement

$\Rightarrow$ easily added to any other tagger

HEPTopTagger

Mass drop algorithm [TP, Salam, Spannowsky, Takeuchi]

1– C/A fat jet, $R = 1.5$ and $p_T > 200$ GeV [FastJet limitation]

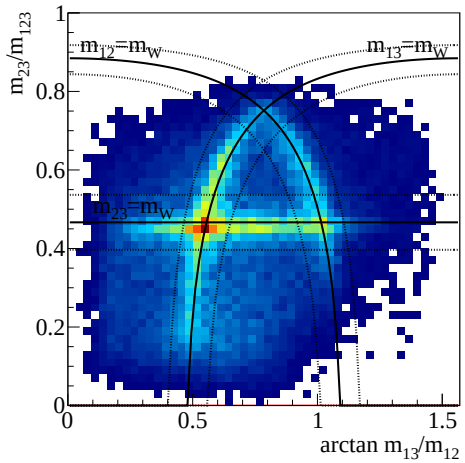
2– mass drop, cutoff $m_{\text{sub}} > 30$ GeV

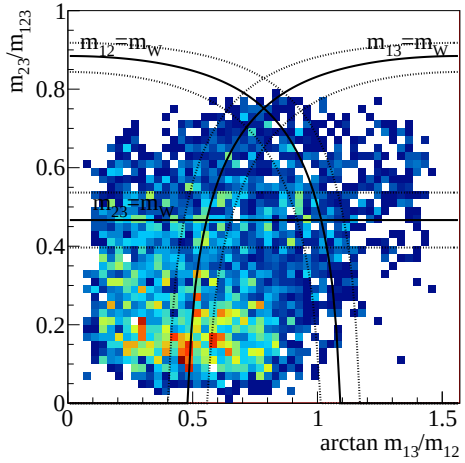
3– filtering leading to hard substructure triple

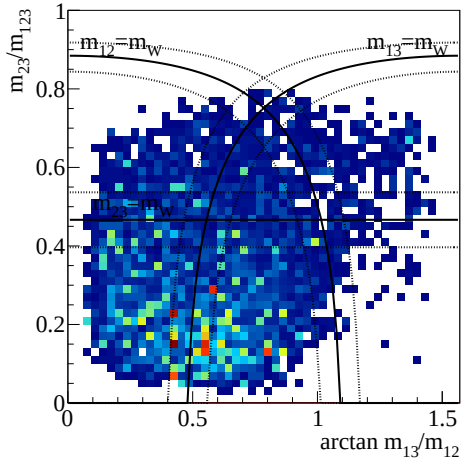
4– top mass window $m_{123} = [150, 200]$ GeV

5– A-shaped mass plane cuts as function of m_W/m_t

6– consistency condition $p_T^{(\text{tag})} > 200$ GeV







HEPTopTagger

Mass drop algorithm [TP, Salam, Spannowsky, Takeuchi]

1– C/A fat jet, $R = 1.5$ and $p_T > 200$ GeV [FastJet limitation]

2– mass drop, cutoff $m_{\text{sub}} > 30$ GeV

3– filtering leading to hard substructure triple

4– top mass window $m_{123} = [150, 200]$ GeV

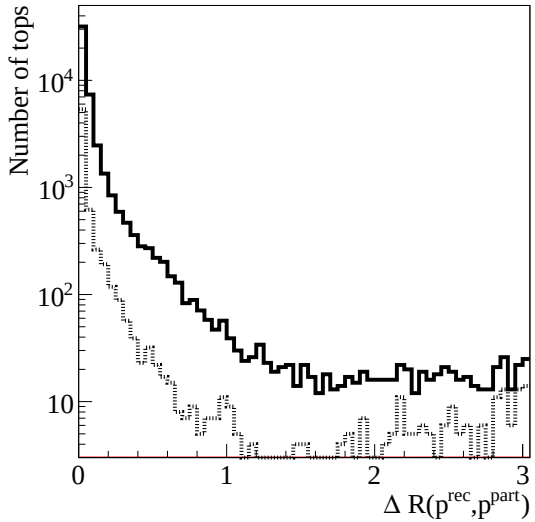
5– A-shaped mass plane cuts as function of m_W/m_t

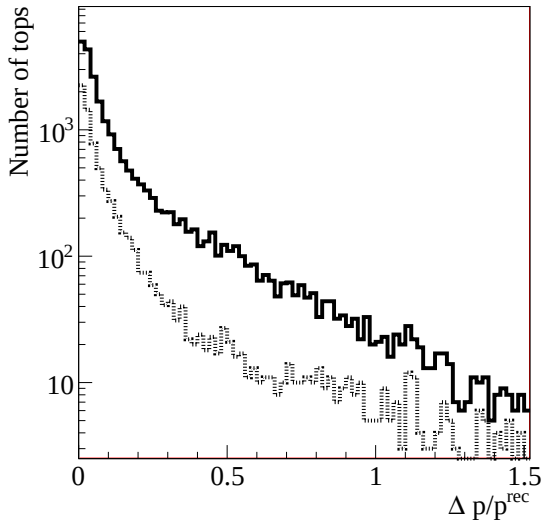
6– consistency condition $p_T^{(\text{tag})} > 200$ GeV

Top reconstruction

– direction less critical

– energy requiring calibration





HEPTopTagger

Mass drop algorithm [TP, Salam, Spannowsky, Takeuchi]

1– C/A fat jet, $R = 1.5$ and $p_T > 200$ GeV [FastJet limitation]

2– mass drop, cutoff $m_{\text{sub}} > 30$ GeV

3– filtering leading to hard substructure triple

4– top mass window $m_{123} = [150, 200]$ GeV

5– A-shaped mass plane cuts as function of m_W/m_t

6– consistency condition $p_T^{(\text{tag})} > 200$ GeV

Improvements for upcoming run

– signal efficiency

– background sculpting

– p_T range

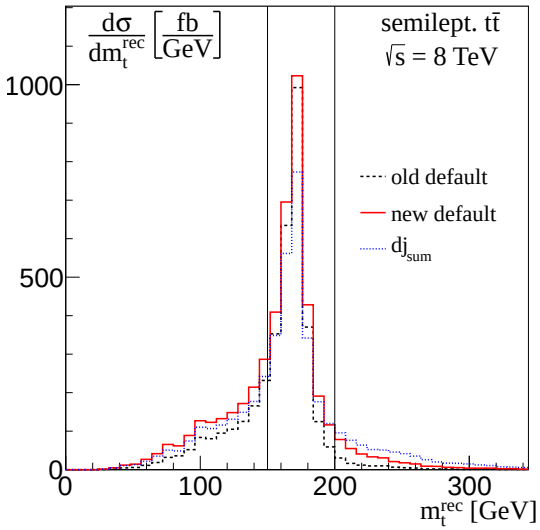
– resonance reconstruction

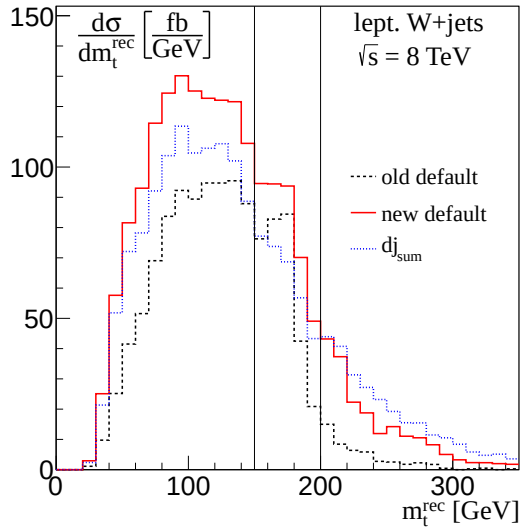
Better HEPTopTagger

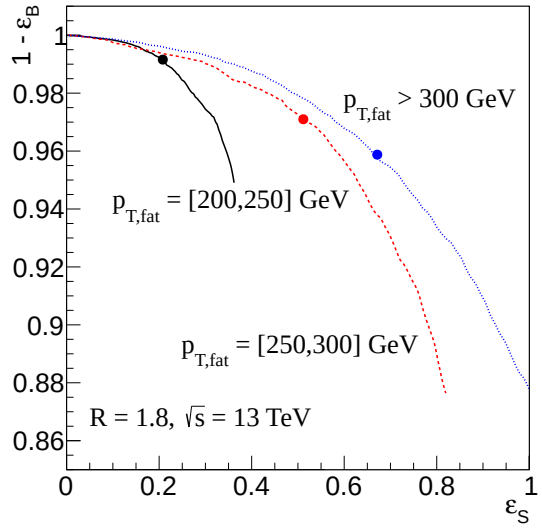
Improved algorithm [TP, Spannowsky, Takeuchi; Anders, Bernaciak, Kasieczka, TP, Schell]

- increase size $R = 1.8$
- change in cut order $3 \leftrightarrow 4$
- alternative triplet selection

  maximal $dj_{\text{sum}} = \sum p_{T,i} p_{T,j} (\Delta R_{ij})^4$
  triplet of hardest subjets
- BDT $\{m_{13}, m_{23}, m_{123}, (m_W/m_t)^{(\text{rec})}\}$ [on semilep sample]







Better HEPTopTagger

Improved algorithm [TP, Spannowsky, Takeuchi; Anders, Bernaciak, Kasieczka, TP, Schell]

- increase size $R = 1.8$
- change in cut order $3 \leftrightarrow 4$
- alternative triplet selection

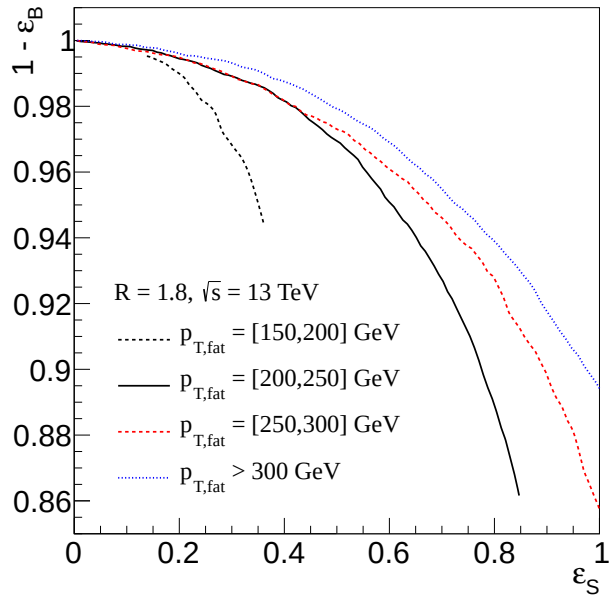
  maximal $dj_{\text{sum}} = \sum p_{T,i} p_{T,j} (\Delta R_{ij})^4$
  triplet of hardest subjets
- BDT $\{m_{13}, m_{23}, m_{123}, (m_W/m_t)^{(\text{rec})}\}$ [on semilep sample]

Towards low p_T [Anders, Bernaciak, Kasieczka, TP, Schell]

- focus on $p_T = [150, 200]$ GeV
- target type-2 tags [two hardest subjets matched]
- correlations via Fox–Wolfram moments

$$H_\ell^U = \sum_{i,j} \frac{1}{N^2} P_\ell(\cos \Omega_{ij})$$

- $\{m_{13}, m_{23}, m_{123}, (m_W/m_t)^{(\text{rec})}, \text{FWMs}\}$



MultiR HEPTopTagger

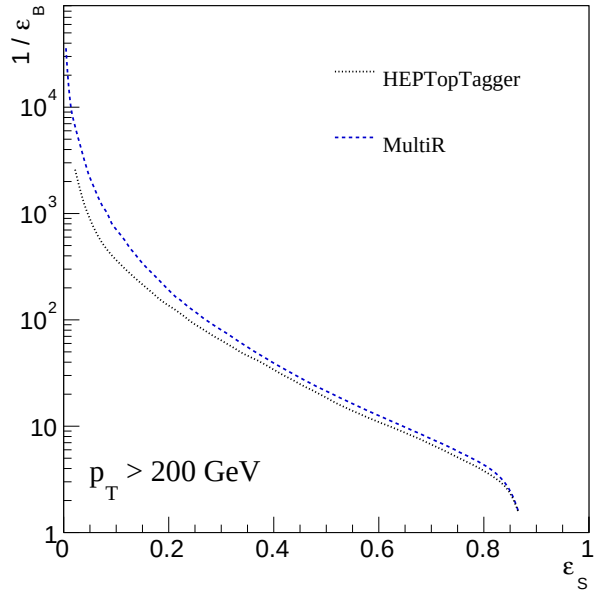
Extended algorithm [Kasieczka, TP, Salam, Schell, Strebler (prelim)]

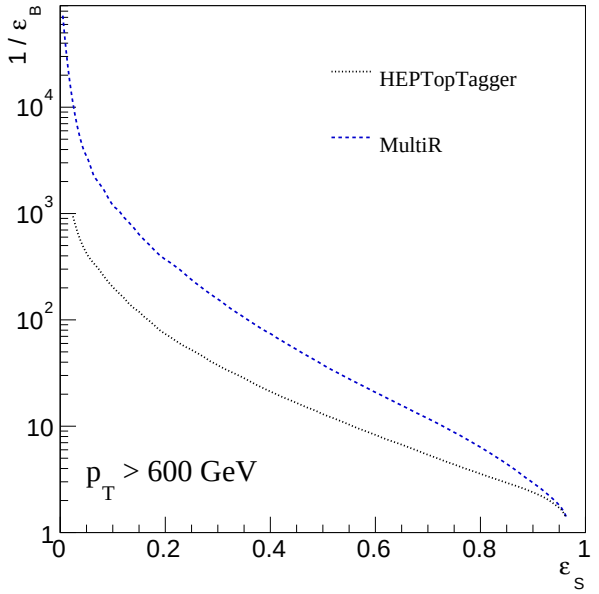
- optimal R_{min}

  large to include all decay jets
  small to avoid combinatorics, ISR, pile-up
- reduce R until we leave jet mass plateau

$$|m_{123} - m_{123}^{(R_{\text{max}})}| < 0.2\, m_{123}^{(R_{\text{max}})} \quad \Rightarrow \quad R_{\text{min}}$$

- estimate $R_{\text{min}}^{(\text{calc})}$ from kinematics
- $\{m_{123}^{(R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}\}$ $[f_W = \min|m_{ij}/m_{123} - m_W/m_t|]$





MultiR HEPTopTagger

Extended algorithm [Kasieczka, TP, Salam, Schell, Strebler (prelim)]

- optimal R_{min}

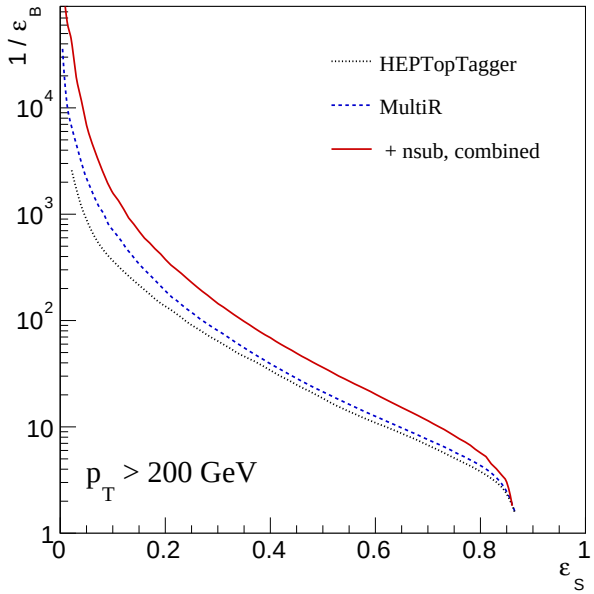
  large to include all decay jets
  small to avoid combinatorics, ISR, pile-up
- reduce R until we leave jet mass plateau

$$|m_{123} - m_{123}^{(R_{\text{max}})}| < 0.2\, m_{123}^{(R_{\text{max}})} \quad \Rightarrow \quad R_{\text{min}}$$

- estimate $R_{\text{min}}^{(\text{calc})}$ from kinematics
- $\{m_{123}^{(R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}\}$ $[f_W = \min|m_{ij}/m_{123} - m_W/m_t|]$

Combined with N-Subjettiness [DESY group]

- fixed multiR working point
- also include rejected events $[R_{\text{filt}} = 0.2,\ N_{\text{filt}} = 5]$
- combine with N-Subjettiness
- $\{m_{123}^{(R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}, \tau_j, \tau_j^{(\text{filt})}\}$



MultiR HEPTopTagger

Extended algorithm [Kasieczka, TP, Salam, Schell, Strebler (prelim)]

- optimal R_{min}

  large to include all decay jets
  small to avoid combinatorics, ISR, pile-up
- reduce R until we leave jet mass plateau

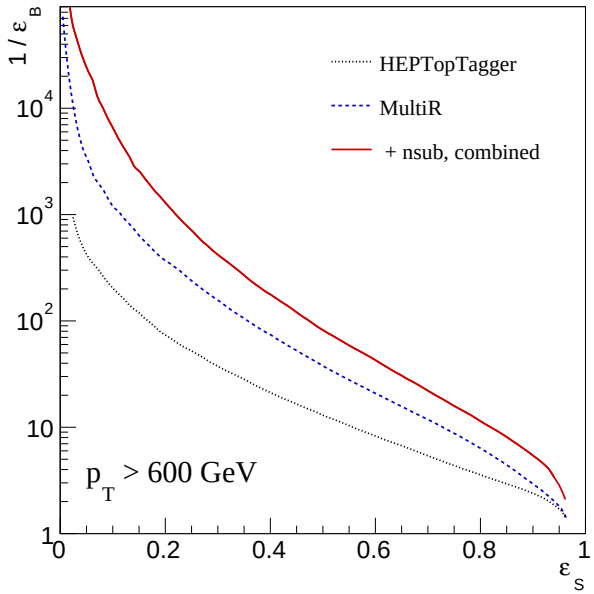
$$|m_{123} - m_{123}^{(R_{\text{max}})}| < 0.2\, m_{123}^{(R_{\text{max}})} \quad \Rightarrow \quad R_{\text{min}}$$

- estimate $R_{\text{min}}^{(\text{calc})}$ from kinematics
- $\{m_{123}^{(R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}\}$ $[f_W = \min|m_{ij}/m_{123} - m_W/m_t|]$

Combined with N-Subjettiness [DESY group]

- fixed multiR working point
- also include rejected events $[R_{\text{filt}} = 0.2,\ N_{\text{filt}} = 5]$
- combine with N-Subjettiness
- $\{m_{123}^{(R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}, \tau_j, \tau_j^{(\text{filt})}\}$

$\Rightarrow$ stay tuned for HEPTopTagger2.0



Shower Deconstruction

Remember matrix element method [Tevatron]

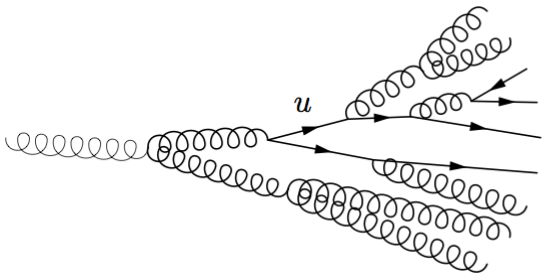
- measured fully exclusive cross section: $d\sigma$
  computed matrix element squared: $|\mathcal{M}|^2(m_t)$
- direct comparison to determine m_t
- Neyman–Pearson: log likelihood ratio best test statistic [minimum false positive]

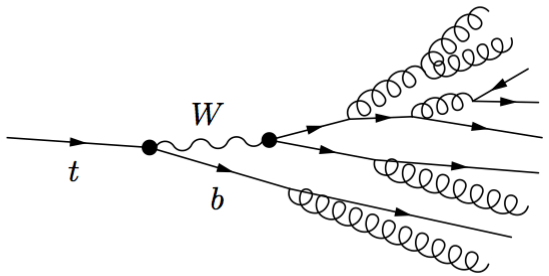
$$q(\vec{r}) = -\sigma_{\text{tot},s}\ \mathcal{L}\ + \ln\left(1 + \frac{d\sigma_s(\vec{r})}{d\sigma_b(\vec{r})}\right) \equiv -\sigma_{\text{tot},s}\ \mathcal{L}\ + \ln\chi$$

- combinatorics by adding likelihoods [problem for taggers, QJets]

Same for subjets [Soper, Spannowsky]

- background from QCD splittings [parton shower]
  signal from hard decays
  Sudakovs for non–splitting
- compute LLR for signal and background assumption as ‘top-ness’ measure





Shower Deconstruction

Remember matrix element method [Tevatron]

- measured fully exclusive cross section: $d\sigma$
  computed matrix element squared: $|\mathcal{M}|^2(m_t)$
- direct comparison to determine m_t
- Neyman–Pearson: log likelihood ratio best test statistic [minimum false positive]

$$q(\vec{r}) = -\sigma_{\text{tot},s}\ \mathcal{L}\ + \ln\left(1 + \frac{d\sigma_s(\vec{r})}{d\sigma_b(\vec{r})}\right) \equiv -\sigma_{\text{tot},s}\ \mathcal{L}\ + \ln\chi$$

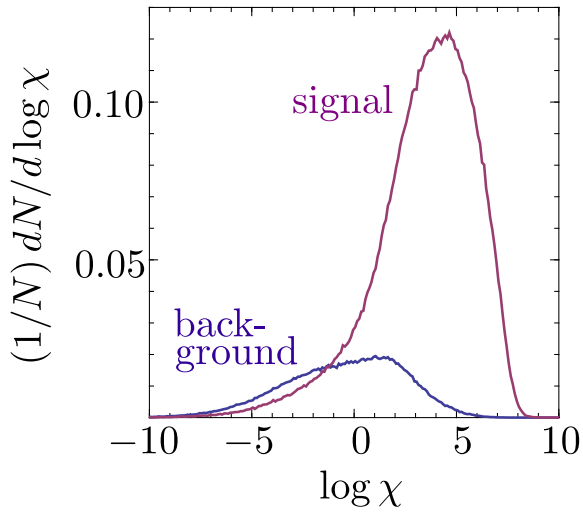
- combinatorics by adding likelihoods [problem for taggers, QJets]

Implementation [1211.3140]

- look at microjets inside fat jet $[R_{k_T} = 0.2, p_T < 5 - 10\ \text{GeV}, N = 9]$
- approximate parton shower as description [shower time, analytic computation]
- compute χ for signal/background hypothesis
  $\chi > 0$ for 68% (14%) for S (B)

$\Rightarrow$ tagger with χ_{min}

- combined with MEM to Event Deconstruction

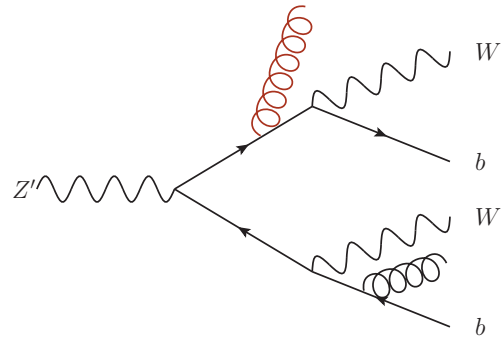


Resonance Searches and FSR

Shower/Event Deconstruction setup [Soper, Spannowsky]

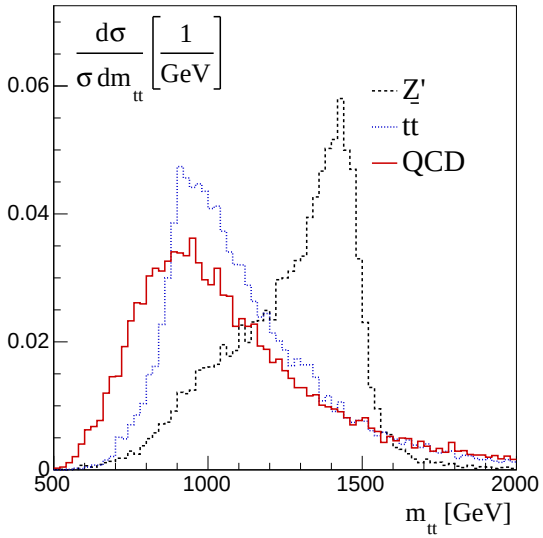
- signal: $Z' \to t_h \bar{t}_h$, $m_{Z'} = 1.5$ TeV, $\Gamma_{Z'} = 65$ GeV
- background: QCD di-jets, SM $t_h \bar{t}_h$,
- no detector simulation
- fat jets $p_T > 400$ GeV, $|y| < 2.5$

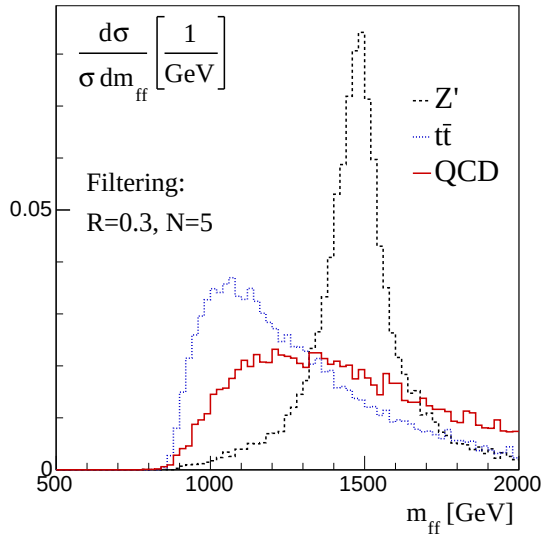
Final state radiation

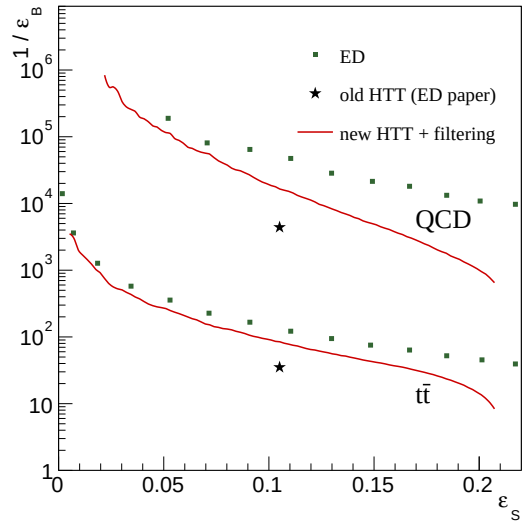


- use reconstructed 4-momentum of tagged top
- tail in $m_{tt}^{(\text{rec})}$ from tagged momentum and FSR

$\Rightarrow$ use 4-momentum of fat jet: $\{m_{tt}, p_{T,t}, m_{jj}^{(\text{filt})}, p_{T,j}^{(\text{filt})}\}$







Resonance Searches and FSR

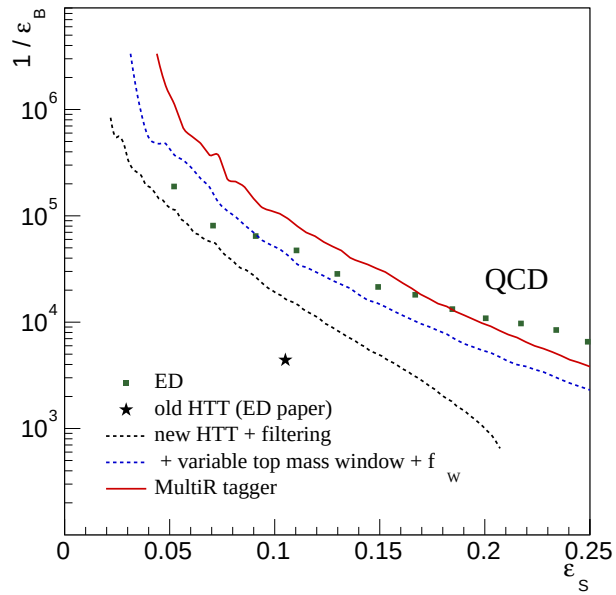
Shower/Event Deconstruction setup [Soper, Spannowsky]

- signal: $Z' \to t_h \bar{t}_h$, $m_{Z'} = 1.5$ TeV, $\Gamma_{Z'} = 65$ GeV
- background: QCD di-jets, SM $t_h \bar{t}_h$,
- no detector simulation
- fat jets $p_T > 400$ GeV, $|y| < 2.5$

Preliminary compariaon with HEPTopTagger2.0

- full BDT $\{m_{tt}, p_{T,t}, m_{jj}^{(\text{filt})}, p_{T,j}^{(\text{filt})}, m_{123}^{(min)}, m_{123}^{(\text{max})}, f_W\}$
- multiR $\{m_{tt}, p_{T,t}, m_{jj}^{(\text{filt})}, p_{T,j}^{(\text{filt})}, m_{123}^{(\text{min},R_{\text{min}})}, m_{123}^{(\text{max},R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}\}$
- N-Subjettiness still missing
- fair comparison of approaches
- high efficiencies still a challenge [NN instead of BDT?]

$\Rightarrow$ definite progress!



Resonance Searches and FSR

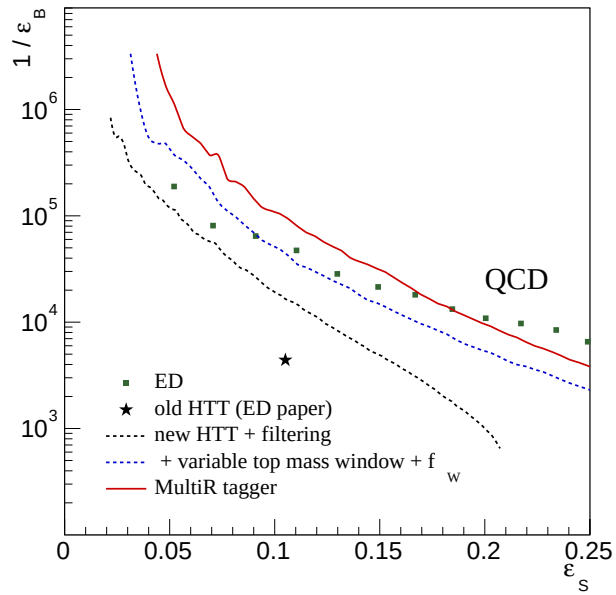
Shower/Event Deconstruction setup [Soper, Spannowsky]

- signal: $Z' \to t_h \bar{t}_h$, $m_{Z'} = 1.5$ TeV, $\Gamma_{Z'} = 65$ GeV
- background: QCD di-jets, SM $t_h \bar{t}_h$,
- no detector simulation
- fat jets $p_T > 400$ GeV, $|y| < 2.5$

Preliminary compariaon with HEPTopTagger2.0

- full BDT $\{m_{tt}, p_{T,t}, m_{jj}^{(\text{filt})}, p_{T,j}^{(\text{filt})}, m_{123}^{(min)}, m_{123}^{(\text{max})}, f_W\}$
- multiR $\{m_{tt}, p_{T,t}, m_{jj}^{(\text{filt})}, p_{T,j}^{(\text{filt})}, m_{123}^{(\text{min},R_{\text{min}})}, m_{123}^{(\text{max},R_{\text{min}})}, f_W^{(R_{\text{min}})}, R_{\text{min}} - R_{\text{min}}^{(\text{calc})}\}$
- N-Subjettiness still missing
- fair comparison of approaches
- high efficiencies still a challenge [NN instead of BDT?]

$\Rightarrow$ definite progress!



Outlook

Fat Jets are...

...turning jet physics into a cool topic

...a fast–moving and happy field

...bringing together experiment and theory

...an opportunity for young people to have impact

...always honoring good ideas

Thank you

to all experimenters who make this work

to former and current ATLAS–Heidelberg

to all groups using our tagger