

Top Taggers

Tilman Plehn

Fat jets

Analyses

N-Subjettiness

HEPTopTagger

Beyond Cuts

Shower Deco

Resonances

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Universität Heidelberg

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Resonances

## Boosted particles at the LHC

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

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

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

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

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

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

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

2009 boosted  $t \rightarrow 3$  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 done



# Jet Algorithms

## Definition of jets

- jet–parton duality  $\Leftrightarrow$  what are partons in detector?
- need algorithm to reconstruct what was one parton [IR safe recombination algos]
- crucial for any LHC analysis [ILC analyses without jets?]
- extension to  $b$  and  $t$  perturbative QCD problem

## Different measures [FASTJET: Cacciari, Salam, Soyez]

- define jet–jet and jet–beam distance [exclusive with resolution  $y_{\text{cut}}$ ]

$$k_T \quad y_{ij} = \frac{\Delta R_{ij}}{R} \min(p_{T,i}, p_{T,j}) \quad y_{iB} = p_{T,i}$$

$$C/A \quad y_{ij} = \frac{\Delta R_{ij}}{R} \quad y_{iB} = 1$$

$$\text{anti-}k_T \quad y_{ij} = \frac{\Delta R_{ij}}{R} \min(p_{T,i}^{-1}, p_{T,j}^{-1}) \quad y_{iB} = p_{T,i}^{-1} .$$

- (1) find minimum  $y^{\min} = \min_{ij}(y_{ij}, y_{iB})$
- (2a) if  $y^{\min} = y_{ij}$  merge subjects  $i$  and  $j$ , back to (1)
- (2b) if  $y^{\min} = y_{iB}$  remove  $i$  from subjects, go to (1)
- theoretical and experimental trade-off decisions
- **fat jets: use clustering history**

Analysis:  $Z' \rightarrow t\bar{t}$ 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]

- hadronic top identification and reconstruction
- jet separation challenging for heavy  $Z'$
- combination of calo and tracker great
- usually combined with  $b$ -tag

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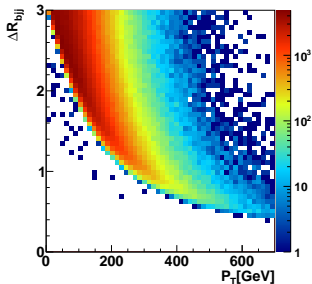
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Validation and systematics

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



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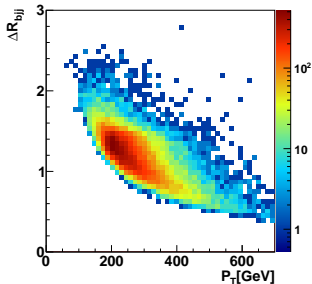
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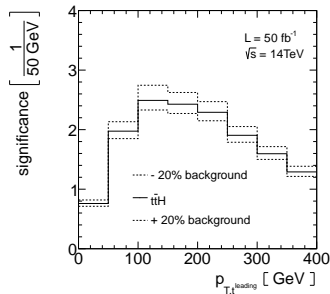


Analysis:  $t\bar{t}H, H \rightarrow b\bar{b}$ Sad story of  $t\bar{t}H, H \rightarrow b\bar{b}$  [CMS-TDR]

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

## Tagger [TP, Salam, Spannowsky; MadMax: TP, Schichtel, Wiegand]

- boost solving combinatorics [buckets]
- significance known to be in boosted regime
- side band in  $m_{bb}$  possible
- **fun: fat Higgs jet + fat top jet** [similar  $HH \rightarrow b\bar{b}b\bar{b}$ ]



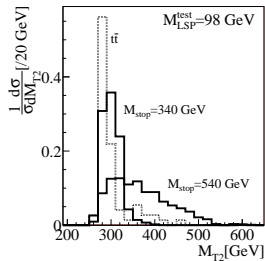
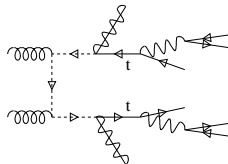
## Analysis: top partners

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

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

$$m_{T2}(\hat{m}_\chi) = \min_{\cancel{p}_T=q_1+q_2} \left[ \max_j m_{T,j}(q_j; \hat{m}_\chi) \right] \stackrel{!}{<} m_{\tilde{t}}$$

⇒ hadronic search as easy as  $b\bar{b} + \cancel{E}_T$





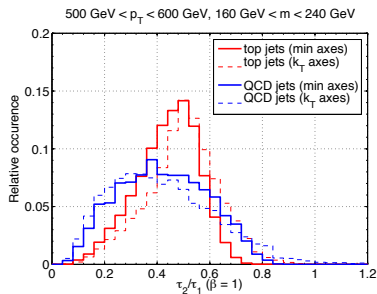
# N-Subjettiness

## 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  $\hat{n}_j$  [ $\beta > 0$ ]

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

- choice of reference axes
  - 1- from subjet algorithm
  - 2- from minimization of  $\tau_N$
- $\tau_N \rightarrow 1$  means many calo entries away from  $N$  axes
- $\tau_N \rightarrow 0$  means perfect matching
- systematics cancelled in ratios  
 $\tau_{N+1}/\tau_N$  with dip for  $N + 1$  subjets



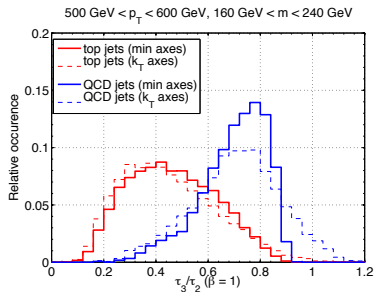
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## Tagger

- simple selection

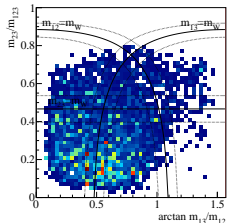
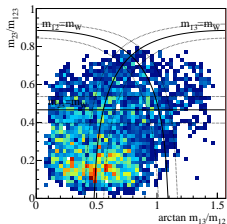
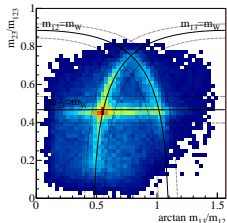
$$m_{\text{fat jet}} = 160 \dots 240 \text{ GeV} \quad \frac{\tau_3}{\tau_2} < 0.6$$

- multi-variate in  $N$  and  $\beta$  with some improvement
- ⇒ 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



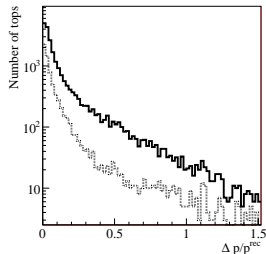
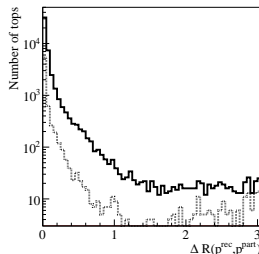
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## Top reconstruction

- direction less critical
- energy requiring calibration



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## Improvements for upcoming run

- signal efficiency
- background sculpting
- $p_T$  range
- resonance reconstruction

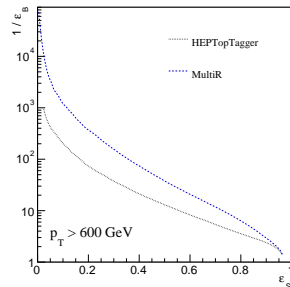
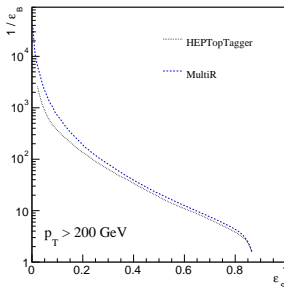
## MultiR HEPTopTagger

## 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

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

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



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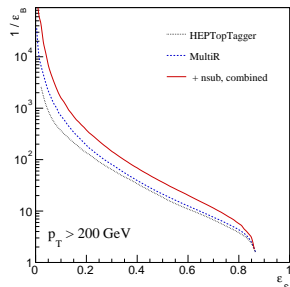
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## Combined with N-Subjettiness [DESY group]

- fixed multiR working point
- also include rejected events [ $R_{\text{filt}} = 0.2, N_{\text{filt}} = 5$ ]
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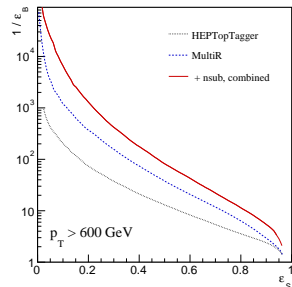
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  - $\{m_{123}^{(R_{\min})}, f_W^{(R_{\min})}, R_{\min} - R_{\min}^{(\text{calc})}, \tau_j, \tau_j^{(\text{filt})}\}$
- ⇒ stay tuned for HEPTopTagger2.0



# Taggers beyond cuts

## Best clustering history

- BDRS-like taggers asking for mass drop in best clustering history
- deterministic means conceptionally simple
- limited in efficiency
- limited in observables

## Beyond single clustering history

- shower deconstruction: Sudakov weighting
- Qjets weighted by [Ellis, Hornig, Roy, Krohn, Schwartz]

$$\omega_{ij} = \exp \left[ -\alpha \frac{y_{ij} - y_{ij}^{\min}}{y_{ij}^{\min}} \right]$$

then using distributions like  $\langle m^2 \rangle - \langle m \rangle^2$

- Jet Sampling applying Qjets and weights to full event [Kahawala, Krohn, Schwartz]
- ⇒ few convincing studies around, maybe because of  $W$  tagging?

## Shower Deconstruction

## Remember matrix element method [Tevatron]

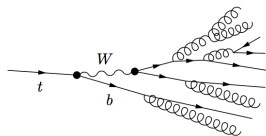
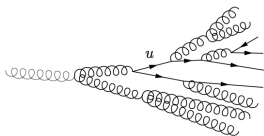
- measured fully exclusive cross section:  $d\sigma$
- computed matrix element squared:  $|\mathcal{M}|^2(m_t)$
- direct comparison to determine  $m_t$
- Neyman–Pearson: log likelihood ratio best test statistic [minimum false positive]

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

- combinatorics by adding likelihoods

## 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

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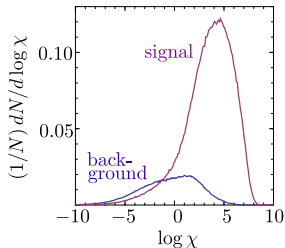
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## Implementation [1211.3140]

- 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  $\chi$  for signal/background hypothesis  
 $\chi > 0$  for 68% (14%) for S (B)
- ⇒ **tagger with  $\chi_{\text{min}}$**
- combined with MEM to Event Deconstruction



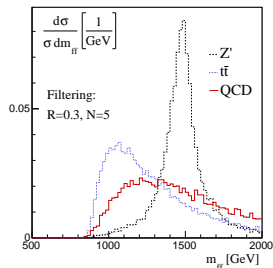
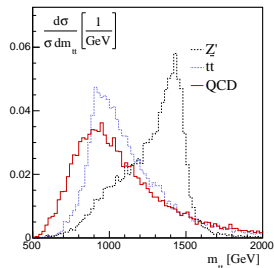
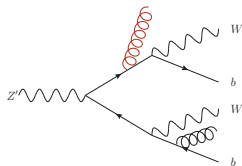
# Resonance Searches and FSR

## Shower/Event Deconstruction setup [Soper, Spannowsky]

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

## Final state radiation

- use reconstructed 4-momentum of tagged top
  - tail in  $m_{tt}^{(rec)}$  from tagged momentum and FSR
- ⇒ use 4-momentum of fat jet:  $\{m_{tt}, p_{T,t}, m_{jj}^{(filt)}, p_{T,j}^{(filt)}\}$



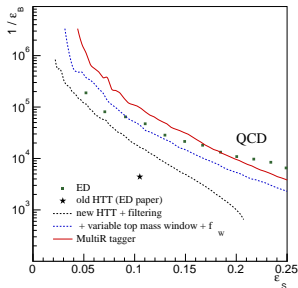
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## Preliminary comparison with HEPTopTagger2.0

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



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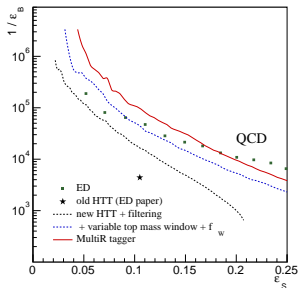
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## Open theory questions

- more and more algorithms/variables included
  - less and less perturbative QCD
  - multivariate analyses standard
- ⇒ Do we (does Gavin) know what we are doing?



# 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

## Sorry for not discussing...

- ...template taggers
- ...wavelet taggers
- ...your favorite tagger

## Thank you to...

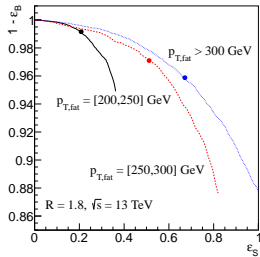
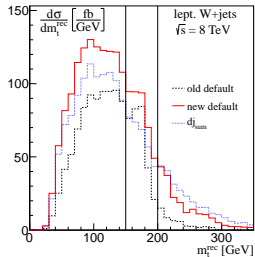
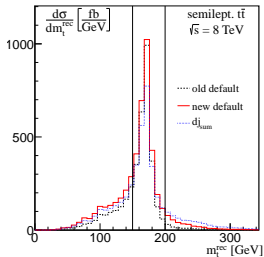
- ...former and current ATLAS-Heidelberg
- ...all groups working with and on taggers



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

Towards low  $\rho_T$  [Anders, Bernaciak, Kasieczka, TP, Schell]

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

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

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

