

Fat Jets

Tilman Plehn

Higgs searches

Higgs tagger

HEPTopTagger

Leptonic tag

Pileup

Fat Jets

Tilman Plehn

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Orsay 07/2011

Higgs, top, W , and other taggers for 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 heavy resonances [Agashe, Belyaev, Krupovnickas, Perez, Virzi]

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

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

2009 boosted $\tilde{\chi}_1^0 \rightarrow 3$ jets in R parity violating SUSY [Butterworth, Ellis, Raklev, Salam]

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

2010 boosted $t \rightarrow 3$ jets from top partners [HEPTopTagger: TP, Spannowsky, Takeuchi, Zerwas]

2010 boosted $H \rightarrow 4$ jets in the NMSSM [Falkowski et al; Nojiri et al]

...

2009 own conference series [2010 BOOST proceedings, Ed: Karagoz, Spannowsky, Vos]

...



Definition of jets

- jet–parton duality \Leftrightarrow what are partons in detector?
- need algorithm to reconstruct what was one parton
- stable w.r.t inclusion of soft radiation [IR safe]

Different measures [tool: FASTJET]

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

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

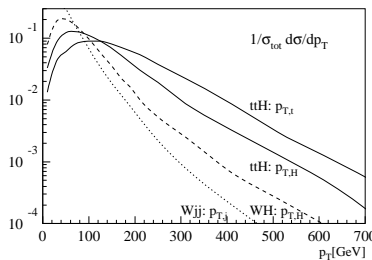
$$C/A \quad y_{ij} = \frac{\Delta R_{ij}}{D} \quad y_{iB} = 1$$

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

- (1) find minimum $y_{\min} = \min_{kl}(y_{kl}, y_{kB})$
- (2a) if $y_{\min} = y_{kl} < y_{\text{cut}}$ combine k and l , go to (1)
- (2b) if $y_{\min} = y_{kB} < y_{\text{cut}}$ remove k , go to (1)
- (2c) if $y_{\min} > y_{\text{cut}}$, done
- fat jets: use clustering history
- tag heavy states like bottom or tau jet

Example 1: $VH, H \rightarrow b\bar{b}$ New strategy for $H \rightarrow b\bar{b}$ [Butterworth, Davison, Rubin, Salam]

- desperately needed [2/3 of all light Higgses; impact Dührssen & SFitter] but killed by continuum $Vb\bar{b}$ background
- S: large m_{bb} , boost-dependent R_{bb}
- B: large m_{bb} only for large R_{bb}
- S/B: go for large m_{bb} and small R_{bb} , so boost Higgs
- fat Higgs jet $R_{bb} \sim 2m_H/p_T < 1.5$ [like b tag for now]



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- ⇒ best performance: C/A algorithm

jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B_{30}}$
C/A, $R = 1.2$	0.57	0.51	4.4
k_{\perp} , $R = 1.0$	0.19	0.74	1.2
SISCone, $R = 0.8$	0.49	1.33	2.3

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Bottom line

- combined channels $V \rightarrow \ell\ell, \nu\nu, \ell\nu$
- NLO rates [bbV notorious, not from data alone]
- Z peak as sanity check
- checked by Freiburg [Piquadio]
- subjet b tag excellent [70%/1%]
- charm rejection challenging
- $m_H \pm 8$ GeV tough

Example 2: $t\bar{t}H, H \rightarrow b\bar{b}$ Sad story of $t\bar{t}H, H \rightarrow b\bar{b}$

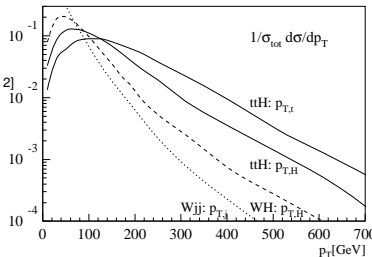
- trigger: $t \rightarrow bW^+ \rightarrow b\ell^+\nu$
reconstruction and rate: $\bar{t} \rightarrow \bar{b}W^- \rightarrow \bar{b}jj$
- continuum background $t\bar{t}b\bar{b}, t\bar{t}jj$ [weighted by b-tag]
- not a chance:
 - 1- combinatorics: m_H in $pp \rightarrow 4b_{tag} 2j \ell\nu$
 - 2- kinematics: peak-on-peak
 - 3- systematics: $S/B \sim 1/9$

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Fat jets idea [TP, Salam, Spannowsky]

- $pp \rightarrow t_\ell t_h H_b$ even harder than VH
- S/B: $R_{bb} < 1.2$; $b\bar{b}$ pair boosted [solves 1]
- boosted regime different for S and B [solves 2]
- see how far we get... [watch S/B for 3]
- bottom line: still hard
- new: fat Higgs jet + fat top jet

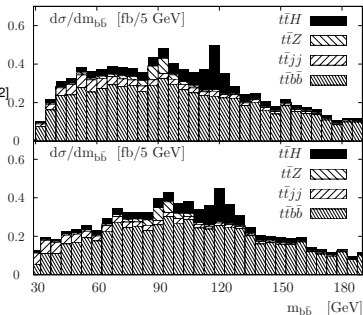


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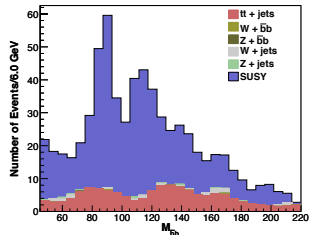


Example 3: $H \rightarrow b\bar{b}$ in SUSY cascades

Blind Higgs searches [Kribs, Martin, Roy, Spannowsky]

- idea: find Higgs in cascade decays [Cambridge]
- BSM sample after missing energy or hard γ cut
- Higgs tag over remaining event [QCD rejection?]
- side bin analysis in $m_{b\bar{b}}$

$b\bar{b}$ invariant mass, $L = 10 \text{ fb}^{-1}, \sqrt{s} = 14 \text{ TeV}$



Higgs tag for busy QCD environment [BDRS; TP, Salam, Spannowsky]

- uncluster one-by-one: $j \rightarrow j_1 + j_2$
 - 1- unbalanced $m_{j_1} > 0.8m_j$ means QCD; discard j_2
 - 2- soft $m_{j_1} < 30$ GeV means QCD; keep j_1
- double b tag [possibly add balance criterion]
 three leading $J = p_{T,1}p_{T,2}(\Delta R_{12})^4$ vs m_{bb}
- no mass constraint — side bin
 typical mis-tag probability $< 10^{-5}$
- **underlying event and pileup deadly**
 filter reconstruction jets [Butterworth–Salam, cf pruning, trimming]
 zoomed-in C/A analysis with $R_{\text{filt}} = \min(0.3, R_{bb}/2)$
- reconstruct m_H w/ one QCD jet
- **testable in $Z \rightarrow b\bar{b}$?**

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Better than traditional b jets

- no combinatorial choices
- more soft partons included in m_H
- b tagging easier than in continuum
- QCD features useful [Soper & Spannowsky]

...

Highly boosted top quarks [Kaplan, Rehermann, Schwartz, Tweedie; Princeton, Seattle...]

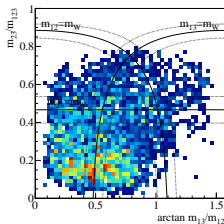
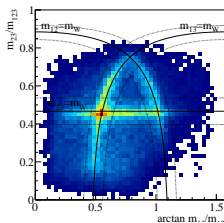
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reconstruct m_W, m_t
remaining m_{jj} [helicity angle]
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- filtering w/ 2 QCD jets

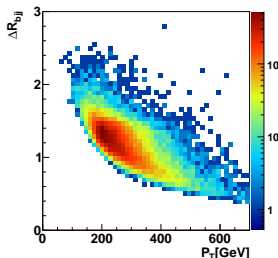


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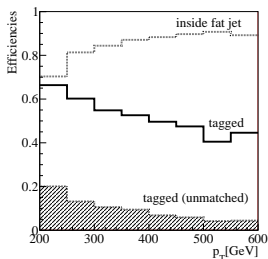


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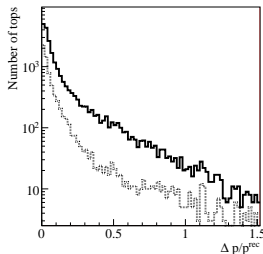


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- momentum reconstruction for free



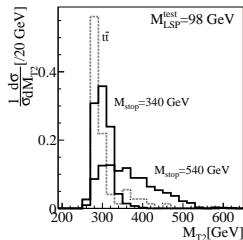
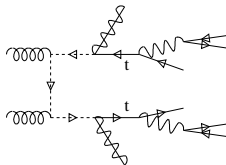
Stop pairs

Top partner crucial for hierarchy problem

- dark matter means difficult semi-leptonic channel
- hadronic: $\tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 \bar{t}\tilde{\chi}_1^0$ [Meade & Reece somewhat optimistic]
- stop mass from m_{T2} endpoint [like sleptons or sbottoms]

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

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



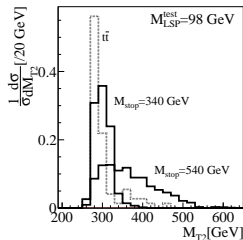
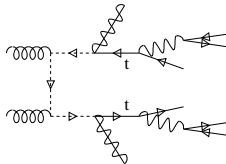
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events in 1 fb^{-1}	$\tilde{t}_1 \tilde{t}_1^*$						$t\bar{t}$	QCD	$W+\text{jets}$	$Z+\text{jets}$	S/B	S/\sqrt{B}
$m_{\tilde{t}} [\text{GeV}]$	340	390	440	490	540	640					340	
$p_{T,j} > 200 \text{ GeV}, \ell \text{ veto}$	728	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$3.0 \cdot 10^{-5}$	
$\cancel{E}_T > 150 \text{ GeV}$	283	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$1.2 \cdot 10^{-3}$	
first top tag	100	91	75	57	42	15	743	7590	90	114	$1.2 \cdot 10^{-2}$	
second top tag	15	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	$8.3 \cdot 10^{-2}$	
b tag	8.7	7.4	6.3	5.0	3.8	1.4	19	2.6	$\ll 0.2$	$\ll 0.05$	0.40	5.9
$m_{T2} > 250 \text{ GeV}$	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\ll 0.6$	$\ll 0.1$	$\ll 0.03$	0.88	6.1

Leptonic tag [Thaler & Wang; Rehermann & Tweedie; TP, Spannowsky, Takeuchi]

- unknown: 3-momentum of neutrino
 W and t mass constraints; 3rd parameter elsewhere
do not use measured \vec{p}_T vector

- neutrino coordinates
 leading in $b - \ell$ direction
 sub-leading in $b - \ell$ decay plane
 sub-leading orthogonal to decay plane

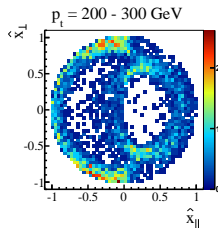
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[decay plane approx $p_\nu^\perp = 0$]

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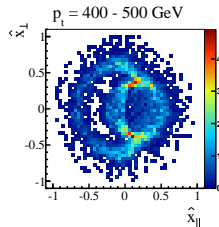
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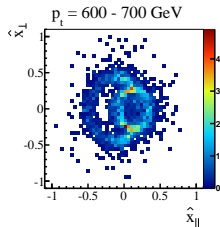
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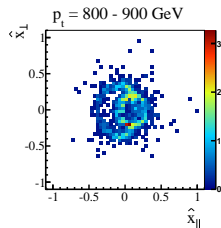
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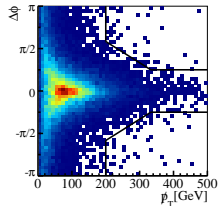
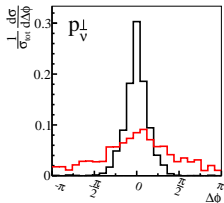
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- use approximate $\Delta\Phi(\hat{p}_T, \hat{p}_t)$
- top partner decays observable

[orthogonal approx $p_\nu^\parallel = 0$][decay plane approx $p_\nu^\perp = 0$]

Filtering [BDRS, adapted for HEPTopTagger]

- designed for C/A algorithm
- reduce effective fat-jet area
zoom in on relevant final subjects
- number of jets and size negotiable

Pruning [Ellis, Vermillion, Walsh]

- designed for k_T algorithm
- extract relevant collinear splittings in splitting history
- soft/collinearity condition negotiable

Trimming [Krohn, Thaler, Wang]

- designed for anti- k_T algorithm
- remove soft fat jet regions [inverse to filtering]

- filtering + pruning useful [Spannowsky & Soper]
- should we use more/less of the clustering history? [Jankowiak, Lankorski]
- **and can we do this with pileup?**

Fat jets — made for the LHC

- VH : bringing back 2/3 of light Higgses
- $t\bar{t}H$: curing combinatorics and backgrounds
- SUSY cascades: curing lack of analysis idea
- ...
- Z' etc: improving mass resolution
- $\tilde{t}\tilde{t}^*$: curing backgrounds
- ...
- $H \rightarrow aa \rightarrow 4g$: making it possible
- ...
- HEPTopTagger code as FASTJET add-on [www.thphys.uni-heidelberg.de/~plehn/HEPTopTagger]
implemented and tested by ATLAS, improvements welcome
proofs of concept on data any time now

LHC lecture notes arXiv:0910.4182

BOOST review arXiv:1012.5412

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Higgs searches

Higgs tagger

HEPTopTagger

Leptonic tag

Pileup