Fat Jets

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Fat jets

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

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

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

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

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

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

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

...

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

...

Jet Algorithms (early backup slide)

Definition of jets

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

Different measures [tool: FASTJET]

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

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

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

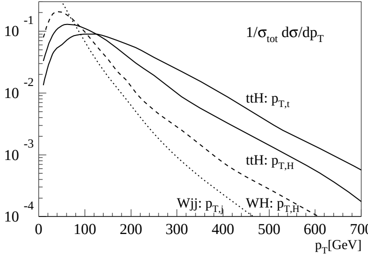
Example 1: $VH, H \to b\bar{b}$

New strategy for $H \to bb$ [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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$\Rightarrow$ 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 $V \to \ell\ell, \nu\nu, \ell\nu$
- 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: $t\bar{t}H, H \to b\bar{b}$

Sad story of $t\bar{t}H, H \to b\bar{b}$

– 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]

– not a chance:
  1– combinatorics: m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$
  2– kinematics: peak-on-peak
  3– systematics: $S/B \sim 1/9$

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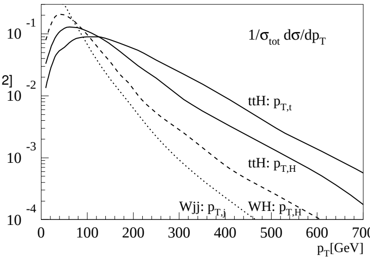
Fat jets idea [TP, Salam, Spannowsky]

- $pp \to t_\ell t_h H_b$ 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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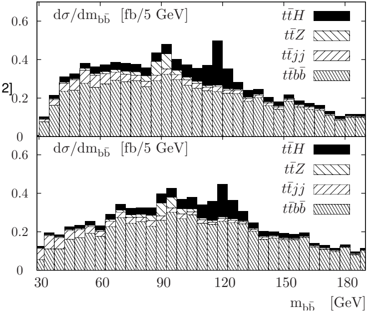
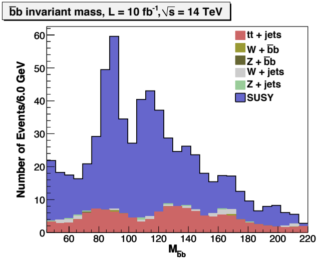


Example 3: $H \to b\bar{b}$ in SUSY cascades

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_{bb}



Higgs tagger

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

- uncluster one-by-one: $j \to j_1 + j_2$
  1– unbalanced $m_{j_1} > 0.8 m_j$ 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 $Z \to b\bar{b}$?

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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]
  ...

Top tagger

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

- identify hadronic tops with $p_T \gtrsim 800$ GeV
  isolation and b tagging challenging
- C/A algorithm with p_T drop criterion [Hopkins tagger, no b tag]
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- extend to $p_T \gtrsim 250$ GeV
  testable in Standard Model $t\bar{t}$
- start with C/A jet [$R = 1.5$] [Johns Hopkins]
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  remaining m_{jj} [helicity angle]
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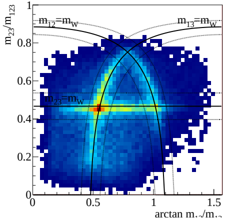
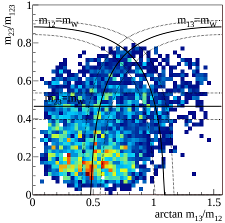
- filtering w/ 2 QCD jets





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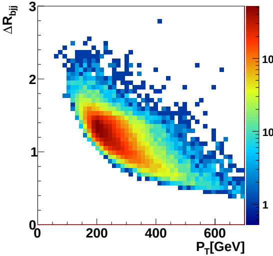

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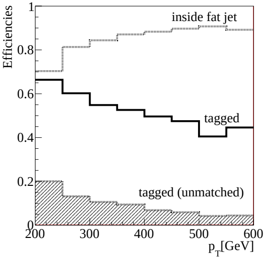

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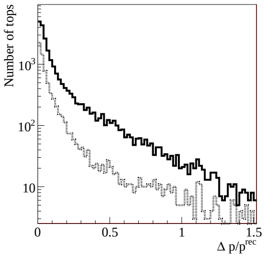
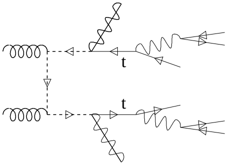
– momentum reconstruction for free



Stop pairs

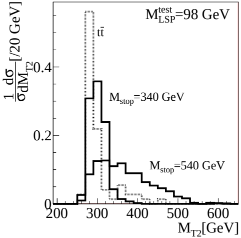


Top partner crucial for hierarchy problem

- dark matter means difficult semi-leptonic channel
- hadronic: $\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0 \, \bar{t}\tilde{\chi}_1^0$ [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 $b\bar{b} + \not{E}_T$



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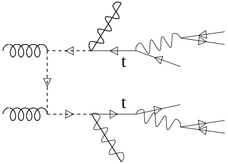

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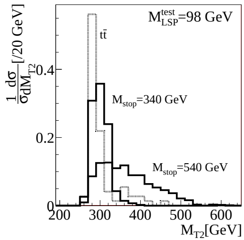

events in 1 fb^{-1}	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\text{ fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	340	390	440	490	540	640					340	
$p_{T,j} > 200$ GeV, ℓ veto	728	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$3.0 \cdot 10^{-5}$	
$\not{E}_T > 150$ 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	$\lesssim 0.2$	$\lesssim 0.05$	0.40	5. 9
$m_{T2} > 250$ GeV	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	0.88	6. 1

Leptonic top tag (skipping because of time)

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 $\not{p}_T$ vector

– neutrino coordinates
  leading in $b - \ell$ direction
  sub-leading in $b - \ell$ decay plane [orthogonal approx $p_\nu^{||} = 0$]
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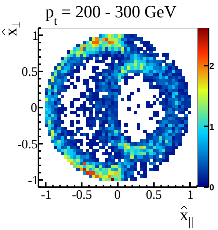

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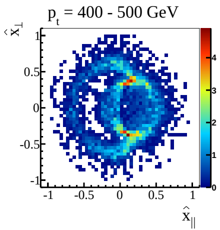

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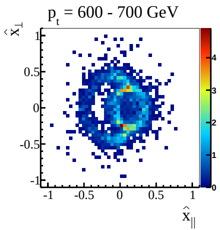

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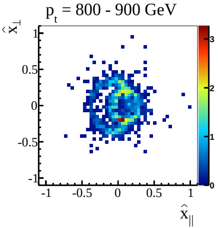

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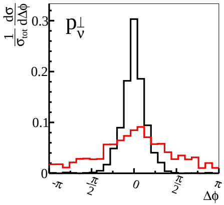
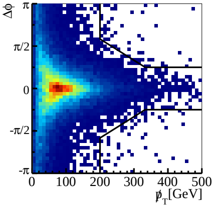
- use approximate $\Delta\Phi(\not{p}_T, \hat{p}_t)$
- top partner decays observable





Dealing with pileup

Filtering [BDRS, adapted for HEPTopTagger]

– designed for C/A algorithm
– reduce effective fat-jet area
  zoom in on relevant final subjets
– 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?

Outlook

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

  ...

- $H \to aa \to 4g$: 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