Boosted tops / jet substructures

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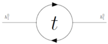
introduction

top quark

– copiously produced via strong interaction at LHC

– strongly coupled with Higgs sector

– from naturalness, cancellation expected via top partner (ex. SUSY, Little Higgs)

$\delta m_h^2 \sim$ 

$-\frac{3}{4\pi} y_t^2 \Lambda_{\mathrm{SM}}^2$

– tool for new physics search at LHC

hadronic top: $t \longrightarrow 3j$

– high p_T top end up a top-jet

– several top taggers available

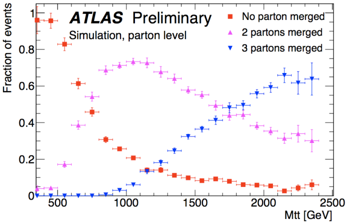
· looking into jet substructure

· top $\leftrightarrow$ QCD

[Kaplan, Rehermann, Schwartz, Tweedie] [Thaler, Wang]

[Almeida, Lee, Perez, Sterman, Sung]

– inspired by very heavy $X \longrightarrow t\bar{t}$ [RS model]



introduction

boosted particles at the LHC

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

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

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

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

2008 boosted $H \longrightarrow b\bar{b}$ [Butterworth, Davison, Rubin, Salam]

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

2009 boosted $t \longrightarrow$ 3 jets from top partners [Plehn, Zerwas, Spannowsky, MT]

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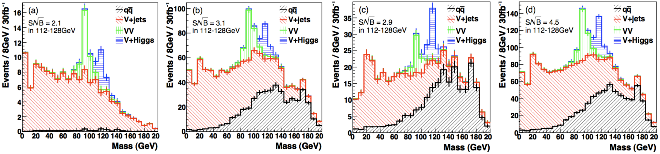


$ZH(\rightarrow b\bar{b}), WH(\rightarrow b\bar{b})$ channel as discovery channel

introduction

modestly boosted tops at the LHC

– top taggers are originally designed for $p_T > 500$ GeV

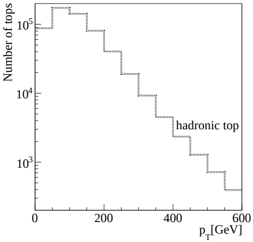
– not expected many in SM

– for LHC 7TeV

$p_T > 500$ GeV – 105fb

$200 < p_T < 500$GeV – 8970fb

$\longrightarrow$ need top tagger valid down to low p_T range



– light top partner ($\sim$ 500 GeV) favored to avoid little hierarchy problem

– top from the stop decay also in the range

high p_T vs. low p_T

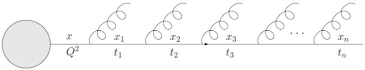
	high p_T	$\leftrightarrow$	low p_T
source	heavy massive resonance		relatively light particles + continuum
difficulty	too collimated $\rightarrow$ difficult resolve		well separated, need large R $\rightarrow$ splash-in from UE, ISR $\rightarrow$ combinatorics

plan of talk

0. introduction
1. jet substructure
   - clustering algorithm
   - mass drop
   - filtering
2. HEPTopTagger (Heidelberg- Eugine-Paris) – tagger for modestly boosted top
   - algorithm
   - efficiency & momentum reconstruction
   - application to stop pairs
3. summary

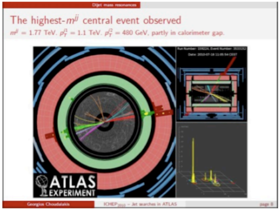
jet and QCD

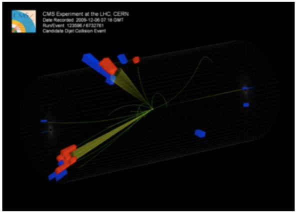
- jet = collimated hadronic activity in the detector
- well described by QCD – soft-collinear property



$$Q^2 > t_1 > t_2 > \ldots$$
$$t = E_1 E_2 (1 - \cos\theta)$$
$$\mathcal{M} \propto \frac{1}{t_1}\frac{1}{t_2}\cdots$$

$\longrightarrow$ parton shower $\longrightarrow$





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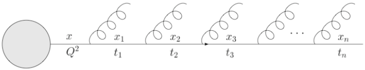

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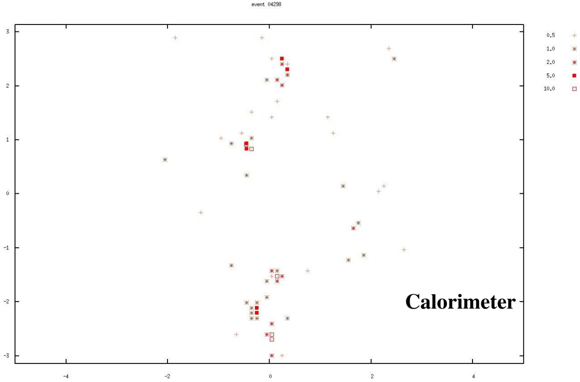
⟶ parton shower ⟶



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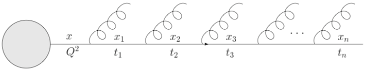

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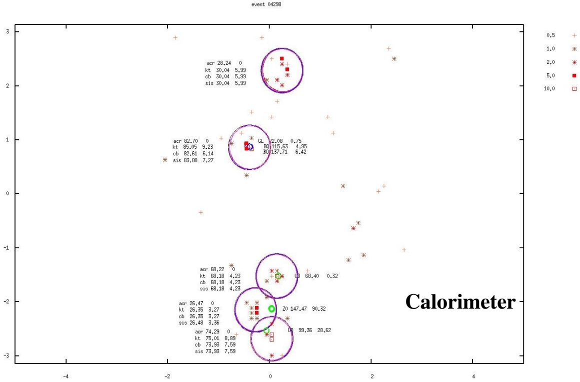

clustering algorithm

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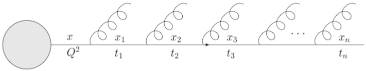
- well described by QCD – soft-collinear property



$$Q^2 > t_1 > t_2 > \ldots$$
$$t = E_1 E_2 (1 - \cos\theta) \sim E^2\theta^2/2$$
$$\mathcal{M} \propto \frac{1}{t_1}\frac{1}{t_2}\cdots$$

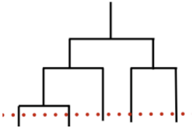
$\longrightarrow$ parton shower $\longrightarrow$

$\longleftarrow$ clustering $\longleftarrow$

clustering algorithm – sequential reconbination

1. find smallest d_{ij}, d_{iB}
2. if d_{ij}, recombine ij

   if d_{iB}, call i as a jet
3. repeat 1-2 until no particles left



distance measure – based on QCD (soft-collinear nature)

$$C/A \qquad d_{ij} = \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = 1$$

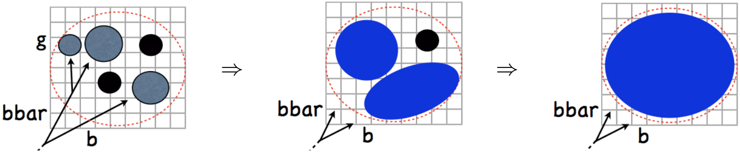
$$kT \qquad d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_T^2,$$

$$anti-kT \qquad d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_T^{-2},$$

basic idea of subjet analysis

clustering

- collinear singularity of QCD $\longrightarrow$ naturally collects FSR
- collects decay products from boosted object
- collects ISR and UE at the same time



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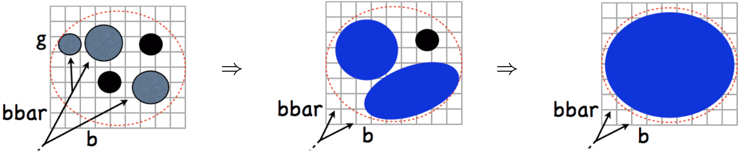
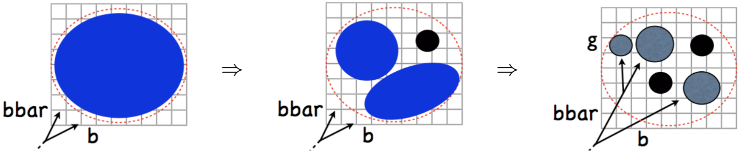


undoing clustering

- no soft-collinear singularity for decay of boosted object $\longrightarrow$ mass drop, p_T drop

$$j = j_1 + j_2, \quad \boxed{m_j \gg m_{j1}, m_{j2} \text{ (massive particle)}} \leftrightarrow \boxed{m_j \sim m_{j1} \gg m_{j2} \text{ (QCD)}}$$

- want collect FSR but reject ISR and UE



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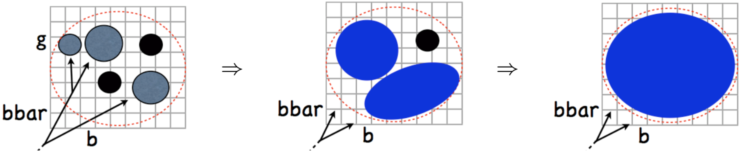

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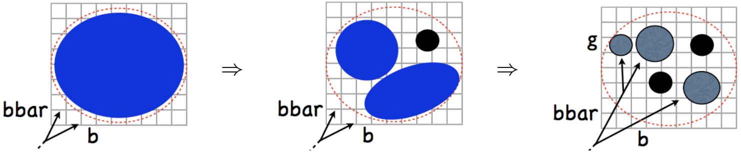
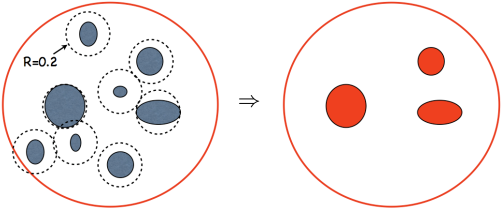
- want collect FSR but reject ISR and UE → need filtering



jet filtering

jet filtering [Butterworth et al.]

- take a jet defined with R, for example $R = 1.0$
- recombine the constituents with smaller R_{filt}, for example $R_{\text{filt}} = 0.2$
- take only first hardest n_{filt} subjets (discard others)



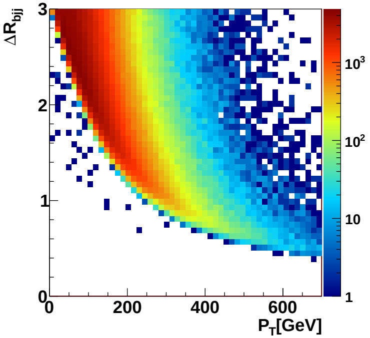
- R_{filt} and n_{filt}: tunable parameter $\leftarrow$ depends on what want to tag
- $H \to b\bar{b}$, take 3 hardest subjets (for 1 gluon radiation $H \to b\bar{b}g$)
- $t \to bjj$, take 5 hardest subjets (for 2 gluon radiation $t \to bg(jjg)$)

HEPTopTagger [JHEP 1010:078,2010. arXiv:1006.2833 [hep-ph] T. Plehn, M. Spannowsky, D. Zerwas, MT]

fat jets

– focus on low p_T tops with heavy m_t
$\longrightarrow$ decay products well separated, need large R

– $R = 1.5$ to have top with $p_T \sim 200$ GeV



– valid seamlessly from low p_T to high p_T

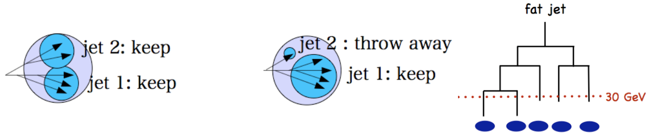
HEPTopTagger

[JHEP 1010:078,2010. arXiv:1006.2833 [hep-ph] T. Plehn, M. Spannowsky, D. Zerwas, MT]

1. fat jets – C/A($R = 1.5$), $p_T^{\text{fatjet}} > 200$ GeV

2. mass drop criterion

– find hard proto-jets $m_j < 30$ GeV, $m_{j1} < 0.8 m_j$ to keep j_1 and j_2

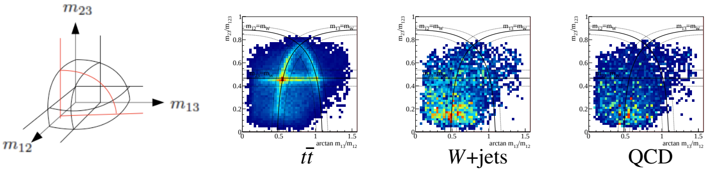


3. choose 3 hard proto-jets with best filtered mass

– $|m_{jjj}^{\text{filt}} - m_t| < 25$ GeV and $p_T^{\text{rec}} > 200$ GeV $\rightarrow$ top candidate

4. check mass ratios

– m_t condition: $m_t^2 = m_{123}^2 = m_{12}^2 + m_{13}^2 + m_{23}^2 \rightarrow$ spherical surface: 2D mass ratios

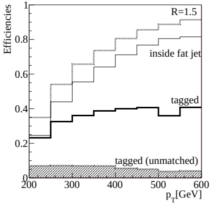


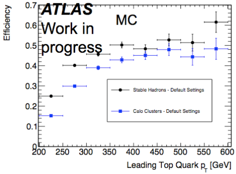
– W mass condition, soft-collinear cut $\rightarrow$ tagged top

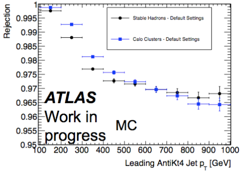
HEPTopTagger

[JHEP 1010:078,2010. arXiv:1006.2833 [hep-ph] T. Plehn, M. Spannowsky, D. Zerwas, MT]

efficiency







– efficiency $\sim$ 35% for hadronic tops, 2 $\sim$ 4% mis-tag rate

– validation with ATLAS experimentalists in Heidelberg

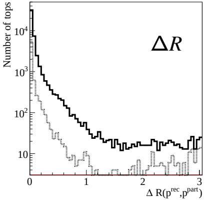
momentum reconstruction

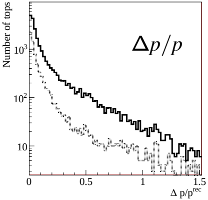
– momentum well reconstructed

– better reconstruction for larger p_T

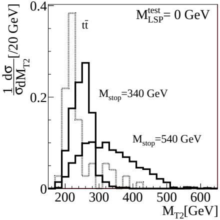
solid: $p_T^{\text{rec}} > 200\text{GeV}$

dotted: $p_T^{\text{rec}} > 300\text{GeV}$





stop pairs



hadronic $\tilde{t}\tilde{t}^*$ [T. Plehn, M. Spannowsky, MT, D. Zerwas]

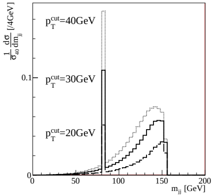
- $m_{\tilde{\chi}^0_1} = 98$ GeV, $\tilde{t}_1 \to t\tilde{\chi}^0_1$ (100%)
- main BG: $t\bar{t}$+jets, W+jets and QCD *(Alpgen-Pythia)*
- set of cuts
  - no lepton, $\not{E}_T > 150$ GeV
  - 2 tagged tops with $p_T^{rec} > 200/200$GeV $\longrightarrow$ W+jets, Z+jets negligible
  - b-tag for 1st tagged top $\longrightarrow$ QCD negligible
  - $m_{T2} > 250$GeV $\longrightarrow$ reduce $t\bar{t}$

events in 1 fb^{-1}	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\ \mathrm{fb}^{-1}}$
$m_{\tilde{t}}$[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

- $S/B \sim 1, S/\sqrt{B} > 5$ for 10fb^{-1}
- stop mass from $m_{T2}(m_{\tilde{\chi}^0_1})$ endpoint [C. G. Lester, D. J. Summers] [like sleptons or sbottoms]

stop pairs

semileptonic $\tilde{t}_1\tilde{t}_1^* \to (b\ell\nu\tilde{\chi}_1^0)\,(\bar{b}jj\tilde{\chi}_1^0)$ [arXiv:1102.0557 [hep-ph] T. Plehn, M. Spannowsky, MT]



1. exactly one lepton ($p_T > 20$ GeV, $|\eta| < 2.5$)
2. $\not{E}_T > 150$ GeV
3. one tagged hadronic top (HEPTopTagger, $p_T > 200$ GeV)
4. one b tag among the leading 3 jets outside the tagged top ($p_T > 25$ GeV, $|\eta| < 2.5$)
5. $m_{b\ell} < \sqrt{m_t^2 - m_W^2} = 154.6$ GeV. [cf. CDF m_{jj} by tops (arXiv:1104.4087 T. Plehn, MT)]

	$\tilde{t}_1\tilde{t}_1^*$				$t\bar{t}$	W+jets	S/B	$S/\sqrt{B}_{20\text{fb}-1}$
$m_{\tilde{t}}$[GeV]	340	440	540	640			440	440
0. cross section	5090	1280	402	146	$9.2 \cdot 10^5$	$2.1 \cdot 10^5$	0.001	3.8
1. one lepton	1471	373	118	42.5	$2.6 \cdot 10^5$	$1.3 \cdot 10^5$	0.001	2.7
2. $\not{E}_T > 150$ GeV	569	239	90.2	35.5	9825	4512	0.017	8.9
3. hadronic top tag	74.5	38.0	16.8	7.72	1657	141	0.021	4.0
4. tagged b jet	31.2	15.9	7.33	3.38	668	4.35	0.024	2.7
5. $m_{b\ell} < m_{b\ell}^{\max}$	27.5	13.7	6.34	2.90	642	2.61	0.021	2.4

- cut basis method:
  - · use $\not{E}_T = p_{\nu,T}$
  - · check solution for $p_{\nu,z}$
- not promissing $S/B \sim 0.1$, $S/\sqrt{B}_{10\text{ fb}^{-1}} \sim 2.2$
- not reasonable with additional $\not{E}_T$ sources.

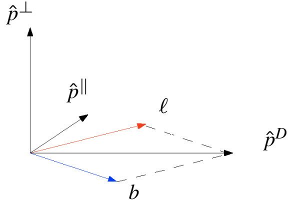
$\to$ our approach:

· reconstruct top momentum

· compare with $\not{E}_T$

Leptonic Top Tagger

[arXiv:1102.0557 [hep-ph] T. Plehn, M. Spannowsky, MT]



only 3 observable in lab. frame

$$E_\ell, \quad E_b, \quad m_{b\ell} \ \text{(equivalent to } \theta_{bl})$$

$$\vec{p}_\nu = x_{\rm D}\hat{p}^{\rm D} + x_{||}\hat{p}^{||} + x_\perp \hat{p}^{\perp}$$

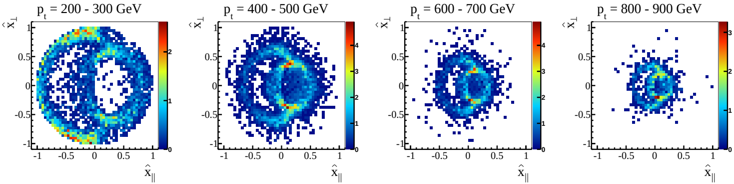
2 constraints

$$(p_\ell + p_b + p_\nu)^2 = m_t^2, \qquad (p_\ell + p_\nu)^2 = m_W^2 \ .$$

one additional assumption needed to solve

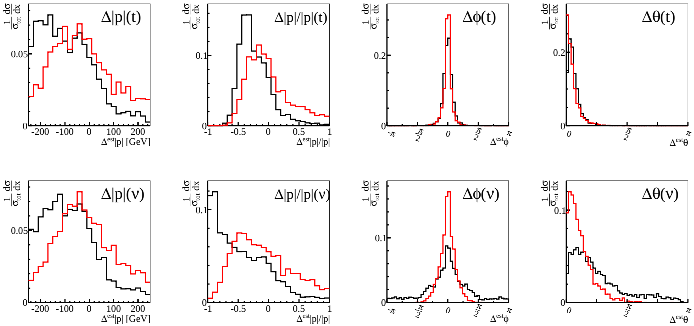
orthogonal approximation

- $x_{||} = 0$



Leptonic Top Tagger [arXiv:1102.0557 [hep-ph] T. Plehn, M. Spannowsky, MT]

momentum reconstruction ($\not{E}_T > 200$GeV)



– red: orthogonal approx. black: decay plane approx.

– $\Delta|p|(t) = |p^{\rm rec}_{\rm top}| - |p^{\rm parton}_{\rm top}|, \;\; \Delta|p|(\nu) = |p^{\rm rec}_{\nu}| - |p^{\rm parton}_{\nu}|$

– better top momentum reconstruction (compared with ν)

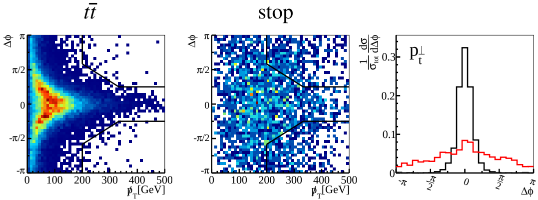
– in particular, good ϕ reconstruction.

Leptonic Top Tagger

[arXiv:1102.0557 [hep-ph] T. Plehn, M. Spannowsky, MT]

$\phi_{\rm top}$ vs. $\not{E}_T$ correlation

$$\Delta\phi_{\rm top} = \phi_{\rm top}^{\rm rec} - \phi(\not{E}_T)$$



for events with large $\not{E}_T$, top direction and neutrino direction is aligned.

$$|\Delta\phi| > \frac{13}{12}\pi - \frac{\not{E}_T}{400\text{ GeV}}\pi \qquad \not{E}_T > 200\ \text{ GeV} \qquad |\Delta\phi| > \frac{\pi}{4}.$$

	orthogonal approximation							decay plane approximation						
	$\tilde{t}_1\tilde{t}_1^*$				$t\bar{t}$	W+jets	S/B	$\tilde{t}_1\tilde{t}_1^*$				$t\bar{t}$	W+jets	S/B
$m_{\tilde{t}}$[GeV]	340	440	540	640			440	340	440	540	640			440
1.-5. base cuts	27.38	13.71	6.33	2.89	642.72	2.63	0.021							
6. approximation	14.81	7.69	3.61	1.66	285.16	1.41	0.027	27.33	13.67	6.31	2.89	642.37	2.63	0.021
7. $p_T^{\rm est} >$ 200GeV	8.61	4.53	2.41	1.24	215.62	0.60	0.021	9.13	5.16	2.87	1.61	242.21	0.54	0.021
8. $\not{E}_T$ vs. $\Delta\phi$ cut	0.97	1.52	1.23	0.76	0.72	0.02	2.06	1.22	1.82	1.53	1.02	1.31	0.06	1.33

– $S/B \sim 2, S/\sqrt{B}_{10{\rm fb}^{-1}} \sim 5$ (cut basis: $S/B \sim 0.1, S/\sqrt{B}_{10{\rm fb}^{-1}} \sim 2.2$)

summary

- top – closest to new physics
- jet substructure
  - distinguish boosted object and QCD
  - mass drop
  - filetring

- HEPTopTagger: (Heidelberg-Eugine-Paris)
  - focus on low p_T tops ($p_T > 200$GeV)
  - fat jets kill combinatorics
  - efficiency: top $\sim 35\%$, mis-tag rate$W$+jets: 4%, QCD: 2%
  - hadronic top momentum well reconstructed
  - leptonic top direction well reconstructed
  - stop pairs: hadronic channel: $S/B \sim 1, S/\sqrt{B} > 5$ for 10fb^{-1}
    semi-leptonic channel: $S/B \sim 2, S/\sqrt{B} > 5$ for 10fb^{-1}

code available on

http://www.thphys.uni-heidelberg.de/∼plehn/heptoptagger/index.html