Stop reconstruction using the HEPTopTagger

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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)

$$\delta m_h^2 \sim \quad t \quad -\frac{3}{4\pi} y_t^2 \Lambda_{\mathrm{SM}}^2$$

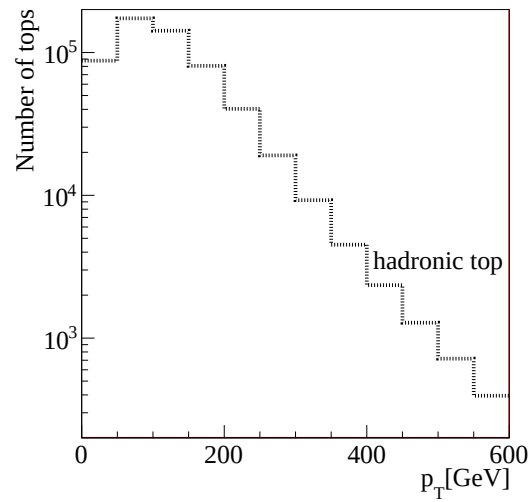
- tool for new physics search at LHC $\longrightarrow$ top tagger

hadronic top: $t \longrightarrow 3j$

- full momentum reconstruction possible in principle [QCD]
- high p_T top end up a top-jet
  looking into substructure, several top taggers available

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

  [Almeida, Lee, Perez, Sterman, Sung]
- inspired by very heavy $X \longrightarrow t\bar{t}$ [RS model]
- designed for $p_T > 500$ GeV, not expected in SM
  $\longrightarrow$ need top tagger for low p_T range
  $(200 < p_T < 500$ GeV)



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]

...

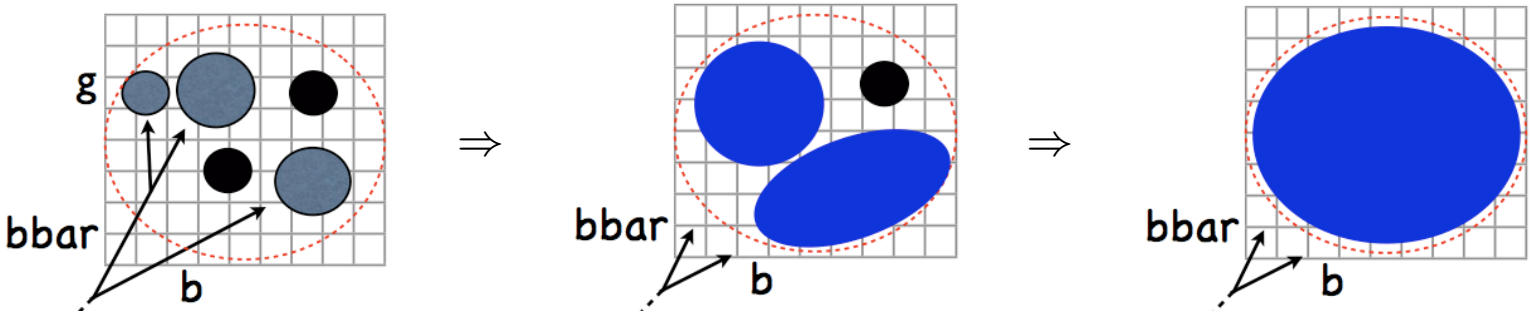
high p_T vs. low p_T

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

introduction

clustering

- collinear singularity of QCD ($d_{ij} = \Delta R_{ij}$) $\rightarrow$ naturally collects FSR
- collects decay products from boosted object
- collects ISR and UE at the same time



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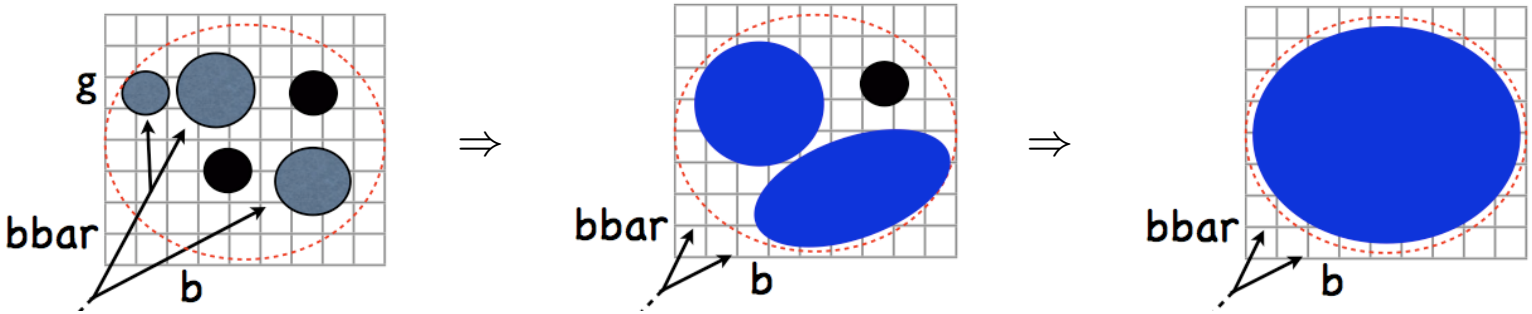

undoing clustering

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

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

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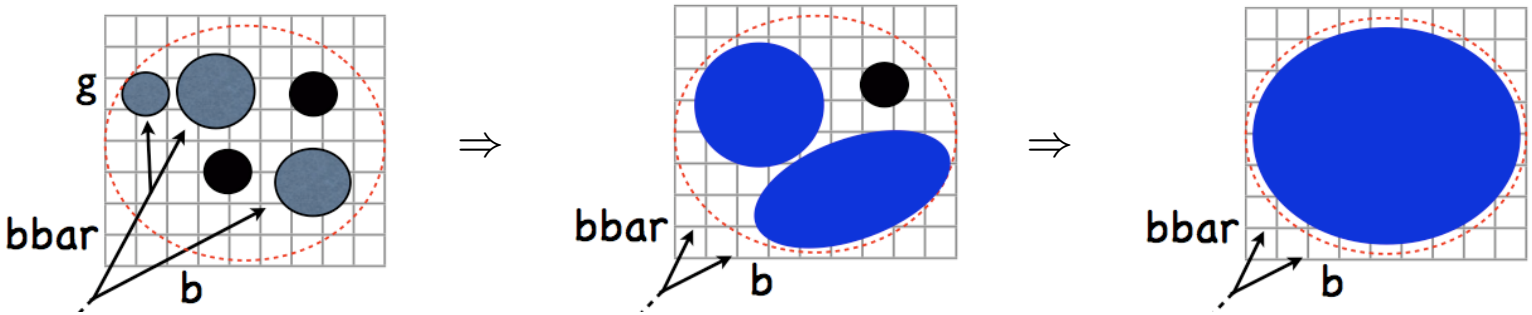

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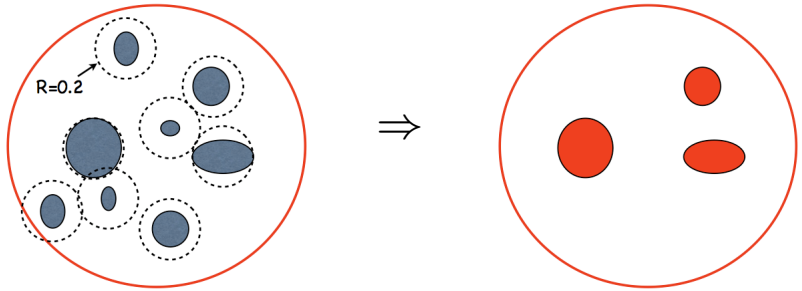
- want collect FSR but reject ISR and UE $\longrightarrow$ need filtering



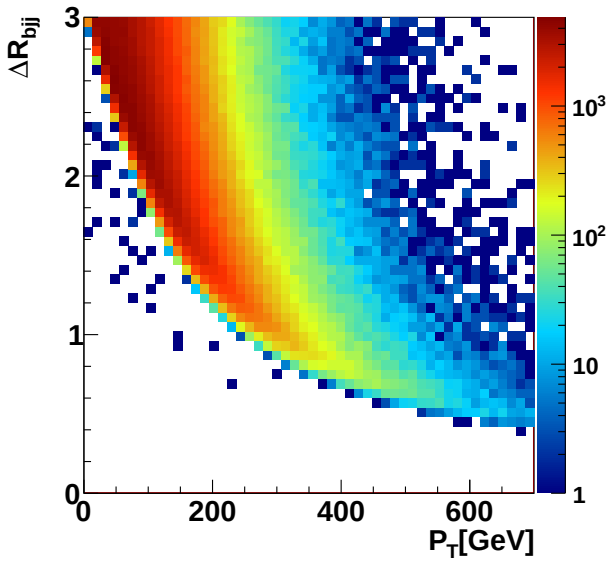
Plan of talk

HEPTopTagger

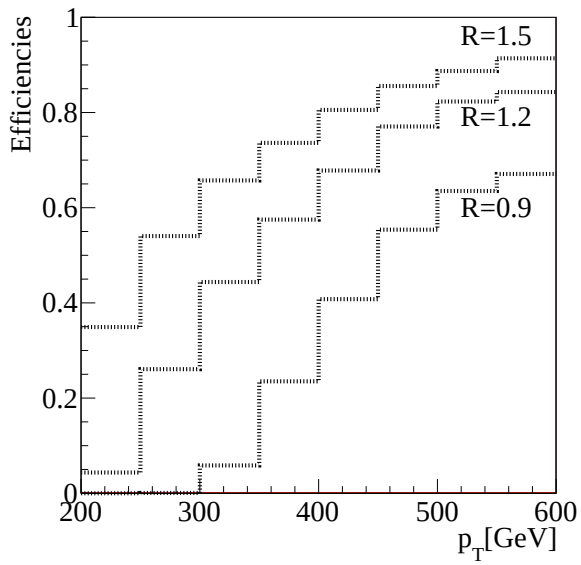
fat jets

- "fat jet" : jet with large R
  jet include heavy (fat) particle inside
- top with $p_T < 500$ GeV expected in SM $\rightarrow$ focus on low p_T tops
- heavy $m_t \rightarrow$ decay products well separated with modest $p_T \rightarrow$ need large R

C/A distance at parton level



fraction of tops within various R



- at least $R = 1.5$ to have top with $p_T \sim 200$ GeV
- underlying event scales $R^2 \rightarrow$ need filtering

HEPTopTagger

algorithm

1. **Find fat jets using C/A algorithm with R = 1.5, $p_T > 200$ GeV**

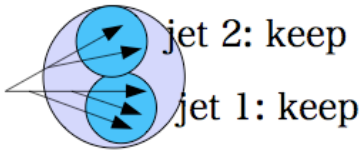
   large R collects QCD (ISR, FSR, UE and other jets).

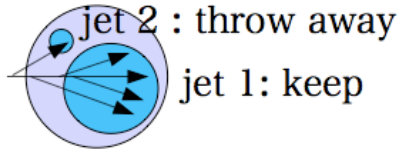
2. **Find all hard proto-jets inside fat jet using mass drop criterion**

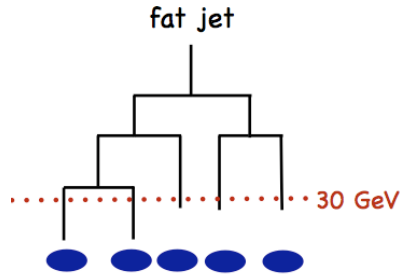
   – undoing clustering, $m_{j1} < 0.8 m_j$ to keep j_1 and j_2

   (mass drop in $t \to Wb$ and $W \to jj$)

   – stop when $m_j < 30$ GeV







3. **Choose 3 hard proto-jets giving best filtered mass**

   – take 3 hard proto-jets, and compute filtered mass m_{jjj}^{filt}

   m_{jjj}^{filt}: re-cluster with $R_{\mathrm{filt}} = \min\{0.3, R_{jj}/2\}$, compute mass of first 5 filtered jets

   $(t \to Wbg \to jjg\ bg)$

   – iterate through all pairing of hard proto-jets, keep pairing with best top mass

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

HEPTopTagger

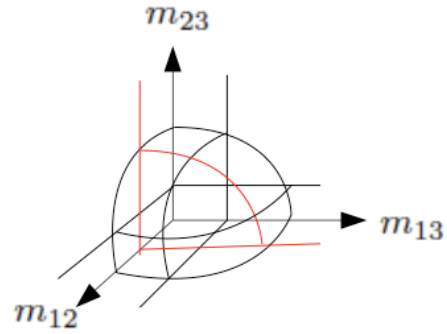
4. Check mass ratios → tagged top

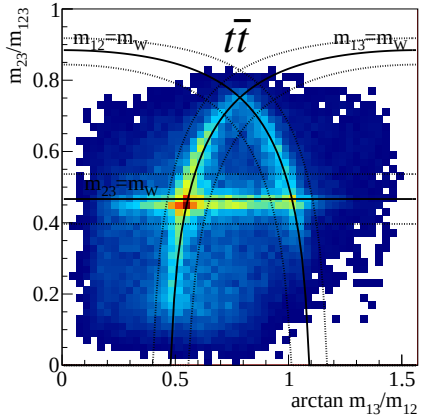
– cluster filtered constituents into 3 subjets: p_1, p_2, p_3

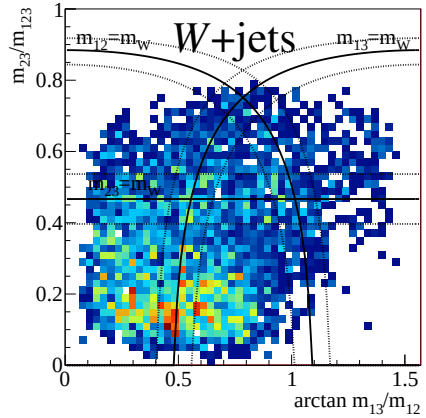
top mass condition: $m_t^2 = m_{123}^2 = m_{12}^2 + m_{13}^2 + m_{23}^2$

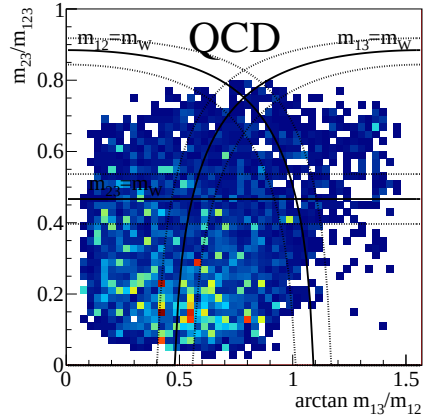
→ spherical surface with $r = m_t$ in (m_{12}, m_{13}, m_{23})

→ 2 independent mass ratios









$$R_{\text{min}} < \frac{m_{23}}{m_{123}} < R_{\text{max}} \quad \text{and} \quad 0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

$$R_{\text{min}}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\text{max}}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.35$$

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W mass condition — cut soft-collinear region

$$R_{\text{max / min}} = 100 \pm 15\% \times m_W/m_t$$

HEPTopTagger

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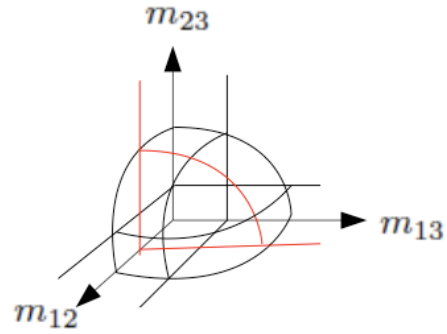

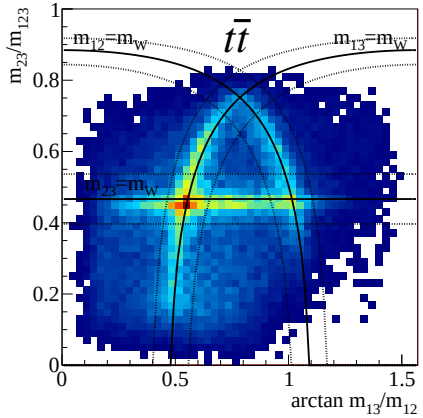

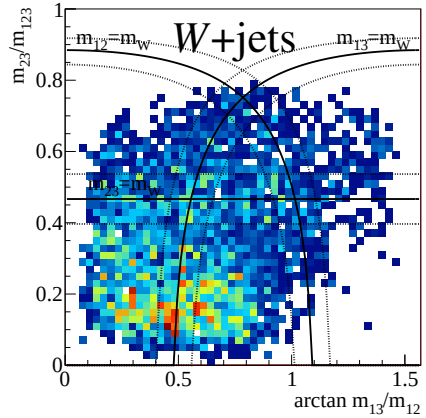

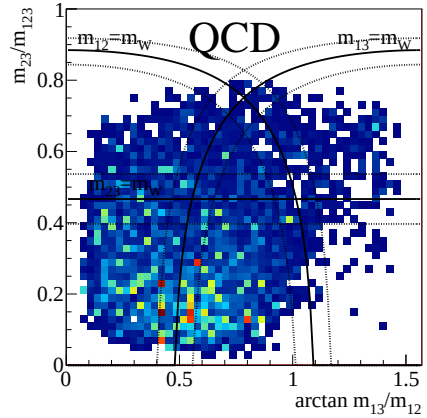

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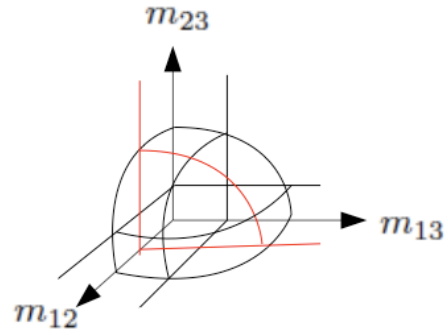

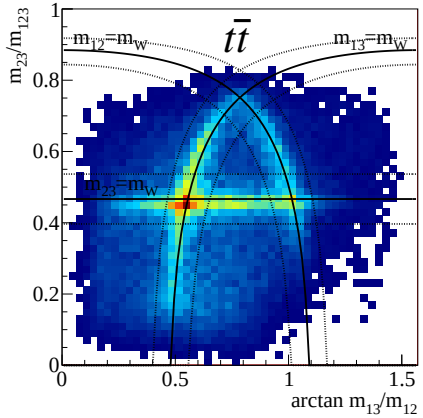

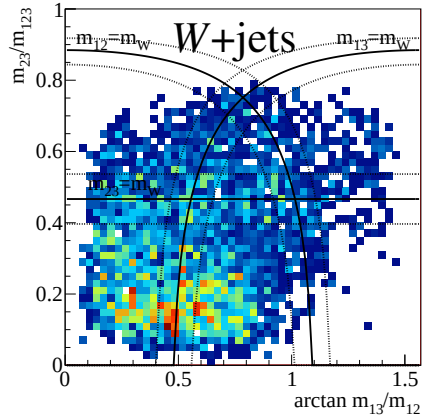

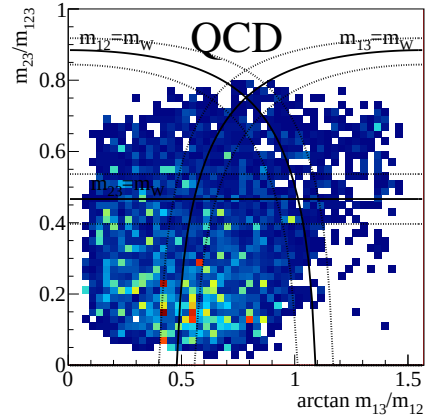

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W mass condition — cut soft-collinear region

$$R_{\text{max / min}} = 100 \pm 15\% \times m_W/m_t$$

– imposing m_t condition first, large fraction of W+jets doesn't satisfy m_W condition

– m_{jb} is close to m_W, best W mass often fails

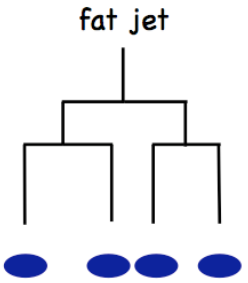
comparison

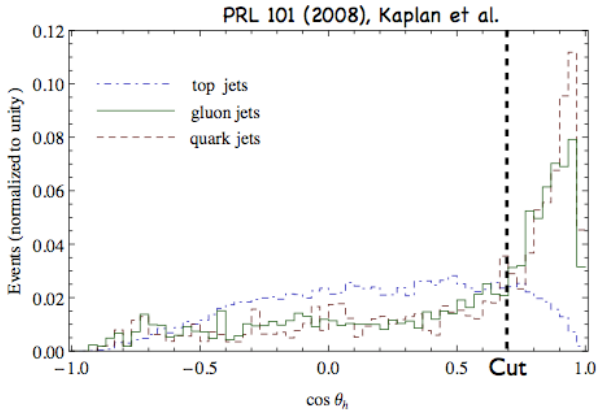
Johns Hopkins tagger [Kaplan, Rehermann, Schwartz, Tweedie]

- find 2 subjets based on δ_p^{cut} ($\delta_p = p_T^{\text{sub}}/p_T^{\text{fat}}$)

  $\rightarrow$2 subjets or fail
- repeat for 2 subjets

  $\rightarrow$3 subjets or 4 subjets or fail
- 3 kinematic conditions
  - top mass condition
  - W mass condition
  - helicity angle cos θ_h
- for θ_h
  - need jet pair from W
  - need boost for W rest frame





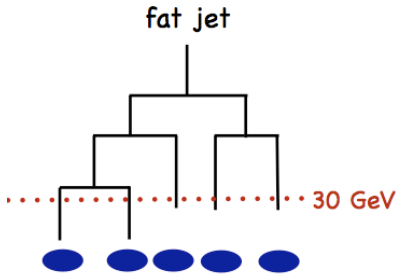
HEPTopTagger [Plehn, Zerwas, Spannowsky, MT]

- find all hard proto-jets based on mass drop criteria

  $\rightarrow$valid for fat jet with more than 4 hard proto-jets

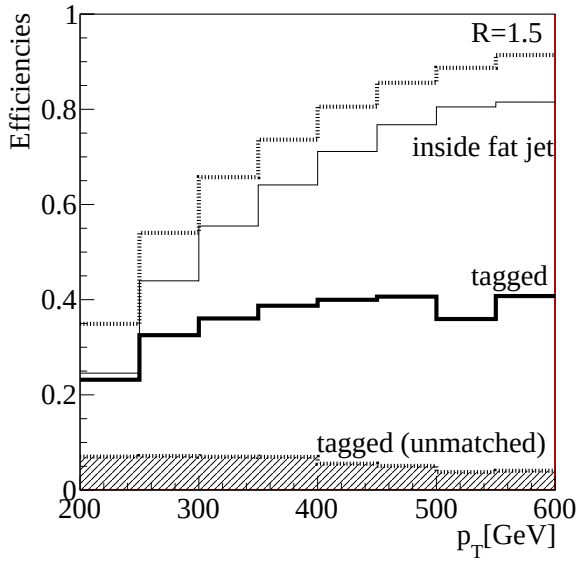
  (valid for busy environment)
- 3 kinematic conditions
  - top mass condition
  - 2 mass ratio condition

  $\rightarrow$ no boost nor jet pair ambiguity



HEPTopTagger

efficiency



$N(\text{tagged tops})/N(\text{hadronic tops})$

$\sim 35\%$ hadronic tops tagged

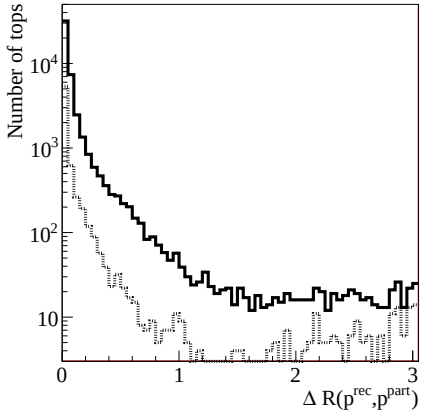
	$t\bar{t}$	QCD	W+jets	
$p_{T,t}^{\min}$[GeV]	200			
one fat jet	100%	100%	100%	
two fat jets	57%	53%	50%	relative to one fat jet
one top tag	37%	2.0%	3.9%	relative to one fat jet
two top tags	4.5%	0.027%	0.07%	relative to one fat jet
	8.0%	0.05%	0.15%	relative to two fat jets

- $2 \sim 4\%$ mis-tag rate
- efficiency depends on the definition (normalization)

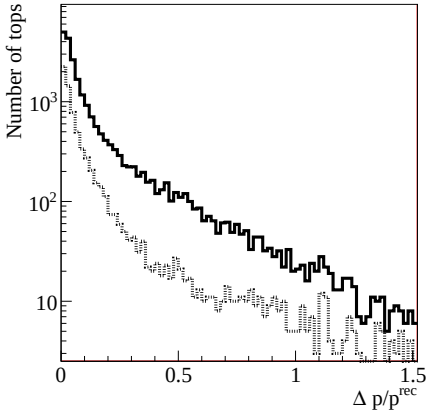
HEPTopTagger

momentum reconstruction

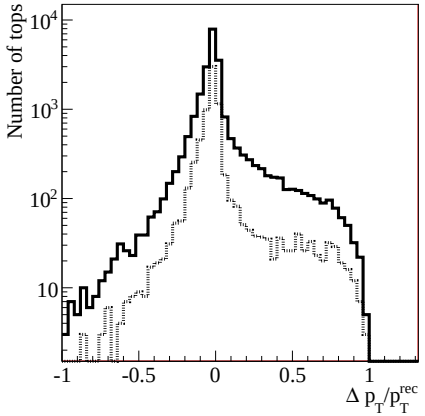
solid: $p_T^{\text{rec}} > 200\text{GeV}$, dotted: $p_T^{\text{rec}} > 300\text{GeV}$



$\Delta R(p^{\text{rec}}, p^{\text{part}})$



$\Delta p/p^{\text{rec}}$



$\Delta p_T/p_T^{\text{rec}}$

- 95% in $\Delta R < 0.5$
- 80% in $\Delta p/p^{\text{rec}} < 20\%$, 68% in $\Delta p/p^{\text{rec}} < 10\%$
- 85% in $\Delta p_T/p_T^{\text{rec}} < 20\%$
- momentum reconstructed well

stop pairs

stop pairs [T. Plehn, M. Spannowsky, MT, D. Zerwas]

- stop: most important particle for hierarchy problem
  comparison to other top partners [Meade & Reece]
- $m_{\tilde{t}_1} = 340$ GeV and $m_{\tilde{\chi}_1^0} = 98$ GeV assumed

  $\tilde{t}_1 \to t\tilde{\chi}_1^0$ (100%)

semileptonic $\tilde{t}\tilde{t}^*$

- $pp \to \tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)\,(\bar{t}\tilde{\chi}_1^0) \to (b\ell^+\nu\tilde{\chi}_1^0)\,(\bar{b}jj\tilde{\chi}_1^0) + (bjj\tilde{\chi}_1^0)\,(\bar{b}\ell^-\bar{\nu}\tilde{\chi}_1^0)$

hadronic $\tilde{t}\tilde{t}^*$

- $pp \to \tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)\,(\bar{t}\tilde{\chi}_1^0) \to (bjj\tilde{\chi}_1^0)\,(\bar{b}jj\tilde{\chi}_1^0)$

stop pairs

semileptonic $\tilde{t}\tilde{t}^*$

- main BG: $t\bar{t}$+jets, W+4jets and $W + bbjj$
- set of cuts (PW) [M. Perelstein, A. Weiler]
  - exactly four jets
  - $|m_t^{\text{rec}} - m_t| < 5$ GeV (hadronic top)
  - $|m_W^{\text{rec}} - m_W| > 40$ GeV (leptonic top veto with m_t constraint)

  etc...

$\longrightarrow$ slightly realistic and optimized cuts (PSTZ)

$\longrightarrow$ at least four jets

$\longrightarrow$ $|m_t^{\text{rec}} - m_t| < 15$ GeV

	σ [pb]	ϵ_{PW}	ϵ_{PSTZ}	$\sigma \cdot \epsilon_{\text{PW}}$ [fb]	$\sigma \cdot \epsilon_{\text{PSTZ}}$ [fb]
$\tilde{t}_1\tilde{t}_1^*$	3.2	$(1.5 \pm 0.1) \cdot 10^{-3}$	$(1.2 \pm 0.03) \cdot 10^{-2}$	4.8	38
$t\bar{t}$	550	$(8.6 \pm 1.3) \cdot 10^{-5}$	$(4.3 \pm 0.3) \cdot 10^{-4}$	47.3	237
$W + 4j$	56.5	$(3.5 \pm 0.9) \cdot 10^{-5}$	$(3.8 \pm 0.3) \cdot 10^{-4}$	2.0	21.5
$W + bbjj$	0.63	$(3.1 \pm 0.2) \cdot 10^{-4}$	$(2.7 \pm 0.06) \cdot 10^{-3}$	0.2	1.7
SM total				49.5	260.2
S/B				0.096	0.15
$S/\sqrt{B}_{10\text{ fb}-1}$				2.2	7.5

- not promissing, large combinatorics

stop pairs

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

- main BG: $t\bar{t}$+jets, W+jets and QCD
- upto $t\bar{t}$+2jets, W+4jets and 5jets (QCD) by *Pythia-Alpgen*
- signal by *Herwig++*
- set of cuts
  - 2 fat jets with $p_{T,j} > 200/200$GeV
  - veto isolated lepton
  - $\not{E}_T > 150$ GeV

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$m_{\tilde{t}}$[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	$1.2 \cdot 10^{-3}$	

stop pairs

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stop pairs

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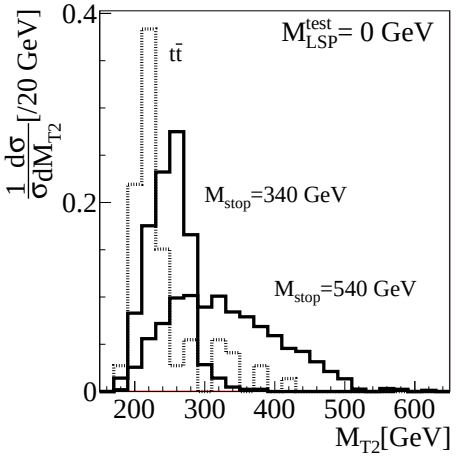

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$m_{T2} > 250$ GeV	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	0.88	6.1

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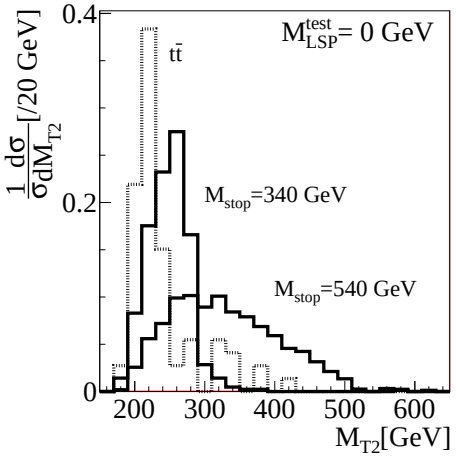

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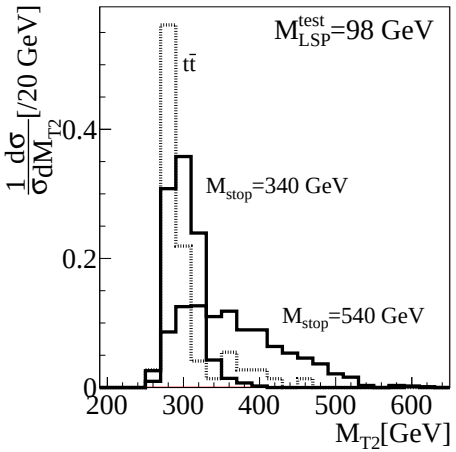

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- $S/B \sim 1, S/\sqrt{B} > 5$ for 10fb^{-1}
- stop mass from $m_{T2}(m_{\tilde{\chi}_1^0})$ endpoint [Lester, Summers] [like sleptons or sbottoms]
- not harder analysis than $b\bar{b} + \not{E}_T$

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Summary

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- 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%
- Top momentum well reconstructed
- Stop pairs: hadronic channel, $S/B \sim 1, S/\sqrt{B} > 5$ for 10fb^{-1}
- HEPTopTagger: (Heidelberg-Eugene-Paris)

will be available on

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