Stop reconstruction using the HEPTopTagger

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in collaboration with T.Plehn, M. Spannowsky, D. Zerwas.

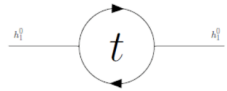
JHEP 1010:078,2010 (arXiv:1006.2833 [hep-ph])
arXiv:1102.0557 [hep-ph]

Madison, 10th May. 2011

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)

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

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

top expected at the LHC

- several top taggers available, looking into substructure

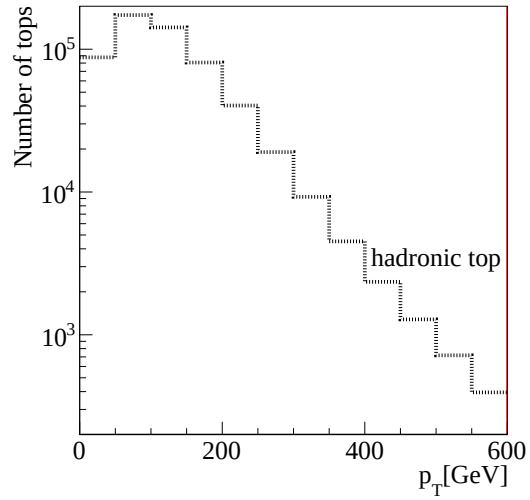
  [Kaplan, Rehermann, Schwartz, Tweedie] [Thaler, Wang]

  [Almeida, Lee, Perez, Sterman, Sung]

  designed for $p_T > 500$ GeV,

  heavy $X \longrightarrow t\bar{t}$, not expected in SM
- our target: modest p_T range ($200 < p_T < 500$ GeV),

  testable in SM, expected in top-partner decay



Plan of talk

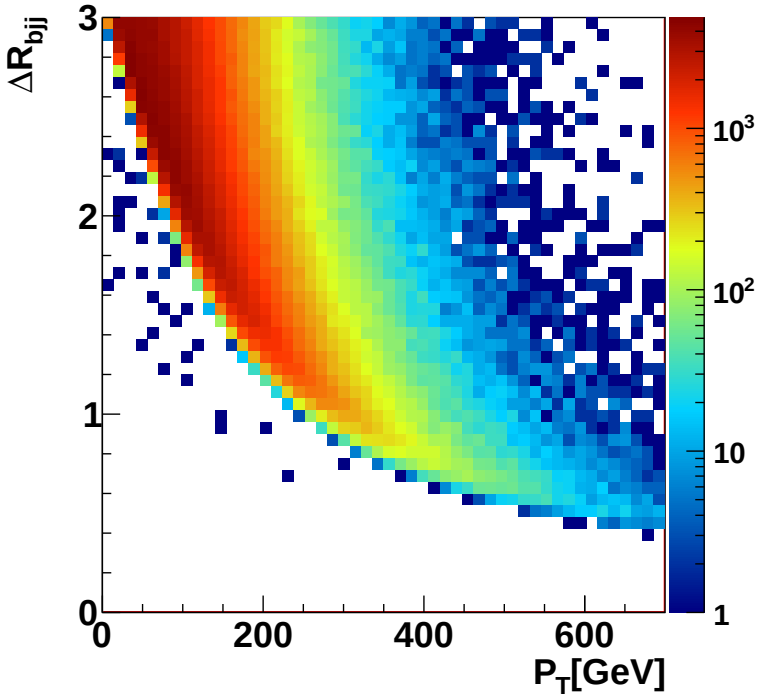
0. Introduction
1. HEPTopTagger (Heidelberg- Eugine-Paris)
2. Stop pairs - hadronic mode
3. Stop pairs - semi-leptonic mode
   - leptonic top tagger
   - result
4. A_{FB}^t with HEPTopTagger
5. W+jets CDF anomaly
6. Summary

HEPTopTagger

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

fat jets: jet with large R, include heavy (fat) particle

- top with $p_T < 500$ GeV expected in SM $\longrightarrow$ focus on low p_T tops
- heavy $m_t \longrightarrow$ decay products well separated with modest $p_T \longrightarrow$ need large R

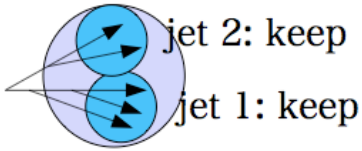


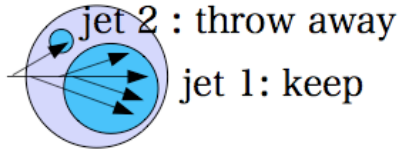
- $R = 1.5$ to have top with $p_T \sim 200$ GeV

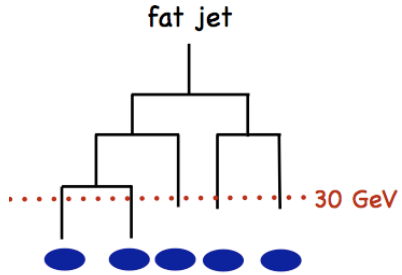
HEPTopTagger

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

1. **Find fat jets: C/A algorithm with R = 1.5, $p_T > 200$ GeV**
2. **Find all hard proto-jets using mass drop criterion**
   - undoing clustering, $m_{j1} < 0.8 m_j$ to keep j_1 and j_2 (mass drop in $t \to Wb$, $W \to jj$)
   - stop when $m_i < 30$ GeV

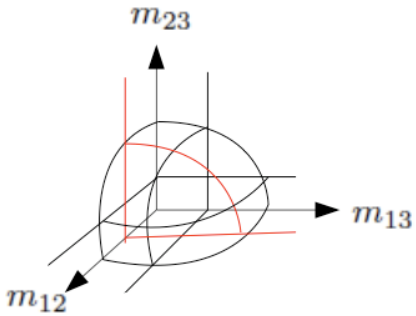


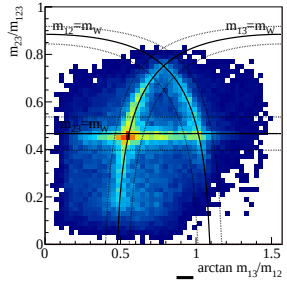




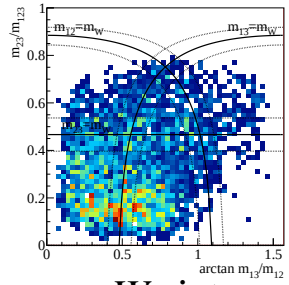
3. **Choose 3 hard proto-jets giving best filtered mass**
   - $|m_{jjj}^{\text{filt}} - m_t| < 25$ GeV and $p_T^{\text{rec}} > 200$ GeV $\to$ top candidate
4. **Check mass ratios**
   - cluster filtered constituents into 3 subjets: p_1, p_2, p_3

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

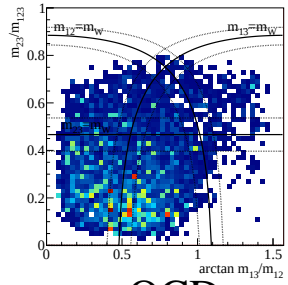




$t\bar{t}$



W+jets



QCD

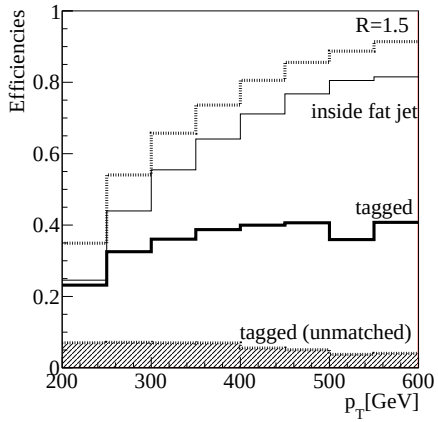
W mass condition, soft-collinear cut $\to$ tagged top

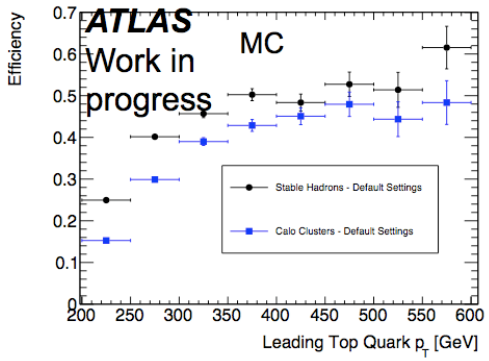
HEPTopTagger

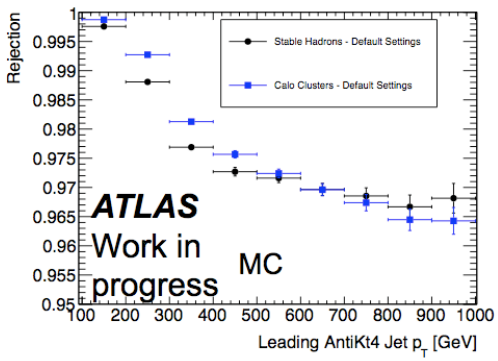
[JHEP 1010:078,2010. arXiv:1006.2833 [hep-ph] T. Plehn, M. Spannowsky, D. Zerwas, MT]

efficiency

number of tagged tops/number of hadronic tops







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

- efficiency $\sim$ 35% for hadronic tops
- 2 $\sim$ 4% mis-tag rate (number of tagged tops/number of fat jets)
- validation with ATLAS experimentalists in Heidelberg

stop pairs

stop pairs

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

hadronic $\tilde{t}\tilde{t}^*$ [JHEP 1010:078,2010. arXiv:1006.2833 [hep-ph] T. Plehn, M. Spannowsky, D. Zerwas, MT]

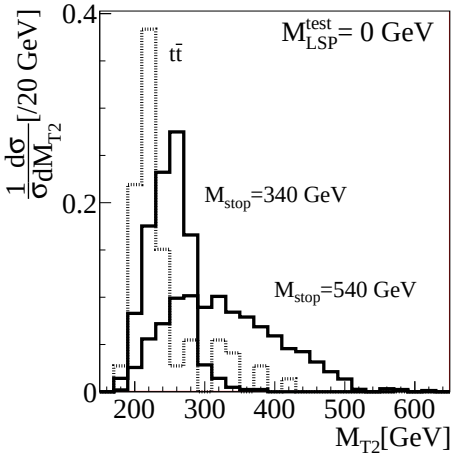
- $pp \to \tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)\,(\bar{t}\tilde{\chi}_1^0) \to (bjj\tilde{\chi}_1^0)\,(\bar{b}jj\tilde{\chi}_1^0)$
- main BG: $t\bar{t}$+jets, W+jets and QCD
- large combinatorics → HEPTopTagger

semileptonic $\tilde{t}\tilde{t}^*$ [arXiv:1102.0557 [hep-ph] T. Plehn, M. Spannowsky, MT]

- $pp \to \tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)\,(\bar{t}\tilde{\chi}_1^0) \to (b\ell^+\nu\tilde{\chi}_1^0)\,(\bar{b}jj\tilde{\chi}_1^0) + (bjj\tilde{\chi}_1^0)\,(\bar{b}\ell^-\bar{\nu}\tilde{\chi}_1^0)$
- main BG: $t\bar{t}$+jets, W+jets
- traditional cut basis analysis: $S/B \sim 0.1$, $S/\sqrt{B}_{10\ \mathrm{fb}^{-1}} \sim 2.2$
- large combinatorics, not promising → HEPTopTagger, leptonic top tagger

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
  - 2 tagged tops with $p_T^{\rm rec} > 200/200$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	$S/\sqrt{B}_{10\,\text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	340	390	440	490	540	640					340	
$p_{T,j} > 200$ GeV, ℓ veto	728	447	292	187	124	46	87850	$2.4\cdot10^7$	$1.6\cdot10^5$	n/a	$3.0\cdot10^{-5}$	
$\not{E}_T > 150$ GeV	283	234	184	133	93	35	2245	$2.4\cdot10^5$	1710	2240	$1.2\cdot10^{-3}$	
first top tag	100	91	75	57	42	15	743	7590	90	114	$1.2\cdot10^{-2}$	
second top tag	15	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	$8.3\cdot10^{-2}$	
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

- $\boxed{S/B \sim 1, S/\sqrt{B} > 5 \text{ for } 10\text{fb}^{-1}}$
- stop mass from $m_{T2}(m_{\tilde{\chi}_1^0})$ endpoint [Barr, Lester, Stephens] [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 ($p_T > 200$ GeV, HEPTOPTAGGER)
4. one b tag among the leading 3 jets outside the tagged top ($p_T > 25$ GeV, $|\eta| < 2.5$)
5. a bottom-lepton invariant mass $m_{b\ell} < \sqrt{m_t^2 - m_W^2} = 154.6$ GeV.

	$\tilde{t}_1\tilde{t}_1^*$				$t\bar{t}$	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: check solution for $p_{\nu,z}$ using $p_{\nu,T} = \not{E}_T$

$S/B \sim 0.1$, $S/\sqrt{B}_{10\ \text{fb}^{-1}} \sim 2.2$: not reasonable with additional $\not{E}_T$ sources.

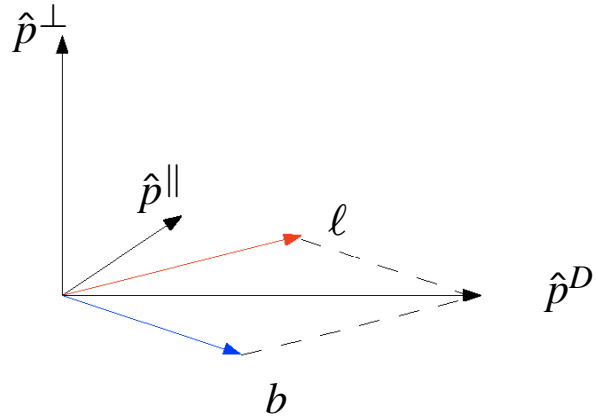
→ Our approach: [1] Reconstruct top momentum, [2] compare with $\not{E}_T$

Leptonic Top Tagger

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

only 3 observable in lab. frame

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



ν momentum in lab. frame

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

$$\hat{p}^{\rm D} = \frac{\vec{p}_{b\ell}}{|\vec{p}_{b\ell}|} \qquad \text{leading } \vec{p}_{b\ell} \text{ direction in } b-\ell \text{ decay plane}$$

$$\hat{p}^{||} = \frac{\vec{p}_\ell - (\vec{p}_\ell \cdot \hat{p}^{\rm D})\,\hat{p}^{\rm D}}{|\vec{p}_\ell - (\vec{p}_\ell \cdot \hat{p}^{\rm D})\,\hat{p}^{\rm D}|} \qquad \text{subleading direction in } b-\ell \text{ decay plane}$$

$$\hat{p}^\perp = \hat{p}^{\rm D} \times \hat{p}^{||} \qquad \text{subleading direction to } b-\ell \text{ decay plane.}$$

2 constraints

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

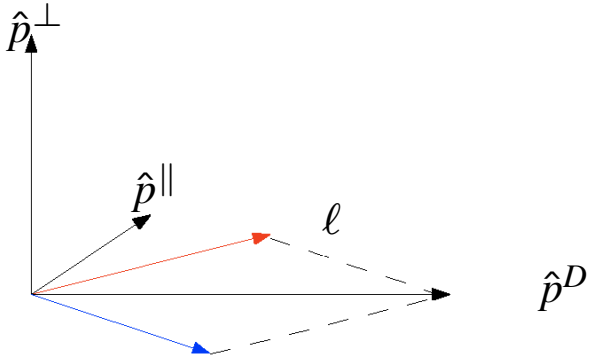
one additional assumption is needed to solve neutrino momentum.

Leptonic Top Tagger

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

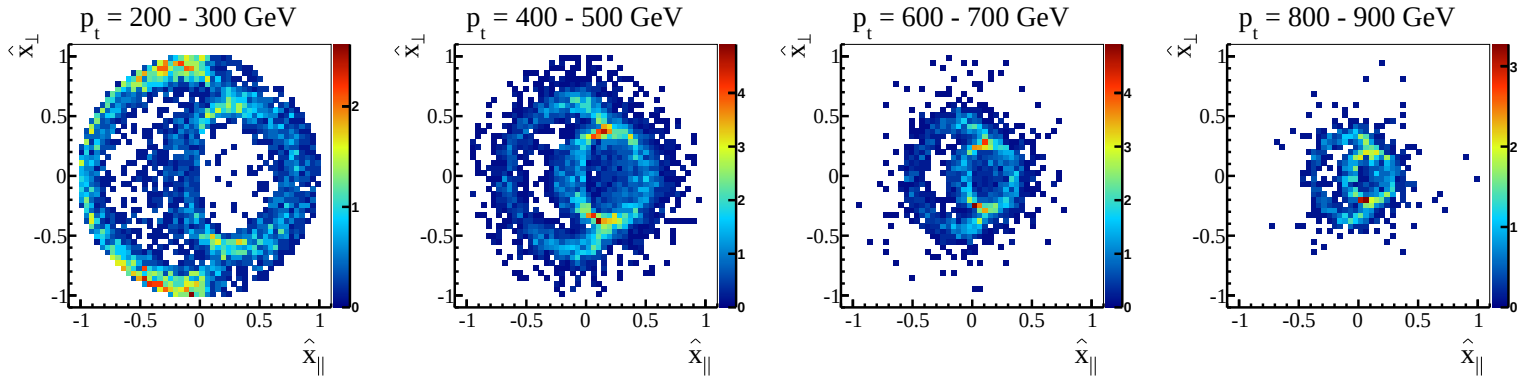
Additional assumptions

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



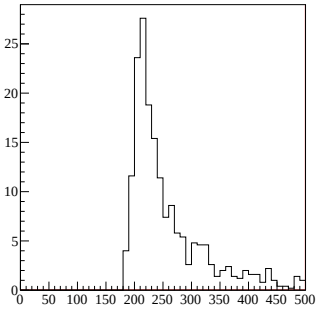
orthogonal approximation

- $x_{||} = 0$



decay plane approximation

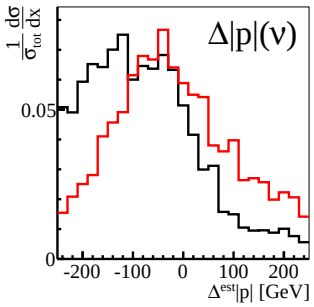
- $x_\perp = 0$
  - to take smallest allowed p_{top}
    suggested by constrained probabilty distribution
    $P(p_{\mathrm{top}}, E_b, E_l, m_{bl})|_{E_b, E_l, m_{bl}}$
  - small error for $|p_{\mathrm{top}}|$

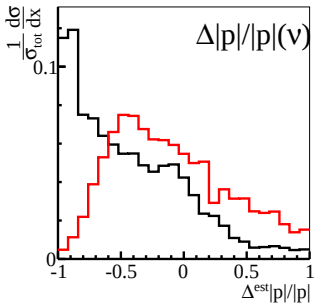


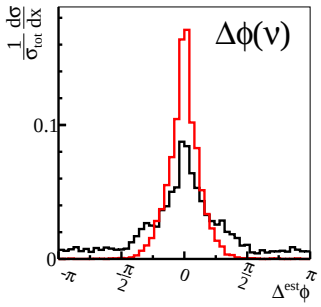
Leptonic Top Tagger

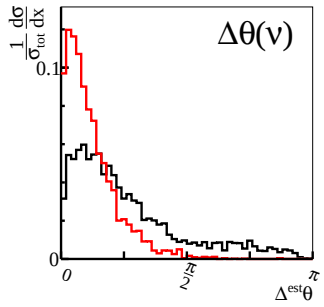
[arXiv:1102.0557 [hep-ph] T. Plehn, M. Spannowsky, MT]

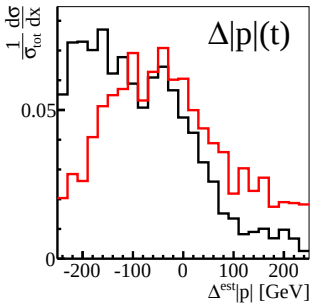
momentum reconstruction

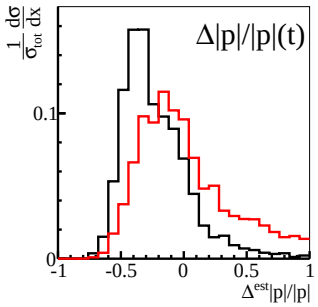


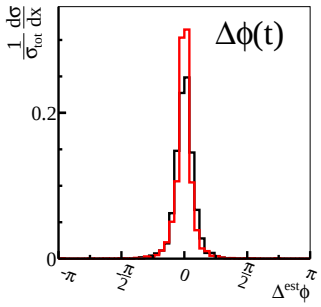


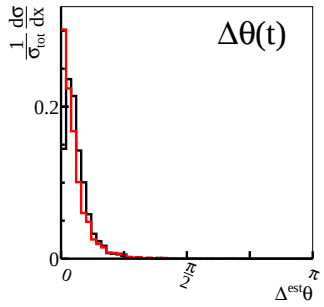












- $\Delta p(t) = p_{\text{top}}^{\text{rec}} - p_{\text{top}}^{\text{parton}}$, $\Delta p(\nu) = p_{\nu}^{\text{rec}} - p_{\nu}^{\text{parton}}$
- Red: orthogonal approx. Black: decay plane approx.
- better momentum reconstruction for t than ν
- In particular, good ϕ reconstruction.

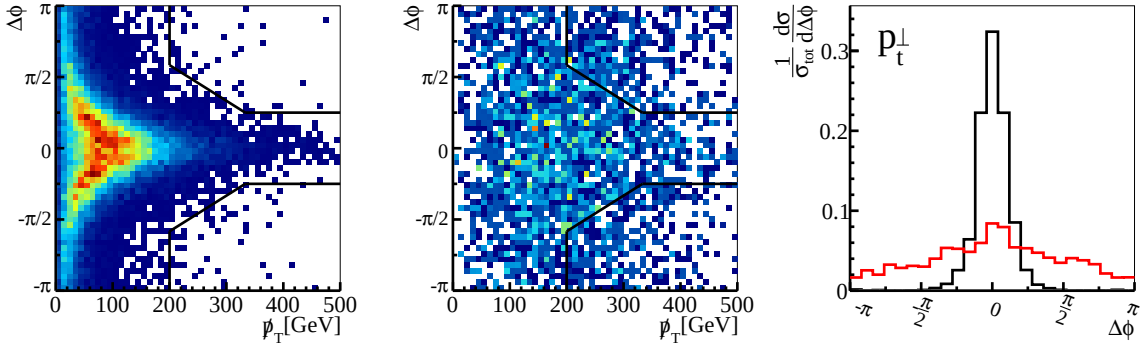
Leptonic Top Tagger

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

ϕ_{top} vs. $\not{E}_T$ correlation

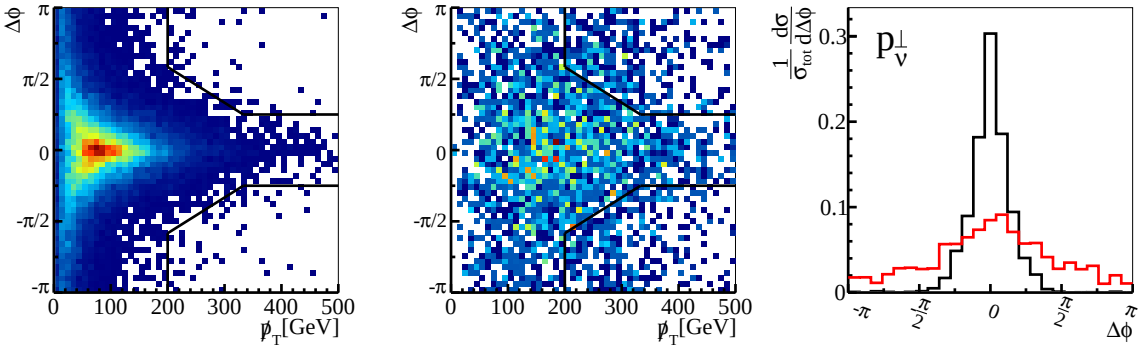
$\Delta\phi = \phi_{\text{top}}^{\text{rec}} - \phi(\not{E}_T)$

$t\bar{t}$ stop



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

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



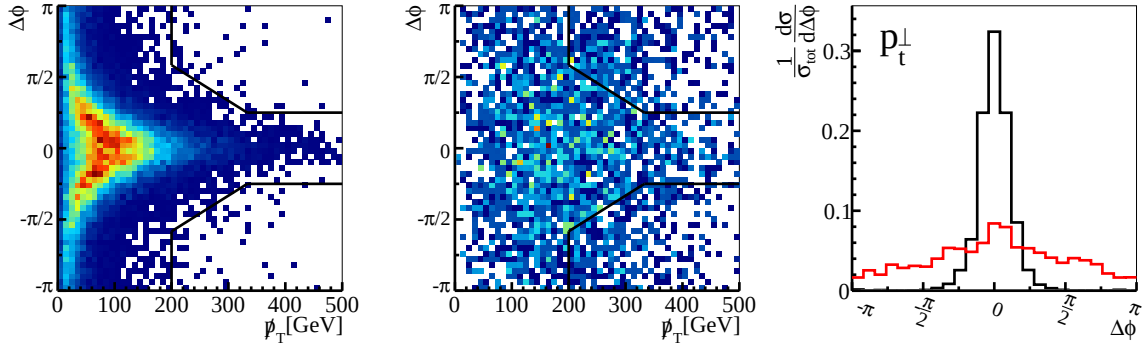
Leptonic Top Tagger

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

ϕ_{top} vs. $\not{E}_T$ correlation

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

$t\bar{t}$ stop



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

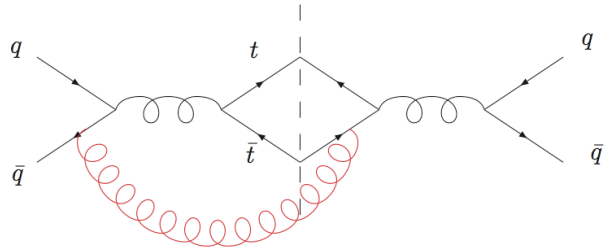
$$|\Delta\phi| > \frac{13}{12}\pi - \frac{\not{E}_T}{400\ \text{GeV}}\pi \qquad \not{E}_T > 200\ \ \text{GeV} \qquad |\Delta\phi| > \frac{\pi}{4}.$$

	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. $p_T^{\text{est}} > 200$GeV	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

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

Top forward backward asymmetry A^t_{FB}

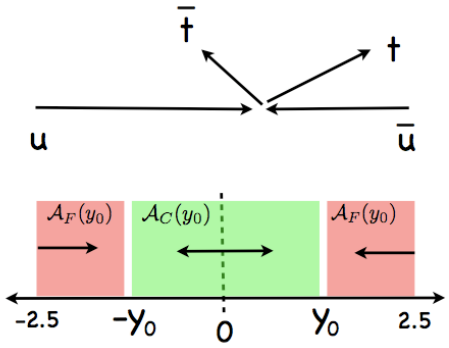
[arXiv:1103.4618 [hep-ph], J. L. Hewett, J. Shelton, M. Spannowsky, T.M.P. Tait, MT]



- QCD A^t_{FB}: small NLO effect ($\sim 6\%$)
- D0 and CDF observed anomalously large A^t_{FB}

  D0: $A^t_{FB} = 8 \pm 4 \pm 1\%$

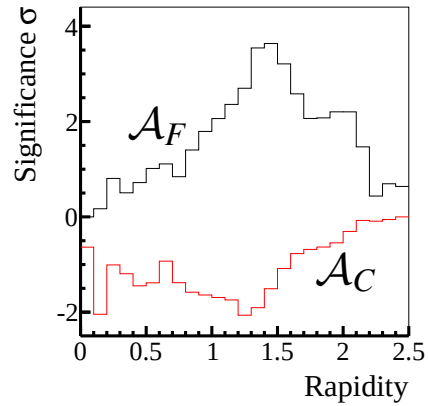
  CDF: $A^t_{FB} = 15 \pm 5 \pm 2.4\%$,
- LHC (pp collider): charge asymmetry in forward-central region



Anti-tops are more central

- semi-leptonic mode: $t\bar{t} \to (bjj)(bl\nu)$
  - one isolated lepton
  - one hadronic top tagged with HEPTopTagger
  - b-tag in tagged top $\to$ W+jets negligible
- top charge determined by lepton
- SM: 5σ after 60fb^{-1}(14TeV)
- BSM: 5σ after 2fb^{-1}(14TeV)

  2.8σ after 10fb^{-1} (7TeV)



W+jets CDF anomaly [arXiv:1104.4087 [hep-ph] T. Plehn, MT]

di-boson production cross section

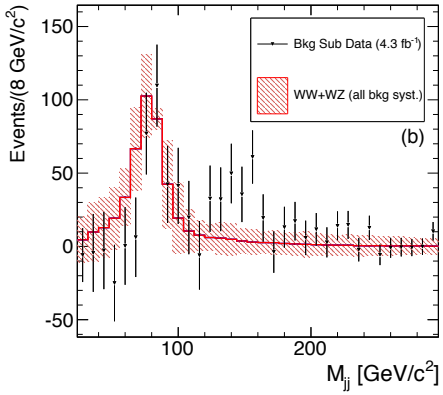
- $\sigma(WW + WZ) = 18.1 \pm 3.3(\text{stat}) \pm 2.5(\text{syst})$ pb (combined channels)

  $\sigma(WW + WZ) = 23.5 \pm 4.9$pb (muon channel)

  $\sigma(WW + WZ) = 13.5 \pm 4.4$pb (electron channel)
- large systematic uncertainty?

hard cuts

- second peak at $\sim$ 150GeV
  - one isolated lepton
  - exactly 2 jets with $E_T > 30$GeV
  - second lepton veto
- $\Delta N_{[120,170]} > 100$ events including syst. uncertainty.

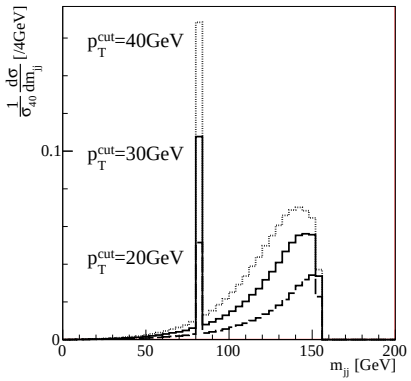


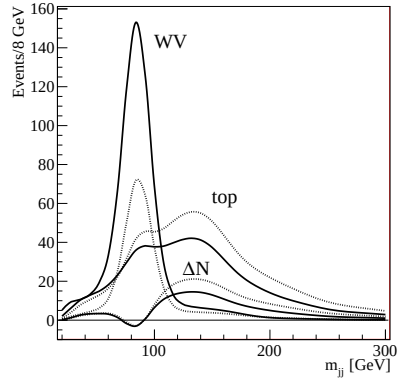
Intrinsic peak from hadronic top

- $t \longrightarrow bjj$ (combinatorics)
- m_{bj} peak $\sim$ 140 GeV
- $\Delta N_{[120,170]} \sim 230 \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}}$

  (including cut acceptance)

$\longrightarrow \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}} \sim 40\%$ needed





Summary

Summary

- top: closest to new physics
- focus on modest p_T tops ($p_T > 200$GeV), testable in SM
- fat jets kill combinatorics
- efficiency: top $\sim 35\%$, mis-tag rate$W$+jets: 4%, QCD: 2%
- hadronic top momentum well reconstructed
- leptonic top: orthogonal approx. $\longrightarrow$ good direction reconstruction

- 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}
- A_{FB}^t
  - SM: 5σ after 60fb^{-1}(14TeV)
  - BSM: 5σ after 2fb^{-1}(14TeV) 2.8σ after 10fb^{-1} (7TeV)

- HEPTopTagger: (Heidelberg-Eugine-Paris)

  will be available on http://www.thphys.uni-heidelberg.de/∼plehn/heptoptagger/index.html

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