Boosted tops as a window to new physics

Michihisa Takeuchi

Universität Heidelberg

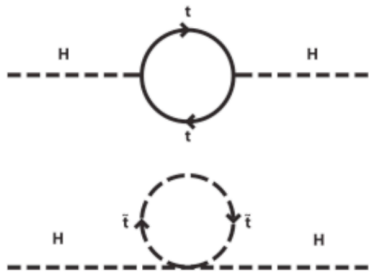
at Pittsburgh, 8th May 2012

Top at the LHC

closest to new physics $\rightarrow$ probe for new physics

- fine tuning problem

  $\rightarrow$ cancellation via top partner



- Tevatron anomalies (A^t_{FB}, single top etc.)
- copiously produced via strong interaction at LHC

  7TeV LHC $\sim 800,000\ t\bar{t}$

  Tevatron $\sim 40,000\ t\bar{t}$

  $\rightarrow$ precision physics

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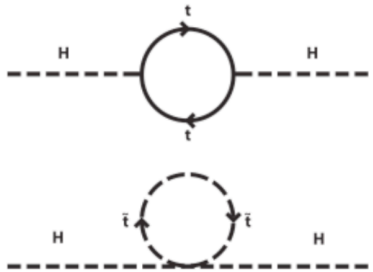


- Tevatron anomalies (A^t_{FB}, single top etc.)
- copiously produced via strong interaction at LHC

  7TeV LHC $\sim 800,000\ t\bar{t}$

  Tevatron $\sim 40,000\ t\bar{t}$

  → precision physics

HEPTopTagger: hadronic top $t \to 3j$

- full momentum reconstruction possible in principle

  → important beyond discovery

- top against 10^3 larger QCD, how to identify?

  $\sigma_{tt}^{14\text{TeV}} = 918\text{ pb} \leftrightarrow \sigma_{3j}^{14\text{TeV}} \sim 2 \cdot 10^6\text{ pb}$

- take 3 jets with simple m_t, m_W condition

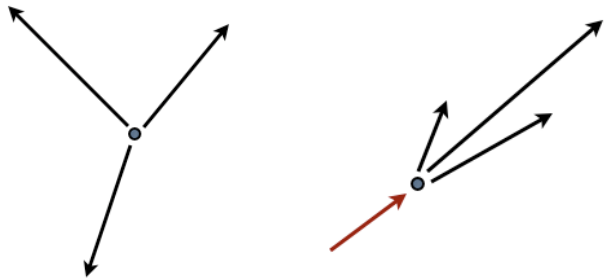
  → large QCD combinatorial BG kill us

Boosted Tops at the LHC

top jet

- top at rest $\longrightarrow$ separate 3 jets
- boosted top $\longrightarrow$ massive jet

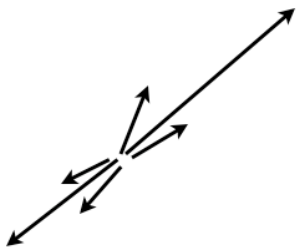
$$R \sim 2m/p_T$$



QCD jet

- 2 jet events dominate QCD
- soft-collinear nature in its substructure
- take massive jet & look into jet substructure

  combinatorics significantly reduced

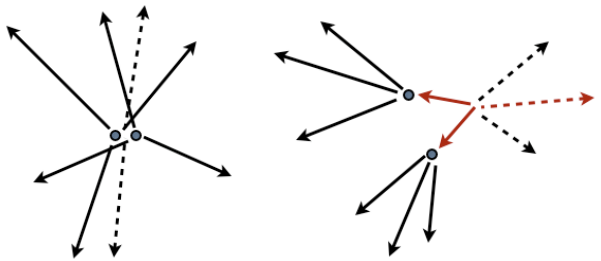


Boosted Tops at the LHC

top as a probe

– new physics search with $\not{E}_T$

→ need recoil



· top at rest: not useful

· boosted tops: carry information on dark matter

better S/B (cf. M_{T2} end point.)

Boosted Tops at the LHC

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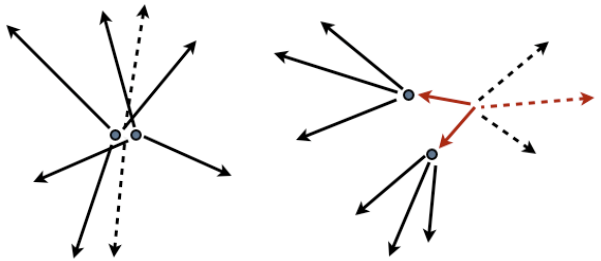

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top taggers

several top taggers available: focus on $p_T > 500$ GeV.

[Kaplan, Rehermann, Schwartz, Tweedie] [Thaler, Wang] [Almeida, Lee, Perez, Sterman, Sung]

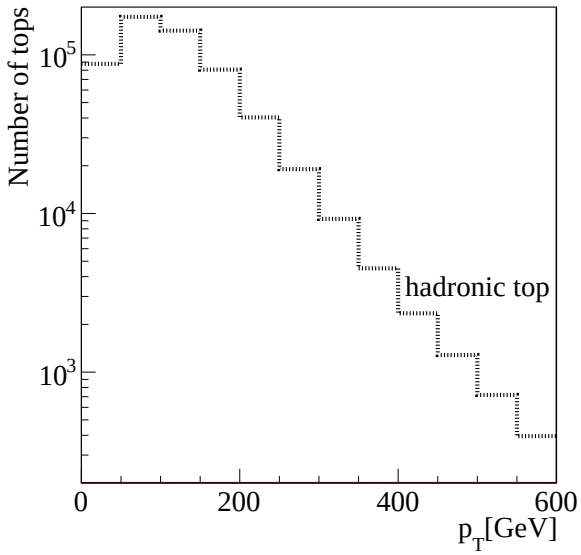
Moderately Boosted Tops at the LHC

top p_T distribution

- $p_T > 500$ GeV: not many in SM

$$\sigma_{>200\text{GeV}} \sim 50\sigma_{>500\text{GeV}}$$

- need top tagger valid down to low p_T range $\rightarrow$ testable



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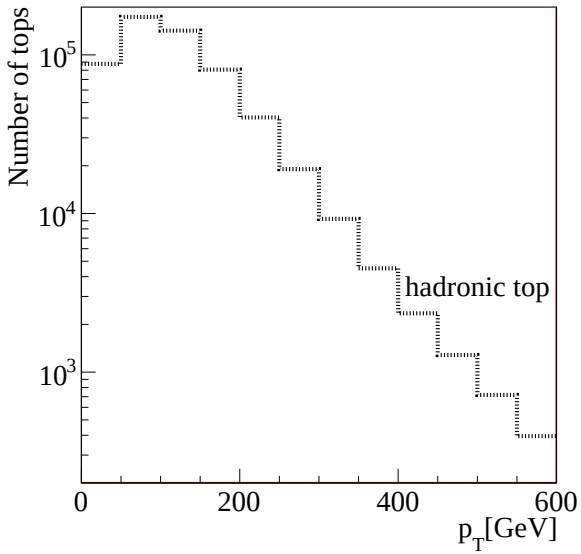
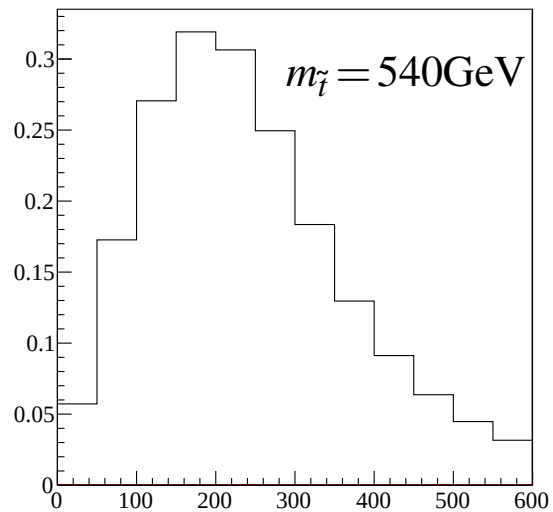


- light top partners also provide tops in the same range

we focus on $p_T > 200$GeV

$\rightarrow$ need fat jet with $R = 1.5$



HEPTopTagger

[JHEP 1010:078,2010. arXiv:1006.2833 T. Plehn, M. Spannowsky, D. Zerwas, MT]
[Phys.Rev. D85 (2012) 034029, arXiv:1111.5034]

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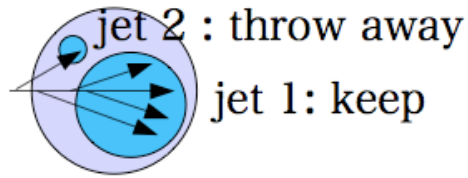
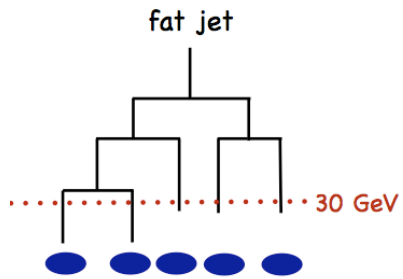
2. **find subjets by mass drop criterion**

$j = j_1 + j_2$

$$\boxed{m_j \gg m_{j1}, m_{j2}\ \text{(decay)}} \leftrightarrow \boxed{m_j \sim m_{j1} \gg m_{j2}\ \text{(QCD)}}$$



– keep j_1 and j_2 for $m_{j_1} < 0.8 m_j$ until $m_j < 50$ GeV



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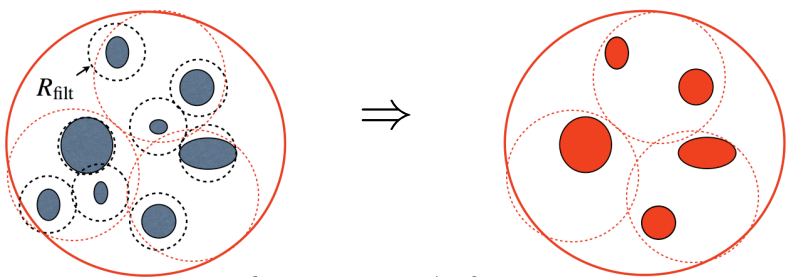
3. **take 3 subjets with best filtered mass**
   - $|m_{jjj}^{\text{filt}} - m_t| < 25$ GeV $\rightarrow$ top candidate

filtering [Butterworth et al.]

- effect of pile-up, underlying events $\sim R^2$
- reduce effective area with smaller R_{filt} and n_{filt}



- $R_{\text{filt}} = \min\{0.3, R_{ij}/2\}$ and $n_{\text{filt}} = 5$ $(t \rightarrow bWg \rightarrow bgjjg)$

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4. **check mass ratios**
   - 3 subjets: $p_1, p_2, p_3 \rightarrow m_{12}, m_{13}, m_{23}$
   - $m_t^2 = m_{123}^2 = m_{12}^2 + m_{13}^2 + m_{23}^2 \rightarrow$ 2D mass ratios

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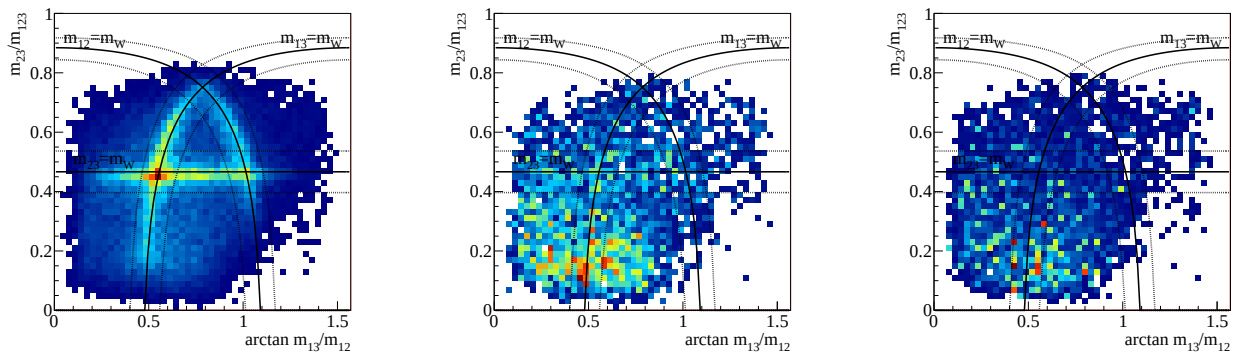
$m_{23} \downarrow 0$
$0 \leftarrow m_{13}$
$m_{12} \rightarrow 0$

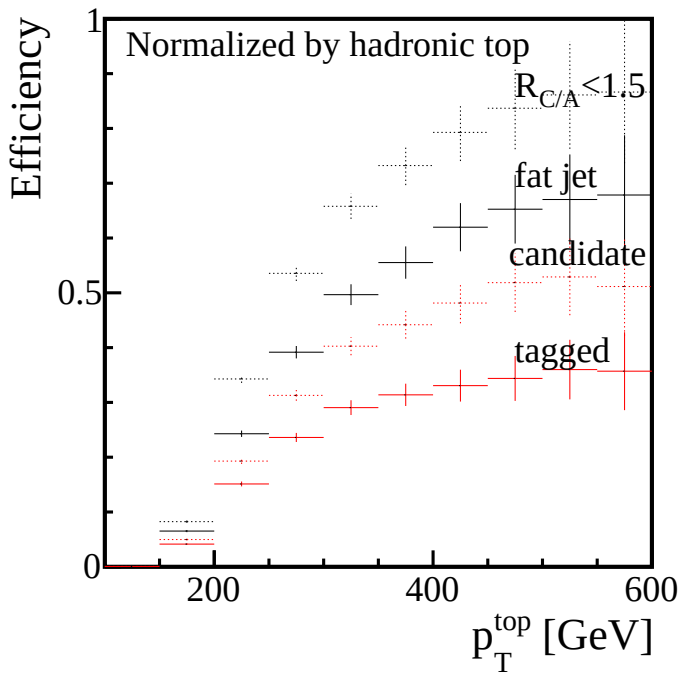


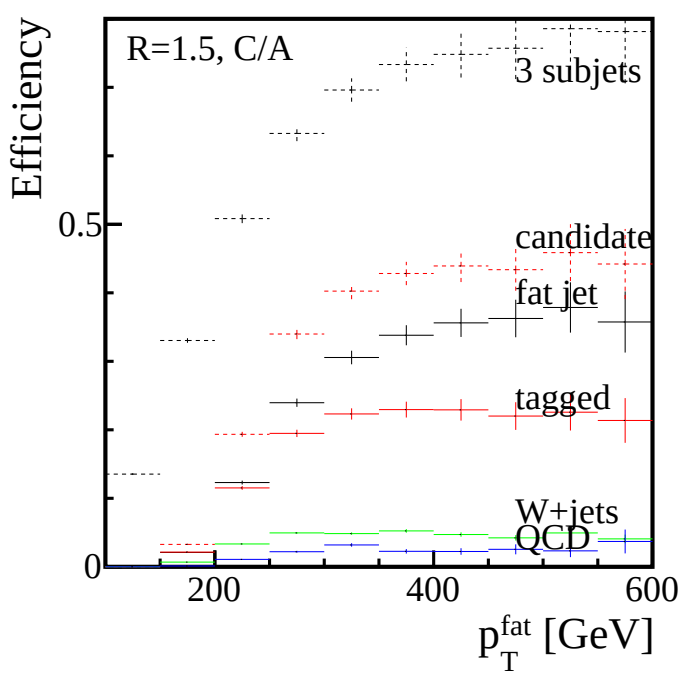
$t\bar{t}$ W+jets QCD

- W mass condition, soft-collinear cut $\rightarrow$ tagged top
- no b-tag information

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

efficiency





- efficiency $\sim$ 30% for hadronic tops, 2 $\sim$ 4% mis-tag rate
- momentum well reconstructed
- validation with ATLAS experimentalists in Heidelberg

[G. Kasieczka, S. Schätzel, A. Schöning]

Improving HEPTopTagger

[Phys.Rev. D85 (2012) 034029, arXiv:1111.5034]
[T. Plehn, M. Spannowsky, MT]

different algorithms (kt, C/A, anti-kt)

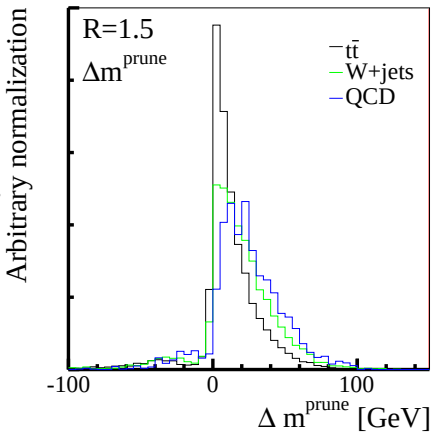
- better subjet reconstruction with kT in high p_T

  $\longrightarrow$ better ϵ_{tag} with worse rejection for BG

additional pruning [Ellis et al.]

- veto recombination $z = \frac{\min\{p_{Ti}, p_{Tj}\}}{|\vec{p}_{Ti} + \vec{p}_{Tj}|} < z_{\text{cut}}$
- pruned mass $\Delta m^{\text{pruned}} = m^{\text{pruned}} - m^{\text{filter}}$
- $\epsilon_{\text{tag}} / \epsilon_{\text{mis}}$ rate improves factor 2

  with $\Delta m^{\text{pruned}} < 15$ GeV



b-tag information

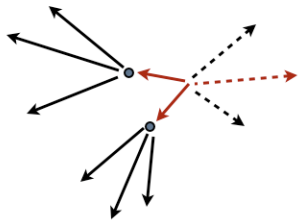
- not help to use b-tag information in selecting subjets
- without b-tag, 77% top tag already select $j_b = b$
- only BG has factor $3 \times \epsilon_b^{\text{mis}}$
- use b-tag after top tag

Applications

Scalar Top Pairs at 14 TeV

hadronic mode [T. Plehn, M. Spannowsky, MT, D. Zerwas]

- $\tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)(\bar{t}\tilde{\chi}_1^0)$: $m_{\tilde{t}1} = 100$ GeV
- main BG: $t\bar{t}$+jets, W+jets and QCD



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$m_{\tilde{t}}$[GeV]	390	440	490	540	640					390	
$p_{T,j} > 200$ GeV, ℓ veto	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$\sim 10^{-5}$	
$\not{E}_T > 150$ GeV	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$\sim 10^{-3}$	
first top tag	91	75	57	42	15	743	7590	90	114	0.01	
second top tag	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	0.07	
b-tag for 1$^{\text{st}}$ top tag	7.4	6.3	5.0	3.8	1.4	19	2.6	$\lesssim$ 0.2	$\lesssim$ 0.05	0.34	5.0
$m_{T2} > 250$ GeV	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim$ 0.6	$\lesssim$ 0.1	$\lesssim$ 0.03	1.0	7.1

W+jets, Z+jets negligible with 2 top tag

QCD negligible with additional b-tag

$t\bar{t}$ reduced with m_{T2} cut

Scalar Top Pairs at 14 TeV

hadronic mode [T. Plehn, M. Spannowsky, MT, D. Zerwas]

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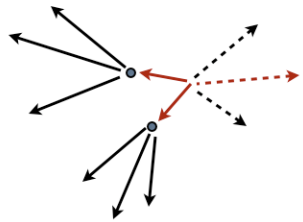

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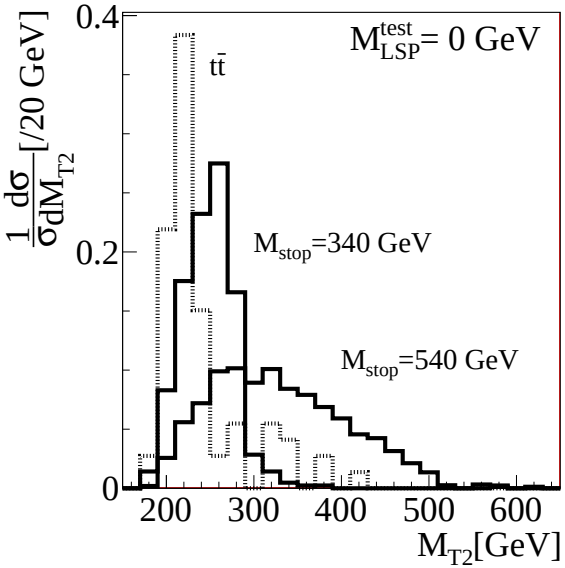

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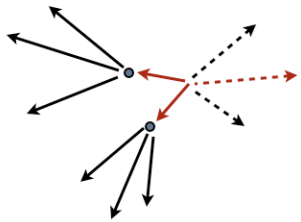

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$$S/B = 1, S/\sqrt{B} > 5 \text{ at 14 TeV with } 10\text{fb}^{-1}$$

- stop mass from $m_{T2}(m_{\tilde{\chi}_1^0})$ endpoint [C. G. Lester, D. J. Summers]

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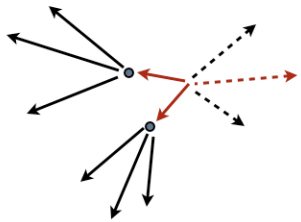

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  like sleptons or sbottoms

semi-leptonic mode [JHEP 1105 (2011) 135 [arXiv:1102.0557], T. Plehn, M. Spannowsky, MT]

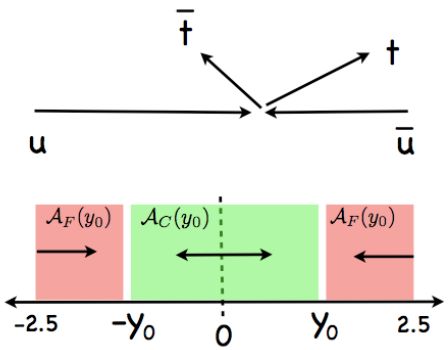
boosted leptonic top $S/B \sim 2, S/\sqrt{B} > 5$ at 14 TeV with 10fb^{-1}

Top forward backward asymmetry A^t_{FB}

[Phys.Rev. D84 (2011) 054005 arXiv:1103.4618, 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} especially in large m_{tt}
- LHC (pp collider):

  charge asymmetry in forward-central region



anti-tops are more central

$$\mathcal{A}_C(y_0) = \frac{N_t(|y|<y_0) - N_{\bar{t}}(|y|<y_0)}{N_t(|y|<y_0) + N_{\bar{t}}(|y|<y_0)} < 0$$

$$\mathcal{A}_F(y_0) = \frac{N_t(|y|>y_0) - N_{\bar{t}}(|y|>y_0)}{N_t(|y|>y_0) + N_{\bar{t}}(|y|>y_0)} > 0$$

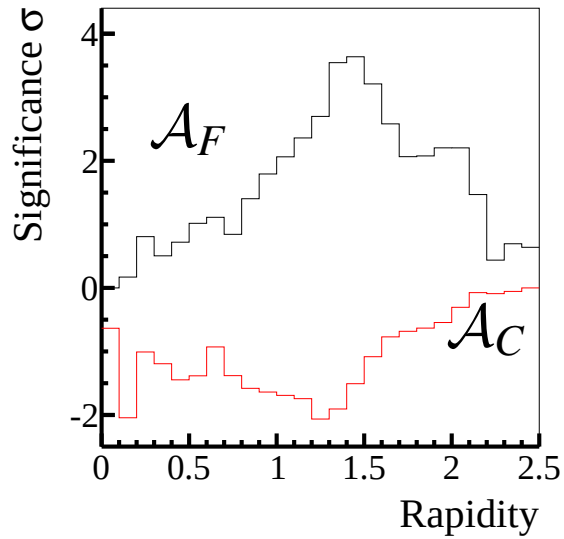
Top forward backward asymmetry A^t_{FB}

[Phys.Rev. D84 (2011) 054005 arXiv:1103.4618, J. L. Hewett, J. Shelton, M. Spannowsky, T.M.P. Tait, MT]

- semi-leptonic mode: $t\bar{t} \to (bjj)(bl\nu)$
  - one isolated lepton & one hadronic top tag
  - b-tag in top tag $\to$ W+jets negligible
  - top charge determined by lepton

$$\mathcal{A}_C(y_0) = \frac{N_t(|y|<y_0) - N_{\bar{t}}(|y|<y_0)}{N_t(|y|<y_0) + N_{\bar{t}}(|y|<y_0)} < 0$$

$$\mathcal{A}_F(y_0) = \frac{N_t(|y|>y_0) - N_{\bar{t}}(|y|>y_0)}{N_t(|y|>y_0) + N_{\bar{t}}(|y|>y_0)} > 0$$

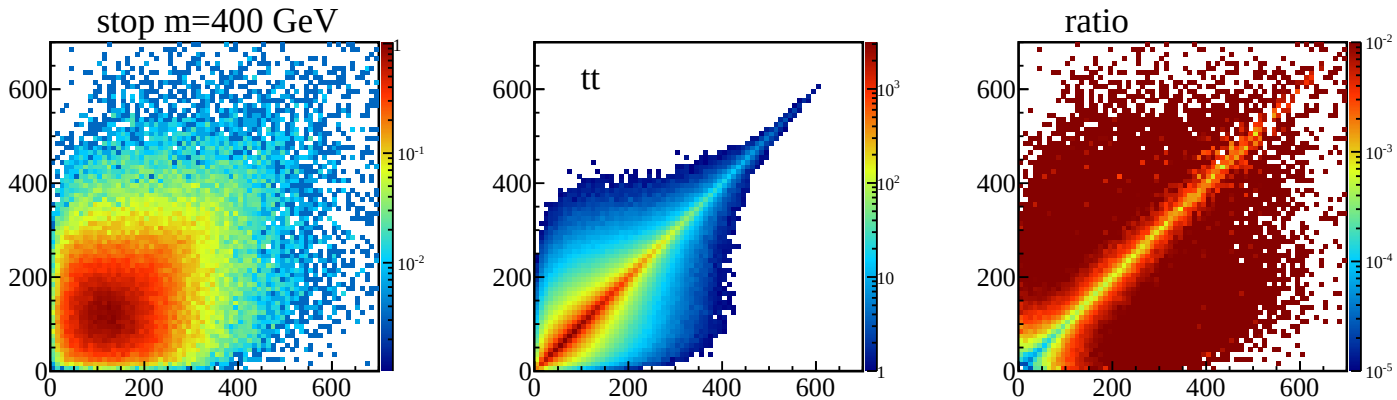


- SM: 5σ after 60fb^{-1}(14TeV)
- BSM: with 4 quark contact interactions for Tevatron
  5σ after 2fb^{-1}(14TeV)
  2.8σ after 10fb^{-1} (7TeV)

Scalar Top Pairs at 8TeV

[arXiv:1205.XXXX T. Plehn, M. Spannowsky, MT]

- $\sigma^{8\text{TeV}} \sim \frac{1}{10}\sigma^{14\text{TeV}}$: both for $t\bar{t}$ and $\tilde{t}_1\tilde{t}_1^*$
- 2 boosted tops: not enough signal left
- $t\bar{t}$: dominant background at the end

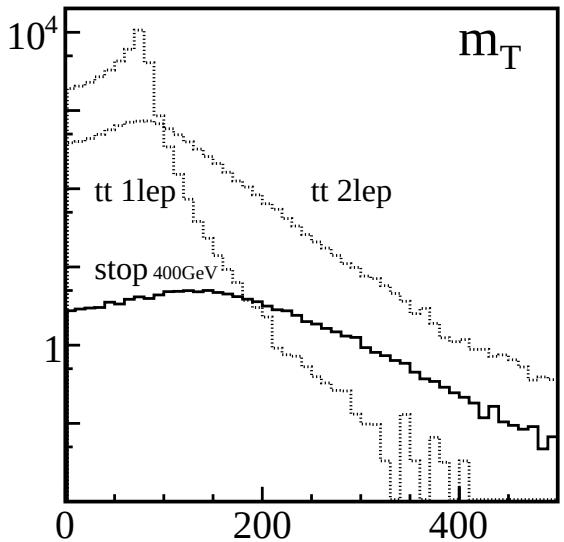


- 1 boosted top and 1 non-boosted top
  - · hadronic mode: 1 hadronic top-tag + b-jet + $\not{E}_T$
  - · semi-leptonic mode: 1 hadronic top-tag + $\ell, \not{E}_T$

Scalar Top Pairs at 8TeV

[arXiv:1205.XXXX T. Plehn, M. Spannowsky, MT]

– semi-leptonic mode: 1 hadronic top-tag + $\ell, \not{E}_T$



$t\bar{t} \to t_h + b\ell\nu$

negligible with $m_T(\ell, \not{E}_T) > 150$ GeV

$t\bar{t} \to b\bar{b} + \tau_h\ell + 2\nu$

fake hadronic top tag with ISR or τ_h

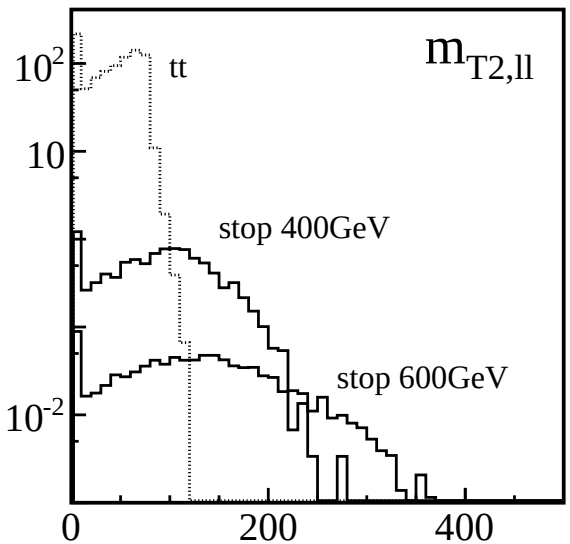
$\to$ subjet id: b-tag, τ_h rejection.

$\sqrt{s} = 8$ TeV, $R = 1.5$	$\tilde{t}1\tilde{t}1^*$						$t\bar{t}$	S/B	$S/\sqrt{B}_{10\text{fb}-1}$
$m_{\tilde{t}}$[GeV]	350	400	450	500	600	700		400	
cross section [fb]	760	337	160	80.5	23.0	7.19	$2.34 \cdot 10^5$		
$n_\ell = 1$, $\not{E}_T > 100$ GeV, $n_{\text{fat}} \geq 1$	104.37	61.49	34.81	19.54	6.28	2.11	5631		
$n_{\text{tag}} = 1$	13.09	9.02	5.80	3.60	1.33	0.50	788.79		
$m_T > 150$ GeV	4.63	4.27	3.25	2.19	0.94	0.38	3.28	1.0	6.5
$j_b = b$	1.47	1.38	1.06	0.70	0.31	0.13	0.63	2.1	5.4
$(j_b, j_{W1}, j_{W2}) = (b, j, j)$	1.33	1.27	0.96	0.65	0.29	0.12	0.50	2.4	5.5
$(j_b, j_{W1}, j_{W2}) = (b, j, j)$, reject τ_h	1.20	1.16	0.88	0.60	0.27	0.11	0.25	4.1	6.9

Scalar Top Pairs at 8TeV

[arXiv:1205.XXXX T. Plehn, M. Spannowsky, MT]

– di-lepton mode



$$t\bar{t} \to b\bar{b} + \ell\ell + 2\nu$$

negligible with $m_{T2}^{\ell\ell} > 100$ GeV

$$m_{T2} = \min_{\not{E}_T \ split} \left[\max\{ m_T^{\ell_1}, m_T^{\ell_2} \} \right]$$

$\sqrt{s} = 8$ TeV	$\tilde{t}1\tilde{t}1^*$						$t\bar{t}$	$t\bar{t}Z$	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	350	400	450	500	600	700			400	
$n_\ell = 2$	30.98	14.27	7.07	3.58	1.04	0.33	7650.88	n.a.		
$\not{E}_T > 100$GeV	19.04	9.99	5.40	2.94	0.91	0.30	1312.74	0.35		
$m_{T2}^{\ell\ell} > 100$ GeV	6.05	4.30	2.70	1.65	0.56	0.20	0.65	0.09	5.8	16
$m_{T2}^{\ell\ell} > 150$ GeV	0.81	1.21	1.06	0.81	0.34	0.14	0.00	0.02	60	27

Summary

HEPTopTagger available on http://www.thphys.uni-heidelberg.de/∼plehn/

- moderate p_T tops (> 200GeV) $\rightarrow$ testable in SM
- fat jets kill combinatorics
- jet substructure

  thrown information $\rightarrow$ use all available infomation
- momentum well reconstructed
- general idea: tops at LHC identified just like bottoms

Applications

- stop pairs at 14 TeV (2 boosted tops)
  $S/B \sim 1$(hadronic), $S/B \sim 2$(semi-leptonic), with $S/\sqrt{B} > 5$
- A^t_{FB} at 14 TeV

  SM: 5σ with 60fb^{-1}

  BSM: 5σ with 2fb^{-1} (2.8σ at 7TeV with 10fb^{-1})
- stop pairs at 8 TeV with 10fb^{-1}

  hadronic: $S/B \sim 1, S/\sqrt{B} \sim 1.5$

  semi-leptonic: $S/B \sim 4, S/\sqrt{B} \sim 7$

  di-leptonic: $S/B \sim 6, S/\sqrt{B} \sim 16$