Probing NMSSM via Higgs signatures from stop decays at the LHC

Dilip Kumar Ghosh

Department of Theoretical Physics
Indian Association for the Cultivation of Science, India

in collaboration with A. Chakrabory,S. Mondal, S.Poddar and D. Sengupta
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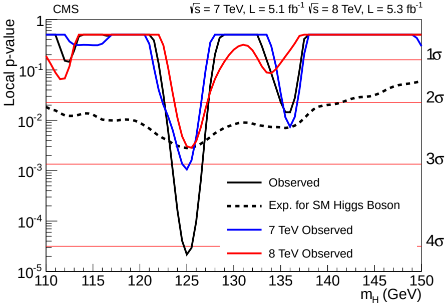
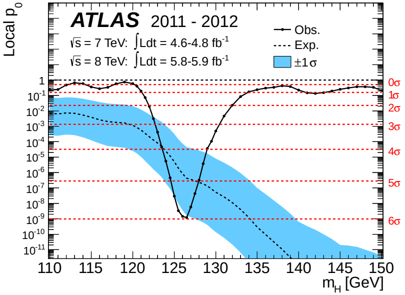
Outline

- Motivation of this analysis
- NMSSM
- Constraints imposed on the parameter space
- Jet Substructure method
- Conventional method
- Summary

A new resonance (Higgs like) has been found at the LHC

A new resonance of mass about 125 GeV has been discovered by the ATLAS and CMS experiments





[arXiv:1207.7214v1(ATLAS Collaboration); arXiv:1207.7235v1 (CMS Collaboration)]

Higgs Mass@LHC

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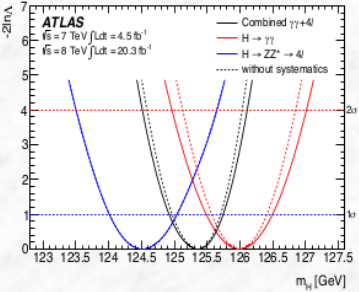
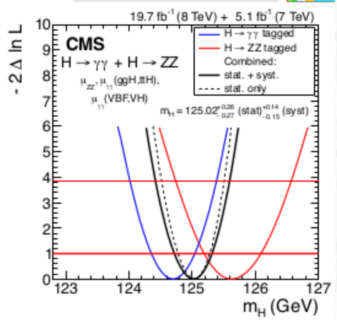


EPJ C75 (2015) 5, 212



ATLAS: $m_H = 125.36 \pm 0.37\ (stat) \pm 0.18\ (syst)$ GeV

CMS: $m_H = 125.02\ ^{+0.26}_{-0.27}\ (stat)\ ^{+0.14}_{-0.15}\ (syst)$ GeV

[Karl Jakobs (on behalf of ATLAS & CMS collab.), talk @WIN 2015]

Motivation

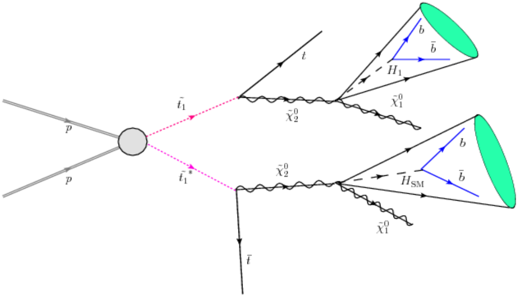
- A new resonance has been found.
- Have we really found the SM Higgs boson ? or is it part of some larger Higgs multiplet ?
- At the LHC so far no signal of any BSM physics; no SUSY particles have been observed
- Squark and gluino masses are excluded $\gtrsim 1.3 - 1.7$ TeV.
- Search for light third generation squarks with mass $\lesssim 1$ TeV in all possible final state topologies are under way
- Can one use this new resonance as a tool to probe physics beyond the SM ?

Motivation

- NMSSM : Add one singlet superfield with MSSM field content
- It is a well motivated supersymmetric model which can accommodate 125 GeV SM-like Higgs mass at the tree-level.
- Solve the μ problem in SUSY
- Higgses : $H_{1,2,3}$ and $A_{1,2}$: Extra CP-even and CP-odd Higgs particles
- 5×5 neutralino mass matrix : singlino component in the LSP have non-trivial implications in dark matter phenomenology.
- One can have very light Higgs boson, with $H_2 \equiv H_{\rm SM} = 125$ GeV.
- We study the production of the Higgs bosons from the cascade decay of $\tilde{t}_1$ in NMSSM: $\tilde{t}_1 \to t + \tilde{\chi}_i^0 (i = 2, ...5)$, followed by $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + H_{1,\rm SM}/A_1$.
- top decays inclusively.
- Higgs $(H_1, H_{\rm SM}) \to b\bar{b}$.

Analysis

- Sample Feynman diagram for cascade under consideration:



We consider 13 TeV run of the LHC.

- Analysis divided into two parts:
  $\rightarrow$ Jet substructure technique to analyze boosted Higgs (if $m_{\tilde{\chi}_i^0} - m_{\tilde{\chi}_1^0}$ is large).
  $\rightarrow$ Standard leptonic search st the LHC.

Constraints

We take into account following constraints to find benchmark points:

- SM-like Higgs boson mass lie within the range 123 GeV $< M_{H_{SM}} <$ 129 GeV.
- SM-like Higgs couplings lie within 2σ of the measured values provided by ATLAS and CMS.
- BR of the rare b-decays $B \to X_s\gamma$ and $B_s \to \mu^+\mu^-$ lie within 2σ of the experimental results.
- LEP lower bound on the chargino mass, $M_{\widetilde{\chi}_1^\pm} > 103.5$ GeV.
- Upper bounds on the DM direct detection cross-section from LUX.
- Relic density lie within 2σ of PLANCK data : $0.115 < \Omega_{\rm DM}h^2 \leq 0.126$

Benchmark Points

- Benchmark points chosen for our analysis:

	P1	P2	P3	P4	P5
$m_{\widetilde{Q_3}}$	830	920	1000	1180	1350
$\tan\beta$	10.2	12.2	10.4	10.3	10.2
λ	0.34	0.15	0.52	0.6	0.44
κ	0.06	0.03	0.09	0.09	0.07
A_λ	2700	2700	2700	2700	2700
A_κ	-1200	-1200	-1200	-1200	-1200
μ_{eff}	280	264	262	268	277
$m_{H_{SM}}$	124.3	124.9	124.3	125.1	124
m_{H_1}	67.1	67.1	62.3	73.8	67.2
m_{A_1}	214	226.8	194.4	154.0	193
$m_{\tilde{t}_1}$	804.2	908.2	1003.7	1211	1392.5
$m_{\tilde{b}_1}$	821.4	923.1	1018	1226	1408.6
$m_{\chi_1^0}$	98.6	107.2	87.3	77.6	87.4
$m_{\chi_2^0}$	290.1	268.0	282.7	293.2	292.4
$m_{\chi_3^0}$	293.5	273	283.1	294.2	295.1
$m_{\chi_1^\pm}$	284.7	268.5	266.5	273.2	282.5

Properties of Benchmark Points

- Relevant constraints and BR's of our benchmark points:

	P1	P2	P3	P4	P5
$\mu_{h_2}^{\gamma\gamma}(ggF)$, $\mu_{h_2}^{\gamma\gamma}(VBF/VH)$	0.95, 0.96	0.94, 0.94	0.96, 0.96	0.92, 0.91	0.92, 0.91
$\mu_{h_2}^{\tau\tau}(ggF)$, $\mu_{h_2}^{\tau\tau}(VBF/VH)$	1.0, 0.99	0.99, 0.97	0.99, 0.98	1.0, 1.0	1.0, 1.0
$\mu_{h_2}^{bb}(ttH)$, $\mu_{h_2}^{bb}(VBF/VH)$	1.0, 0.97	0.95, 0.95	1.0, 1.0	1.01, 0.93	1.0, 1.0
Ωh^2, $\sigma_{SI}(\times 10^{47}\ \mathrm{cm}^{-2})$	0.123, 6.4	0.122, 1.9	0.115, 8.1	0.125, 1.8	0.126, 9.3
$\mathrm{BR}(\widetilde{\mathrm{t}}_1 \to \mathrm{t}\,\chi^0_{2,3,4})(\%)$	92	94	97	81	88
$\mathrm{BR}(\widetilde{\mathrm{t}}_1 \to \mathrm{b}\,\chi^\pm_{1,2})(\%)$	7	6	3	4	4
$\mathrm{BR}(\chi^0_2 \to \chi^0_1 \mathrm{H}_{1,\mathrm{SM}})(\%)$	6, 60	8, 61	20, 57	18, 49	14, 54
$\mathrm{BR}(\chi^0_3 \to \chi^0_1 \mathrm{H}_{1,\mathrm{SM}})(\%)$	3, 14	8, 1	3, 15	6, 16	4, 16.3
$\mathrm{BR}(\mathrm{H}_1 \to \mathrm{b}\bar{\mathrm{b}})(\%)$	86	69	91	90	85
$\mathrm{BR}(\mathrm{H}_2 \to \mathrm{b}\bar{\mathrm{b}})(\%)$	64	64	64	64	66
$\mathrm{BR}(\mathrm{A}_1 \to \mathrm{b}\bar{\mathrm{b}})(\%)$	1	1	1	90	1.5

- Large Higgsino component in $\tilde{\chi}^0_{2,3} \Longrightarrow$ lage $\mathrm{Br}(\tilde{t}_1 \to t\tilde{\chi}^0_{2,3})$
- Dominantly Higgsino-like $\tilde{\chi}^0_2$ and largely singlino-like $\tilde{\chi}^0_1$ ensure large $\mathrm{Br}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 H_{\mathrm{SM}})$
- H_{SM} has large branching ratio into $b\bar{b}$ mode, while H_1 due large singlet component, it also dominantly decays into $b\bar{b}$ final state.

Analysis

- We use NMSSMTOOLS-4.2.1 to generate the NMSSM mass spectrum
- Both signal & background events were simulated using MADGRAPH5 and passed to PYTHIA6 for showering and hadronization.

The entire analysis is divided into two parts :

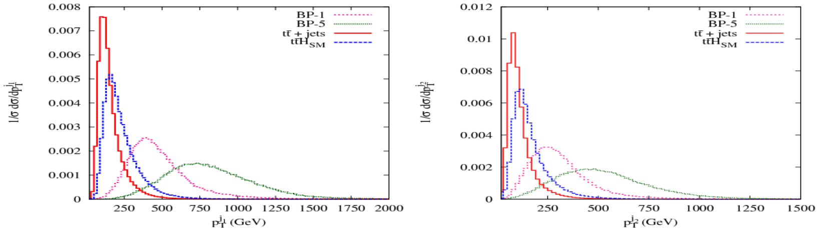
- Jet substructure technique to analyse the boosted Higgs scenario;
- the standard leptonic search strategy.

Jet Substructure Analysis

- Higgs originating from heavier neutralino decays to the LSP tagged using BDRS technique.
- BDRS technique provides a superior mass resolution using a filtering technique to discard contamination from underlying events.
- Powerful tool against backgrounds containing multiple b-jets: $t\bar{t}$+jets, $t\bar{t}b\bar{b}$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H_{SM}$.
- Mass difference between the heavier neutralino and the LSP not large enough to generate large boost.
- Boost can also originate from two step decay of the stop.
- Achieved a modest Higgs tagging efficiency: $\epsilon \sim 5 - 6\%$ for $p_T \sim 200 - 300$ GeV.

[Butterworh-Davidson-Rubin-Salam(BDRS), PRL, 2008]

- Two leading fat jets reconstructed using Cambridge-Aachen algorithm with jet radius R=1.2.
- p_T distribution of these fat jets for benchmark points and dominant background channels:



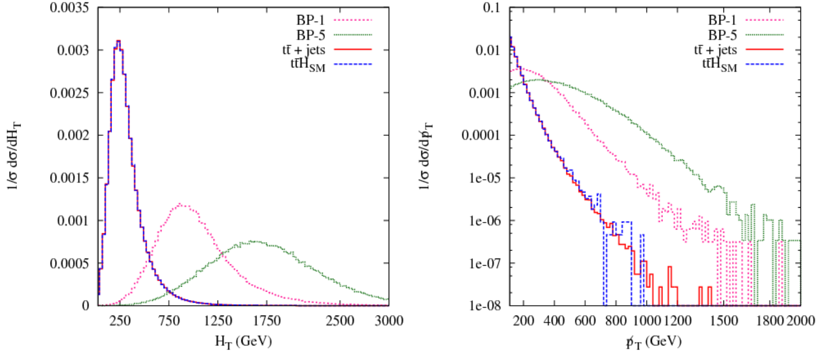
- Peak of the distribution moves to higher p_T region with the increase in the stop mass from BP1 to BP5.
- Jet radius R=1.2 and jet p_T threshold of 200 GeV provides the best efficiency in terms of enhancement of the signal over backgrounds.

- Once one (or multiple) SM-like Higgs boson(s) are tagged, we remove those particles from the fat-jet list and recluster the remaining stable hadrons using anti-k_T jet algorithm with a jet radius $R = 0.4, p_T \geq 20$ GeV.
- We select jets with $p_T^j \geq 30$ GeV and $\mid \eta \mid < 3$ for further collider analysis.
- Leptons (electrons & muons) are selected with $p_T > 10$ GeV and $\mid \eta \mid < 2.5$.
- Isolation of leptons are performed by demanding that the sum of the scalar p_T of all stable visible particles within a cone of radius $\Delta R = 0.2$ around the lepton should not exceed 10% (15% for muons) of $p_T^e (p_T^\mu)$.
- Missing E_T is constructed using all the stable final state visible particles with all jets with $p_T^j > 20$ GeV and $\mid \eta_j \mid < 4.5$ and all leptons with $p_T^\ell > 10$ GeV and $\mid \eta^\ell \mid < 2.5$.
- Following the ATLAS collaboration, we consider a p_T dependent b-tagging efficiency :

$$\eta_b = \begin{cases} 0 & \text{for } \; p_T^b \leq 20 \text{ GeV} \\ 0.6 & \text{for } \; 20 \text{ GeV} < p_T^b < 50 \text{ GeV} \\ 0.75 & \text{for } \; 50 \text{ GeV} < p_T^b < 400 \text{ GeV} \\ 0.5 & \text{for } \; p_T \geq 400 \text{ GeV} \end{cases}$$

Cuts to Reduce Background

- At least one of the fat jets is identified as the SM-like Higgs boson with the criteria 110 GeV $< m_J >$ 140 GeV and only if two b-jets are identified within it. In the signal process, however, there are additional Higgs bosons which can be tagged and therefore at the end we look at the fat-jet mass (m_J) distribution to find any additional peaks over the background.
- Lepton veto imposed. (Signal contains no leptons in the final state)
- For signal events, additional b-jets are present (from top decay) even after tagging the SM-like Hiigs boson. no extra b-jets are present in $Z \to (b\bar{b}) +$ jets, $t\bar{t} +$ jets after satisfying the M_H criteria. Hence, we demand at least one additional b-jet in the event.
- Additional selection criteria of $H_T = \sum_j p_T^j > 800$ GeV imposed since larger hadronic activity in the signal implies larger value of H_T compared to the backgrounds.
- Final selection criteria of $\not{p}_{\mathrm{T}} > 175$ GeV imposed. Signal $\not{p}_{\mathrm{T}}$ distribution is harder than that of Standard Model backgrounds because of the heavy LSP.



0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
250
750
1250
1750
2500
3000
$1/\sigma\ d\sigma/dH_T$
H_T (GeV)
BP-1
BP-5
$t\bar{t}$ + jets
$t\bar{t}H_{SM}$
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
200
400
600
800
1000
1200
1500
1800
2000
$1/\sigma\ d\sigma/d\not{p}_T$
$\not{p}_T$ (GeV)
BP-1
BP-5
$t\bar{t}$ + jets
$t\bar{t}H_{SM}$

Event Summary

		Effective cross-section after the cuts (in fb)				
Signal	Production c.s. (fb)	C1	C2	C3	C4	C5
P1	27.2	1.18	0.58	0.48	0.25	0.146
P2	12	0.42	0.21	0.17	0.11	0.0794
P3	6	0.22	0.11	0.09	0.07	0.0529
P4	1.5	0.0497	0.0262	0.0225	0.0193	0.0161
P5	0.5	0.0258	0.0139	0.0121	0.0115	0.0096

		Effective cross-section after the cuts (in fb)				
SM Bkgs	Production c.s. (fb)	C1	C2	C3	C4	C5
$t\bar{t}$+ jets	700000	751.02	554.85	7.5	0	0
ttH_{SM}	500	14.45	9.76	7.47	0.5	0.028
Total bkg						0.028

Signal Significance

- Summary of signal and background events obtained:

		Signal(N_S) (Background(N_B))			Significance($\mathcal{S}$) for $\kappa = 10\%$		
	$m_{\tilde{t}_1}$ (GeV)	100 fb^{-1}	300 fb^{-1}	1000 fb^{-1}	100 fb^{-1}	300 fb^{-1}	1000 fb^{-1}
P1	804.3	14.6 (2.8)	43.8 (8.4)	146 (28)	8.6	14.5	24.37
P2	908.2	7.94 (2.8)	23.82 (8.4)	79.4 (28)	2.75	7.9	13.25
P3	1003.7	5.29 (2.8)	15.87 (8.4)	52.9 (28)	1.83	5.25	8.83
P4	1211.5	1.61 (2.8)	4.83 (8.4)	16.1 (28)	0.55	1.6	2.69
P5	1392.5	0.96 (2.8)	2.88 (8.4)	9.6 (28)	0.33	0.95	1.6

- For each value of the integrated luminosity, the signal significances are shown considering $\kappa = 10\%$ systematic uncertainty.
- Signal significance is defined as $S/\sqrt{(B + \kappa B)^2}$.

▶ **Discovery: $m_{\tilde{t}_1} \sim$ 1.1 TeV (P3) at 13 TeV LHC with 300 fb^{-1} of luminosity.**

▶ **Exclusion: 1.2 TeV with 300 fb^{-1} integrated luminosity.**

Lets see how traditional search works ...

Final state with two Lepton

Applied cuts:

- C6 : We demand at least 3 jets with $\mathrm{p_T^{j1}} > 150$ GeV, $\mathrm{p_T^{j2}} > 100$ GeV, $\mathrm{p_T^{j3}} > 50$ GeV.
- C7 : At least two b-tagged jets are required.
- C8 : We demand two isolated leptons with $\mathrm{p_T^{\ell}} > 20$ GeV and $|\eta_\ell| < 2.5$.
- C9 : To suppress the backgrounds like $\mathrm{t\bar{t}}$ + jets, $\mathrm{t\bar{t}H_{SM}}$, we use the variable $\mathrm{M_{T2}}$, defined as,

$$\mathrm{M_{T2}}(\overrightarrow{\mathrm{p}}_\mathrm{T}^{\ell 1}, \overrightarrow{\mathrm{p}}_\mathrm{T}^{\ell 2}, \overrightarrow{\not{p}}_\mathrm{T}) = \min_{\overrightarrow{\not{p}}_\mathrm{T} = \overrightarrow{\not{p}}_\mathrm{T}^{1} + \overrightarrow{\not{p}}_\mathrm{T}^{2}} \left[\max\{\mathrm{M_T}(\overrightarrow{\mathrm{p}}_\mathrm{T}^{\ell 1}, \overrightarrow{\not{p}}_\mathrm{T}^{1}), \mathrm{M_T}(\overrightarrow{\mathrm{p}}_\mathrm{T}^{\ell 2}, \overrightarrow{\not{p}}_\mathrm{T}^{2})\} \right],$$

  where $\ell 1$ and $\ell 2$ are the two isolated leptons, $\not{p}_\mathrm{T}$ is the total missing transverse momentum of the event and $\mathrm{M_T}(\overrightarrow{\mathrm{p}}_\mathrm{T}^{v_1}, \overrightarrow{\mathrm{p}}_\mathrm{T}^{v_2})$ is the transverse mass of the system, defined as

$$\mathrm{M_T}(\overrightarrow{\mathrm{p}}_\mathrm{T}^{v_1}, \overrightarrow{\mathrm{p}}_\mathrm{T}^{v_2}) = \sqrt{2|\overrightarrow{\mathrm{p}}_\mathrm{T}^{v_1}||\overrightarrow{\mathrm{p}}_\mathrm{T}^{v_2}|(1 - \cos\phi)},$$

  ϕ being the (azimuthal) angle between $\overrightarrow{\mathrm{p}}_{T}^{v_1}$ and $\overrightarrow{\mathrm{p}}_{T}^{v_2}$. We set $\mathrm{M_{T2}} > 150$ GeV.
- C10 : Additionally we impose a criteria on the total missing transverse momentum, $\not{p}_\mathrm{T} > 400$ GeV.

Event Summary

		Effective cross-section after the cuts (in fb)				
Signal	Production c.s. (fb)	C6	C7	C8	C9	C10
P1	27.2	24.61	15.29	1.49	0.17	0.038
P2	12	11.31	7.17	0.63	0.096	0.0264
P3	6	5.65	3.19	0.297	0.061	0.0262
P4	1.5	1.43	0.875	0.065	0.019	0.012
P5	0.5	0.494	0.314	0.026	0.0069	0.0035

		Effective cross-section after the cuts (in fb)				
Signal	Production c.s. (fb)	C6	C7	C8	C9	C10
$t\bar{t}$+ jets	700000	105014.18	38630.79	515.89	0	0
tth	500	179.56	116.06	3.01	0.007	0.001
W + jets	83315178	123064.92	0	0	0	0
Z + jets	42070505	78891.62	4799	0	0	0
Total bkg						0.001

Signal Significance

- Summary of signal and background events obtained:

		Signal(N_S) (Background(N_B))			Significance($\mathcal{S}$) for $\kappa = 10\%$		
	$m_{\tilde{t}_1}$ (GeV)	100 fb^{-1}	300 fb^{-1}	1000 fb^{-1}	100 fb^{-1}	300 fb^{-1}	1000 fb^{-1}
P1	804.3	3.8 (0.1)	11.4 (0.3)	38 (1)	12.1	20.8	37.8
P2	908.2	2.64 (0.1)	7.92 (0.3)	26.4 (1)	8.34	14.4	26.3
P3	1003.7	2.62 (0.1)	7.86 (0.3)	26.2 (1)	8.28	14.3	26.0
P4	1211.5	1.2 (0.1)	3.6 (0.3)	12.0 (1)	3.79	6.56	11.9
P5	1392.5	0.35 (0.1)	1.1 (0.3)	3.5 (1)	1.1	2.0	3.48

▶ **Discovery:** $m_{\tilde{t}_1} \sim$ **1.2** TeV **at 13** TeV **LHC with 300** fb^{-1} **of luminosity.**

▶ **Exclusion: 1.4 TeV with 300** fb^{-1} **integrated luminosity.**

▶ Marginally better sensitivity with traditional search !

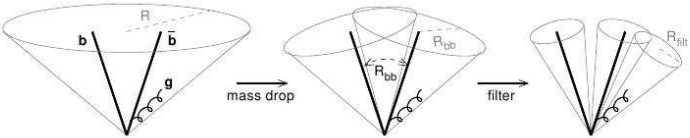
Summary

- NMSSM can accommodate 125 GeV Higgs boson at tree-level.
- We studied Higgs signatures from the cascade decay of the light stop ($\tilde{t}_1$) in this framework.
- Our benchmark points are consistent with current data on Higgs, LHC constraints on SUSY particles, DM relic density & direct detection constraints as well as heavy flavour physics constraints.
- We probe this channel using the jet substructure method and via the conventional leptonic searches.
- Jet substructure method : we can discover $m_{\tilde{t}_1}$ up to 1.0 TeV with 300 fb^{-1} luminosity.
- di-lepton channel: discover $m_{\tilde{t}_1}$ up to 1.2 TeV with 300 fb^{-1} luminosity.

Back up slides

BDRS Higgs tagger

- Break jet j into two subjets (j_1,j_2) by undoing its last stage of clustering s.t $m_{j_1} > m_{j_2}$.
- a) Significant mass drop (MD): $m_{j_1} < \mu m_j$
  b) Symmetric splitting : y = $[min(P^2_{T_{j_1}}, P^2_{T_{j_2}})/m_j^2]\Delta R^2_{j_1,j_2} > y_{cut}$
- Fairly efficient in eliminating QCD jets, but not so efficient for underlying events: $\propto R^4_{j_1,j_2}$
- Filtering: $R_{filt} = min(R_{j_1,j_2}/2, 0.3)$
- Consider 3 hardest p_T subjets with two tagged as b-jets.



[Ref: J.M. Butterworth, A.R. Davison, M. Rubin and G.P. Salam, Phys. Rev. Lett. **100**, 242001 (2008).]

Final state with one Lepton

Applied cuts:

- C6: We demand at least 4 jets with $p_T^{j1} > 200$ GeV, $p_T^{j2} > 150$ GeV, $p_T^{j3} > 100$ GeV, $p_T^{j4} > 50$ GeV, since the signal has a significantly larger number of hard jets as compared to the background.
- C7: We demand at least 2 b-tagged jets, to suppress backgrounds like W $(\rightarrow l\nu)$+jets.
- C8: A single isolated lepton is required with $p_T^{\ell} \geq 20$ GeV and $|\eta_\ell| \leq 2.5$.
- C9 : Since the leptonic mode is under investigation, a large $\not{p}_T$ is required to suppress backgrounds; $\not{p}_T > 400$ GeV is imposed.
- C10 : Due to the significantly larger jet activity in the signal, we impose $H_T = \Sigma p_T^j > 600$ GeV.
- C11 : The SM process $t\bar{t}H_{SM}$, with one of the tops decaying leptonically is the largest background. To suppress this, we demand that the transverse mass of the lepton and missing transverse energy of the system, $M_T(\ell, \not{p}_T) = \sqrt{2p_T^{\ell} \times \not{p}_T \times (1 - \cos\phi(\ell, \not{p}_T))} > 200$ GeV.
- C12: Events with number of jets greater than six are accepted.

Event Summary

		Effective cross-section after the cuts (in fb)						
Signal	Production c.s. (fb)	C6	C7	C8	C9	C10	C11	C12
P1	27.2	16.39	10.44	3.55	0.442	0.441	0.27	0.239
P2	12	8.49	5.5	1.88	0.315	0.314	0.2	0.176
P3	6	4.34	2.54	0.88	0.259	0.259	0.169	0.139
P4	1.5	1.17	0.74	0.246	0.109	0.109	0.077	0.061
P5	0.5	0.45	0.29	0.098	0.040	0.040	0.028	0.0255

		Effective cross-section after the cuts (in fb)						
SM bkgs	Production c.s. (pb)	C6	C7	C8	C9	C10	C11	C12
$t\bar{t}$+ jets	700000	20465.1	8130.2	1410.6	9.13	8.96	5.6	2.28
tth	500	54.75	37.12	8.1	0.089	0.089	0.054	0.036
W + jets	83315178	6153.2	0	0	0	0	0	0
Z + jets	42070505	4115.1	470.3	0	0	0	0	0
Total bkg								2.316

Signal Significance

- Summary of signal and background events obtained:

		Signal(N_S) (Background(N_B))			Significance($\mathcal{S}$) for $\kappa = 10\%$		
	$m_{\tilde{t}_1}$(GeV)	100 fb^{-1}	300 fb^{-1}	1000 fb^{-1}	100 fb^{-1}	300 fb^{-1}	1000 fb^{-1}
P1	804.3	23.9 (231.6)	71.7 (694.8)	239 (2316)	0.86	0.96	1.01
P2	908.2	17.6 (231.6)	52.8 (694.8)	176 (2316)	0.64	0.71	0.74
P3	1003.7	13.9 (231.6)	41.7 (694.8)	139 (2316)	0.51	0.56	0.58
P4	1211.5	6.1 (231.6)	18.3 (694.8)	61 (2316)	0.22	0.25	0.26
P5	1392.5	2.55 (231.6)	7.65 (694.8)	25.5 (2316)	0.09	0.10	0.11