Stop quark searches at the LHC with boosted tops and transverse variables.

Works done in association with D.K. Ghosh, D. Ghosh, A. Chakraborty.
arXiv:1303.5776. JHEP 1310 (2013) 122.

Dipan Sengupta

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April 16, 2014

SUSY in a nutshell

- Although the Higgs has been found, defficiencies of the SM like hierarchy problem, absence of DM candidate,.... force us to look beyond SM.
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	Superfield	Particle	Spin	Superpartner	Spin
Matter Fields	Q	$(u,\ d)_L$	$\frac{1}{2}$	$(\tilde{u}_L,\ \tilde{d}_L)$	0
	U^c	$\bar{u}_R$	$\frac{1}{2}$	$\tilde{u}_R^*$	0
	D^c	$\bar{d}_R$	$\frac{1}{2}$	$\tilde{d}_R^*$	0
	L	$(\nu,\ e)_L$	$\frac{1}{2}$	$(\tilde{\nu}_L,\ \tilde{e}_L)$	0
	E^c	$\bar{e}_R$	$\frac{1}{2}$	$\tilde{e}_R^*$	0
Gauge Fields	V_1	B_μ	1	$\tilde{B}$	$\frac{1}{2}$
	V_2	W_μ^i	1	$\tilde{W}^i$	$\frac{1}{2}$
	V_3	G_μ^a	1	$\tilde{g}^a$	$\frac{1}{2}$
Higgs Fields	H_1	$(H_1^0,\ H_1^-)$	0	$(\tilde{H}_1^0,\ \tilde{H}_1^-)$	$\frac{1}{2}$
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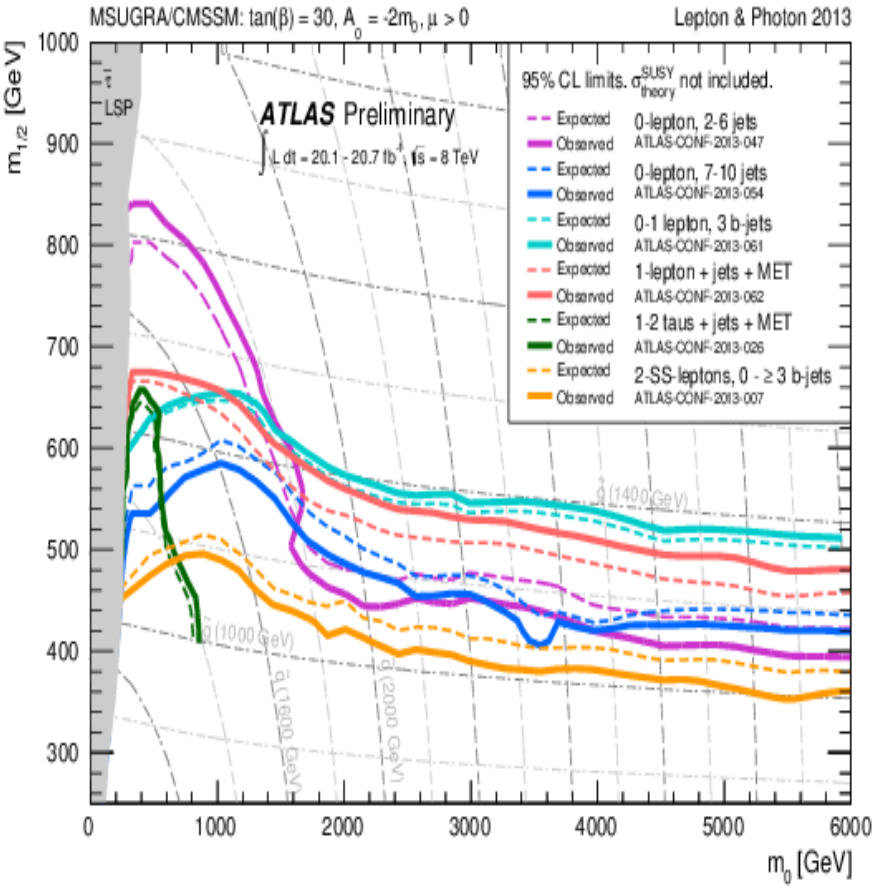
Table: MSSM particle content.

- Early SUSY searches relied on specific models of SUSY breaking scenarios, in particular CMSSM/mSUGRA.
- However absence of SUSY signatures have prompted a more generic approach.

CMSSM reach latest

CMSSM: Specified by 4 parameters and a sign at GUT scale. $\mathrm{m}_0, \mathrm{m}_{1/2}, \tan\beta, \mathrm{A}_0, \mathrm{sgn}(\mu)$



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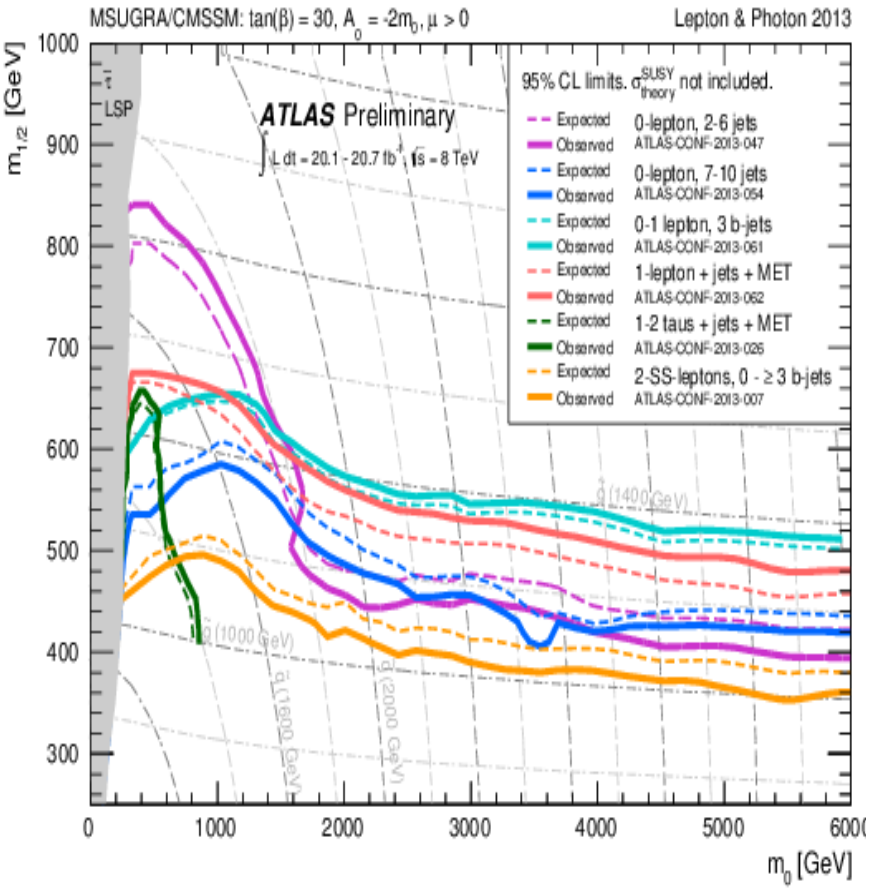

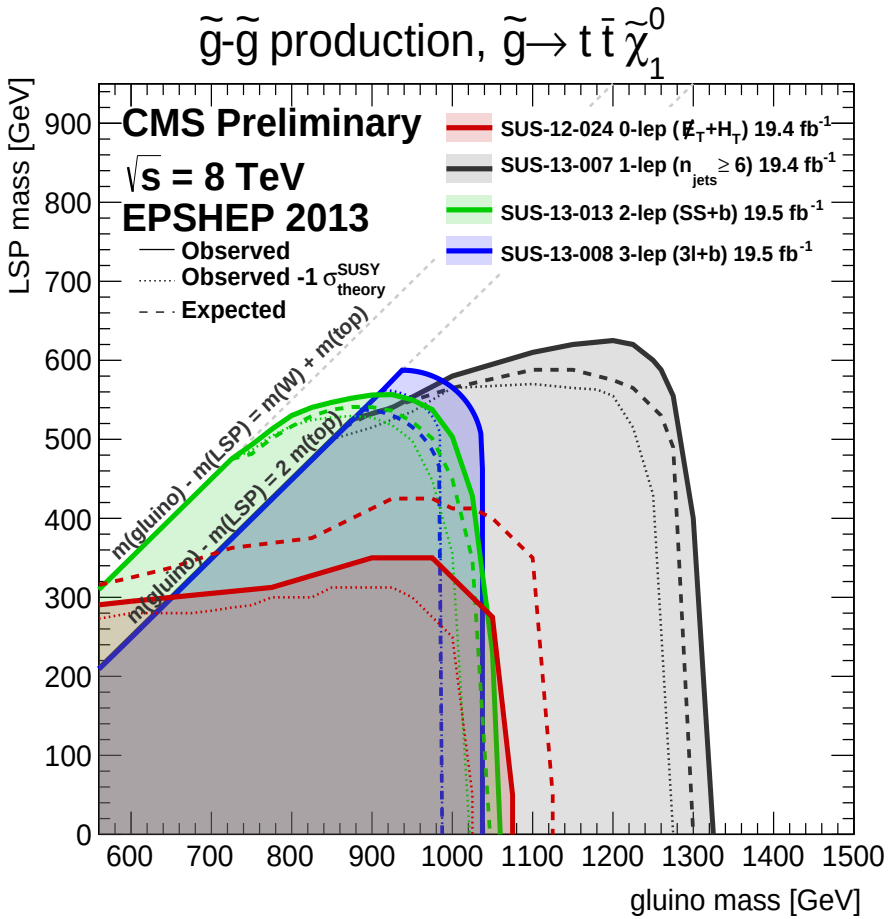

$m_{\tilde{g}} \simeq m_{\tilde{q}} \simeq$ 1.6 *TeV*, $m_{\tilde{g}} << m_{\tilde{q}} \simeq$ 1.4 *TeV*

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$$M^2_{\tilde{f}} = \begin{pmatrix} M^2_{\tilde{f}_{LL}} & M^2_{\tilde{f}_{LR}} \\ M^2_{\tilde{f}_{RL}} & M^2_{\tilde{f}_{RR}} \end{pmatrix}.$$

- Third Generation : Large mixings, resulting in a splitting in third generation mass eigen states.

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} m^2_{\tilde{q}_3} + (1/2 - 2/3 sin^2\theta_w) M^2_Z cos2\beta + m^2_t & -m_t(A^*_t - \mu cot\beta) \\ -m_t(A_t - \mu^* cot\beta) & m^2_{\tilde{t}} + 2/3 sin^2\theta_w M^2_Z cos2\beta + m^2_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$(m_{\tilde{t}_1,\tilde{t}_2})^2 = \frac{1}{2}\left\{ m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} \pm \sqrt{[(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4X^2_t m^2_t]} \right\}$$

$$\mathrm{X_t} = \mathrm{A_t} - \mu \mathrm{cot}\beta$$

- Intimately Connected to the Higgs loop correction.

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- Reason 3 : Principal loop contributor to the increase of Higgs mass
- Lightest Higgs mass : $m_h^2 \leq m_Z^2 cos^2 2\beta \leq \ 90 \ GeV$
- Loop Corrections : dominated by top-stop loops:

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left[log \frac{M_{SUSY}^2}{m_t^2} + \left(\frac{X_t^2}{M_{SUSY}^2} \left(1 - \frac{X_t^2}{12 M_{SUSY}^2} \right) \right) \right] \leq 135 GeV$$

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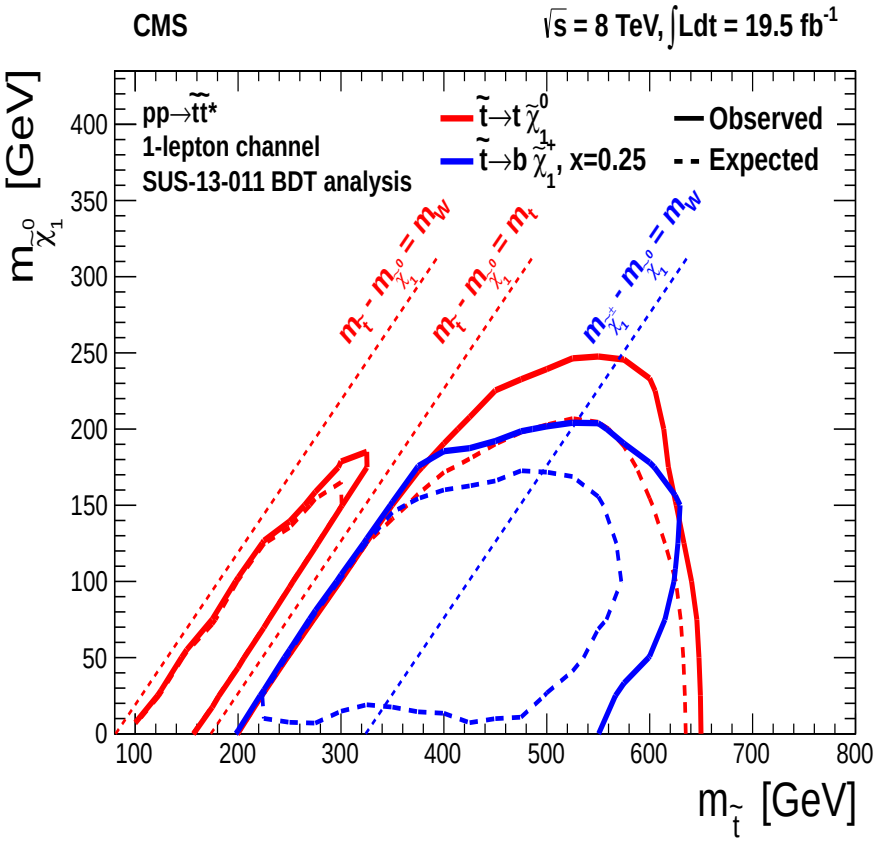
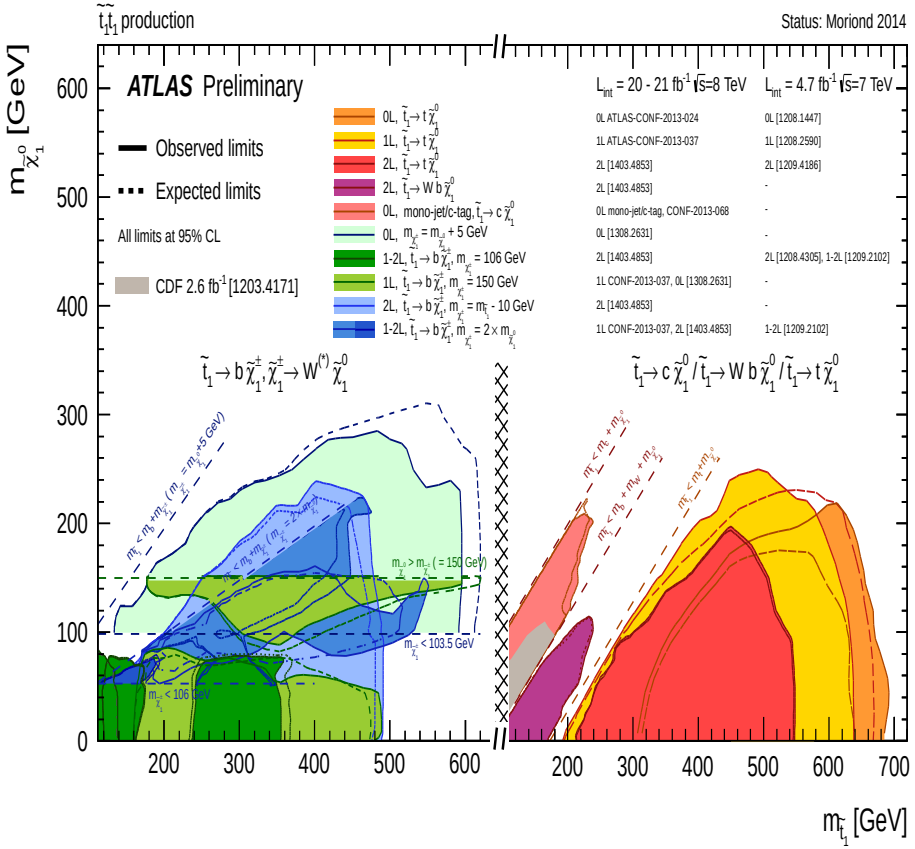
- **tops squarks : below 500–1000 GeV**
- **Lighter Chargino and two lighter neutralinos: 200–450 GeV**
- **A Not too heavy Gluino 1–1.5 TeV**

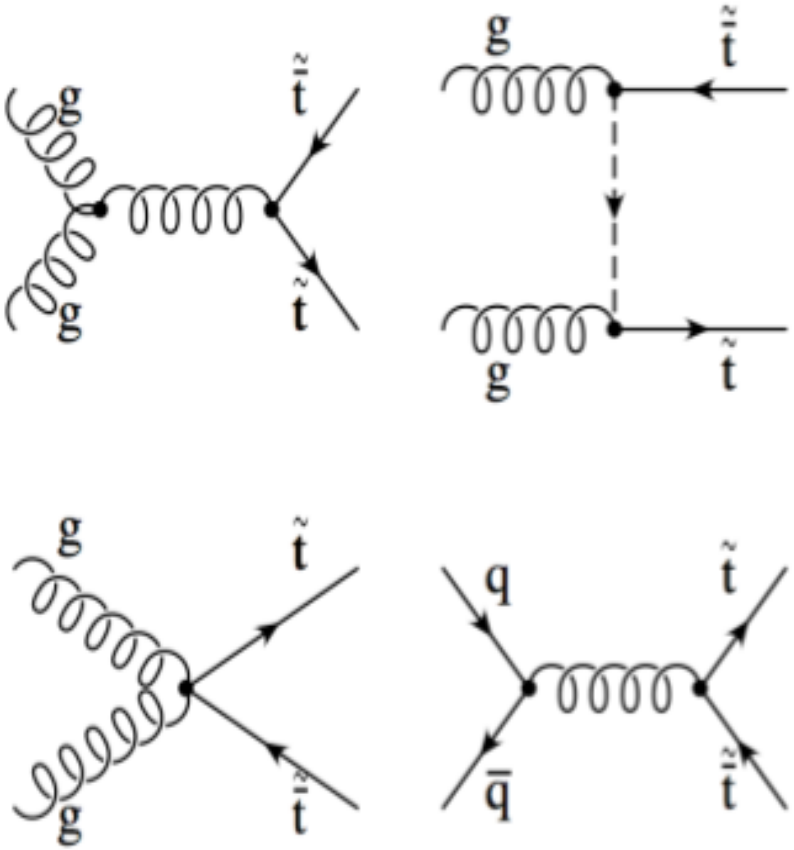
Limits on stop masses: CMS and ATLAS

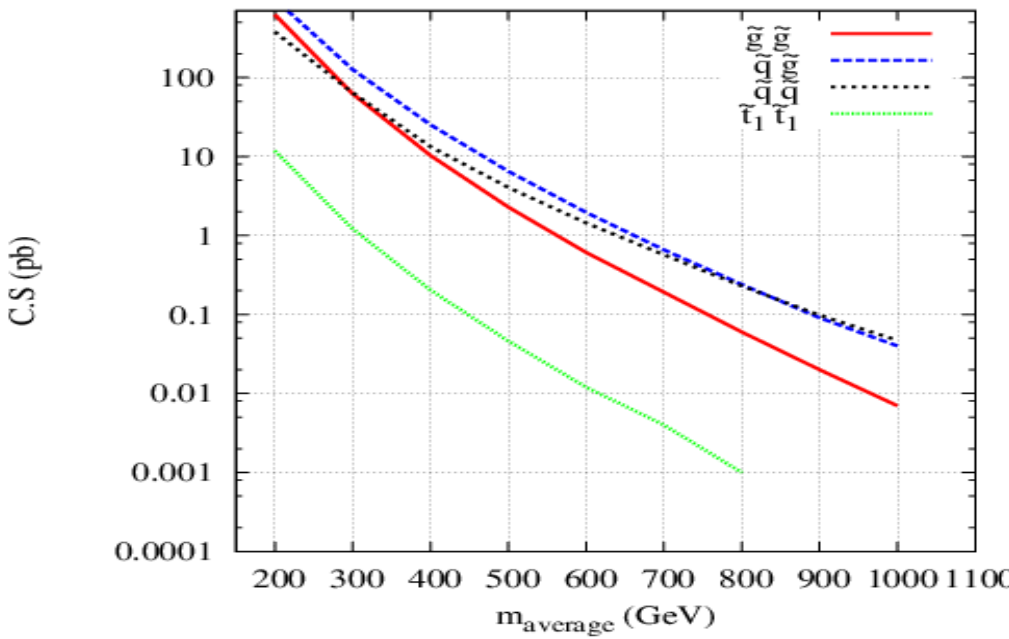




$m_{\tilde{t}_1} = 600,\ m_{\chi_1^0} = 250\ GeV,\ \tilde{t} \to t\chi_1^0.$

Production modes, Cross Section at 8 TeV





The parameter spaces of interest

- Most of the early stop searches assumed simplified models with $\tilde{t}_1 \to t\chi_1^0$. Predominantly right handed stops.
- Efficiency dependent on $\Delta m = m_{\tilde{t}_1} - m_{\chi_1^0}$. Kinematic edges difficult to probe due to large $t\bar{t}$ background.

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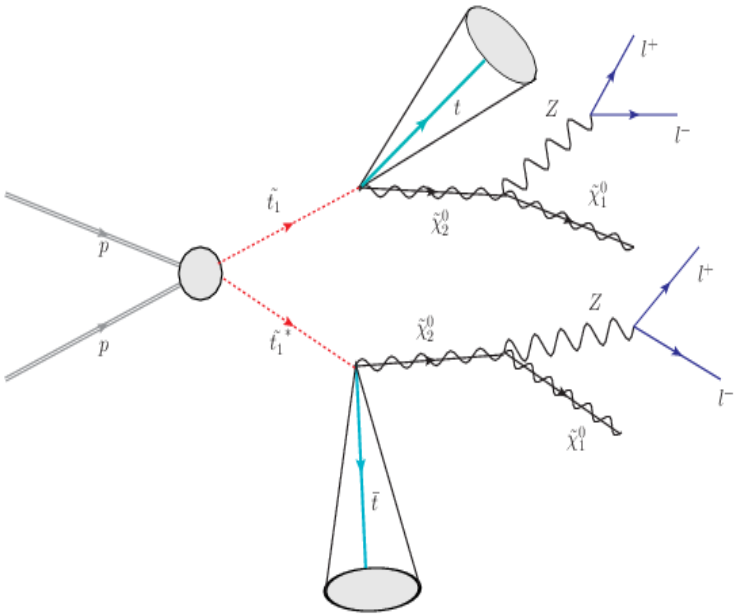

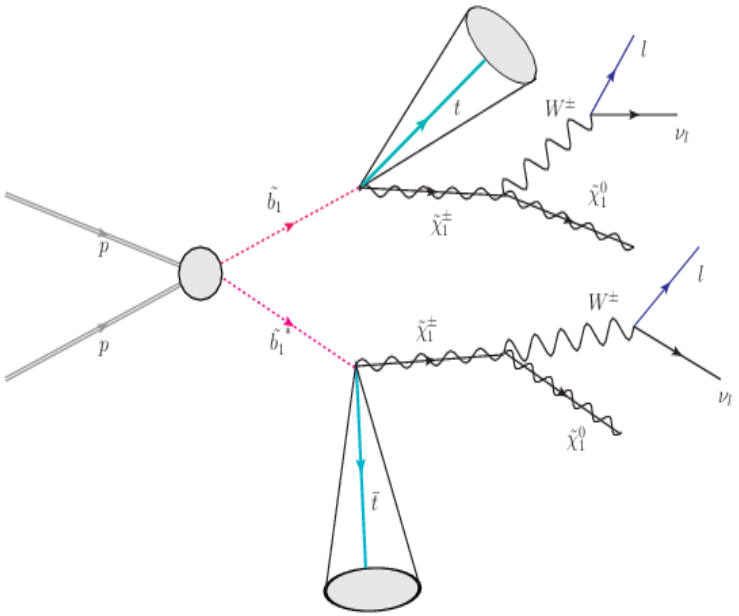

Signature and benchmark points

$$
\begin{array}{lcccccccc}
pp & \to & \tilde{t}_1\,\tilde{t}_1^* & \to & t\,\bar{t}\,\tilde{\chi}_2^0\,\tilde{\chi}_2^0 & \to & t\,\bar{t} + 2Z + 2\tilde{\chi}_1^0 & \to & t/\bar{t} + \ell\,\ell + \not{p}_T + X \\
pp & \to & \tilde{t}_1\,\tilde{t}_1^* & \to & t\,\bar{b}\,\tilde{\chi}_2^0\,\tilde{\chi}_1^- & \to & t\,\bar{b} + W^-Z + 2\tilde{\chi}_1^0 & \to & t + \ell\,\ell + \not{p}_T + X \\
pp & \to & \tilde{t}_1\,\tilde{t}_1^* & \to & t\,\bar{b}\,\tilde{\chi}_2^0\,\tilde{\chi}_1^- & \to & t\,\bar{b} + W^-h + 2\tilde{\chi}_1^0 & \to & t + \ell\,\ell + \not{p}_T + X \\
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\end{array}
$$

	P1	P2	P3	P4	P5	P6
$m_{\widetilde{Q_3}}$	500	500	700	700	900	900
$m_{\tilde{t}_1}$	501.7	501.7	714.2	714.2	918.1	918.1
$m_{\tilde{b}_1}$	525.4	525.4	748.4	748.4	918.1	918.1
$m_{\tilde{\chi}_1^0}$	48.5	97.9	146.3	97.8	149.0	198.3
$m_{\tilde{\chi}_2^0}$	193.3	193.9	245.9	244.3	297.9	298.6
$m_{\tilde{\chi}_1^\pm}$	192.8	192.8	242.7	242.7	297.0	297.0
$BR(\tilde{b}_1 \to b\,\tilde{\chi}_{2,3,4}^0)(\%)$	34.6	34.5	19.3	19.4	19.4	19.4
$BR(\tilde{b}_1 \to t\,\tilde{\chi}_{1,2}^\pm)(\%)$	65.4	65.5	80.7	80.6	80.6	80.6
$BR(\tilde{t}_1 \to t\,\tilde{\chi}_{2,3,4}^0)(\%)$	34.9	35.2	62.5	62.4	62.5	62.5
$BR(\tilde{t}_1 \to b\,\tilde{\chi}_{1,2}^\pm)(\%)$	65.1	64.8	37.5	37.6	37.5	37.5
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z)(\%)$	33.9	100.0	100.0	22.1	12.8	100.0
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h)(\%)$	66.1	0.0	0.0	77.9	87.2	0.0

The rest of the parameter space is irrelevant for this study, and is decoupled from this set.

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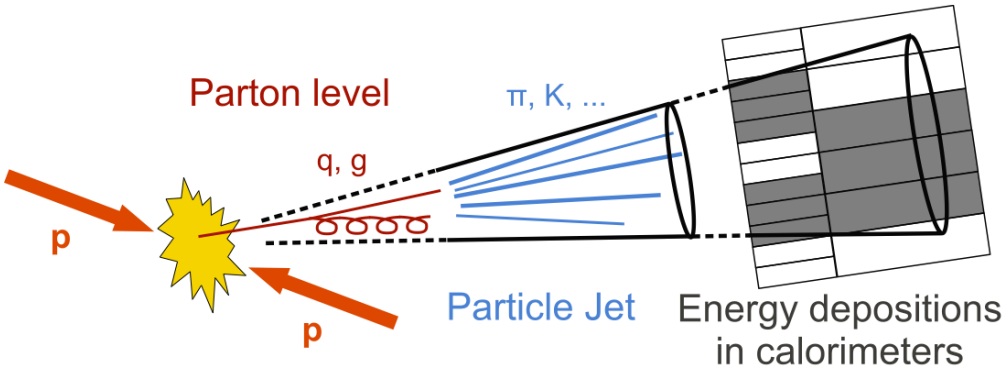
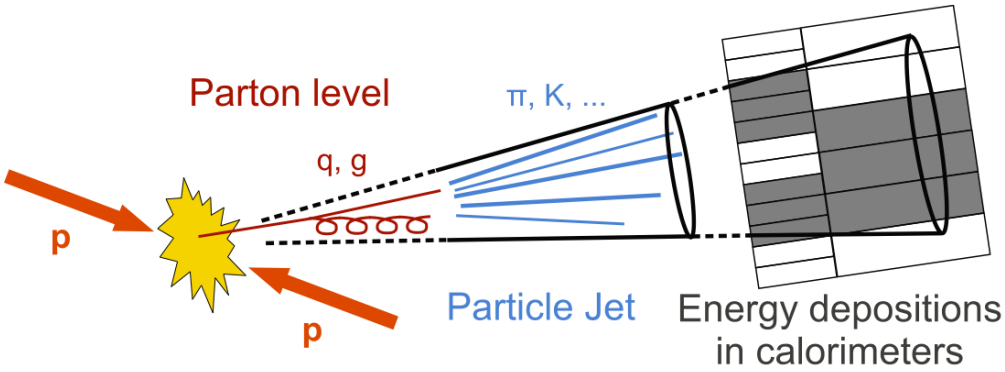
- Literature on the use of top tagger in stop searches:
  T Plehn at al. arXiv:1006.2833. D.E Kaplan et. al arXiv : 1205.5816. M. Perelstein et al. arXiv:1111.6594.
- Literature on the use of dileptonic M_{T2} : B. Tweedie et al. arXiv:1211.6106.

Jets


Parton level
π, K, ...
q, g
p
p
Particle Jet
Energy depositions
in calorimeters

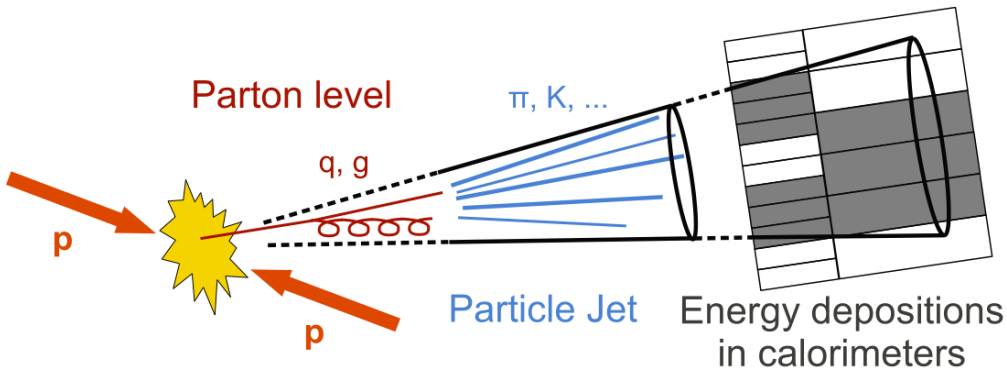
Jets



The Snowmass Accord:

- Simple to implement in expt and calculate theoretically.
- Defined at any order of perturbation theory and yields finite cross sections at all orders.
- Yields cross sections independent of hadronization procedure.
- IRC safe.

Jets



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- Defined at any order of perturbation theory and yields finite cross sections at all orders.
- Yields cross sections independent of hadronization procedure.
- IRC safe.
- Recombination Scheme : Distance measure: $d_{ij} = min(p_{Ti}^{2p}, p_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$.

  R= $\sqrt{\eta^2 + \phi^2}$

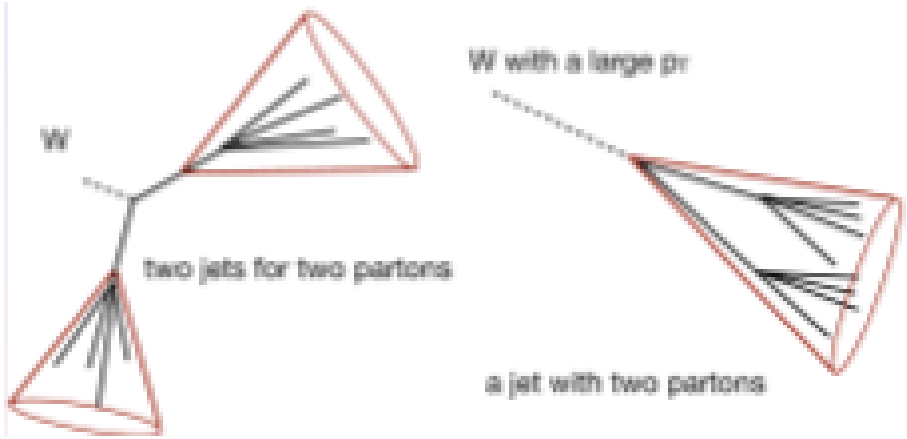
  p=1$\rightarrow$ $\mathrm{k_T}$; p=-1 $\rightarrow$ $\mathrm{anti-k_T}$; p=0 $\rightarrow$ C/A.
- $k_T, C/A$: Cluster the softest particle first. $\mathrm{anti-k_T}$: Cluster the hardest particles first.
- C/A being angular ordered is most suited to Jet Substructure.

Jet Substructures: Higgs tagger

- Digression: Jet Substructure : Higgs tagger

$$R_{b\bar{b}} \simeq 2\frac{m_H}{p_T}\,, \qquad (p_T >> m_H)$$

- For $m_H \simeq 125$, $p_T > 250$ GeV, implies $\mathrm{R} \simeq 1$
- As the boost increases, the jets get collimated.



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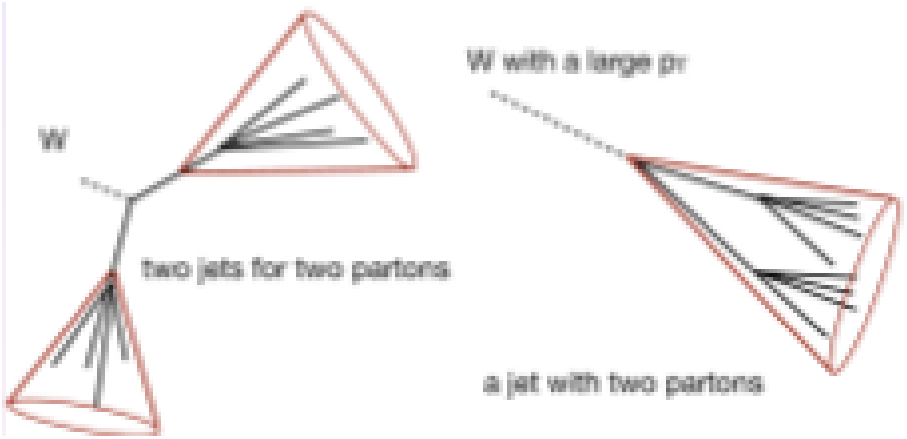
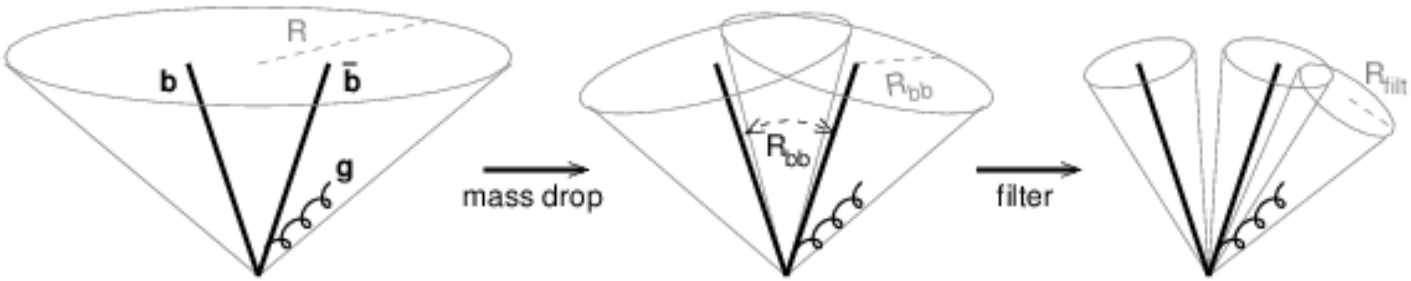
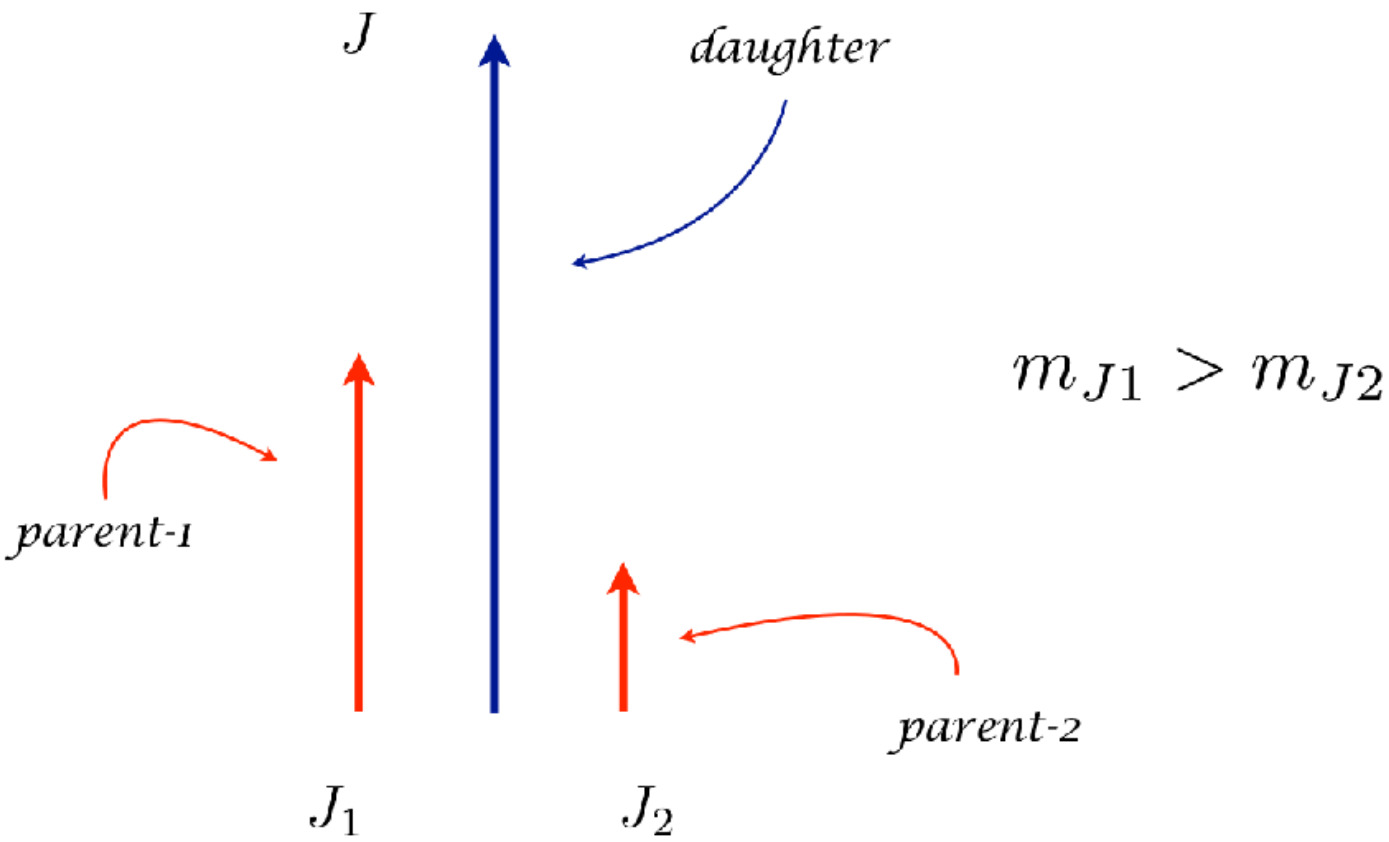




- Butterworth ,Rubin, Davison, Salam, 0802.2470.

Jet Substructure: BDRS Higgs tagger

break a C/A b-jet J into two parents by undoing its last stage of clustering

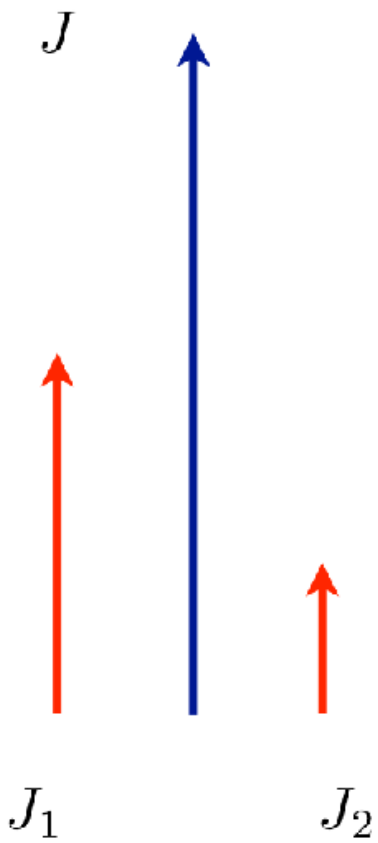


is J a suspect ?

check if

$$m_{J1} < 0.68\, m_J$$

$$\min\left(p_{t1}^2, p_{t2}^2\right) \frac{\Delta R_{12}^2}{m_J^2} > (0.3)^2$$



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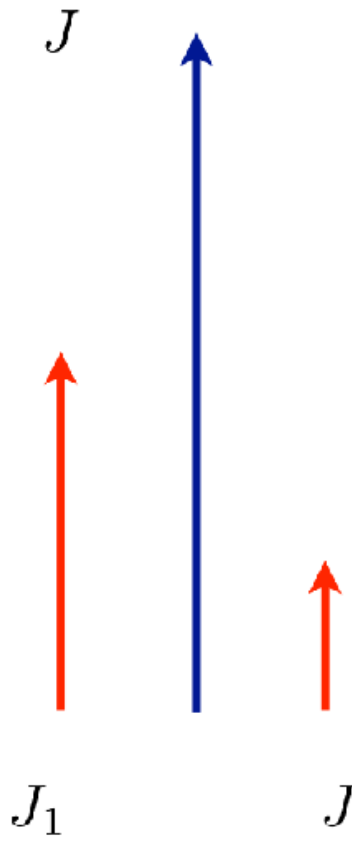

if yes

J is at heavy particle threshold

exit

is J a suspect ?

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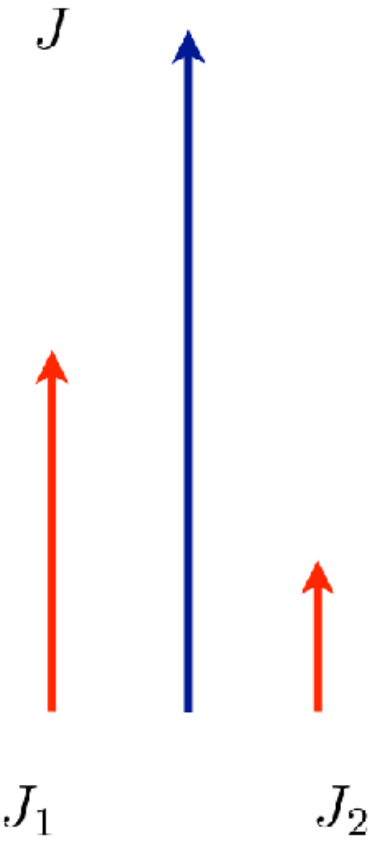


if no

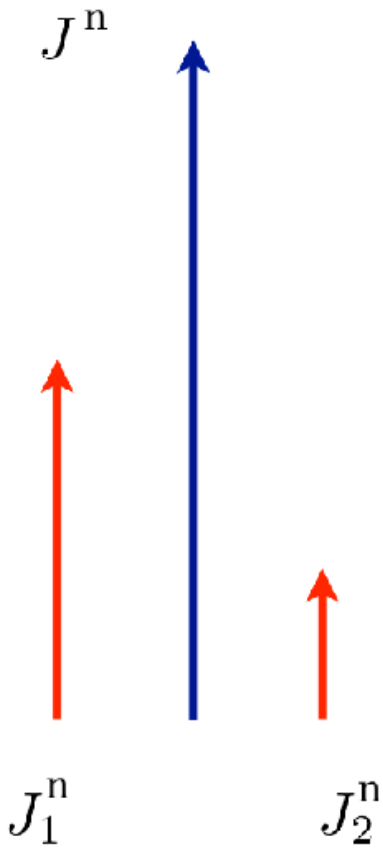
replace J by J1

repeat

(Butterworth et al 0802.2470)

Filtering

J^n is a Higgs candidate



(Butterworth et al 0802.2470)

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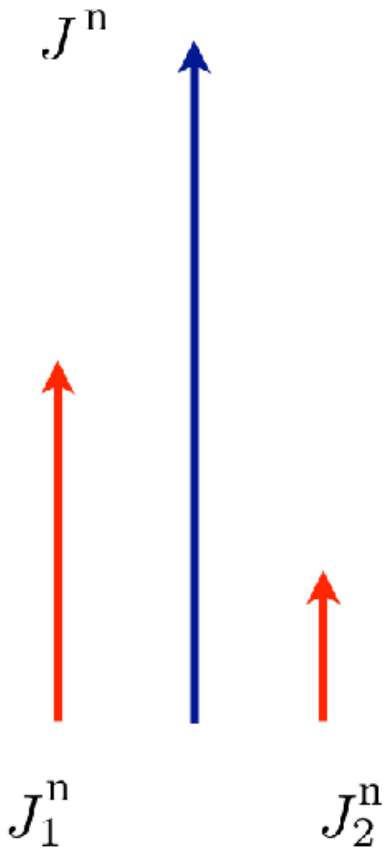
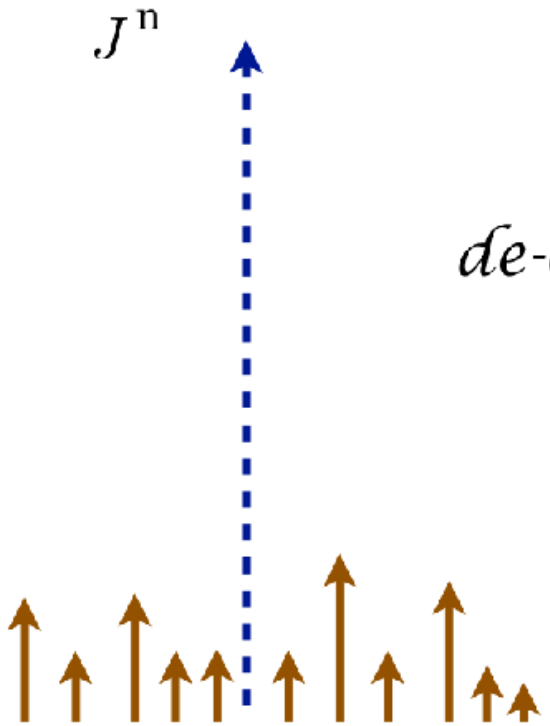


record $\Delta R_{J_1^n, J_2^n}$

(Butterworth et al 0802.2470)

Filtering

J^n is a Higgs candidate



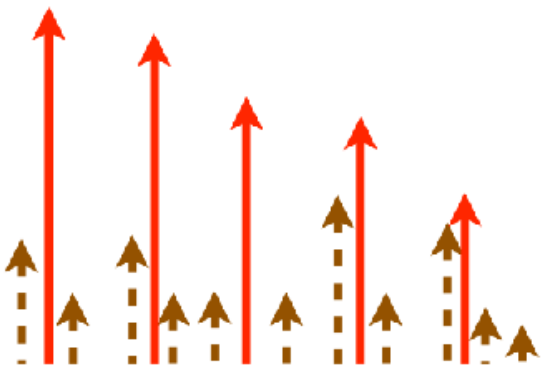
de-cluster J^n completely

(Butterworth et al 0802.2470)

Filtering

re-cluster using

$$R_{\text{filt}} = \min\left(\frac{\Delta R_{J_1^n, J_2^n}}{2},\ 0.3\right)$$

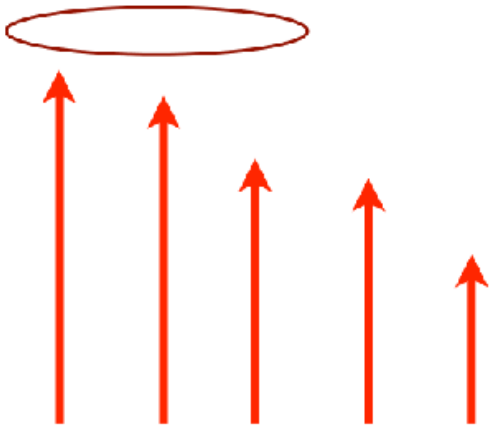


Pt order the jets

(Butterworth et al 0802.2470)

Filtering

- *retain only three hardest component and combine. call it Higgs Jet*



Jet Substructure: John Hopkins Top tagger

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- Cluster with C/A algorithm with a fat jet radius R.
- For each jet, decluster by undoing the last step of clustering.($j \to j1, j2$) For the first decluster, if $p_T^{j1}/p_T^j < \delta_p$, throw p_T^{j1}, decluster p_T^{j2} and repeat. Typical values of $\delta_{\rm p} = 0.19$, for $\rm p_T \geq 1\ TeV$.

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- Stop when either:
  1. $j1, j2$ both harder than δ_p.
  2. $j1, j2$ both softer than δ_p.
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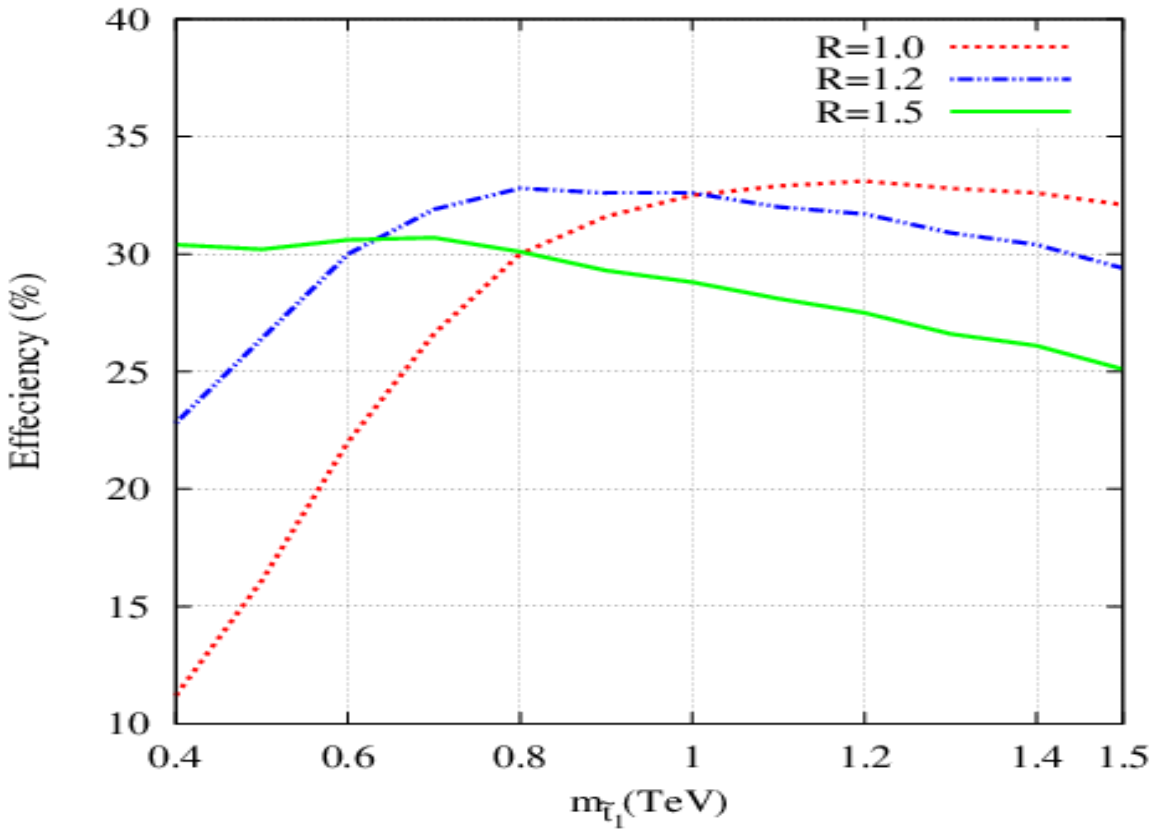
- For cases 2,3,4 deem j to be irreducible.
- For case 1 repeat till 3,4 total subjets are found.
- For 3 subjets, demand $145\ \text{GeV} < \rm m_{inv}^{j1,j2,j3} < 205\ GeV$, and $65\ \text{GeV} < \rm m_{inv}^{j2,j3} < 95\ GeV$
- Additionally to ensure proper W identification demand that the W helicity angle satisfies $cos\theta_h < 0.7$
- To suppress the UE contamination, run the filtering algorithm.

Kaplan et al. -arXiv:0806.0848

Top tagging Efficiencies

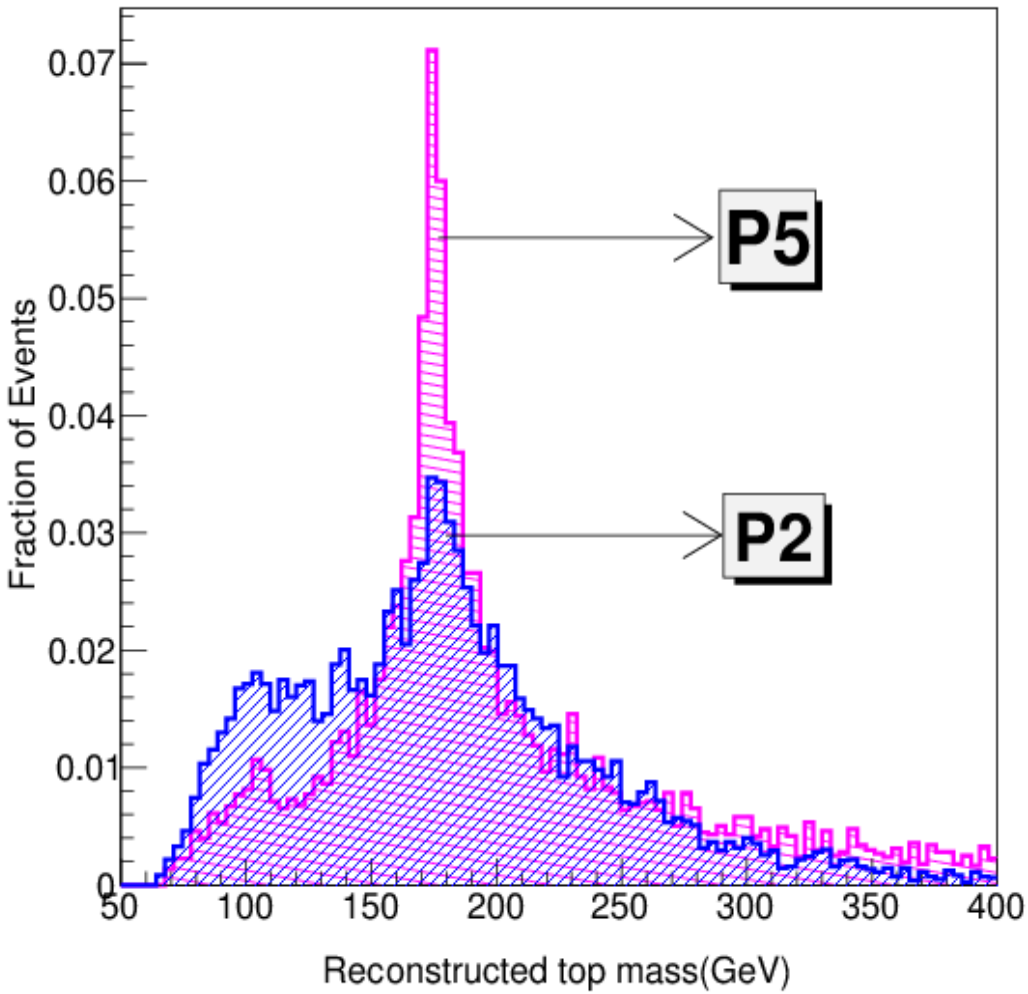
Decay: $\tilde{t}_1 \to t\chi_2^0$. Fix $\chi_2^0 = 150$ GeV. Fat jet $p_T = 200$ GeV. Tag at least 1 top.



Optimal choice: R=1.5, $p_T = 200$ GeV.

Mass distributions for top tagging.

P2: $m_{\tilde{t}_1} \simeq 500$ GeV, $\chi_2^0 = 200$ GeV.
P5: $m_{\tilde{t}_1} \simeq 900$ GeV, $\chi_2^0 = 300$ GeV



Analysis over the rest of the objects

- Note that all tops/jets are not tagged. Should we throw out these objects?
- Instead recluster untagged jets with $\mathrm{anti}-\mathrm{k_T}$ algorithm with R=0.5.
- Identify the hadrons entering the fat jet, remove them from the jet list and run the $\mathrm{anti}-\mathrm{k_T}$ algorithm on the rest, with $\mathrm{p_T^j} = 50\ \mathrm{GeV}$
- Apply the dileptonic $\mathrm{M_{T2}}$ on the dileptonic system.

M_{T2}

- The idea is to locate the end point in the mass distribution for decays with two branches of invisible particles.
- $$M_T^2 \equiv m_v^2 + m_i^2 + 2\left(E_v E_i - \mathbf{v}_T \cdot \not{\mathbf{p}}_\mathbf{T}\right),$$

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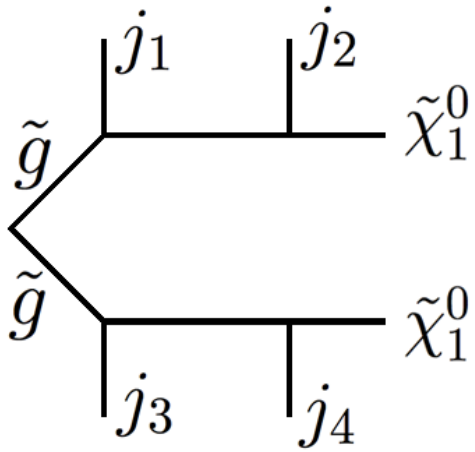

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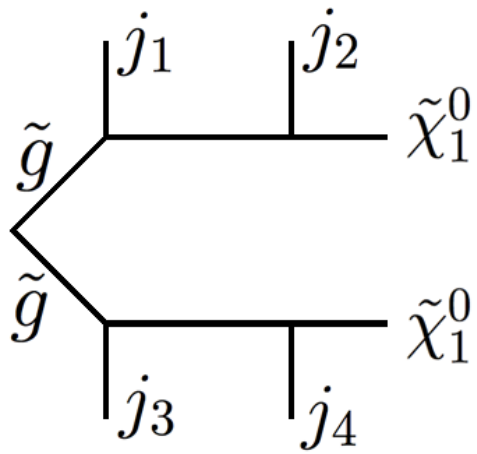

$$\mathrm{M_{T2}}(\mathrm{v_1}, \mathrm{v_2}, \not{p}_\mathrm{T}) = \min\left[\max\{\mathrm{M_T}(\mathrm{v_1}, \chi), \mathrm{M_T}(\mathrm{v_2}, \chi)\}\right]$$

- minimization is performed over $\not{p}_T^1 + \not{p}_T^2 = \not{p}_T$ where $\not{p}_T^1, \not{p}_T^2$ are all possible partitions.
- arXiv:0304226. A.Barr,C.Lester and P.Stephens

Lemma

When a pair of particles are produced, both with mass m_0, and each parent decays to a visible system v and an invisible system i, then $M_{T2}(v_1, v_2, \not{p}_T, 0, 0) \leq m_0$.

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- arXiv:0907.2713.A.Barr,C.Gwelan.
- Caveat : Not always an endpoint at parent mass.
  ISR, FSR, uncorrelated jets/leptons with $\not{p}_T$ can spoil the party.
- In our case M_{T2} for $t\bar{t}$ is expected to have an end point at the mass of W.
- For signal since the mother particles from which these leptons come originate from $\chi_1^{\pm}$, χ_2^0, one expects an end point a higher values.

M_{T2}

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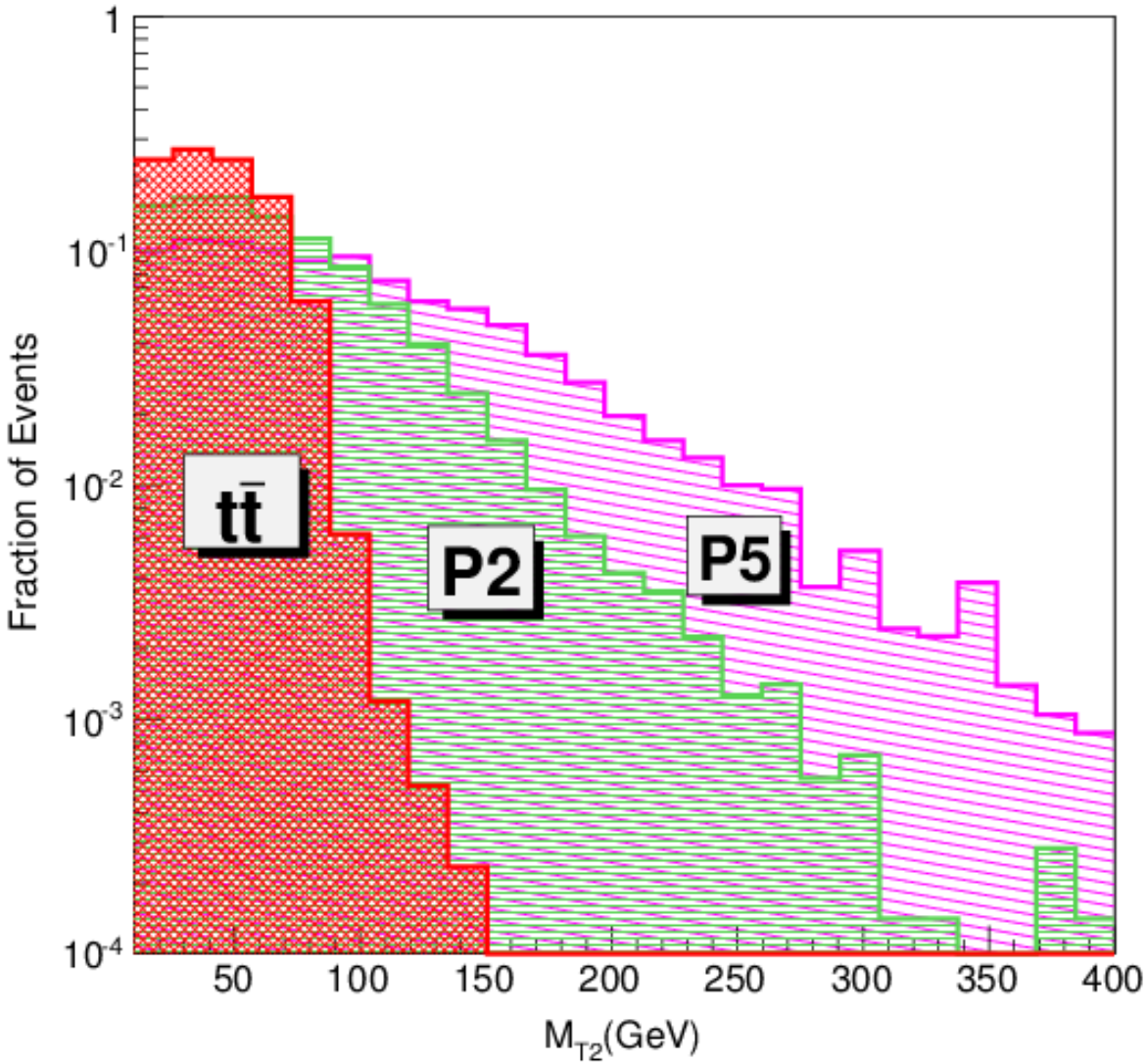
P5: $m_{\tilde{t}_1} \simeq 900$ GeV, $\chi_2^0 = 300$ GeV



Summary of all cuts

- C1 : Demand at least two isolated leptons (electron and muon) with $\mathrm{p}_{\mathrm{T}}^{\ell} \geq 25$ GeV and $|\eta| \leq 3$.
- C2 : Consider M_{T2} defined as,

$$\mathrm{M}_{\mathrm{T2}}(\overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell 1}, \overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell 2}, \not{p}_{\mathrm{T}}) = \min_{\not{p}_{\mathrm{T}} = \not{p}_{\mathrm{T}}^{1} + \not{p}_{\mathrm{T}}^{2}} \left[\max\{\mathrm{M}_{\mathrm{T}}(\overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell 1}, \not{p}_{\mathrm{T}}^{1}), \mathrm{M}_{\mathrm{T}}(\overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell 2}, \not{p}_{\mathrm{T}}^{2})\} \right] > 125 \text{ GeV},$$

-
- C3 : Effective mass of the system $\mathrm{m}_{\mathrm{eff}} = \Sigma \mathrm{p}_{\mathrm{T}}^{\mathrm{j}} + \Sigma \mathrm{p}_{\mathrm{T}}^{\ell}$.
- C4 : $\not{p}_{\mathrm{T}} > 150$ GeV.
- C5 : At least 1 top tag in the system.

Results: Cut flow

			No. of events after the cut					
Signal	Production Cross-section (fb)	Simulated events (in units of 10^4)	2l	$\mathrm{M_{T2}}$	m_{eff}	$\not{p}_T$	top tag	Final Cross-section (in units of 10^{-2} fb)
P1	1130	10	10573	821	339	267	55	62.2
P2	1130	10	11091	657	248	205	48	60.5
P3	135	5	8043	1132	712	645	153	41.3
P4	135	5	7713	1207	749	663	178	43.1
P5	27	5	8623	1720	1414	1322	295	15.9
P6	27	5	8543	1679	1343	1281	322	17.4

			No. of events after the cut					
SM backgrounds	Production Cross-section (fb)	Simulated events (in units of 10^4)	C1	C2	C3	C4	C5	Final Cross-section (in units of 10^{-2} fb)
$\mathrm{t\bar{t}}+$ jets	918000	4320	1587596	601	39	29	4	8.5
tbW	61000	600	215807	80	4	2	1	1.0
$\mathrm{t\,\bar{t}Z}$	1121	7	6255	253	52	20	2	3.2
$\mathrm{t\,\bar{t}W}$	769	5	4471	31	3	2	1	1.5
$\mathrm{t\,\bar{t}W^+W^-}$	10	1	1588	33	14	13	6	0.6
$\mathrm{t\,\bar{t}\,t\,\bar{t}}$	10	1	1781	31	14	10	4	0.4
Total Background								15.2

Results

Define significance :

$$\mathcal{S} = \frac{\mathrm{N_S}}{\sqrt{\mathrm{N_B} + (\kappa \mathrm{N_B})^2}} \ , \tag{1}$$

where $\mathrm{N_S}$ and $\mathrm{N_B}$ are the number of signal and background events respectively and κ is the measure of the systematic uncertainty.

		Signal($\mathrm{N_S}$) (Background($\mathrm{N_B}$))			Significance($\mathcal{S}$) for $\kappa = 10\%\,(30\%, 50\%)$		
	$\mathrm{m_{\tilde{t}_1}}$ (GeV)	10 fb^{-1}	50 fb^{-1}	100 fb^{-1}	10 fb^{-1}	50 fb^{-1}	100 fb^{-1}
P1	501.6	6.2(1.6)	31.1(8)	62.2(16)	4.9(4.6, 4.1)	10.8(8.4, 6.3)	14.4(9.9, 6.9)
P2	501.6	6.05(1.6)	30.2(8)	60.5(16)	4.7(4.5, 4.05)	10.6(8.3, 6.1)	14.1(9.6, 6.5)
P3	714.2	4.1(1.6)	20.7(8)	41.3(16)	3.2(3.0, 2.7)	7.0(5.6, 4.2)	9.6(6.6, 4.6)
P4	714.2	4.3(1.6)	21.55(8)	43.1(16)	3.6(3.3, 2.9)	7.4(5.9, 4.5)	9.9(6.8, 4.8)
P5	918.1	1.6(1.6)	7.9(8)	15.9(16)	1.3(1.2, 1.1)	2.7(2.1, 1.6)	3.7(2.5, 1.8)
P6	918.1	1.7(1.6)	8.7(8)	17.4(16)	1.3(1.2, 1.1)	2.9(2.3, 1.8)	4.0(2.8, 1.9)

Results in a simplified scenario

Consider the simplified models : $\tilde{t}_1 \to t\chi_2^0$, $\tilde{b}_1 \to t\chi_1^\pm$. $\chi_2^0 \to Z\chi_1^0$, $\chi_1^\pm \to W\chi_1^0$, with $\chi_1^0 = 50$ GeV

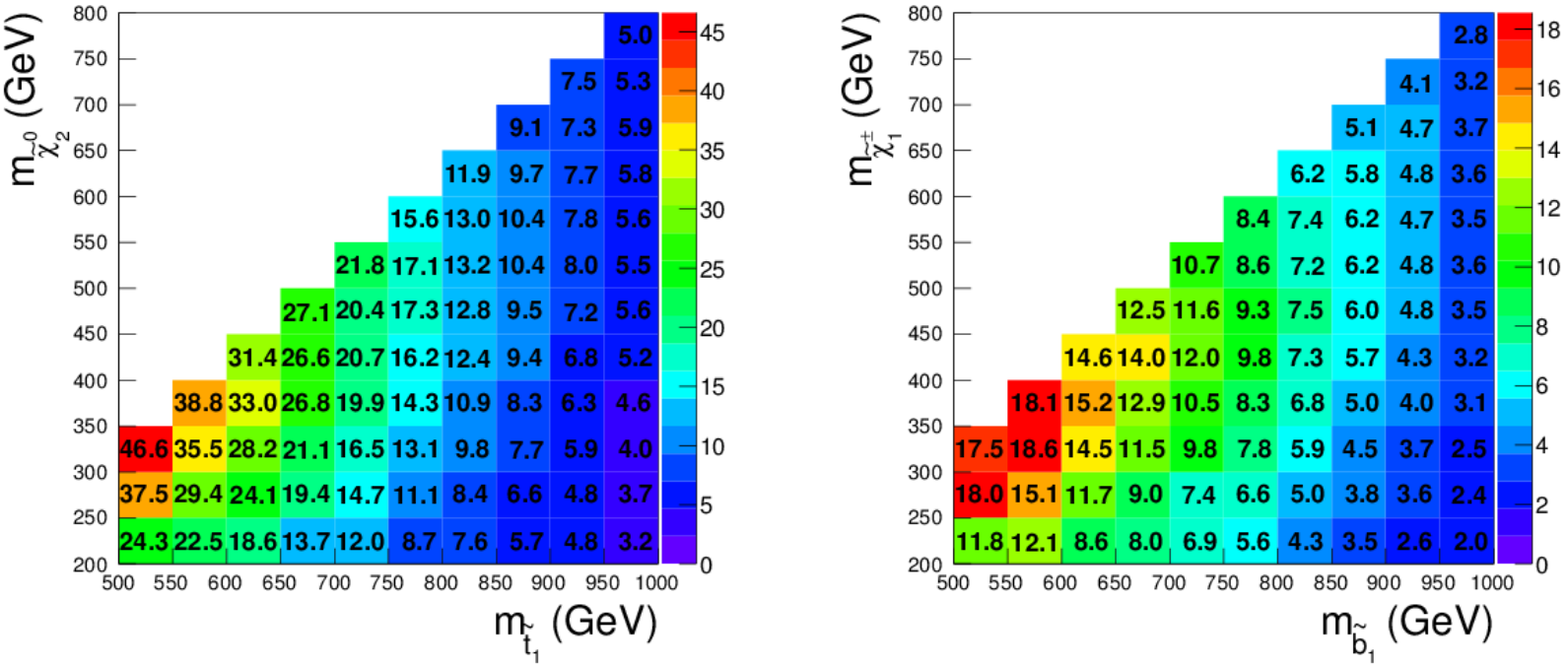


Figure: The signal significance at 100 fb^{-1} in the $\widetilde{\mathrm{t}}_1$–$\widetilde{\chi}_2^0$ plane (left panel) and $\widetilde{\mathrm{b}}_1$–$\widetilde{\chi}_1^\pm$ plane.

Conclusions

- The use of Jet Substructures and M_{T2} will have significant impacts in stop searches.
- In this study we studied the impact of the boosted stop startegy in a scenario where the stops were predominantly left handed.
- The optimized discovery reach of our strategy is about 900 GeV at 14 TeV center of mass energy with 100 fb^{-1} luminosity.

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"One day, all of these will be supersymmetric phenomenology papers."