Stop and sbottom search using dileptonic M_{T2} variable and boosted top technique at the LHC

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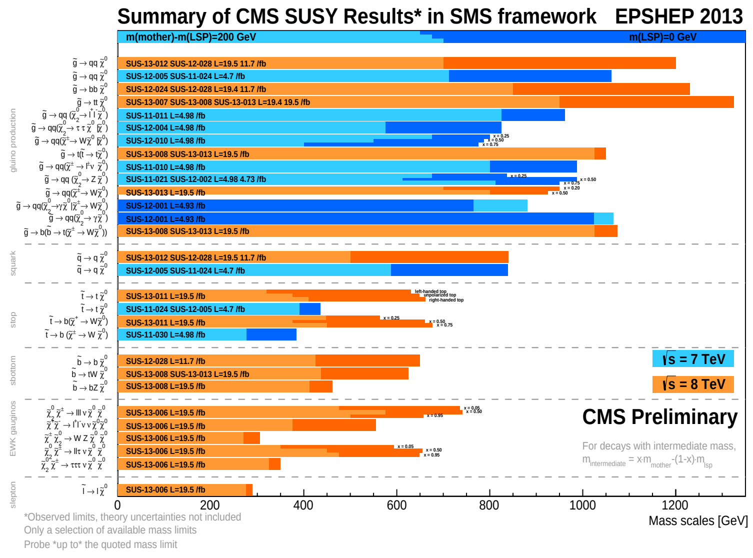
Plan of the talk

- Introduction
- Current status and Our Strategy
- Choice of model parameters and Benchmark Points
- Collider analysis and results
- Summary

Introduction

- Observation of a new particle at the LHC with mass $m_h \sim 125$ GeV compatible with the SM Higgs.
- This mass value agrees well with prediction of MSSM.
- In MSSM, the large quadratic divergence in m_h^2 due to top quark loop is cancelled by the scalar partner of top quarks (called stop $\tilde{t}_i$, with $i = 1, 2$).
- Stop sector plays a crucial role in determining the Higgs mass $\Longrightarrow$ the experimental determination of the stop properties is crucial to understand the nature of SUSY protecting the Higgs mass at EW scale.
- So far LHC has not seen any evidence of SUSY particles, only lower bounds have been put on different SUSY particles.
- Limits on gluino ($\tilde{g}$) and squarks ($\tilde{q}$) currently stands at about 1.5 TeV for $\mathrm{m}_{\tilde{\mathrm{g}}} \simeq \mathrm{m}_{\tilde{\mathrm{q}}}$ and about 1.2 TeV for $\mathrm{m}_{\tilde{\mathrm{g}}} \ll \mathrm{m}_{\tilde{\mathrm{q}}}$.

CMS SUSY exclusion

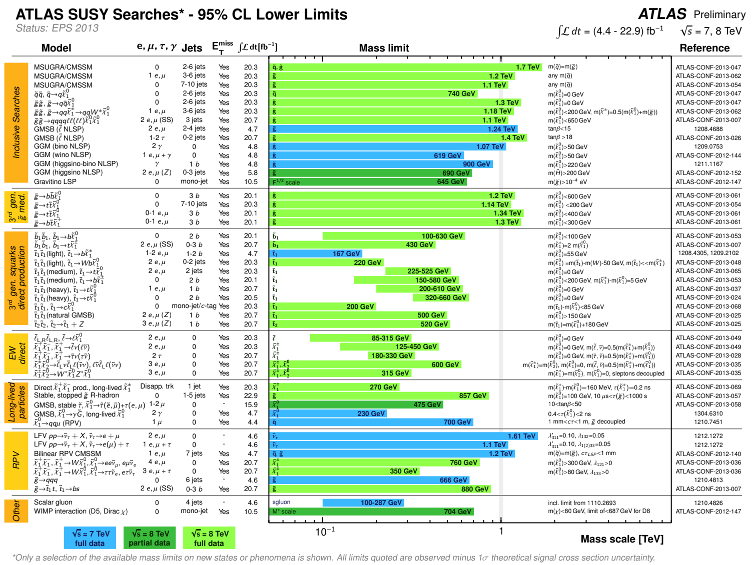


Summary of CMS SUSY Results* in SMS framework EPSHEP 2013

For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} - (1-x) \cdot m_{lsp}$

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

ATLAS SUSY exclusion



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.4 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e,μ (SS)	3 jets	Yes	20.7	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta<15$	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta>18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	0	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.14 TeV	$m(\tilde{\chi}_1^0)$ <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-630 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	430 GeV	$m(\tilde{\chi}_1^\pm)=2\,m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0Z^*\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	857 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	0	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$	700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	0	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	0	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q},\tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, $\lambda_{121}>0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	0	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, $\lambda_{133}>0$	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$	666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

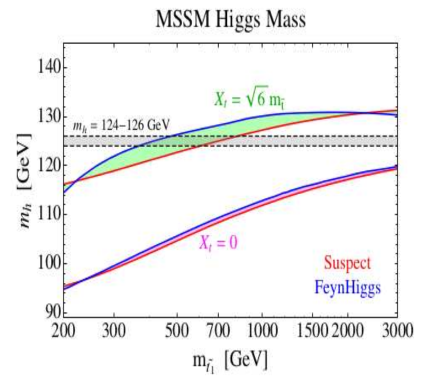
Natural SUSY

- Natural Supersymmetry: superparticles responsible for cancellation of quadratic divergence in Higgs mass are the third generation squarks, can be comparatively light to cure the fine-tuning problem of SM.

$$\begin{aligned} m_h^2 &= m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}(1 - \frac{X_t^2}{12M_S^2})\right) \\ M_S^2 &= m_{\tilde{t}_1} m_{\tilde{t}_2} \\ X_t &= A_t - \mu \cot\beta \end{aligned}$$

- Lighter stop/sbottom : large stop/sbottom tri-linear couplings.
- $m_h \sim 125$ GeV for maximal $L - R$ mixing $X_t = \sqrt{6} M_S$

[talk by Carlos Wagner, SUSY 2013]

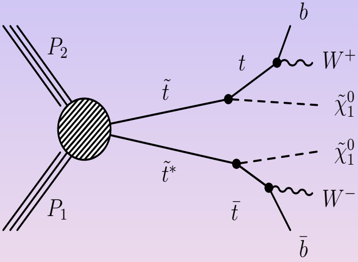


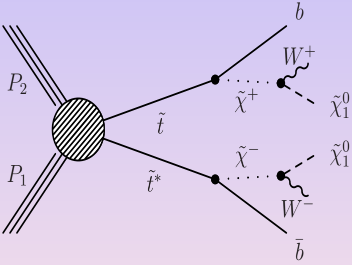
[L.J.Hall et.al, JHEP 04, 131 (2012)]

- Light third generation scenario has an extremely attractive prospect for both the theorists and the experimentalists

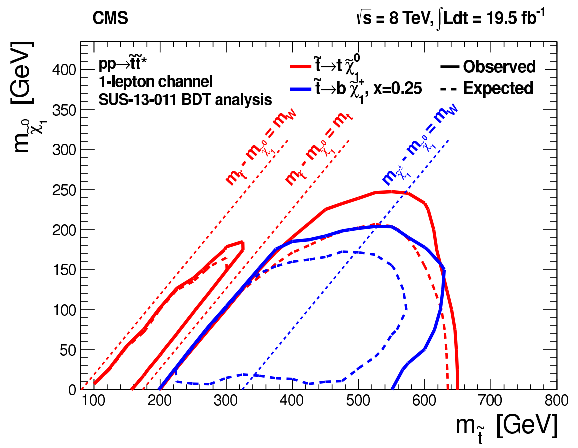
Stop search @LHC

Di-stop production resulting in $b\bar{b}W^+W^- + \not{E}_T$ in two possible intermediate steps:



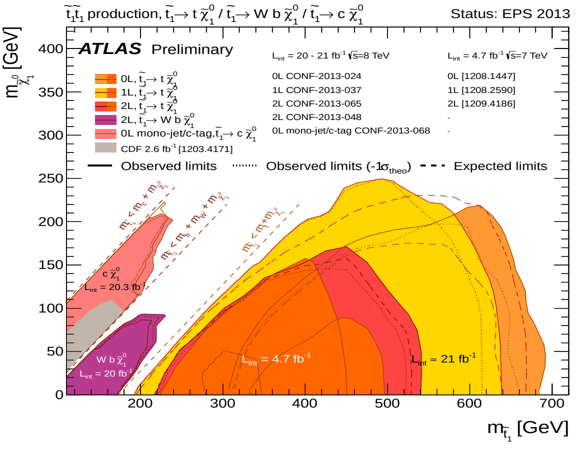


Stop search @LHC



[see also talk by J. Richman in susy 2013]

Stop search @LHC

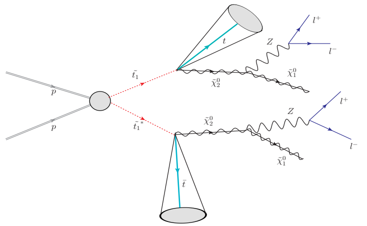


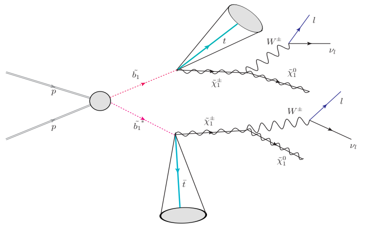
[see also talk by J. Boyd in susy 2013]

Our Strategy

- Most phenomenological studies assume predominantly right handed stops/sbottom decaying as $\widetilde{\mathrm{t}} \rightarrow \mathrm{t}\widetilde{\chi}_1^0$ and $\widetilde{\mathrm{b}}_1 \rightarrow \mathrm{b}\widetilde{\chi}_1^0$
- Decay of top and bottom squarks to the heavier neutralinos and charginos are quite motivated in natural SUSY spectrum.
- Easy to achieve with lighter stops/sbottoms predominantly left handed.
- We start with Stop and Sbottom pair production having a multi-leptonic final state.

Typical Process:





The Signature

- A hadronically decaying top quark, two additional hard leptons and missing transverse momentum (for both stop and sbottom).
- Relatively heavy stop/sbottom, large mass gap $\widetilde{\mathrm{b}}_1 - \widetilde{\chi}_1^{\pm}$ and $\widetilde{\mathrm{t}}_1 - \widetilde{\chi}_2^0$, sufficiently energetic top quark, apply Jet substructure.
- Two hard leptons with moderately large missing transverse energy, a clean signal.
- A hard cut on $\mathrm{M_{T2}}$: constructed using the momenta of two hard leptons and missing transverse energy, helps to combat the background.

NOTE:

1. ATLAS and CMS searched for electroweak gauginos, $\mathrm{pp} \rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \rightarrow \mathrm{W}\widetilde{\chi}_1^0\mathrm{Z}\widetilde{\chi}_1^0$, ruled out a range $\widetilde{\chi}_1^{\pm} = \widetilde{\chi}_2^0$ masses as a function of the LSP mass.
2. Second neutralino is always assumed to decay exclusively to the LSP and Z boson, limits will not apply directly when second neutralino has non zero branching ratio to the Higgs boson.

Choice of model parameters

1. We vary the left handed third generation mass parameter $\mathrm{m}_{\widetilde{\mathrm{Q}_3}}$ keeping $\mathrm{m}_{\widetilde{\mathrm{t}_\mathrm{R}}}$ = $\mathrm{m}_{\widetilde{\mathrm{b}_\mathrm{R}}}$ = 2 TeV.
2. M_3 = 1.5 TeV while M_1 and M_2 are varied providing various values of $\widetilde{\chi}_\mathrm{i}^0$ and $\widetilde{\chi}_\mathrm{i}^\pm$
3. Higgsino mass parameter μ = 300 GeV and tanβ is fixed at 10.
4. A_t = -2800 GeV, keeping other Trilinear coupling set to zero.
5. $\mathrm{m}_{\widetilde{\mathrm{Q}_\mathrm{i}}}$ =$\mathrm{m}_{\widetilde{\ell}}$ = 5 TeV.
6. To generate the particle spectrum we use SuSpect, while decay/branching ratios are calculated using SUSYHIT.

Benchmark Points

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

NOTE: Two scenarios:: Second lightest neutralino dominantly decays via Z boson (benchmarks P2, P3, P6) and/or it decays dominantly via the Higgs (benchmarks P1, P4, P5).

Signal & Background

$$\begin{array}{ccccccccc}
pp & \rightarrow & \widetilde{t}_1\,\widetilde{t}_1^* & \rightarrow & t\bar{t}\widetilde{\chi}_2^0\,\widetilde{\chi}_2^0 & \rightarrow & t\,\bar{t}+2Z+2\widetilde{\chi}_1^0 & \rightarrow & t/\bar{t}+\ell\,\ell+\not{p}_{\mathrm{T}} \\
pp & \rightarrow & \widetilde{t}_1\,\widetilde{t}_1^* & \rightarrow & t\,\bar{b}\,\widetilde{\chi}_2^0\,\widetilde{\chi}_1^- & \rightarrow & t\,\bar{b}+W^-Z+2\widetilde{\chi}_1^0 & \rightarrow & t+\ell\,\ell+\not{p}_{\mathrm{T}} \\
pp & \rightarrow & \widetilde{b}_1\,\widetilde{b}_1^* & \rightarrow & t\,\bar{t}\,\widetilde{\chi}_1^+\chi_1^- & \rightarrow & t\,\bar{t}+W^+W^-+2\chi_1^0 & \rightarrow & t/\bar{t}+\ell\,\ell+\not{p}_{\mathrm{T}} \\
pp & \rightarrow & \widetilde{b}_1\,\widetilde{b}_1^* & \rightarrow & t\,\bar{b}\,\widetilde{\chi}_1^-\chi_2^0 & \rightarrow & t\,\bar{b}+W^-Z+2\chi_1^0 & \rightarrow & t+\ell\,\ell+\not{p}_{\mathrm{T}}\,.
\end{array}$$

- Signal: Two hard leptons associated with atleast a top quark,and missing transverse momentum.
- SM backgrounds: $t\bar{t}+n\ jets$, $t\bar{t}Z$, $t\bar{t}W$, tbW,$t\bar{t}t\bar{t}$, $t\bar{t}WW$.
- We also check, tW and tZ events, do not contribute to the background.

Selection Cuts I

- C1: At least two isolated leptons (electron and muon) with the transverse momentum $\mathrm{p}_{\mathrm{T}}^{\ell} \geq 25$ GeV and the pseudo-rapidity $|\eta| \leq$ 3.
- C2: Impose $\mathrm{M}_{\mathrm{T2}} > 125$ GeV

$$\mathrm{M}_{\mathrm{T2}}(\overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell_1}, \overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell_2}, \overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}}) = \min_{\overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}} = \overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}}^{1} + \overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}}^{2}} \left[\max\{\mathrm{M}_{\mathrm{T}}(\overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell_1}, \overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}}^{1}), \mathrm{M}_{\mathrm{T}}(\overrightarrow{\mathrm{p}}_{\mathrm{T}}^{\ell_2}, \overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}}^{2})\} \right]$$

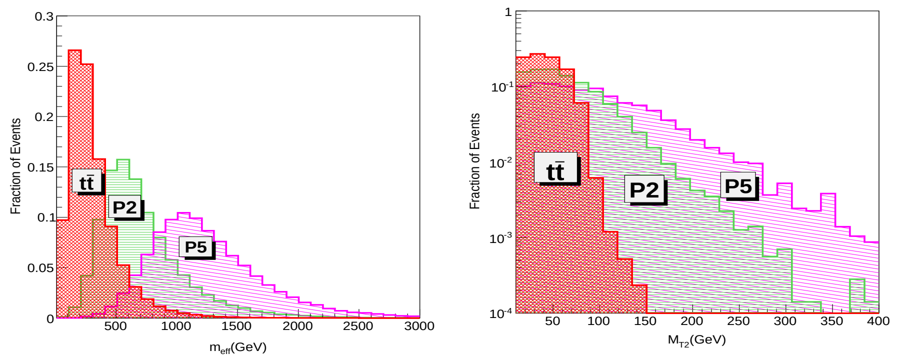
where ℓ_1 and ℓ_2 are the two hard leptons and $\mathrm{M}_{\mathrm{T}}(\overrightarrow{\mathrm{v}}_1, \overrightarrow{\mathrm{v}}_2)$ is the transverse mass of the $(\overrightarrow{\mathrm{v}}_1, \overrightarrow{\mathrm{v}}_2)$ system which is defined as

$$\mathrm{M}_{\mathrm{T}}(\overrightarrow{\mathrm{v}}_1, \overrightarrow{\mathrm{v}}_2) = \sqrt{2|\overrightarrow{\mathrm{v}}_1|\,|\overrightarrow{\mathrm{v}}_2|(1 - \cos\phi)},$$

ϕ being the (azimuthal) angle between $\overrightarrow{\mathrm{v}}_1$ and $\overrightarrow{\mathrm{v}}_2$ while $\overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}}^{1}$ and $\overrightarrow{\not{\mathrm{p}}}_{\mathrm{T}}^{2}$ are a hypothetical split of the total observed missing transverse momentum into two parts.

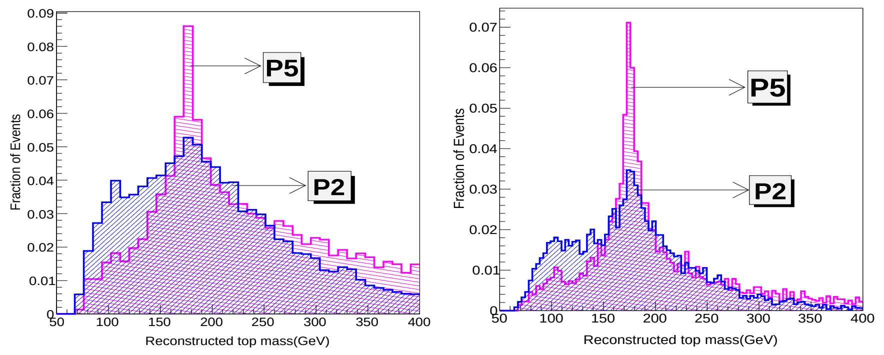
Selection Cuts II

- C3: Define $m_{eff} = \Sigma p_T^j + \Sigma p_T^\ell$, where the first sum runs over all the hard jets and the second sum is over all the hard and isolated leptons present in an event.
  We choose $\mathrm{m_{eff}} > 800$ GeV.



Selection Cuts III

- C4: Our signal final state consists of a number of stable neutralinos and neutrinos, a moderately hard missing transverse momentum cut $\not{p}_{\mathrm{T}} > 150$ GeV.
- C5: At least one top quark reconstructing its invariant mass using the jet substructure technique.
  (Johns Hopkins top tagger with the choice of the parameters $\mathrm{R} = 1.5$, $\delta_{\mathrm{p}} = 0.10$ and $\delta_{\mathrm{r}} = 0.19$)


Fraction of Events
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
50
100
150
200
250
300
350
400
Reconstructed top mass(GeV)
P5
P2
Fraction of Events
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
50
100
150
200
250
300
350
400
Reconstructed top mass(GeV)
P5
P2

Signal & Background events

			No. of events after the cut					
Signal	Production Cross-section (fb)	Simulated events (in units of 10^4)	C1	C2	C3	C4	C5	$\sigma_S \times 10^2$(fb)
P1	1130	10	10573	821	339	267	55	62.2
P2	1130	10	11091	657	248	205	55	62.2
P3	135	5	8043	1132	712	645	153	41.3
P4	27	5	7713	1207	749	663	153	41.3
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	$\sigma_B \times 10^2$(fb)
$t\bar{t}+$ jets	918000	4320	1587596	601	39	29	4	8.5
tbW	61000	600	215807	80	4	2	1	1.0
$t\bar{t}Z$	1121	7	6255	253	52	20	2	3.2
$t\bar{t}W$	769	5	4471	31	3	2	1	1.5
$t\bar{t}W^+W^-$	10	1	1588	33	14	13	6	0.6
$t\bar{t}t\bar{t}$	10	1	1781	31	14	10	4	0.4
Total Background								15.2

Results

		Signal($\mathrm{N_S}$) (Background($\mathrm{N_B}$))			Significance($\mathcal{S}$) for $\kappa = 10\%$ ($30\%, 50\%$)		
	$m_{\tilde{t}_1}$ (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	6.2(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)
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	4.1(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)
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)

- To take into account the theoretical uncertainty in the estimation of different SM backgrounds, jet energy measurement etc. we calculate significance in the following way :
- Signal significance : $\mathcal{S} = \frac{\mathrm{N_S}}{\sqrt{\mathrm{N_B} + (\kappa \mathrm{N_B})^2}}$

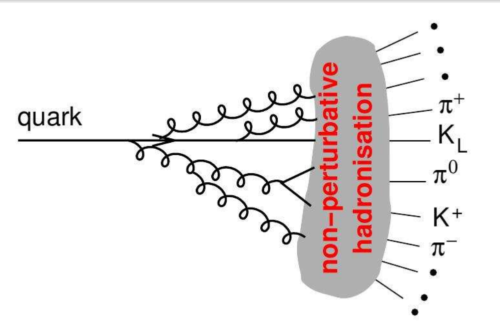
Conclusions

- A Standard Model like Higgs boson of mass $m_h \simeq 125$ GeV has been discovered at the LHC .
- Current Higgs data $\Longrightarrow$ light 3^{rd} Generation SUSY particles
- stop and sbottom have been probed up to 650 GeV depending on the decay.
- 14 TeV LHC run will have a rich program to discover the stop and sbottom.
- Signal studied : A top quark with two hard leptons along with substantial missing energy.
- Method used : M_{T2}, m_{eff} and jet substructure technique to hadronically decaying top quark.
- Outcome : the third generation squarks with masses $\sim$ 900 GeV can be probed at the 14 TeV LHC with a $100\ \text{fb}^{-1}$ data set.

Thank You!

Backup Slides

Jets: Footprints of Partons



Jets can serve two purposes:

They can be **observables**, that one can calculate and measure in an experiment.
They can be **Tools** that one can employ to extract specific properties of the final state.

Construction of Jets

- The Construction of Jets is ambiguous.

Why ?

1. Which particles get together into a common Jet?

⇒ There is NO Unique way to group hadrons.

⇒ **JET Algorithm**

2. How to combine the particles?

⇒ **Recombination Scheme**

• Most Commonly used: Direct 4-Vector sum (E Scheme)

Jet Algorithm + Recombination Scheme = Jet Definition

Jet Algorithms

- Jets Algorithms are broadly of two classes:
  - **Cone Algorithms :**
  - **Sequential Recombination Algorithms**

Jet Algorithms ....Contd

- **Sequential Recombination Algorithms**

Sequential Recombination Algorithm repeatedly combine closest pair of particles into a single one, according to some distance measurement.

The most general form:

d_{ij}= min$(p_{T_i}^{2a}, p_{T_j}^{2a})\Delta R_{ij}{}^2/R^2$

$d_{iB} = p_{T_i}^{2a}$

Where, $\acute{}\mathbf{R_{ij}}^{\mathbf{2}}$=$(\mathbf{y_i} - \mathbf{y_j})^{\mathbf{2}} + (\phi_{\mathbf{i}} - \phi_{\mathbf{j}})^{\mathbf{2}}$

- a = 1: k_t algorithm
- a = 0: Cambridge/Aachen algorithm
- a = -1: Anti-k_t algorithm
- y : Pseudo-rapidity.
- Φ : Azimuthal angle

R : Sets the minimal interjet separation in the y-ϕ plane

Sequential algorithm

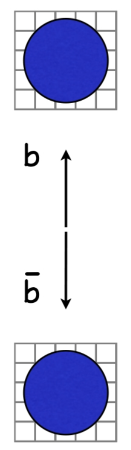
1. Start with list of particles
2. Calculate distance between all pairs of particles using d_{ij} and the beam distance for each particles using d_{iB}
3. Find the minimum distance in the set $\{d_{iB}, d_{ij}\}$
4. If the minimum is d_{ij}, recombine i and j into a single new particle $(p_k = p_i + p_j)$ and return to step 1
5. Otherwise, if the minimum is d_{iB} declare i to a jet and remove it from the list of particles
6. Stop when no particles remain

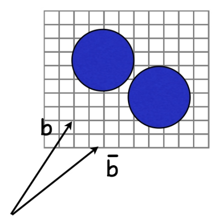
- Arbitrarily soft particles can form jets $\Longrightarrow p_{T\,\mathrm{min}}^{\mathrm{jets}}$ for hard physics

Sequential algorithm

- d_{ij} determines the order in which particles are merged in the jet with recombinations that minimizes d_{ij} first
- k_t algorithm tends to merge low-p_T particles earlier
- CA merges pairs in strict angular order
- Anti-k_t tends to cluster particles with hard p_T earlier producing jet with less interesting substructure

No Boost vs Boost





$m_H = 120$ GeV, $p_T \gtrsim 200 - 300$ GeV $\Longrightarrow$ large boost $\Longrightarrow$

$\Delta R \approx 2m_H/p_T \approx 1.2 - 0.8$

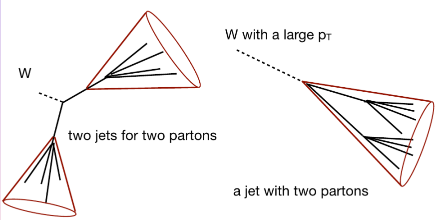
$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

$H \rightarrow b\bar{b}$ at rest $\Longrightarrow$ Two back to back jets

G. Kribs talk @ Fermilab (2011)

Fat jets

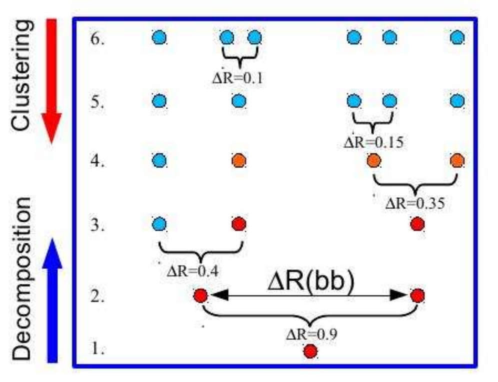
- Quantitatively, consider the following thumb rule for a two-body decay: To resolve the two partons of a X → q $\bar{q}$ decay,choose a radius (or more generally a jet size) of $\mathrm{R} < 2M_X / P_T$
- For $P_T \gg M_h$ $R \rightarrow$ very small (Overlap of Jet areas !)
- **These highly boosted jets are called "Fat Jets"**
- Example: Consider a hadronically decaying W Boson..



- Question : How do I see the inside of this fat jet ?

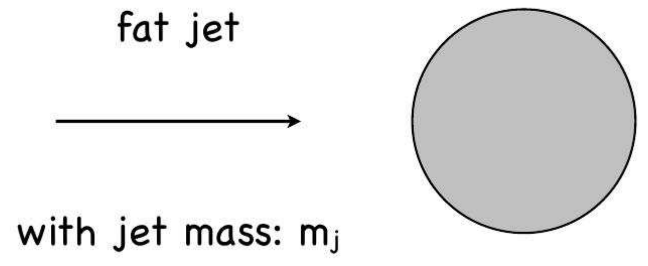
Jet Substructure

The basis of this technique involves an iterative jet clustering algorithm (e.g C/A), examining subjet kinematics step-by-step, and finally choosing the “best“ subjets to form the fat-jet mass.



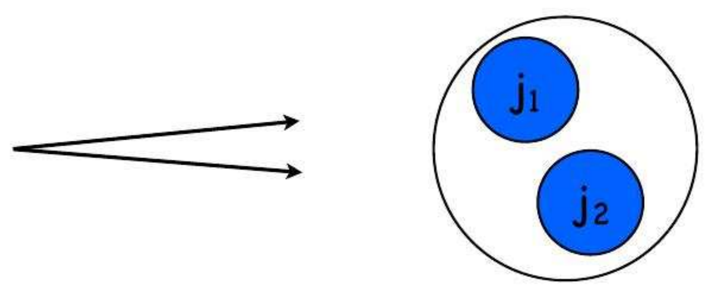
**Ref: Phys. Rev. Lett. 100.242001, Butterworth, Davison, Rubin & Salam

Jet Decomposition 1



Jet Decomposition 2

Step 1: Break the jet j into two subjets(j_1,j_2) by undoing its last stage of clustering s.t $m_{j_1} > m_{j_2}$.



Jet Decomposition 3

Step 2: a) Significant mass drop (MD),

$$m_{j_1} < \mu m_j$$

b) Splitting is nearly Symmetric

$$y = [min(P^2_{T_{j_1}}, P^2_{T_{j_2}})/m^2_j]\Delta R^2_{j_1,j_2} > y_{cut}$$

- Two parameters μ and y_{cut} are independent of Higgs mass and Higgs p_t.
- $$\mu = 0.667$$ $$y_{cut} = (0.3)^2$$

$\Rightarrow$ Helps to reject/minimize QCD contamination.

Jet Decomposition 4

Step 3: If y$>$ y_{cut}, consider j as heavy particle neighborhood and exit the loop.

Otherwise

Redefine j to be j_1 and go back to Step 1.

In practice, above procedure is not optimal for LHC, when the transverse momentum can be around 250-300 GeV.
Since,

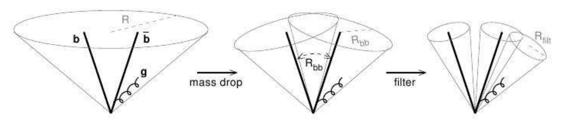
$$m_x \sim 150 \text{ GeV} \quad \Rightarrow \quad R_{j_1,j_2} \sim 1.0 \rightarrow \text{Large}$$

$\Rightarrow$ Significant degradation due the Underlying Events (UE)

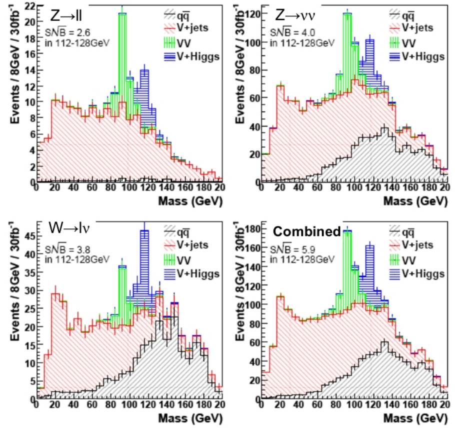
$\rightarrow$ UE $\propto R^4_{j_1,j_2}$

Filtering

- To minimize UE contamination $\Rightarrow$ Filter the subjets j_1, j_2 within a finer angular region, $R_{filt} < R_{j_1,j_2}$
- Consider 3 hardest p_T subjets 2b & gluon
- Most Effective result (In the context of Higgs search) $\Rightarrow$ $R_{filt} = min(R_{j_1,j_2}/2, 0.3)$
- (provided, both the subjets have tagged b's)



Application : $pp \to VH, \ (V = W^{\pm}, Z)$



- $pp \to VH$, with $V = W^{\pm}, Z \Longrightarrow$
- $\ell\nu b\bar{b}$, $\ell\ell b\bar{b}$, $\nu\bar{\nu}b\bar{b}$ final state
- For Higgs to be boosted $p_T(H) > 200$ GeV
- Such a high $p_T(H) \Longrightarrow$ $\sigma_{\rm boosted}(WH/ZH) \sim$ 5% of $\sigma_{\rm tot}(WH/ZH)$ @ 14 TeV

- ATLAS simulation @14 TeV with $30 {\rm fb}^{-1}$ luminosity : $N_S(m_H \sim 120 \ {\rm GeV}) \sim 13.5$ and $N_B \sim 20.3 \Longrightarrow \frac{S}{\sqrt{B}} = 3$

[J.Buttherworth *etal.*, PRL (2008)], ATL-PHYS-PUB-2009-088, G. Kribs talk @ Fermilab (2011)

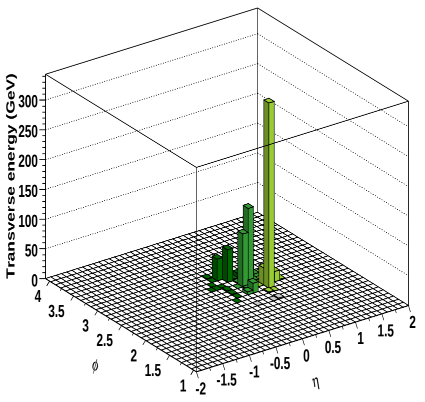
Top Tagging using Jet Substructure technique

- Particles are clustered into jets of size R using CA algorithm.
- Each fat jet in the event (for $t\bar{t}$ this would be one of the two hardest two) is declustered, to look into subjets.
- Done by reversing each step in the CA clustering, iteratively separating each jet into two objects.
- Demand $p_T(i)/p_T(J) > \delta_p$, else throw away softer jet.
- Continue declustering until one of four things happens:

1. Both objects are harder than δ_p.
2. Both objects are softer than δ_p.
3. the two objects are too close, $\mid \Delta\eta \mid + \mid \Delta\phi \mid < \delta_r$, where δ_r is an additional parameter.
4. or there is only one calorimeter cell left.

D.E. Kaplan etal. PRL 101, 142001 (2008)

Top Tagging using Jet Substructure technique



D.E. Kaplan etal. PRL 101, 142001 (2008)

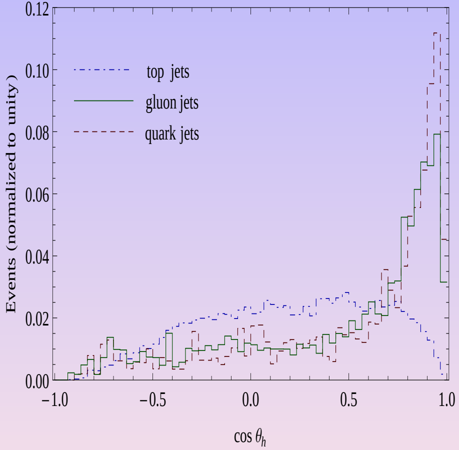
Top Tagging using Jet Substructure technique

- In case of (1), the two hard objects are considered subjets.
- In cases (2), (3), and (4), the original jet is considered irreducible.

- If an original jet declusters into two subjets, the previous step is repeated on those subjets $\Longrightarrow$ 2,3,or 4 subjets of the original jet.
- The cases with 3 or 4 subjets are kept, the 4th representing an additional soft gluon emission, while the 2 subjets are rejected.

- Demand : $M_{3j/4j} \simeq m_t$.
- Demand : $M_{2j} \simeq m_W$.
- Finally we demand that the W helicity angle satisfy $\cos\theta_h < 0.7$.
- For top jets, the distribution is flat, W decays on-shell, its decay products are isotropically distributed in the W-rest frame.
- The light quark/ gluon jets distribution diverges as $1/(1 - \cos\theta_h)$.

Top Tagging using Jet Substructure technique



D.E. Kaplan etal. PRL 101, 142001 (2008)