E_6SSM vs MSSM gluino phenomenology

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Introduction

Supersymmetry (SUSY) is a popular theory of physics beyond the Standard Model (SM) because by extending the Lorentz symmetry in the only possibly way you find

- A solution to the SM hierarchy problem,
- A dark matter (DM) canditate,
- An indication of a grand unification theory (GUT)
- A support for String Theory

SUSY has to be tested model by model. The simplest, most studied variant, the constrained variant of the minimal supersymmetric standard model (MSSM), is already largely excluded. To test more complicated SUSY models than the constrained MSSM or MSSM one needs to change current search strategies. The study presented here investigates the differences of gluino decays in MSSM and the E_6 inspired supersymmetric standard model (E_6SSM).

E_6SSM

In MSSM there is a bilinear Higgs coupling, μ, which needs to be in the TeV order to give an acceptable electroweak symmetry breaking (EWSB). Naturally, this SUSY preserving coupling would be zero or of the order of the Planck scale. To naturally get a μ of order 1 TeV one may extend MSSM with a scalar field S, which couples to the Higgs fields through the interaction $\lambda S H_u H_d$ and then let S get a VEV, $\langle S\rangle \equiv \frac{s}{\sqrt{2}}$.

$$\frac{\lambda s}{\sqrt{2}} H_u H_d \leftrightarrow \mu H_u H_d$$

A consequence of this is that one has introduced a global U(1) Peccei-Quinn (PQ) symmetry and broken it to end up with a so far unobserved massless axion. There are various proposed solutions:

- In NMSSM a cubic term S^3 is added to break the global PQ U(1) to a descrete Z_3 symmetry. The breaking of this Z_3 could however lead to cosmological domain walls which would overclose the universe.
- In USSM the U(1) is gauged and a massive Z' boson appear instead but the theory is not anomaly free.
- In E_6SSM the gauged U(1)' is a remnant of the breaking of a larger gauge group at the GUT scale - E_6. Anomalies are cancelled naturally since the particles forms complete 27's of E_6.

The E_6 is broken down to the standard model with one extra surviving $U(1)$:

$$E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi \times U(1)_\psi \to SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$$

Each SM generation is contained in a 27 and it is the singlet, S, and the two Higgs doublets, H_u and H_d, of the third 27 that is assumed to acquire VEVs. The particle content is much bigger in the E_6SSM than in the MSSM or USSM because of these three 27's. For example six more, naturally light, neutralino states are introduced in addition to the six neutralinos of the USSM. This provides an interesting gluino phenomenology.

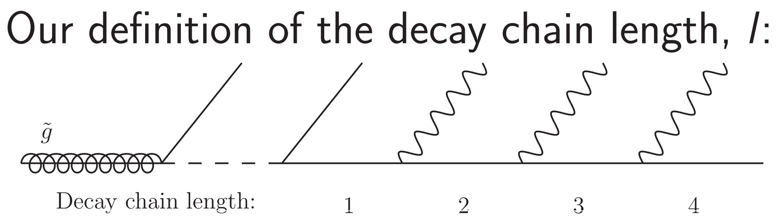
Parameter spaces

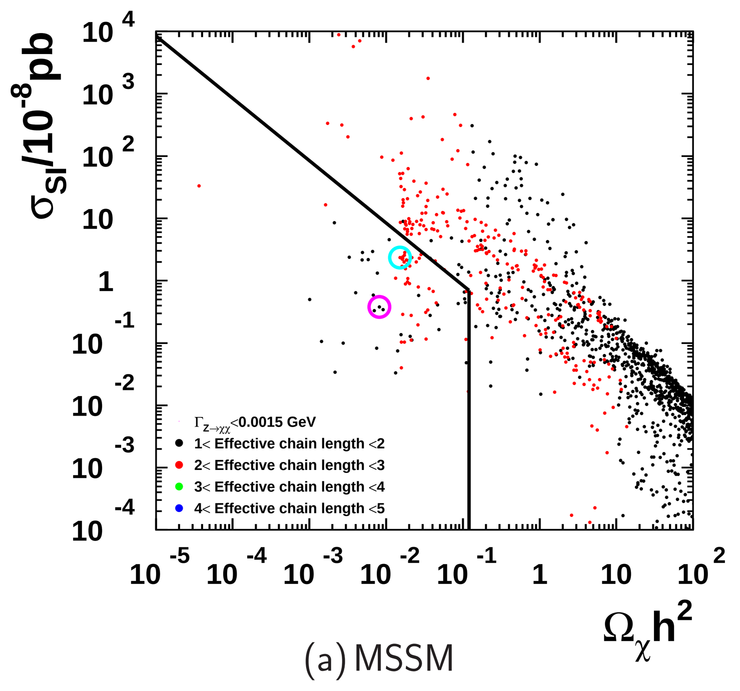
The recent XENON100 experiment puts a bound on the direct detection cross sections for the LSP and WMAP puts a bound on its relic density. These constraints excludes large portions of the parameter space for SUSY theories. Parameter scans has been performed to pick out benchmarks for further analysis which satisfy these constraints as well as constraints from collider experiments.

parameter	MSSM min	MSSM max	E_6SSM min	E_6SSM max	
$\tan\beta$	2	60	1.4	2	
$\lvert\lambda\rvert$	-	-	0.3	0.7	
s	-	-	2	5	[TeV]
μ	-2	2	-	-	[TeV]
$A_t = A_b = A_\tau = A_\mu$	-3	3	-3	3	[TeV]
M_A	0.1	2	1	3	[TeV]

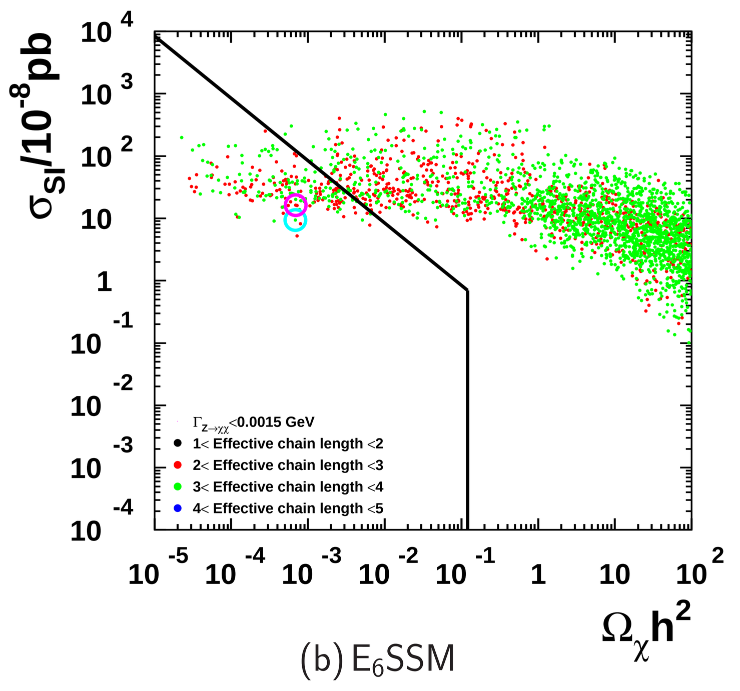
Table: The scanning region. To be able to compare the models on a common basis the gaugino masses were fixed so that a gluino mass close to 800 GeV and a lightest chargino mass close to 300 GeV were provided. A common squark and slepton mass scale was fixed to $M_S = 2$ TeV. For the E_6SSM a large number of Yukawa couplings were scanned over which is omitted from this table.

Our definition of the decay chain length, l:





(a) MSSM



(b) E_6SSM

Figure: The scanned regions of the parameter spaces projected onto the plane spanned by the spin independent cross section, σ_{SI}, and the relic density, Ωh^2. The area right of the solid line is excluded by XENON100 and WMAP. The colouring represents the effective gluino decay chain length $l_{eff} = \sum_l l \cdot P(l)$ for each point, where $P(l)$ is the probability for a chain length of l, as defined in the diagram above. The chosen benchmarks are encircled: MSSM-A and E_6SSM-A in cyan and MSSM-A and E_6SSM-A in magenta. These points do not provide a sufficient amount of dark matter and another source of dark matter is assumed in this study.

References

- *S. F. King, S. Moretti and R. Nevzorov*, Phys. Rev. D **73** (2006) 035009 [arXiv:hep-ph/0510419].
- *J. P. Hall and S. F. King*, JHEP **0908** (2009) 088 [arXiv:0905.2696].
- *J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher*, Phys. Rev. D **83** (2011) 075013 [arXiv:1012.5114].
- *A. Belyaev, J. P. Hall, S. F. King and P. Svantesson*, (in preparation).

Benchmarks

	MSSM-A	MSSM-B	E_6SSM-A	E_6SSM-B	
$\tan\beta$	9.9	39.2	1.42	1.77	
λ	-	-	0.65	-0.4767	
s	-	-	3099	3187	[GeV]
μ	-112.6	1578	(1425)	(-1074)	[GeV]
$A_t = A_b = A_\tau$	-724.6	-566.1	-2684	476.2	[GeV]
M_A	1593	302.5	2791	2074	[GeV]
M_1	150	150	150	150	[GeV]
M_2	285	285	300	300	[GeV]
$M_{1'}$	-	-	151	151	[GeV]
$m_{\tilde g}$	800.3	800.2	800.0	800.0	[GeV]
$m_{\tilde\chi^0_{M1}}$	94.1	148.9	148.6	151.2	[GeV]
$m_{\tilde\chi^0_{M2}}$	128.8	302.8	294.6	303.7	[GeV]
$m_{\tilde\chi^0_{M3}}$	163.0	1580	1434	1066	[GeV]
$m_{\tilde\chi^0_{M4}}$	323.5	1581	1452	1068	[GeV]
$m_{\tilde\chi^\pm_{M1}}$	112.2	302.8	298.6	300.9	[GeV]
$m_{\tilde\chi^\pm_{M2}}$	323.5	1582	1427	1076	[GeV]
$m_{\tilde\chi^0_{U1}}$	-	-	1040	1110	[GeV]
$m_{\tilde\chi^0_{U2}}$	-	-	1215	1254	[GeV]
$m_{\tilde\chi^0_{E1}}$	-	-	43.5	45.2	[GeV]
$m_{\tilde\chi^0_{E2}}$	-	-	48.6	53.2	[GeV]
$m_{\tilde\chi^0_{E3}}$	-	-	131.3	141.6	[GeV]
$m_{\tilde\chi^0_{E4}}$	-	-	163.6	187.4	[GeV]
$m_{\tilde\chi^0_{E5}}$	-	-	197.0	227.8	[GeV]
$m_{\tilde\chi^0_{E6}}$	-	-	224.3	265.6	[GeV]
$m_{\tilde\chi^\pm_{E1}}$	-	-	119.9	122.7	[GeV]
$m_{\tilde\chi^\pm_{E2}}$	-	-	185.8	225.1	[GeV]
m_h	120.4	119.0	133.8	116.3	
$P(l=1)$	0.09847	0.188	$< 10^{-5}$	$< 10^{-5}$	
$P(l=2)$	0.4705	0.812	0.01524	0.1723	
$P(l=3)$	0.387	0	0.2336	0.7986	
$P(l=4)$	0.04387	0	0.7512	0.02915	
$P(l=5)$	$< 10^{-4}$	0	$< 10^{-7}$	0	
Ωh^2	0.01513	0.00816	0.0006842	0.0006937	
σ_{SI}	2.35×10^{-8}	0.3808×10^{-8}	9.35×10^{-8}	16.35×10^{-8}	[pb]

Table: Benchmarks chosen from the parameter scans presented in Figure 1 and Table 1. The $\tilde\chi^{0(\pm)}_{Mi}$ are MSSM-like states, the $\tilde\chi^0_{Ui}$ are USSM-like states, being mainly mixtures of $\tilde S$ and $\tilde B'$. The $\tilde\chi^{0(\pm)}_{Ei}$ are states introduced by the inert sector of E_6SSM. The scale for squark and slepton masses are M_S=2 TeV in all benchmarks.

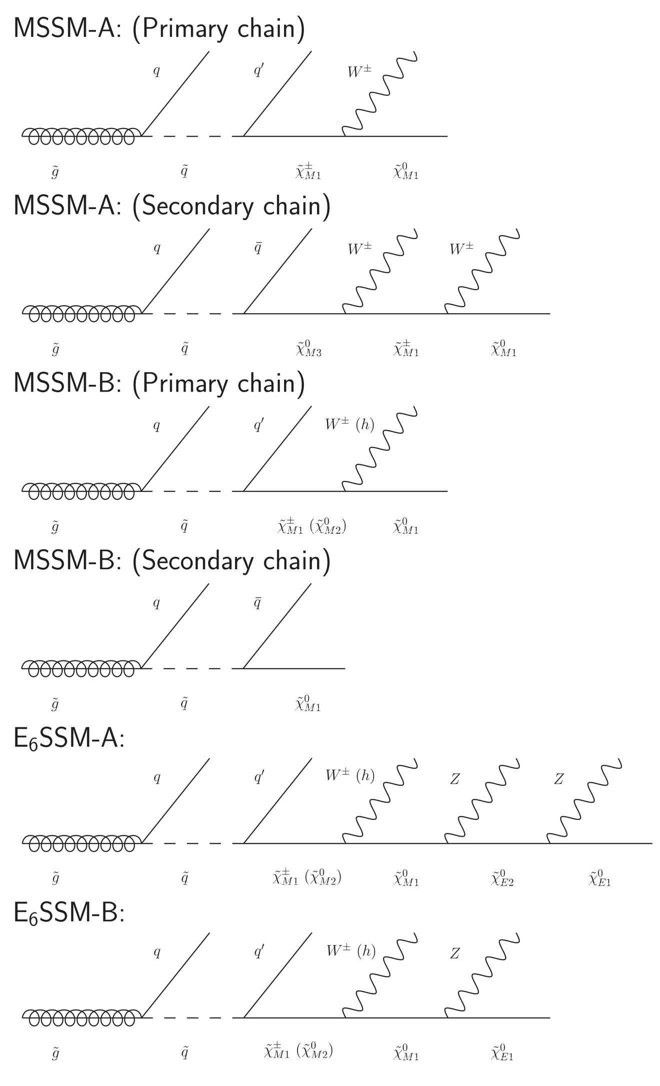


Figure: Feynman diagrams for the leading gluino decay chains for each benchmark. In E_6SSM-A the two lightest neutralinos are closely degenerate and the last radiated Z-boson is produced off-shell.

Event analysis

Since the E_6SSM introduces new neutralinos, naturally lighter than the MSSM LSP, the gluino decay chains will be longer than the MSSM's in general. This is confirmed and illustrated by the parameter scans and benchmarks above. An effect of longer decay chains is that there will be less missing momenta in collider experiments. Another important feature is the increase in lepton multiplicity as well as jet multiplicity. An effective variable for distinguishing models with different gluino decay chain lengths, like the MSSM and the E_6SSM is $\not{p}_T/M_{eff}$ or even better, $\not{p}_T/\sum_{visible}|p_T^{visible}|$.

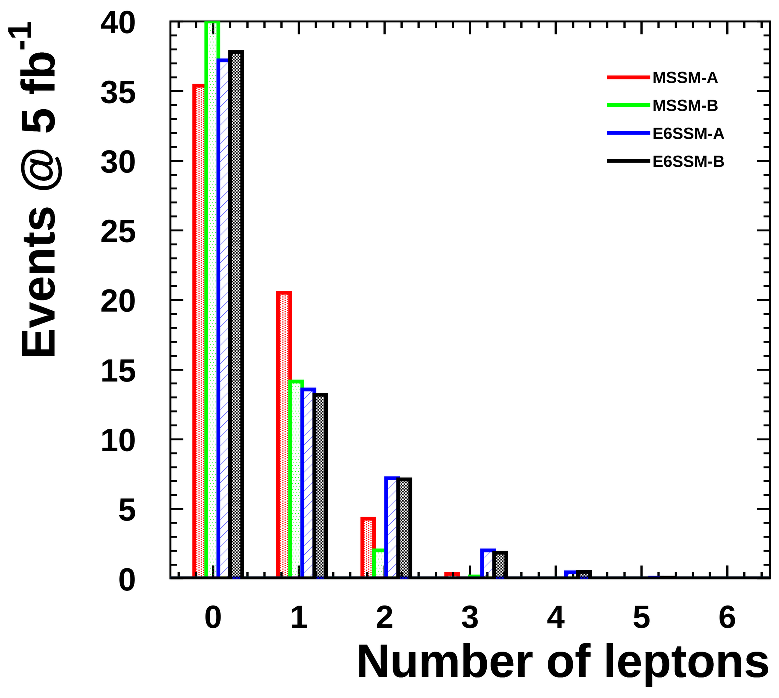


Figure: Lepton multiplicity before selection cuts. $p_T > 15$ GeV was used for lepton identification.

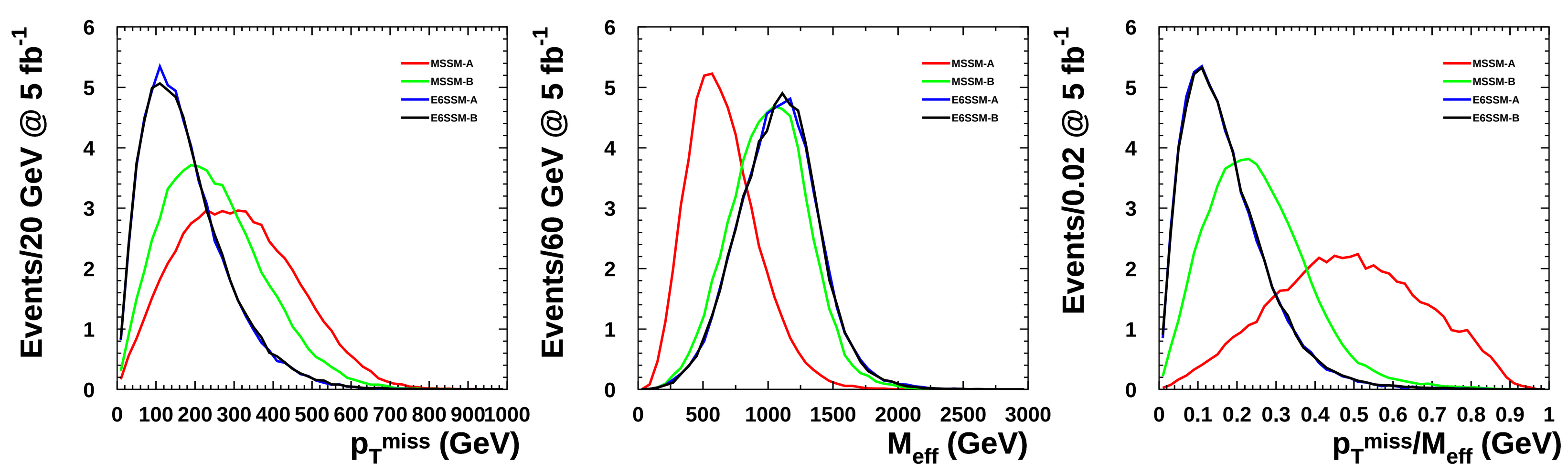


Figure: Missing transverse momentum, $\not{p}_T$, the effective mass, M_{eff} and their ratio before selection cuts.

No.	CUT limit	MSSM-A Eff.	MSSM-A Frac.	MSSM-B Eff.	MSSM-B Frac.	E_6SSM-A Eff.	E_6SSM-A Frac.	E_6SSM-B Eff.	E_6SSM-B Frac.
0	no cut	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1	$\not{p}_T$ >130	0.12	0.88	0.19	0.81	0.40	0.60	0.40	0.60
2	$p_T^{jet_1}$ >130	0.42	0.51	0.04	0.77	0.03	0.58	0.03	0.59
3	$p_T^{jet_2}$ >40	0.13	0.44	0.01	0.76	0.00	0.58	0.00	0.58
4	$p_T^{jet_3}$ >40	0.36	0.28	0.11	0.68	0.04	0.56	0.04	0.56
5	$p_T^{jet_4}$ >40	0.55	0.13	0.20	0.54	0.11	0.50	0.11	0.50
6	$\Delta\phi(\not{p}_T, jet)_{min} > 0.4$	0.28	0.09	0.37	0.34	0.59	0.20	0.58	0.21
7	$\not{p}_T/M_{eff}$ >0.25	0.15	0.08	0.49	0.17	0.69	0.06	0.68	0.07

Table: *ATLAS style cuts*: The efficiency (fraction of events removed my the cut) and fraction of events left after 0 to 7 cuts applied.

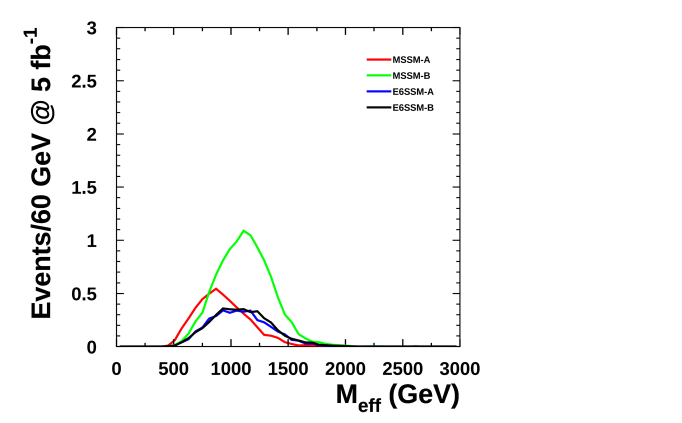


Figure: The effective mass after 7 ATLAS style cuts

No.	CUT limit	MSSM-A Eff.	MSSM-A Frac.	MSSM-B Eff.	MSSM-B Frac.	E_6SSM-A Eff.	E_6SSM-A Frac.	E_6SSM-B Eff.	E_6SSM-B Frac.
0	no cut	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1	$\not{H}_T > 200$ GeV	0.58	0.42	0.34	0.66	0.47	0.53	0.47	0.53
2	$p_T^{jet_1}$ >50 GeV	0.00	0.42	0.00	0.66	0.00	0.53	0.00	0.53
3	$p_T^{jet_2}$ >50 GeV	0.13	0.37	0.02	0.64	0.01	0.52	0.01	0.53
4	$p_T^{jet_3}$ >50 GeV	0.43	0.21	0.13	0.56	0.06	0.49	0.06	0.50
5	$\Delta\phi(\not{p}_T, jet_1) > 0.5$	0.02	0.21	0.02	0.55	0.03	0.48	0.03	0.48
6	$\Delta\phi(\not{p}_T, jet_2) > 0.5$	0.05	0.19	0.08	0.50	0.12	0.42	0.12	0.42
7	$\Delta\phi(\not{p}_T, jet_3) > 0.3$	0.04	0.19	0.07	0.47	0.10	0.38	0.10	0.38
8	$\Delta R(jet, lep)_{min} < 0.3$	0.18	0.15	0.24	0.36	0.37	0.24	0.36	0.25
9	$H_T > 800$ GeV	0.88	0.02	0.49	0.18	0.38	0.15	0.38	0.15

Table: *CMS style cuts*: The efficiency (fraction of events removed my the cut) and fraction of events left after 0 to 9 cuts applied.

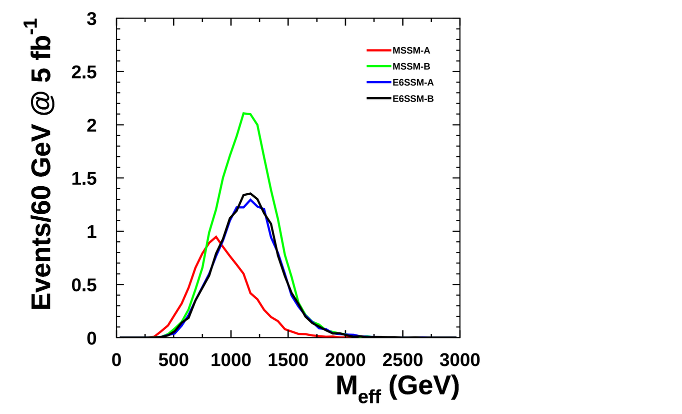


Figure: The effective mass after 8 CMS style cuts

Conclusions

Careful analysis has to be made to distinguish SUSY models. The models studied here are very different but conventional cuts and the effective mass makes them blend into each other. Cuts on $\not{p}_T$ and $\not{p}_T/M_{eff}$ or equivalents are severe for models with long decay chains like the E_6SSM. The E_6SSM has large visible and small missing p_T. The effect of these features cancels in M_{eff}, while it is enhanced in $\not{p}_T/\sum_{visible}|p_T^{visible}|$. Requiring leptons is also an important task when identifying models like the E_6SSM.

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