SUSY LHC signatures without prejudice

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Outline

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SUSY must be broken

- Exact SUSY means every particle has a partner with exactly the same properties (except spin).
- Most if not all of these partners would have been discovered by now if they exist.
- Therefore, if SUSY exists, it is broken and sparticles are heavy.

A lot of freedom

- Unbroken SUSY is economical–no new parameters!
- Most general SUSY-breaking introduces 105 new parameters.
- Theoretical considerations and/or experimental constraints can reduce this number.

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Handling MSSM parameter space

In an ideal world, we could examine signatures of 105-dimensional space in detail. This is impractical.

Top-down approaches

- One can adopt a constraining theoretical assumption (usually on high-scale parameters).
- This is often a specific SUSY-breaking model.
- Pros: highly constraining ($\lesssim$ 5 params.), theoretically motivated.
- Cons: Many different possible scenarios, correlations in spectrum/observables.

Handling MSSM parameter space

In an ideal world, we could examine signatures of 105-dimensional space in detail. This is impractical.

Bottom-up approaches

- One can instead restrict the low-energy parameter space to a phenomenologically viable subset.
- Assumptions are typically made to automatically satisfy flavor and CP-violation observables, in particular.
- Pros: no reliance on unproven theoretical assumptions, physically motivated.
- Cons: Parameter space is still large unless some additional assumptions are made.

The breadth of the MSSM

Because of practical limitations, we may not have explored all interesting regions of the MSSM. The above approaches have been limited to certain corners of parameter space, and we have only seen a subset of signatures. We would like, though, to be ready for anything at the LHC and beyond.

Our goal

Is it feasible to study MSSM parameter space in full generality? Our goal is to take a step towards that. We:

- Use a bottom-up approach, taking the minimum set of phenomenologically motivated assumptions;
- Randomly scan the broadest possible range of parameter space;
- Check each point against all experimental constraints;
- And investigate the properties and signatures of the remaining models.

Berger, Gainer, Hewett, and Rizzo; JHEP 0902:023,2009

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Phenomological assumptions

- CP-conserving
- minimal flavor violation
- degenerate 1st & 2nd gen. sfermions
- neglect 1st and 2nd generation Yukawas

These assumptions are motivated by observation.

Scanning the MSSM parameter space

After applying our assumptions

- We're left with 19 real, weak-scale parameters (pMSSM).
- We scan 10^7 points.

$$100\,\mathrm{GeV} \leq m_{\tilde{f}} \leq 1\,\mathrm{TeV}$$
$$50\,\mathrm{GeV} \leq |M_{1,2}, \mu| \leq 1\,\mathrm{TeV}$$
$$100\,\mathrm{GeV} \leq M_3 \leq 1\,\mathrm{TeV}$$
$$|A_{b,t,\tau}| \leq 1\,\mathrm{TeV}$$
$$1 \leq \tan\beta \leq 50$$
$$43.5\,\mathrm{GeV} \leq m_A \leq 1\,\mathrm{TeV}$$

Outline

Enforcing theoretical and experimental constraints

Theoretical constraints

- No tachyons, no charge- or color-breaking minima, consistent EWSB
- LSP is lightest neutralino and thermal relic

Experimental constraints

- Precision electroweak and flavor measurements
- Relic density $<$ WMAP value
- Dark matter direct detection
- LEP and Tevatron sparticle and Higgs searches
  - Required the use of fast detector simulation

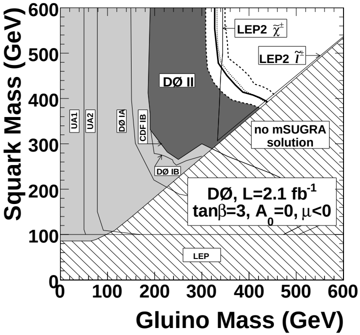
Tevatron multijet plus missing energy constraint

To be model-independent required a full Monte Carlo study.

Preselection Cut	All Analyses		
$\not\!\!E_T$	≥ 40		
$\lvert$Vertex z pos.$\rvert$	< 60 cm		
Acoplanarity	$< 165°$		
Selection Cut	**"dijet"**	**"3-jets"**	**"gluino"**
Trigger	dijet	multijet	multijet
jet$_1$ p_T[a]	≥ 35	≥ 35	≥ 35
jet$_2$ p_T[a]	≥ 35	≥ 35	≥ 35
jet$_3$ p_T[b]	–	≥ 35	≥ 35
jet$_4$ p_T[b]	–	–	≥ 20
Electron veto	yes	yes	yes
Muon veto	yes	yes	yes
$\Delta\phi(\not\!\!E_T, \text{jet}_1)$	$\geq 90°$	$\geq 90°$	$\geq 90°$
$\Delta\phi(\not\!\!E_T, \text{jet}_2)$	$\geq 50°$	$\geq 50°$	$\geq 50°$
$\Delta\phi_{\min}(\not\!\!E_T, \text{any jet})$	$\geq 40°$	–	–
H_T	≥ 325	≥ 375	≥ 400
$\not\!\!E_T$	≥ 225	≥ 175	≥ 100

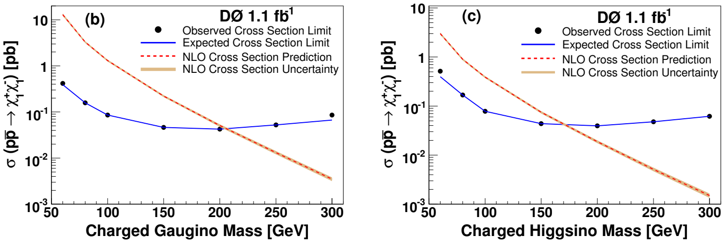
[a] First and second jets are also required to be central ($|\eta_{\text{det}}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.

[b] Third and fourth jets are required to have $|\eta_{\text{det}}| < 2.5$, with an electromagnetic fraction below 0.95.



Outside MSUGRA, constraints can be weaker!

Tevatron stable chargino search



- We have many charginos nearly degenerate with the LSP, so this is an important constraint.
- We interpolate between Wino and Higgsino bounds for arbitrary charginos.

Survival rates

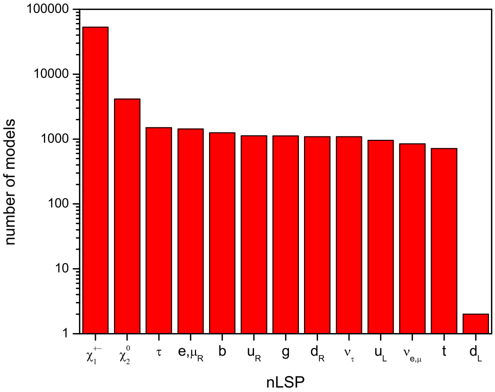
file	Description	Percent of Models Remaining
slha-okay.txt	SuSpect generates SLHA file	99.99 %
error-okay.txt	Spectrum tachyon, other error free	77.29%
lsp-okay.txt	LSP the lightest neutralino	32.70 %
deltaRho-okay.txt	$\Delta\rho$	32.61 %
gMinus2-okay.txt	$g-2$	21.69 %
b2sGamma-okay.txt	$b \to s\gamma$	6.17 %
Bs2MuMu-okay.txt	$B \to \mu\mu$	5.95 %
vacuum-okay.txt	No CCB, potential not UFB	5.92 %
Bu2TauNu-okay.txt	$B \to \tau\nu$	5.83 %
LEP-sparticle-okay.txt	LEP sfermion checks	4.72 %
invisibleWidth-okay.txt	Invisible Width of Z	4.71 %
susyhitProb-okay.txt	Heavy Higgs not problematic for SUSY-HIT	4.69 %
stableParticle-okay.txt	Tevatron stable chargino search	4.19 %
chargedHiggs-okay.txt	LEP/ Tevatron charged Higgs search	4.19 %
neutralHiggs-okay.txt	LEP neutral Higgs search	0.84 %
neutralHiggs-marginal.txt	LEP neutral Higgs search (3 GeV)	0.89 %
directDetection-okay.txt	WIMP direct detection	1.32 %
directDetection-marginal.txt	WIMP direct detection within factor of 4	0.23 %
omega-okay.txt	Ωh^2	0.74 %
Bs2MuMu-2-okay.txt	$B \to \mu\mu$	0.74 %
stableChargino-2-okay.txt	Tevatron stable chargino search	0.72 %
triLepton-okay.txt	Tevatron trilepton	0.72 %
jetMissing-okay.txt	Tevatron jet plus missing	0.70 %
final-okay.txt	Final after cutting models with e.g. light stop, sbottoms	0.68 %

Only 0.68%, or 68,422 survive all constraints.

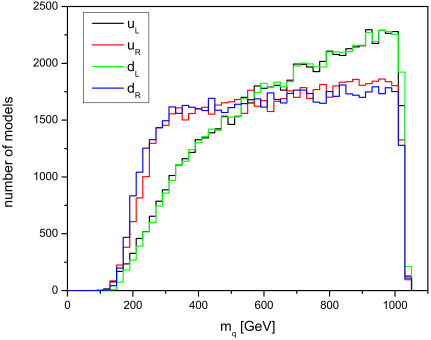
Outline

NLSP identity

The NLSP can be anyone!



Squark masses



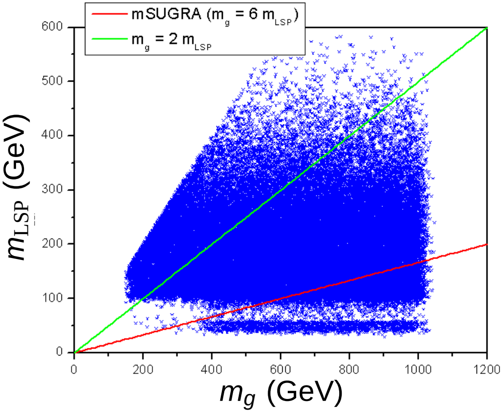
Squarks can be light

They can evade Tevatron constraints because of cascade decays, soft jets, or small cross sections.

Gluino mass

Gluino can be very light!

- LSP mass vs. gluino mass



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ATLAS SUSY analyses

To explore the signatures of the MSSM, we start by passing our entire set of $\sim 7 \times 10^4$ models through a standard set of analyses (arXiv:0901.0512), to see how they fare.

ATLAS analyses

- We use the ATLAS inclusive SUSY analyses.
- 2,3,4 jets; 1-lepton; SSDL; OSDL; trileptons; τ; b-jets...
- To check our analysis, we first compare to ATLAS results for the set of benchmark models they use.
- Then we will explore sensitivity of ATLAS (mSUGRA) analyses to our set of models.
- There are necessarily some differences between the ATLAS analysis and ours.

Comparison to ATLAS SUSY analyses

	ATLAS	**Us**
Spectrum & decays	ISASUGRA	SUSY-HIT[1]
Event generation, hadronization, and showering	HERWIG	PYTHIA
K-factors	Prospino	Prospino[2]
Detector simulation	full GEANT	PGS4 LHC tune
Backgrounds	Generated large set of SM processes	Obtained from ATLAS

[1] negative QCD corrections turned off
[2] negative K-factors fixed

Computationally intensive

Approaches to our LHC study, in order of increasing realism:

1. For all $7 \cdot 10^4$ models, do full detector simulation for 1 fb^{-1}.
   $7 \cdot 10^4$ weeks $\sim$ 1 millenium
2. For all $7 \cdot 10^4$ models, run PGS for 1 fb^{-1}
   $70 \cdot 10^4$ hours $\sim$ 1 century
3. For all $7 \cdot 10^4$ models, run PGS but cap high-cross section processes at $\sim 10^4$ events. $2 \cdot 10^4$ hours $\sim$ 2 years

Batch is your friend

The SLAC batch system is necessary to complete this in finite time, by analyzing many models simultaneously.

Workflow

For each model:

1. Generate spectrum and decay table with SUSY-HIT.
2. Generate K-factors with Prospino
3. Generate at least 10 and at most 10^4 events for each of 85 processes with Pythia and ATLAS-tuned PGS.
4. Pass PGS events for each process through analysis chain.
5. Zip and store events on SLAC ATLAS disk space. ☺
6. Take analysis results for each process, weight by NLO cross section, and combine into results for model.
7. Determine if signal-background difference is statistically significant; plot if desired.

Repeat 70,000 times!

Modifications to SUSY-HIT width and BR calculations

1. Turned off QCD corrections to avoid negative widths and BRs
2. Include 1st and 2nd generation particle masses
   1. 2 body decays: correct phase space
   2. 3 body decays: cutoff kinematically disallowed decays (consider hadronic final states)
3. Include exact formulae for close mass chargino decays
4. Remove models with Planck scale Higgs width HDECAY bug
5. Remove models with slightly off-shell $H \to h^* h$ HDECAY bug.

List of processes 1

Number	Final State Particles	PYTHIA Code
1	chi01, g	MSUB(237)=1
2	chi02, g	MSUB(238)=1
3	chi03, g	MSUB(239)=1
4	chi04, g	MSUB(240)=1
5	chi+1, g	MSUB(241)=1; PLUS
6	chi+2, g	MSUB(242)=1; PLUS
7	chi-1, g	MSUB(241)=1; MINUS
8	chi-2, g	MSUB(242)=1; MINUS
9	chi01, s	MSUB(246)=1; MSUB(247)=1
10	chi02, s	MSUB(248)=1; MSUB(249)=1
11	chi03, s	MSUB(250)=1; MSUB(251)=1
12	chi04, s	MSUB(252)=1; MSUB(253)=1
13	chi+1, s	MSUB(254)=1; PLUS PLUS
14	chi+2, s	MSUB(256)=1; PLUS PLUS
15	chi-1, s	MSUB(254)=1; MINUS MINUS
16	chi-2, s	MSUB(256)=1; MINUS MINUS
17	chi01, chi01	MSUB(216)=1
18	chi02, chi01	MSUB(220)=1
19	chi03, chi01	MSUB(221)=1
20	chi04, chi01	MSUB(222)=1
21	chi+1, chi01	MSUB(229)=1; PLUS
22	chi+2, chi01	MSUB(233)=1; PLUS
23	chi-1, chi01	MSUB(229)=1; MINUS
24	chi-2, chi01	MSUB(233)=1; MINUS
25	chi02, chi02	MSUB(217)=1
26	chi03, chi02	MSUB(223)=1
27	chi04, chi02	MSUB(224)=1
28	chi+1, chi02	MSUB(230)=1; PLUS

List of processes 2

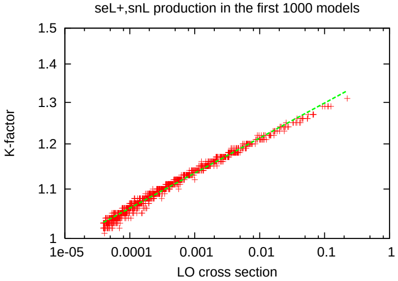
29	chi+2, chi02	MSUB(234)=1; PLUS
30	chi-1, chi02	MSUB(230)=1; MINUS
31	chi-2, chi02	MSUB(234)=1; MINUS
32	chi03, chi03	MSUB(218)=1
33	chi04, chi03	MSUB(225)=1
34	chi+1, chi03	MSUB(231)=1; PLUS
35	chi+2, chi03	MSUB(235)=1; PLUS
36	chi-1, chi03	MSUB(231)=1; MINUS
37	chi-2, chi03	MSUB(235)=1; MINUS
38	chi04, chi04	MSUB(219)=1
39	chi+1, chi04	MSUB(232)=1; PLUS
40	chi+2, chi04	MSUB(236)=1; PLUS
41	chi-1, chi04	MSUB(232)=1; MINUS
42	chi-2, chi04	MSUB(236)=1; MINUS
43	chi-1, chi+1	MSUB(226)=1
44	chi-2, chi+1	MSUB(228)=1; *
45	chi-1, chi+2	MSUB(228)=1; *
46	chi-2, chi+2	MSUB(227)=1
47	BLANK †	BLANK
48	seL, seL$_a$	MSUB(201)=1; MSUB(204)=1
49	seR, seR	MSUB(202)=1; MSUB(205)=1
50	snL, snL	MSUB(213)=1
51	seL+, snL	MSUB(210)=1; PLUS
52	seL-, snL	MSUB(210)=1; MINUS
53	stau1, stau1	MSUB(207)=1
54	stau2, stau2	MSUB(208)=1
55	stau1, stau2	MSUB(209)=1
56	sntau, sntau	MSUB(214)=1
57	stau1+, sntau	MSUB(211)=1; PLUS
58	stau1-, sntau	MSUB(211)=1; MINUS

List of processes 3

59	stau2+, sntau	MSUB(212)=1; PLUS
60	stau2-, sntau	MSUB(212)=1; MINUS
61	H+, H-	MSUB(301)=1
62	s, sbar	MSUB(274-280) = 1 (7 processes)
63	s, s	MSUB(271)=1; MSUB(272)=1; MSUB(273)=1
64	stop1, stop1	MSUB(261)=1; MSUB(264)=1
65	stop2, stop2	MSUB(262)=1; MSUB(265)=1
66	sbot1, sbot1	MSUB(287)=1; MSUB(289)=1
67	sbot2, sbot2	MSUB(288)=1; MSUB(290)=1
68	g, g	MSUB(243)=1; MSUB(244)=1
69	s, g	MSUB(258)=1; MSUB(259)=1
70	el,eR* + eR,eL* + muon analog †	MSUB(203)=1; MSUB(206)=1
71	t1. t2* + t1*, t2	MSUB(263)=1
72	b1, b2* + b1*, b2	MSUB(296)=1
73	b1, b1	MSUB(291)=1
74	b2, b2,	MSUB(292)=1
75	b1, b2	MSUB(293)=1
76	b, q	MSUB(281)=1; MSUB(282)=1; MSUB(283)=1
77	b, q*	MSUB(284)=1; MSUB(285)=1; MSUB(286)=1
78	b1, g	MSUB(294)=1
79	b2, g	MSUB(295)=1
80	Single Neutral Higgs	MSEL=19
81	Single Charged Higgs	MSEL=23
82	H+/- h	MSUB(297)=1
83	H+/- H	MSUB(298)=1
84	A h	MSUB(299)=1
85	A H	MSUB(300)=1

K-factors

Actually calculating K-factors for 85 processes for each model is too time-consuming.



- For non-QCD K-factors, we only calculate them for a thousand models.
- We use those to fit the K-factor as a function of the LO cross section.

Pythia and PGS

PYTHIA customizations

- We link LHAPDF and use CTEQ 6.6
- We generate processes (production channels) independently so we can consistently apply K-factors

PGS customizations

- We remove the isolation routine.
- ATLAS detector card.

ATLAS detector in PGS

Value	Comment
LHC	parameter set name
196	eta cells in calorimeter
126	phi cells in calorimeter
0.05	eta width of calorimeter cells
0.0499	phi width of calorimeter cells
0.007	electromagnetic calorimeter resolution const
0.1	electromagnetic calorimeter resolution * sqrt(E)
0.6	hadronic calolrimeter resolution * sqrt(E)
0.2	MET resolution
0.01	calorimeter cell edge crack fraction
cone	jet finding algorithm (cone or ktjet)
5.0	calorimeter trigger cluster finding seed threshold (GeV)
1.0	calorimeter trigger cluster finding shoulder threshold (GeV)
0.5	calorimeter kt cluster finder cone size (delta R)
2.0	outer radius of tracker (m)
2.0	magnetic field (T)
0.00005	sagitta resolution (m)
0.98	track finding efficiency
0.5	minimum track pt (GeV/c)
2.5	tracking eta coverage
2.5	e/gamma eta coverage
2.4	muon eta coverage
2.0	tau eta coverage

Analysis code

- We wrote our own analysis package using the R programming language.
- We implented ATLAS's:
  - Triggers
  - Lepton isolation
  - Analysis cuts
- It's easy to add and change routines, and because are events are stored we can re-analyze quickly

Advertisement for R

R is a great package and easy to use (and free). Lots of built in statistical methods that a theorist like me may never understand...

Super muons from SU2

Muon momentum reconstruction in PGS

1. Calculate sagitta from truth momentum.
2. Fluctuate sagitta with gaussian; take width from sagitta resolution.
3. Calculate measured momentum from fluctuated sagitta.

Hard muons can become super muons!

$p_T \gtrsim 1\ TeV \implies$ sagitta is of the order of the sagitta resolution. Thus arbitrarily small fluctuated sagitta $\implies$ arbitrarily big momentum!

Decay of 3 TeV smuon from SU2 should have made hard muons, but 60 TeV muons were a surprise! Shouldn't happen in our models.

Outline

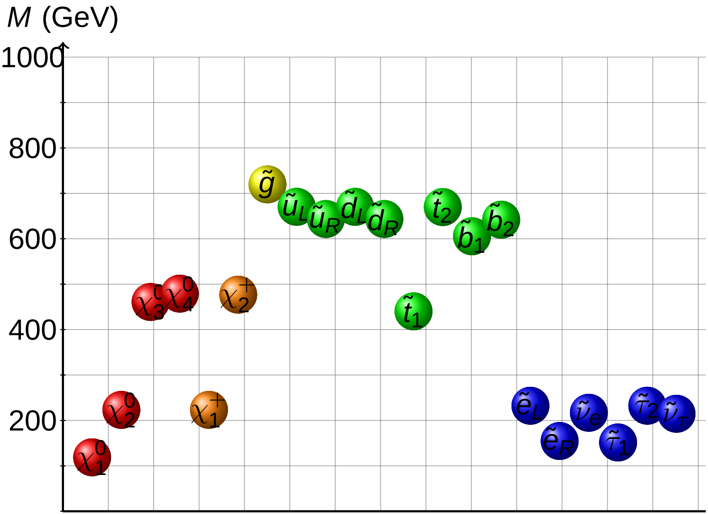
Verification of our analysis

ATLAS benchmarks

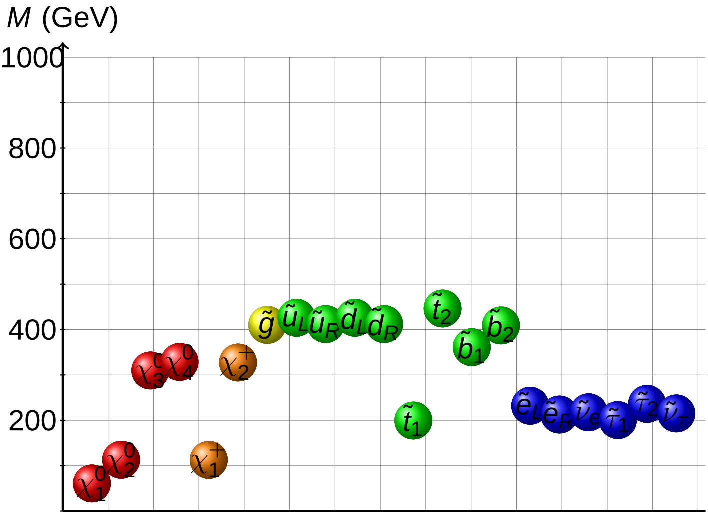
ATLAS used a set of SUSY models in all its analyses. They are labeled SU1, 2, 3, 4, 6, 8.1, and 9.

- We generated spectra and decay tables for these benchmark points.
- We ran them through all the analyses and compared to ATLAS.
- The results suggest our analyses reproduce the ATLAS analyses faithfully.

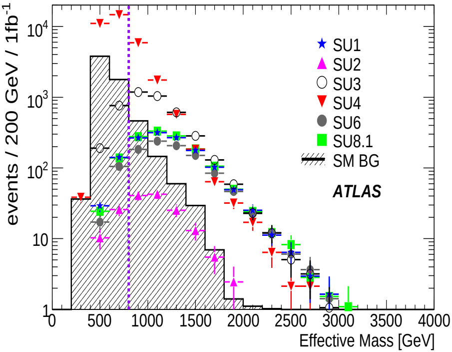
Example spectrum: SU3

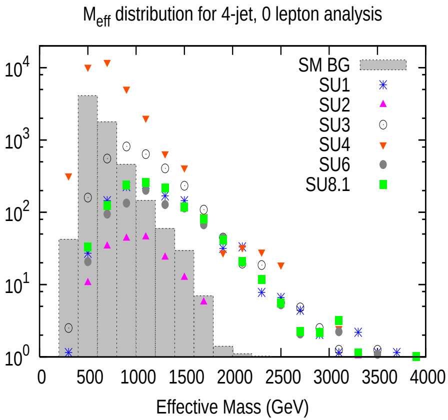


Example spectrum: SU4

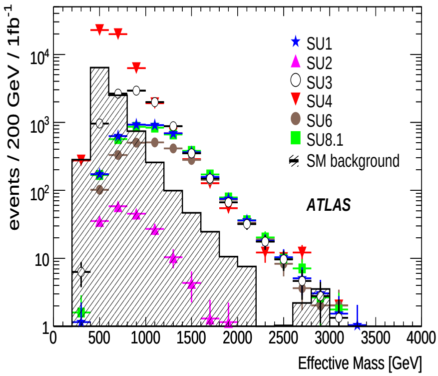


M_{eff} distribution for 4-jet analysis

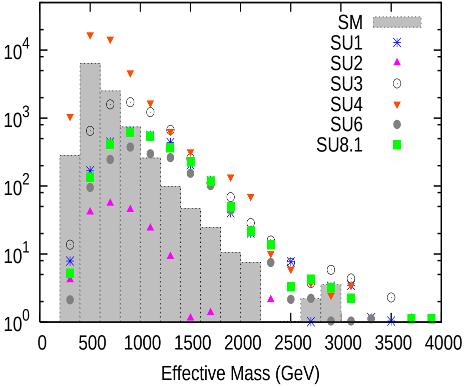




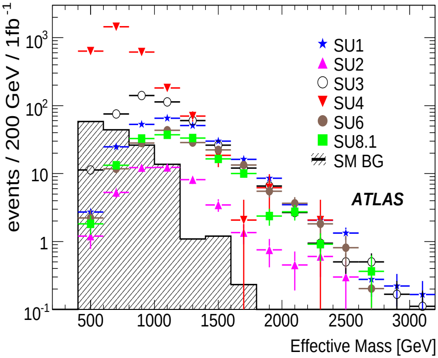
M_{eff} distribution for 2-jet analysis

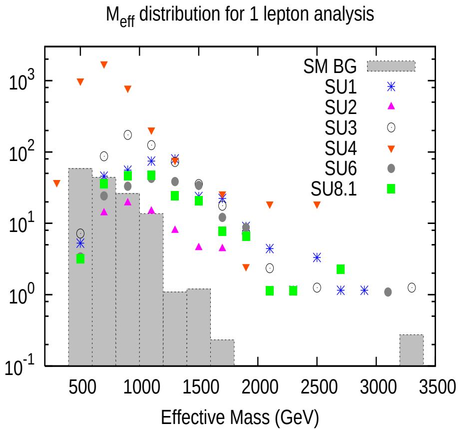


Meff distribution for 2-jet, 0 lepton analysis

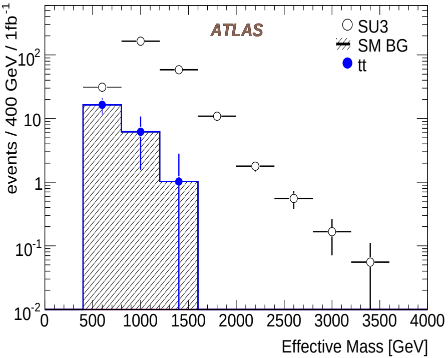


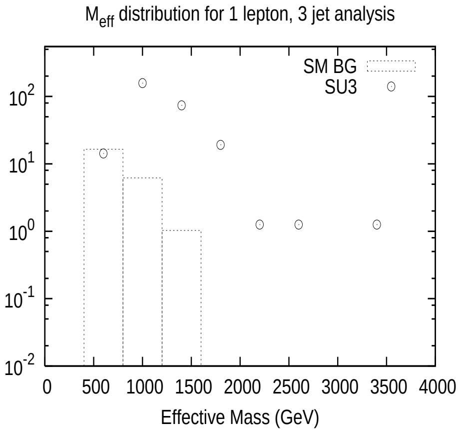
M_{eff} distribution for 1-lepton + 4 jet analysis



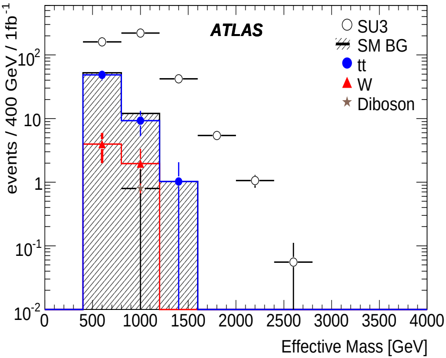


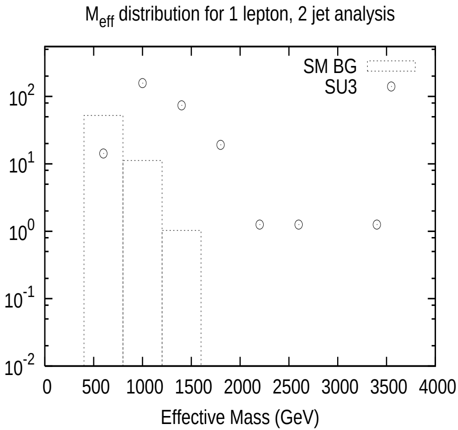
$M_{\rm eff}$ distribution for 1-lepton + 3 jet analysis



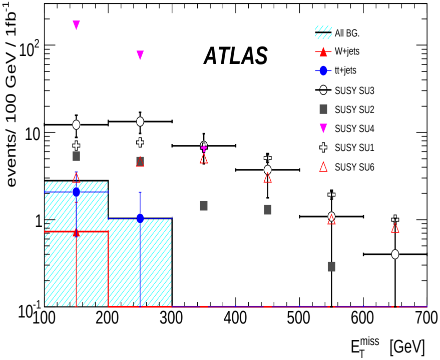


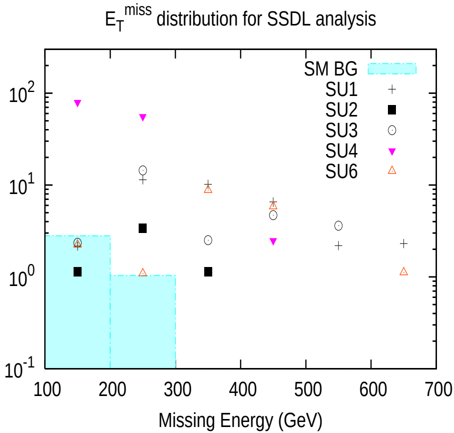
M_{eff} distribution for 1-lepton + 2 jet analysis



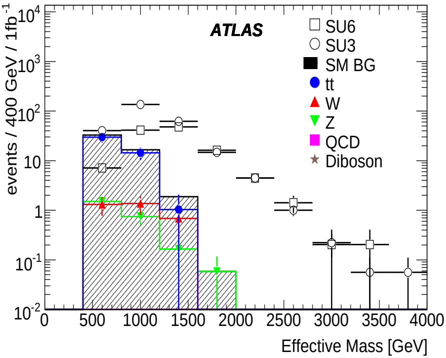


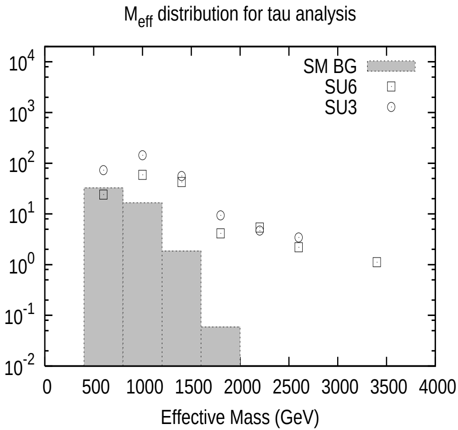
M_{eff} distribution for same-sign dilepton analysis



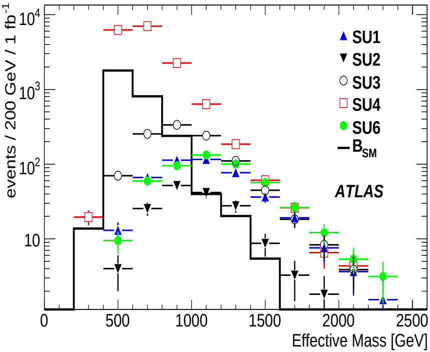


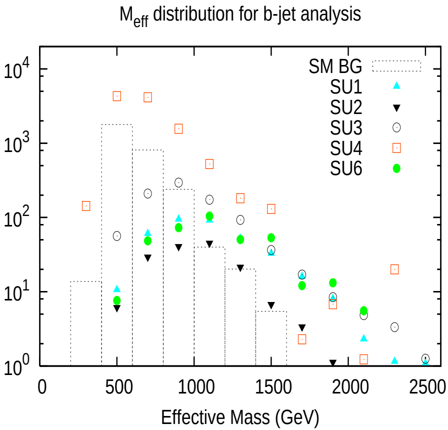
M_{eff} distribution for τ analysis





M_{eff} distribution for b-jet analysis





Outline

Status

Analyzing our models

- Passing all $\sim$ 70,000 models through analyses is underway.
- Because of computer time and aforementioned issues, it takes some time.

Preliminary results promising

We currently have results from 20,000 models.

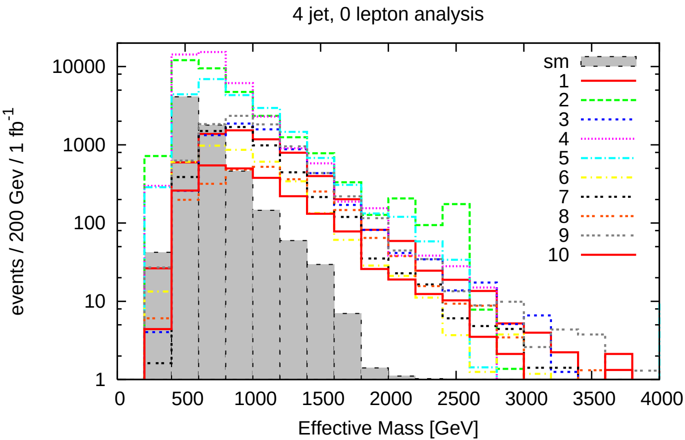
Ten random models

First we look at results from the first ten models off the top of the pile to get a sense of what the results can look like.

After that, we will take a more systematic look at the signatures of the model space.

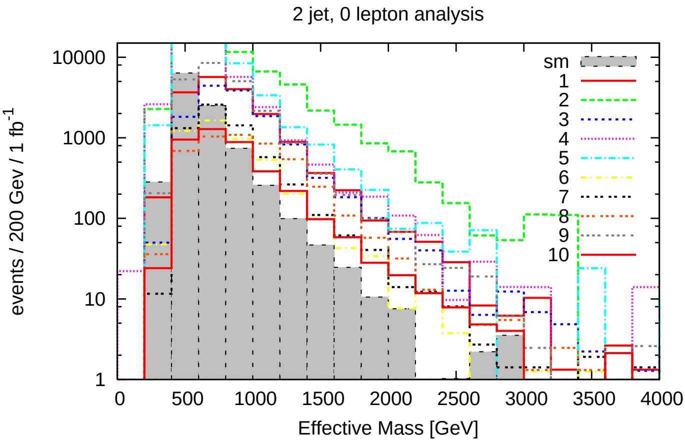
M_{eff} distribution for 4-jet analysis

Models 1-10



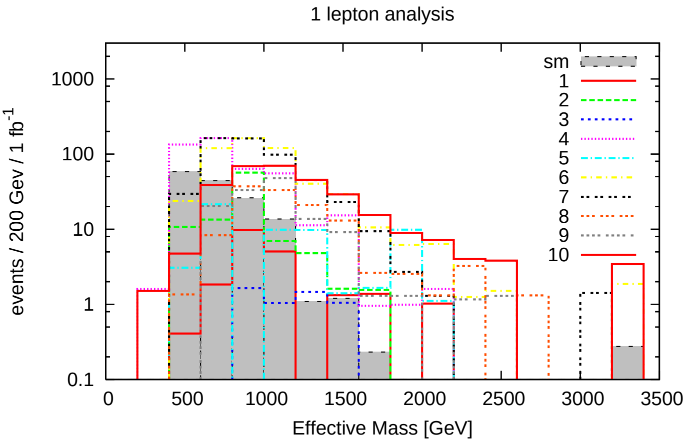
M_{eff} distribution for 2-jet analysis

Models 1-10



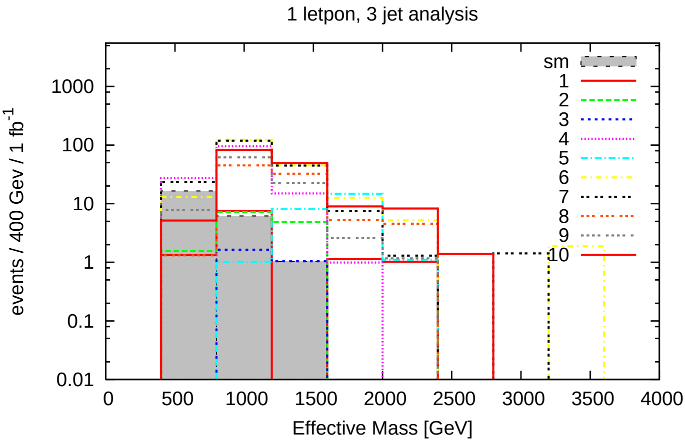
M_{eff} distribution for 1-lepton, 4 jet analysis

Models 1-10



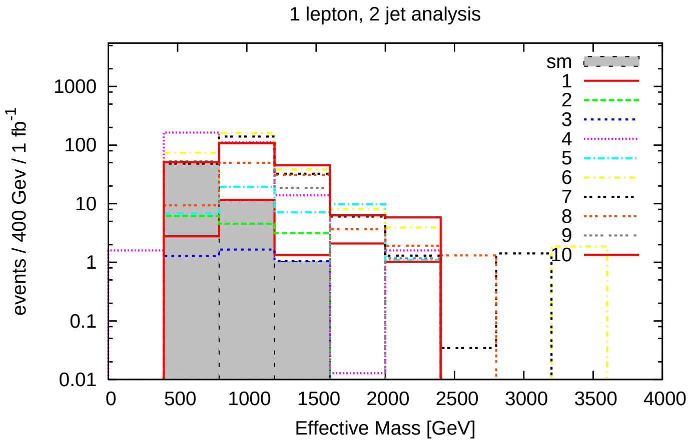
M_{eff} distribution for 1-lepton, 3 jet analysis

Models 1-10



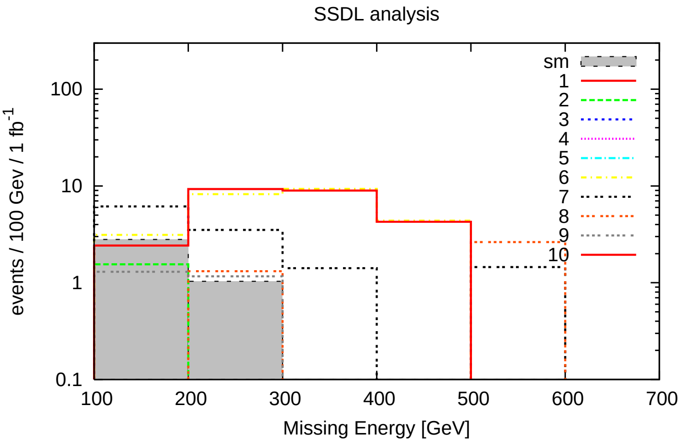
M_{eff} distribution for 1-lepton, 2 jet analysis

Models 1-10



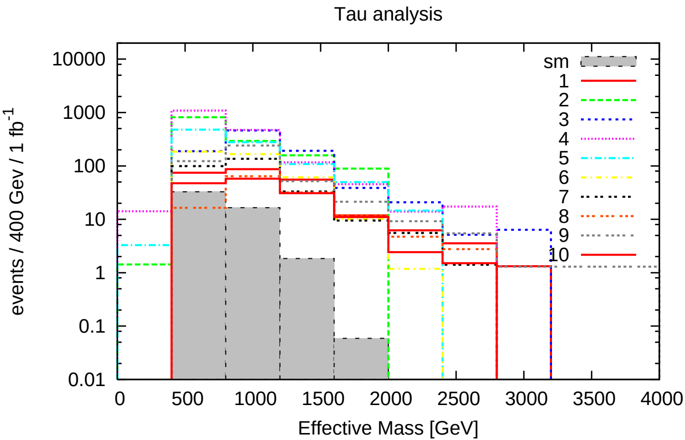
M_{eff} distribution for SSDL analysis

Models 1-10



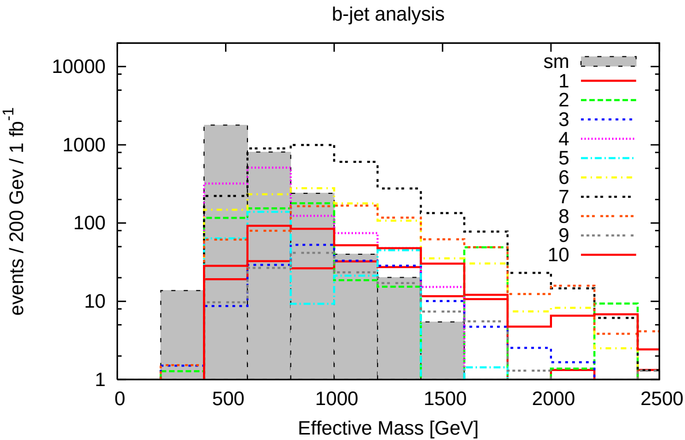
M_{eff} distribution for τ analysis

Models 1-10



$M_{\rm eff}$ distribution for b-jet analysis

Models 1-10



PYSTOPs

- In many models, Pythia errors $\rightarrow$ PYSTOP for one or more processes
- These models often feature close-mass decays
- Working hypothesis: caused by phase space issues in hadronization
- These models have been set aside for further study

Stable particles

- Many models have relatively long-lived particles
- If detector-stable, they don't show up in current analyses $\rightarrow$ will be subject to stable-particle searches
- If metastable on detector scales, our analysis does not treat these correctly $\rightarrow$ need to heavily modify PYTHIA and PGS to treat these decays right and, e.g. do displaced vertex studies
- Both of these are work in progress!

Performance of Analyses (2×10^4 models)

5σ bounds

First question: how many models cannot be discovered at 5σ by these analyses?

Determining significance

Take total signal and background events above an M_{eff} cut (for most analyses), and obtain χ^2 using statistical error and a 20% systematic error on the background.

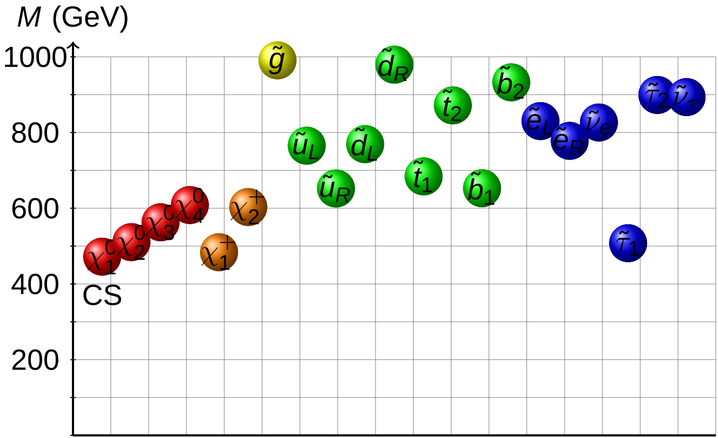
Performance of Analyses (2×10^4 models)

Percentage of models missed by ATLAS analyses		
Analysis	with PYSTOPS	without PYSTOPS
4 jets + M_{E_T}	2.62	1.53
2 jets + M_{E_T}	3.47	2.43
1 lepton + 4 jets + M_{E_T}	42.10	40.52
1 lepton + 2 jets + M_{E_T}	45.68	44.09
1 lepton + 3 jets + M_{E_T}	38.94	37.41
SSDL + 4 jets + M_{E_T}	78.73	76.99
τ + 4 jets + M_{E_T}	3.04	1.95
b jets + M_{E_T}	54.82	53.38
SSDL + 4 jets + M_{E_T}	92.42	90.62
3 leptons + jet	83.64	81.87
3 leptons + M_{E_T}	97.32	95.51

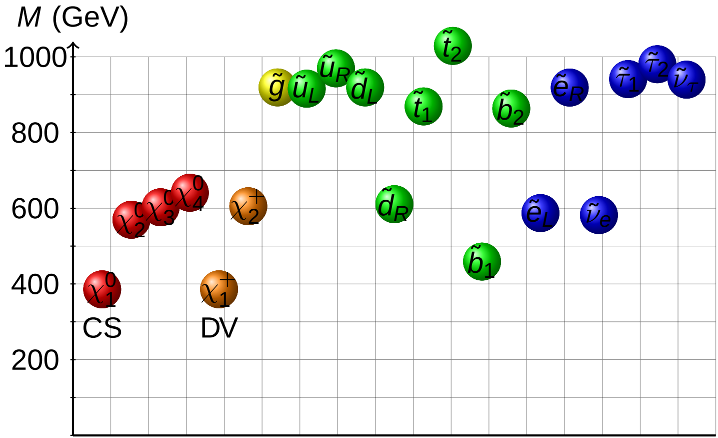
Models bad and good

Percentage of models missed by ATLAS analyses	
Number of analyses missed	% of models
0	2.87
1	3.55
2	5.07
3	10.22
4	17.54
5	16.56
6	5.83
7	13.89
8	23.42
9	0.78
10	0.19
11	0.09

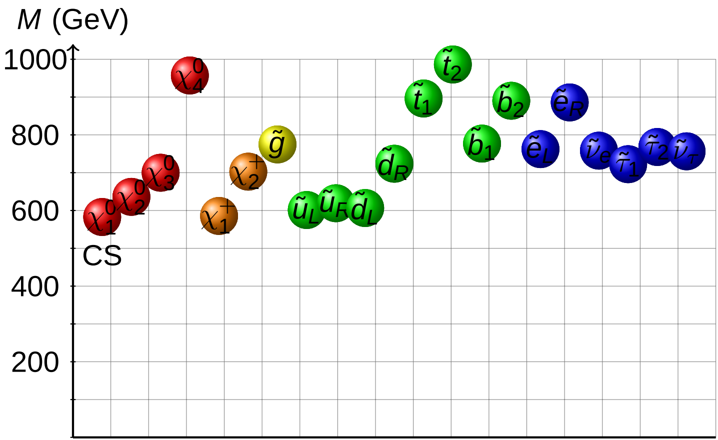
Example bad models



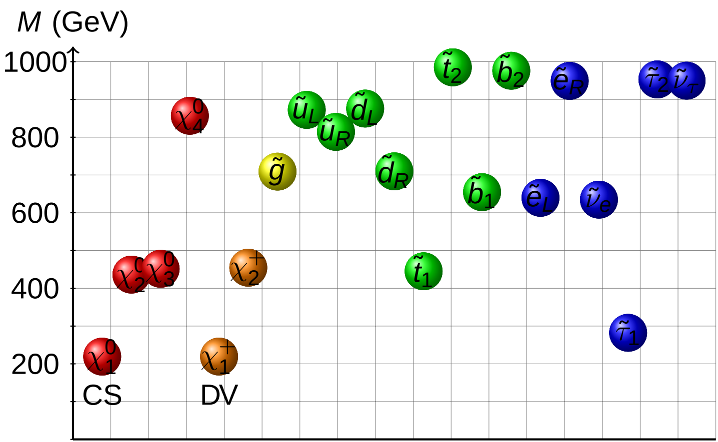
Example bad models



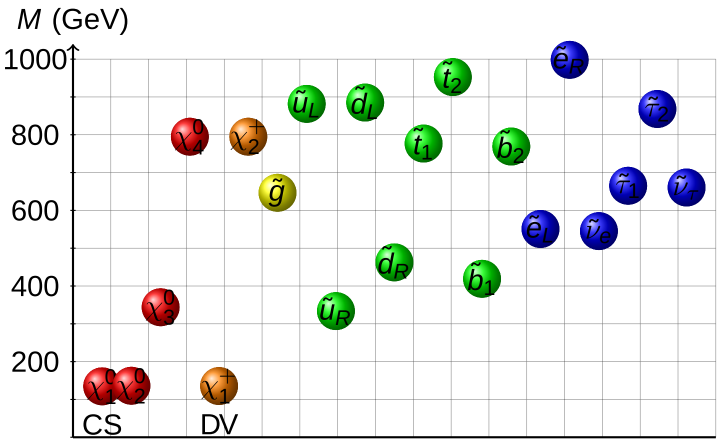
Example bad models



Example bad models

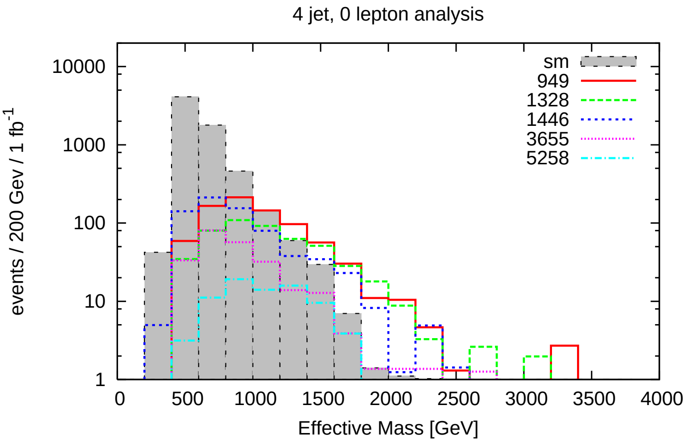


Example bad models



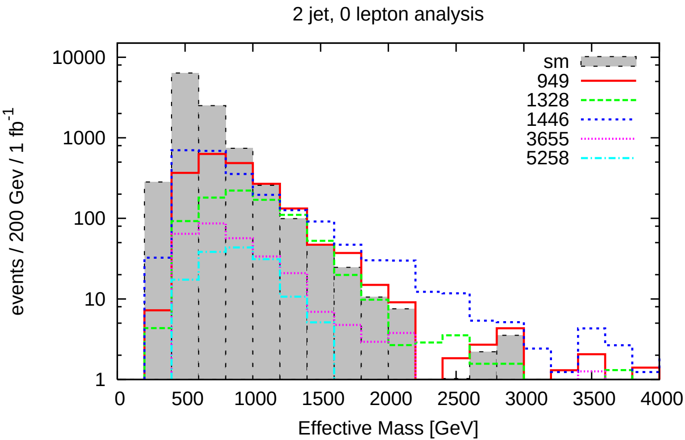
M_{eff} distribution for 4-jet analysis

5 bad models



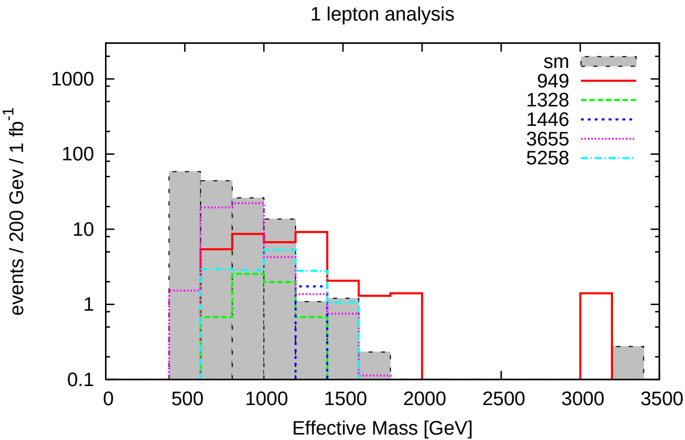
M_{eff} distribution for 2-jet analysis

5 bad models

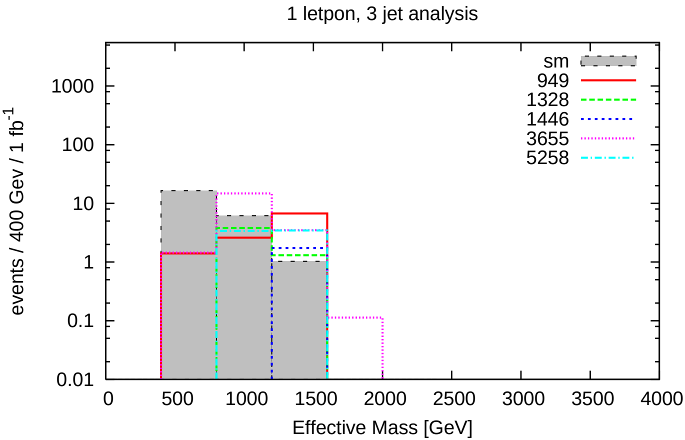


M_{eff} distribution for 1-lepton, 4 jet analysis

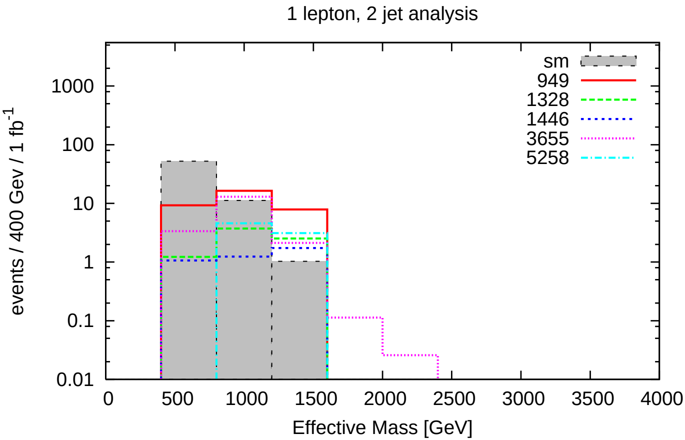
5 bad models



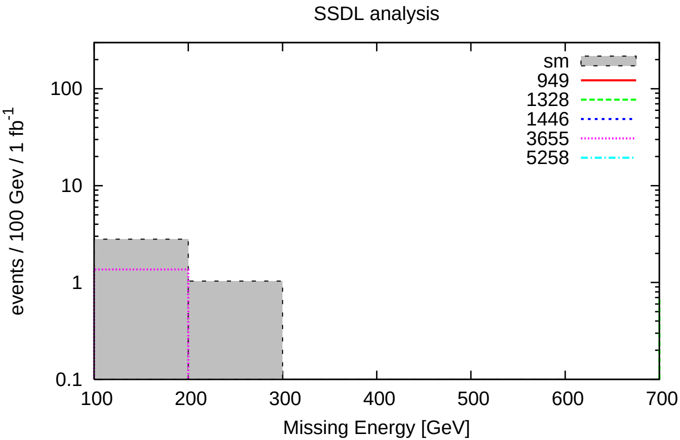
M_{eff} distribution for 1-lepton, 3 jet analysis 5 bad models



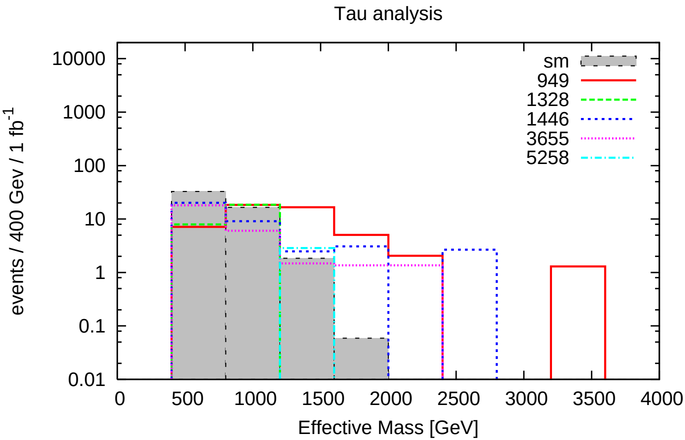
M_{eff} distribution for 1-lepton, 2 jet analysis 5 bad models



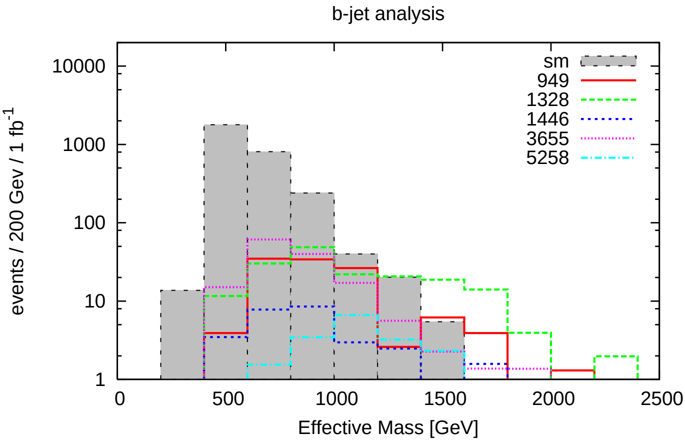
M_{eff} distribution for SSDL analysis 5 bad models



M_{eff} distribution for τ analysis 5 bad models



M_{eff} distribution for b-jet analysis 5 bad models



Outline

Summary and outlook

- We've shown that it is possible to do an extensive scan of MSSM parameter space.
- We have obtained a large sample of viable MSSM models.
- Analysis of the LHC signatures is well underway.
- An understanding of issues with event generation and detector simulation is very important!
- We aim to systematically characterize the model set and uncover novel models and signatures.
- Look for results soon!