SUSY LHC signatures without prejudice

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Outline

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

- Most general SUSY-breaking introduces 105 new parameters.
- Theoretical considerations and/or experimental constraints can reduce this number.

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.

Our goal

In a very thorough and general example of the bottom-up approach (JHEP 0902:023), Berger, Gainer, Hewett, and Rizzo

- Took the minimum set of phenomenologically motivated assumptions;
- Randomly scanned the broadest possible range of parameter space;
- Checked each point against all experimental constraints;
- And thus obtained a general sample of viable MSSM models.

Our goal

To explore the properties and signatures of the MSSM through these models, especially at the LHC

Phenomological assumptions

- CP-conserving
- minimal flavor violation
- degenerate 1^{st} & 2^{nd} gen. sfermions
- neglect 1^{st} and 2^{nd} 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 random points (also separate, log prior scan).

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

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
- Detailed LEP and Tevatron sparticle and Higgs searches

$\sim 68,000$ of $10,000,000$ models survive all constraints.

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 (ATLAS CSC: arXiv:0901.0512), to see how they fare.

ATLAS analyses

- We use the ATLAS inclusive SUSY analyses.
- Multi-jet; 1-lepton + jets; 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

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.

Analysis code

- We wrote an 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...

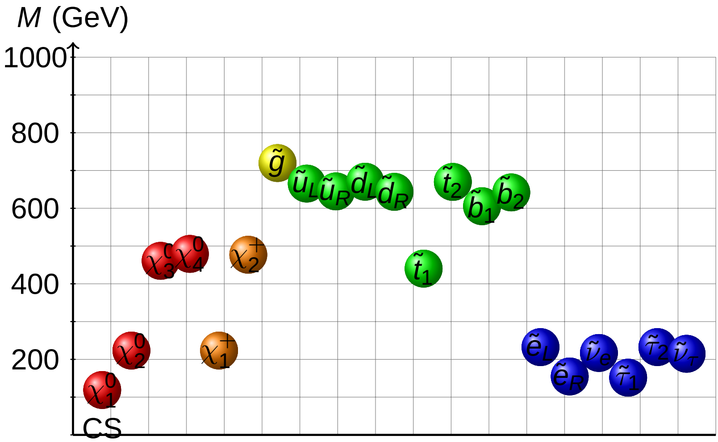
Verification of our analysis

ATLAS benchmarks

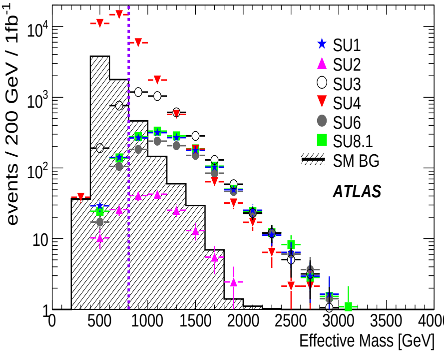
ATLAS used a set of SUSY models in all its analyses. They are labeled SU1, 2, 3, 4, 6, 8.1, and 9.

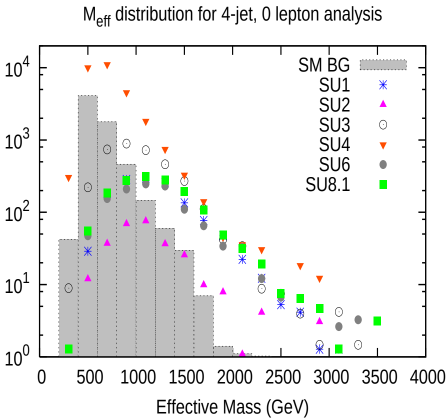
- We generated spectra and decay tables for these benchmark points.
- We ran them through all the analyses and compared to ATLAS.
- The results suggest our analyses reproduce the ATLAS analyses faithfully.

Example spectrum: SU3



M_{eff} distribution for 4-jet analysis





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 analyzed over 50,000 models, and the results in this talk are from 20,000 models.

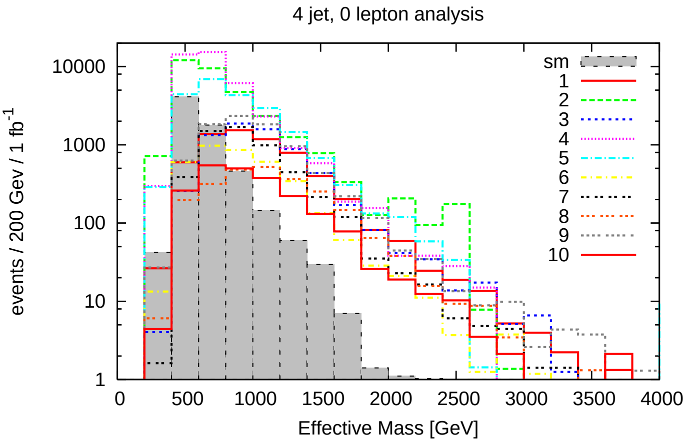
Ten random models

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



PYSTOPs

- In many models, Pythia errors $\longrightarrow$ 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 $\longrightarrow$ 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.

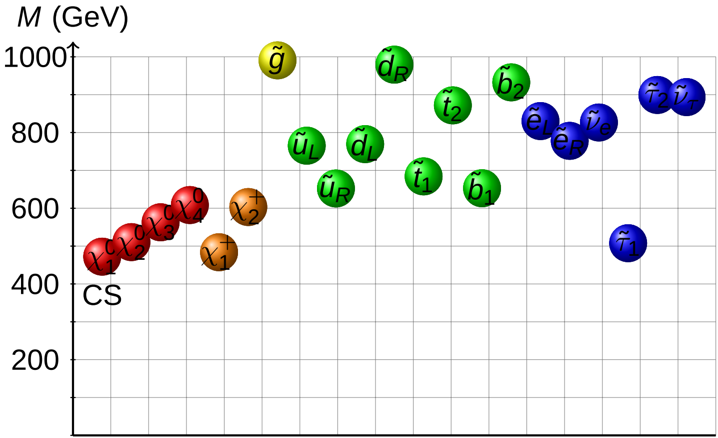
Performance of Analyses (2×10^4 models)

Percentage of models observed by ATLAS analyses		
Analysis	with PYSTOPS	without PYSTOPS
4 jets + M_{E_T}	97.38	98.47
2 jets + M_{E_T}	96.53	97.57
1 lepton + 4 jets + M_{E_T}	47.90	59.48
1 lepton + 2 jets + M_{E_T}	54.32	55.91
1 lepton + 3 jets + M_{E_T}	61.06	62.59
SSDL + 4 jets + M_{E_T}	21.27	13.01
τ + 4 jets + M_{E_T}	TBD	TBD
b jets + M_{E_T}	45.18	46.62
SSDL + 4 jets + M_{E_T}	7.58	9.38
3 leptons + jet	16.36	18.13
3 leptons + M_{E_T}	2.68	4.49

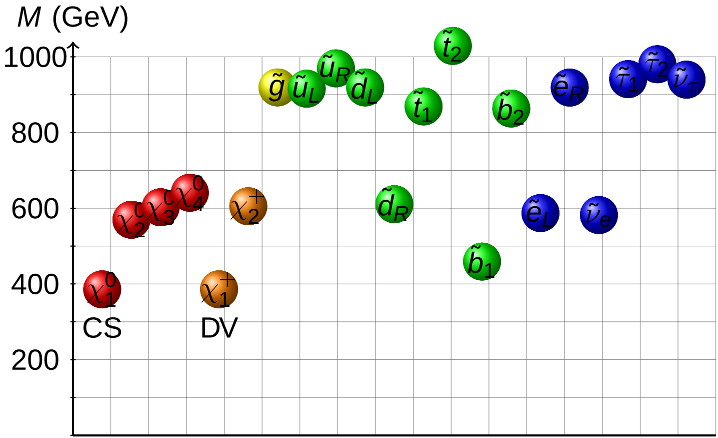
Models bad and good

Percentage of models observed in different nos. of analyses	
Number of analyses observed	% of models
11	2.87
10	3.55
9	5.07
8	10.22
7	17.54
6	16.56
5	5.83
4	13.89
3	23.42
2	0.78
1	0.19
0	0.09

Example bad models

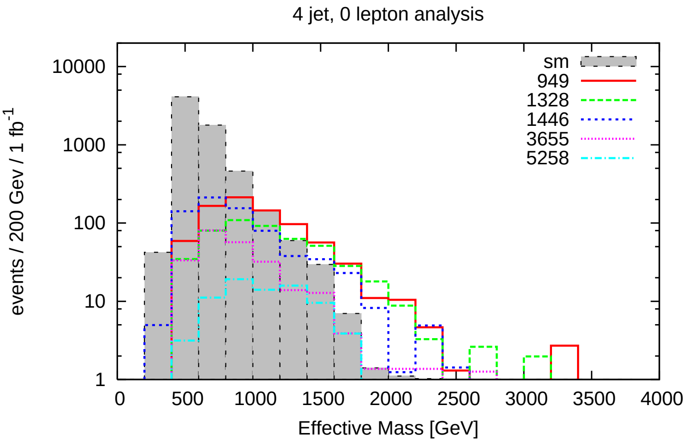


Example bad models



M_{eff} distribution for 4-jet analysis

5 bad models



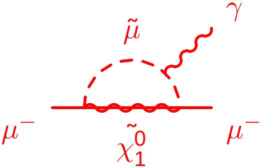
Summary and outlook

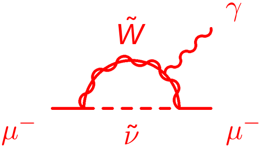
- We've shown that it is possible to do an extensive scan of MSSM parameter space.
- We have obtained a large sample of viable MSSM models.
- Analysis of the LHC signatures is well underway.
- An understanding of issues with event generation and detector simulation is very important!
- We aim to systematically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

Precision and flavor constraints

Precision constraints

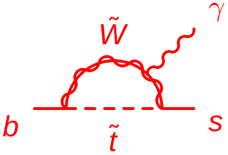
$\Delta\rho\,, \quad (g-2)_\mu\,, \quad \Gamma(Z \to \text{invisible})\,.$

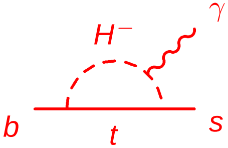




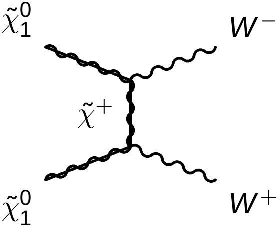
Flavor constraints

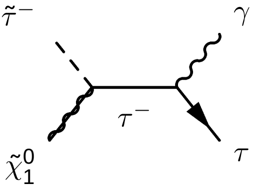
$b \to s\gamma\,, \quad B \to \tau\nu\,, \quad B \to \mu\mu\,.$

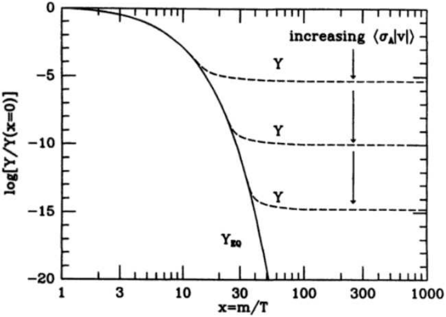




Relic density constraint



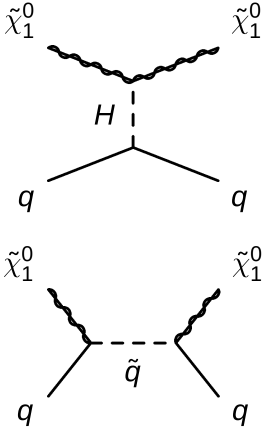


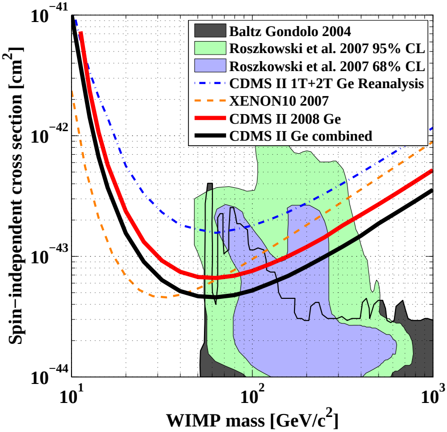


We only apply WMAP measurement as upper bound, allowing for other sources of DM.

DM direct detection constraints

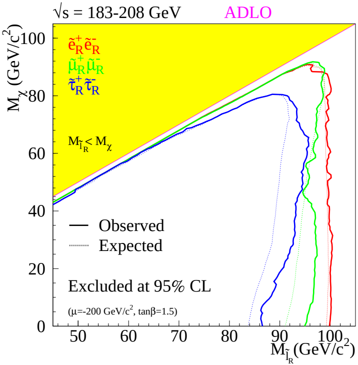
- We allow a factor of 4 uncertainty for nuclear matrix element uncertainties.
- Spin-independent limits are dominant.



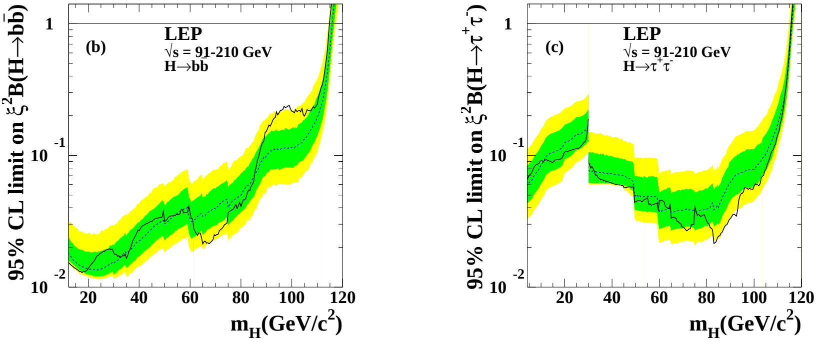


LEP slepton constraints

- The LEP-II RH slepton search is one of many LEP constraints we apply.
- The limit is $m_{\tilde{l}} \gtrsim 100\ \mathrm{GeV}$, as long as slepton isn't too degenerate with LSP, making leptons too soft.



LEP Higgs constraints



- Another LEP constraint comes from Higgs searches.
- This constraint applies to the product of the *ZZh* coupling and the $h \to \tau\tau$ or *bb* branching ratio.

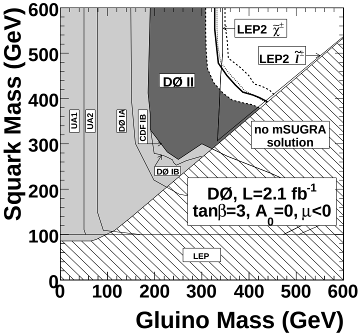
Tevatron multijet plus missing energy constraint

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

Preselection Cut	All Analyses		
$\not\!\!E_T$	≥ 40		
|Vertex z pos.|	< 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

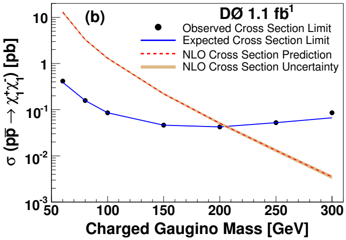
[a] First and second jets are also required to be central ($|\eta_{\rm det}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.

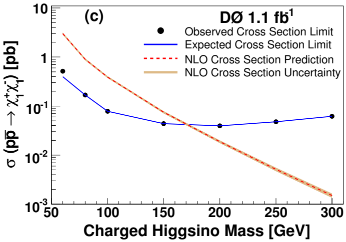
[b] Third and fourth jets are required to have $|\eta_{\rm det}| < 2.5$, with an electromagnetic fraction below 0.95.



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.

Model 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.

Use of Pythia and PGS

PYTHIA

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

PGS

- 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

4-jet + $E_T^{\rm miss}$ cuts

1. At least 4 jets with $p_T > 50\ \mathrm{GeV}$, at least one of which has $p_T > 100\ \mathrm{GeV}$.
2. $E_T^{\rm miss} > 100\ \mathrm{GeV}$ and $E_T^{\rm miss} > 0.2 M_{\rm eff}$.
3. Transverse sphericity $S_T > 0.2$
4. $\Delta\phi(\mathrm{jet}_{1,2,3} - E_T^{\rm miss}) > 0.2$
5. Reject events with an e or a μ.

3-jet + E_T^{miss} cuts

1. At least 3 jets with $p_T > 100\ \mathrm{GeV}$, at least one of which has $p_T > 150\ \mathrm{GeV}$.
2. $E_T^{\mathrm{miss}} > 100\ \mathrm{GeV}$ and $E_T^{\mathrm{miss}} > 0.25 M_{\mathrm{eff}}$.
3. $\Delta\phi(\mathrm{jet}_{1,2,3} - E_T^{\mathrm{miss}}) > 0.2$
4. Reject events with an e or a μ.

2-jet + E_T^{miss} cuts

1. At least 2 jets with $p_T > 100$ GeV, at least one of which has $p_T > 150$ GeV.
2. $E_T^{\text{miss}} > 100$ GeV and $E_T^{\text{miss}} > 0.3 M_{\text{eff}}$.
3. $\Delta\phi(\text{jet}_{1,2} - E_T^{\text{miss}}) > 0.2$
4. Reject events with an e or a μ.

1 lepton + 4 jets + E_T^{miss} cuts

1. Exactly one isolated lepton with $p_T > 20\ \text{GeV}$.
2. No additional leptons with $p_T > 10\ \text{GeV}$.
3. At least 4 jets with $p_T > 50\ \text{GeV}$, at least one of which has $p_T > 100\ \text{GeV}$.
4. $E_T^{\text{miss}} > 100\ \text{GeV}$ and $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$.
5. Transverse sphericity $S_T > 0.2$.
6. Transverse mass $M_T > 100\ \text{GeV}$.
7. $\Delta\phi(\text{jet}_{1,2,3} - E_T^{\text{miss}}) > 0.2$.
8. Reject events with an e or a μ.

OSDL + 4 jets + E_T^{miss} cuts

1. Exactly two same-sign leptons with $p_T > 20$ GeV.
2. At least 4 jets with $p_T > 50$ GeV, at least one of which has $p_T > 100$ GeV.
3. $E_T^{\text{miss}} > 100$ GeV and $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$.

Trilepton + jet cuts

1. At least three leptons with $p_T > 10\ \mathrm{GeV}$.
2. At least 1 jets with $p_T > 200\ \mathrm{GeV}$.

Trilepton + E_T^{miss} cuts

1. At least three leptons with $p_T > 10\ \mathrm{GeV}$.
2. At least one OSSF dilepton pair with $M > 20\ \mathrm{GeV}$.
3. Lepton track isolation: $p_{T,\mathrm{trk}}^{0.2} < 1\ \mathrm{GeV}$ for electrons and $< 2\ \mathrm{GeV}$ for muons, where $p_{T,\mathrm{trk}}^{0.2}$ is the maximum p_T of any additional track within a $R = 0.2$ cone around the lepton.
4. $E_T^{\mathrm{miss}} > 30\ \mathrm{GeV}$.
5. $M < M_Z - 10\ \mathrm{GeV}$ for any OSSF dilepton pair.

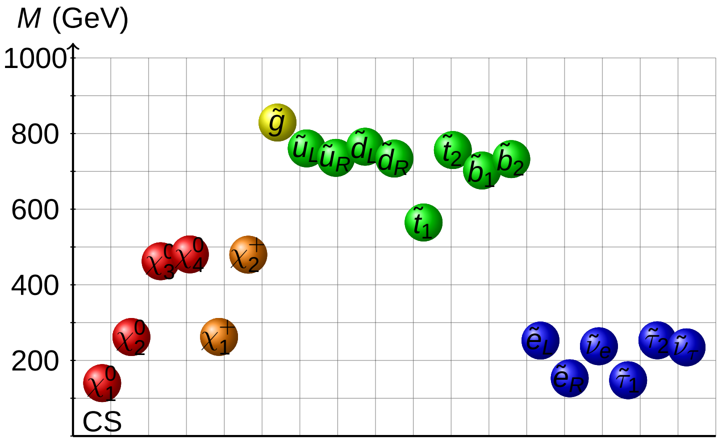
Tau + jets + E_T^{miss} cuts

1. No isolated electrons or muons.
2. At least one τ with $p_T > 40$ GeV and $|\eta| < 2.5$.
3. At least 4 jets with $p_T > 50$ GeV, at least one of which has $p_T > 100$ GeV.
4. $E_T^{\text{miss}} > 100$ GeV and $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$.
5. $\Delta\phi(\text{jet}_{1,2,3} - E_T^{\text{miss}}) > 0.2$.
6. $M_T > 100$ GeV, where M_T is transverse mass of hardest τ and E_T^{miss}.

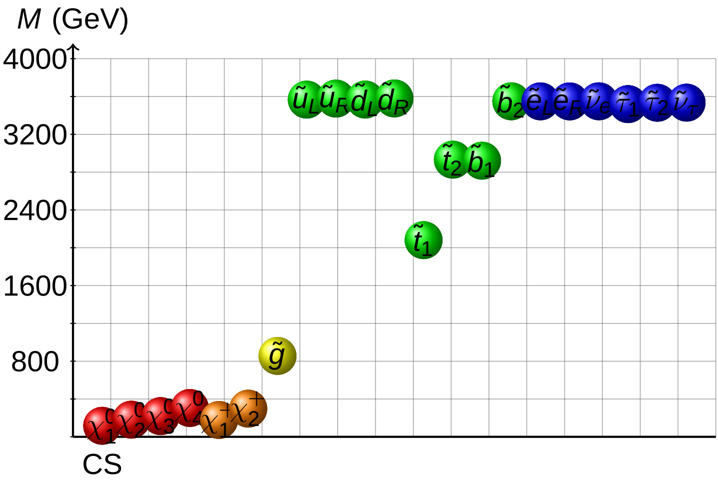
b jets + $E_T^{\rm miss}$ cuts

1. At least 4 jets with $p_T > 50$ GeV, at least one of which has $p_T > 100$ GeV.
2. $E_T^{\rm miss} > 100$ GeV and $E_T^{\rm miss} > 0.2 M_{\rm eff}$.
3. Transverse sphericity $S_T > 0.2$.
4. At least 2 jets tagged as b jets.

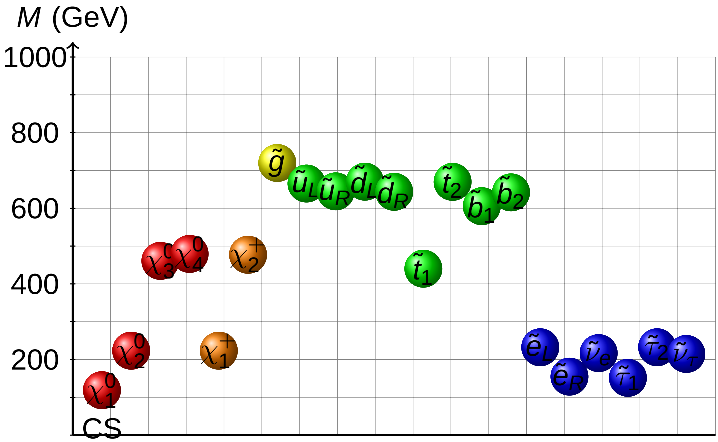
Example spectrum: SU1



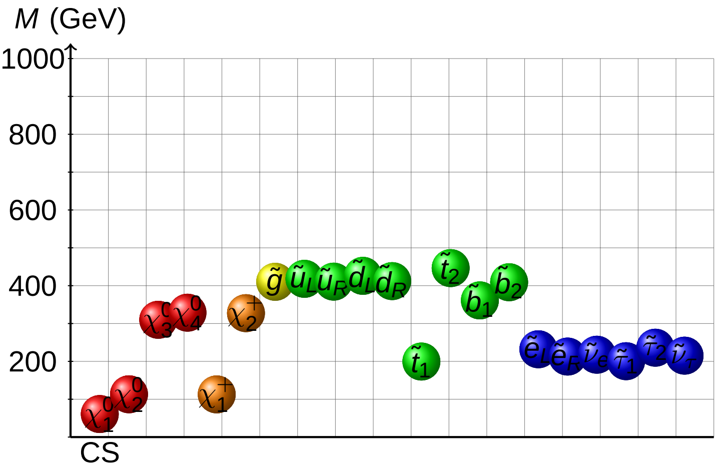
Example spectrum: SU2



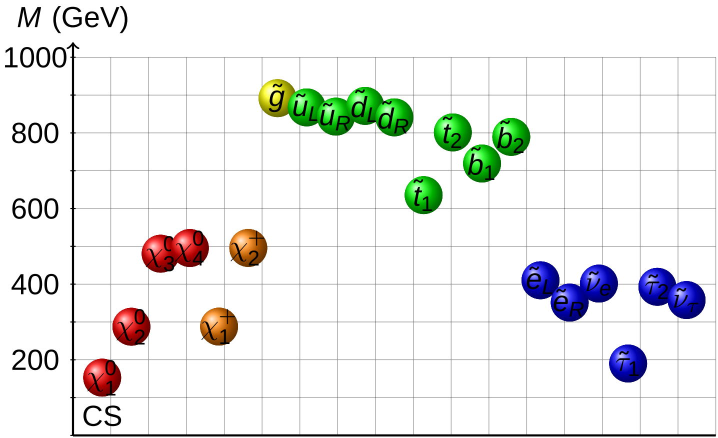
Example spectrum: SU3



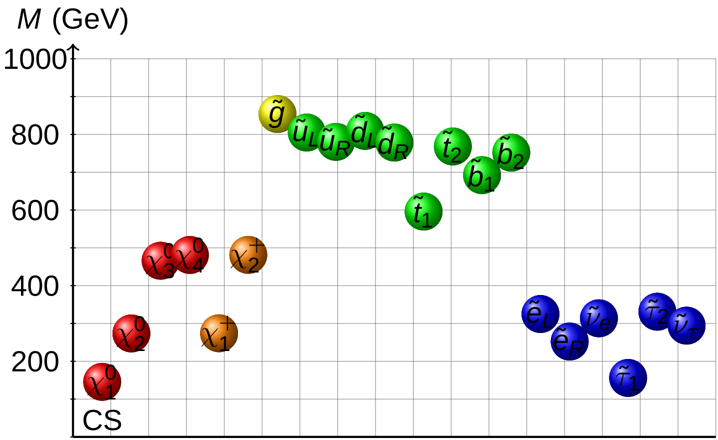
Example spectrum: SU4



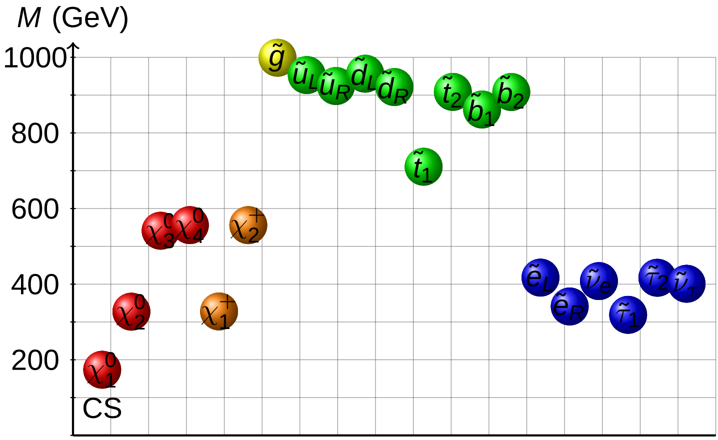
Example spectrum: SU6



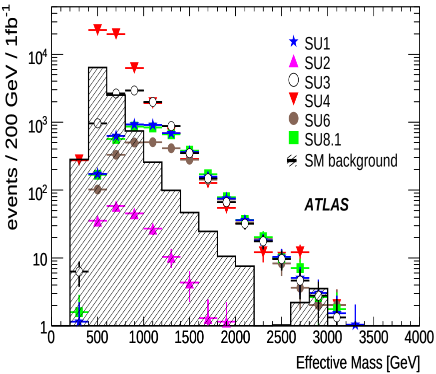
Example spectrum: SU8.1

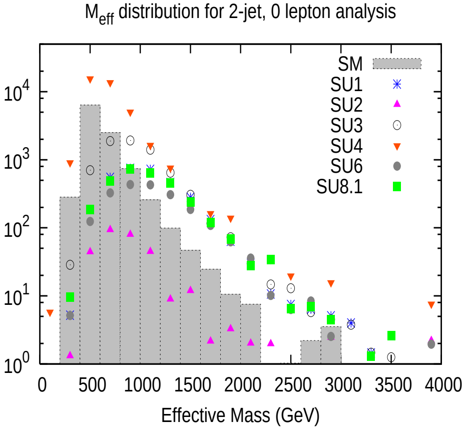


Example spectrum: SU9

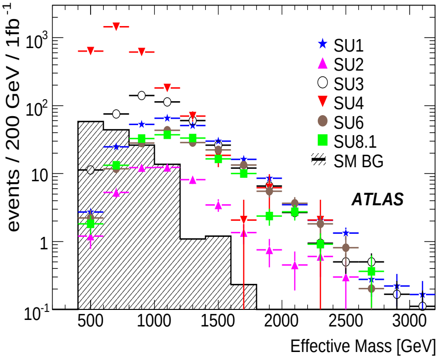


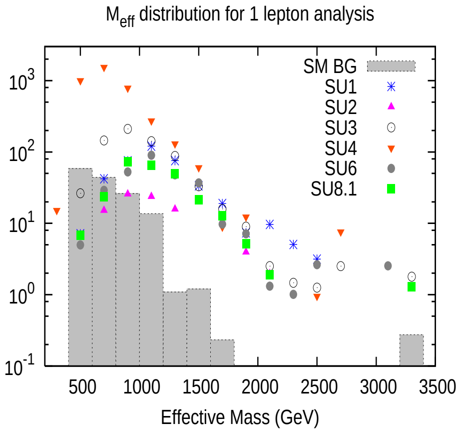
M_{eff} distribution for 2-jet analysis



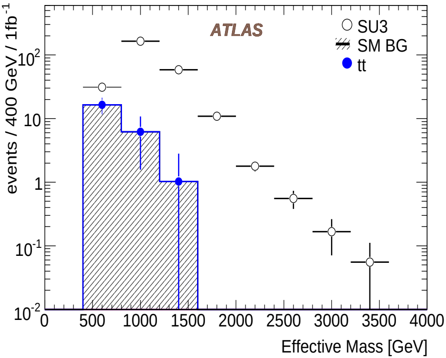


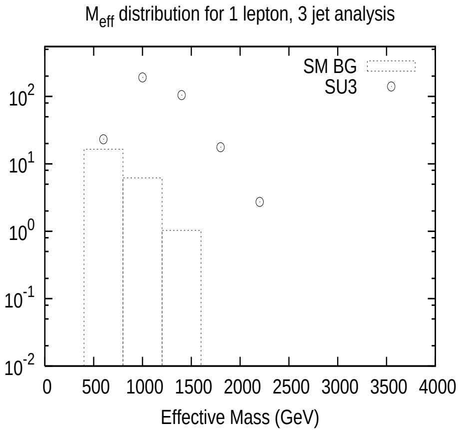
M_{eff} distribution for 1-lepton + 4 jet analysis



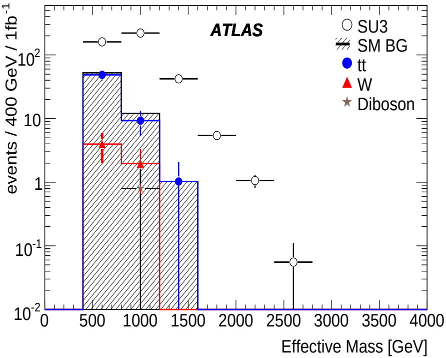


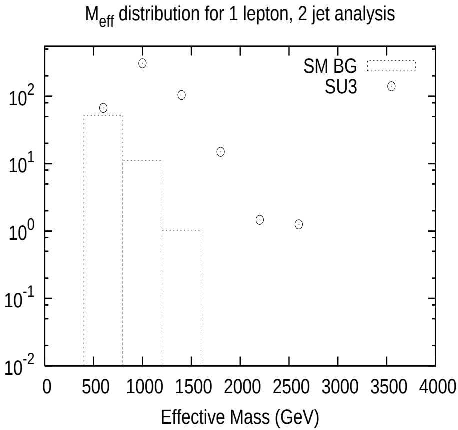
M_{eff} distribution for 1-lepton + 3 jet analysis



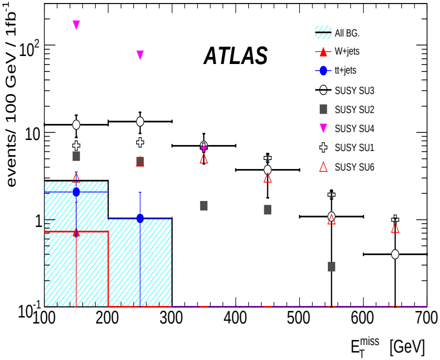


M_{eff} distribution for 1-lepton + 2 jet analysis

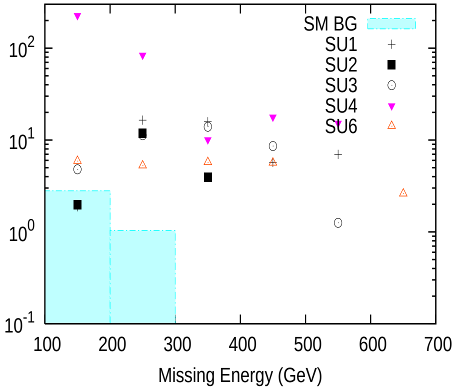




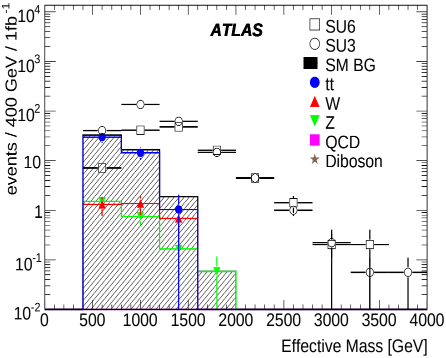
M_{eff} distribution for same-sign dilepton analysis

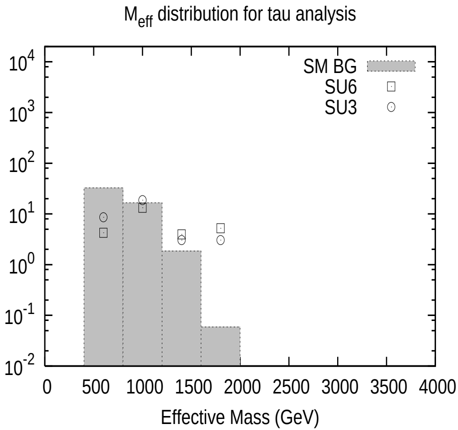


E_T^{miss} distribution for SSDL analysis

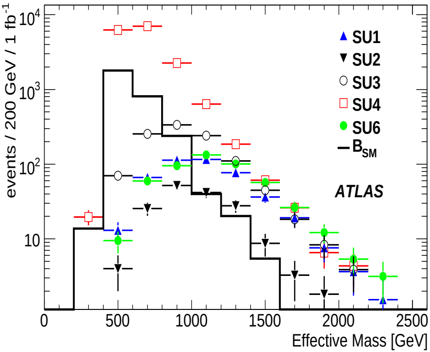


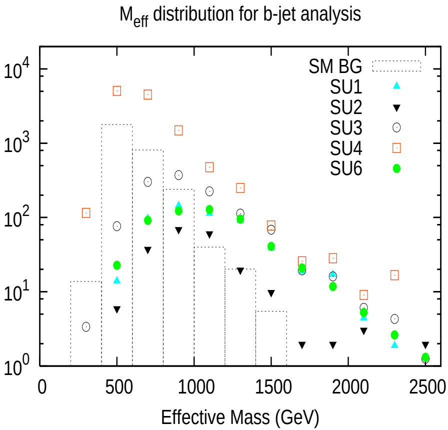
M_{eff} distribution for τ analysis





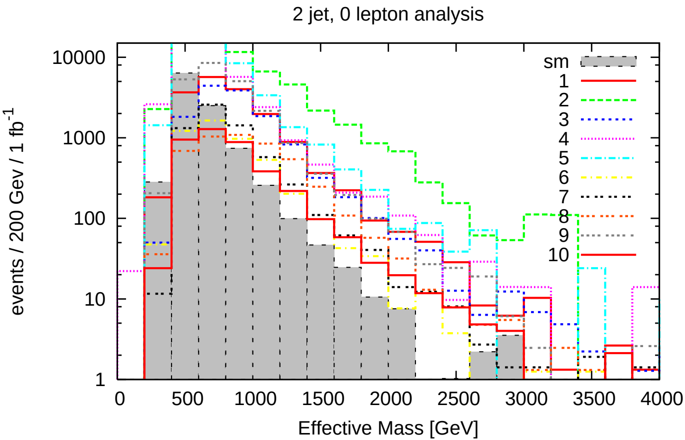
M_{eff} distribution for b-jet analysis





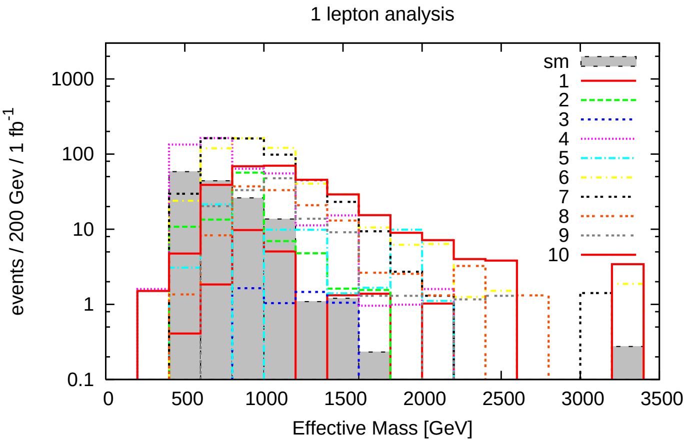
M_{eff} distribution for 2-jet analysis

Models 1-10



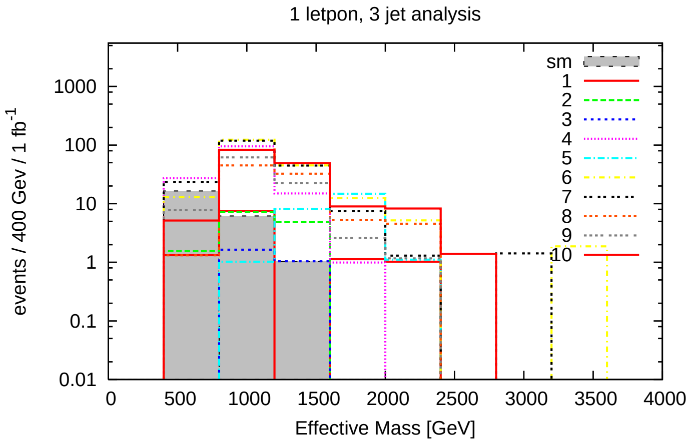
M_{eff} distribution for 1-lepton, 4 jet analysis

Models 1-10



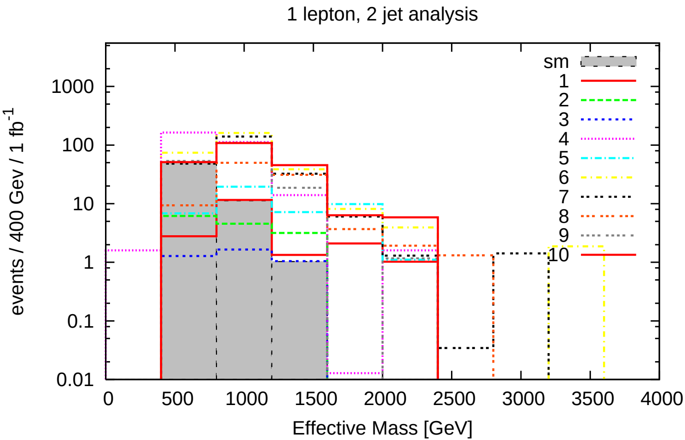
M_{eff} distribution for 1-lepton, 3 jet analysis

Models 1-10



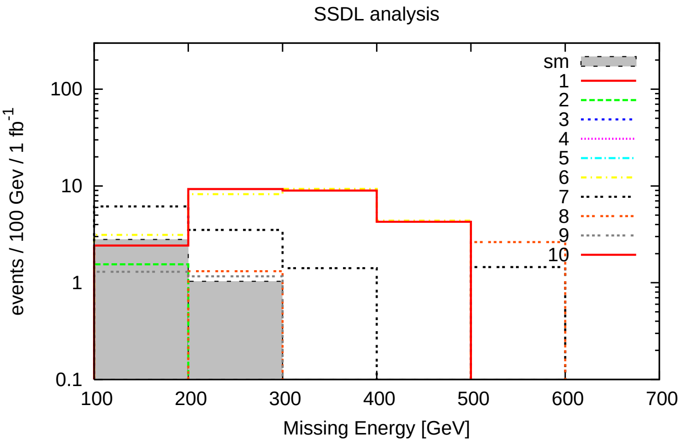
M_{eff} distribution for 1-lepton, 2 jet analysis

Models 1-10



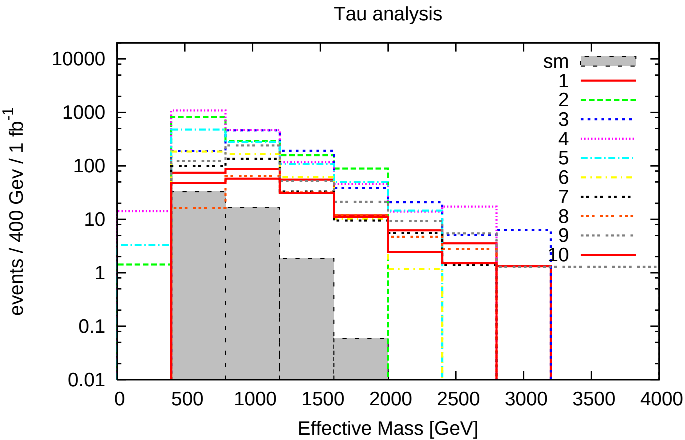
M_{eff} distribution for SSDL analysis

Models 1-10



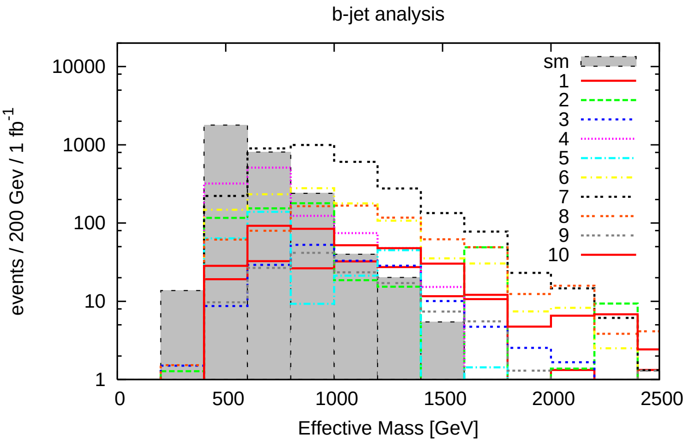
M_{eff} distribution for τ analysis

Models 1-10

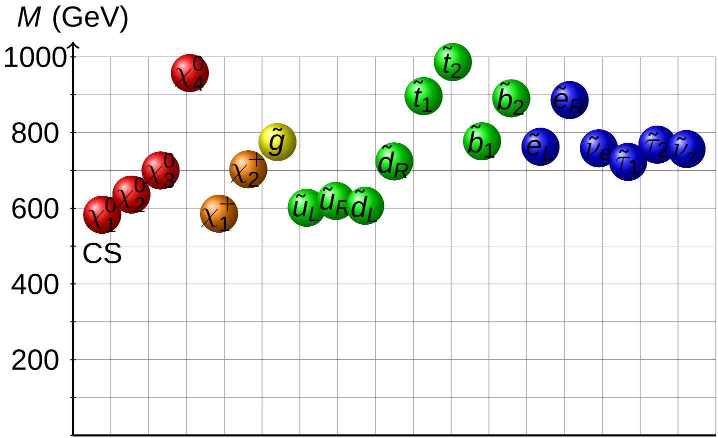


M_{eff} distribution for b-jet analysis

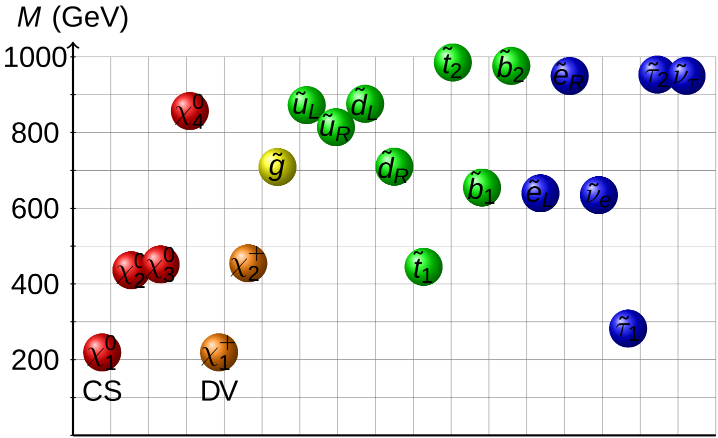
Models 1-10



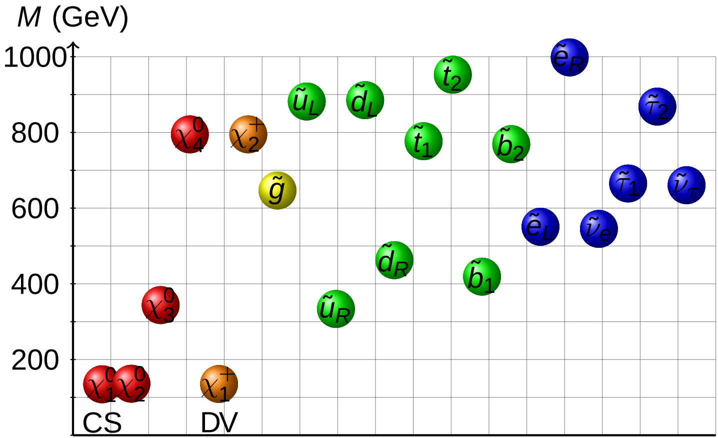
Example bad models



Example bad models

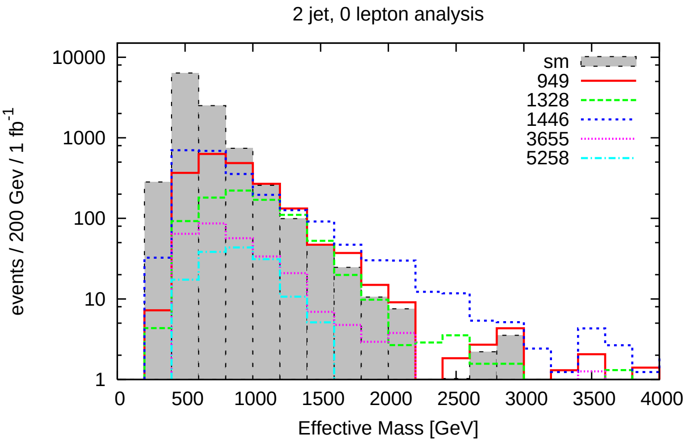


Example bad models



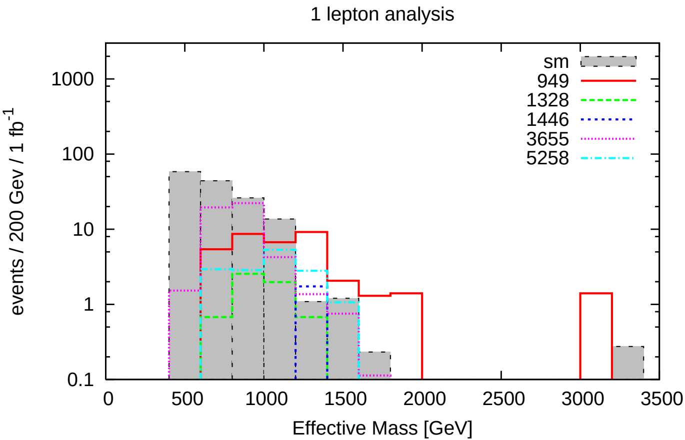
M_{eff} distribution for 2-jet analysis

5 bad models



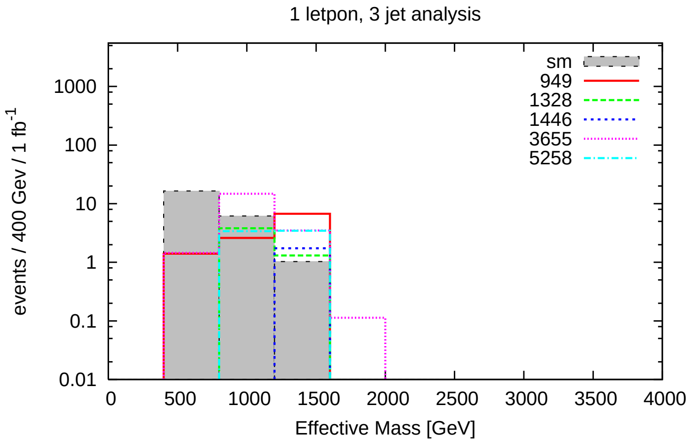
M_{eff} distribution for 1-lepton, 4 jet analysis

5 bad models



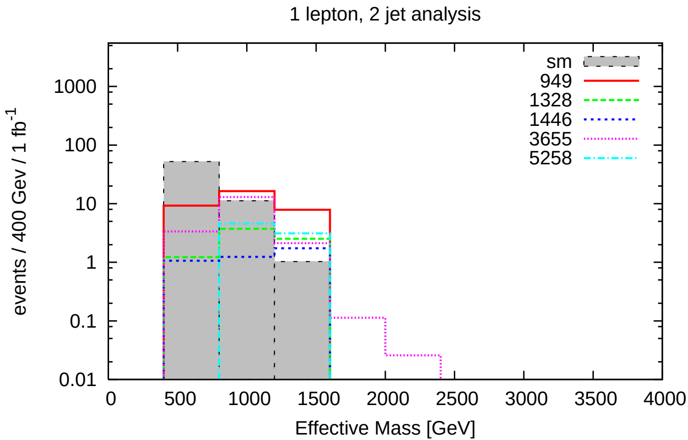
M_{eff} distribution for 1-lepton, 3 jet analysis

5 bad models



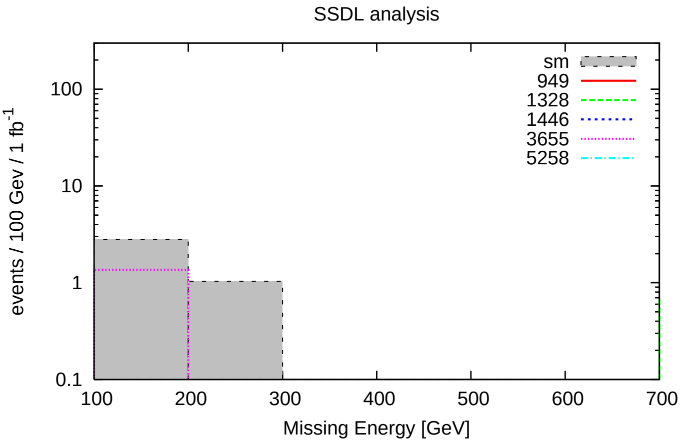
M_{eff} distribution for 1-lepton, 2 jet analysis

5 bad models



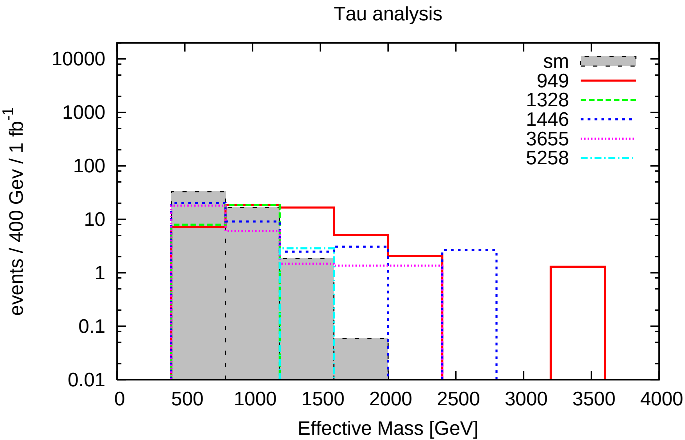
M_{eff} distribution for SSDL analysis

5 bad models



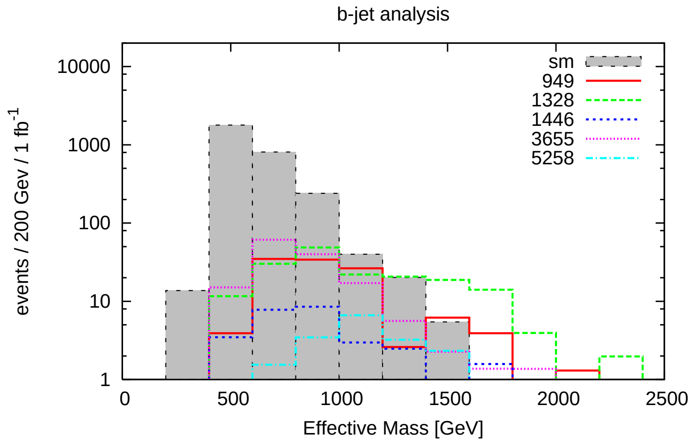
M_{eff} distribution for τ analysis

5 bad models



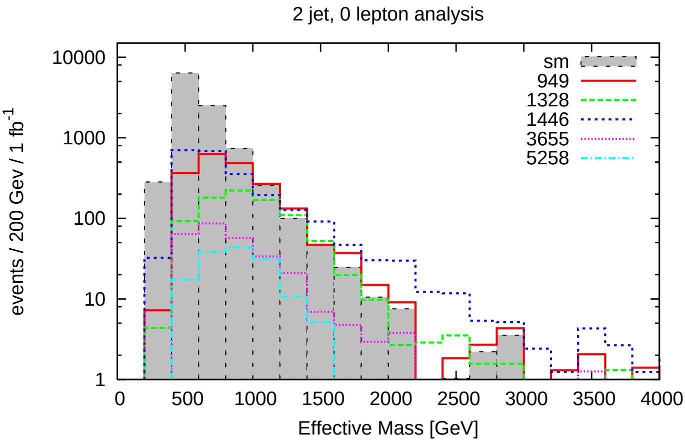
M_{eff} distribution for b-jet analysis

5 bad models



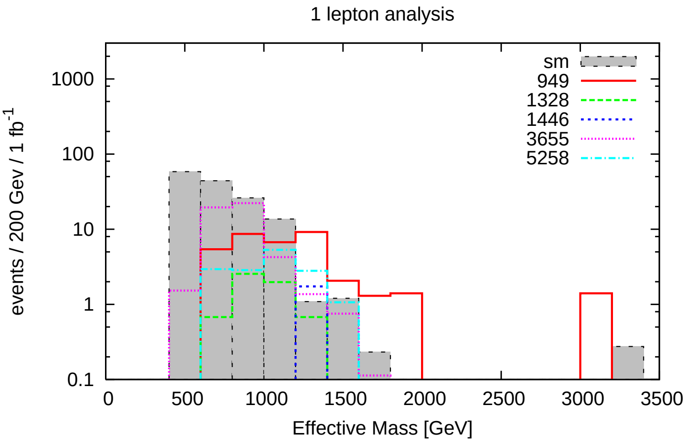
M_{eff} distribution for 2-jet analysis

5 bad models



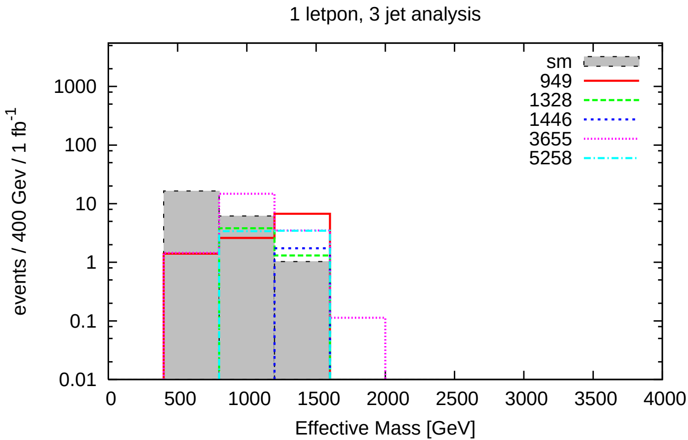
M_{eff} distribution for 1-lepton, 4 jet analysis

5 bad models



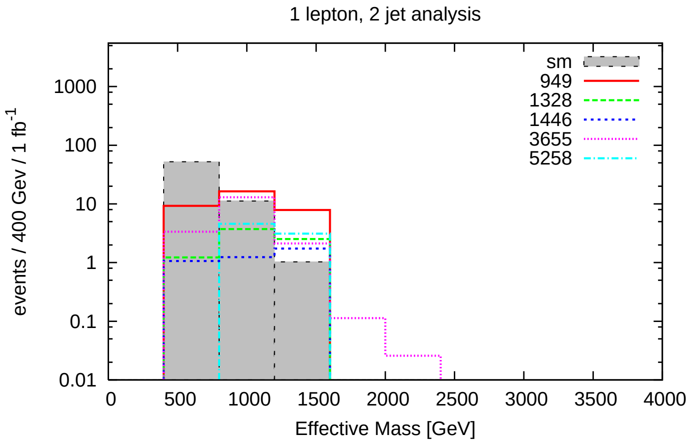
M_{eff} distribution for 1-lepton, 3 jet analysis

5 bad models



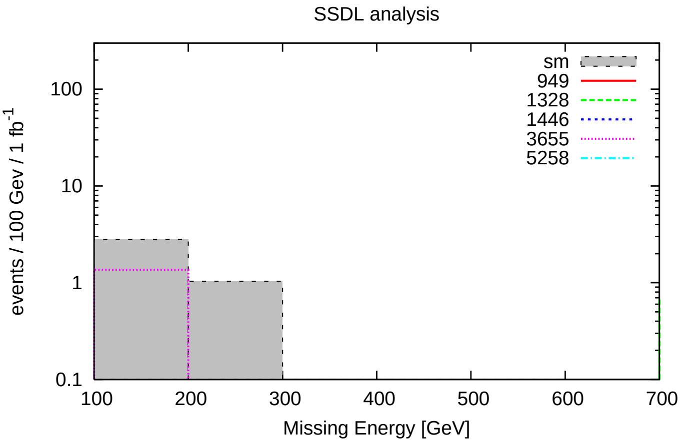
M_{eff} distribution for 1-lepton, 2 jet analysis

5 bad models



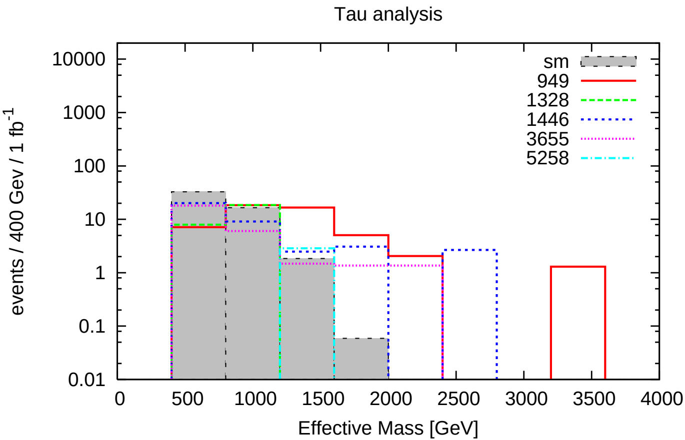
M_{eff} distribution for SSDL analysis

5 bad models



M_{eff} distribution for τ analysis

5 bad models



M_{eff} distribution for b-jet analysis

5 bad models