Distinguishing SUSY models at the LHC

E_6SSM vs MSSM

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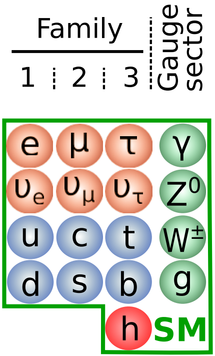
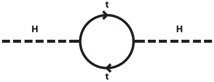
Outline

1. MSSM
   - μ-problem
   - Beyond MSSM
2. E_6SSM
   - A light LSP
   - Dark matter constraints
3. Gluino decays
   - SUSY searches at the LHC
4. Conclusions

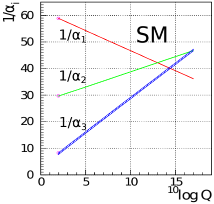
MSSM



Family
1
2
3
Gauge sector
e μ τ γ
υe υμ υτ Z0
u c t W±
d s b g
h
SM

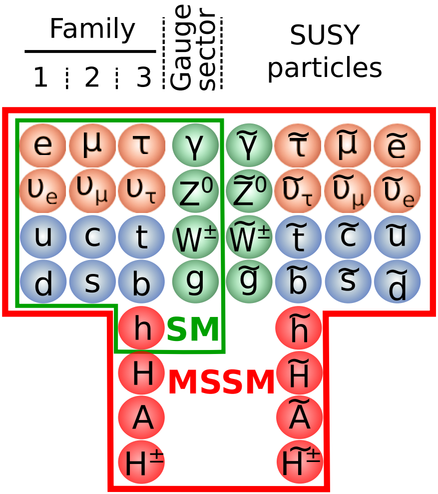


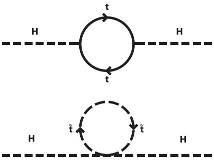
H
H
t
t

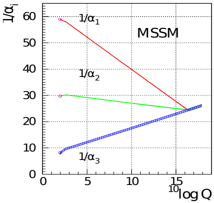


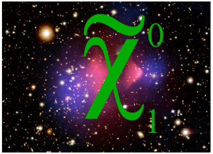
1/αi
SM
1/α1
1/α2
1/α3
10log Q

MSSM


Family
1 2 3
Gauge sector
SUSY particles
e μ τ γ γ̃ τ̃ μ̃ ẽ
ν_e ν_μ ν_τ Z^0 $\tilde{Z}^0$ $\tilde{\nu}_\tau$ $\tilde{\nu}_\mu$ $\tilde{\nu}_e$
u c t $W^\pm$ $\tilde{W}^\pm$ t̃ c̃ ũ
d s b g g̃ b̃ s̃ d̃
h SM h̃
H MSSM H̃
A Ã
$H^\pm$ $\tilde{H}^\pm$


t
H
H
t
t̃
t̃
H
H


$1/\alpha_i$
60
50
40
30
20
10
0
$1/\alpha_1$
MSSM
$1/\alpha_2$
$1/\alpha_3$
0
5
10
15
$^{10}\log Q$


$\tilde{\chi}_1^0$

The μ-problem

MSSM superpotential:

$$W = y_u \bar{u} Q H_u + y_d \bar{d} Q H_d + y_e \bar{e} L H_d + \mu H_u H_d$$

Minimization of Higgs potential gives:

$$\frac{m_Z^2}{2} = -|\mu^2| + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

- We expect $\mu \sim m_{\text{soft}} \sim \mathcal{O}(\text{TeV})$
- But the μ-term is SUSY preserving so why

$$\mu \sim m_{\text{soft}} \quad \text{rather than} \quad \mu \sim M_{Pl} \quad ?$$

Solving the μ-problem

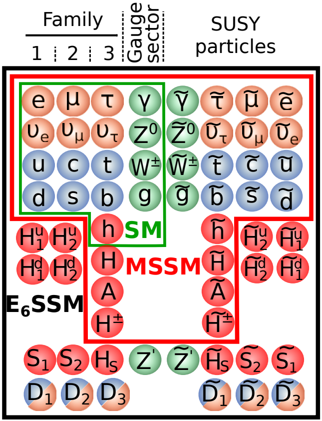
One common way to solve the μ problem is to introduce a scalar, S.

$$\lambda S H_u H_d \qquad \text{and} \qquad \langle S \rangle = \frac{s}{\sqrt{2}} \sim m_{\text{soft}} \sim 1\text{TeV} \qquad \Rightarrow \qquad \mu = \frac{\lambda s}{\sqrt{2}}$$

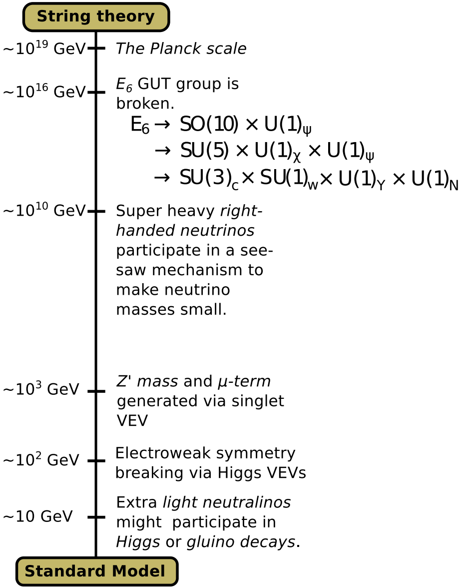
But you have introduced a new global U(1) symmetry and broken it, resulting in a massless axion, which we haven't observed.

- **NMSSM:** A cubic term, S^3, is also added, breaking the U(1) down to a discrete Z_3. This could lead to cosmological domain walls and overclosure of the Universe.
- **USSM:** The U(1) is gauged and a massive Z' appear. However, the theory is not anomaly free.
- **E_6SSM:** The gauged U(1) is a remnant of a broken E_6. Anomaly cancellation is assured by having particles in complete **27**s of E_6 at the TeV scale.

E_6SSM



- String theory motivated model
- One extra surviving $U(1)'$
- Extra particles from complete **27**s of E_6



Neutralinos

Only the third generation H_d, H_u and S get VEVs and can be identified with the MSSM (USSM) states. The first two inert generations of the Higgs sector are still important.

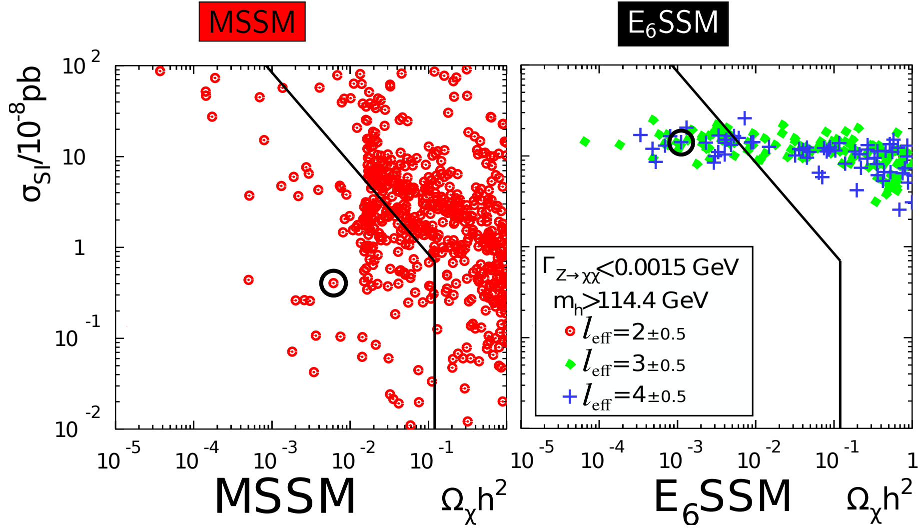
$$\tilde{\chi}^0_{\text{int}} = (\overbrace{\underbrace{\tilde{B}\ \ \tilde{W}^3\ \ \tilde{H}^0_d\ \ \tilde{H}^0_u}_{\text{MSSM}}\ \mid\ \tilde{S}\ \ \tilde{B}'}^{\text{USSM}}\ \mid\ \overbrace{\tilde{H}^0_{d2}\ \ \tilde{H}^0_{u2}\ \ \tilde{S}_2\ \mid\ \tilde{H}^0_{d1}\ \ \tilde{H}^0_{u1}\ \ \tilde{S}_1}^{\text{inert } E_6\text{SSM states}})^T$$

- The lightest neutralino has a mass $m_{\tilde{\chi}^0_1} \sim \frac{v^2}{s}$
- The VEV s determines the Z' mass and needs to be larger than 3.5 TeV

  $$\Rightarrow m_{\tilde{\chi}^0_1} \sim \mathcal{O}(10 GeV)$$
- LSP annihilation can occur at an acceptable rate in the early universe through a Z or h-resonance

Dark matter constraints

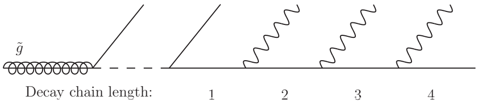
With $m_{\tilde{g}} = 800$ GeV we scan the parameter space to check constraints on the direct detection cross section, σ_{SI}, and relic density, $\Omega_{\tilde{\chi}_1^0} h^2$



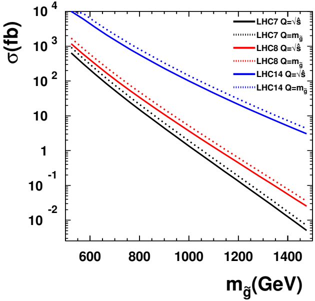
Gluino decays at the LHC

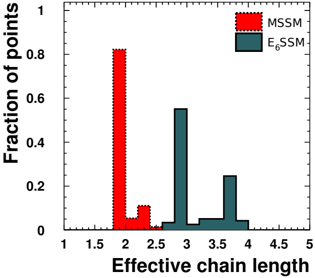
- $pp \to \tilde{g}\tilde{g} \to \tilde{\chi}_1^0\tilde{\chi}_1^0$+SM particles
- We consider the case $m_{\tilde{g}} < m_{\tilde{q}}$
- The gluino, bino and wino masses are matched between the models
- Gluino decay chain length, l:

$$l = N_{\tilde{\chi}^0 \in \text{chain}} + N_{\tilde{\chi}^\pm \in \text{chain}}$$



- Effective gluino decay chain length, $l_{\text{eff}} = \sum_l l \cdot P(l)$, where $P(l)$ is the probability for a decay chain length l





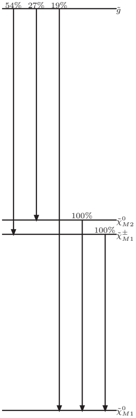
Chargino and neutralino masses

Probabilities of chain lengths

	MSSM	E_6SSM-I	E_6SSM-II	E_6SSM-III	E_6SSM-IV	E_6SSM-V	E_6SSM-VI	
$\tan\beta$	10	1.5	1.42	1.77	3	1.42	1.42	
λ	-	0.55	0.598	-0.462	-0.4	0.598	0.598	
s	-	3700	5268	5418	5500	5268	5268	[GeV]
μ	1578	(1439)	(2228)	(-1770)	(-1556)	(2228)	(2228)	[GeV]
$A_t = A_b = A_\tau$	-2900	-2200	-2684	476.2	4638	-2684	-2684	[GeV]
M_A	302.5	2736	2791	2074	4341	4010	4000	[GeV]
$\tilde{\chi}^0_{M1}$	148.7	148.6	149.1	151.2	150.6	149.1	149.1	[GeV]
$\tilde{\chi}^0_{M2}$	302.2	296.8	296.8	303.7	301.7	296.8	296.8	[GeV]
$\tilde{\chi}^0_{M3}$	1582	1254	2233	1766	1557	2233	2233	[GeV]
$\tilde{\chi}^0_{M4}$	1584	1468	2246	1771	1558	2246	2246	[GeV]
$\tilde{\chi}^{\pm}_{M1}$	302.2	298.7	299.2	300.9	300.4	299.2	299.2	[GeV]
$\tilde{\chi}^{\pm}_{M2}$	1584	1440	2229	1771	1557	2229	2229	[GeV]
$\tilde{\chi}^0_{U1}$	-	1420	1835	1909	1937	1835	1835	[GeV]
$\tilde{\chi}^0_{U2}$	-	1459	2003	2062	2087	2003	2003	[GeV]
$\tilde{\chi}^0_{E1}$	-	62.7	43.5	45.2	0	0	0.00011	[GeV]
$\tilde{\chi}^0_{E2}$	-	62.8	48.6	53.2	0	0	1.53	[GeV]
$\tilde{\chi}^0_{E3}$	-	119.9	131.3	141.6	164.1	119.9	120.1	[GeV]
$\tilde{\chi}^0_{E4}$	-	121.1	163.6	187.4	164.1	119.9	122.8	[GeV]
$\tilde{\chi}^0_{E5}$	-	183.1	197.0	227.8	388.9	185.8	185.8	[GeV]
$\tilde{\chi}^0_{E6}$	-	184.4	224.3	265.6	388.9	185.8	187.0	[GeV]
$\tilde{\chi}^{\pm}_{E1}$	-	109.8	119.9	122.7	164.1	119.9	119.9	[GeV]
$m_{\tilde{\chi}^{\pm}_{E2}}$	-	117.8	185.8	225.1	388.9	185.8	185.8	[GeV]
m_h	124.4	125.4	133.8	116.3	124.7	126.1	125.8	[GeV]
$m_{\tilde{t}_1}$	1878	1917	1916	2042	1885	1917	1917	[GeV]
$P(l = 1)$	0.188	$< 10^{-9}$	$< 10^{-5}$	$< 10^{-5}$	0.1727	$< 10^{-8}$	$< 10^{-12}$	
$P(l = 2)$	0.812	$< 10^{-4}$	0.01524	0.1723	0.8273	0.01	$< 10^{-5}$	
$P(l = 3)$	0	0.1746	0.2336	0.7986	$< 10^{-6}$	0.2	0.1721	
$P(l = 4)$	0	0.8196	0.7512	0.02915	$< 10^{-15}$	0.8	0.8280	
$P(l = 5)$	0	0.0058	$< 10^{-7}$	0	0	$< 10^{-15}$	0	
Ωh^2	0.00628	0.00114	0.0006842	0.0006937	0.101	0.00154		
σ_{SI}	0.401×10^{-9}	15.34×10^{-8}	9.35×10^{-8}	16.35×10^{-8}	3.75×10^{-11}	3.98×10^{-13}		[pb]

Benchmarks

MSSM



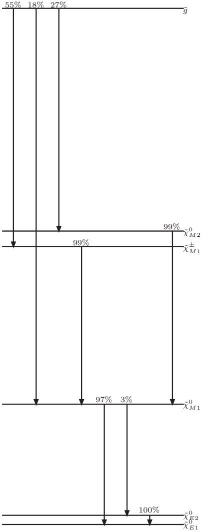
$\Leftarrow$ 800 GeV gluino $\Rightarrow$

$\Leftarrow$ $\approx$ 300 GeV chargino and neutralino $\Rightarrow$

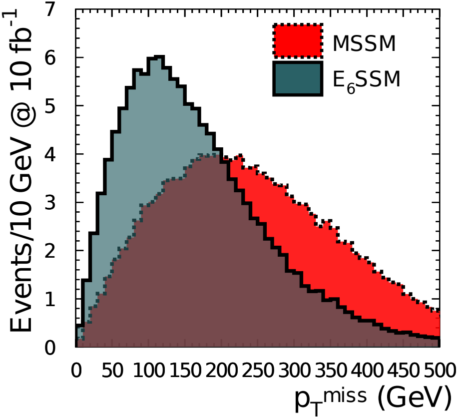
$\Leftarrow$ $\approx$ 150 GeV bino $\Rightarrow$

$\approx$ 63 GeV singlinos $\Rightarrow$

E_6SSM

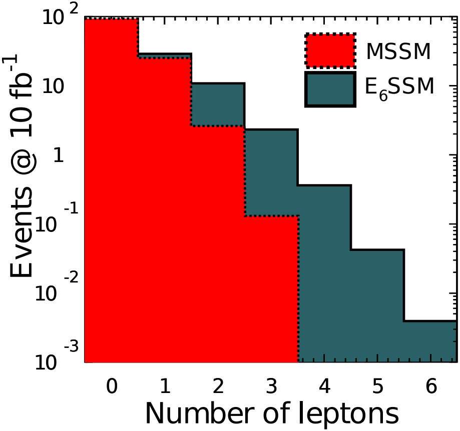


Missing transverse momentum



- A longer decay chain means, in general, more visible particles radiated
  $\Rightarrow$ more p_T is distributed to visible particles
- E_6SSM show less missing transverse momentum in collider experiments

Lepton multiplicity

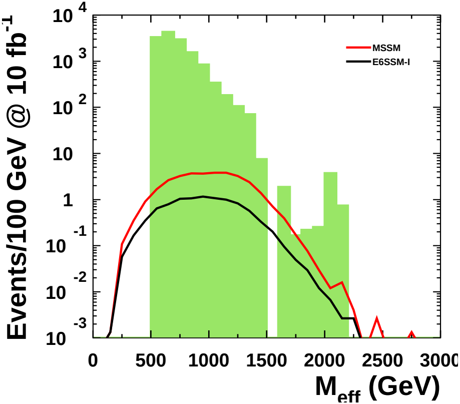


- Longer decay chain
  $\Rightarrow$ more leptons
- Close degeneracy in spectrum
  $\Rightarrow$ soft leptons
- Experiments can manage as low as 5 GeV p_T leptons
- One can use multi lepton requirement instead of p_T^{miss} cuts.

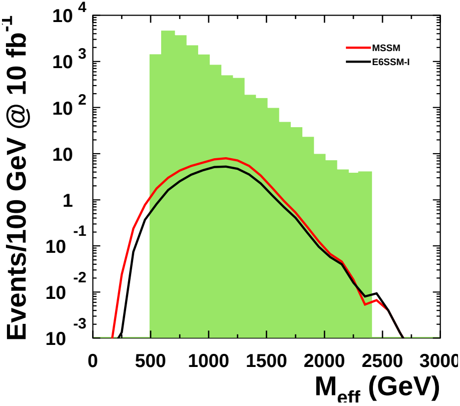
Lepton: μ or e with $|\eta| < 2.5$, $p_T > 10$ GeV and $\Delta R(lep, jet) > 0.5$

LHC @ 7 TeV: 0 leptons

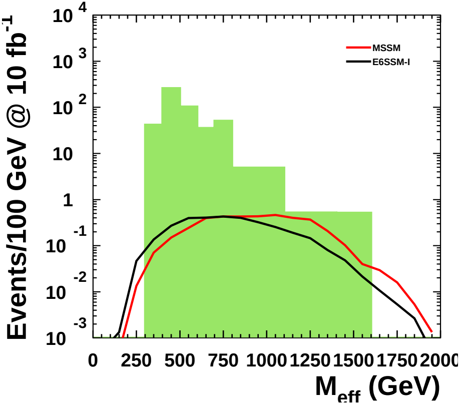
0 leptons, 4 jets: Backgrounds from ATLAS



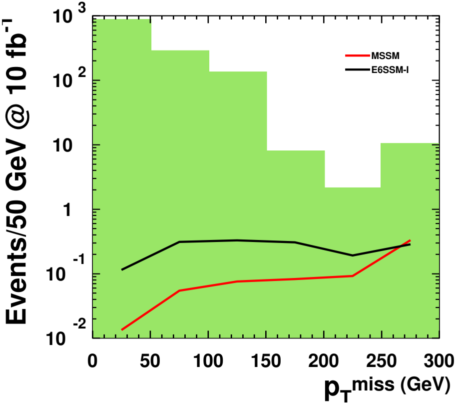
0 leptons, 3 jets: Backgrounds from CMS



1 muon, 4 jets: Backgrounds from ATLAS

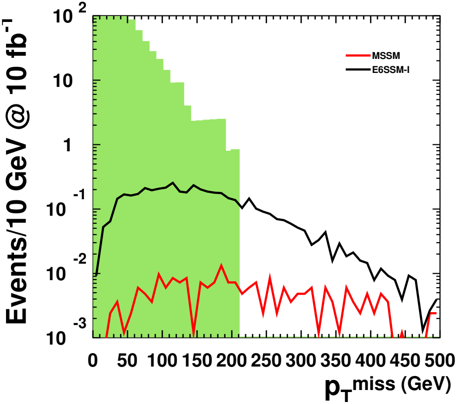


2SS leptons: SS-SR2. Backgrounds from ATLAS

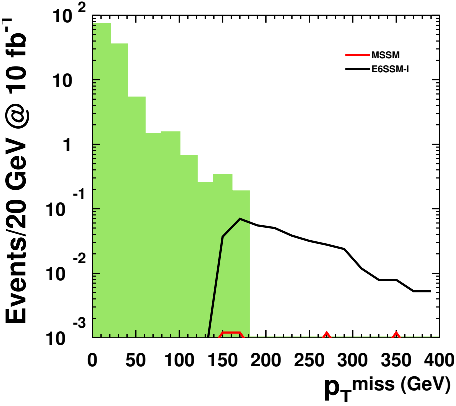


LHC @ 7 TeV: 3-4 leptons

3 leptons: Backgrounds from CMS



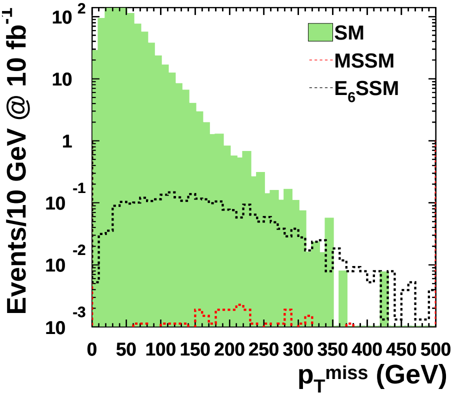
4 leptons: Backgrounds from ATLAS



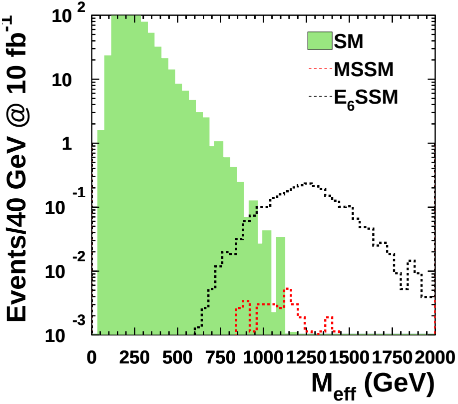
LHC @ 7 TeV: 3 leptons

3 leptons: Backgrounds from CalcHEP

Missing transverse momentum

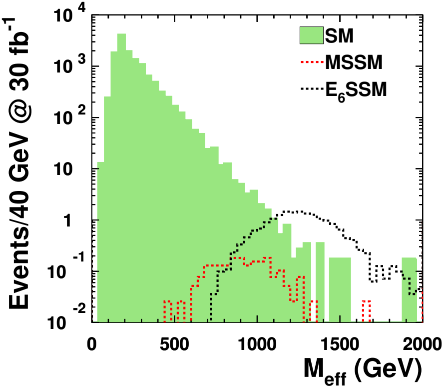


Effective mass

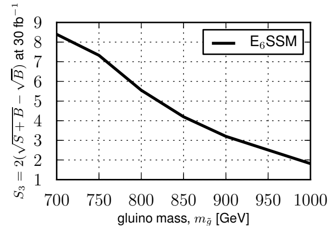


3 leptons: Backgrounds from CalcHEP

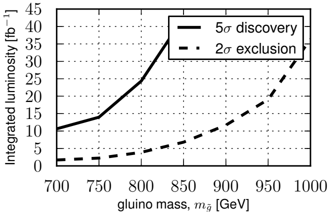
$m_{\tilde{g}} = 800$ GeV



Expected significance at 30 fb^{-1}

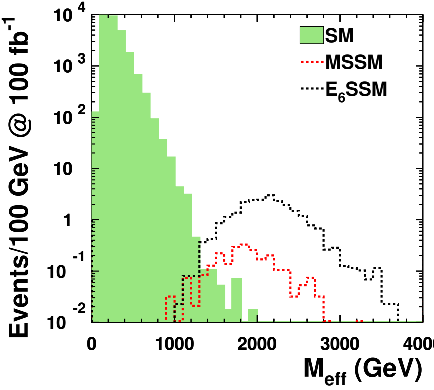


Luminosity required for 5σ discovery and 2σ exclusion

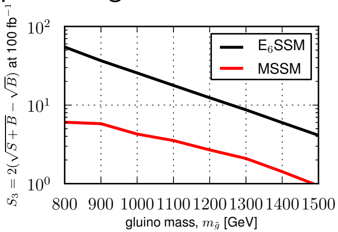


3 leptons: Backgrounds from CalcHEP

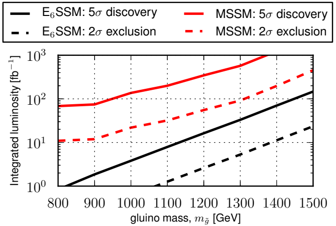
$m_{\tilde{g}} = 1300$ GeV



Expected significance at 100 fb^{-1}



Luminosity required for 5σ discovery and 2σ exclusion



Summary

- Need to look beyond the MSSM.
  - The E_6SSM might have the solution to the μ-problem
- The E_6SSM has a richer phenomenology than the MSSM
- Longer gluino decays at colliders would mean
  - Less missing transverse momentum
  - More visible transverse momentum
  - More leptons
- SUSY searches relying on large p_T^{miss} is not efficient for models with longer decay chains
- Multi-lepton channels provide a tool for distinguishing SUSY models with different decay chain lengths
- Multi-lepton channels are important for discovering models sensitive to p_T^{miss}-cuts

Thanks!