LHC Phenomenology of an E_6 Inspired SUSY SM

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MSSM at a glance

Table 1: The MSSM Particle Spectrum

Superfield		Bosons	Fermions
Gauge			
$\widehat{G}$		g	$\widetilde{g}$
$\widehat{V}^a$		W^a	$\widetilde{W}^a$
$\widehat{V}'$		B	$\widetilde{B}$
Matter			
$\widehat{L}$	leptons	$\widetilde{L} = (\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$
$\widehat{E}^c$	leptons	$\widetilde{E} = \widetilde{e}_R^+$	e_L^c
$\widehat{Q}$	quarks	$\widetilde{Q} = (\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$
$\widehat{U}^c$	quarks	$\widetilde{U}^c = \widetilde{u}_R^*$	u_L^c
$\widehat{D}^c$	quarks	$\widetilde{D}^c = \widetilde{d}_R^*$	d_L^c
$\widehat{H}_d$	Higgs	H_d^i	$(\widetilde{H}_d^0, \widetilde{H}_d^-)_L$
$\widehat{H}_u$	Higgs	H_u^i	$(\widetilde{H}_u^+, \widetilde{H}_u^0)_L$

Higgsino mass

$$\mu \tilde{H}_u \tilde{H}_d$$

More general SUSY models

Focus on models which provide a dynamical origin of μ term:

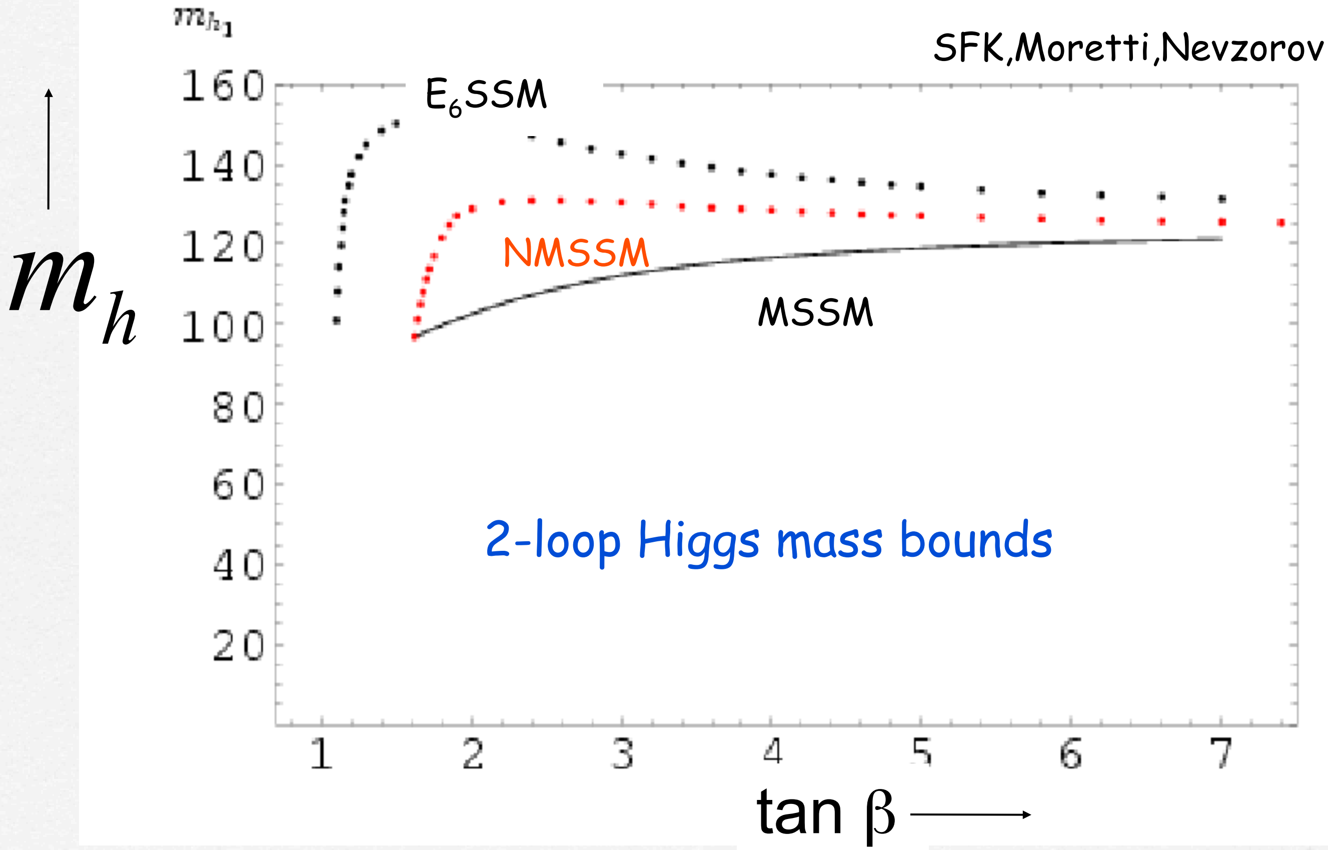
SH_uH_d where singlet $\langle S \rangle \sim \mu \sim$ TeV

Danger from weak scale axion due to global $U(1)$ symmetry

Need to avoid axion somehow

- In NMSSM we add S^3 to break $U(1)$ to Z_3 – but this results in cosmological domain walls ($\mu S^2, \mu^2 S$ reintroduces μ problem)
- In E_6SSM we gauge the $U(1)$ symmetry to eat the axion resulting in a massive Z' gauge boson - anomalies are cancelled by three complete 27's of E_6 at the TeV scale with $U(1) \in E_6$

Higgs mass bounds



Larger tree-level Higgs mass = less tuning

MSSM has a hard time with a 125 GeV Higgs - need heavy stops and large stop mixing

$$W = \lambda S H_u H_d \qquad m_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta + \Delta$$

λ can be larger in E_6SSM than NMSSM

MSSM

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

NMSSM

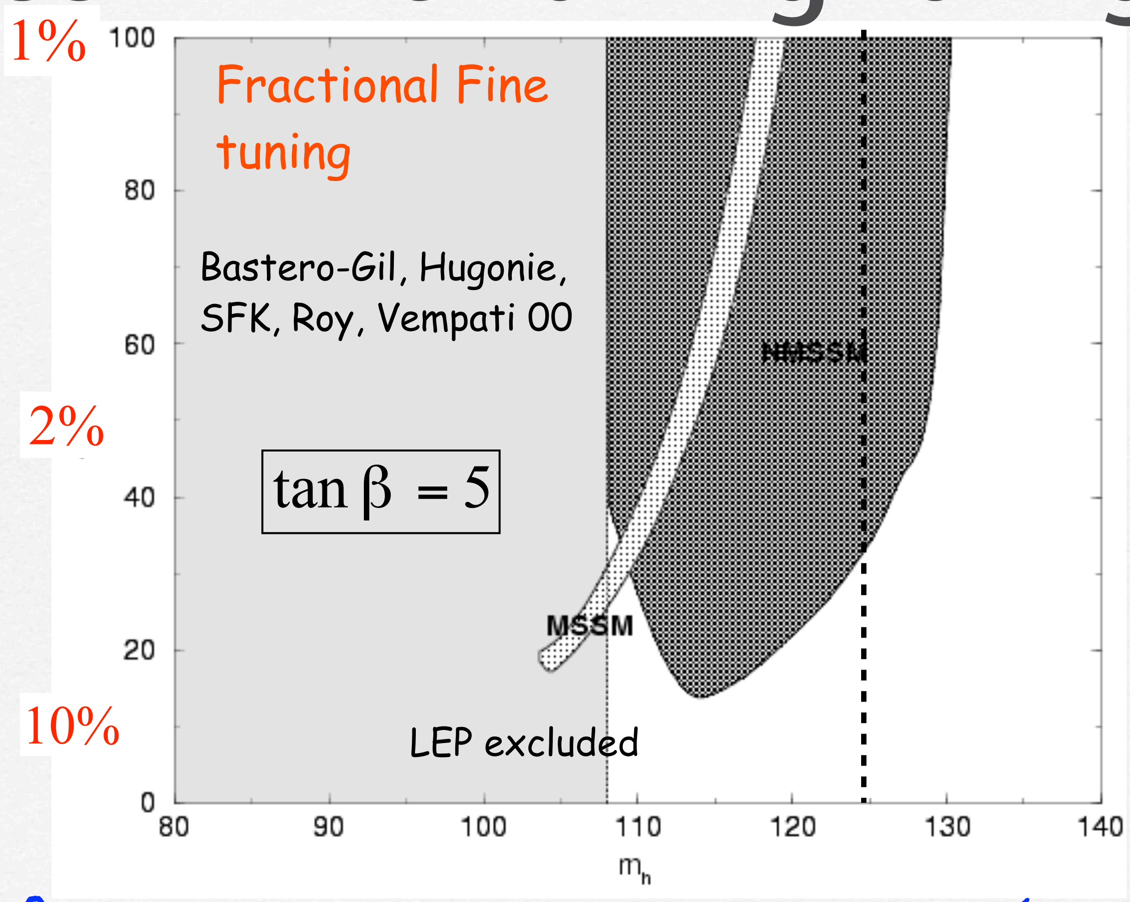
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$$

$$\Delta m_h^2 \approx \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde t}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde t}^2}\right)\right] \qquad X_t = A_t - \mu\cot\beta$$

Δ_{II}

NMSSM fine tuning is reduced due to extra tree-level term which increases Higgs mass

NMSSM Fine Tuning vs Higgs Mass



For 125 GeV Higgs the MSSM fine tuning is much worse than in NMSSM

LEP favours NMSSM over MSSM (10 years ago)

LHC with Higgs @ 125 GeV strengthens conclusion

NMSSM Higgs Benchmarks Near 125 GeV

King, Muhlleitner, Nevzorov

Point	NMP1	NMP2	NMP3
$\tan\beta$	3	2	2
$\mu_{\rm eff}$ [GeV]	200	200	200
λ	0.64	0.6	0.57
κ	0.25	0.18	0.2
A_λ [GeV]	560	405	395
A_κ [GeV]	-10	-10	-80
$M_{Q_{3L}}$ [GeV]	650	700	530
M_{t_R} [GeV]	650	700	530
M_1 [GeV]	106	91	115
M_2 [GeV]	200	200	200
M_3 [GeV]	600	600	600
SM-like Higgs boson H_1			
M_{H_1} [GeV]	124.5	126.5	124.6
$R_{\gamma\gamma}(H_1)$	1.06	1.24	1.47
$R_{WW}(H_1)$	0.85	0.93	1.02
$R_{ZZ}(H_1)$	0.76	0.85	0.90
$R_{b\bar b}(H_1)$	1.12	1.09	1.04
$R_{\Gamma_{tot}}(H_1)$	1.02	0.93	0.76
$R_{\sigma_{gg}}(H_1)$	0.97	0.96	0.77
$R_{\sigma_{tot}}(H_1)$	0.84	0.91	0.82
$m_{\tilde t_1}$ [GeV]	548	587	358
$m_{\tilde t_2}$ [GeV]	782	838	686
$X_t/m_{\tilde t}$	1.74	1.86	2.26
Relic density			
Ωh^2	0.9819	0.1170	0.1100

Point	NMP4	NMP5	NMP6
$\tan\beta$	3	3	2
$\mu_{\rm eff}$ [GeV]	200	200	140
λ	0.67	0.66	0.55
κ	0.1	0.12	0.31
A_λ [GeV]	650	650	210
A_κ [GeV]	-10	-10	-210
$M_{Q_{3L}}$ [GeV]	600	600	800
M_{t_R} [GeV]	600	600	600
M_1 [GeV]	200	200	145
M_2 [GeV]	400	400	300
M_3 [GeV]	600	600	800
SM-like Higgs boson H_2			
M_{H_2} [GeV]	123.8	126.5	124.5
$R_{\gamma\gamma}(H_2)$	1.09	1.19	1.431
$R_{WW}(H_2)$	0.91	0.98	1.00
$R_{ZZ}(H_2)$	0.80	0.89	0.89
$R_{b\bar b}(H_2)$	1.08	1.06	1.04
$R_{\Gamma_{tot}}(H_2)$	0.96	0.90	0.78
$R_{\sigma_{gg}}(H_2)$	1.00	0.96	0.91
$R_{\sigma_{tot}}(H_2)$	0.92	0.95	0.93
$m_{\tilde t_1}$ [GeV]	517	483	549
$m_{\tilde t_2}$ [GeV]	724	741	892
$X_t/m_{\tilde t}$	1.56	1.89	-1.83
Relic density			
Ωh^2	0.0999	0.1352	0.1258

Key features:

- Stops below 1 TeV in all cases
- Two photon Higgs BR enhanced
- WW and ZZ Higgs BR suppressed

King, Moretti, Nevzorov

Exceptional SUSY SM (E_6SSM)

$$E_6 \to SO(10) \times U(1)_\psi \qquad SO(10) \to SU(5) \times U(1)_\chi$$

M_{string} — $SU(3) \times SU(2) \times U(1)_Y \times U(1)_N$

M_3

M_2 — RH neutrinos neutral under: $U(1)_N = \frac{\sqrt{15}}{4} U(1)_\psi + \frac{1}{4} U(1)_\chi$

M_1

Energy

remaining matter content of 3 families of 27's of E_6 survives down to the TeV scale

TeV — $U(1)_N$ broken, Z' and exotics get mass, μ term generated

M_W — $SU(2)_L \times U(1)_Y$ broken

Matter Content of 27's of E_6

All the SM matter fields are contained in one 27-plet of E_6 per generation.

Miller

$$[27]_i \Rightarrow [10, 1]_i + [5^*, 2]_i + [5^*, -3]_i + [5, -2]_i + [1, 5]_i + [1, 0]_i$$

$[10, 1]_i$	$Q_i,\ u_i^c,\ e_i^c$	
$[5^*, 2]_i$	$L_i,\ d_i^c$	
$[5^*, -3]_i$	$H_{1\,i} = \begin{pmatrix} H_{1\,i}^0 \\ H_{1\,i}^- \end{pmatrix}, \bar{D}_i$	3 generations of "Higgs"; exotic quarks
$[5, -2]_i$	$H_{2\,i} = \begin{pmatrix} H_{2\,i}^+ \\ H_{2\,i}^0 \end{pmatrix}, D_i$	3 generations of "Higgs"; exotic quarks
$[1, 5]_i$	S_i	singlets
$[1, 0]_i$	N_i^c	right handed neutrino

SU(5) reps.

$U(1)_N$ charge $\times \sqrt{40}$

E6SSM Couplings

$S \subset S_i,$ $D \subset D_i, \bar{D}_i,$

$H \subset H_i^u, H_i^d$ $F \subset Q_i, L_i, U_i^c, D_i^c, E_i^c, N_i^c$

$$W = SHH + SDD + HFF + DFF$$

Singlet-Higgs-Higgs couplings includes effective μ term

Singlet-D-D couplings includes effective D mass terms

Yukawa couplings but extra Higgs give FCNCs

DQQ, DQL allows D decay but also proton decay. Need to:
– either forbid one of DQQ or DQL
- or allow both with Yukawas $\sim 10^{-12}$

LHC phenomenology of E_6SSM

- SUSY - typical spectrum has heavier squarks and lighter gluinos, with gluinos having longer decay chains than MSSM, due to extra neutralinos and charginos, giving less missing energy and more soft leptons and jets
- Higgs - Richer Higgs spectrum than MSSM or NMSSM (incl. inert Higgs)
- Exotics - Z', D-leptoquarks/diquarks

Neutralinos in E_6SSM

Hall, King

- 3 Higgs families = 1 MSSM family H_u H_d + 2 inert families H_{u1} H_{d1} H_{u2} H_{d2}
- 3 families of Singlets = 1 NMSSM singlet S + 2 inert singlets S_1 S_2

The full neutralino mass matrix

$$\tilde{\chi}^0_{\rm int} = (\underbrace{\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}^0_d \quad \tilde{H}^0_u}\ |\ \underbrace{\tilde{S} \quad \tilde{B}'}\ |\ \underbrace{\tilde{H}^0_{d2} \quad \tilde{H}^0_{u2} \quad \tilde{S}_2}\ |\ \underbrace{\tilde{H}^0_{d1} \quad \tilde{H}^0_{u1} \quad \tilde{S}_1})^{\rm T}$$

$$M^n_{\rm E_6SSM} = \begin{pmatrix} M^n_{\rm USSM} & B_2 & B_1 \\ B_2^{\rm T} & A_{22} & A_{21} \\ B_1^{\rm T} & A_{21}^{\rm T} & A_{11} \end{pmatrix}$$

12x12 matrix!!

Hall, King

The Inert Neutralino Sector

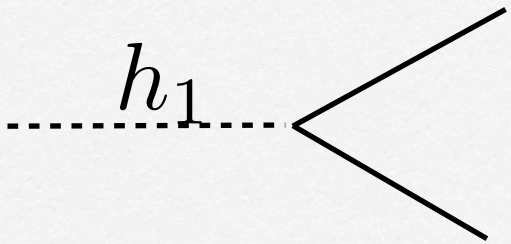
$$A_{\alpha\beta} = -\frac{1}{\sqrt{2}} \begin{array}{cc} \begin{array}{ccc} \tilde{H}^0_{d\beta} & \tilde{H}^0_{u\beta} & \tilde{S}_\beta \end{array} & \\ \begin{pmatrix} 0 & \lambda_{\alpha\beta} s & \tilde{f}_{\beta\alpha} v \sin\beta \\ \lambda_{\beta\alpha} s & 0 & f_{\beta\alpha} v \cos\beta \\ \tilde{f}_{\alpha\beta} v \sin\beta & f_{\alpha\beta} v \cos\beta & 0 \end{pmatrix} & \begin{array}{c} \tilde{H}^0_{d\alpha} \\ \tilde{H}^0_{u\alpha} \\ \tilde{S}_\alpha \end{array} \end{array}$$

$$m_{\chi^0_1} \approx \frac{f^2}{\lambda} \frac{v^2}{s} \sin 2\beta \quad \left\{ \begin{array}{l} \text{Inert LSP is naturally light} \sim v^2/s \\ \\ \text{Inert LSP is inert Higgsino/singlino} \end{array} \right.$$

- ☐ Inert LSP would be natural dark matter candidate
- ☐ Higgs and gluinos can decay into inert LSP (invisible Higgs decays, longer gluino chains)

Hall, King, Pakvasa Nevzorov, Sher

Invisible Higgs Decays



To get a 125 GeV SM-like visible Higgs need one of :

(i) $M_\chi > 62$ GeV

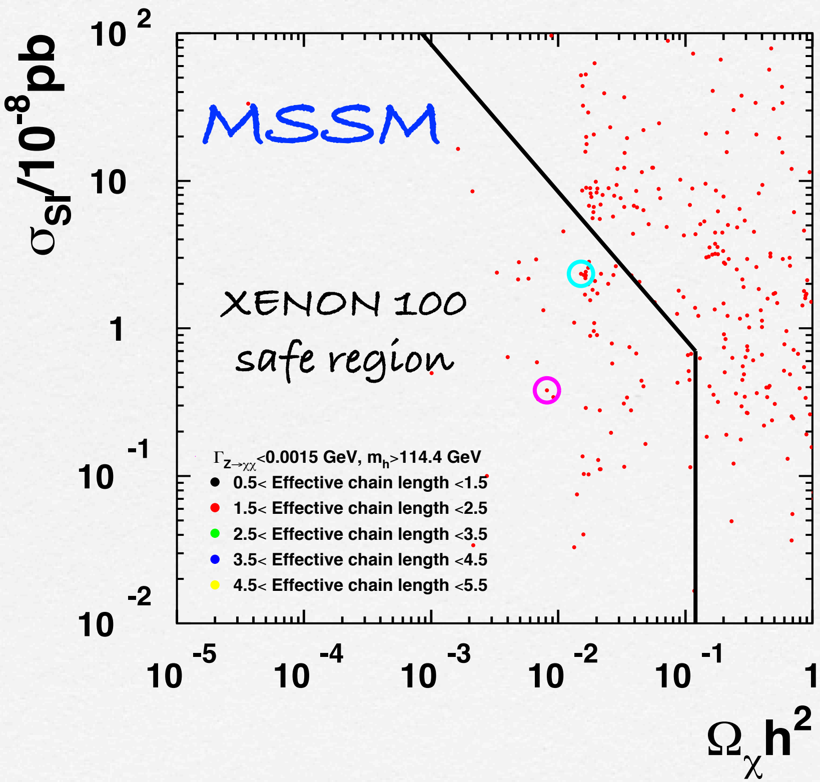
(ii) $M_\chi < 1$ GeV

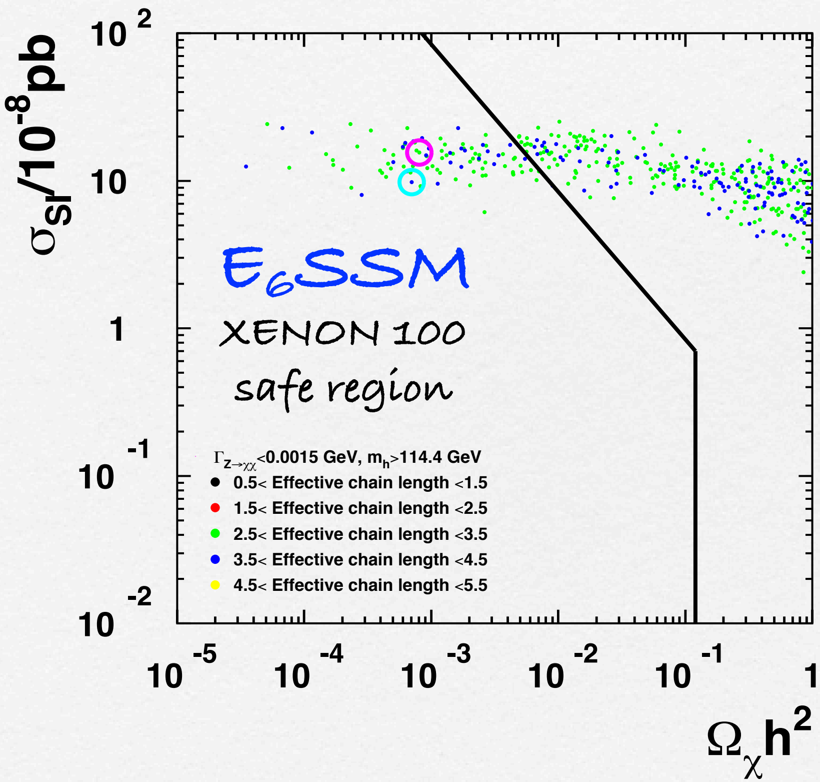
$$\Gamma(h_1 \to \chi^0_\alpha \chi^0_\beta) \gg \Gamma(h_1 \to f\bar{f})$$

- due to large coupling of inert neutralinos to Higgs $\sim M_\chi / v$ with $M_\chi \sim M_Z/2$ can get "invisible" Higgs
- gives large SI DD cross-sections -- challenged by XENON 100

Belyaev, Hall, King, Svantesson (preliminary)

Dark Matter Constraints





Also shown are gluino decay chain lengths

E6SSM Benchmarks

MSSM-inos →

USSM-inos →

E_6SSM-inos →

LSP

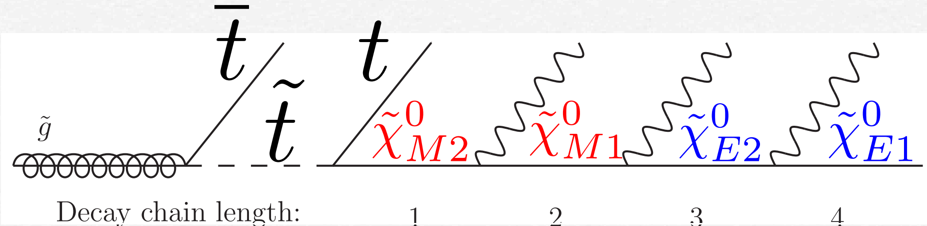
Higgs

Belyaev, Hall, King, Svantesson (preliminary)

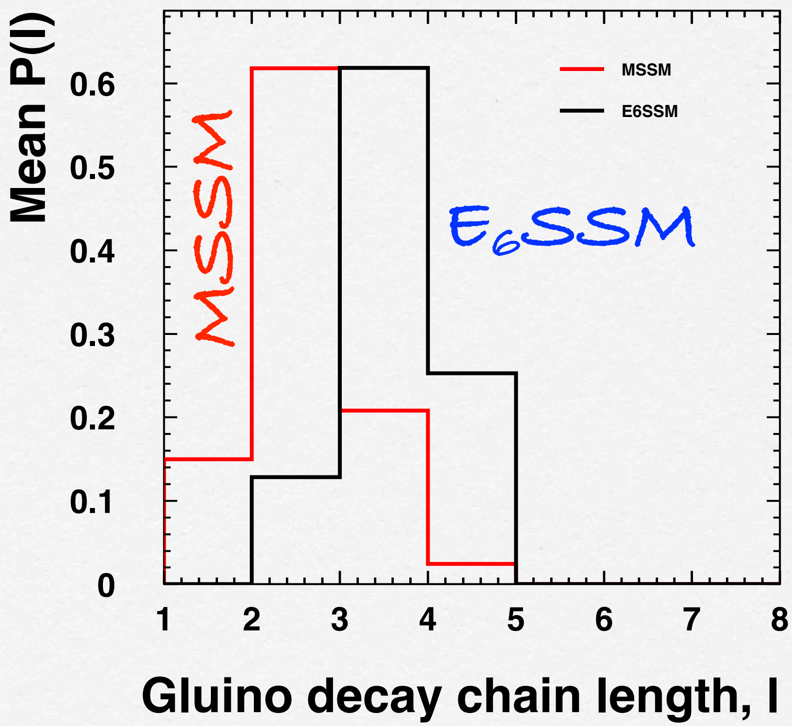
	MSSM-A	MSSM-B	E_6SSM-A	E_6SSM-B	E_6SSM-C	E_6SSM-D	E_6SSM-E	E_6SSM-F	
$\tan\beta$	9.9	39.2	1.42	1.77	1.42	1.5	1.42	3	
λ	-	-	0.598	-0.462	0.598	0.55	0.598	-0.4	
s	-	-	5268	5418	5268	3700	5268	5500	[GeV]
μ	-112.6	1578	(2228)	(1770)	(2228)	(1439)	(2228)	(-1556)	
$A_t = A_b = A_\tau$	-724.6	-566.1	-2684	476.2	-2684	-2200	-2684	4638	
M_A	1593	302.5	2791	2074	4000	2736	4010	4341	
M_1	150	150	150	150	150	150	150	150	
M_2	285	285	300	300	300	300	300	300	
$M_{1'}$	-	-	151	151	151	151	151	151	
$m_{\tilde{g}}$	800.3	800.2	800.0	800.0	800.0	800.0	800.0	800.0	
$m_{\tilde{\chi}^0_{M1}}$	94.1	149.9	149.1	151.2	149.1	148.6	149.1	150.6	[GeV]
$m_{\tilde{\chi}^0_{M2}}$	128.8	302.8	296.8	303.7	296.8	296.8	296.8	301.7	
$m_{\tilde{\chi}^0_{M3}}$	163.0	1580	2233	1766	2233	1254	2233	1557	
$m_{\tilde{\chi}^0_{M4}}$	323.5	1581	2246	1771	2246	1468	2246	1558	
$m_{\tilde{\chi}^\pm_{M1}}$	112.2	302.8	299.2	300.9	299.2	298.7	299.2	300.4	
$m_{\tilde{\chi}^\pm_{M2}}$	323.5	1582	2229	1771	2229	1440	2229	1557	
$m_{\tilde{\chi}^0_{U1}}$	-	-	1835	1909	1835	1420	1835	1937	[GeV]
$m_{\tilde{\chi}^0_{U2}}$	-	-	2003	2062	2003	1459	2003	2087	
$m_{\tilde{\chi}^0_{E1}}$	-	-	43.5	45.2	0.00011	62.7	0	0	[GeV]
$m_{\tilde{\chi}^0_{E2}}$	-	-	48.6	53.2	1.53	62.8	0	0	
$m_{\tilde{\chi}^0_{E3}}$	-	-	131.3	141.6	120.1	119.9	119.9	164.1	
$m_{\tilde{\chi}^0_{E4}}$	-	-	163.6	187.4	122.8	121.1	119.9	164.1	
$m_{\tilde{\chi}^0_{E5}}$	-	-	197.0	227.8	185.8	183.1	185.8	388.9	
$m_{\tilde{\chi}^0_{E6}}$	-	-	224.3	265.6	187.0	184.4	185.8	388.9	
$m_{\tilde{\chi}^\pm_{E1}}$	-	-	119.9	122.7	119.9	109.8	119.9	164.1	
$m_{\tilde{\chi}^\pm_{E2}}$	-	-	185.8	225.1	185.8	117.8	185.8	388.9	
m_h	120.4	119.0	133.8	116.3	125.8	125.4	126.1	124.7	[GeV]
$m_{\tilde{t}_1}$	1979	1992	1916	2042	1917	1917	1917	1885	
$P(l=1)$	0.09847	0.188	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-12}$	$< 10^{-9}$	$< 10^{-8}$	0.1727	
$P(l=2)$	0.4705	0.812	0.01524	0.1723	$< 10^{-5}$	$< 10^{-4}$	0.0061	0.8273	
$P(l=3)$	0.387	0	0.2336	0.7986	0.1721	0.1746	0.1953	$< 10^{-6}$	
$P(l=4)$	0.04387	0	0.7512	0.02915	0.8280	0.8196	0.7987	$< 10^{-15}$	
$P(l=5)$	$< 10^{-4}$	0	$< 10^{-7}$	0	0	0.0058	$< 10^{-15}$	0	
Ωh^2	0.01513	0.00816	0.0006842	0.0006937		0.00114	$< 10^{-2}$	0.101	
σ_{SI}	2.35×10^{-8}	0.38×10^{-8}	9.35×10^{-8}	16.35×10^{-8}		15.34×10^{-8}	$< 10^{-12}$	3.75×10^{-11}	[pb]

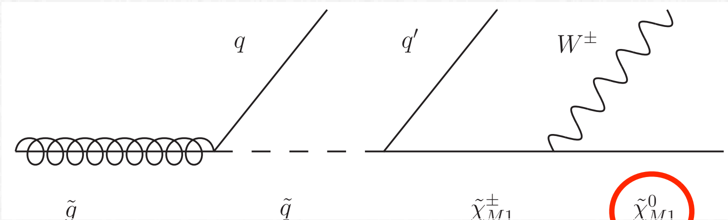
Gluino decay chains

Belyaev, Hall, King, Svantesson (preliminary)

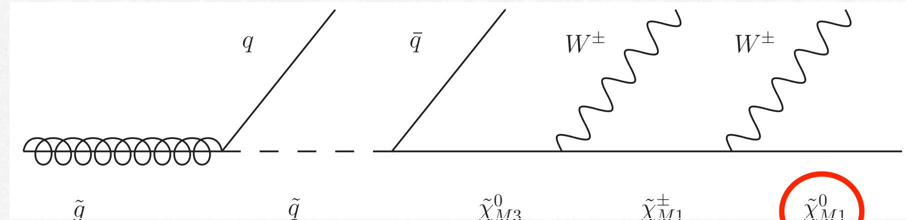


E_6SSM has longer gluino chains with a lighter LSP at the end

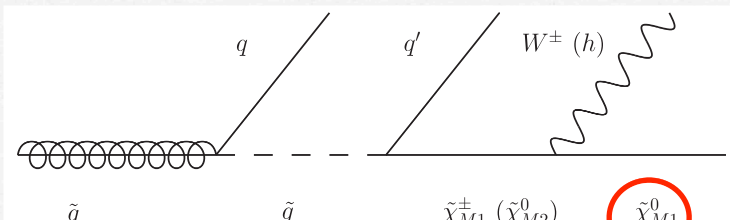




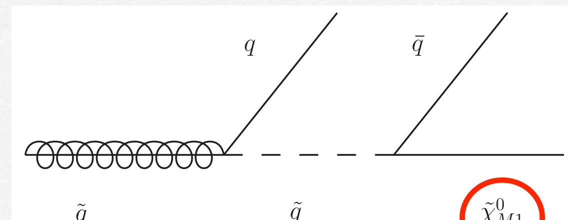
(a)MSSM-A (Primary chain)



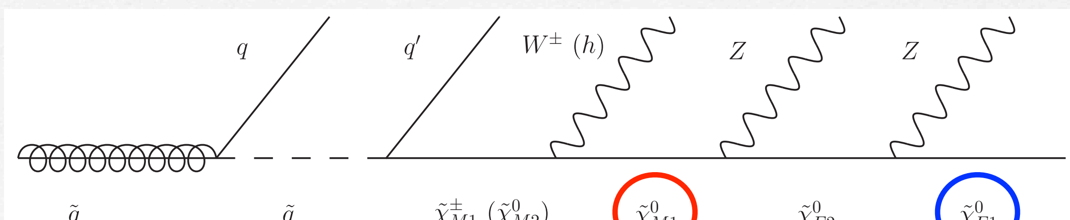
(b)MSSM-A (Secondary chain)



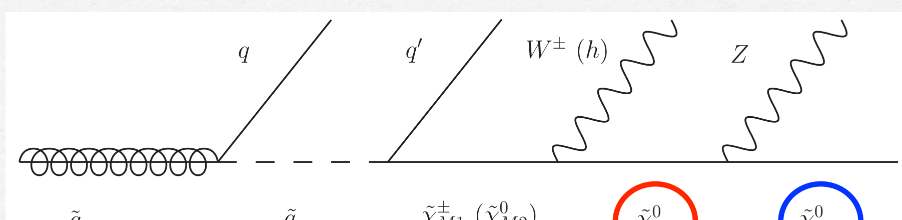
(c)MSSM-B (Primary chain)



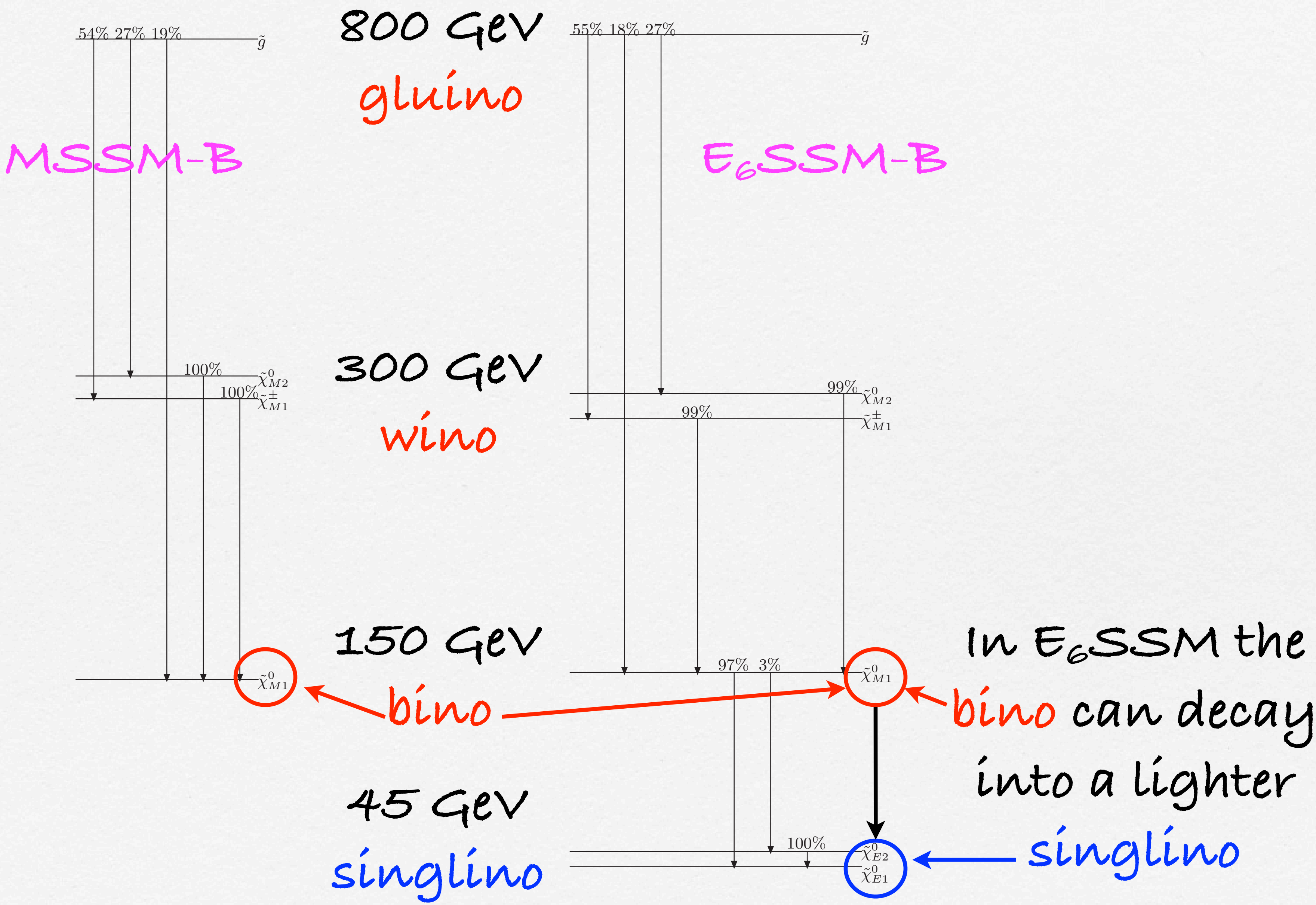
(d)MSSM-B (Secondary chain)



(e)E_6SSM-A

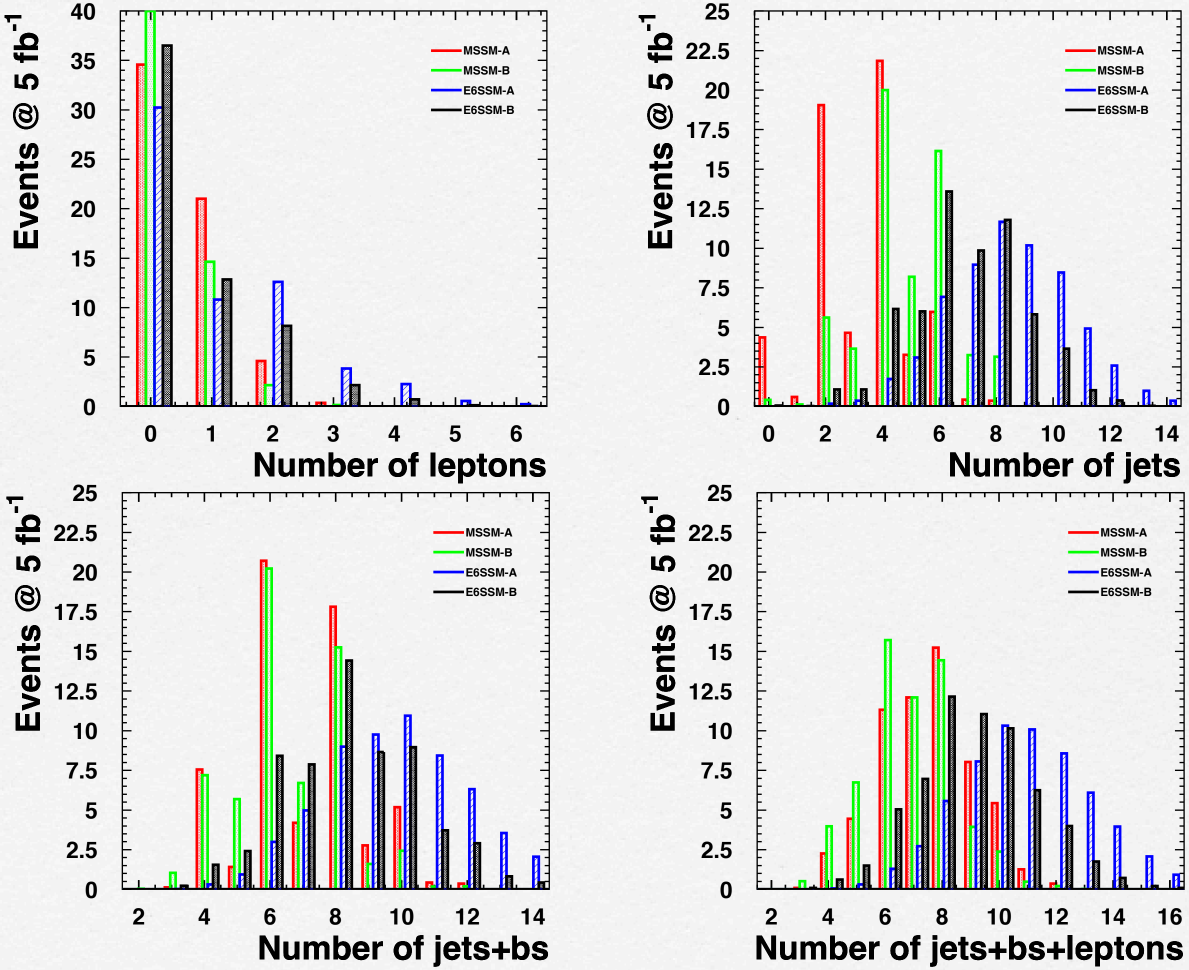


(f)E_6SSM-B



800 GeV
gluino
300 GeV
wino
150 GeV
bino
45 GeV
singlino
MSSM-B
E_6SSM-B
54% 27% 19%
$\tilde{g}$
100%
$\tilde{\chi}^0_{M2}$
100%
$\tilde{\chi}^\pm_{M1}$
$\tilde{\chi}^0_{M1}$
55% 18% 27%
$\tilde{g}$
99%
$\tilde{\chi}^0_{M2}$
99%
$\tilde{\chi}^\pm_{M1}$
97% 3%
$\tilde{\chi}^0_{M1}$
100%
$\tilde{\chi}^0_{E2}$
$\tilde{\chi}^0_{E1}$
In E_6SSM the bino can decay into a lighter singlino

Lepton/jet multiplicity



Belyaev, Hall, King, Svantesson (preliminary)

Lepton multiplicity assuming perfect lepton identification

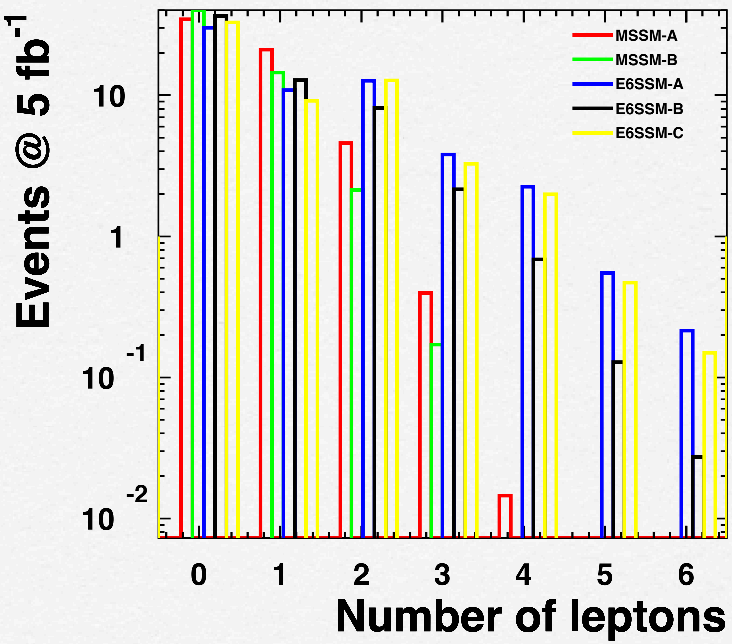


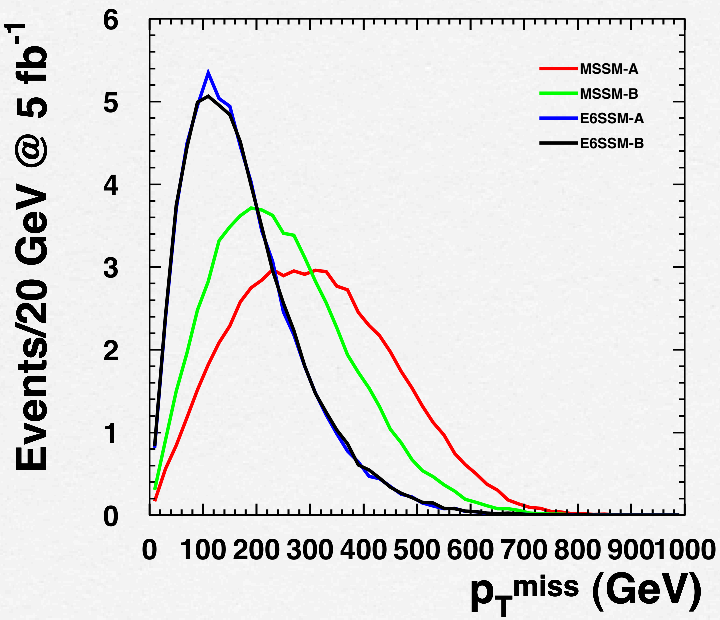
FIG. 8: Lepton multiplicities, where all leptons are assumed to be identified.

Soft Lepton multiplicity is a clear signal of E6SSM

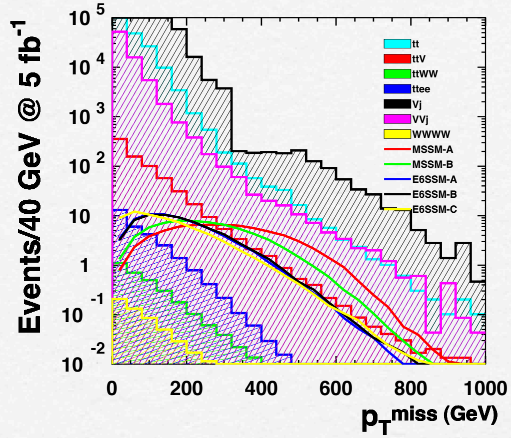
de Santo, King

Including cuts and b/g

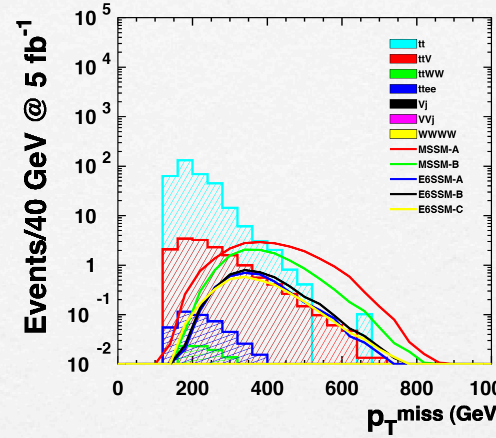
E_6SSM gives less p_T^{miss}



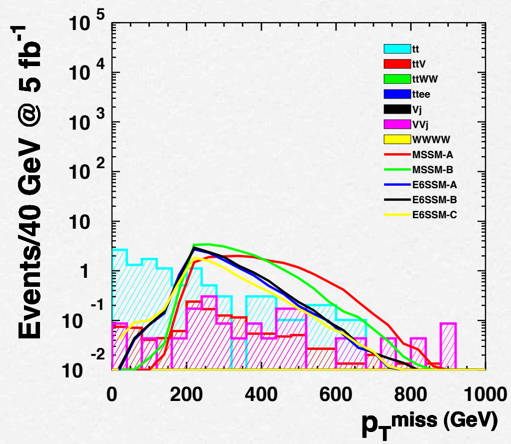
Belyaev, King, Svantesson
(preliminary)



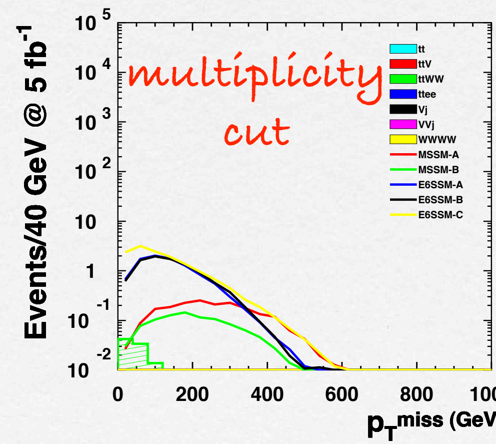
(a)p_T^{miss} without cuts.



(b)p_T^{miss} after 8 ATLAS cuts.



(c)p_T^{miss} after 9 CMS cuts.



(d)p_T^{miss} with $N_l + N_j > 8$, with one muon (or electron) with p_T >15 GeV (20 GeV).

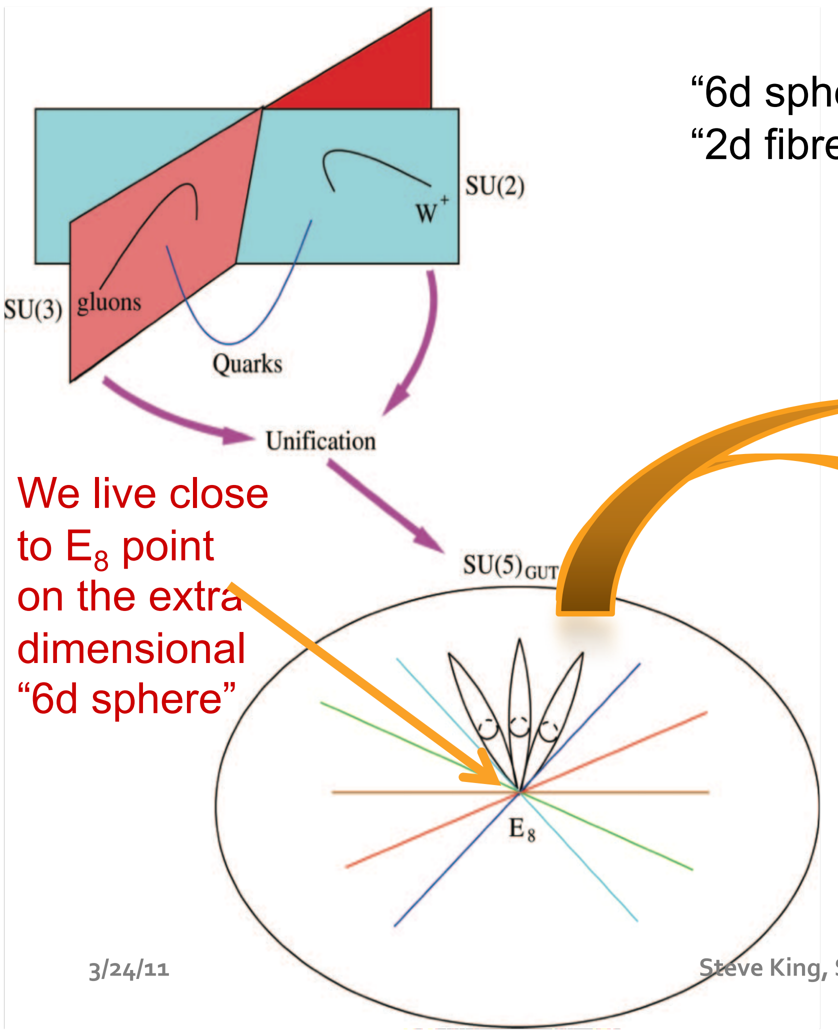
Conclusion

- Hierarchy problem addressed by SUSY...
- ...but SUSY is a symmetry not a model
- LHC can only test individual SUSY models
- Focus on dynamical solutions to mu problem
- NMSSM→E_6SSM (string theory) gives spectacular signals
- SUSY - typical spectrum has heavier squarks and lighter gluinos, with gluinos having longer decay chains than MSSM, due to extra neutralinos and charginos, giving less missing energy and more soft leptons and jets
- Higgs -may have invisible decays or be SM-like depending on the (inert) LSP mass
- Exotics - Z', D-leptoquarks/diquarks (maybe long lived)

Extra Slides

F-Theory GUTs: a 12d string theory

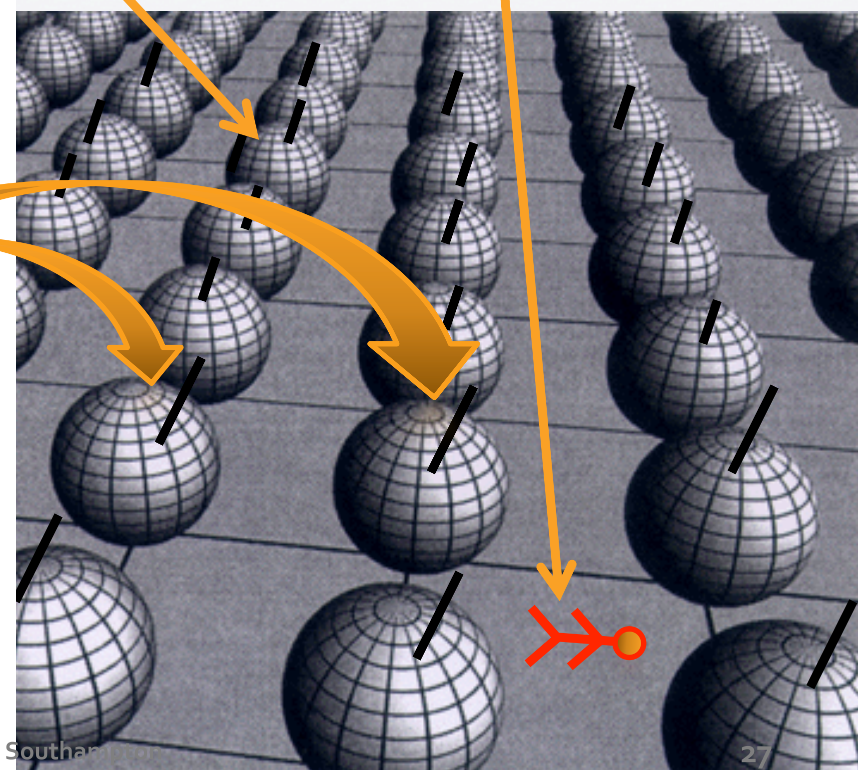
Heckman and Vafa



We live close to E_8 point on the extra dimensional "6d sphere"

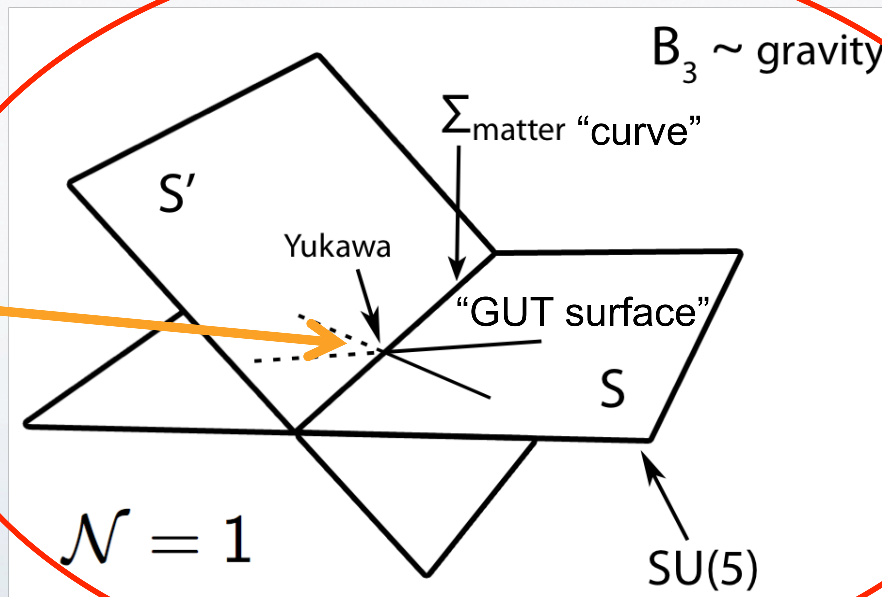
"6d spheres" with "2d fibres"

"4d Flatlander"



The “6d sphere”

We live close to here



dim.	internal dim.	feature
10	$6 = \dim(B_3)$	gravity
8	$4 = \dim(S)$	gauge fields
6	$2 = \dim(S \cap S')$	matter
4	$0 = \dim(S \cap S' \cap S'')$	interactions

“gravity bulk”
“GUT surface S”
“matter curve Σ”
“Yukawa point”

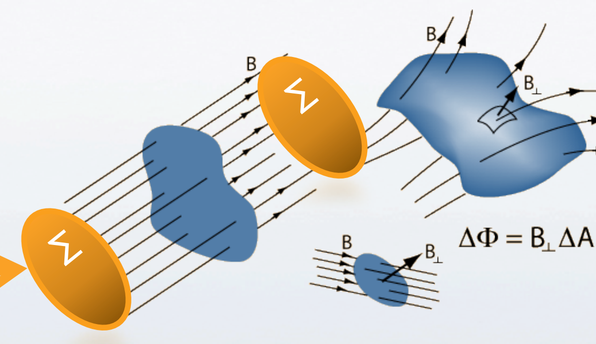
Figure 1: The structure of an F-theory GUT

GUT breaking is achieved not with Higgs but with Hypercharge Flux

$$SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$5 \to (1,2)_{1/2} + (3,1)_{-1/3}.$$

Think of magnetic flux PHYS2001



2-d Matter curve Σ

Index theorem gives number of chiral doublets and triplets (think of Gauss's law):

$$(1,2)_{1/2} : n_L - n_R = 3\int_\Sigma F_{U(1)_Y} + q\int_\Sigma F_{U(1)_\perp}$$

$$(3,1)_{-1/3} : n_L - n_R = -2\int_\Sigma F_{U(1)_Y} + q\int_\Sigma F_{U(1)_\perp}$$

Doublet-triplet Higgs splitting requires:

$$\text{Higgs:} \int_\Sigma F_{U(1)_Y} \neq 0$$

$$\text{Matter:} \int_\Sigma F_{U(1)_Y} = 0.$$

Typically predicts exotics

Callaghan, King, Leontaris , Ross

E6SSM from F-theory

E_6	$SO(10)$	$SU(5)$	Weight vector	N_Y	$M_{U(1)}$	SM particle content	Low energy spectrum
$27_{t'_1}$	16	$\bar{5}_3$	t_1+t_5	1	4	$4d^c+5L$	$3d^c+3L$
$27_{t'_1}$	16	10_M	t_1	-1	4	$4Q+5u^c+3e^c$	$3Q+3u^c+3e^c$
$27_{t'_1}$	16	θ_{15}	t_1-t_5	0	n_{15}	$3\nu^c$	-
$27_{t'_1}$	10	5_1	$-t_1-t_3$	-1	3	$3D+2H_u$	$3D+2H_u$
$27_{t'_1}$	10	$\bar{5}_2$	t_1+t_4	1	3	$3\bar{D}+4H_d$	$3\bar{D}+3H_d$
$27_{t'_1}$	1	θ_{14}	t_1-t_4	0	n_{14}	θ_{14}	-
$27_{t'_3}$	16	$\bar{5}_5$	t_3+t_5	-1	-1	$\bar{d^c}+2\bar{L}$	-
$27_{t'_3}$	16	10_2	t_3	1	-1	$\bar{Q}+2\bar{u^c}$	-
$27_{t'_3}$	16	θ_{35}	t_3-t_5	0	n_{35}	$-$	-
$27_{t'_3}$	10	5_{H_u}	$-2t_1$	1	0	H_u	H_u
$27_{t'_3}$	10	$\bar{5}_4$	t_3+t_4	-1	0	$\bar{H_d}$	-

F-theory model predicts incomplete multiplets with matter content of 3 copies of 27s of E6

Standard Model Puzzles

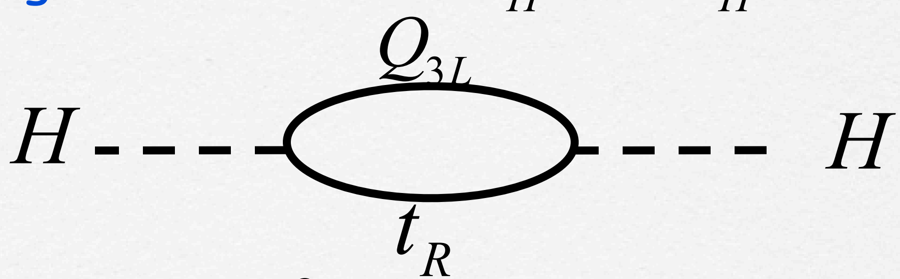
- ❑ The origin and fate of the Universe – and why is it so big and flat?
- ❑ The dark side of the Universe – why is 95% of mass-energy in a form that is presently unknown, including 23% dark matter and 72% dark energy?
- ❑ The origin of matter – the problem of why there is a tiny excess of matter over antimatter in the Universe, at a level of one part in a billion.
- ❑ The origin of mass - the origin of the weak scale, its stability under radiative corrections, and the solution to the hierarchy problem.
- ❑ The quest for unification - the question of whether the three known forces of the standard model (and gravity) may be unified.
- ❑ The problem of flavour - the problem of the three generations with fermion (incl. neutrino) masses and mixing angles and CPV phases, giving small FCNCs and tiny strong CPV.

In SM, top loops dominate

Higgs potential $$V = m_H^2 \left|H\right|^2 + \tfrac{1}{2}\lambda\left|H\right|^4$$

Tree-level min cond $$m_H^2 = -\lambda v^2 = -\lambda\left(246\,GeV\right)^2$$

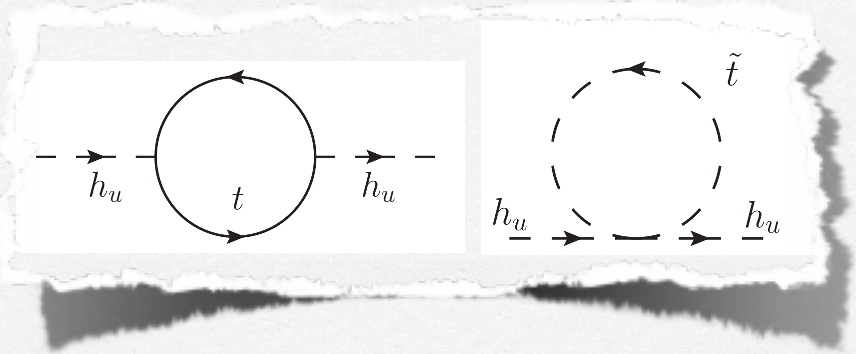
Including rad corr $$m_H^2 + \delta m_H^2 = -\lambda\left(246\,GeV\right)^2$$



$$\delta m_H^2(top\,loop) = -\frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 = -\left(100\,GeV\right)^2 \left(\frac{\Lambda}{1\,TeV}\right)^2$$

Fine-tuning is required if the cut-off $\Lambda \gg 1\,TeV$

In SUSY, stop loops dominate

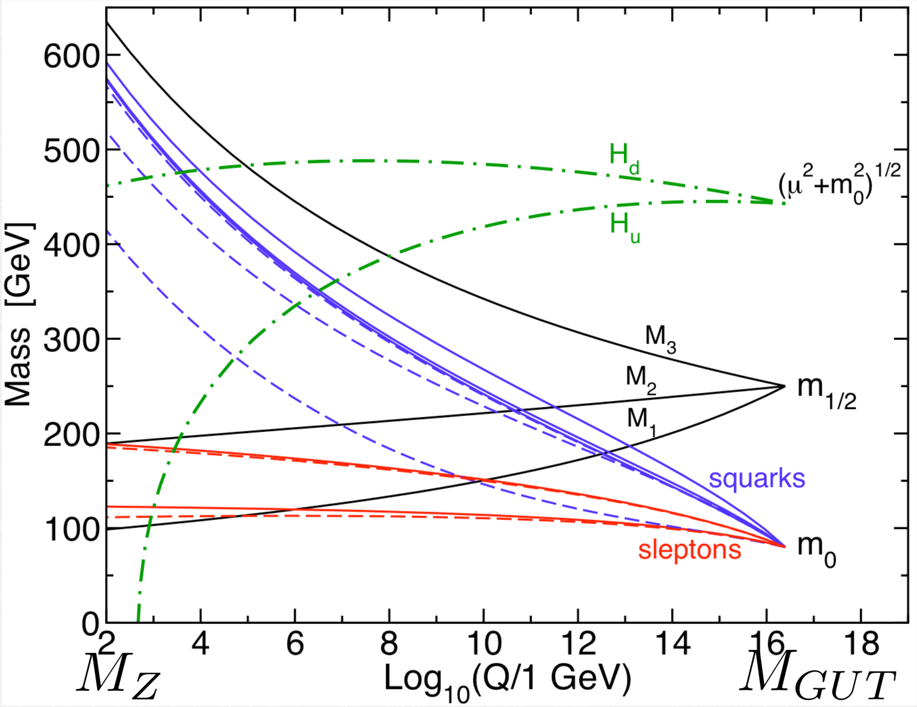


Leading quadratic divergence cancels

$$\delta m_{h_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda_{UV}}{m_{\tilde{t}}}\right)$$

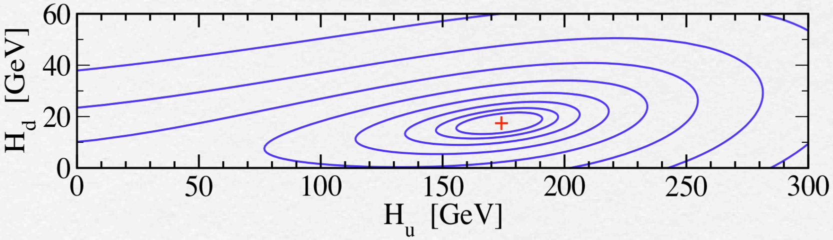
To avoid tuning need $m_{\tilde{t}} \lesssim 400\text{GeV}.$

Constrained MSSM



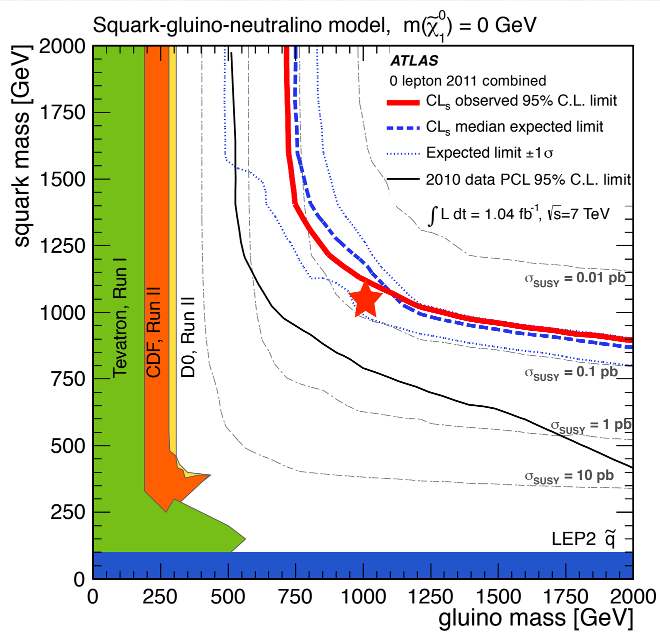
Two Higgs doublets get VEVs

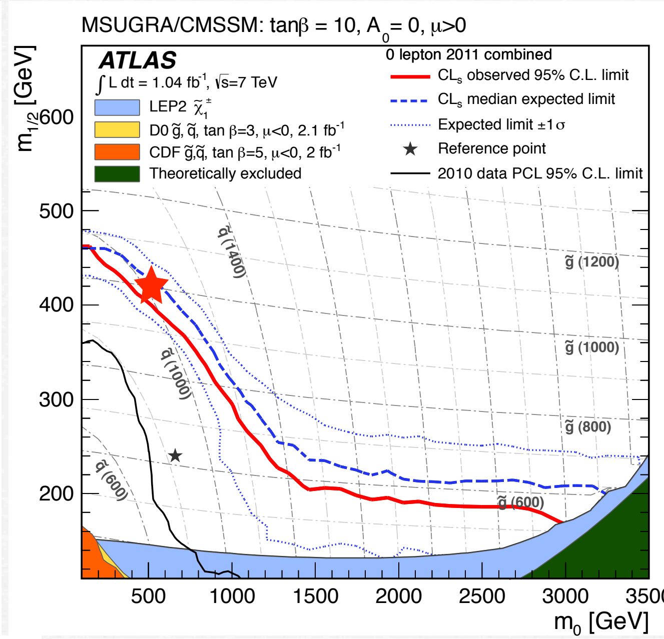
$$H_u = \begin{pmatrix} H_u^{\,+} \\ H_u^{\,0} \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^{\,0} \\ H_d^{\,-} \end{pmatrix}$$

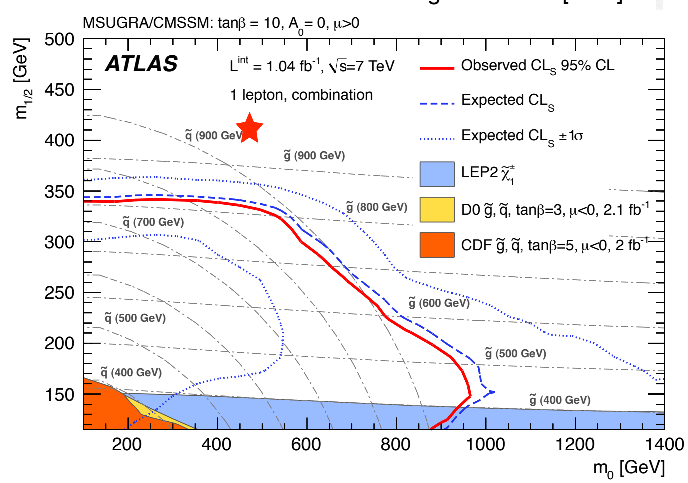


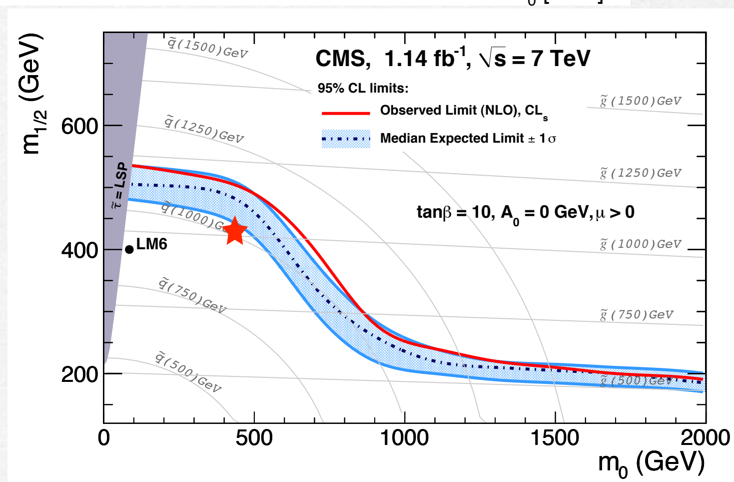
$$\tan\beta = \frac{v_u}{v_d}$$

LHC SUSY limits









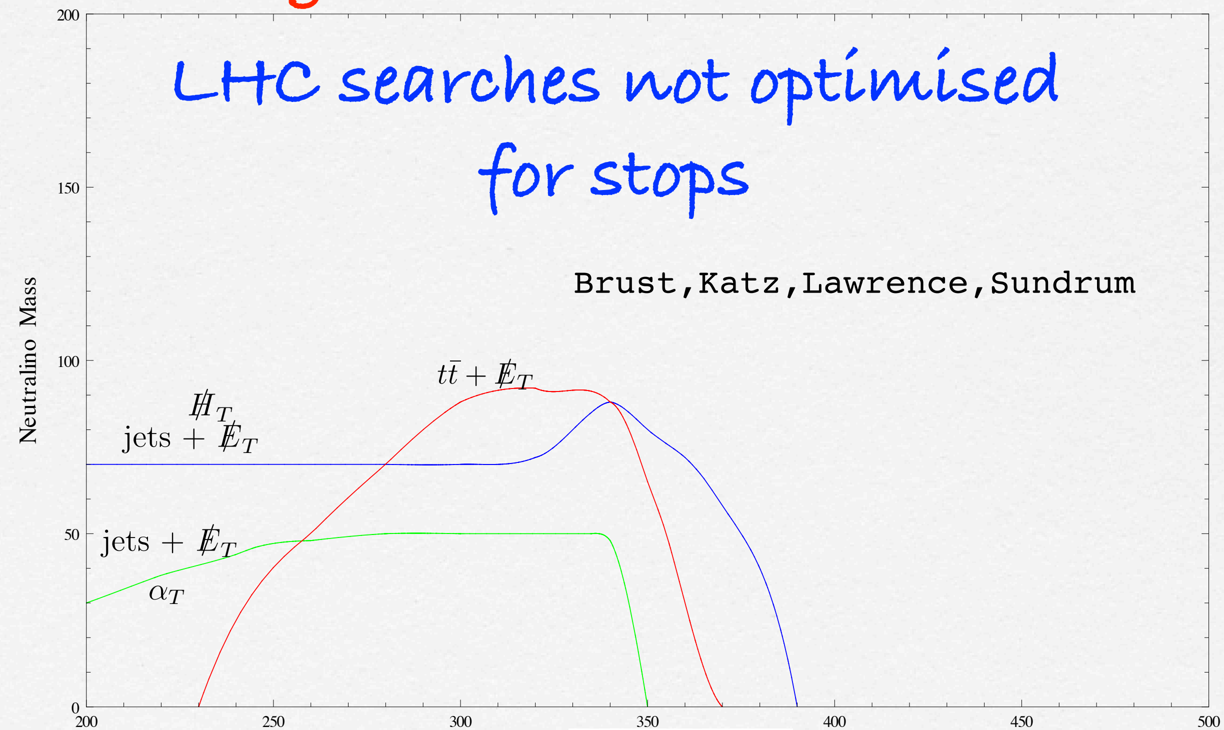
★ stars indicate squark = gluino = 1 TeV

Limits don't apply to stops

Recall to avoid tuning need

$$m_{\tilde{t}} \lesssim 400\text{GeV}. \quad m_{\tilde{g}} \lesssim 2m_{\tilde{t}}.$$

Allowed by current data



300 stop mass 400 GeV

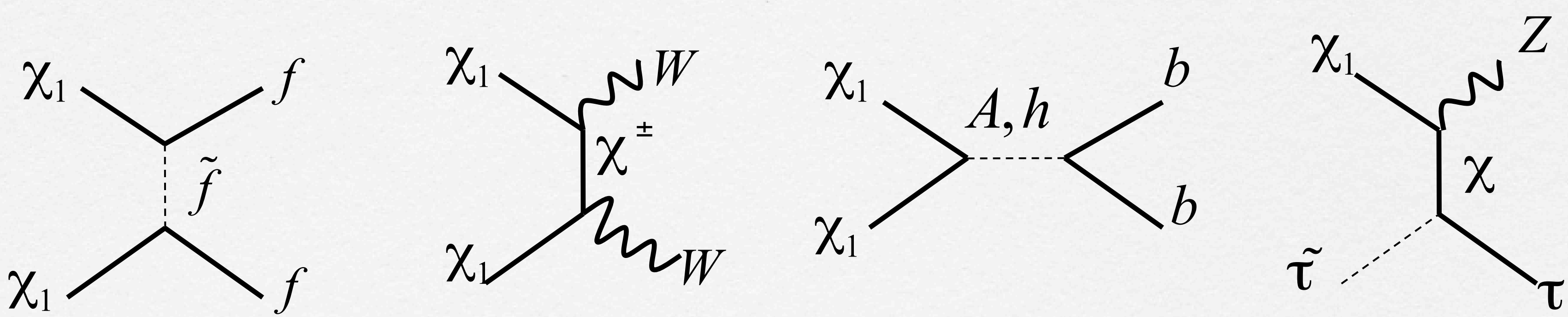
CMSSM Dark Matter

Neutralino mass matrix

$$\chi_1 = N_1\tilde{B} + N_2\tilde{W} + N_3\tilde{H}_d + N_4\tilde{H}_u$$

$$\begin{array}{c}
\begin{array}{cccc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u \end{array} \\
\begin{pmatrix} M_1 & & & \\ & M_2 & & \\ & & 0 & -\mu \\ & & -\mu & 0 \end{pmatrix}
\end{array}$$

$$\Omega_{DM} h^2 = C\,\frac{T_0^3}{M_P^2}\,\frac{1}{\langle \sigma v \rangle}$$

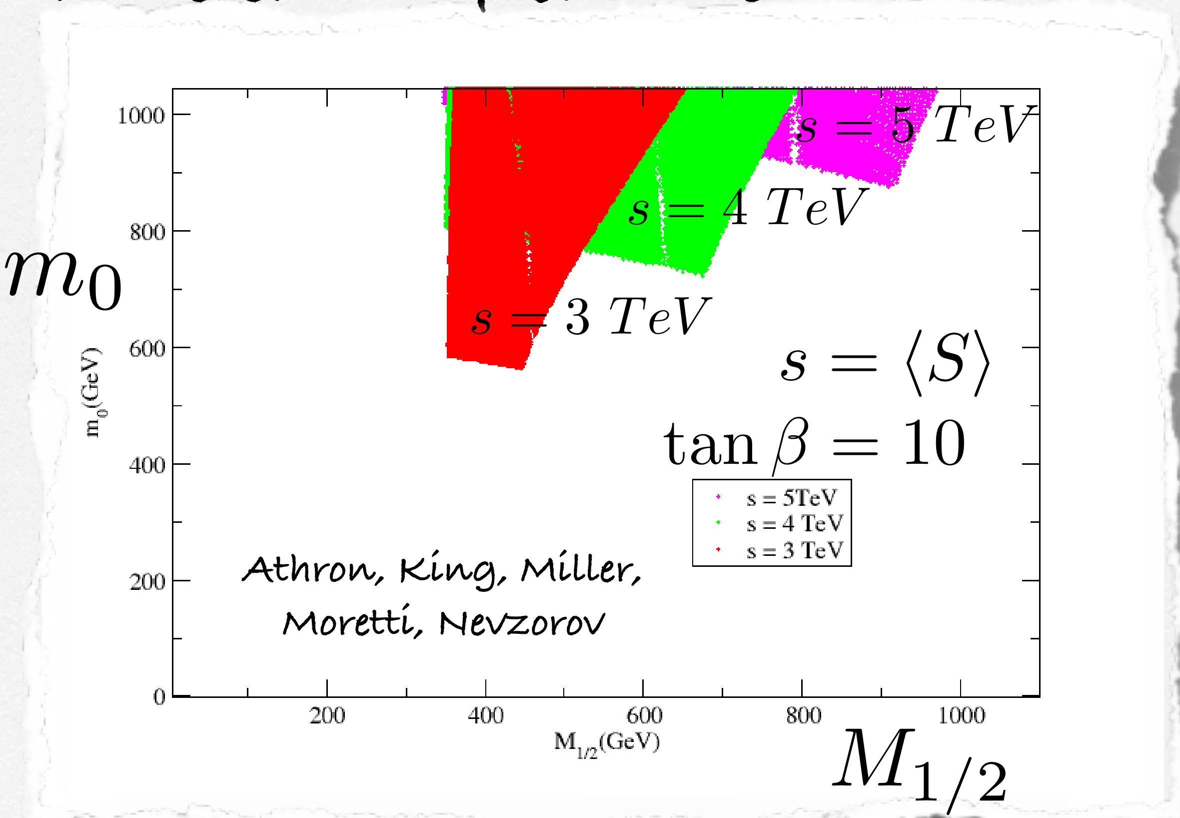


Bulk | Focus | Funnel | Co-annihilation

$m_{\tilde{f}} \approx m_{\chi_1}$ | Higgsino LSP | $m_{A,h} \approx 2m_{\chi_1}$ | $m_{\tilde{\tau}} \approx m_{\chi_1}$

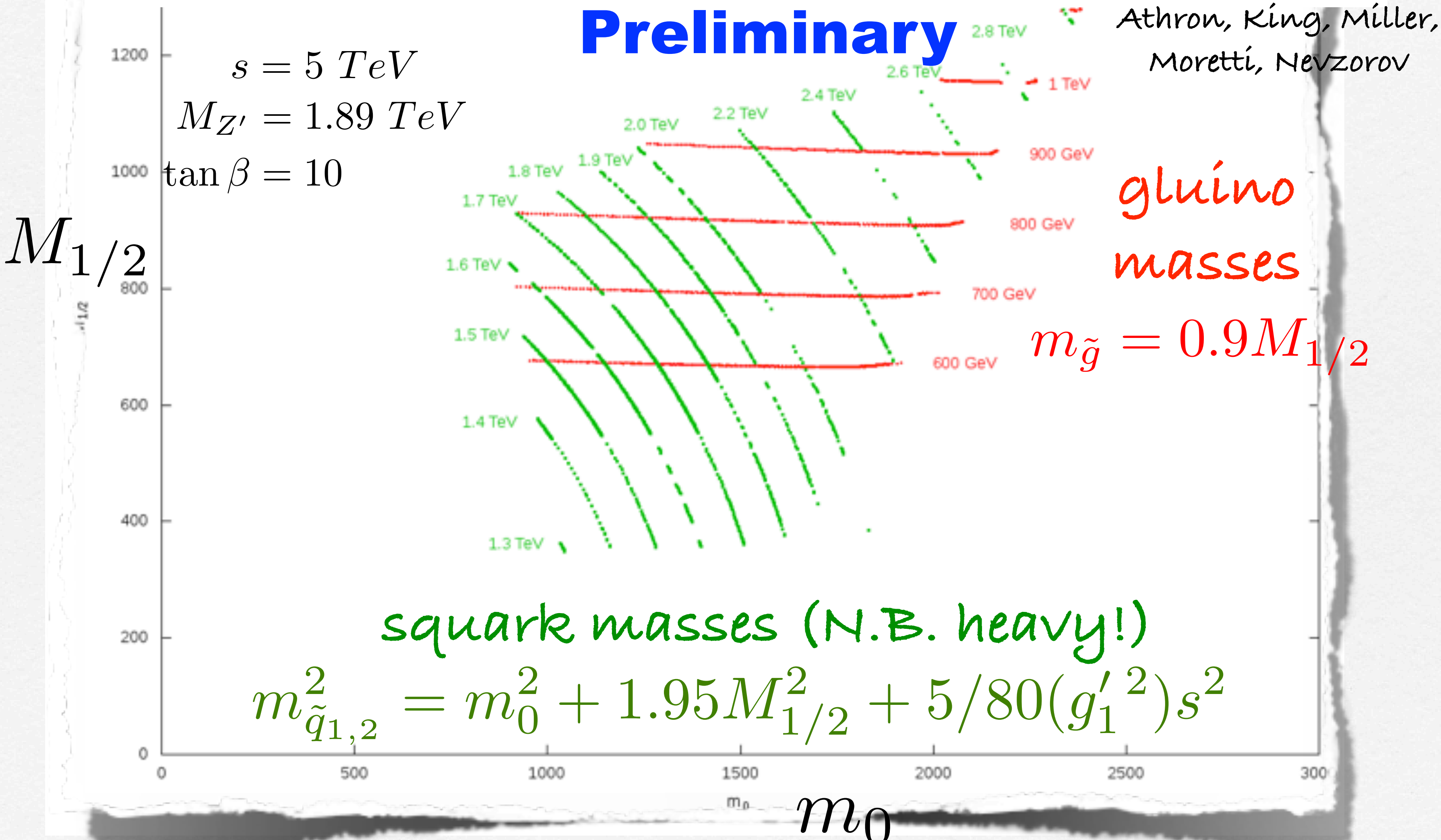
Constrained E_6SSM

Assume universal soft parameters at GUT scale $m_0^2 27_i 27_i^* + A_0 Y_{ijk} 27_i 27_j 27_k$

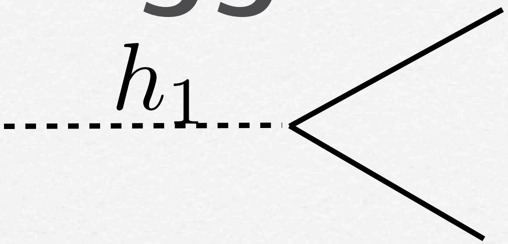


Allowed regions of parameter space with correct EWSB and $m_h > 115$ GeV

Squark and gluino masses



Invisible Higgs Decays



$$\Gamma(h_1 \to \chi^0_\alpha \chi^0_\beta) \gg \Gamma(h_1 \to f\bar{f})$$

- due to large coupling of inert neutralinos to Higgs ~M_χ/v with $M_\chi \sim M_Z/2$
- gives large SI DD cross-sections -- challenged by XENON 100

Hall, King, Pakvasa
Nevzorov, Sher

	i	ii	iii	iv	v
λ	0.6	0.6	0.468	0.468	0.468
$\tan(\beta)$	1.7	1.564	1.5	1.5	1.5
A_λ	1600	1600	600	600	600
$m_{H^\pm} \simeq m_A \simeq m_{h_3}$/GeV	1977	1990	1145	1145	1145
m_{h_1}/GeV	133.1	134.8	115.9	115.9	115.9
λ_{22}	0.094	0.0001	0.094	0.001	0.468
λ_{21}	0	0.06	0	0.079	0.05
λ_{12}	0	0.06	0	0.080	0.05
λ_{11}	0.059	0.0001	0.059	0.001	0.08
f_{22}	0.53	0.001	0.53	0.04	0.05
f_{21}	0.05	0.476	0.053	0.68	0.9
f_{12}	0.05	0.466	0.053	0.68	0.002
f_{11}	0.53	0.001	0.53	0.04	0.002
$\tilde{f}_{22}$	0.53	0.001	0.53	0.04	0.002
$\tilde{f}_{21}$	0.05	0.4	0.053	0.49	0.002
$\tilde{f}_{12}$	0.05	0.408	0.053	0.49	0.05
$\tilde{f}_{11}$	0.53	0.001	0.53	0.04	0.65
$m_{\tilde{\chi}^0_1}$/GeV	33.62	-36.69	35.42	-45.08	-46.24
$m_{\tilde{\chi}^0_2}$/GeV	47.78	36.88	51.77	55.34	46.60
$m_{\tilde{\chi}^0_3}$/GeV	108.0	-103.11	105.3	-133.3	171.1
$m_{\tilde{\chi}^0_4}$/GeV	-152.1	103.47	-152.7	136.9	-171.4
$m_{\tilde{\chi}^0_5}$/GeV	163.5	139.80	162.0	178.4	805.4
$m_{\tilde{\chi}^0_6}$/GeV	-200.8	-140.35	-201.7	-192.2	-805.4
$m_{\tilde{\chi}^\pm_1}$/GeV	100.1	101.65	100.1	133.0	125.0
$m_{\tilde{\chi}^\pm_2}$/GeV	159.5	101.99	159.5	136.8	805.0
$\Omega_\chi h^2$	0.109	0.107	0.107	0.0324	0.00005
R_{Z11}	-0.144	-0.132	-0.115	-0.0217	-0.0224
R_{Z12}	0.051	0.0043	-0.045	-0.0020	-0.213
R_{Z22}	-0.331	-0.133	-0.288	-0.0524	-0.0226
$\sigma_{SI}/10^{-44}$ cm^2	1.7-7.1	2.0-8.2	3.5-14.2	6.0-24.4	6.1-25.0
Br($h \to \tilde{\chi}^0_1\tilde{\chi}^0_1$)	57.8%	49.1%	76.3%	83.4%	49.3%
Br($h \to \tilde{\chi}^0_1\tilde{\chi}^0_2$)	0.34%	3.5×10^{-11}	0.26%	7.6×10^{-9}	3.0×10^{-8}
Br($h \to \tilde{\chi}^0_2\tilde{\chi}^0_2$)	39.8%	49.2%	20.3%	12.3%	47.9%
Br($h \to b\bar{b}$)	1.87%	1.59%	2.83%	3.95%	2.58%
Br($h \to \tau\bar{\tau}$)	0.196%	0.166%	0.30%	0.41%	0.27%
Γ^{tot}/MeV	141.2	169.0	82.0	58.8	90.1

Belyaev, Hall, King, Svantesson (preliminary)

Scanning regions

MSSM

parameter	min	max
$\tan\beta$	2	60
	[TeV]	[TeV]
$A_t = A_b = A_\tau = A_\mu$	-3	3
M_A	0.1	2
μ	-2	2

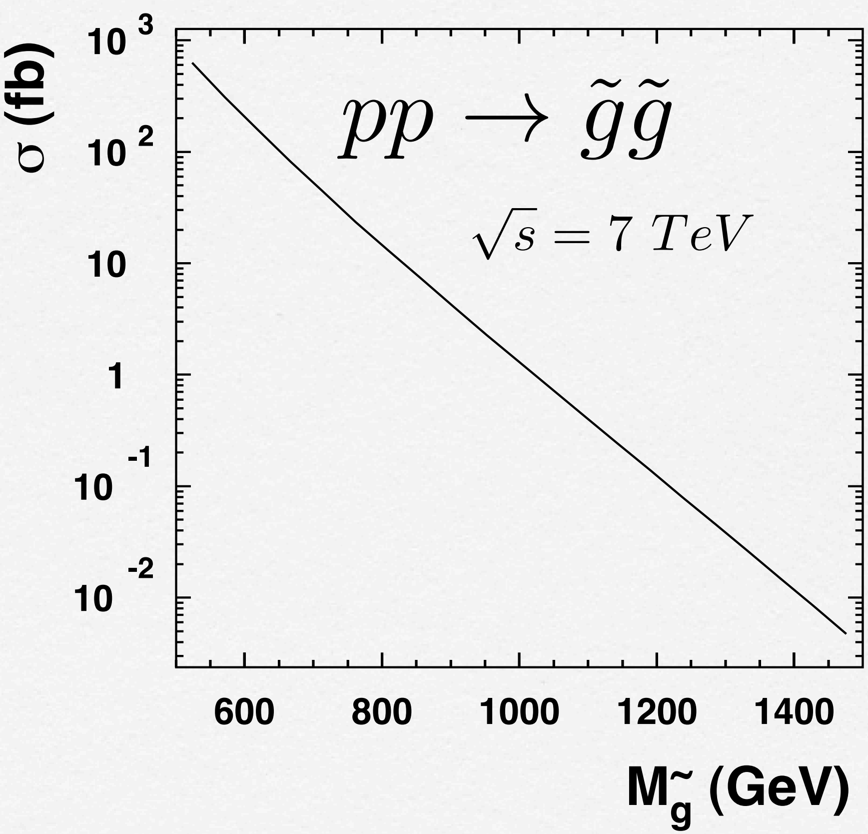
TABLE I: The MSSM scanning region. A common squark and slepton mass scale was fixed to $M_S = 2$ TeV. The gaugino masses were fixed to $M_1 = 150$ GeV, $M_2 = 285$ GeV and $M_3 = 619$ GeV, providing a gluino mass close to 800 GeV.

E_6SSM

parameter	min	max
$\tan\beta$	1.4	2
$\lvert\lambda\rvert$	0.3	0.7
λ_{22}	0.0001	0.01
λ_{21}	0.01	0.1
λ_{12}	0.01	0.1
λ_{11}	0.0001	0.01
f_{22}^d	0.0001	0.01
f_{21}^d	0.1	1
f_{12}^d	0.1	1
f_{11}^d	0.0001	0.01
f_{22}^u	0.0001	0.01
f_{21}^u	0.1	1
f_{12}^u	0.1	1
f_{11}^u	0.0001	0.01
x_2^d	10^{-4}	10^{-2}
x_1^d	10^{-4}	10^{-2}
x_2^u	10^{-4}	10^{-2}
x_1^u	10^{-4}	10^{-2}
z_1	10^{-3}	10^{-1}
z_2	10^{-3}	10^{-1}
	[TeV]	[TeV]
$A_t = A_b = A_\tau$	-3	3
M_A	1	3
s	2	5

TABLE II: The E_6SSM scanning region. A common squark and slepton mass scale was fixed to $M_S = 2$ TeV. The gaugino masses were fixed to $M_1 = 150$ GeV, $M_1' = 150$ GeV, $M_2 = 300$ GeV and $M_{\tilde{g}} = 800$ GeV.

Gluino production cross-section

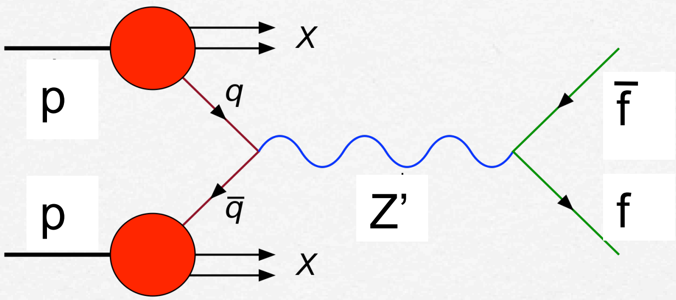


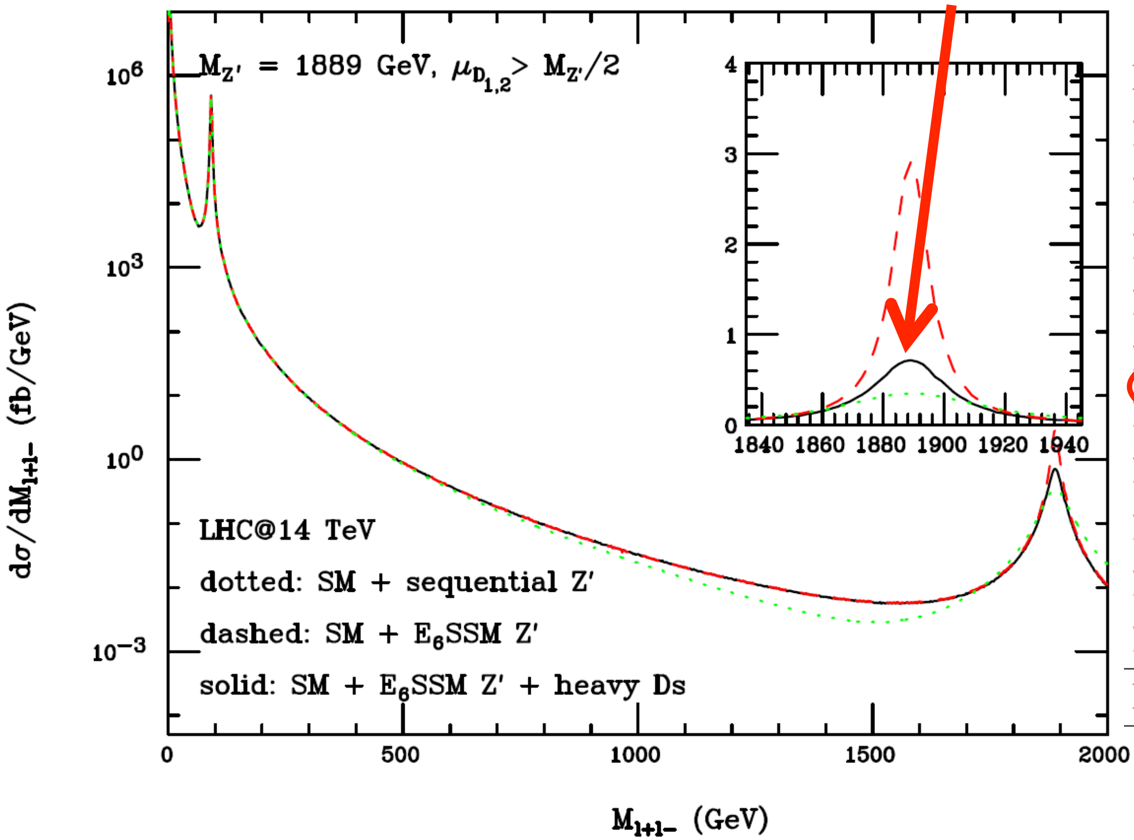
Belyaev, Hall, King, Svantesson (preliminary)

Athron, SFK, Miller, Moretti, Nevzorov

Z' N

Latest ATLAS limit is
$M_{Z'_N} > 1520\ GeV$
but exotic decays
makes Z' peak smaller
and harder to discover





$\Gamma(Z'_N \to l^+l^-)$ ($l = e, \mu$ or τ)	0.77
$\Sigma_l\Gamma(Z'_N \to \nu_l\bar{\nu}_l)$ (all neutrinos)	1.64
$\Sigma_l\Gamma(Z'_N \to l^+l^-, \nu_l\bar{\nu}_l)$ (all leptons)	3.96
$\Sigma_q\Gamma(Z'_N \to q\bar{q})$ (all quarks)	10.08
$\Sigma_i\Gamma(Z'_N \to D_i\bar{D}_i)$ (exotic fermions)	0.00
$\Sigma_\alpha\Gamma(Z'_N \to \tilde{H}_\alpha\tilde{H}_\alpha)$ (inert Higgsinos	5.19
$\Sigma_\alpha\Gamma(Z'_N \to \tilde{S}_\alpha\tilde{S}_\alpha)$ (singlinos)	7.63
$\Sigma_i\Gamma(Z'_N \to D_iD_i)$ (exotic scalars)	0.19
$\Sigma_f\Gamma(Z'_N \to \tilde{f}\tilde{f})$ (sfermions)	0.010
$\Sigma_\alpha\Gamma(Z'_N \to H_\alpha H_\alpha)$ (inert Higgses)	0.39
$\Sigma_j\Gamma(Z'_N \to \tilde{\chi}_j\tilde{\chi}_j)$ (gauginos)	7.92×10^{-5}
Γ_{tot} (all)	27.45

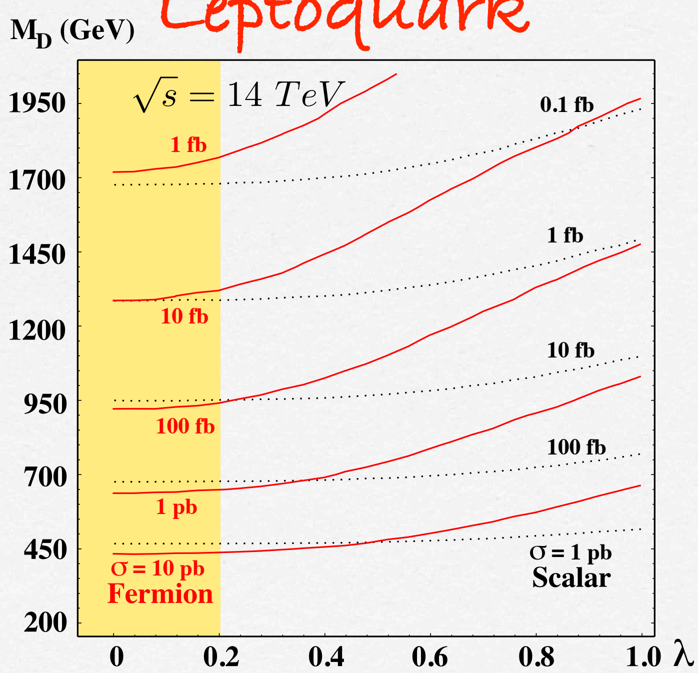
Exotic D-particles

Kang, Langacker, Nelson

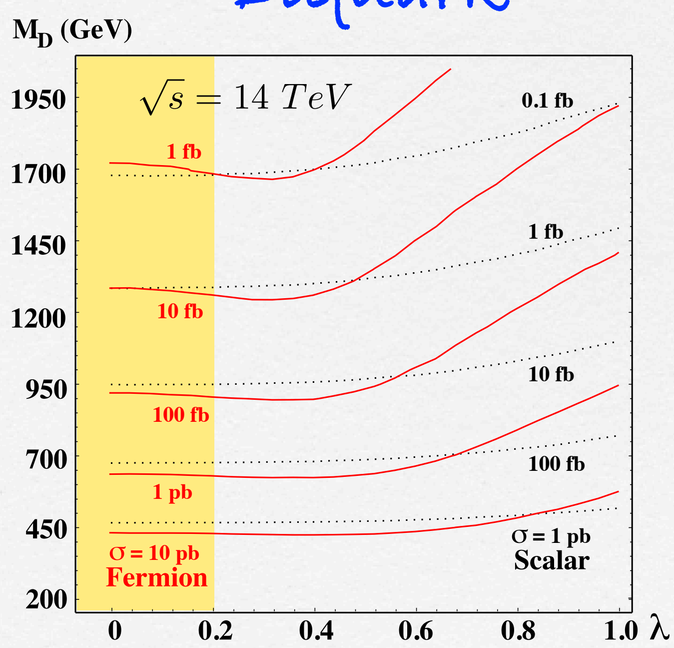
D-particles are coloured and may be pair produced at LHC

D-particles may be Leptoquarks D→LQ or Diquarks D→QQ

Leptoquark

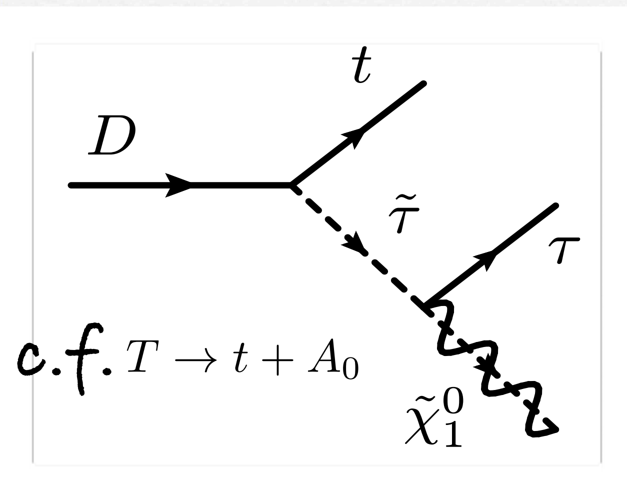


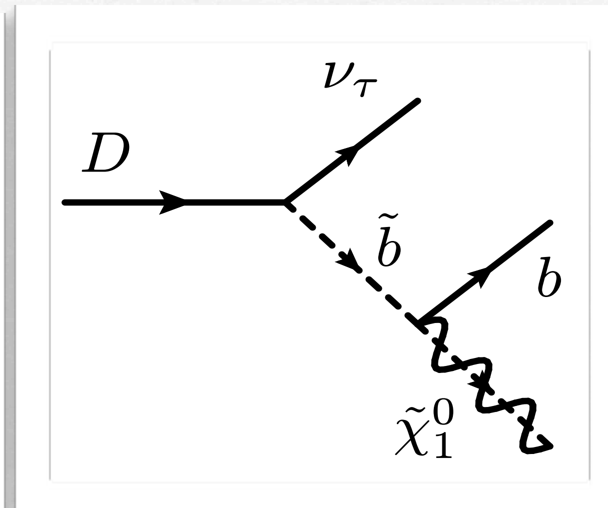
Diquark

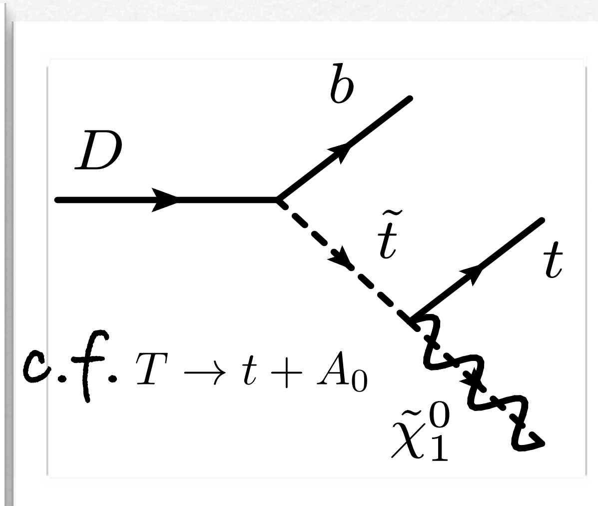


D-fermion decays

Leptoquark	Leptoquark	Diquark







$$pp \to t\bar{t}\tau^+\tau^- + E_T^{miss} + X$$

$$pp \to b\bar{b} + E_T^{miss} + X$$

$$pp \to t\bar{t}b\bar{b} + E_T^{miss} + X$$

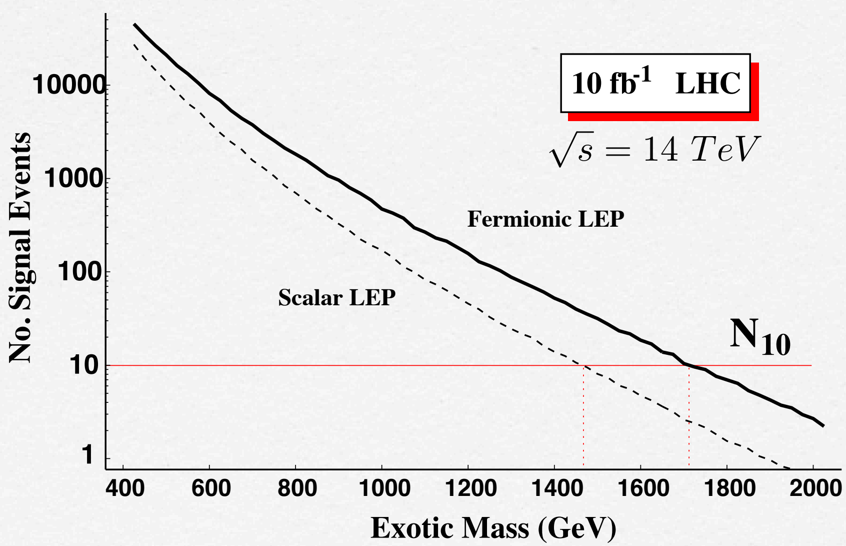
spectacular signals!

Kang, Langacker, Nelson

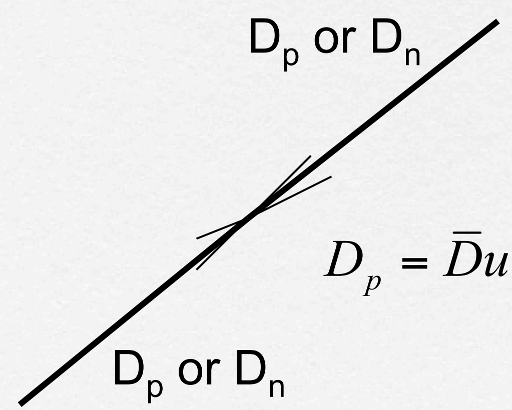
D-fermion as R-hadron

- Imposing B and L all couplings DFF forbidden
- D-particle are quasi-stable R-hadrons, decay via

$$\mathrm{dim}5\ :\ D^c Q H_d S,\ D^c Q Q u^c,\ D^c Q L \nu^c$$



punch through to muon chambers

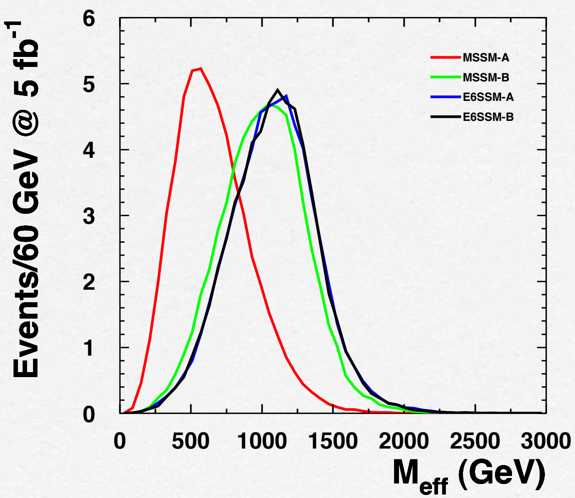


$$D_p = \bar{D}u,\ D_n = \bar{D}d$$

Belyaev, Hall, King, Svantesson (preliminary)

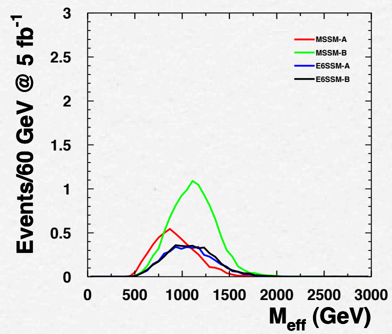
M_{eff}

$$M_{eff} = p_T^{miss} + \sum_{jets} |p_T^{jet}|$$



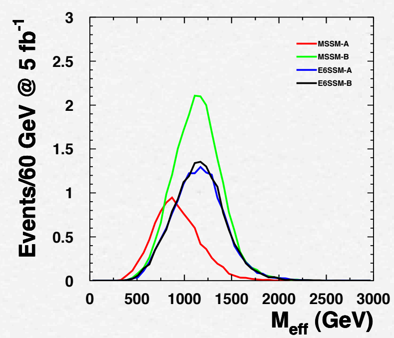
M_{eff} does not really help to distinguish models

ATLAS style cuts



CUT No.	limit	MSSM-A Eff.	MSSM-A Frac.	MSSM-B Eff.	MSSM-B Frac.	E$_6$SSM-A Eff.	E$_6$SSM-A Frac.	E$_6$SSM-B Eff.	E$_6$SSM-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

CMS style cuts



CUT No.	limit	MSSM-A Eff.	MSSM-A Frac.	MSSM-B Eff.	MSSM-B Frac.	E$_6$SSM-A Eff.	E$_6$SSM-A Frac.	E$_6$SSM-B Eff.	E$_6$SSM-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

Two potential problems: rapid proton decay + FCNCs

- FCNC problem may be tamed by introducing a Z_2^H under which third family Higgs and singlet are even all else odd → only allows Yukawa couplings involving third family Higgs and singlet H_u , H_d , S

- Z_2^H also forbids all DFF and hence forbids D decay (and p decay)

→ Z_2^H cannot be an exact symmetry!

How do we reconcile D decay with p decay?

In E_6SSM can have extra discrete symmetries:

Z_2^L under which L are odd → forbids DQL, allows DQQ → exotic D are diquarks

Z_2^B with L & D odd → forbids DQQ, allows DQL → exotic D are leptoquarks

Or:-- small DFF couplings $\sim 10^{-12}$ will suppress p decay sufficiently while couplings $\sim 10^{-12}$ will allow D decay with lifetime <0.1 s (nucleosynth) N.B. $\Gamma_D \propto g^2$, $\Gamma_p \propto g^4$ (Howl, SFK)