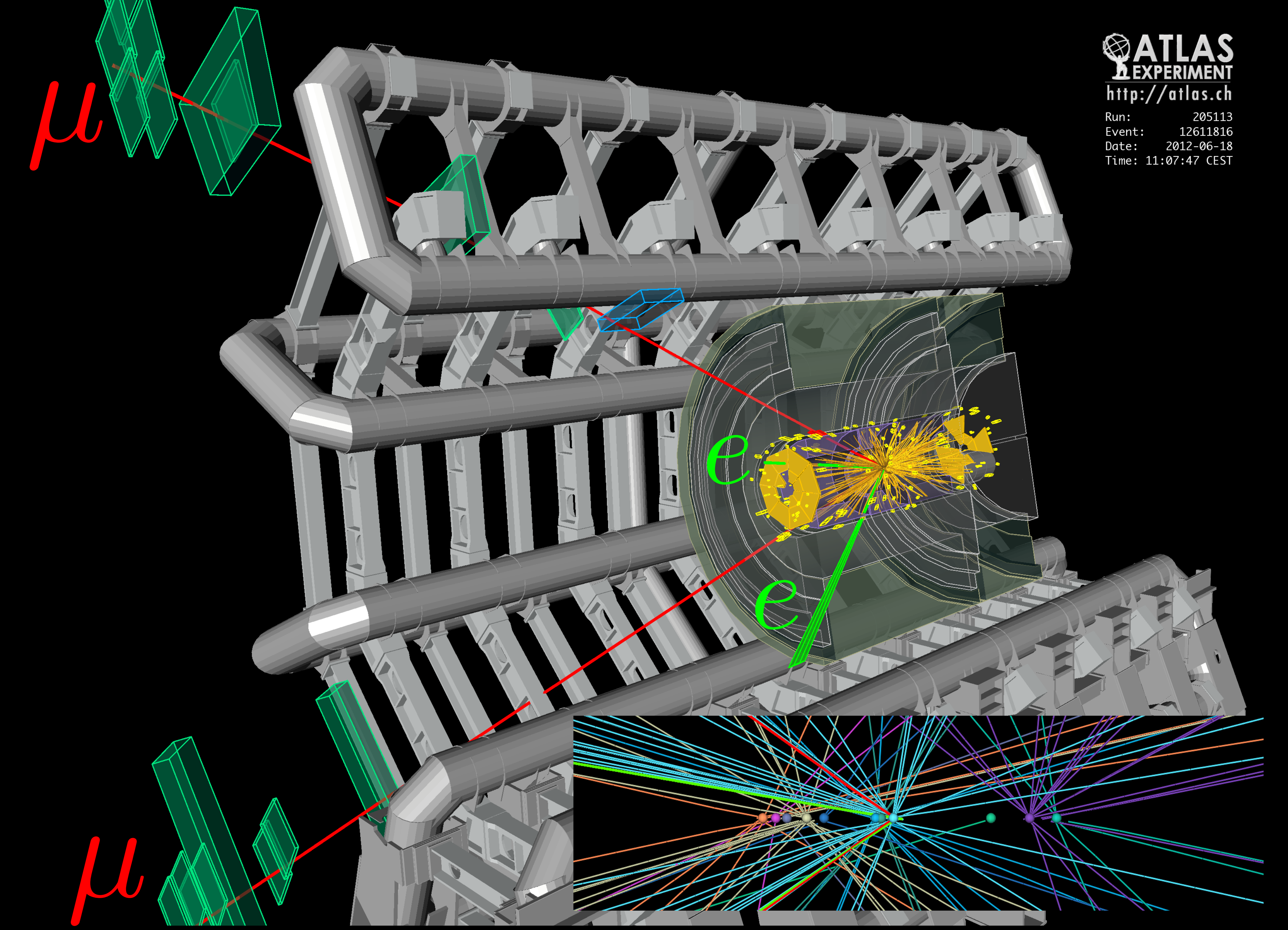
UNIVERSITY OF Southampton
School of Physics and Astronomy

A Higgs Near 125 GeV Beyond the MSSM

Part 1 Higgs in SM and NMSSM
Part 2 Higgs and Gluinos in E6SSM

Steve King
Sussex, Mon 22nd Oct 2012


ATLAS EXPERIMENT
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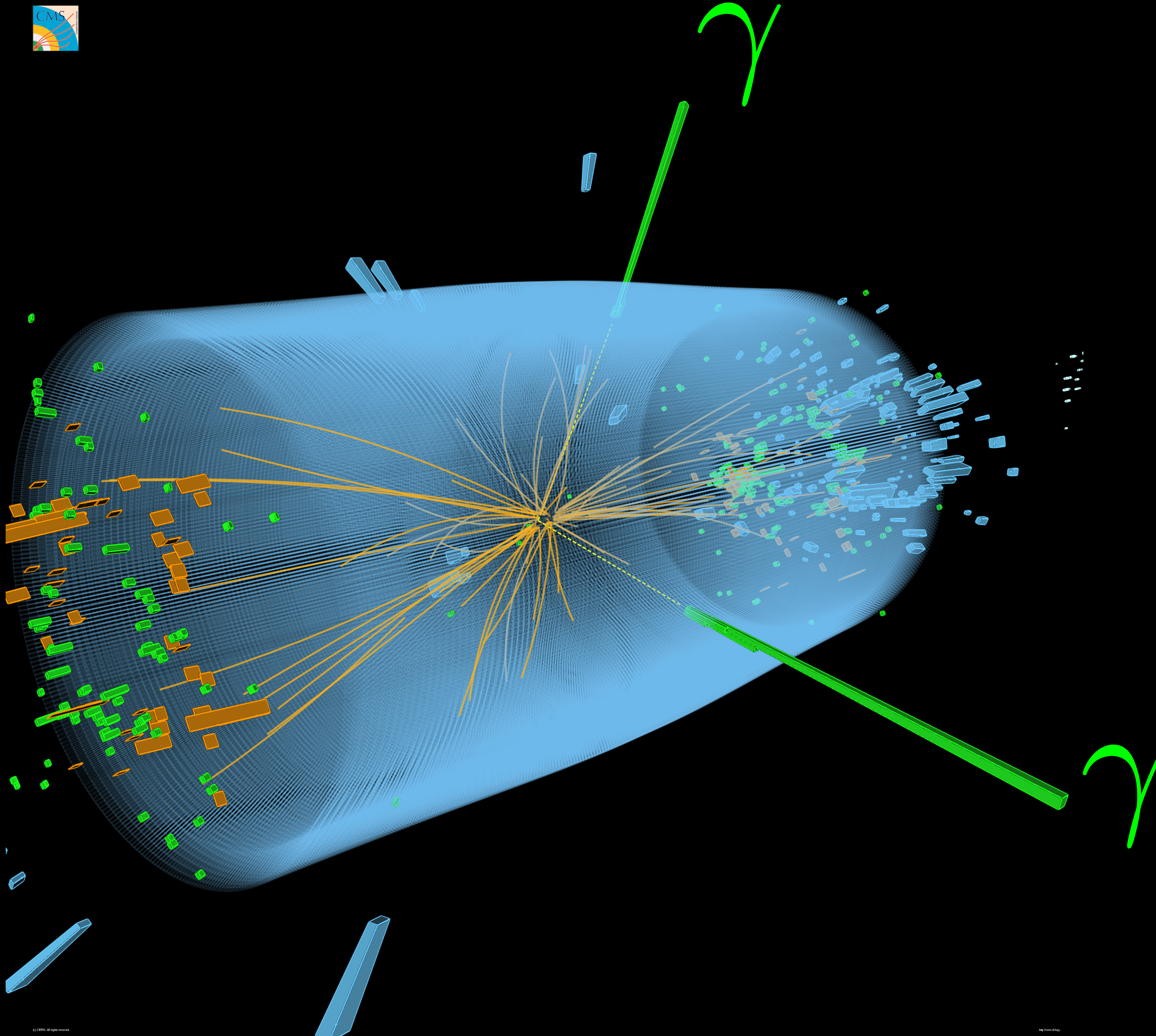

γ
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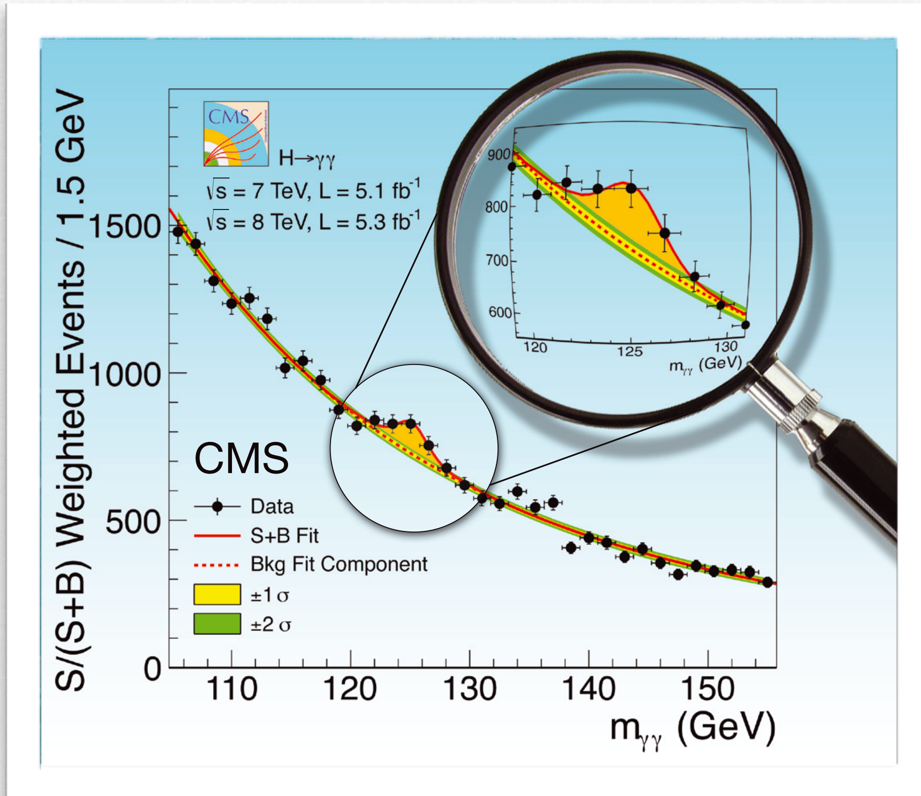
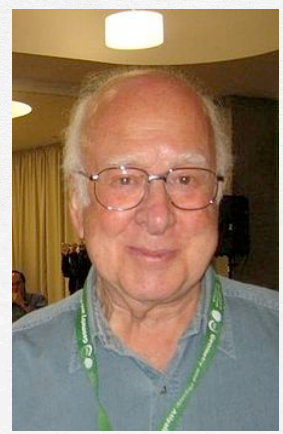
LHC has discovered a new particle



Congratulations to both
Atlas and CMS Collaborations
and to the builders of the LHC
on a magnificent achievement!



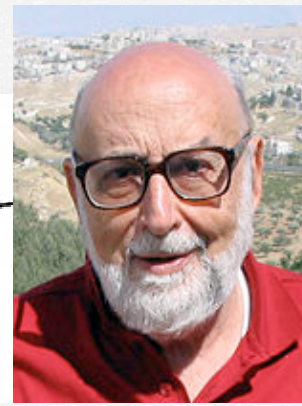
Peter Higgs
30 August 2012

" … The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, … with expectations for a standard model Higgs boson."

\- CMS Collaboration

Not only does the discovery yield the missing link to the present Standard Model theory of elementary particles, but a detailed analysis of the decays, in particular of the decay of the Scalar to two photons which is sensitive to loops of intermediated charged particles, will possibly yield information about the spectrum beyond the Standard Model.

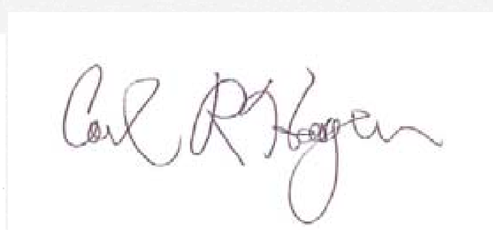
Prof. François Englert

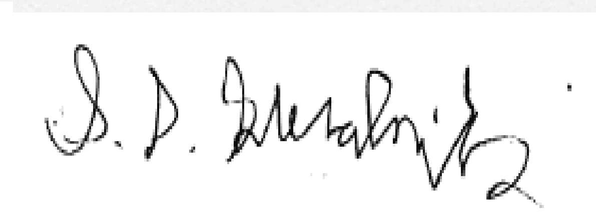

It is great to know that the famous boson almost certainly exists, and we are eagerly waiting for detailed measurement of its properties.

Prof. Tom Kibble

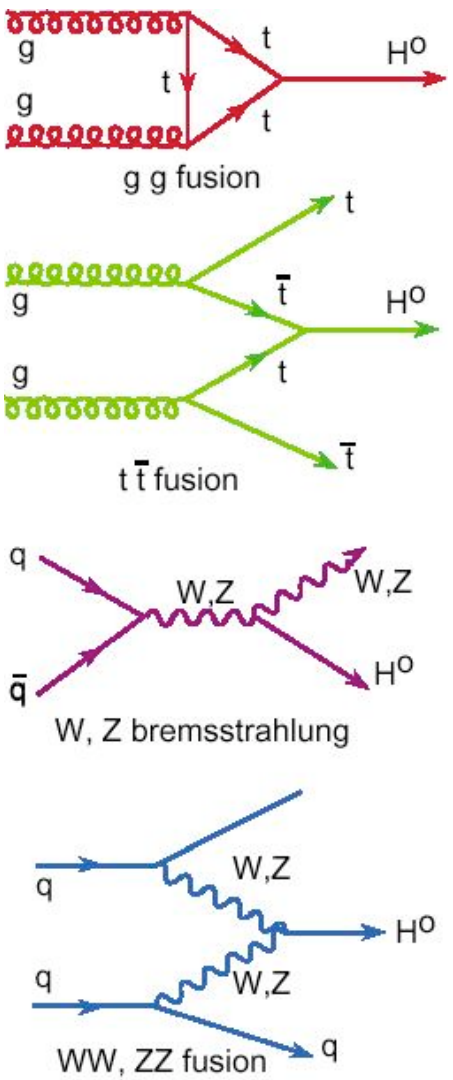
Prof. Carl R. Hagen

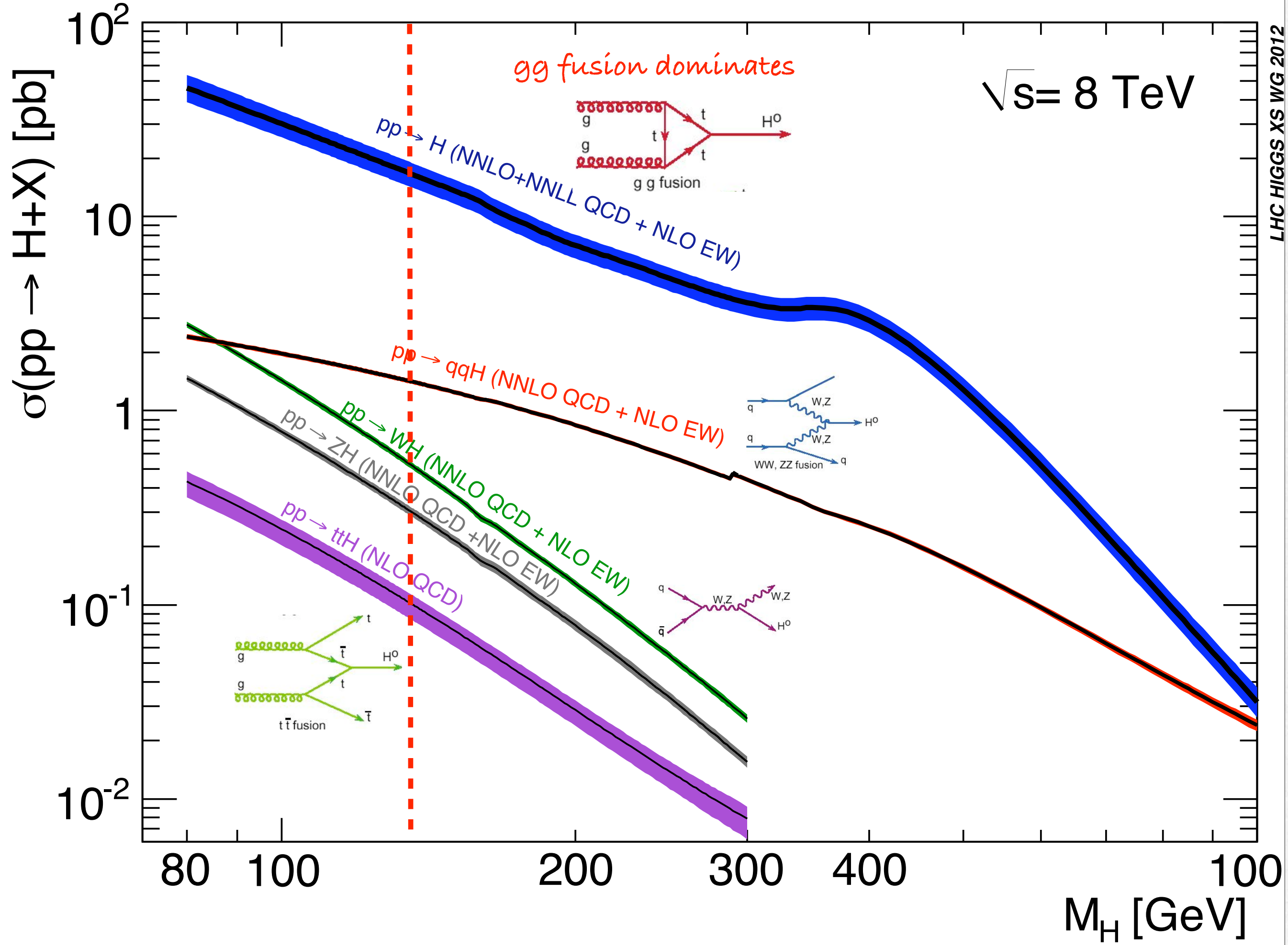


Prof. Gerald Guralnik

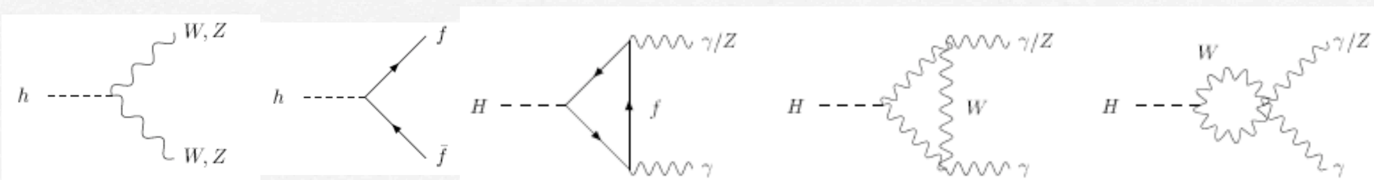


• Higgs production mechanisms and cross sections

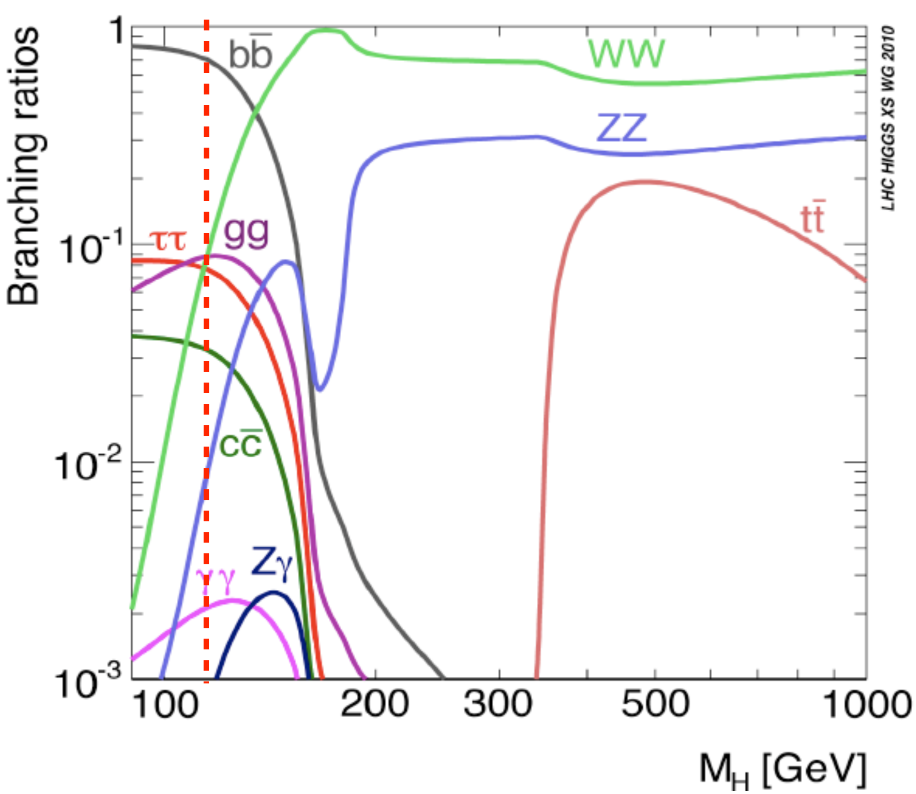


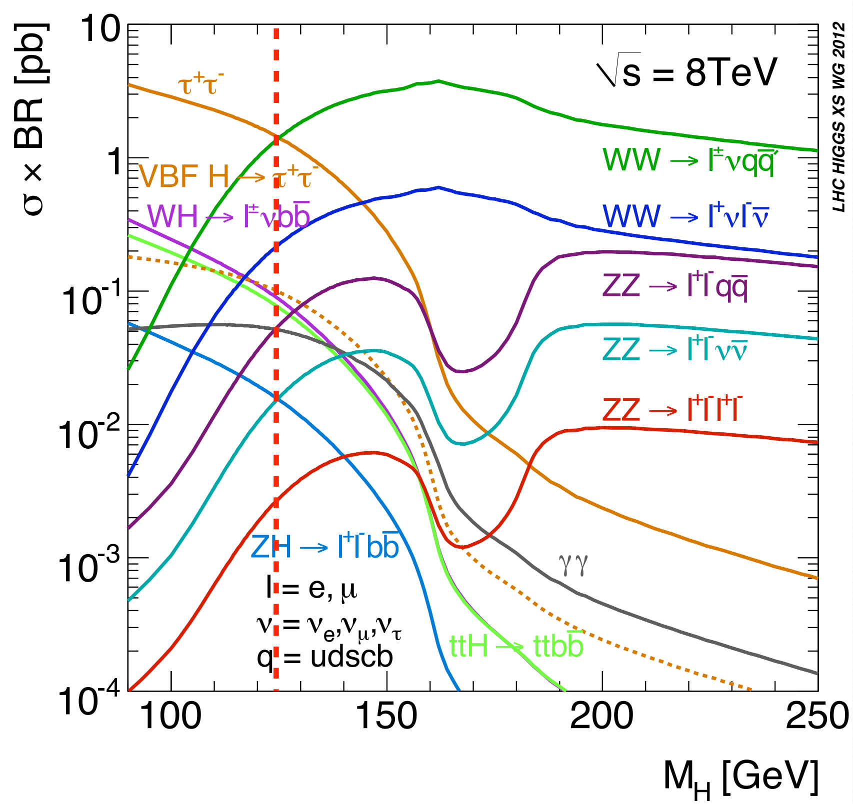


Higgs Decays



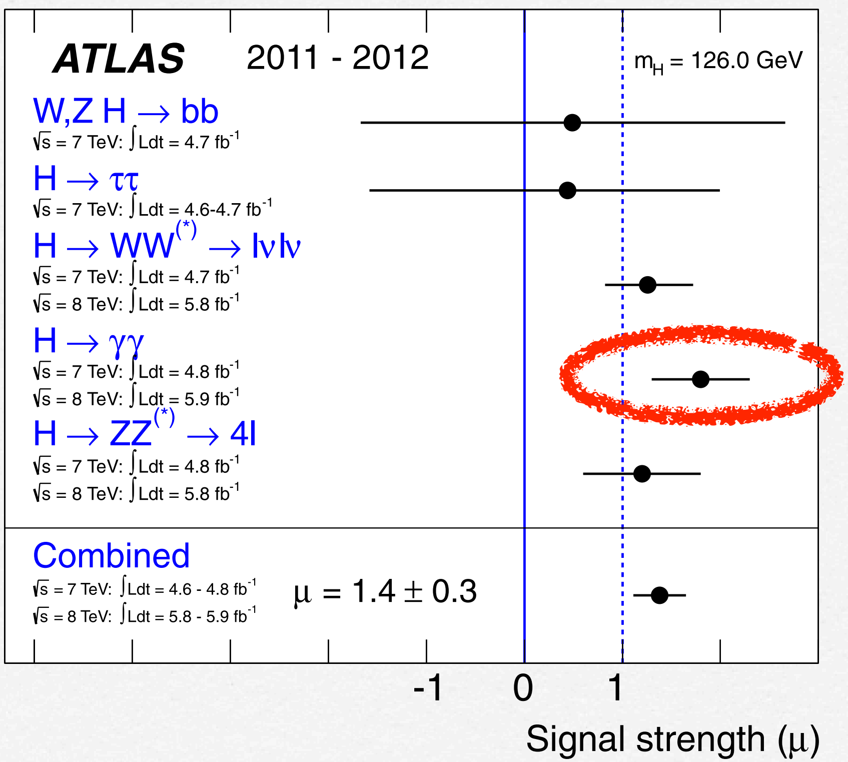
LHC search channels

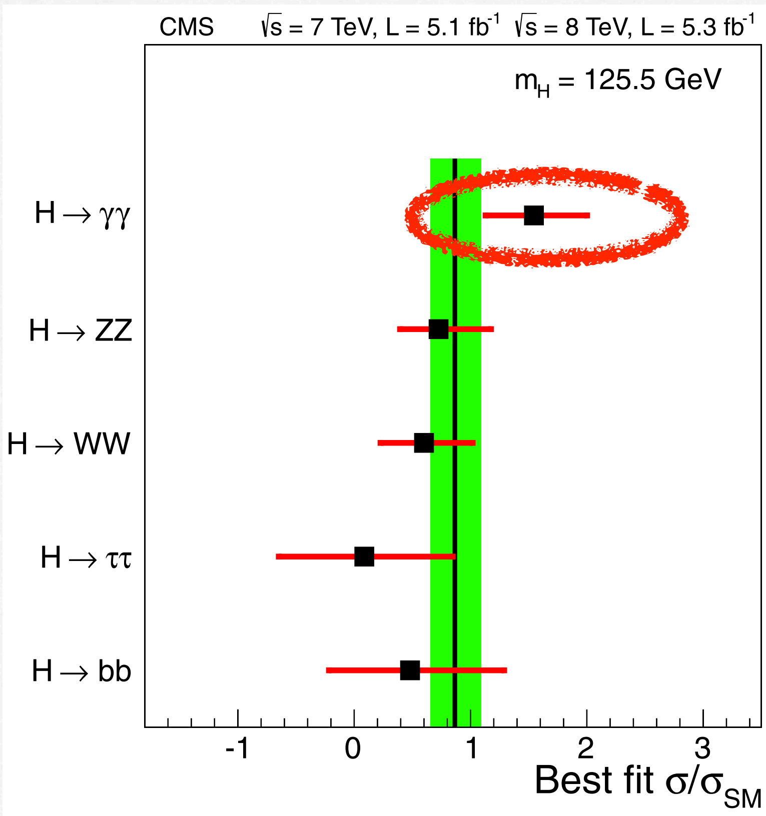




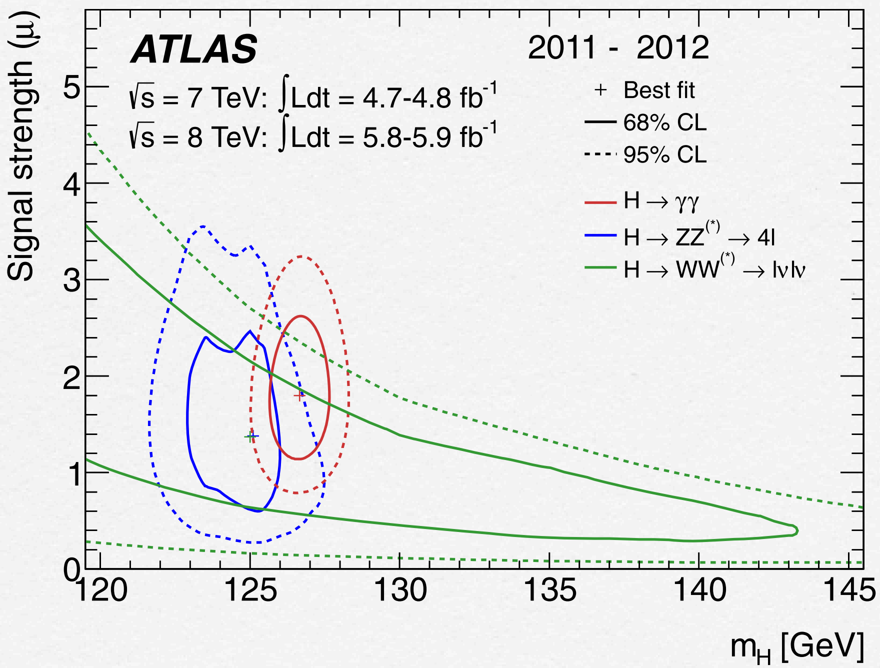
Higgs decay LHC signal strengths

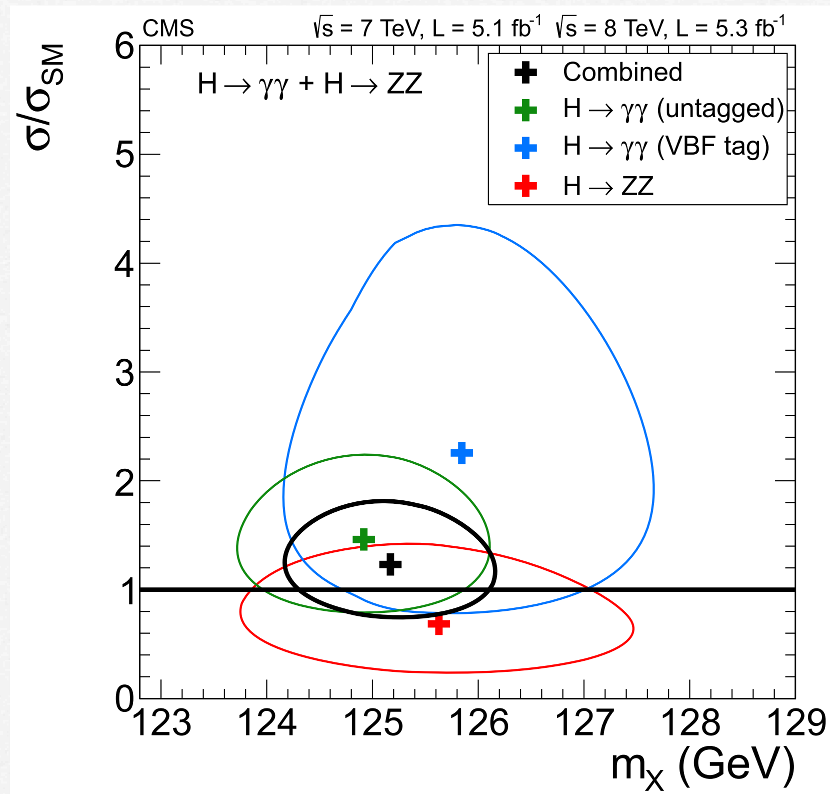
Two photon rate too high in both experiments





Higgs mass 124-127 GeV

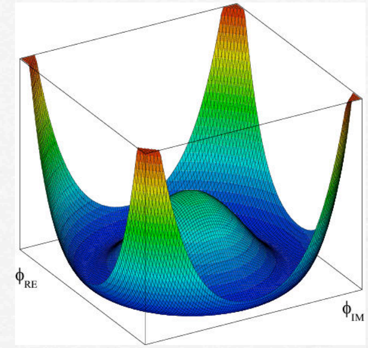




126.0 ± 0.4 (stat) ± 0.4 (sys) GeV

125.3 ± 0.4(stat.) ± 0.5(syst.) GeV.

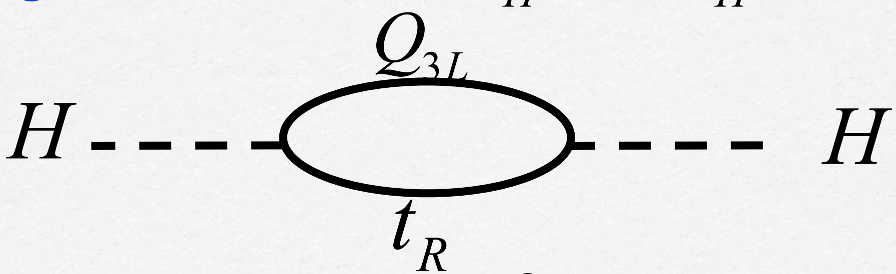
Higgs Theory in SM



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

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

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



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

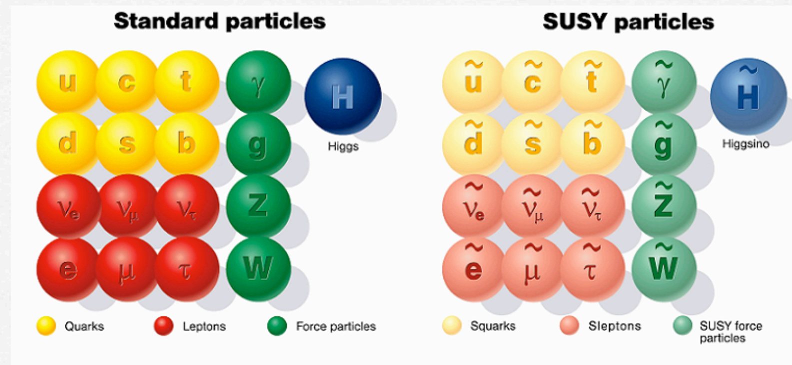
Fine-tuning is required if the cut-off $\Lambda \gg 1\,TeV$

Motivates new physics at TeV scale e.g. SUSY

Minimal SUSY SM (MSSM)

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	$(\widetilde{H}_u^+, \widetilde{H}_u^0)_L$



Higgs/Higgsino mass parameter

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

$$|\mu| \lesssim 200 \text{ GeV}.$$

to avoid tree-level tuning since

$$m_H^2 = \mu^2 + m_0^2$$

Higgs Theory in MSSM

$$\mathcal{W} = \mu \widehat{H}_u \widehat{H}_d$$

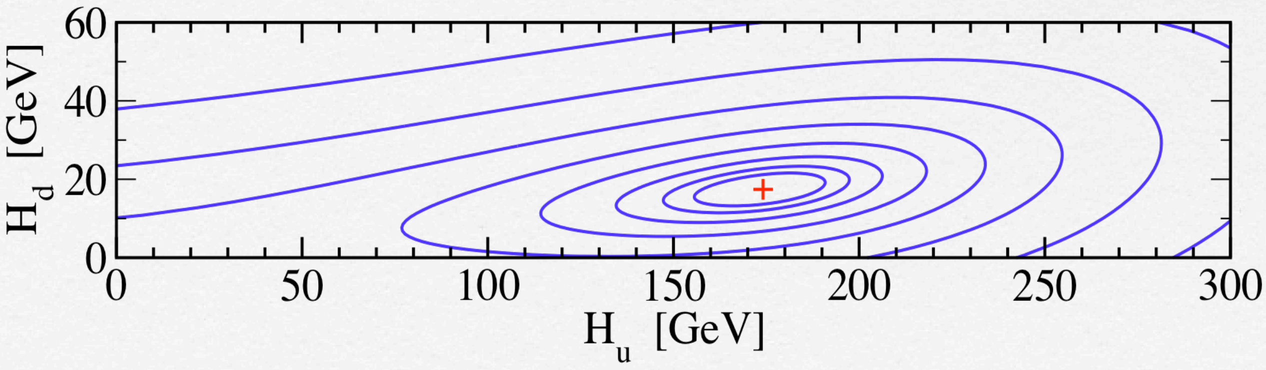
Higgs doublets

$$H_u = (H_u^+,\ H_u^0) \qquad H_d = (H_d^0,\ H_d^-)$$

Higgs potential

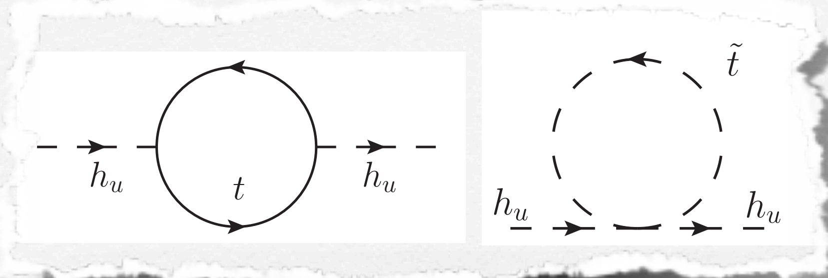
$$\begin{aligned} V &= (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) \\ &\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}$$

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



In SUSY, stop loops dominate Higgs mass parameter correction

$$\delta m_H^2(stop\ loop)$$



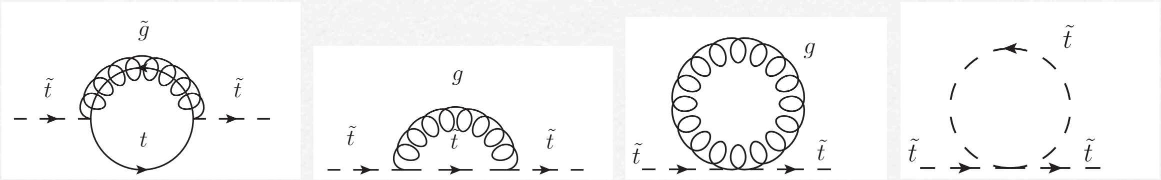
Leading quadratic divergence cancels

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

To avoid tuning need $m_{\tilde{t}} \lesssim 400\text{GeV}.$ 500 GeV OK

LHC should find stops SOON

Gluino corrections to stop

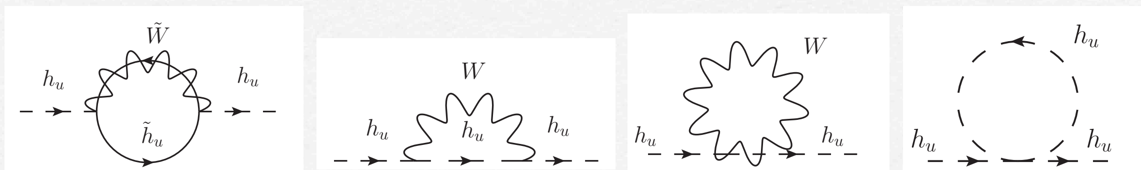


$$\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln \frac{\Lambda_{UV}}{m_{\tilde{g}}}.$$

To avoid tuning need $m_{\tilde{g}} \lesssim 2m_{\tilde{t}}.$ 1 TeV OK

LHC should find gluinos SOON

Other important loops



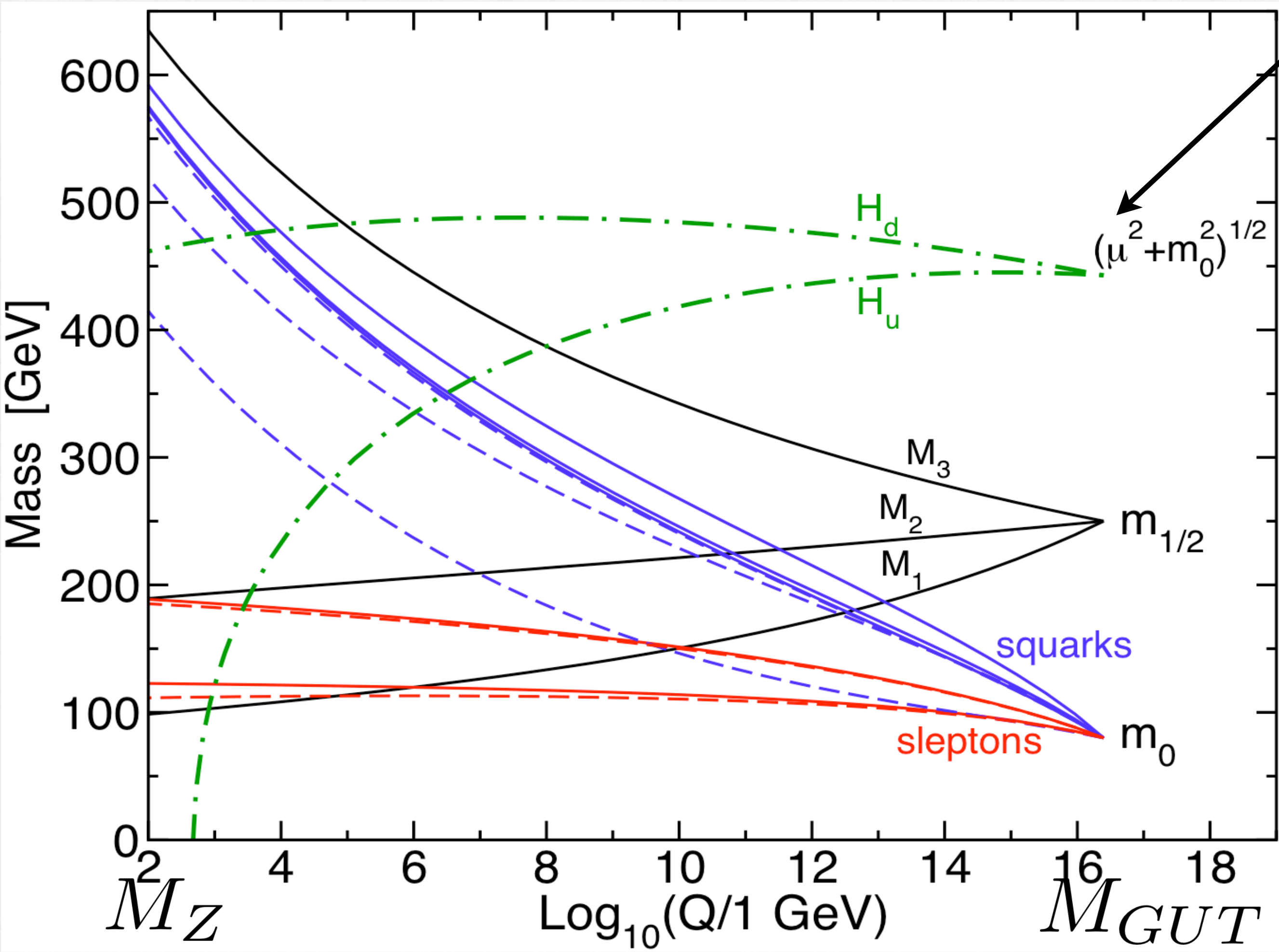
$$\delta m_{h_u}^2 = \frac{3g^2}{8\pi^2}(m_{\tilde{W}}^2 + m_{\tilde{h}}^2)\ln\frac{\Lambda_{UV}}{m_{\tilde{W}}}.$$

To avoid tuning need $m_{\tilde{W}} \lesssim \text{TeV}.$ 1 TeV OK

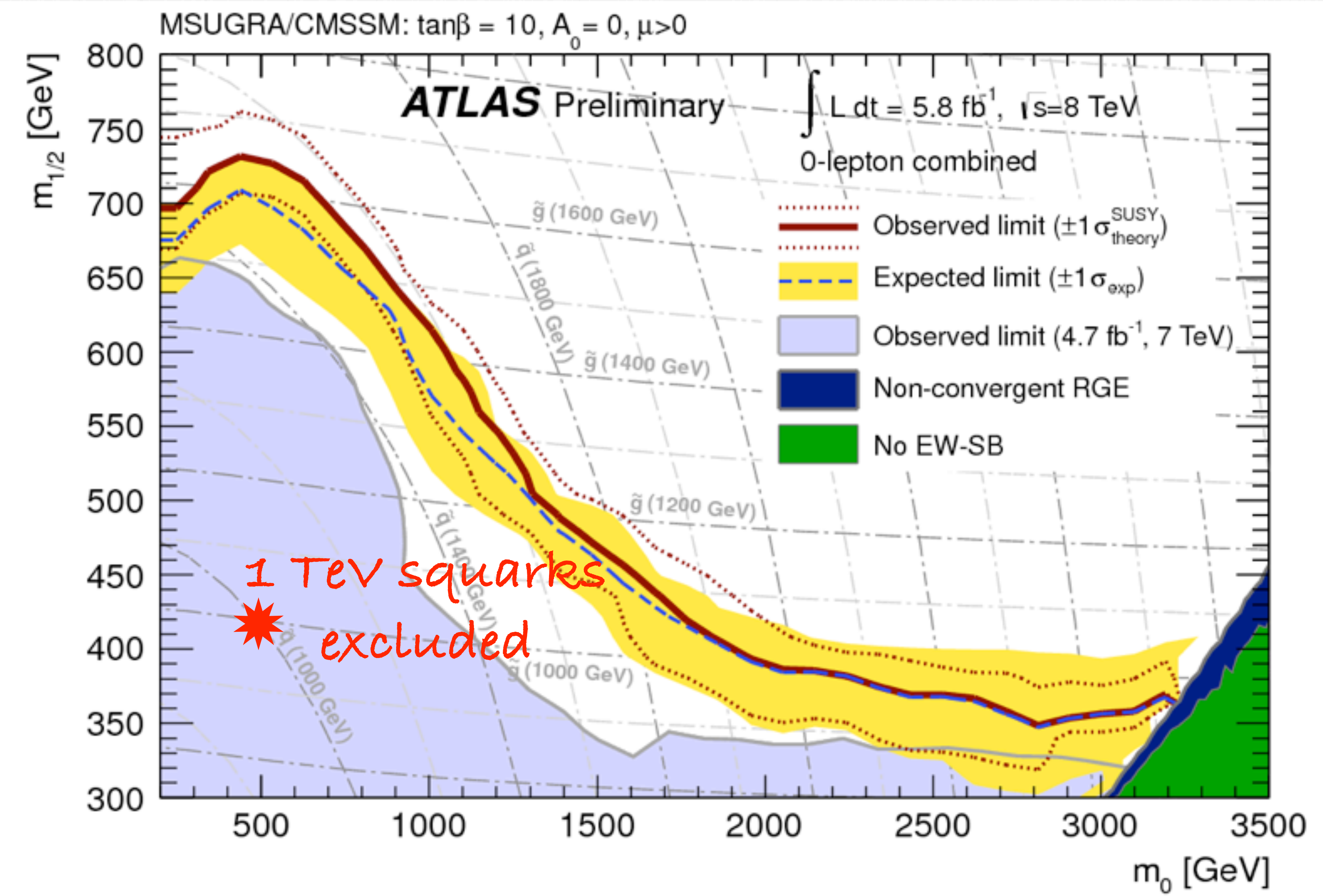
Difficult to find colour singlets at LHC

Constrained MSSM

$$m_H^2 = \mu^2 + m_0^2$$

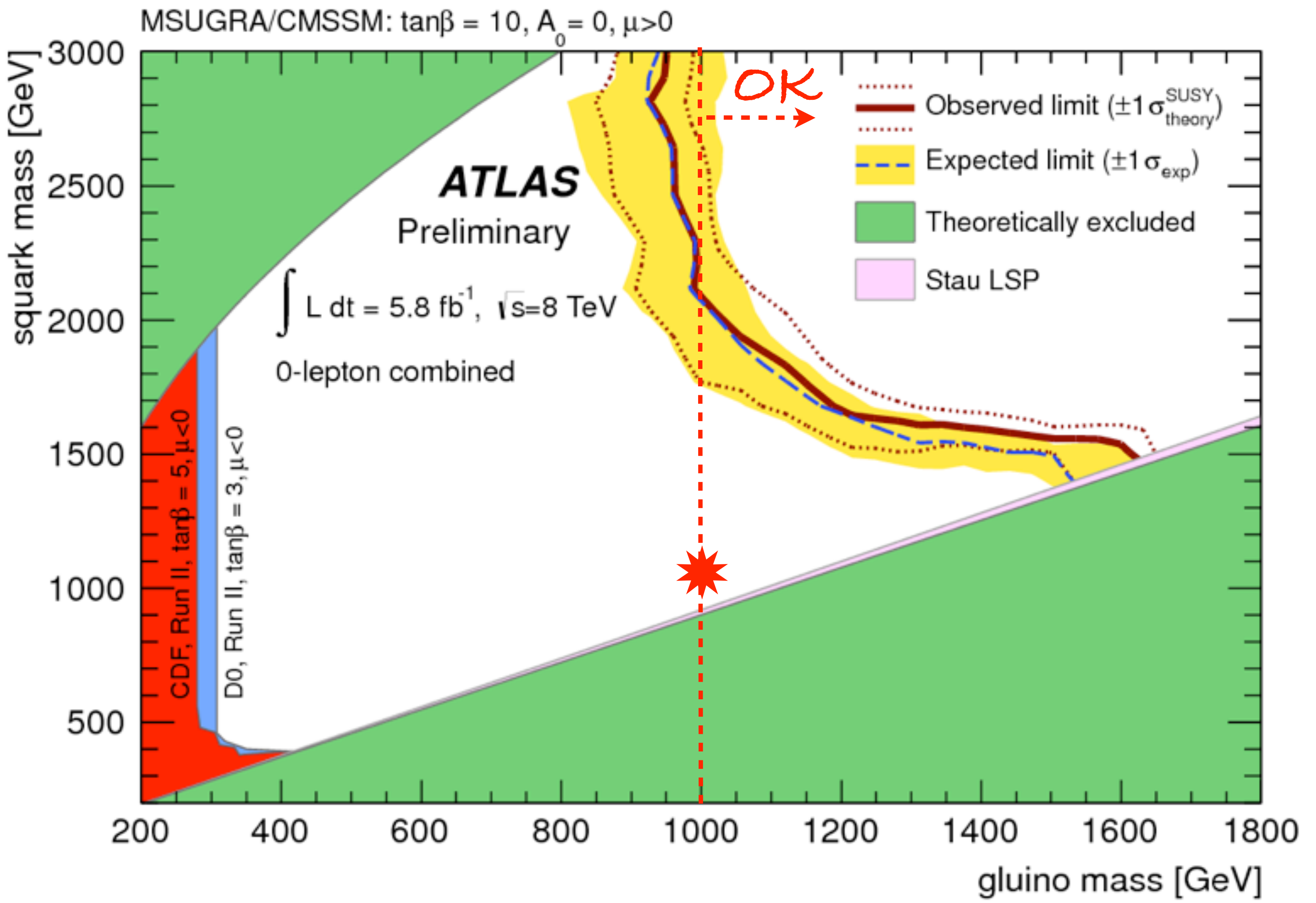


M_Z M_{GUT}

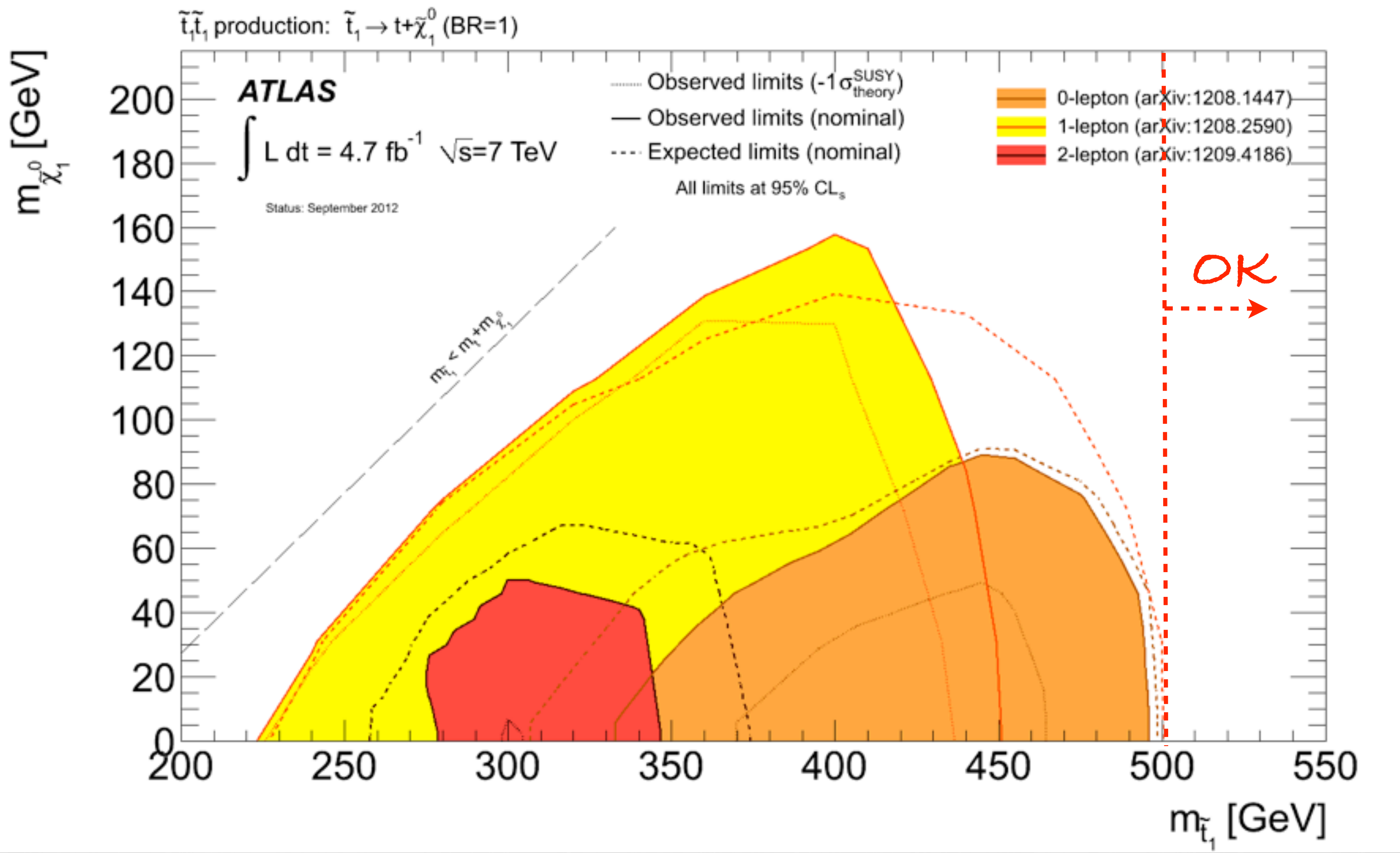


MSUGRA/CMSSM: tanβ = 10, A0 = 0, μ>0
ATLAS Preliminary
∫ L dt = 5.8 fb-1, √s=8 TeV
0-lepton combined
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σ exp)
Observed limit (4.7 fb-1, 7 TeV)
Non-convergent RGE
No EW-SB
g̃ (1600 GeV)
q̃ (1800 GeV)
g̃ (1400 GeV)
g̃ (1200 GeV)
q̃ (1400 GeV)
g̃ (1000 GeV)
q̃ (1000 GeV)
1 TeV squarks
excluded
m1/2 [GeV]
m0 [GeV]
800
750
700
650
600
550
500
450
400
350
300
500
1000
1500
2000
2500
3000
3500

Gluinos at 1 TeV not excluded



Stops at 500 GeV not excluded



Mass Spectrum in MSSM

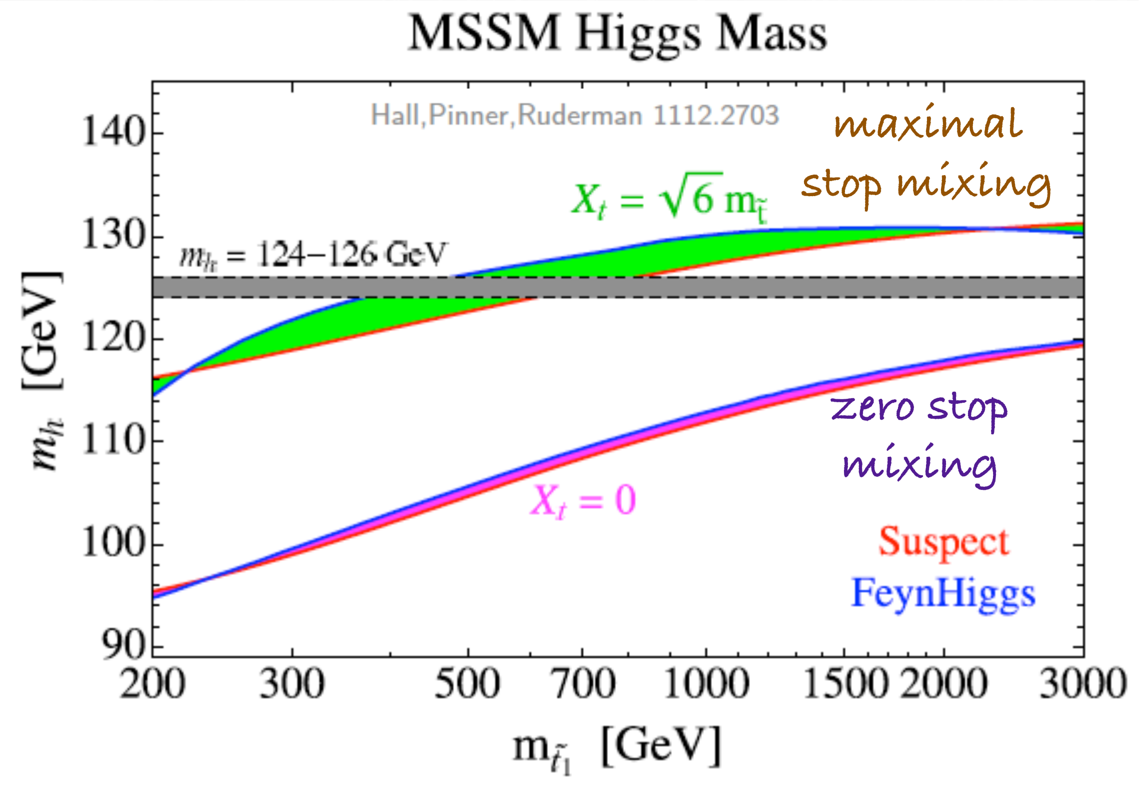
LHC Higgs

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0 \ H_d^0 \ H_u^+ \ H_d^-$	$h^0 \ H^0 \ A^0 \ H^\pm$
squarks	0	−1	$\widetilde{u}_L \ \widetilde{u}_R \ \widetilde{d}_L \ \widetilde{d}_R$	(same)
			$\widetilde{s}_L \ \widetilde{s}_R \ \widetilde{c}_L \ \widetilde{c}_R$	(same)
			$\widetilde{t}_L \ \widetilde{t}_R \ \widetilde{b}_L \ \widetilde{b}_R$	$\widetilde{t}_1 \ \widetilde{t}_2 \ \widetilde{b}_1 \ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L \ \widetilde{e}_R \ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L \ \widetilde{\mu}_R \ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L \ \widetilde{\tau}_R \ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1 \ \widetilde{\tau}_2 \ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0 \ \ \widetilde{W}^0 \ \ \widetilde{H}_u^0 \ \ \widetilde{H}_d^0$	$\widetilde{N}_1 \ \widetilde{N}_2 \ \widetilde{N}_3 \ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm \ \ \widetilde{H}_u^+ \ \ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm \ \ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Higgs h Mass in MSSM

$$\mathcal{W} = \mu \widehat{H}_u \widehat{H}_d$$

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



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

$$m_{\tilde{t}}^2 = m_{\tilde{Q}_3} m_{\tilde{t}_R} \qquad X_t = A_t - \mu \cot\beta.$$

Must have at least one stop mass heavier than 500 GeV --> Fine Tuning!

Next-to-Minimal SUSY SM (NMSSM)

Model gives dynamical origin of μ term via complex singlet S:

SH_uH_d where singlet <S> ~ μ ~ TeV

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

Need to avoid axion somehow

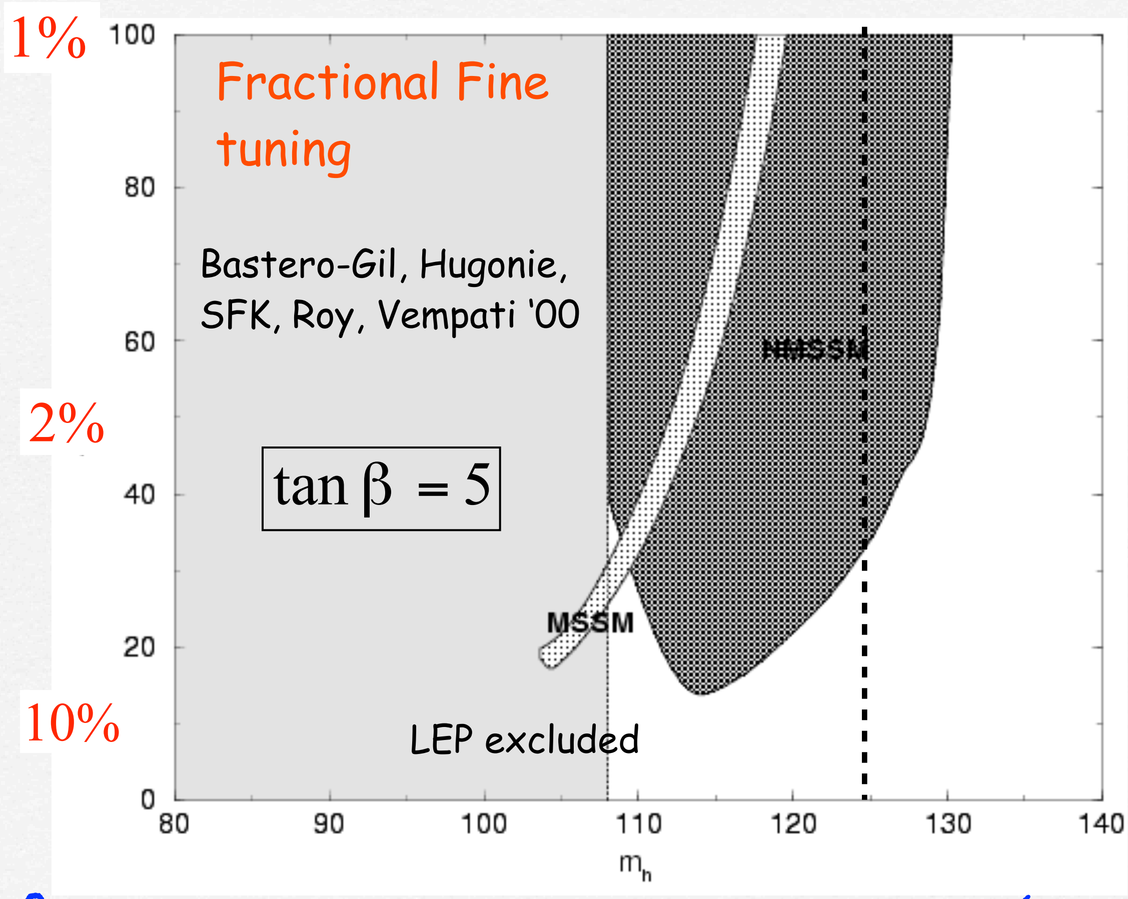
In NMSSM we add S^3 to break U(1) to Z_3

$$\mathcal{W} = \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

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

Extra tree-level contribution to Higgs mass reduces fine-tuning

Fine Tuning vs. Higgs Mass



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

LEP favours NMSSM over MSSM (12 years ago)

LHC with Higgs @ 125 GeV strengthens conclusion

NMSSM Higgs Theory

Spectrum has an extra CP even S plus extra CP odd A (both singlets) compared to MSSM

CP even mass eigenstates

$$
\begin{aligned}
H_1 &= S_{1,d}\, H_d + S_{1,u}\, H_u + S_{1,s}\, S\ , \\
H_2 &= S_{2,d}\, H_d + S_{2,u}\, H_u + S_{2,s}\, S\ , \\
H_3 &= S_{3,d}\, H_d + S_{3,u}\, H_u + S_{3,s}\, S\ .
\end{aligned}
$$

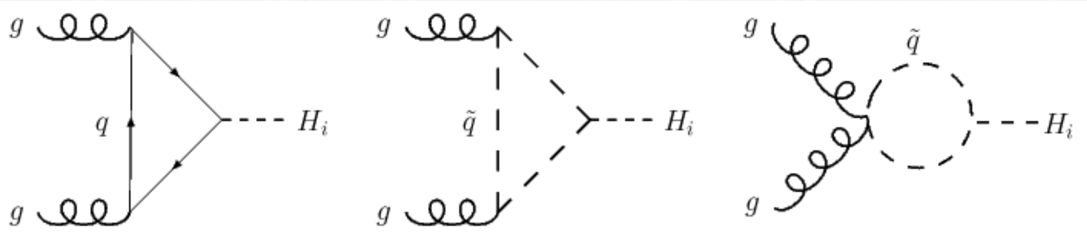
H1 or H2 have reduced couplings due to the singlet component

$h^{125\,\mathrm{GeV}}$ can be H_1, H_2

NMSSM Higgs Phenomenology

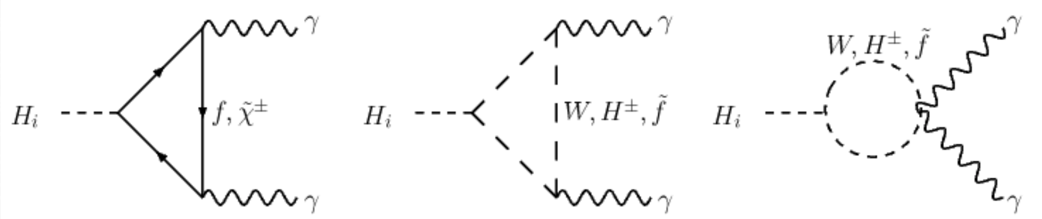
Enhanced gluon fusion production

Stop and sbottom loop contributions in $gg \to H_i$



$$BR(h^{125\text{ GeV}} \to \gamma\gamma) = \frac{\Gamma(h^{125\text{ GeV}} \to \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + ...)[h^{125\text{ GeV}}]}$$

Suppression of $\Gamma(h^{125\text{ GeV}} \to b\bar{b})$ due to strong singlet-doublet mixing



Enhanced $\Gamma(h^{125\text{ GeV}} \to \gamma\gamma)$ due to chargino loop contributions

NMSSM Higgs Benchmarks Near 125 GeV

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

King, Muhlleitner, Nevzorov
arXiv:1201.2671

Key features:

- Stops below 1 TeV in all cases
- Two photon Higgs rate enhanced

$$R_{\gamma\gamma}(H_i) \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{\gamma\gamma}(H_i)$$

$$R_{VV}(H_i) \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{VV}(H_i)$$

$$R_{b\bar{b}}(H_i) \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{b\bar{b}}(H_i)$$

Summary of Part 1

- Particle discovered at LHC consistent with SM Higgs boson
- But LHC Higgs decay signal strengths have large errors (two photon rate too high)
- Higgs may be window into BSM physics
- Higgs theory fine-tuning problem solved by SUSY
- Natural SUSY requires stops = 500 GeV, gluino = 1 TeV (or less)
- These are not excluded by LHC searches (so far!)
- Stops>500 GeV required for Higgs mass in MSSM
- Stops = 500 GeV possible for Higgs mass in NMSSM
- NMSSM can lead to large di-photon rate especially with h(125)=H2
- Other decays such as WW, ZZ, bb, tau tau can also have different rates
- We eagerly await the next LHC results!

King, Moretti, Nevzorov

Exceptional SUSY SM (E_6SSM)

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

Energy

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

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

Miller

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

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

SU(5) reps.

$U(1)_N$ charge × √40

$[10, 1]_i$: $Q_i,\ u_i^c,\ e_i^c$

$[5^*, 2]_i$: $L_i,\ d_i^c$

$[5^*, -3]_i$: $H_{1\,i} = \begin{pmatrix} H_{1\,i}^0 \\ H_{1\,i}^- \end{pmatrix}, \bar{D}_i$

$[5, -2]_i$: $H_{2\,i} = \begin{pmatrix} H_{2\,i}^+ \\ H_{2\,i}^0 \end{pmatrix}, D_i$

$[1, 5]_i$: S_i

$[1, 0]_i$: N_i^c

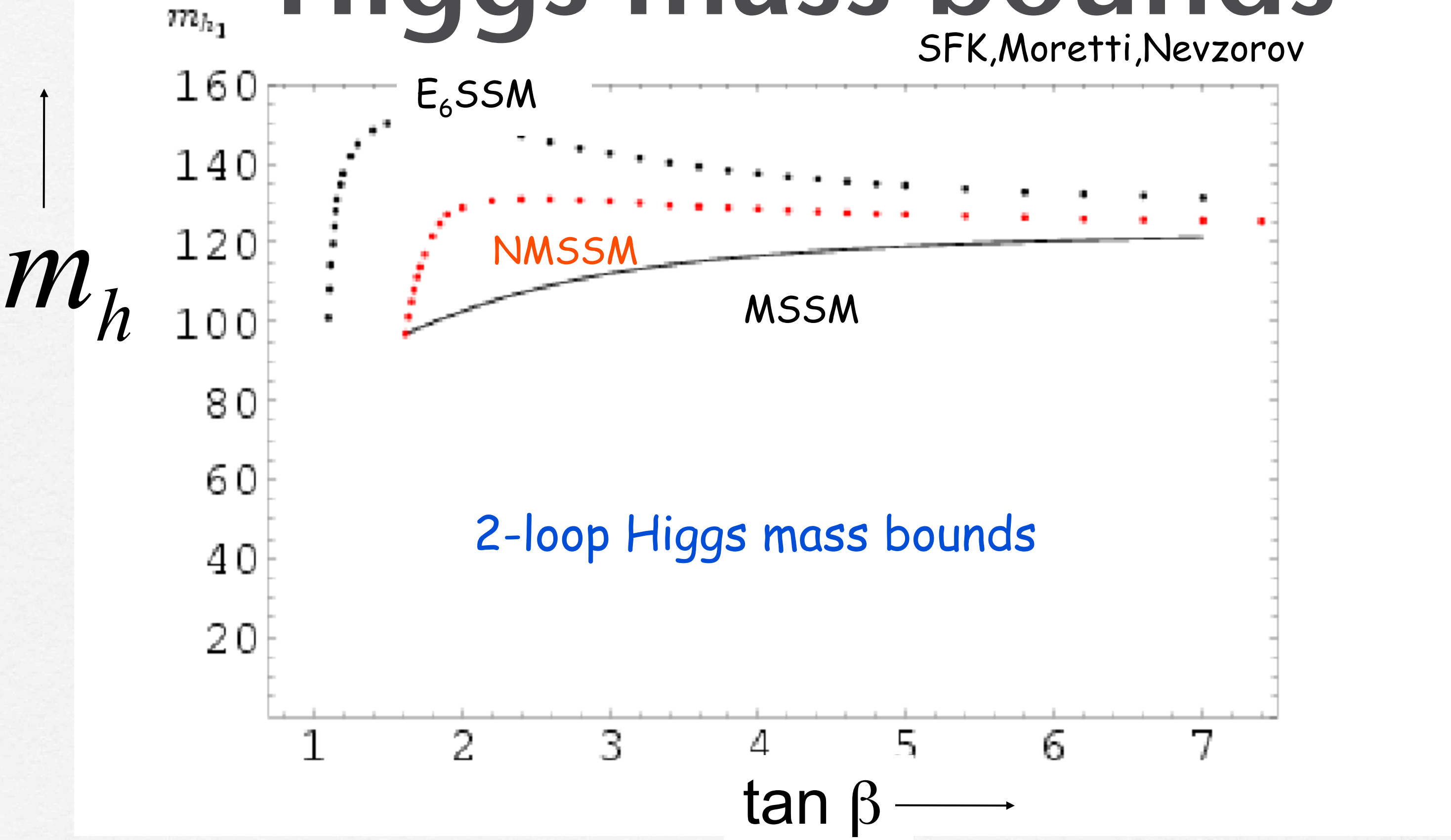
3 generations of "Higgs"

exotic quarks

singlets

right handed neutrino

Higgs mass bounds

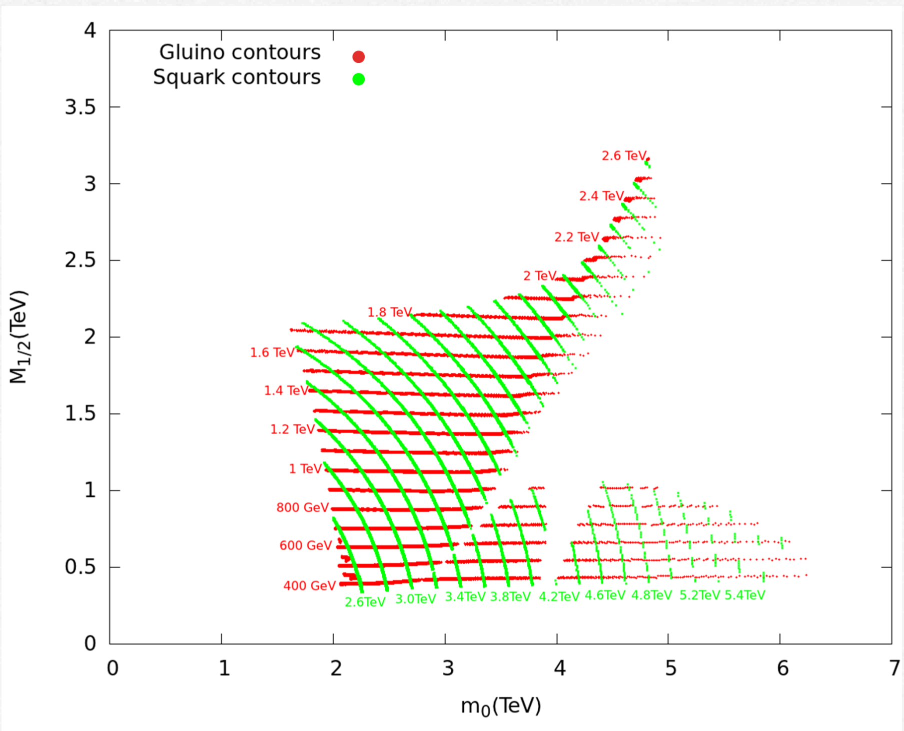


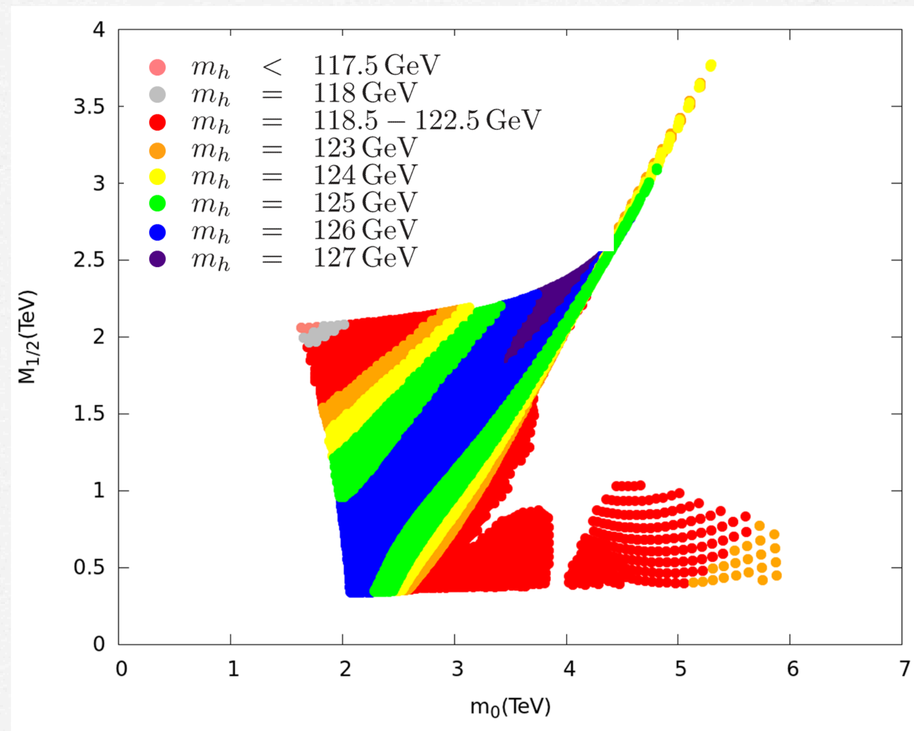
$$m_h^2 \approx \underbrace{\underbrace{\underbrace{M_Z^2 \cos^2 2\beta}_{MSSM} + \frac{\lambda^2}{2} v^2 \sin^2 2\beta}_{NMSSM} + \frac{M_Z^2}{4}\left(1 + \frac{1}{4}\cos 2\beta\right)^2}_{E_6SSM} + \Delta m_h^2$$

Higgs, Squarks, Gluinos in CE6SSM

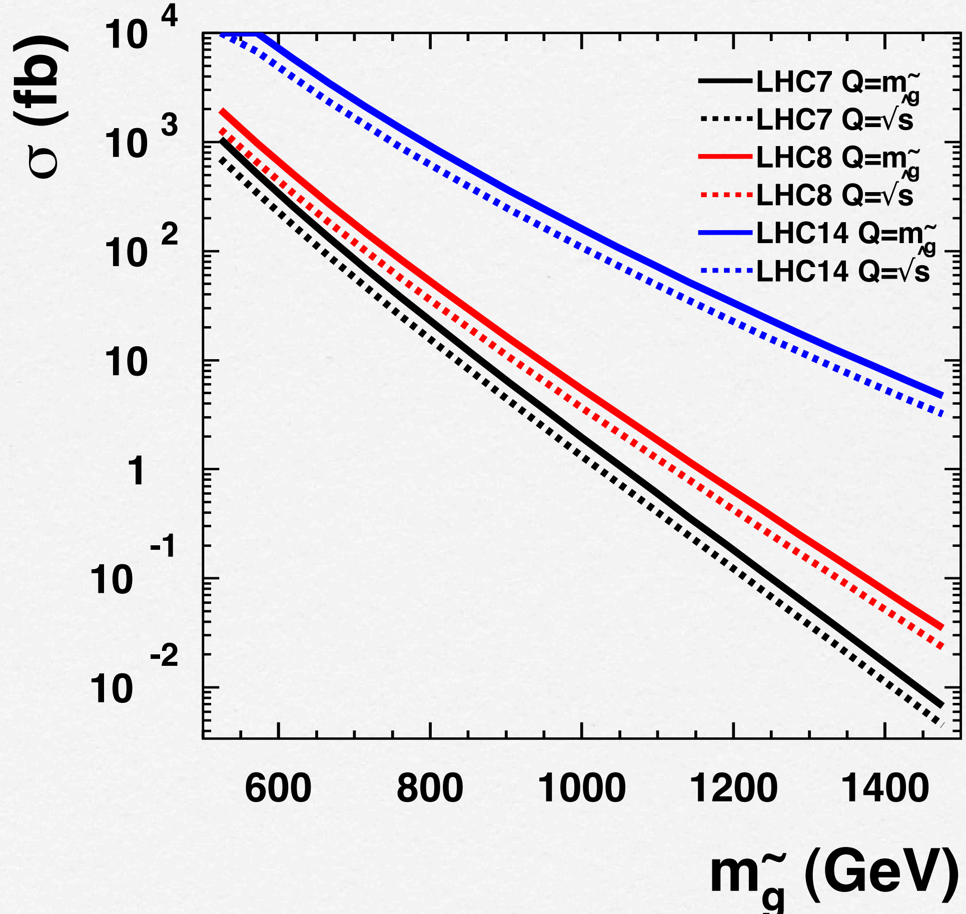
Athron, King, Miller, Moretti, Nevzorov

$$\tan\beta = 10,\ \lambda_{12} = 0.1,\ s = 10\ \text{TeV},$$



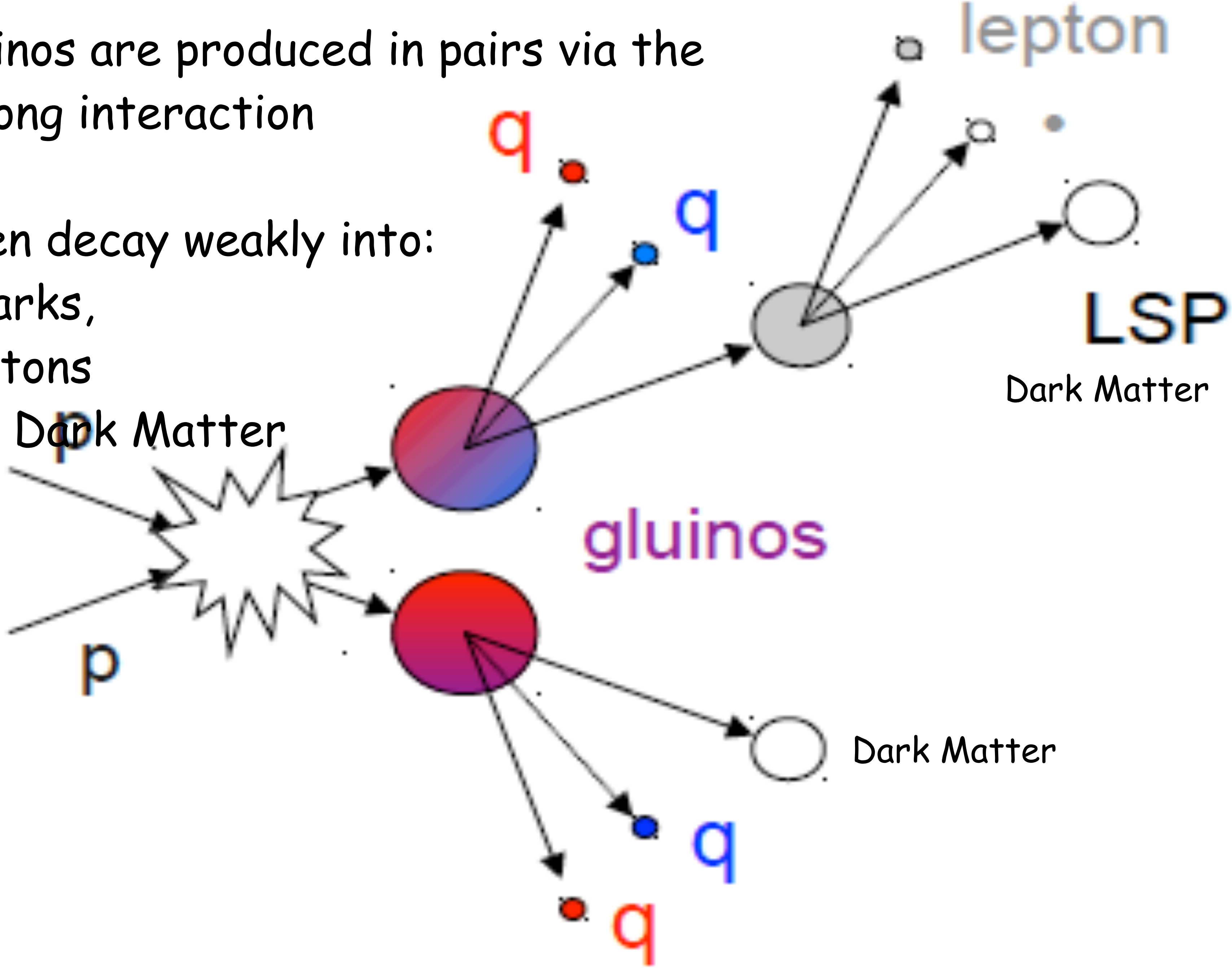


Gluino pair production



Gluinos are produced in pairs via the strong interaction

Then decay weakly into:
Quarks,
Leptons
and Dark Matter



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

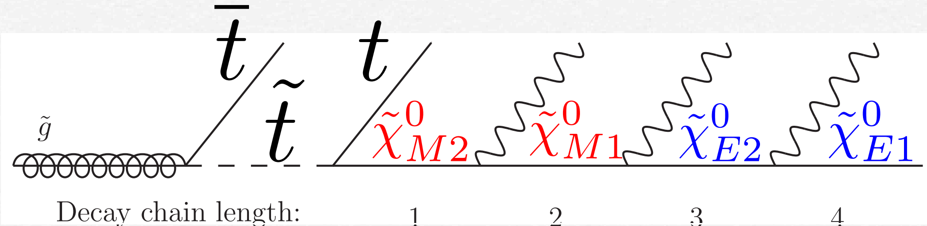
$$\tilde{\chi}^0_{\rm int} = (\ \tilde{B}\quad \tilde{W}^3\quad \tilde{H}^0_d\quad \tilde{H}^0_u \ |\ \tilde{S}\quad \tilde{B}'\ |\ \tilde{H}^0_{d2}\quad \tilde{H}^0_{u2}\quad \tilde{S}_2\ |\ \tilde{H}^0_{d1}\quad \tilde{H}^0_{u1}\quad \tilde{S}_1\ )^{\rm T}$$

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

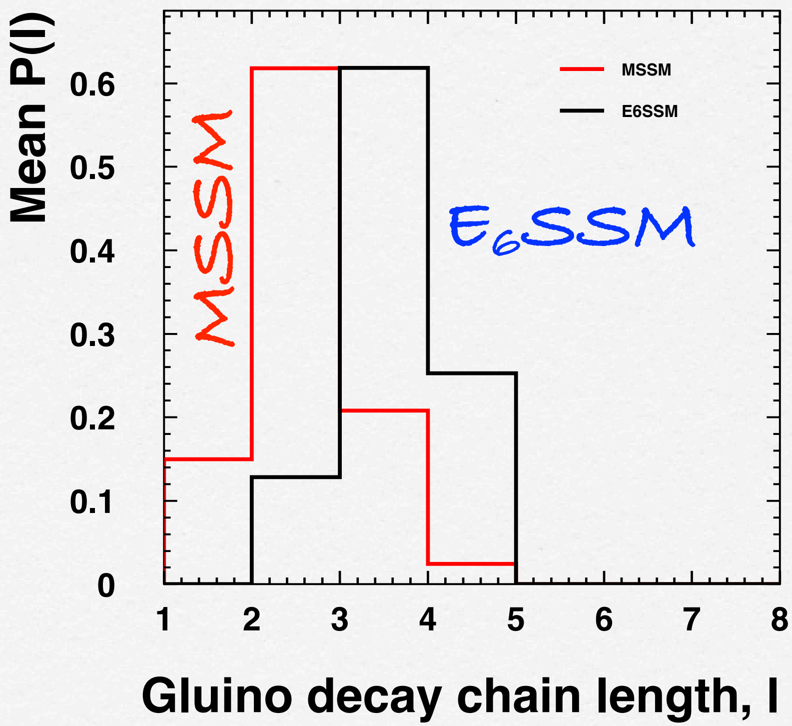
12x12 matrix!!

Gluino decay chains

Belyaev, Hall, King, Svantesson (preliminary)



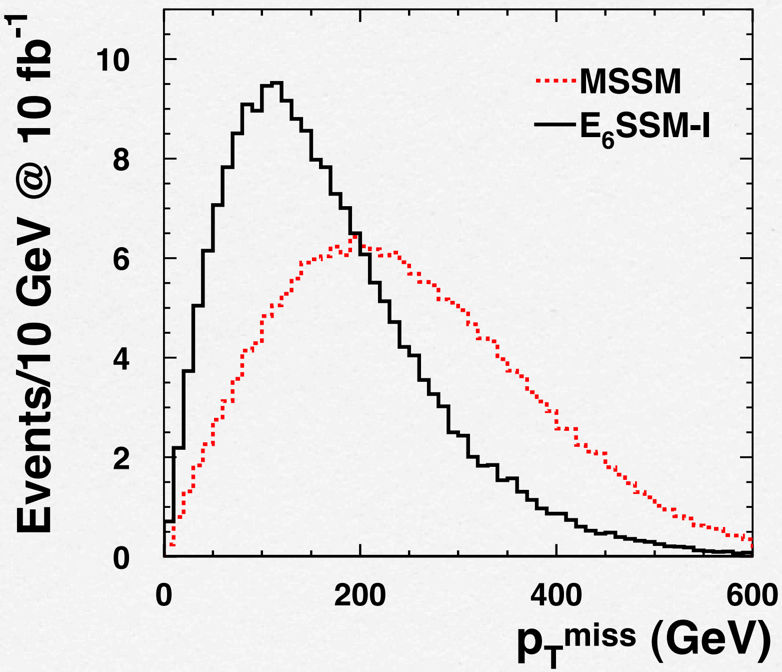
E_6SSM has longer gluino chains with a lighter LSP at the end

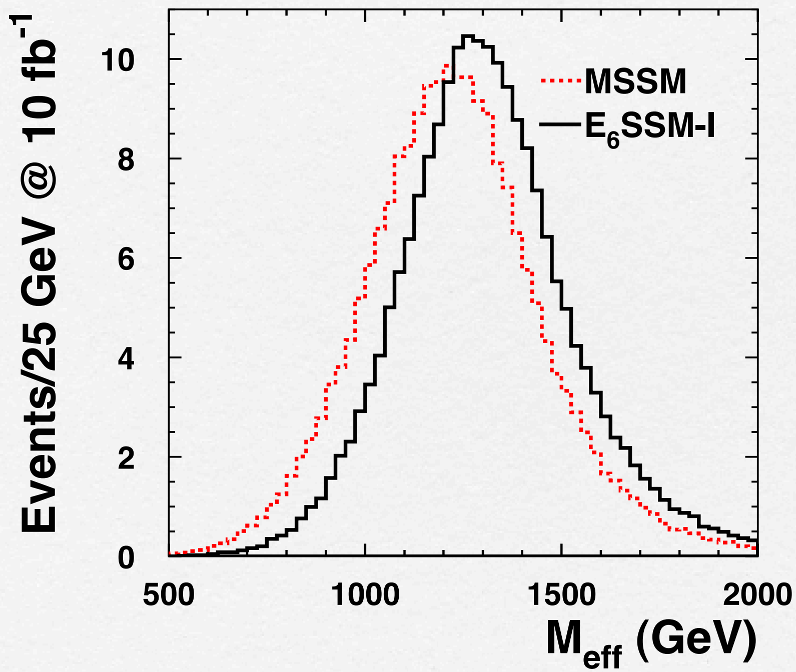


	MSSM	E_6SSM-I	E_6SSM-II	E_6SSM-III	E_6SSM-IV	E_6SSM-V	E_6SSM-VI	
$\tan\beta$	10	1.5	1.42	1.77	3	1.42	1.42	
λ	-	0.497	0.598	-0.462	-0.4	0.598	0.598	
s	-	5180	5268	5418	5500	5268	5268	[GeV]
μ	1578	(1820)	(2228)	(1770)	(-1556)	(2228)	(2228)	
$A_t = A_b = A_\tau$	-2900	-3110	-3100	476.2	4638	-2684	-2684	
M_A	302.5	3666	4365	2074	4341	4010	4000	
M_1	150	150	150	150	150	150	150	
M_2	285	300	300	300	300	300	300	
$M_{1'}$	-	151	151	151	151	151	151	
$m_{\tilde{g}}$	800.2	800.0	800.0	800.0	800.0	800.0	800.0	
$m_{\tilde{\chi}^0_{M1}}$	148.7	148.9	149.1	151.2	150.6	149.1	149.1	[GeV]
$m_{\tilde{\chi}^0_{M2}}$	302.2	296.1	296.8	303.7	301.7	296.8	296.8	
$m_{\tilde{\chi}^0_{M3}}$	1582	1763	2233	1766	1557	2233	2233	
$m_{\tilde{\chi}^0_{M4}}$	1584	1823	2246	1771	1558	2246	2246	
$m_{\tilde{\chi}^\pm_{M1}}$	302.2	299.0	299.2	300.9	300.4	299.2	299.2	
$m_{\tilde{\chi}^\pm_{M2}}$	1584	1822	2229	1771	1557	2229	2229	
$m_{\tilde{\chi}^0_{U1}}$	-	1878	1835	1909	1937	1835	1835	
$m_{\tilde{\chi}^0_{U2}}$	-	1973	2003	2062	2087	2003	2003	
$m_{\tilde{\chi}^0_{E1}}$	-	62.7	43.5	45.2	0	0	0.00011	
$m_{\tilde{\chi}^0_{E2}}$	-	62.8	48.6	53.2	0	0	1.53	
$m_{\tilde{\chi}^0_{E3}}$	-	119.8	131.3	141.6	164.1	119.9	120.1	
$m_{\tilde{\chi}^0_{E4}}$	-	121.0	163.6	187.4	164.1	119.9	122.8	
$m_{\tilde{\chi}^0_{E5}}$	-	183.0	197.0	227.8	388.9	185.8	185.8	
$m_{\tilde{\chi}^0_{E6}}$	-	184.4	224.3	265.6	388.9	185.8	187.0	
$m_{\tilde{\chi}^\pm_{E1}}$	-	109.8	119.9	122.7	164.1	119.9	119.9	
$m_{\tilde{\chi}^\pm_{E2}}$	-	117.7	185.8	225.1	388.9	185.8	185.8	
m_h	124.4	125.4	133.8	116.3	124.7	126.1	125.8	
$P(l=1)$	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]

E_6SSM gluino gives less p_T^{miss}

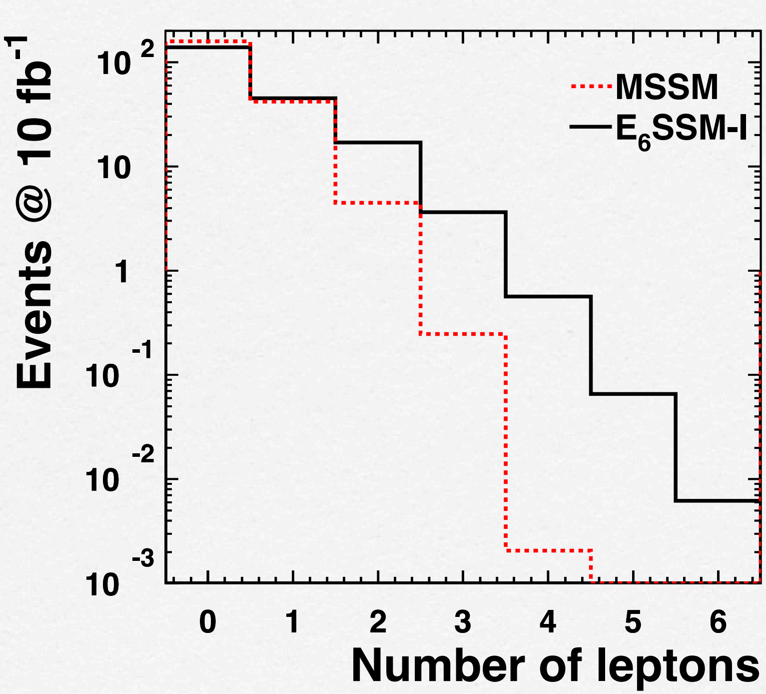
Belyaev, Hall, King, Svantesson (preliminary)

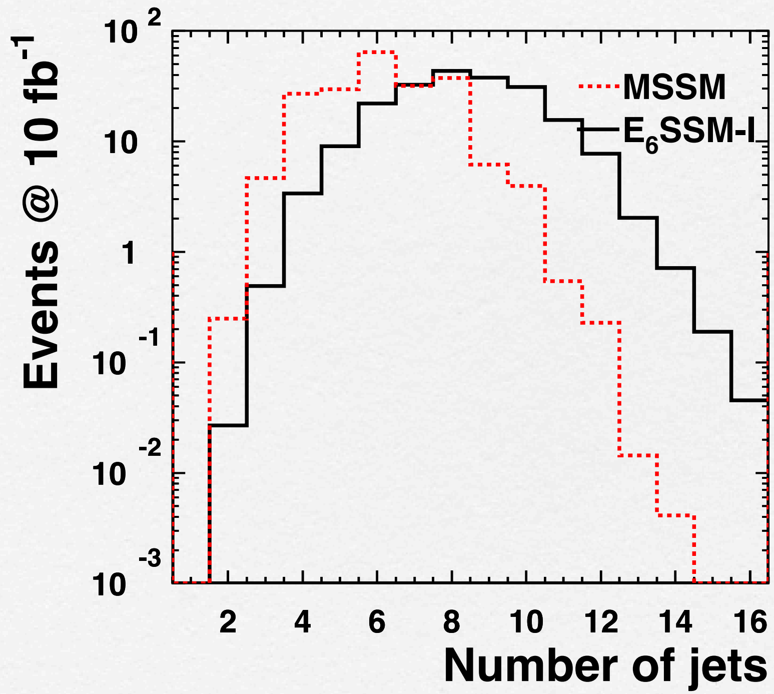




E_6SSM gluino gives more jets and leptons

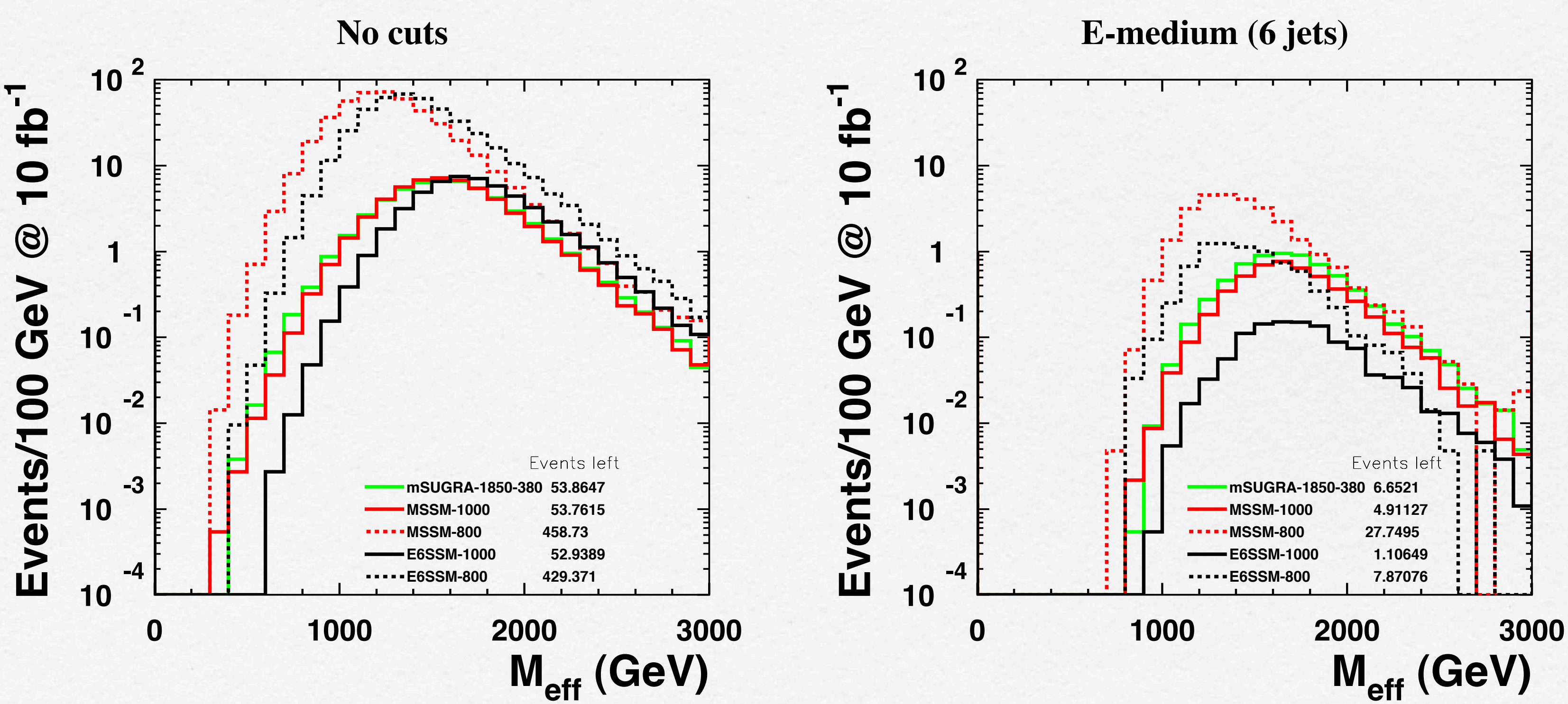
Belyaev, Hall, King, Svantesson (preliminary)



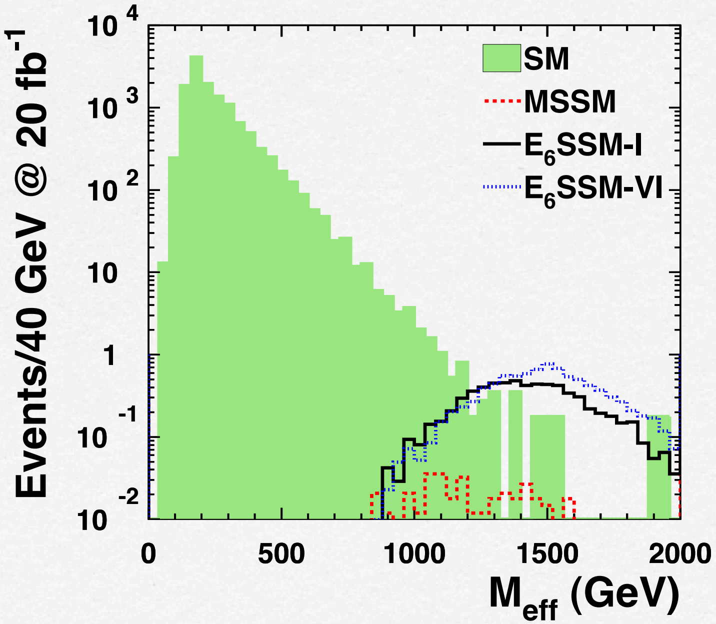


LHC@7 TeV, gluino@800 GeV

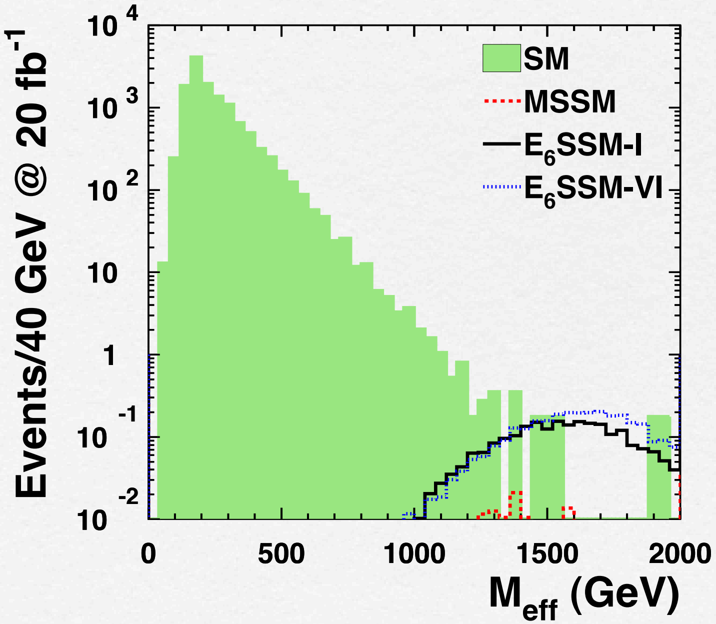
E_6SSM gluino harder to see in 6 jet channel



E_6SSM gluino easier to see in 3 lepton channel at 8 TeV

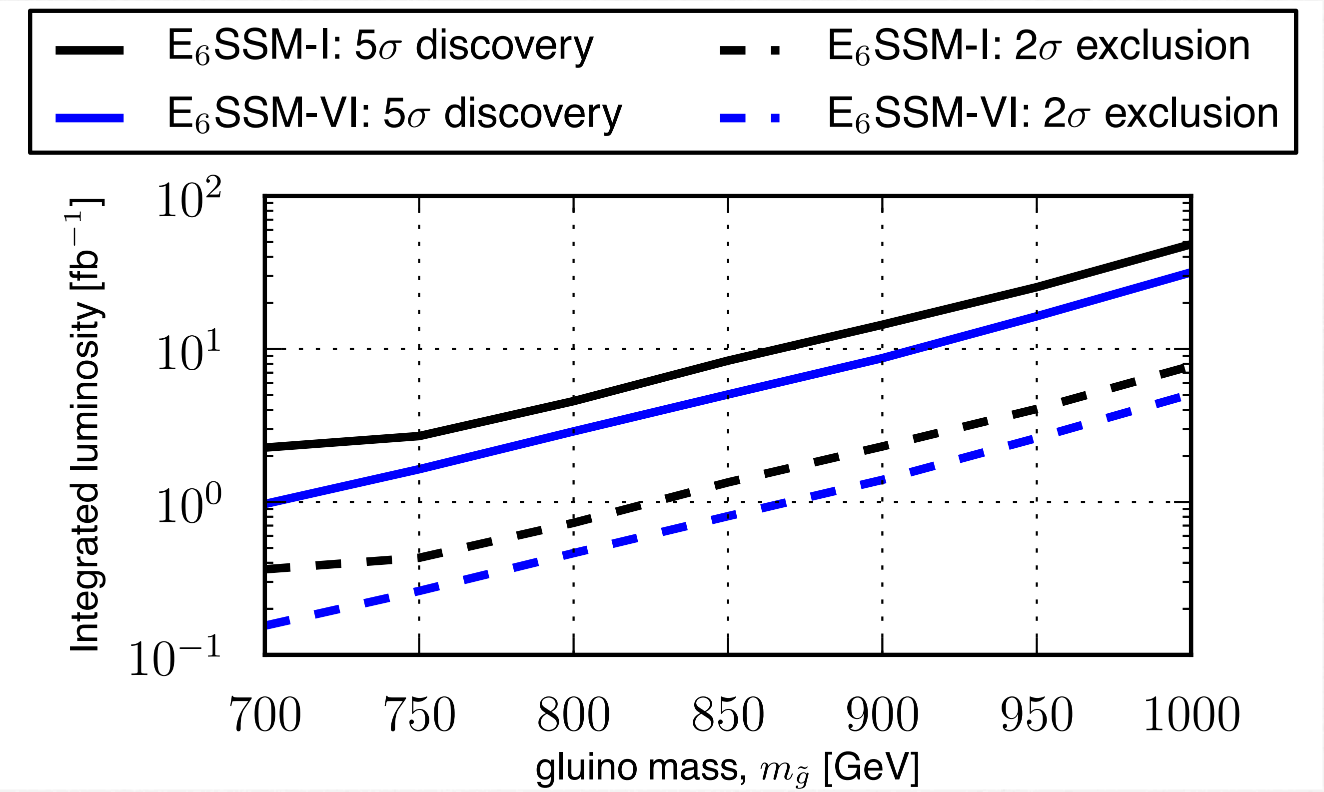


(c)$m_{\tilde{g}} = 900$ GeV



(d)$m_{\tilde{g}} = 1000$ GeV

Luminosity required for 5σ discovery and 2σ exclusion, $\sqrt{s} = 8\text{TeV}$ in 3 lepton channel

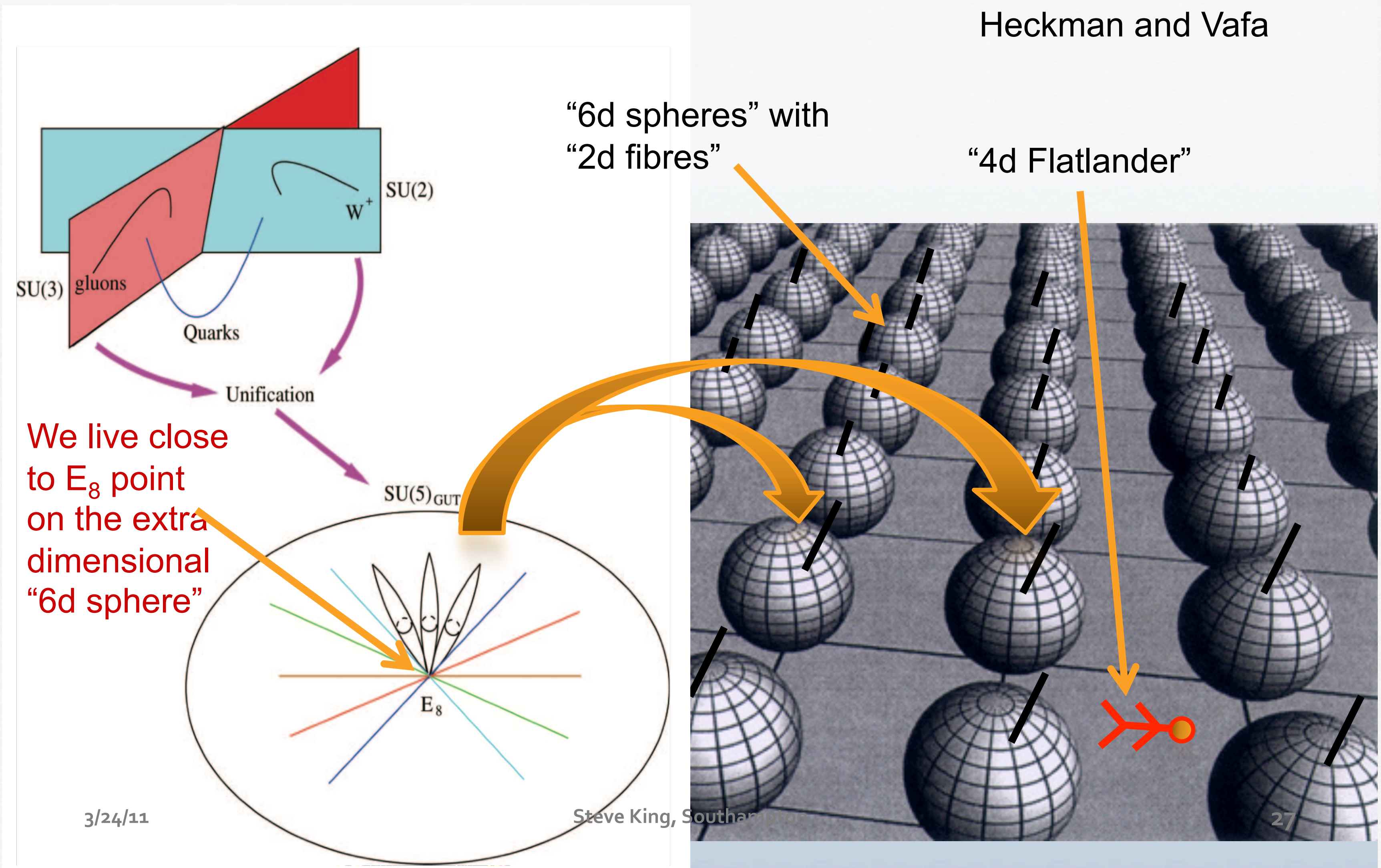


Summary of Part 2

- E6SSM is richer theory with many LHC signals
- Matter spectrum with 3 families of 27 dimensional particle reps and a Z′
- Higgs at 125 GeV possible in E6SSM
- Typical spectrum is heavy squarks but lighter gluino
- Gluino has longer decay chains with more jets and leptons and less missing transverse momentum
- E6SSM Gluino is harder to see in 6 jet channel
- But easier to see in 3 lepton channel
- We eagerly await the next LHC results!

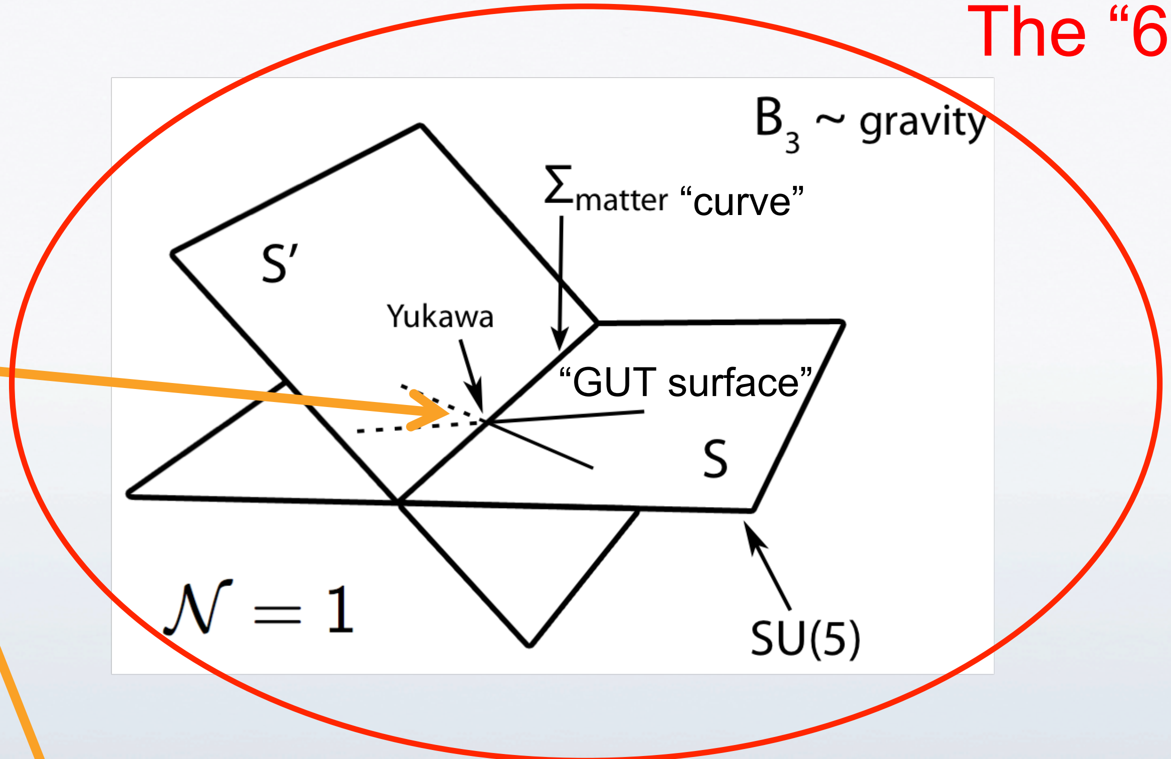
Extra Slides

F-Theory GUTs: a 12d string theory



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"

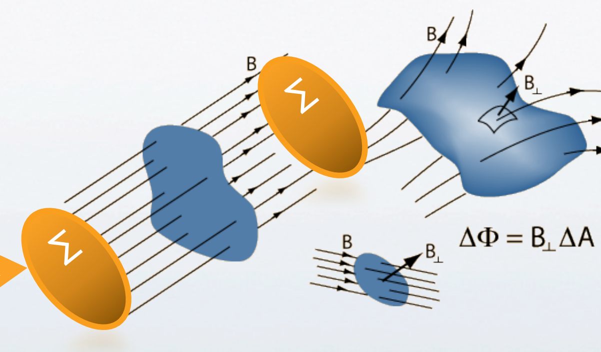
Figure 1: The structure of an F-theory GUT

GUT breaking is achieved not with Higgs but with Hypercharge Flux

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

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

2-d Matter curve Σ



Think of magnetic flux PHYS2001

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	$\overline{5}_3$	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	$\overline{5}_2$	t_1+t_4	1	3	$3\overline{D}+4H_d$	$3\overline{D}+3H_d$
$27_{t_1'}$	1	θ_{14}	t_1-t_4	0	n_{14}	θ_{14}	-
$27_{t_3'}$	16	$\overline{5}_5$	t_3+t_5	-1	-1	$\overline{d^c}+2\overline{L}$	-
$27_{t_3'}$	16	10_2	t_3	1	-1	$\overline{Q}+2\overline{u^c}$	-
$27_{t_3'}$	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	$\overline{5}_4$	t_3+t_4	-1	0	$\overline{H_d}$	-

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

CMSSM Dark Matter

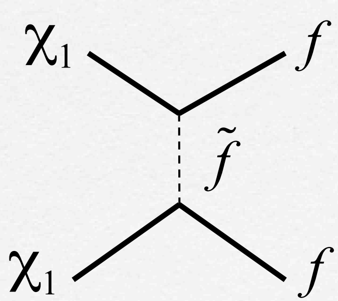
Neutralino mass matrix

$$\begin{array}{cccc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u \end{array}$$

$$\begin{pmatrix} M_1 & & & \\ & M_2 & & \\ & & 0 & -\mu \\ & & -\mu & 0 \end{pmatrix}$$

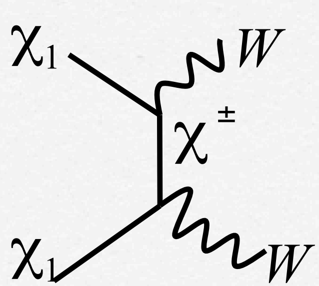
$$\chi_1 = N_1\tilde{B} + N_2\tilde{W} + N_3\tilde{H}_d + N_4\tilde{H}_u$$

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



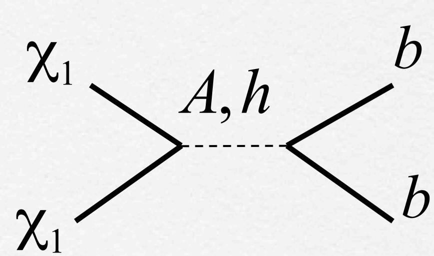
Bulk

$m_{\tilde{f}} \approx m_{\chi_1}$



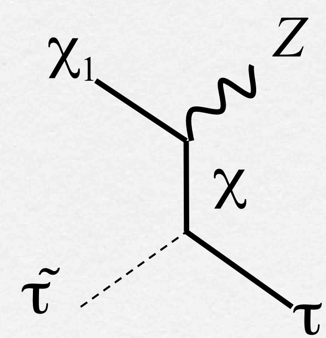
Focus

Higgsino LSP



Funnel

$m_{A,h} \approx 2m_{\chi_1}$



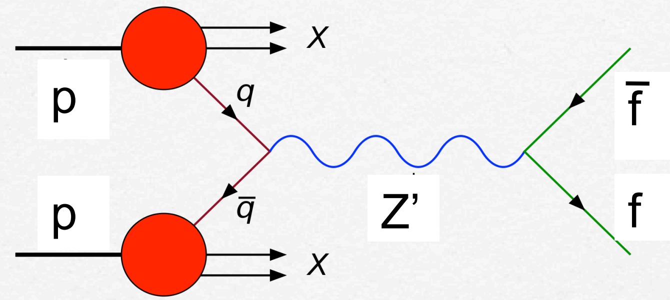
Co-annihilation

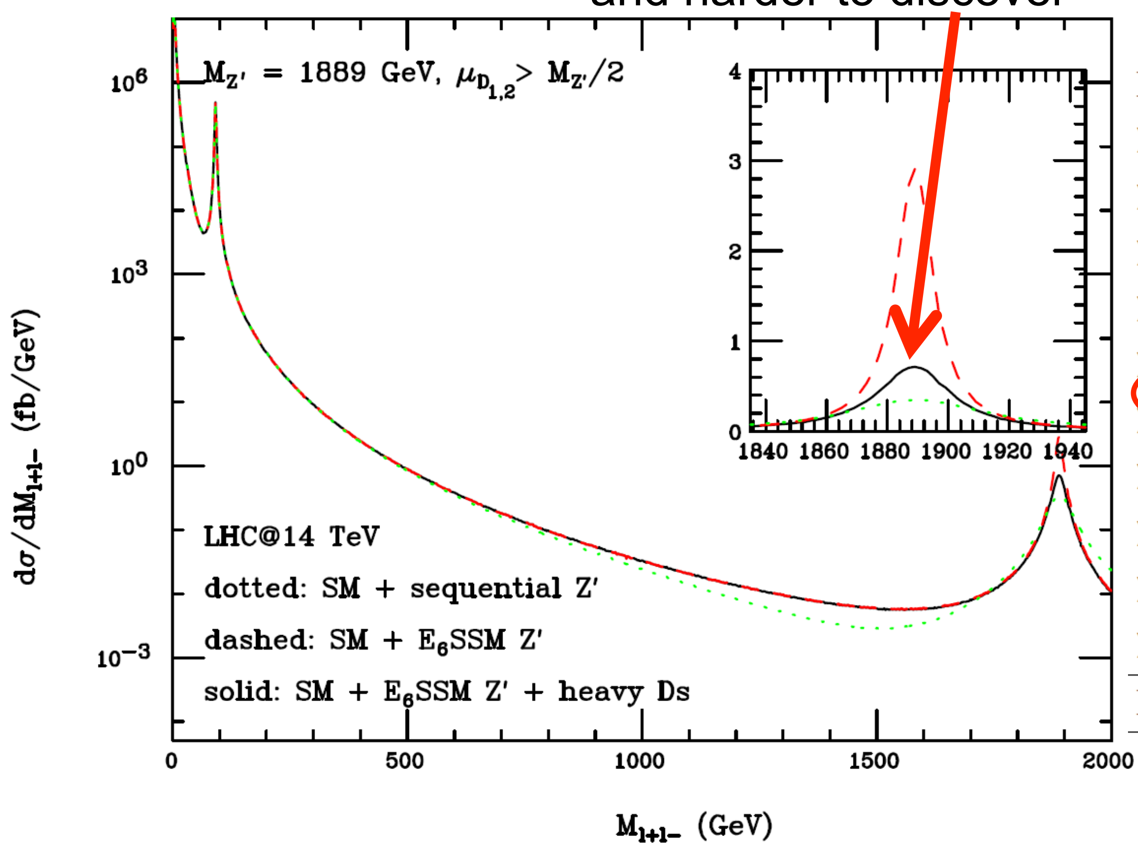
$m_{\tilde{\tau}} \approx m_{\chi_1}$

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
$\Sigma_l\Gamma(Z'_N \to \nu_l\overline{\nu}_l)$ (all neutrinos)	1.64
$\Sigma_l\Gamma(Z'_N \to l^+l^-, \nu_l\overline{\nu}_l)$ (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

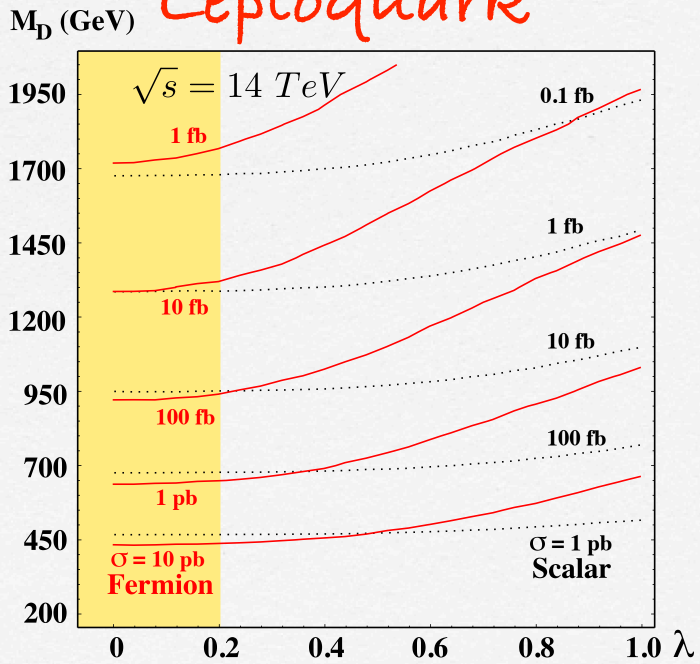
Exotic D-particles

Kang, Langacker, Nelson

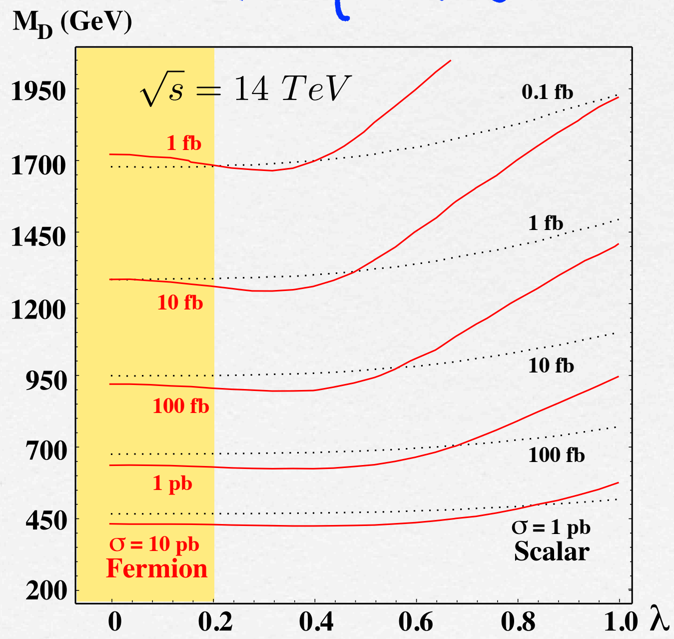
D-particles are coloured and may be pair produced at LHC

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

Leptoquark

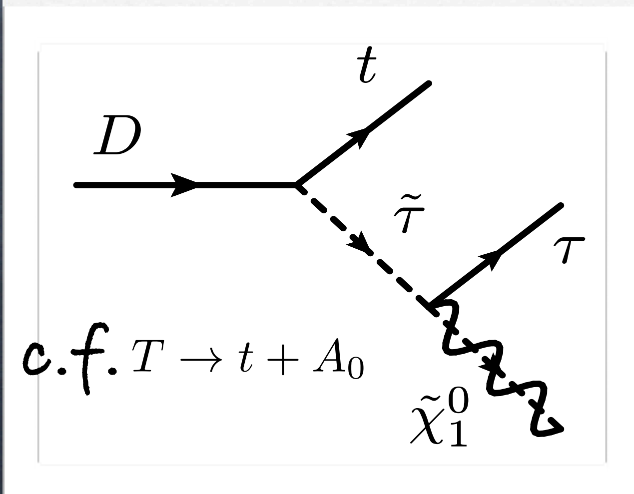


Diquark



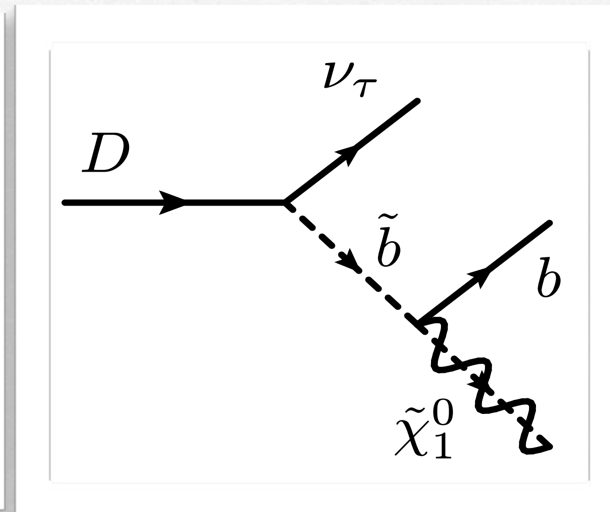
D-fermion decays

Leptoquark



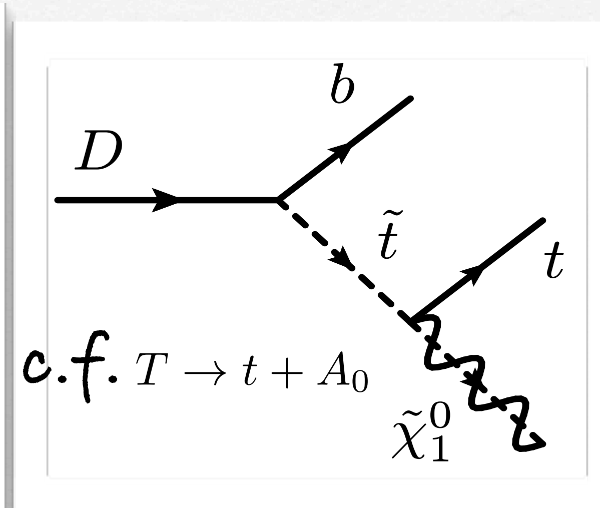
$$pp \to t\bar{t}\tau^+\tau^- + E_T^{miss} + X$$

Leptoquark



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

Diquark



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

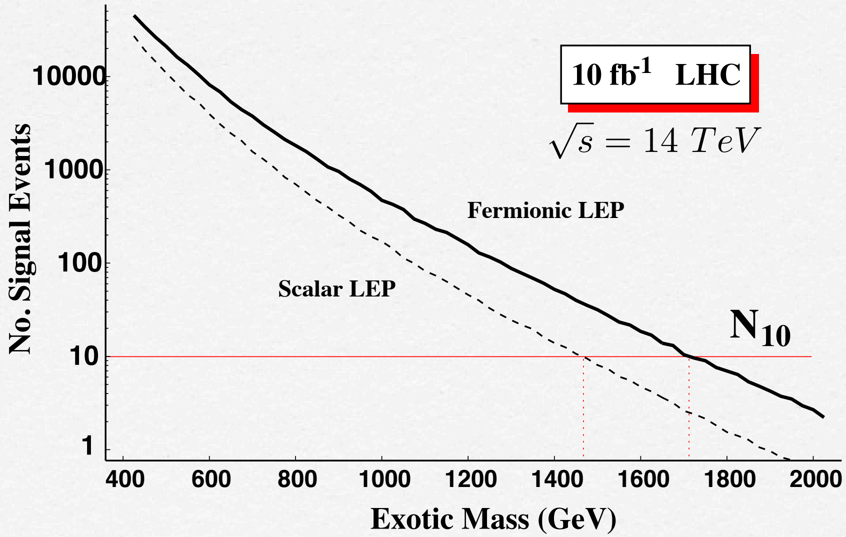
spectacular signals!

Kang, Langacker, Nelson

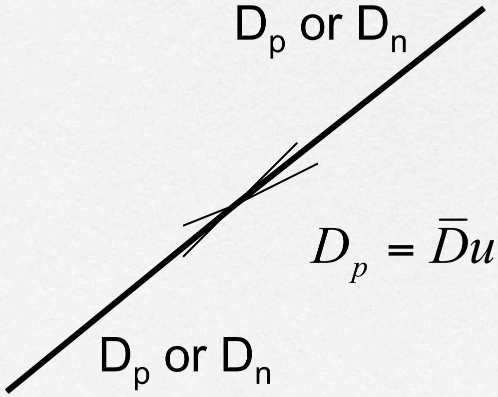
D-fermion as R-hadron

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

$$\text{dim5} \; : \; D^c Q H_d S, \; D^c Q Q u^c, \; D^c Q L \nu^c$$



punch through to muon chambers



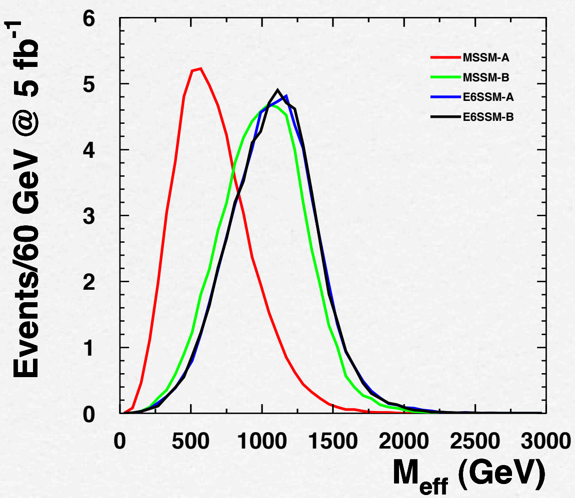
$$D_p = \bar{D}u, D_n = \bar{D}d$$

Belyaev, Hall, King,
Svantesson (preliminary)

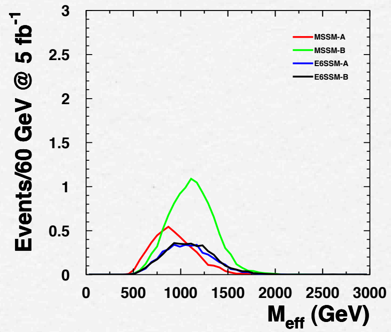
M_{eff}

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

M_{eff} does not really help to distinguish models

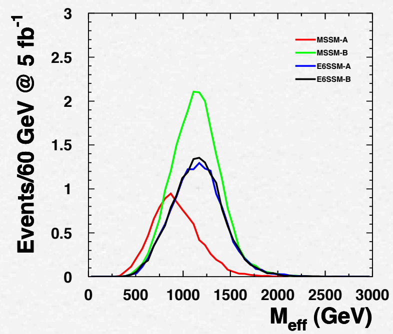


ATLAS style cuts



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

CMS style cuts



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

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)