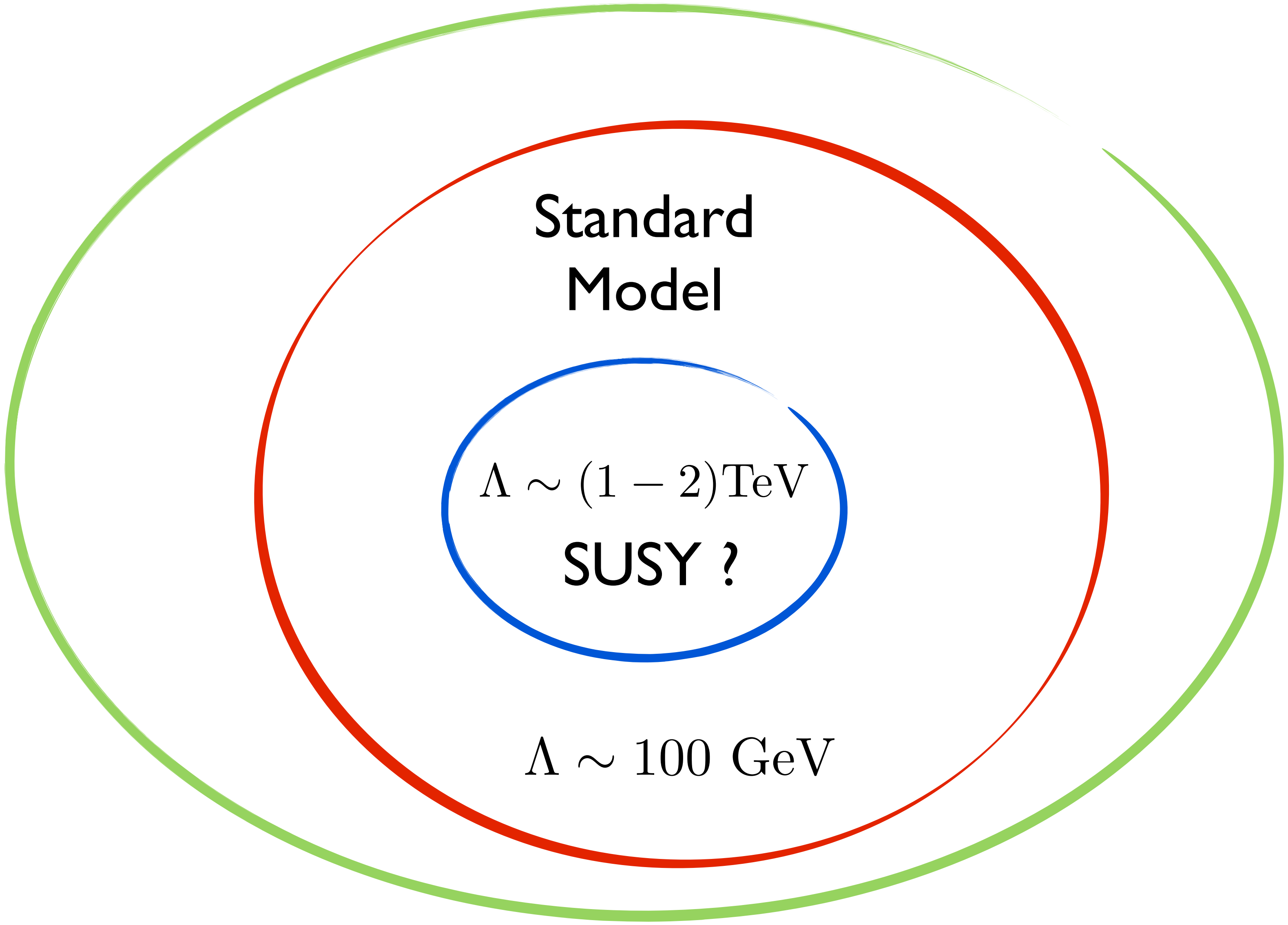


Standard
Model

$\Lambda \sim (1-2)\mathrm{TeV}$

SUSY ?

$\Lambda \sim 100\ \mathrm{GeV}$

Status of *Some* Supersymmetric Models

Sudhir K Vempati
CHEP, IISc Bangalore

ICTDHEP, Jammu
Sept 9-14, 2013

Outline

- Why Supersymmetry ?
- Structure of MSSM
- Direct Experimental Constraints
- Higgs implications
- Status of Constrained Models in SUGRA
- Status of GMSB
- Non-Traditional Models
- Summary and Outlook

Recent review on status
arXiv:1309.0528 [hep-ph]

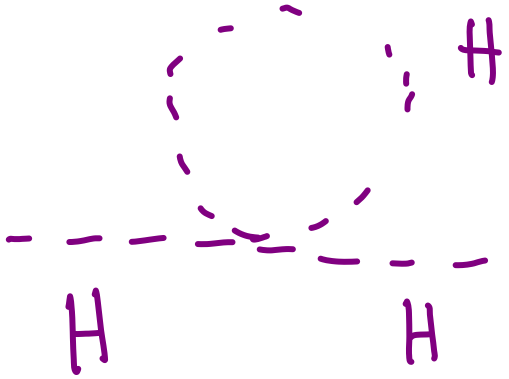
M_{Planck}

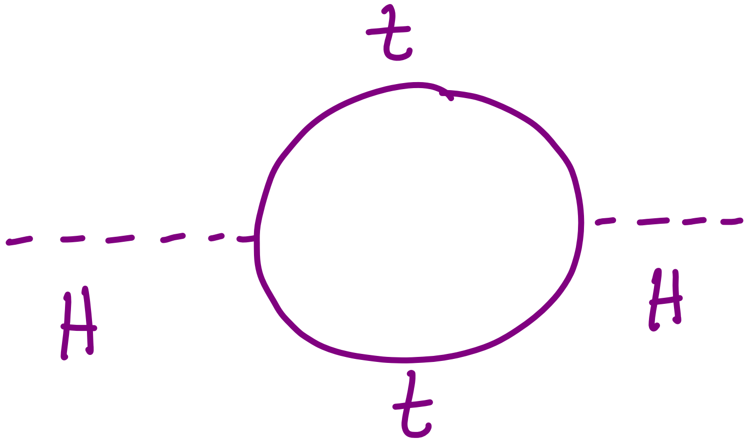
$$\delta m_h^2 \approx \frac{1}{16\pi^2}\Lambda^2 \approx \frac{1}{16\pi^2}M_{\mathrm{Planck}}^2$$

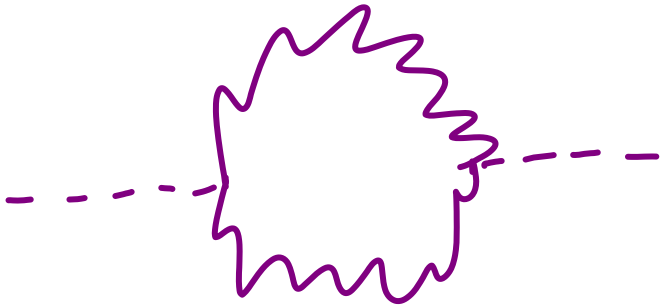
M_{Weak}

If SM is an effective theory below Planck Scale with an elementary scalar, the mass of such a scalar would be unstable under radiative corrections

Wilson,
Susskind,
Buras et. al







& so on

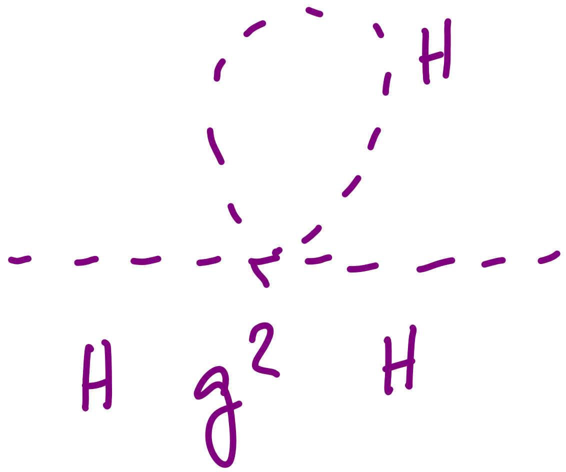
Two Choices

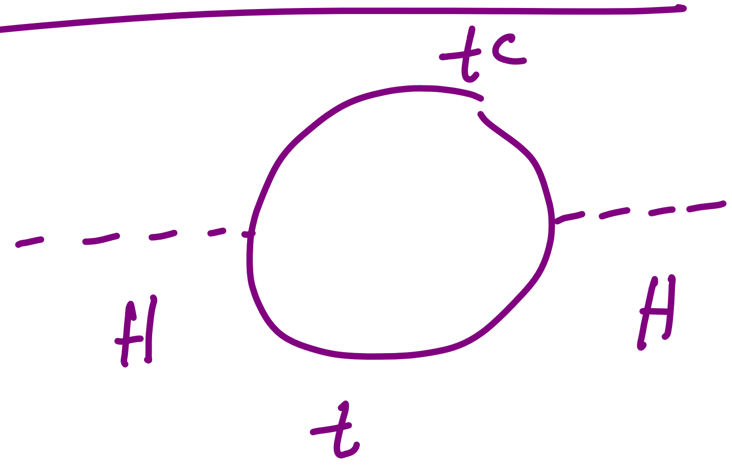
(a) Either the cut-off is low (new physics scale (non-perturbative) like composite scale or extra dimensions etc)

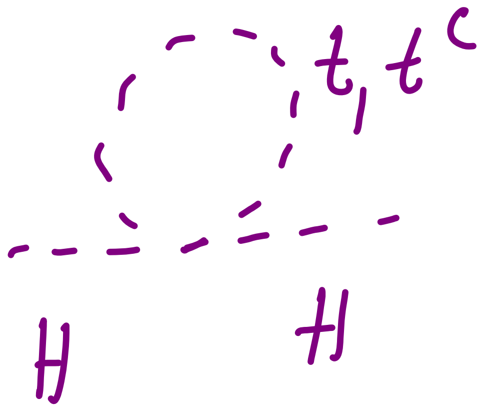
(b) There is some symmetry protecting the Higgs Mass

Supersymmetry is a symmetry which protects the higgs mass but also introduces a new physics scale

How SUSY works

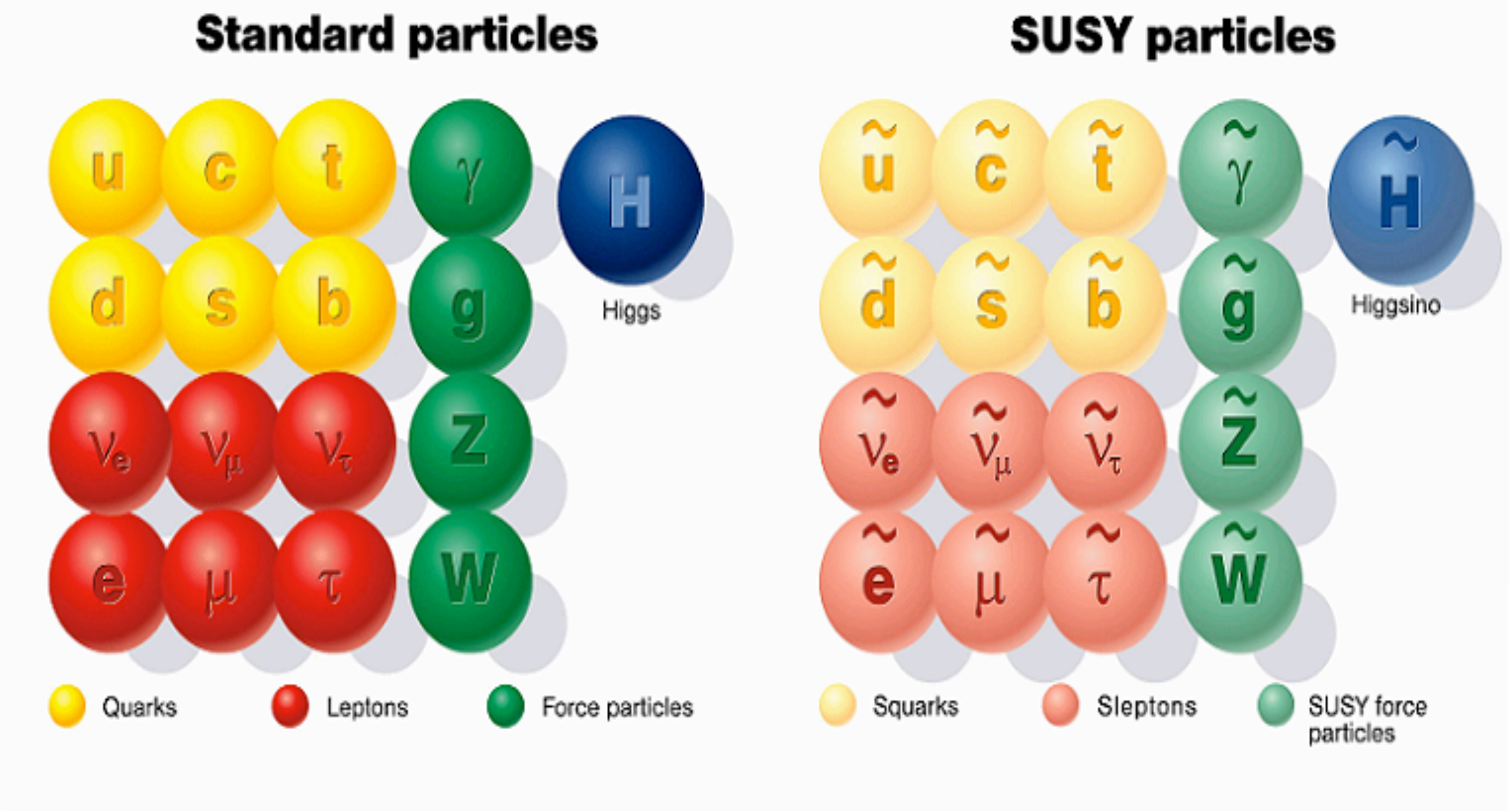






quartic coupling replaced by gauge coupling

If $m_t \approx m_{\tilde{t}}$ quadratic divergences cancel from both the diagrams


Standard particles
SUSY particles
u
c
t
γ
H
d
s
b
g
Higgs
ν_e
ν_μ
ν_τ
Z
e
μ
τ
W
Quarks
Leptons
Force particles
$\tilde{u}$
$\tilde{c}$
$\tilde{t}$
$\tilde{\gamma}$
$\tilde{H}$
$\tilde{d}$
$\tilde{s}$
$\tilde{b}$
$\tilde{g}$
Higgsino
$\tilde{\nu}_e$
$\tilde{\nu}_\mu$
$\tilde{\nu}_\tau$
$\tilde{Z}$
$\tilde{e}$
$\tilde{\mu}$
$\tilde{\tau}$
$\tilde{W}$
Squarks
Sleptons
SUSY force particles

Other advantages of SUSY

- Its calculable and thus in principle, predictable.
- Dark Matter candidate if R-parity is conserved.
- Gauge coupling unification (GUTs with neutrino masses and mixing)
- Lightest Higgs boson can be SM -like in regions of parameter space.

soft susy breaking

Spontaneous Supersymmetry breaking leads to soft supersymmetry breaking terms.

SUSY ⇒ Equal Couplings for particles and super-particles
Equal Masses for particles and super-particles

~~SUSY~~ ⇒ Super-particles have different couplings and different masses

soft susy breaking

Giradello -Grisaru
Dimpolous-Georgi

gaugino masses $M_1\tilde{B}\tilde{B}, M_2\tilde{W}_I\tilde{W}_I, M_3\tilde{G}_A\tilde{G}_A,$

scalar mass terms $m^2_{Q_{ij}}\tilde{Q}^\dagger_i\tilde{Q}_j, m^2_{u_{ij}}\tilde{u^c}^\star_i\tilde{u^c}_j, m^2_{d_{ij}}\tilde{d^c}^\star_i\tilde{d^c}_j, m^2_{L_{ij}}\tilde{L}^\dagger_i\tilde{L}_j, m^2_{e_{ij}}\tilde{e^c}^\star_i\tilde{e^c}_j, m^2_{H_1}H^\dagger_1H_1, m^2_{H_2}H^\dagger_2H_2.$

trilinear couplings $A^u_{ij}\tilde{Q}_i\tilde{u}^c_jH_2, A^d_{ij}\tilde{Q}_i\tilde{d}^c_jH_1, A^e_{ij}\tilde{L}_i\tilde{e}^c_jH_1$

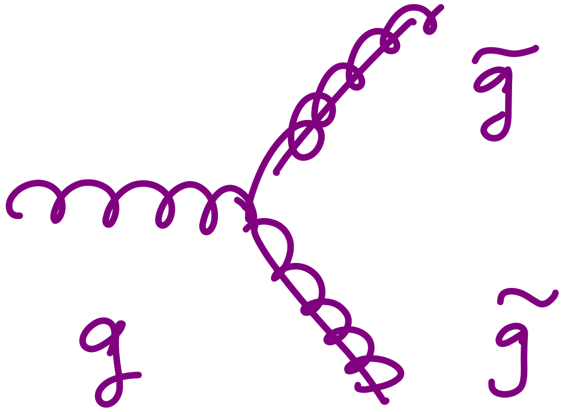
bilinear couplings BH_1H_2

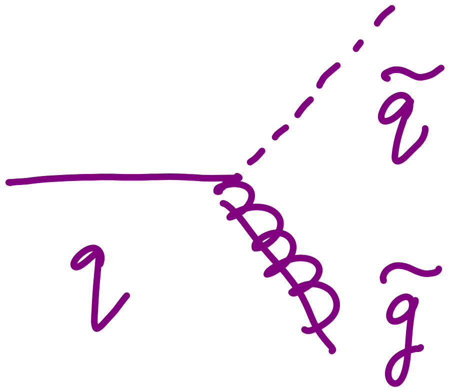
A total of about 105 parameters

But many of them constrained due to flavour/cp

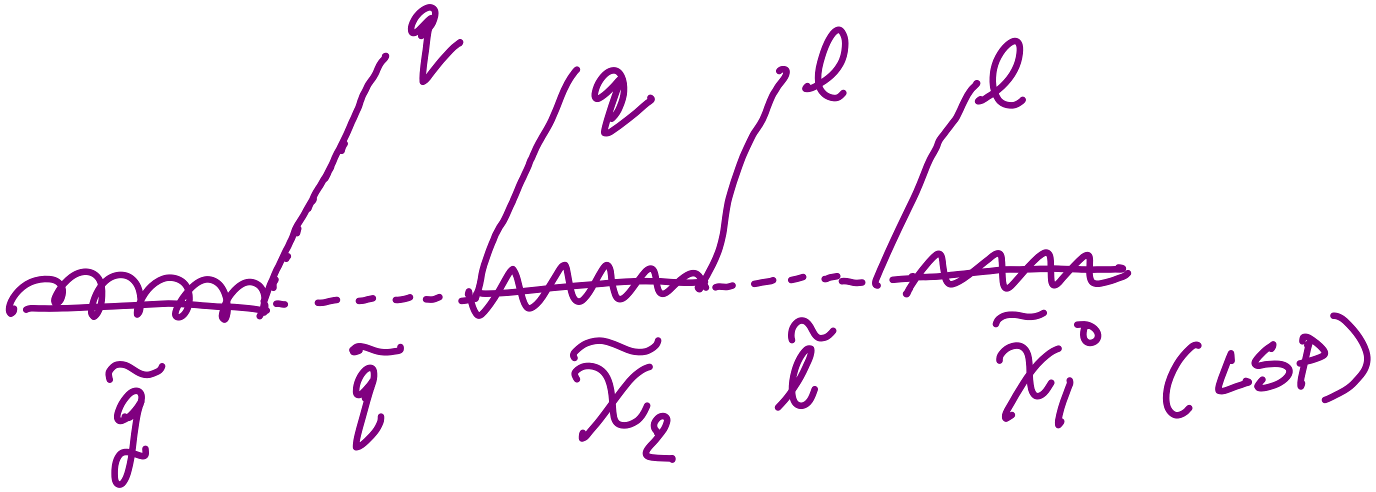
Experimental Status

Large Hadron Collider





Dominant production sections.



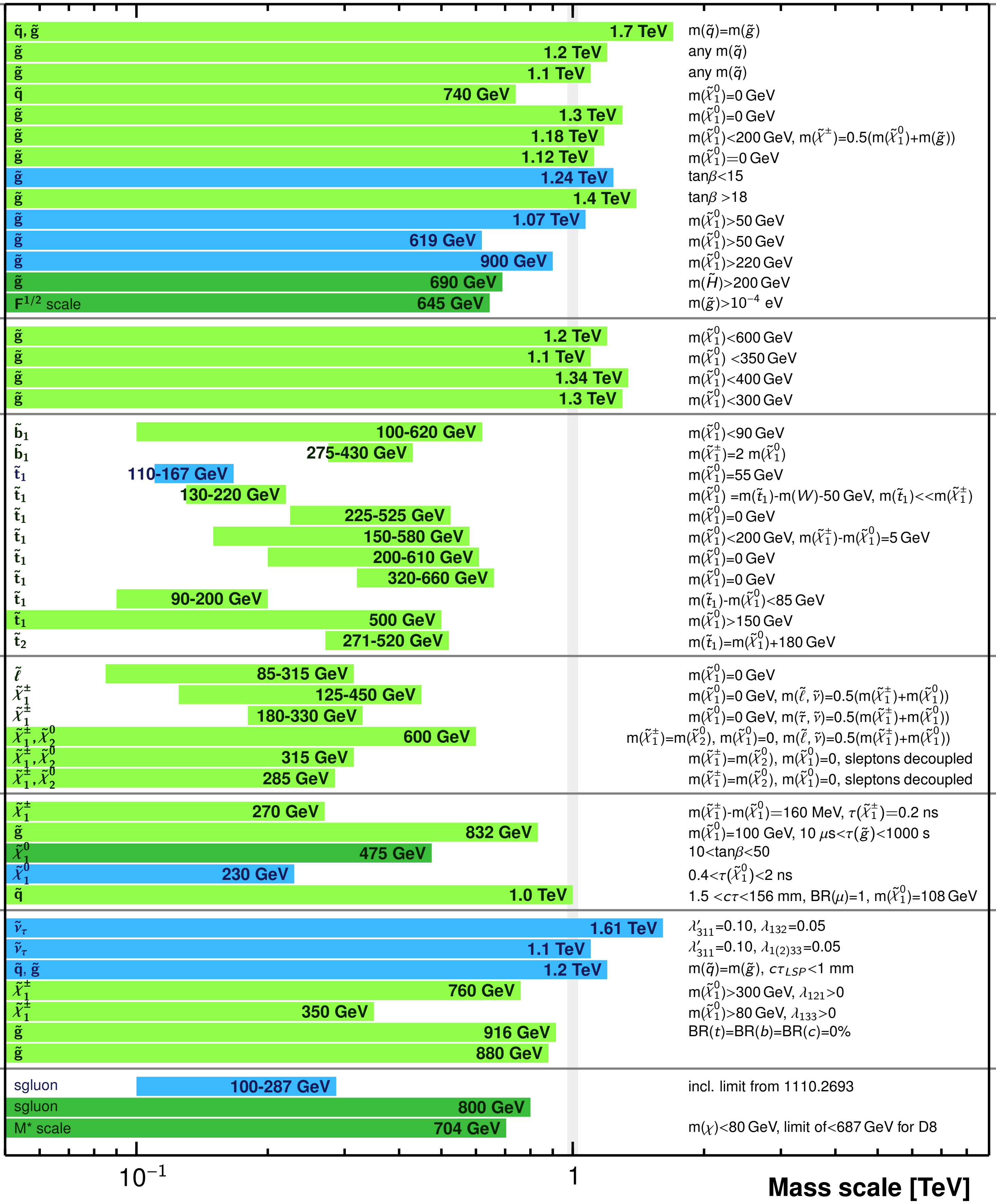
The decay chains depend on mass orderings

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

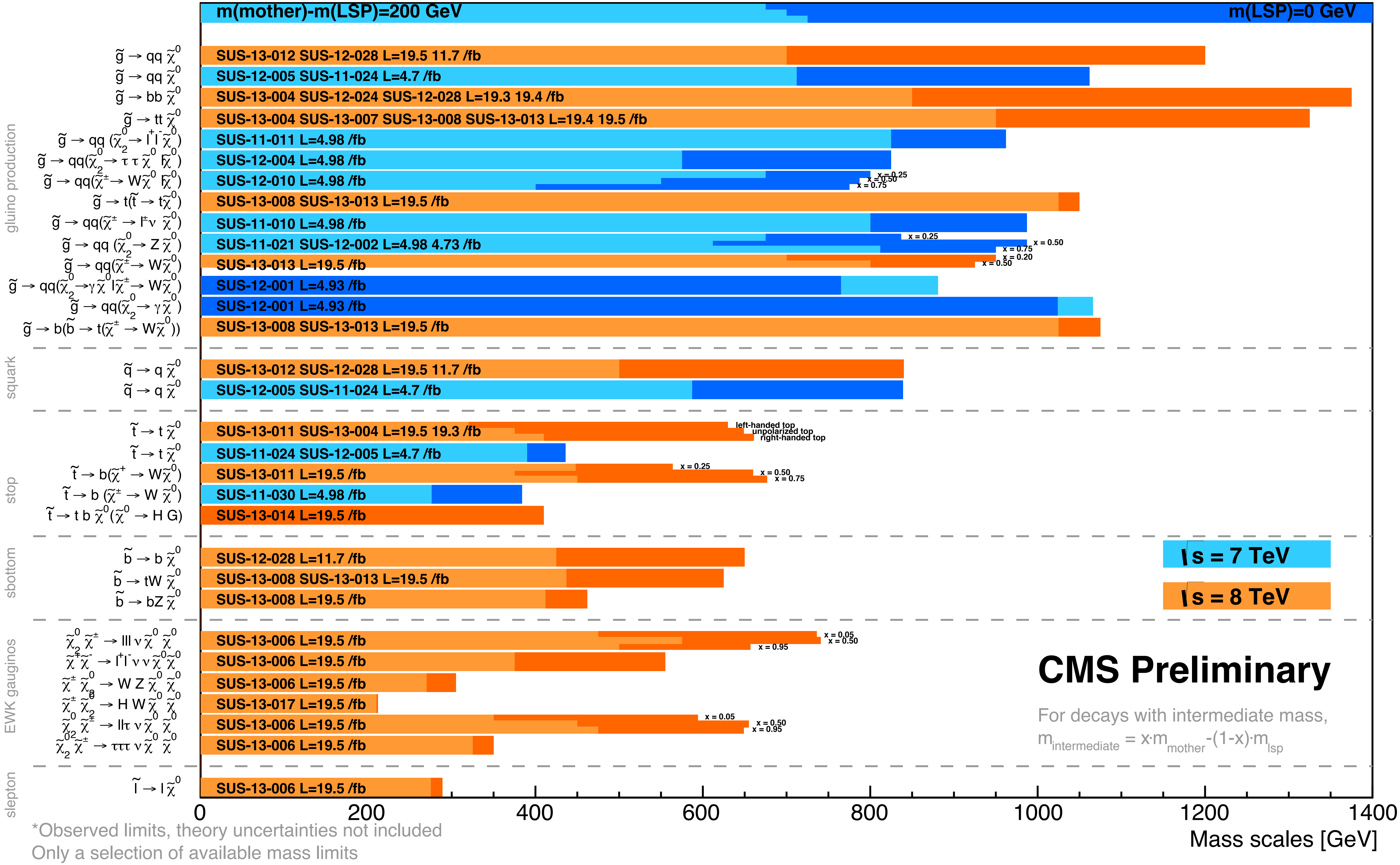


	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^\pm\rightarrow qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta<15$	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta >18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\rightarrow\tilde{t}_1 t, \tilde{t}_1\rightarrow bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\rightarrow q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\rightarrow t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data **$\sqrt{s}$ = 8 TeV partial data** **$\sqrt{s}$ = 8 TeV full data**

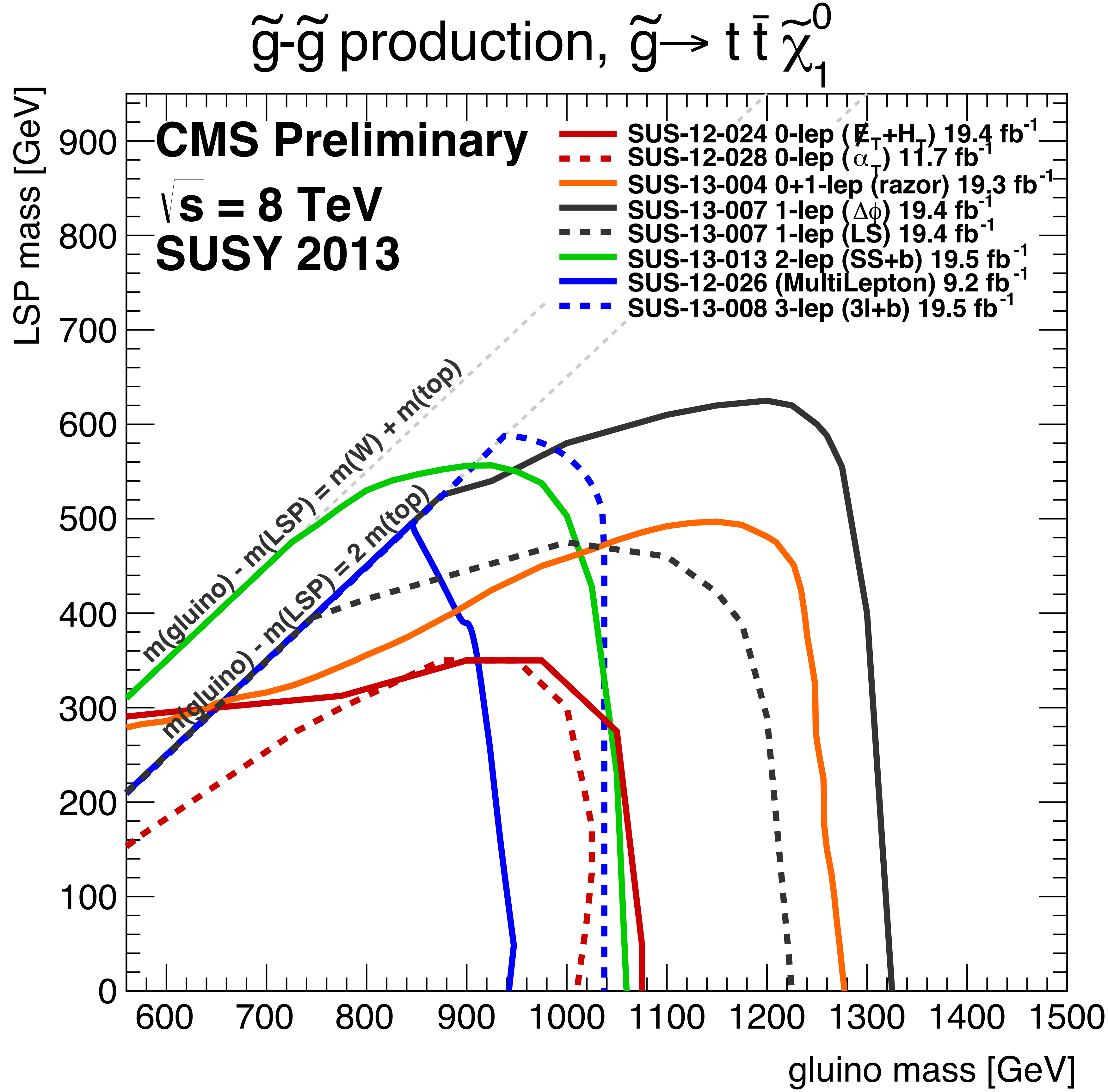
**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

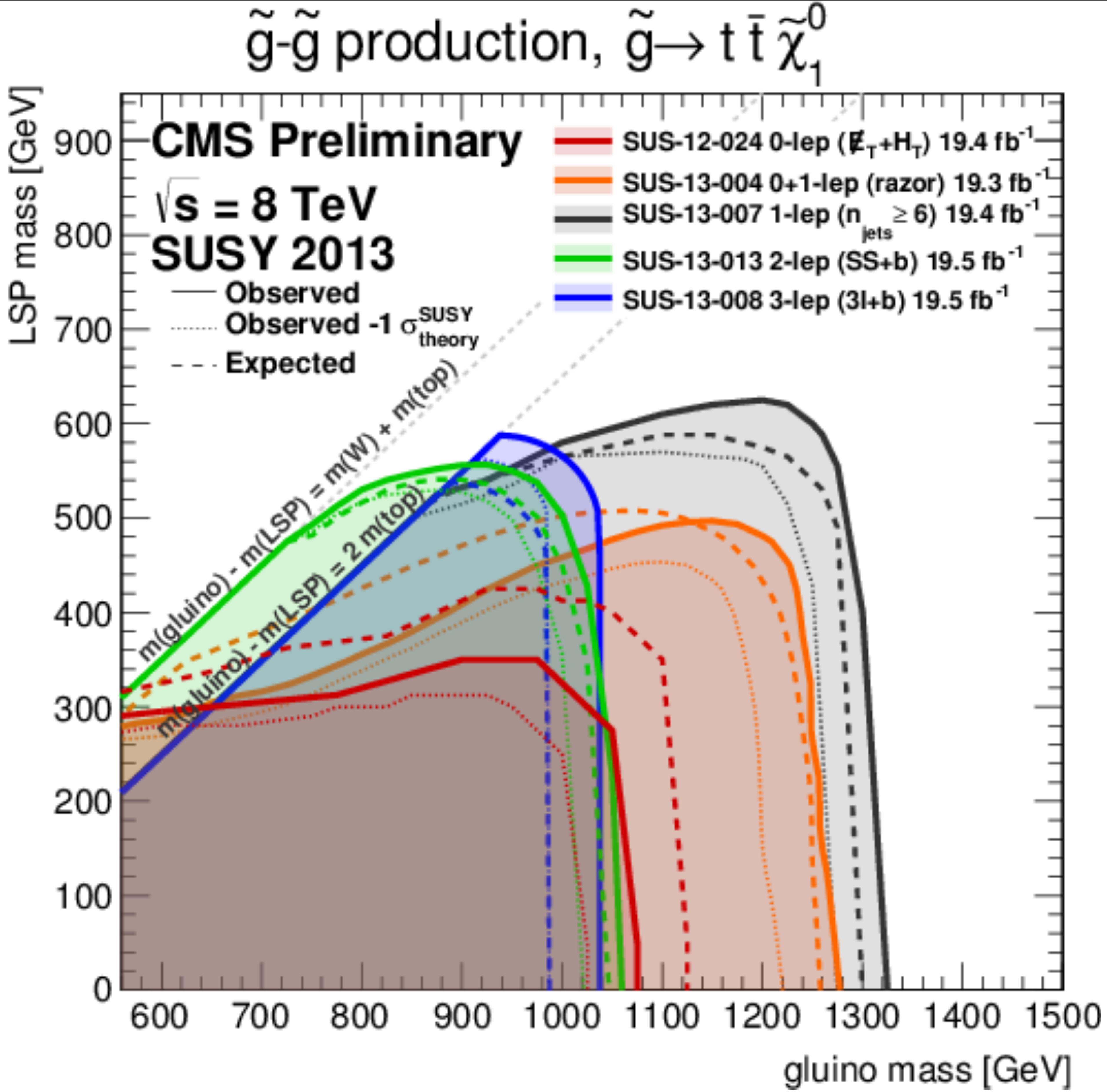
Summary of CMS SUSY Results* in SMS framework SUSY 2013



*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Tuesday, 10 September 13


$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}^0_1$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
SUSY 2013
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-12-028 0-lep (α_T) 11.7 fb^{-1}
SUS-13-004 0+1-lep (razor) 19.3 fb^{-1}
SUS-13-007 1-lep ($\Delta\phi$) 19.4 fb^{-1}
SUS-13-007 1-lep (LS) 19.4 fb^{-1}
SUS-13-013 2-lep (SS+b) 19.5 fb^{-1}
SUS-12-026 (MultiLepton) 9.2 fb^{-1}
SUS-13-008 3-lep (3l+b) 19.5 fb^{-1}
m(gluino) - m(LSP) = m(W) + m(top)
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
0
100
200
300
400
500
600
700
800
900
600
700
800
900
1000
1100
1200
1300
1400
1500
gluino mass [GeV]


g̃-g̃ production, g̃→ t t̄ χ̃$_1^0$
CMS Preliminary
√s = 8 TeV
SUSY 2013
Observed
Observed -1 σ$^{SUSY}_{theory}$
Expected
SUS-12-024 0-lep (E̸$_T$+H$_T$) 19.4 fb^{-1}
SUS-13-004 0+1-lep (razor) 19.3 fb^{-1}
SUS-13-007 1-lep (n$_{jets}$ ≥ 6) 19.4 fb^{-1}
SUS-13-013 2-lep (SS+b) 19.5 fb^{-1}
SUS-13-008 3-lep (3l+b) 19.5 fb^{-1}
m(gluino) - m(LSP) = m(W) + m(top)
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
0
100
200
300
400
500
600
700
800
900
600
700
800
900
1000
1100
1200
1300
1400
1500
gluino mass [GeV]

Summary

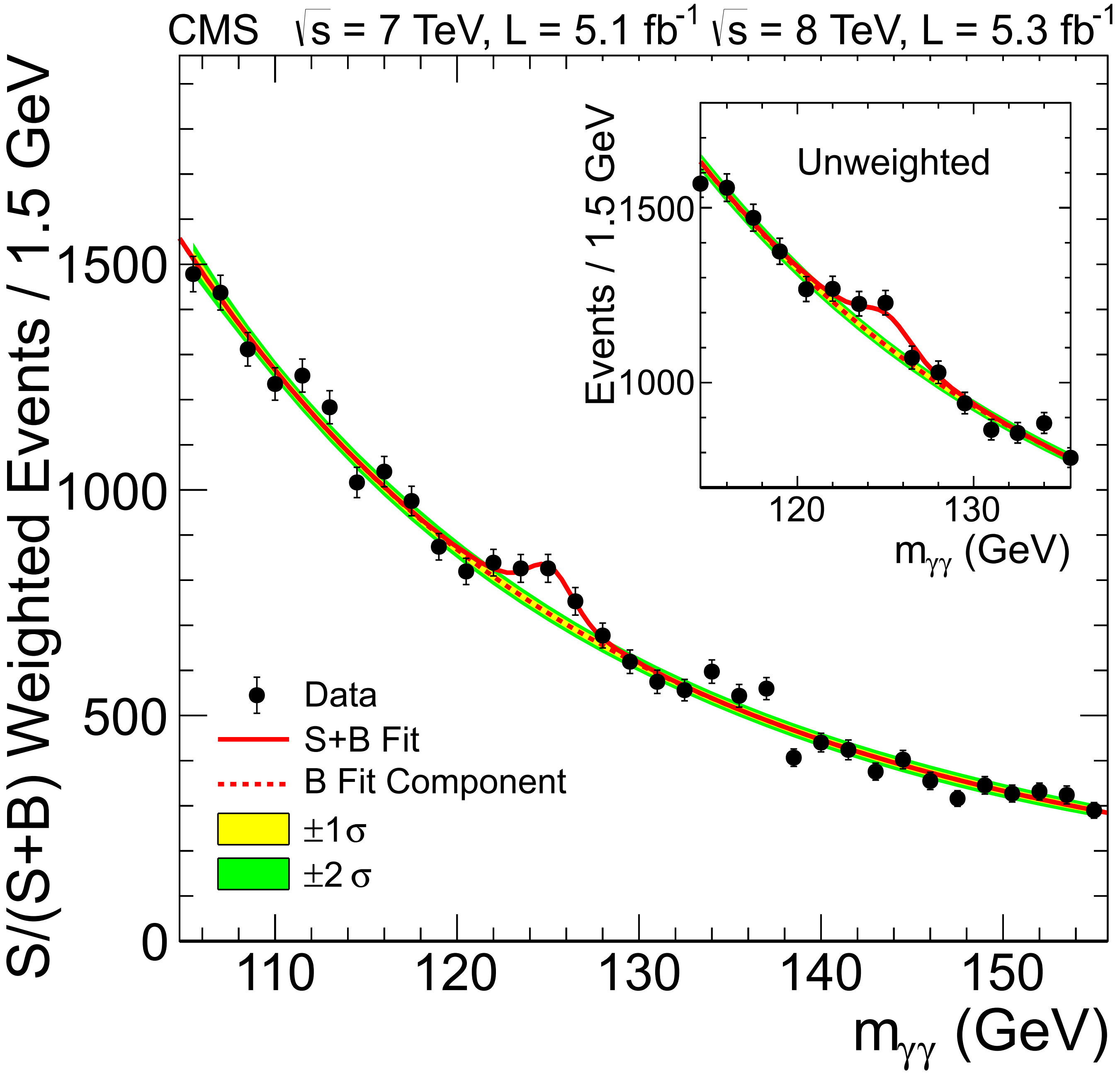
Gluinos are ruled out up to masses 1- 1.25 TeV

Stops and sbottoms are ruled out up to masses 300-600 GeV

First two generations should be greater than 800 GeV -1.25 TeV

(especially if degenerate with the gluino mass)

The Higgs bump at LHC



Speed breakers to Zero Stop mixing ??

Tree Level Mass

M. Guchait' talk

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

$$Y_{H_u} = +1 \qquad Y_{H_d} = -1$$

$$V_H = (|\mu|^2 + m_{H_d}^2)|H_d|^2 + (|\mu|^2 + m_{H_u}^2)|H_u|^2 - B_\mu \epsilon_{ij}(H_u^i H_d^j + \text{c.c.}) + \frac{g_2^2 + g_1^2}{8}(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2} g_2^2 |H_d^\dagger H_u|^2$$

$$V_H = (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) + (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) - [B_\mu(H_d^- H_u^+ - H_d^0 H_u^0) + \text{c.c.}] + \frac{g_2^2 + g_1^2}{8}(|H_d^0|^2 + |H_d^-|^2 - |H_u^0|^2 - |H_u^+|^2)^2 + \frac{g_2^2}{2}|H_d^{-*} H_u^0 + H_d^{0*} H_u^+|^2$$

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

$$B_\mu = \frac{1}{2}\left[\left(m_{H_d}^2 - m_{H_u}^2\right)\tan 2\beta + M_Z^2 \sin 2\beta\right]$$

where $\tan\beta = \frac{v_2}{v_1}$ and $v_1^2 + v_2^2 = v^2 = (246\ \mathrm{GeV})^2$

A type II two higgs doublet model with gauge couplings for quartics !!

$$\langle H_u^0 \rangle = \frac{v_2}{\sqrt{2}} \qquad \langle H_d^0 \rangle = \frac{v_1}{\sqrt{2}} \qquad \frac{\partial V_H}{\partial H_u^0} = \frac{\partial V_H}{\partial H_d^0} = 0$$

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

$$B_\mu = \frac{1}{2}\left[\left(m_{H_d}^2 - m_{H_u}^2\right)\tan 2\beta + M_Z^2 \sin 2\beta\right]$$

where $\tan\beta = \frac{v_2}{v_1}$ and $v_1^2 + v_2^2 = v^2 = (246\ \text{GeV})^2$

A type II two higgs doublet model with gauge couplings for quartics !!

$$M_A^2 = \frac{2B_\mu}{\sin 2\beta} \qquad M_{H^\pm}^2 = M_A^2 + M_W^2$$

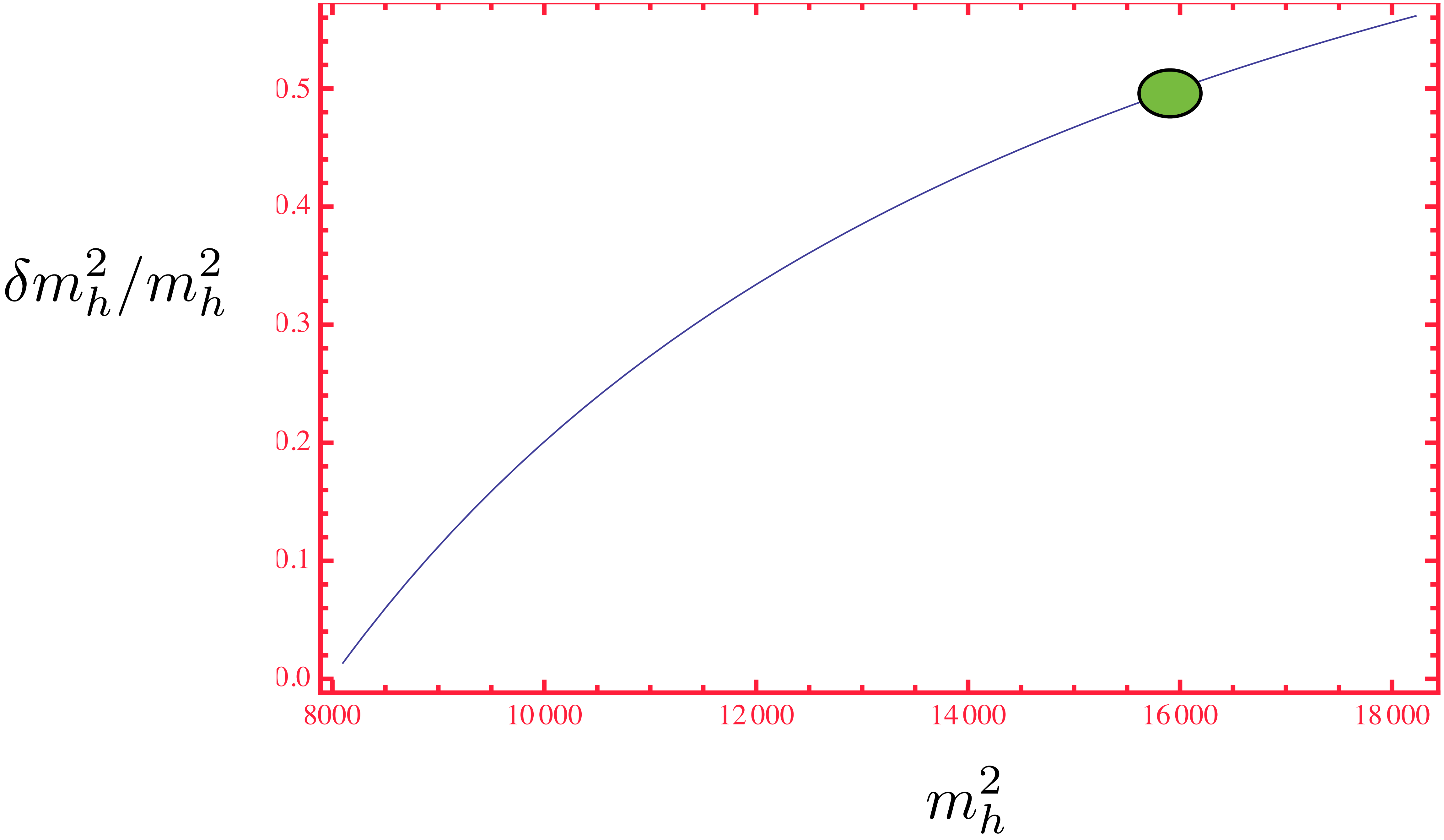
$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\tan 2\beta \qquad -\frac{\pi}{2} < \alpha < 0$$

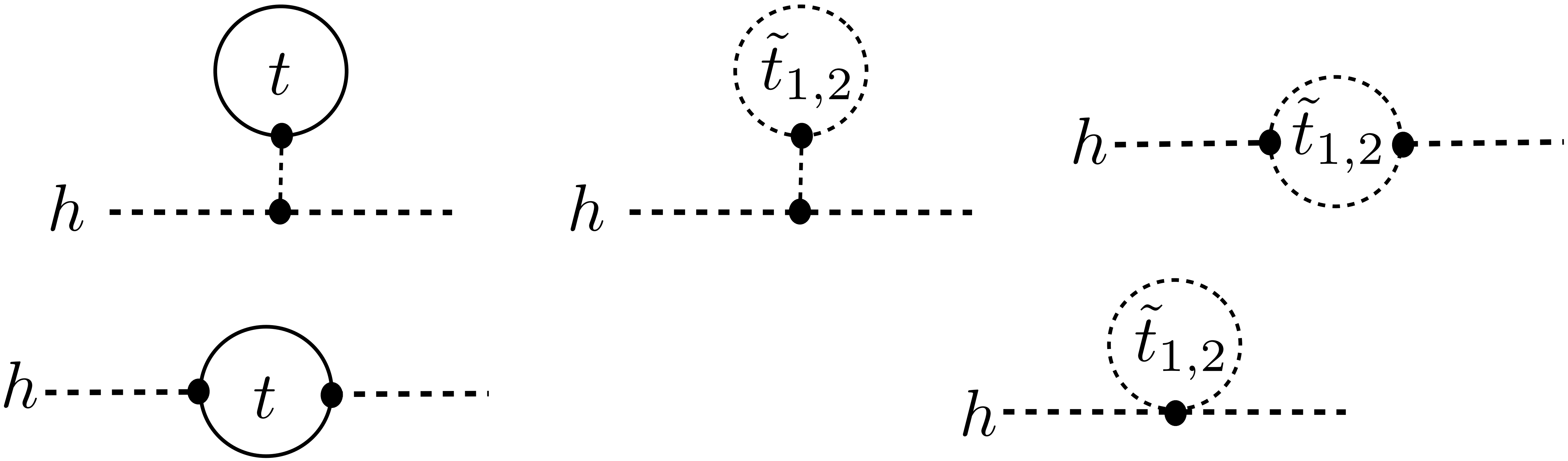
at tree level the lightest Higgs mass upper limit is

$$M_h \leq M_Z |\cos 2\beta| \leq M_Z$$

About 50% of the light higgs mass comes from loop contributions



Lightest Higgs mass @ 1-loop (top-stop enhanced)



in the limit of
no-mixing

$$\Delta m_h^2 = \frac{3g_2^2}{8\pi^2 M_W^2} m_t^4 \log\left(\frac{M_S^2}{m_t^2}\right)$$

$$M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

in the case of non-zero mixing the correction is (but small)

$$\Delta m_h^2 \simeq \frac{3g_2^2 m_t^4}{8\pi^2 M_W^2}\left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$$

where $X_t = A_t - \mu \cot\beta$

$$M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Haber, Hempfling and Hoang,9609331

1-loop correction adds ~20 GeV to the tree-level, assuming the sparticles are < 1 TeV (in no-mixing scenario).

Effective potential methods are more useful

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2\sin^2\beta \end{pmatrix}$$

$$\Bigg\downarrow \quad \text{diagonalizing}$$

$$\begin{pmatrix} m^2_{H,tree} & 0 \\ 0 & m^2_{h,tree} \end{pmatrix}$$

$$M^{2,\text{corr}}_{\text{Higgs}} = M^{2,\text{tree}}_{\text{Higgs}} - \begin{pmatrix} \Pi_{\phi_1} & \Pi_{\phi_1\phi_2} \\ \Pi_{\phi_1\phi_2} & \Pi_{\phi_2} \end{pmatrix} \qquad \Pi_{\phi_i} = \text{self energy of } \phi_{\text{i}}$$

One loop terms +
dominant 2-loop contribution due to top-stop loops

$$\Pi_{\phi_1}^{(2-\text{loop})}(0) = 0 \qquad \Pi_{\phi_1\phi_2}^{(2-\text{loop})}(0) = 0$$

$$\Pi_{\phi_2}^{(2-\text{loop})}(0) = \frac{G_F\sqrt{2}}{\pi^2}\frac{\alpha_s}{\pi}\frac{\bar{m}_t^4}{\sin^2\beta}\left[4 + 3\log^2\left(\frac{\bar{m}_t^4}{M_S^4}\right) + 2\log\left(\frac{\bar{m}_t^4}{M_S^4}\right) - 6\frac{X_t}{M_S} - \frac{X_t^2}{M_S^2}\left\{3\log\left(\frac{\bar{m}_t^2}{M_S^2}\right) + 8\right\} + \frac{17}{12}\frac{X_t^4}{M_S^4}\right]$$

$$\bar{m}_t = \bar{m}_t(m_t) \approx \frac{m_t^{\text{pole}}}{1 + \frac{4}{3\pi}\alpha_s(m_t)} \qquad +\mathcal{O}(G_F^2 m_t^6)$$

Heinemeyer et.al, 9812472

dominant 2-loop correction increases the lightest Higgs mass <10 GeV to the tree-level, assuming the sparticles are < 1 TeV (in no-mixing scenario).

3-loop correction

calculated up to $\mathcal{O}(\alpha_t \alpha_s^2)$

keeping only the leading terms $\sim m_t^4$

no mixing in the stop sector $\Rightarrow X_t = 0$

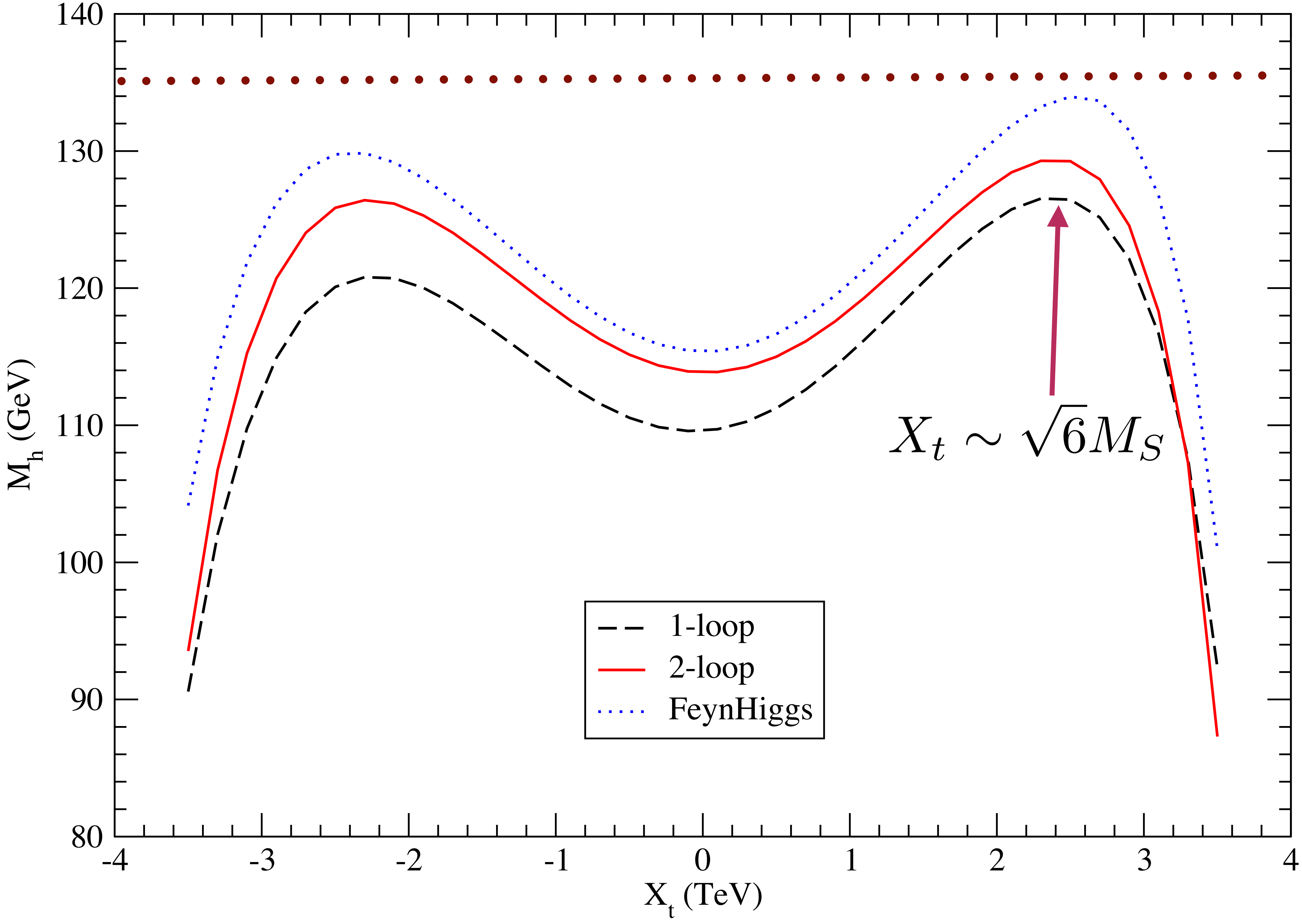
Harlander et al. ‘08
Martin ‘07

$$\Delta m_h^{3-\mathrm{loop}} \approx 500 \text{ MeV}$$

Most Publicly available spectrum generators calculate the CP-even Higgs spectrum at the 2-loop order.

$\tan\beta = 10, M_A = M_S = 1$ TeV

phenomenological models

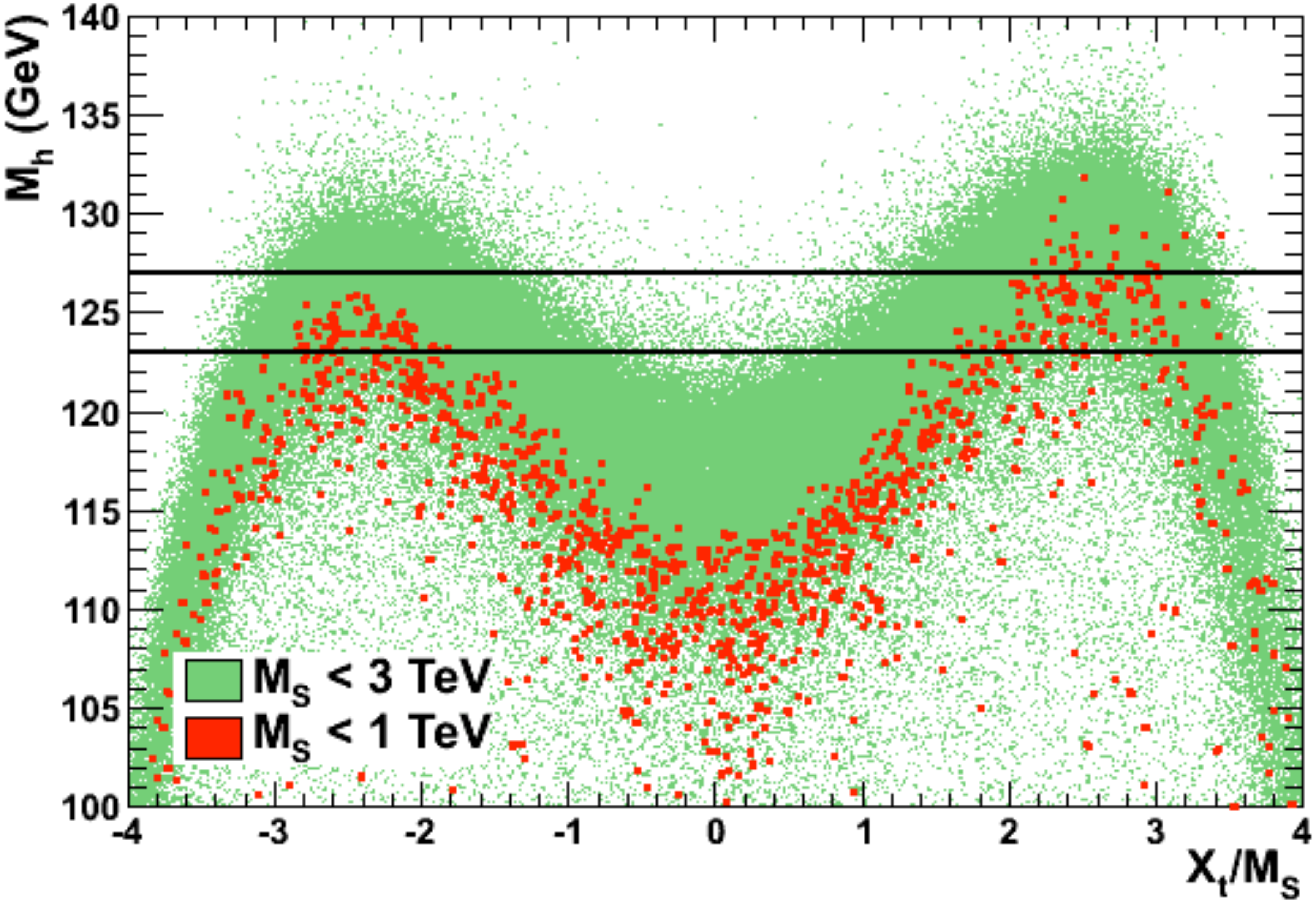


Very close to the upper bound in MSSM

Allanach et al. ’04

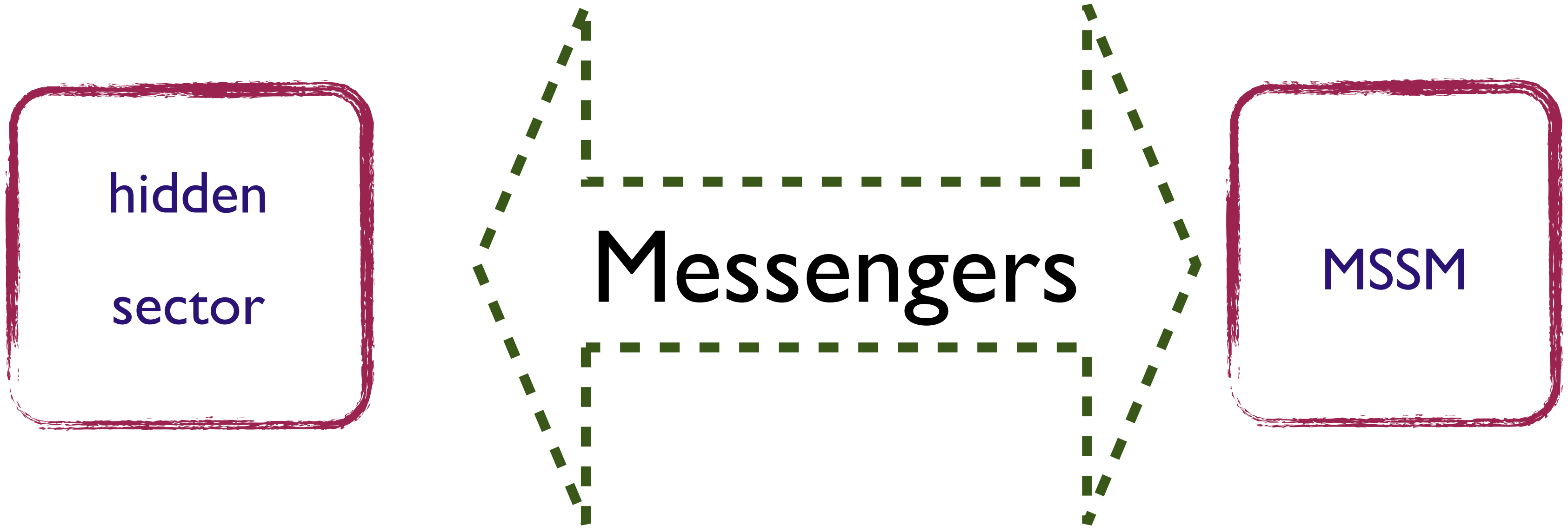
phenomenological models

Abrey et al.
1112.3028;
2012 updates



For zero mixing, we need multi TeV Stops !!!

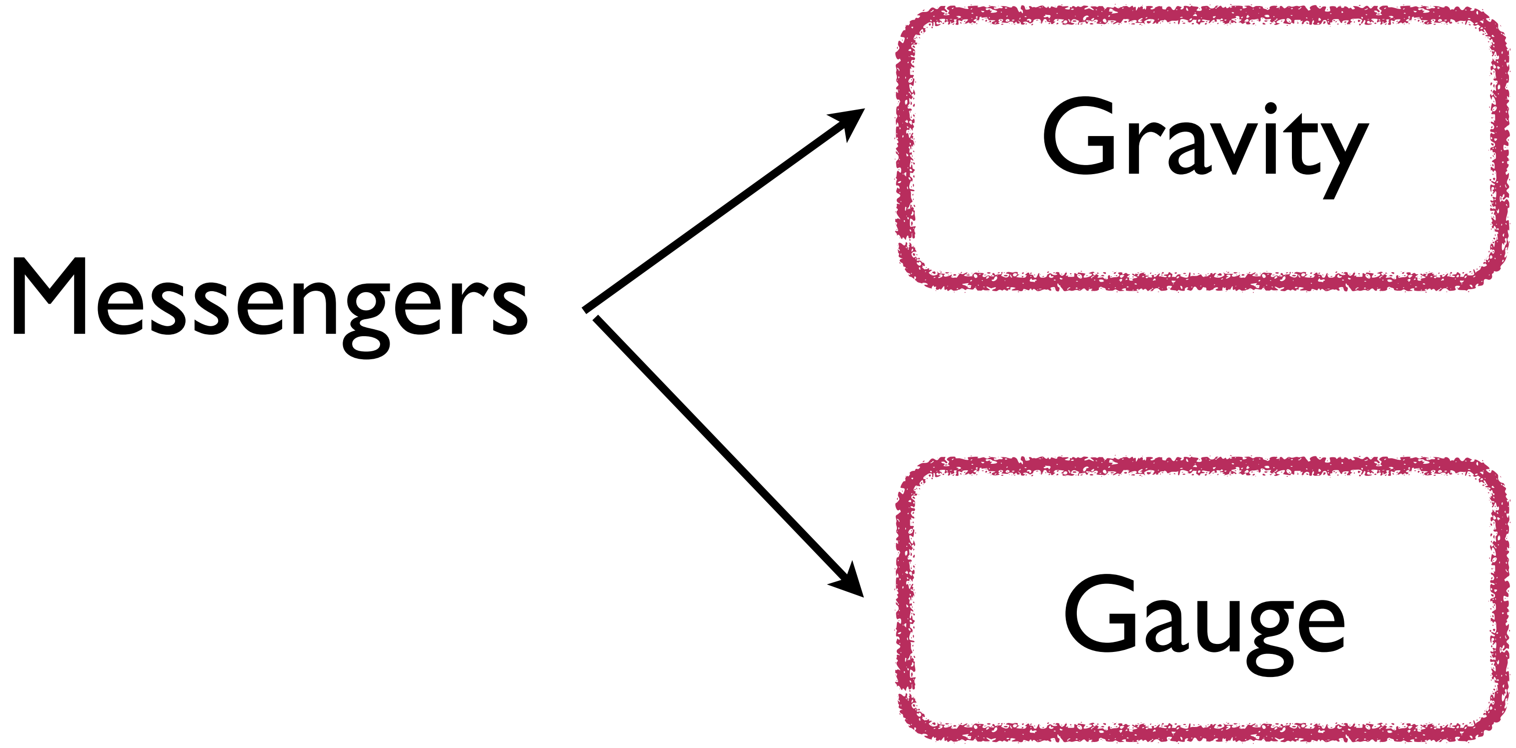
Other option is to have maximal mixing : $|X_t| \sim \sqrt{6} M_S$



hidden sector

Messengers

MSSM



Messengers

Gravity

Gauge

Hidden and Visible sector fields need not be at the same space time points

(non-traditional models)

Some traditional Models

Constrained Models

minimal Supergravity

$$K = X_i^{\dagger} X_i + \Phi_i^{\dagger} \Phi_i + \cdots\cdots$$

$$W = W_{\text{hidden}} + W_{\text{MSSM}}$$

$$G = K + \ln |W|^2$$

$$V = e^{G} \left(G_i G^i - 3 \right)$$

$$G_i = \frac{\partial G}{\partial \Phi_i}$$

Model with only five parameters ; possible in minimal Supergravity

* As long as Kahler potential is in Canonical form:

$m_{\tilde{f}}^2 = m_0^2$

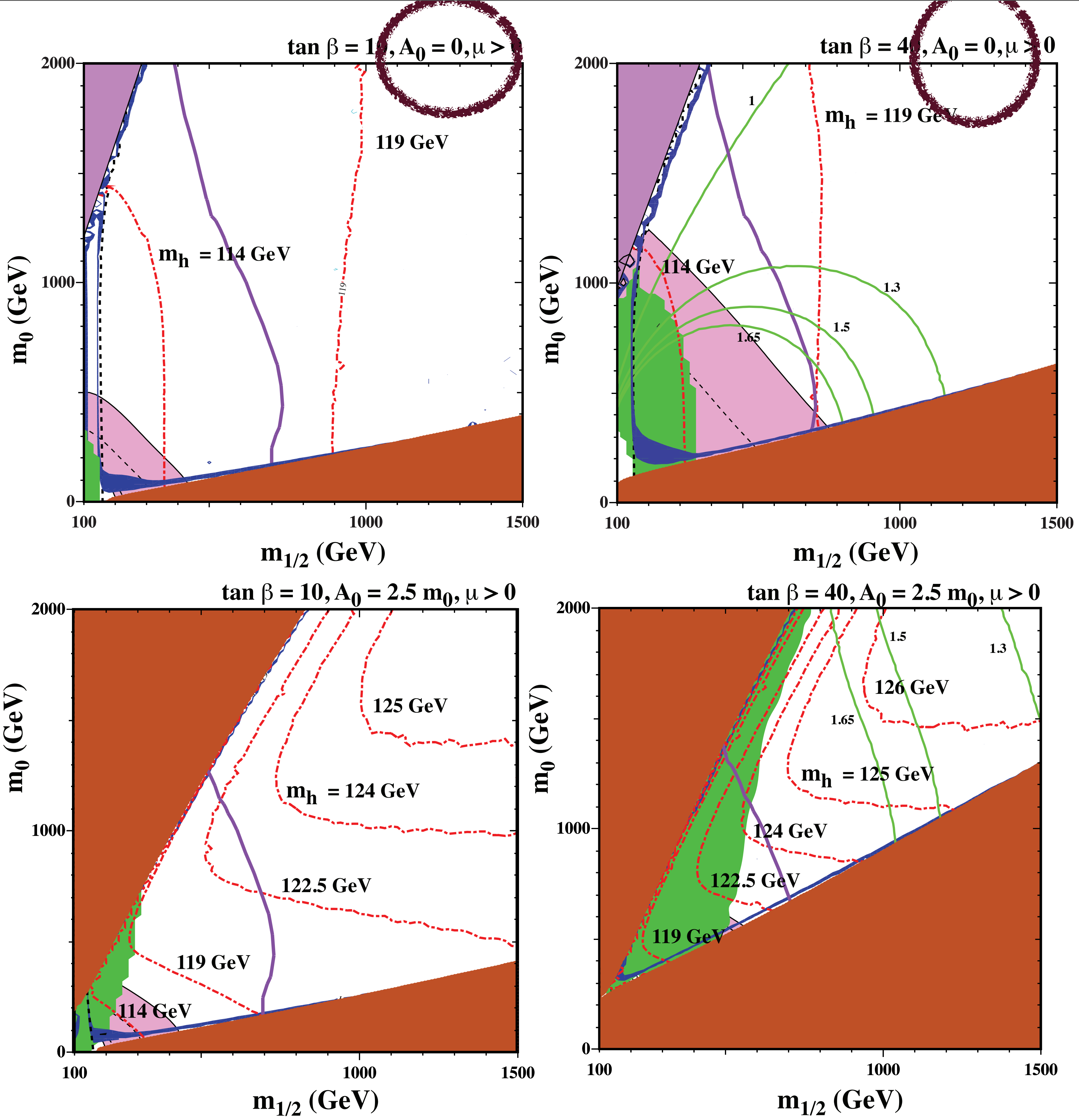
$M_i = M_{1/2}$

$A_{ijk} = A_0$

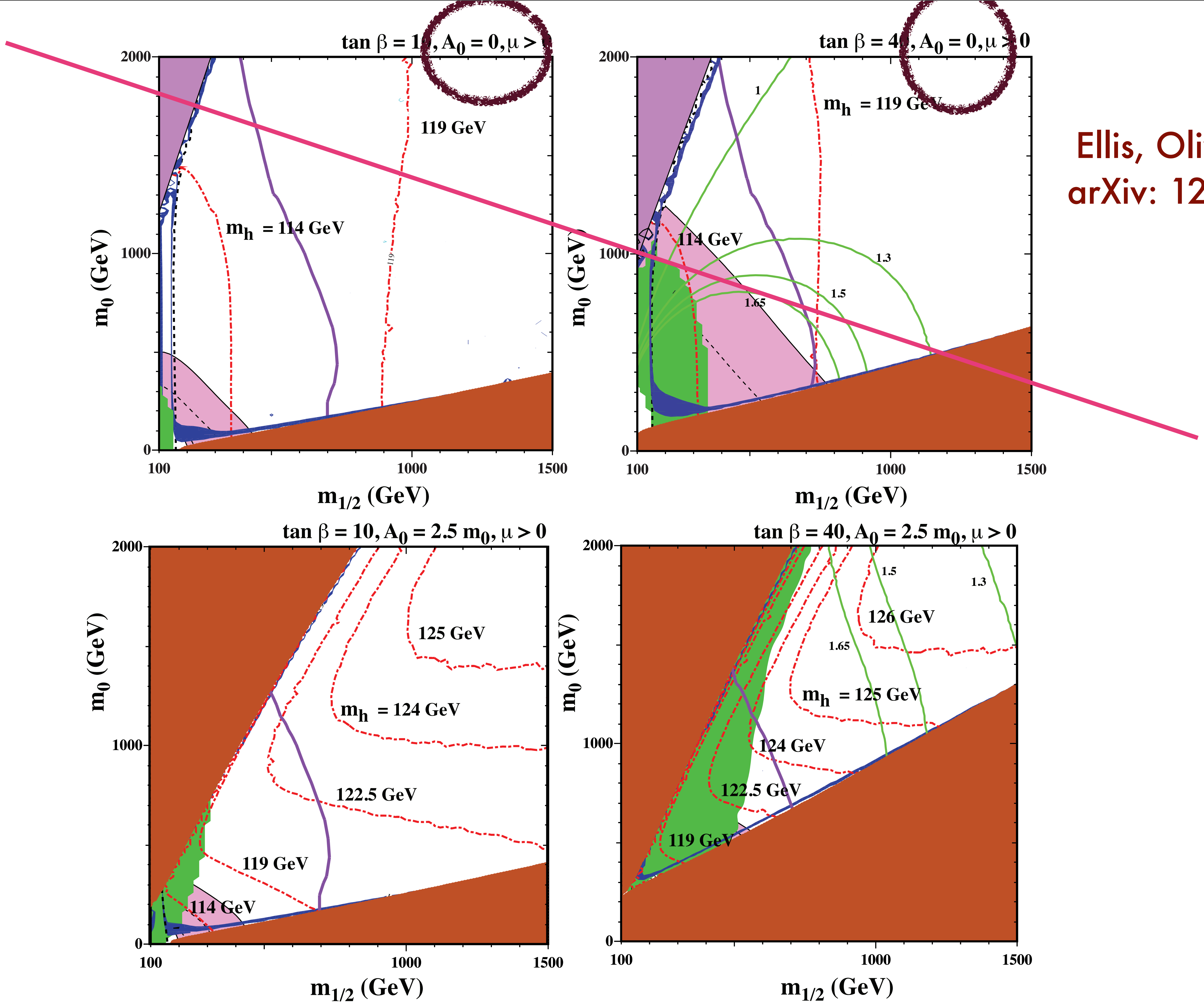
$B_{ij} = B$

A small set of parameters describing the entire supersymmetric spectrum at weak scale

Renormalisable theory after integrating out the gravity Multiplet ($M_{pl} \to \infty$; $m_{3/2}$ fixed)



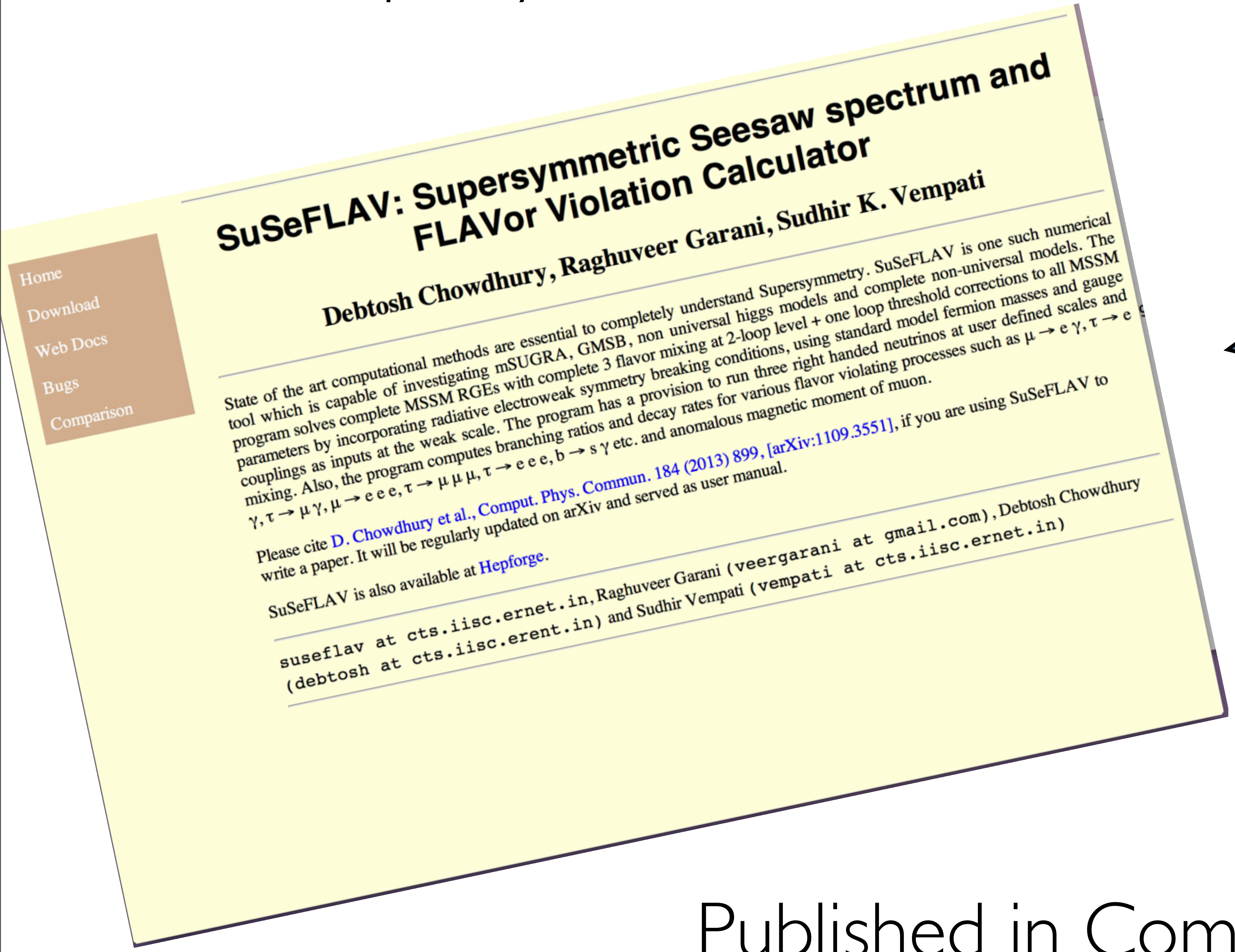
Ellis, Olive et.al,
arXiv: 1212.4476



Ellis, Olive et.al,
arXiv: 1212.4476

SuSeFLAV

SUpersymmetric SEesaw and Flavour Violation



SuSeFLAV: Supersymmetric Seesaw spectrum and FLAVor Violation Calculator

Debtosh Chowdhury, Raghuveer Garani, Sudhir K. Vempati

State of the art computational methods are essential to completely understand Supersymmetry. SuSeFLAV is one such numerical tool which is capable of investigating mSUGRA, GMSB, non universal higgs models and complete non-universal models. The program solves complete MSSM RGEs with complete 3 flavor mixing at 2-loop level + one loop threshold corrections to all MSSM parameters by incorporating radiative electroweak symmetry breaking conditions, using standard model fermion masses and gauge couplings as inputs at the weak scale. The program has a provision to run three right handed neutrinos at user defined scales and mixing. Also, the program computes branching ratios and decay rates for various flavor violating processes such as $\mu \to e\gamma$, $\tau \to e$ γ, $\tau \to \mu\gamma$, $\mu \to eee$, $\tau \to \mu\mu\mu$, $\tau \to eee$, $b \to s\gamma$ etc. and anomalous magnetic moment of muon.

Please cite D. Chowdhury et al., Comput. Phys. Commun. 184 (2013) 899, [arXiv:1109.3551], if you are using SuSeFLAV to write a paper. It will be regularly updated on arXiv and served as user manual.

SuSeFLAV is also available at Hepforge.

`suseflav at cts.iisc.ernet.in`, Raghuveer Garani (`veergarani at gmail.com`), Debtosh Chowdhury (`debtosh at cts.iisc.erent.in`) and Sudhir Vempati (`vempati at cts.iisc.ernet.in`)

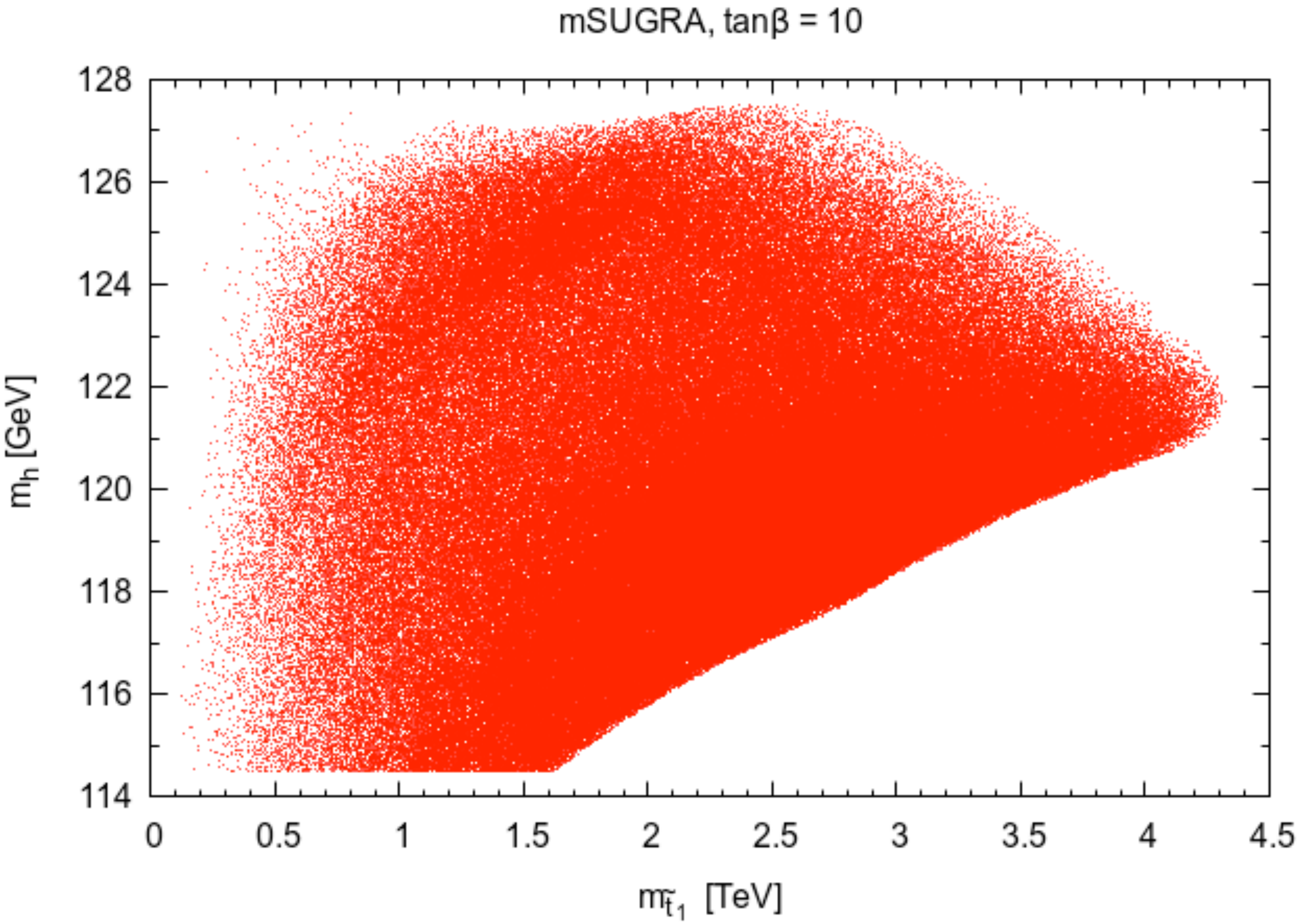
Our Webpage

Published in Computer Physics Communications 184 (2013) 899

Range we chose

$$
\begin{aligned}
m_0 &\in [0,\ 5]\ \text{TeV} \\
\Delta m_H &\in \begin{cases} 0 & \text{for mSUGRA} \\ [0,\ 5] & \text{for NUHM1} \end{cases} \\
m_{1/2} &\in [0.1,\ 2]\ \text{TeV} \\
A_0 &\in [-3m_0,\ +3m_0] \\
\text{sgn}(\mu) &\in \{-,+\}
\end{aligned}
$$

M Raidal et. al arxiv/1112.3647
P. Nath et.al and other groups
Baer et.al arXiv: 1112.3017



D. Chowdhury, S. Vempati, et. al

M Raidal et. al arxiv/1112.3647
P. Nath et.al and other groups
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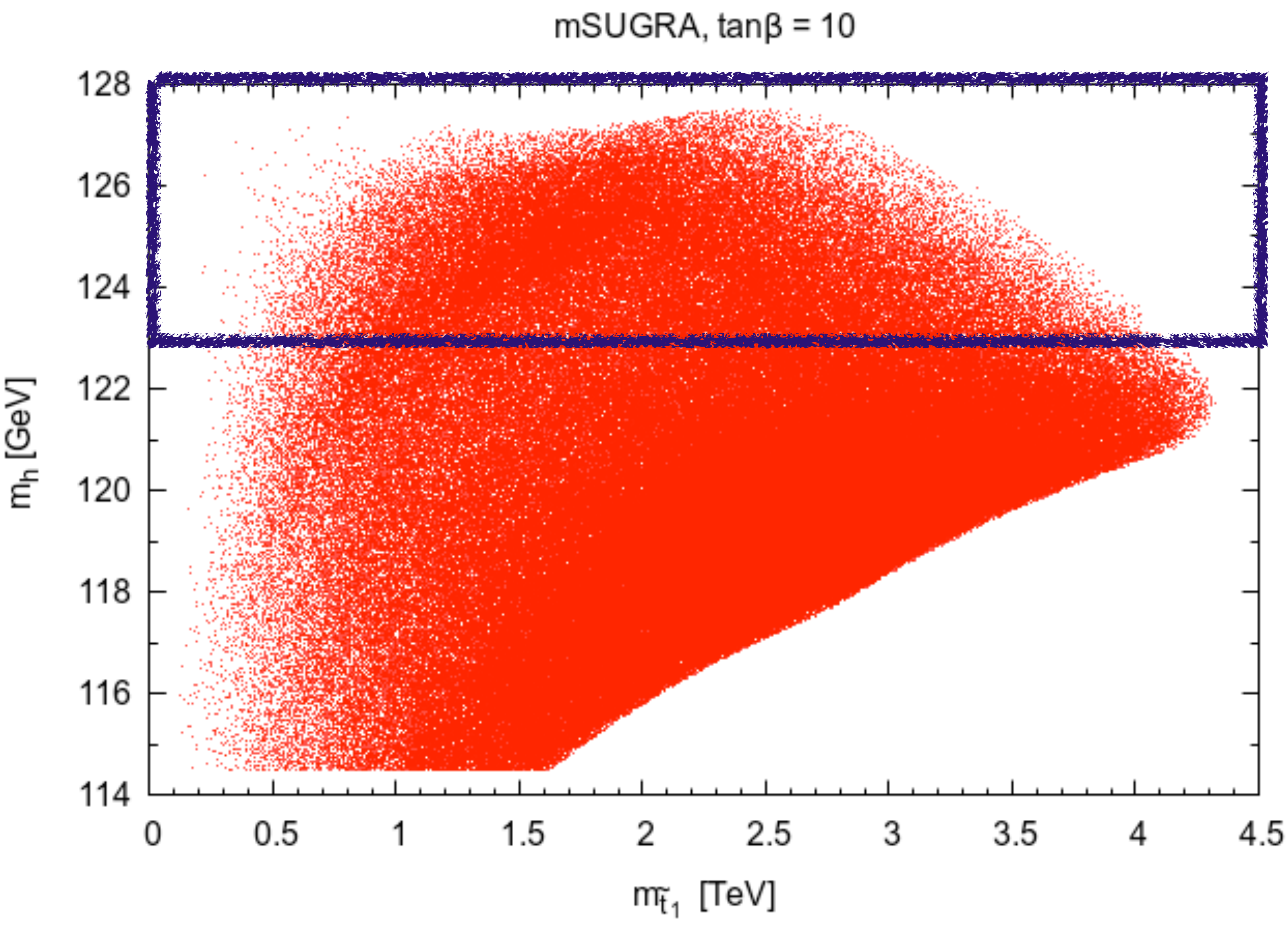
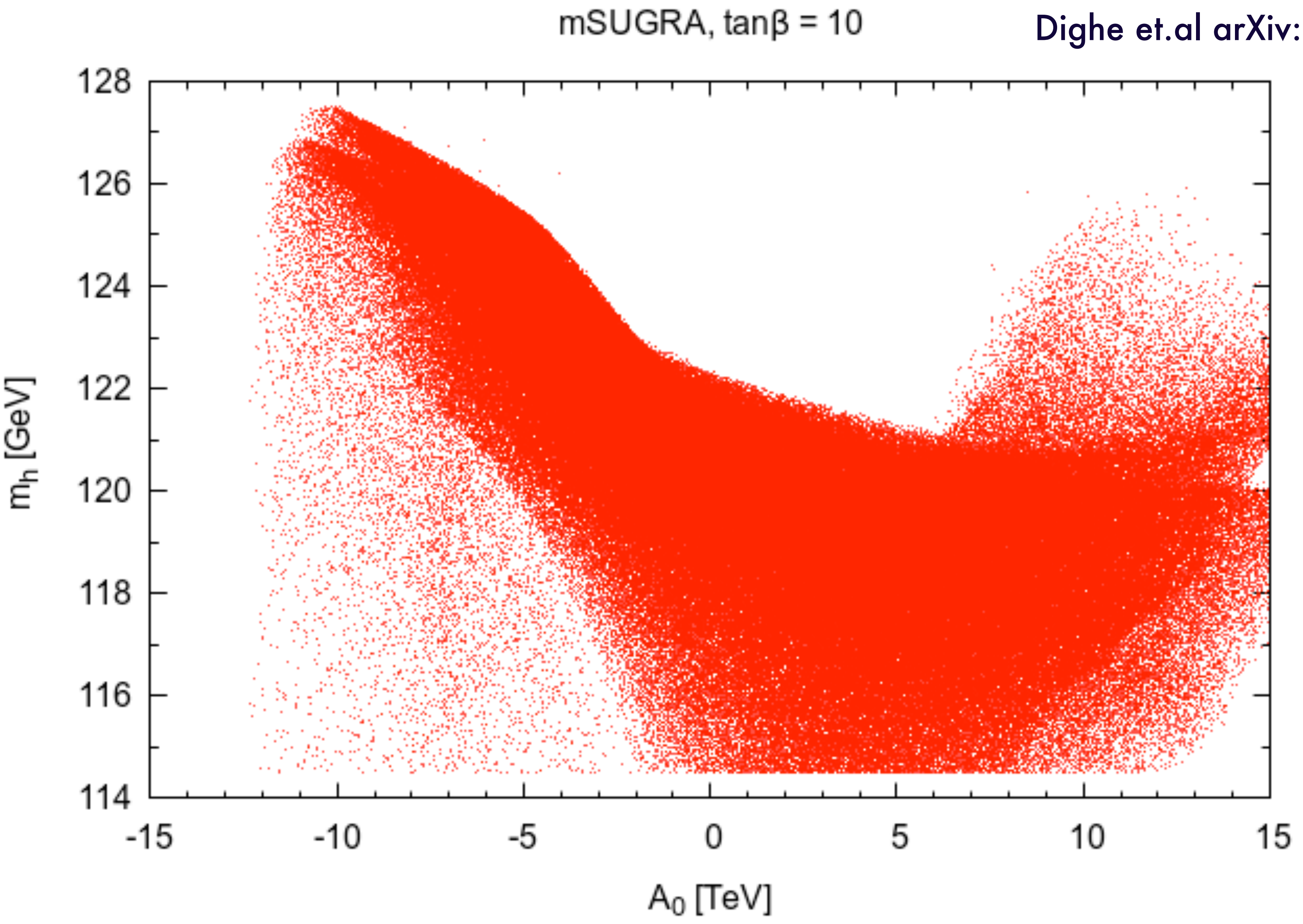


D. Chowdhury, S. Vempati, et. al

M Raidal et. al arxiv/1112.3647
P. Nath et.al and other groups
Baer et.al arXiv: 1112.3017

Dighe et.al arXiv: 1112.3017



D. Chowdhury, S. Vempati, et. al ,

M Raidal et. al arxiv/1112.3647
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Baer et.al arXiv: 1112.3017

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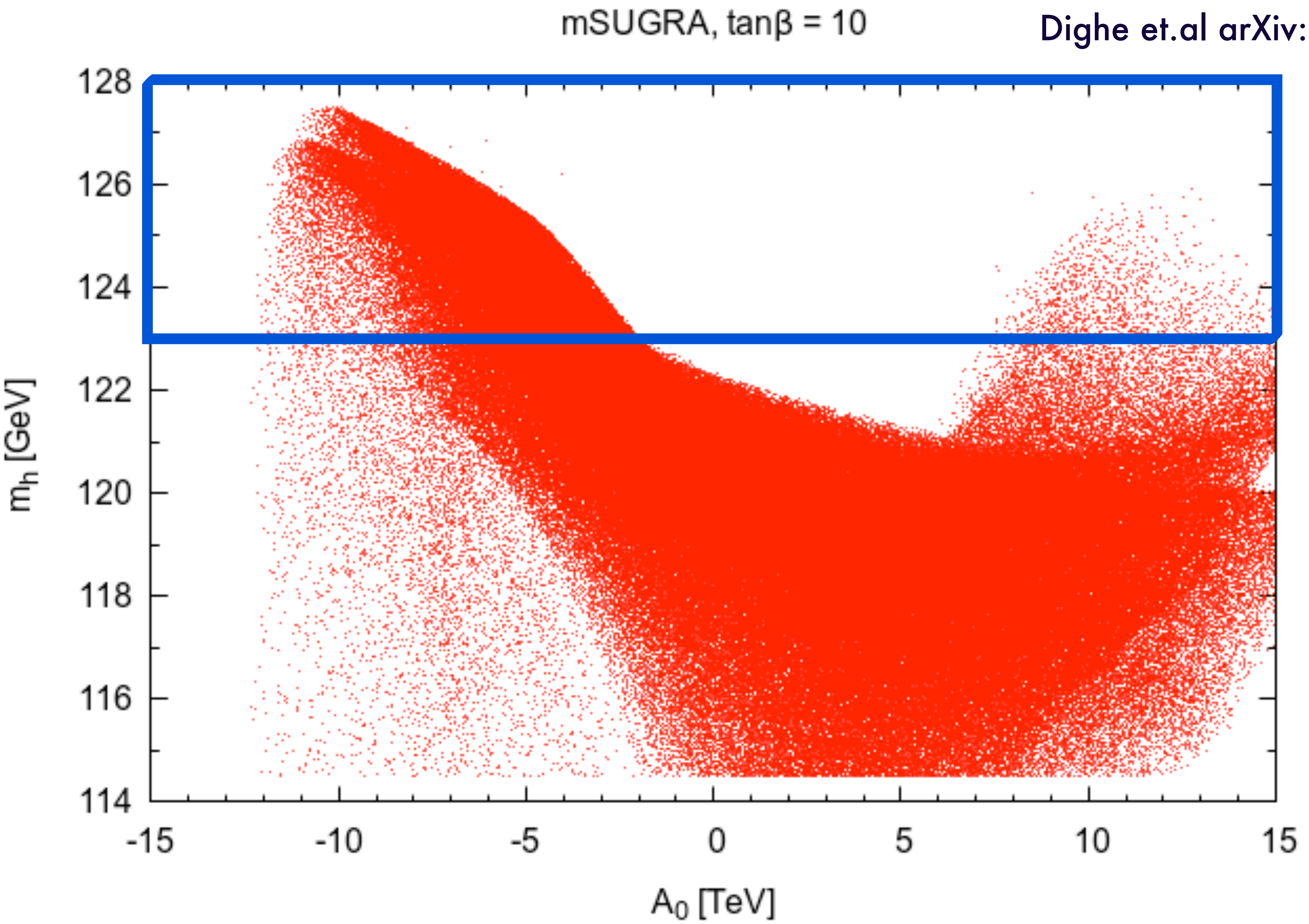


D. Chowdhury, S. Vempati, et. al ,

moving away from CMSSM- I

Non-Universal Higgs Models

Ellis, Olive et.al

$$m^2_{H_u} \neq m^2_{H_d} \neq m^2_0$$

Natural SUSY models

X. Tata et.al

$$(m^2_0)_{1,2} \gg m^2_{0\,3}$$

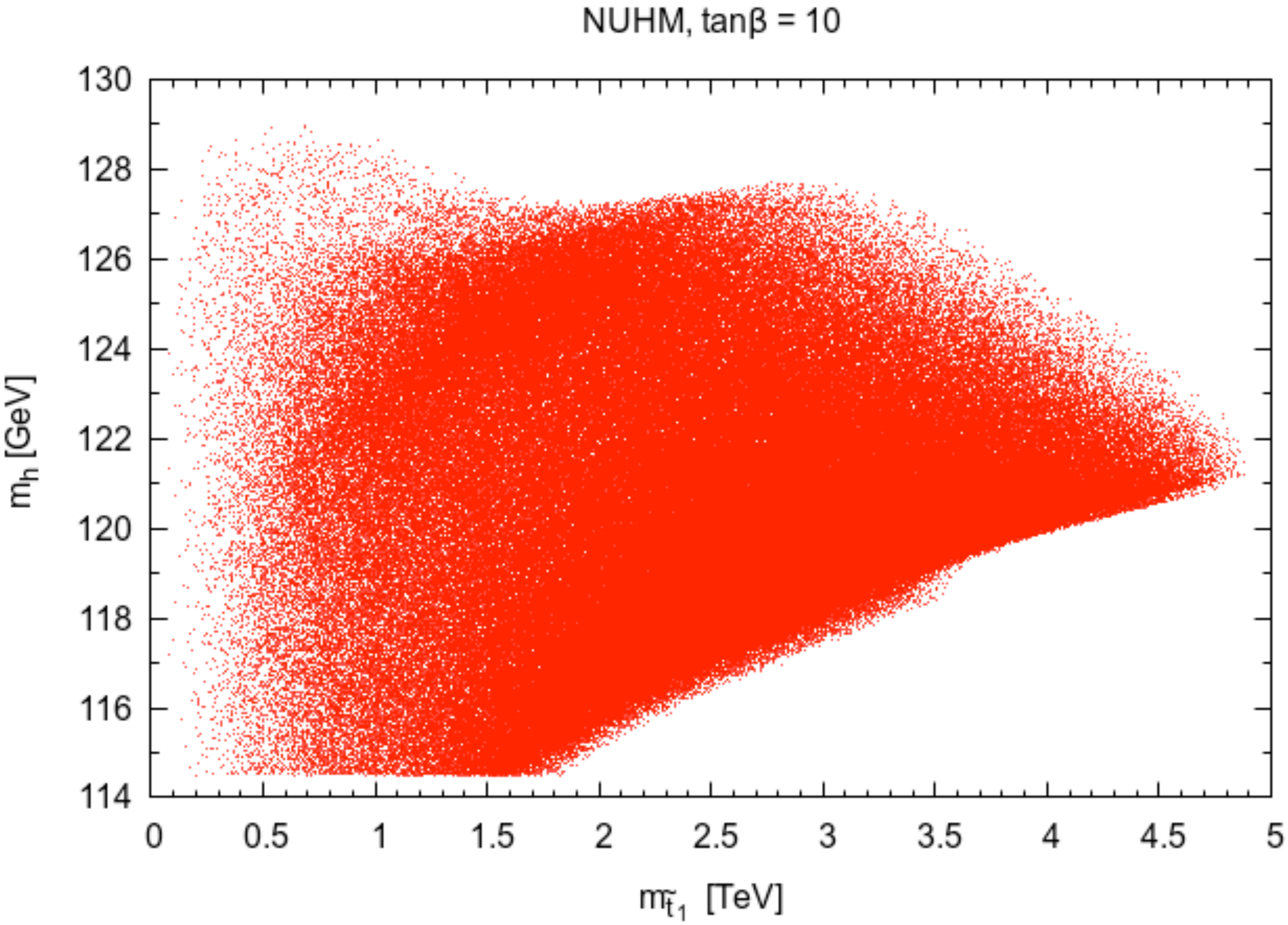
Non-Universal Gaugino models

P. Nath et. al

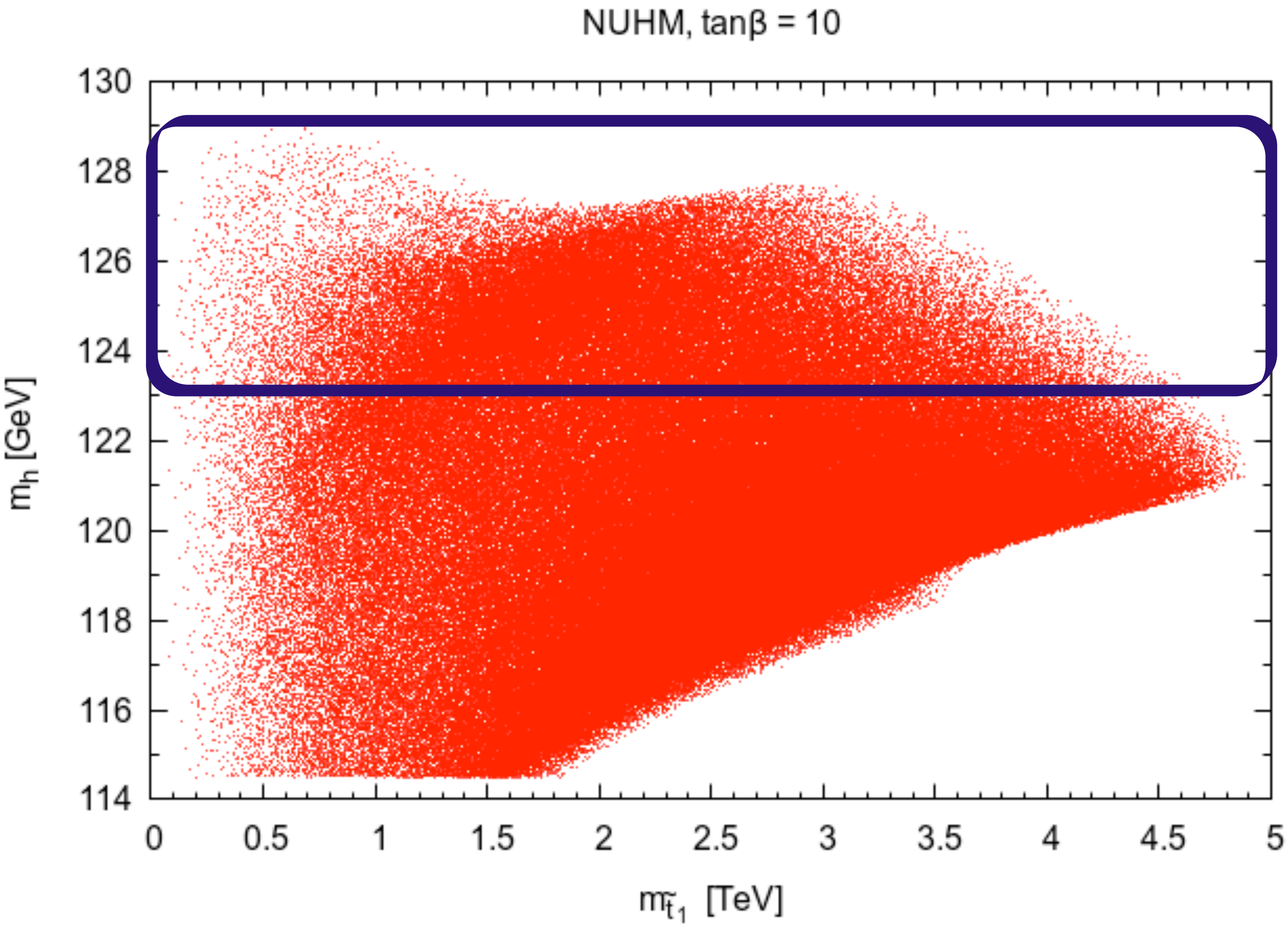
$$M_1 \neq M_2 \neq M_3$$

Non-Universal Scalar Mass models

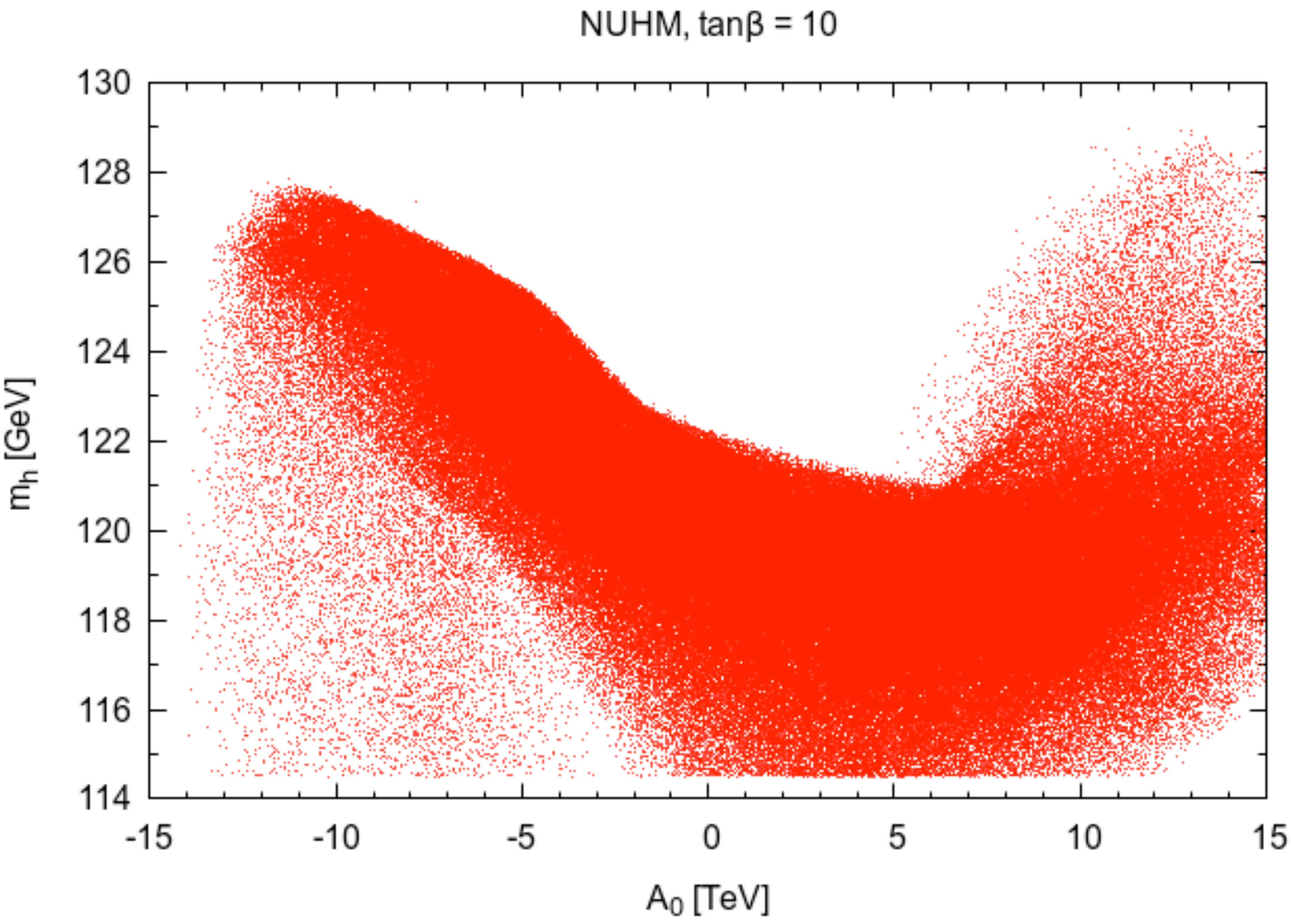
Chattopadhyaya et. al



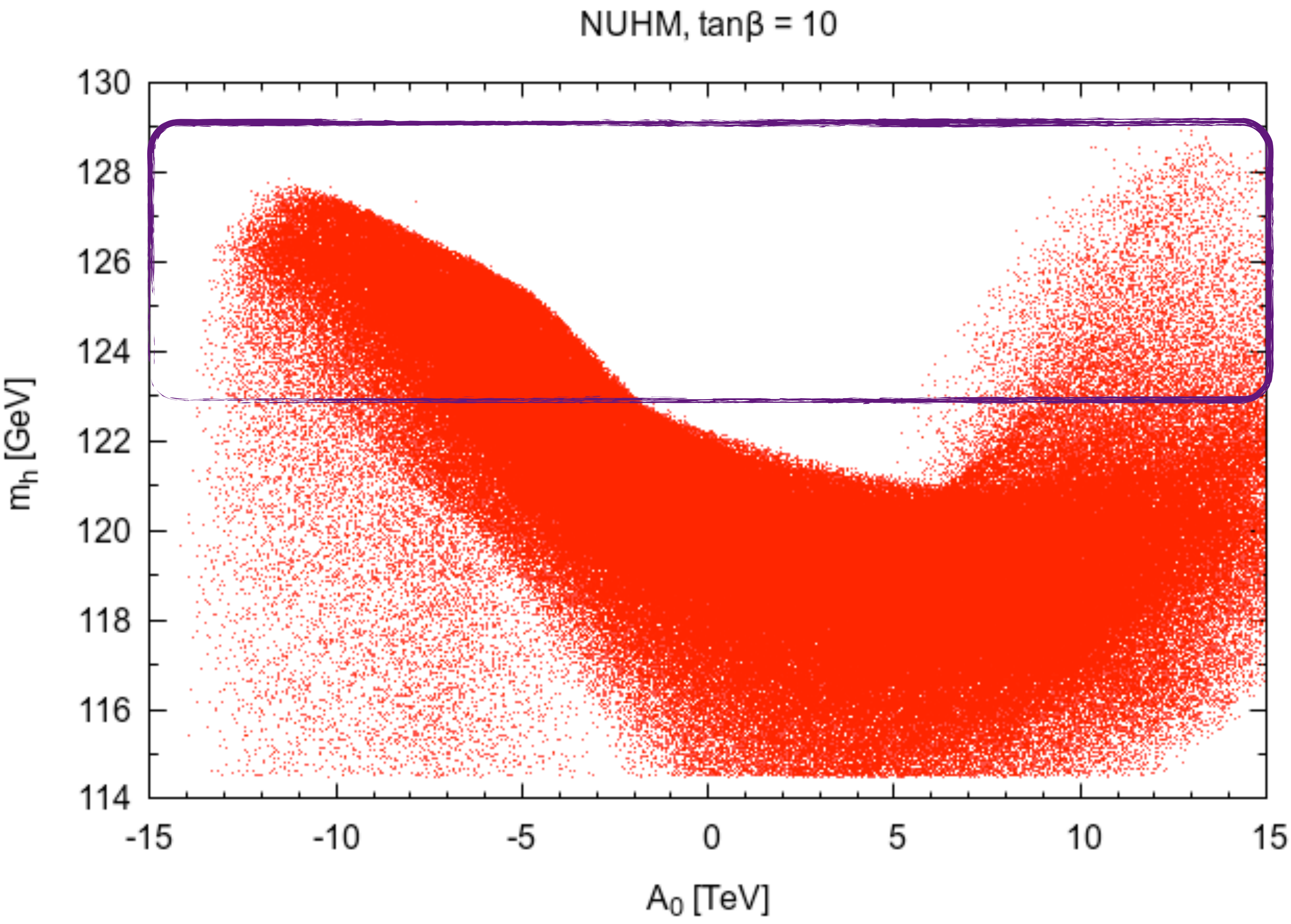
D. Chowdhury, S. Vempati, et. al



D. Chowdhury, S. Vempati, et. al



D. Chowdhury, S. Vempati, et. al ,



D. Chowdhury, S. Vempati, et. al ,

GUT [SO(10)] models

New Physics at Intermediate Scales

$10^{18}\mathrm{GeV}$ → M_{Pl} For simplification, neglect running above GUT

$10^{16}\mathrm{GeV}$ → M_{GUT} Gauge couplings unify

$(10^{14} - 10^{3})\mathrm{GeV?}$ → M_{seesaw}

$10^{3}\mathrm{GeV}$ → M_{SUSY}

→ M_{Z}

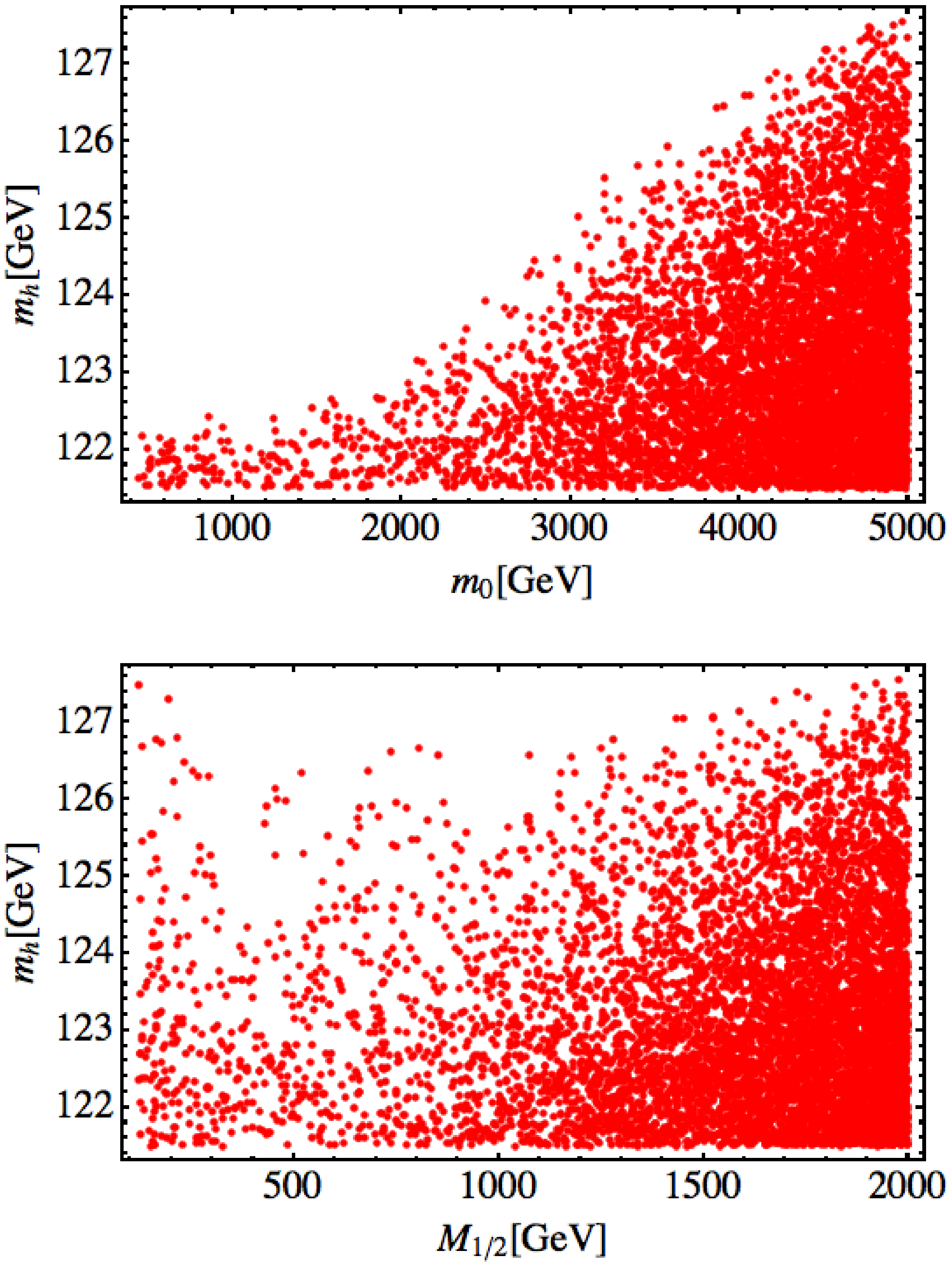
new running due to Intermediate scales

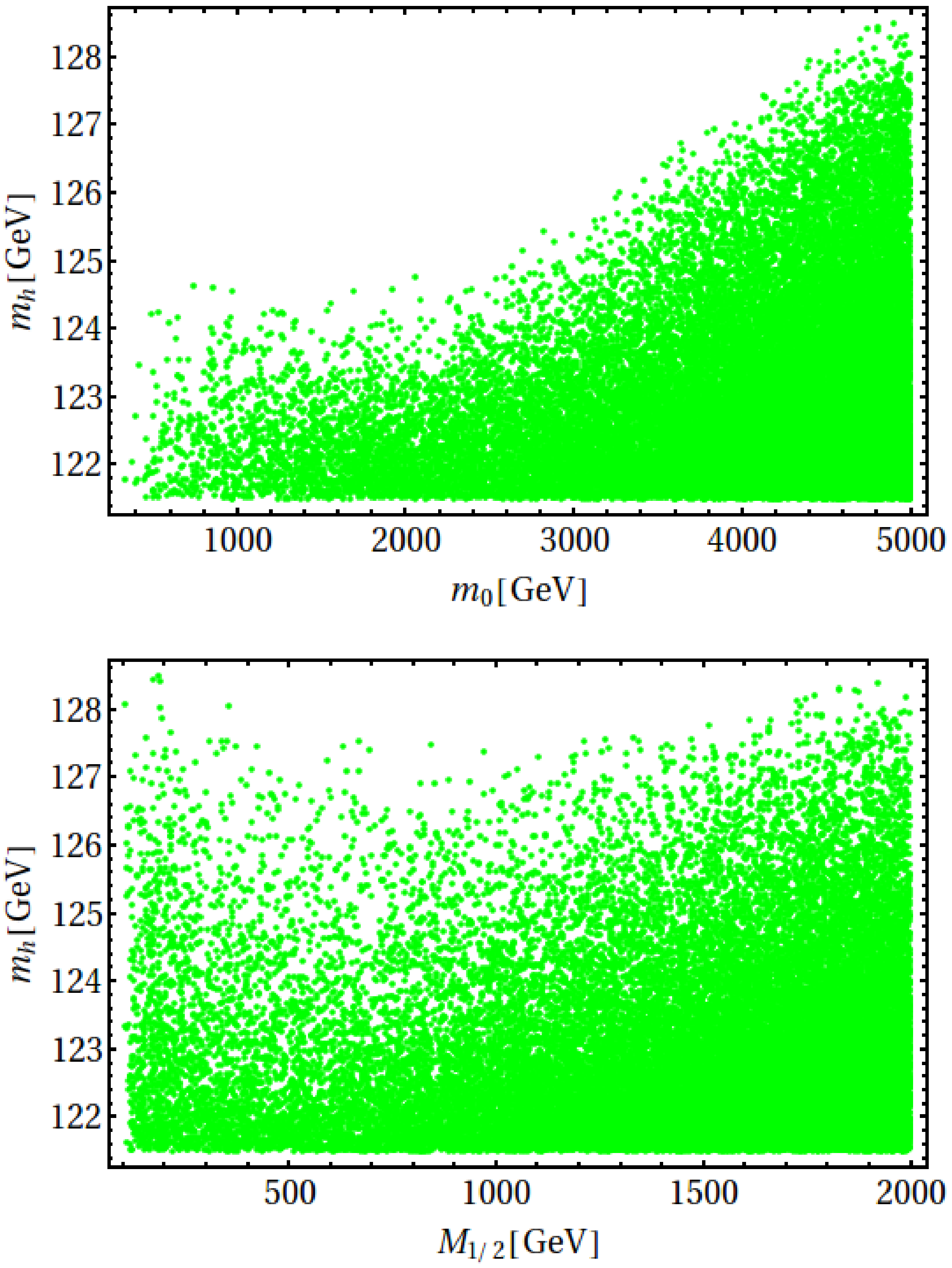
Three types of Seesaws,
Coloured Particles
Vector like particles
Strongly coupled sectors

Model Dependent Results

Present Constraints on mSUGRA + Seesaw

Calibbi, Chowdhury, Masiero, Patel,Vempati
JHEP 1211 (2012) 040

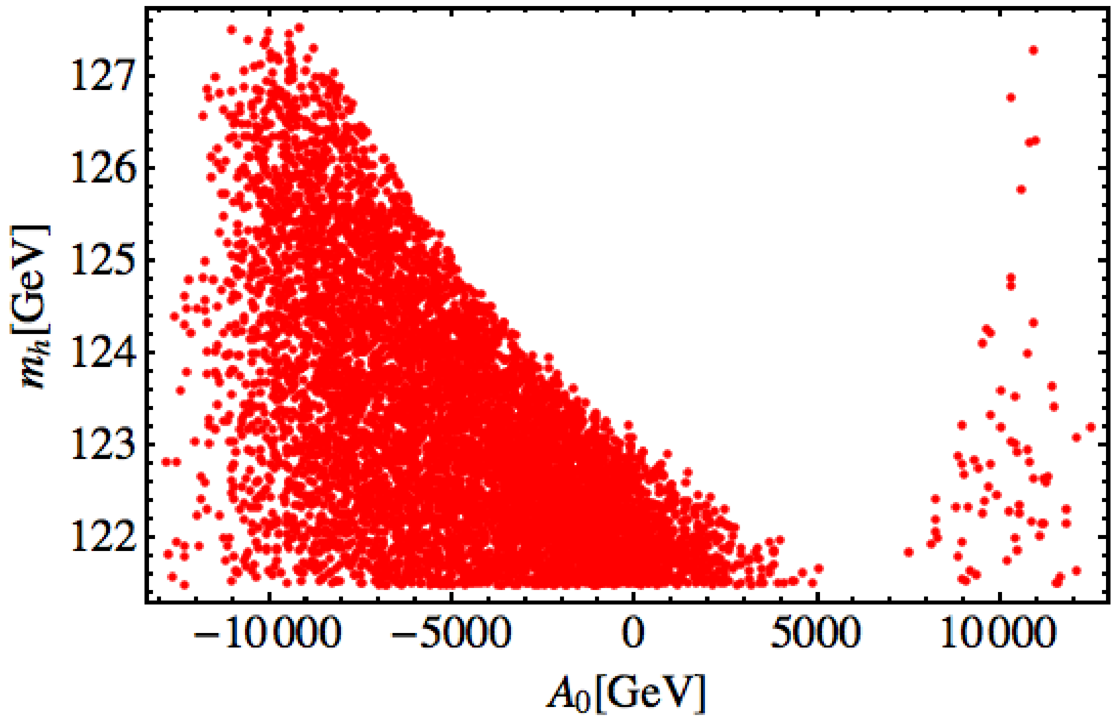


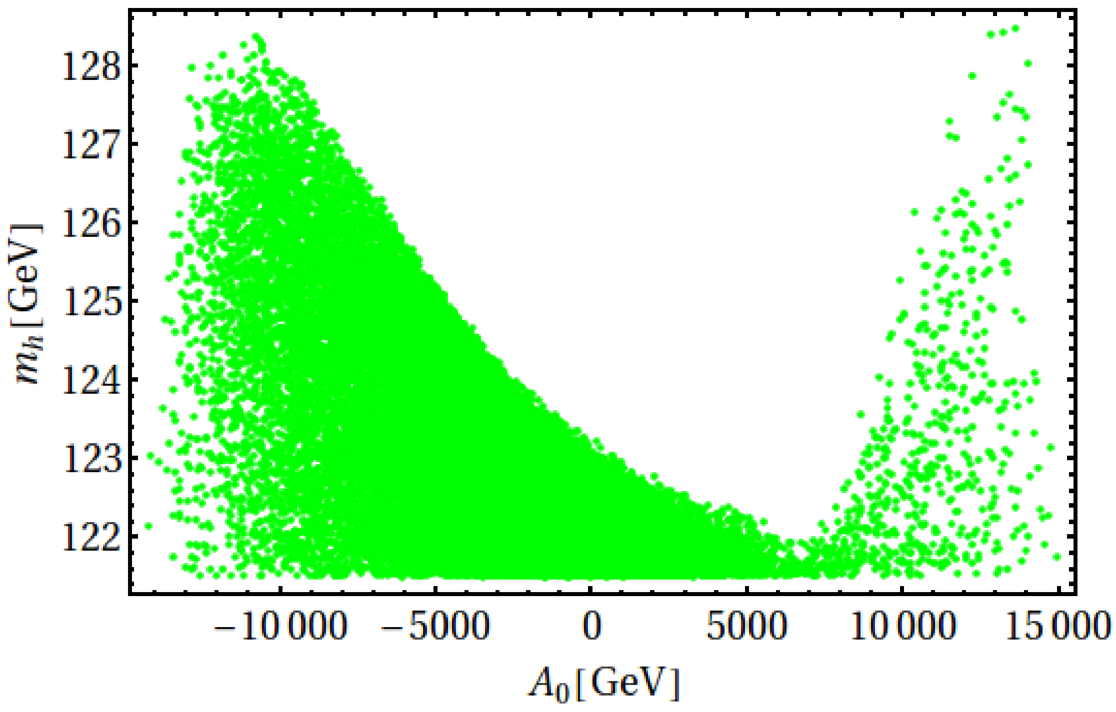


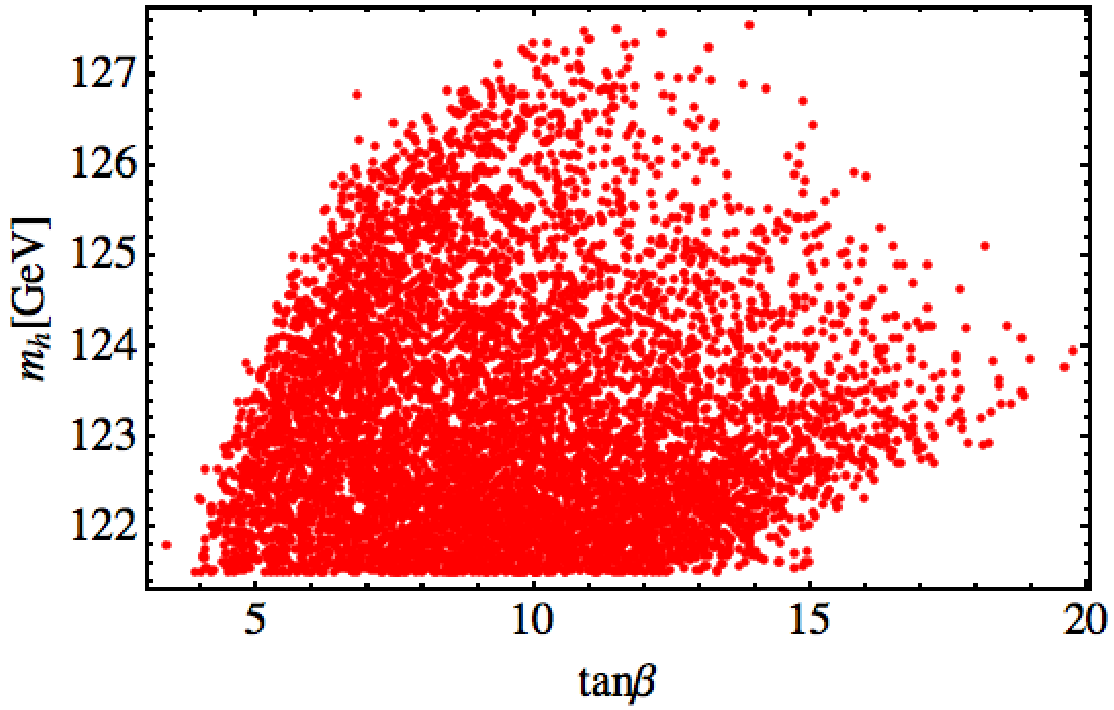
mSUGRA + seesaw

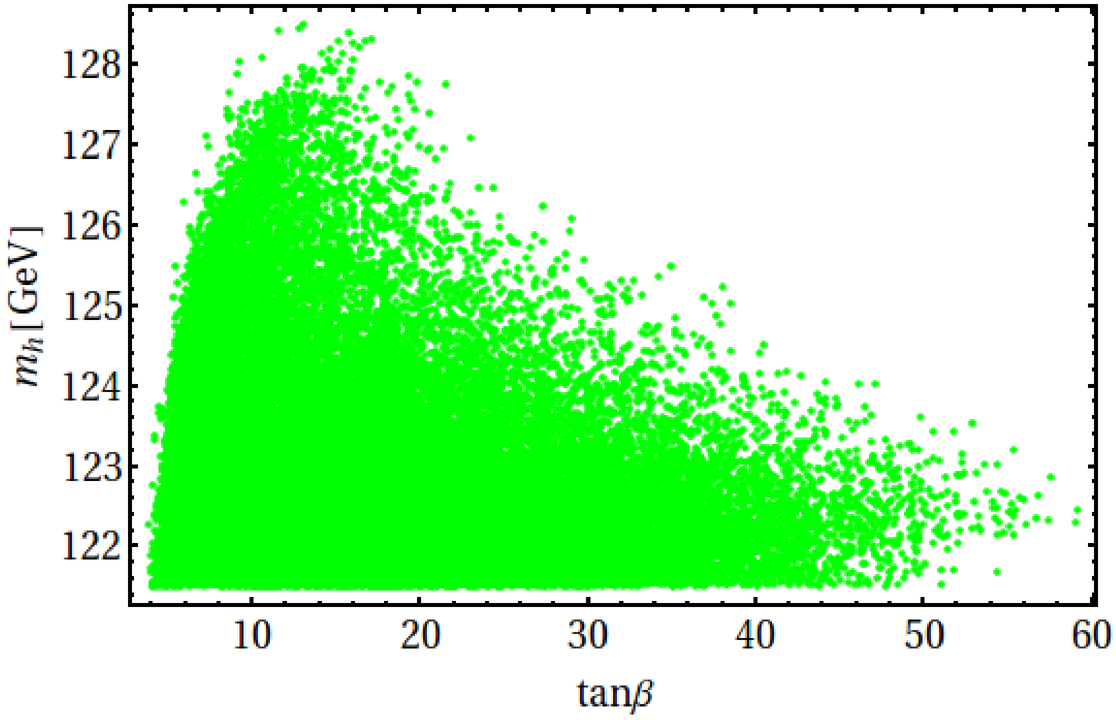
NUHM+ seesaw

Present Constraints on mSUGRA + Seesaw

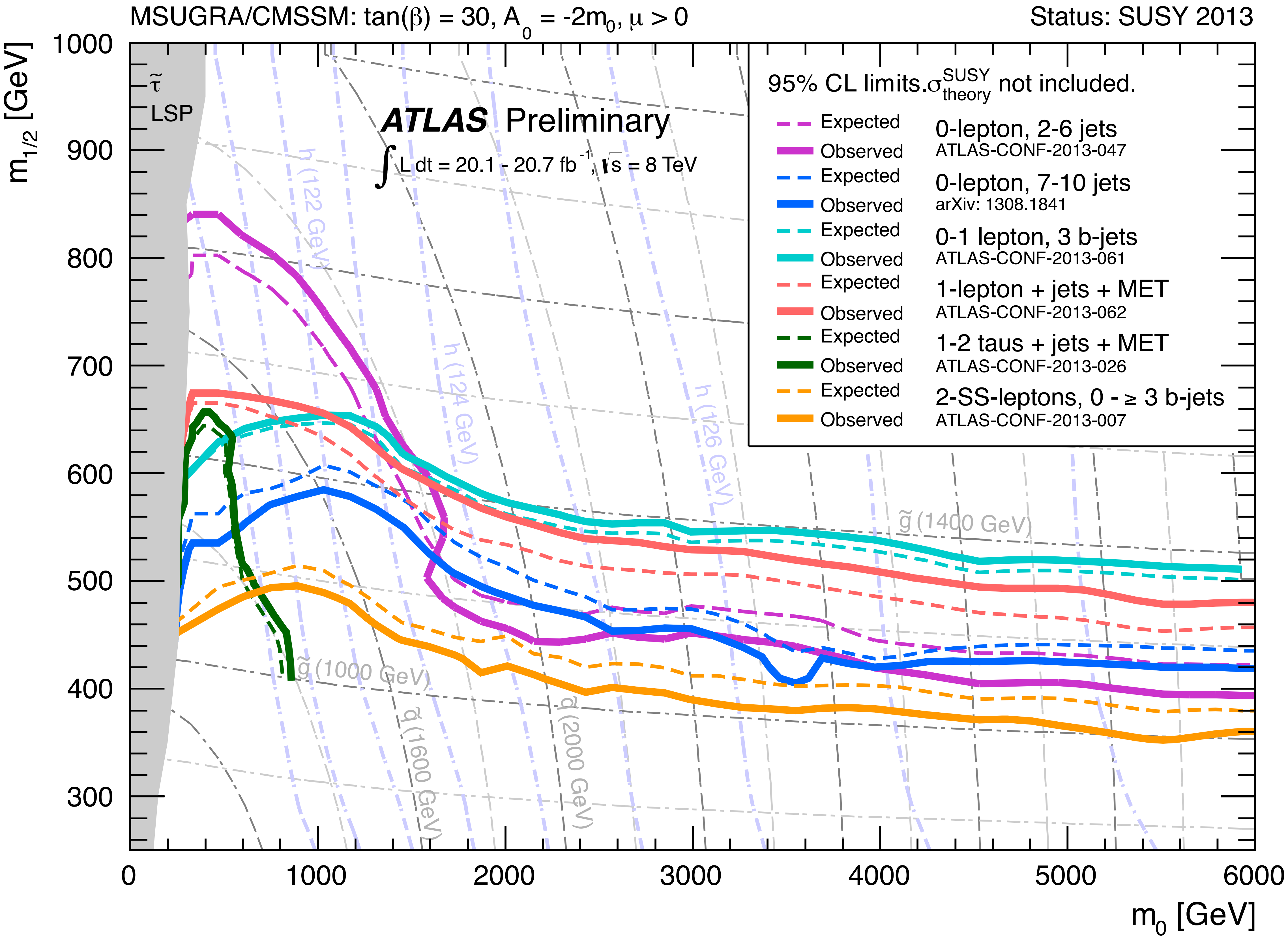








Calibbi, Chowdhury, Masiero, Patel,Vempati
JHEP 1211 (2012) 040


MSUGRA/CMSSM: tan(β) = 30, A_0 = -2m_0, μ > 0
Status: SUSY 2013
$m_{1/2}$ [GeV]
m_0 [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000
$\tilde{\tau}$ LSP
ATLAS Preliminary
$\int L\,dt$ = 20.1 - 20.7 fb^{-1}, $\sqrt{s}$ = 8 TeV
95% CL limits. σ_{theory}^{SUSY} not included.
Expected
Observed
0-lepton, 2-6 jets
ATLAS-CONF-2013-047
Expected
Observed
0-lepton, 7-10 jets
arXiv: 1308.1841
Expected
Observed
0-1 lepton, 3 b-jets
ATLAS-CONF-2013-061
Expected
Observed
1-lepton + jets + MET
ATLAS-CONF-2013-062
Expected
Observed
1-2 taus + jets + MET
ATLAS-CONF-2013-026
Expected
Observed
2-SS-leptons, 0 - ≥ 3 b-jets
ATLAS-CONF-2013-007
h (122 GeV)
h (124 GeV)
h (126 GeV)
$\tilde{g}$ (1000 GeV)
$\tilde{g}$ (1400 GeV)
$\tilde{q}$ (1600 GeV)
$\tilde{q}$ (2000 GeV)

minimal gauge mediation

Gauge Mediation

- * Introduce a bunch of Matter superfields which are charged under gauge interactions but couple to the hidden sector.

- * $W \supset \lambda X Z \bar{Z}$

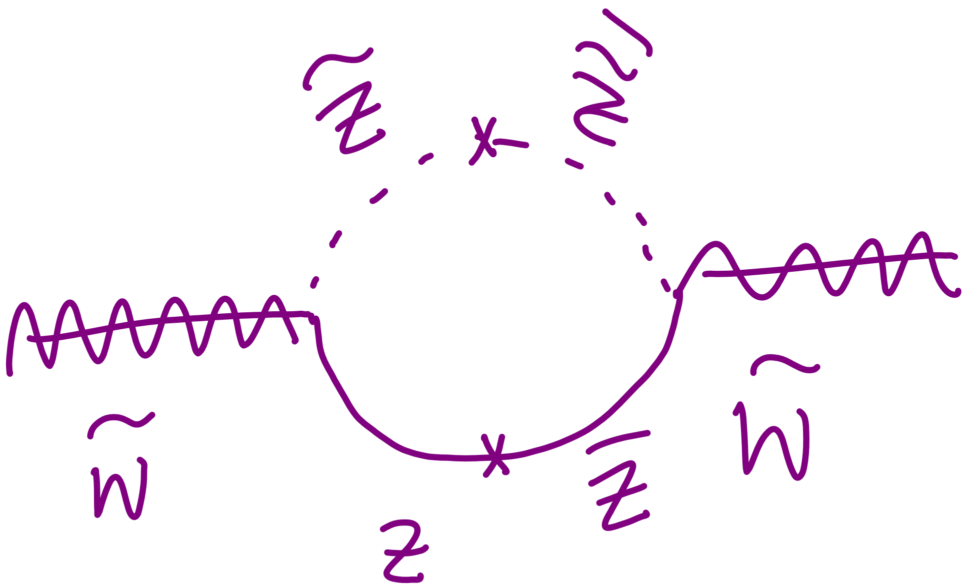
Hidden Sector

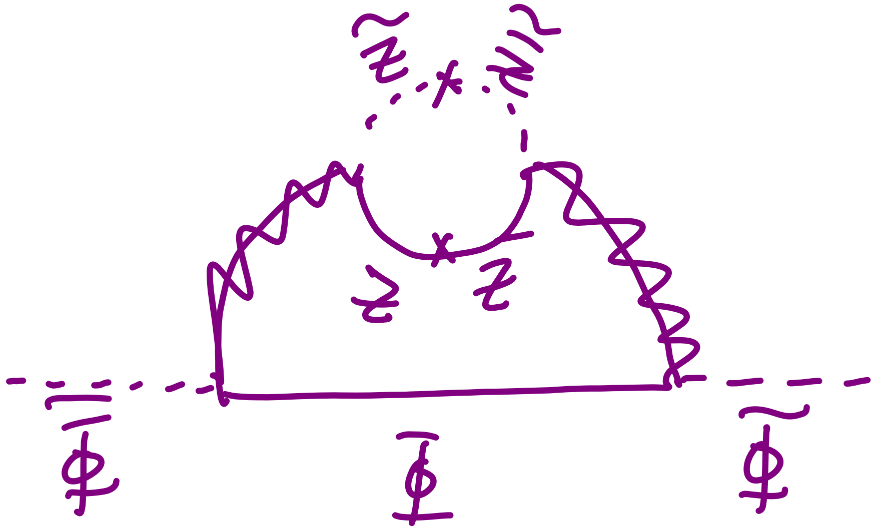
Messenger sector

Giudice and Rattazzi, Phys. Reports Review

The Scale of SUSY breaking mediation is about 100 TeV or so

SUSY broken spontaneously by X

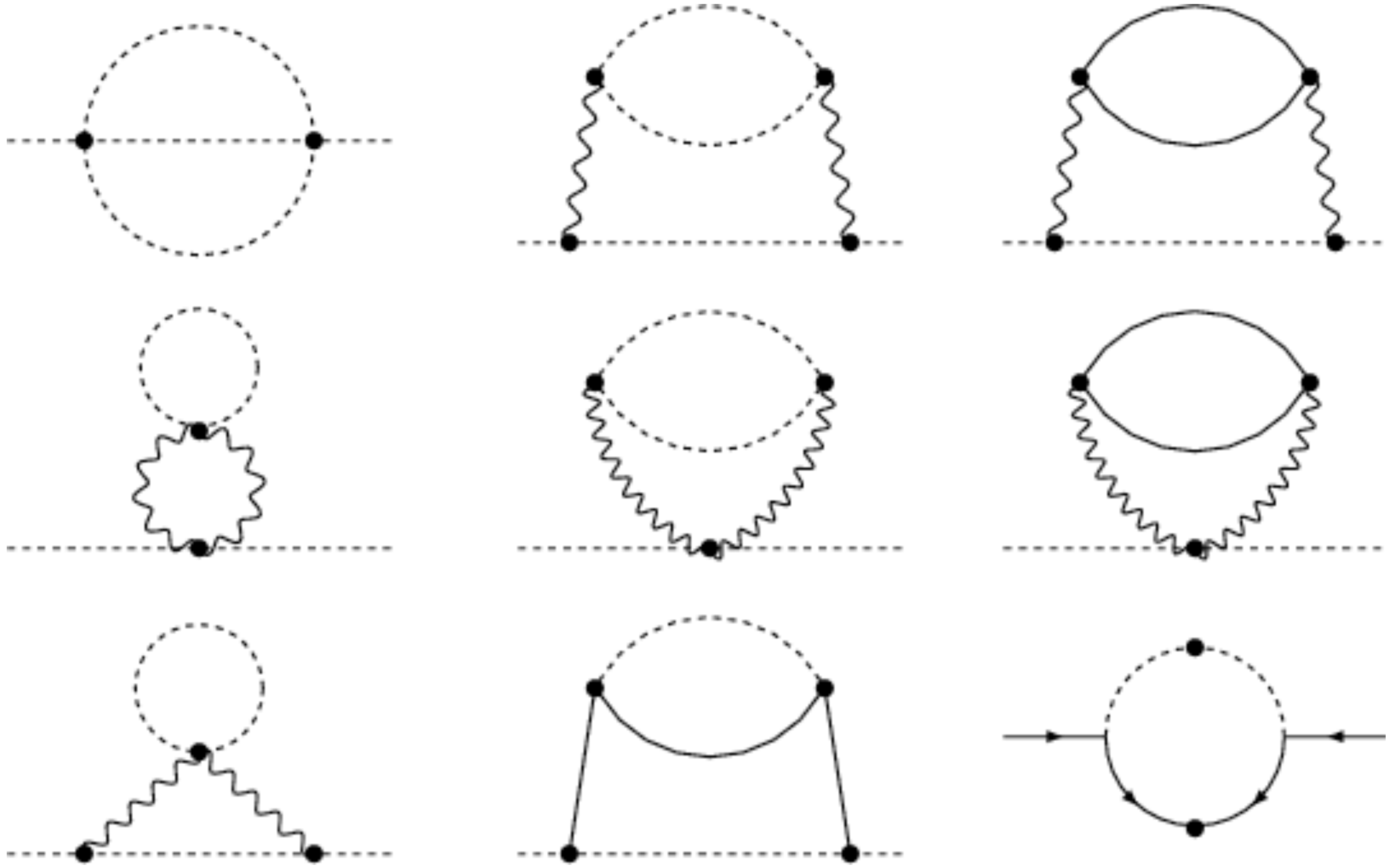




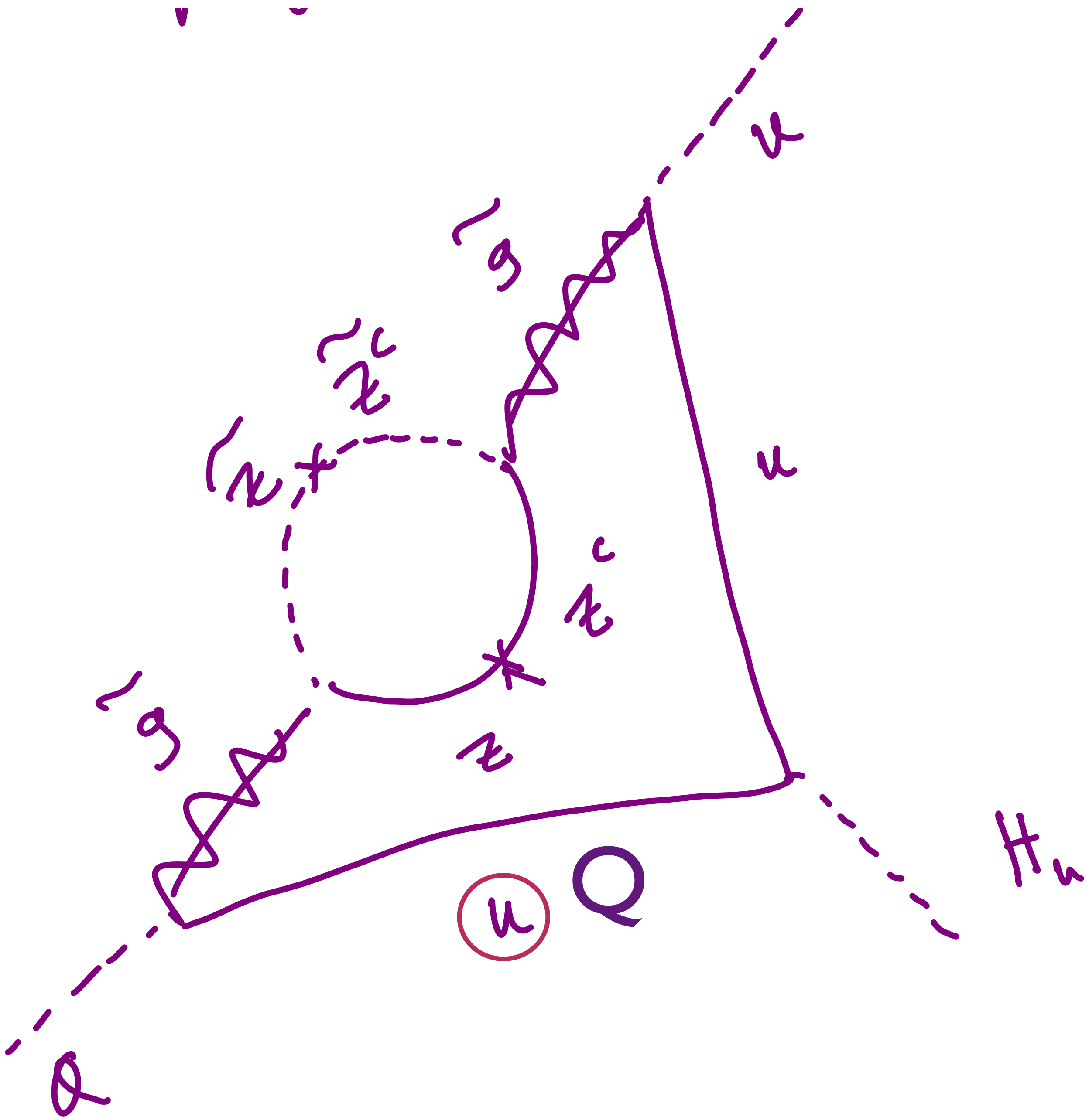
Soft masses in MSSM through loops

+ - - bunch of two loop diagrams

Two loop diagrams contributing to soft masses



Trilinear Couplings



additional
coupling
suppression

A-terms are essentially zero !!!

Draper, Meade, Shih et.al 1112.3068

Gauge Mediation and light higgs mass

the A-terms in the gauge mediation are very small !!

So a 125 GeV Higgs is very difficult unless we have a very heavy stop spectrum (beyond LHC)

Draper, Meade, Shih et.al 1112.3068

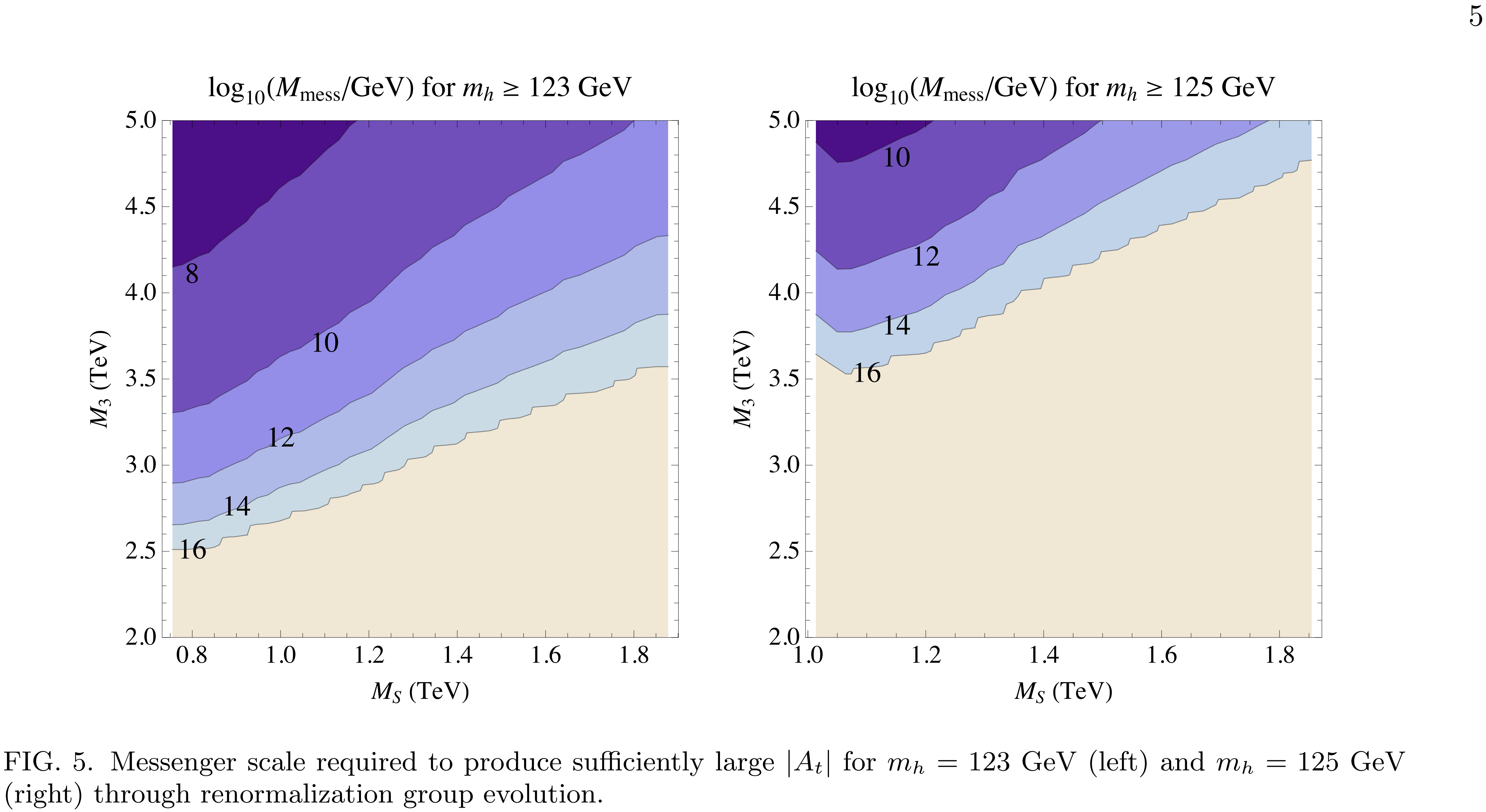


FIG. 5. Messenger scale required to produce sufficiently large $|A_t|$ for $m_h = 123$ GeV (left) and $m_h = 125$ GeV (right) through renormalization group evolution.

The change required in the messenger scale is a bit too large : almost up to GUT scale

Ways out for Gauge Mediation

(1) Have *Yukawa* mediation in addition to gauge mediation. This can be achieved by having matter-messenger fields mixing.

Delgado, Giudice, Rattazzi et. al, Yanagida et.al

review: Shih et.al, 1303.0228

(2) Have additional matter in the higgs sector.

Langacker et. al, Yanagida et. al

(3) Additional strongly coupled sectors

Yanagida et. al

V. Sooryanarayana and Vempati

NMSSM and gauge mediation

$$W = \lambda S H_u H_d + \kappa S^3 + h^u Q u^c H_2 + \ldots$$

Higgs Mass Matrix is a 3 x 3 mass matrix

A linear combination with the singlet can increase the light higgs mass

But the singlet is massless at the mediation scale !!!

Can be made to work with an extra gauge group !!

V. Sooryanarayana and Vempati

NMSSM and gauge mediation

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V. Sooryanarayana and Vempati

NMSSM and gauge mediation

$$W = \boxed{\lambda S H_u H_d + \kappa S^3} + h^u Q u^c H_2 + \ldots$$

Higgs Mass Matrix is a 3 x 3 mass matrix

A linear combination with the singlet can increase the light higgs mass

But the singlet is massless at the mediation scale !!!

Can be made to work with an extra gauge group !!

Non-Traditional Models

- Supergravity models without Singlets (roughly, Mediation through supergravity loops) : Anomaly Mediation Models and their variants Luty, Shirman Reviews
- Extra Dimensional Models : Gaugino Mediation Models, Randall-Sundrum Models, Strongly coupled models Luty, Shirman Reviews, Nomura et.al, Terning Text book + lecture notes, Nelson-Strassler etc.
- String Inspired Models : Moduli Mediation, KKLT, Hybrid Mediation models,
- F-Theory Inspired Models (more gauge Mediation) Choi et.al , Nilles et.al

Maharana and Palti, 1212.0555,
Heckman, 1001.4084

Phenomenological Models

- Do not consider a specific model of Supersymmetric Breaking

- Intelligent choice of parameters

- For ex: flavor violating and CP violating parameters set to zero. Degenerate first two generations etc.

- 15-20 remaining parameters determine the entire weak scale spectrum.

Jo Anne Hewett, T. Rizzo et. al
N. Mahmoudi et.al
Carena, Wagner et. al
Buchmuller et. al

Summary

If the discovered Higgs like particle is the lightest Higgs
of the MSSM, it puts severe constraints,
especially on the stop sector

Constrained gravity mediated models require almost maximal
stop mixing. But, are in a really tight spot
if constraints from flavour physics and Dark matter
are taken in to account.

Non universality in the Higgs sector gives some freedom
but not so much.

review: J. Feng arXiv:1302.6587

Fine tuning can be reduced only with non-universal gaugino masses (non-universality in scalar sector doesn't matter)

Antusch et. al, 1207.7236 JHEP 2013

A new definition of fine tuning will make it natural

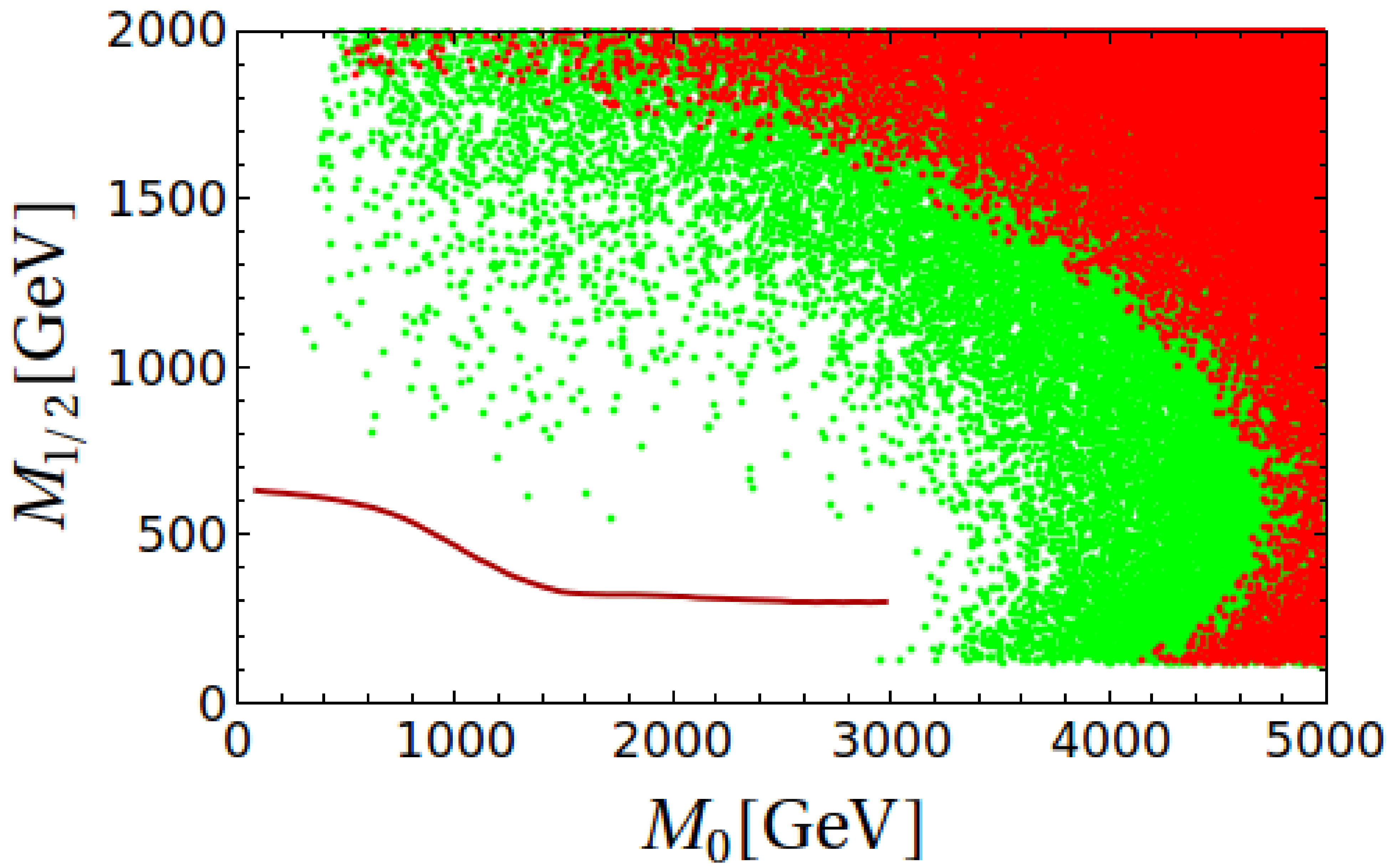
Baer et.al , 1207.3343

(or just live with it)

Large stop mixing requirement rules out
minimal gauge mediated models with light stops
without extended particle content.

Simple examples based on NMSSM type extensions can be constructed

BACK UP SLIDES



tanbeta = 10, red line corresponds to LHC search limit

Uncertainties in the calculation

- scheme dependence: Between $\overline{DR}$ and OS scheme there is mass difference ~ 2 GeV.

- renormalization scale: at 1-loop the mh changes ~ 10 GeV from M_Z to 1 TeV, while at 2-loop difference comes down to 2-3 GeV.

Allanach et al. ’04

- external momentum dependence: $1 - \text{loop} \ \sim 1 - 2 \text{ GeV}$

  $2 - \text{loop} \ \sim 0.5 \text{ GeV}$

- top mass uncertainty: $173.5 \pm 0.6 \pm 0.8 \text{ GeV} \ (\text{PDG } 2012)$

2 GeV shift in top mass leads to ~ 1 GeV change in the lightest Higgs mass value in MSSM.

- other uncertainties include: $\Delta m_b, \ \Delta\alpha_s \text{ and } \Delta\alpha_{\text{em}}$

total shift in the mh due to these 3 parameters is < 100 MeV.

- The total theoretical uncertainty in the lightest Higgs mass calculation is ~ 4-5 GeV.

- Fixing the scheme of calculation and renormalization scale the only uncertainty comes from the approximation of external momentum being zero while calculating higgs mass at 2-loop or more.

- This uncertainty (~500 MeV) is within the experimental error of LHC.

flavourful susy from RS

An Alternative to Froggatt-Nielsen Models

Consider RS as a theory of flavour
rather than
a solution to hierarchy problem.

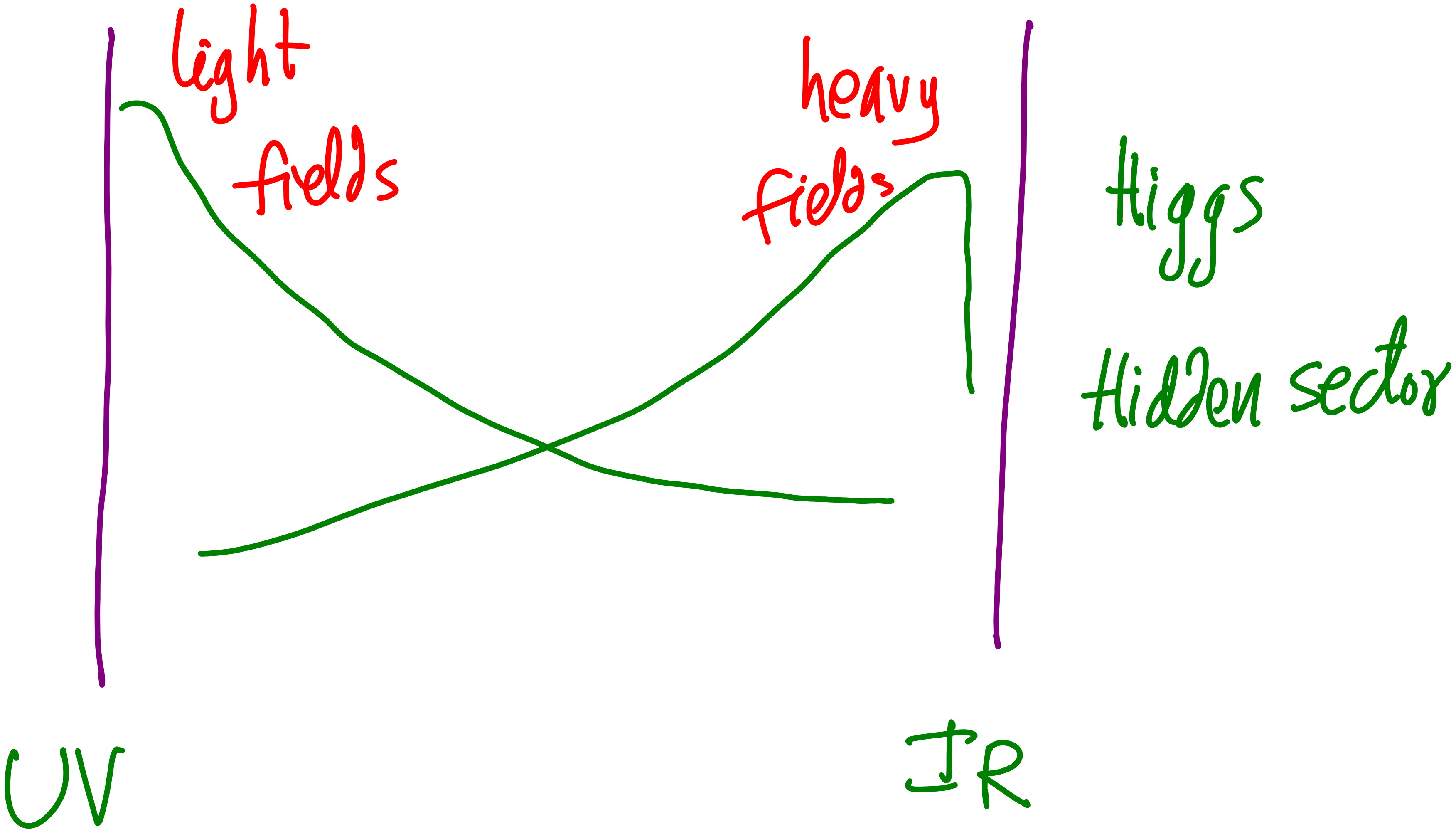
SUSY is still present to solve the hierarchy problem

RS between Planck Scale and GUT scale : May be more Natural

Bulk masses of N=1 Superfields are fit to the fermion masses at the GUT scale !

Soft terms are given by profiles which fix the fermion masses at GUT scale

Iyer, Dudas & Vempati, in progress



Profiles of the matter fields determined by 5D bulk masses

$$m_{\tilde{f}}^2 = \begin{bmatrix} \epsilon & \epsilon & \epsilon' \\ \epsilon & \epsilon & \epsilon' \\ \epsilon' & \epsilon' & 1 \end{bmatrix} m_{3/2}^2 \qquad \epsilon \leq \epsilon' \leq 1$$

$$A_{ij} = m_{3/2} f(c_i) f(c_j)$$

$f(c_i)$ = Profile of superfields with bulk mass c_i

* One of the eigenvalues is -ve at high scale.

But the weak scale spectrum is interesting!

Example Point

All the O(1) parameters are considered to be 1.

Point	Hadron	Lepton
c_{Q,L_1}	1.8211	1.9595
c_{Q,L_2}	1.9441	1.1760
c_{Q,L_3}	0.7545	1.4195
c_{D,E_1}	1.8144	1.4110
c_{D,E_2}	0.9781	1.2135
c_{D,E_3}	0.8986	-0.9321
c_{U,N_1}	2.4262	6.3178
c_{U,N_2}	0.0967	7.7178
c_{U,N_3}	-3.7868	6.7101

```
      mQ  =

 4.1793E+00  -1.5895E+00   2.4778E+01

-1.5895E+00   6.0456E-01  -9.4239E+00

 2.4778E+01  -9.4239E+00   1.4690E+02

    mU  =

 2.4692E-01  -9.7687E+00   2.2101E+01

-9.7687E+00   3.8647E+02  -8.7437E+02

 2.2101E+01  -8.7437E+02   1.9782E+03

    mD  =

 3.2966E+00  -3.4599E+00   2.2901E+01

-3.4599E+00   3.6313E+00  -2.4035E+01

 2.2901E+01  -2.4035E+01   1.5909E+02

    mL  =

 2.5593E+00  -1.0666E+01   2.2770E+00

-1.0666E+01   4.4454E+01  -9.4896E+00

 2.2770E+00  -9.4896E+00   2.0258E+00

    mE  =

 8.8083E-01   6.7365E+00  -3.0175E+01

 6.7365E+00   5.1520E+01  -2.3078E+02

-3.0175E+01  -2.3078E+02   1.0337E+03
```

$$m_{3/2} = 871.2 \text{ GeV}$$

$$M_{1/2} = 1.2 \text{ TeV}$$

Typical Example