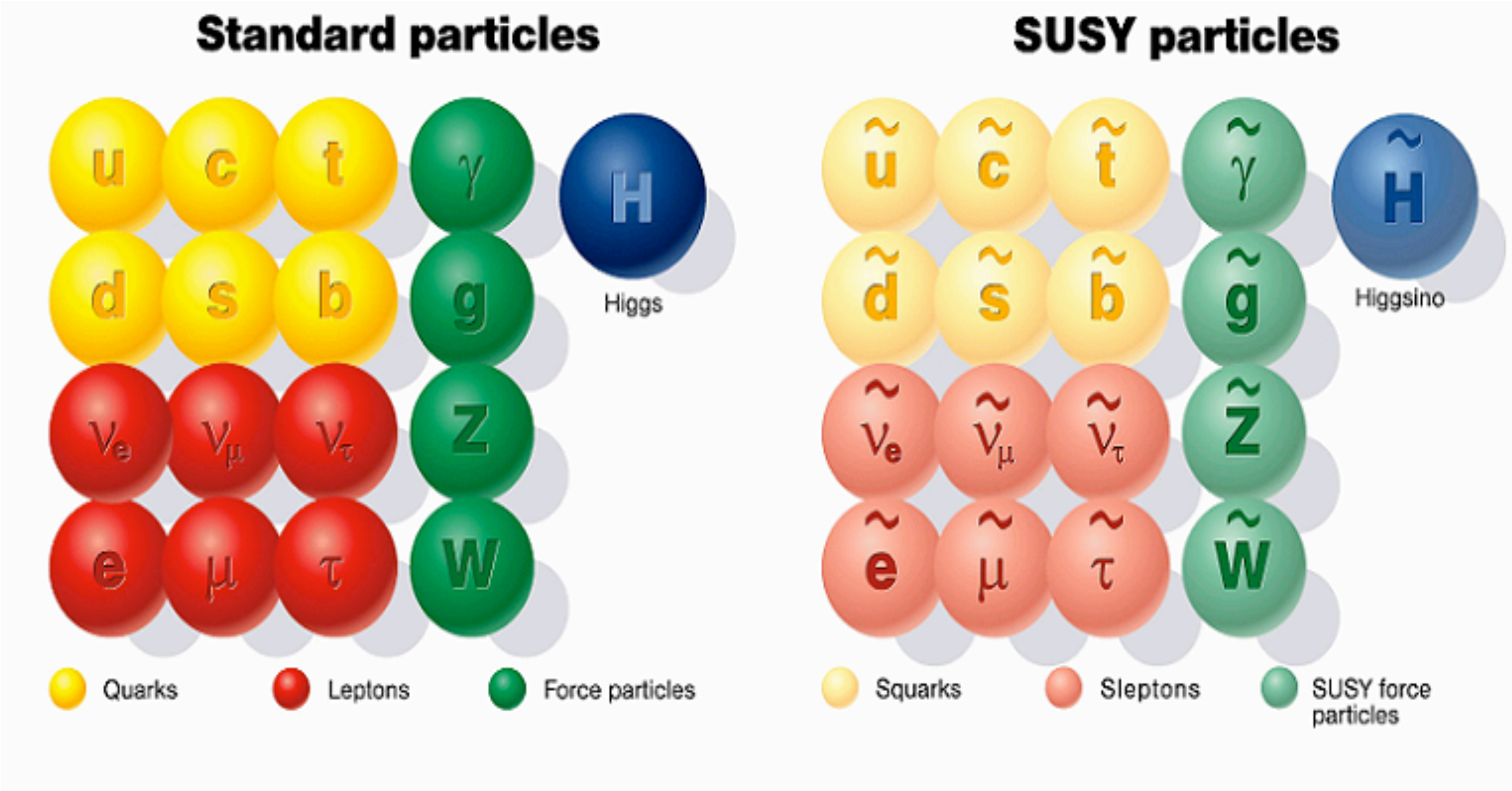


Status of *Some* Supersymmetric Models

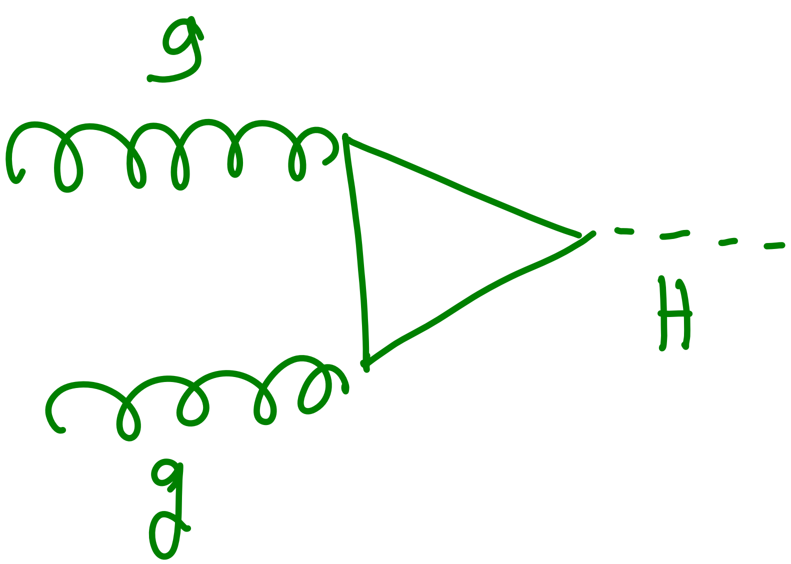
Sudhir K Vempati
CHEP, IISc Bangalore

Sangam@HRI, Allahabad
Mar 25-30, 2013

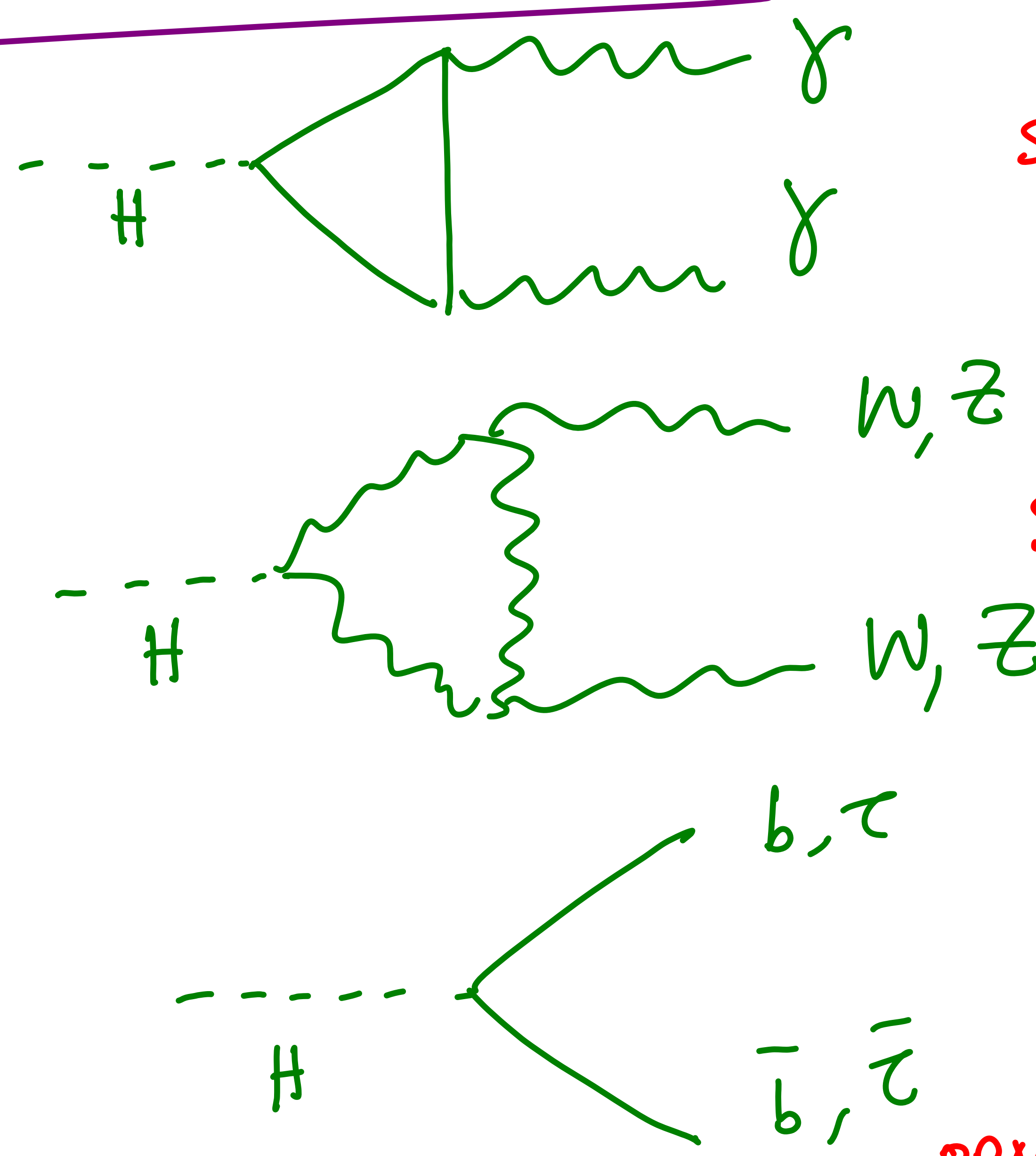
Outline

- Why Supersymmetry ?
- Structure of MSSM
- Experimental Constraints
- Status of Constrained Models

The discovery of Higgs like boson @ LHC :



production



seen

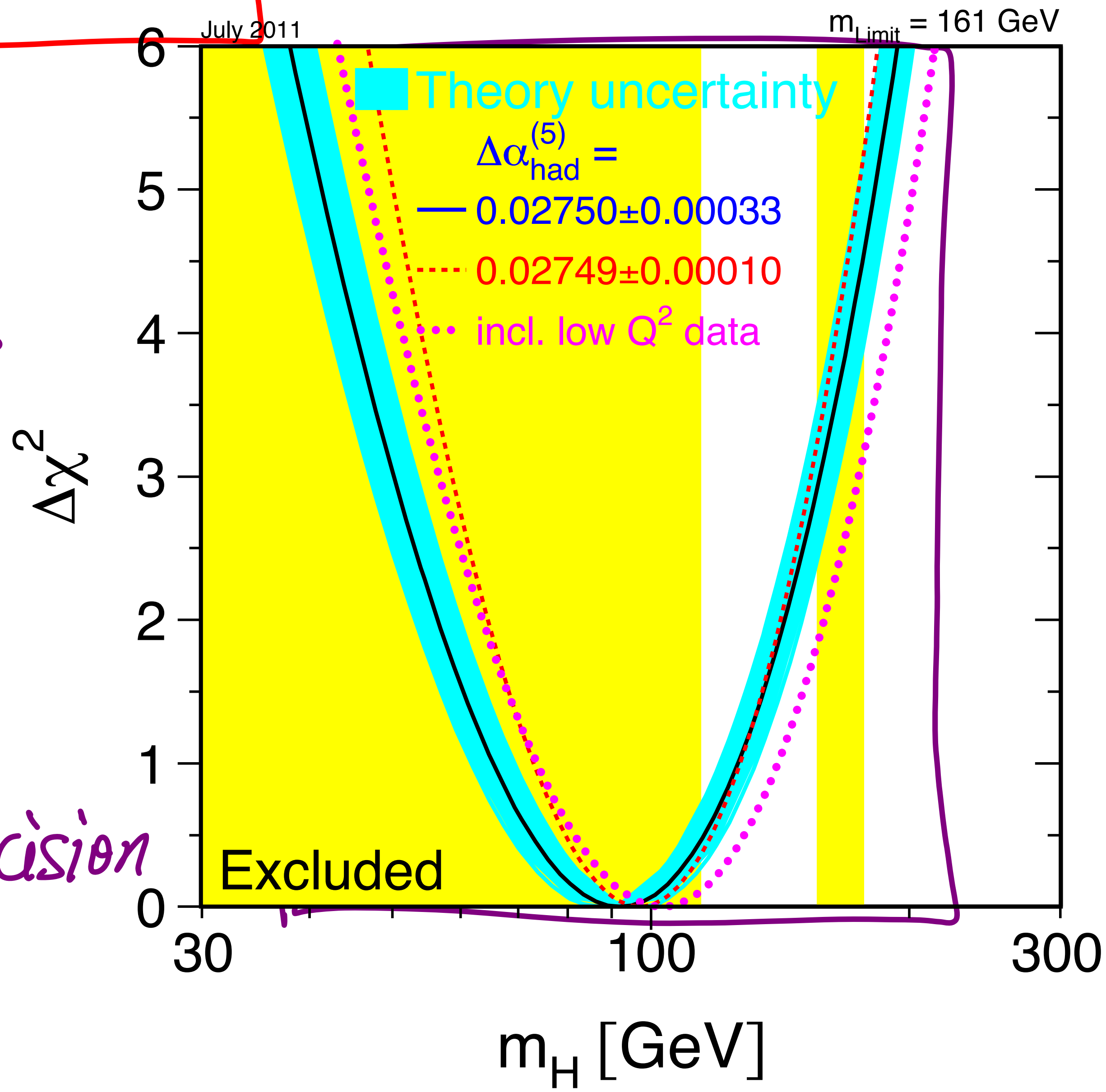
seen

perhaps

Tao Han's Lectures

$m_H \simeq 126 \pm 3$ GeV

Precision Measurement



* Broadly consistent with electroweak theory expectations of production cross sections & decay rates

* Consistent with Electroweak Precision measurements.

Tao Han's Lectures

Perhaps a weakly coupled Scalar of spin zero

Elementary Scalar

Composite

Tao Han's lectures

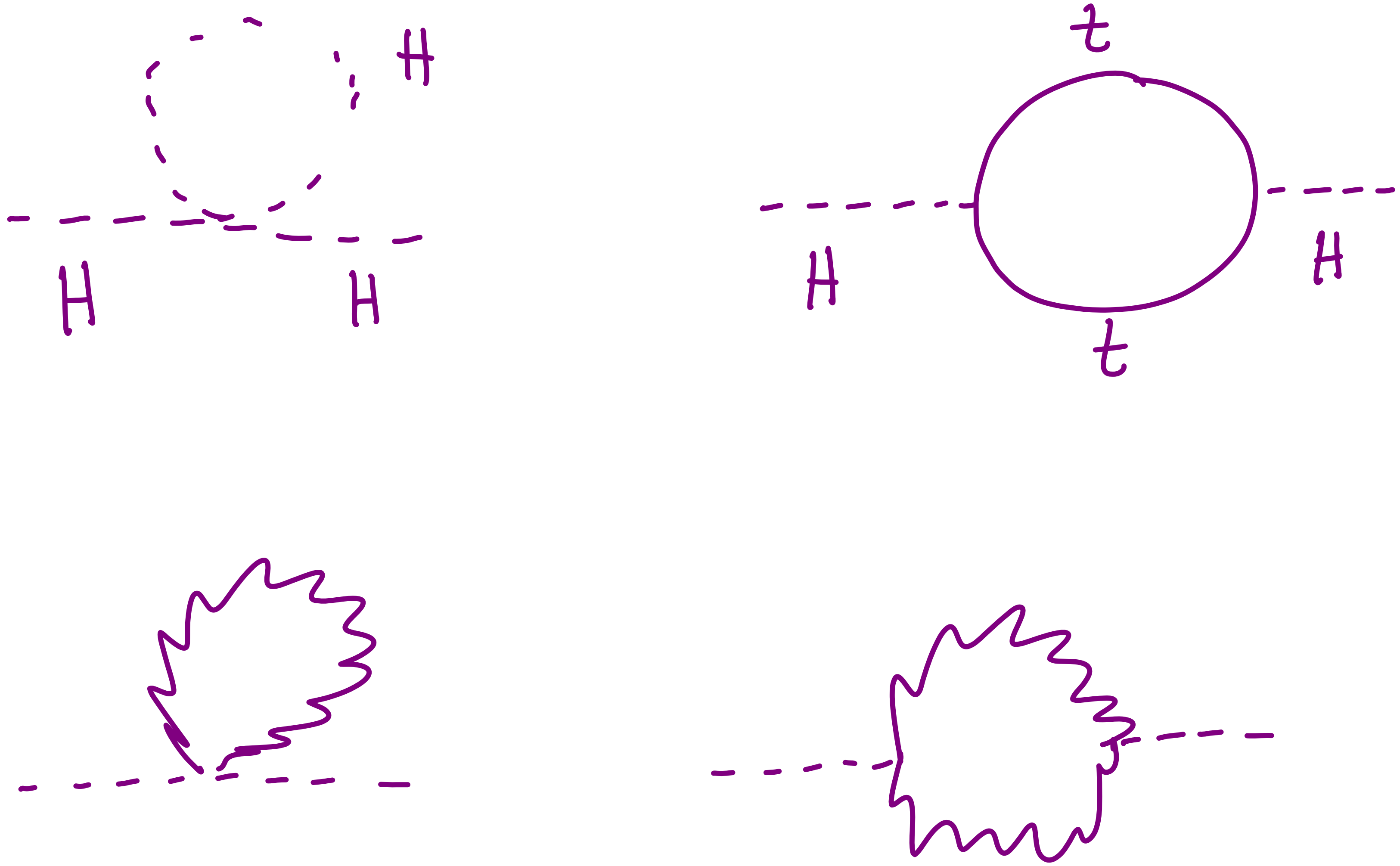
M_{Planck}

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

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

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.

The Structure of MSSM

Wess and Bagger, Text Book
Baer and Tata , Text Book
Drees, Godbole, Roy, Text Book
S. P. Martin, Primer hep-ph/9709356

SUSY

$N=1$ $\{Q_\alpha, Q^\dagger_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P^\mu$ massless representation

Changes the particle spin by ½

$(0, \frac{1}{2})$ chiral superfields
$(\frac{1}{2}, 1)$ Vector superfield
} two multiplets

Construction of MSSM

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \Longrightarrow \begin{pmatrix} (\nu_e \;\; \tilde{\nu}_e) \\ (e, \; \tilde{e}) \end{pmatrix}$$

every matterfield with chiral multiplet

$$W \longrightarrow (W, \tilde{W})$$

every vector field with vector multiplet

S. Vempati, SERC Lecture Notes, arXiv:1201.0334

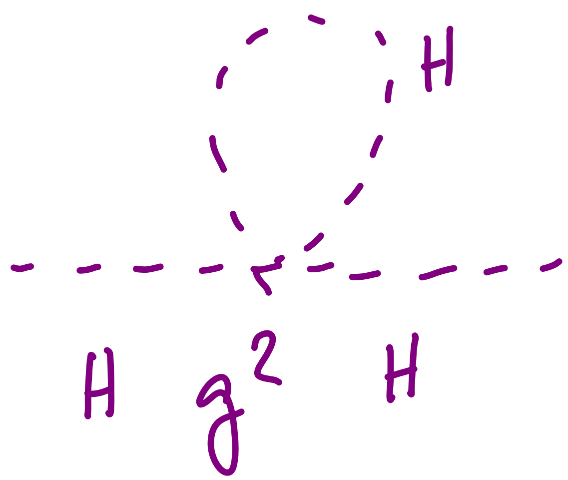
Three functions of superfields

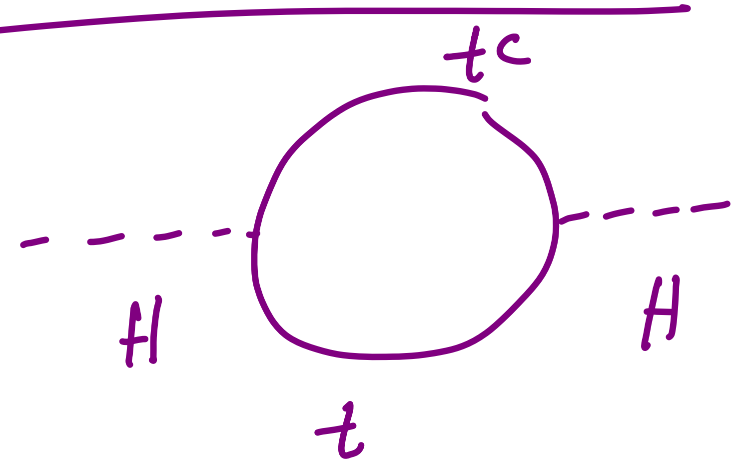
$\mathcal{L}_{Kinetic;\,gauge} \supset \int d^4\theta\, K = \Phi^{\dagger} e^{gV} \Phi$ real fn of chiral and vector multiplets

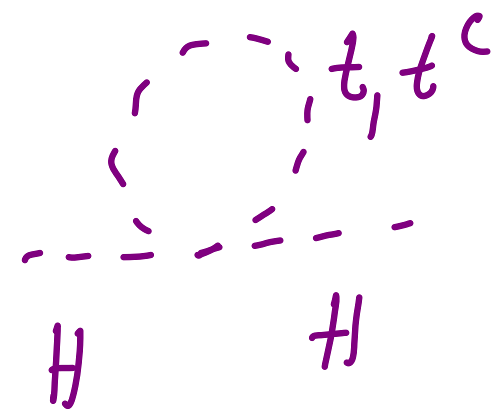
$\mathcal{L}_{Yukawa} \supset \int d^2\theta\, W = \Phi_i \Phi_j \Phi_k$ analytic fn of chiral multiplets

two Higgs doublets required to cancel anomalies

How SUSY works







quartic coupling replaced by gauge coupling

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

MSSM Superpotential

$$W = W_0 + W_1$$

$$W_0 = h_u Q u^c H_u + h_d Q d^c H_d + h_e L e^c H_d + \mu H_u H_d$$

$$W_1 = \lambda L L e^c + \lambda' L Q d^c + \lambda'' u^c d^c d^c + \epsilon L H_u$$

Baryon and Lepton Number Violating !

Imposing R-parity $\Rightarrow$ $W_1 = 0$

LSP stable

Dark Matter Candidate

$$R_p = (-1)^{(3B+L+2S)}$$

Xerxes Tata's talk

Supersymmetry breaking

E. Witten, Nucl. Phys B. 188(1981)513;
B. 202 (1982)253,
M. Luty, hep-ph/0509029
Y.Shirman, hep-ph/0907.0039
E. Dudas ,Pramana, 72,(2009) 131

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 $m^2_{Q_{ij}} \tilde{Q}^\dagger_i \tilde{Q}_j, m^2_{u_{ij}} \tilde{u^c}^\star_i \tilde{u^c}_j, m^2_{d_{ij}} \tilde{d^c}^\star_i \tilde{d^c}_j, m^2_{L_{ij}} \tilde{L}^\dagger_i \tilde{L}_j, m^2_{e_{ij}} \tilde{e^c}^\star_i \tilde{e^c}_j, m^2_{H_1} H^\dagger_1 H_1, m^2_{H_2} H^\dagger_2 H_2.$

trilinear couplings $A^u_{ij} \tilde{Q}_i \tilde{u}^c_j H_2, A^d_{ij} \tilde{Q}_i \tilde{d}^c_j H_1, A^e_{ij} \tilde{L}_i \tilde{e}^c_j H_1$

bilinear couplings $B H_1 H_2$

A total of about 105 parameters

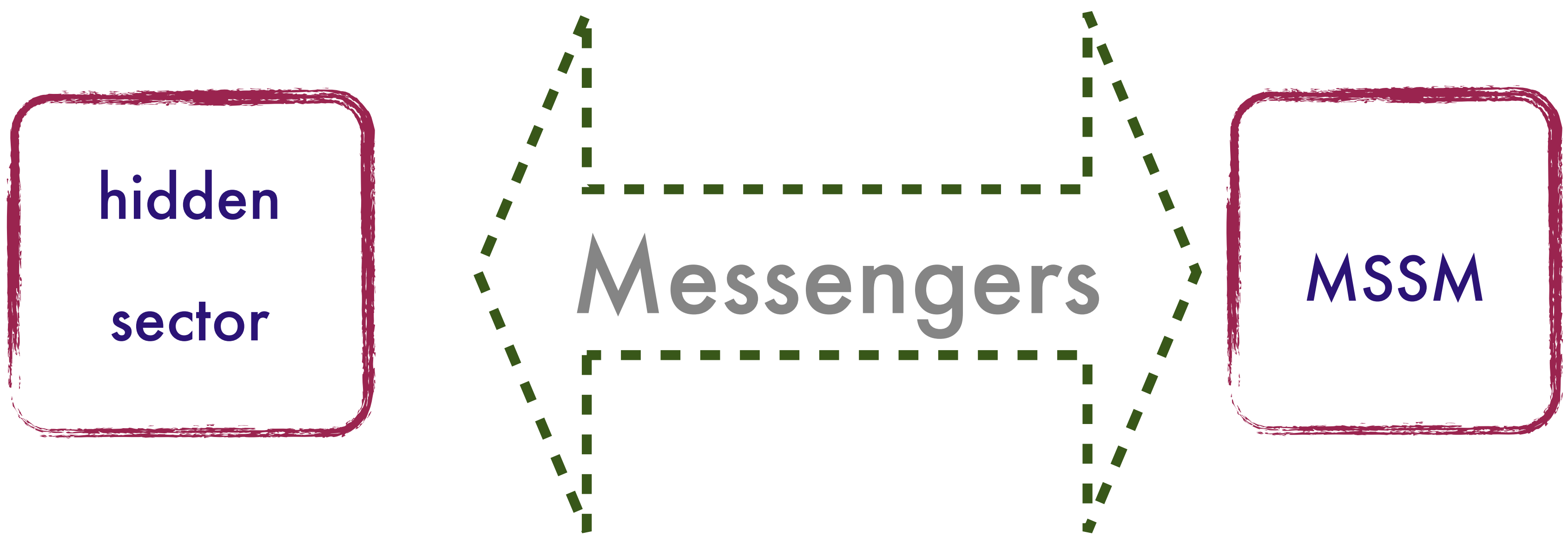
BUT, SUSY cannot be broken spontaneously in any of the MSSM multiplets including Higgs

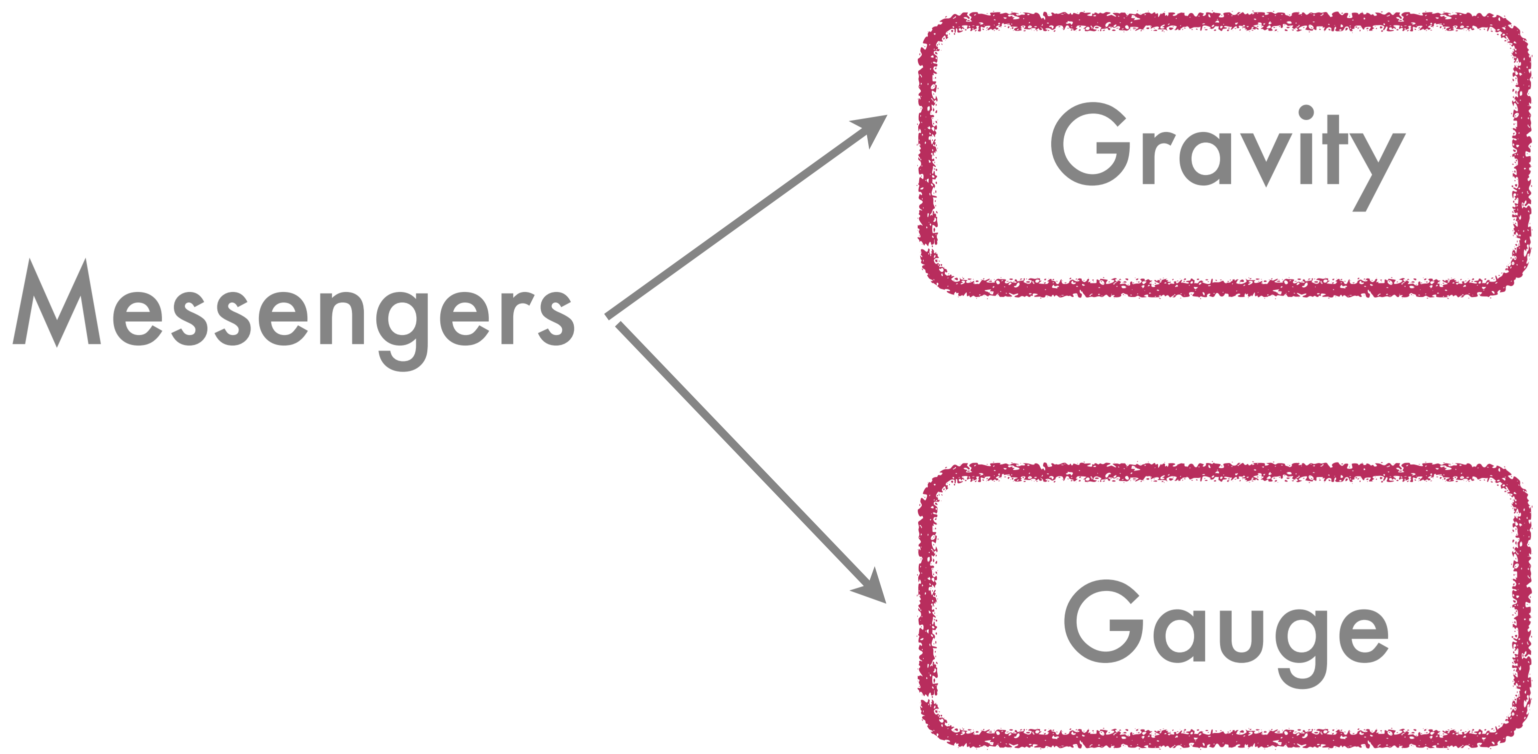
Constraints from Phenomenology

HIDDEN SECTOR IDEAS

Consider a set of fields neutral (uncharged) under the Standard Model Gauge Group

Break supersymmetry spontaneously in that sector and propagate the breaking to the MSSM sector





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

(non-traditional models)

Some traditional Models

minimal Supergravity

$$K = X_i^\dagger X_i + \Phi_i^\dagger \Phi_i + \ldots\ldots$$

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

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

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

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

* As long as Kahler potential is in canonical form:

$$m^2_{\tilde{f}} = m_0^2$$

$$M_i = M_{1/2}$$

$$A_{ijk} = A_0$$

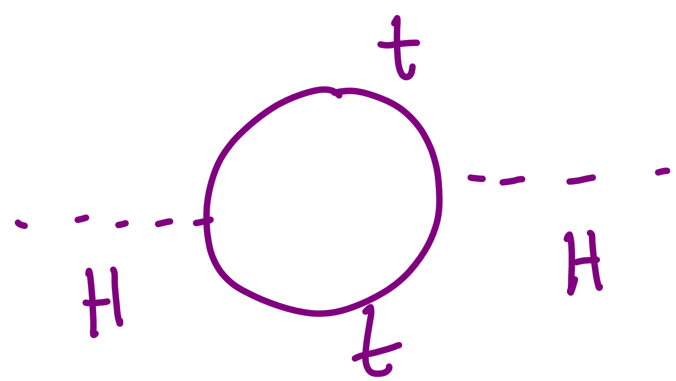
$$B_{ij} = B$$

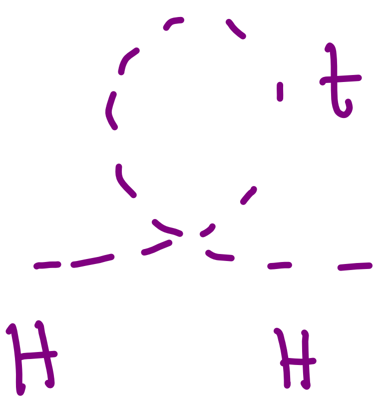
A small set of parameters describing the entire supersymmetric spectrum at weak scale

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

Dynamical understanding of Electroweak Symmetry Breaking

$m^2_{H_u, H_d} > 0$ $\qquad q^2 \simeq m^2_{pl}$ or m^2_{GUT}





RG

$$\mu \frac{d m^2_{H_u}}{d\mu} \propto h_t^2 \, m^2_{\tilde{q}}$$

$$\boxed{m^2_{H_u} < 0}$$ @ weak scale

Ibanez, Lopez, Barbieri, Hall, Ross etc.

Gauge Mediation

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

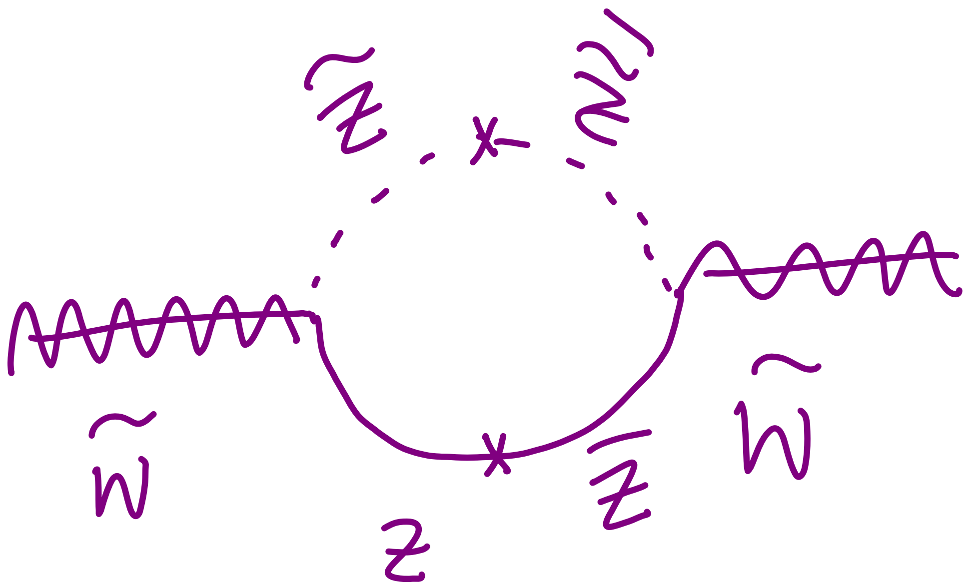
* $W \supset \lambda X Z \bar{Z}$

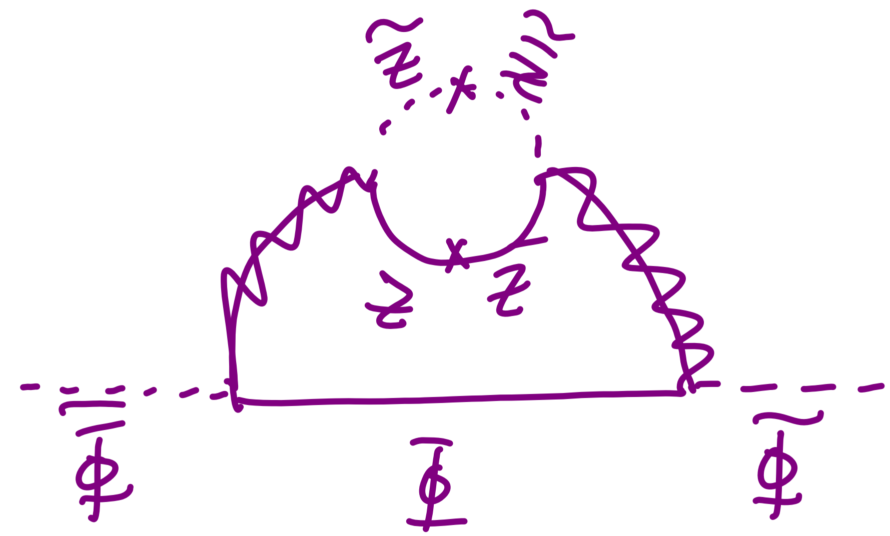
Hidden sector → X

Messenger sector → $Z \bar{Z}$

Giudice and Rattazzi, Phys. Reports Review

SUSY broken spontaneously by X

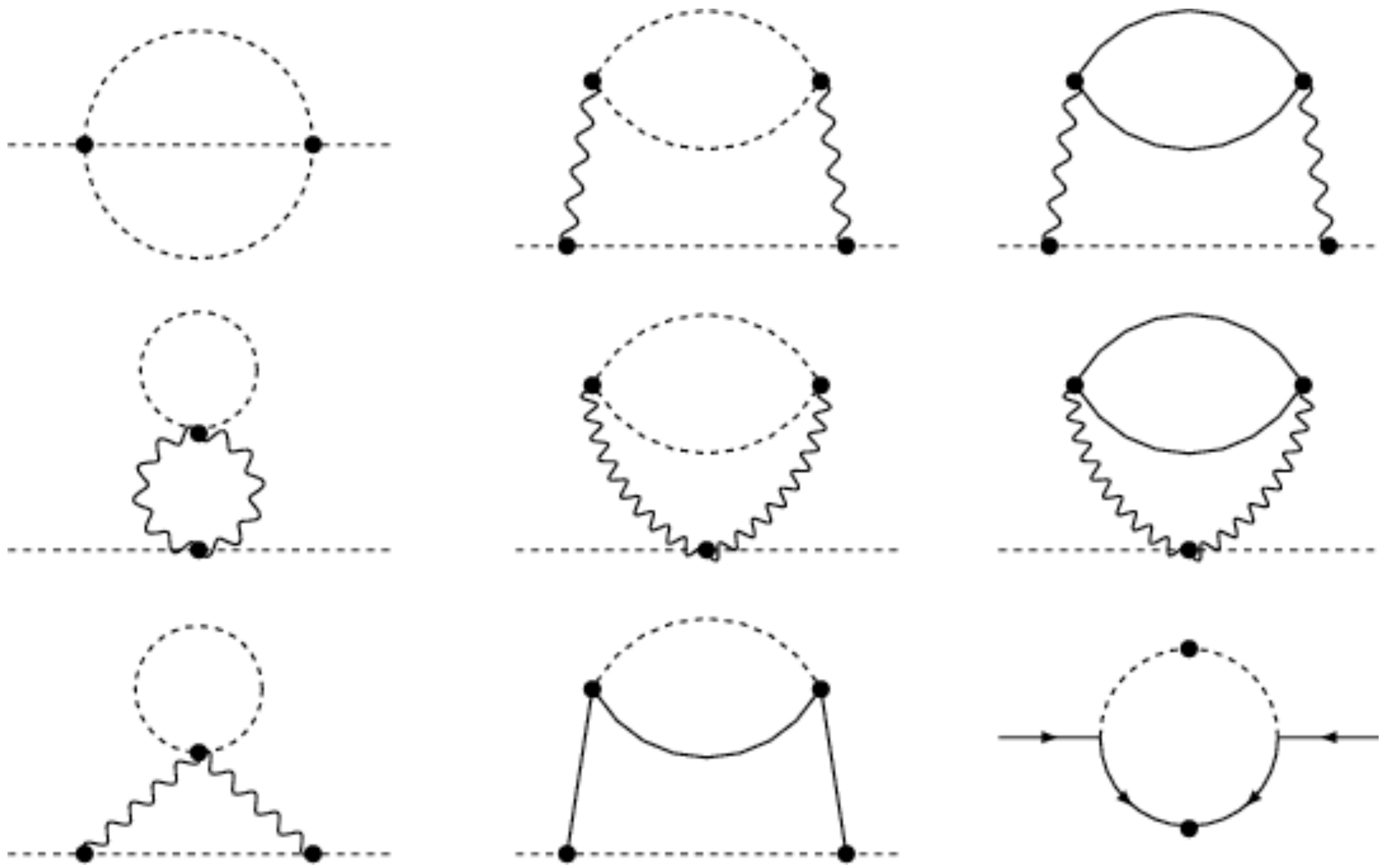




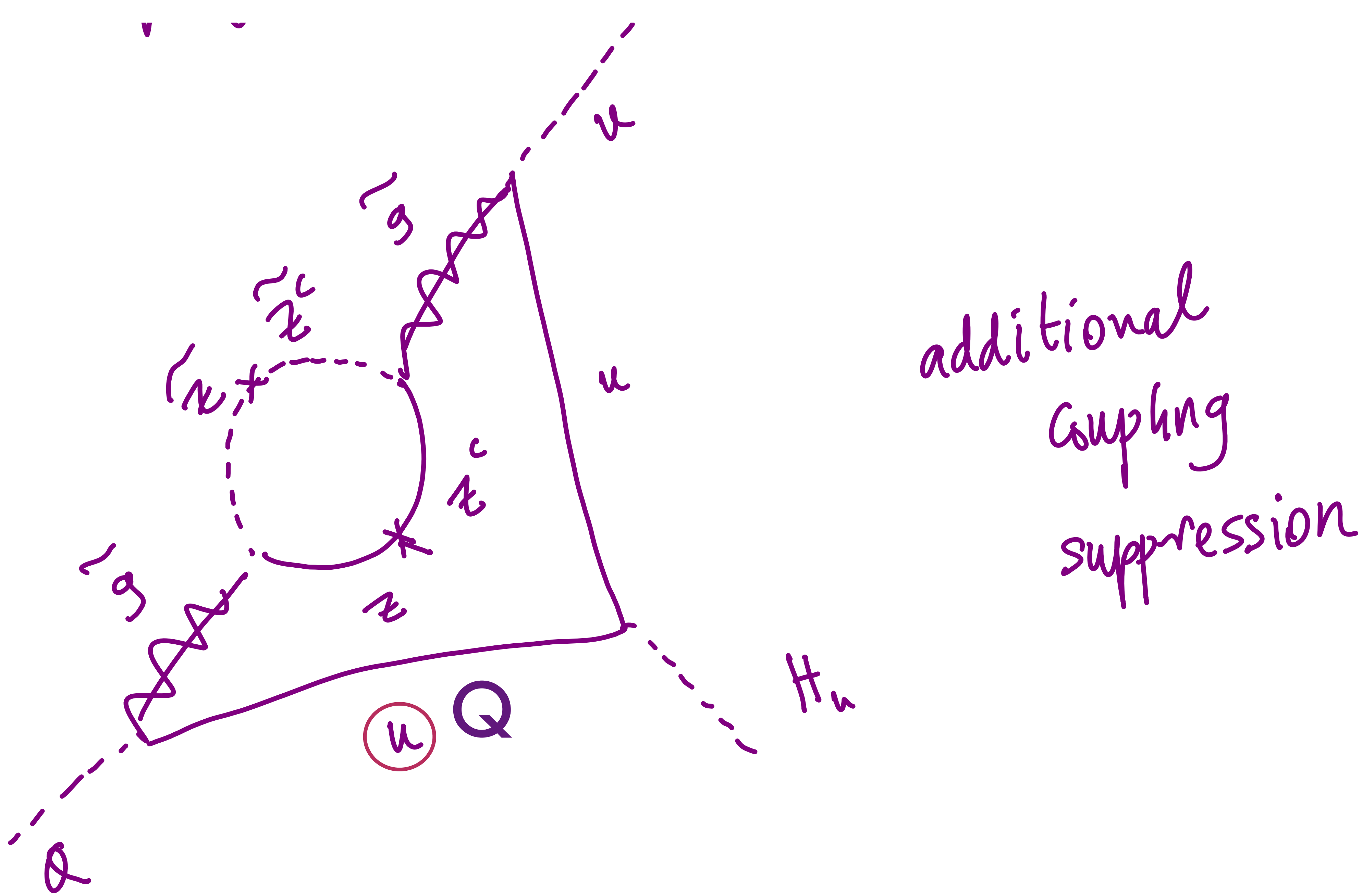
Soft masses in MSSM through loops

+ - - bunch of two loop diagrams

Two loop diagrams contributing to soft masses



Trilinear Couplings



A-terms are essentially zero !!!

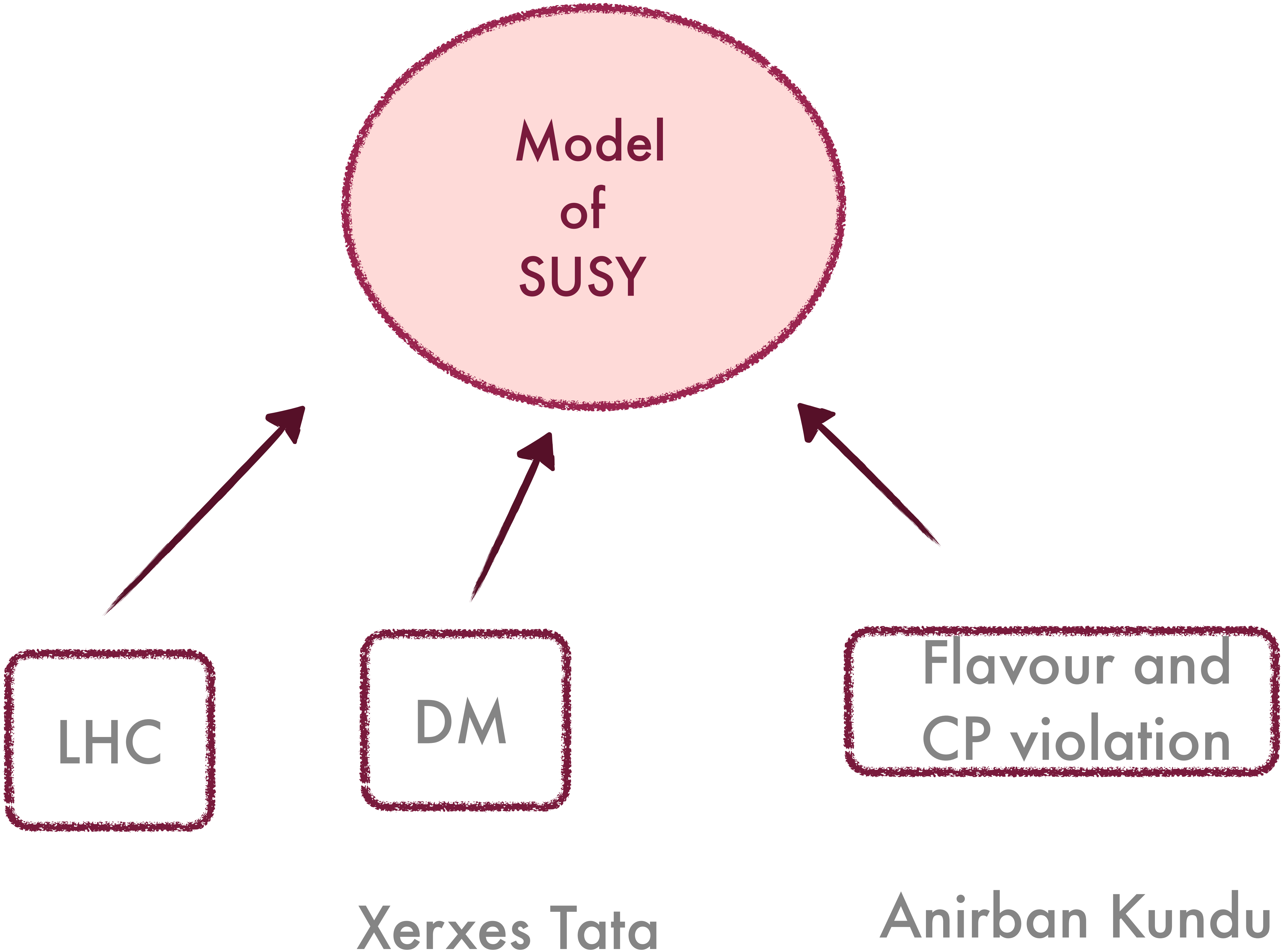
Non-Traditional Models

- 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,
  Choi et.al , Nilles et.al
- F-Theory Inspired Models (more gauge Mediation)
  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


Model
of
SUSY
LHC
DM
Flavour and
CP violation
Xerxes Tata
Anirban Kundu

Some SUSY CODES

Spectrum Generators

SPHENO
SOFTSUSY
ISASUSY
SUSPECT
SUSEFLAV

Dark Matter

ISADM
SuperISoRelic
MicroOmegas
Dark SUSY

Flavour Physics

SuperIso
SUSYFLAVOR
SuperLFV
ISABSMU
SUSEFLAV

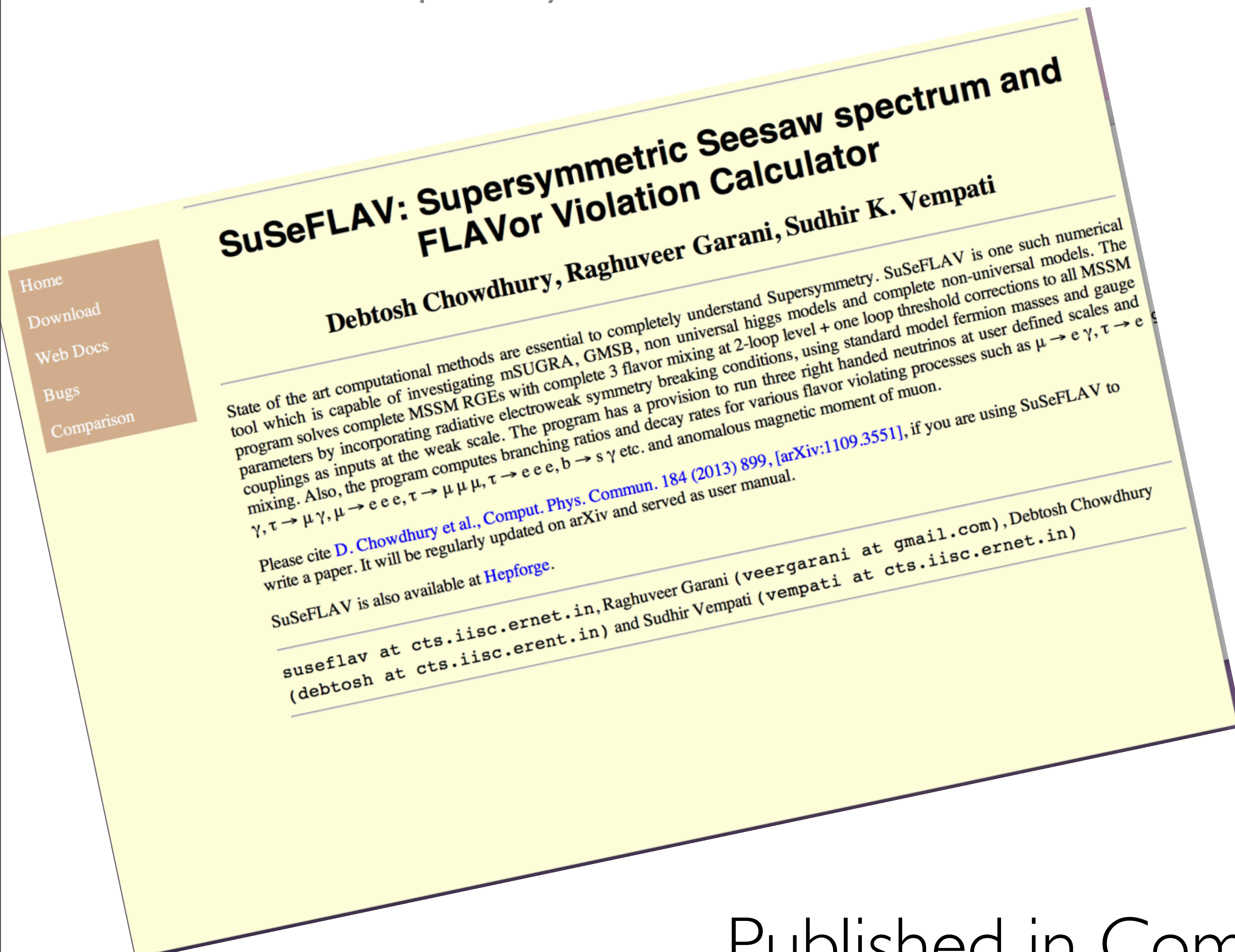
Collider Physics

ISAJET
Prospino
Higlu
SUSHI
MADGRAPH

http://www.hepforge.org

SuSeFLAV

SUpersymmetric SEesaw and Flavour Violation



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Bugs
Comparison

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, $\tau \to \mu\gamma$, $\mu \to e e e$, $\tau \to \mu\mu\mu$, $\tau \to e e e$, $b \to s\gamma$ 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

Computing with SUSEFLAV

**Extremely* user friendly *

Full Two loop RGE including Flavour (CKM, user defined)

Full 1-loop corrections to Sparticle masses

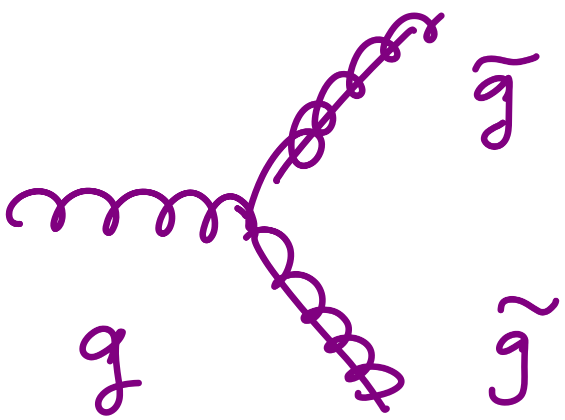
Full 1-loop SUSY threshold corrections to top, bottom and tau

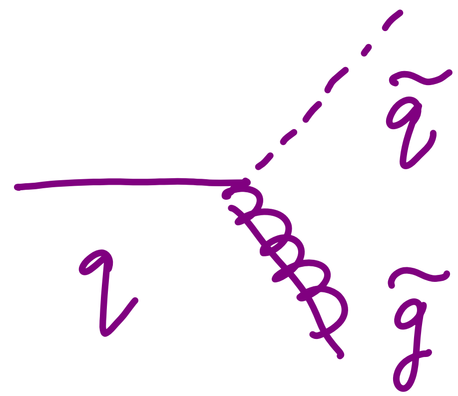
Option to add Type-I and compute lepton flavour violation at the same precision

A lot more to be done, you are welcome to join us

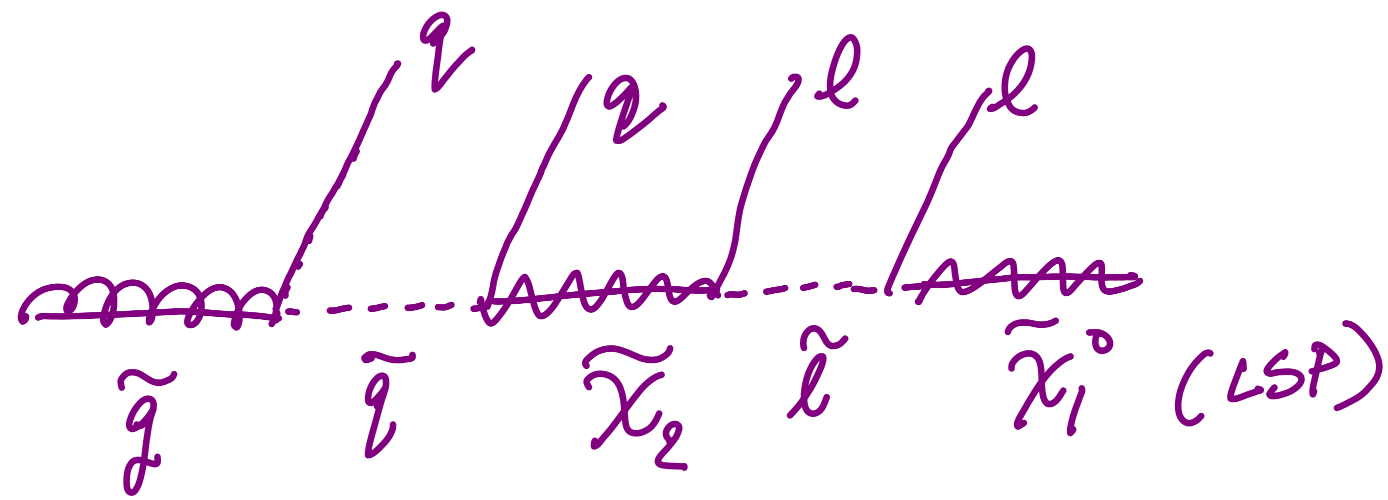
Experimental Status

Large Hadron Collider

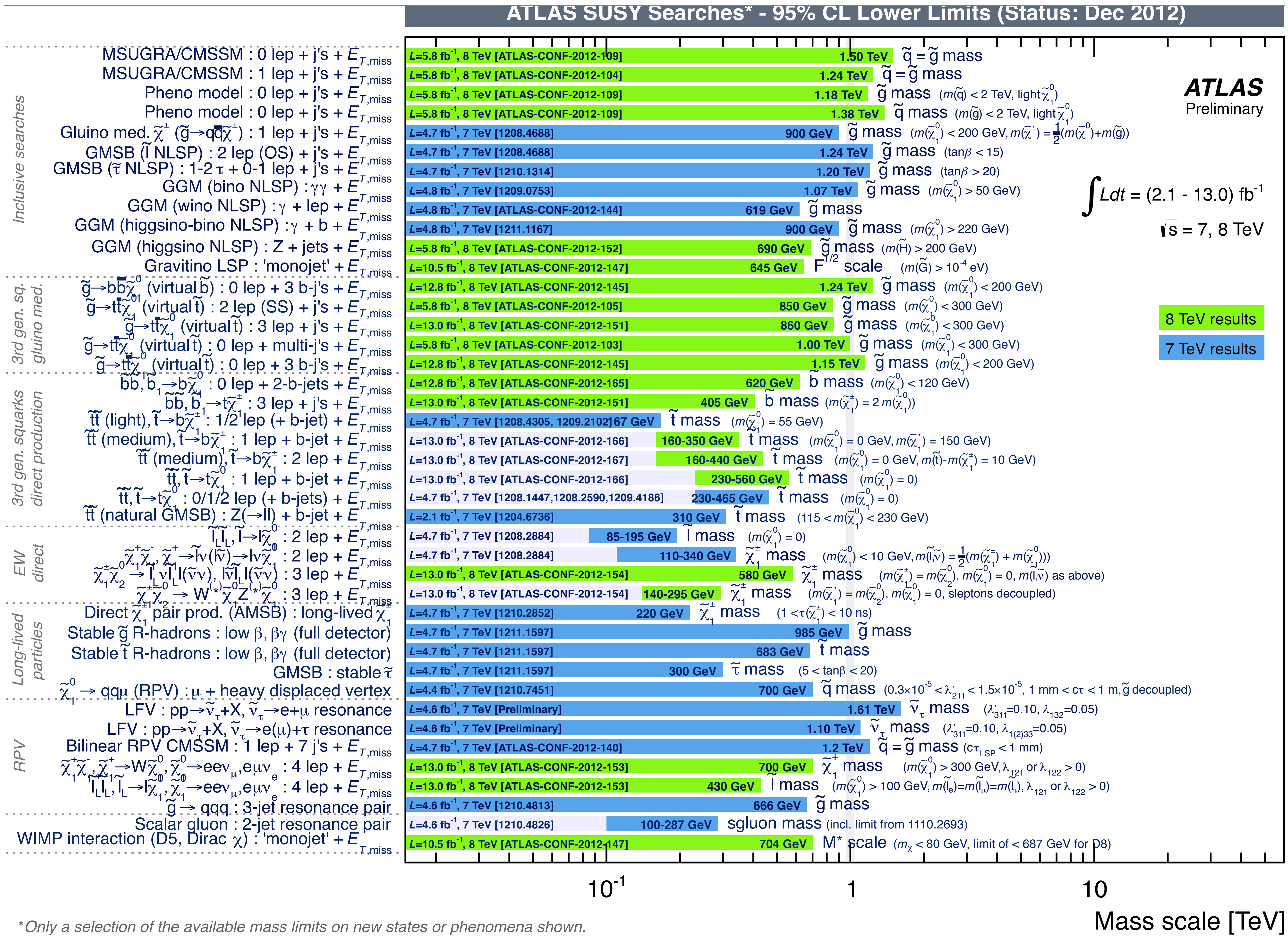


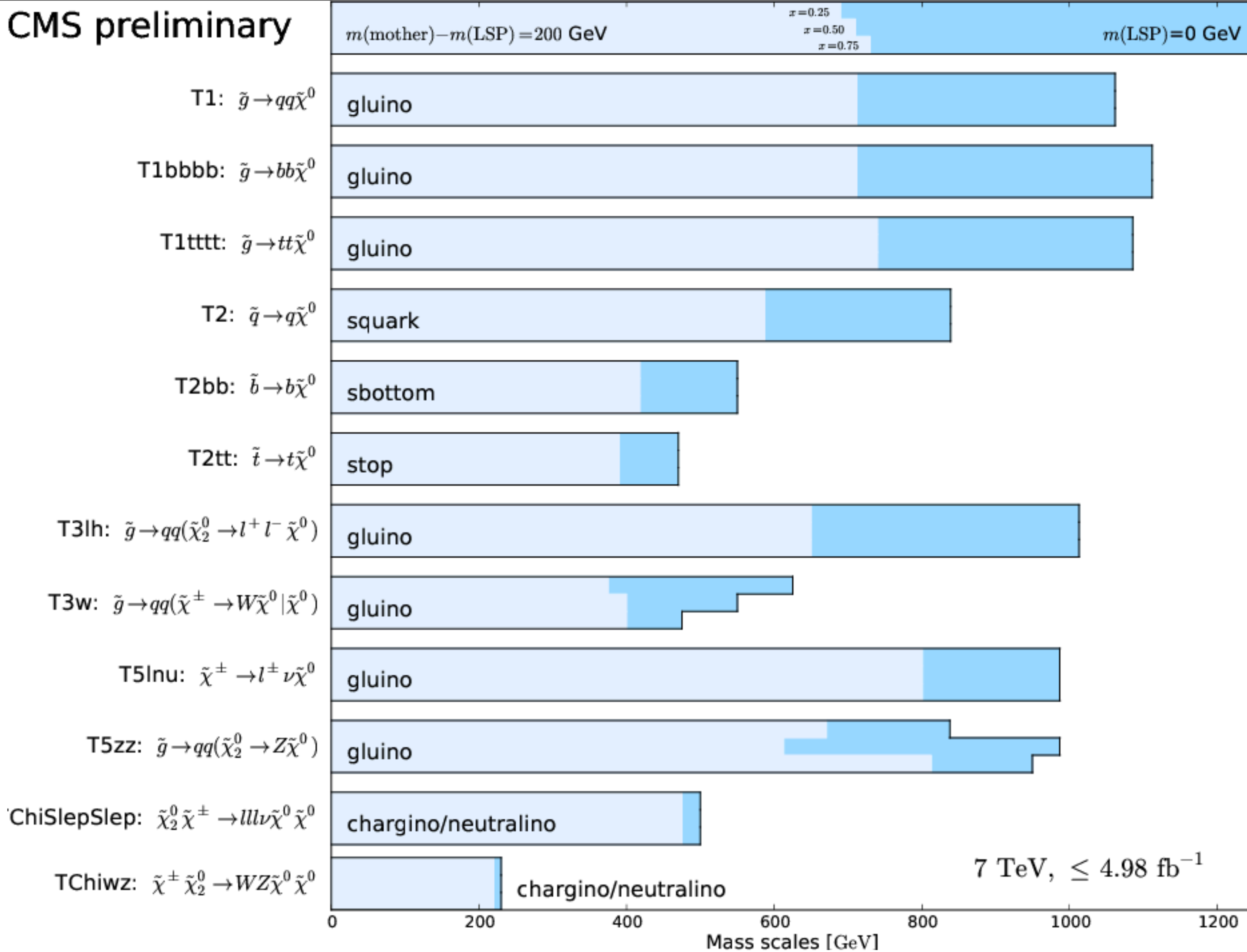


Dominant production sections.



The decay chains depend on mass orderings


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)
ATLAS
Preliminary
∫Ldt = (2.1 - 13.0) fb-1
√s = 7, 8 TeV
8 TeV results
7 TeV results
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + ET,miss | L=5.8 fb-1, 8 TeV [ATLAS-CONF-2012-109] | 1.50 TeV | q̃ = g̃ mass
MSUGRA/CMSSM : 1 lep + j's + ET,miss | L=5.8 fb-1, 8 TeV [ATLAS-CONF-2012-104] | 1.24 TeV | q̃ = g̃ mass
Pheno model : 0 lep + j's + ET,miss | L=5.8 fb-1, 8 TeV [ATLAS-CONF-2012-109] | 1.18 TeV | g̃ mass (m(q̃) < 2 TeV, light χ̃10)
Pheno model : 0 lep + j's + ET,miss | L=5.8 fb-1, 8 TeV [ATLAS-CONF-2012-109] | 1.38 TeV | q̃ mass (m(g̃) < 2 TeV, light χ̃10)
Gluino med. χ̃± (g̃→qq̄χ̃±) : 1 lep + j's + ET,miss | L=4.7 fb-1, 7 TeV [1208.4688] | 900 GeV | g̃ mass (m(χ̃10) < 200 GeV, m(χ̃±) = 1/2(m(χ̃10)+m(g̃))
GMSB (l̃ NLSP) : 2 lep (OS) + j's + ET,miss | L=4.7 fb-1, 7 TeV [1208.4688] | 1.24 TeV | g̃ mass (tanβ < 15)
GMSB (τ̃ NLSP) : 1-2 τ + 0-1 lep + j's + ET,miss | L=4.7 fb-1, 7 TeV [1210.1314] | 1.20 TeV | g̃ mass (tanβ > 20)
GGM (bino NLSP) : γγ + ET,miss | L=4.8 fb-1, 7 TeV [1209.0753] | 1.07 TeV | g̃ mass (m(χ̃10) > 50 GeV)
GGM (wino NLSP) : γ + lep + ET,miss | L=4.8 fb-1, 7 TeV [ATLAS-CONF-2012-144] | 619 GeV | g̃ mass
GGM (higgsino-bino NLSP) : γ + b + ET,miss | L=4.8 fb-1, 7 TeV [1211.1167] | 900 GeV | g̃ mass (m(χ̃10) > 220 GeV)
GGM (higgsino NLSP) : Z + jets + ET,miss | L=5.8 fb-1, 8 TeV [ATLAS-CONF-2012-152] | 690 GeV | g̃ mass (m(H̃) > 200 GeV)
Gravitino LSP : 'monojet' + ET,miss | L=10.5 fb-1, 8 TeV [ATLAS-CONF-2012-147] | 645 GeV | F1/2 scale (m(G̃) > 10-4 eV)
3rd gen. sq. gluino med.
g̃→bb̄χ̃10 (virtual b̃) : 0 lep + 3 b-j's + ET,miss | L=12.8 fb-1, 8 TeV [ATLAS-CONF-2012-145] | 1.24 TeV | g̃ mass (m(χ̃10) < 200 GeV)
g̃→tt̄χ̃10 (virtual t̃) : 2 lep (SS) + j's + ET,miss | L=5.8 fb-1, 8 TeV [ATLAS-CONF-2012-105] | 850 GeV | g̃ mass (m(χ̃10) < 300 GeV)
g̃→tt̄χ̃10 (virtual t̃) : 3 lep + j's + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-151] | 860 GeV | g̃ mass (m(χ̃10) < 300 GeV)
g̃→tt̄χ̃10 (virtual t̃) : 0 lep + multi-j's + ET,miss | L=5.8 fb-1, 8 TeV [ATLAS-CONF-2012-103] | 1.00 TeV | g̃ mass (m(χ̃10) < 300 GeV)
g̃→tt̄χ̃10 (virtual t̃) : 0 lep + 3 b-j's + ET,miss | L=12.8 fb-1, 8 TeV [ATLAS-CONF-2012-145] | 1.15 TeV | g̃ mass (m(χ̃10) < 200 GeV)
3rd gen. squarks direct production
b̃b̃, b̃1→bχ̃10 : 0 lep + 2-b-jets + ET,miss | L=12.8 fb-1, 8 TeV [ATLAS-CONF-2012-165] | 620 GeV | b̃ mass (m(χ̃10) < 120 GeV)
b̃b̃, b̃1→tχ̃1± : 3 lep + j's + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-151] | 405 GeV | b̃ mass (m(χ̃1±) = 2 m(χ̃10))
t̃t̃ (light), t̃→bχ̃1± : 1/2 lep (+ b-jet) + ET,miss | L=4.7 fb-1, 7 TeV [1208.4305, 1209.2102] | 167 GeV | t̃ mass (m(χ̃10) = 55 GeV)
t̃t̃ (medium), t̃→bχ̃1± : 1 lep + b-jet + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-166] | 160-350 GeV | t̃ mass (m(χ̃10) = 0 GeV, m(χ̃1±) = 150 GeV)
t̃t̃ (medium), t̃→bχ̃1± : 2 lep + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-167] | 160-440 GeV | t̃ mass (m(χ̃10) = 0 GeV, m(t̃)-m(χ̃1±) = 10 GeV)
t̃t̃, t̃→tχ̃10 : 1 lep + b-jet + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-166] | 230-560 GeV | t̃ mass (m(χ̃10) = 0)
t̃t̃, t̃→tχ̃10 : 0/1/2 lep (+ b-jets) + ET,miss | L=4.7 fb-1, 7 TeV [1208.1447,1208.2590,1209.4186] | 230-465 GeV | t̃ mass (m(χ̃10) = 0)
t̃t̃ (natural GMSB) : Z(→ll) + b-jet + ET,miss | L=2.1 fb-1, 7 TeV [1204.6736] | 310 GeV | t̃ mass (115 < m(χ̃10) < 230 GeV)
EW direct
l̃Ll̃L, l̃→lχ̃10 : 2 lep + ET,miss | L=4.7 fb-1, 7 TeV [1208.2884] | 85-195 GeV | l̃ mass (m(χ̃10) = 0)
χ̃1+χ̃1-, χ̃1+→l̃ν(lν̃)→lνχ̃10 : 2 lep + ET,miss | L=4.7 fb-1, 7 TeV [1208.2884] | 110-340 GeV | χ̃1± mass (m(χ̃10) < 10 GeV, m(l̃,ν̃) = 1/2(m(χ̃1±) + m(χ̃10)))
χ̃1±χ̃20 → l̃Lνl̃Ll(ν̃ν), lν̃l̃Ll(ν̃ν) : 3 lep + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-154] | 580 GeV | χ̃1± mass (m(χ̃1±) = m(χ̃20), m(χ̃10) = 0, m(l̃,ν̃) as above)
χ̃1±χ̃20 → W(*)χ̃10Z(*)χ̃10 : 3 lep + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-154] | 140-295 GeV | χ̃1± mass (m(χ̃1±) = m(χ̃20), m(χ̃10) = 0, sleptons decoupled)
Long-lived particles
Direct χ̃1± pair prod. (AMSB) : long-lived χ̃1± | L=4.7 fb-1, 7 TeV [1210.2852] | 220 GeV | χ̃1± mass (1 < τ(χ̃1±) < 10 ns)
Stable g̃ R-hadrons : low β, βγ (full detector) | L=4.7 fb-1, 7 TeV [1211.1597] | 985 GeV | g̃ mass
Stable t̃ R-hadrons : low β, βγ (full detector) | L=4.7 fb-1, 7 TeV [1211.1597] | 683 GeV | t̃ mass
GMSB : stable τ̃ | L=4.7 fb-1, 7 TeV [1211.1597] | 300 GeV | τ̃ mass (5 < tanβ < 20)
χ̃10 → qqμ (RPV) : μ + heavy displaced vertex | L=4.4 fb-1, 7 TeV [1210.7451] | 700 GeV | q̃ mass (0.3×10-5 < λ'211 < 1.5×10-5, 1 mm < cτ < 1 m, g̃ decoupled)
RPV
LFV : pp→ν̃τ+X, ν̃τ→e+μ resonance | L=4.6 fb-1, 7 TeV [Preliminary] | 1.61 TeV | ν̃τ mass (λ'311=0.10, λ132=0.05)
LFV : pp→ν̃τ+X, ν̃τ→e(μ)+τ resonance | L=4.6 fb-1, 7 TeV [Preliminary] | 1.10 TeV | ν̃τ mass (λ'311=0.10, λ1(2)33=0.05)
Bilinear RPV CMSSM : 1 lep + 7 j's + ET,miss | L=4.7 fb-1, 7 TeV [ATLAS-CONF-2012-140] | 1.2 TeV | q̃ = g̃ mass (cτLSP < 1 mm)
χ̃1+χ̃1-, χ̃1+→Wχ̃10, χ̃10→eeνμ, eμνe : 4 lep + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-153] | 700 GeV | χ̃1+ mass (m(χ̃10) > 300 GeV, λ121 or λ122 > 0)
l̃Ll̃L, l̃L→lχ̃10, χ̃10→eeνμ, eμνe : 4 lep + ET,miss | L=13.0 fb-1, 8 TeV [ATLAS-CONF-2012-153] | 430 GeV | l̃ mass (m(χ̃10) > 100 GeV, m(l̃e)=m(l̃μ)=m(l̃τ), λ121 or λ122 > 0)
g̃ → qqq : 3-jet resonance pair | L=4.6 fb-1, 7 TeV [1210.4813] | 666 GeV | g̃ mass
Scalar gluon : 2-jet resonance pair | L=4.6 fb-1, 7 TeV [1210.4826] | 100-287 GeV | sgluon mass (incl. limit from 1110.2693)
WIMP interaction (D5, Dirac χ) : 'monojet' + ET,miss | L=10.5 fb-1, 8 TeV [ATLAS-CONF-2012-147] | 704 GeV | M* scale (mχ < 80 GeV, limit of < 687 GeV for D8)
10-1
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.


CMS preliminary
$m(\mathrm{mother}) - m(\mathrm{LSP}) = 200$ GeV
$x = 0.25$
$x = 0.50$
$x = 0.75$
$m(\mathrm{LSP}) = 0$ GeV
T1: $\tilde{g} \to qq\tilde{\chi}^0$
gluino
T1bbbb: $\tilde{g} \to bb\tilde{\chi}^0$
gluino
T1tttt: $\tilde{g} \to tt\tilde{\chi}^0$
gluino
T2: $\tilde{q} \to q\tilde{\chi}^0$
squark
T2bb: $\tilde{b} \to b\tilde{\chi}^0$
sbottom
T2tt: $\tilde{t} \to t\tilde{\chi}^0$
stop
T3lh: $\tilde{g} \to qq(\tilde{\chi}^0_2 \to l^+ l^- \tilde{\chi}^0)$
gluino
T3w: $\tilde{g} \to qq(\tilde{\chi}^\pm \to W\tilde{\chi}^0 | \tilde{\chi}^0)$
gluino
T5lnu: $\tilde{\chi}^\pm \to l^\pm \nu \tilde{\chi}^0$
gluino
T5zz: $\tilde{g} \to qq(\tilde{\chi}^0_2 \to Z\tilde{\chi}^0)$
gluino
TChiSlepSlep: $\tilde{\chi}^0_2 \tilde{\chi}^\pm \to lll\nu\tilde{\chi}^0\tilde{\chi}^0$
chargino/neutralino
TChiwz: $\tilde{\chi}^\pm \tilde{\chi}^0_2 \to WZ\tilde{\chi}^0\tilde{\chi}^0$
chargino/neutralino
7 TeV, ≤ 4.98 fb^{-1}
0
200
400
600
800
1000
1200
Mass scales [GeV]

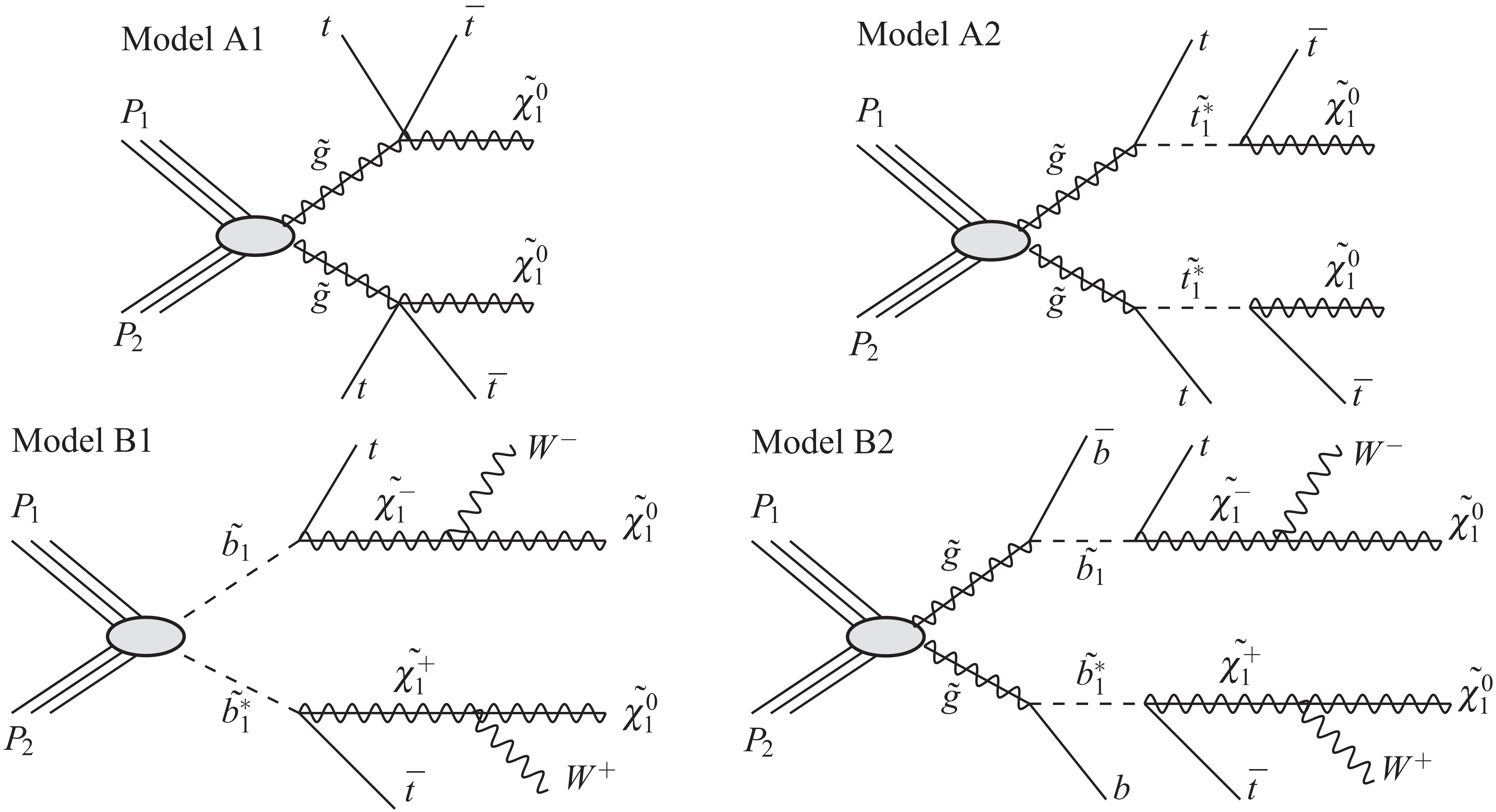
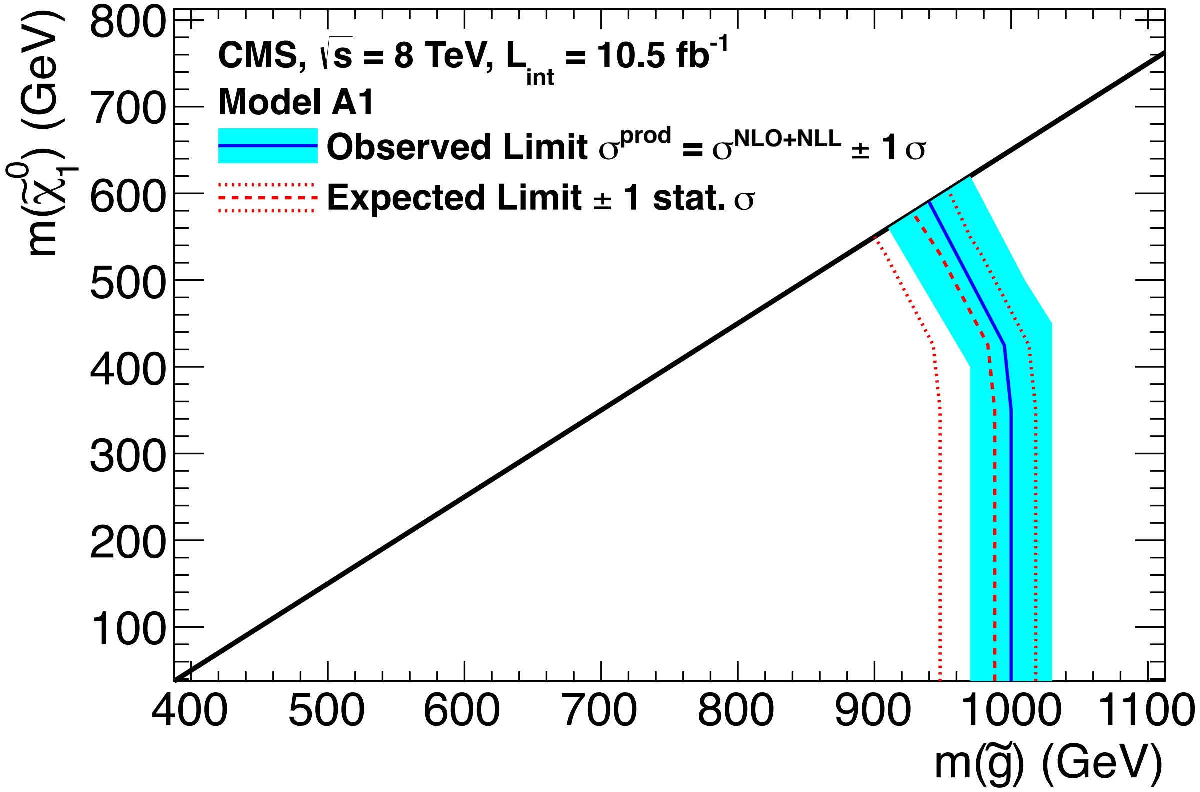
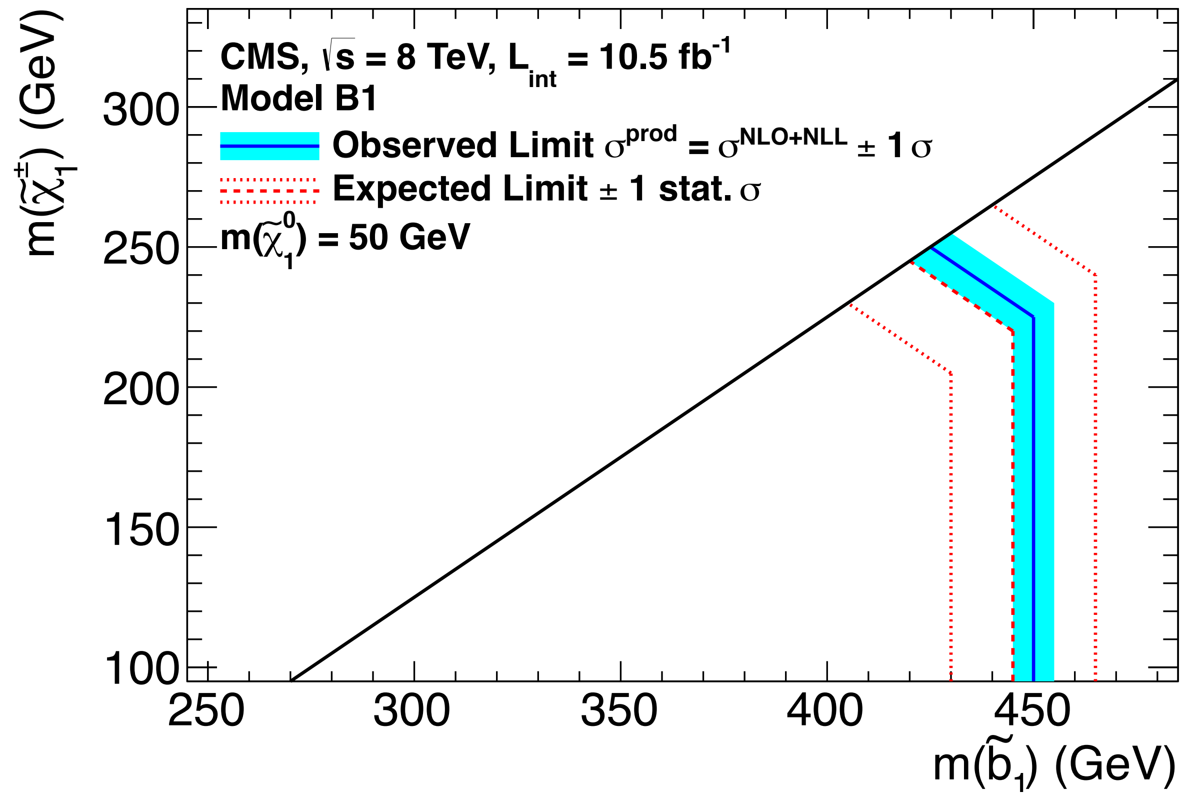
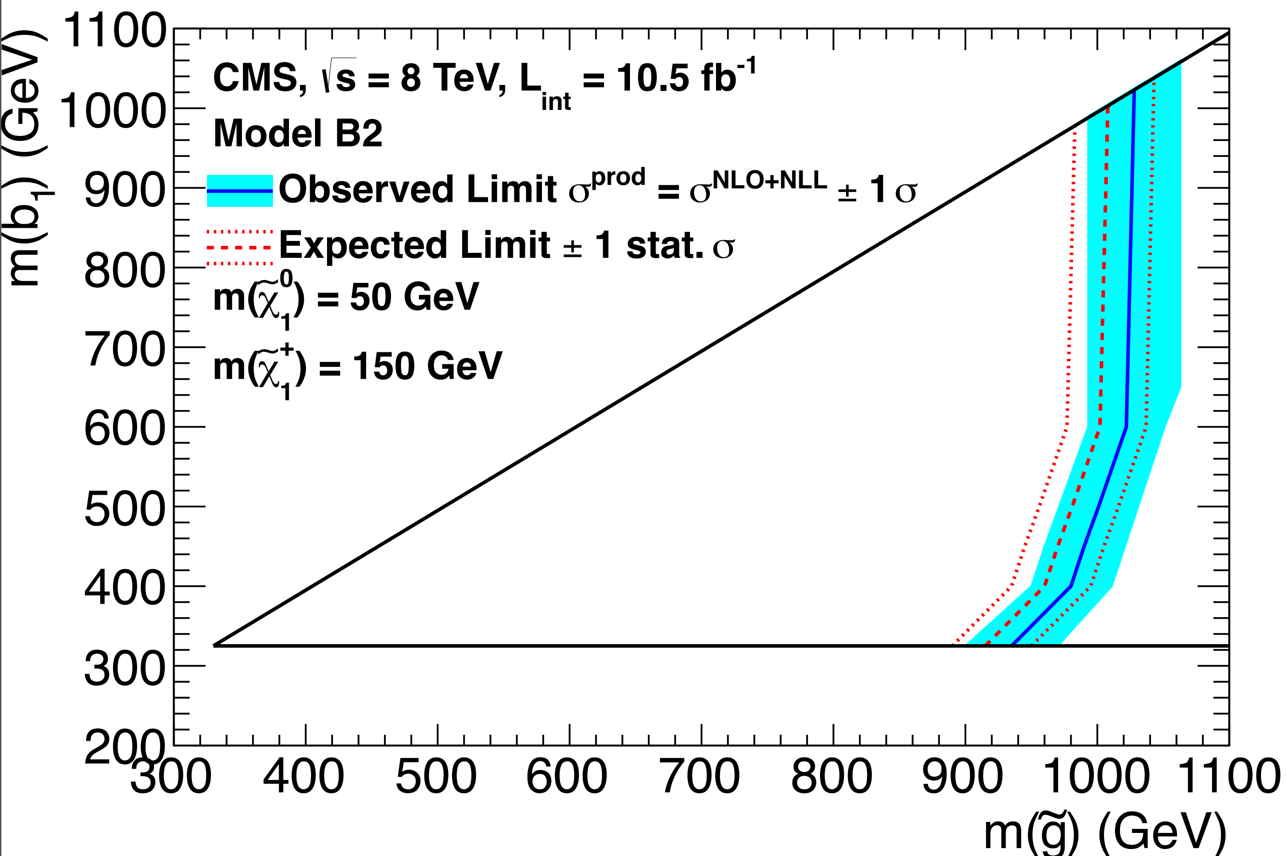
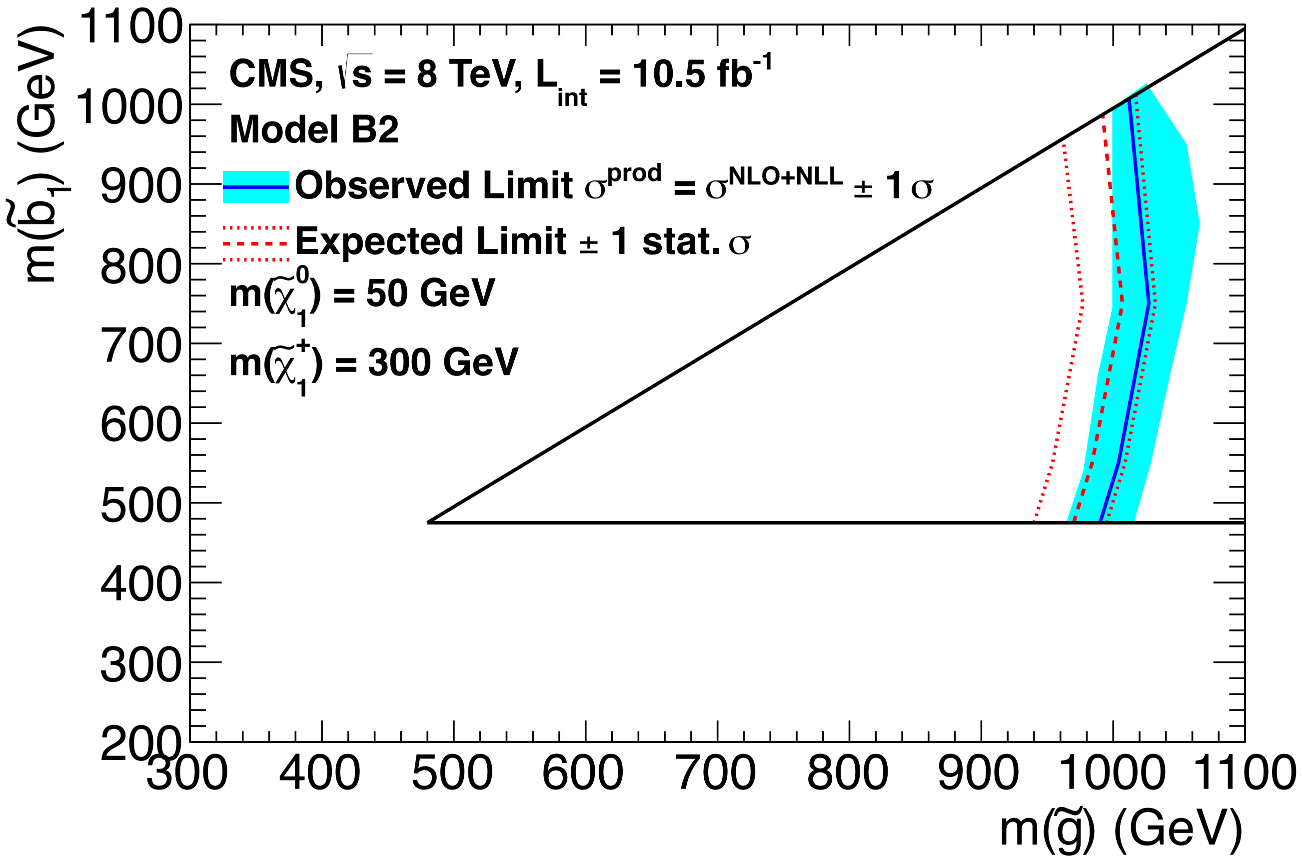


Figure 3: Diagrams for the four SUSY models considered (A1, A2, B1, and B2).


CMS, √s = 8 TeV, L_int = 10.5 fb^-1
Model A1
Observed Limit σ^prod = σ^NLO+NLL ± 1 σ
Expected Limit ± 1 stat. σ
m(χ̃₁⁰) (GeV)
m(g̃) (GeV)


CMS, √s = 8 TeV, L_int = 10.5 fb^-1
Model B1
Observed Limit σ^prod = σ^NLO+NLL ± 1 σ
Expected Limit ± 1 stat. σ
m(χ̃₁⁰) = 50 GeV
m(χ̃₁±) (GeV)
m(b̃₁) (GeV)


CMS, √s = 8 TeV, L_int = 10.5 fb^-1
Model B2
Observed Limit σ^prod = σ^NLO+NLL ± 1 σ
Expected Limit ± 1 stat. σ
m(χ̃₁⁰) = 50 GeV
m(χ̃₁⁺) = 150 GeV
m(b̃₁) (GeV)
m(g̃) (GeV)


CMS, √s = 8 TeV, L_int = 10.5 fb^-1
Model B2
Observed Limit σ^prod = σ^NLO+NLL ± 1 σ
Expected Limit ± 1 stat. σ
m(χ̃₁⁰) = 50 GeV
m(χ̃₁⁺) = 300 GeV
m(b̃₁) (GeV)
m(g̃) (GeV)

Summary

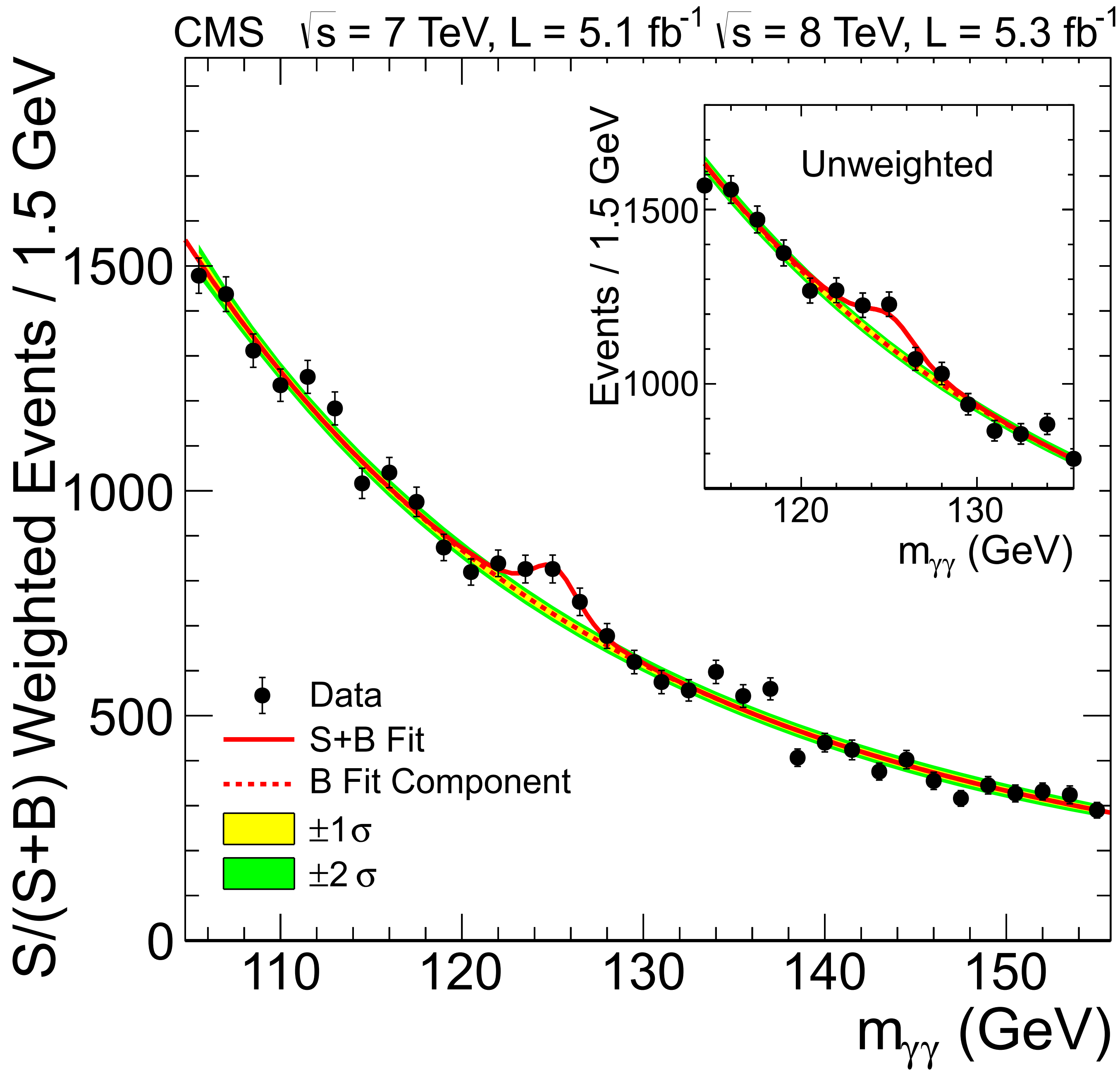
Gluinos are ruled out up to masses 1- 1.25 TeV

Stops and sbottoms are ruled out up to masses 500-600 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

Tao Han's lectures

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

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

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

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

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

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

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

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

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

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

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

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

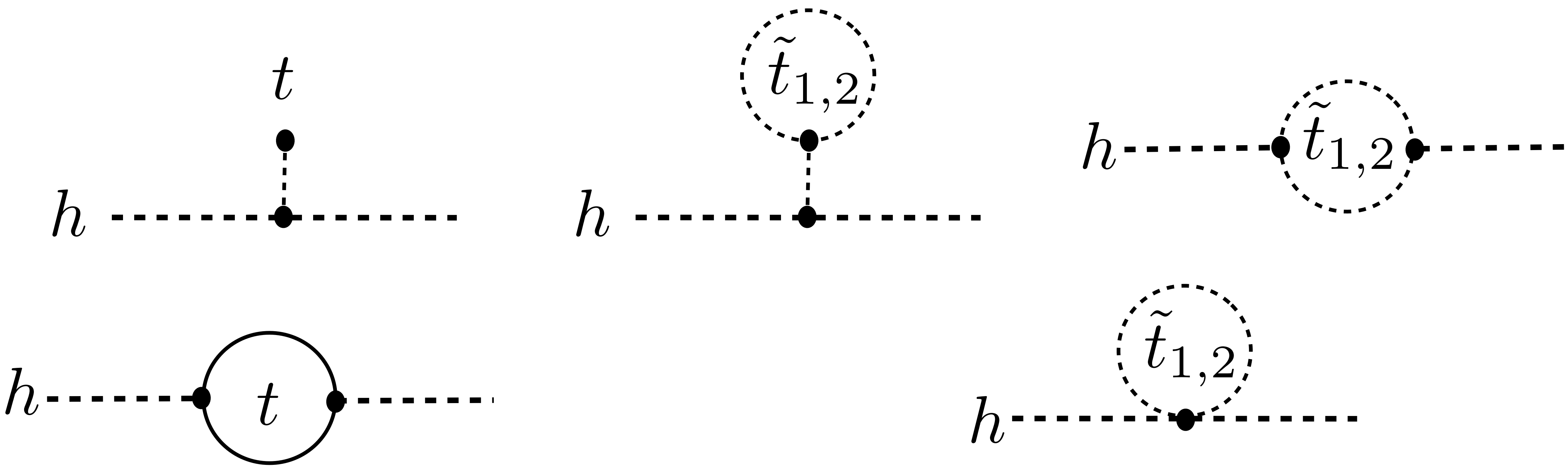
$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

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

at tree level the lightest Higgs mass upper limit is

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

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

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

diagonalizing

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

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

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

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

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

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

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 $\sim m_t^4$

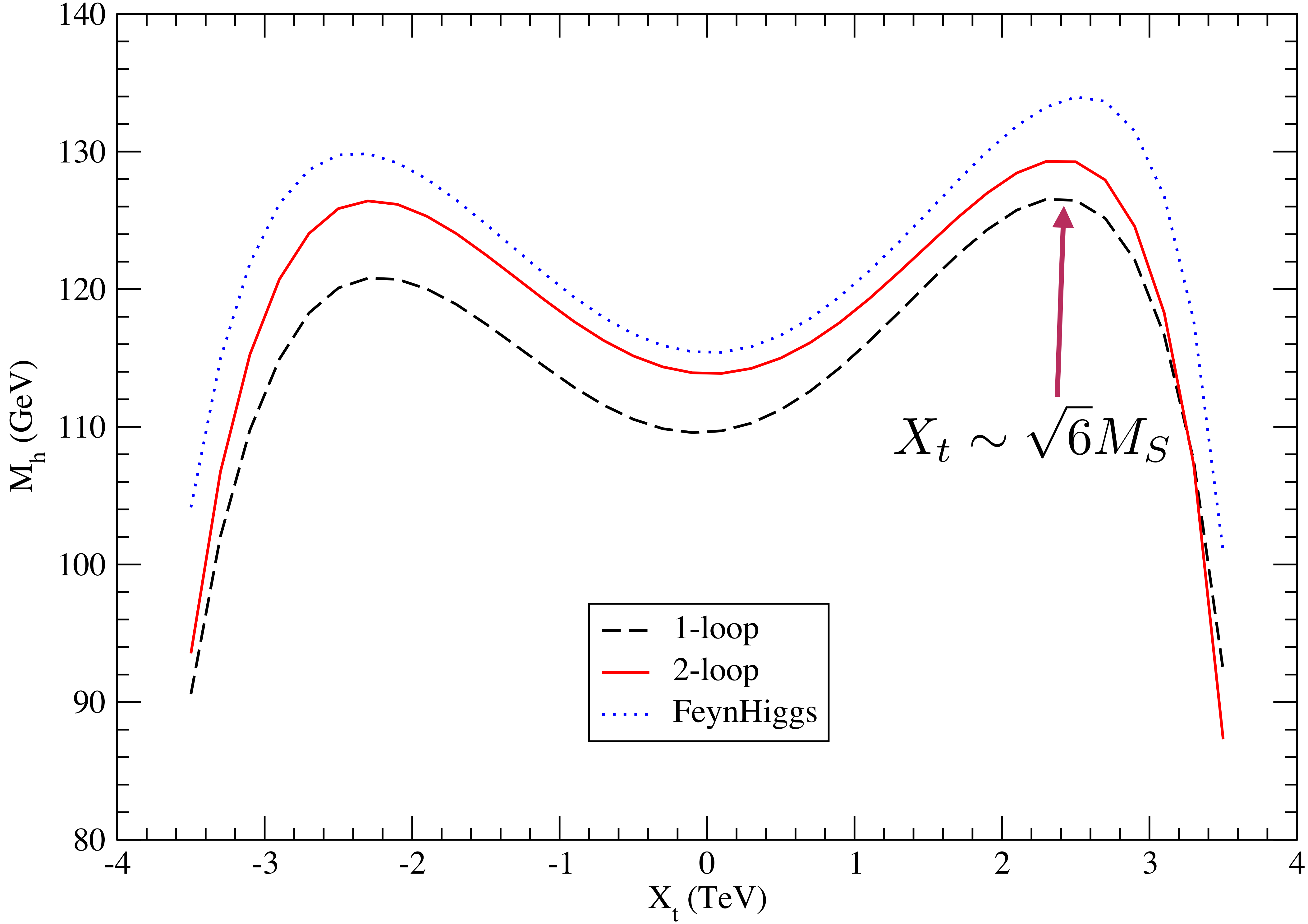
no mixing in the stop sector $\Rightarrow X_t = 0$

Harlander et al. '08
Martin '07

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

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

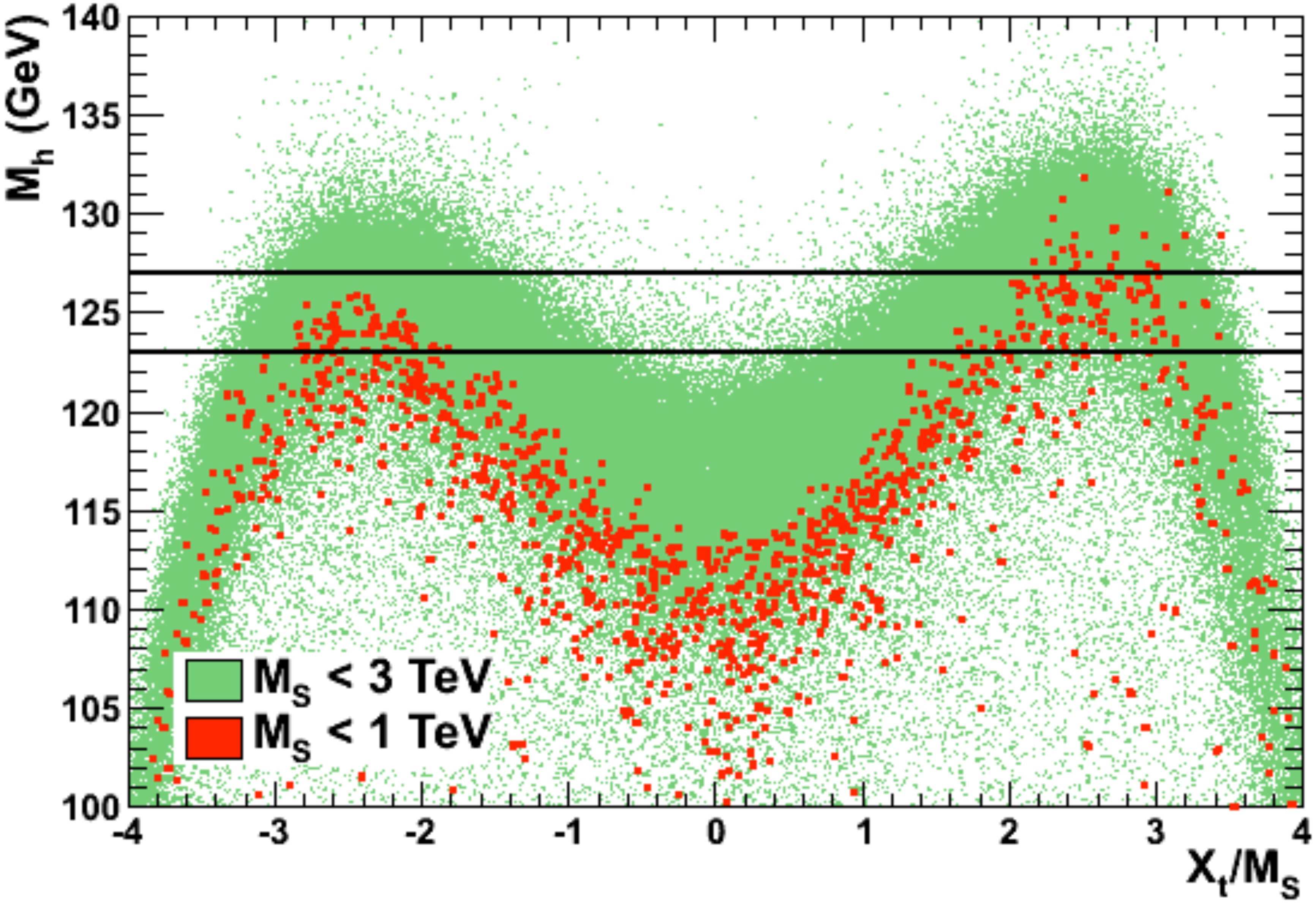
$\tan\beta = 10, M_A = M_S = 1$ TeV **phenomenological models**



Allanach et al. '04

phenomenological models

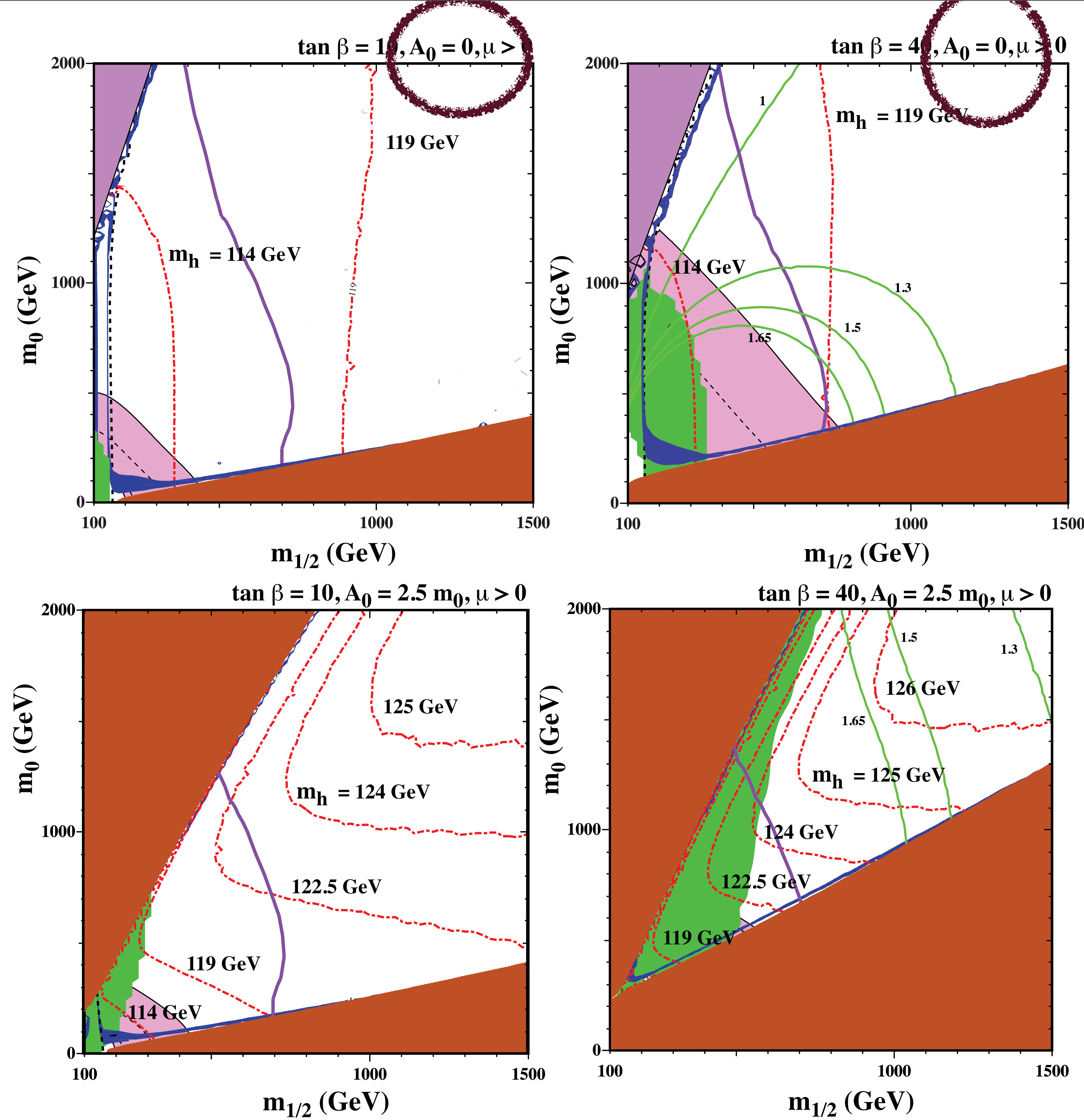
Abrey et al.
1112.3028;
2012 updates



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

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

Constrained Models



Ellis, Olive et.al,
arXiv: 1212.4476

Range we chose

$$m_0 \in [0,\ 5]\ \mathrm{TeV}$$

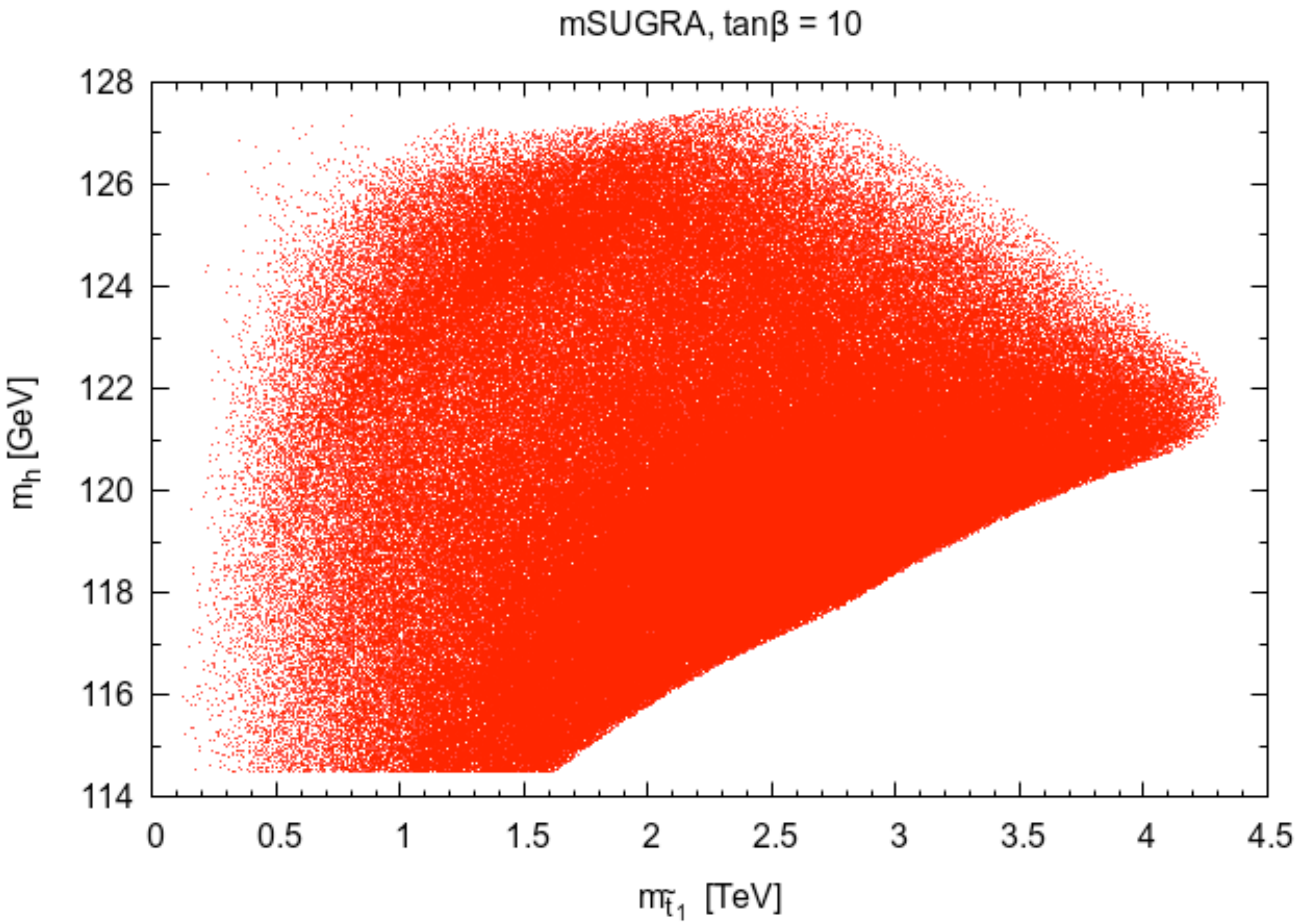
$$\Delta m_H \in \begin{cases} 0 & \text{for mSUGRA} \\ [0,\ 5] & \text{for NUHM1} \end{cases}$$

$$m_{1/2} \in [0.1,\ 2]\ \mathrm{TeV}$$

$$A_0 \in [-3m_0,\ +3m_0]$$

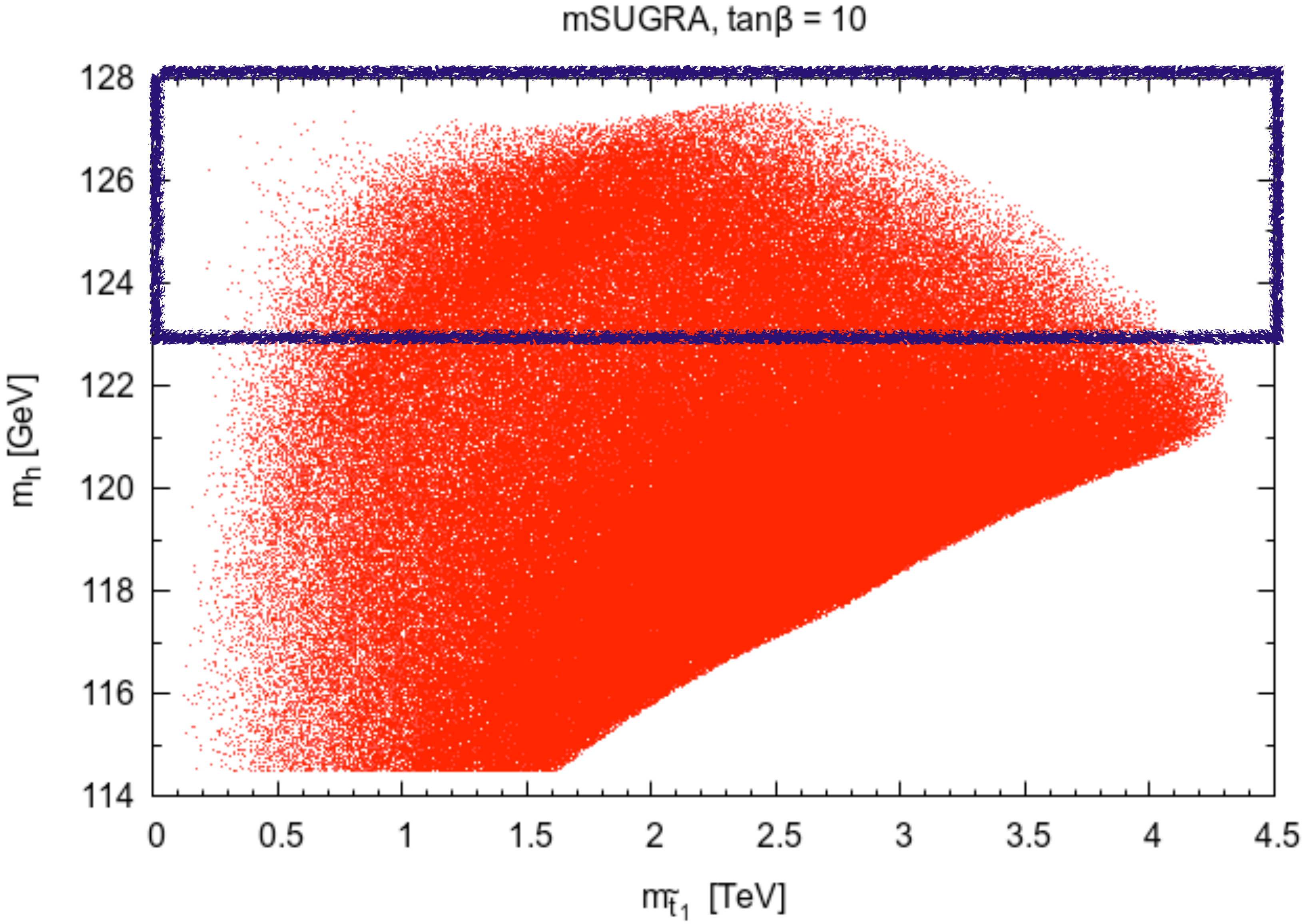
$$\mathrm{sgn}(\mu) \in \{-,+\}$$

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



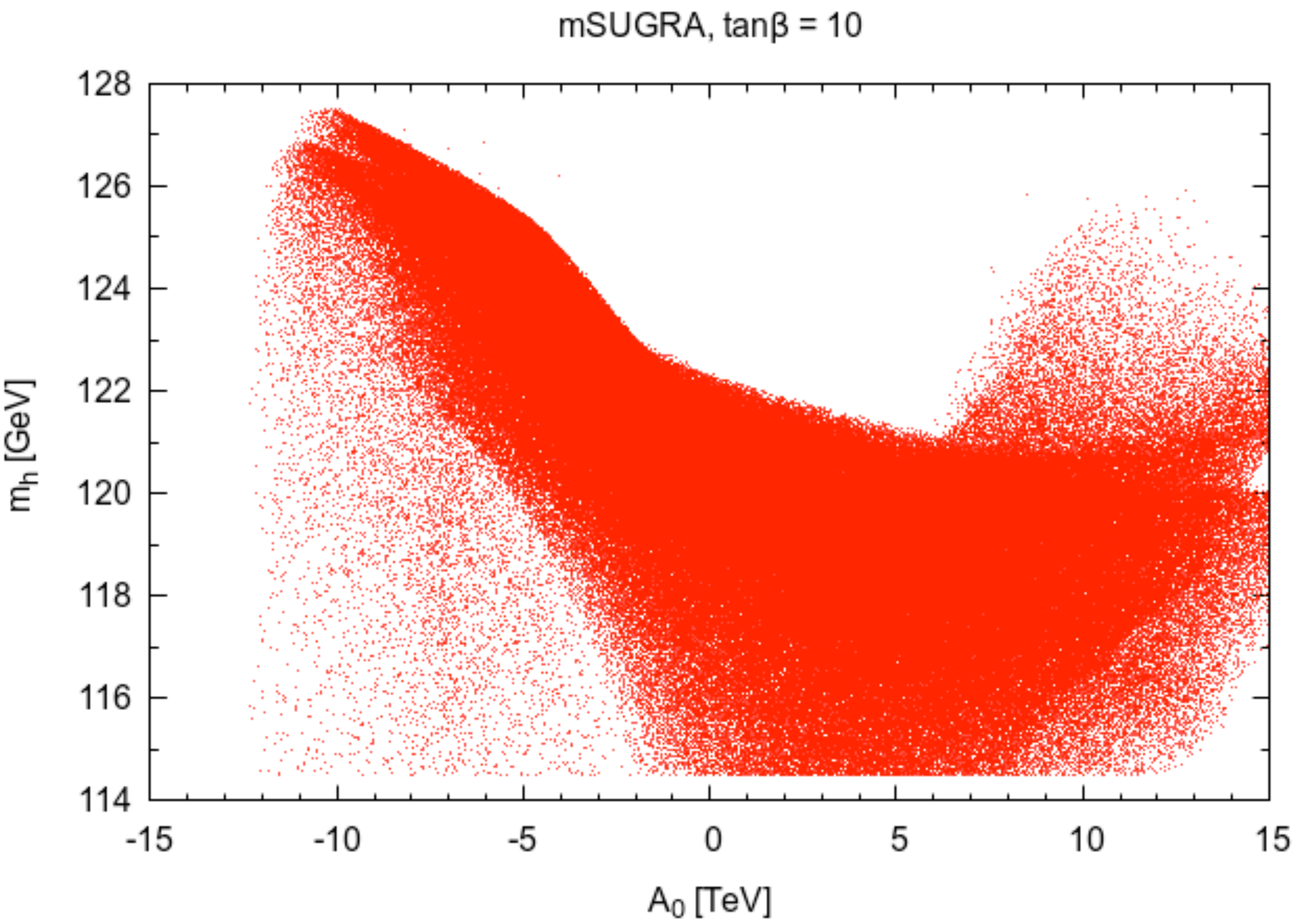
D. Chowdhury, S. Vempati, et. al

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



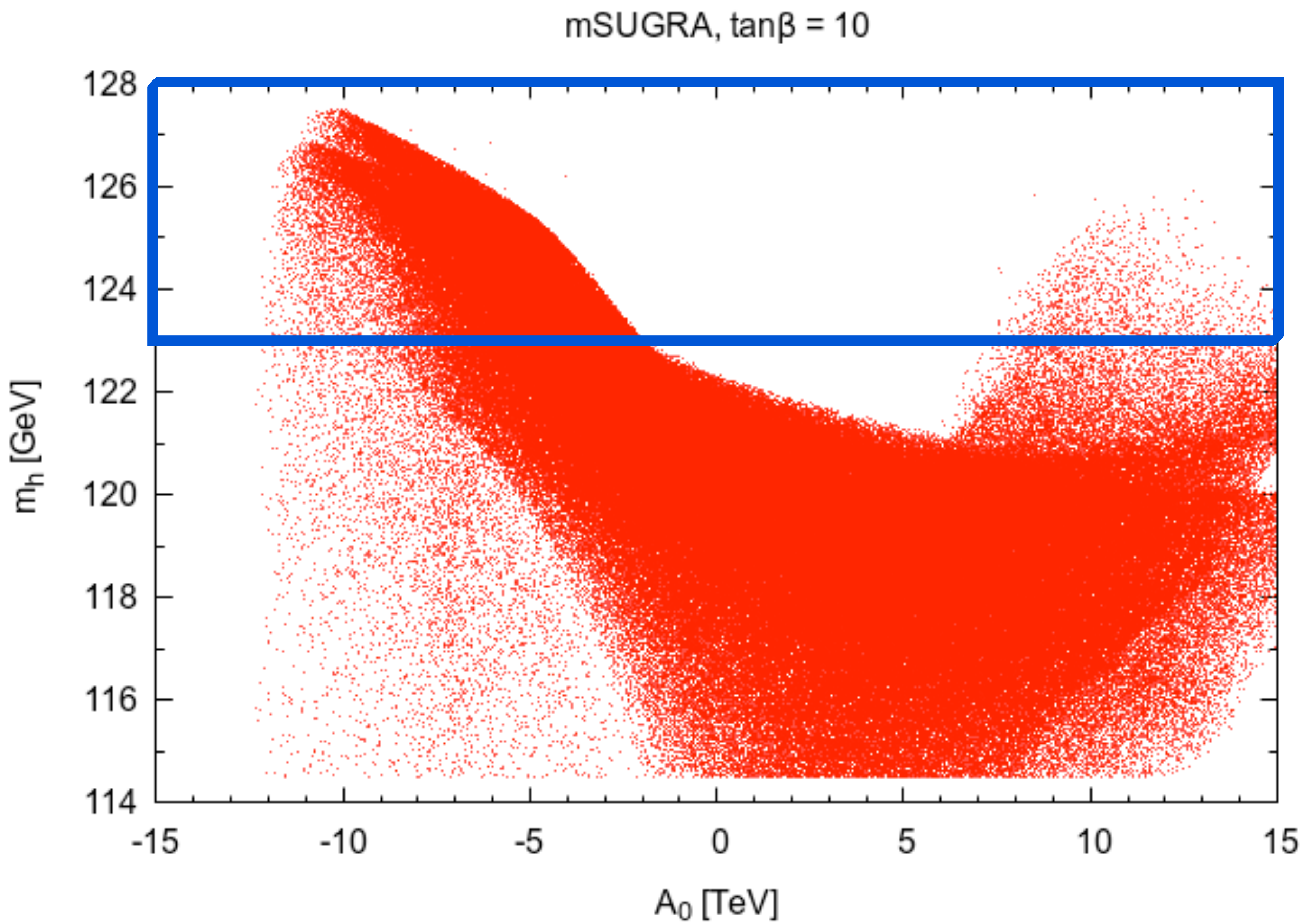
D. Chowdhury, S. Vempati, et. al

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



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

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



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

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

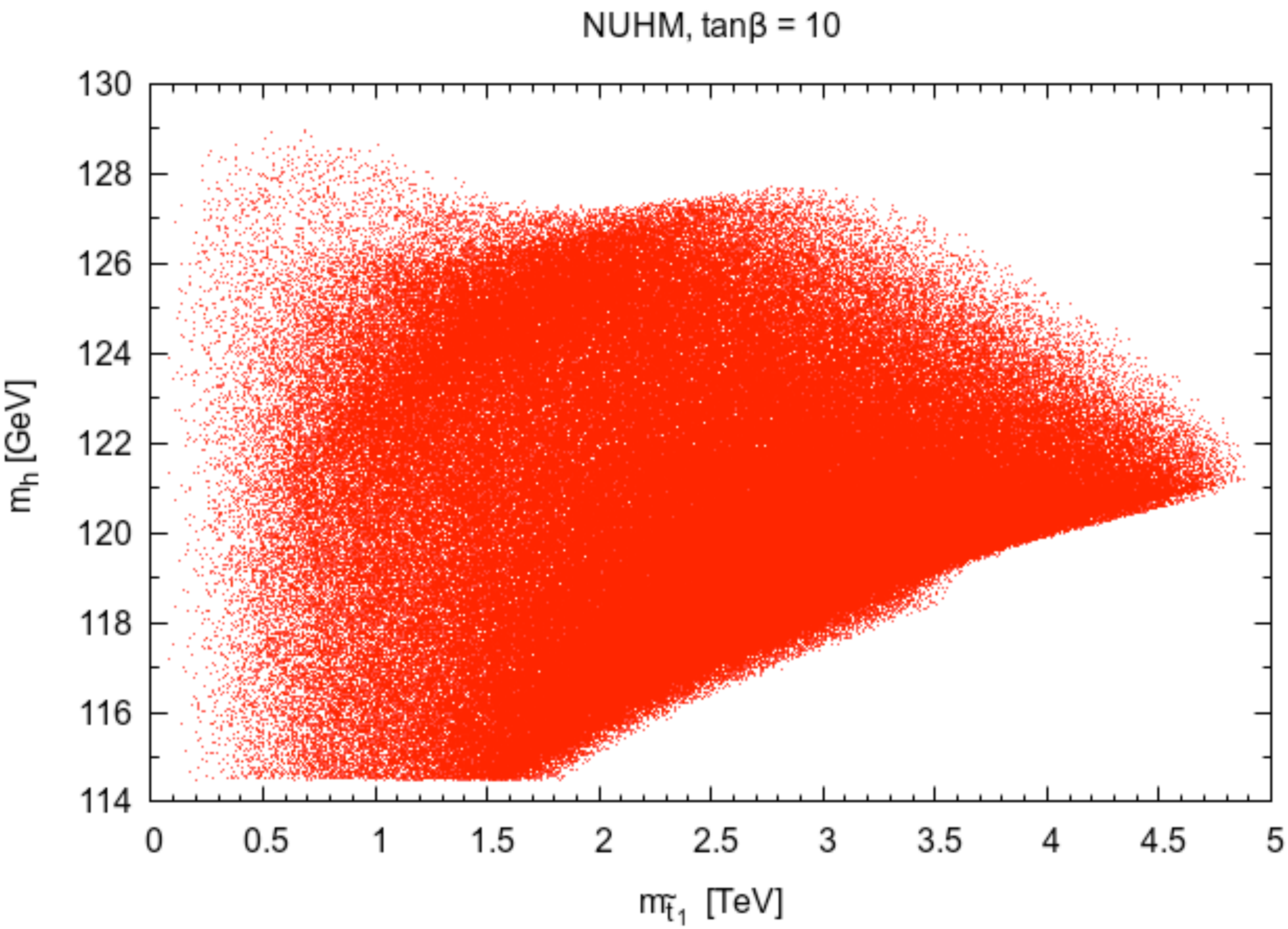
Non-Universal Gaugino models

P. Nath et. al

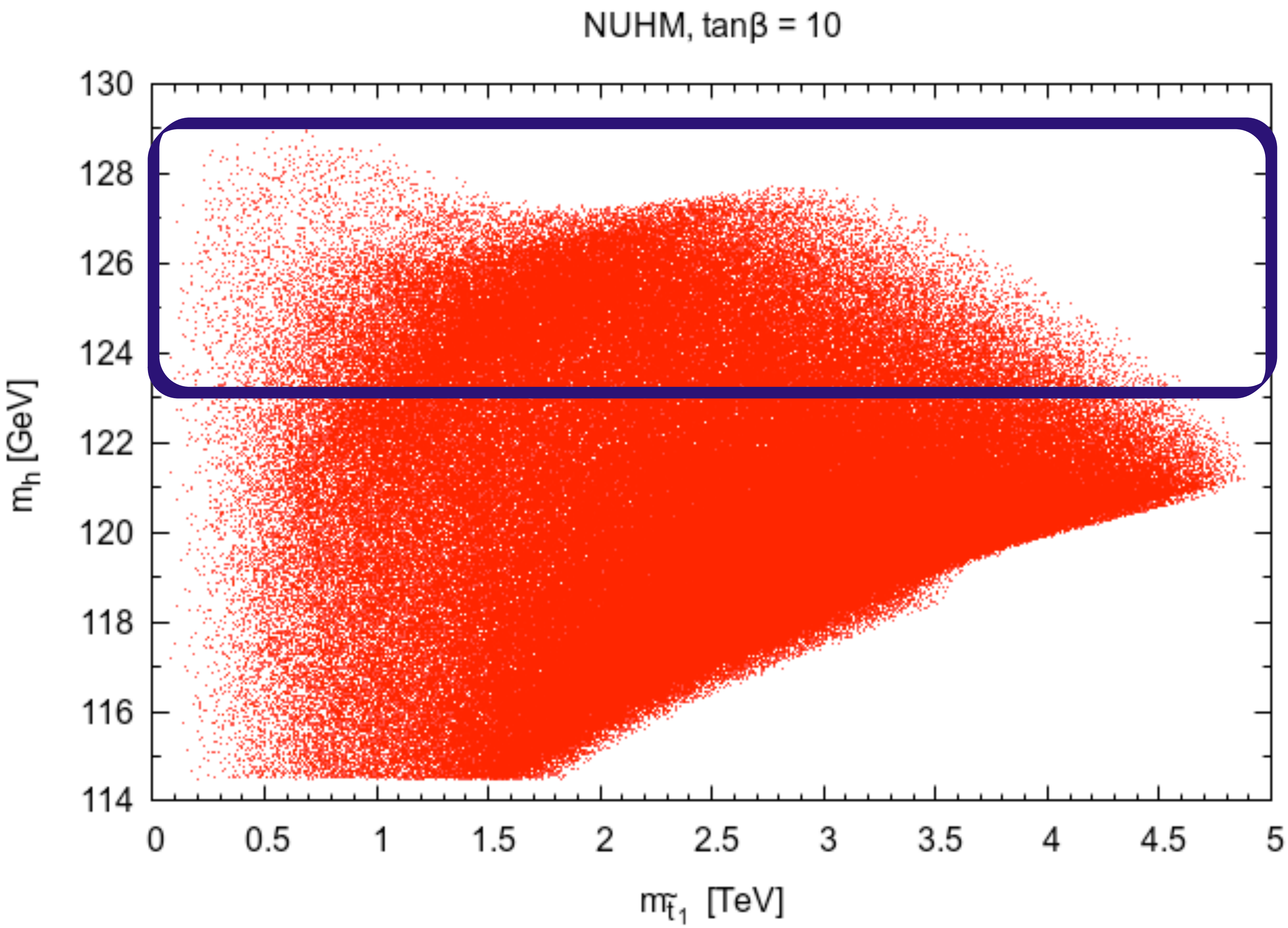
$$M_1 \neq M_2 \neq M_3$$

Non-Universal Scalar Mass models

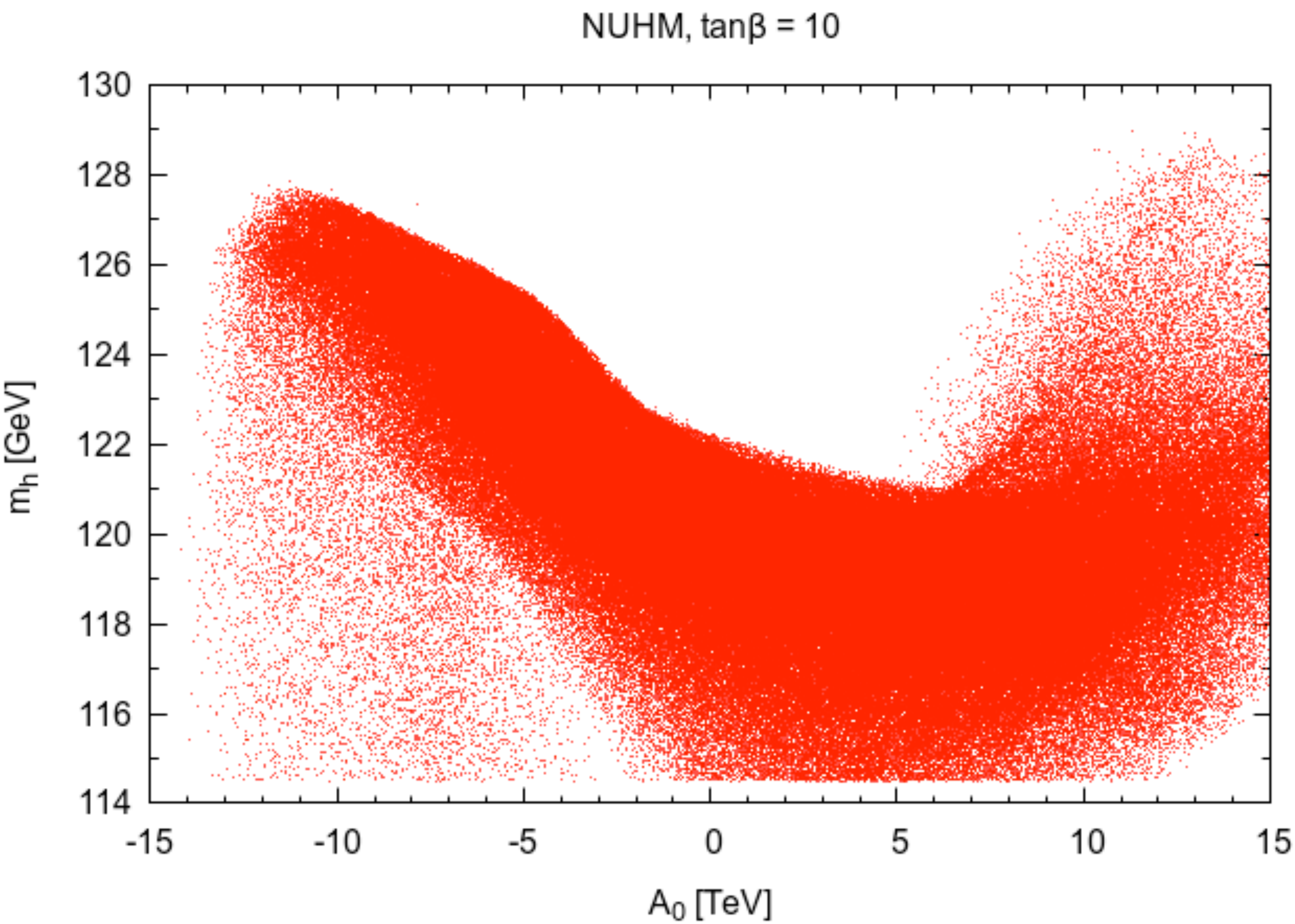
Chattopadhyaya et. al



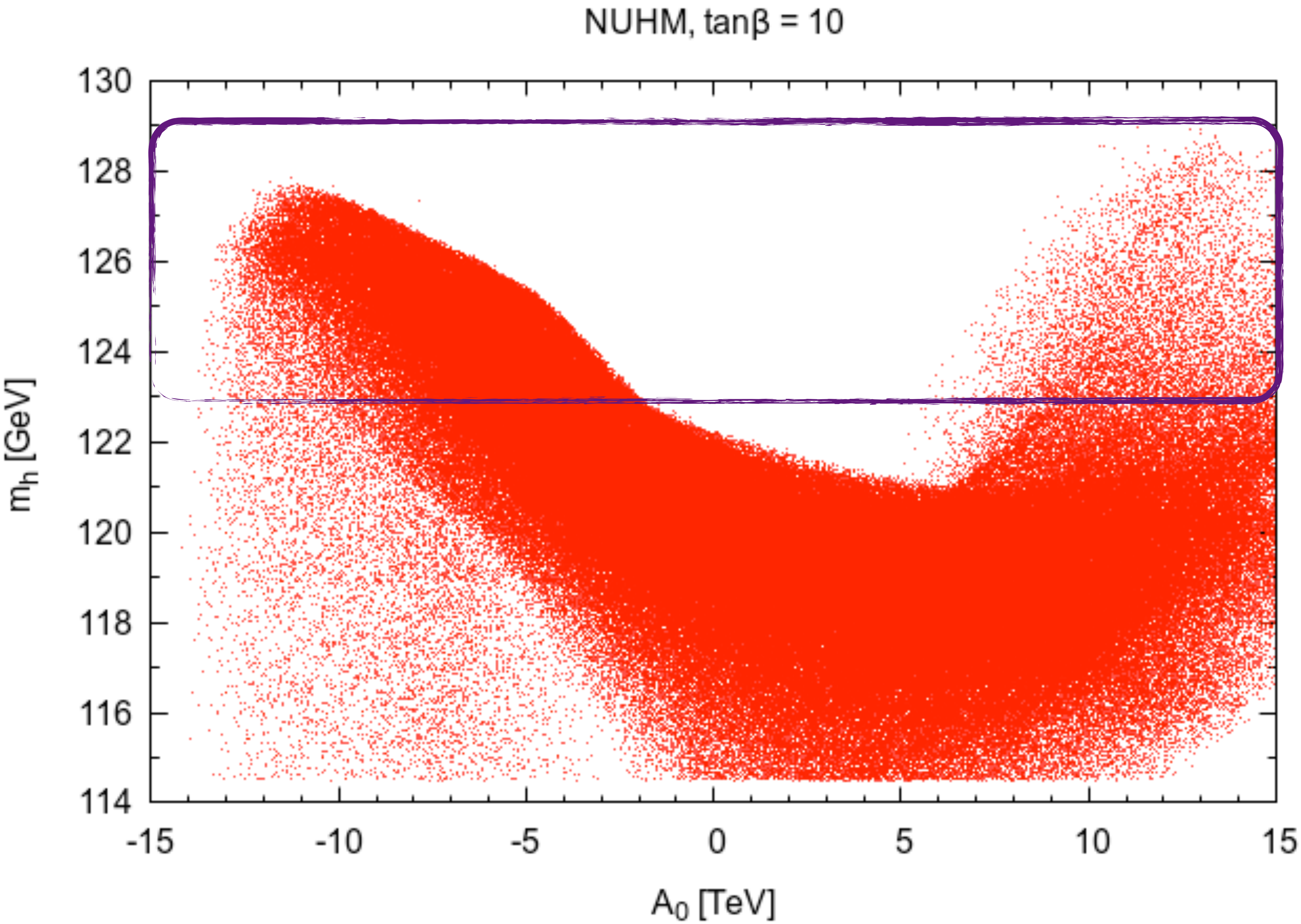
D. Chowdhury, S. Vempati, et. al



D. Chowdhury, S. Vempati, et. al



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



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

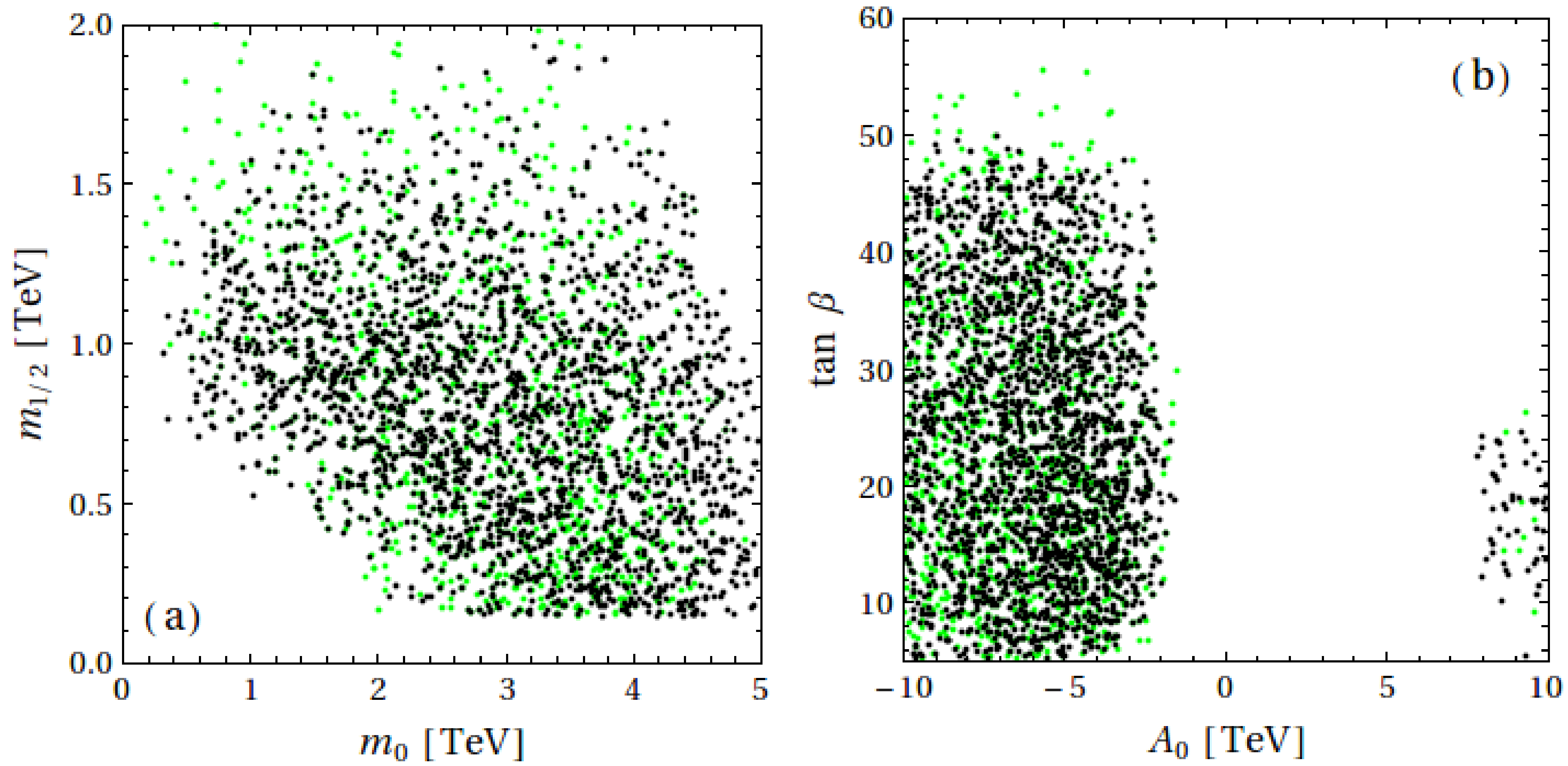


FIG. 1: Allowed regions in the parameter space for $\mu > 0$. We consider two sections of the parameter space, viz. (a) the $m_{1/2}$–m_0 plane, and the (b) A_0–$\tan\beta$ plane. The black dots indicate the cMSSM, while the green (grey) ones indicate the NUHM.

Updated with latest B-> mu mu and B -> nu tau

Statistical approaches

- Frequentist Analysis
- Bayesian PDF's (Probability Distribution Functions) for various parameters.
- Inspired by such analysis in astro-physics.

Review: R.Trotta astro-ph/0803.4089

- Several different approaches (multi-nest MCMC etc..)

P. Nath et. al
B. Allanach et. al
BayesFITS group (Roszkowski et.al
FITTINO group(Porod, Driener et.al)

Buchmuller et.al, hep-ph/1207.7315

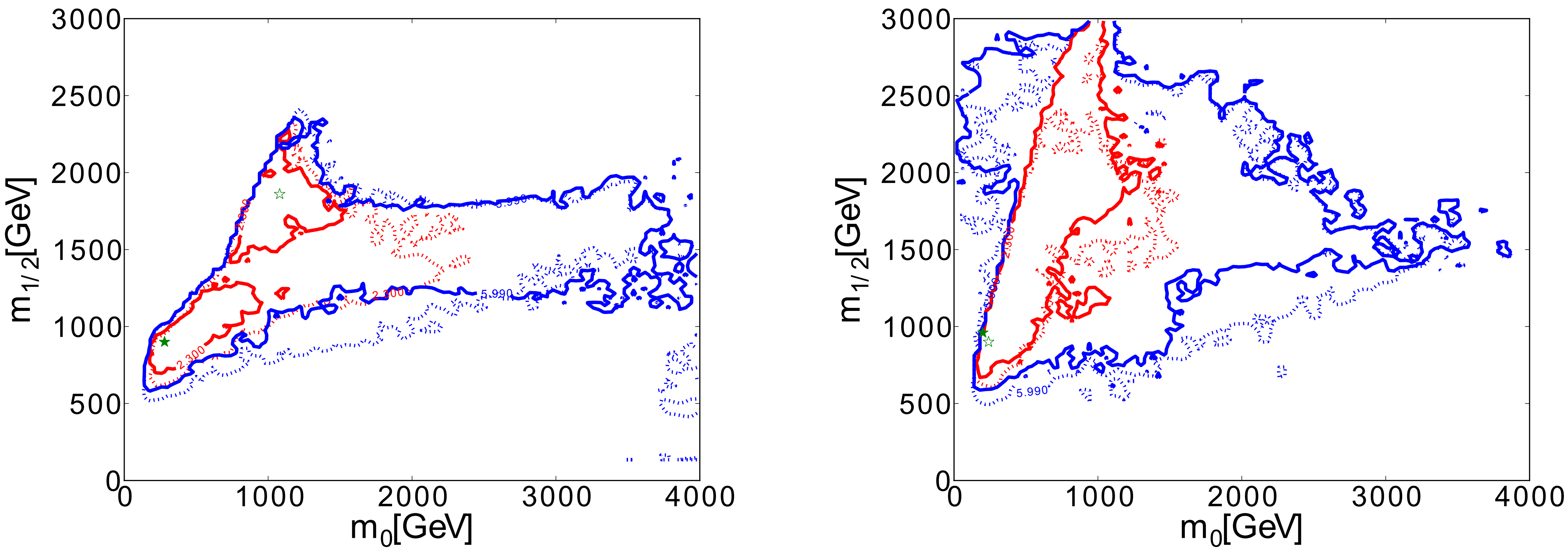


Figure 6. *The* $(m_0, m_{1/2})$ *planes in the CMSSM (left panel) and the NUHM1 (right panel) including the ATLAS 5/fb jets +* $\not{E}_T$ *constraint [12], a combination of the ATLAS [21], CDF [22], CMS [23] and LHCb [24] constraints on* $\mathrm{BR}(B_s \to \mu^+\mu^-)$ *[25] and the recent XENON100 result [27], assuming* $M_h = 125 \pm 1$ (exp.) $\pm\, 1.5$ (theo.) GeV. *The results of the current fits are indicated by solid lines and filled stars, and previous fits based on* ~ 1*/fb of LHC data are indicated by dashed lines and open stars. The blue lines denote 68% CL contours, and the red lines denote 95% CL contours.*

moving away from CMSSM- II

New Physics at Intermediate Scales

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

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

new running due to Intermediate scales

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

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

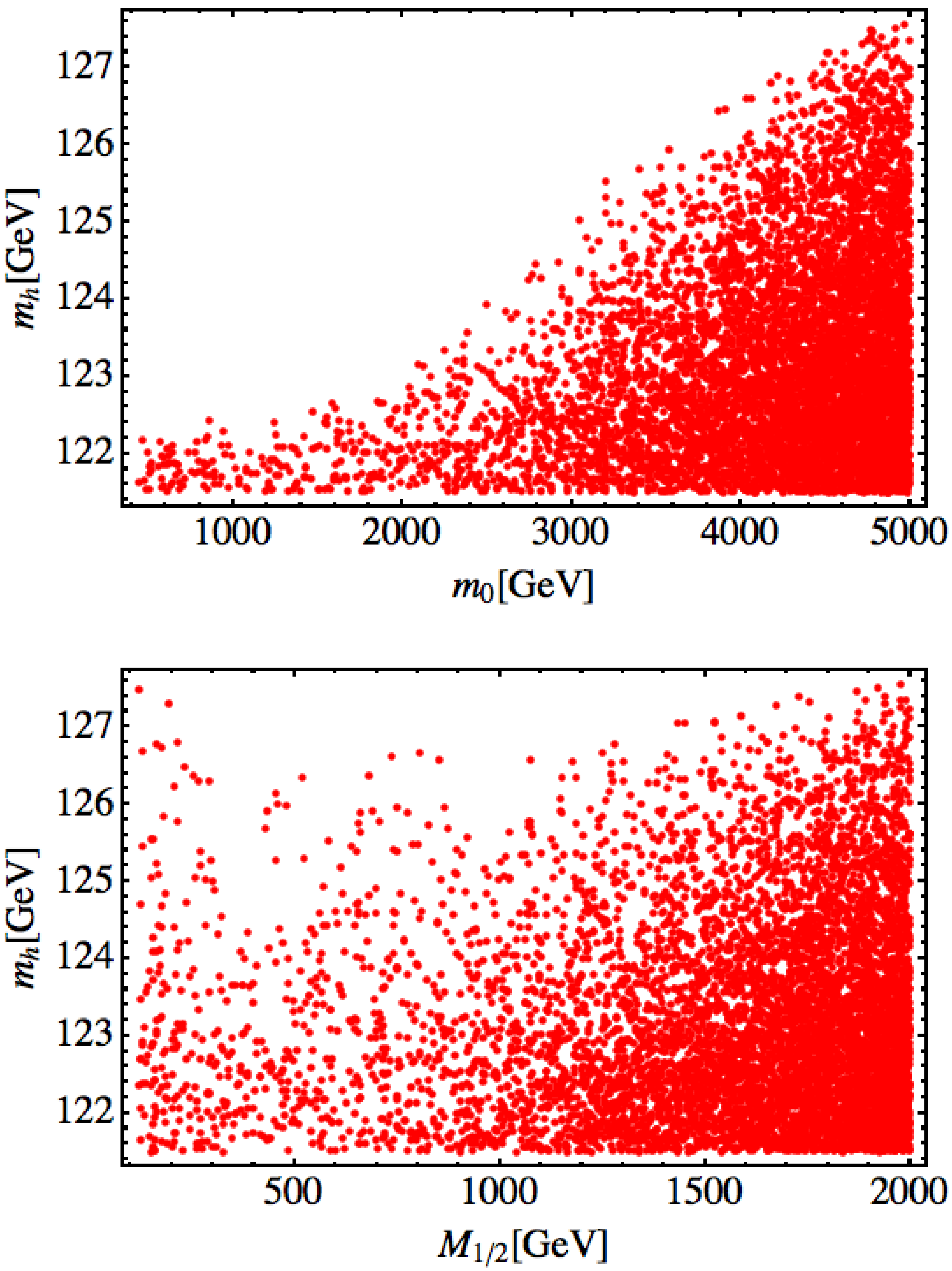
$10^{3}\,\mathrm{GeV}$ → $M_{\rm SUSY}$

→ $M_{\rm Z}$

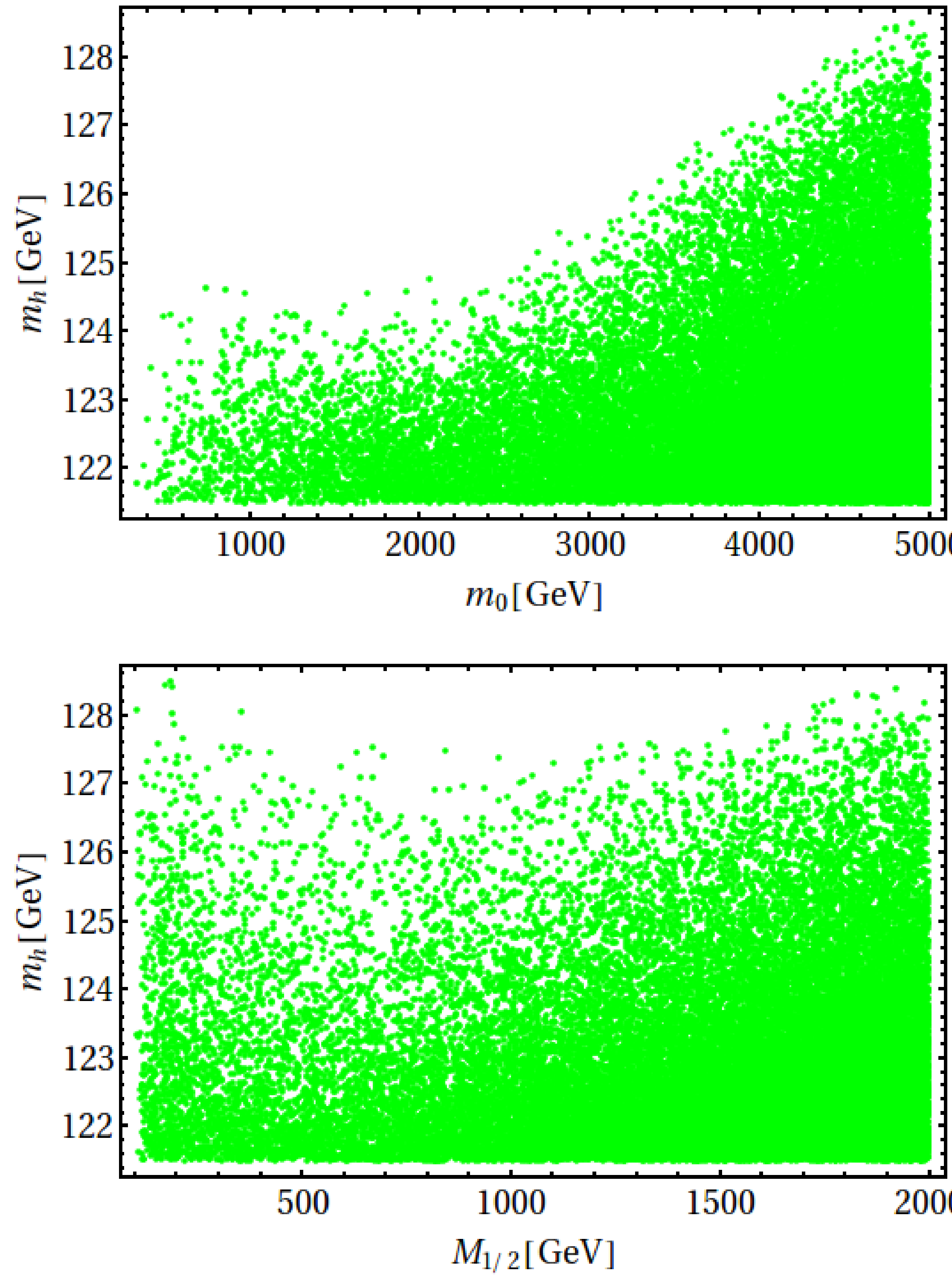
Model Dependent Results

Present Constraints on mSUGRA + Seesaw

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

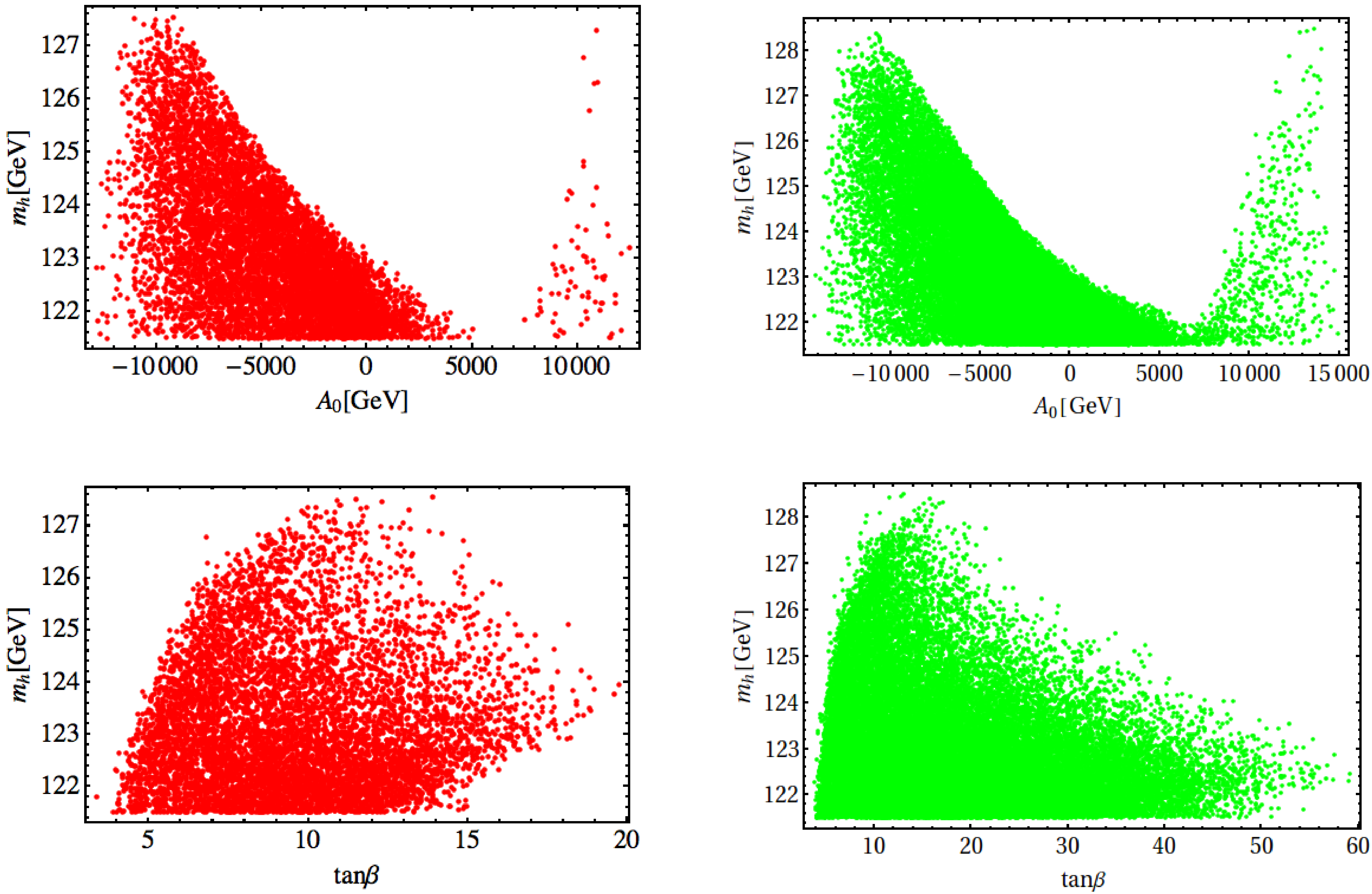


mSUGRA + seesaw



NUHM+ seesaw

Present Constraints on mSUGRA + Seesaw



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

minimal gauge mediation

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

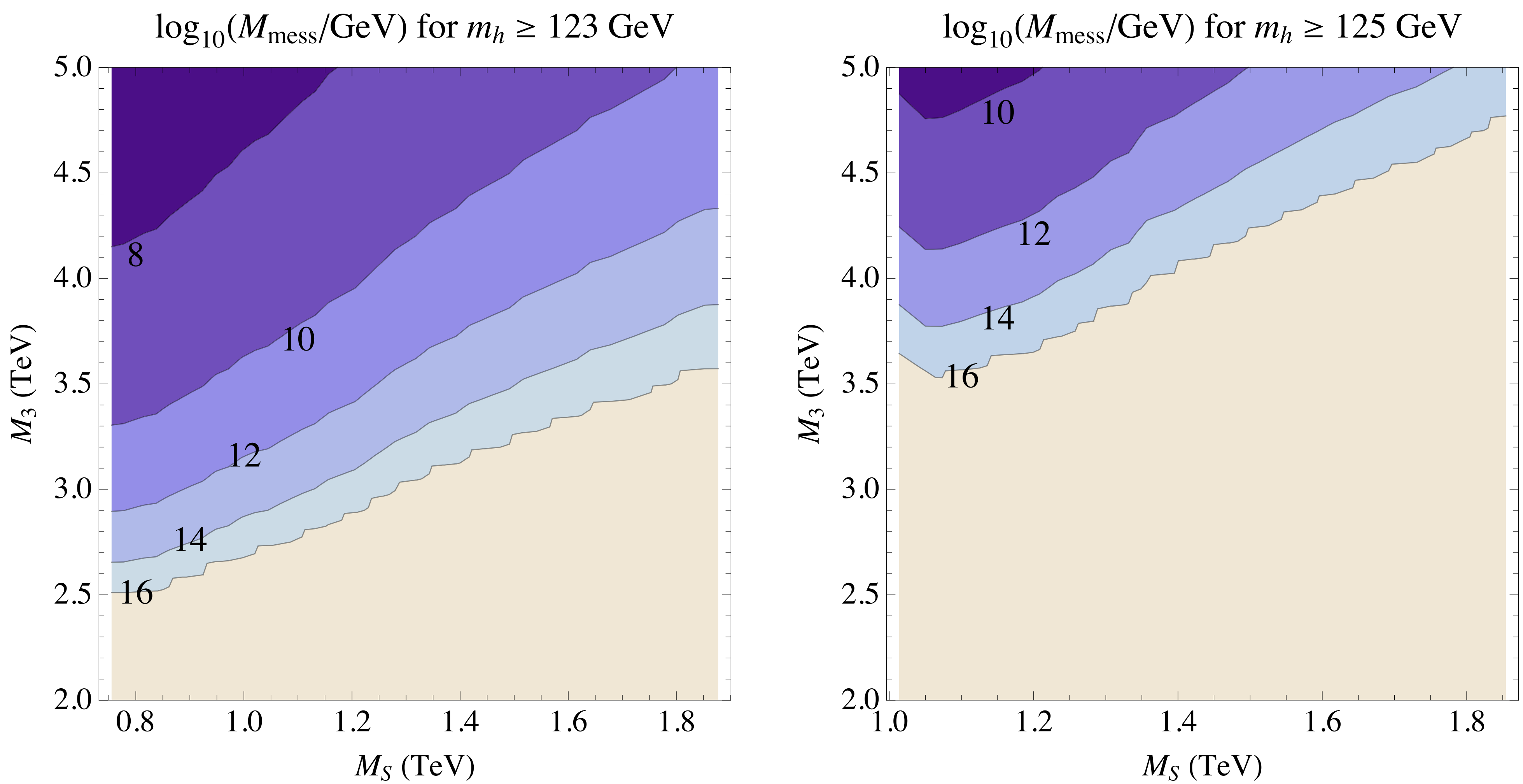


FIG. 5. Messenger scale required to produce sufficiently large $|A_t|$ for $m_h = 123$ GeV (left) and $m_h = 125$ GeV (right) through renormalization group evolution.

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

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 !!!

NMSSM and gauge mediation

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

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 !!!

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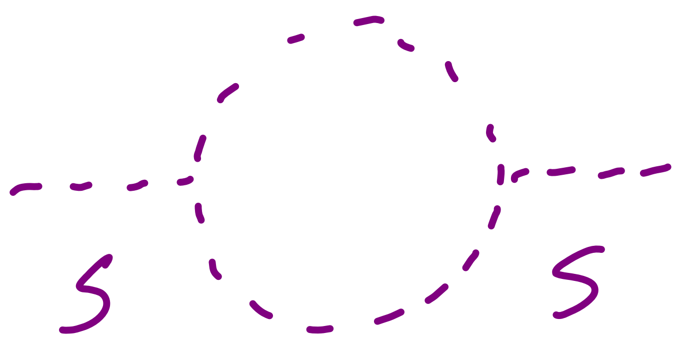
The problem with GMSB & NMSSM

No Diagram to give mass to the singlet scalar from susy breaking gauge mediation.

$$m_S^2(\Lambda) \simeq 0$$



$$S^2 \simeq \frac{-m_S^2 - A_\kappa^2 - A_\lambda^2}{k^2} \simeq 0$$

all zero in GMSB

Our Solution to the problem

V. Sooryanarayana & SV to appear

* Add an additional $U(1)_X$
* Add an extra singlet S

$$W = h^u Q u H_u + h^d Q d H_d + h^e L e H_d + \lambda S H_u H_d$$

"NMSSM" without cubic term !

$m_S^2(\Lambda) \simeq$

V. Sooryanarayana & SV to appear

* $U(1)_X$ anomalies to be cancelled ✓ to appear

* S should get a 'heavy' vev $\gtrsim$ 1 TeV ✓

$$\langle S \rangle \simeq \frac{-m_s^2}{g_4^2}$$

* $M_{Z'} \gtrsim 1$ TeV ✓

* light higgs mass $\approx$ 125 GeV ✓

GMSB is not ruled out

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

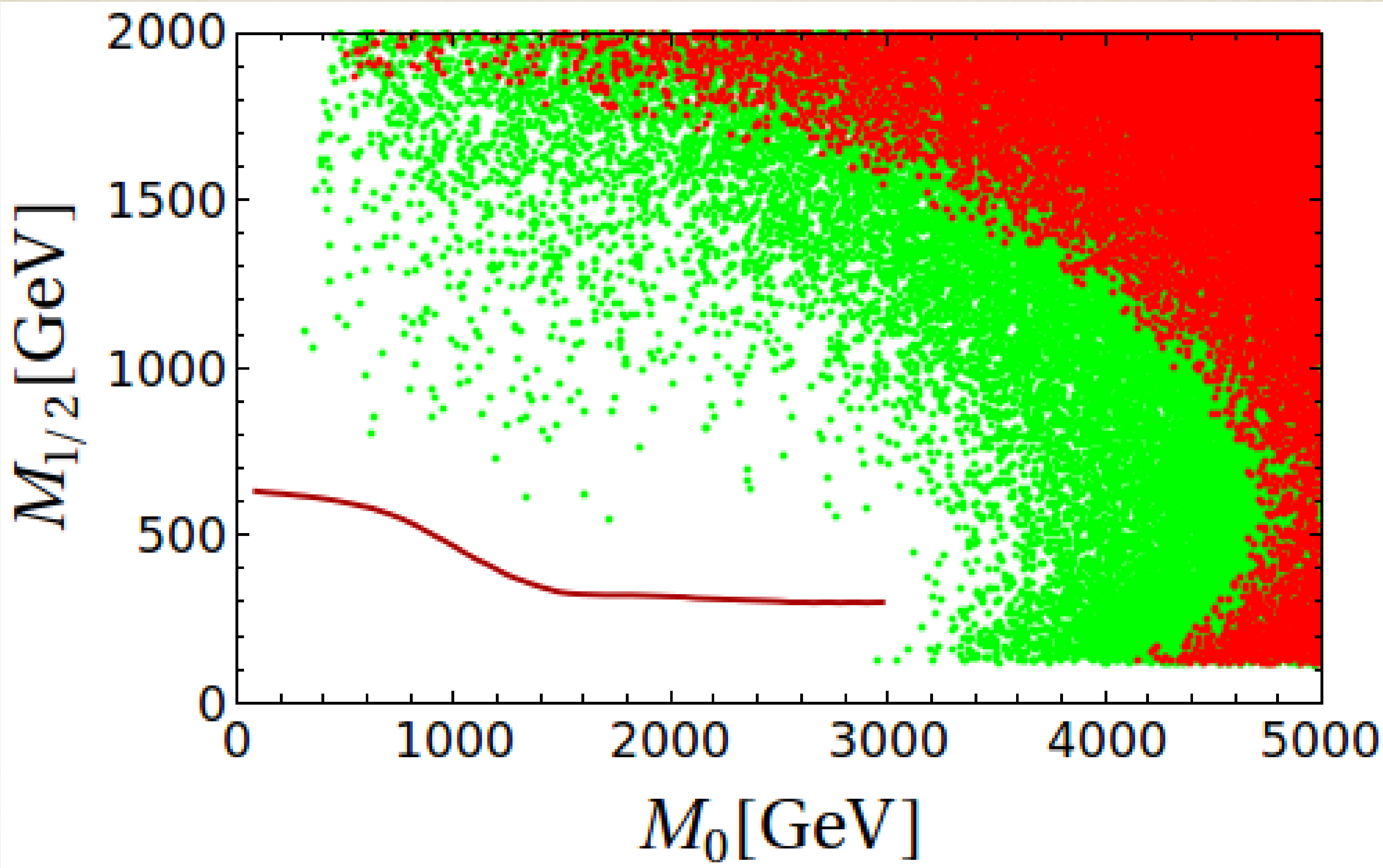
A new definition of fine tuning will make it natural

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: $173.5 \pm 0.6 \pm 0.8$ GeV (PDG 2012)

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

* other uncertainties include: $\Delta m_b, \ \Delta\alpha_s$ and $\Delta\alpha_{\rm em}$

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.

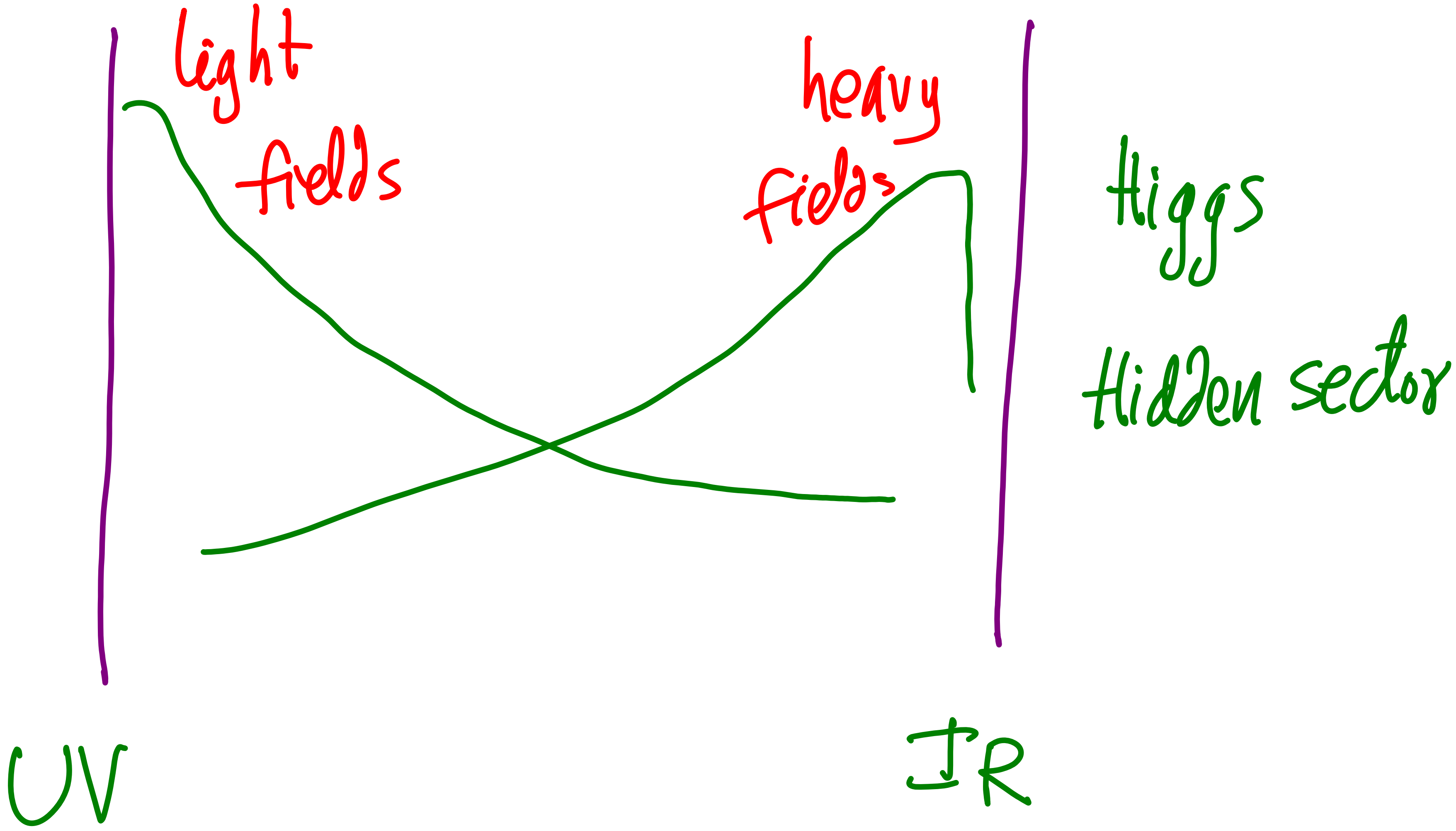
SUSY is still present to solve the hierarchy problem

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

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

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

$f(c_i)$ = 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