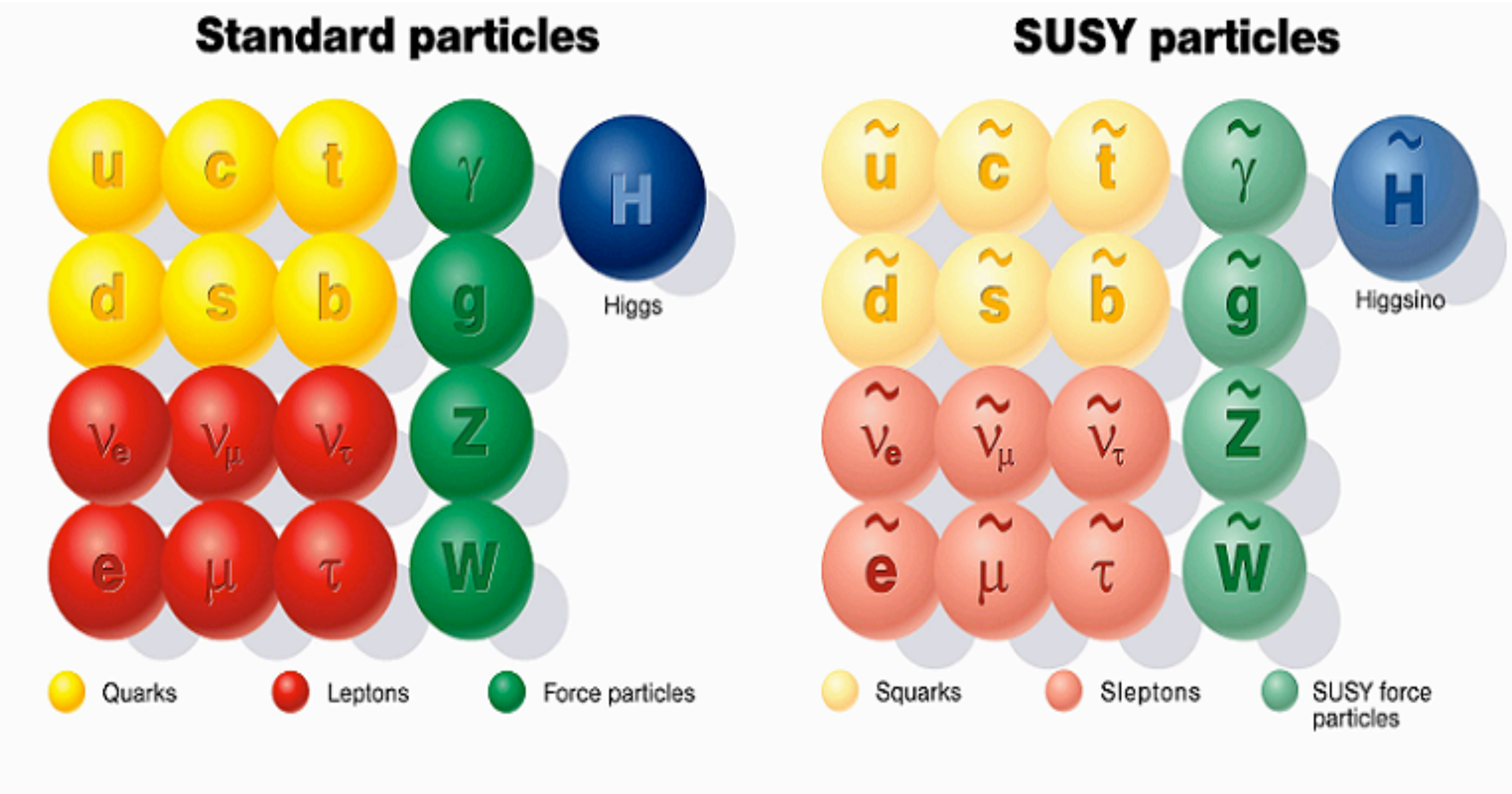


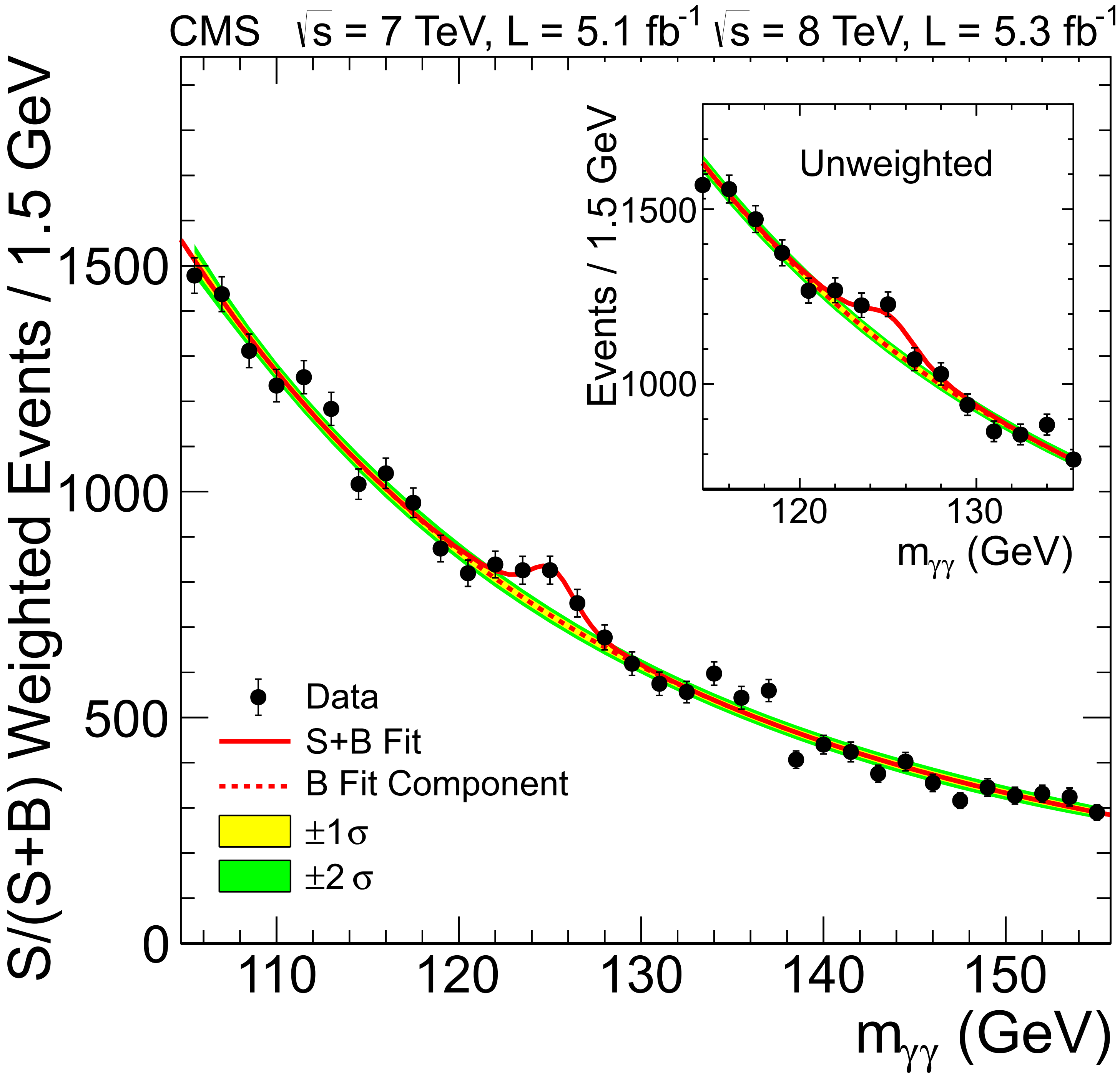
Status of Supersymmetric Models

Sudhir K Vempati
CHEP, IISc Bangalore

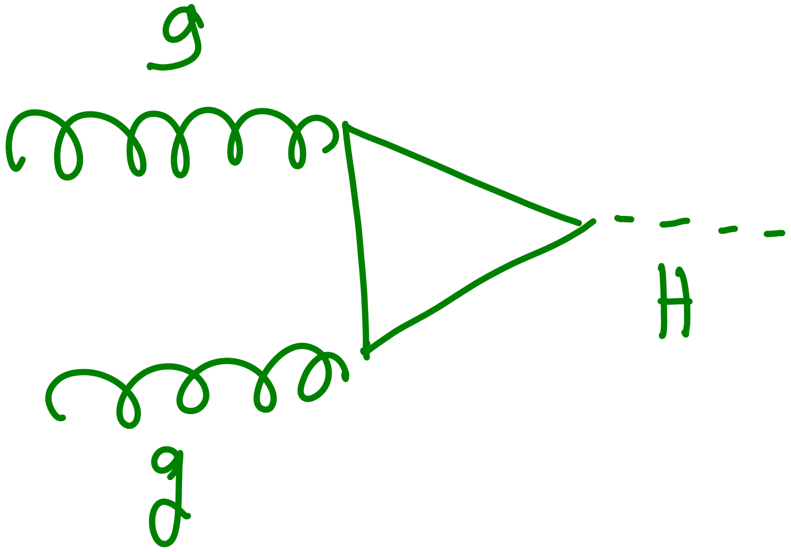
Institute of Physics, Bhubhaneswar
Feb 11, 2013

Outline

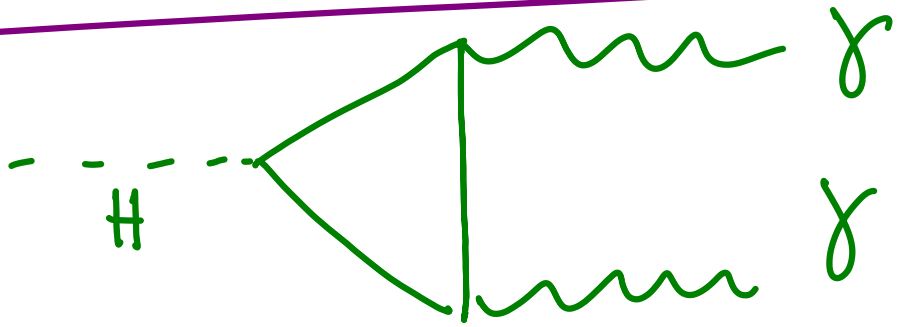
- Why Supersymmetry ?
- Structure of MSSM
- Experimental Status
- New models of SUSY


CMS √s = 7 TeV, L = 5.1 fb^{-1} √s = 8 TeV, L = 5.3 fb^{-1}
S/(S+B) Weighted Events / 1.5 GeV
0
500
1000
1500
110
120
130
140
150
$m_{\gamma\gamma}$ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2 σ
Unweighted
Events / 1.5 GeV
1000
1500
120
130
$m_{\gamma\gamma}$ (GeV)

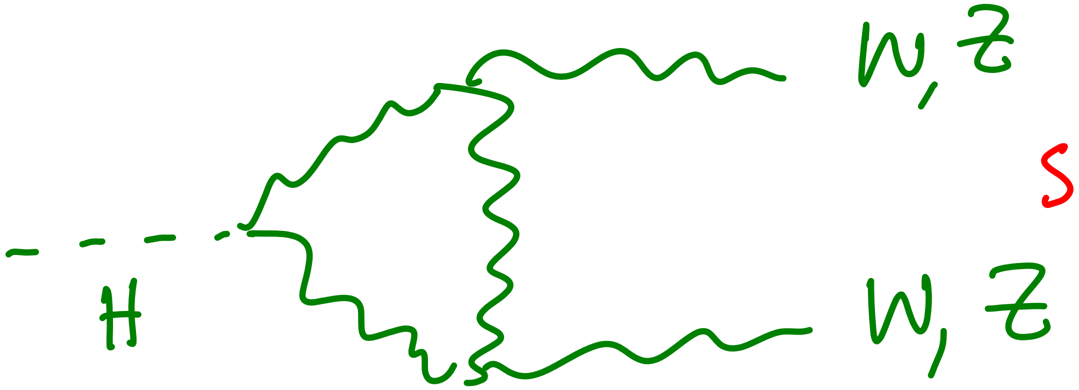
The discovery of Higgs like boson @ LHC:



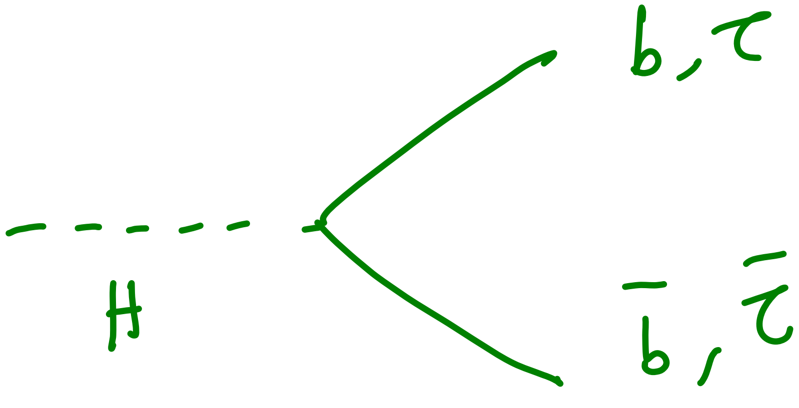
production



seen



seen



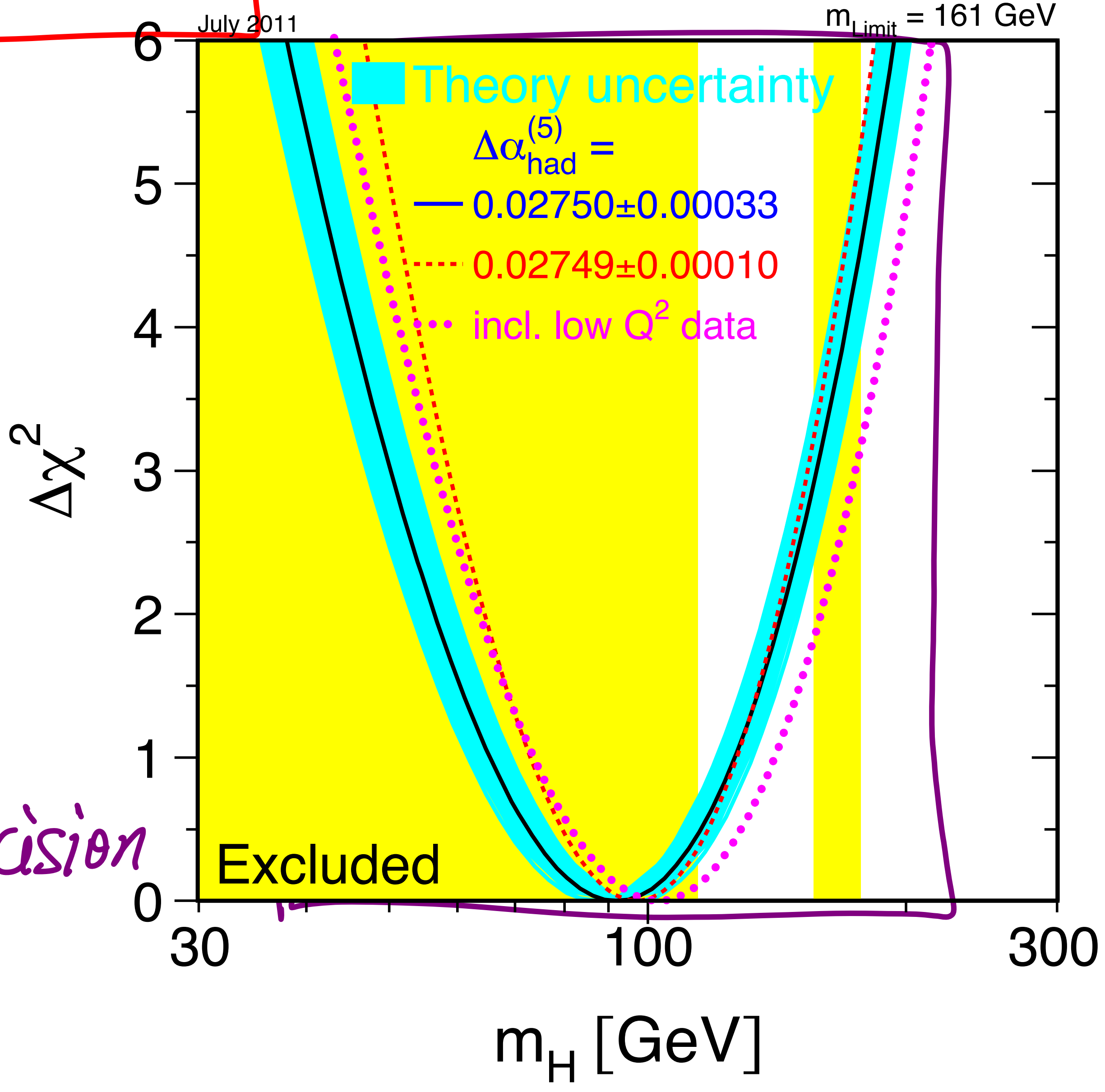
perhaps

$$\boxed{m_H \simeq 126 \pm 3 \text{ GeV}}$$

Precision Measurement

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

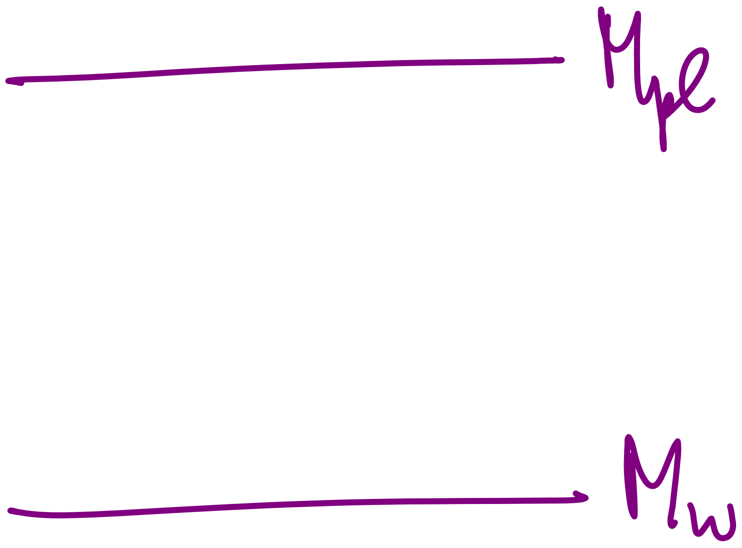
- Consistent with Electroweak Precision measurements.



* Perhaps a weakly coupled boson of spin zero!!

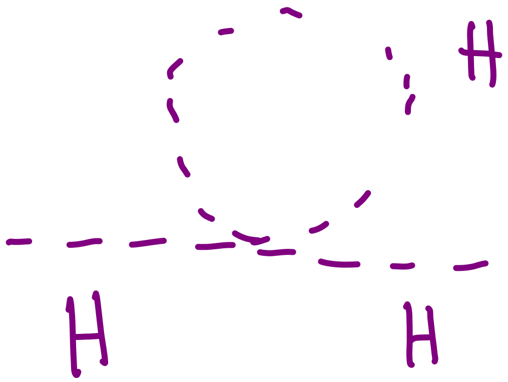
elementary scalar

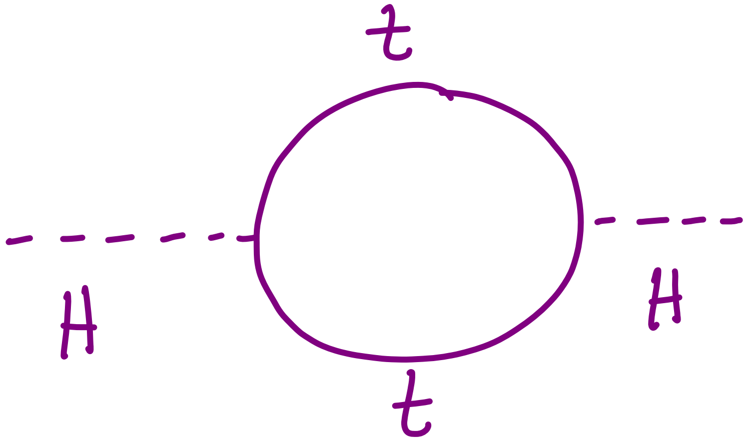
composite

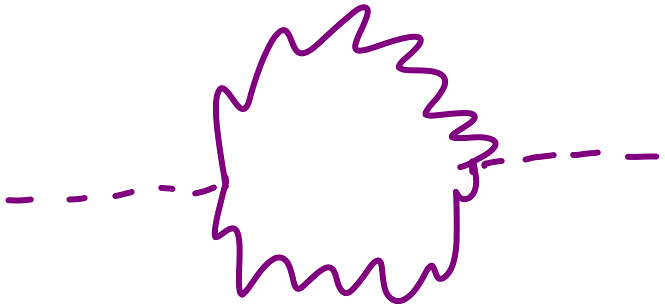


If SM is an effective theory below M_{pl} with an elementary scalar, the mass of such a scalar would be unstable under radiative corrections

$$\delta M_h^2 \propto \Lambda^2 \approx M_{pl}^2$$







& so on

Ⓐ Either the cut-off is low (some new physics takes over, composite scale or lower M_{pl} by introducing extra Dimensions etc)

Ⓑ There is some symmetry protecting the Higgs mass $\Longrightarrow$ $\boxed{\text{SUPERSYMMETRY}}$

Other advantages of SUSY

- In reasonable models, lightest higgs mass is predicted to be $\lesssim 135$ GeV.
- Higgs can be SM like (production & decay in large regions of parameter space)
- Dark Matter, gauge coupling unification, etc etc.

The Structure of MSSM

SUSY

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

Changes the particle spin by $\frac{1}{2}$

$$\left.\begin{array}{ll} (0, \frac{1}{2}) & \text{chiral superfields} \\ (\frac{1}{2}, 1) & \text{Vector superfield} \end{array}\right\} \text{two multiplets}$$

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

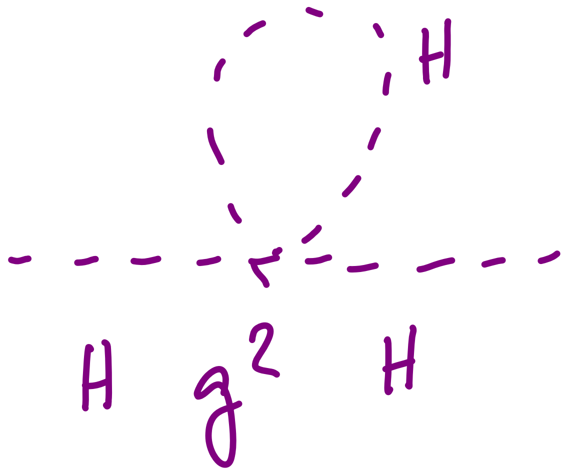
Three functions of superfields

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

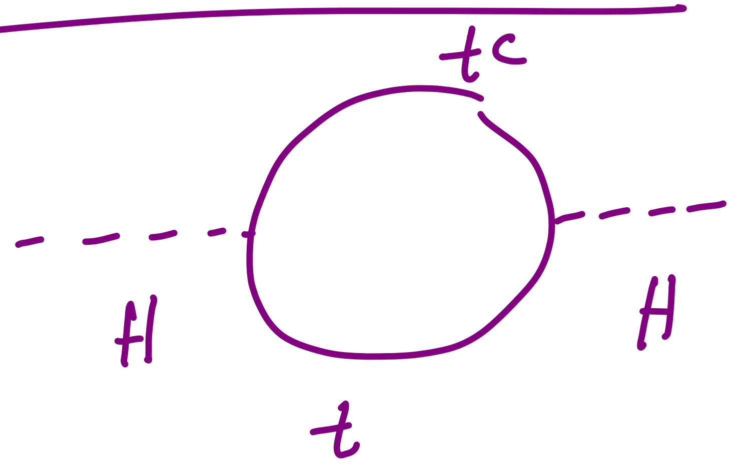
$\mathcal{L}_{\text{Yukawa}} \supset \int d^2\theta\, W = \Phi_i \Phi_j \Phi_k$ analytic fn of chiral multiplets

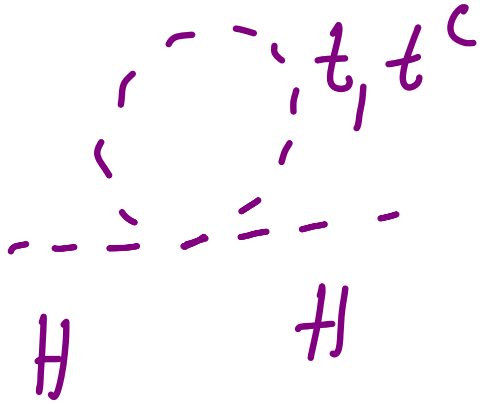
two Higgs doublets required to cancel anomalies

How SUSY works



quartic coupling replaced by gauge coupling





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

Supersymmetry breaking

- Spontaneous supersymmetry breaking leads to softly broken supersymmetry terms in the lagrangian.

$\Rightarrow$ mass terms for SM superpartners and dimensionful couplings (gauge invariant)

- Spontaneous SUSY breaking cannot be incorporated within MSSM supermultiplets.

Hidden Sector ideas

- * Break SUSY spontaneously in a sector of superfields not charged under SM gauge group
- * This information should then pass to the MSSM sector leading to soft terms also for the MSSM supermultiplets.


Hidden Sector
Messenger Sector
MSSM visible

Some traditional Models

minimal Supergravity

$$K = X_i^\dagger X_i + \bar{\Phi}_i^\dagger \bar{\Phi}_i + \cdots\cdots$$

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

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

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

$$G_i = \frac{\partial G}{\partial \bar{\Phi}_i}$$

* As long as Kahler potential is in Canonical form:

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

$M_i = M_{1/2}$

$A_{ijk} = A_0$

$B_{ij} = B$

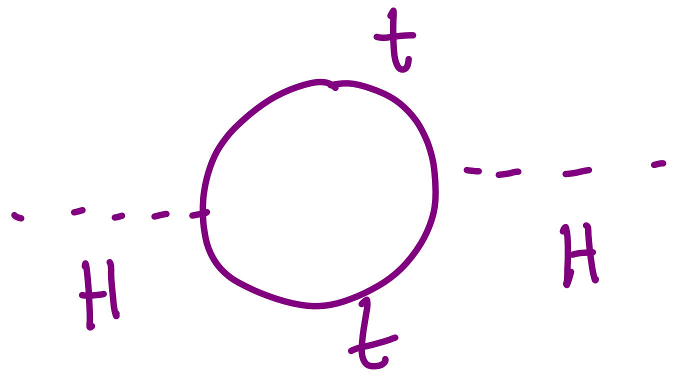
A small set of parameters describing the entire supersymmetric spectrum at weak scale

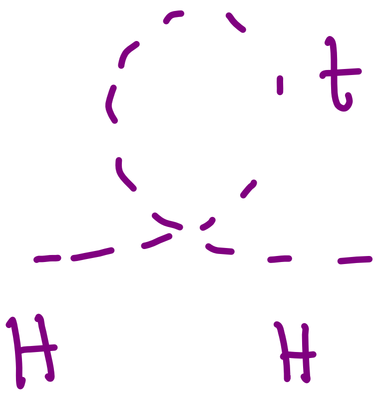
Renormalisable theory after integrating out the gravity Multiplet ($M_{pl} \to \infty$; $m_{3/2}$ fixed)

Dynamical understanding of Electroweak Symmetry Breaking

$m^2_{H_u, H_d} > 0$

$q^2 \simeq m^2_{pl}$ or m^2_{GUT}





RGE

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

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

@ weak scale

Gauge Mediation

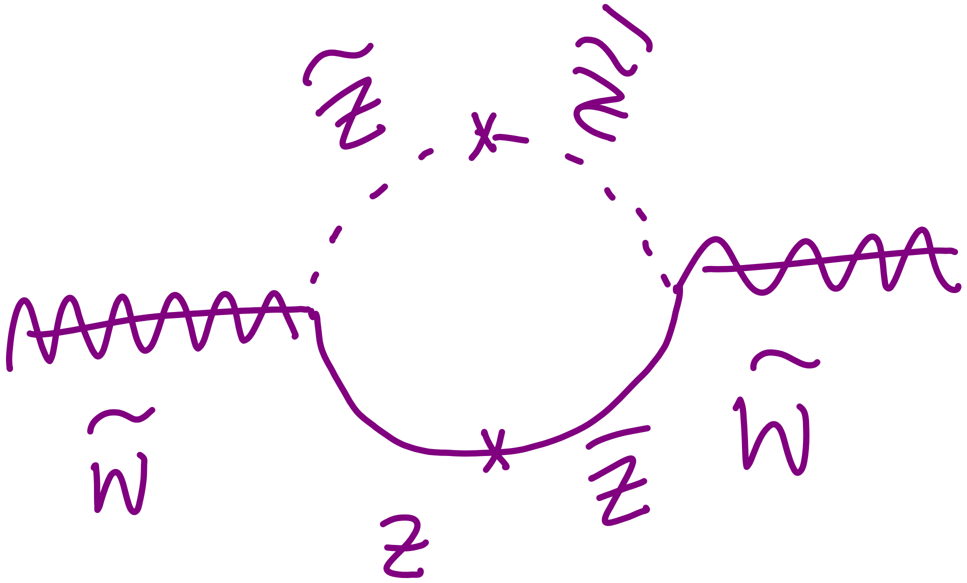
- * Introduce a bunch of Matter superfields which are charged under gauge interactions but couple to the hidden sector.

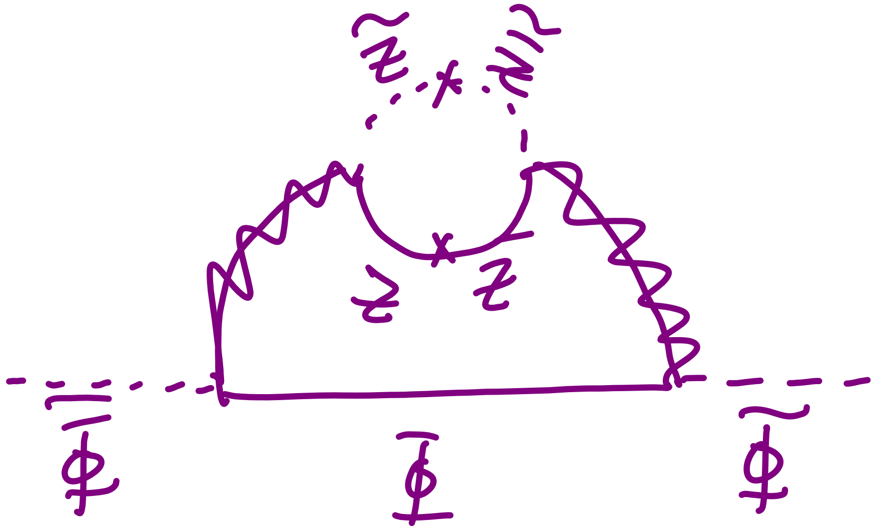
- * $$W \supset \lambda X Z \bar{Z}$$

Hidden Sector

Messenger sector

SUSY broken spontaneously by X

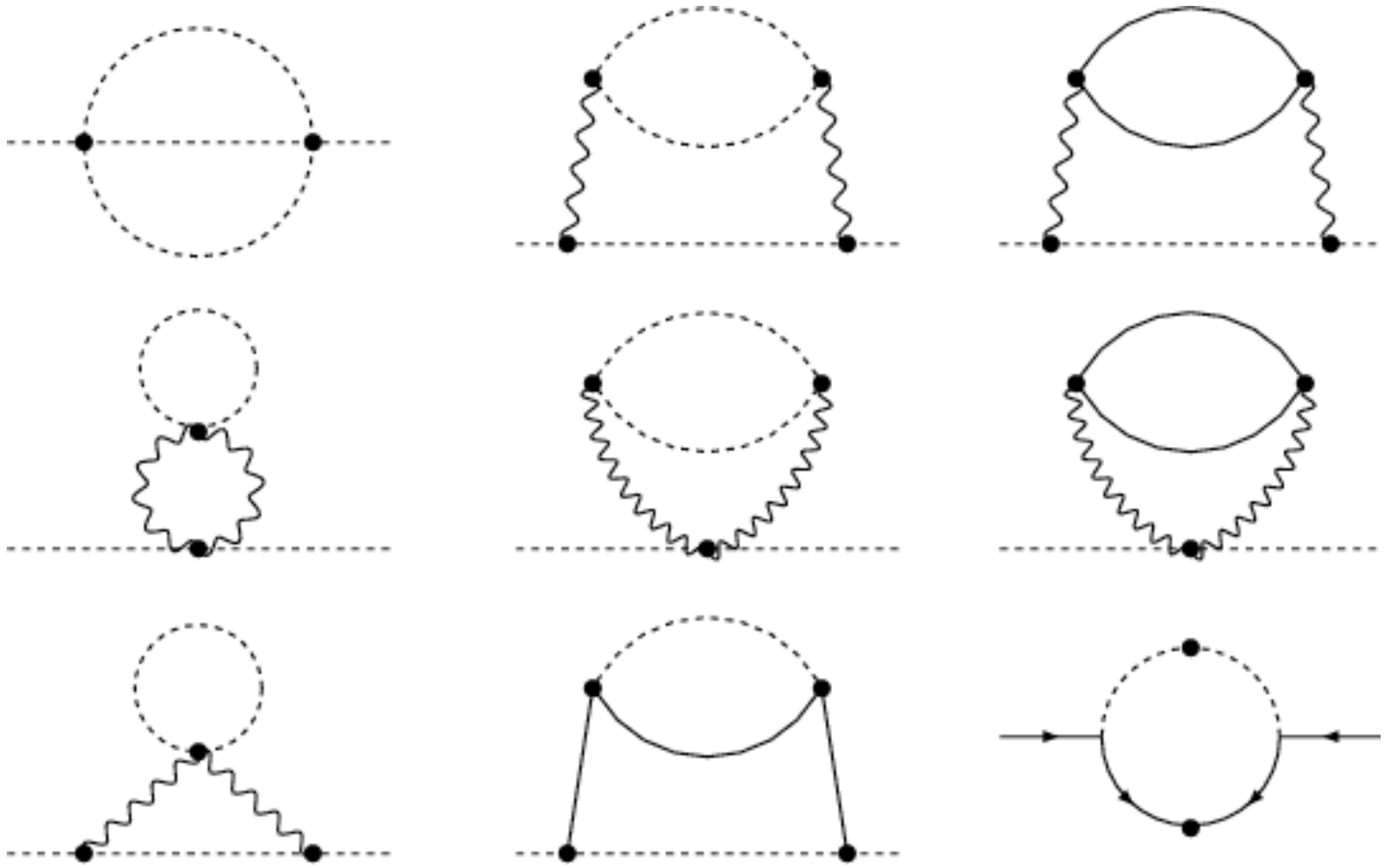




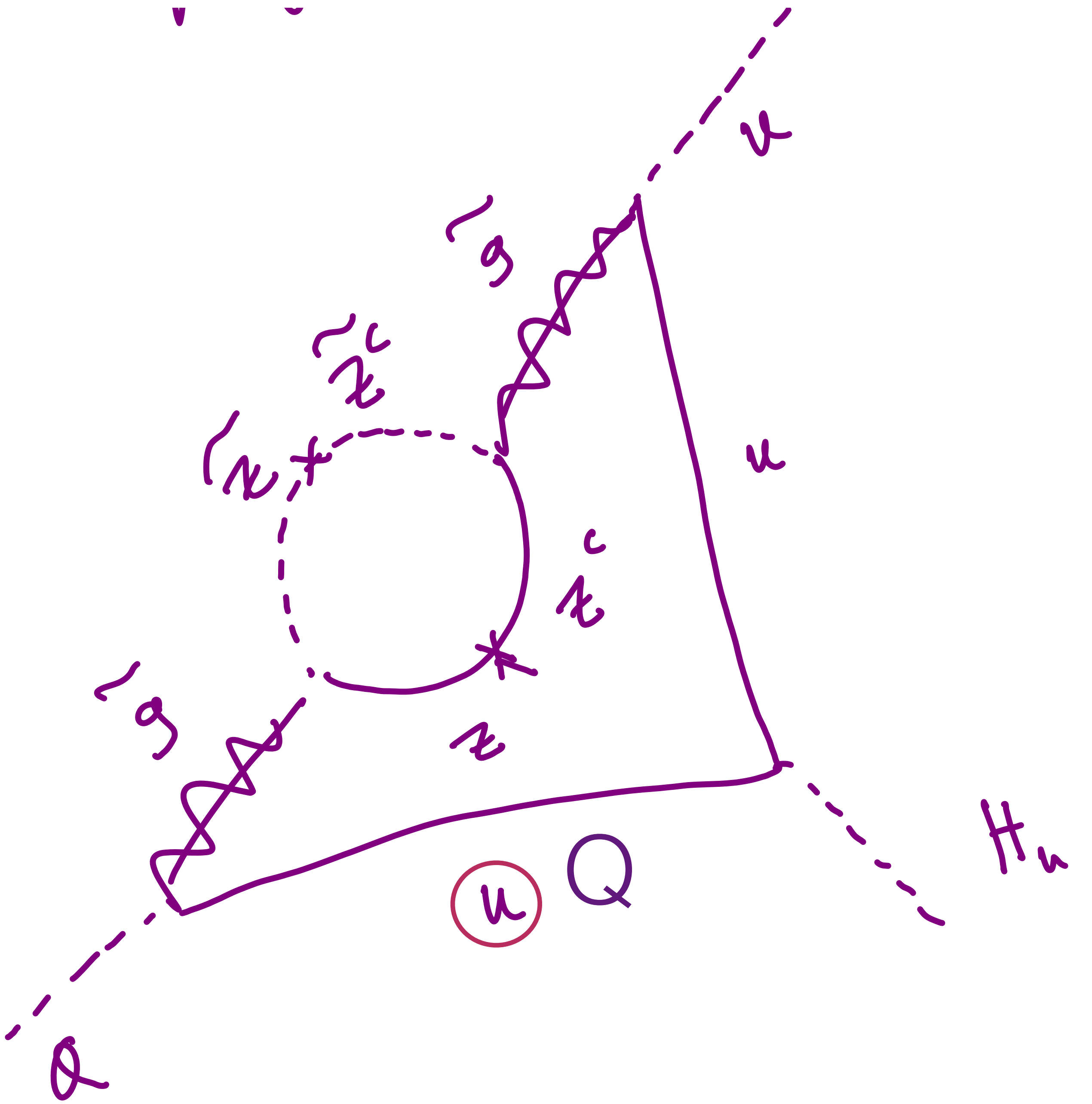
Soft masses in MSSM through loops

+ - - bunch of two loop diagrams

Two loop diagrams contributing to soft masses



dimensional-full couplings



additional
coupling
suppression

A-terms are essentially zero !!!

Experimental Status

Three Roads to SUSY

Collider Physics

LHC

Dark Matter

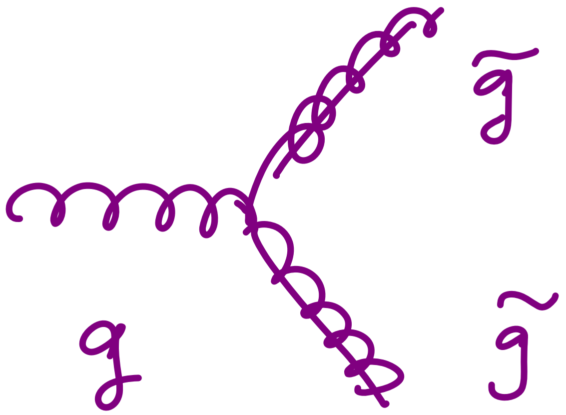
relic density

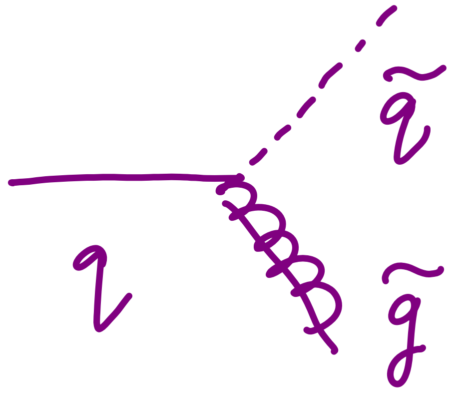
Flavour Physics

B-factories

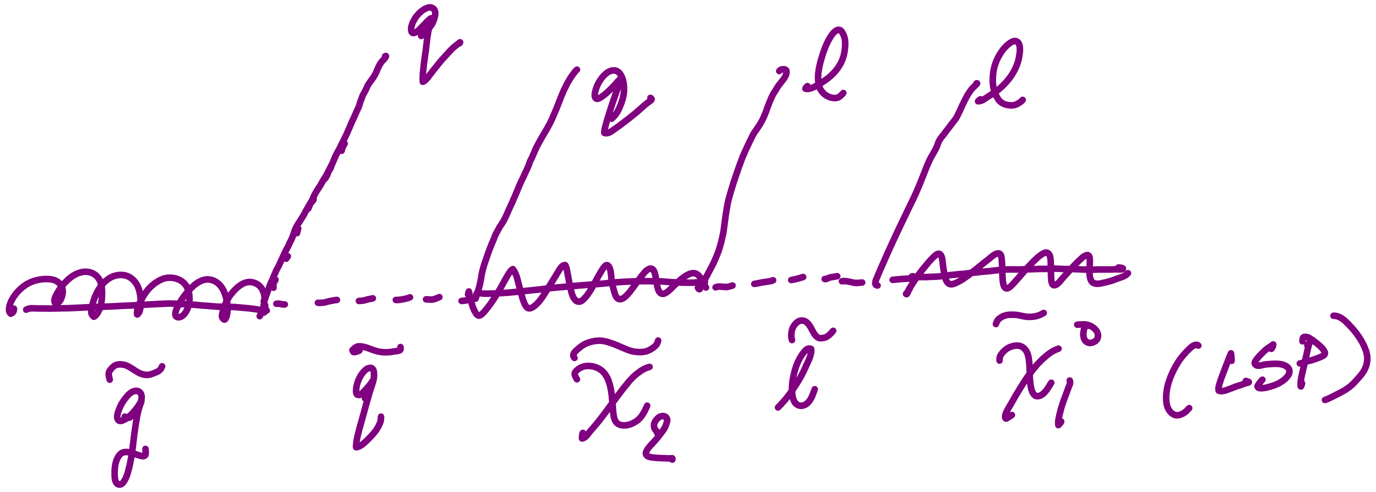
MEG

Large Hadron Collider

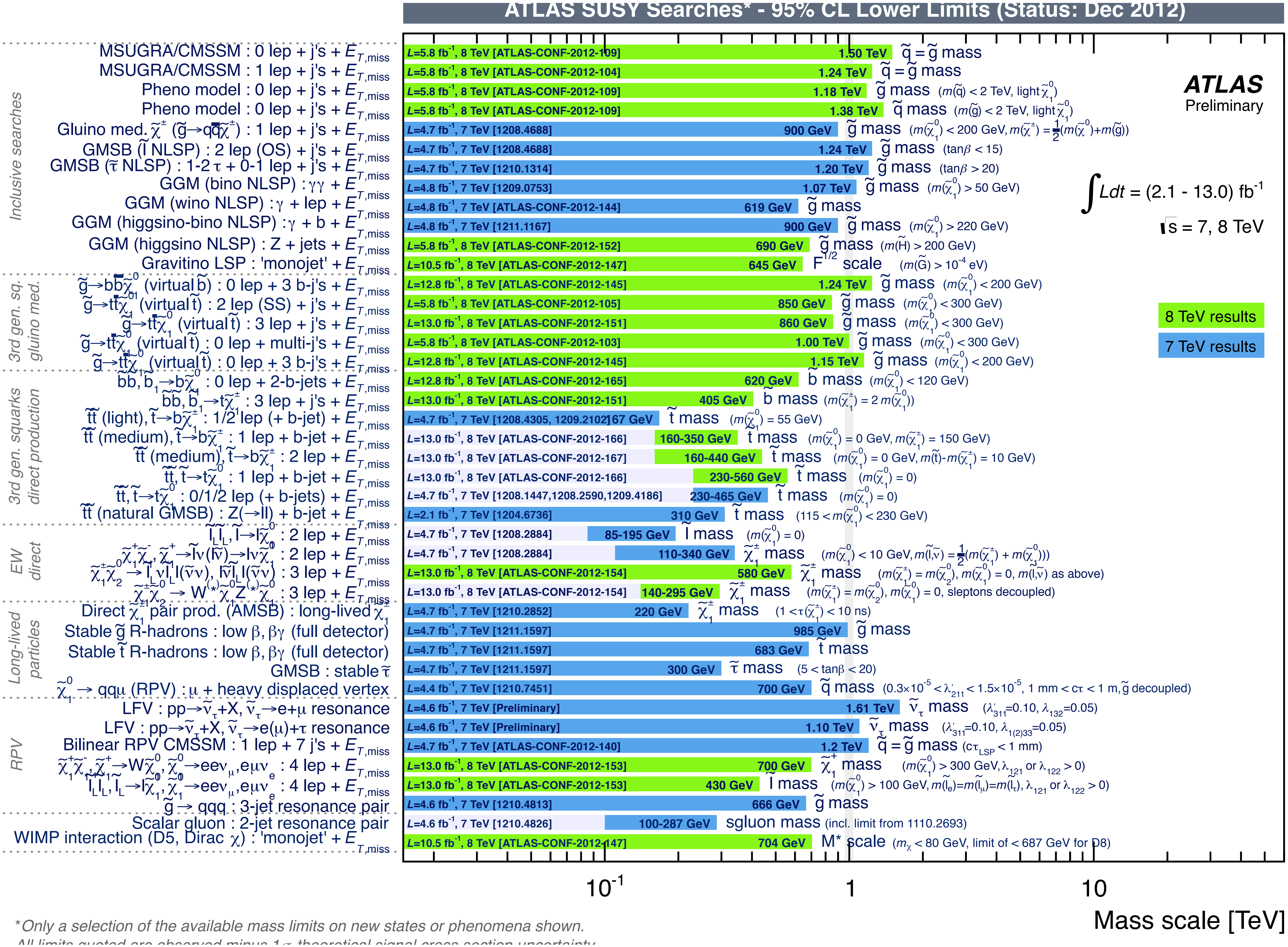




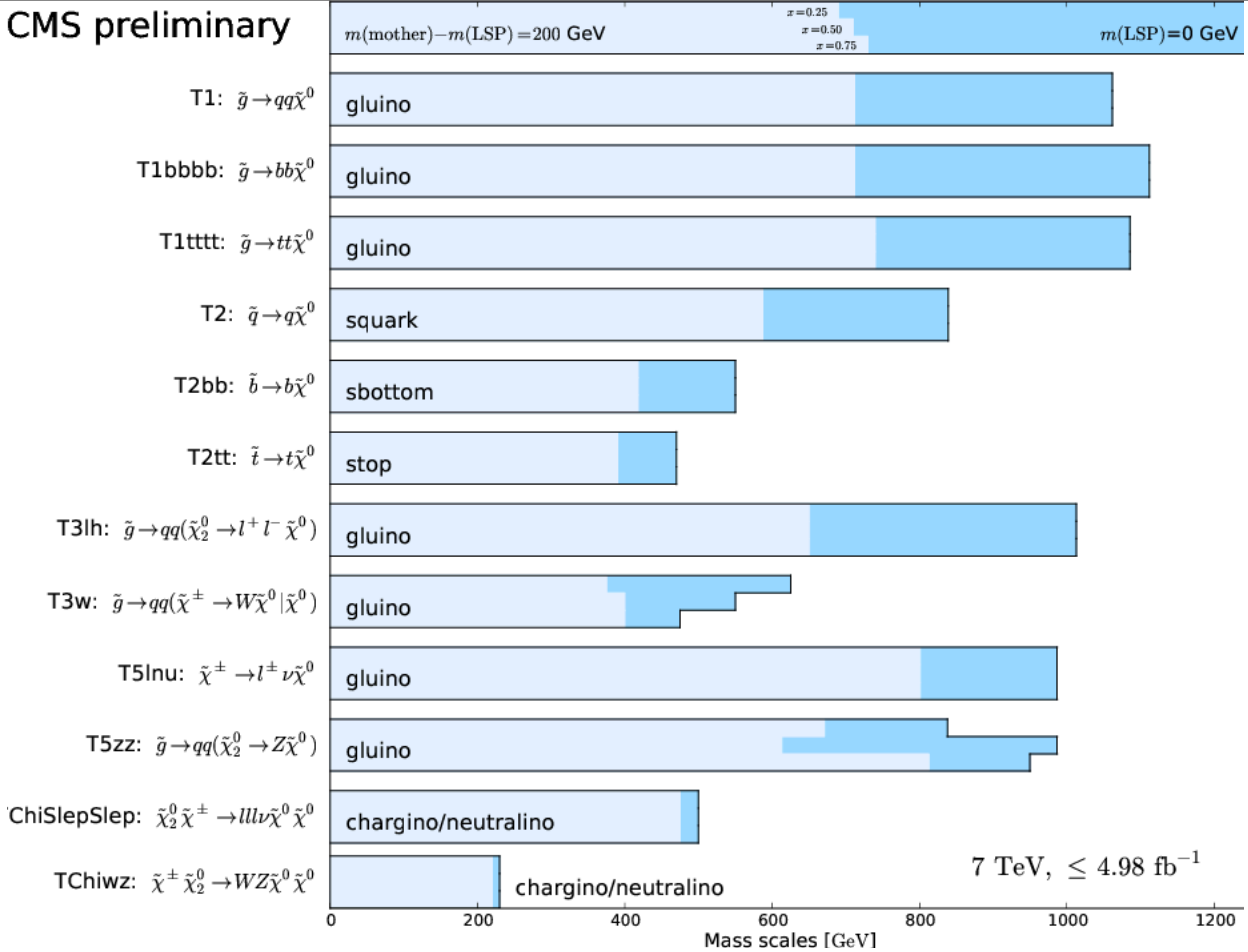
Dominant production sections.



The Decay chains depend on mass orderings

# ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)

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


CMS preliminary
m(mother)−m(LSP)=200 GeV
x=0.25
x=0.50
x=0.75
m(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: $\tilde{g}\to qq(\tilde{\chi}_2^0\to l^+l^-\tilde{\chi}^0)$
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: $\tilde{g}\to qq(\tilde{\chi}_2^0\to Z\tilde{\chi}^0)$
gluino
'ChiSlepSlep: $\tilde{\chi}_2^0\tilde{\chi}^\pm\to lll\nu\tilde{\chi}^0\tilde{\chi}^0$
chargino/neutralino
TChiwz: $\tilde{\chi}^\pm\tilde{\chi}_2^0\to WZ\tilde{\chi}^0\tilde{\chi}^0$
chargino/neutralino
7 TeV, ≤ 4.98 fb^{-1}
0
200
400
600
800
1000
1200
Mass scales [GeV]

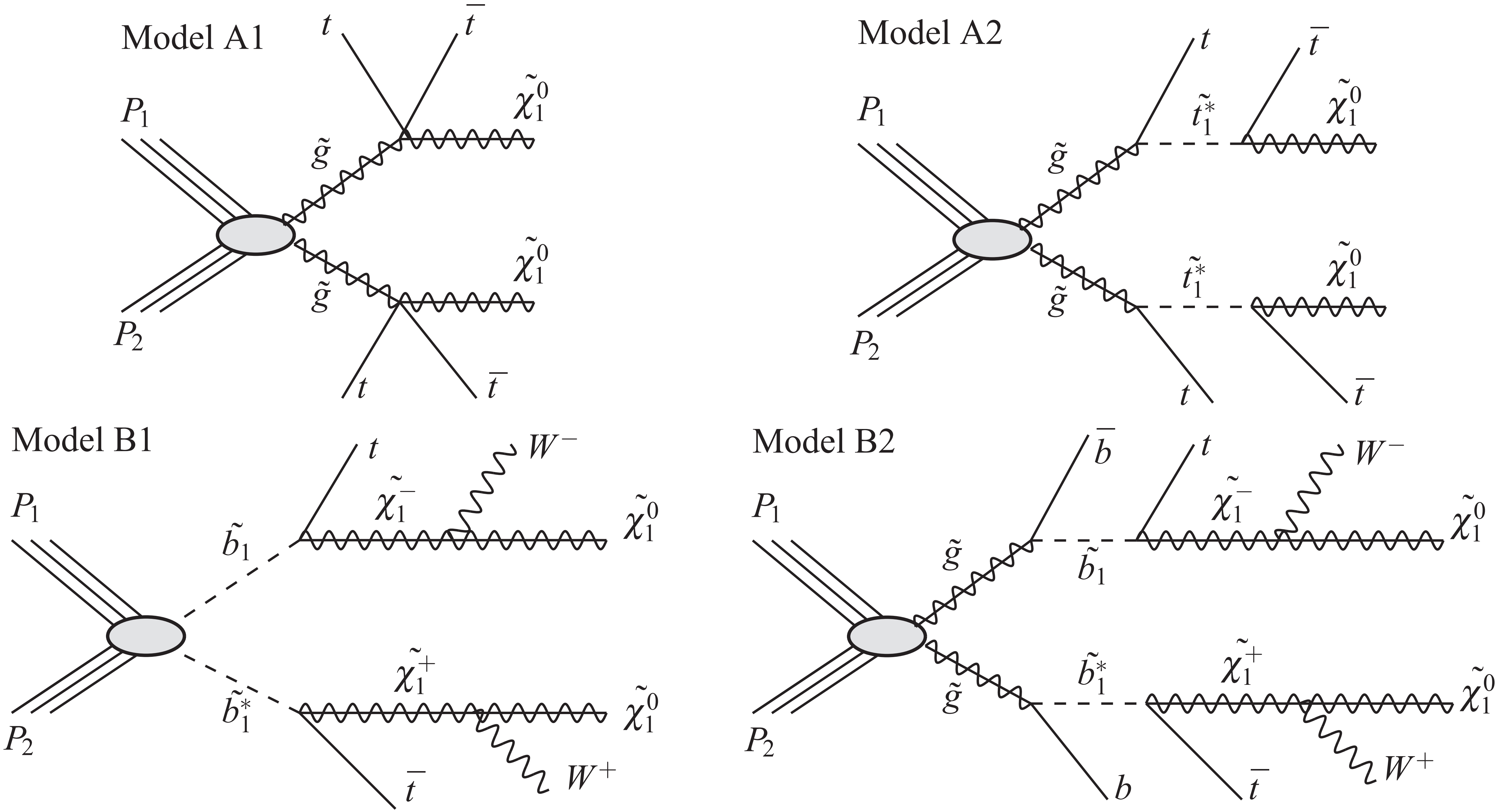
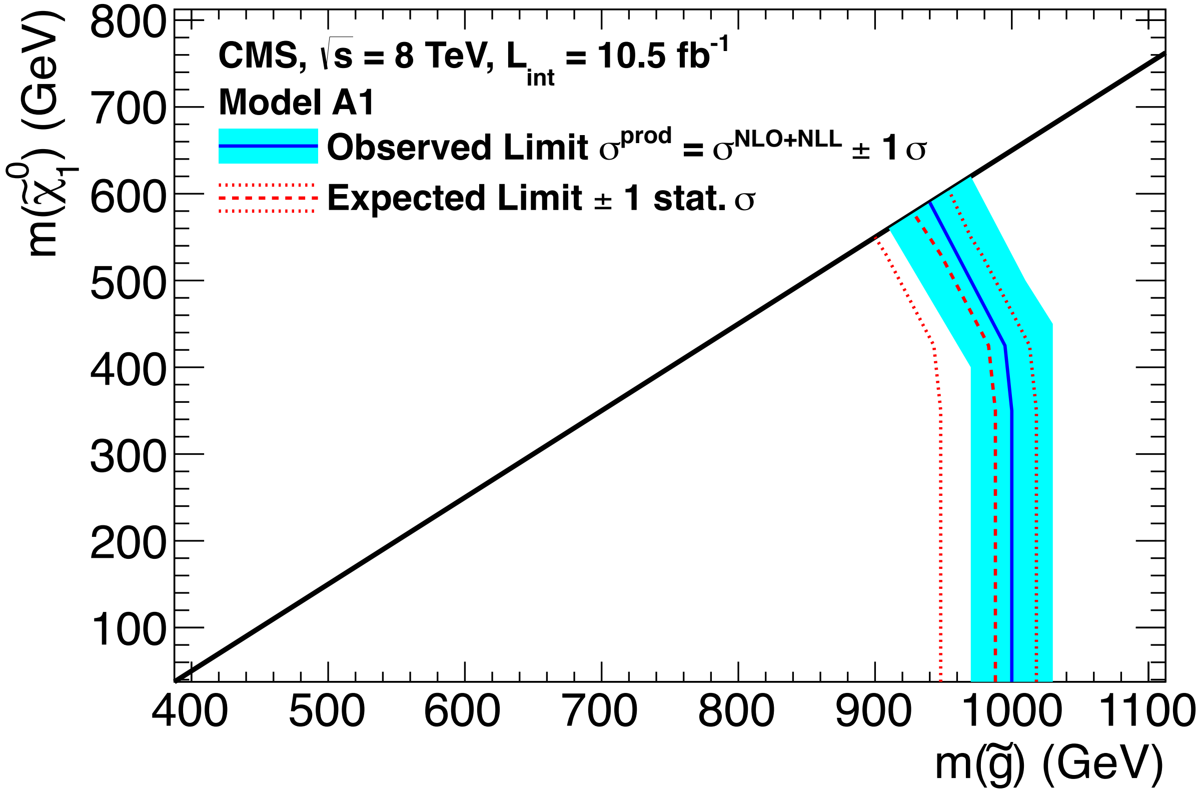
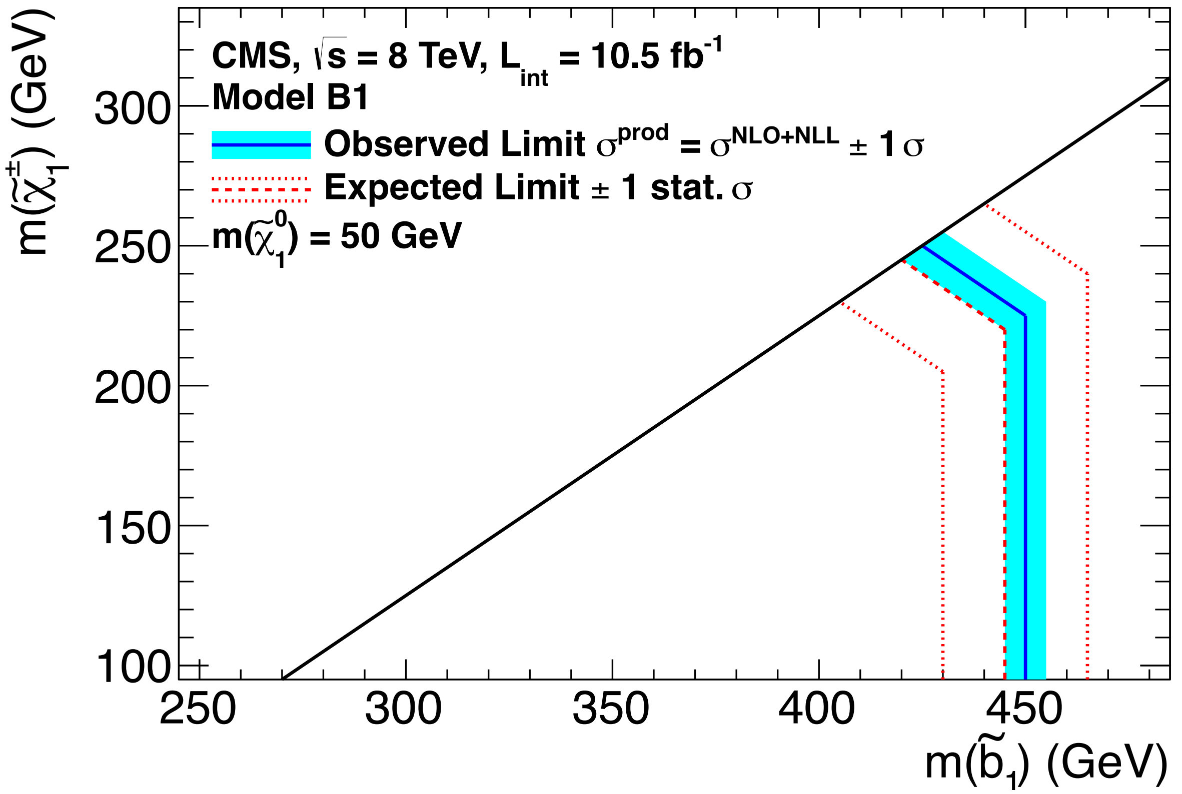
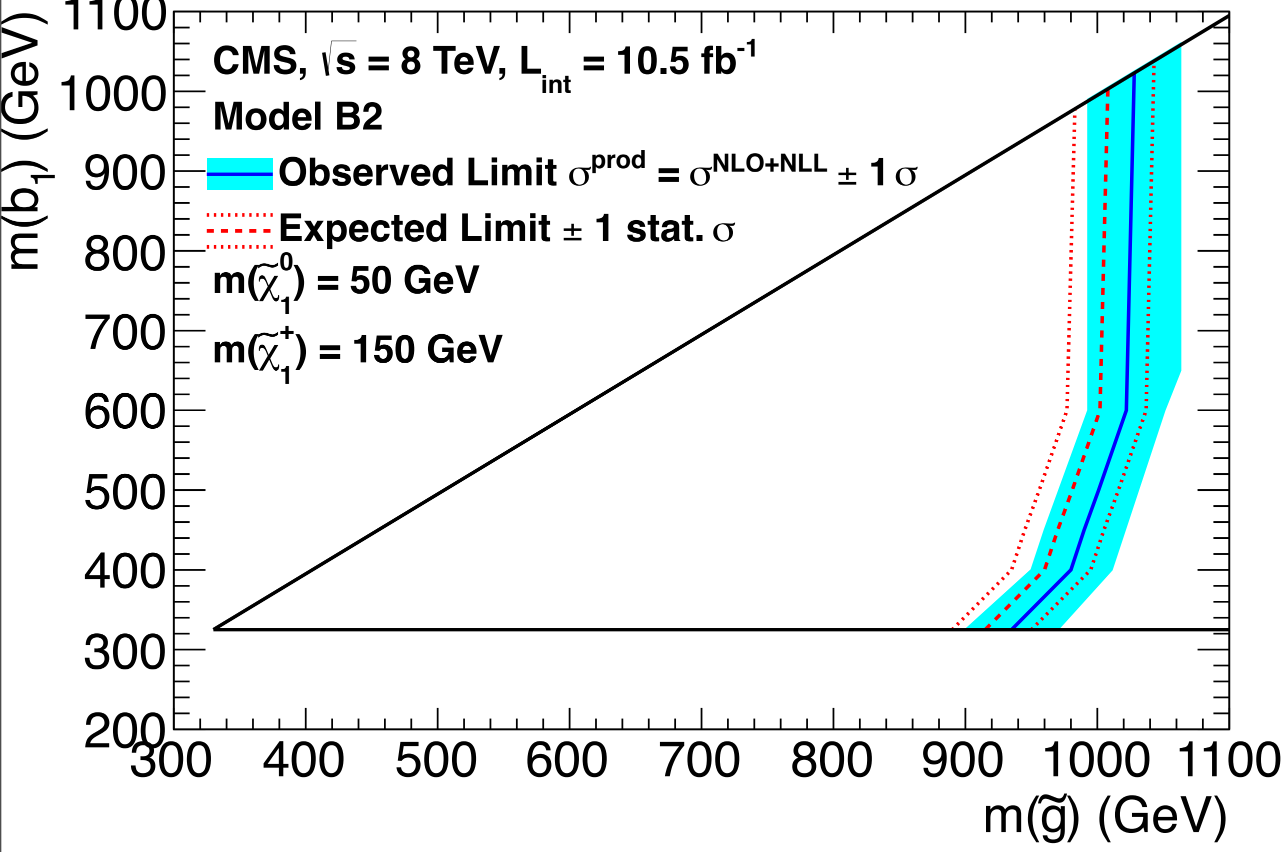
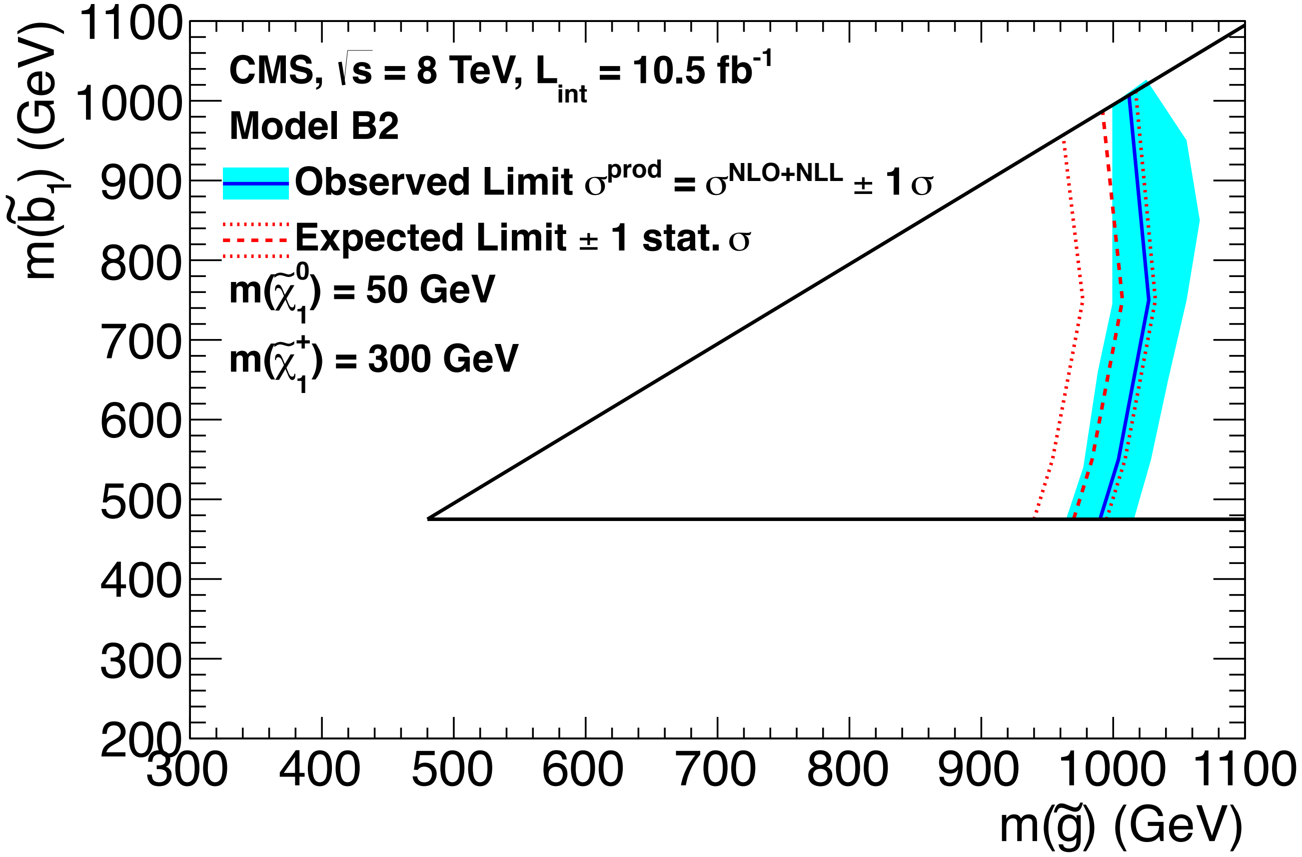


Figure 3: Diagrams for the four SUSY models considered (A1, A2, B1, and B2).


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)
800
700
600
500
400
300
200
100
400
500
600
700
800
900
1000
1100
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)
300
250
200
150
100
250
300
350
400
450
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(b₁) (GeV)
1100
1000
900
800
700
600
500
400
300
200
300
400
500
600
700
800
900
1000
1100
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)
1100
1000
900
800
700
600
500
400
300
200
300
400
500
600
700
800
900
1000
1100
m(g̃) (GeV)

Tree Level Mass

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

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

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

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

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

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

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

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

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

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

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

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

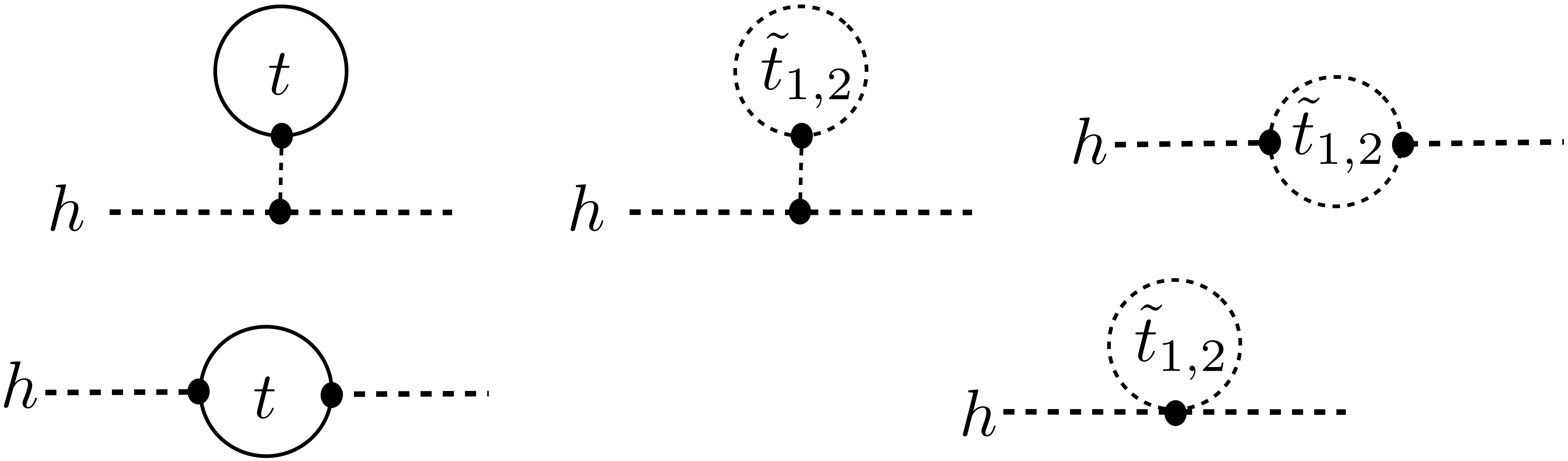
$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

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

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

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

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

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

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

dominant 2-loop contribution due to top-stop loops

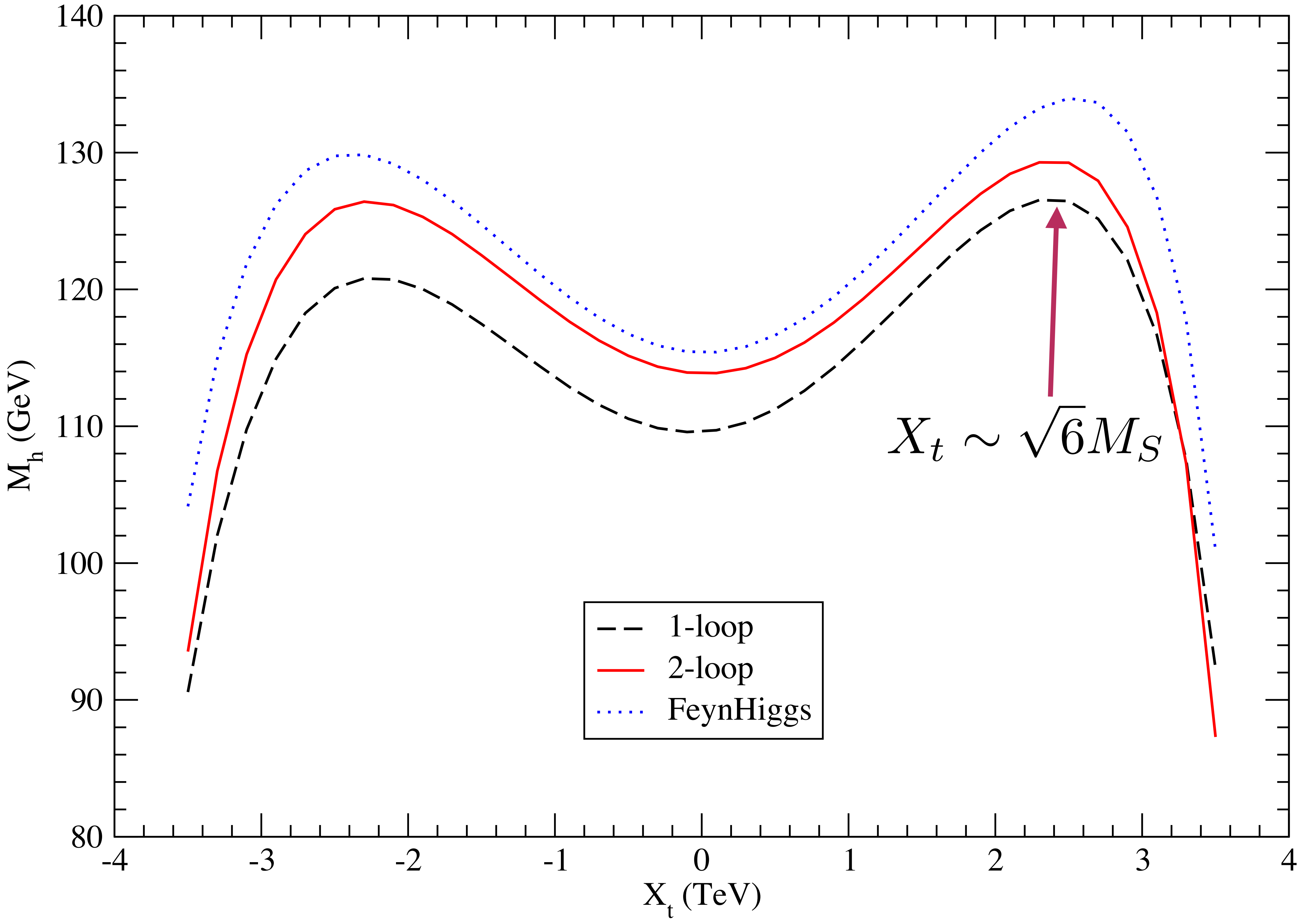
$$\Pi_{\phi_1}^{(2-\mathrm{loop})}(0) = 0 \qquad \Pi_{\phi_1\phi_2}^{(2-\mathrm{loop})}(0) = 0$$

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

$$\bar{m}_t = \bar{m}_t(m_t) \approx \frac{m_t^{\mathrm{pole}}}{1 + \frac{4}{3\pi}\alpha_s(m_t)}$$

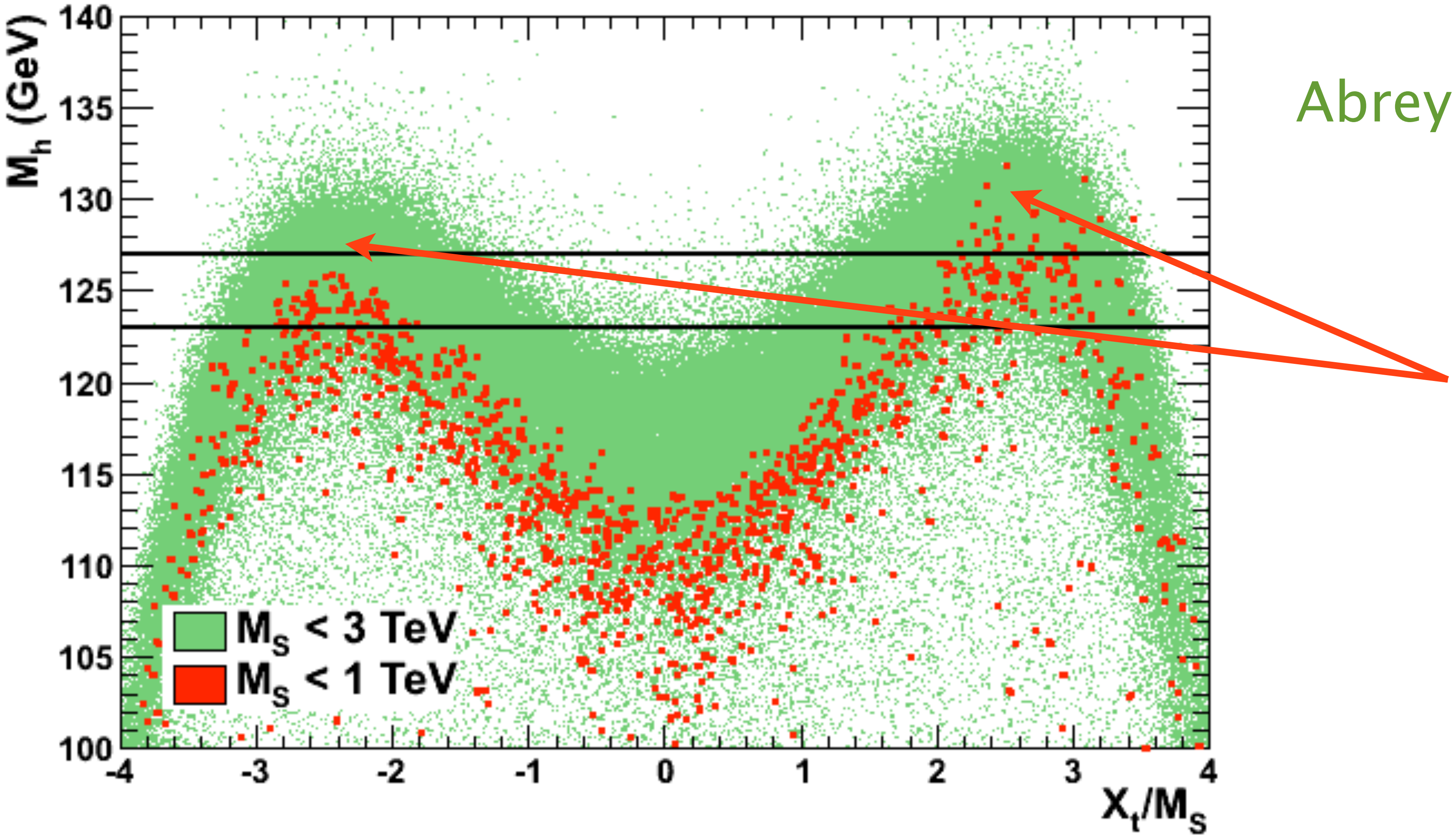
dominant 2-loop correction increases the lightest Higgs mass <10 GeV to the tree-level, assuming the sparticles are < 1 TeV (in no-mixing scenario).

$$\tan\beta = 10, M_A = M_S = 1 \text{ TeV}$$



$X_t \sim \sqrt{6} M_S$

Allanach et al. ’04

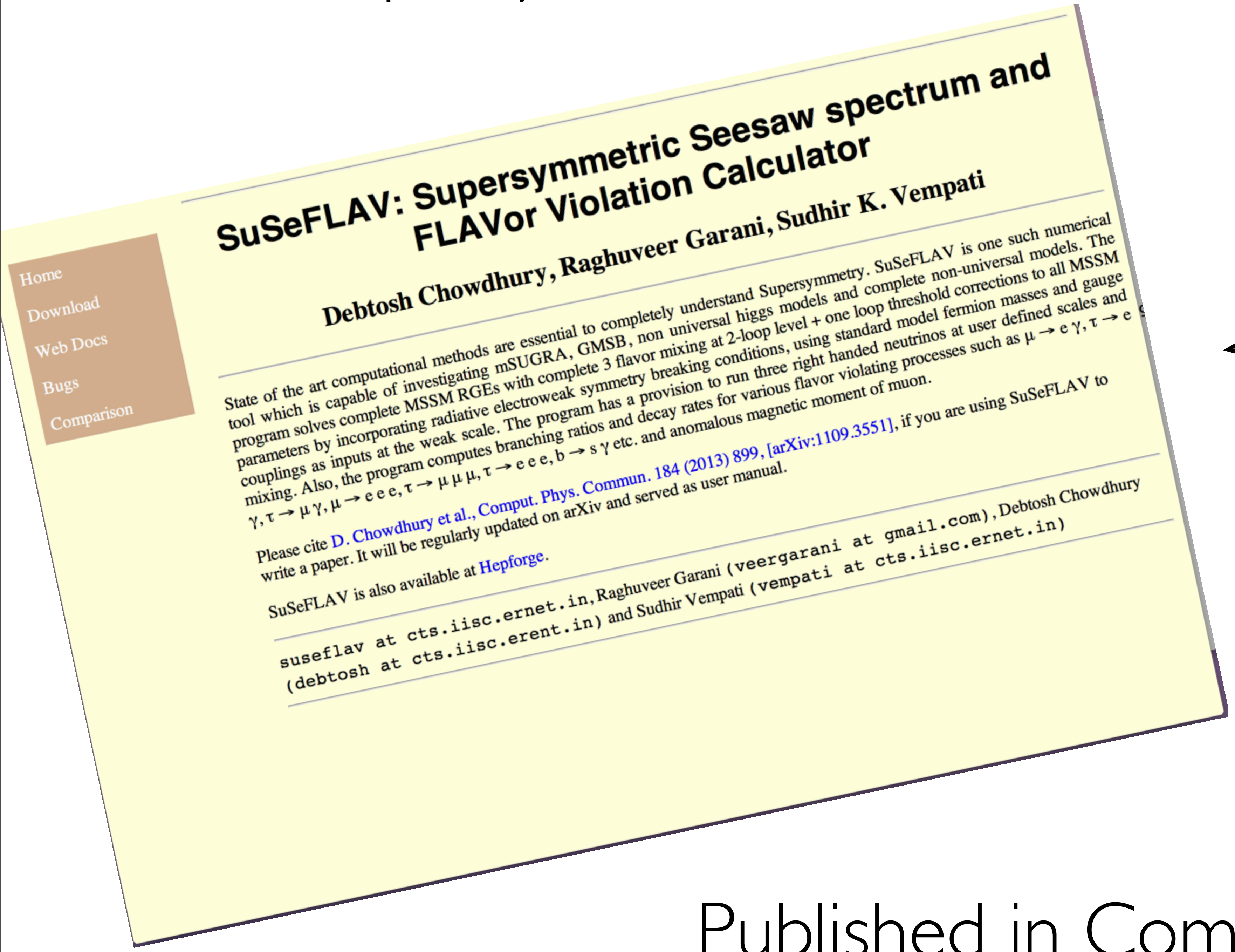


Abrey et al. ’11,’12

$$|X_t| \sim \sqrt{6} M_S$$

SuSeFLAV

SUpersymmetric SEesaw and Flavour Violation



Home
Download
Web Docs
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 $\mu \to e\,\gamma, \tau \to e$
$\gamma, \tau \to \mu\,\gamma, \mu \to e\,e\,e, \tau \to \mu\,\mu\,\mu, \tau \to e\,e\,e, b \to s\,\gamma$ 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

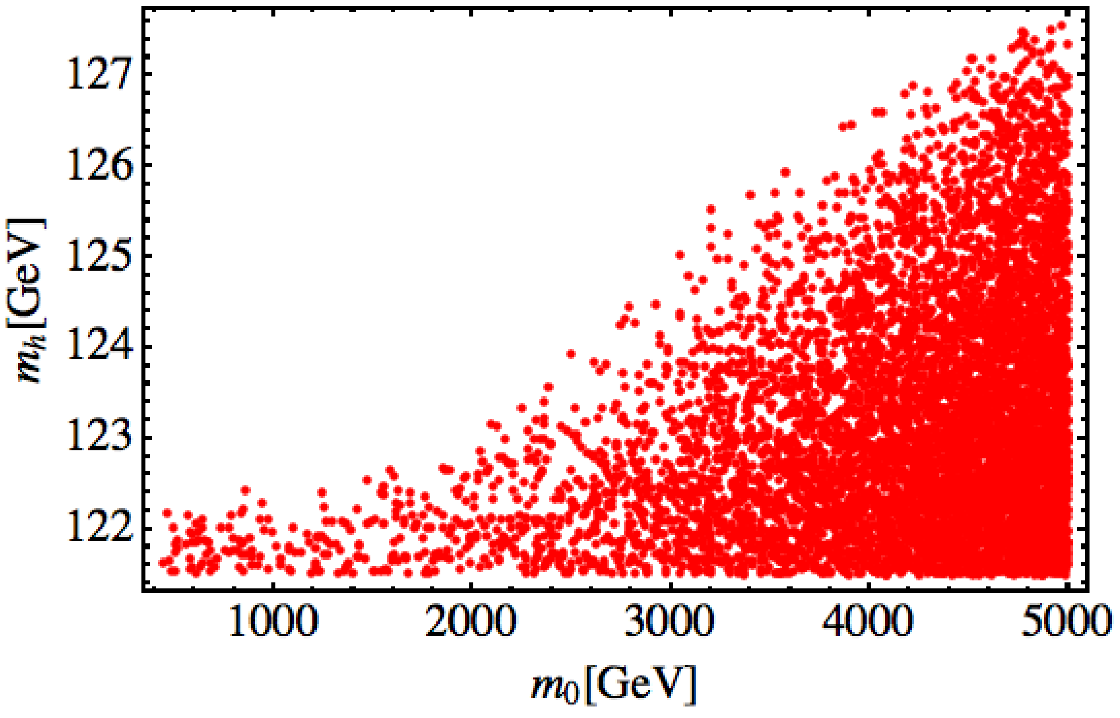
Published in Computer Physics Communications 184 (2013) 899

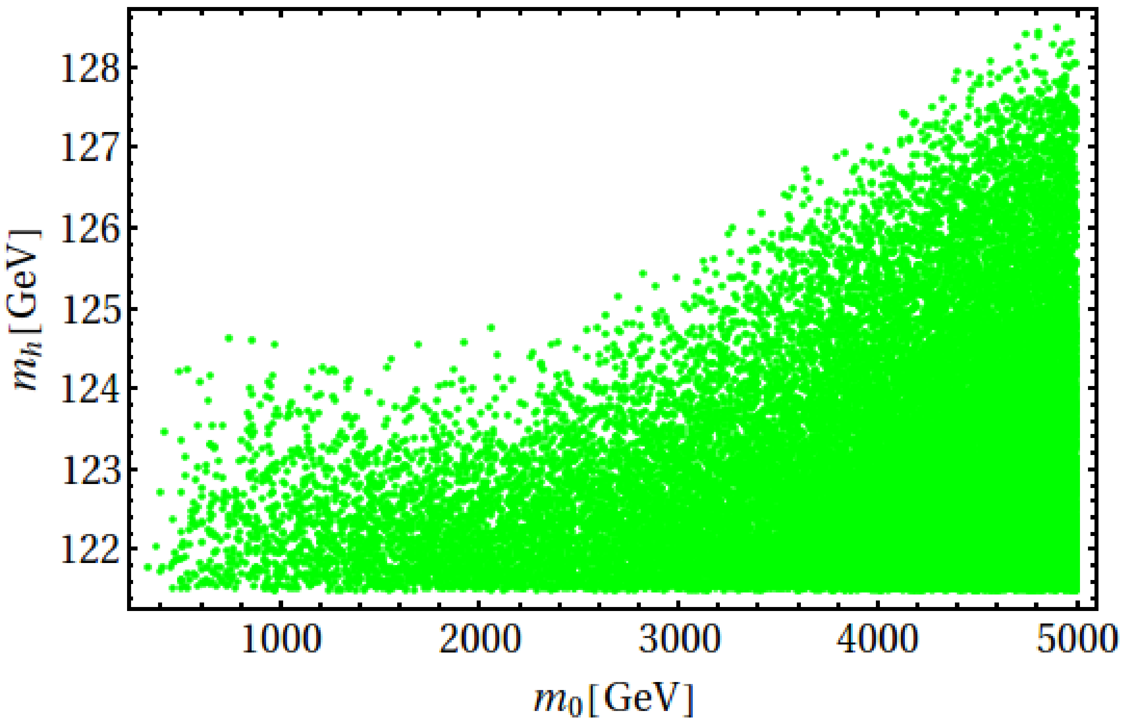
Computing the SUSY spectrum

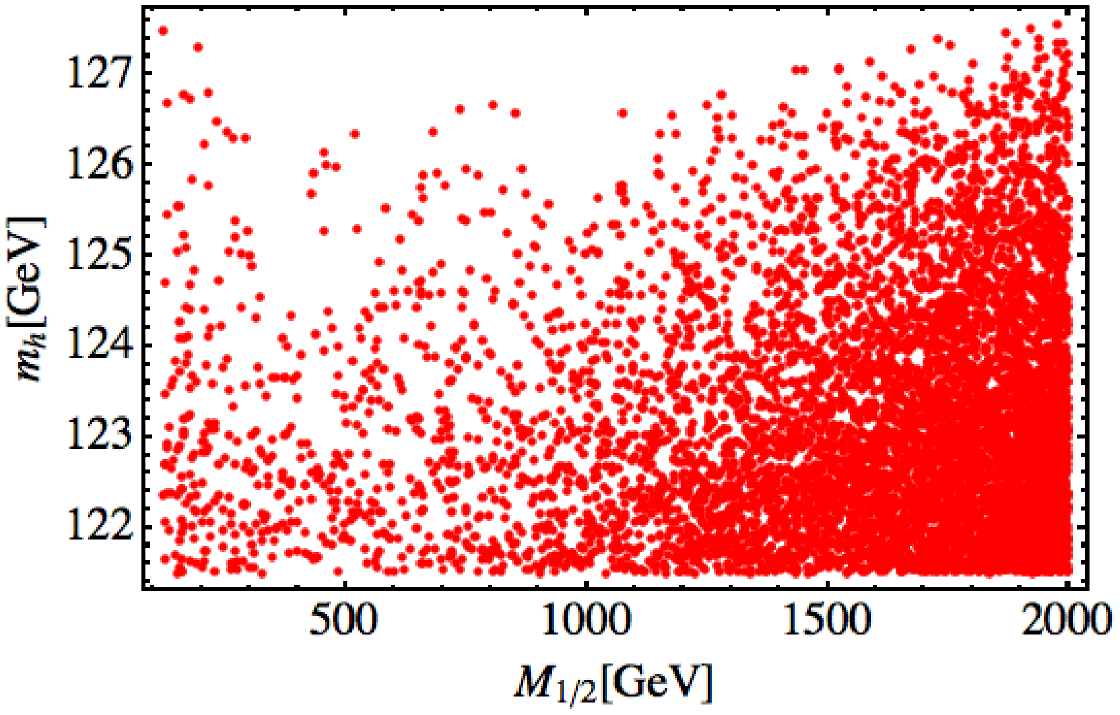
SUSEFLAV

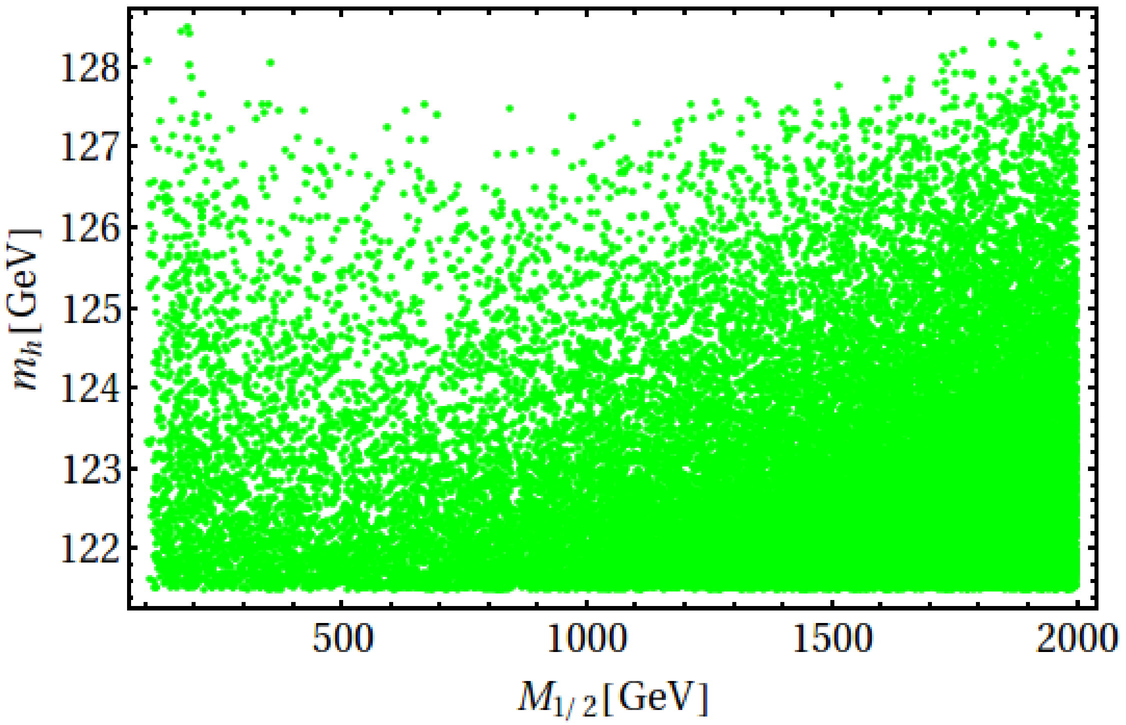
- two loop RGE with full flavour structure
- 1 loop corrections to all SUSY masses
- 1-loop SUSY thresholds to top, bottom, tau Yukawas
- Right handed neutrinos and seesaw mechanism

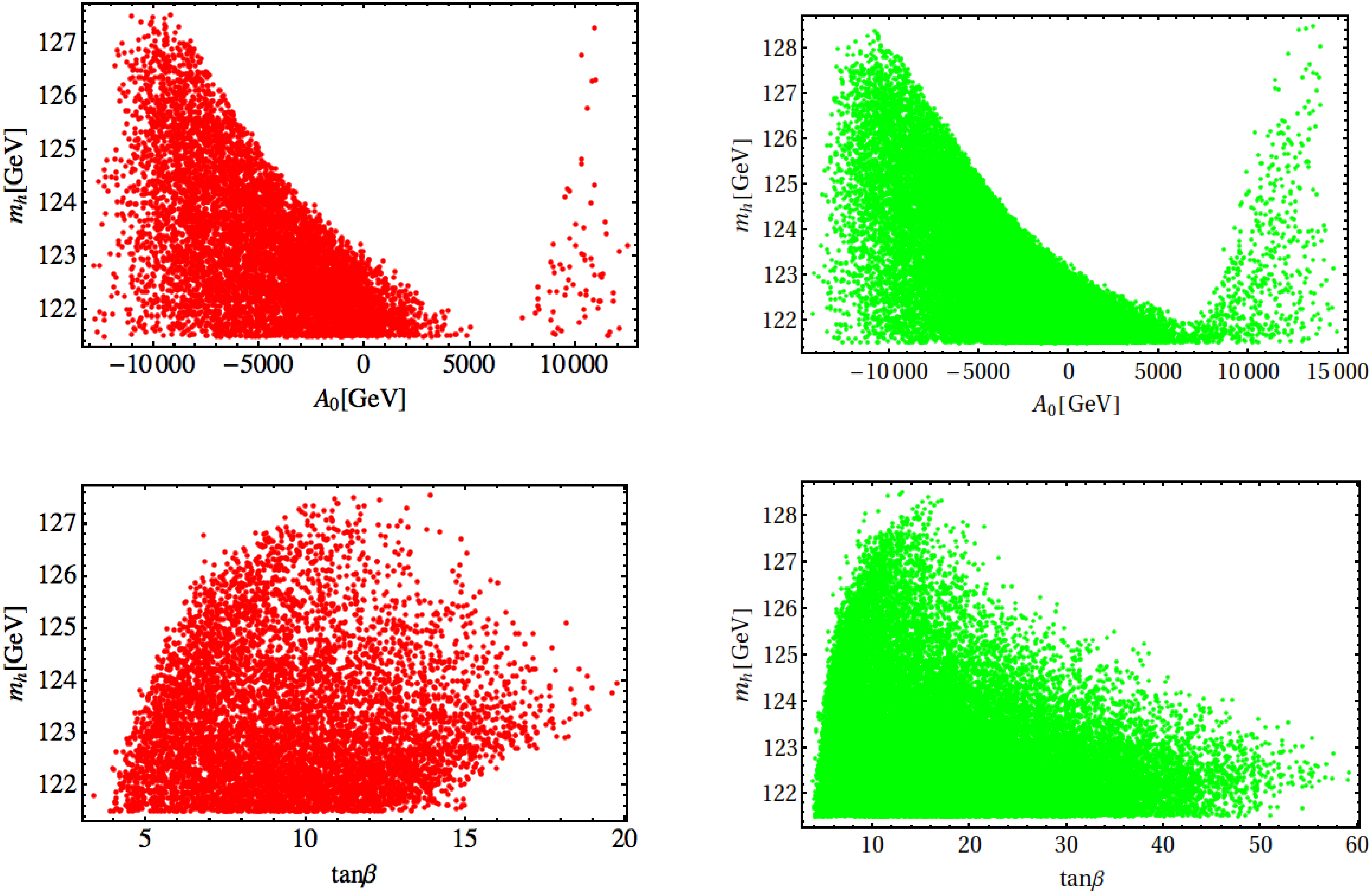
Present Constraints on mSUGRA + Seesaw










m_h[GeV]
122
123
124
125
126
127
128
−10000
−5000
0
5000
10000
15000
A_0[GeV]
5
10
15
20
30
40
50
60
tanβ

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)

Novel SUSY Scenarios

A little more gauge Mediation

gauge Mediation has many nice features

- * very few parameters
- * no flavour violation
- * light higgs mass ~ 125 GeV is difficult as $A_t \simeq 0$

- * electroweak breaking dynamical is possible but is a bit fine tuned (μ problem)
- * None of the known solutions for μ problem can be applied in GMSB

Consider NMSSM. as a solution to μ problem.

$$W = h^u Q u H_u + h^d Q d H_d + h^e L e H_d + \lambda S H_u H_d + k S^3$$

$$\left.\begin{array}{c|ccc} & S & H_u & H_d \\ \hline S & € & ƒ & £ \\ H_u & \ast & \$ & \% \\ H_d & \ast & \ast & ¥ \end{array}\right\}$$

Higgs mass matrix 3×3

$S \longrightarrow \langle S \rangle$ along with

H_u, H_d

a linear combination with singlet can increase the mass of the Higgs.

The problem with GMSB & NMSSM

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

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

$$S^2 \simeq \frac{\overbrace{-m_S^2 - A_\kappa^2 - A_\lambda^2}^{\text{all zero in GMSB}}}{\kappa^2}$$

$\simeq 0$

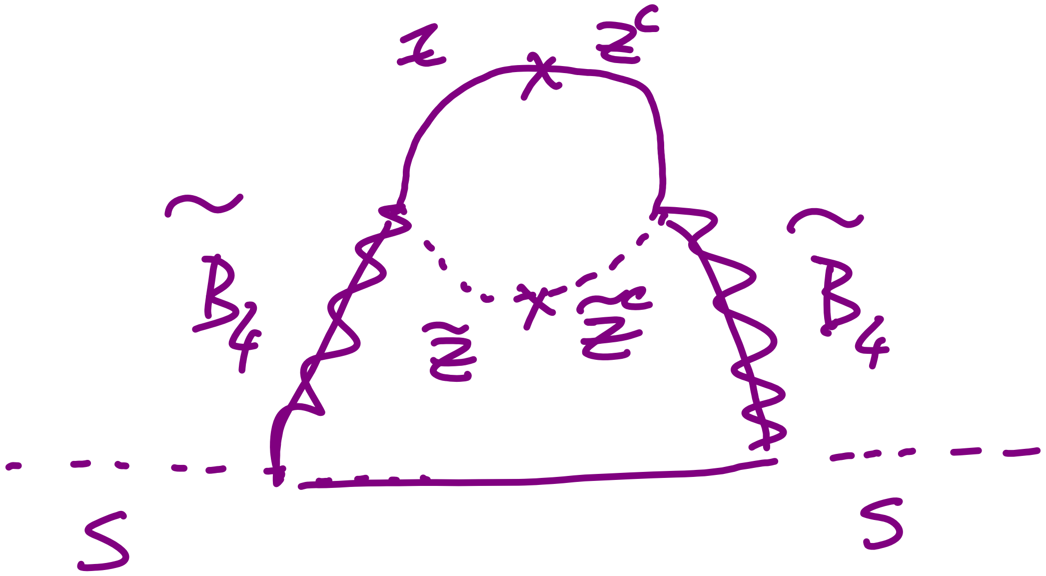
Our Solution to the problem

- 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 !

$m_S^2(\Lambda) \simeq$



- * $U(1)_X$ 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 $\gtrsim$ 125 GeV ✓

GMSB is not ruled out

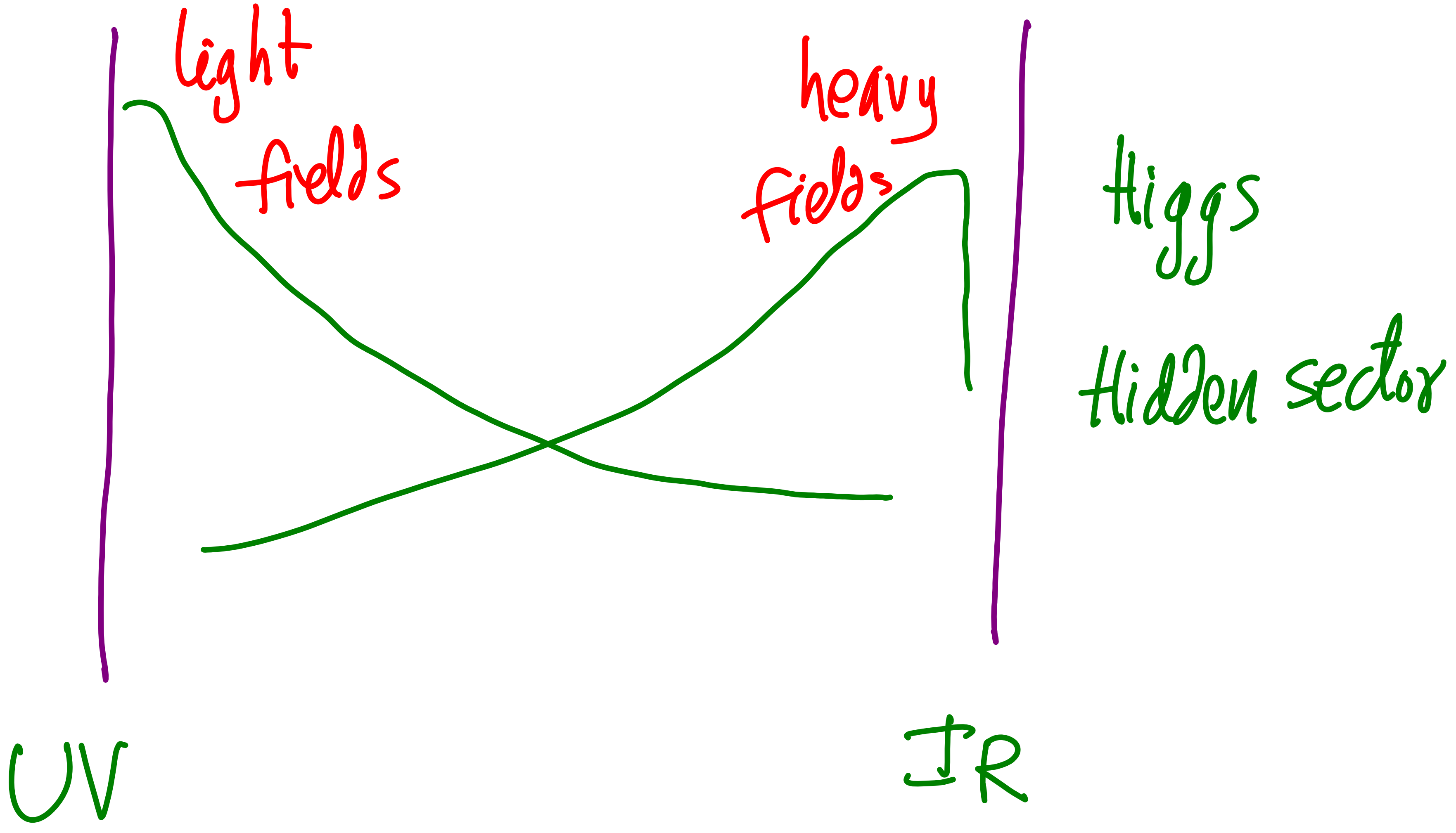
RS and compressed Spectrum

An Alternative to Froggatt-Nielsen

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

Supersymmetry is uses solve the hierarchy problem

No constraints from anomaly cancellation conditions as in FN models.



Profiles of the matter fields determined by 5D bulk masses

The bulk masses of superfields Q_i, U_i, D_i, L_i, E_i

not only fit Yukawa matrices Y_U, Y_D and Y_E

but also determine all the <u>105</u> soft terms!!

Some sample solutions:

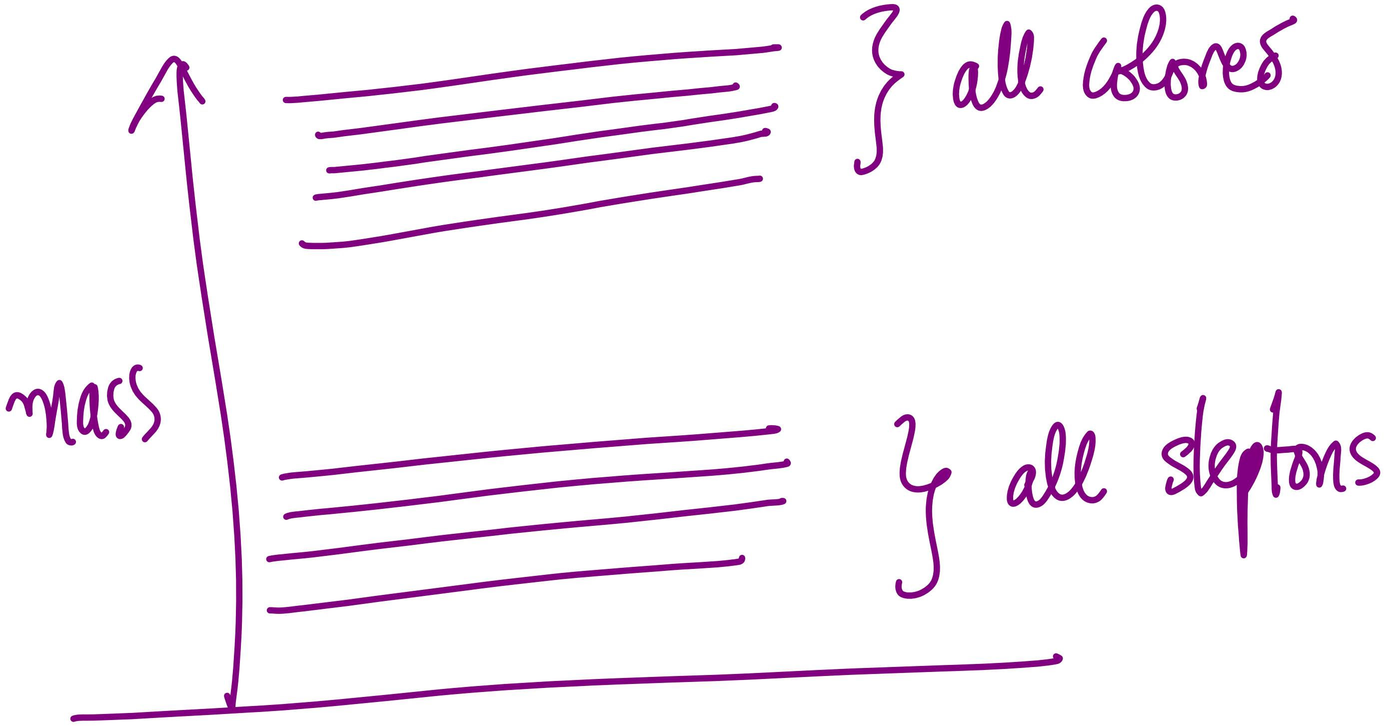
$$m_{\tilde{f}}^2 = \begin{bmatrix} \varepsilon & \varepsilon & \varepsilon' \\ \varepsilon & \varepsilon & \varepsilon' \\ \varepsilon' & \varepsilon' & 1 \end{bmatrix} m_{3/2}^2 \qquad \varepsilon \leq \varepsilon' \leq 1$$

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

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

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

But the weak scale spectrum is interesting!



sort of Compressed spectra

Fully Compressed spectra does'nt leave any trace @ LHC.

But this compression is unique & different.

We get spectra which satisfy all constraints

- * flavour violation
- * $m_h^2 = (125\,\text{GeV})^2$
- * Compressed spectra

Summary :

Supersymmetric models are receiving strong constraints from direct experimental results.

the upgraded LHC will check whether our ideas are correct or not.