Supersymmetry: A status report

Charan Fest

UNICOS Panjan University,
Chandigarh

May 13-15 2014

Sudhir Vempati,

Centre for High Energy Physics,
Indian Institute of Science,
Bangalore

Congratulations to Charan on his 60th birthday.

Wish much deeper understanding of SUSY SO(10) GUTS from him.
Over the last few years, his work on Supersymmetric SO(10) GUTs has been outstanding..perhaps for the first time we seem to have a solid effort towards a "realistic" grand unified theory .

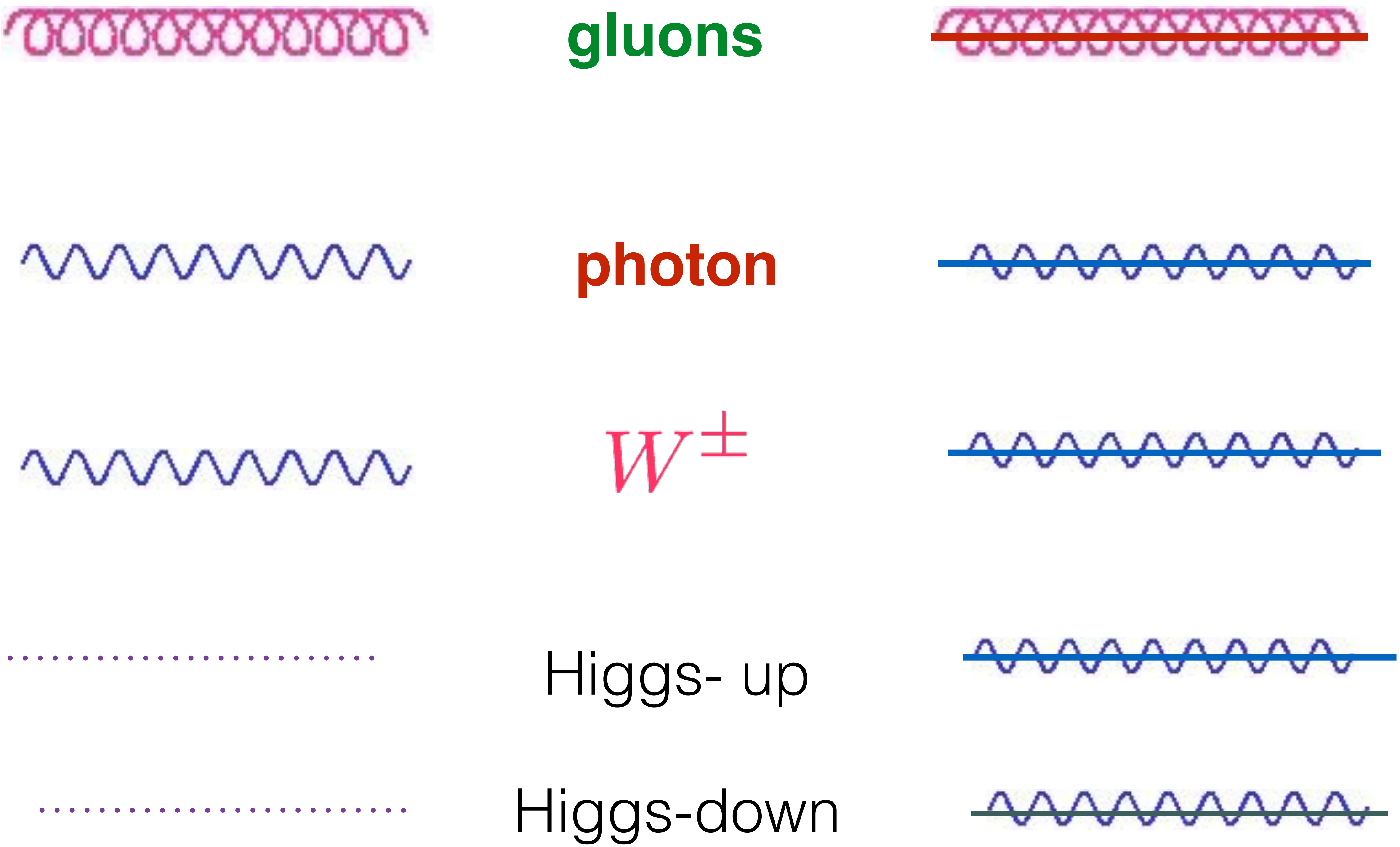
I learnt supersymmetry from Parthasarathy Majumdar and Charan Aulakh on this campus about 18 years ago !

Charan is terrific teacher !!

Charan serves as an inspiration for many of us who have learnt supersymmetry from him.

$\tilde{u}_L$	u	$\tilde{u}_R$	$\tilde{c}_L$	c	$\tilde{c}_R$	$\tilde{t}_L$	t	$\tilde{t}_R$
$\tilde{d}_L$	d	$\tilde{d}_R$	$\tilde{s}_L$	s	$\tilde{s}_R$	$\tilde{b}_L$	b	$\tilde{b}_R$
$\tilde{\nu}_{e_L}$	ν_e		$\tilde{\nu}_{\mu_L}$	ν_μ		$\tilde{\nu}_{\tau_L}$	ν_τ	
$\tilde{e}_L$	e	$\tilde{e}_R$	$\tilde{\mu}_L$	μ	$\tilde{\mu}_R$	$\tilde{\tau}_L$	τ	$\tilde{\tau}_R$

Supersymmetric Standard Model -1



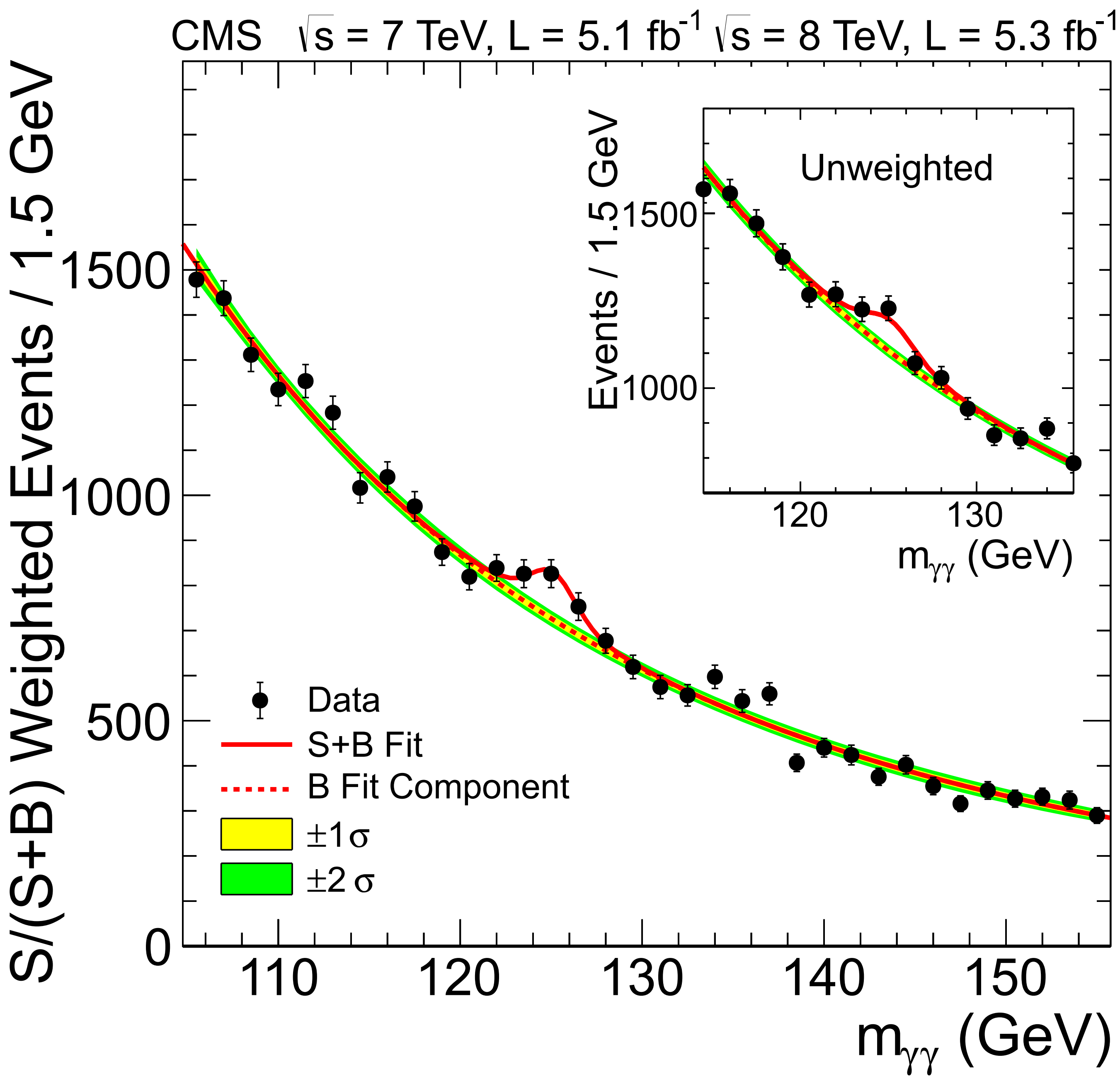
Supersymmetric Standard Model Spectrum -2

Features of SUSY

- It is a technically Natural theory. (Romesh's talk)
- 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.

Higgs and stops

The Higgs bump at LHC



Speed breakers to Zero Stop mixing ??

Upper bound on Light Higgs (one loop)

$$m_t(m_{SUSY}) \approx 157 \quad \text{GeV}$$

$$m_h^2 = m_Z^2 \cos^2 2\beta + \Delta m_h^2$$

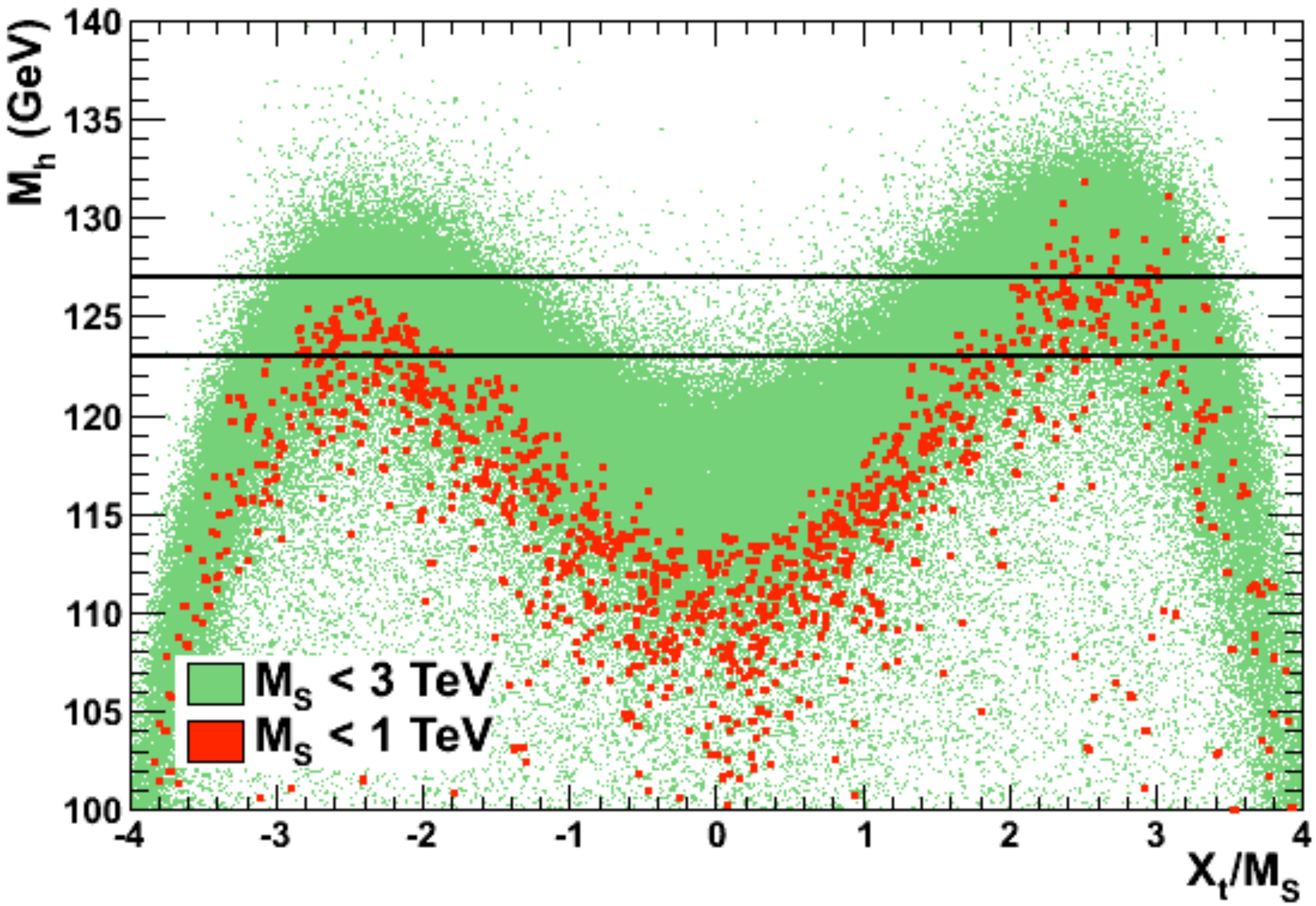
$$\Delta m_h^2 \simeq \frac{3 g_2^2 m_t^4}{8\pi^2 M_W^2} \left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}} \left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}} \right) \right]$$

for m_{SUSY} = 1 TeV, we have an upper bound of 135 GeV

pretty robust prediction.

Fixed Order

phenomenological models



Abrey et al.
1112.3028;
2012 updates

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

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

Theoretical Status of the Higgs mass computation

One loop terms +

dominant 2-loop contribution due to top-stop loops

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

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

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

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).

Fixed Order

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 $\Rightarrow X_t = 0$

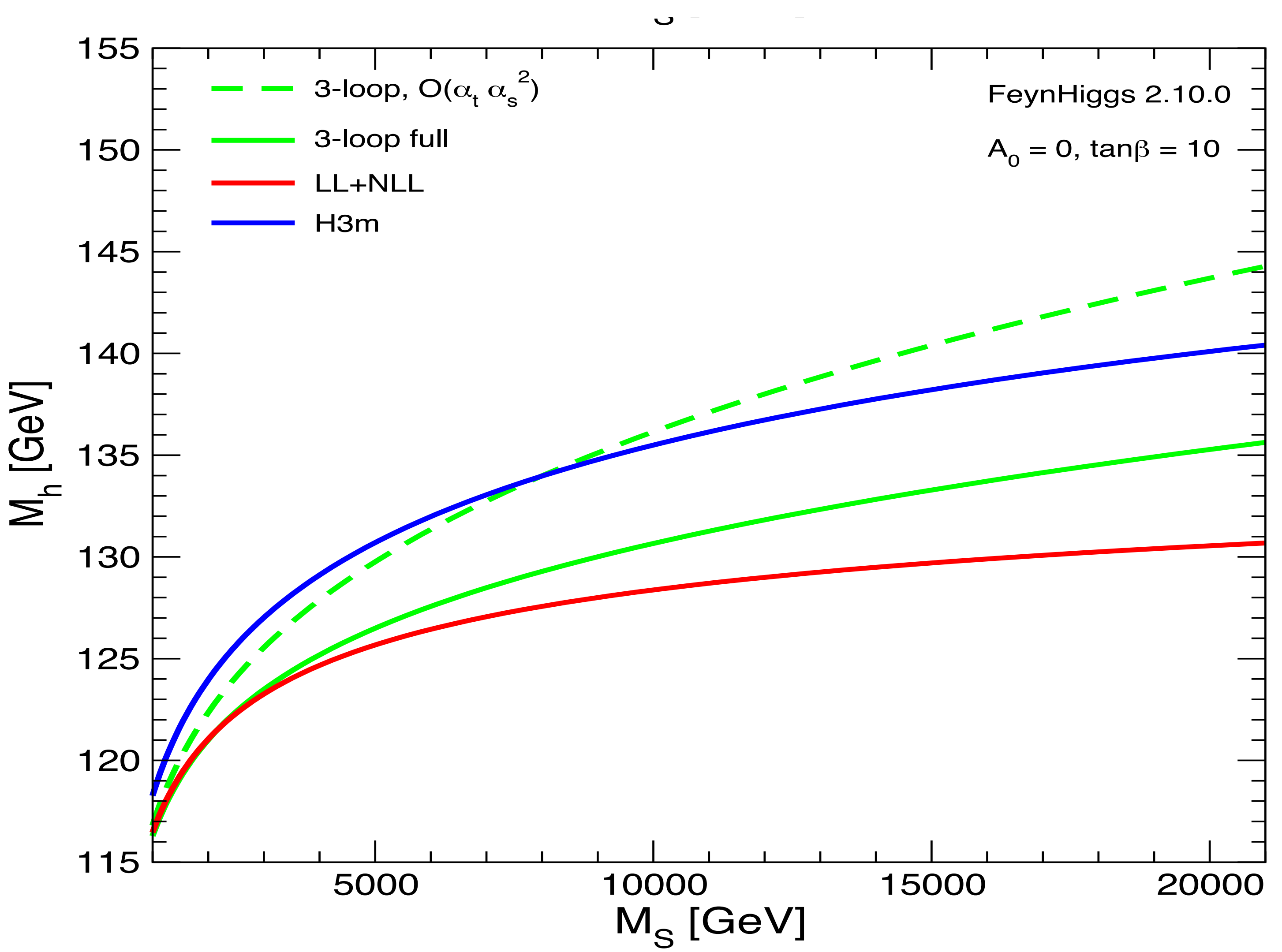
Harlander et al. ‘08
Martin ‘07

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

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

Fixed Order

Theoretical Status of the Higgs mass computation



T.Hahn et. al,
arXiv: 1312.4937.
Buchmueller et. al,
arXiv:1312.5233
Draper et. al
1312.5743

Theorem

- If LHC discovers light stops (less than TeV) and they are strongly mixed: then MSSM structure is true.

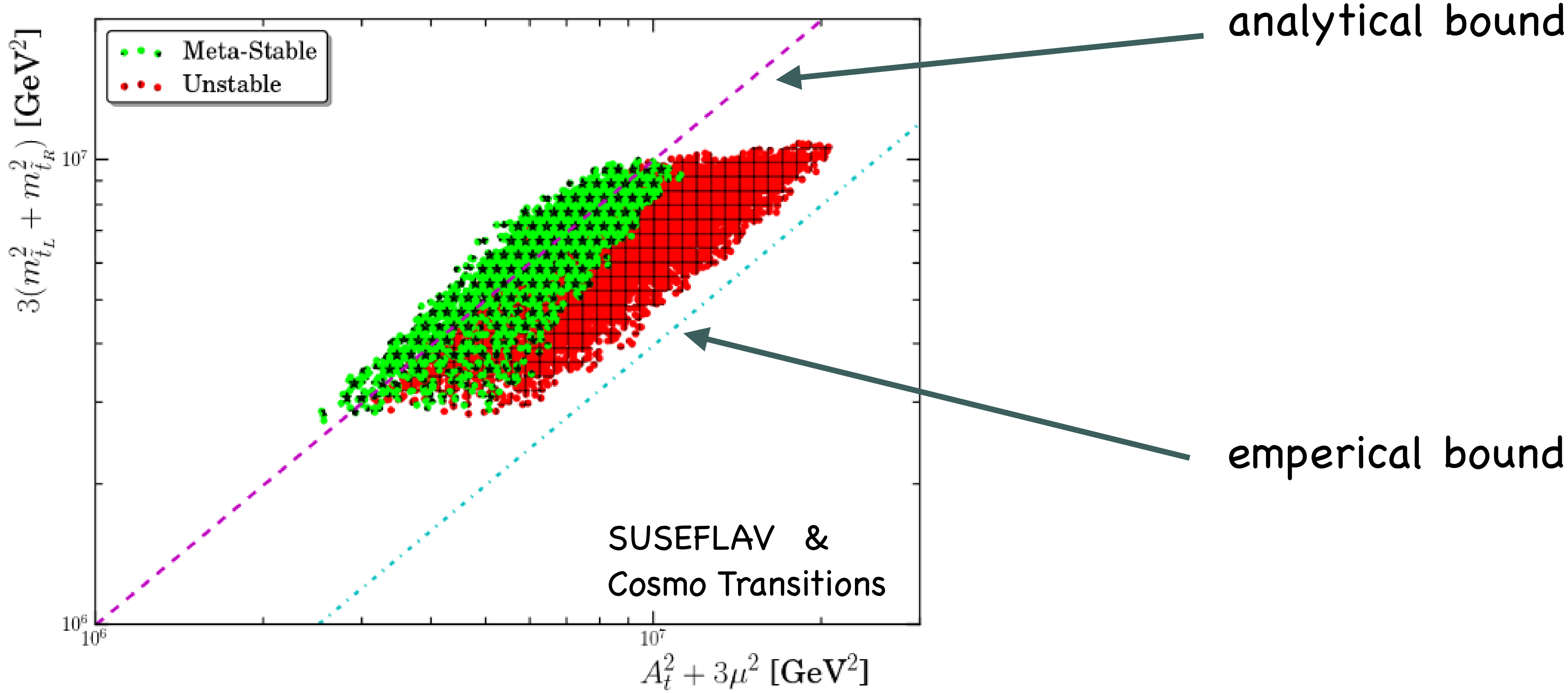
- If LHC discovers light stops and they have zero mixing, it points to structures beyond MSSM (like NMSSM , D-terms etc..)

Charge and Colour breaking Minima

Chowdhury,
Godbole, Mohan,
Vempati,
arXiv: 1310.1932
JHEP

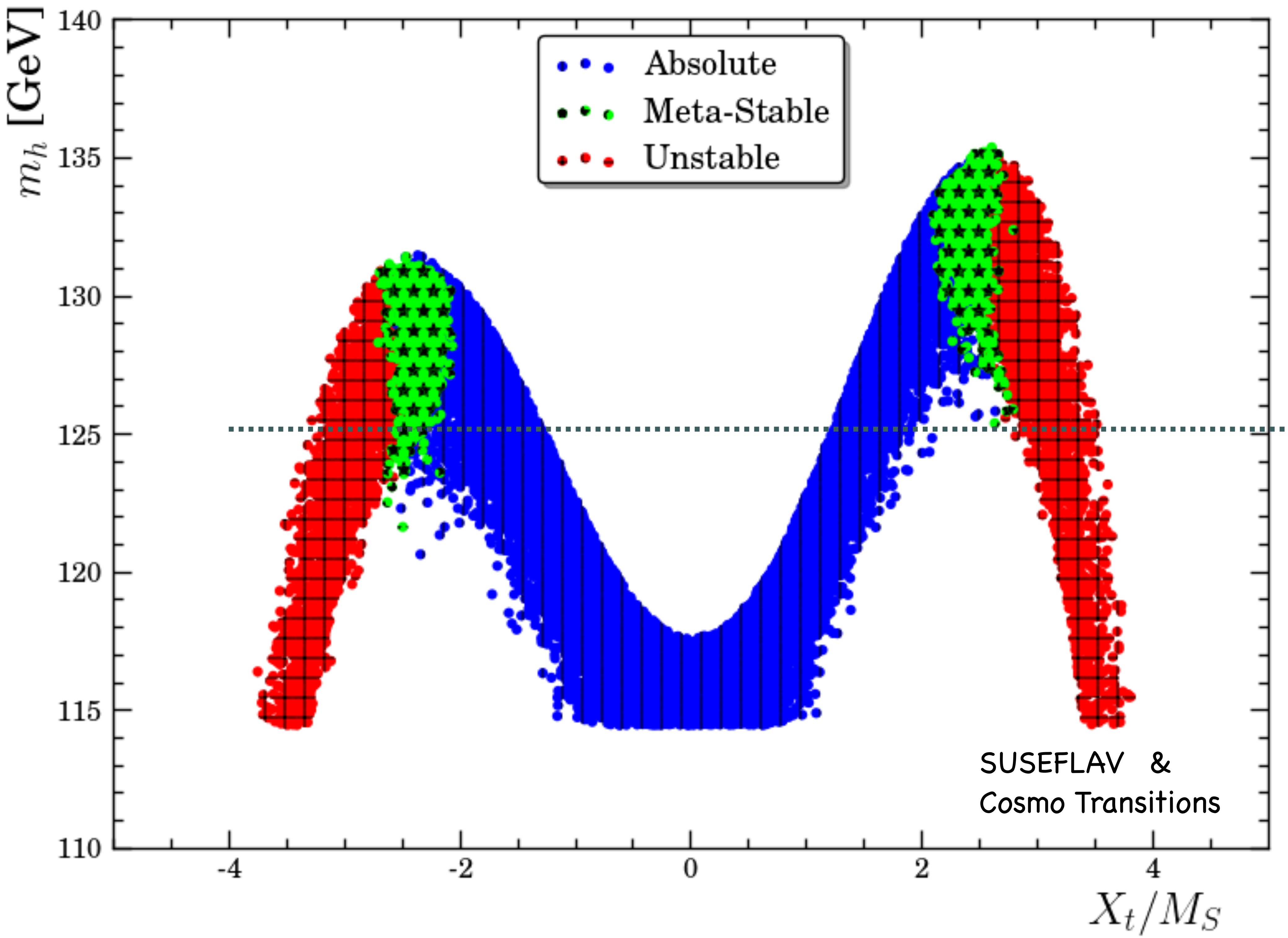
$$\mathcal{V}_3 = \left(m_{H_u}^2 + \mu^2\right)|H_u|^2 + m_{\tilde{t}_L}^2 |\tilde{t}_L|^2 + m_{\tilde{t}_R}^2 |\tilde{t}_R|^2 + \left(y_t A_t\, H_u^* \tilde{t}_L \tilde{t}_R + \text{c.c.}\right)$$
$$+ y_t^2\left(|\tilde{t}_L\tilde{t}_R|^2 + |H_u\tilde{t}_L|^2 + |H_u\tilde{t}_R|^2\right) + \frac{g_1^2}{8}\left(|H_u|^2 + \frac{1}{3}|\tilde{t}_L|^2 - \frac{4}{3}|\tilde{t}_R|^2\right)^2$$
$$+ \frac{g_2^2}{8}\left(|H_u|^2 - |\tilde{t}_L|^2\right)^2 + \frac{g_3^2}{6}\left(|\tilde{t}_L|^2 - |\tilde{t}_R|^2\right)^2 .$$

Full Four Field Numerical Analysis



Is the universe in a *critical* parameter SUSY parameter space ?

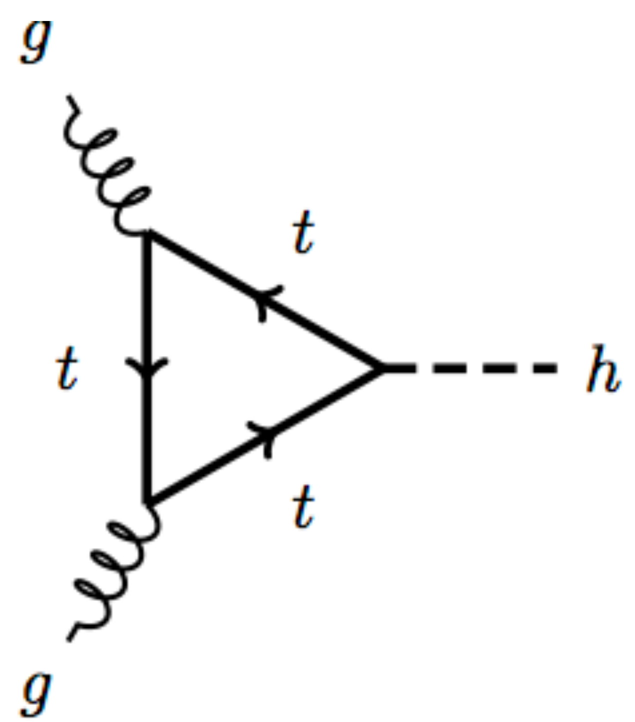
Stability of MSSM vacuum analysis with four fields, the two Higgs fields and the stop fields (considering they are light)

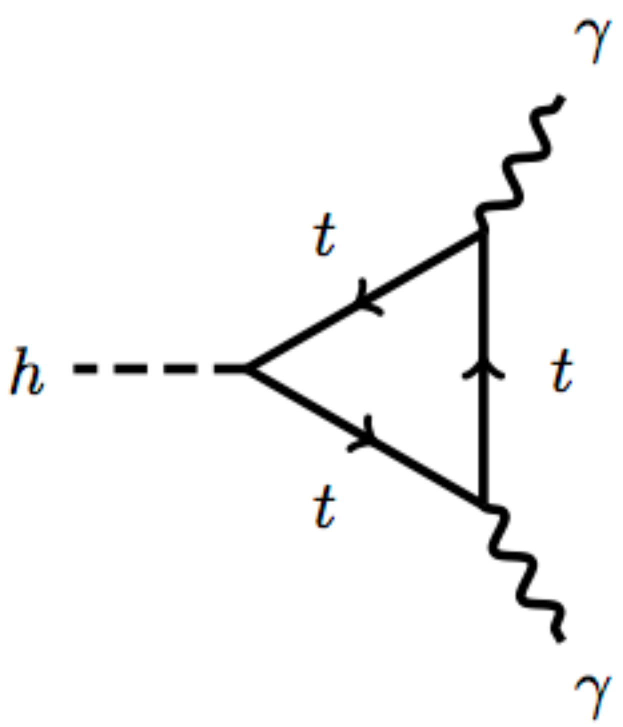


Chowdhury, Godbole, Mohan, Vempati, arXiv: 1310.1932 JHEP

and other groups

Higgs productions, decays

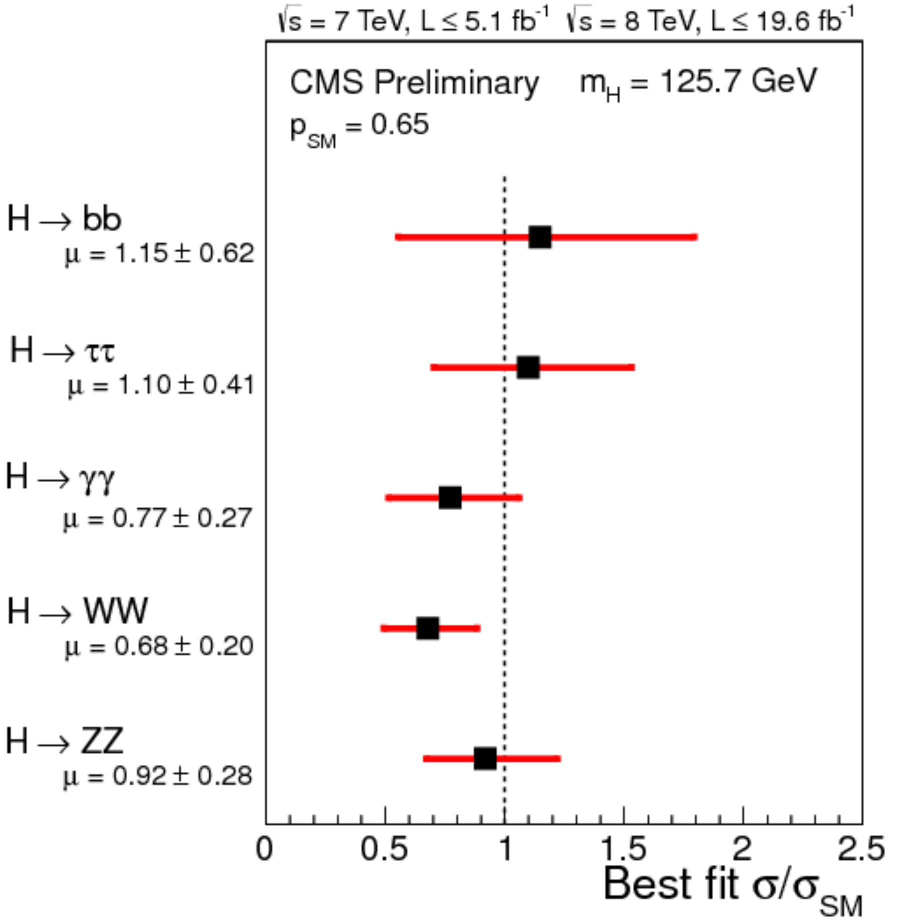


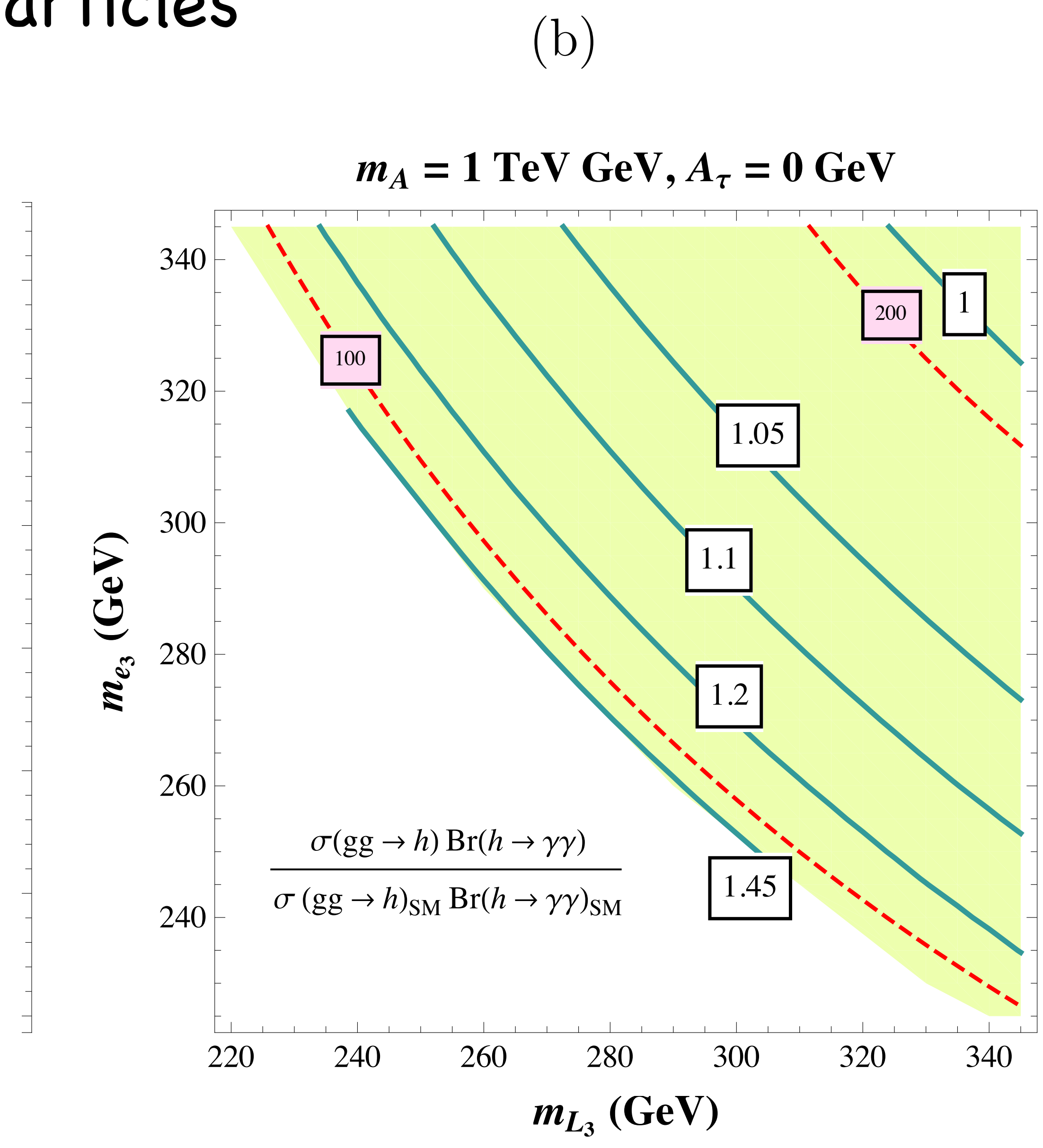


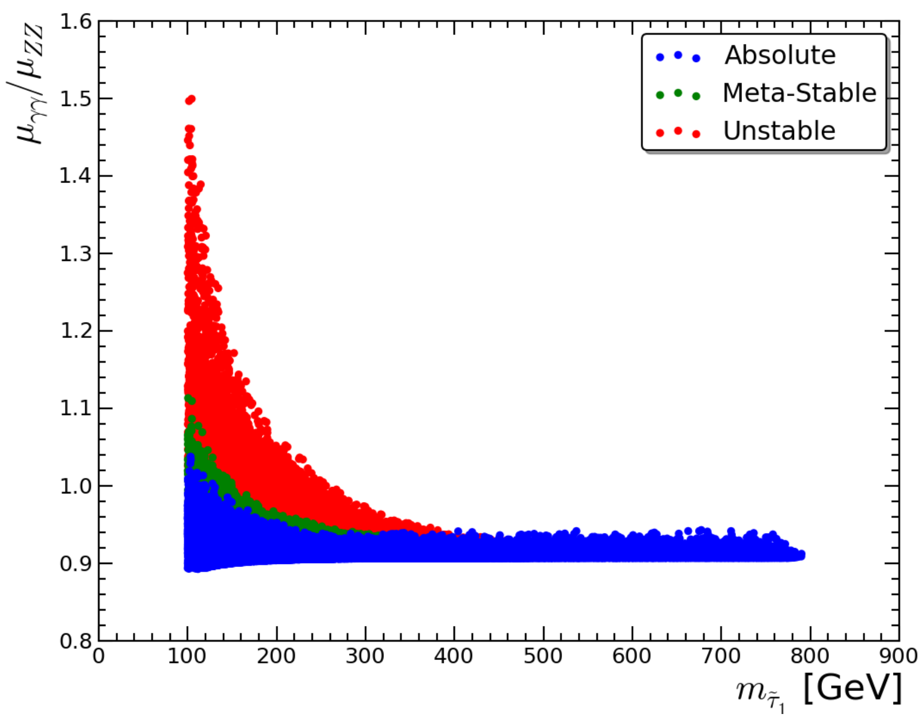
Light stops, light staus can significantly modify them...

Carena et. al
1205.5842

Signal strengths can be used to constrain light particles



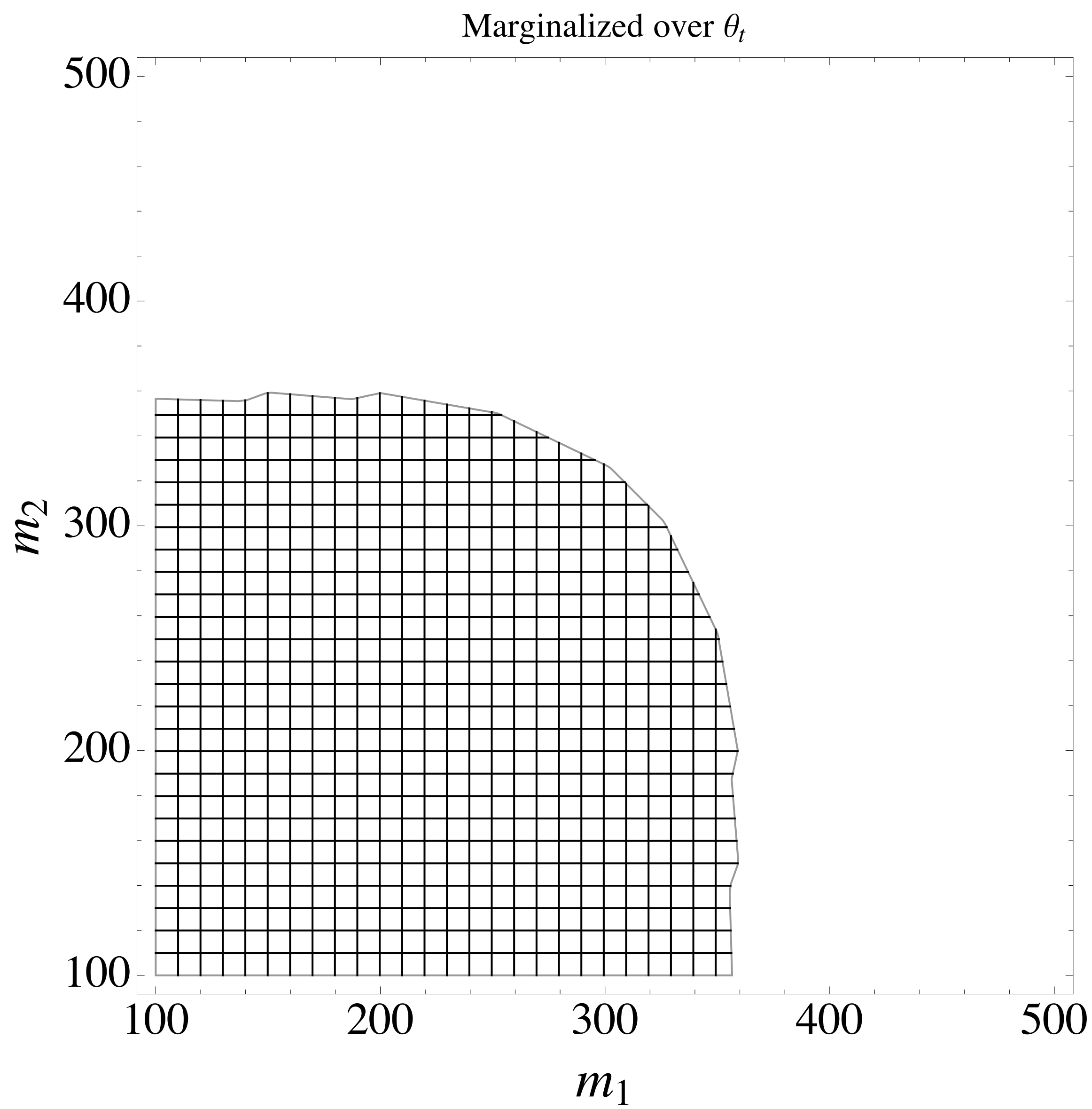




Chowdhury et. al

Limits on Stop masses

Adam Falkowski et. al



Flavour Constraints on third generation

Mostly in sbottom sector

Combined B-physics constraints

$$\frac{(\Delta m^2_{\tilde{f}})_{23}}{m^2_{\tilde{f}}} \lesssim \quad 10^{-2} \;\; \text{to} \;\; 10^{-1}$$

for about 500 GeV sbottoms

For larger sbottoms 1 TeV or so, the constraints are much weaker !!

Very similar even in the stau sector

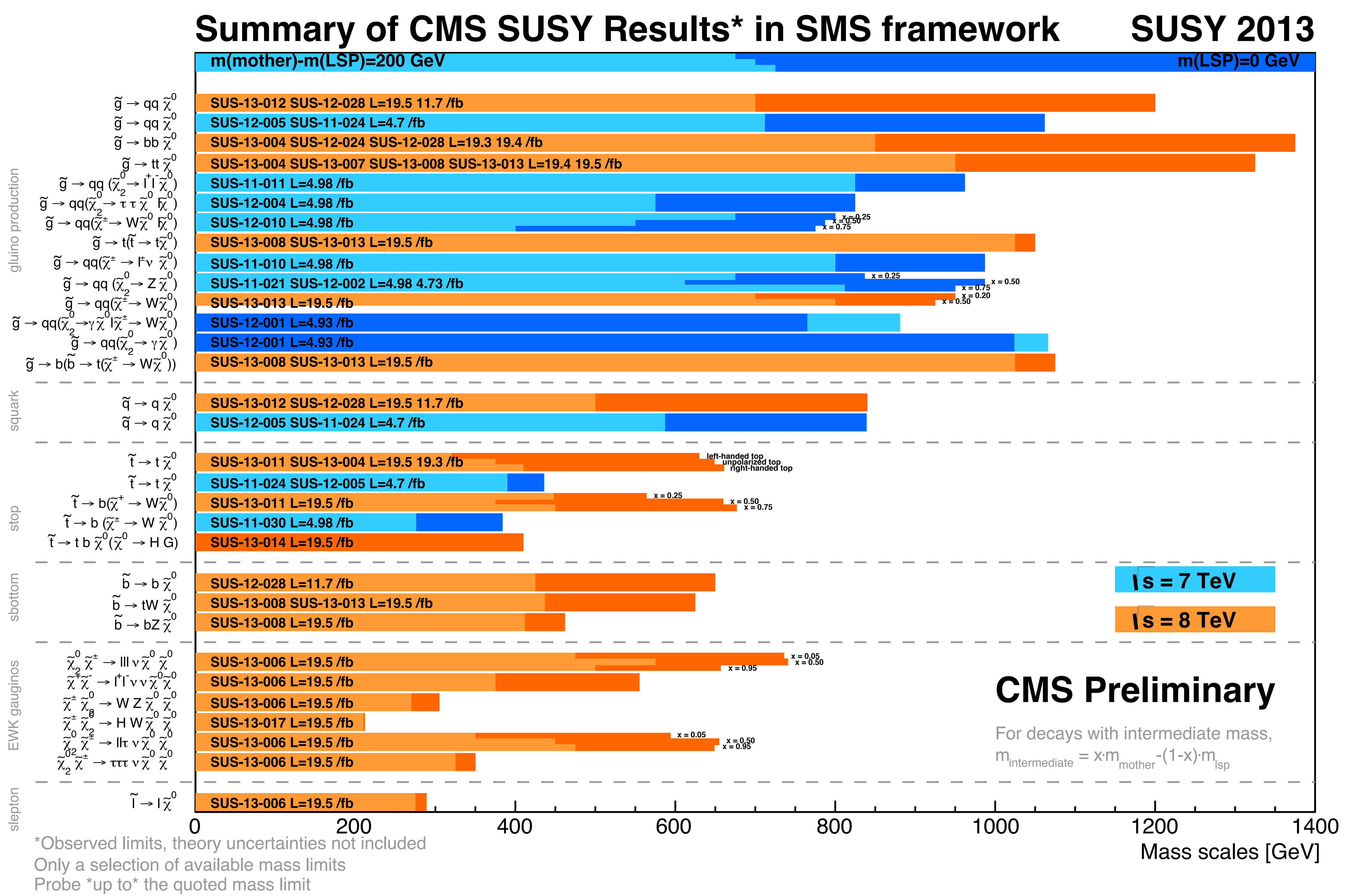
Third generation Summary

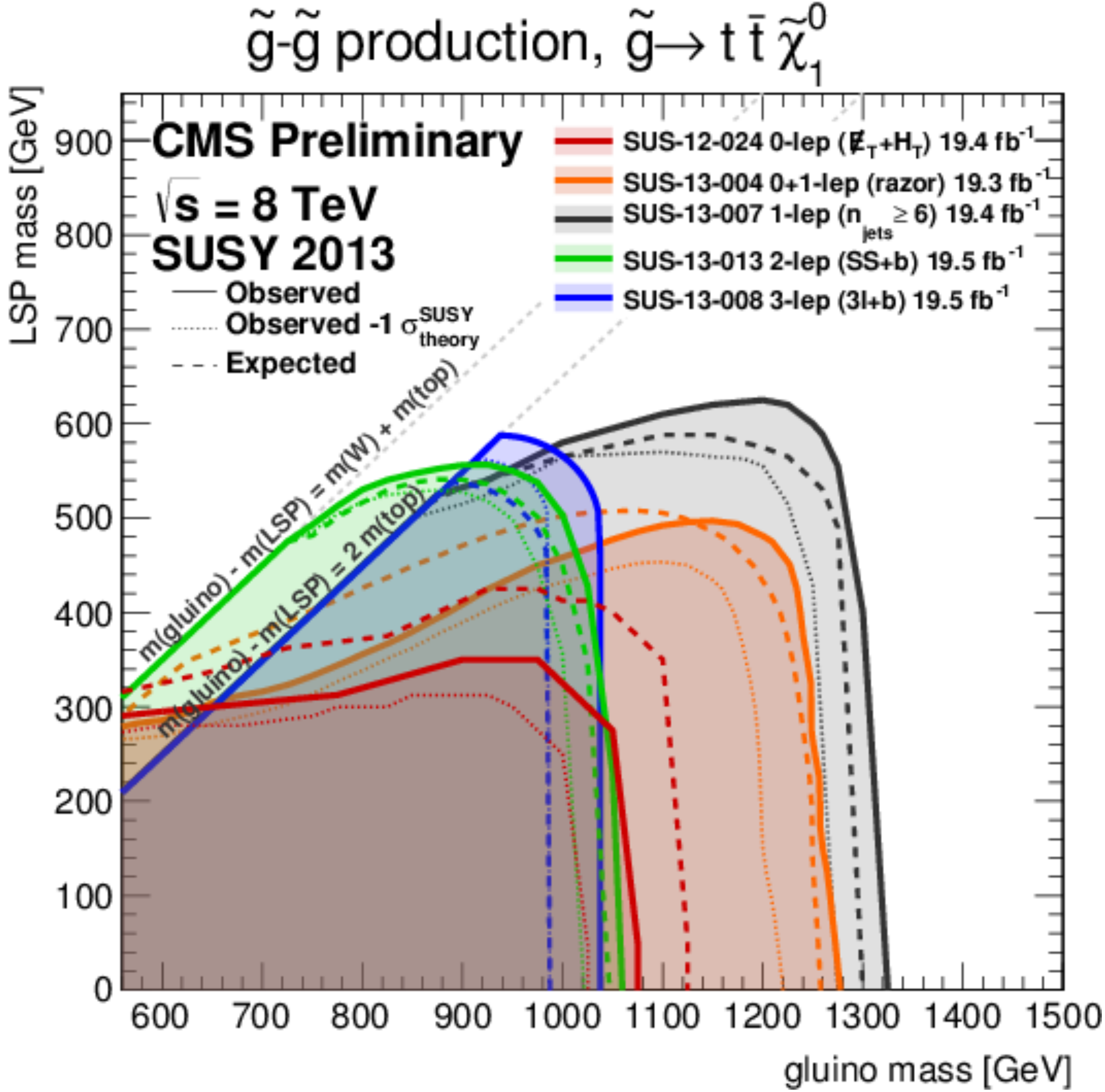
Higgs is the strongest constraint pushing the limits close to 1 TeV

CCB puts constraints on the mixing of the stops !

Direct constraints are around 300-600 GeV

Flavour violation of O(10)% can be allowed as the third generation masses can reach 1 TeV


Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
x = 0.20
x = 0.05
x = 0.95
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} - (1-x) \cdot m_{lsp}$
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit



$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}^0_1$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
SUSY 2013
Observed
Observed -1 σ^{SUSY}_{theory}
Expected
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-13-004 0+1-lep (razor) 19.3 fb^{-1}
SUS-13-007 1-lep ($n_{jets} \geq 6$) 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]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
900
600
700
800
900
1000
1100
1200
1300
1400
1500

charginos/neutralinos

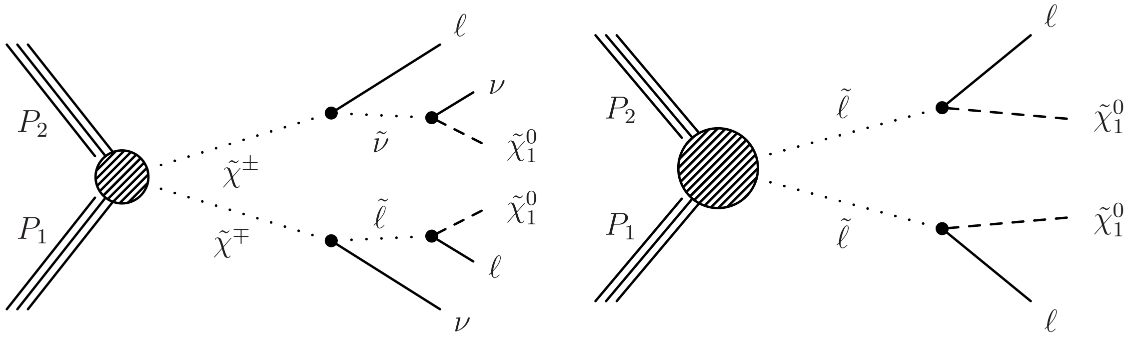


Figure 1: Production of pair of chargions (left) and sleptons (right) in the pp collision.

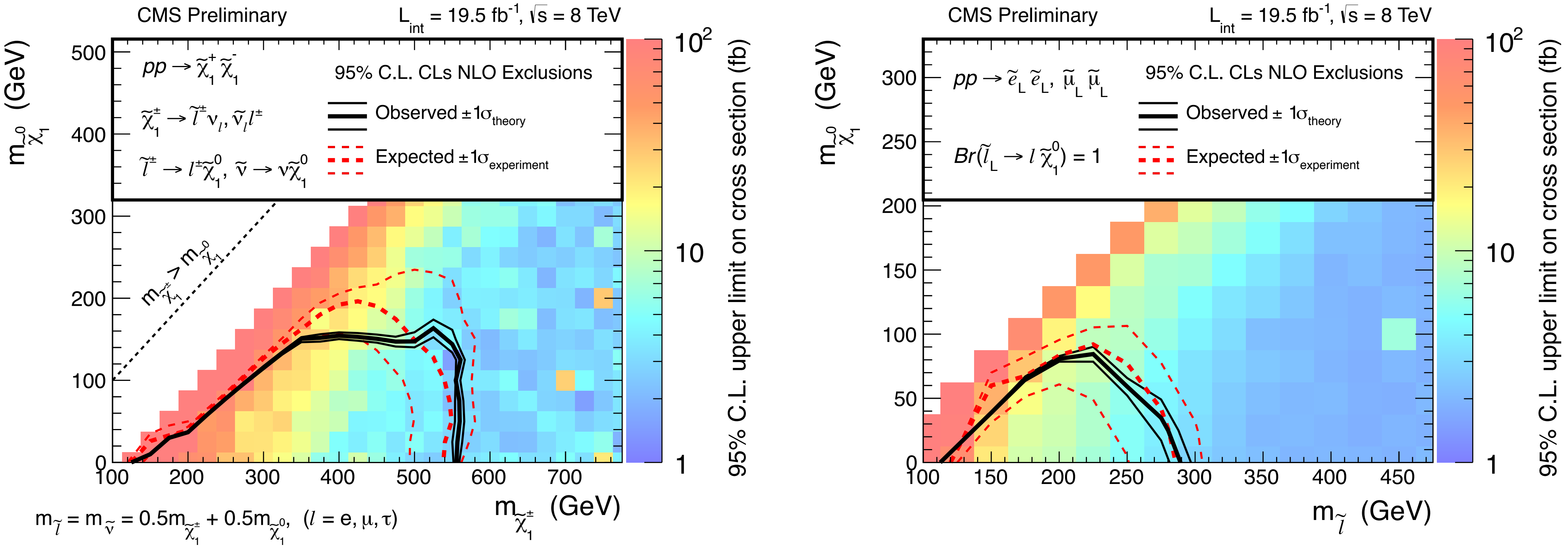


Figure 2: Limits on chargino (left) and slepton (right) pair production

Summary of the data

Gluinos are ruled out up to masses 1- 1.25 TeV

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

(especially if degenerate with the gluino mass)

NO significant constraints on Weakly coupled particles

Flavour Constraints on first two generations

Mostly in squark sector

From \Delta mK

$$\frac{(\Delta m^2_{\tilde{f}})_{12}}{m^2_{\tilde{f}}} \lesssim \quad 10^{-3} \text{ to } 10^{-4}$$

for about 500 GeV squarks

For larger squarks 1 TeV or so, the constraints are slightly weaker !!

In slepton sector

From \mu to e + gamma

$$\frac{(\Delta m^2_{\tilde{f}})_{12}}{m^2_{\tilde{f}}} \lesssim \quad 10^{-6} \text{ to } 10^{-7}$$

for about 500 GeV sleptons

Mini Split Supersymmetric Spectrum

Sundrum et.al
Dimpolous et. al
Randall et. al
Arkani-Hamed et. al

first two generations $16\pi^2$ msusy

gluino

third generation msusy

Flavour violation can be present in the third generation

neutralino can also be heavy about 1 TeV or so (depending on model)

EDM's could be sensitive to this kind of scenario

Model building is very hard in these scenarios !! Typically single scale susy breaking is very unnatural.

Iyer, Sooryanarayana, Vempati, in preparation

Two scale supersymmetry breaking could be viable

Compressed/Degenerate spectrum

Martin, Nojiri, Bhattacherjee and Mohan, and several others

Degenerate gluino and neutralino mass can escape LHC constraints

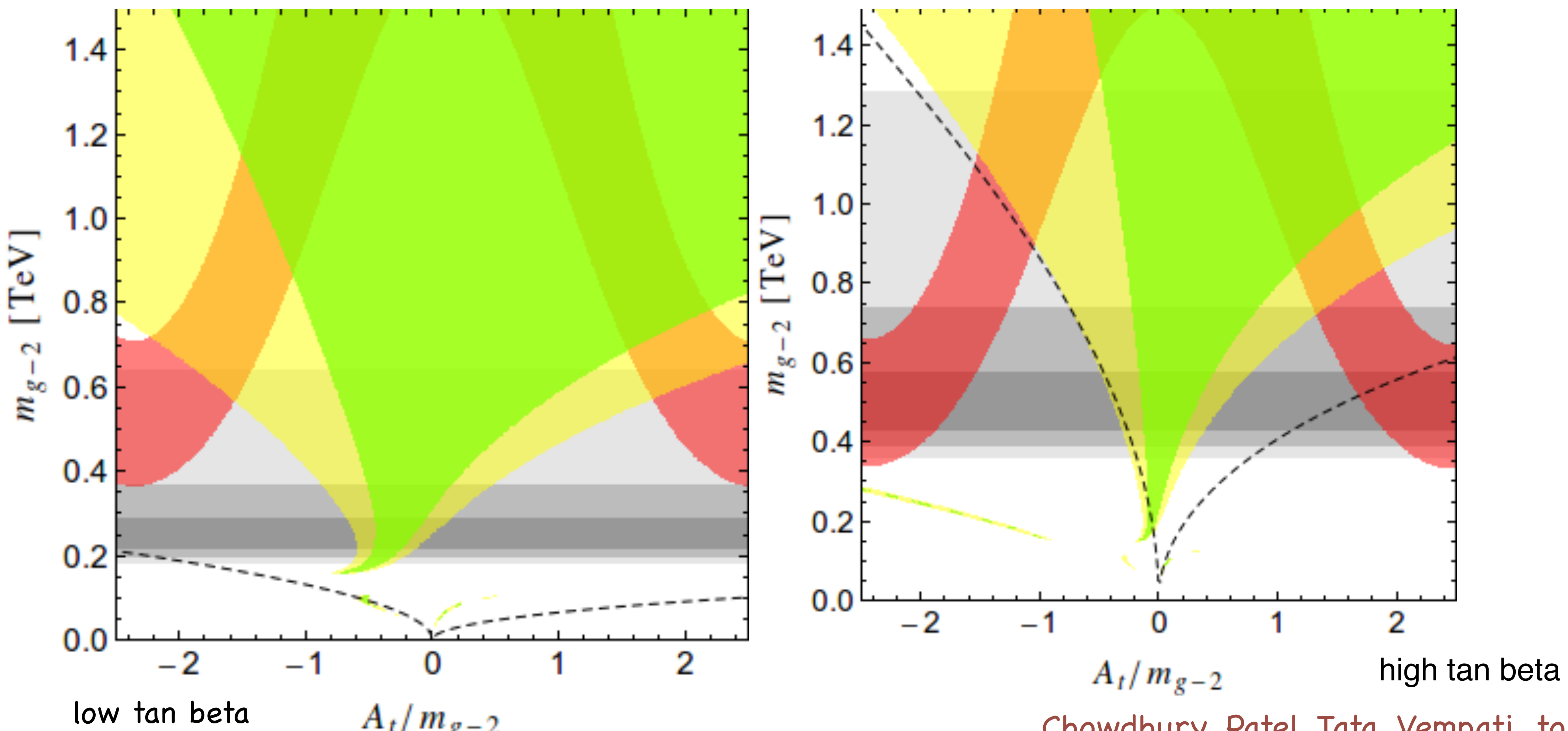
Present limits at around 500-600 GeV from mono jet events

A closer look at degenerate MSSM

No SUSY Flavour violation ; only MFV !!

No LHC constraints up to 500-600 GeV

$(g-2)_\mu$ and $b \to s + \gamma$ play an important role

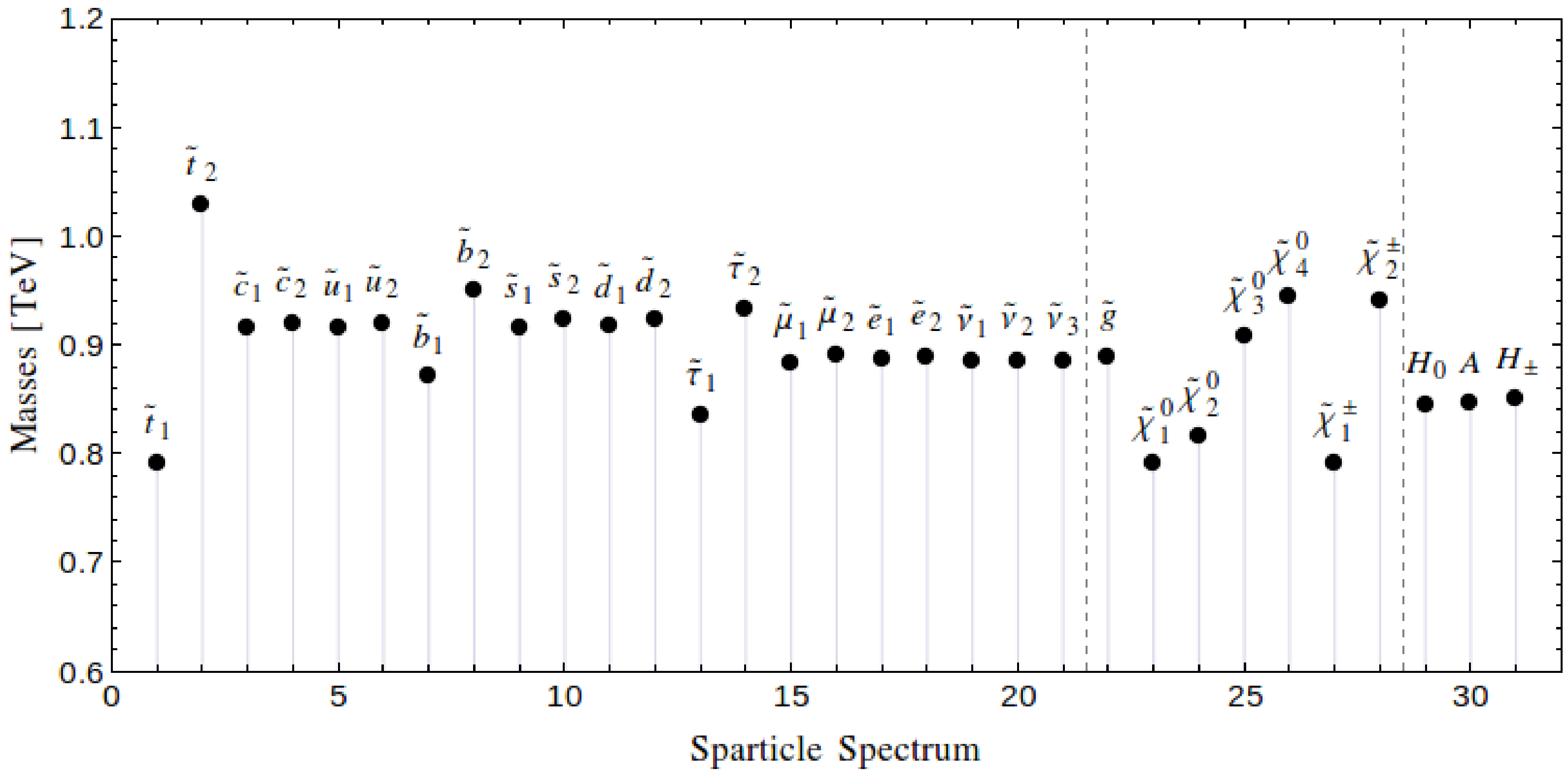


Chowdhury, Patel, Tata, Vempati, to appear

FIG. 2. The parameter space allowed in A_t-m_{g-2} plane by different constraints for $\tan\beta = 10$ (left panel) and $\tan\beta = 40$ (right panel). The horizontal Grey bands show the δa_μ favored values of m_{g-2} at 1σ, 2σ and 3σ (from darker to lighter bands). The red band corresponds to a valid (123-131 GeV) Higgs mass region. The green (yellow) regions are allowed by BR($B \to X_s\gamma$) at 1σ (2σ) while the region above the dashed line is allowed by BR($B_s \to \mu^+\mu^-$) at 95% C.L.

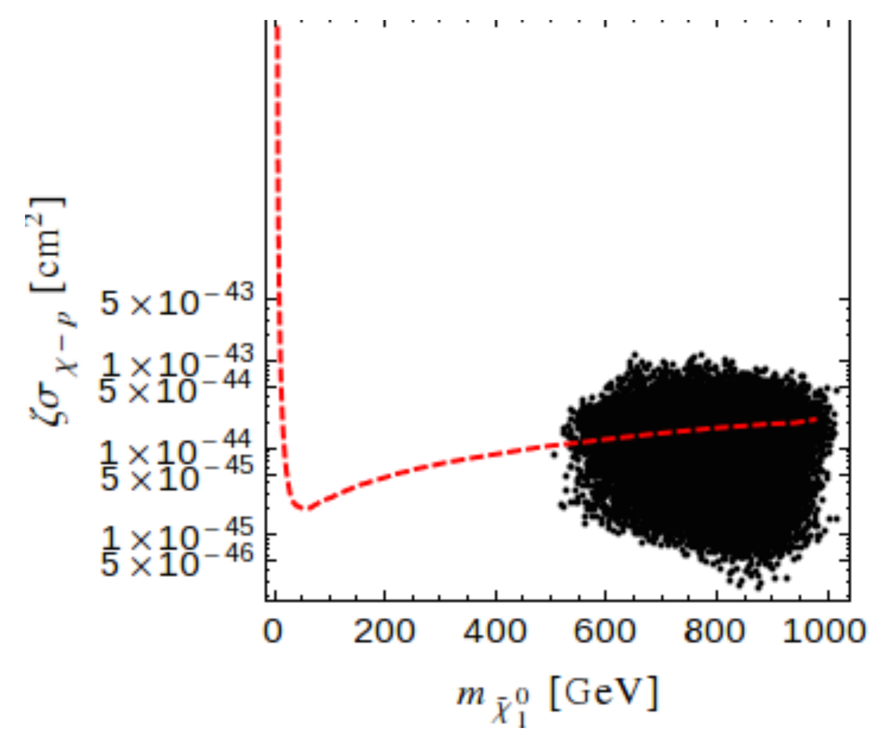
Dark Matter interesting in degenerate MSSM (DMSSM)

Chowdhury, Patel, Tata, Vempati, to appear



Spectrum has a splitting between the stops

Dark Matter relic density is very small due to multiple co-annihilations however direct detection can perhaps find a signal !!



Implications on Models

Range we chose

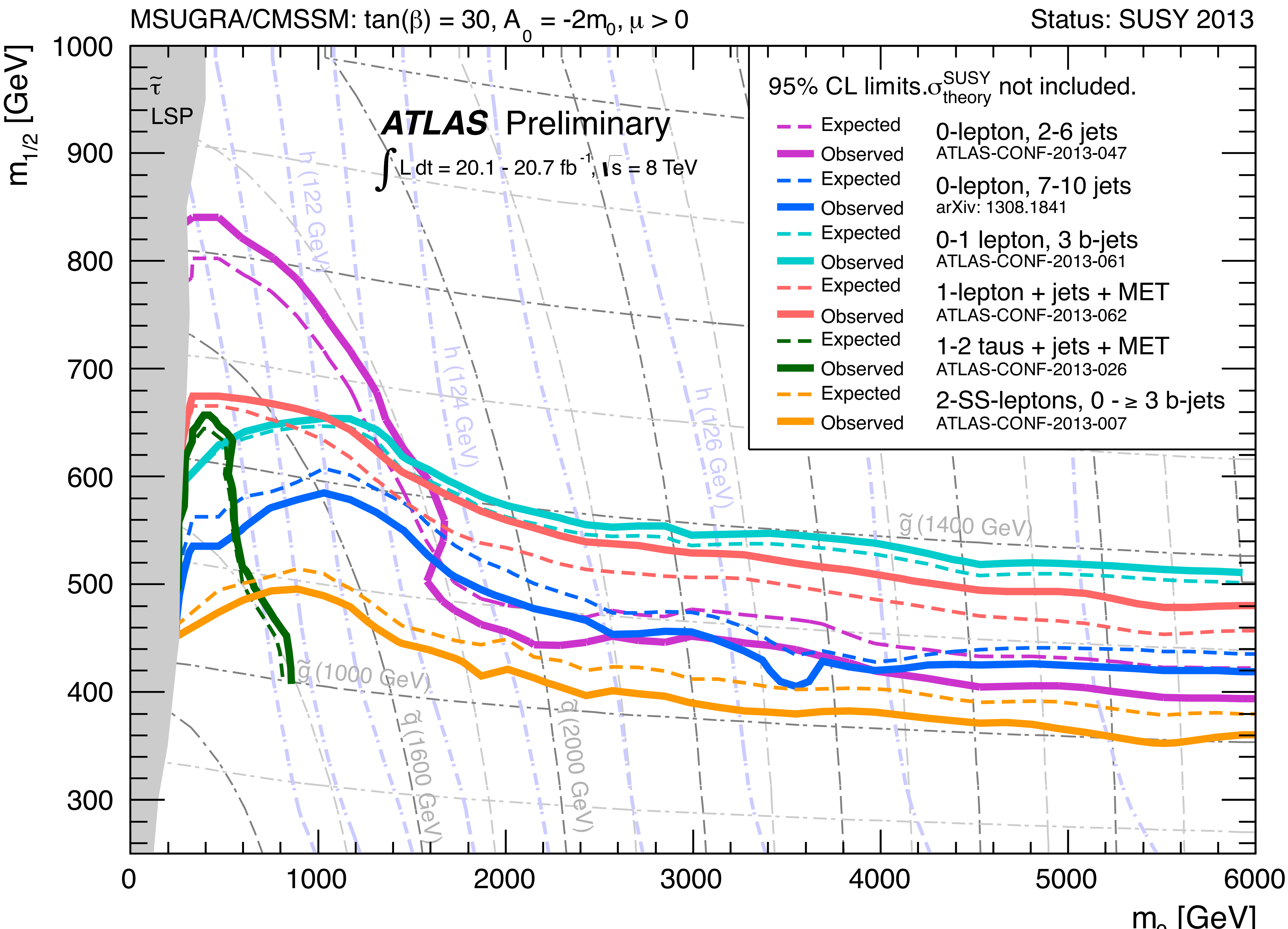
$$m_0 \in [0,\ 5]\ \mathrm{TeV}$$

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

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

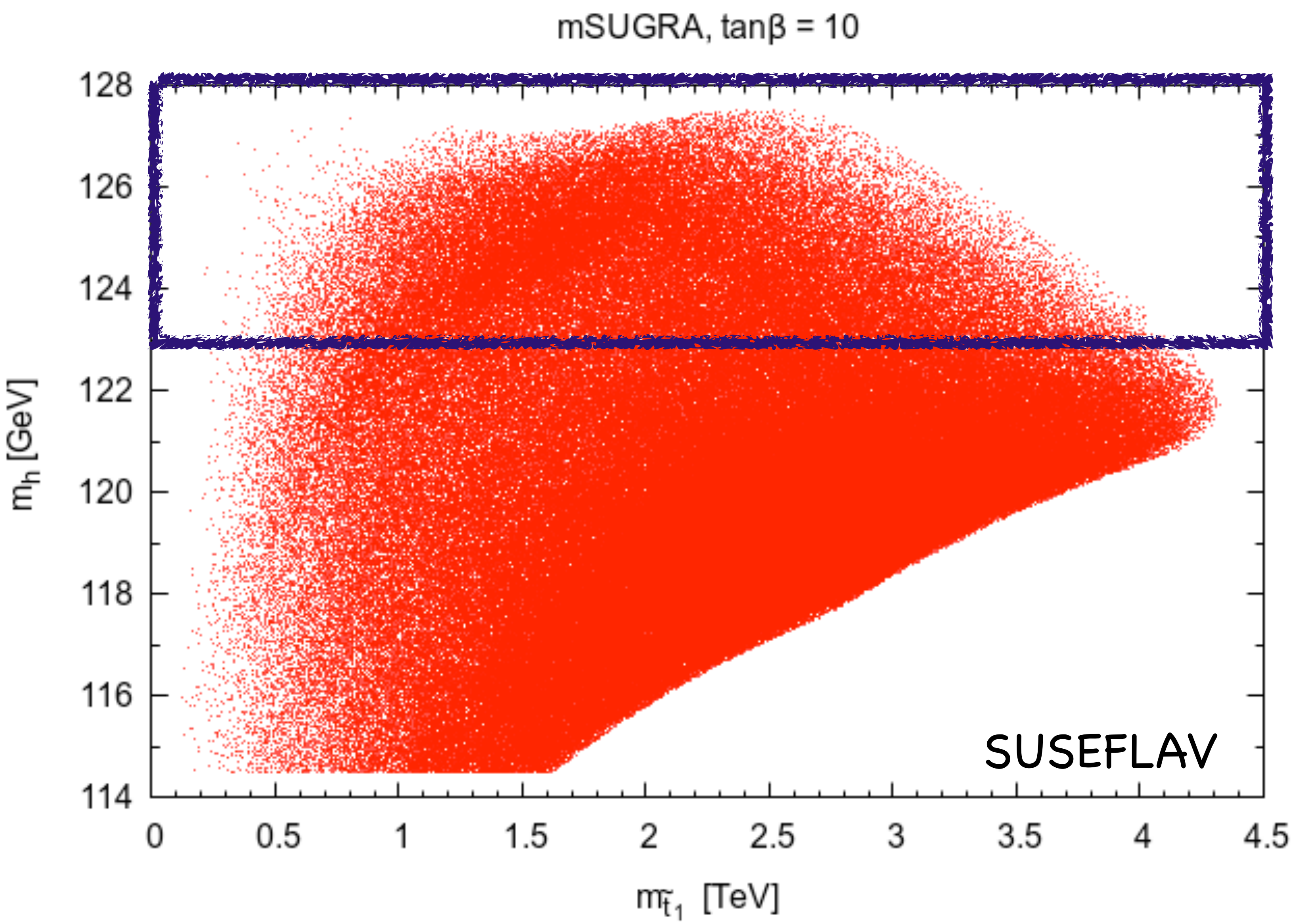
$$A_0 \in [-3m_0,\ +3m_0]$$

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



MSUGRA/CMSSM: tan(β) = 30, A0 = -2m0, μ > 0
Status: SUSY 2013
ATLAS Preliminary
∫L dt = 20.1 - 20.7 fb-1, √s = 8 TeV
95% CL limits. σ SUSY theory not included.
Expected
Observed
0-lepton, 2-6 jets
ATLAS-CONF-2013-047
0-lepton, 7-10 jets
arXiv: 1308.1841
0-1 lepton, 3 b-jets
ATLAS-CONF-2013-061
1-lepton + jets + MET
ATLAS-CONF-2013-062
1-2 taus + jets + MET
ATLAS-CONF-2013-026
2-SS-leptons, 0 - ≥ 3 b-jets
ATLAS-CONF-2013-007
τ̃ LSP
h (122 GeV)
h (124 GeV)
h (126 GeV)
g̃ (1000 GeV)
g̃ (1400 GeV)
q̃ (1600 GeV)
q̃ (2000 GeV)
m1/2 [GeV]
m0 [GeV]

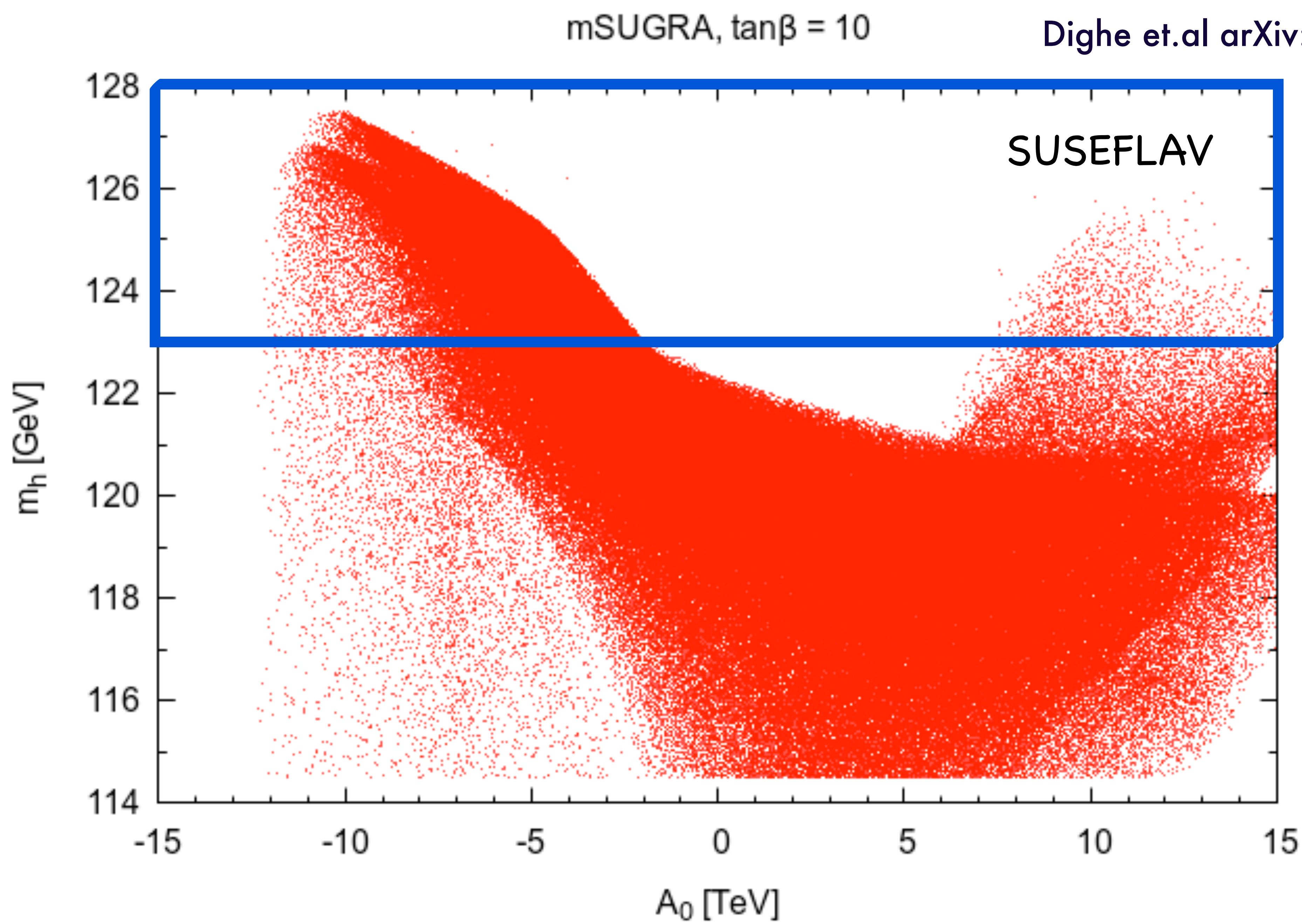
M Raidal et. al arxiv/1112.3647
P. Nath et.al and other groups
Baer et.al arXiv: 1112.3017



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

Dighe et.al arXiv: 1112.3017



Only large negative A -terms are allowed at High scale !!

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

minimal gauge mediation

Minimal Gauge Mediation

No SUSY flavour violation

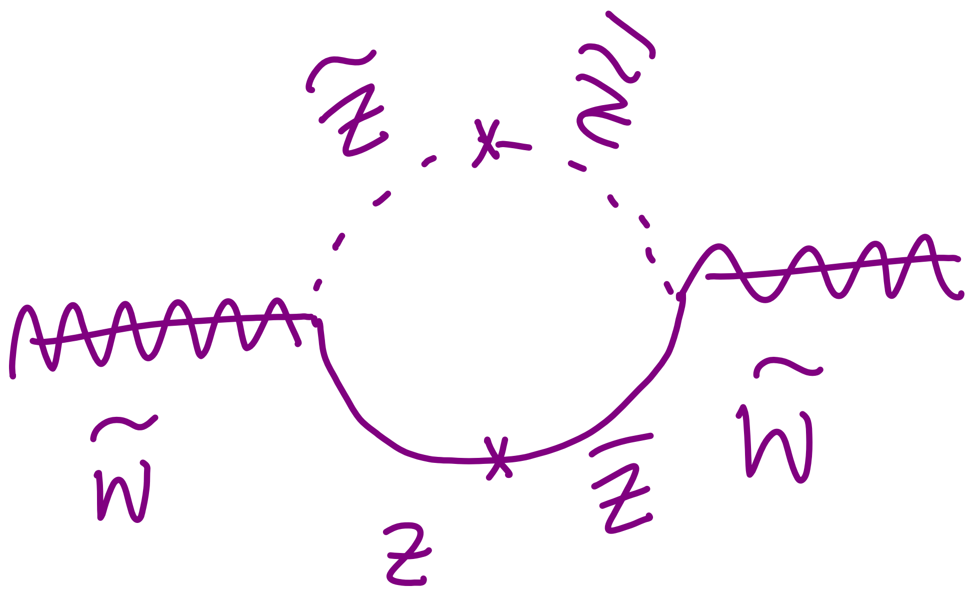
small number of parameters

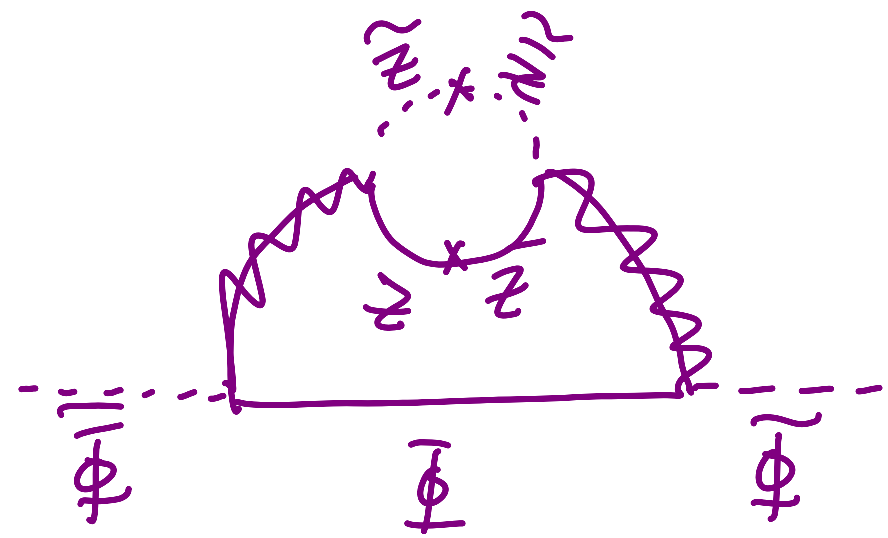
$$W = \lambda \Phi \bar{\Phi} X$$

messengers
(charged under
SM)

SUSY breaking spurion

SUSY broken spontaneously by X

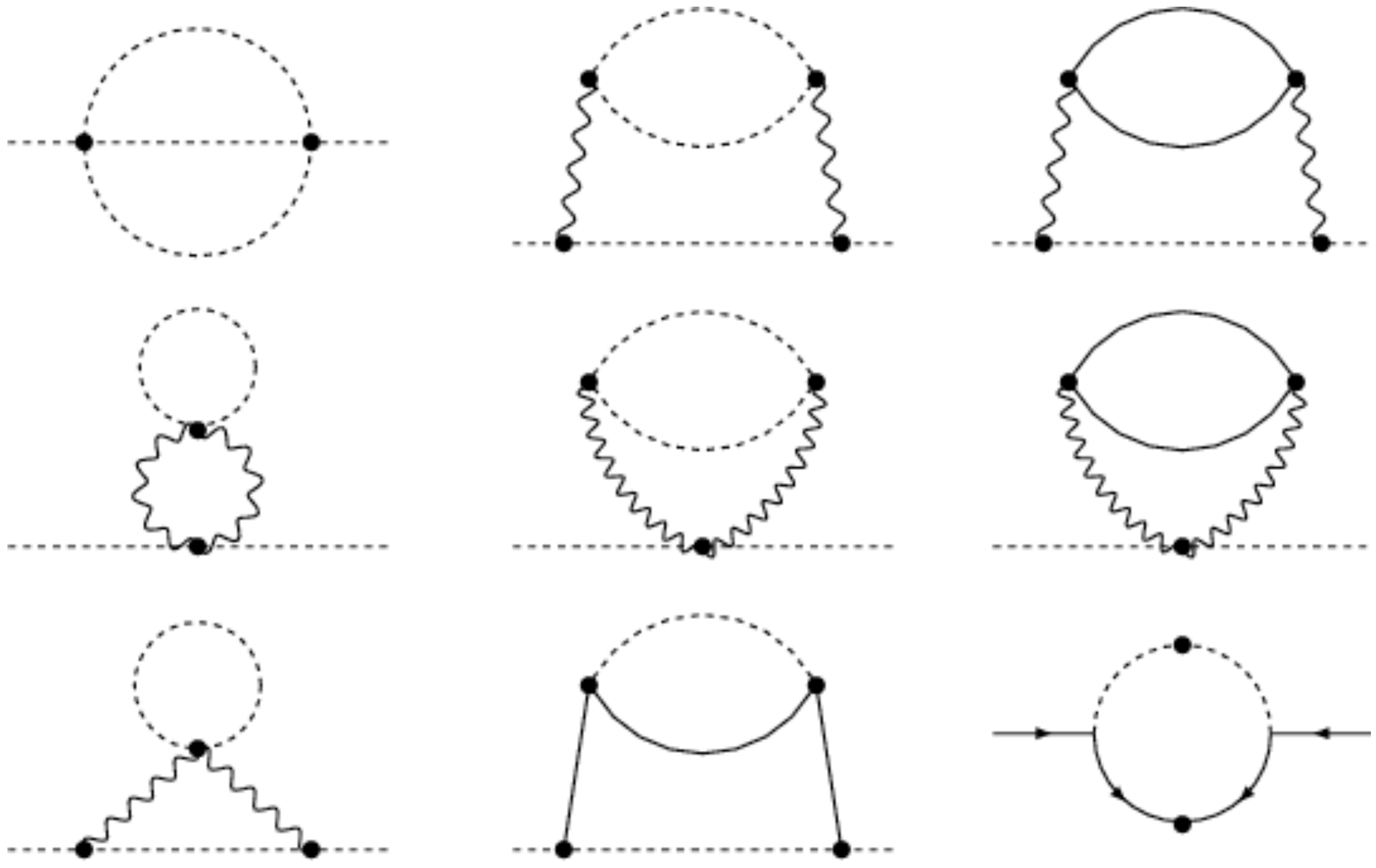




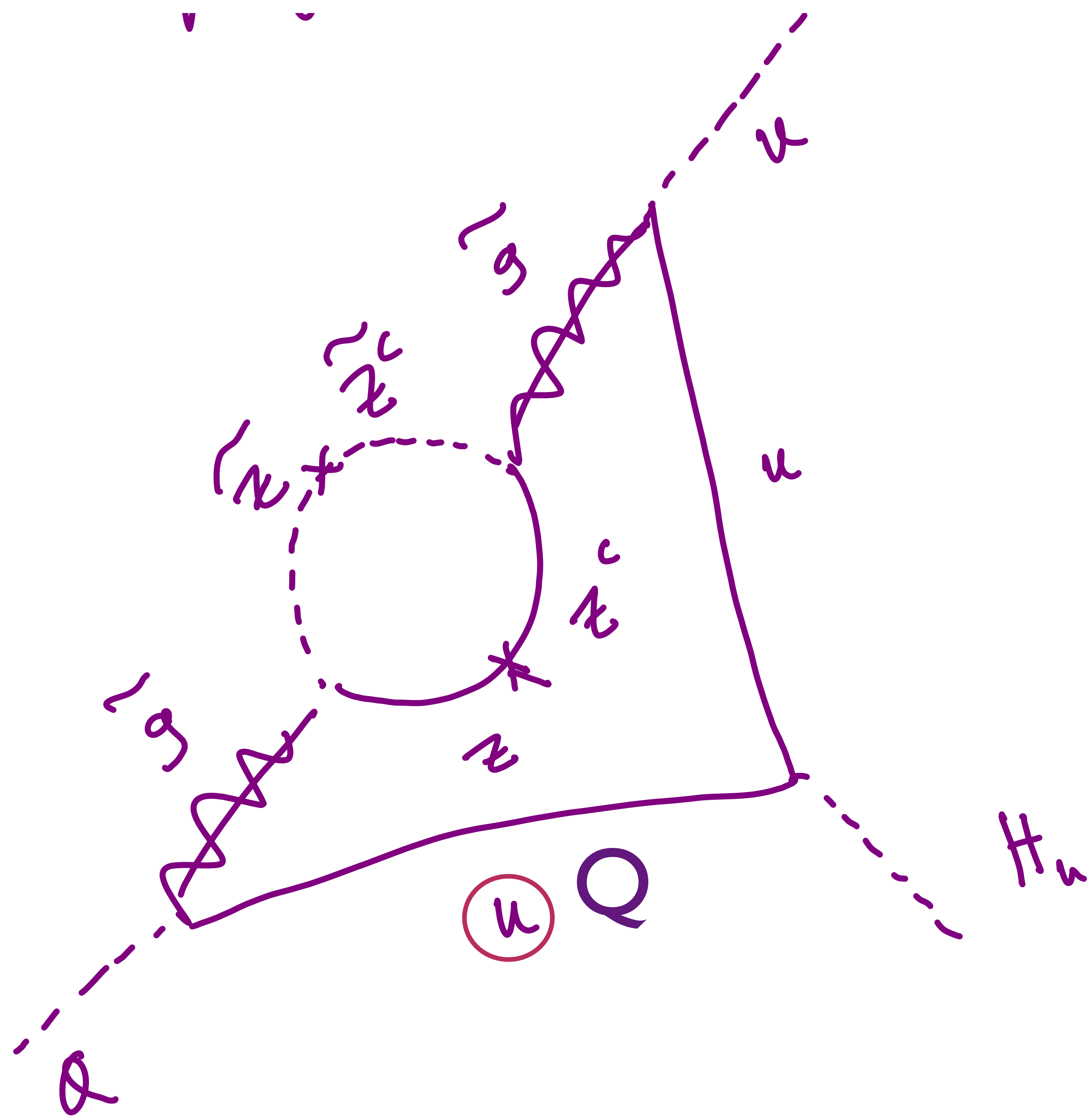
Soft masses in MSSM through loops

+ - - 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

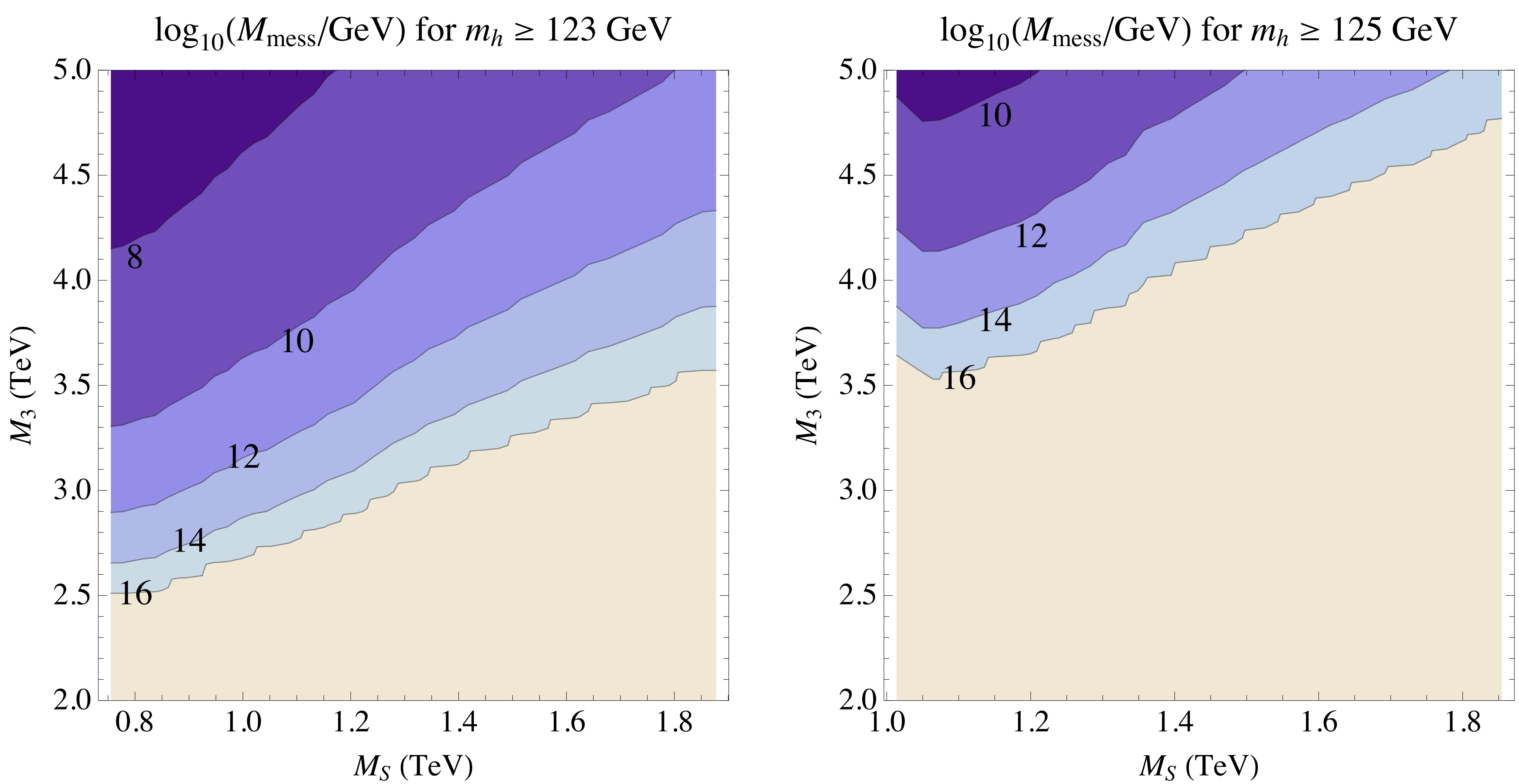


FIG. 5. Messenger scale required to produce sufficiently large $|A_t|$ for $m_h = 123$ GeV (left) and $m_h = 125$ GeV (right) through renormalization group evolution.

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.

flavour violation !!!!

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

some amount of Messenger-Matter mixing !

(3) Additional strongly coupled sectors

Yanagida et. al

A little more gauge mediation

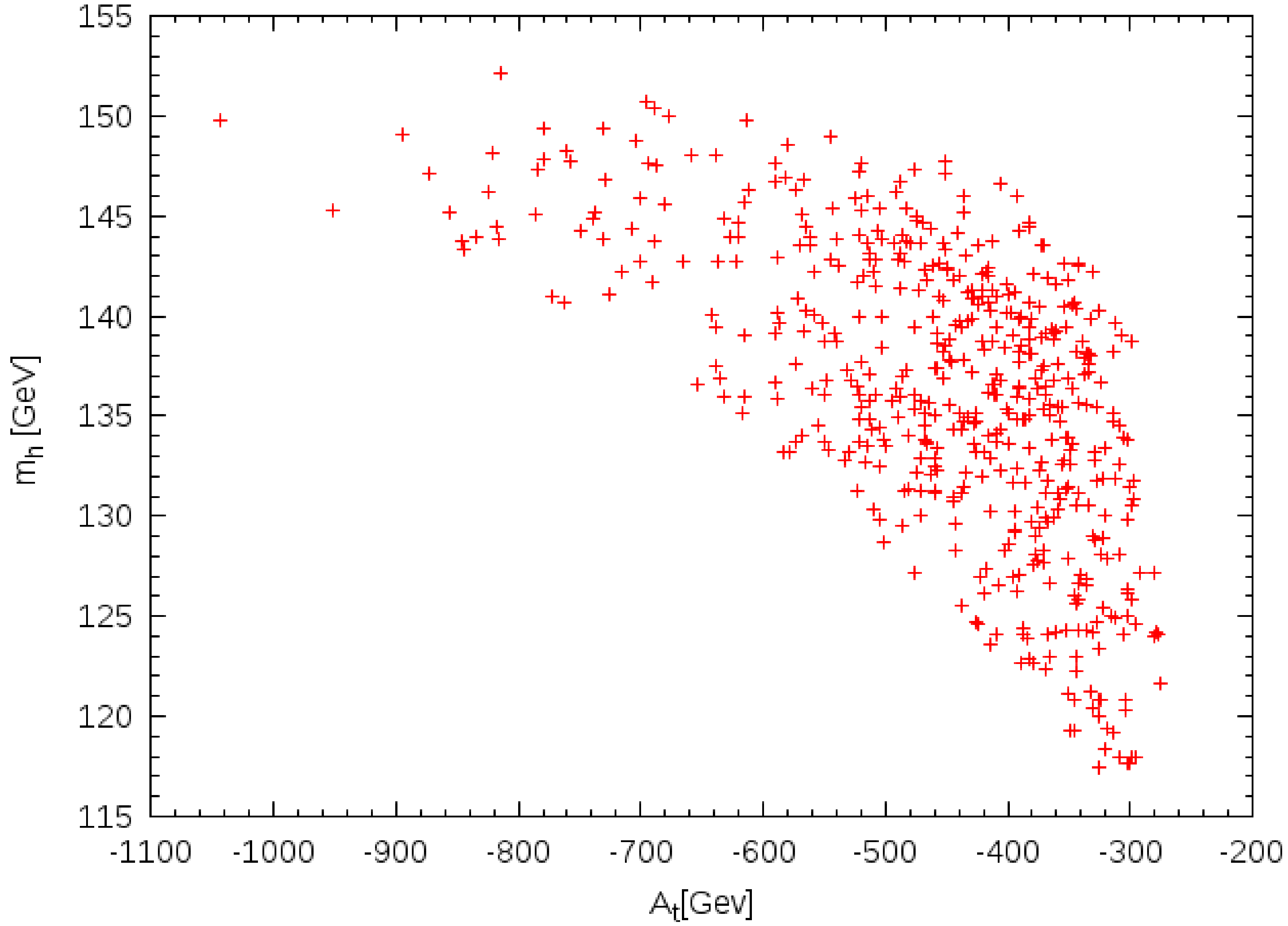
Say NO to messenger-Matter mixing !!!

Add little more gauge mediation to regular SM gauge group !

Add a singlet !!

(Remember NMSSM does not work in Minimal Gauge Mediation)

$$W = \lambda S H_u H_d + W_{Yuk}$$



Sooryanarayana and Vempati, (Nucl Phys B) 884 2014

The RGE generated At is still small !! But the Higgs mass is the in right range !!

Neutrinos can rescue Higgs

Chun, Sooryanarayana, Vempati, to appear

Consider supersymmetric Inverse Seesaw Mechanism

$$W = W_{\rm MSSM} + Y_N L H_u N^c + M_R N^c S + \mu_S S S$$

$$m_\nu = \frac{m_D^2 \mu_S}{M_R^2}$$

This coupling can be large !!! (Mass is called m_D)

$$m_D \lesssim 0.05 M_R$$

From Electroweak precision tests

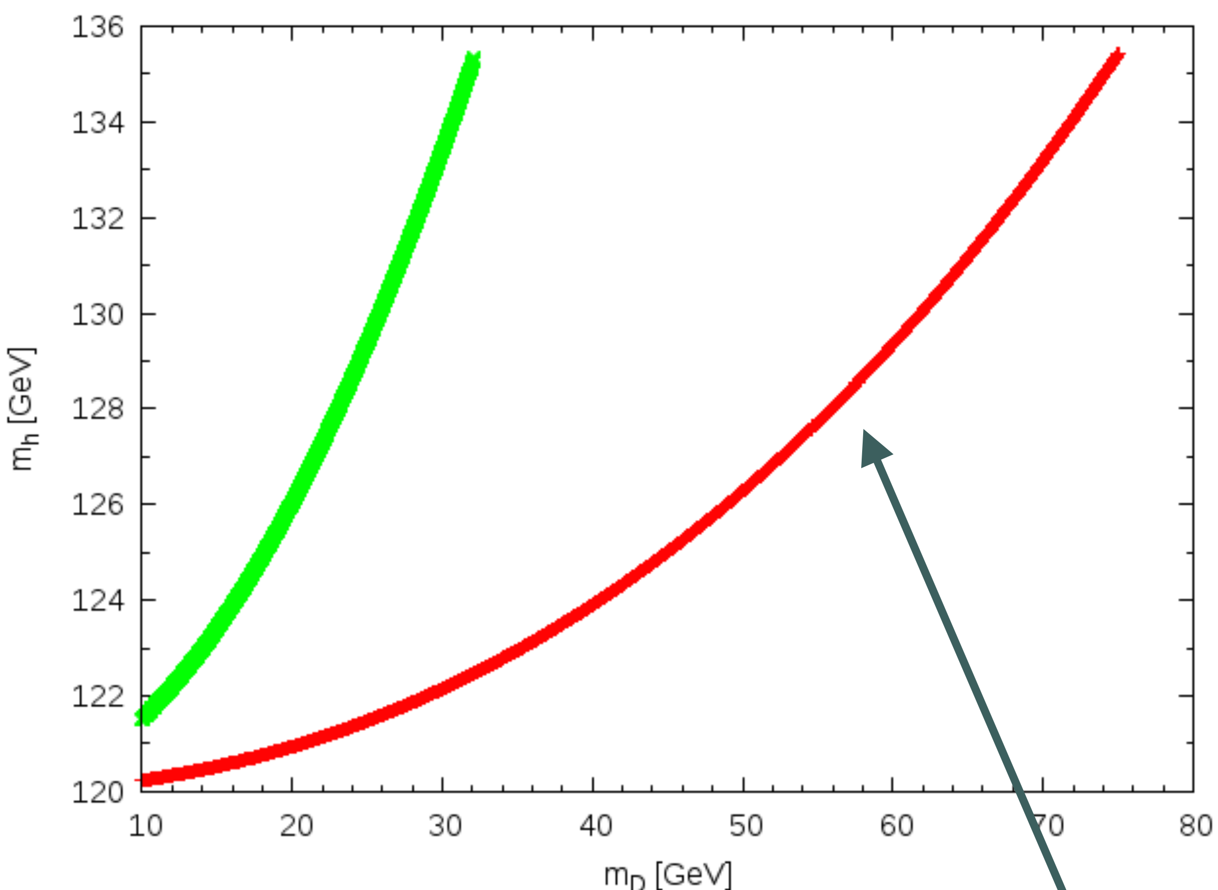
Perez-Victoria et. al

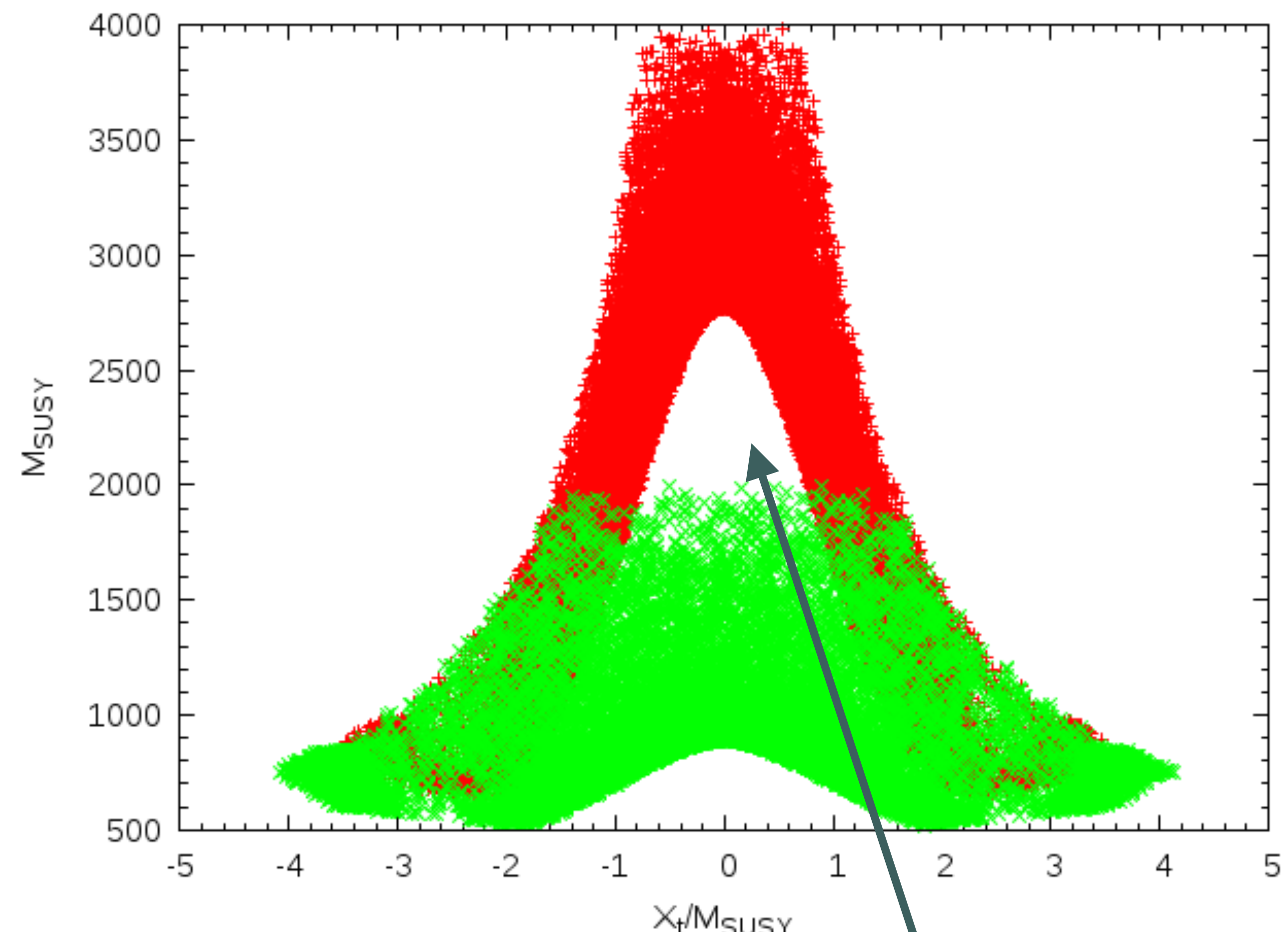
Neutrinos can rescue Higgs

Chun, Sooryanarayana, Vempati, to appear

Complete 1-loop effective potential corrections including neutrino sector for a general susy breaking sector

Guo et. al
Shafi et. al





with mixing X_N

GMSB Region

Summary

126 GeV Higgs is compatible with TeV scale MSSM !!!
Perhaps it is just around the corner.

But, at the same time, the discovery of Higgs has put severe constraints on known Supersymmetric models even more than direct constraints !!

Whether its mini-split or degenerate or RpV susy we hope to have some idea soon !

Of the models minimal gauge mediation models are the most constrained. But, simple ways can be found without introducing messenger-matter mixing.

For example, we have shown a simple extra U(1) or neutrino couplings can give you the required enhancement without generating large A_t