The Higgs as a sneutrino

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based on work done with Claudia Frugiuele, Eduardo Ponton and Piyush Kumar

Electroweak symmetry breaking

$$SU(2)_L \times U(1)_Y \to U(1)_Q$$

condensate: vacuum not invariant

mechanism ~~unknown~~

weak coupling

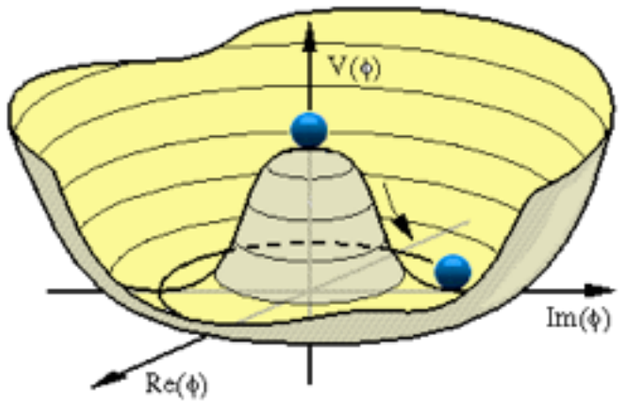
Higgs

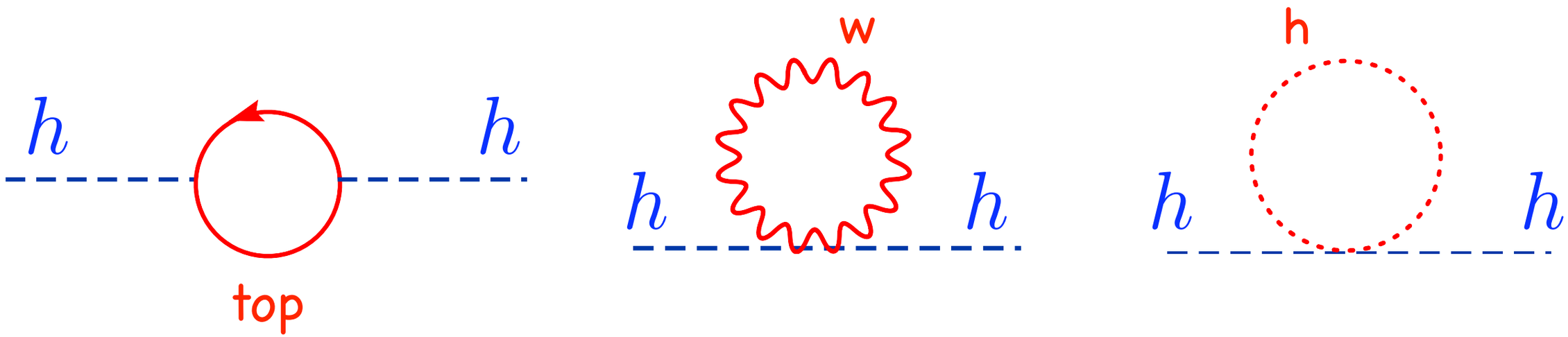
~~strong coupling~~

~~Technicolor~~

Higgs

elementary scalar field





Divergent

cutoff Λ

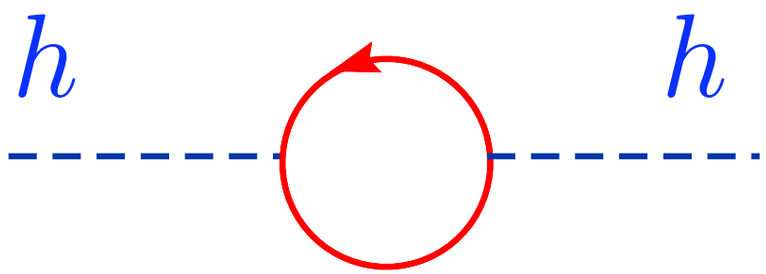
Supersymmetry

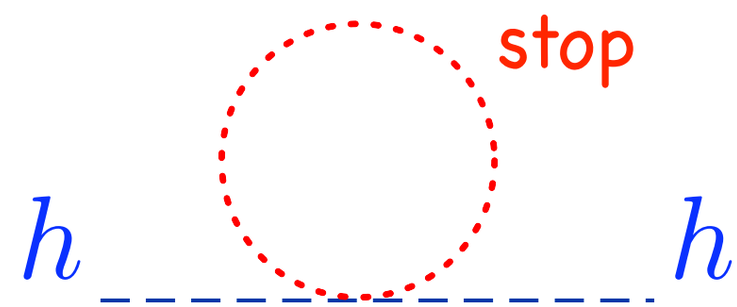
Bosons $\longleftrightarrow$ Fermions

Higgs	h	$\longrightarrow$	$\tilde{h}$	Higgsino
gluon	g	$\longrightarrow$	$\tilde{g}$	gluino
selectron	$\tilde{e}$	$\longleftarrow$	e^-	electron
stop	$\tilde{t}$	$\longleftarrow$	t	top

etc...

quadratic divergences cancelled

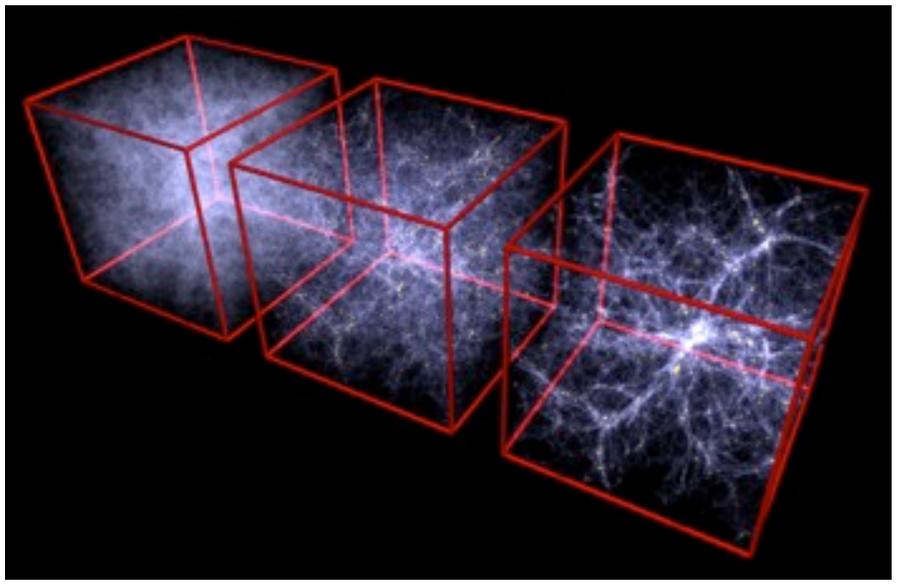


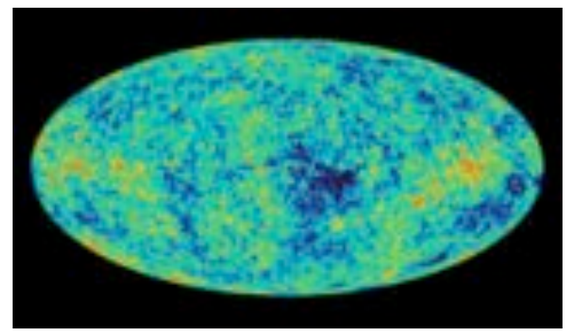


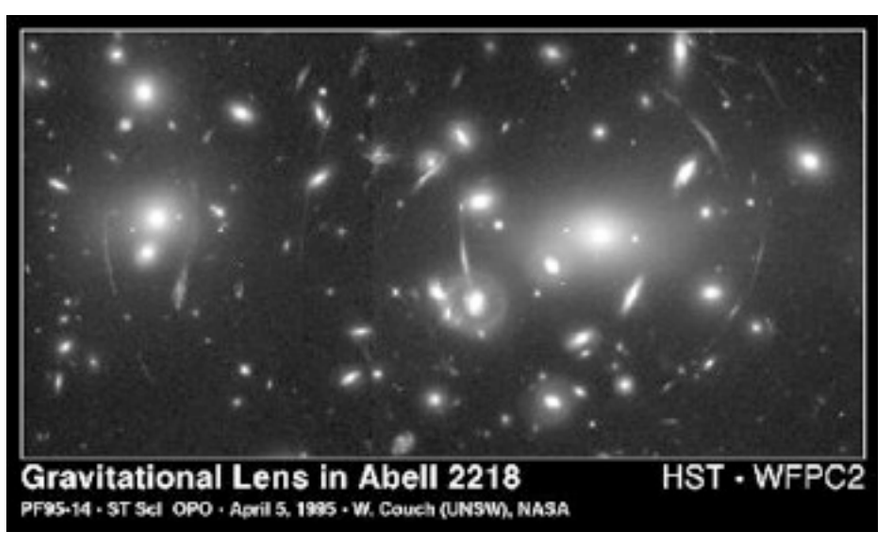
$$m_h^2 \sim \frac{1}{16\pi^2} m_{\rm stop}^2 \log \Lambda^2$$

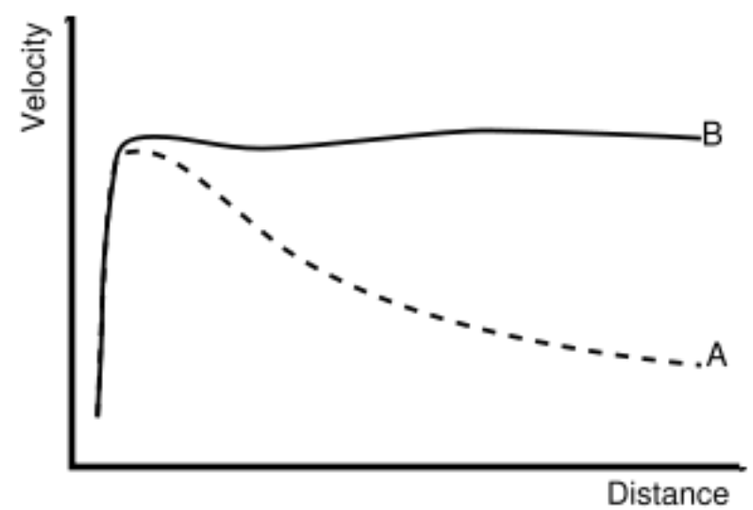
Other successes of (weak-scale) supersymmetry

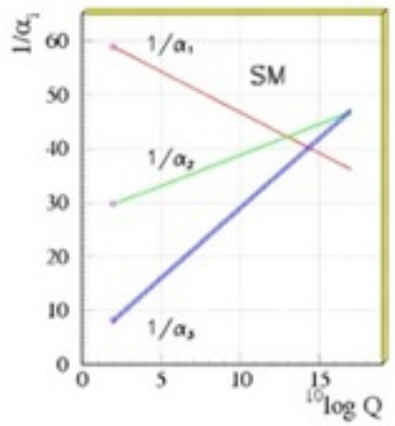
Dark matter candidate



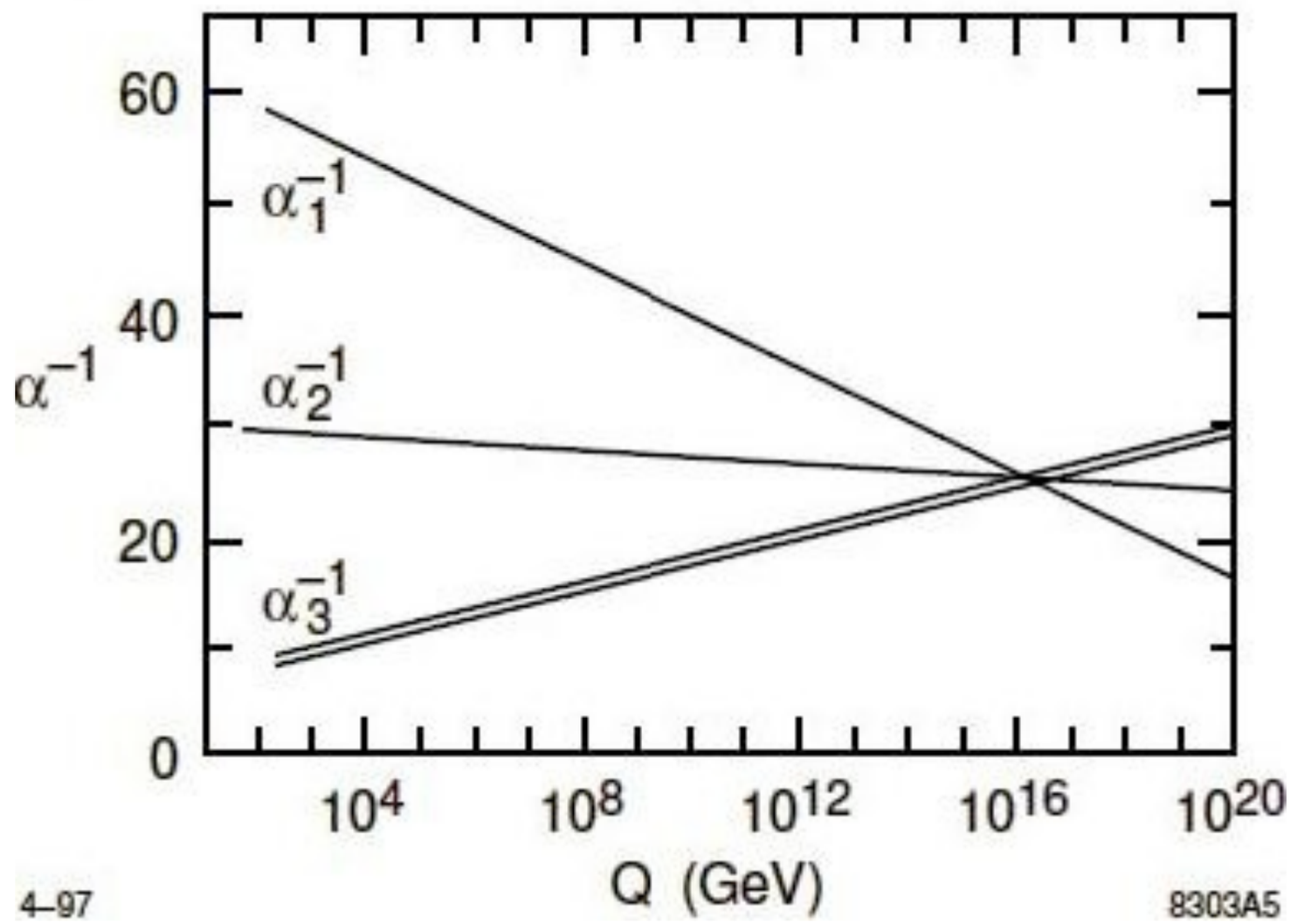








Gauge couplings unification



MSSM (minimal supersymmetry standard model

super

Field content $Q, U^c, D^c, L, E^c, H_u, H_d$

$W_3^\alpha, W_2^\alpha, W_1^\alpha$

Superpotential

$$W = \lambda_u Q U^c H_u + \lambda_d Q D^c H_d + \lambda_e L E^c H_d + \mu H_u H_d$$

not included

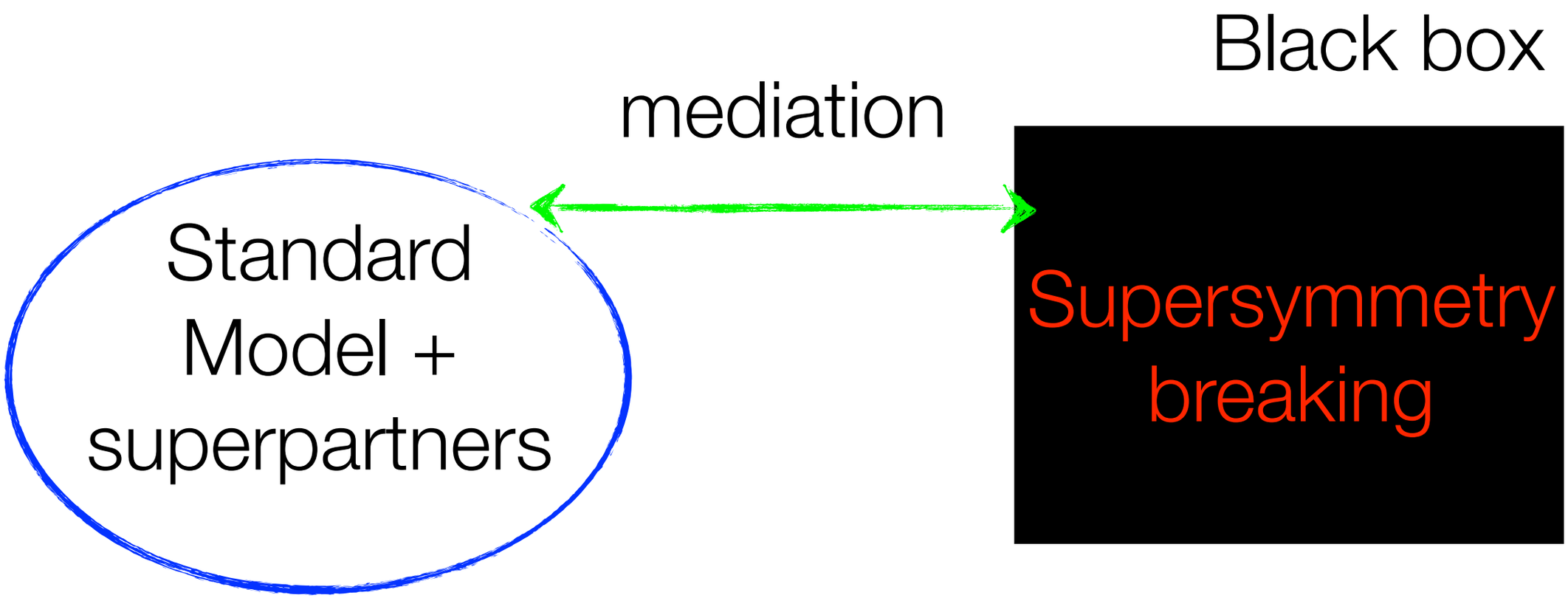
$$W_{\not{R}} = \lambda'' D^c D^c U^c + \lambda' Q D^c L + \lambda L L E^c + \mu_l H_u L$$

Forbidden by R-parity

even Q, U^c, D^c, L, E^c

odd H_u, H_d

Supersymmetry breaking



Superpartners must be heavier than SM particles

Breaking must be soft: no quadratic divergences to the Higgs mass

$$\mathcal{L}_{\rm soft} = \sum_{\Phi} m_{\Phi} \left|\phi\right|^2 + M_a \lambda_a \lambda_a + B_\mu h_u h_d + \text{trilinear}$$

soft scalar masses

Majorana gaugino masses

break any $U(1)_R$

Many new parameters….but many constraints

small FCNC ➡ m_Φ must be close to diagonal

Superpartners not seen ➡ ?????

Simplifying assumption at high scale:

$$m^Q = m^U = m^D = m^L = m^E = m^{H_u} = m^{H_d} = m_0$$

$$M_1 = M_2 = M_3 = M_{1/2}$$

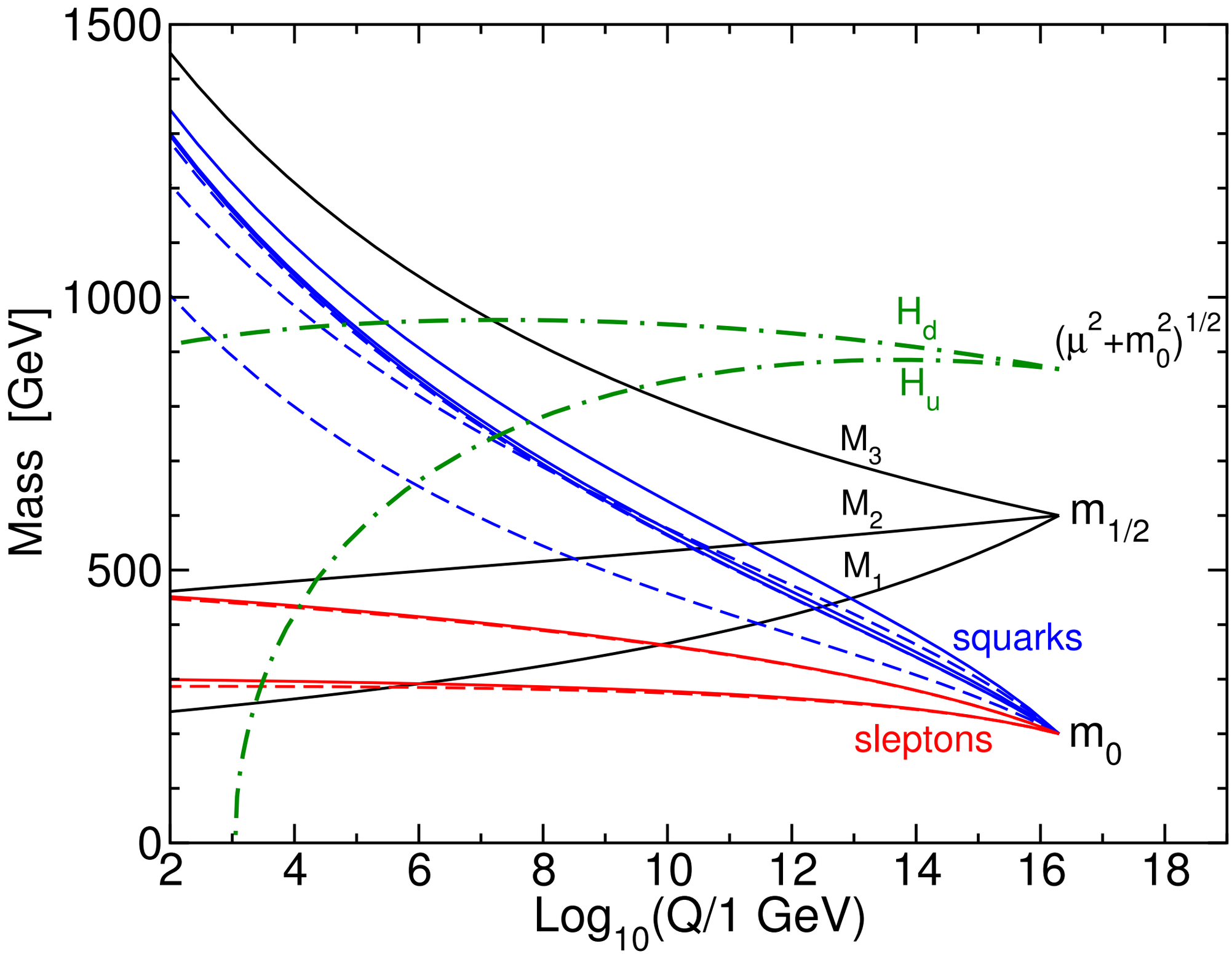
Soft masses run

$$\frac{d}{dt}M_a = \frac{1}{8\pi^2} b_a g_a^2 M_a$$

$$\frac{d}{dt}m_{H_u}^2 = \frac{1}{16\pi^2}\left(3X_t - 6g_2^2 M_2^2 - \frac{6}{5}g_1^2 M_1^2\right)$$

$$X_t = 2y_t^2\left(m_{H_u}^2 + m_{Q_3}^2 + m_{u_3}^2\right) + 2A_t^2$$

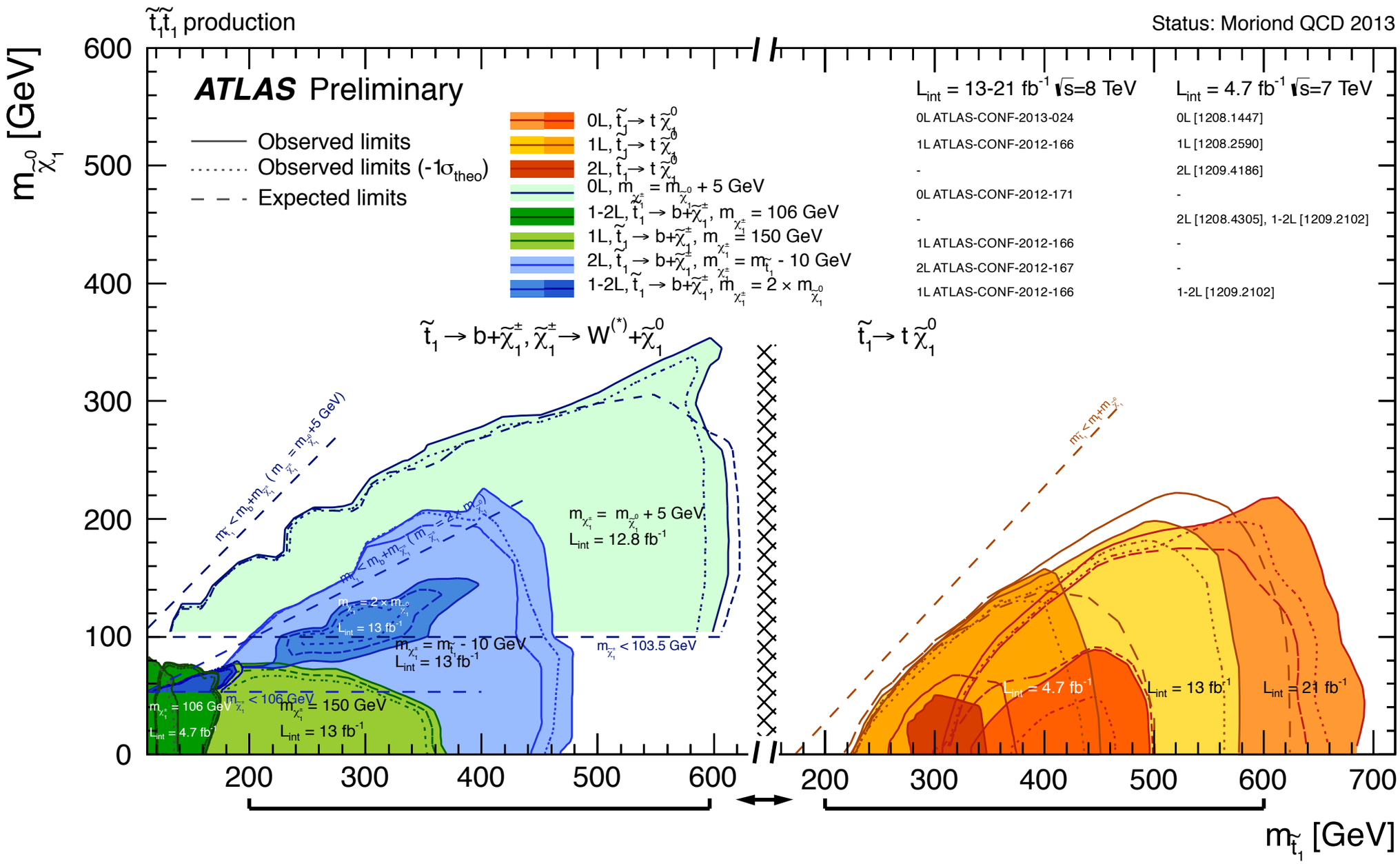
$$\frac{d}{dt}m_{Q_3}^2 = \frac{1}{16\pi^2}\left(X_t - \frac{32}{3}g_3^2 M_3^2 - 6g_2^2 M_2^2 - \frac{2}{15}g_1^2 M_1^2\right)$$

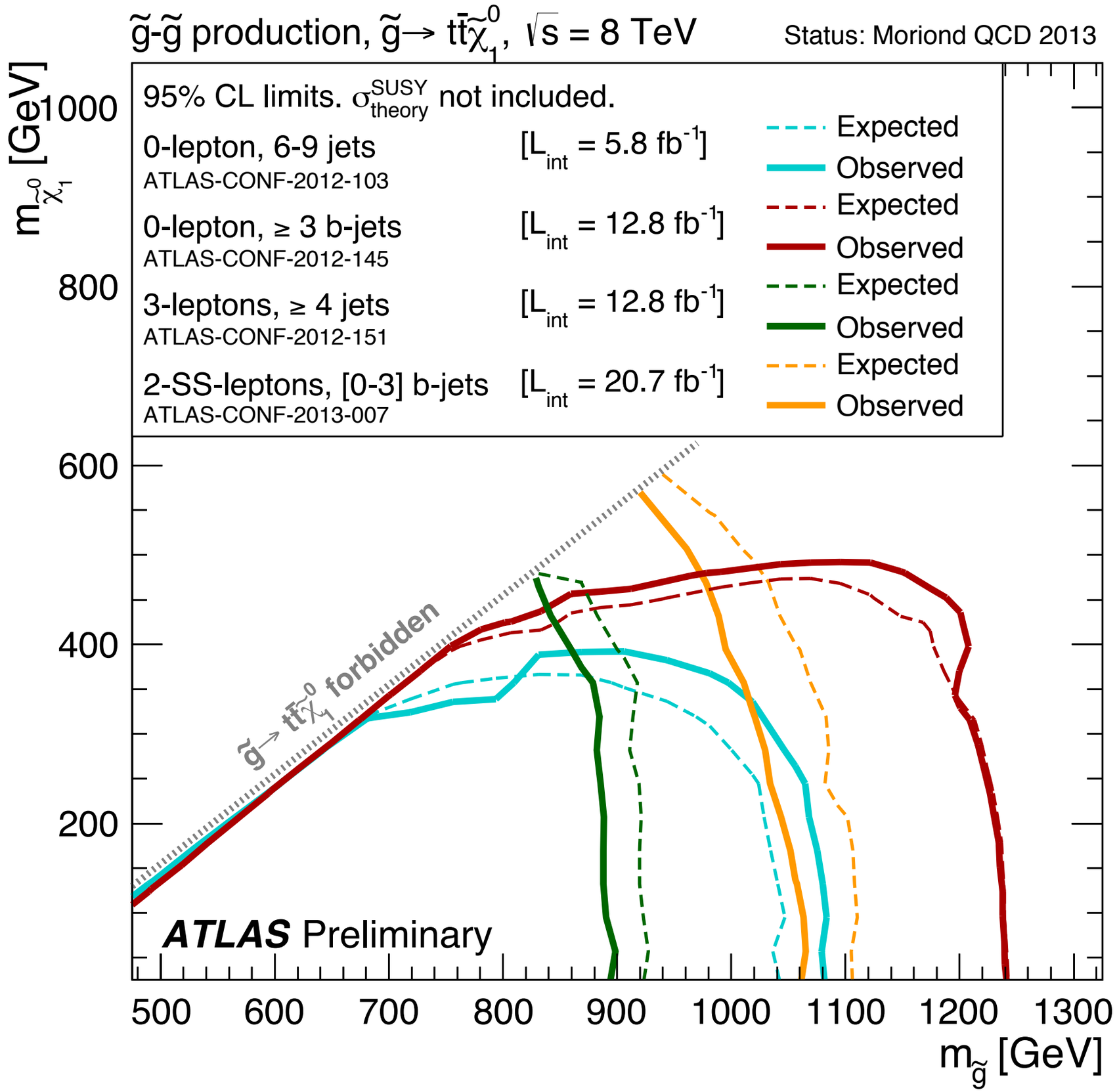

1500
1000
500
0
Mass [GeV]
2
4
6
8
10
12
14
16
18
Log10(Q/1 GeV)
Hd
Hu
(μ2+m02)1/2
M3
M2
M1
m1/2
squarks
sleptons
m0

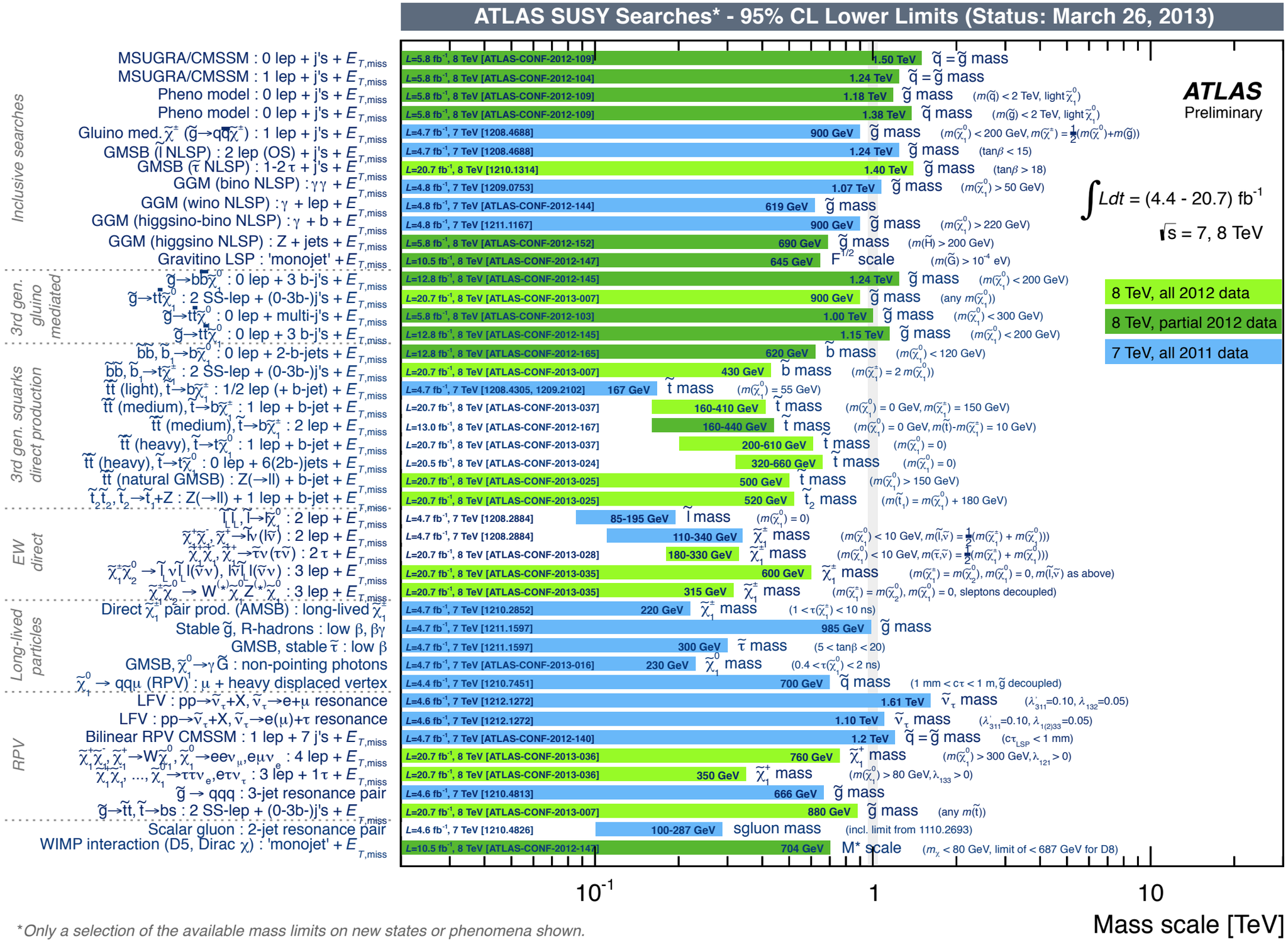
Phenomenology

Superpartners pair produced

Lightest superpartner(LSP) is stable and escape detection

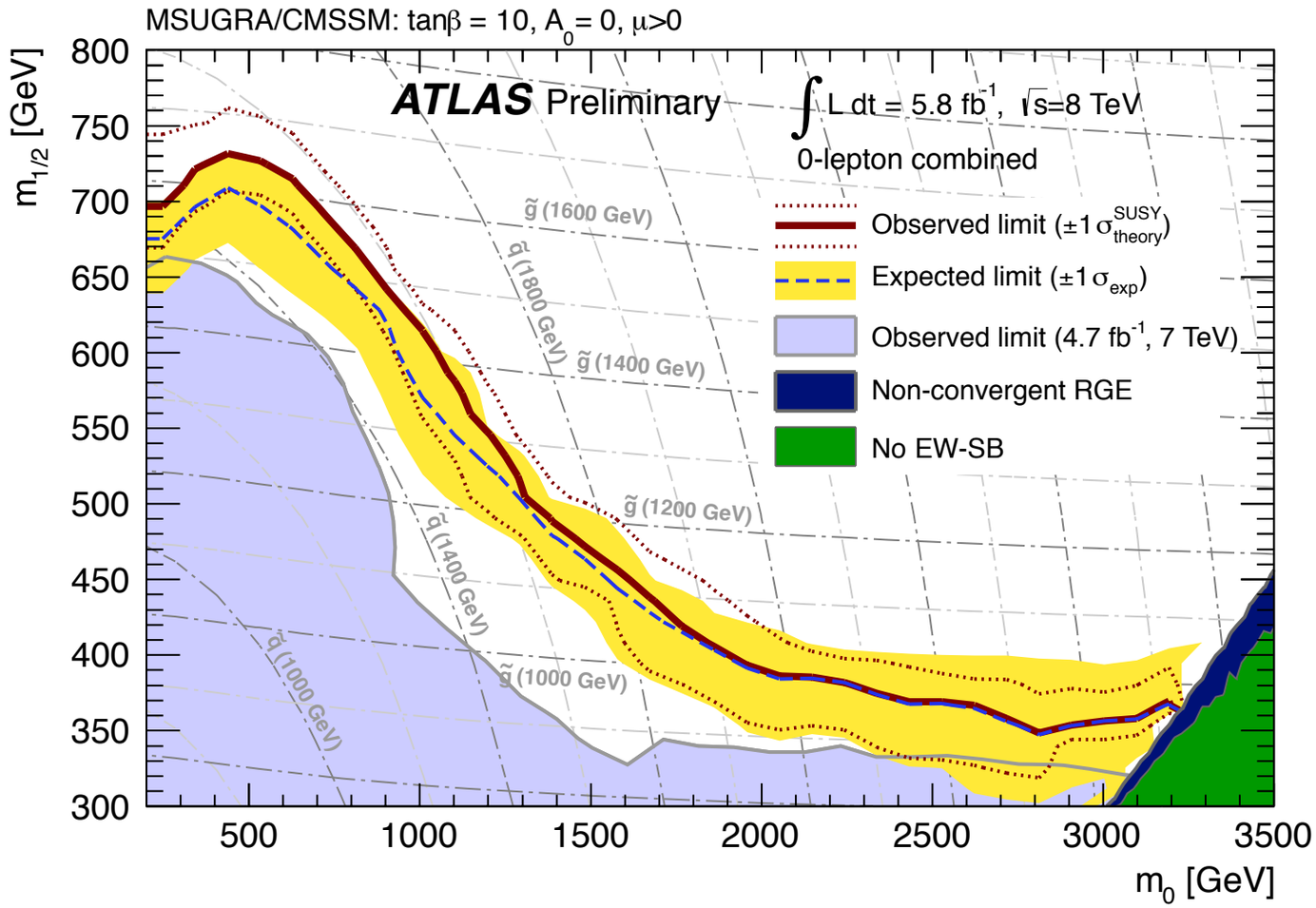

$\tilde{t}_1\tilde{t}_1$ production
Status: Moriond QCD 2013
ATLAS Preliminary
Observed limits
Observed limits ($-1\sigma_{theo}$)
Expected limits
0L, $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
1L, $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
2L, $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
0L, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 5$ GeV
1-2L, $\tilde{t}_1 \to b + \tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 106$ GeV
1L, $\tilde{t}_1 \to b + \tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 150$ GeV
2L, $\tilde{t}_1 \to b + \tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} - 10$ GeV
1-2L, $\tilde{t}_1 \to b + \tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 13-21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L ATLAS-CONF-2013-024
0L [1208.1447]
1L ATLAS-CONF-2012-166
1L [1208.2590]
-
2L [1209.4186]
0L ATLAS-CONF-2012-171
-
-
2L [1208.4305], 1-2L [1209.2102]
1L ATLAS-CONF-2012-166
-
2L ATLAS-CONF-2012-167
-
1L ATLAS-CONF-2012-166
1-2L [1209.2102]
$\tilde{t}_1 \to b + \tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to W^{(*)} + \tilde{\chi}_1^0$
$\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$ ($m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$+5 GeV)
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$ ($m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$)
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 5$ GeV
L_{int} = 12.8 fb^{-1}
$m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 13 fb^{-1}
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} - 10$ GeV
L_{int} = 13 fb^{-1}
$m_{\tilde{\chi}_1^\pm} < 103.5$ GeV
$m_{\tilde{\chi}_1^\pm} = 106$ GeV
L_{int} = 4.7 fb^{-1}
$m_{\tilde{\chi}_1^\pm} < 106$ GeV
$m_{\tilde{\chi}_1^\pm} = 150$ GeV
L_{int} = 13 fb^{-1}
L_{int} = 4.7 fb^{-1}
L_{int} = 13 fb^{-1}
L_{int} = 21 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]


$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$, $\sqrt{s}$ = 8 TeV
Status: Moriond QCD 2013
95% CL limits. σ^{SUSY}_{theory} not included.
0-lepton, 6-9 jets [L_{int} = 5.8 fb^{-1}]
ATLAS-CONF-2012-103
0-lepton, ≥ 3 b-jets [L_{int} = 12.8 fb^{-1}]
ATLAS-CONF-2012-145
3-leptons, ≥ 4 jets [L_{int} = 12.8 fb^{-1}]
ATLAS-CONF-2012-151
2-SS-leptons, [0-3] b-jets [L_{int} = 20.7 fb^{-1}]
ATLAS-CONF-2013-007
Expected
Observed
Expected
Observed
Expected
Observed
Expected
Observed
$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ forbidden
ATLAS Preliminary
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
200
400
600
800
1000
500
600
700
800
900
1000
1100
1200
1300

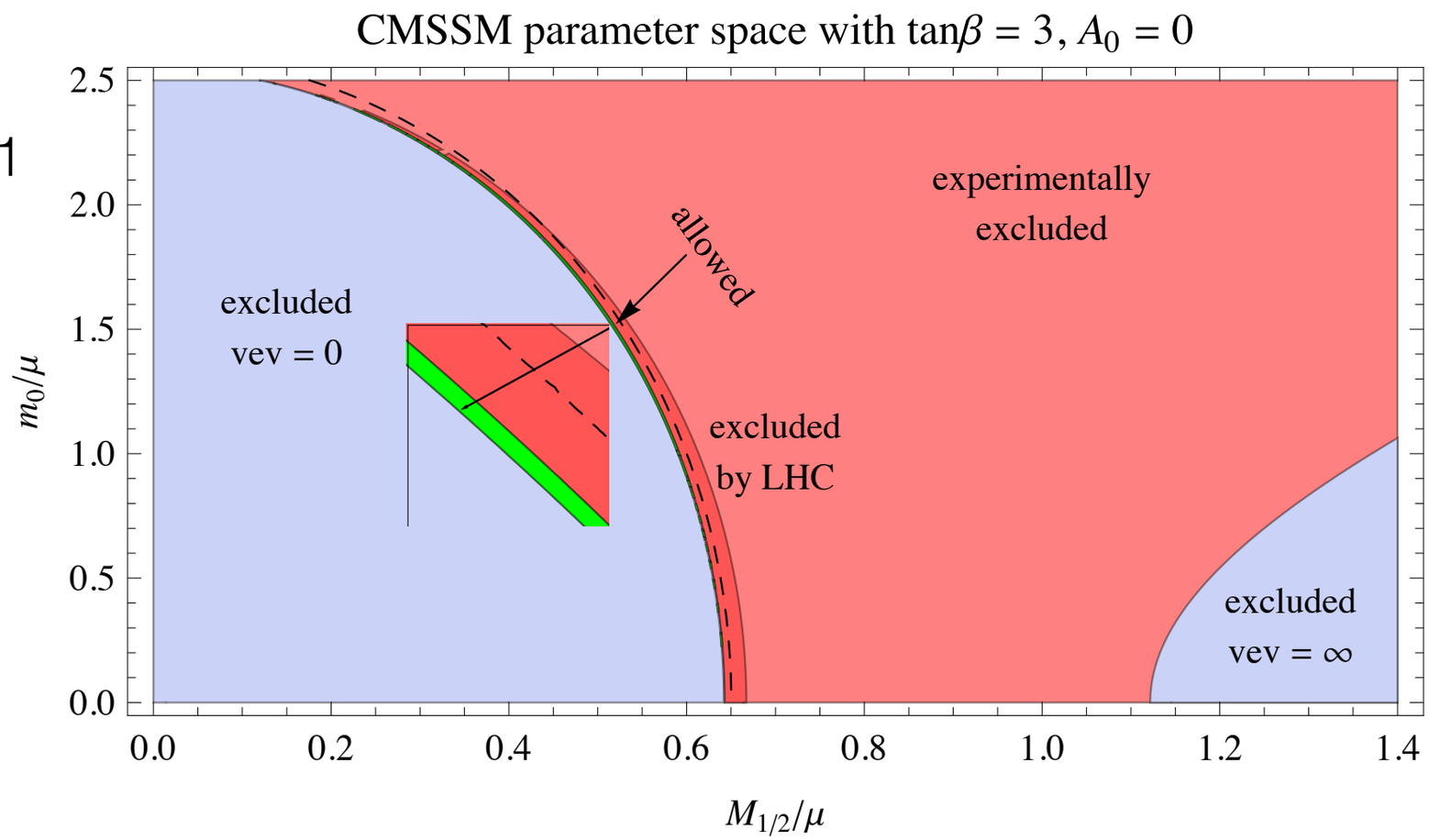


*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

ATLAS (Dec. 12)

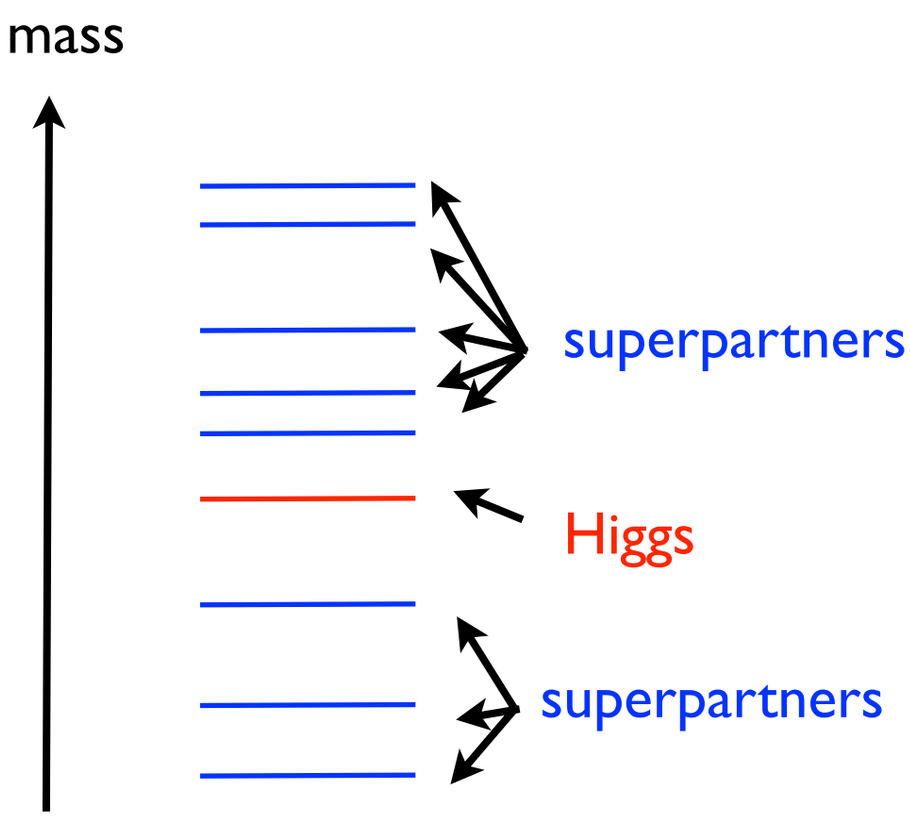


A. Strumia '11
1101.295v3

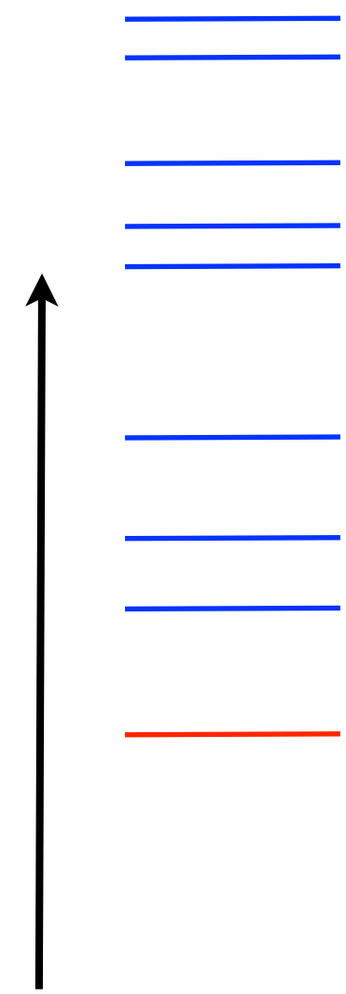


The Higgs is a superpartner

$$Q, U^c, D^c, L, E^c, H_u, H_d$$



μ can be used to lower Higgs mass



Getting away from the MSSM

more minimal SUSY

Stealth

RPV

Degenerate

Dirac gauginos

In the MSSM gauginos are Majorana

$$M\lambda\lambda$$

$$F_X\theta^2 \longleftarrow \int d^2\theta X W_\alpha W^\alpha$$

Can be Dirac if new superfields are added

$$W_1^\alpha, W_2^\alpha, W_3^\alpha, \Phi_1, \Phi_2, \Phi_3$$

$$\searrow \quad \swarrow$$

$$M_D\lambda\Psi$$

N=2 supersymmetry

extra-dimension

Supersoft SUSY breaking

Fox, Nelson, Weiner '02

$D'\theta_\alpha$ ← D-term breaking

$$\int d^2\theta W'_\alpha W_i^\alpha \Phi_i$$

Dirac gauginos do not feed into scalar masses through renormalization

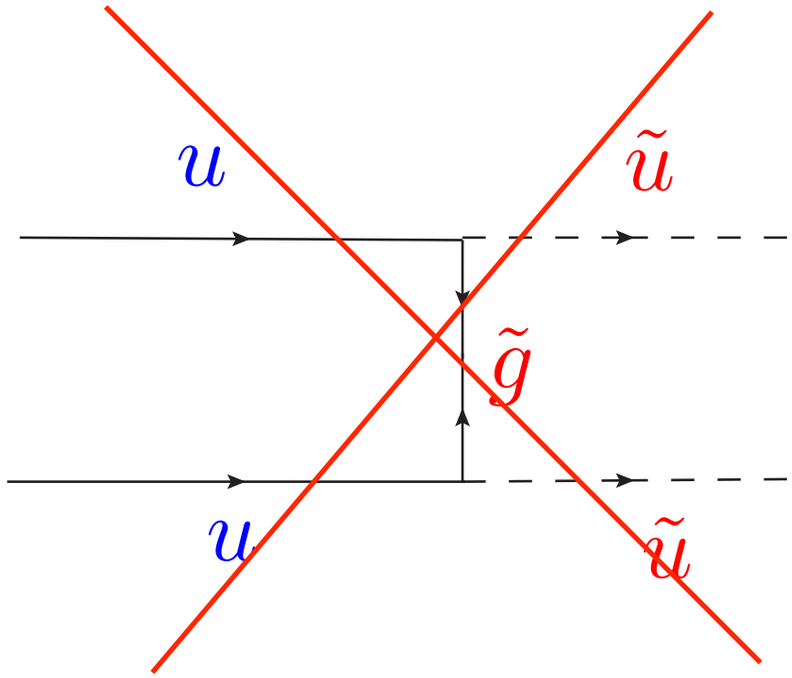
$$m^2 = \frac{C_i(r)\,\alpha_i m_i^2}{\pi} \log\left(\frac{\delta^2}{m_i^2}\right)$$

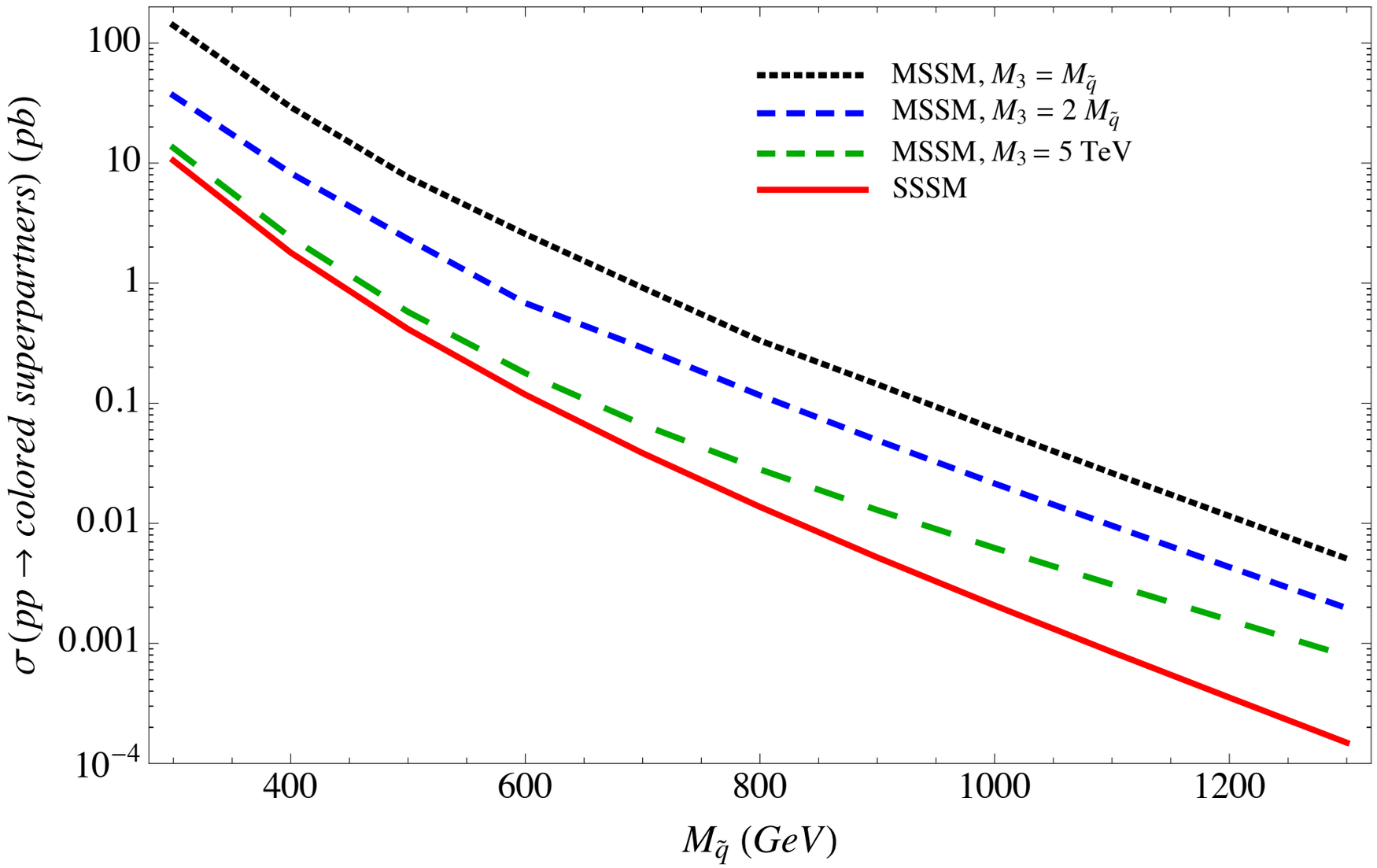
They can be naturally heavier than scalars

LHC will have a harder time seeing the gluino...

M. Heikinheimo, M. Kellerstein, V. Sanz '12
Kribs, Martin '12

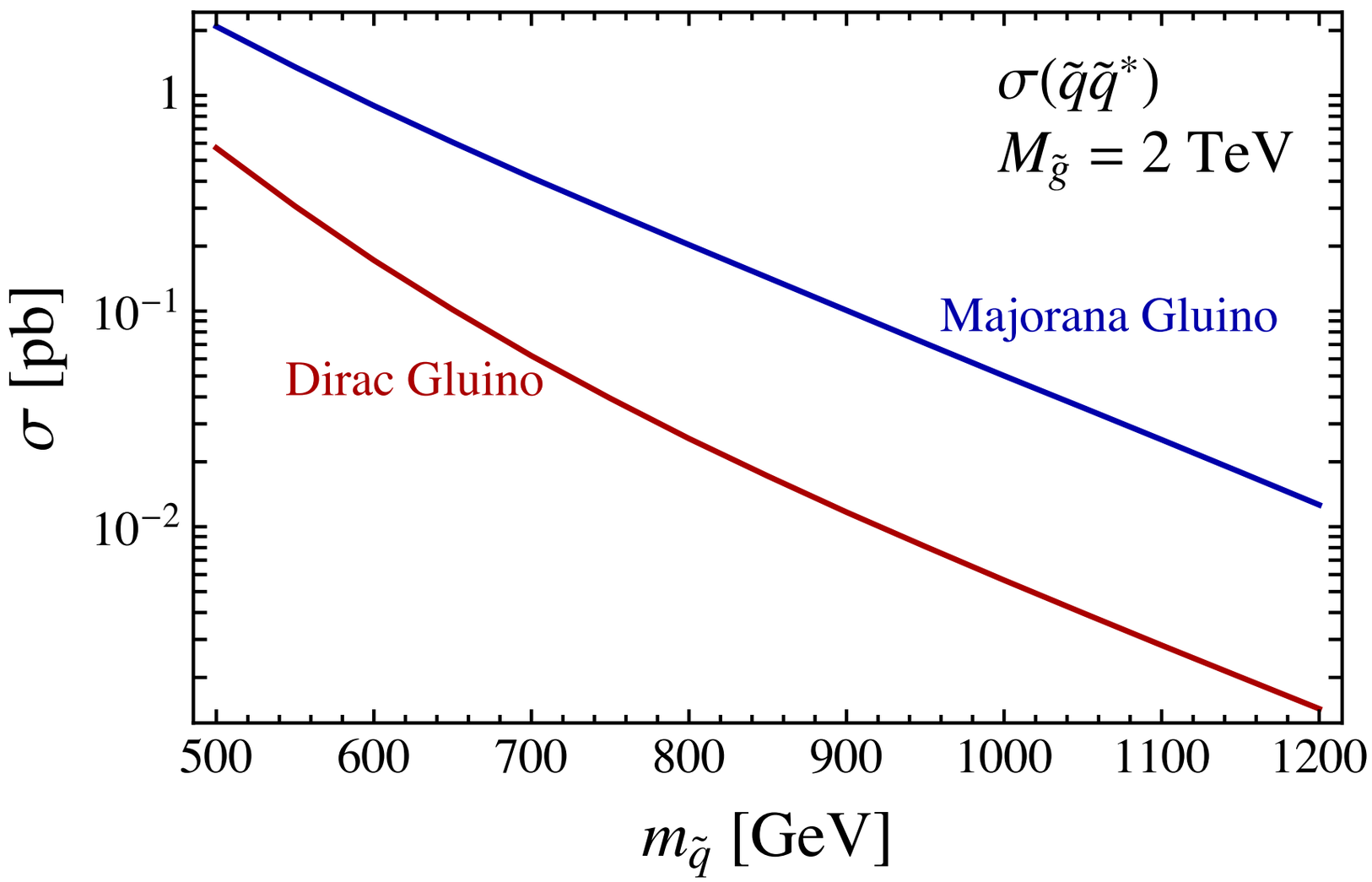
...and squarks





G. Kribs, A. Martin, 2012

Squark production



Frugiuele, T.G., Kumar, Ponton

R-symmetry

With Dirac gaugino: possible to impose an U(1) R-symmetry

$$M_D \lambda \Psi$$

Kribs, Poppitz, Weiner '02

- Bounds from FCNC are weaker: off diagonal m_{ij}

$$R[Q, U^c, D^c, L, E^c] = 1 \qquad R[H_u, H_d] = 0$$

$$\cancel{\mu H_u H_d}$$

Gherghetta,Pomarol '03
T.G., Frugiuele '11

$U(1)_R$ can be identified with lepton number

- Superpartners have different lepton numbers

e.g.: quarks have lepton number 0

squarks have lepton number 1

Q	U^c	D^c	L	E^c	H_u	R_d	Φ_a
1	1	1	0	2	0	2	0

$$W = QH_uU^c + QLD^c + LLE^c + \mu H_u R_d$$

quark masses

lepton masses

Higgsino mass

Respect R-symmetry → Respect lepton number

sneutrino can get a vev without breaking lepton number

$$QLD^c \rightarrow \tilde{\nu} b b^c + \tilde{b} b^c \nu \cdots = v_e b b^c + \cdots$$

Missing lepton mass

LLE^c

anti-symmetric in lepton flavour

one of the flavour doesn't get a mass

Add a SUSY breaking term

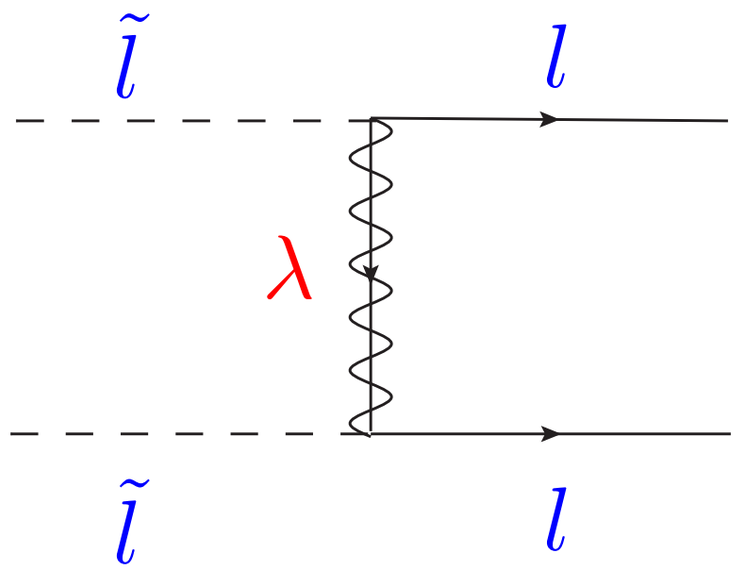
$\theta^2 F$

$$\int d^4\theta \frac{X^\dagger H_u L_a E_a^c}{M^2} \qquad y_a = \frac{F}{M^2}$$

Constraints

Deviation to Z- coupling

mixing of neutrino and lepton with gaugino



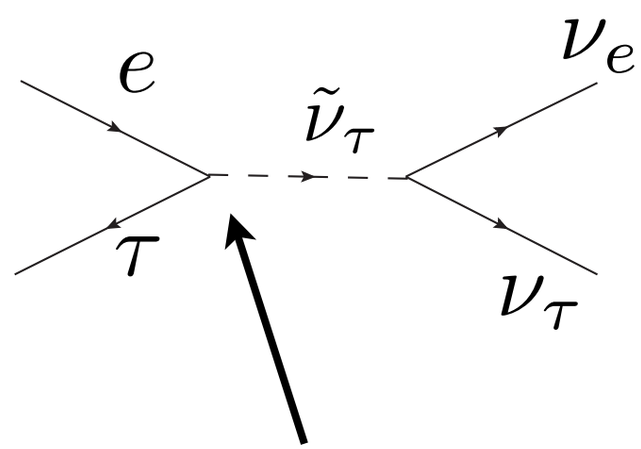
$$\frac{\left(\tilde{l}^\dagger D_\mu \tilde{l}\right)\left(\bar{l}\gamma_\mu l\right)}{M^2}$$

$$v_a \lesssim 60\mathrm{GeV}\frac{M_2}{1.5TeV}$$

$\tan(\beta) \gtrsim 2.7$

New couplings

lead to deviations of EWPO



tau Yukawa

Standard in RPV

$$v_a \gtrsim 8\mathrm{GeV}\left(\frac{300\mathrm{GeV}}{m_{\tilde{\tau}}}\right)$$

$\tan(\beta) \lesssim 22$

Neutrino masses

Breaking of U(1)-R by gravitino mass

$$m_{3/2}\psi_{\frac{3}{2}}\psi_{\frac{3}{2}}$$

Will generate neutrino mass somehow → Anomaly / Gravity

low mediation scale

$$m_{3/2} \lesssim 100\mathrm{MeV}$$

Frugiuele,Gregoire,Kumar,Ponton. 1210.5257

Phenomenology

Large gluino Dirac mass

smaller cross-section for gluino and squark

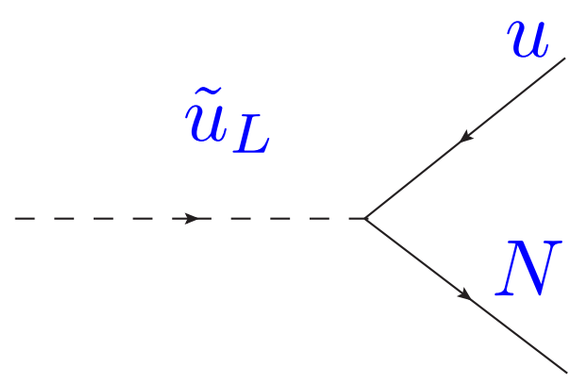
Conventional R-parity breaking

Superpartners unstable

Single production of slepton possible.

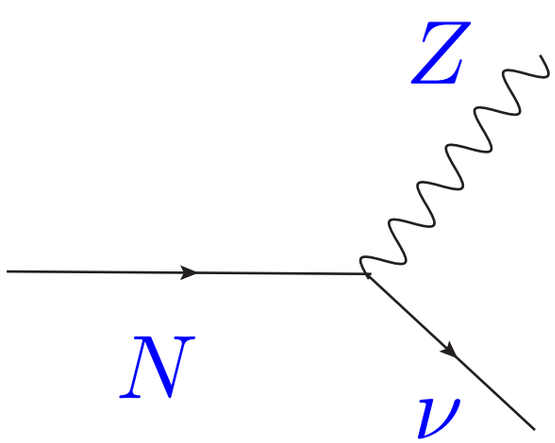
Squark are lepto-quark.

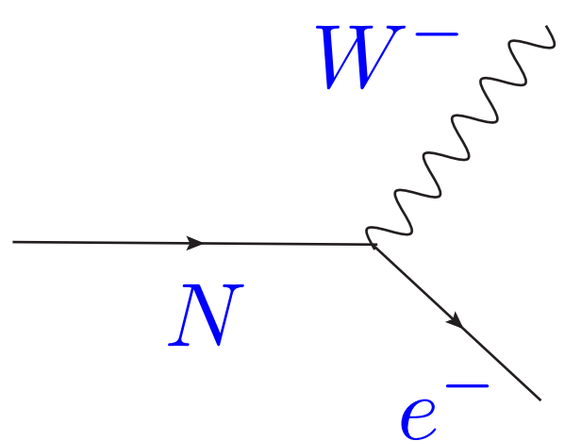
Squark decay

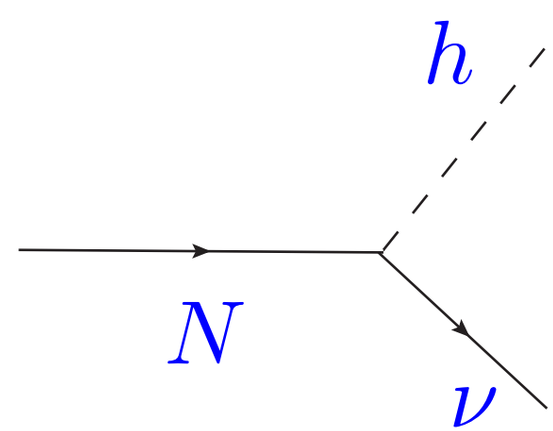


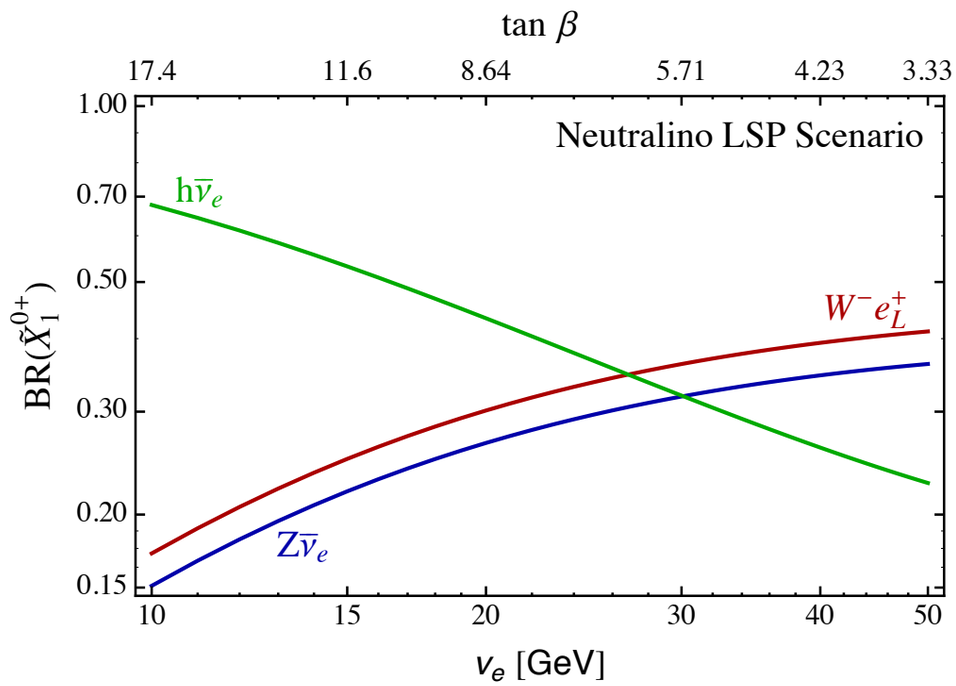
conventional...

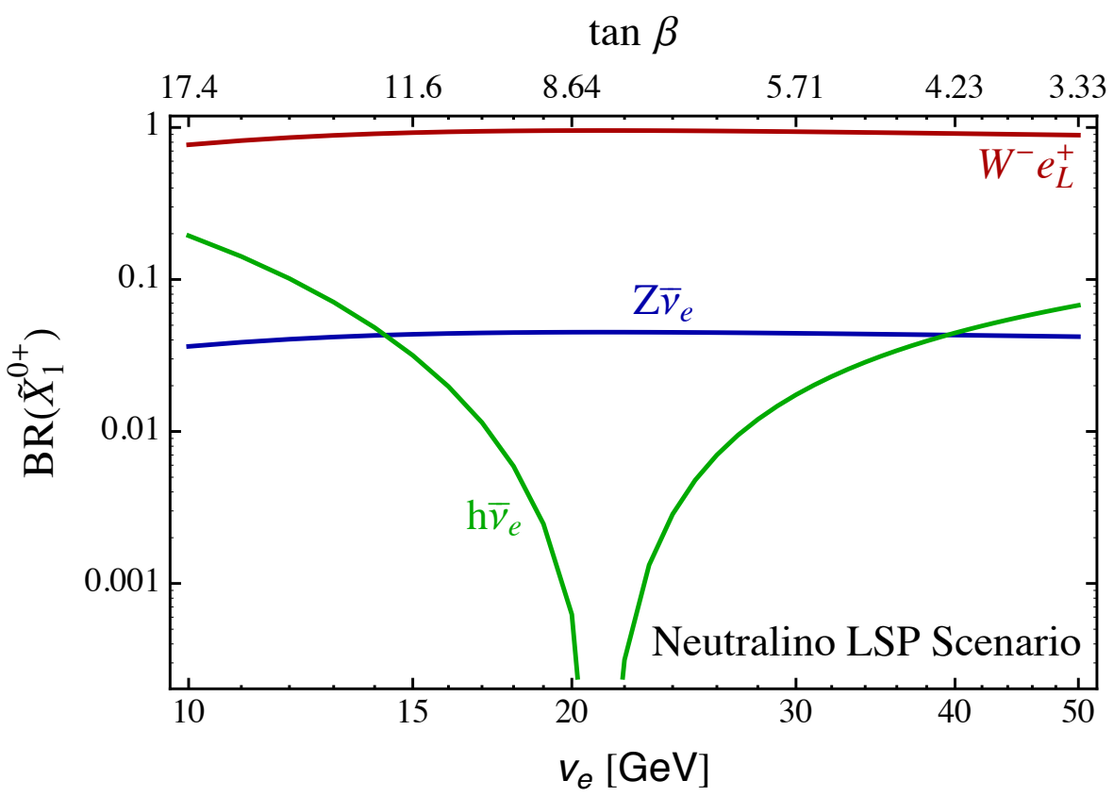
...but the neutralino decay








tan β
17.4
11.6
8.64
5.71
4.23
3.33
Neutralino LSP Scenario
hν̄e
W⁻e⁺L
Zν̄e
BR(X̃⁰⁺1)
1.00
0.70
0.50
0.30
0.20
0.15
10
15
20
30
40
50
ve [GeV]


tan β
17.4
11.6
8.64
5.71
4.23
3.33
W⁻e⁺L
Zν̄e
hν̄e
Neutralino LSP Scenario
BR(X̃⁰⁺1)
1
0.1
0.01
0.001
10
15
20
30
40
50
ve [GeV]

Bounds from many searches

jets + missing energy

$m_{\tilde{q}} \lesssim 690\mathrm{GeV}$

jets + Z + missing energy

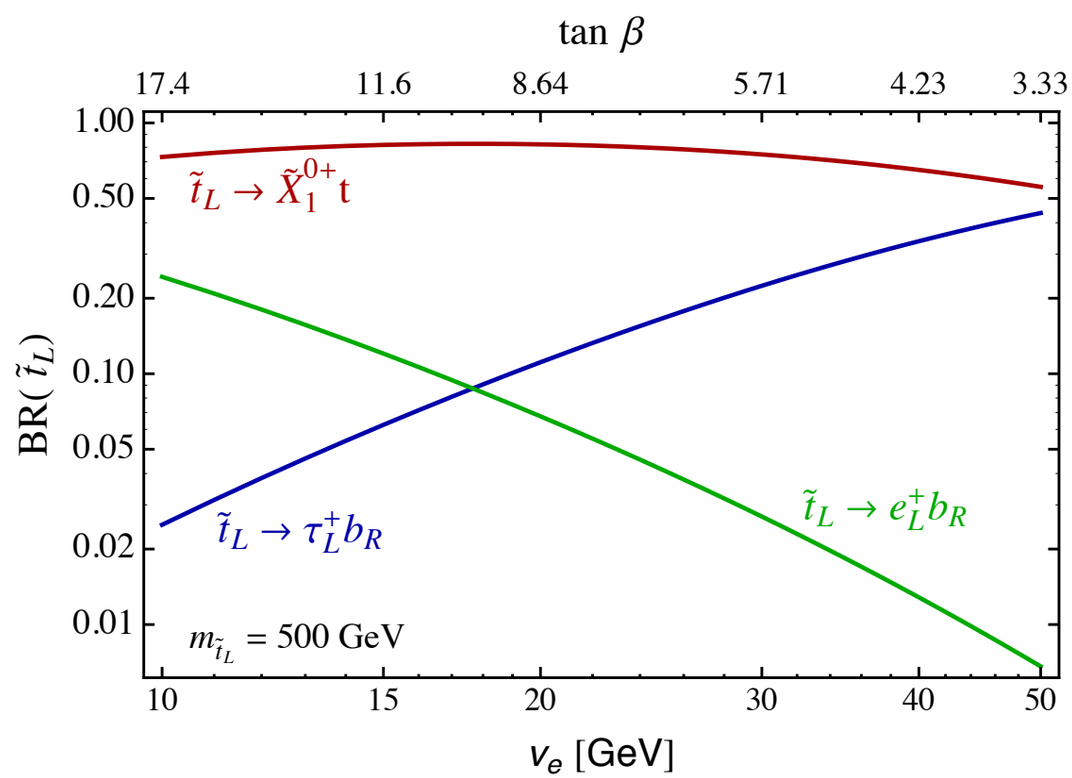
multileptons

Lepto-quark decay modes

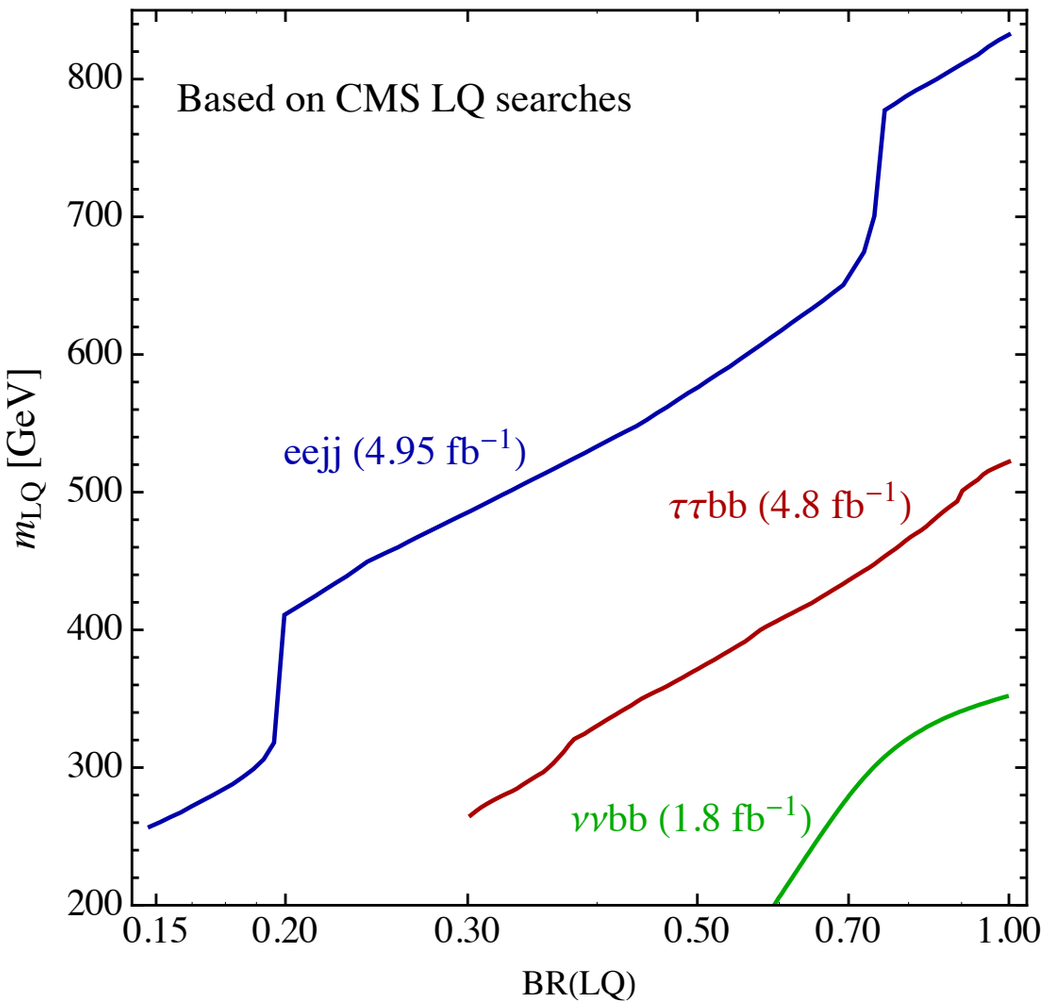
Arise from:

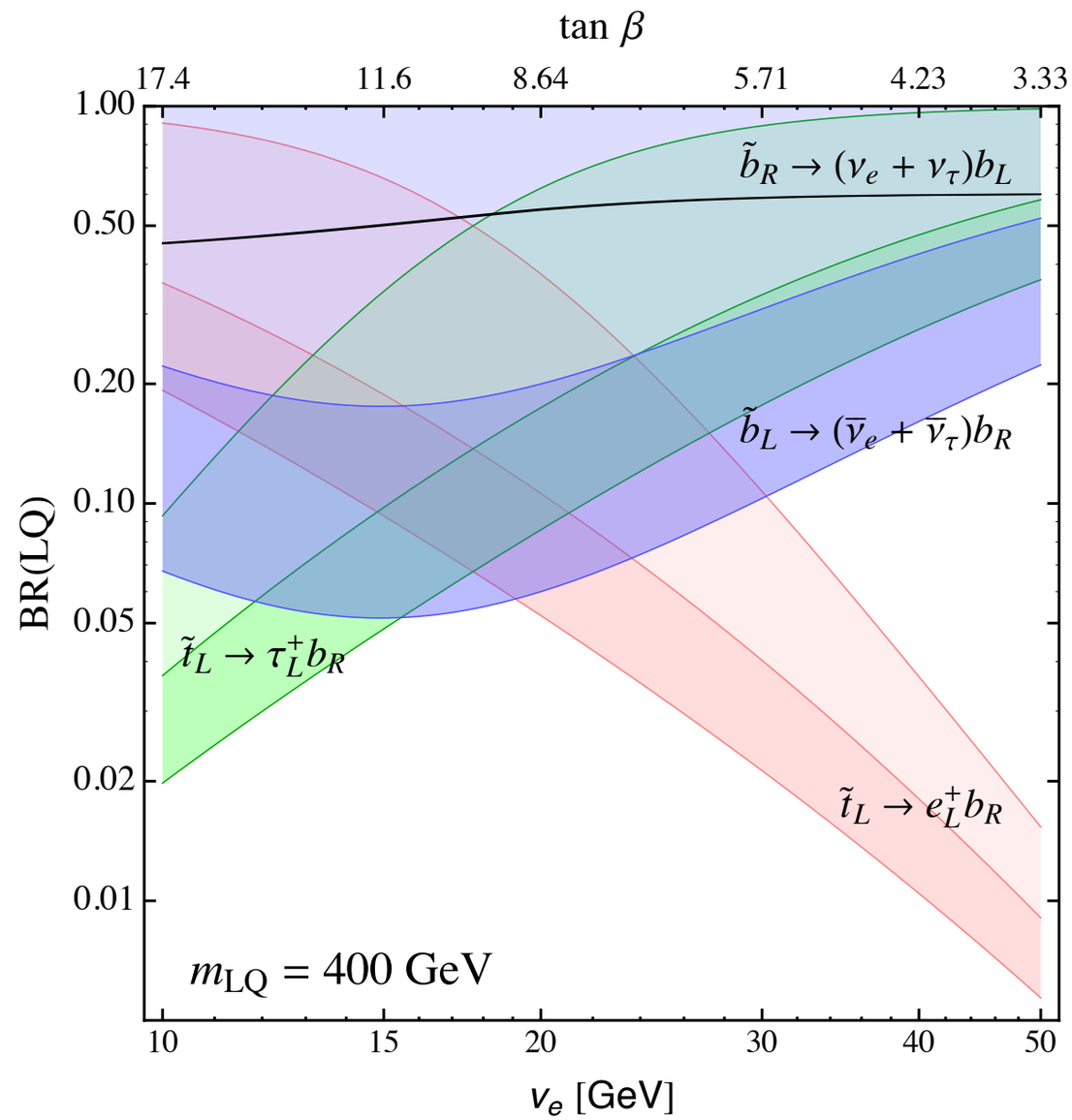
$$\lambda_d \, Q D^c L \; = \tilde{t}_L b e^+ + \cdots$$

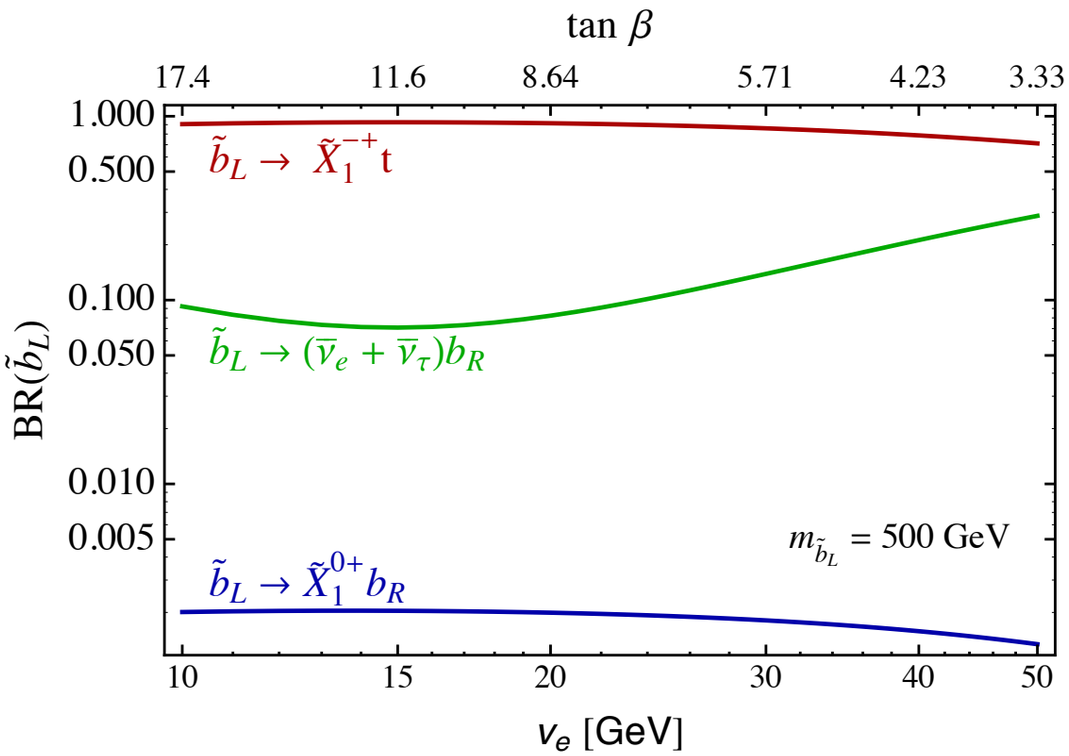
Larger for third generation

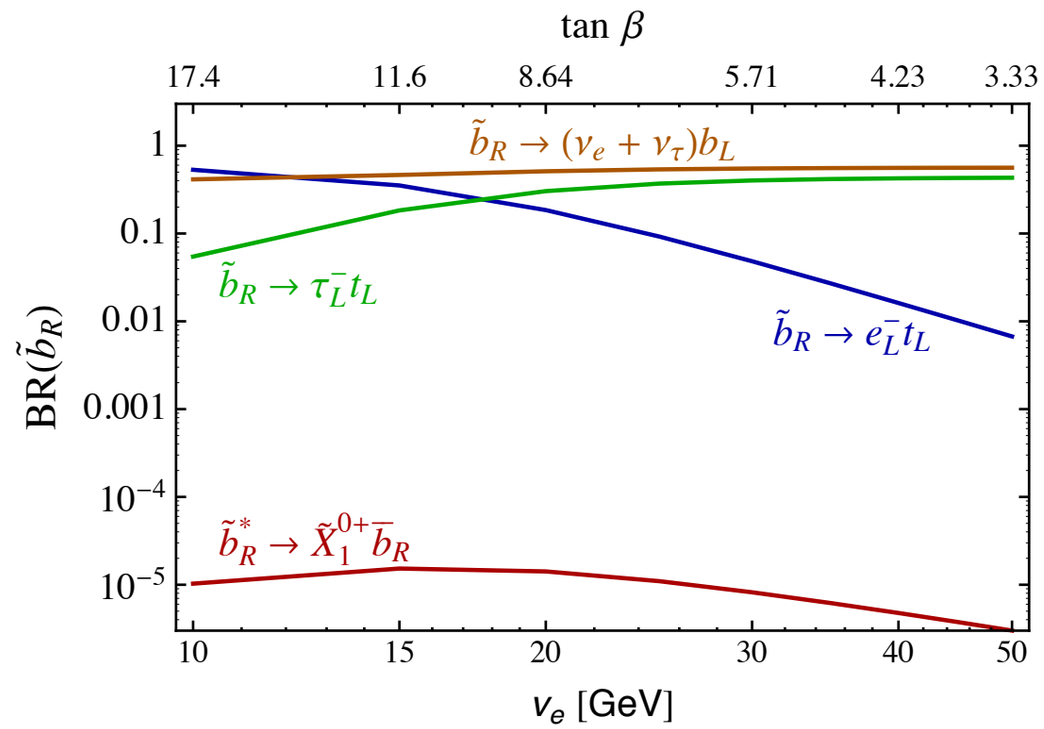


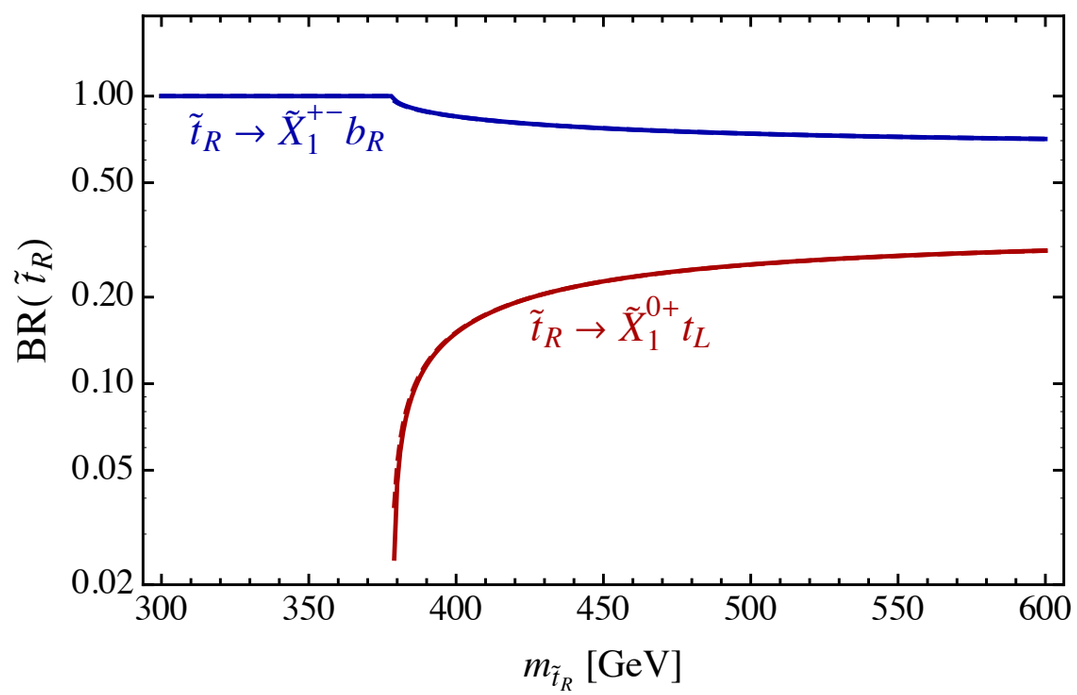
Lepto-quark bounds






tan β
17.4
11.6
8.64
5.71
4.23
3.33
1.000
0.500
0.100
0.050
0.010
0.005
BR($\tilde{b}_L$)
$\tilde{b}_L \to \tilde{X}_1^{-+}$t
$\tilde{b}_L \to (\bar{\nu}_e + \bar{\nu}_\tau) b_R$
$\tilde{b}_L \to \tilde{X}_1^{0+} b_R$
$m_{\tilde{b}_L}$ = 500 GeV
10
15
20
30
40
50
v_e [GeV]


tan β
17.4
11.6
8.64
5.71
4.23
3.33
1
0.1
0.01
0.001
10^{-4}
10^{-5}
BR($\tilde{b}_R$)
$\tilde{b}_R \to (\nu_e + \nu_\tau) b_L$
$\tilde{b}_R \to \tau_L^- t_L$
$\tilde{b}_R \to e_L^- t_L$
$\tilde{b}_R^* \to \tilde{X}_1^{0+} \bar{b}_R$
10
15
20
30
40
50
v_e [GeV]


1.00
0.50
0.20
0.10
0.05
0.02
BR($\tilde{t}_R$)
$\tilde{t}_R \to \tilde{X}_1^{+-} b_R$
$\tilde{t}_R \to \tilde{X}_1^{0+} t_L$
300
350
400
450
500
550
600
$m_{\tilde{t}_R}$ [GeV]

sbottom decay

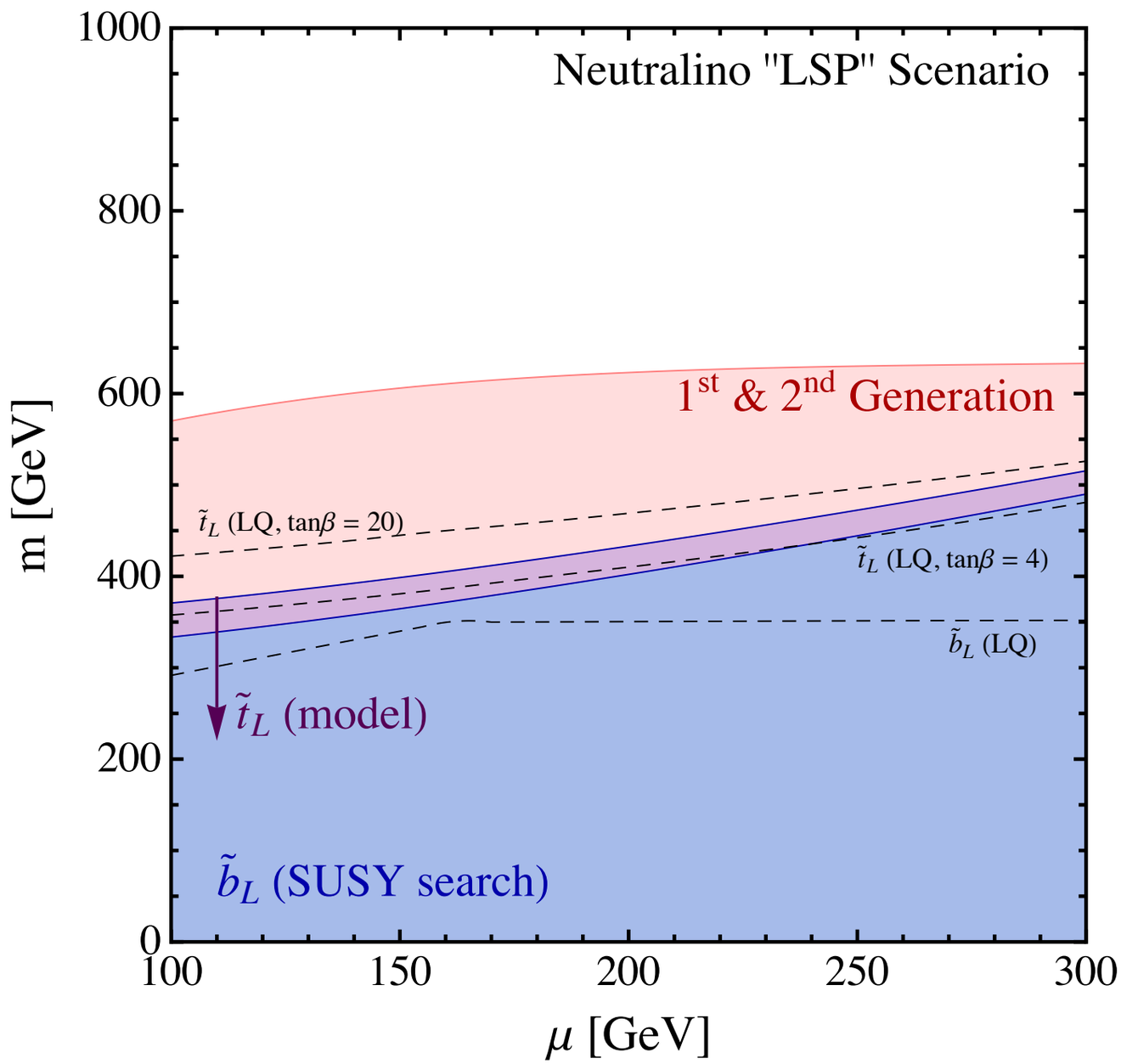
$$\tilde{b}_L \to tC^-$$

$$\hookrightarrow W^-\nu$$

Conventional sbottom searches apply

$$\tilde{b}_L \to tC^-$$

$$\hookrightarrow W^-N$$


Neutralino "LSP" Scenario
1st & 2nd Generation
$\tilde{t}_L$ (LQ, tanβ = 20)
$\tilde{t}_L$ (LQ, tanβ = 4)
$\tilde{b}_L$ (LQ)
$\tilde{t}_L$ (model)
$\tilde{b}_L$ (SUSY search)
m [GeV]
μ [GeV]
0
200
400
600
800
1000
100
150
200
250
300

Electroweak Symmetry Breaking

EWSB is govern by the following terms in the potential:

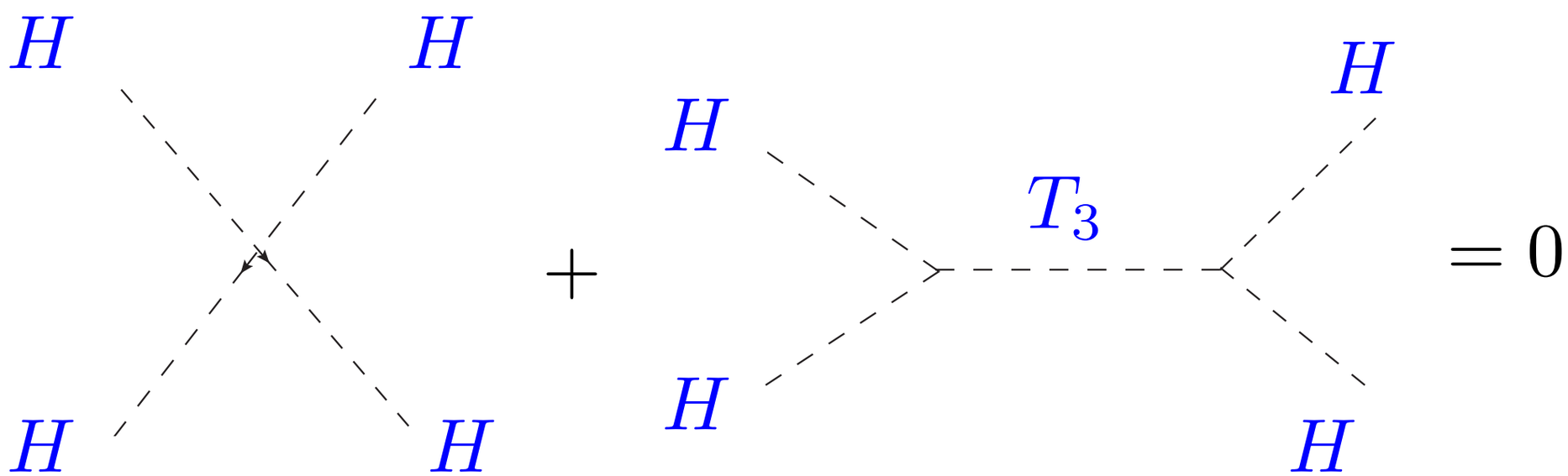
masses: $$(M_H^2 + \mu^2)\,|H_u|^2 + M_L\,|\tilde{\nu}|^2 + B_\mu H_u \tilde{\nu}$$

from adjoint chiral superfield

quartic: $$\frac{g^2}{2}\left[\left(|H_u|^2 - |\tilde{\nu}|^2\right) + \sqrt{2} M_2 T_3\right]^2 + \frac{D_1^2}{2}$$

required for 'supersoftness'

Integrating out adjoint scalar:



No tree level quartic - light Higgs!!

Add to the superpotential:

$$W = \lambda_s S H_u R_d + \lambda_T T H_u R_d$$

Add to the SUSY breaking:

$$t_s S + b_s S^2 + b_T T^a T^a + m_T |T|^2 + m_S |S|^2$$

$$m_{TR}^2 = m_T^2 + 4M_1^2 + b_T \neq 4M_1^2$$

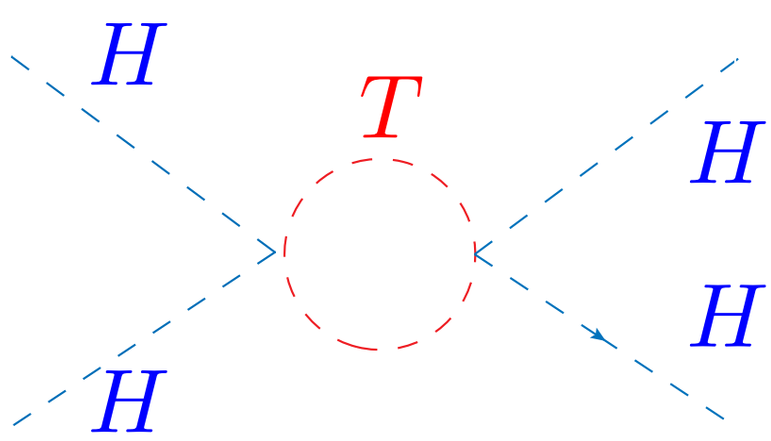
Cancellation of the quartic term is not exact anymore

New quartic terms from $\lambda_{S,T}$:

$$\lambda^2 \left|H_u\right|^2 \left|R_d\right|^2$$

Do not help because they involve the inert doublet

However they generate new loop contributions



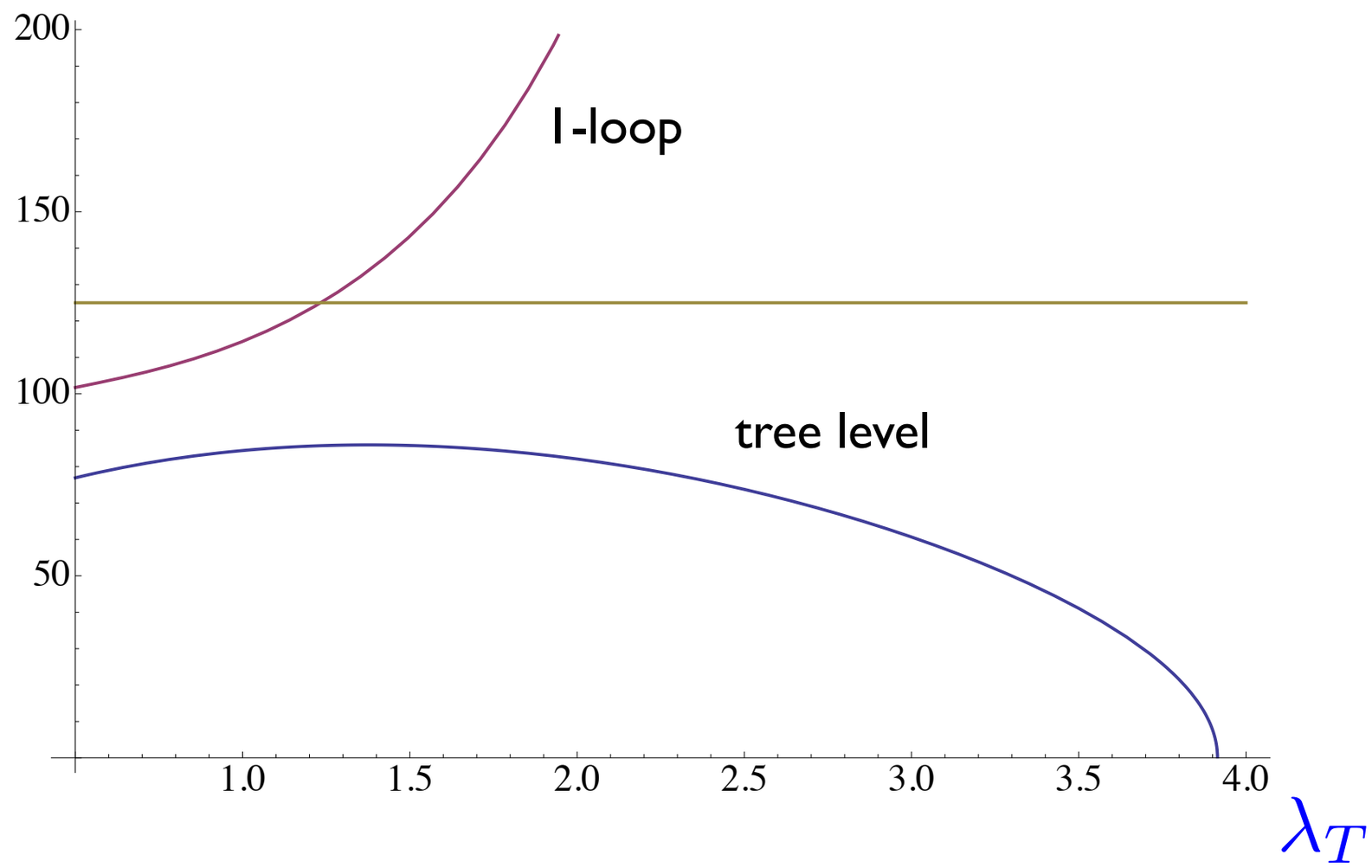
dominant radiative correction to quartic:

$$\delta V = \left[\frac{5}{16\pi^2} \lambda_T^4 \log\left(\frac{m_T^2}{v^2}\right) + \frac{3}{16\pi^2} y_t^4 \log\left(\frac{m_{\tilde{t}}^2}{v^2}\right) \right] |H_u|^4$$

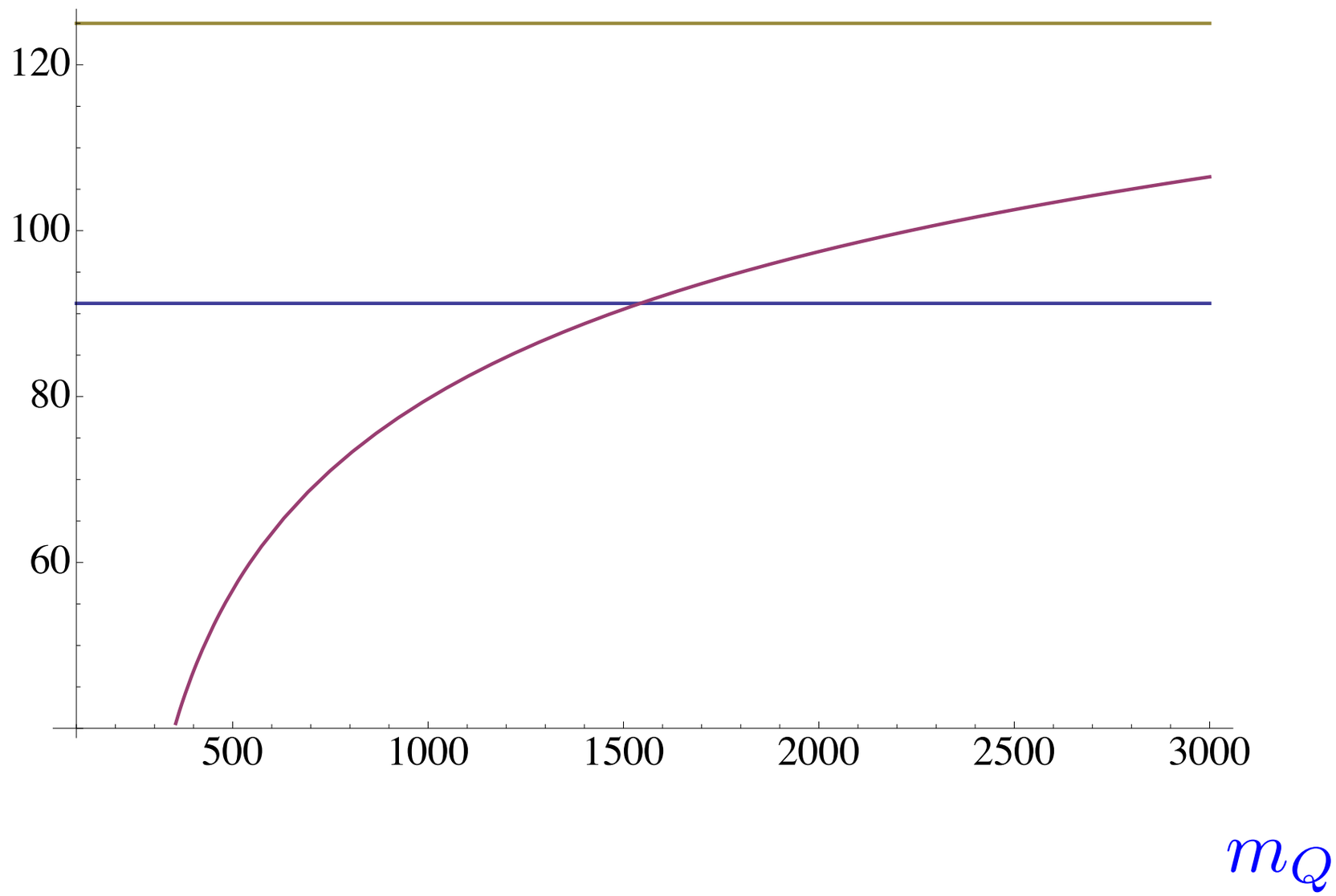
dominant radiative correction to mass:

$$\delta m_H^2 = \frac{3}{16\pi^2} \left[\lambda_T^2 m_T^2 + 2 y_t^2 m_{\tilde{t}}^2 \right] \log \Lambda^2$$

$\tan(\beta) = 10 \;\; M_2 = 500\text{GeV} \;\; \mu = 200\text{GeV} \;\; m_T = 1\text{TeV} \;\; m_Q = 500\text{GeV}$



MSSM (without stop mixing)



Conclusions

- LHC is on the hunt for SUSY
- No sighting yet
- Unconventional models might be the way to save the idea
- A combination of heavy gauginos and R-parity violation might help.

Very exciting times