

**UC Davis – Nov. 19<sup>th</sup>, 2012**

# Mini-Split

*Giovanni Villadoro*



*A.Arvanitaki, N.Craig, S.Dimopoulos – hep-ph/1210.0555*

LHC's main target:

*understand the physics behind EWSB  
(hierarchy problem)*

LHC's main target:

*understand the physics behind EWSB  
(hierarchy problem)*

Many possible solutions.

LHC's main target:

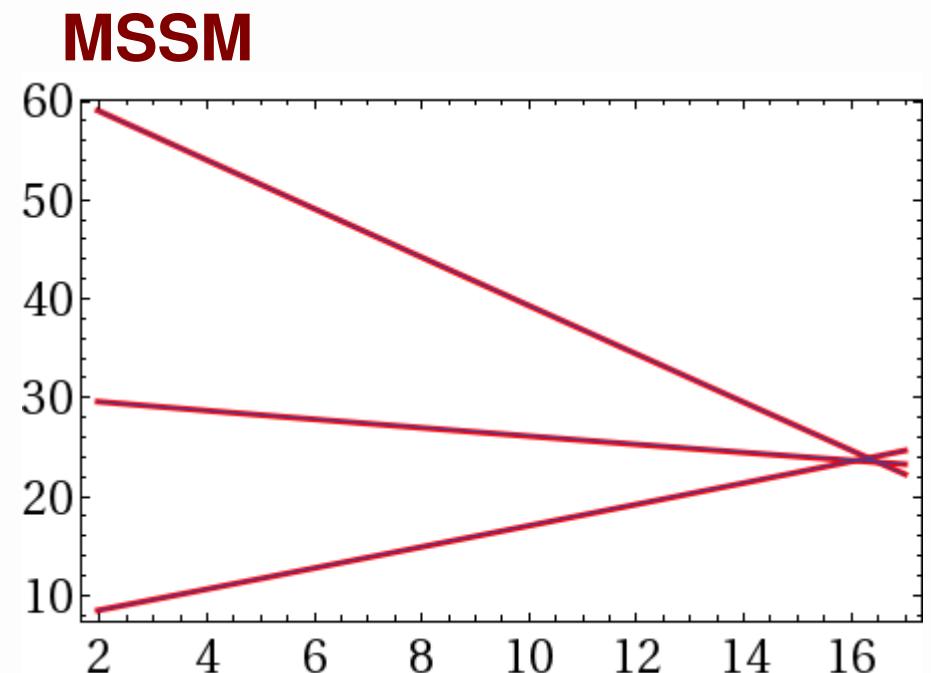
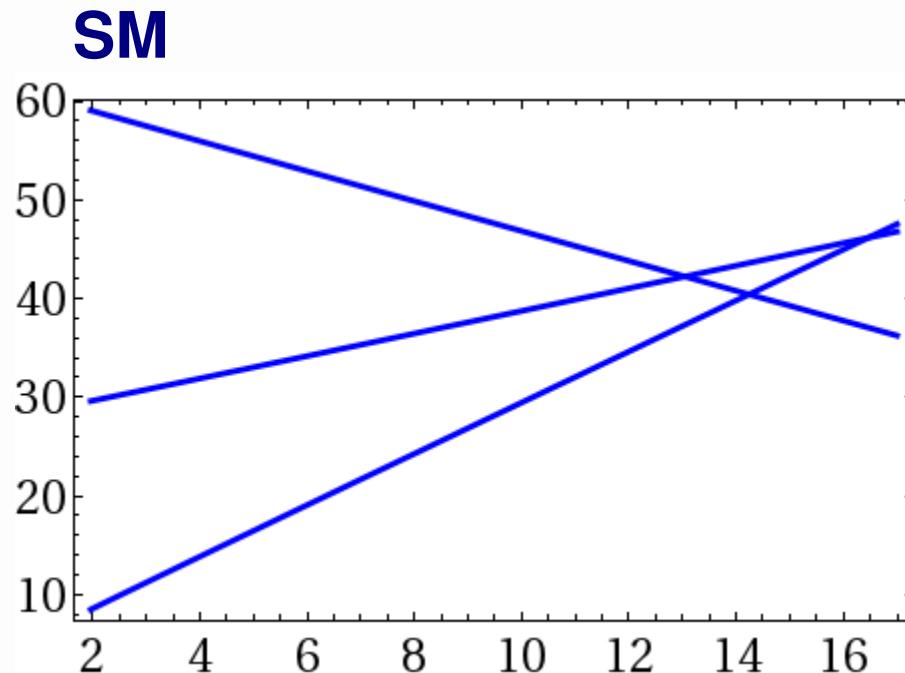
*understand the physics behind EWSB  
(hierarchy problem)*

Many possible solutions. One is special: SUSY

LHC's main target:

*understand the physics behind EWSB  
(hierarchy problem)*

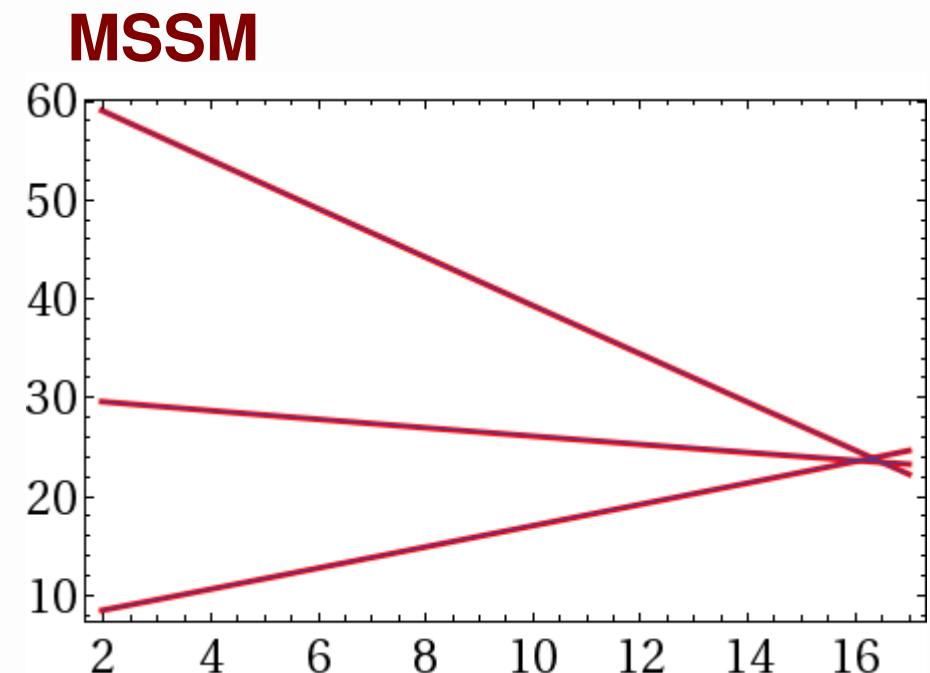
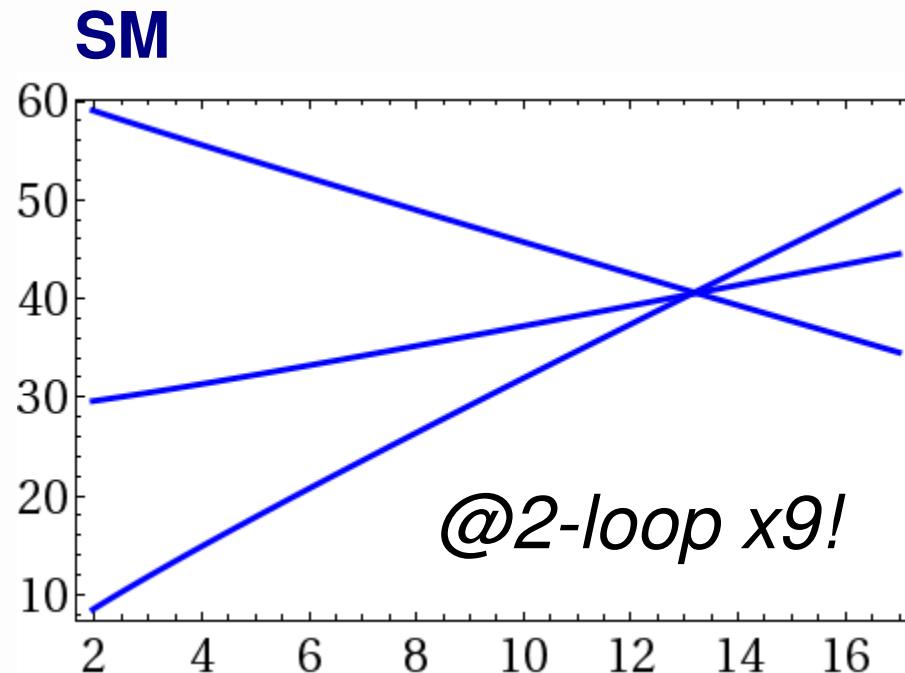
Many possible solutions. One is special: SUSY



LHC's main target:

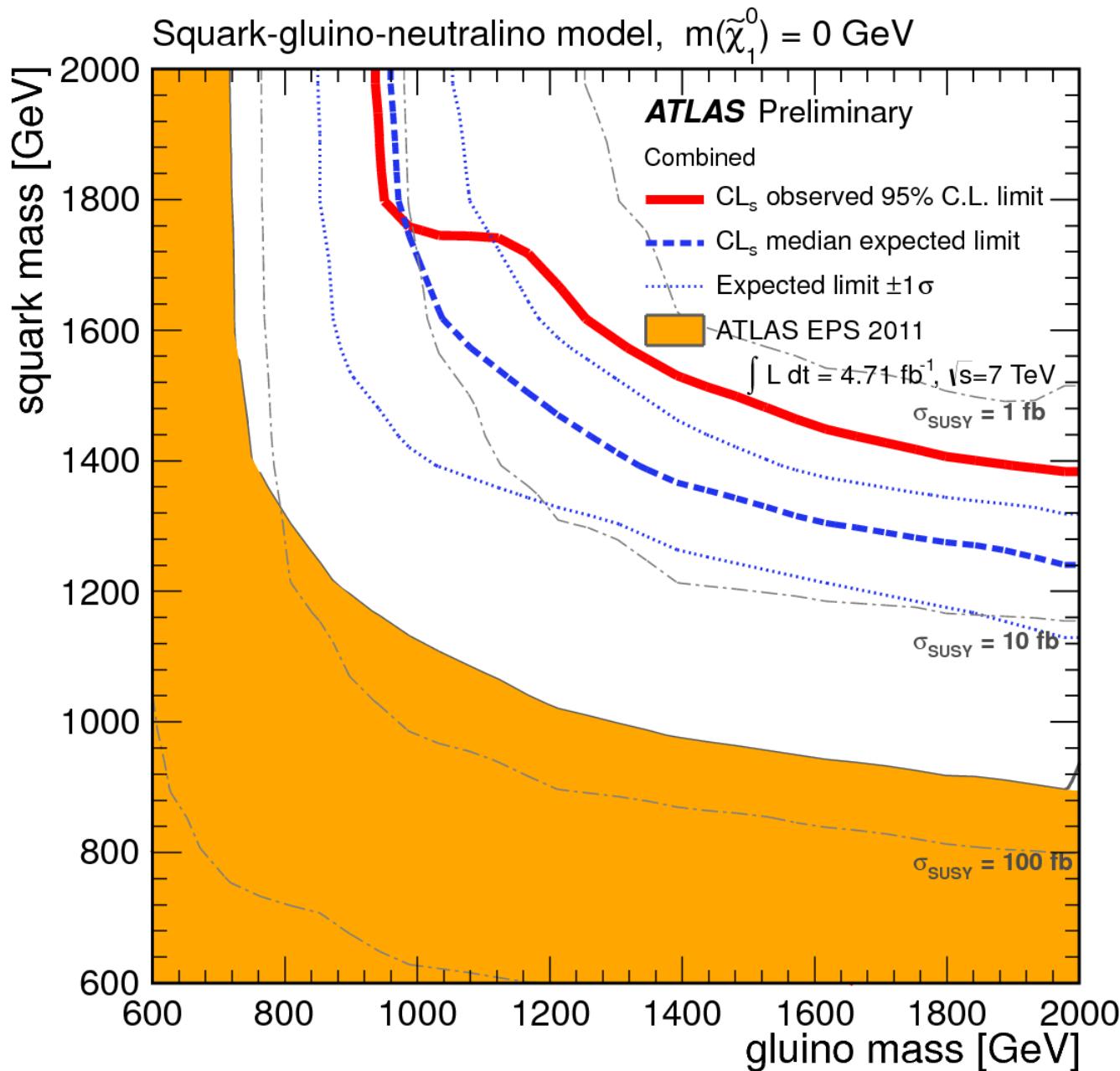
*understand the physics behind EWSB  
(hierarchy problem)*

Many possible solutions. One is special: SUSY



# The Missing Superpartner Problem

# No Vanilla SUSY



# Natural SUSY

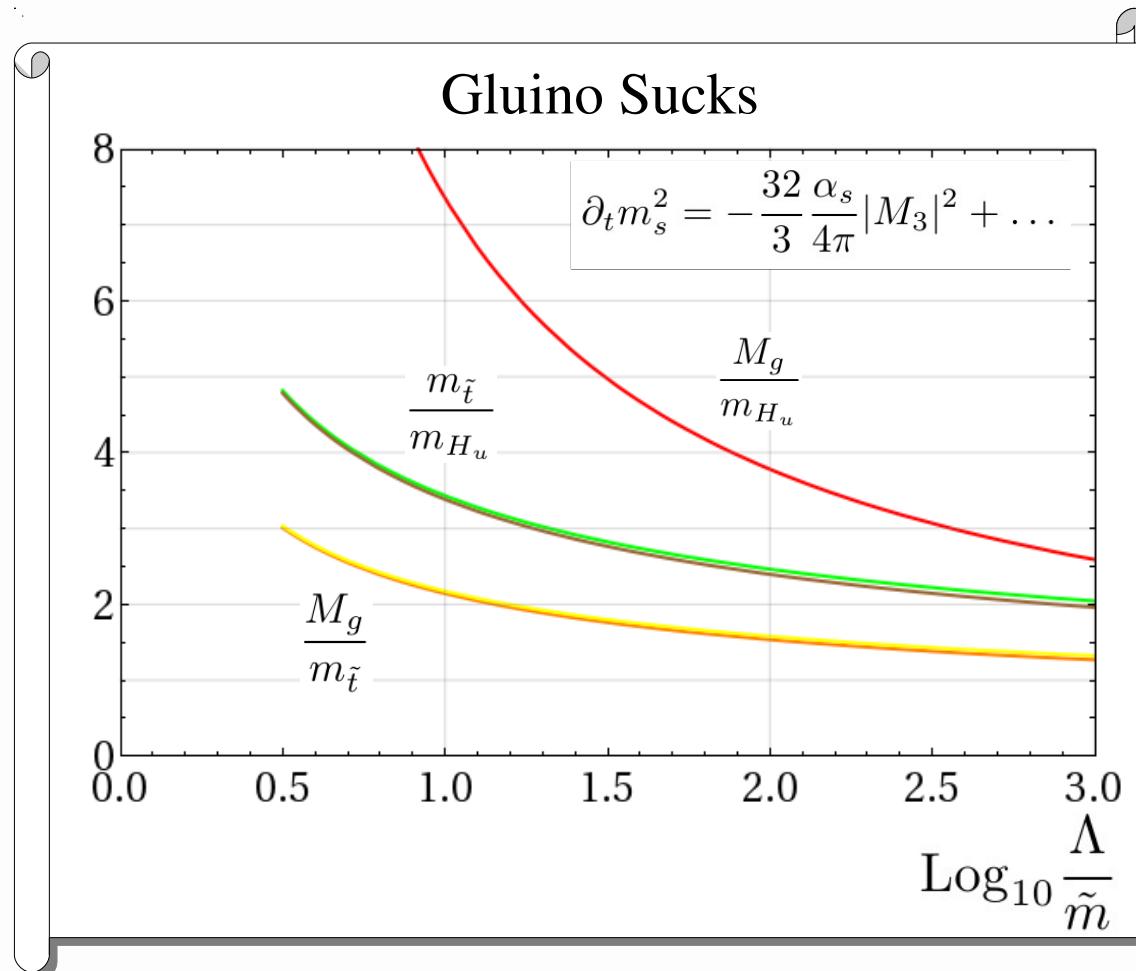
Only main actors of Hierarchy Problem needs to be light:

$$\mu \lesssim 250 \text{ GeV}, \quad m_{stop} \lesssim 700 \text{ GeV}, \quad M_{gluino} \lesssim 1.4 \text{ TeV}$$

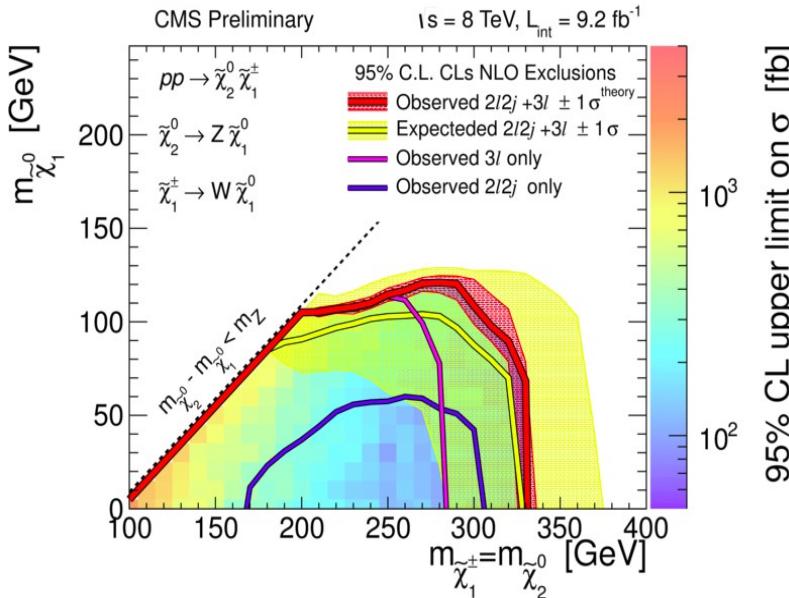
# Natural SUSY

Only main actors of Hierarchy Problem needs to be light:

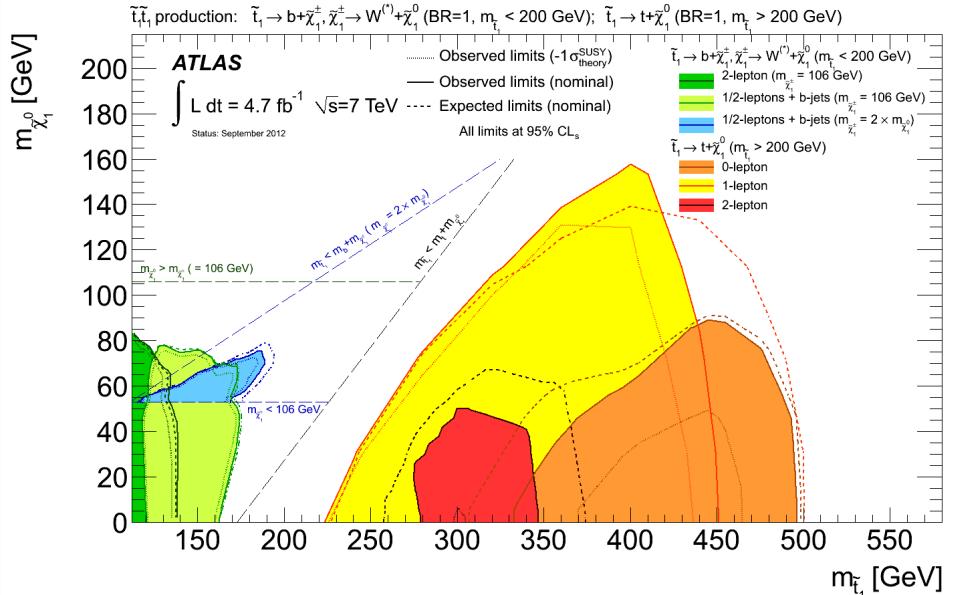
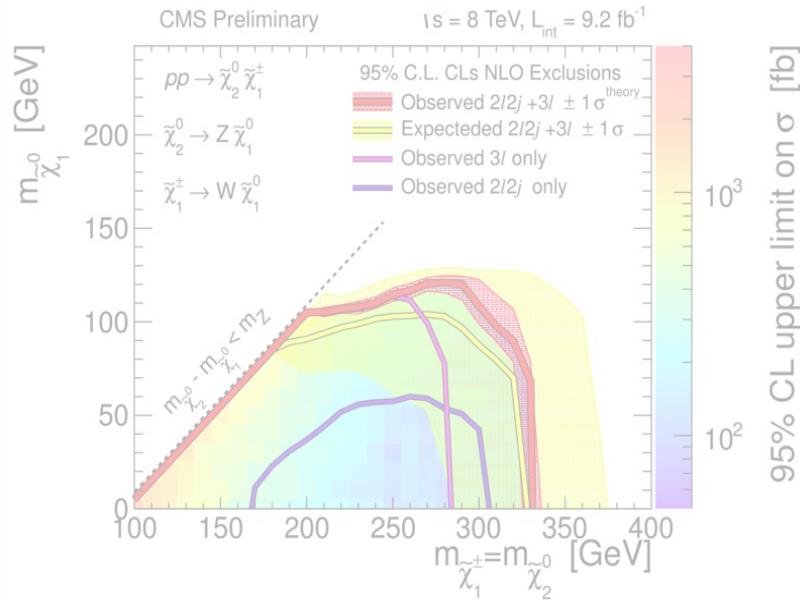
$$\mu \lesssim 250 \text{ GeV}, \quad m_{stop} \lesssim 700 \text{ GeV}, \quad M_{gluino} \lesssim 1.4 \text{ TeV}$$



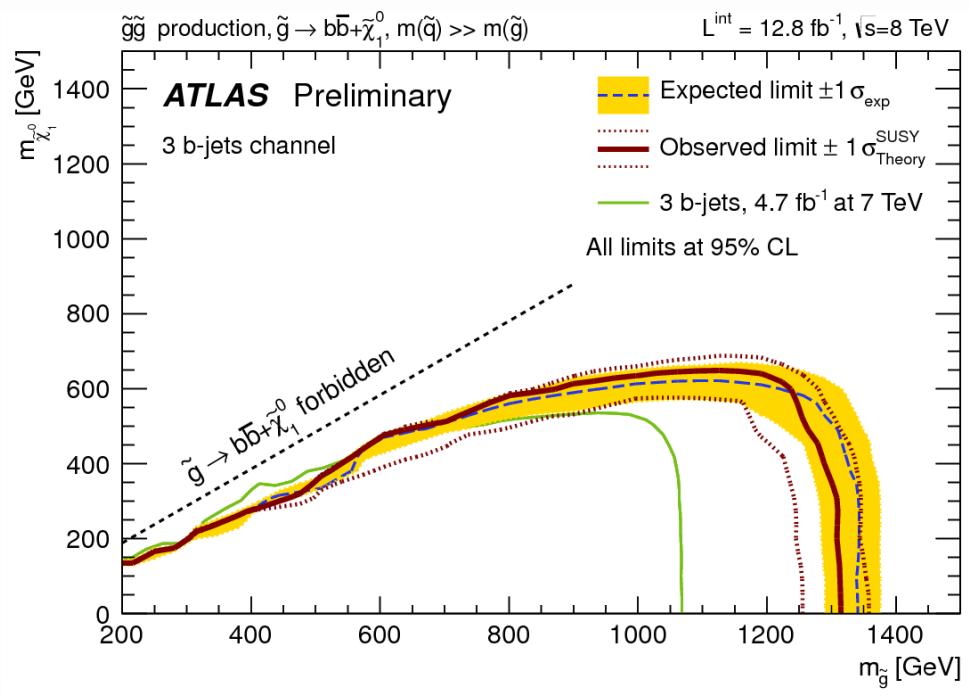
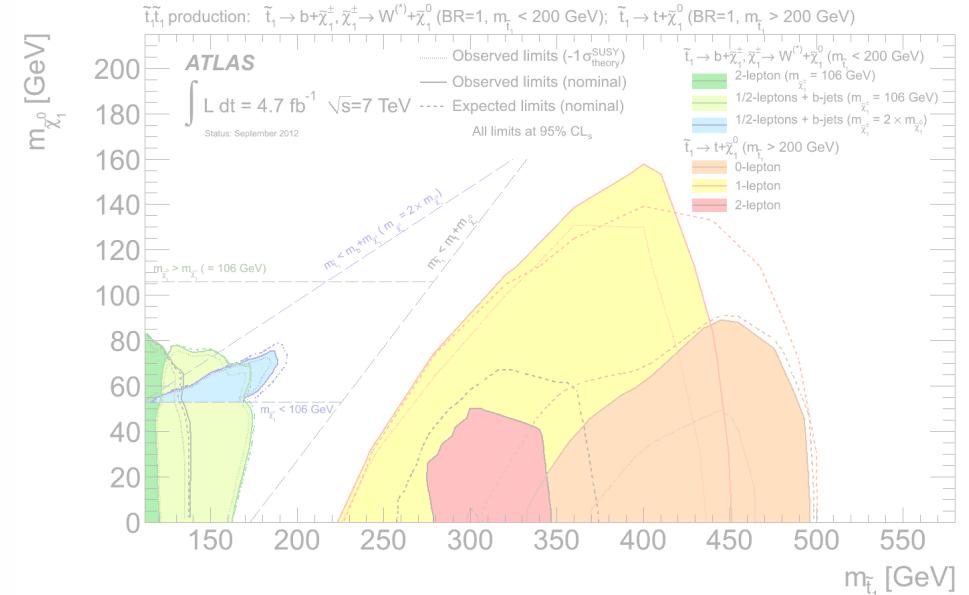
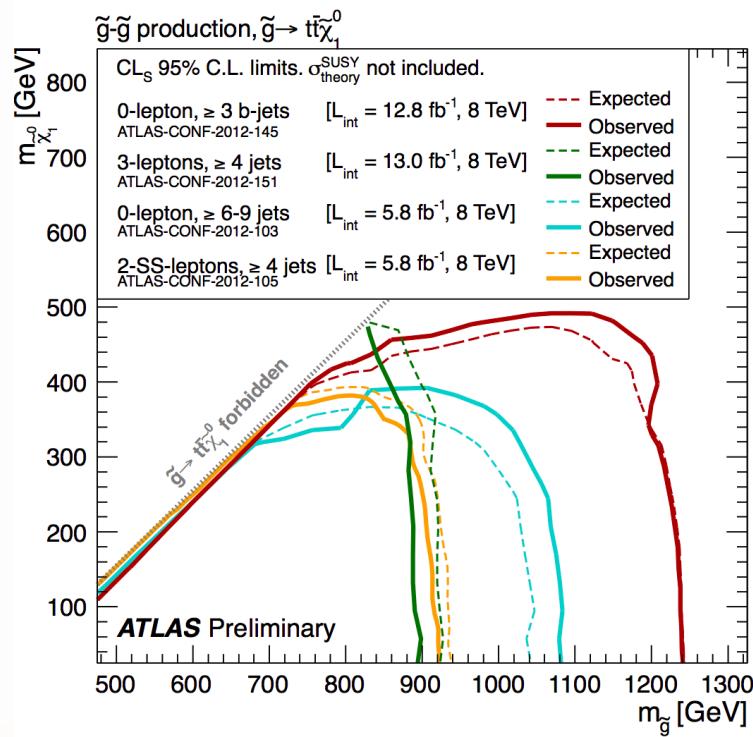
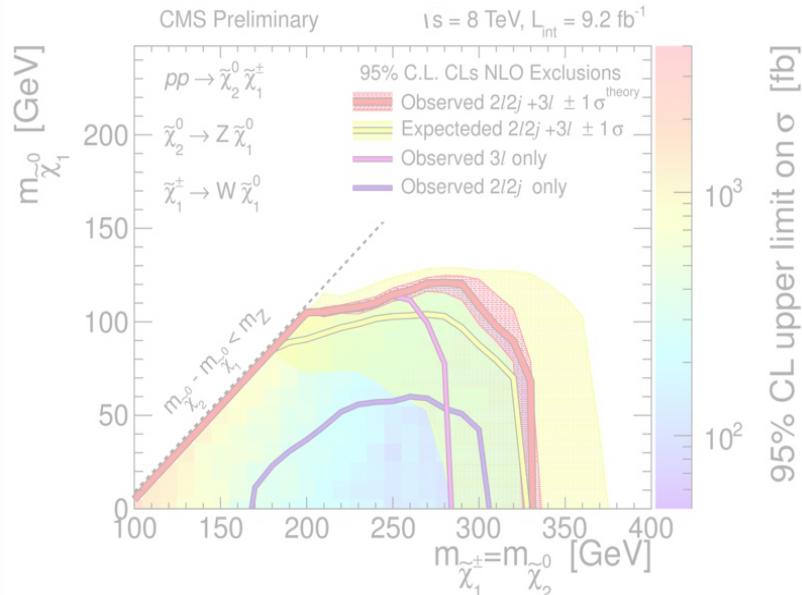
# Testing Natural SUSY



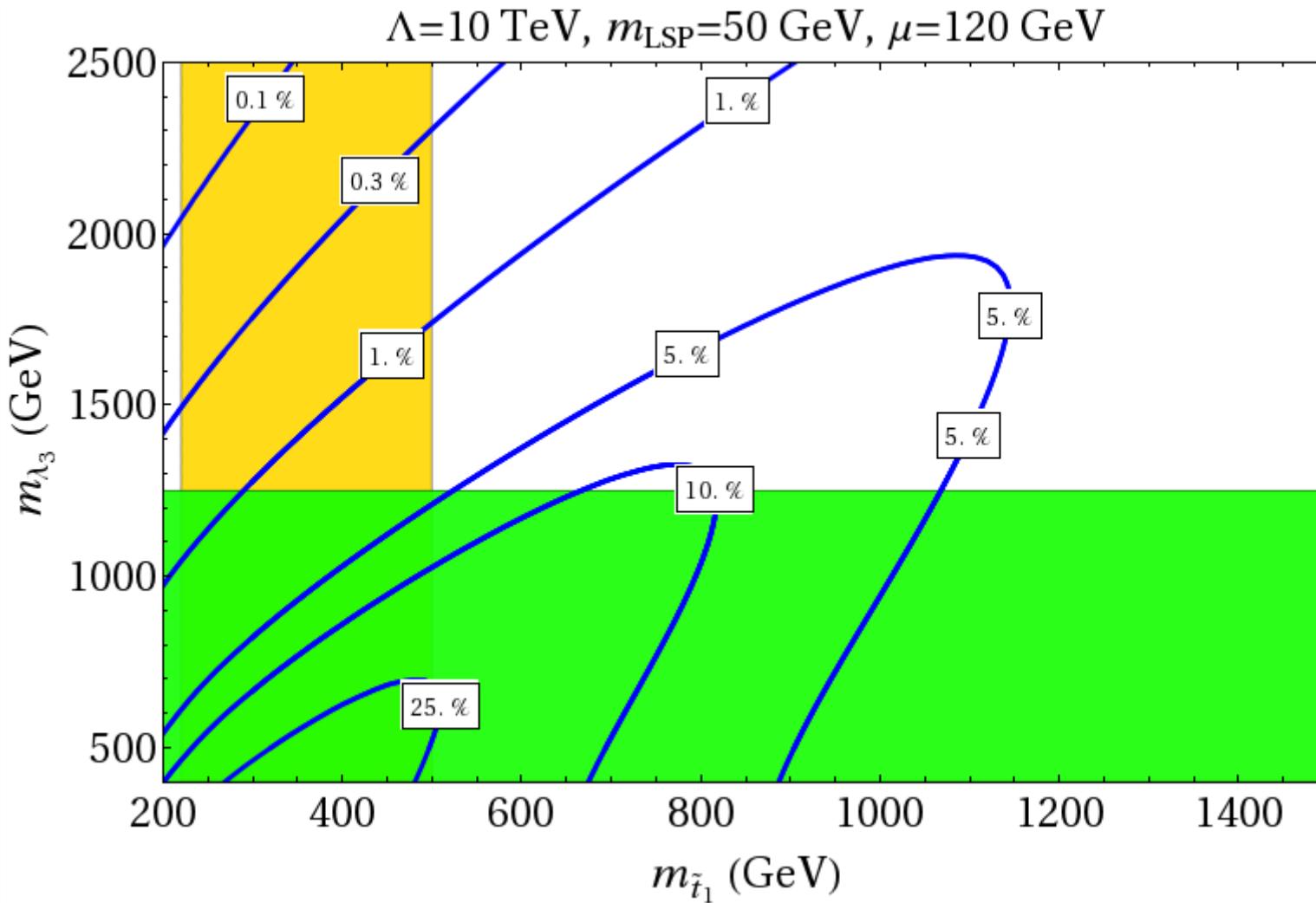
# Testing Natural SUSY



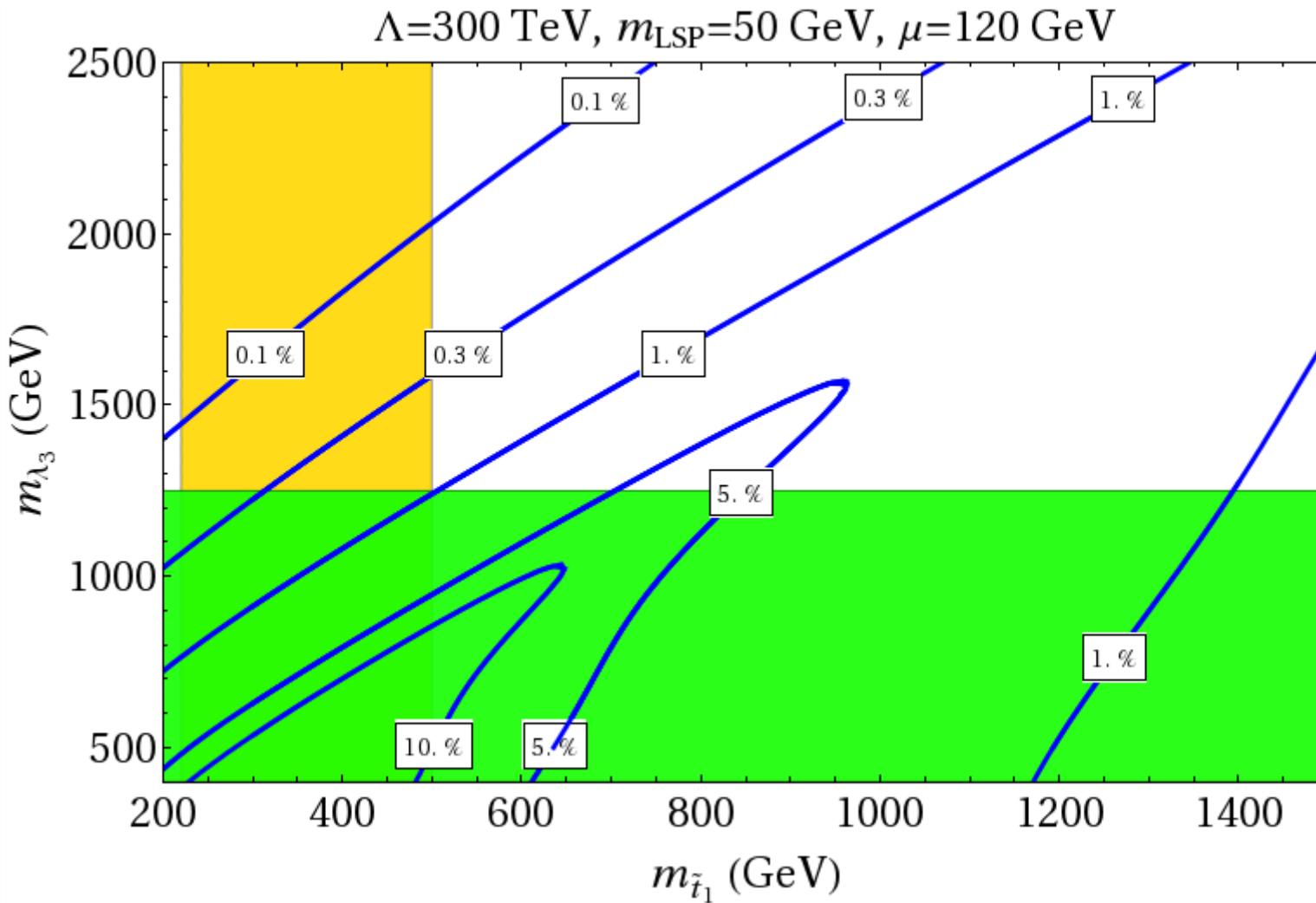
# Testing Natural SUSY



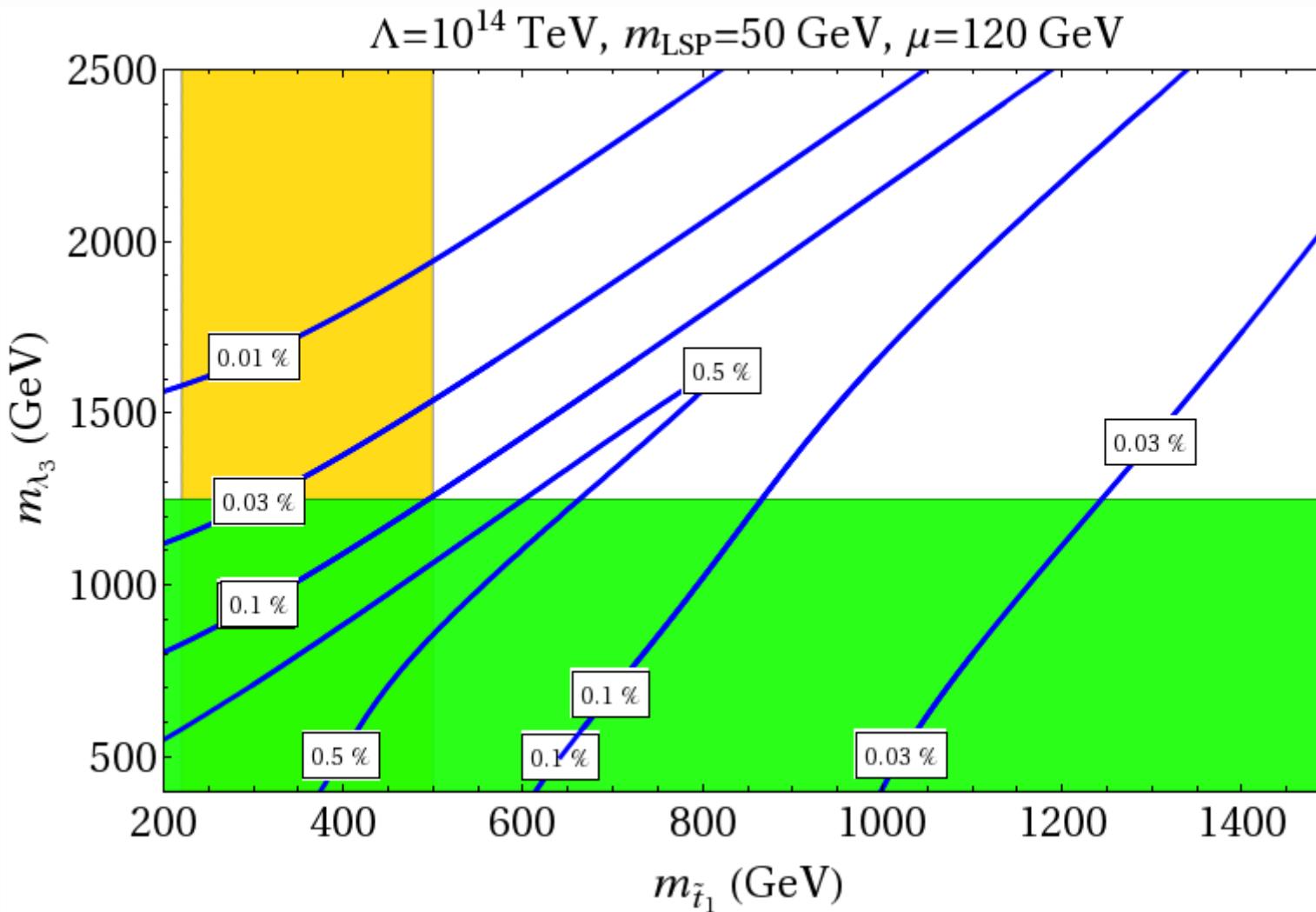
# Natural SUSY – How bad it is?



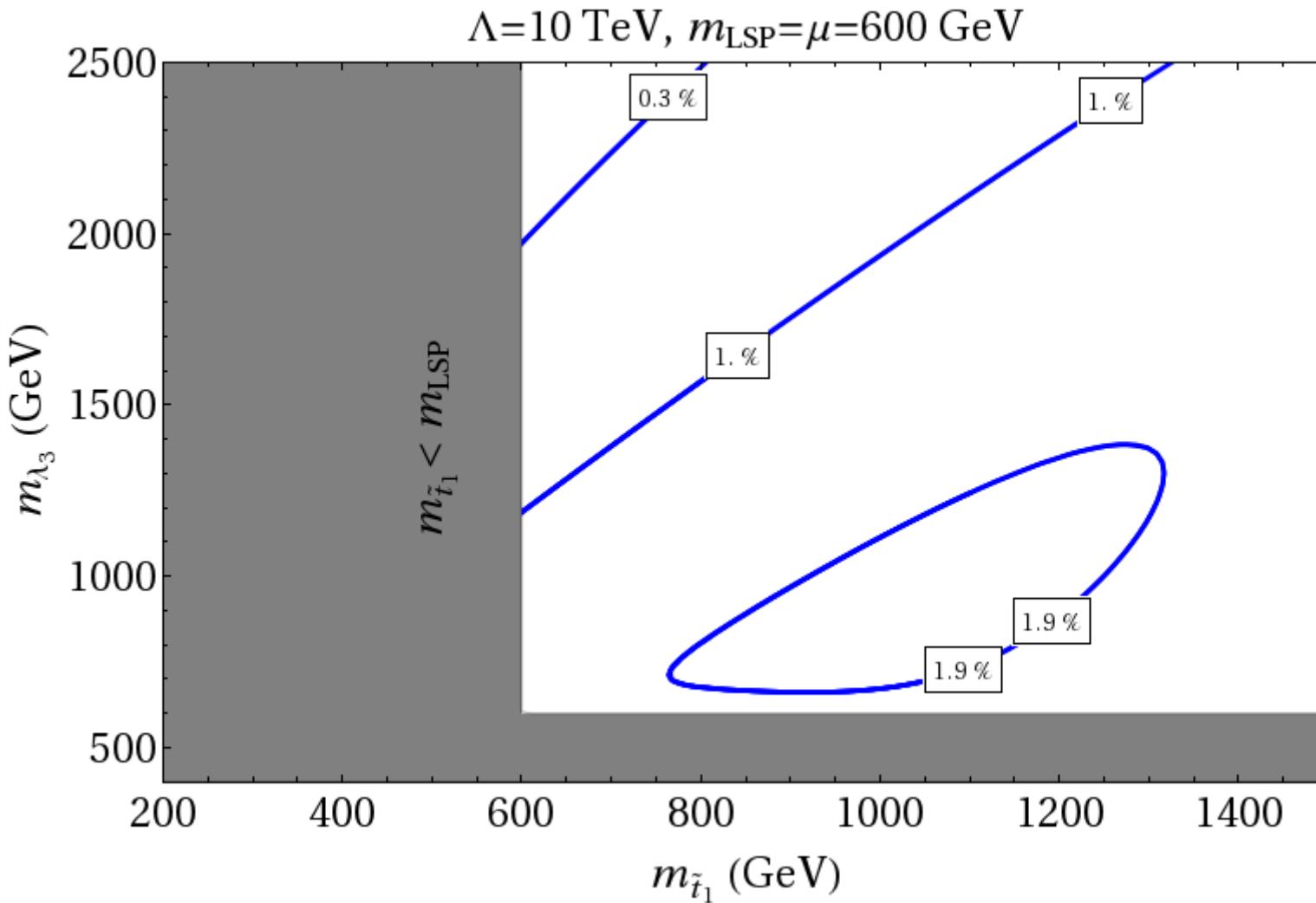
# Natural SUSY – How bad it is?



# Natural SUSY – How bad it is?



# Natural SUSY – How bad it is?



# Alternative SUSY models

- leptonic RPV
- Extra neutralinos (singlino, fotini,...)
- Dirac gauginos
- baryonic RPV
- stealth SUSY
- ...?

# Alternative SUSY models

- leptonic RPV
- Extra neutralinos (singlino, fotini,...)
- Dirac gauginos
- baryonic RPV
- stealth SUSY
- ...?

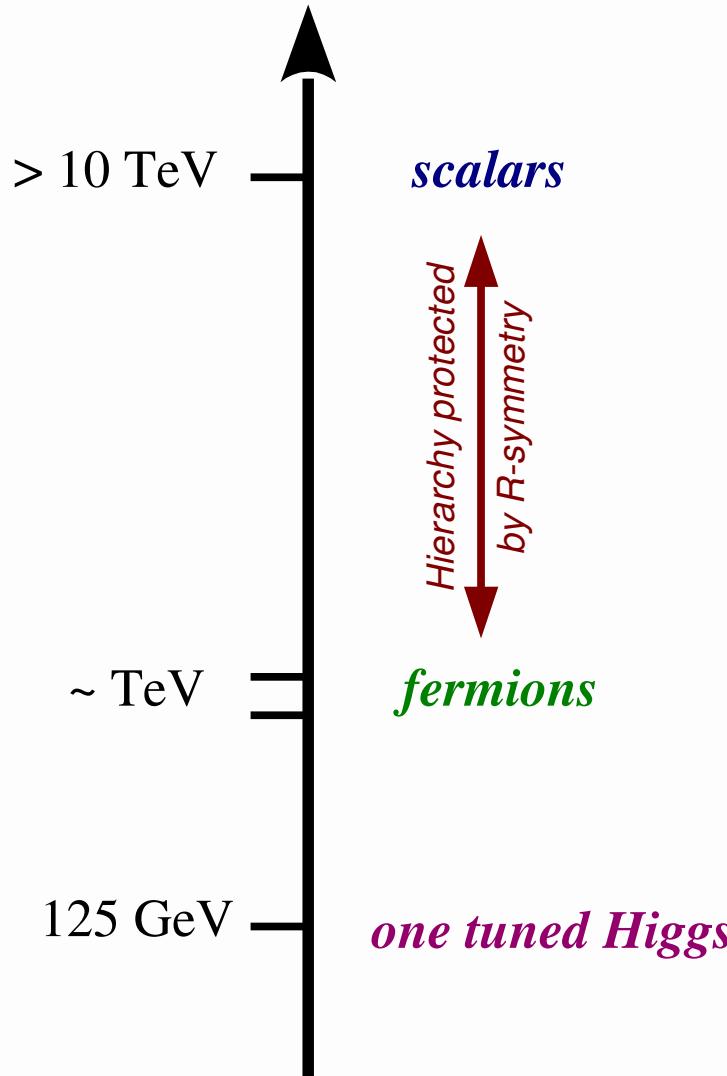
A lot of effort just to hide SUSY, and some degree of tuning often left  
is it really worth it?

time to give up?

# The Alternative: (Mini) Split SUSY

# Split SUSY spectrum

Arkani-Hamed and Dimopoulos '04



*Avoids problems with flavor,  
EDM and collider bounds*

*Preserves successful  
Gauge Coupling Unification  
and Dark Matter*

# “Mini”-Split SUSY

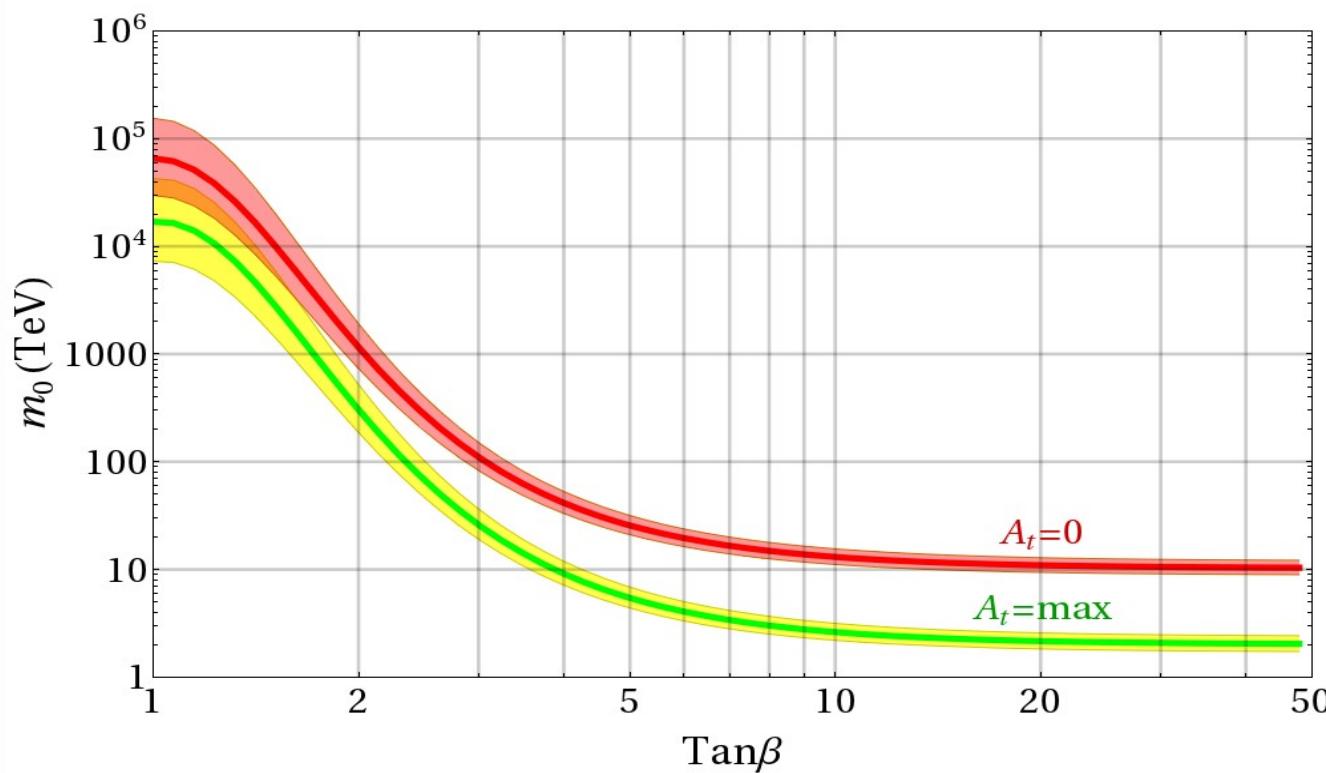
$m_H \sim 125.5$  GeV fixes  $\lambda(m_H)$

$$\text{SUSY fixes } \lambda(\tilde{m}) = \frac{[g^2(\tilde{m}) + g'^2(\tilde{m})]}{4} \cos^2 2\beta$$

# “Mini”-Split SUSY

$m_H \sim 125.5$  GeV fixes  $\lambda(m_H)$

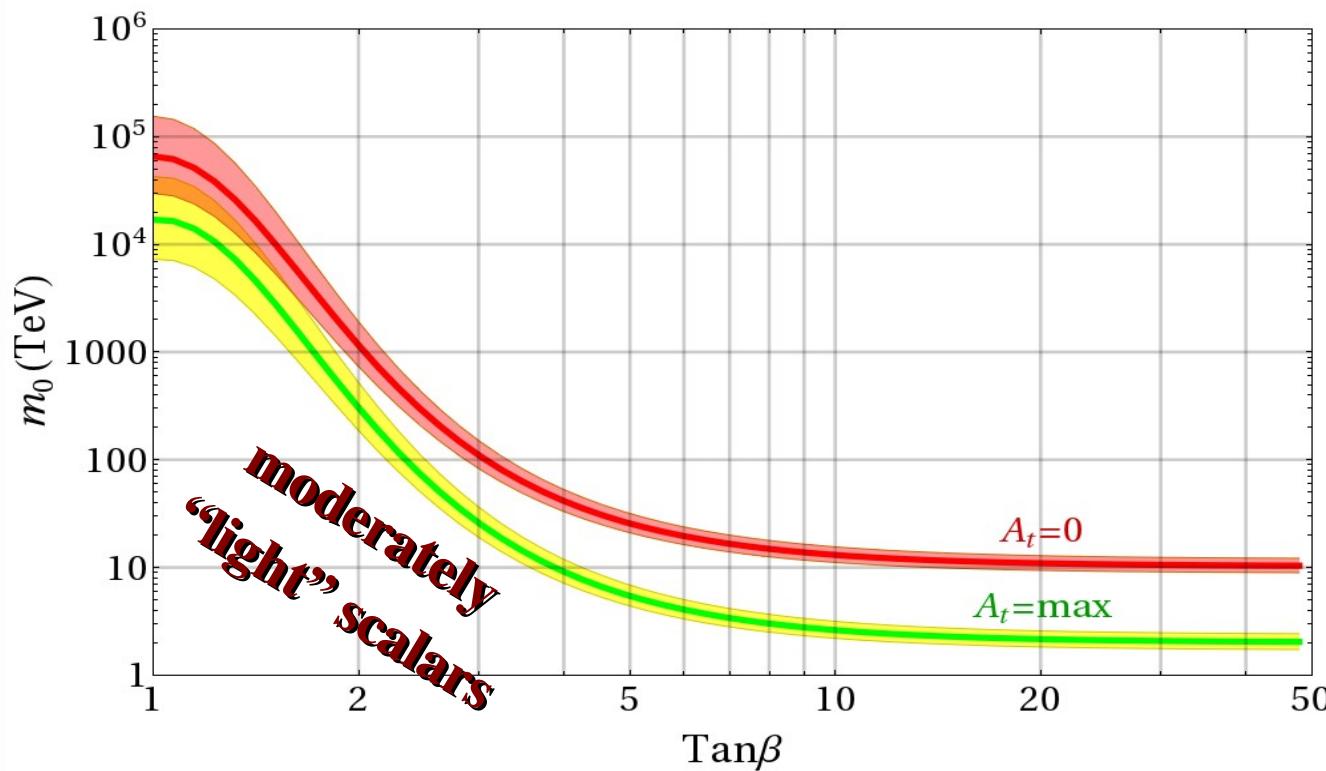
SUSY fixes  $\lambda(\tilde{m}) = \frac{[g^2(\tilde{m}) + g'^2(\tilde{m})]}{4} \cos^2 2\beta$



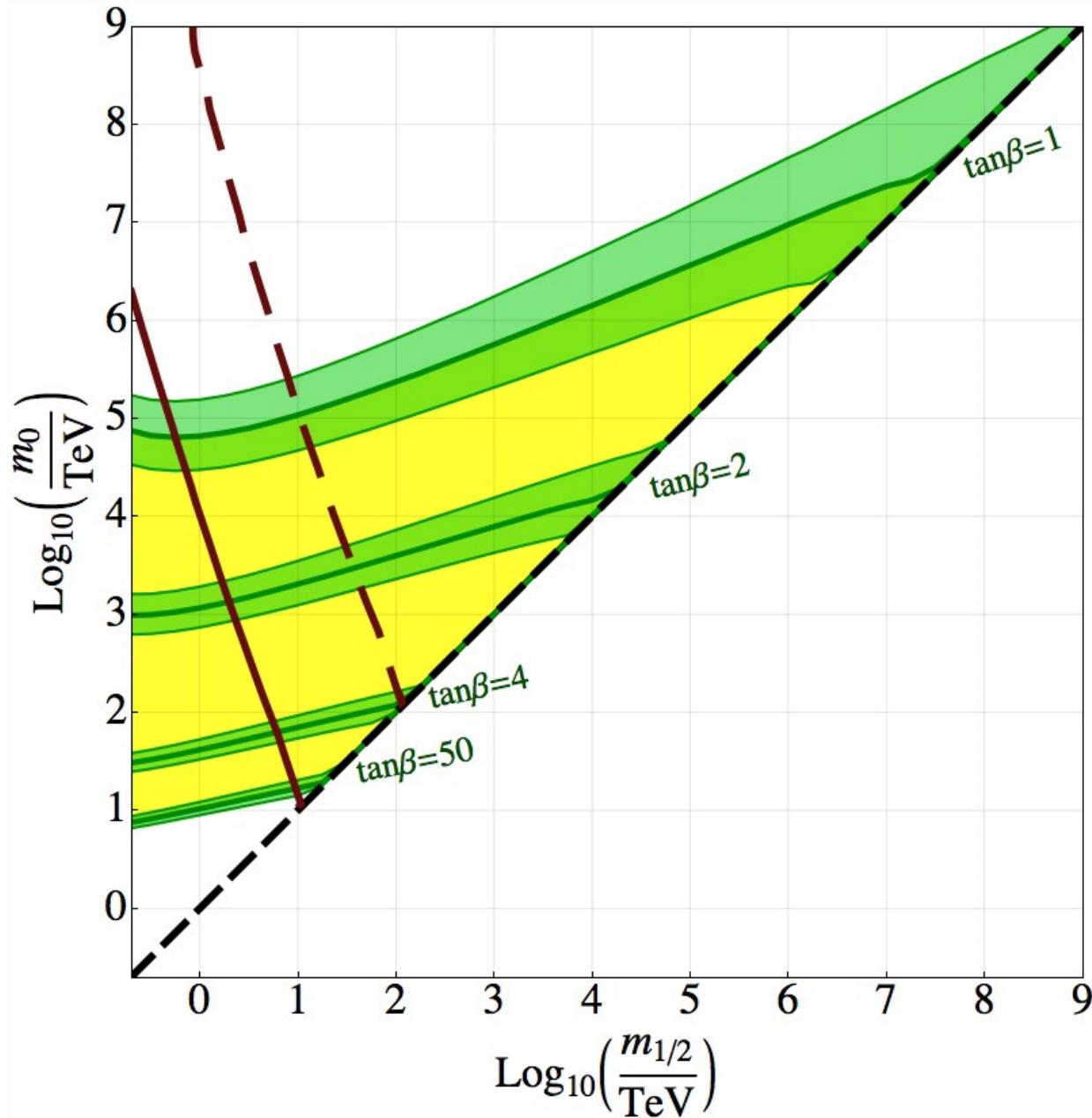
# “Mini”-Split SUSY

$m_H \sim 125.5$  GeV fixes  $\lambda(m_H)$

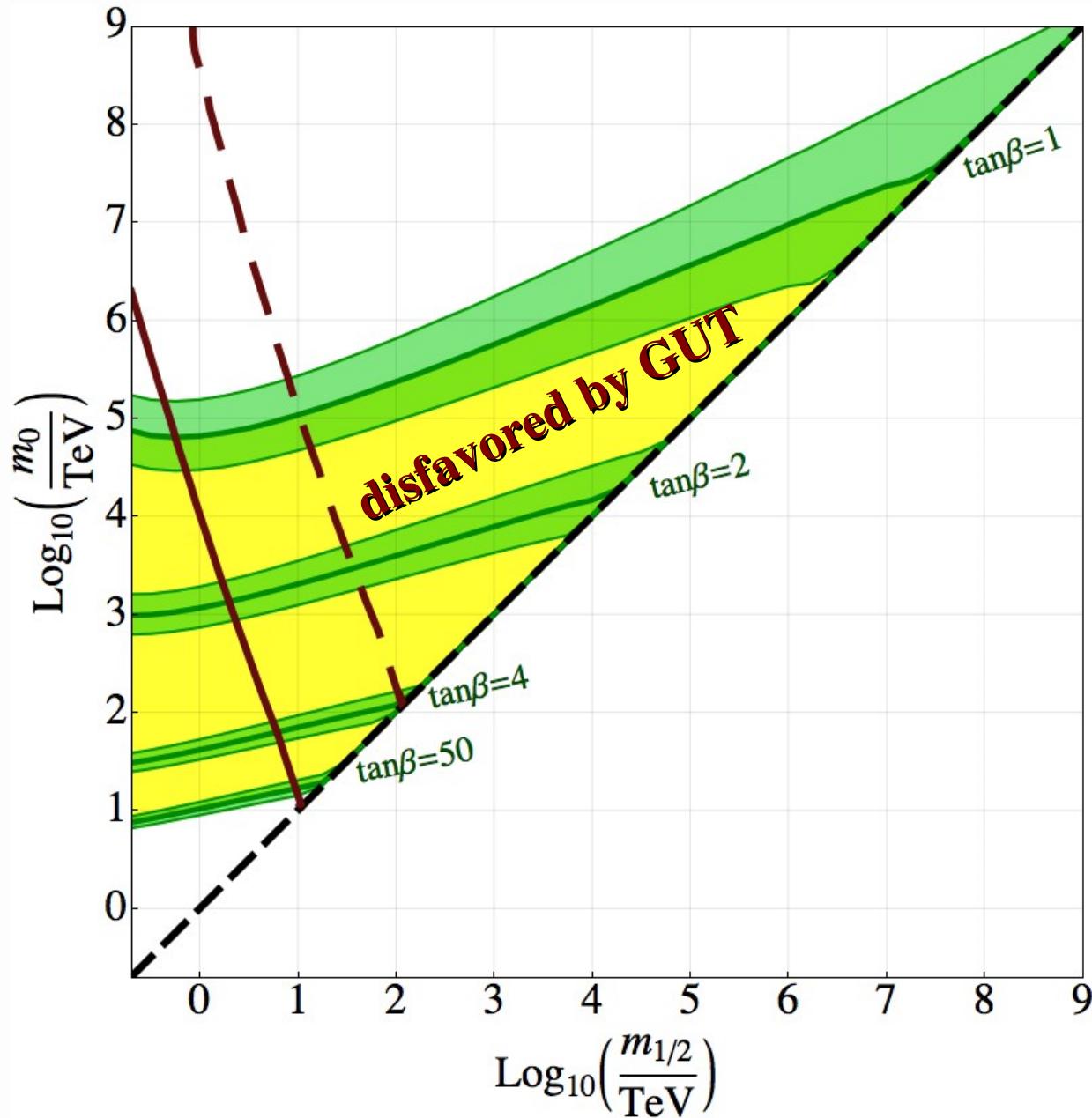
SUSY fixes  $\lambda(\tilde{m}) = \frac{[g^2(\tilde{m}) + g'^2(\tilde{m})]}{4} \cos^2 2\beta$



more in general



more in general

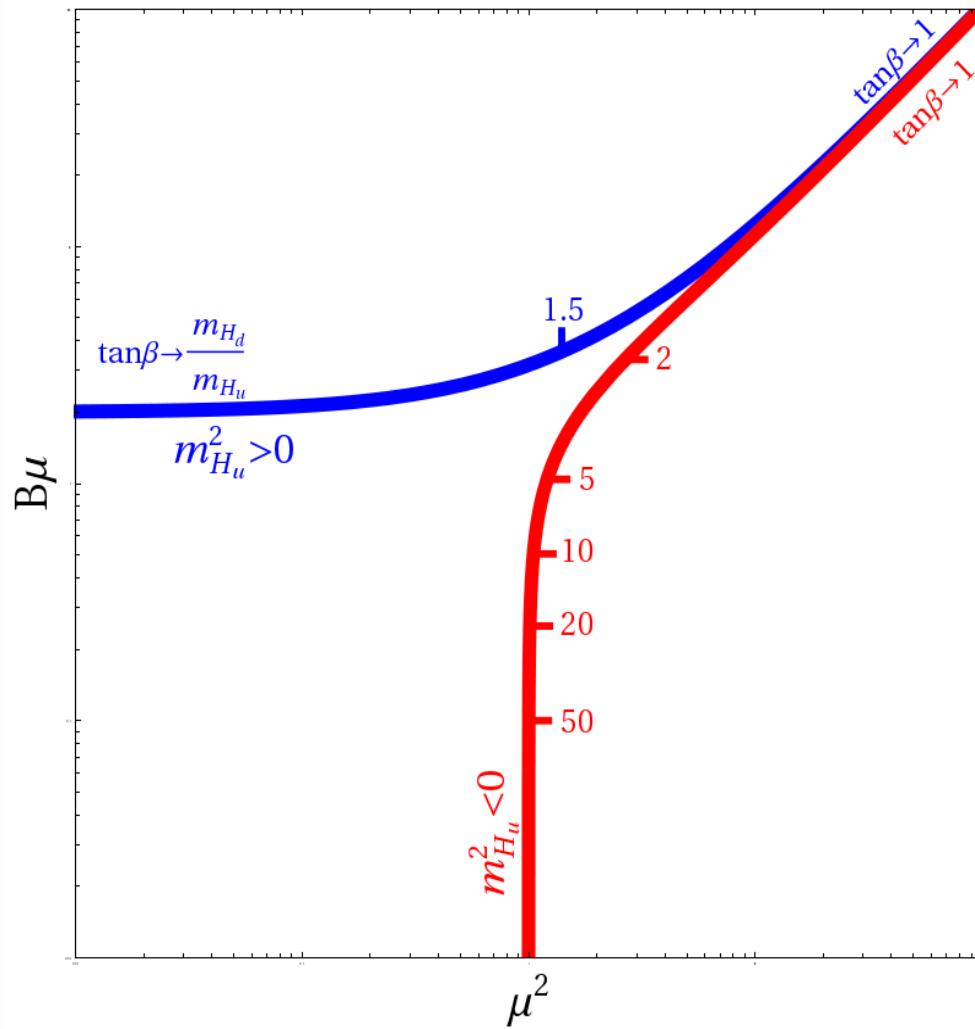


# Tuning the EWSB...

$$\det \begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -B_\mu \\ -B_\mu^* & |\mu|^2 + m_{H_d}^2 \end{pmatrix} \approx 0, \quad \tan \beta = \sqrt{\frac{m_{H_d}^2 + |\mu|^2}{m_{H_u}^2 + |\mu|^2}}$$

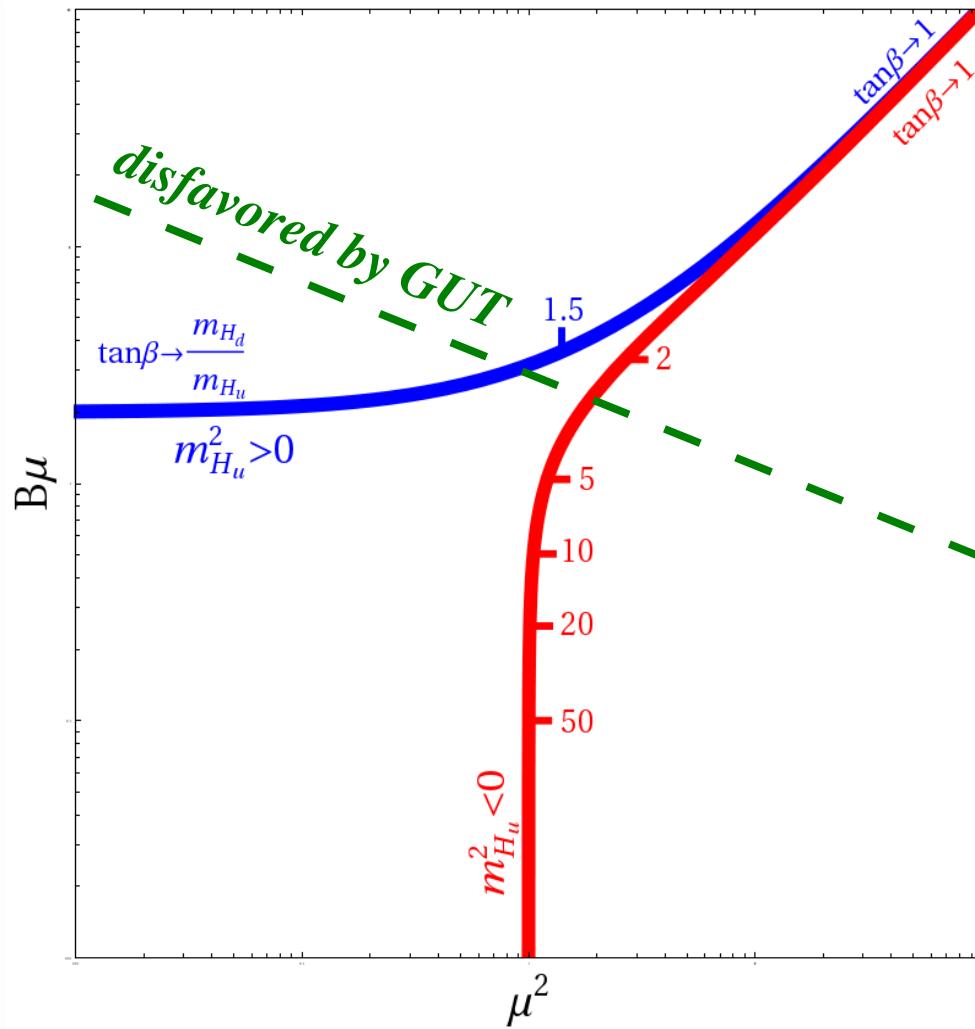
# Tuning the EWSB...

$$\det \begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -B_\mu \\ -B_\mu^* & |\mu|^2 + m_{H_d}^2 \end{pmatrix} \approx 0, \quad \tan \beta = \sqrt{\frac{m_{H_d}^2 + |\mu|^2}{m_{H_u}^2 + |\mu|^2}}$$



# Tuning the EWSB...

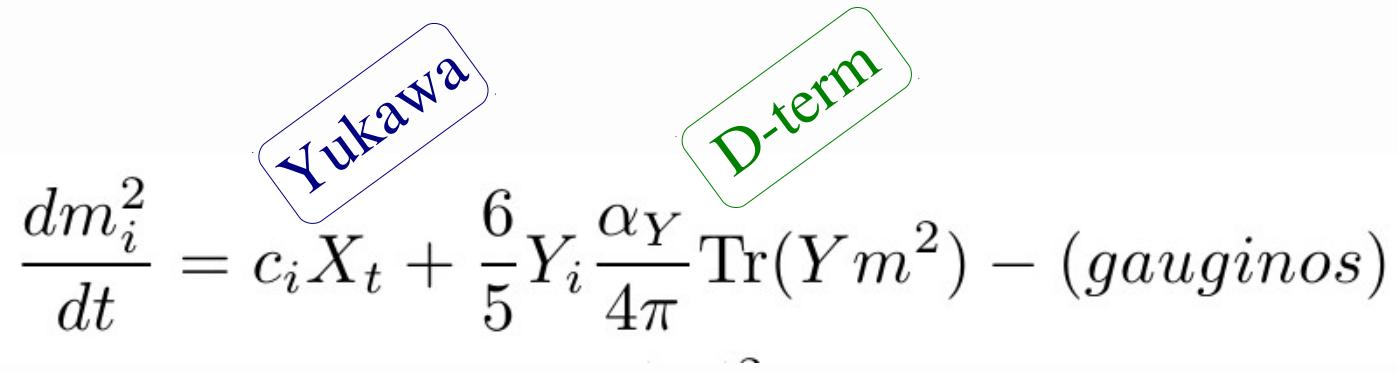
$$\det \begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -B_\mu \\ -B_\mu^* & |\mu|^2 + m_{H_d}^2 \end{pmatrix} \approx 0, \quad \tan \beta = \sqrt{\frac{m_{H_d}^2 + |\mu|^2}{m_{H_u}^2 + |\mu|^2}}$$



# RGE and tachyons in Split

$$\frac{dm_i^2}{dt} = c_i X_t + \frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2) - (\text{gauginos})$$

~



The diagram shows the RGE equation for gaugino mass. The equation is:

$$\frac{dm_i^2}{dt} = c_i X_t + \frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2) - (\text{gauginos})$$

Two terms are highlighted with ovals:

- A blue oval labeled "Yukawa" covers the term  $c_i X_t$ .
- A green oval labeled "D-term" covers the term  $\frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2)$ .

# RGE and tachyons in Split

$$\frac{dm_i^2}{dt} = c_i X_t + \frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2) - \cancel{(gauginos)}$$

Yukawa      D-term

# RGE and tachyons in Split

$$\frac{dm_i^2}{dt} = c_i X_t + \frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2) - (\cancel{\text{gauginos}})$$

↓

**=0 if  $m_{Hu} = m_{Hd}$  + GUT B.C.**

Yukawa      D-term

# RGE and tachyons in Split

$$\frac{dm_i^2}{dt} = c_i X_t + \frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2) - (\text{gauginos})$$

*Yukawa*      *D-term*

= 0 if  $m_{Hu} = m_{Hd}$  + GUT B.C.

$$X_t = \frac{|y_t|^2}{8\pi^2} (m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2)$$

The diagram illustrates the derivation of the equation for  $X_t$ . It starts with the RGE equation for the mass squared of a scalar field  $i$ , which includes terms from the Yukawa and D-term interactions. The D-term interaction involves the trace of the Yukawa matrix  $Y$  times the square of the scalar field. A large red 'X' is drawn over the 'gauginos' term, indicating it is not relevant for the current analysis. Below the equation, the result is given as zero if the masses of the up-type Higgs ( $H_u$ ) and down-type Higgs ( $H_d$ ) are equal, plus the GUT boundary condition. The final expression for  $X_t$  is given as the ratio of the absolute value of the Yukawa coupling  $|y_t|^2$  to  $8\pi^2$  times the sum of the squares of the masses of the up-type Higgs and the two components of the stop squarks ( $\tilde{t}_L$  and  $\tilde{t}_R$ ).

# RGE and tachyons in Split

$$\frac{dm_i^2}{dt} = c_i X_t + \frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2) - (\cancel{\text{gauginos}})$$

Yukawa      D-term

$= 0 \text{ if } m_{Hu} = m_{Hd} + \text{GUT B.C.}$

$$X_t = \frac{|y_t|^2}{8\pi^2} (m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2)$$

IR fixed point:  $X_t \rightarrow 0 \Rightarrow$  tachyon

# RGE and tachyons in Split

$$\frac{dm_i^2}{dt} = c_i X_t + \frac{6}{5} Y_i \frac{\alpha_Y}{4\pi} \text{Tr}(Y m^2) - (\text{gauginos})$$

Yukawa
D-term

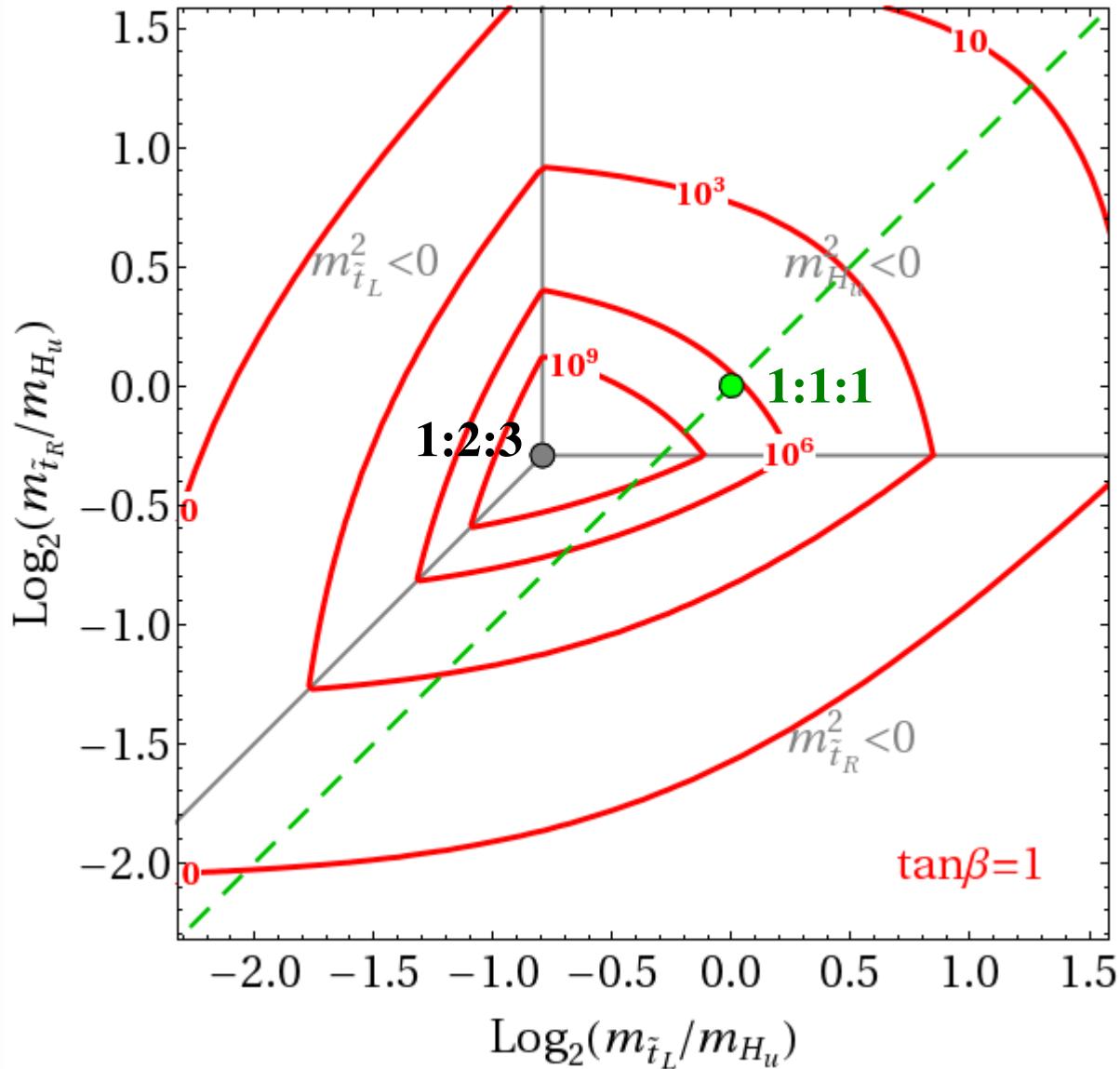
$= 0 \text{ if } m_{H_u} = m_{H_d} + \text{GUT B.C.}$

$$X_t = \frac{|y_t|^2}{8\pi^2} (m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2)$$

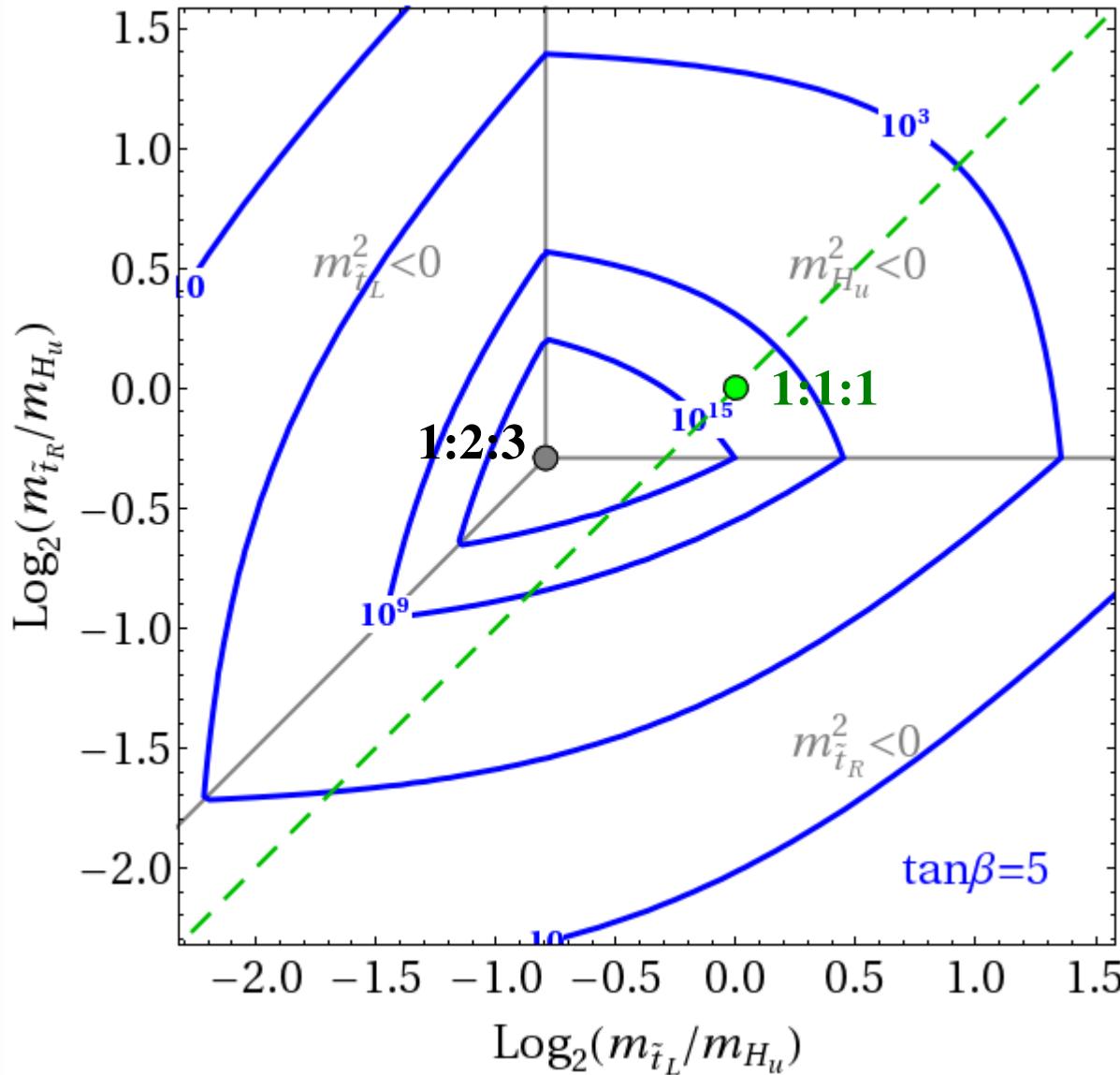
IR fixed point:  $X_t \rightarrow 0 \Rightarrow$  tachyon

UV fixed point:  $m_{\tilde{t}_L}^2 : m_{\tilde{t}_R}^2 : m_{H_u}^2 = 1 : 2 : 3$

# How much you can run...



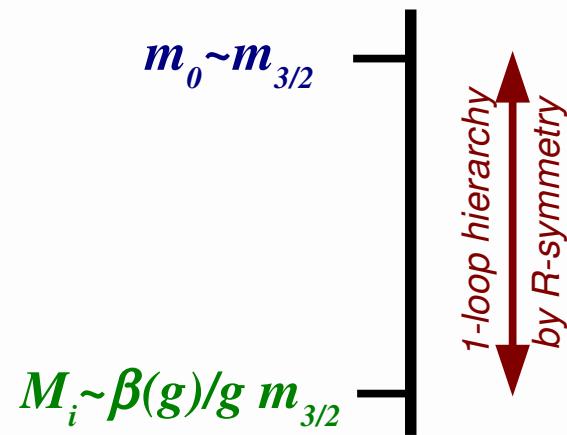
# How much you can run...



# Examples

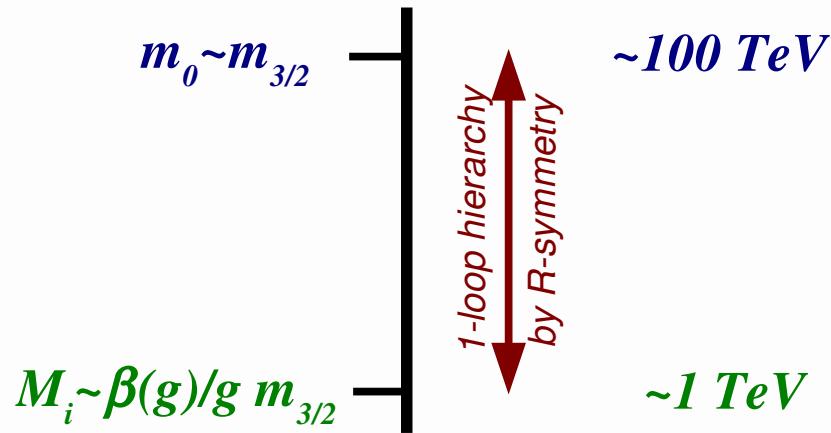
# Anomaly Mediation

*Giudice, Luty, Murayama, Rattazzi '98*



# Anomaly Mediation

*Giudice, Luty, Murayama, Rattazzi '98*

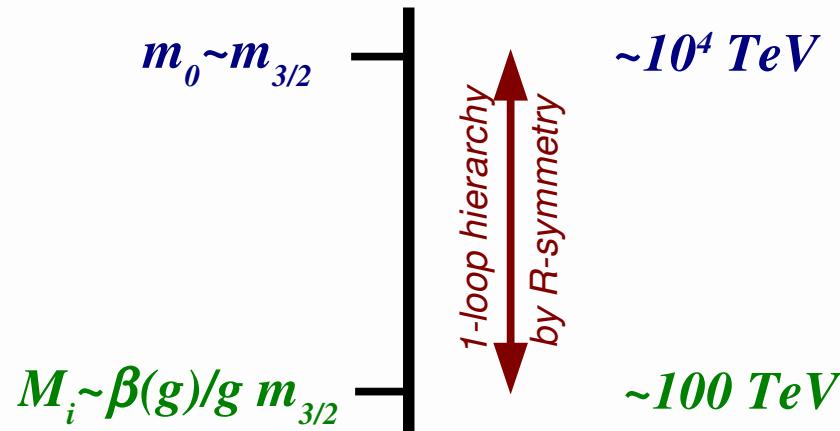


## Light AMSB

- $\mu^2 \sim B_\mu \sim m_{3/2}^2$   
Giudice-Masiero or explicit  $\mu$ -term
- $\tan\beta \sim 4$
- $m_{H_u}^2$  can run negative
- Light gauginos ( $W$ - or  $B$ -ino LSP)
- GUT still OK
- Flavor Problem

# Anomaly Mediation

*Giudice, Luty, Murayama, Rattazzi '98*



## Heavy AMSB

- $B_\mu \sim m_{3/2}^2 \gg \mu^2$   
Giudice-Masiero-ish
- $\tan\beta \sim 1$
- $m_{Hu}^2 > 0$
- Heavy gauginos  
(higgsinos can be light)
- GUT OK
- No Flavor Problem

# Gauge Mediation

Hidden assumption of natural GM:

Efficient breaking of R-symmetry in SUSY breaking sector

# Gauge Mediation

Hidden assumption of natural GM:

Efficient breaking of R-symmetry in SUSY breaking sector

Very easy to get parametrically lighter gauginos:

- by suppression of R-symmetry breaking in the hidden sector
- by accidental cancellations such as gaugino screening

*Arkani-Hamed, Giudice, Luty, Rattazzi '98*

# Gauge Mediation

Hidden assumption of natural GM:

Efficient breaking of R-symmetry in SUSY breaking sector

Very easy to get parametrically lighter gauginos:

- by suppression of R-symmetry breaking in the hidden sector
- by accidental cancellations such as gaugino screening

*Arkani-Hamed, Giudice, Luty, Rattazzi '98*

*Example:*  $W = M_R (\Phi_1 \bar{\Phi}_1 + \Phi_2 \bar{\Phi}_2) + X \Phi_1 \bar{\Phi}_2$        $X = M + F\theta^2$

$$m_{\lambda_i} = \frac{\alpha_i}{6\pi} \frac{M}{M_R} \frac{F^3}{M_R^5} + \mathcal{O}\left(\frac{M^3}{M_R^3} \frac{F^3}{M_R^5}, \frac{F^5}{M_R^9}\right)$$

# Gauge Mediation

Hidden assumption of natural GM:

Efficient breaking of R-symmetry in SUSY breaking sector

Very easy to get parametrically lighter gauginos:

- by suppression of R-symmetry breaking in the hidden sector
- by accidental cancellations such as gaugino screening

*Arkani-Hamed, Giudice, Luty, Rattazzi '98*

*Example:*  $W = M_R (\Phi_1 \bar{\Phi}_1 + \Phi_2 \bar{\Phi}_2) + X \Phi_1 \bar{\Phi}_2$        $X = M + F\theta^2$

$$m_{\lambda_i} = \frac{\alpha_i}{6\pi} \frac{M}{M_R} \frac{F^3}{M_R^5} + \mathcal{O}\left(\frac{M^3}{M_R^3} \frac{F^3}{M_R^5}, \frac{F^5}{M_R^9}\right)$$

- Advantage over AMGB: no flavor problem
- Advantages over natural GM:
  - gravitino can be heavier than LSP  $\rightarrow$  thermal dark matter
  - $\mu$ - $B\mu$  no longer a problem

# U(1)' Split SUSY

**MSSM + U(1)':**

$$U(1)' = \cos(\theta) U(1)_{B-L} + \sin(\theta) U(1)_Y$$

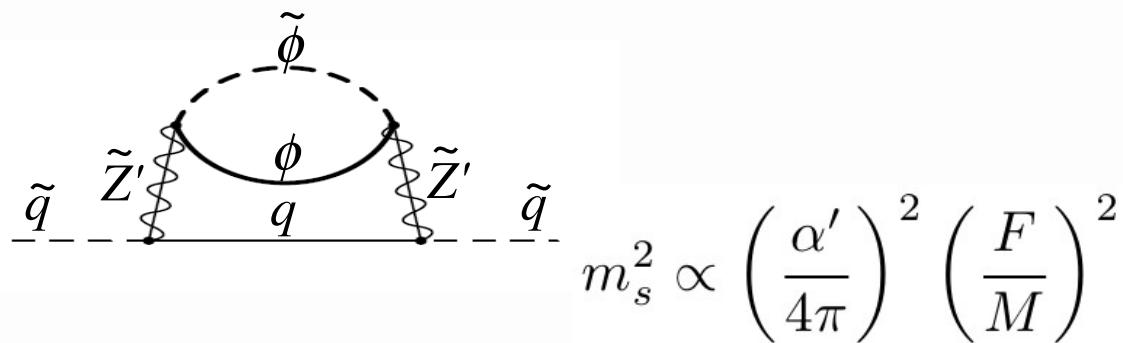
SUSY breaking mediated by U(1)'  
( $\Leftrightarrow$  mediators only charged under  $B-L$ )

# U(1)' Split SUSY

**MSSM + U(1)':**

$$U(1)' = \cos(\theta) U(1)_{B-L} + \sin(\theta) U(1)_Y$$

SUSY breaking mediated by U(1)'  
( $\Leftrightarrow$  mediators only charged under  $B-L$ )



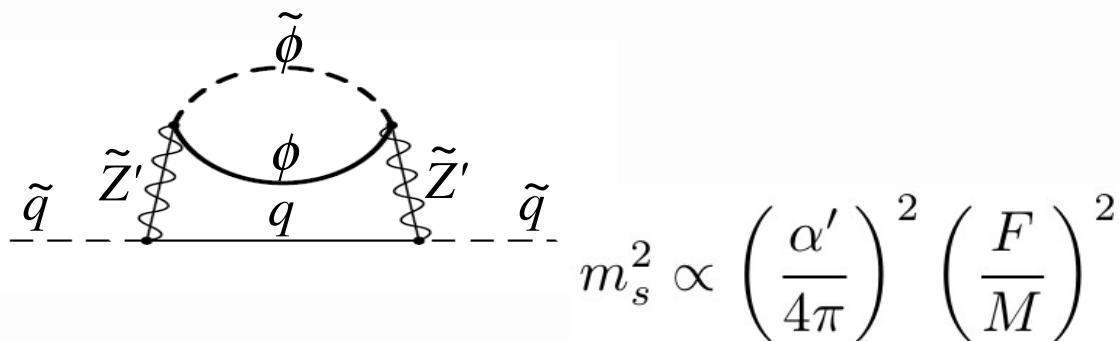
$$m_s^2 \propto \left(\frac{\alpha'}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

# U(1)' Split SUSY

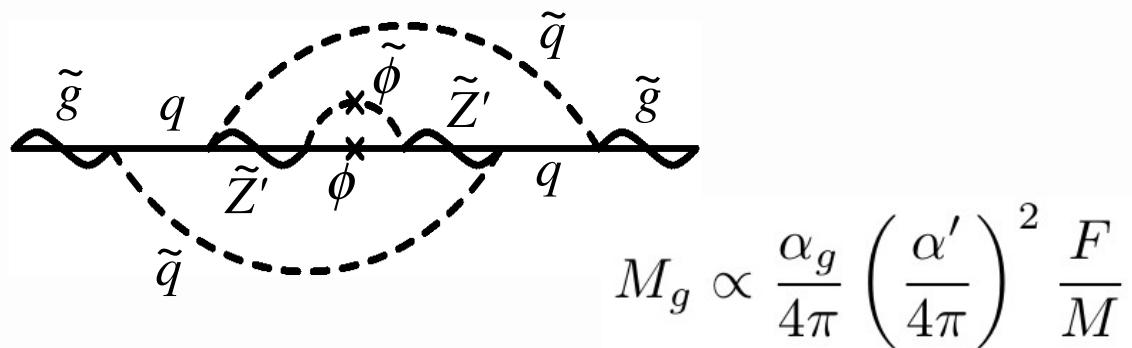
**MSSM + U(1)':**

$$U(1)' = \cos(\theta) U(1)_{B-L} + \sin(\theta) U(1)_Y$$

SUSY breaking mediated by U(1)'  
 ( $\Leftrightarrow$  mediators only charged under  $B-L$ )



$$m_s^2 \propto \left(\frac{\alpha'}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$



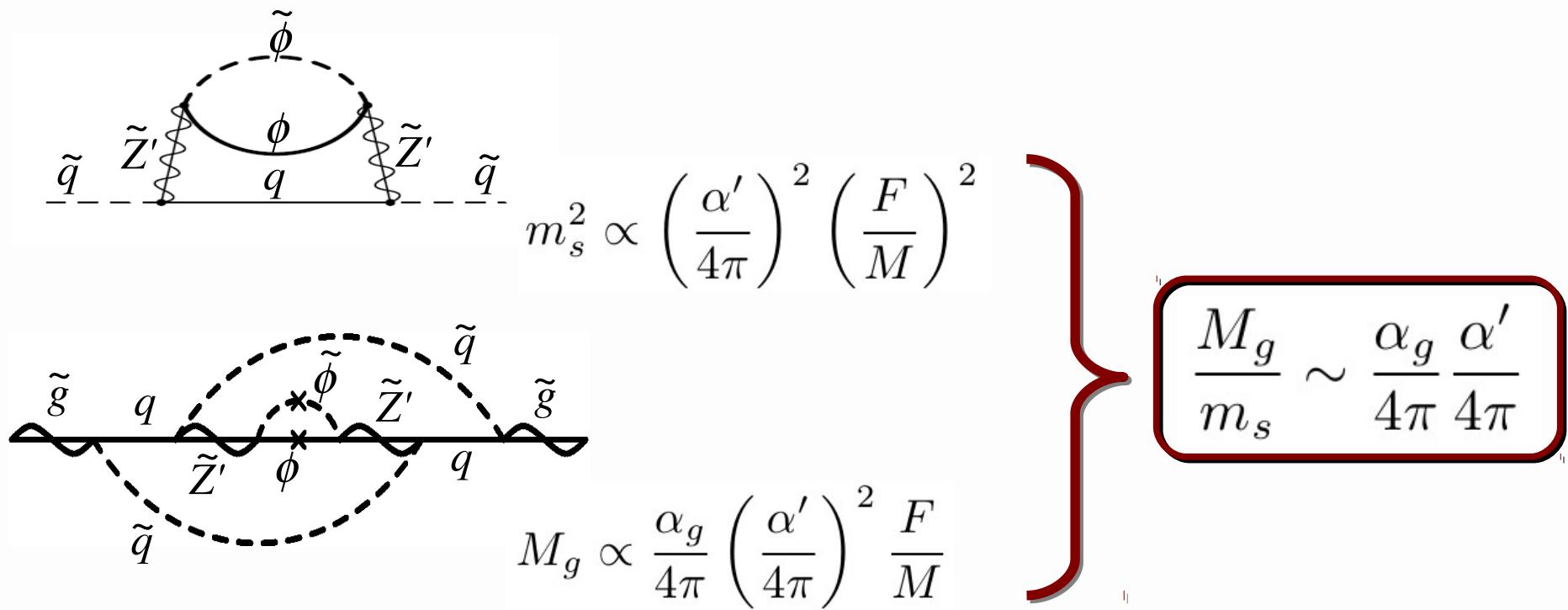
$$M_g \propto \frac{\alpha_g}{4\pi} \left(\frac{\alpha'}{4\pi}\right)^2 \frac{F}{M}$$

# U(1)' Split SUSY

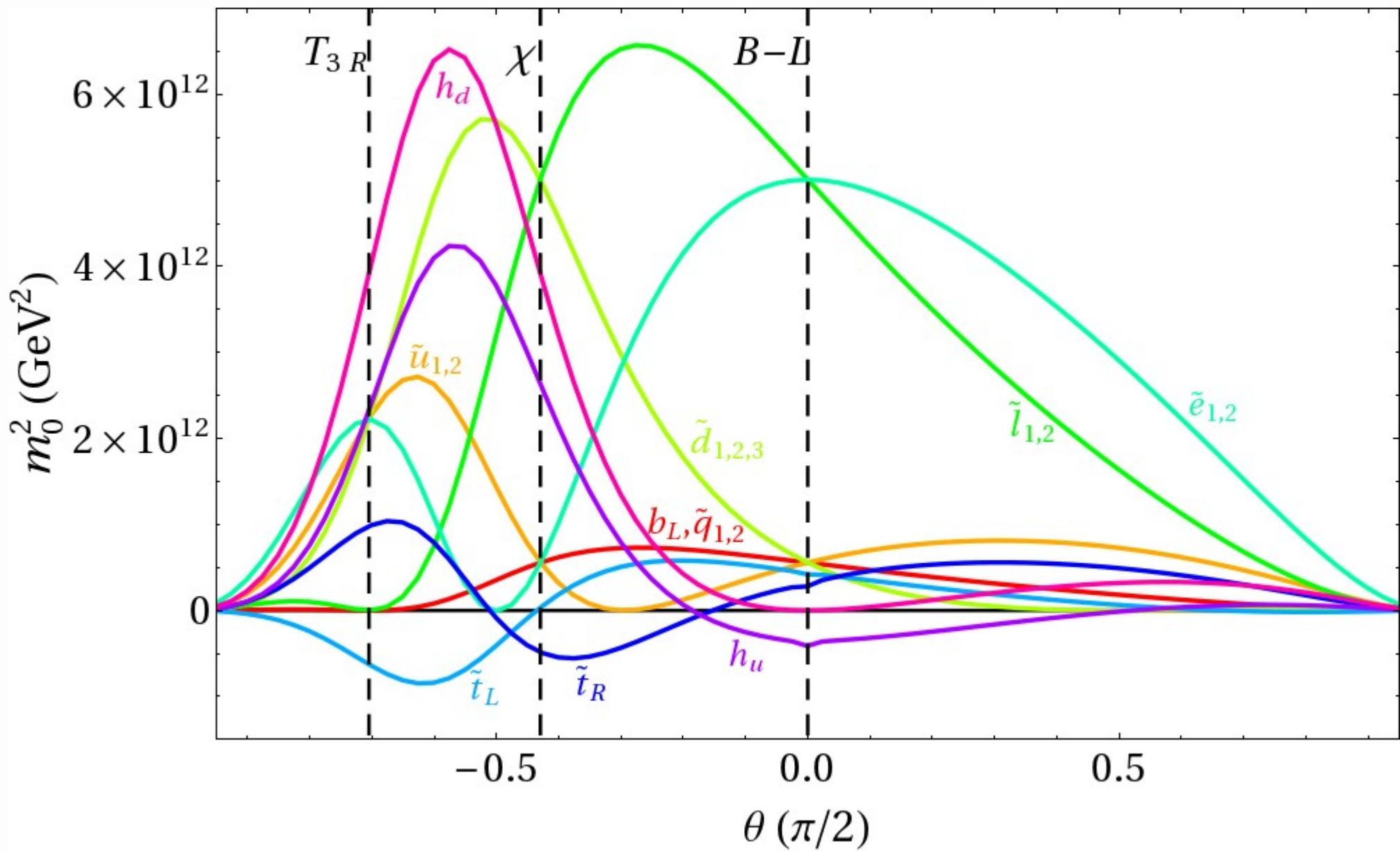
**MSSM + U(1)':**

$$U(1)' = \cos(\theta) U(1)_{B-L} + \sin(\theta) U(1)_Y$$

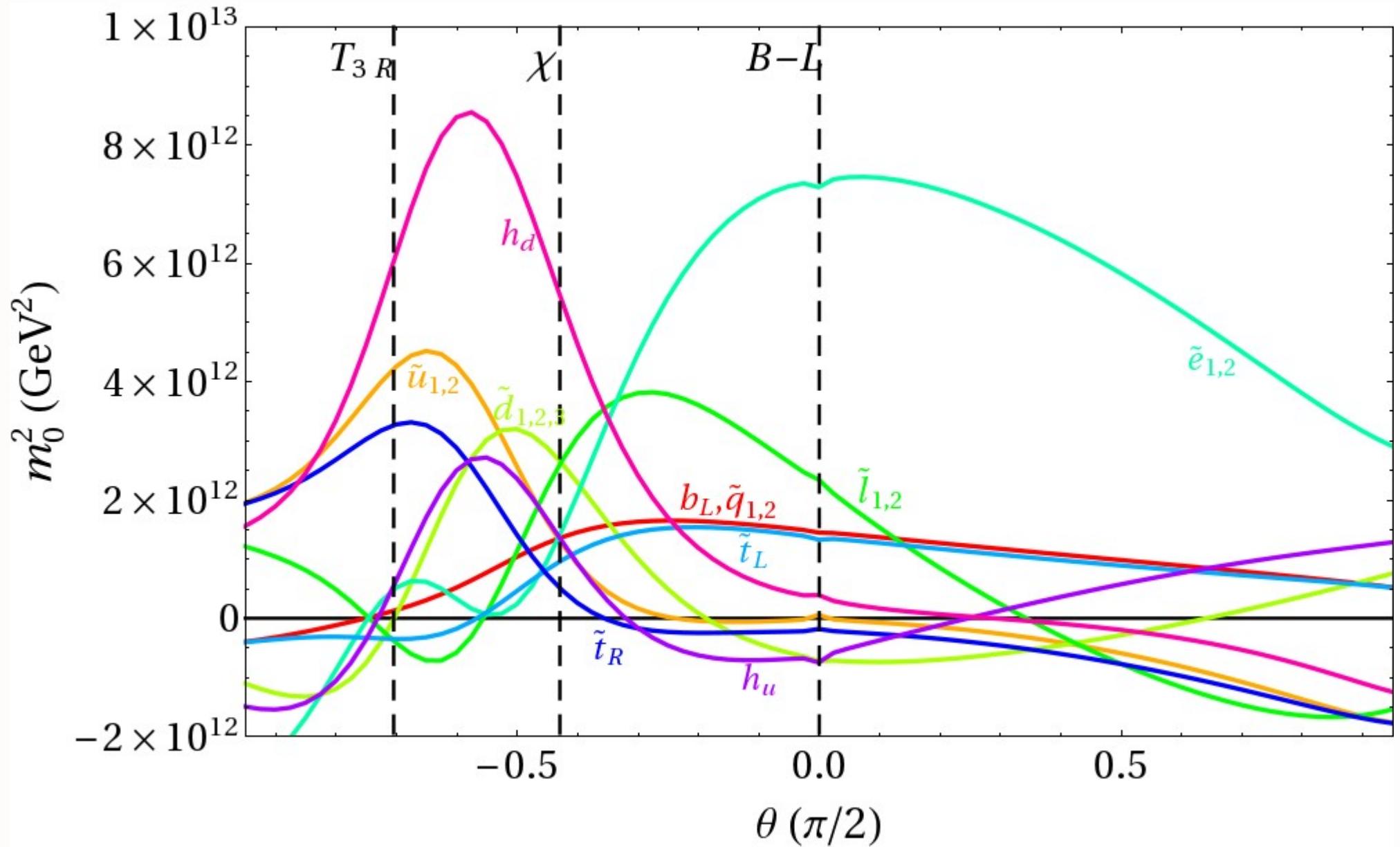
SUSY breaking mediated by U(1)'  
 ( $\Leftrightarrow$  mediators only charged under  $B-L$ )



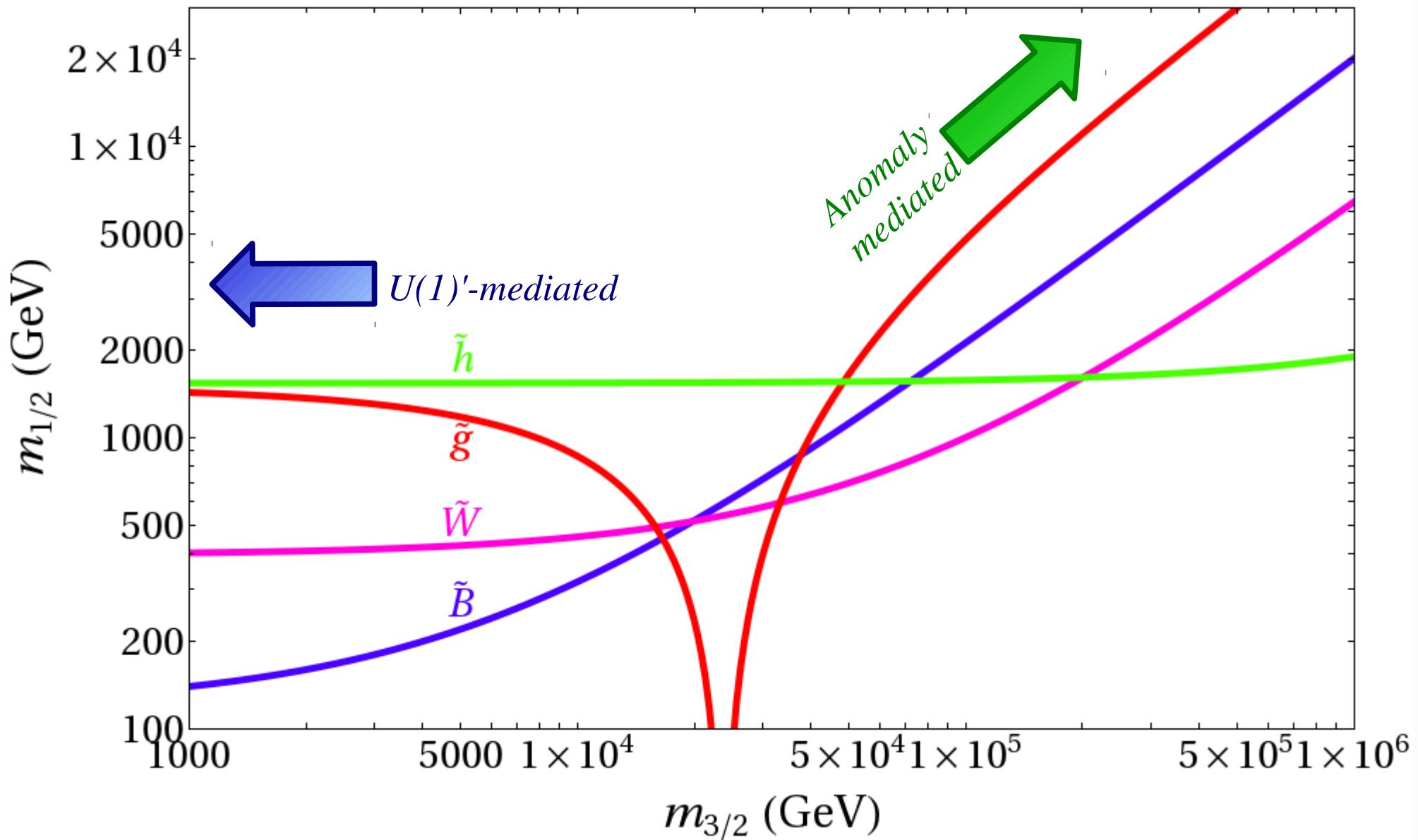
# $U(1)'$ spectrum with no D-terms



# $U(1)'$ spectrum with D-terms

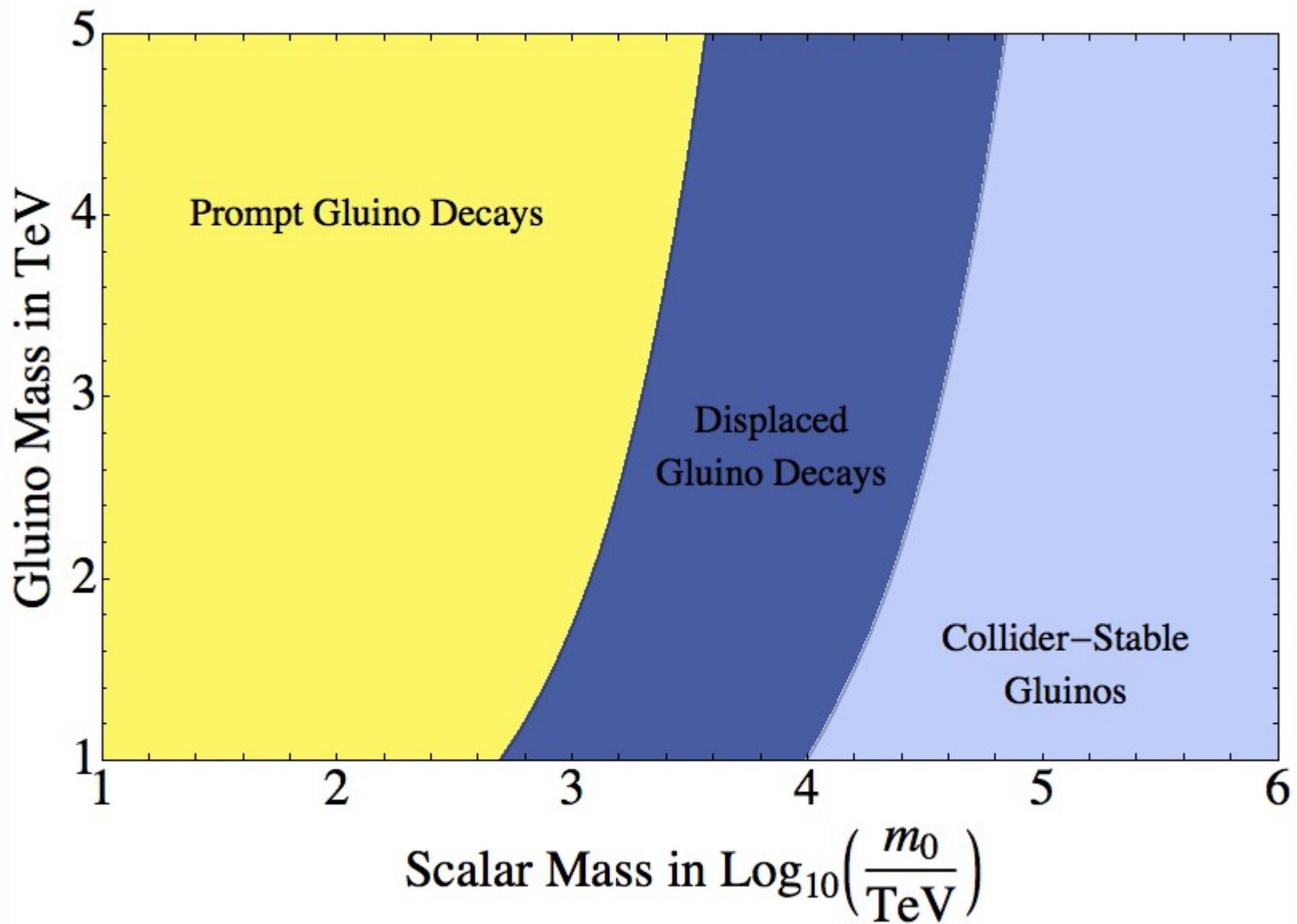


# $U(1)'$ fermion spectrum

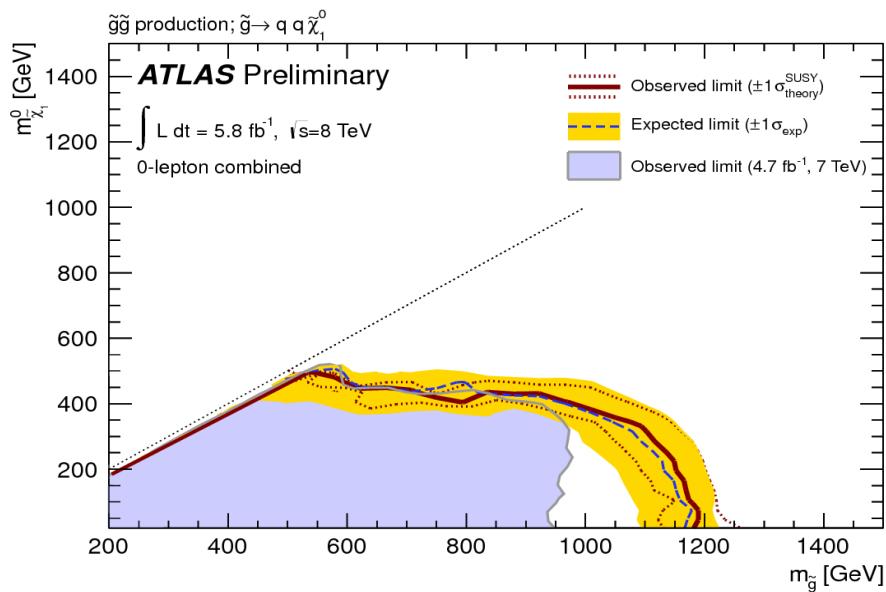


# Phenomenology

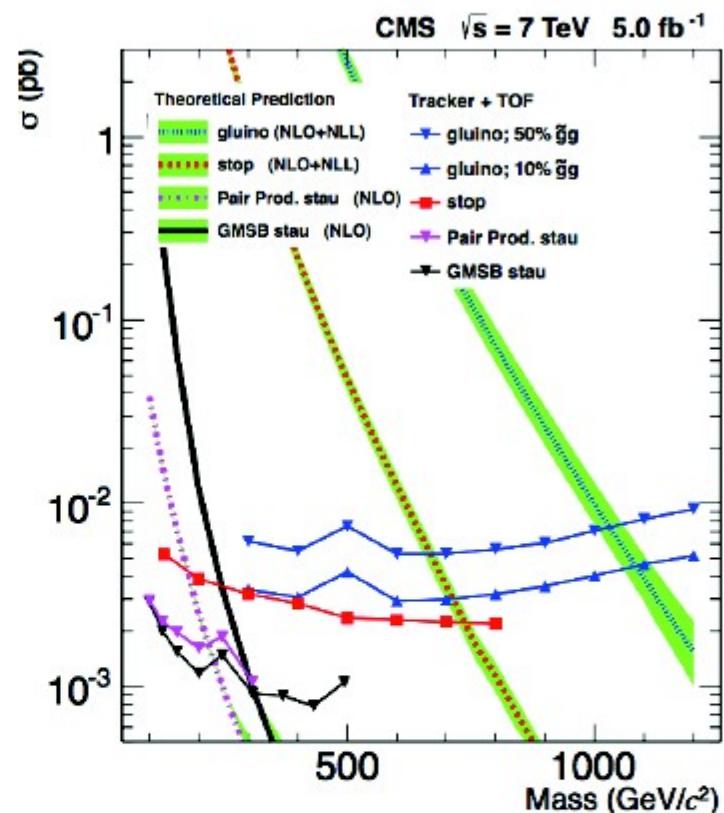
# Phenomenology: Gluino



# Gluino Bounds from the LHC



For prompt or  
slightly displaced gluinos



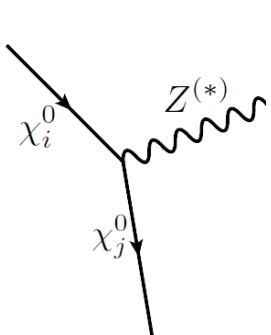
For collider “stable” gluinos

$M_{\text{gluino}} > 1 \text{ TeV}$  for split gluino

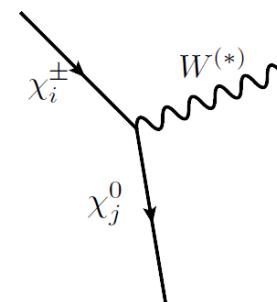
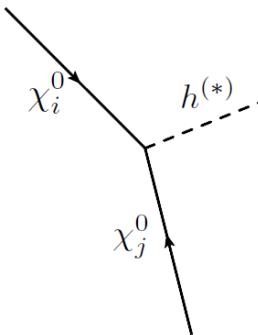
2.5 TeV to 3 TeV ultimate reach for split gluino

# Phenomenology: EWinos

Neutralino decays

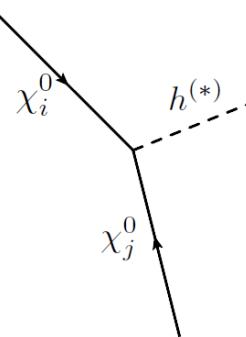
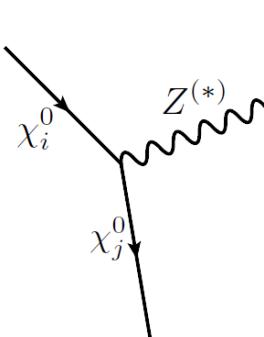


Chargino decays

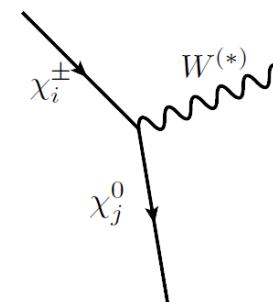


# Phenomenology: EWinos

Neutralino decays



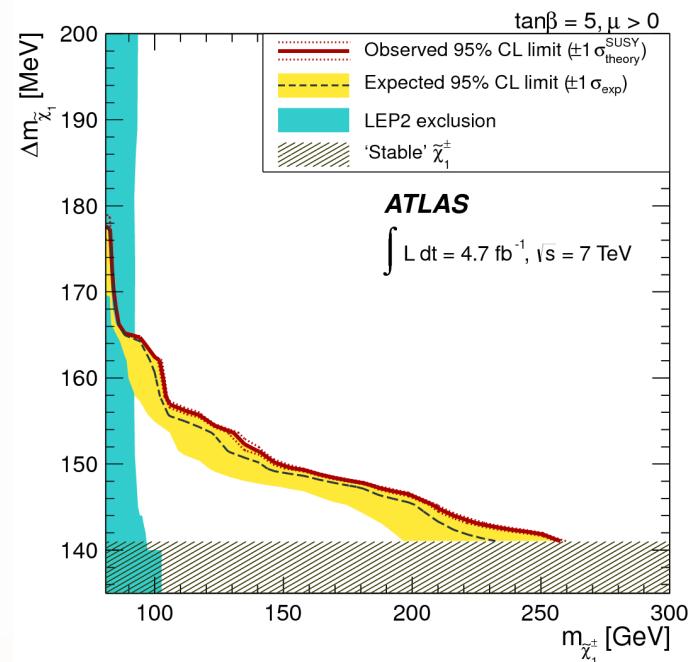
Chargino decays



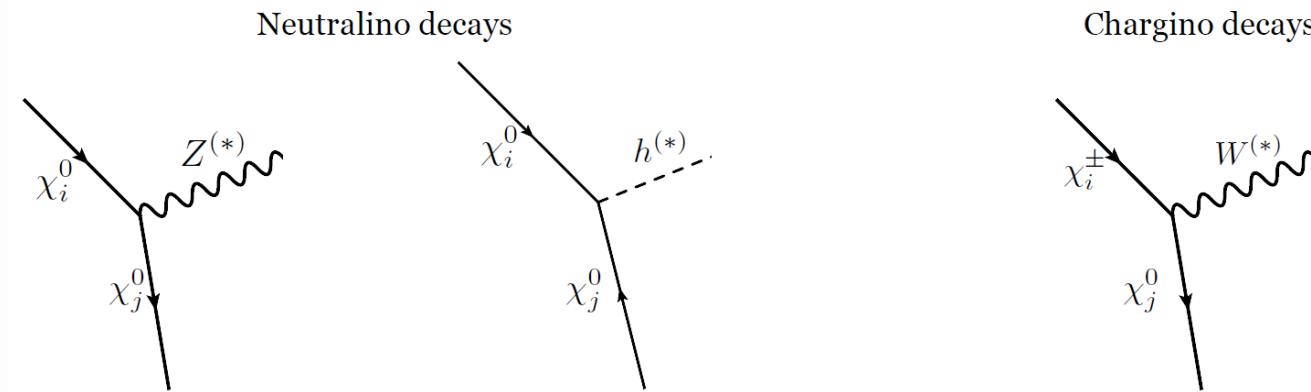
## Heavy Higgsinos:

Bino LSP :  $\chi^\pm\chi^0 \rightarrow Wh + \text{MET}$     $\chi^+\chi^- \rightarrow WW + \text{MET}$

Wino LSP:  $\Delta m \sim 170 \text{ MeV} \rightarrow 10\text{cm} \text{ stubs (trig. on ISR+MET)}$



# Phenomenology: EWinos



## Heavy Higgsinos:

Bino LSP :  $\chi^\pm\chi^0 \rightarrow Wh+\text{MET}$     $\chi^+\chi^- \rightarrow WW+\text{MET}$

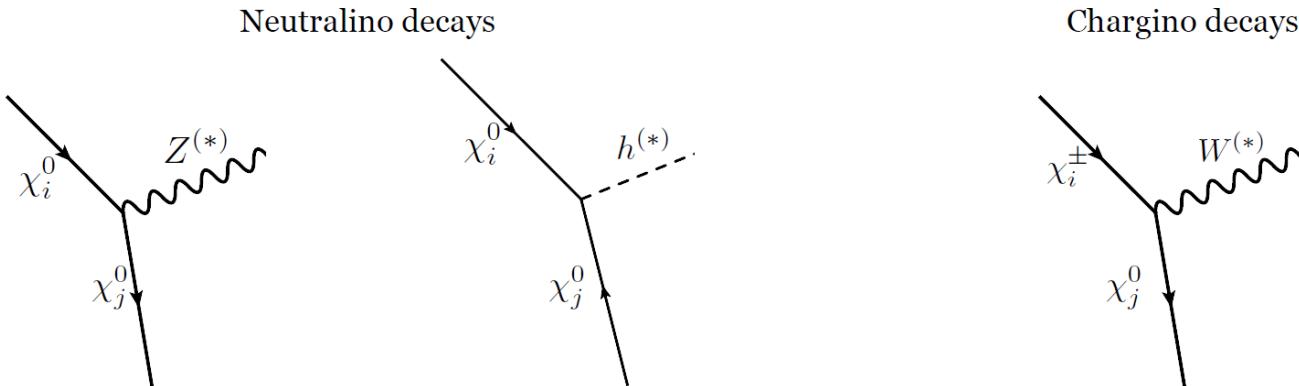
Wino LSP:  $\Delta m \sim 170 \text{ MeV} \rightarrow 10\text{cm stubs (trig. on ISR+MET)}$

## Light Higgsinos:

Usual EWino searches

Possibility of testing all couplings and measuring  $\tan\beta$  at LC

# Phenomenology: EWinos



## Heavy Higgsinos:

Bino LSP :  $\chi^\pm\chi^0 \rightarrow Wh + \text{MET}$     $\chi^+\chi^- \rightarrow WW + \text{MET}$

Wino LSP:  $\Delta m \sim 170 \text{ MeV} \rightarrow 10\text{cm stubs (trig. on ISR+MET)}$

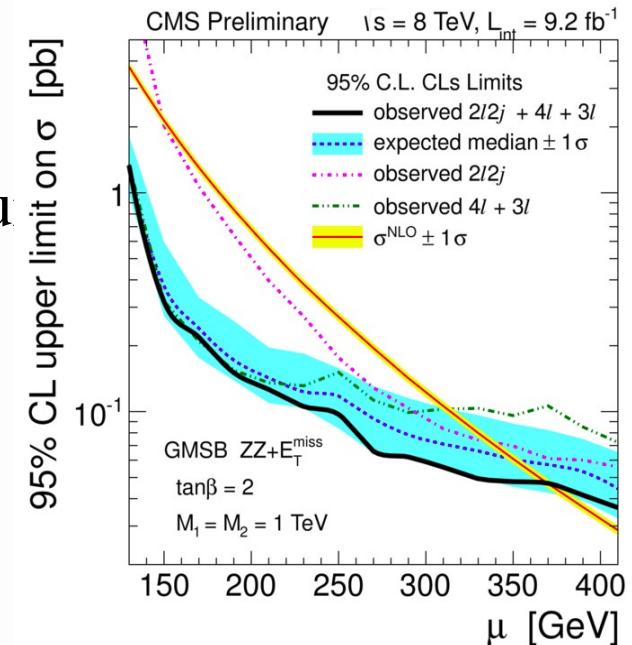
## Light Higgsinos:

Usual EWino searches

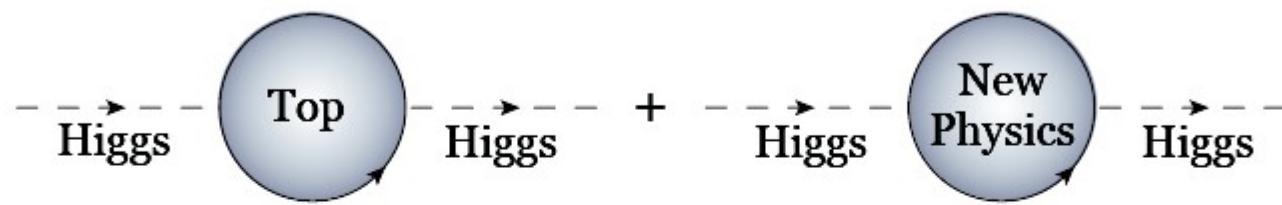
Possibility of testing all couplings and measure

## Only Higgsinos:

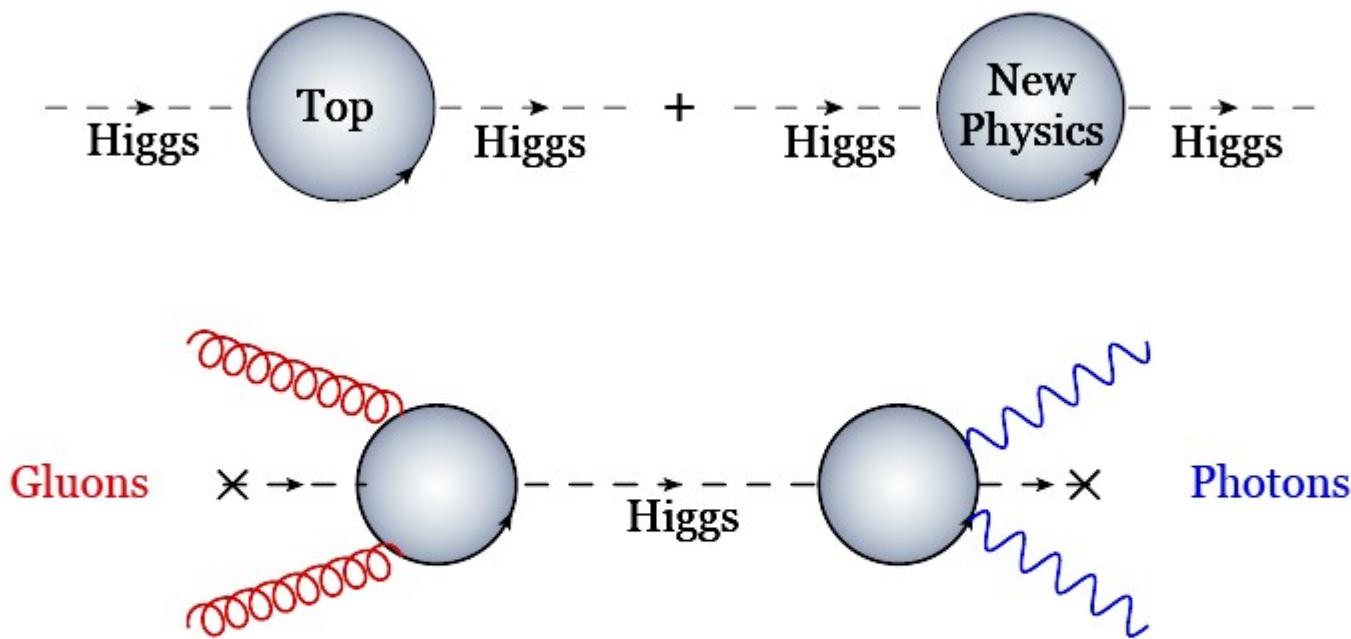
$\Delta m \sim 355 \text{ MeV} \rightarrow <1\text{cm stubs harder to see}$   
if light gravitino h/Z+G decay



# Naturalness and Higgs Properties

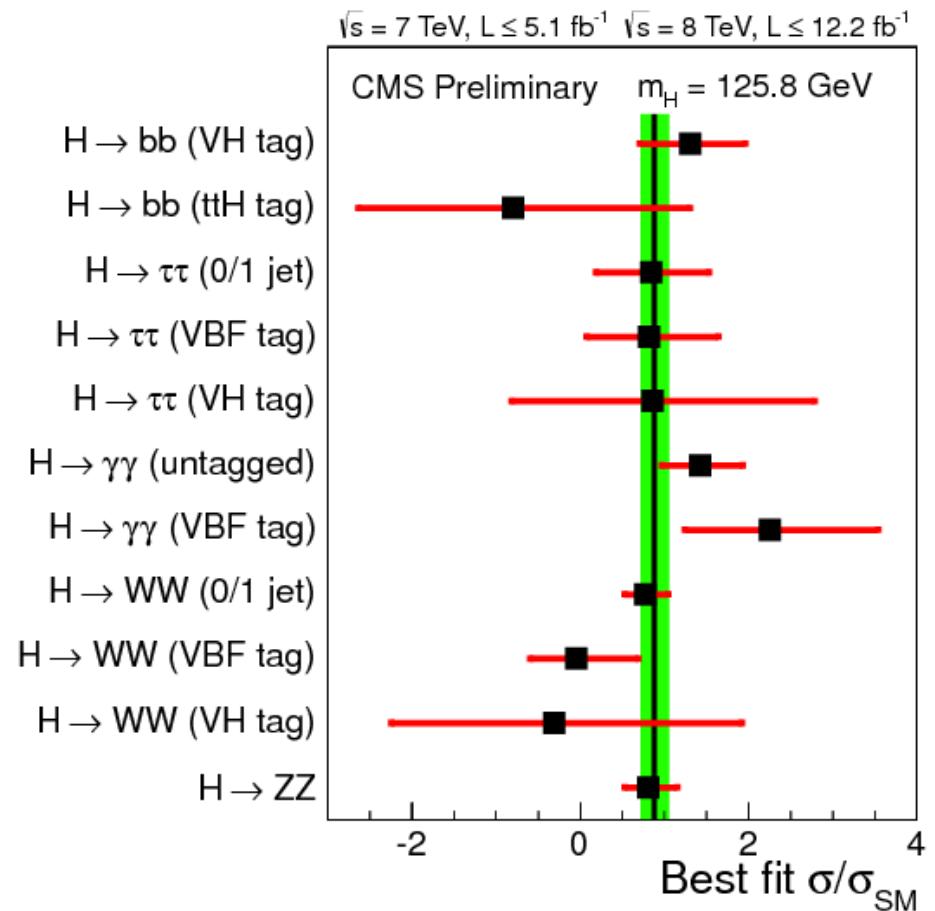
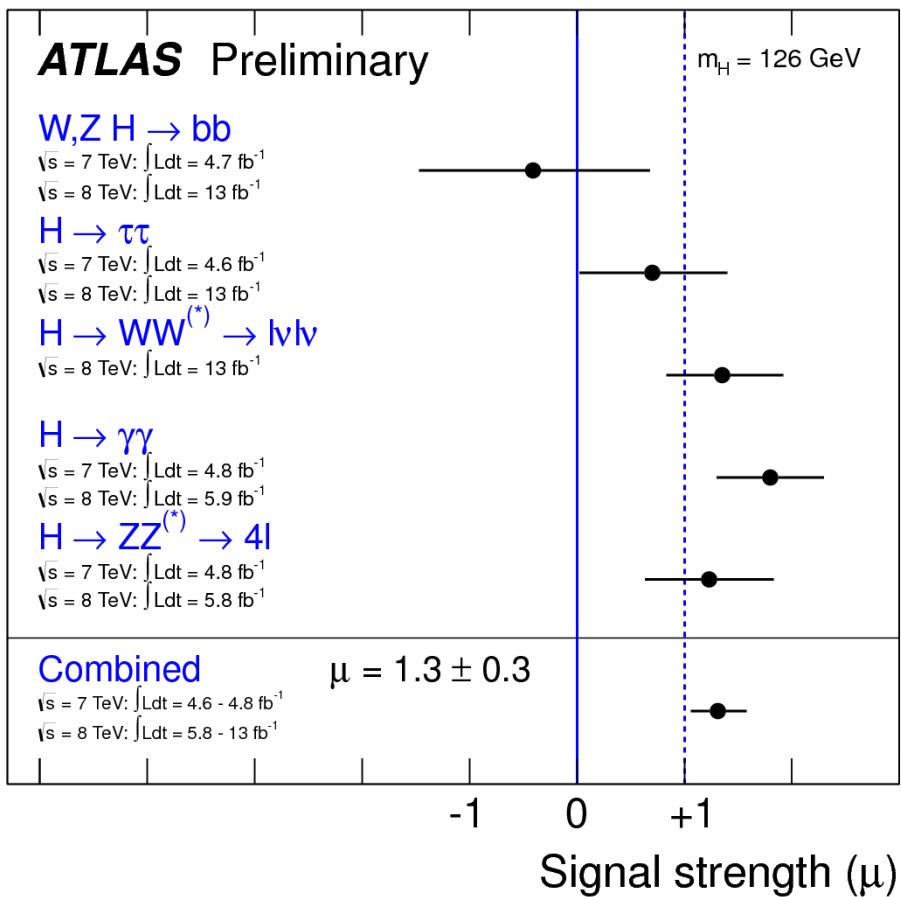


# Naturalness and Higgs Properties



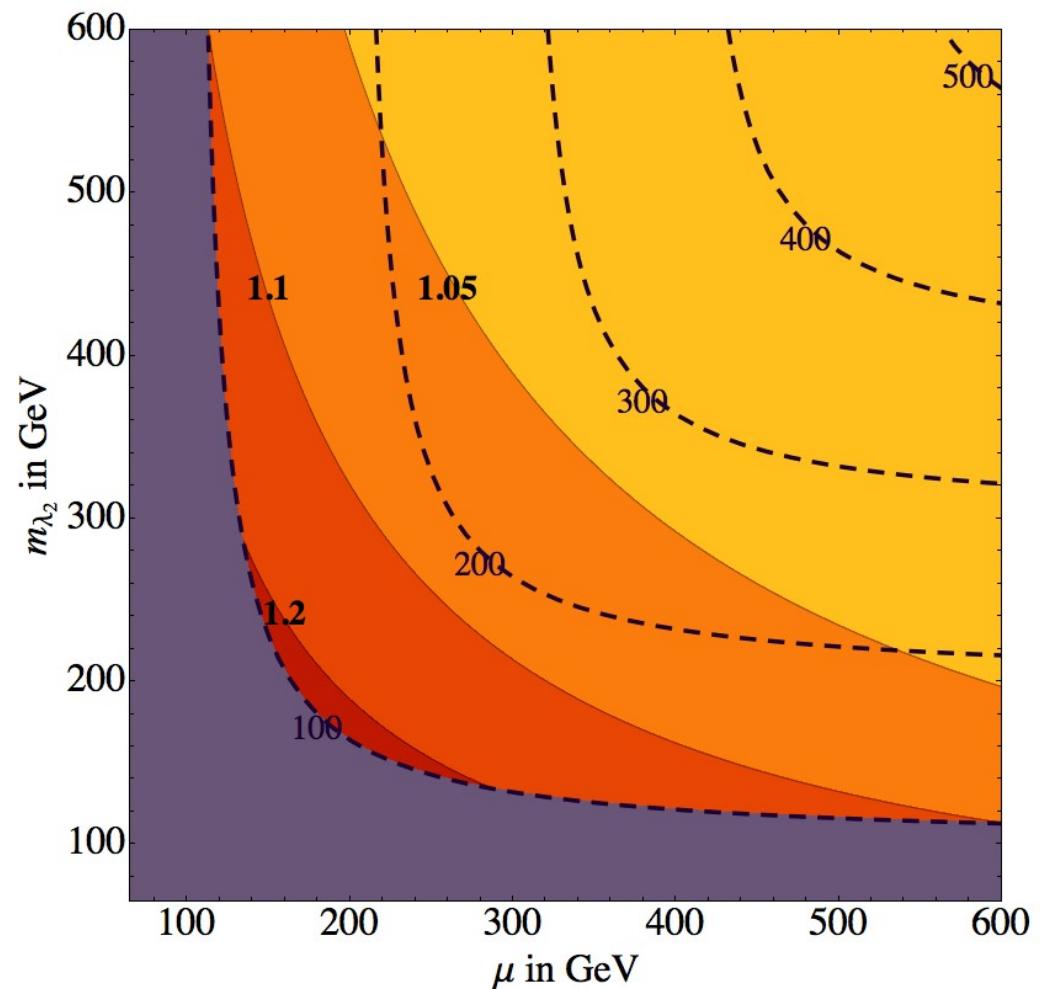
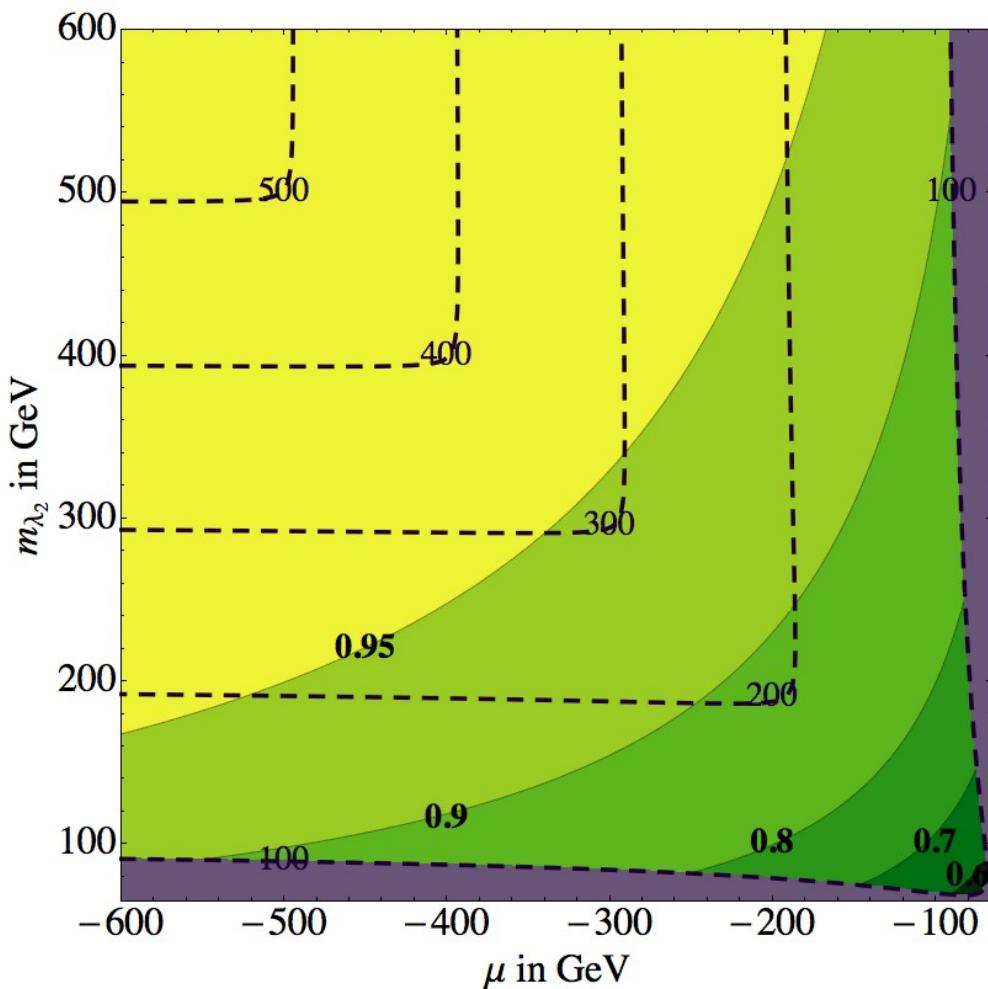
A Natural Higgs is not the SM Higgs

# Higgs couplings

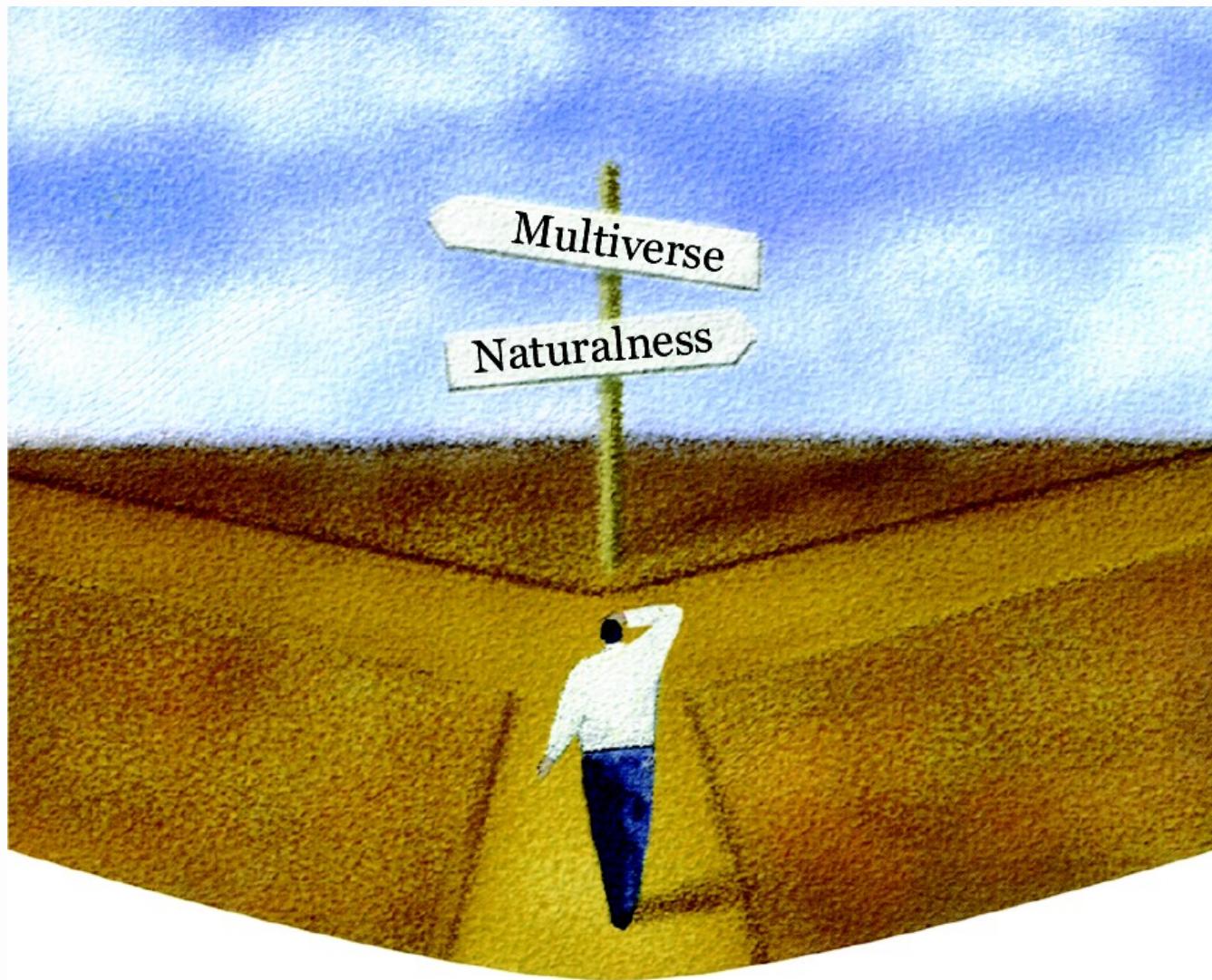


# Higgs couplings in Split

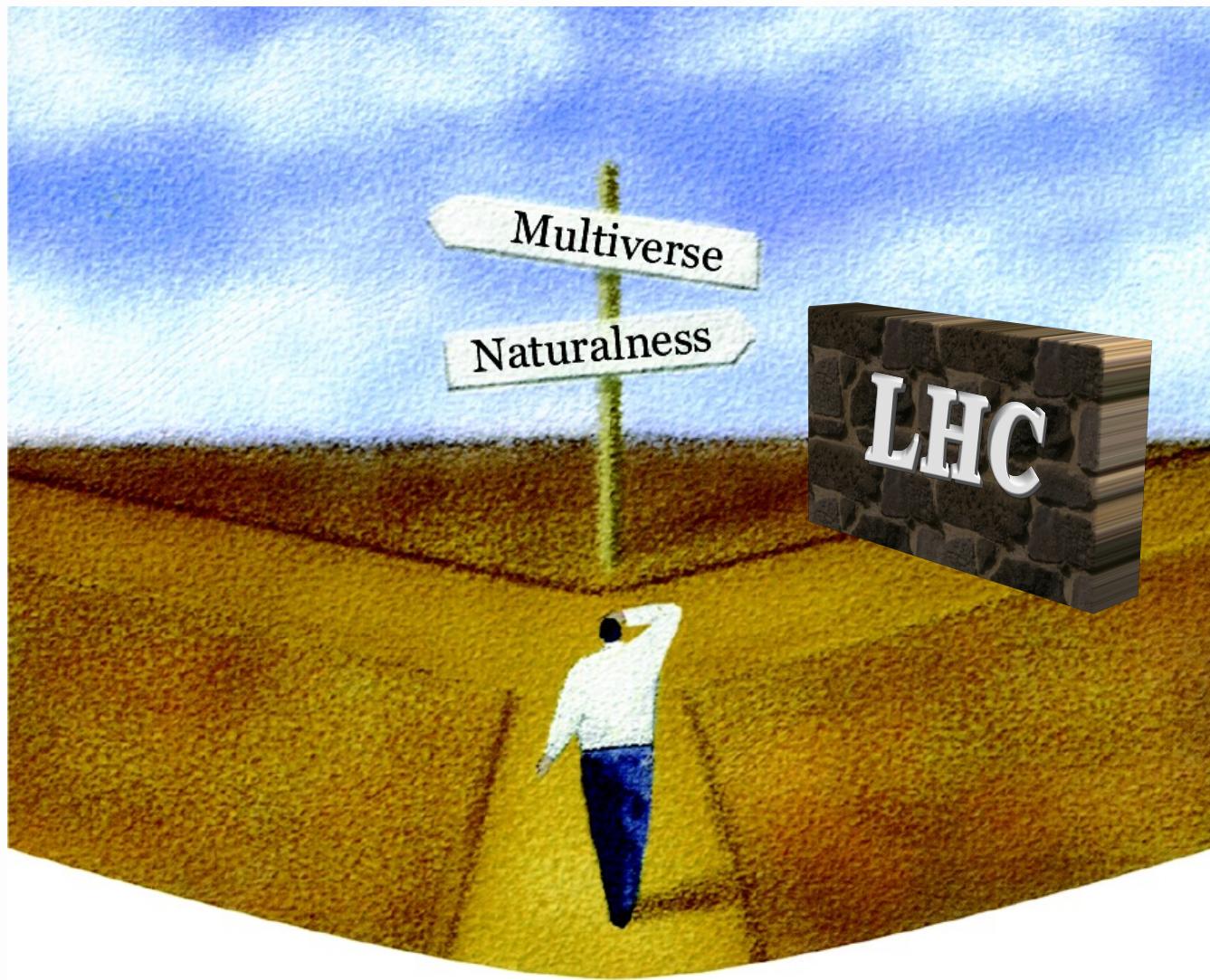
$$\frac{\Gamma_{h \rightarrow \gamma\gamma}}{\Gamma_{h \rightarrow \gamma\gamma}^{SM}} \simeq 1 + \frac{12}{17} \frac{m_W^2 \sin 2\beta}{\mu m_{\lambda_2} - m_W^2 \sin 2\beta}$$



# Conclusions



# Conclusions



# Conclusions

