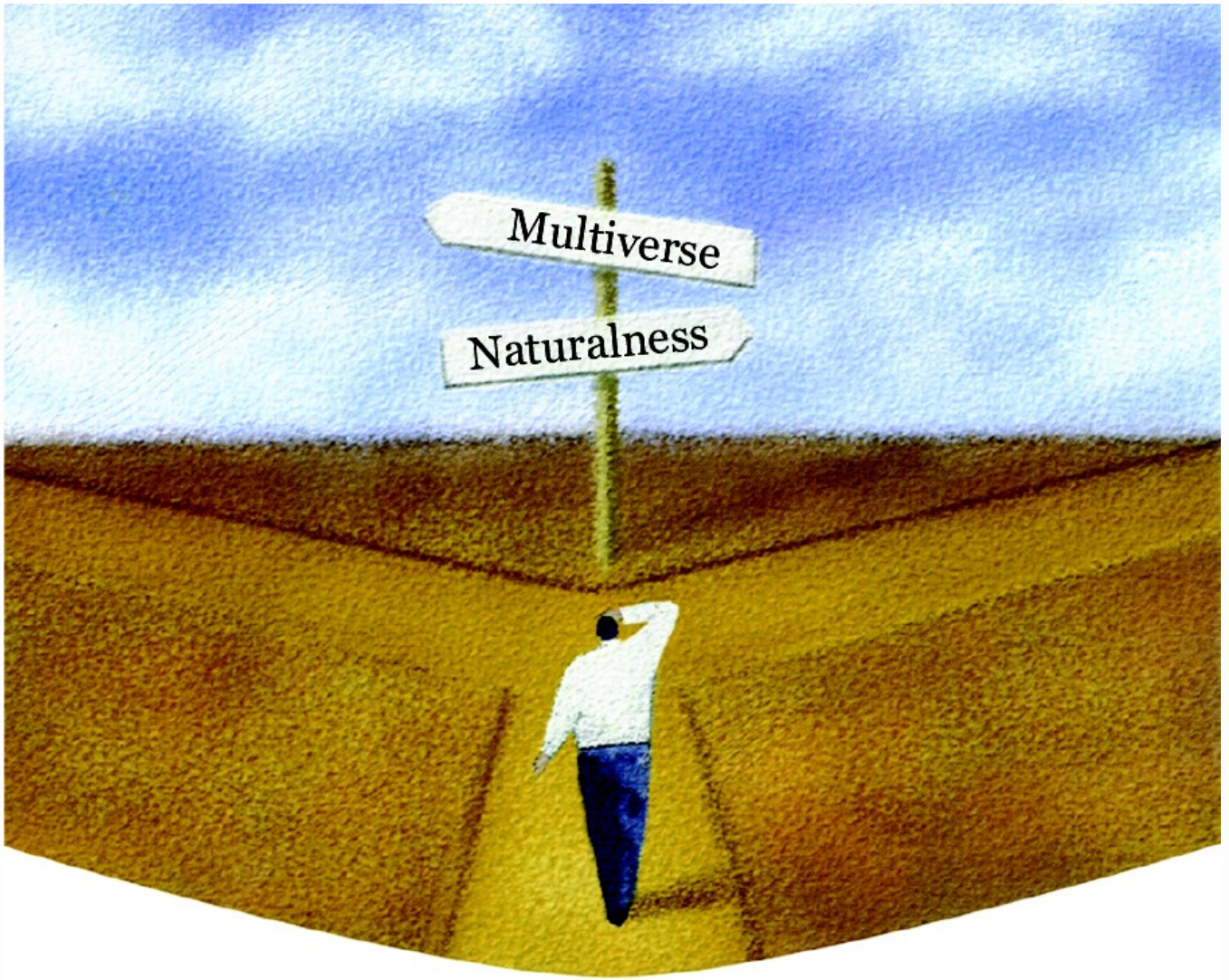
SUSY after the LHC-8

or

"Has Natural SUSY Expired?"

Giovanni Villadoro
ICTP

from collaborations with:
Arvanitaki, Craig, Dimopoulos
Baryakhtar, Gherghetta, Huang, Van Tilburg


Multiverse
Naturalness

Fact #1:

The (not that) light Higgs

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tuning $\delta v^2 \propto m_s^2$ *vs* Higgs mass $\delta m_h^2 \propto v^2 \log m_s^2$

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indirect bound on SUSY

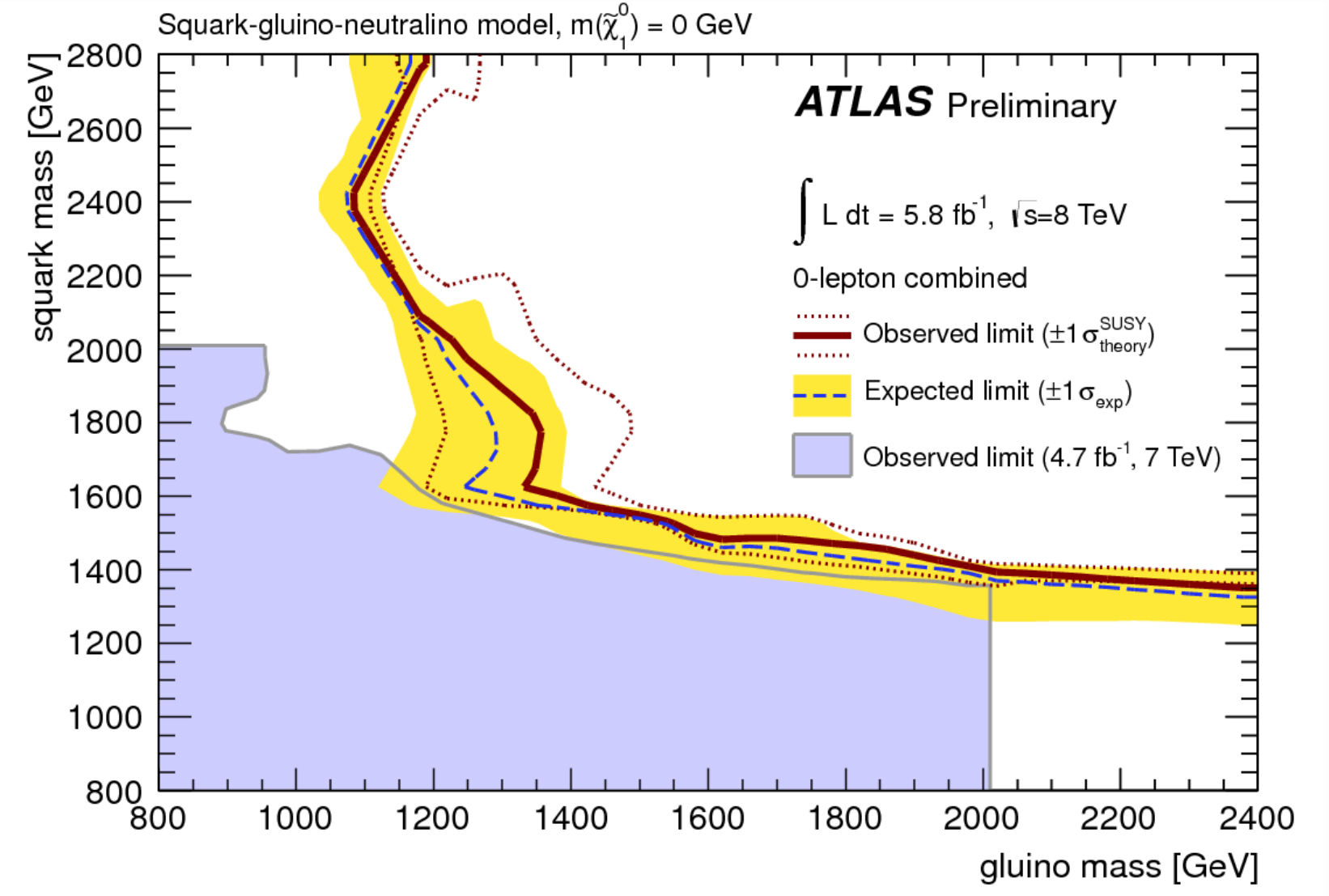
$$\lambda_H = \frac{1}{4}(g^2 + g'^2) + \lambda_{extra}$$

- F-terms: NMSSM / λSUSY
- D-terms: extra gauge groups
- loops: extra vector-like gen.
- ...

Fact #2:

The Missing Superpartner Problem

Fact #2: no 1st gen. squarks



solution #1:

“Natural” SUSY

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Dimopoulos-Giudice, Pomarol-Tommasini '95

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \dots$$

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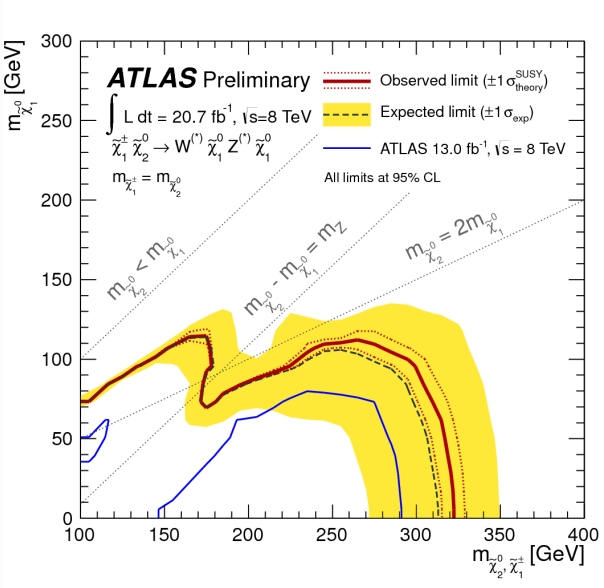
Only need light **higgsinos, stops, gluinos**
(and light mess. scale Λ)

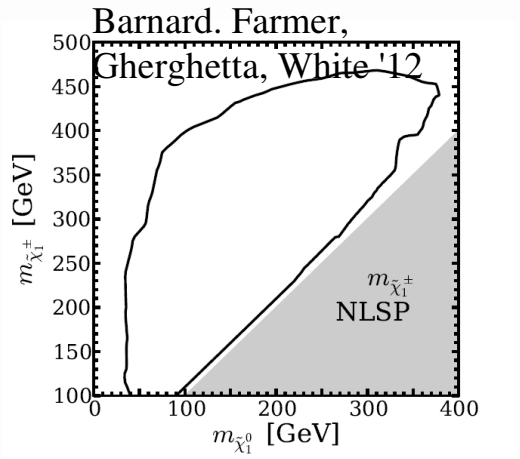
10% tuning $\Rightarrow$ $\mu \lesssim 250$ GeV, $m_{stop} \lesssim 700$ GeV, $M_{gluino} \lesssim 1.4$ TeV

Status of Natural SUSY

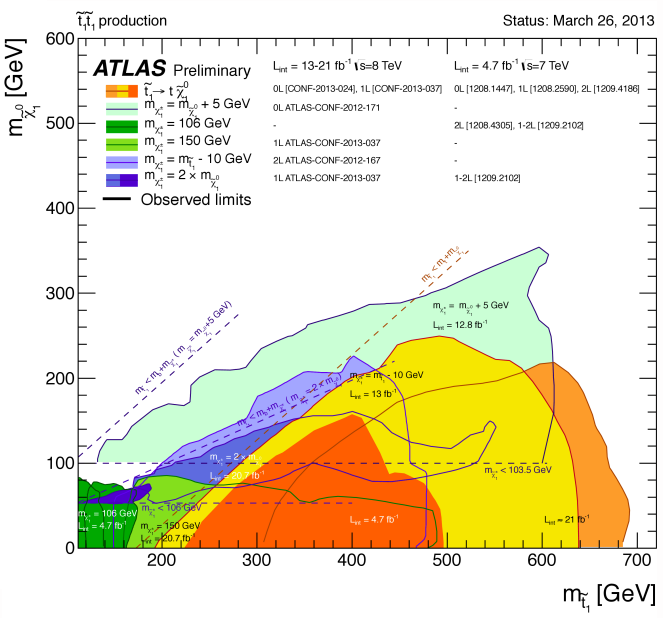
Bounds:

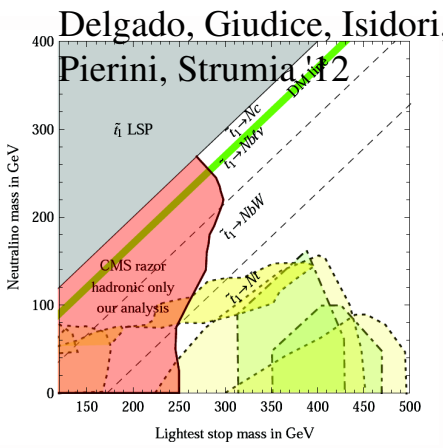
EWino



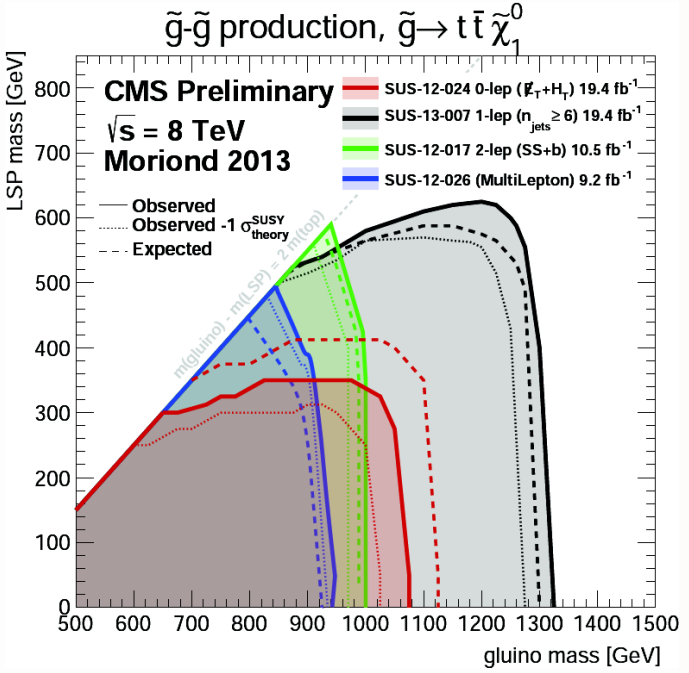


Stops

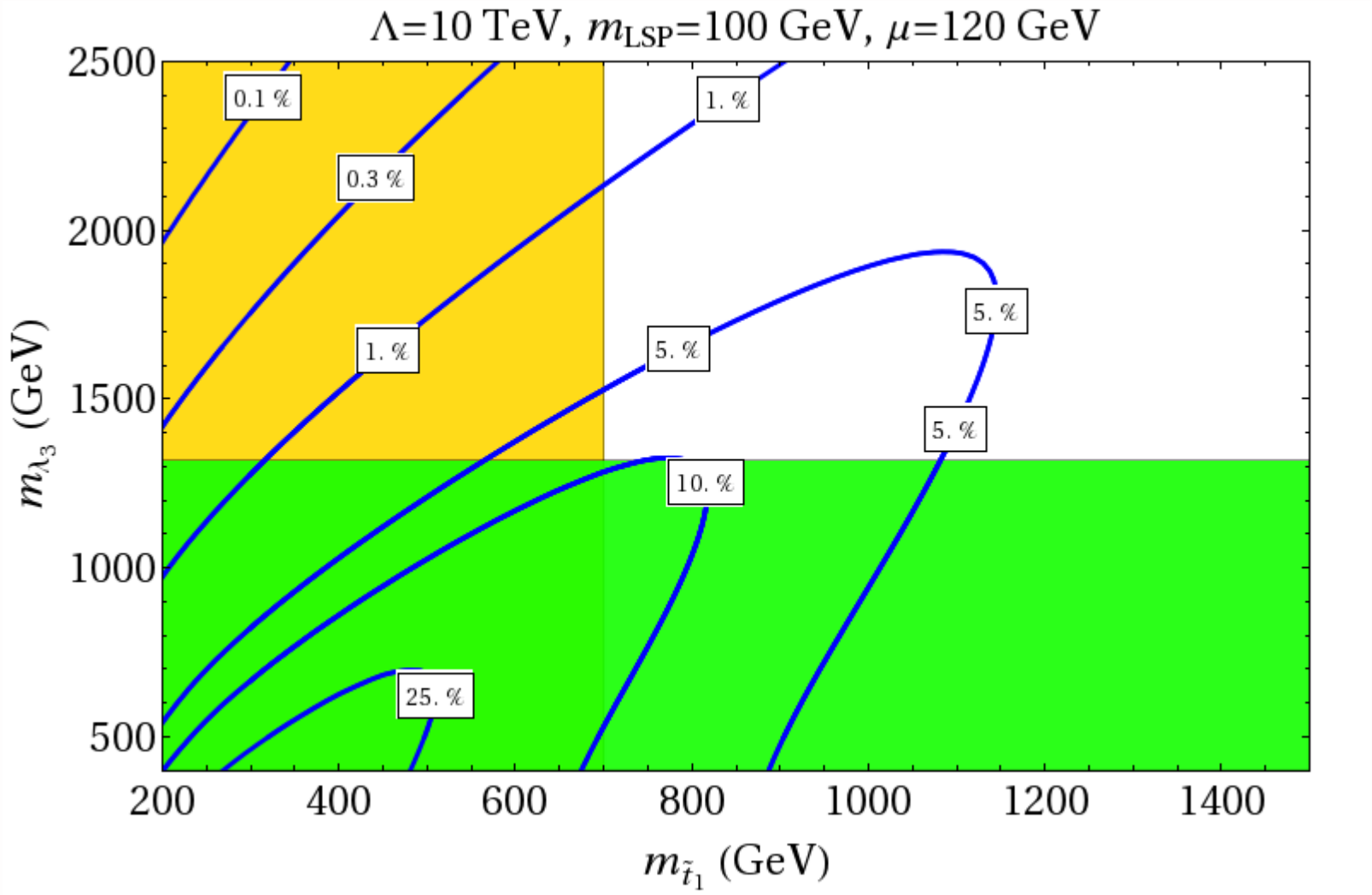




Gluino



Is "Natural" SUSY Natural?



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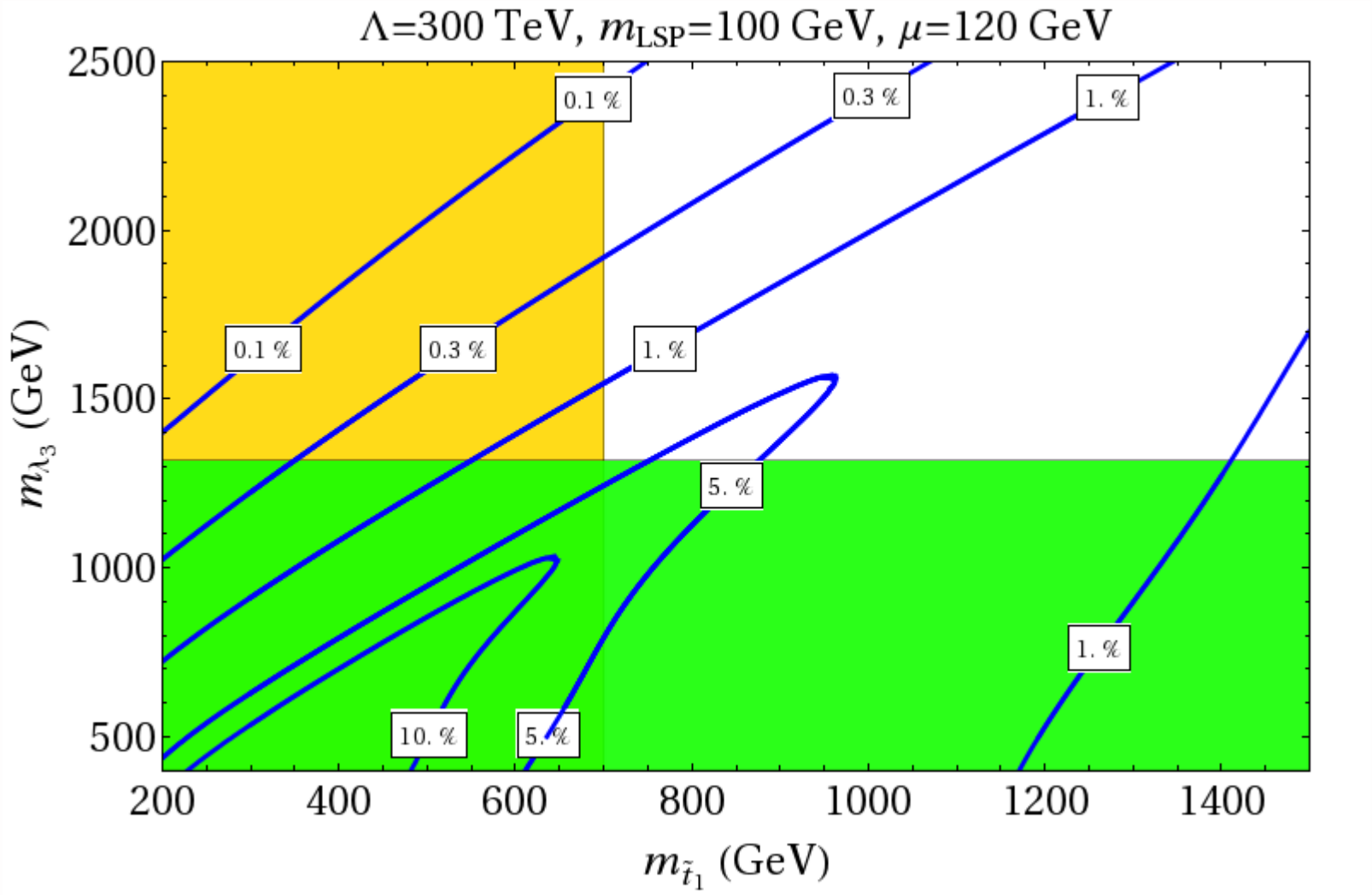

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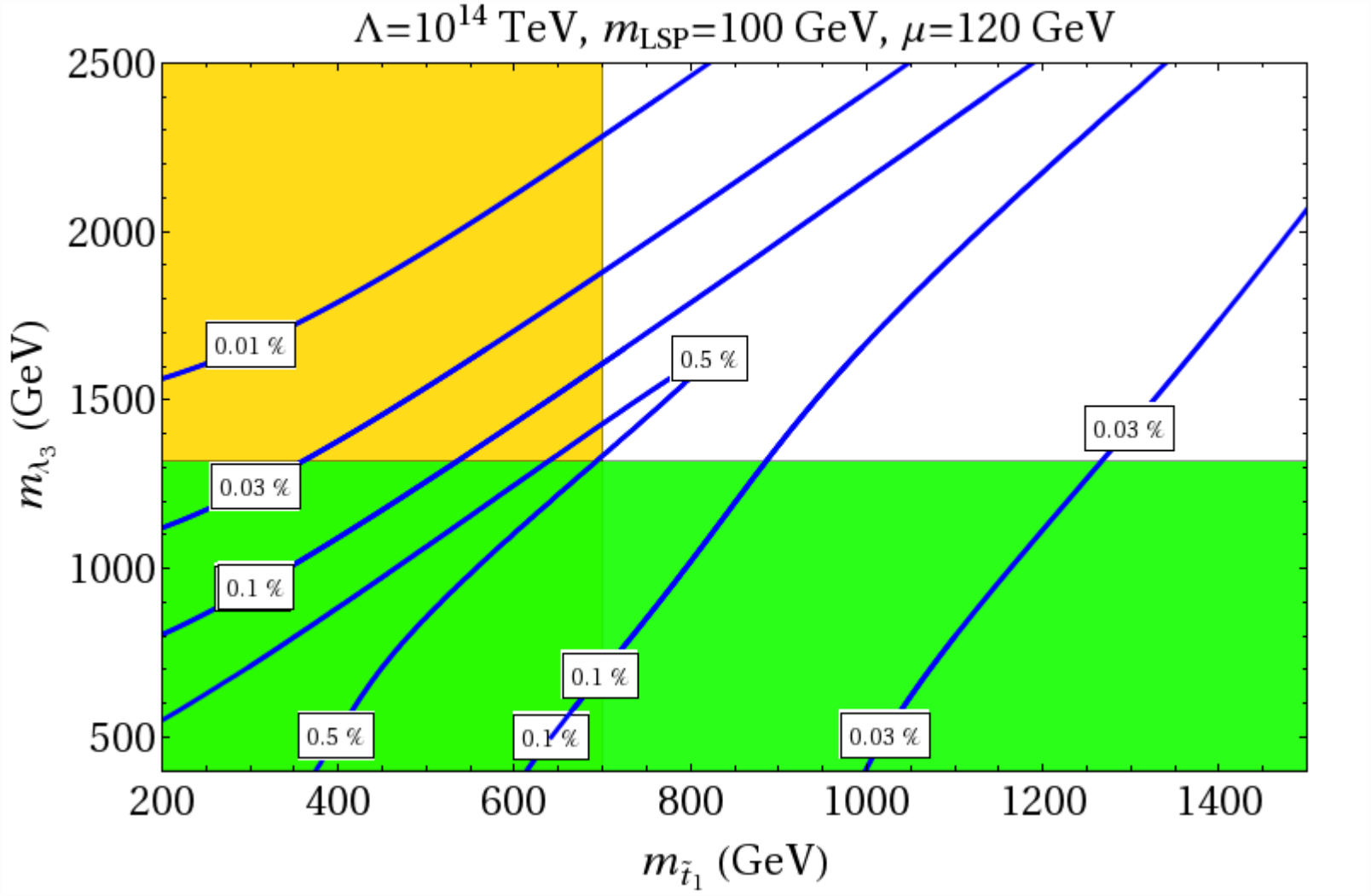

solution #2:

RPV

RPV SUSY

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k.$$

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Leptonic RPV:

many leptons in the final state!

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Leptonic RPV:

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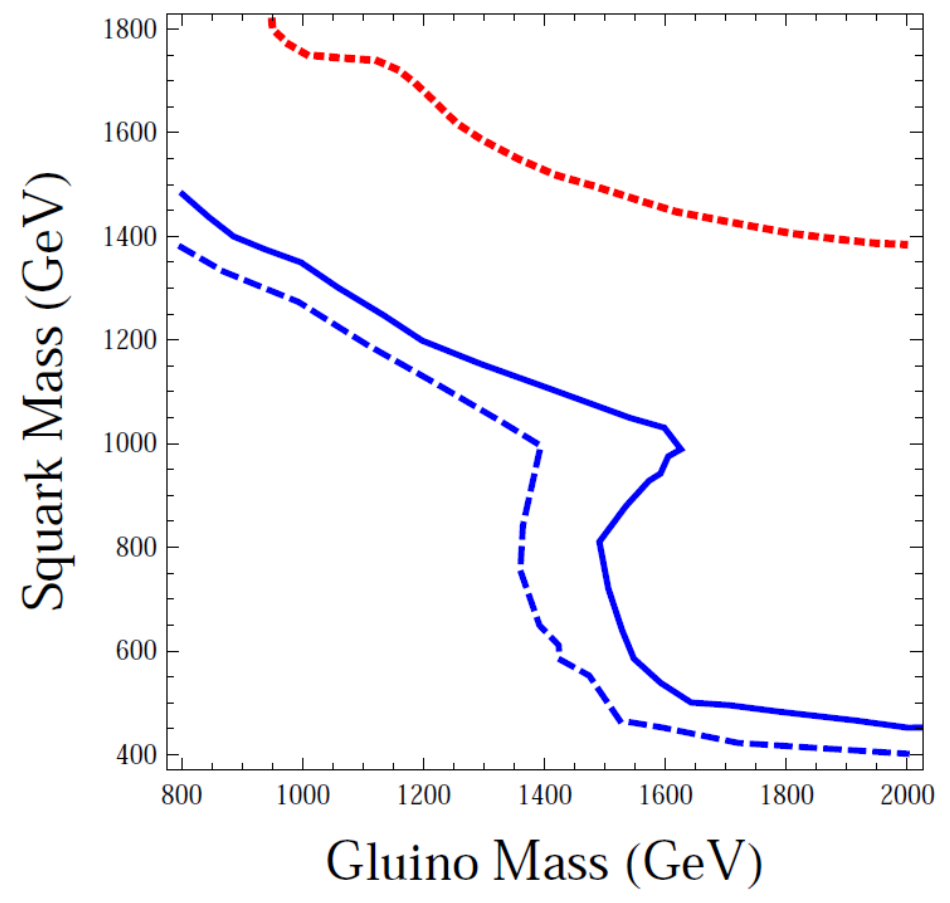
or

play dirty: "displaced susy"

Graham, Kaplan, Rajendran, Saraswat '12



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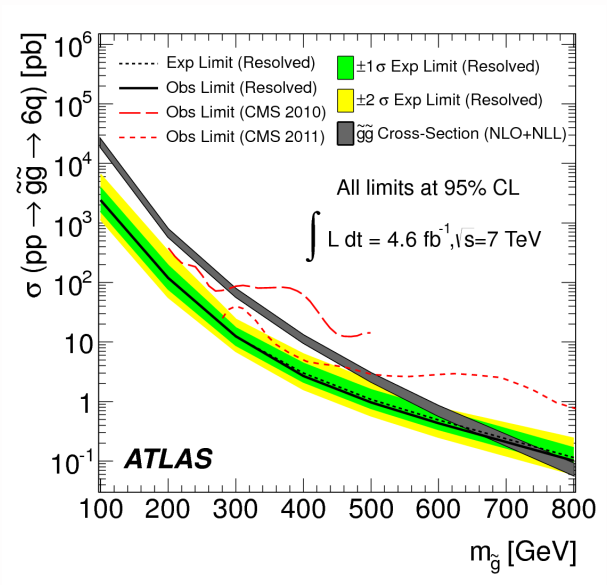
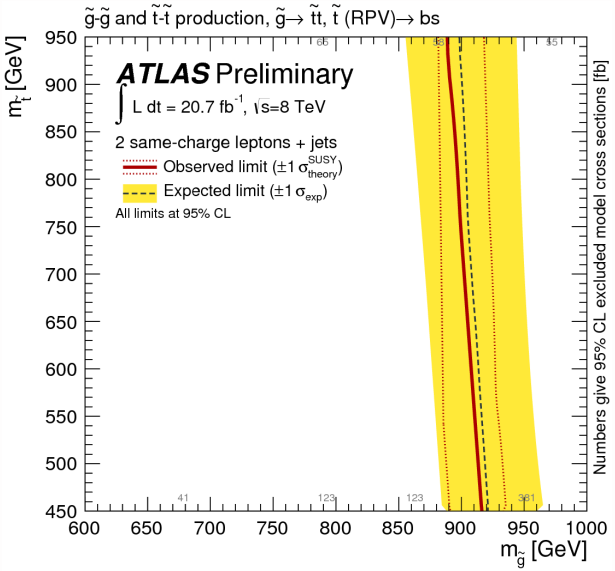
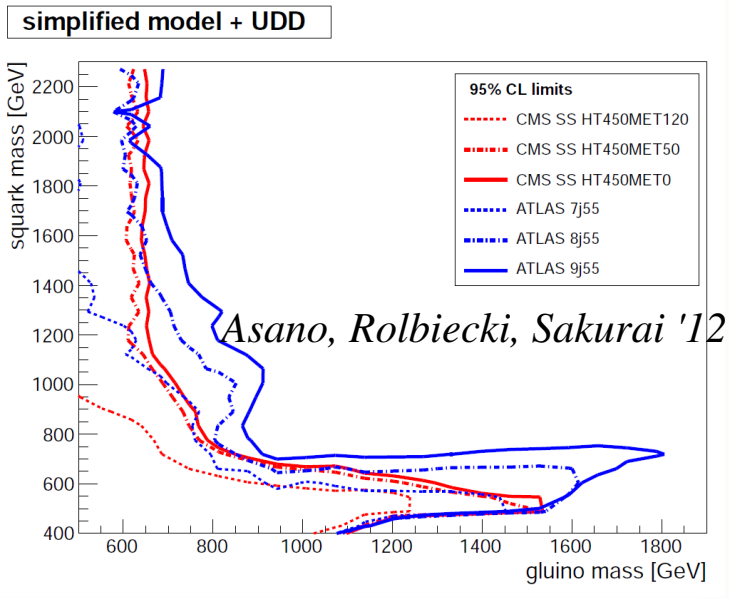
Baryonic RPV:







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Baryonic RPV:

- $p \to K^+ G \Rightarrow \lambda'' \lesssim 10^{-8 \div -17} \Rightarrow m_{3/2} > 1\ GeV$
- *n-n, N-N osc.* $\Rightarrow \lambda''_{11k} \lesssim 10^{-6}$
- $\tau <$ *detector* $\Rightarrow \lambda'' \gtrsim 10^{-6}\,(\chi^0),\ \lambda'' \gtrsim 10^{-9}\,(sq)$
- F_{susy} *not too low*
- *baryon number wash-out...*

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Required ingredients:

- *Higgs fix*
- *low scale mediation (but not too low)*
- *extra susy breaking sector* ($m_p < m_{3/2} < 5\ GeV$)
- *non-universal gaugino masses*
- *avoid vanilla spectra: leptons, W, Z ...*
- *hierarchical* λ''

Less “canonical” tuning?

More “hidden” tunings?

“solution” #3:

Dirac gauginos

Dirac gauginos:

the good:

- *N=2* symm. → no large log corrections to scalars
- suppressed *t*-channel squark production
- suppressed flavor effects

$$\int d^2\theta \sqrt{2} \frac{W'_\alpha W_j^\alpha A_j}{M}$$

$$\int d^2\theta \frac{W'_\alpha W'^\alpha}{M^2} A_j^2$$

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

the bad:

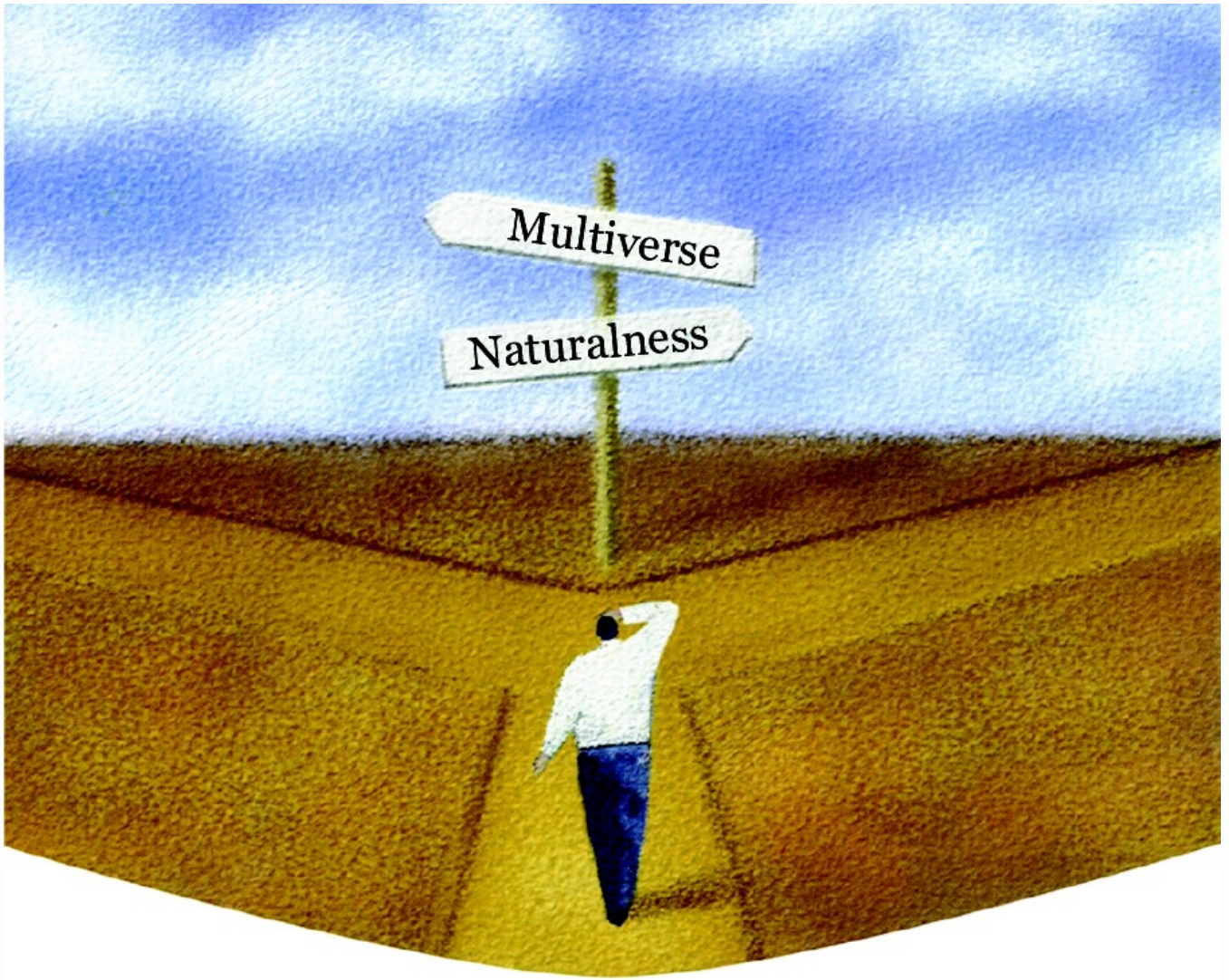
- in general left with a finite ~log(loop) factor
- at best log(few) expected (extra model building)
- larger prod. cross section for gauginos
- unification in trouble
- extra model building for Higgs quartic
- tachyons?
- ...

any improvement?

what about combining more mechanisms?

not really an option if the goal is naturalness...

...tuning in theory space!

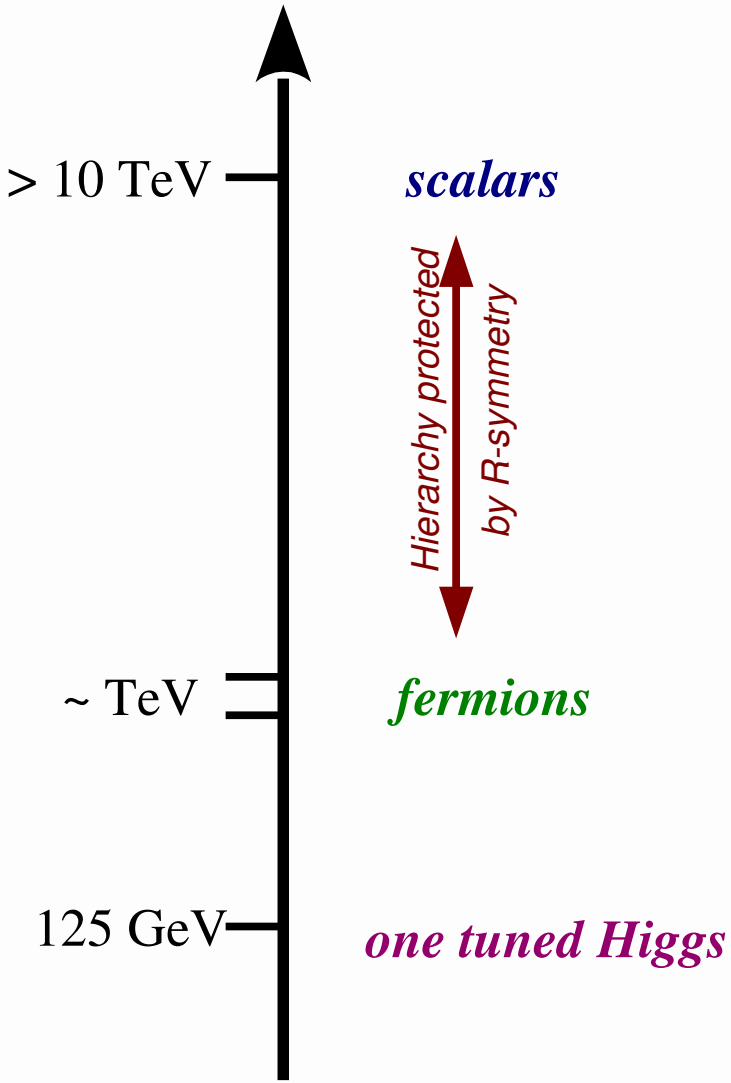

Multiverse
Naturalness


Multiverse
Naturalness
LHC

The Alternative
(Mini) Split SUSY

Split SUSY spectrum

Arkani-Hamed, Dimopoulos
Giudice, Romanino '04

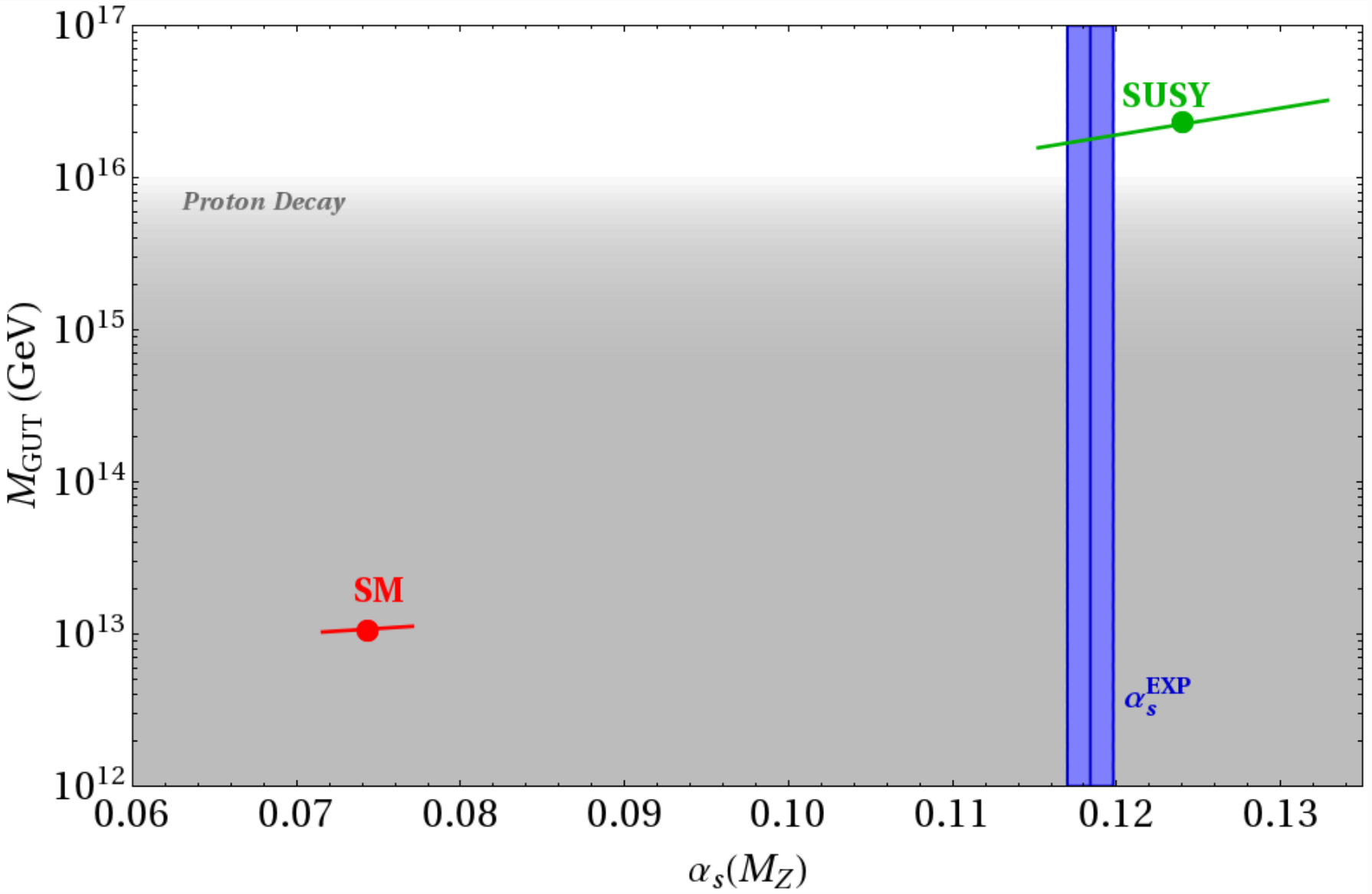


Avoids problems with flavor, EDM and collider bounds

Preserves successful Gauge Coupling Unification and Dark Matter

Why to insist on SUSY?

predicting gauge coupling unification



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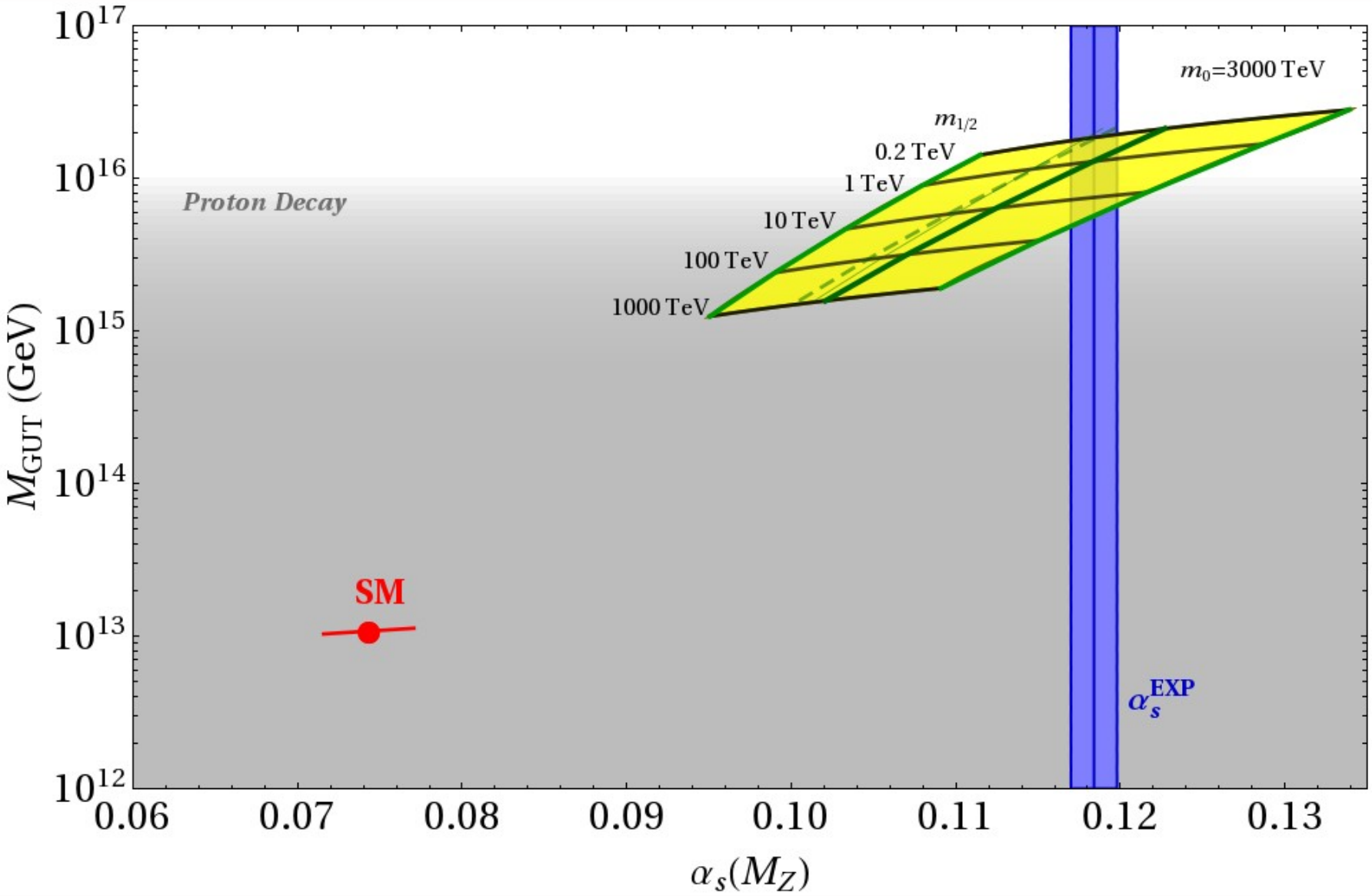

"Mini"-Split SUSY

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

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

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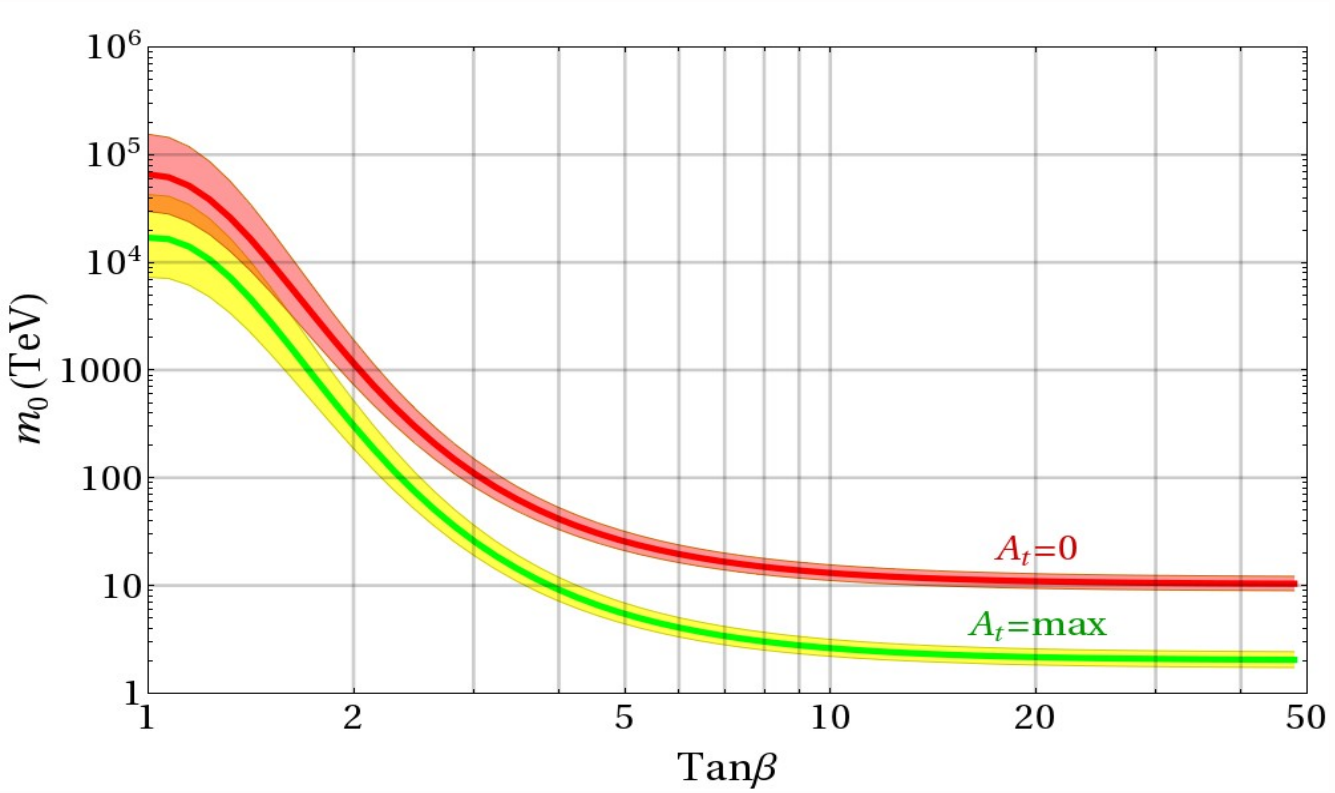

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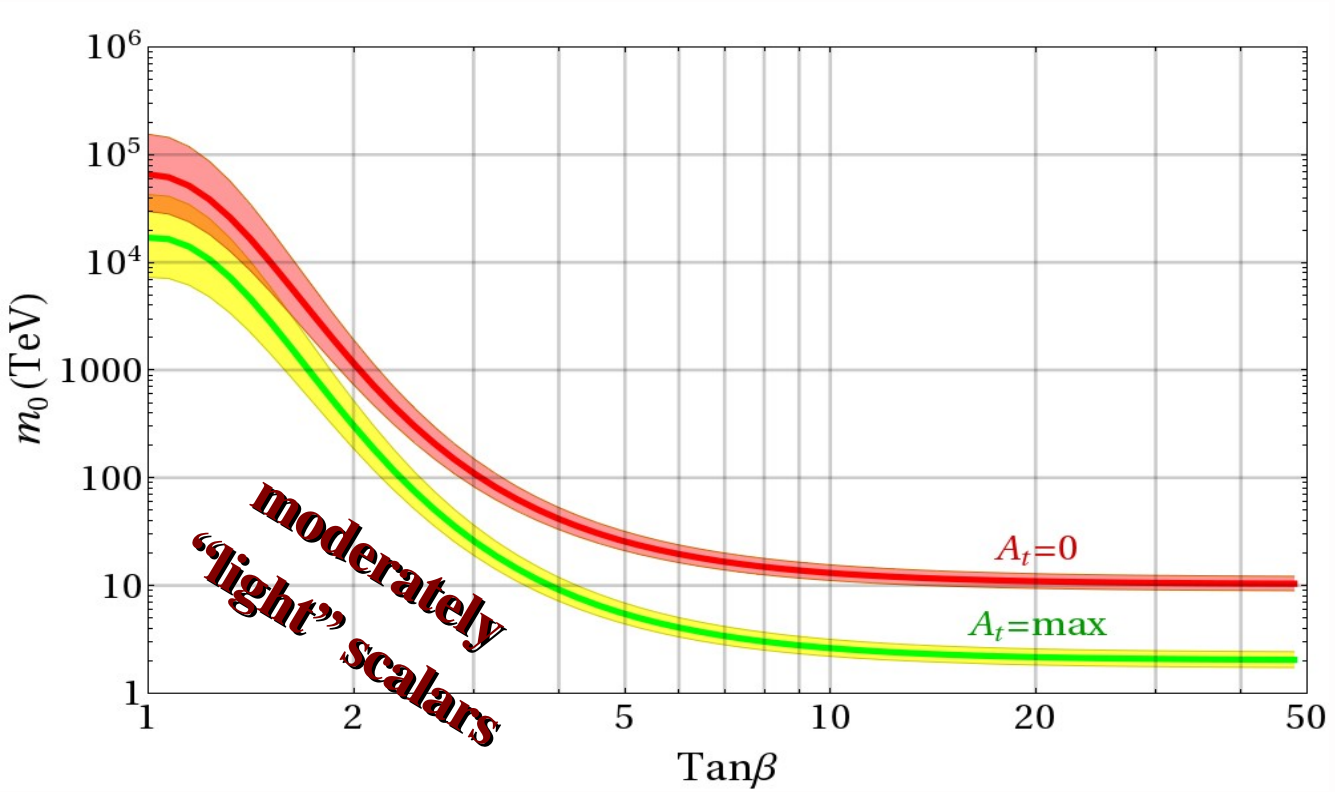
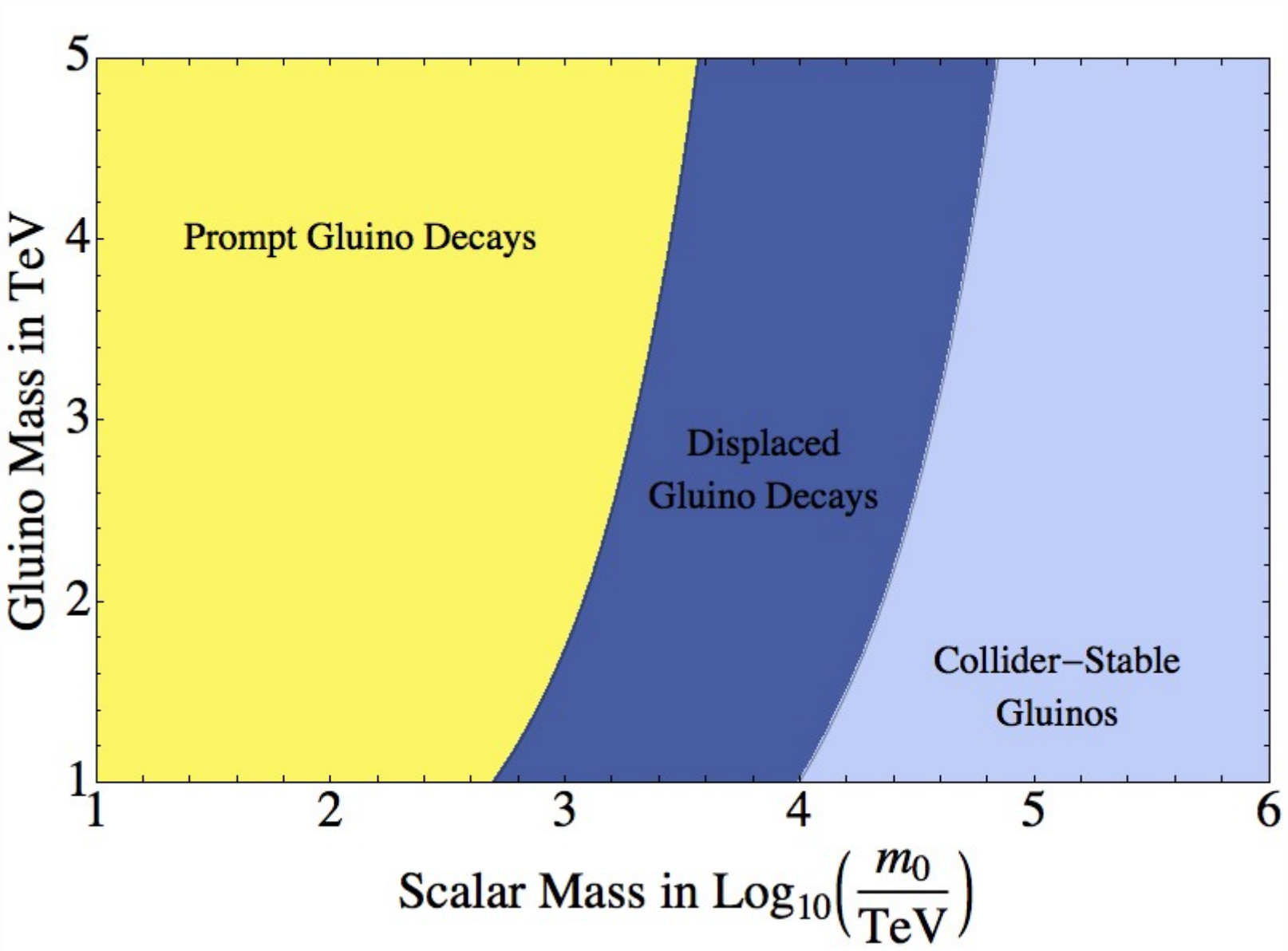
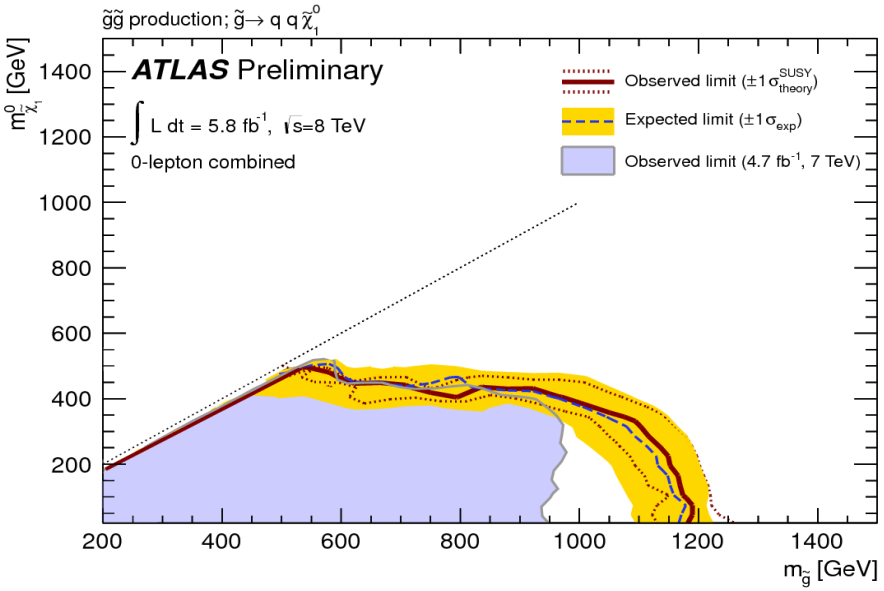


Split Phenomenology

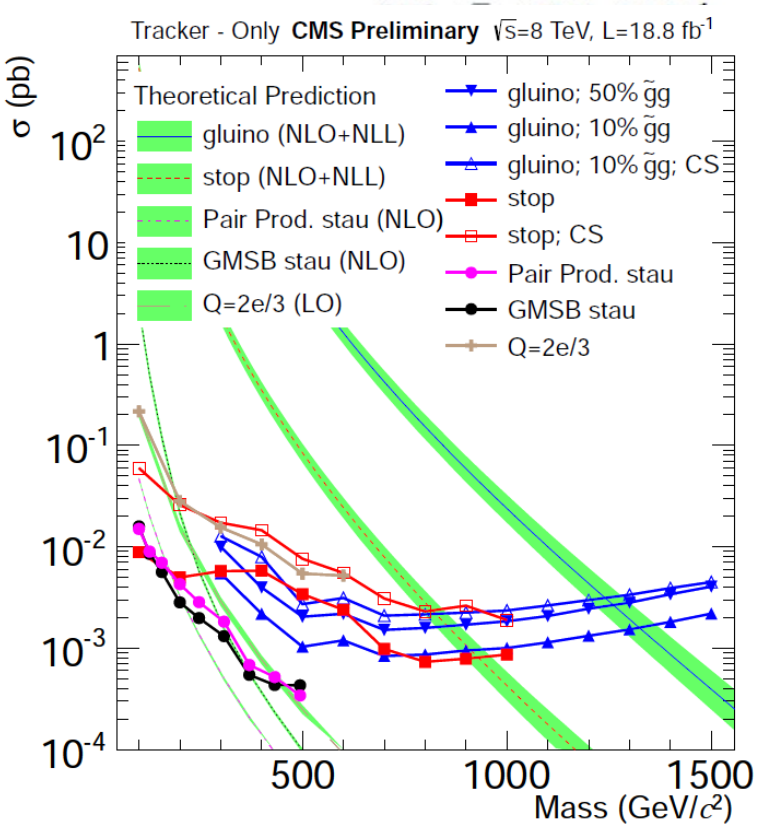
Phenomenology: Gluino



Gluino Bounds from the LHC



For prompt or slightly displaced gluinos



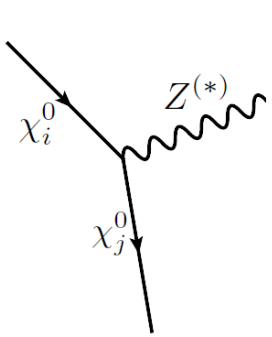
For collider "stable" gluinos

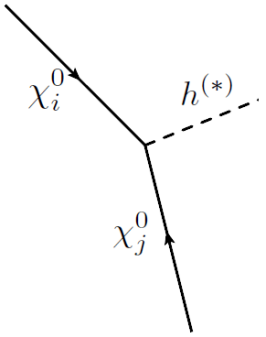
$M_{gluino} > 1.3$ TeV for split gluino

2.5 TeV to 3 TeV ultimate reach for split gluino

Phenomenology: EWinos

Neutralino decays





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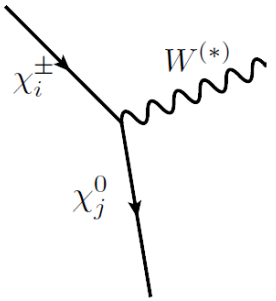

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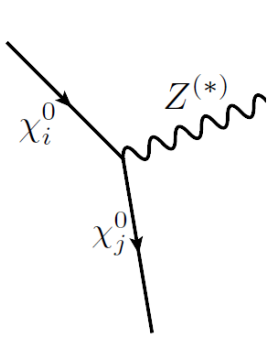

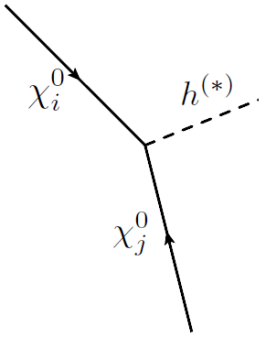

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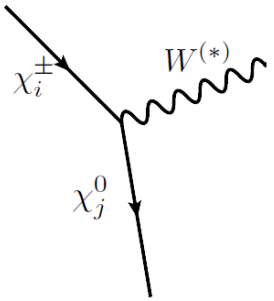
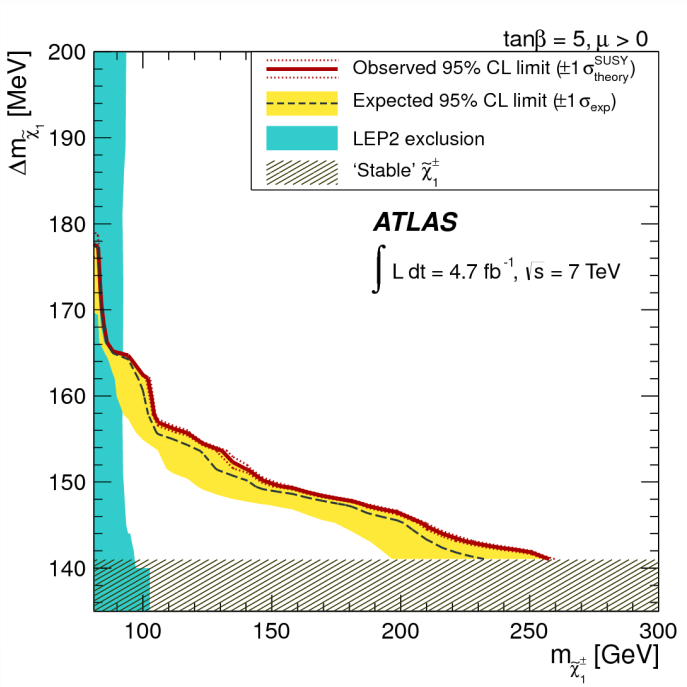


Heavy Higgsinos:

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

Wino LSP: Δm~170 MeV → 10cm stubs (trig. on ISR+MET)



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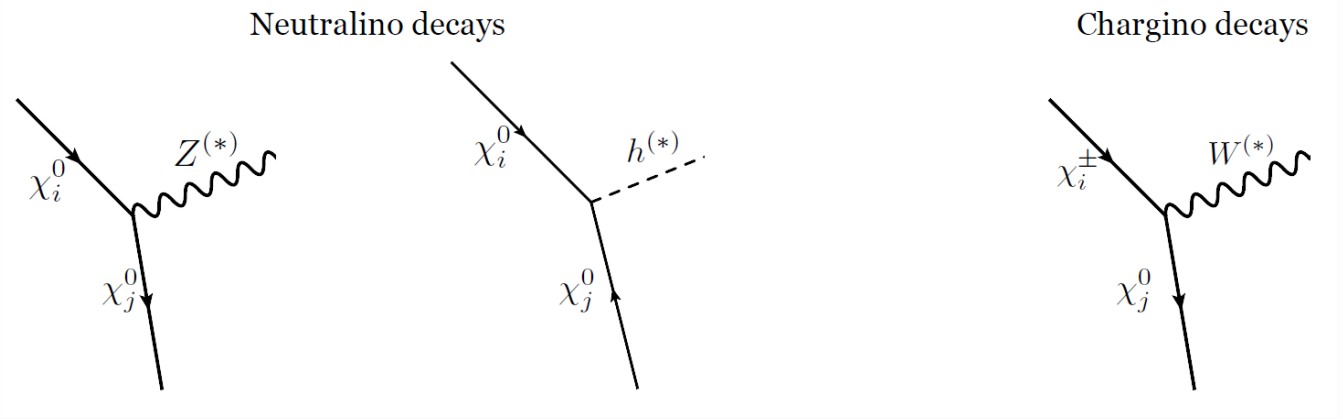

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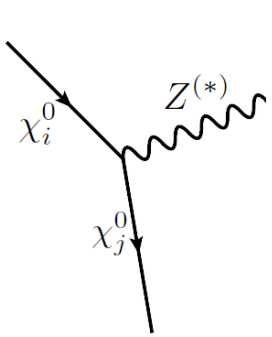
Light Higgsinos:

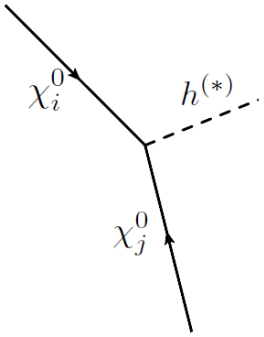
Usual EWino searches

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

Phenomenology: EWinos

Neutralino decays





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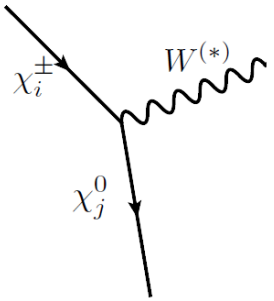

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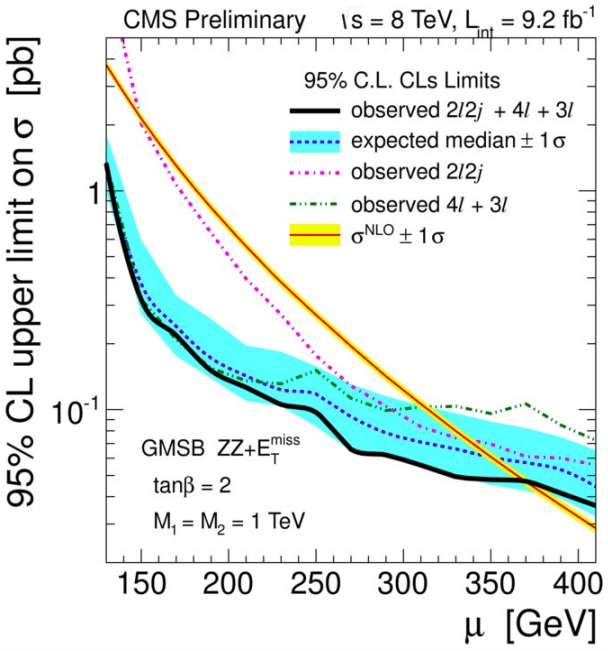
Light Higgsinos:

Usual EWino searches

Possibility of testing all couplings and measu

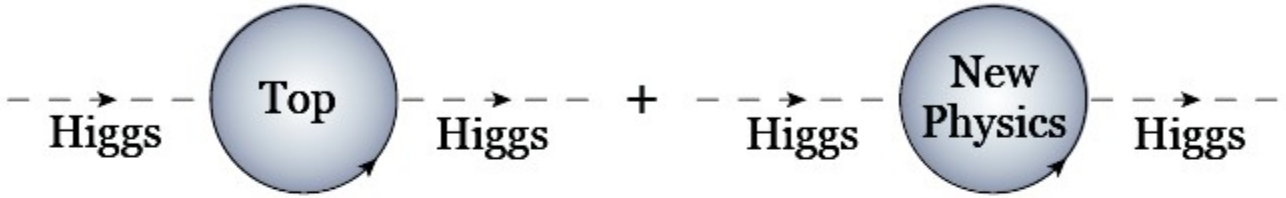
Only Higgsinos:

Δm~355 MeV → <1cm stubs harder to see if light gravitino h/Z+G decay



Higgs couplings and Naturalness

Naturalness and Higgs Properties



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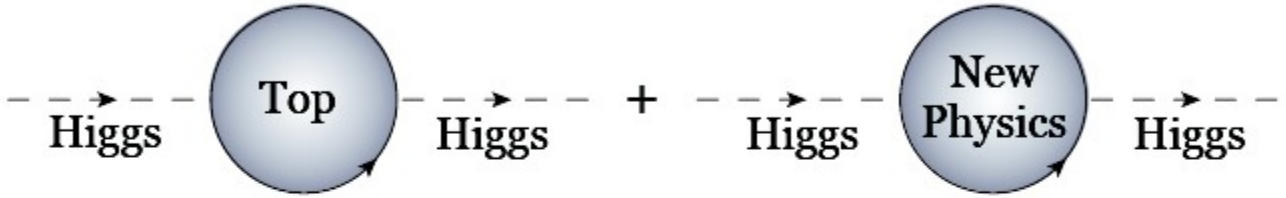
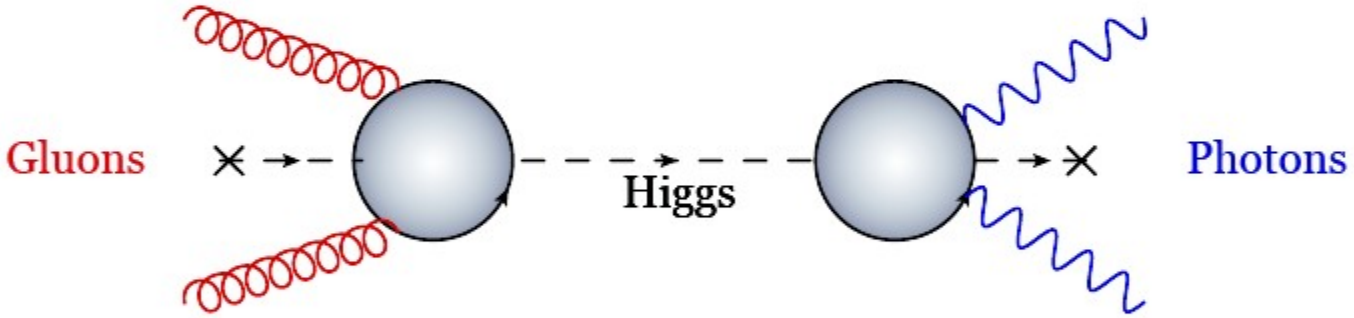
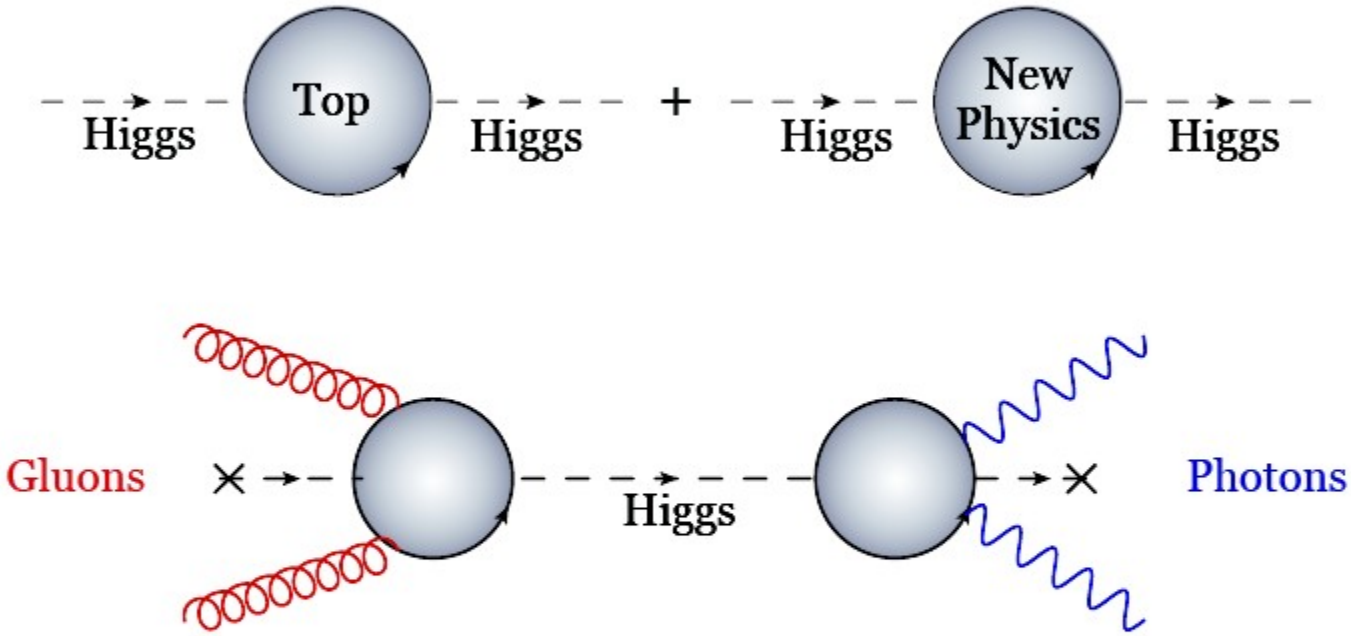




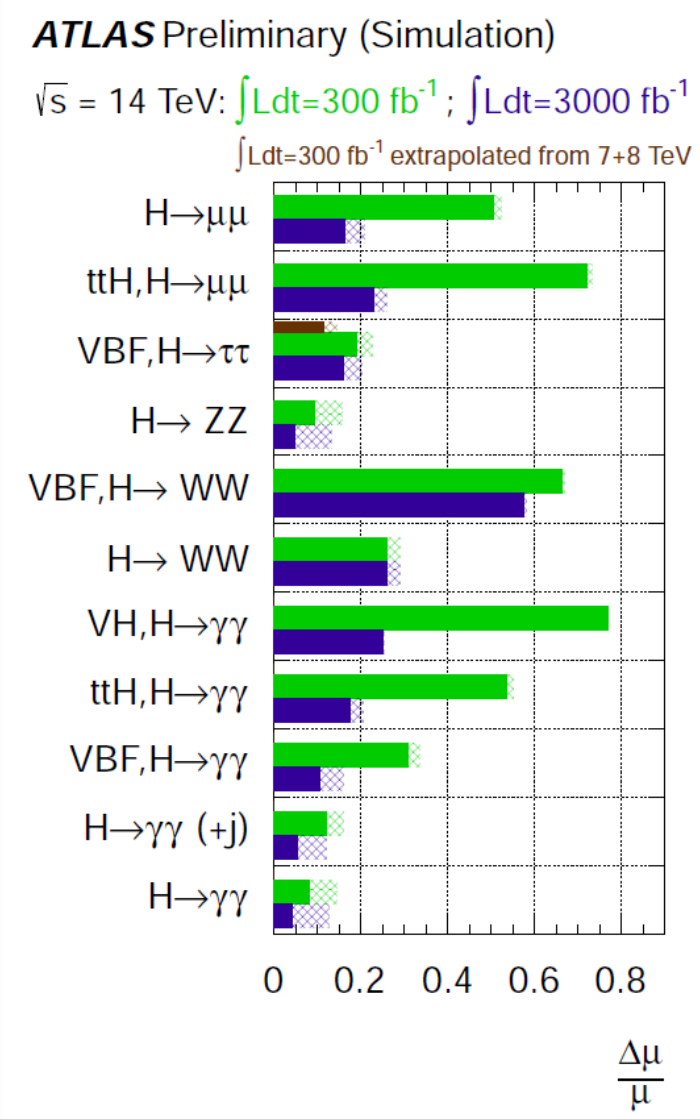
A Natural Higgs is not the SM Higgs

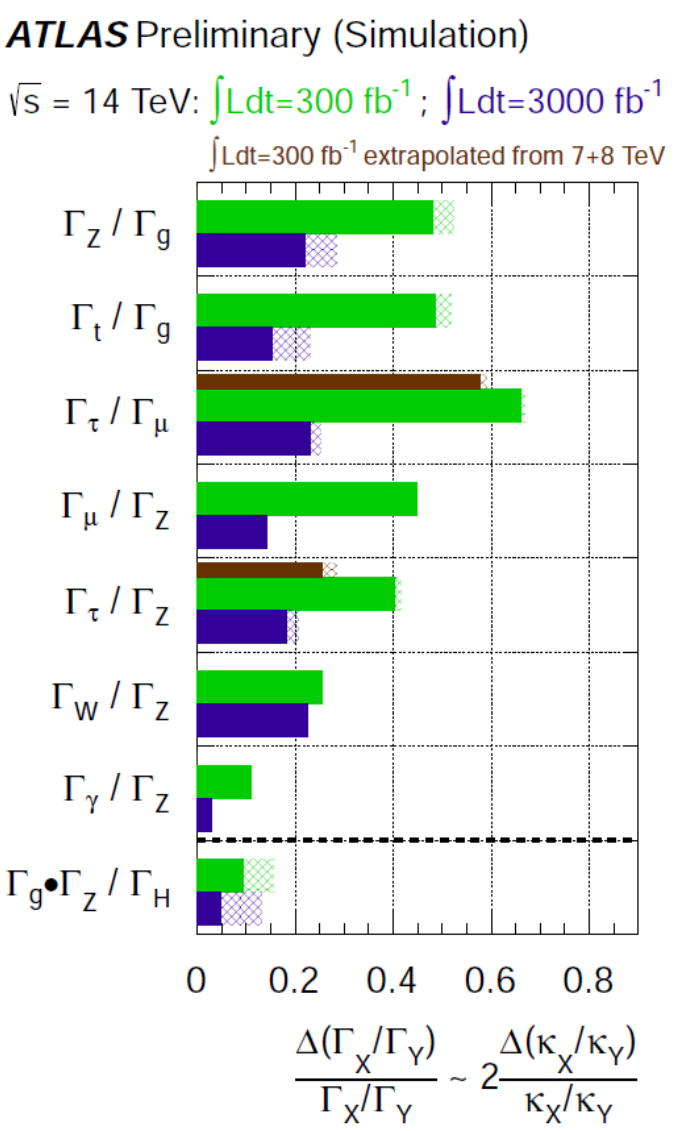
Naturalness and Higgs Properties



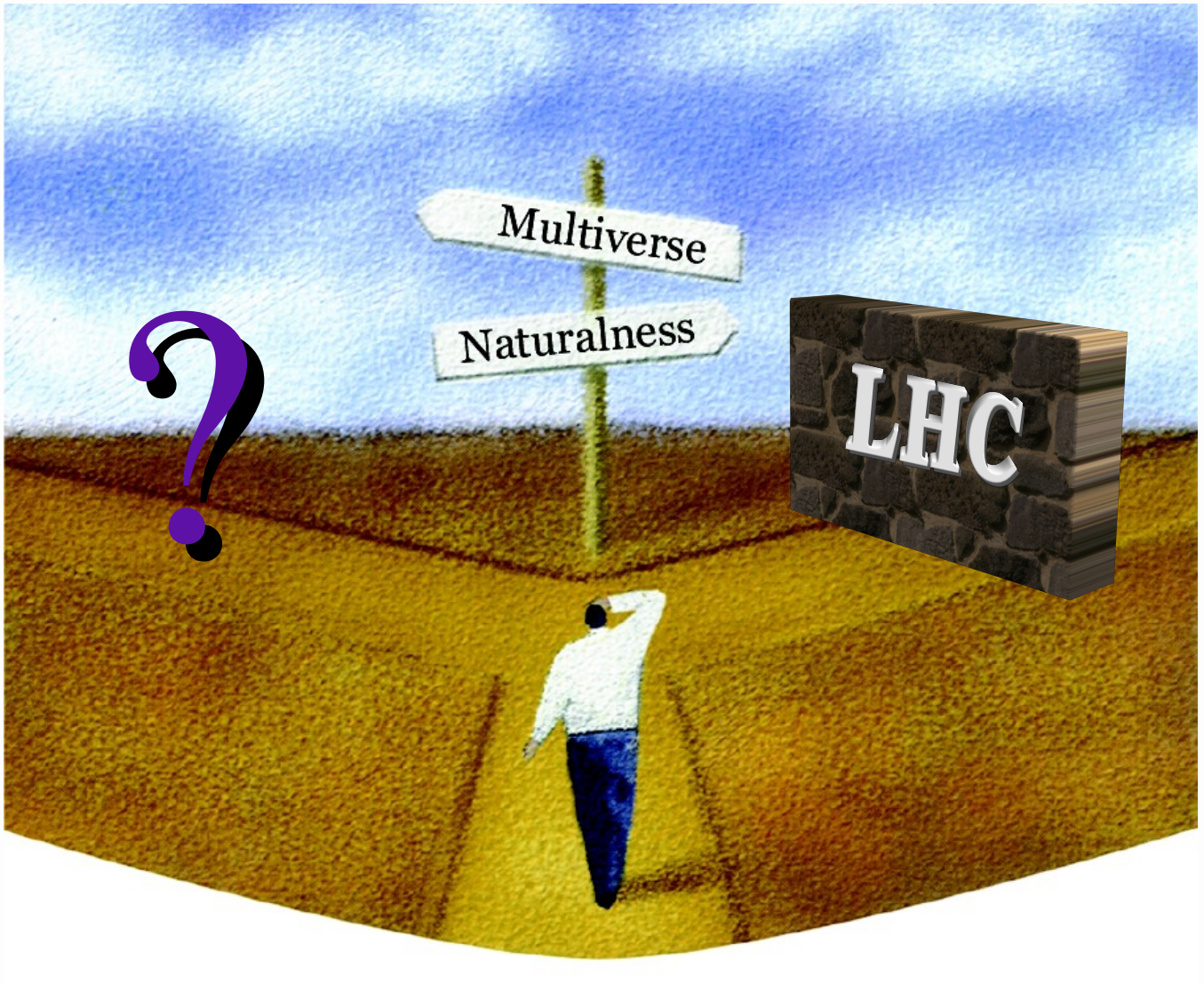
A Natural Higgs is not the SM Higgs

$$\mu_{gg\to h} \approx 1 + \frac{m_t^2}{m_{\tilde{t}}^2} \sim 1 + tuning$$

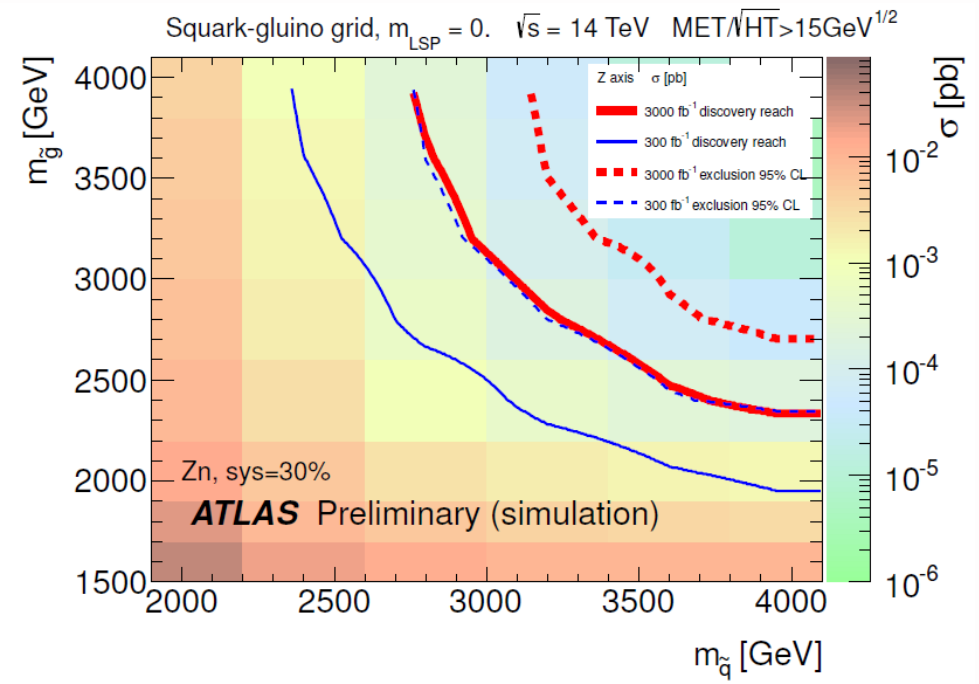

ATLAS Preliminary (Simulation)
√s = 14 TeV: ∫Ldt=300 fb-1 ; ∫Ldt=3000 fb-1
∫Ldt=300 fb-1 extrapolated from 7+8 TeV
H→μμ
ttH,H→μμ
VBF,H→ττ
H→ ZZ
VBF,H→ WW
H→ WW
VH,H→γγ
ttH,H→γγ
VBF,H→γγ
H→γγ (+j)
H→γγ
0
0.2
0.4
0.6
0.8
Δμ/μ

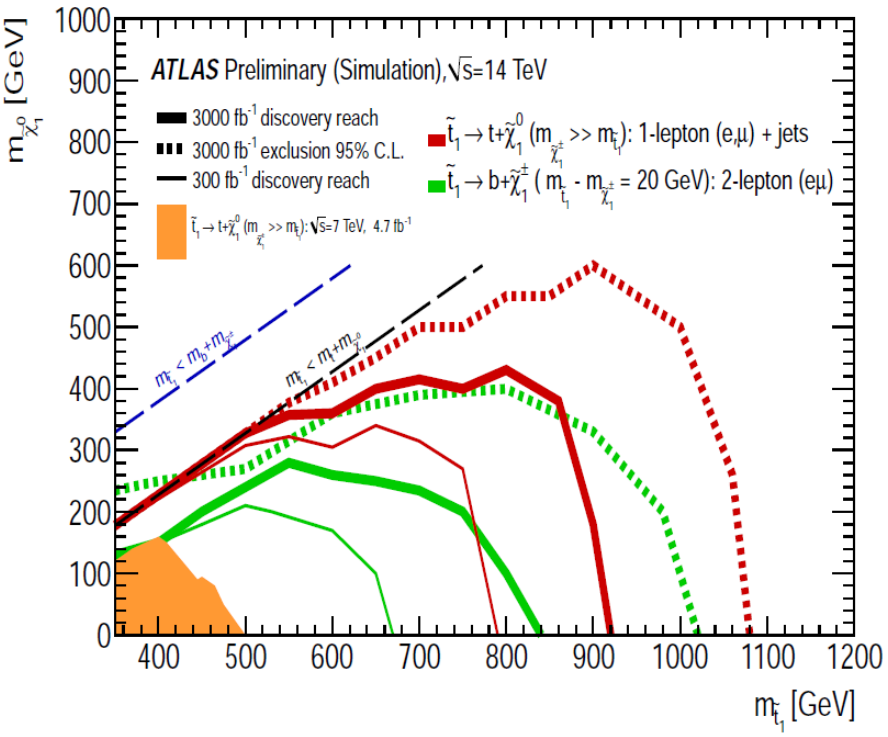

ATLAS Preliminary (Simulation)
√s = 14 TeV: ∫Ldt=300 fb-1 ; ∫Ldt=3000 fb-1
∫Ldt=300 fb-1 extrapolated from 7+8 TeV
Γ_Z / Γ_g
Γ_t / Γ_g
Γ_τ / Γ_μ
Γ_μ / Γ_Z
Γ_τ / Γ_Z
Γ_W / Γ_Z
Γ_γ / Γ_Z
Γ_g•Γ_Z / Γ_H
0
0.2
0.4
0.6
0.8
Δ(Γ_X/Γ_Y)/(Γ_X/Γ_Y) ~ 2 Δ(κ_X/κ_Y)/(κ_X/κ_Y)

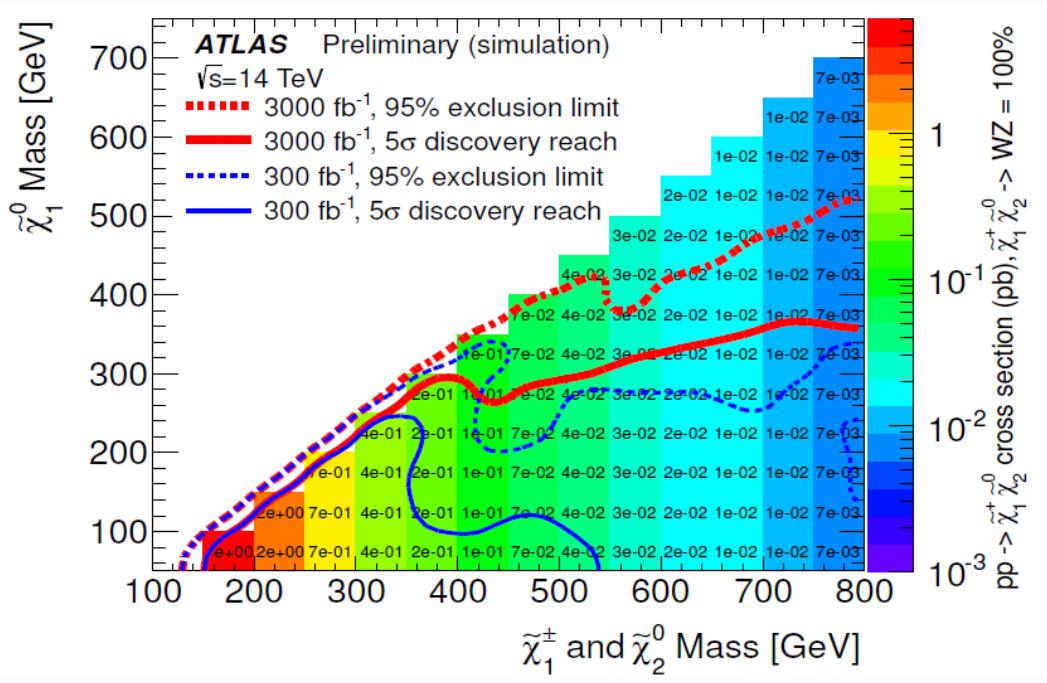
Conclusions



Back-up Slides


Squark-gluino grid, m_LSP = 0. √s = 14 TeV MET/√HT>15GeV^1/2
Z axis σ [pb]
3000 fb-1 discovery reach
300 fb-1 discovery reach
3000 fb-1 exclusion 95% CL
300 fb-1 exclusion 95% CL
Zn, sys=30%
ATLAS Preliminary (simulation)
m_g̃ [GeV]
m_q̃ [GeV]
σ [pb]

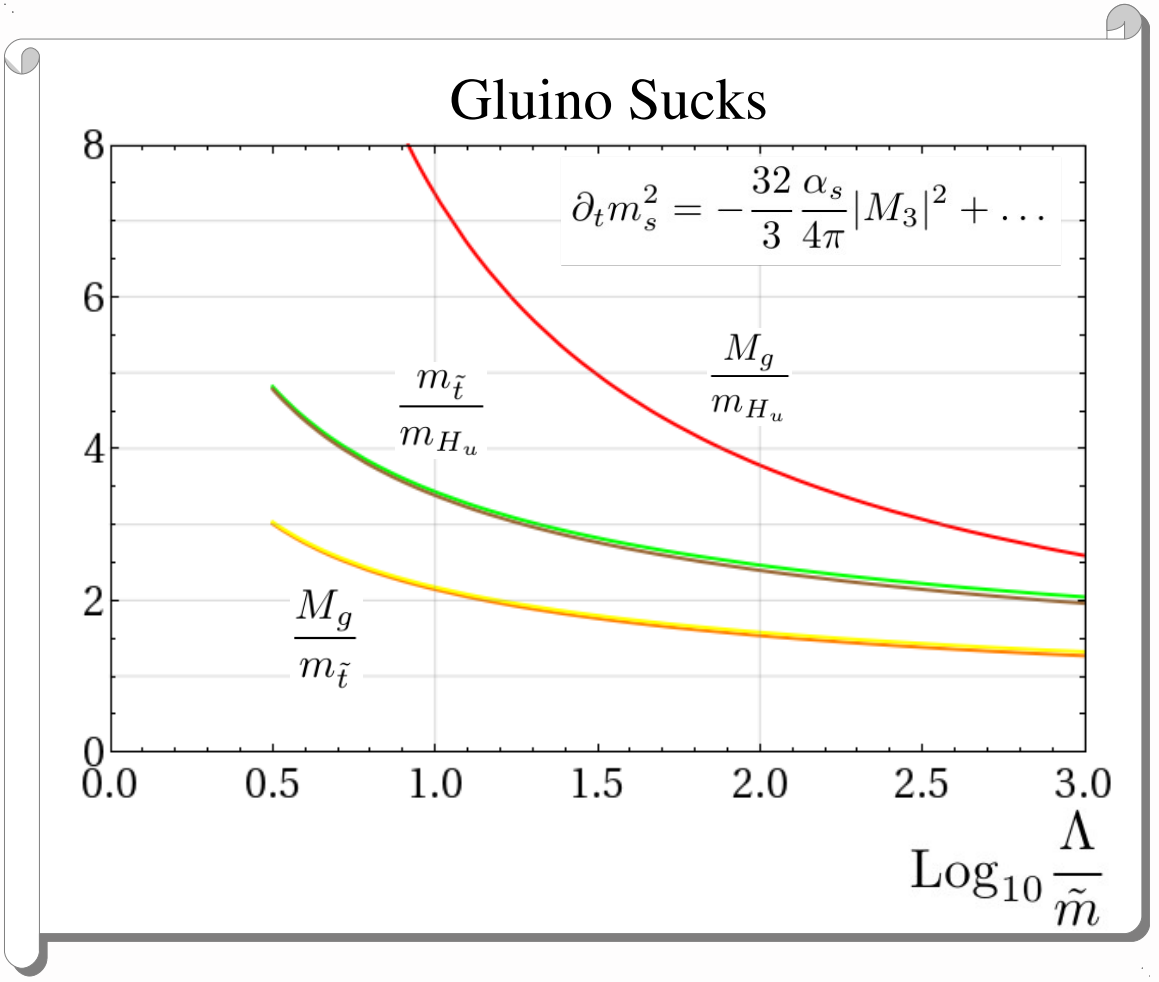

ATLAS Preliminary (Simulation), √s=14 TeV
3000 fb-1 discovery reach
3000 fb-1 exclusion 95% C.L.
300 fb-1 discovery reach
t̃1 → t+χ̃10 (mχ̃± >> mt̃1): 1-lepton (eμ) + jets
t̃1 → b+χ̃± (mt̃1 - mχ̃± = 20 GeV): 2-lepton (eμ)
mχ̃10 [GeV]
mt̃1 [GeV]


ATLAS Preliminary (simulation)
√s=14 TeV
3000 fb-1, 95% exclusion limit
3000 fb-1, 5σ discovery reach
300 fb-1, 95% exclusion limit
300 fb-1, 5σ discovery reach
χ̃10 Mass [GeV]
χ̃1± and χ̃20 Mass [GeV]
pp -> χ̃1+ χ̃20 cross section (pb), χ̃1+ χ̃20 -> WZ = 100%

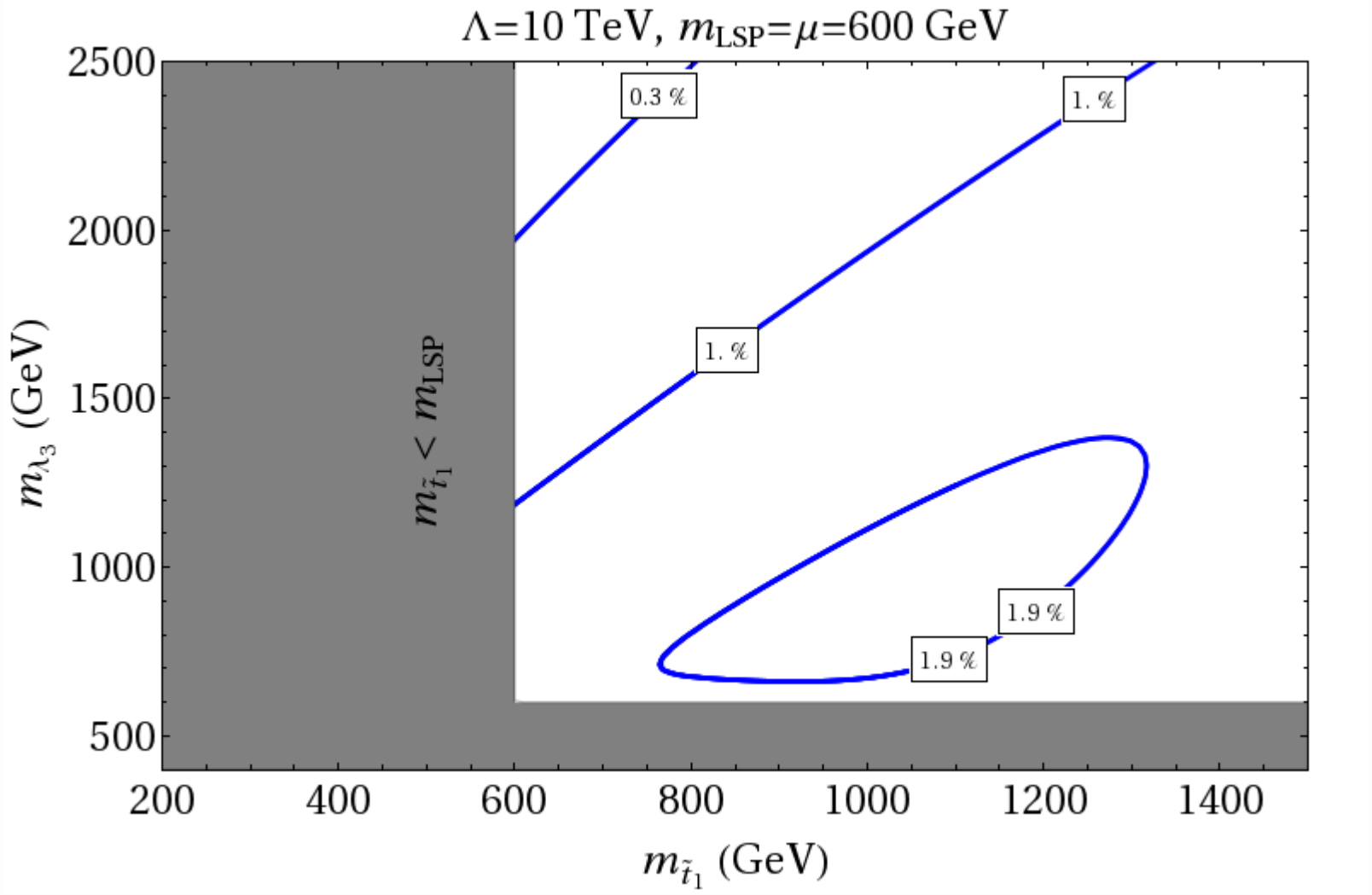
Natural SUSY

Mild cancellation (10% tuning) requires

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

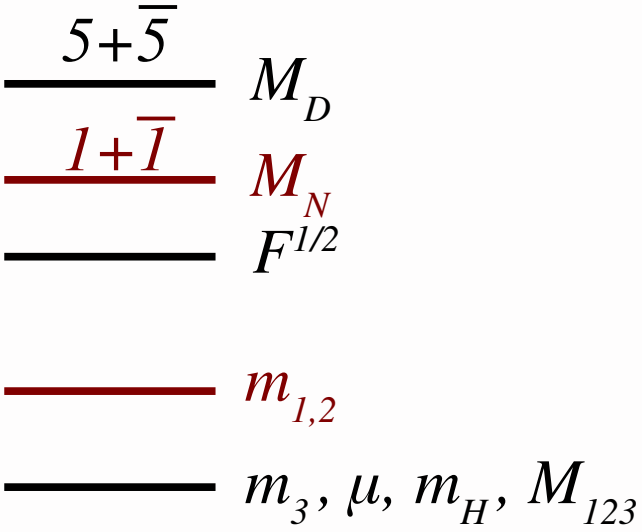


Is “Natural” SUSY Natural?



Is "Natural" SUSY Natural?

in progress with:
Arvanitaki, Baryakhtar, Gherghetta, Huang, Van Tilburg



$U(1)'_{B\text{-}L}$ for the first two generations

Gauge Mediation *(+ some Higgs mass fix)*

CKM mixing from: $\lambda_i Q_i H_d D_3 \frac{\Phi}{X_D}$

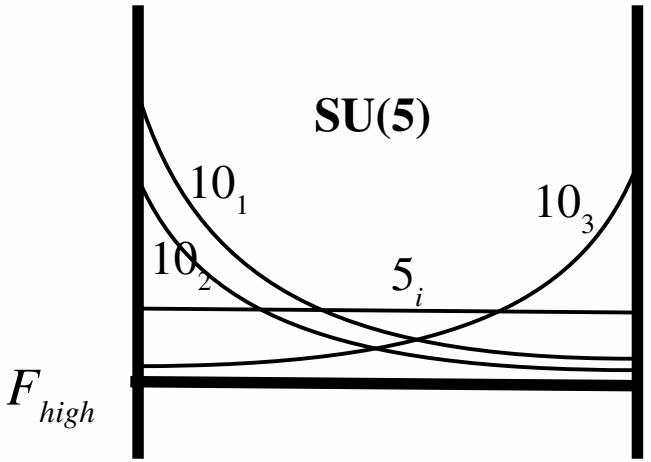
$$\varepsilon_K \text{ constraints } \rightarrow \; m_{1,2} \gtrsim \text{few TeV}$$

$$\Rightarrow \quad M_D > 10^7 \text{ GeV} \quad \Rightarrow \quad \textbf{few \% tuning}$$

*b*RPV SUSY:

- *Higgs fix*
- *low scale mediation (but not too low)*
- *extra susy breaking sector ($m_p < m_{3/2} < 5$ GeV)*
- *non-universal gaugino masses*
- *avoid vanilla spectra: leptons, W, Z ...*
- *hierarchical λ''*

a "simple" model:



SU(3)xSU(2)xU(1)

H_u, H_d

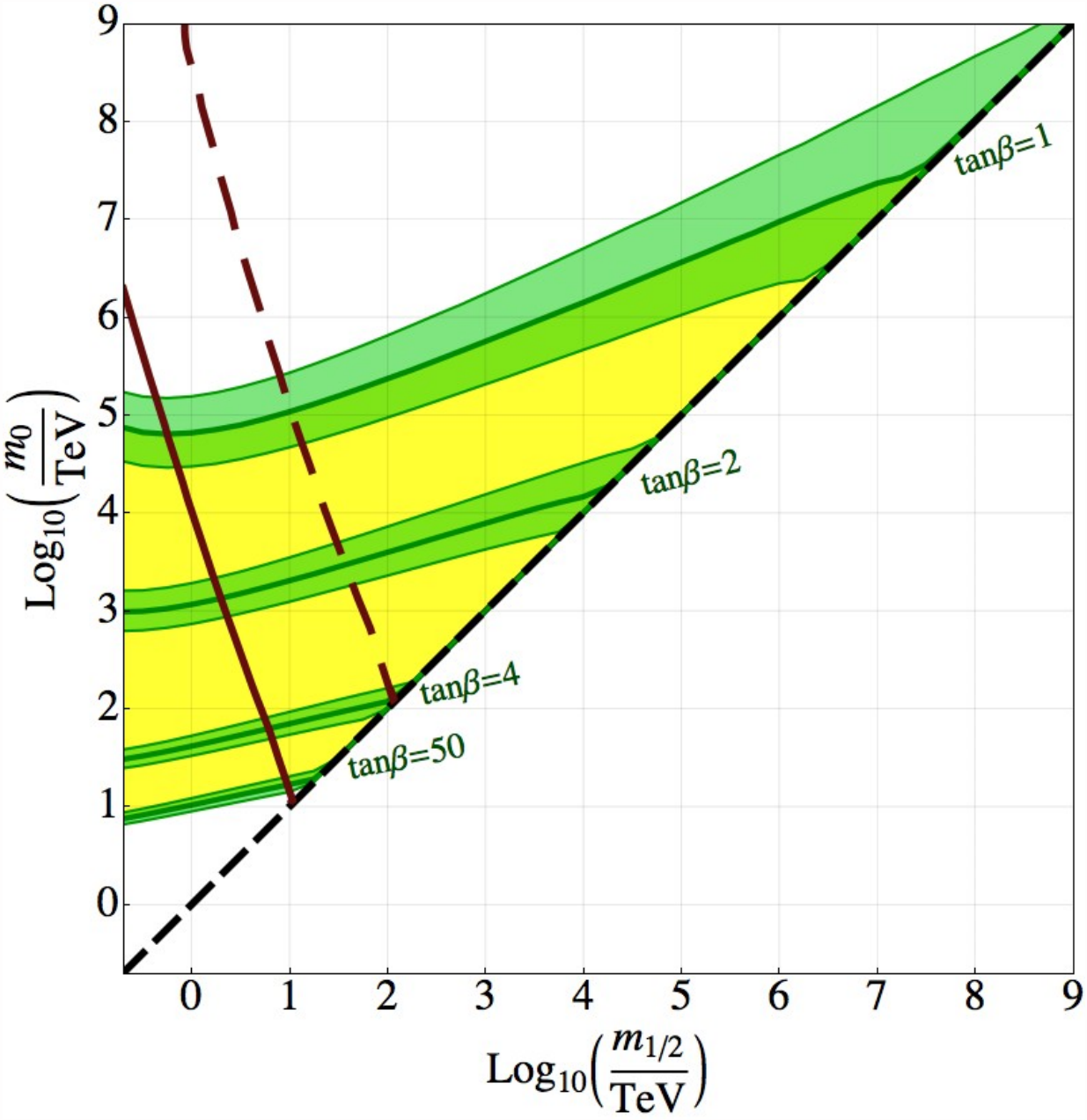
$$UD'D' + \Phi D\overline{D}' + M_D D'\overline{D}' \Rightarrow \frac{\langle\Phi\rangle^2}{M_{pl}^2} UDD$$

GM: F_{low} w/ 5+5 ($M_t > M_d$)

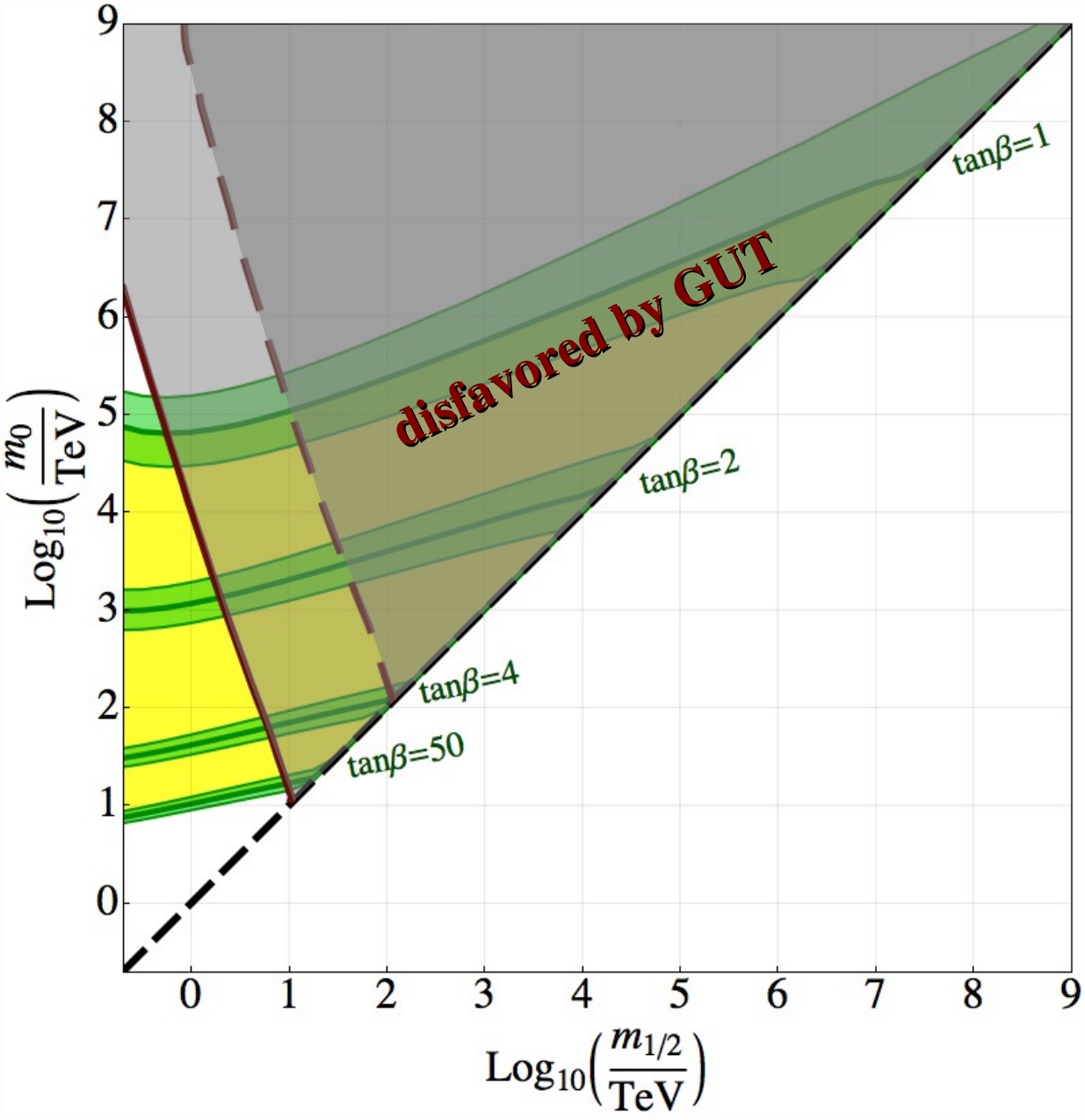
$$\lambda''_{ijk} = \frac{\langle\Phi\rangle^2}{M_{pl}^2} U_i(0) = \frac{\langle\Phi\rangle^2}{M_{pl}^2}\sqrt{y_i^u}$$

in progress with:
Arvanitaki, Baryakhtar, Gherghetta, Huang, Van Tilburg

more in general



more in general



Tuning the EWSB...

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

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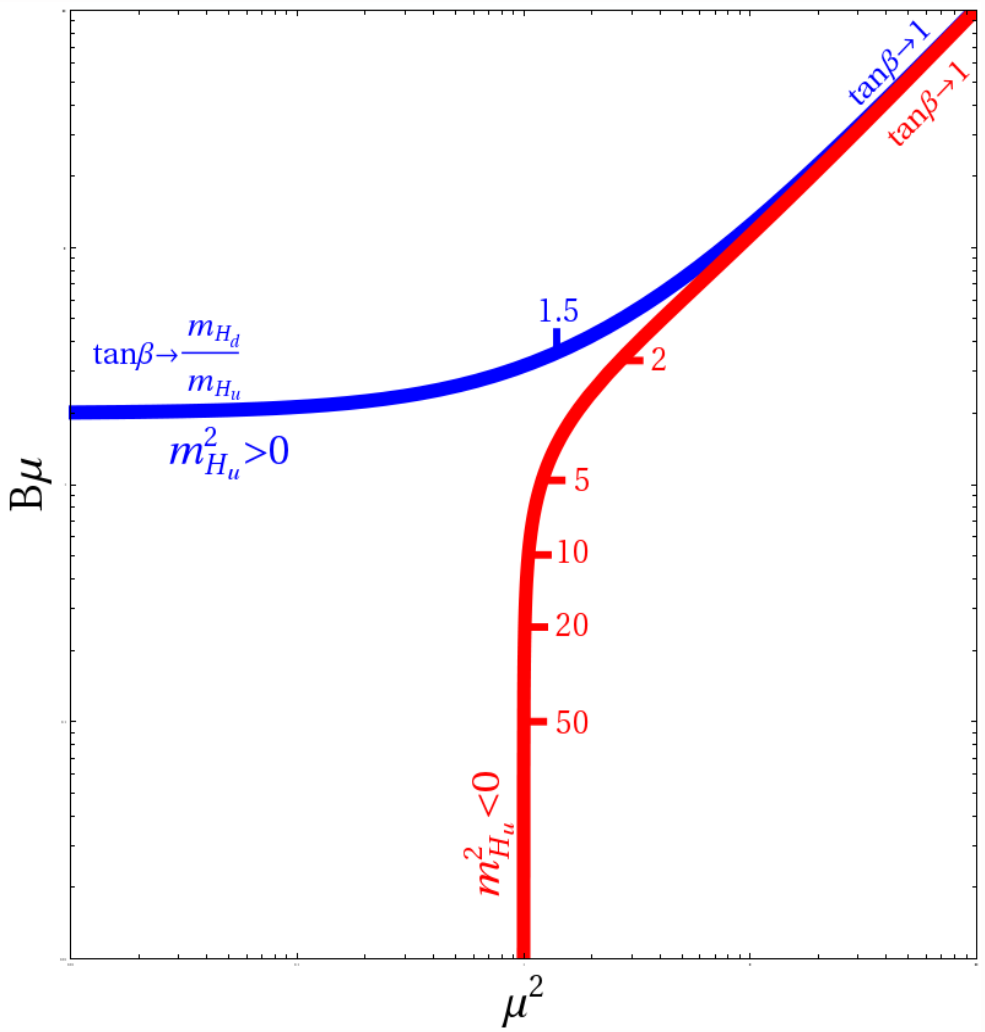

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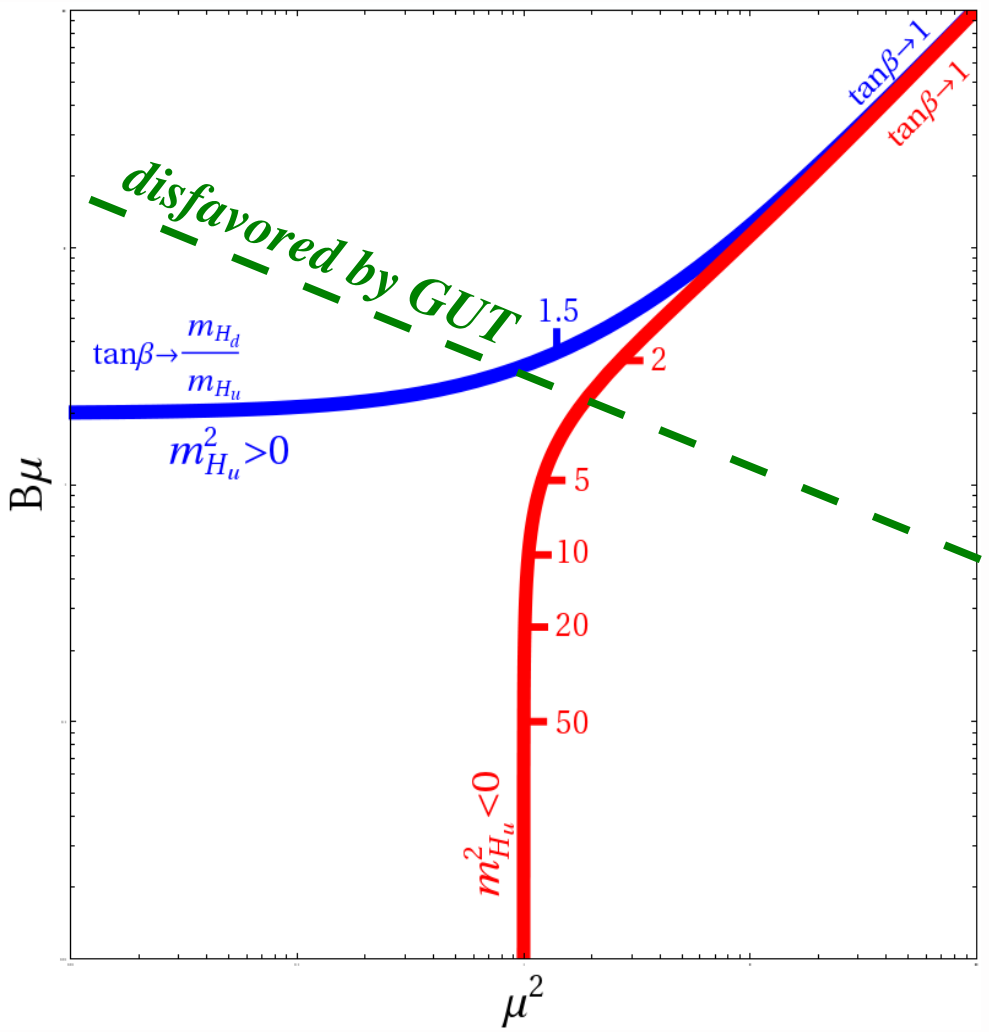

RGE and tachyons in Split

Yukawa

D-term

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

RGE and tachyons in Split

Yukawa

D-term

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

RGE and tachyons in Split

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

RGE and tachyons in Split

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

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

RGE and tachyons in Split

Yukawa

D-term

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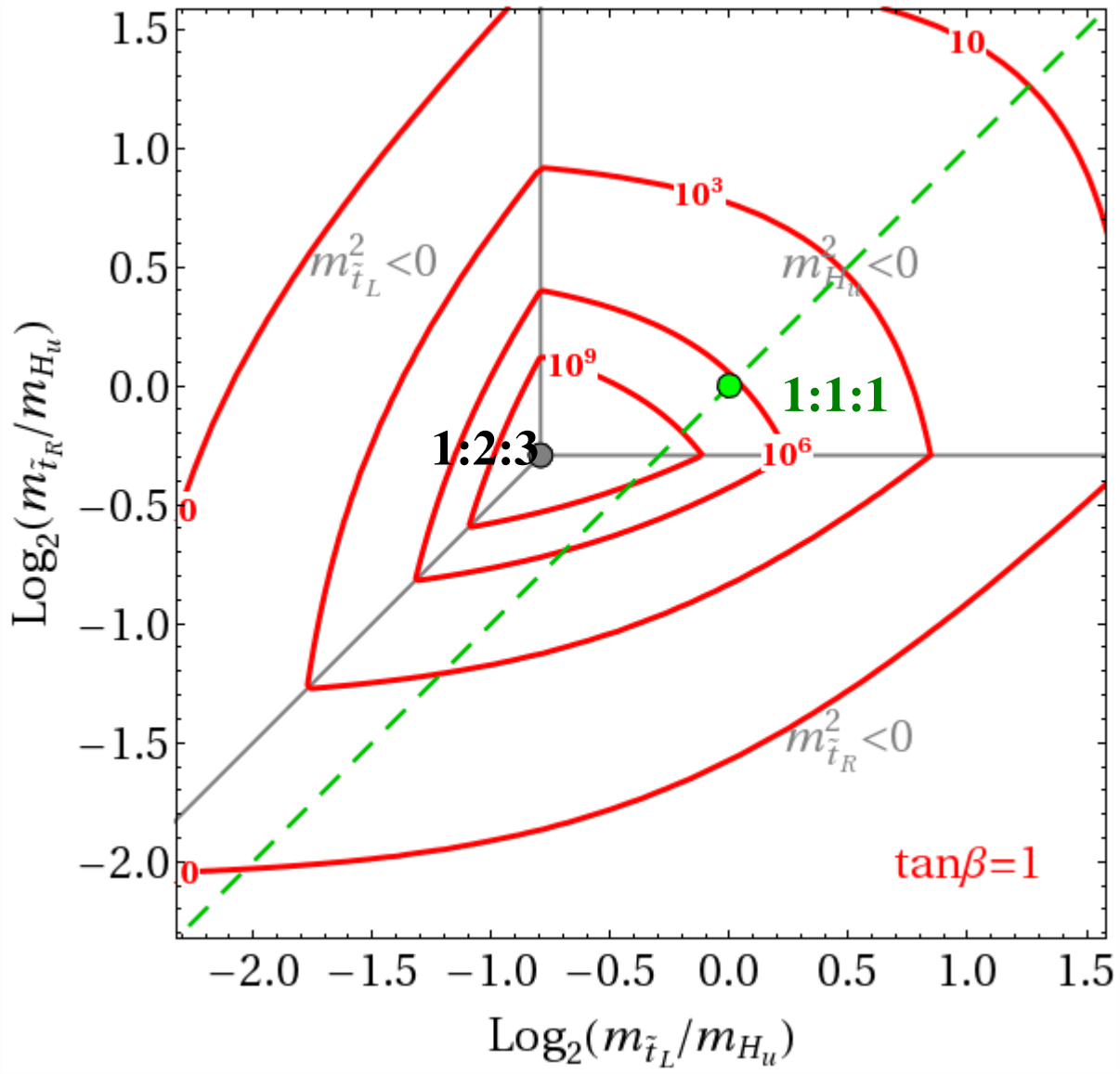
$$X_t = \frac{|y_t|^2}{8\pi^2}(m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2)$$

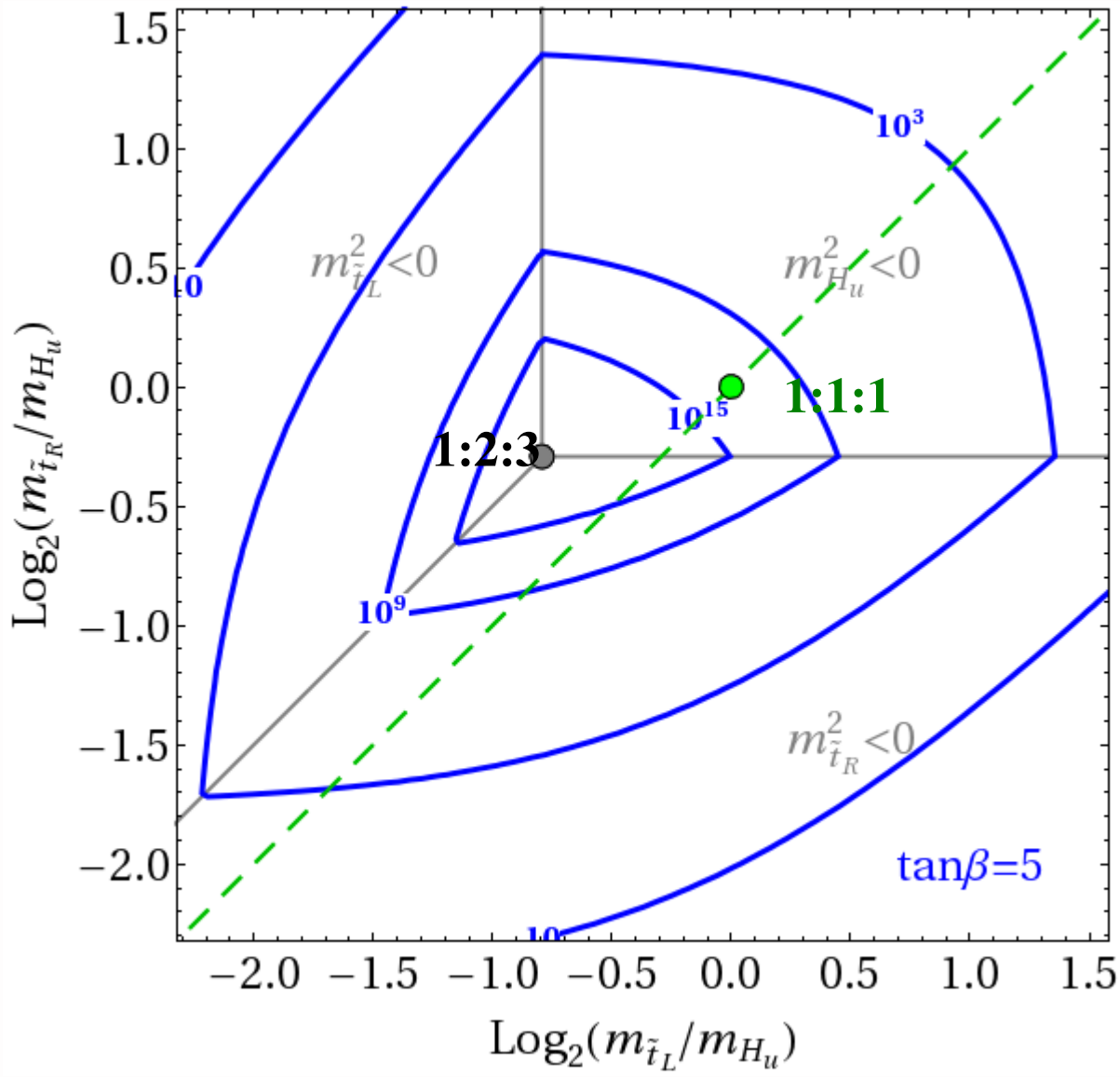
IR fixed point: $X_t \to 0 \quad \Rightarrow$ tachyon

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...

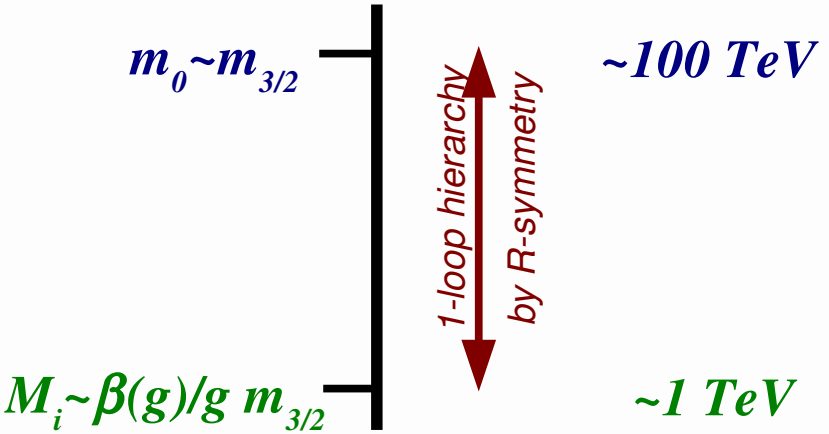


How much you can run...



Anomaly Mediation

Giudice, Luty, Murayama, Rattazzi '98



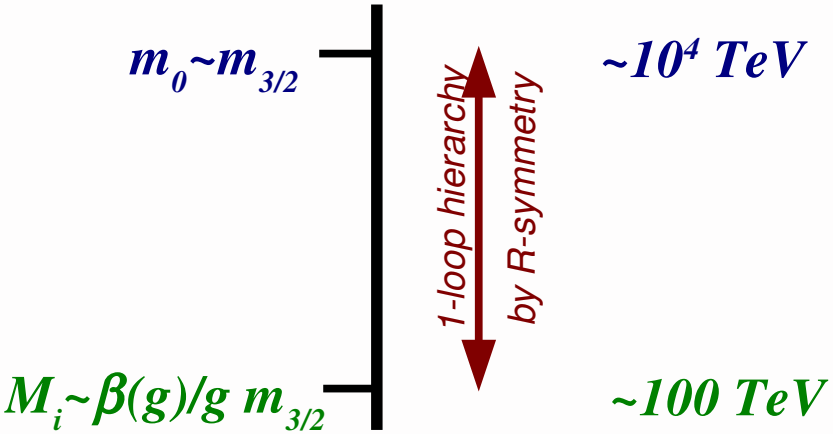
Light AMSB

- $\mu^2 \sim B_\mu \sim m_{3/2}^2$

  Giudice-Masiero or explicit μ-term
- $\tan\beta \sim 4$
- m_{Hu}^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

Very easy to get parametrically lighter gauginos:

– by suppresion of R-symmetry breaking in the hidden sector

– by accidental cancellations such as gaugino screening

Arkani-Hamed, Giudice, Luty, Rattazzi '98

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

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

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

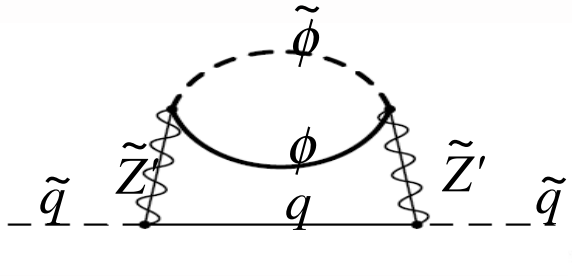
U(1)' Split SUSY

MSSM + U(1)':

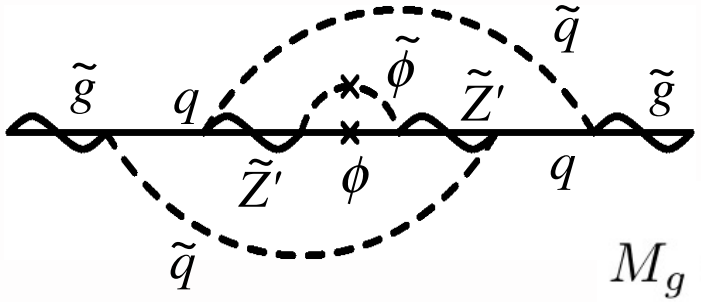
$$U(1)' = \cos(\theta)\, U(1)_{B\text{-}L} + \sin(\theta)\, U(1)_Y$$

SUSY breaking mediated by U(1)'

(⇔ mediators only charged under *B*-*L*)



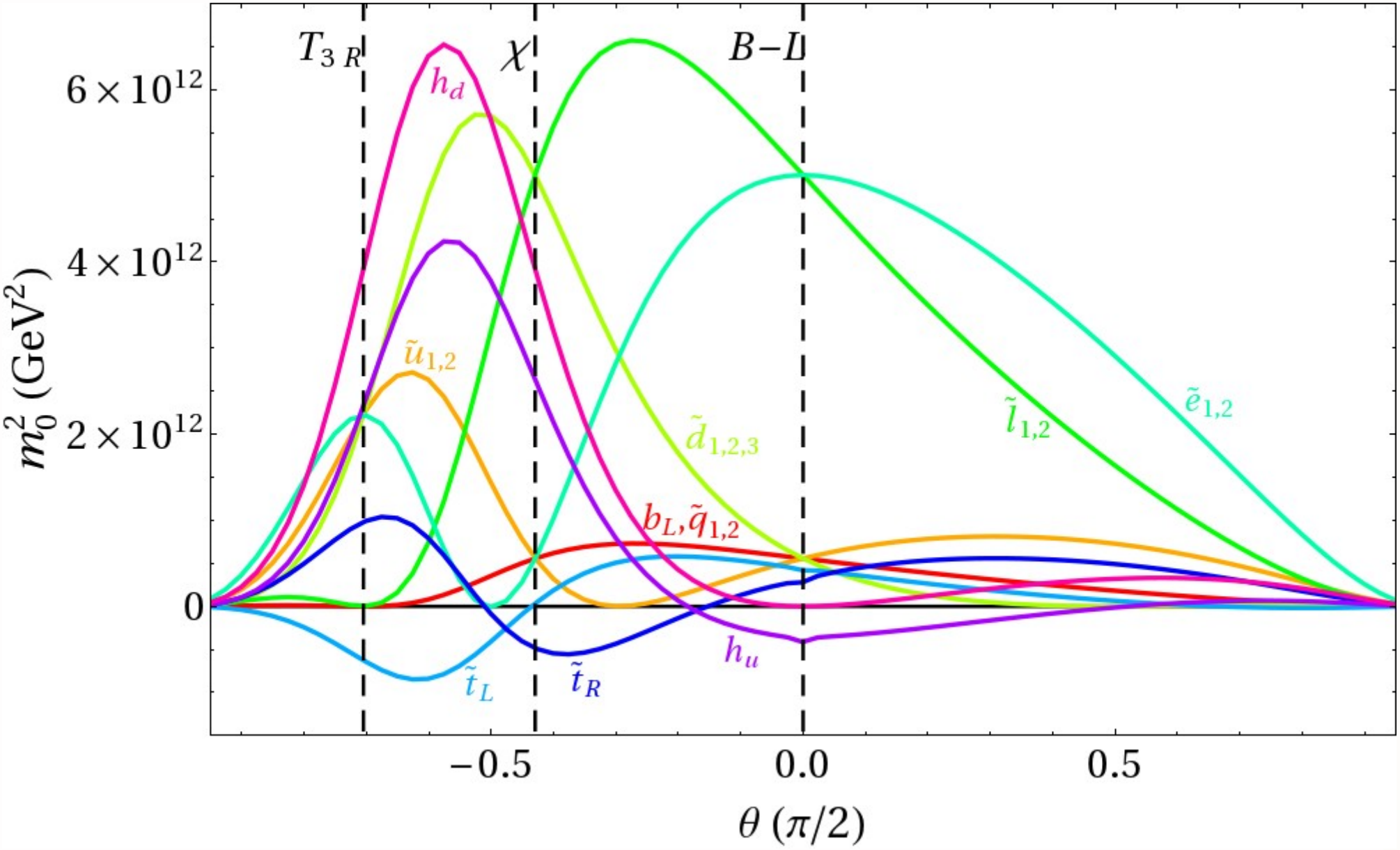
$$m_s^2 \propto \left(\frac{\alpha'}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$



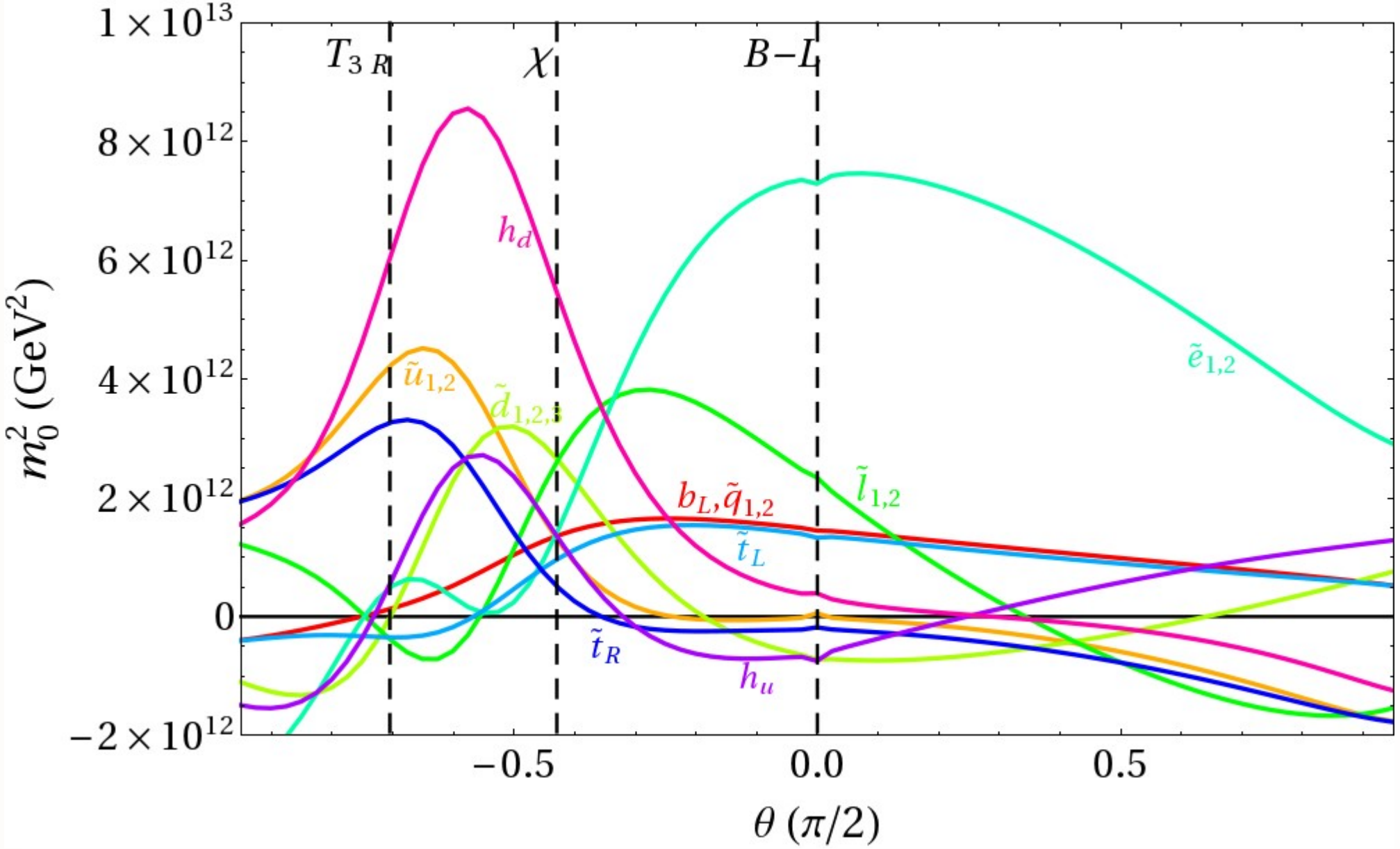
$$M_g \propto \frac{\alpha_g}{4\pi}\left(\frac{\alpha'}{4\pi}\right)^2 \frac{F}{M}$$

$$\frac{M_g}{m_s} \sim \frac{\alpha_g}{4\pi}\frac{\alpha'}{4\pi}$$

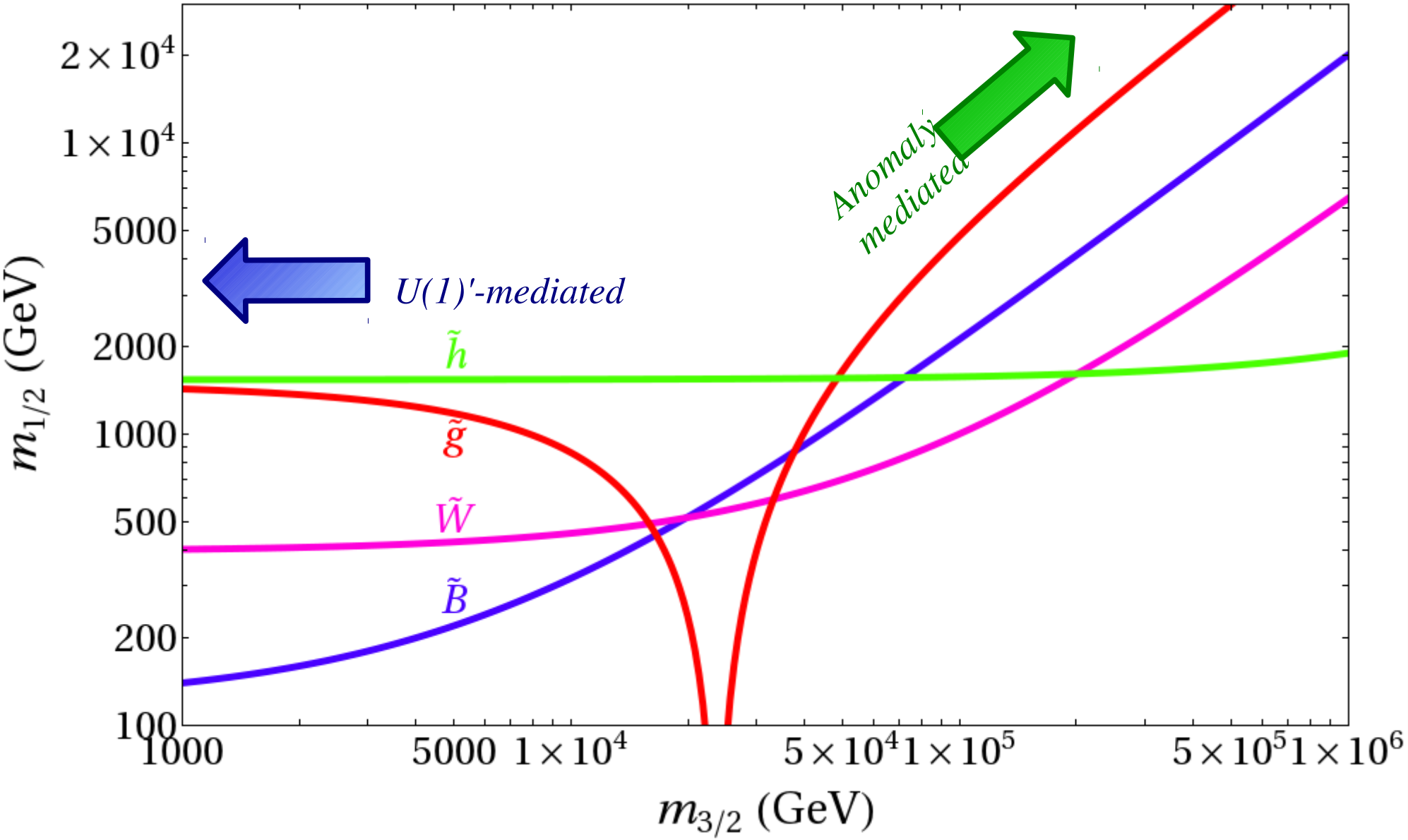
U(1)' spectrum with no D-terms



U(1)' spectrum with D-terms



U(1)' fermion spectrum



Higgs couplings in Split

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