LINKING NATURAL SUSY TO FLAVOUR PHYSICS

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Outline

- Supersymmetry and naturalness
- Flavor and inverted hierarchy/natural SUSY

 - U(1) and U(2) models

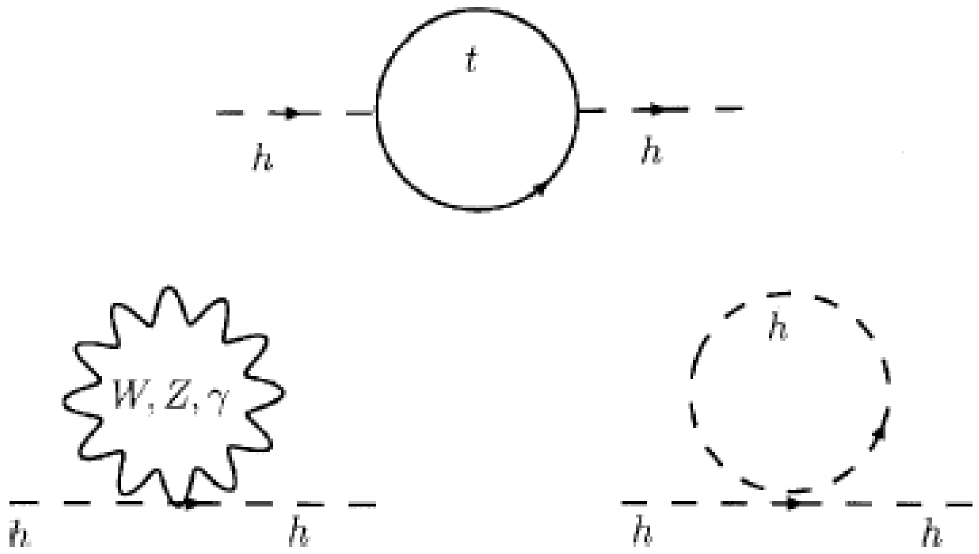
- U(1) x (discrete subgroup of) SU(2)

- Conclusions

Supersymmetry and naturalness

The **hierarchy problem** (mis?)guided BSM physics for the last 30 years.

$$\delta m_h^2 \simeq \frac{3\Lambda^2}{8\pi^2 v^2}(4m_t^2 - 4M_W^2 - 2M_Z^2 - m_h^2)$$



⇨ there should be new physics in the TeV range,
to keep Higgs naturally light ?

Traditional solutions fall into three categories :

a) low-energy supersymmetry (SUSY) $M_{SUSY} \sim TeV$

b) strong dynamics (technicolor, RS, composite Higgs scalar models)

c) TeV strings/quantum gravity, with or without SUSY

$$M_s \sim M_\star \sim TeV$$

a) Supersymmetry is still the simplest and most elegant solution to the hierarchy problem.

$$\delta m_h^2 \approx \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\mathrm{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12 M_{\mathrm{SUSY}}^2}\right)\right]$$

where and M_{SUSY} (A_t) denotes the average stop mass (mass mixing in the stop sector).

Electroweak scale natural for light higgsinos,gluinos,stops and L-handed sbottom:

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

$$\delta m_{H_u}^2 \approx -\frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2}(1 + a^2/2)\log\frac{\Lambda}{m_{\tilde{t}}}$$

$$\delta m_{\tilde{t}}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \log\frac{\Lambda}{M_3}$$

(More) Natural SUSY models:

- Natural SUSY/inverted hierarchy/split families :
light stops,gluinos,higgsinos (TeV)
heavier 1,2 generations (10-15 TeV)
- Extended scalar and/gauge sector (ex: NMSSM)
- RPV models (ex. baryonic RPV, operators UDD)
- Dirac gauginos
- Spectrum more degenerate/decays stealthy…

(Less) Natural SUSY theories :
- Mini-split/Spread SUSY models
- Split SUSY models: $m_{\text{scalars}} >> m_{\text{fermions}}$
- High-scale SUSY

SUSY hints from LHC searches and SM scalar mass :

- LHC direct SUSY searches and Higgs mass

set new limits on superpartner masses for simple (simplified) SUSY models $m_{gluinos}, m_{squarks} \geq 1.5\ TeV$

Popular models: mSUGRA, CMSSM, minimal gauge mediation with TeV superpartner masses have difficulties in accomodating the data in a natural way .

- However, from a UV viewpoint (supergravity, string theory), popular models are unnatural.

It is important to theoretically analyze and experimentally search for non-minimal SUSY models.

Inverted hierarchy/Natural SUSY

An old scenario which became popular recently because of LHC constraints:

- third generations squarks and gauginos in the TeV range (light stops).
- First two generation scalars much heavier (10-15 TeV). They affect little the tuning of the electroweak scale.

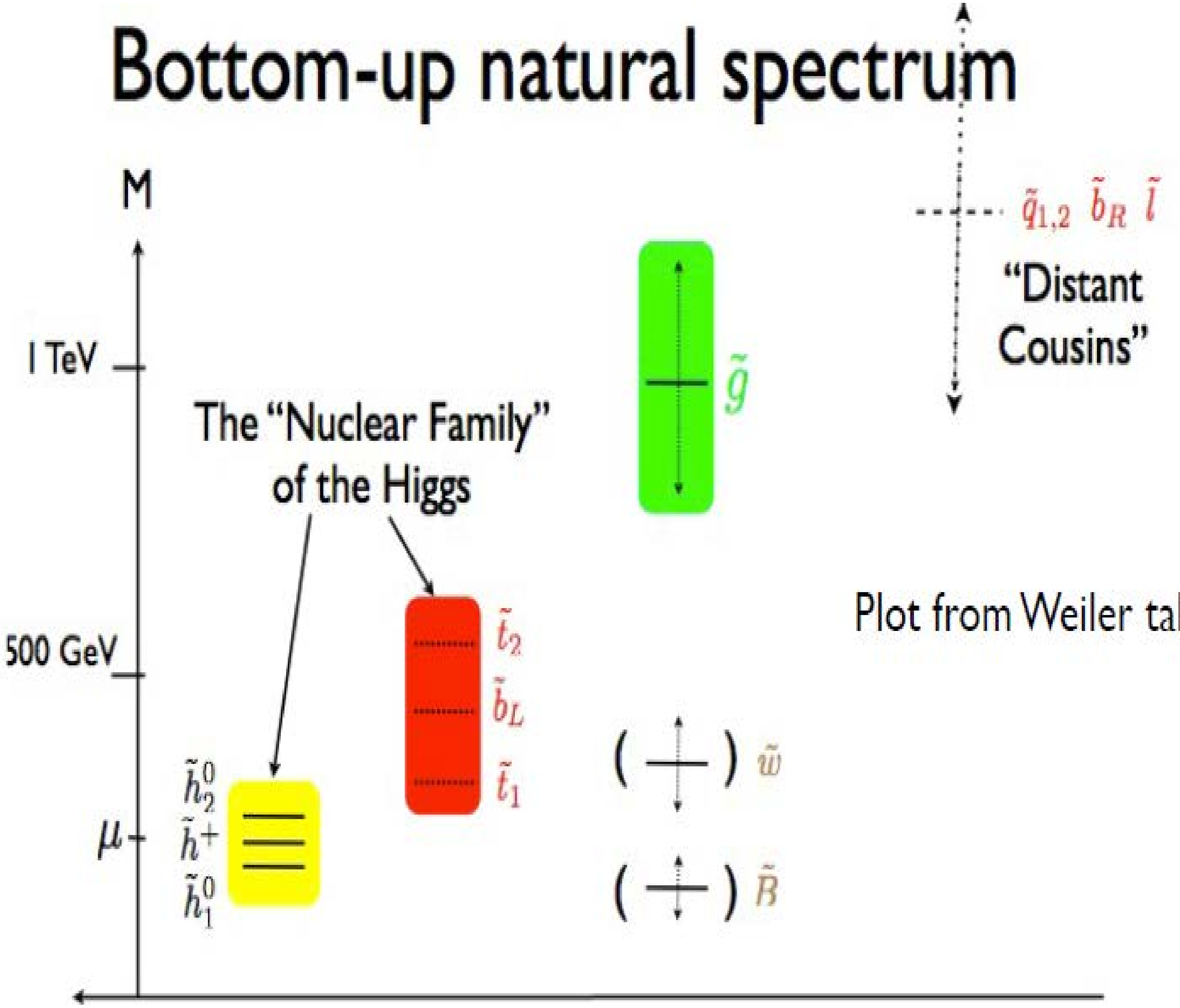
This is natural in flavor models and holographic constructions.

1) Simplest example: U(1) gauged flavor symmetry (Froggatt-Nielsen,79). Quark mass matrices given by

$$h_{ij}^U \sim \epsilon^{q_i+u_j+h_u} \quad , \quad h_{ij}^D \sim \epsilon^{q_i+d_j+h_d} \ ,$$

where typically $\epsilon = \frac{\langle \Phi \rangle}{M} \sim \lambda = 0.22$ and q_i are charges of left-handed quarks, etc.

Bottom-up natural spectrum



Plot from Weiler talk on natural susy

Quarks masses and mixings are given by ($q_{13} = q_1 - q_3$,etc)

$$\frac{m_u}{m_t} \sim \epsilon^{q_{13}+u_{13}} \; , \; \frac{m_c}{m_t} \sim \epsilon^{q_{23}+u_{23}} \; , \; \frac{m_d}{m_b} \sim \epsilon^{q_{13}+d_{13}} \; , \; \frac{m_s}{m_b} \sim \epsilon^{q_{23}+d_{23}}$$

$$\sin\theta_{12} \sim \epsilon^{q_{12}} \quad , \quad \sin\theta_{13} \sim \epsilon^{q_{13}} \quad , \quad \sin\theta_{23} \sim \epsilon^{q_{23}} \; .$$

Good fit to to data ⇨ larger charges for the lighter generations

$$q_1 > q_2 > q_3 \quad , \quad u_1 > u_2 > u_3 \quad , \quad d_1 > d_2 > d_3$$

$$m_t \sim 1 \qquad m_c \sim \epsilon^4 \qquad m_u \sim \epsilon^8$$

$$m_b \sim \epsilon^3 \qquad m_s \sim \epsilon^{5\div 6} \qquad m_d \sim \epsilon^{7\div 8}$$

$$m_\tau \sim \epsilon^3 \qquad m_\mu \sim \epsilon^5 \qquad m_e \sim \epsilon^9$$

$$V_{us} \sim \epsilon \qquad V_{ub} \sim \epsilon^3 \qquad V_{cb} \sim \epsilon^2$$

Gauge anomalies $\Rightarrow$ constraints on the charges

$$K \sim \frac{X^\dagger X}{\Lambda_S^2} \left(\frac{\phi}{\Lambda_F} \right)^{|q_i - q_j|} Q_i^\dagger Q_j$$ $\Rightarrow$ F-term contributions to scalar masses.

There are also D-term contributions, so

scalar masses are of the form

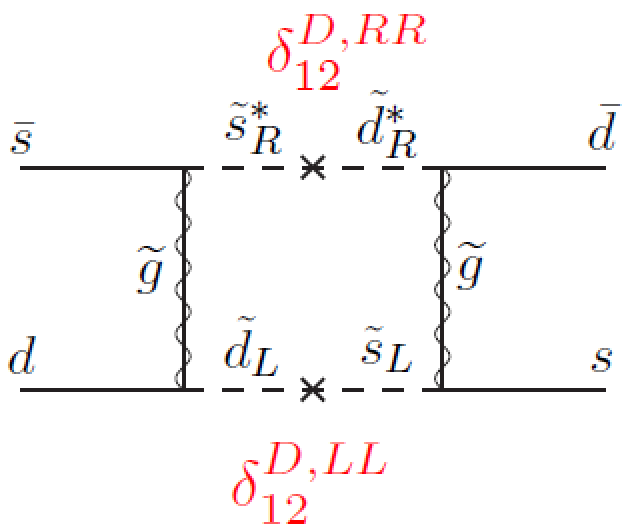
$$m_{ij}^2 = X_i \langle D \rangle + a_{ij} \langle F \rangle$$

If $< D >>>< F >$ then an inverted hierarchy is generated.

This can be realized in explicit models (E.D.,Pokorski,Savoy; Binetruy,E.D.; Dvali,Pomarol,94-96)

Obs: 1-2 generations cannot be too heavy $\Rightarrow$ tachyonic stops (Pomarol,Tommasini;Arkani-Hamed,Murayama)

Nowdays, FCNC constrain seriously these models;
need some degeneracy 1,2 generations.



$$\sim \frac{1}{m^2} \delta_{12}^{D,LL} \delta_{12}^{D,RR} \sim \frac{1}{m^2} \frac{m_d}{m_s}$$

⇨ $q_1 = q_2 \ , q_3 = 0$ if not m > 100 TeV or so.

But then m_{12}^2 squark mass not protected by the U(1) symmetry

There is a challenge to explain simultaneously fermion masses and FCNC within one flavour theory !

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

TABLE I: Bounds on representative dimension-six $\Delta F = 2$ operators. Bounds on Λ are quoted assuming an effective coupling $1/\Lambda^2$, or, alternatively, the bounds on the respective c_{ij}'s assuming $\Lambda = 1$ TeV. Observables related to CPV are separated from the CP conserving ones with semicolons. In the B_s system we only quote a bound on the modulo of the NP amplitude derived from Δm_{B_s} (see text). For the definition of the CPV observables in the D system see Ref. [15].

2) FCNC constraints are better enforced by non-abelian symmetries.

A popular example: U(2) = SU(2) x U(1) flavor symmetry (Pomarol,Tommasini; Barbieri,Dvali,Hall…)

- 1st,2nd generations : U(2) doublets, scalars degenerate
- 3rd generation: singlet

Here, FCNC are largely suppressed.

$$\Delta C_1 \sim \frac{\alpha_s^2}{m_{\tilde{g}}^2} \Big[\underbrace{(Z_D^L)_{13}^* (Z_D^L)_{23}}_{\hat{\delta}_{12}^{D,LL}} \Big]^2 \left[f_4(x_1,x_1) - 2 f_4(x_1,x_3) + f_4(x_3,x_3) \right]$$

$\hat{\delta}_{12}^{D,LL} \longleftarrow$ known from fermion sector

$\sim V_{cb}^2 \sqrt{m_d/m_s}$

where $x_i = \frac{m_i^2}{M_{\tilde{g}}^2}$ and f_4 are loop functions.

However, there are two problems :

- One with the CKM elements:

$$|V_{td}/V_{ts}| = \sqrt{m_d/m_s}\ \left[1+\mathcal{O}(\epsilon^2)\right]$$

$0.22 \pm 0.01 \qquad 0.22 \pm 0.02$

$\mathcal{O}(10^{-3})$

$$|V_{ub}/V_{cb}| = \sqrt{m_u/m_c}\ \left[1+\mathcal{O}(\epsilon^2)\right]$$

$0.085 \pm 0.004 \qquad 0.046 \pm 0.008$

- Another possible problem : $\tan\beta$ typically large. Then the minimal natural SUSY spectrum with heavy $\tilde{b}_R$ had difficulties with RG running from GUT to EW scale

Possible to combine abelian+non-abelian flavor symmetries in a constructive way: U(1) x D'_n, where D'_n is a discrete non-abelian subgroup of SU(2) (DGPZ)

$$U(1) \qquad\qquad\qquad U(2)$$

protect ϵ_K $\qquad$ correct V_{ub}/V_{cb}

$$SU(2) \times U(1)$$

Split spectrum from U(1) D-term

$\tilde{m}_D$ $\quad \sim 10\,\mathrm{TeV} \quad \tilde{q}_{1,2}, \tilde{b}_R, \tilde{\tau}_L$

$\tilde{m}_F$ $\quad \sim 1\,\mathrm{TeV} \quad \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{\tau}_R \quad \mu, B_\mu, \tilde{m}^2_{H_u}, \tilde{m}^2_{H_d}, M_i, A$

	10_a	10_3	$\overline{5}_a$	$\overline{5}_3$	H_u	H_d	ϕ^a	χ
$SU(2)$	2	1	2	1	1	1	$\overline{2}$	1
$U(1)$	X_{10}	0	$X_{\overline{5}}$	X_3	0	0	X_ϕ	-1

Table 1: Flavor group representations of the model.

$$\langle \phi^a \rangle = \epsilon_\phi \Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad , \qquad \langle \chi \rangle = \epsilon_\chi \Lambda$$

Model	ϵ_ϕ	ϵ_χ	$\tan\beta$	X_ϕ	X_{10}	X_5	X_3
A	0.02	0.02	5	-1	1	1	1
B	0.1	0.2	5	-2	3	3	2
B′	0.1	0.2	20	-2	3	2	1
C	0.2	0.1	50	-1	2	1	0

Table 2: Possible choices of parameters compatible with the fit to fermion masses and mixings.

The Yukawa matrices are given by

$$Y_u = \begin{pmatrix} 0 & h^u_{12}\epsilon'_u & 0 \\ -h^u_{12}\epsilon'_u & h^u_{22}\epsilon^2_u & h^u_{23}\epsilon_u \\ 0 & h^u_{32}\epsilon_u & h^u_{33} \end{pmatrix} ,$$

$$Y_d = \begin{pmatrix} 0 & h^d_{12}\epsilon'_u\epsilon_d/\epsilon_u & 0 \\ -h^d_{12}\epsilon'_u\epsilon_d/\epsilon_u & h^d_{22}\epsilon_u\epsilon_d & h^d_{23}\epsilon_3\epsilon_u \\ 0 & h^d_{32}\epsilon_d & h^d_{33}\epsilon_3 \end{pmatrix} ,$$

with

$$\epsilon_u \equiv \epsilon_\phi \epsilon_\chi^{X_{10}+X_\phi}, \qquad \epsilon_d \equiv \epsilon_\phi \epsilon_\chi^{X_{\bar{5}}+X_\phi}, \qquad \epsilon'_u \equiv \epsilon_\chi^{2X_{10}}, \qquad \epsilon_3 \equiv \epsilon_\chi^{X_3}.$$

We find

$$\mathrm{Im}\,\Delta C_4 \approx \frac{2}{3}\alpha_s^2 \frac{m_d}{m_s}|V^d_{23}|^2 s^2_d \sin 2\tilde{\alpha}_{12}\left(\tilde{m}^2_{d_R} - \tilde{m}^2_{b_R}\right) \frac{\log\left(\frac{\tilde{m}_{d_R}}{m_{\tilde{g}}}\right) + \frac{1}{4}}{(\tilde{m}_{d_R})^4}$$

$$\approx 1.6 \times 10^{-8} \left(\frac{|V^d_{23}|}{0.04}\right)^2 \left(\frac{s^2_d}{0.2}\right)\left(\frac{\sin\alpha_{12}}{0.5}\right)\left(\tilde{m}^2_{d_R} - \tilde{m}^2_{b_R}\right) \frac{\log\left(\frac{\tilde{m}_{d_R}}{m_{\tilde{g}}}\right) + \frac{1}{4}}{(\tilde{m}_{d_R})^4}$$

where $t_d \equiv \tan\theta_d \equiv \dfrac{|h^d_{32}|\epsilon_d}{|h^d_{33}|\epsilon_3}$

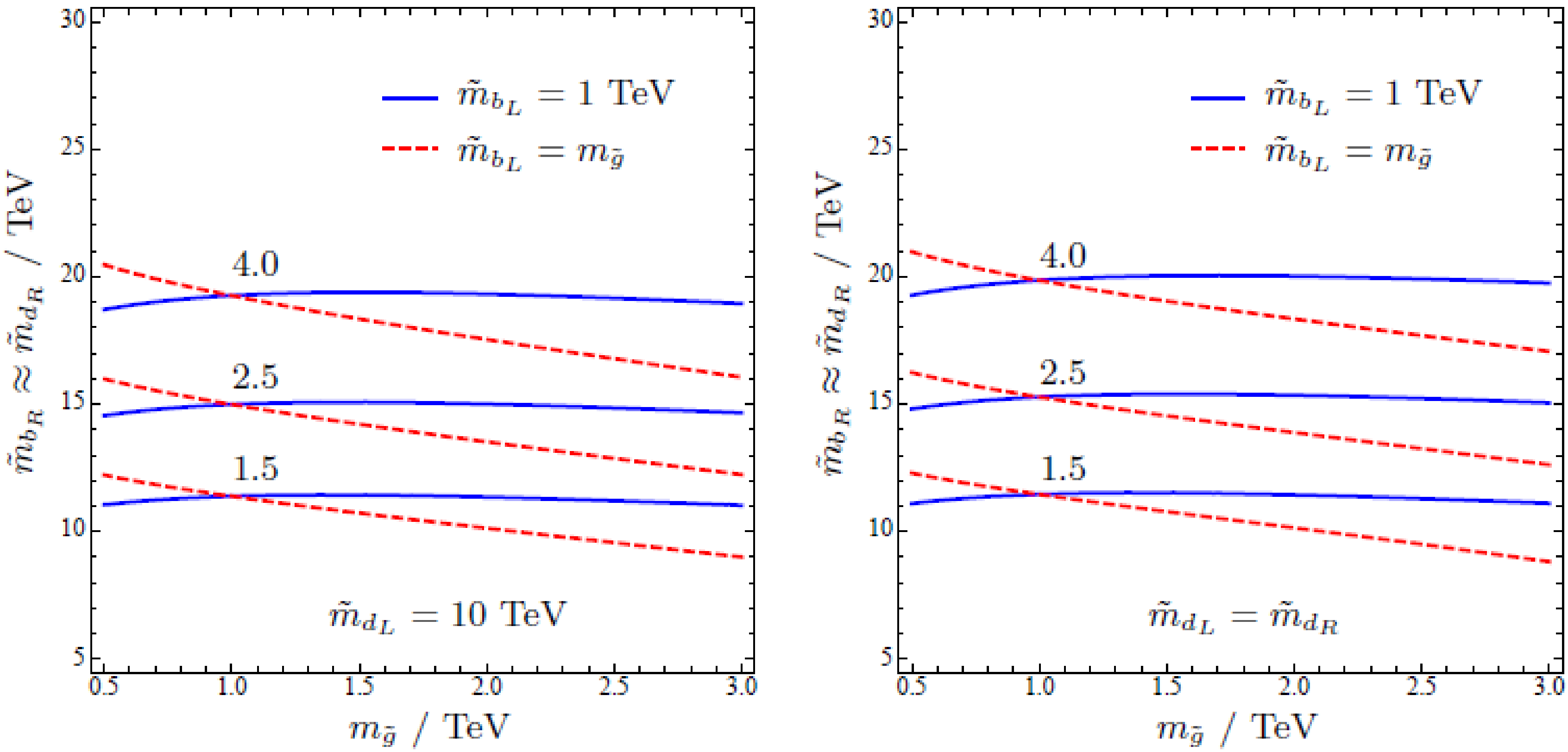


Figure 1: Bounds on the masses of the gluino and the approximately degenerate right handed down squark sector for various choices of the parameters. The region below each line is excluded. The three lines correspond to different choices of the dominant 3-1 splitting, namely $\tilde{m}^2_{d_R} - \tilde{m}^2_{b_R} = (1.5,\ 2.5,\ 4.0\ \text{TeV})^2$. The remaining parameters are chosen as $|V^d_{23}| = 0.04$, $\sin(\alpha_{12}) = 0.5$ and $s^2_d = 0.2$. The decoupling of the gluino occurs outside the displayed range of the gluino mass.

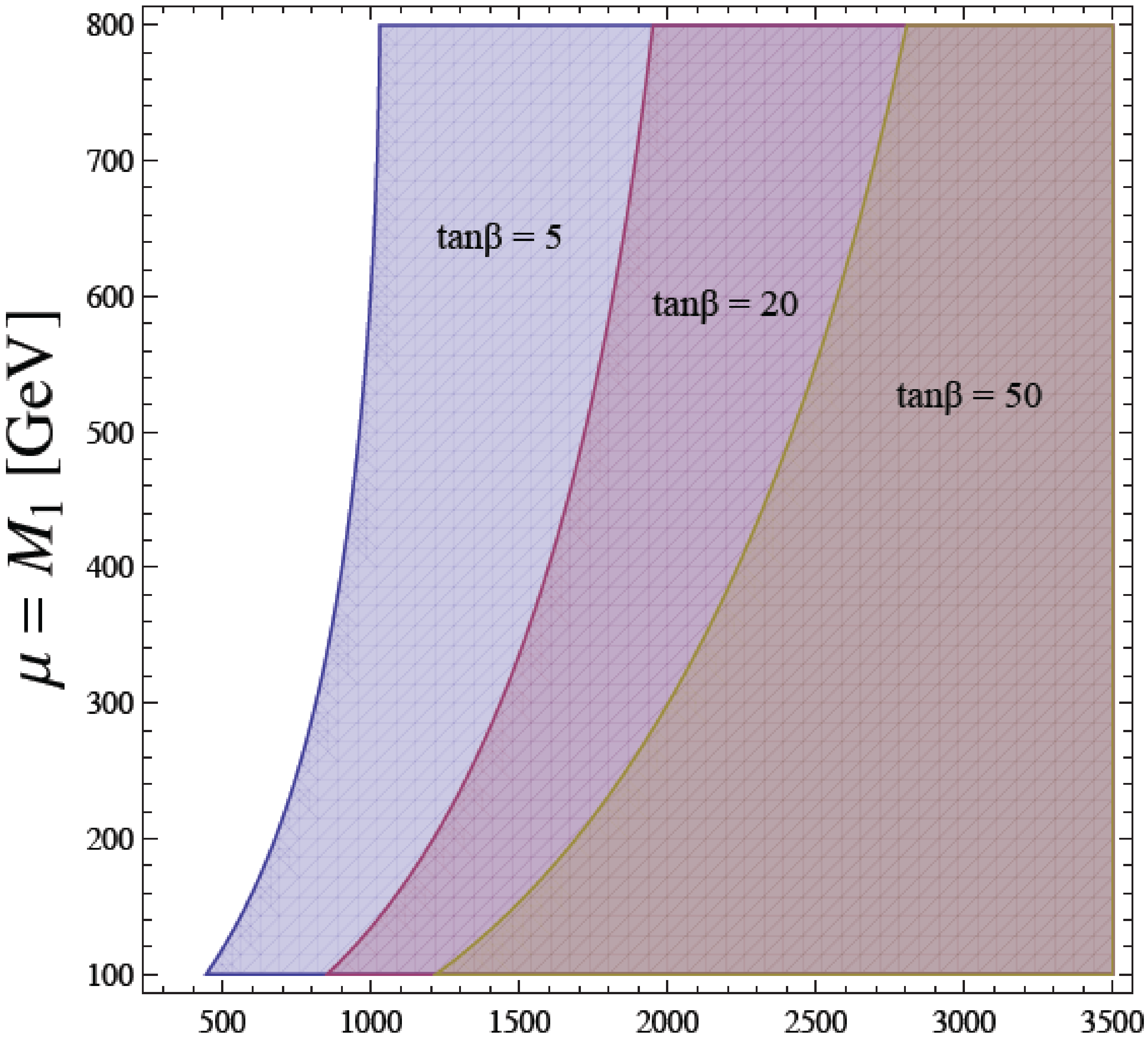


Figure 2: Allowed region from BR($\mu \to e\gamma$) constraint in the $M_1/m_{\tilde{\tau}_R}$ plane for $\mu = M_1$.

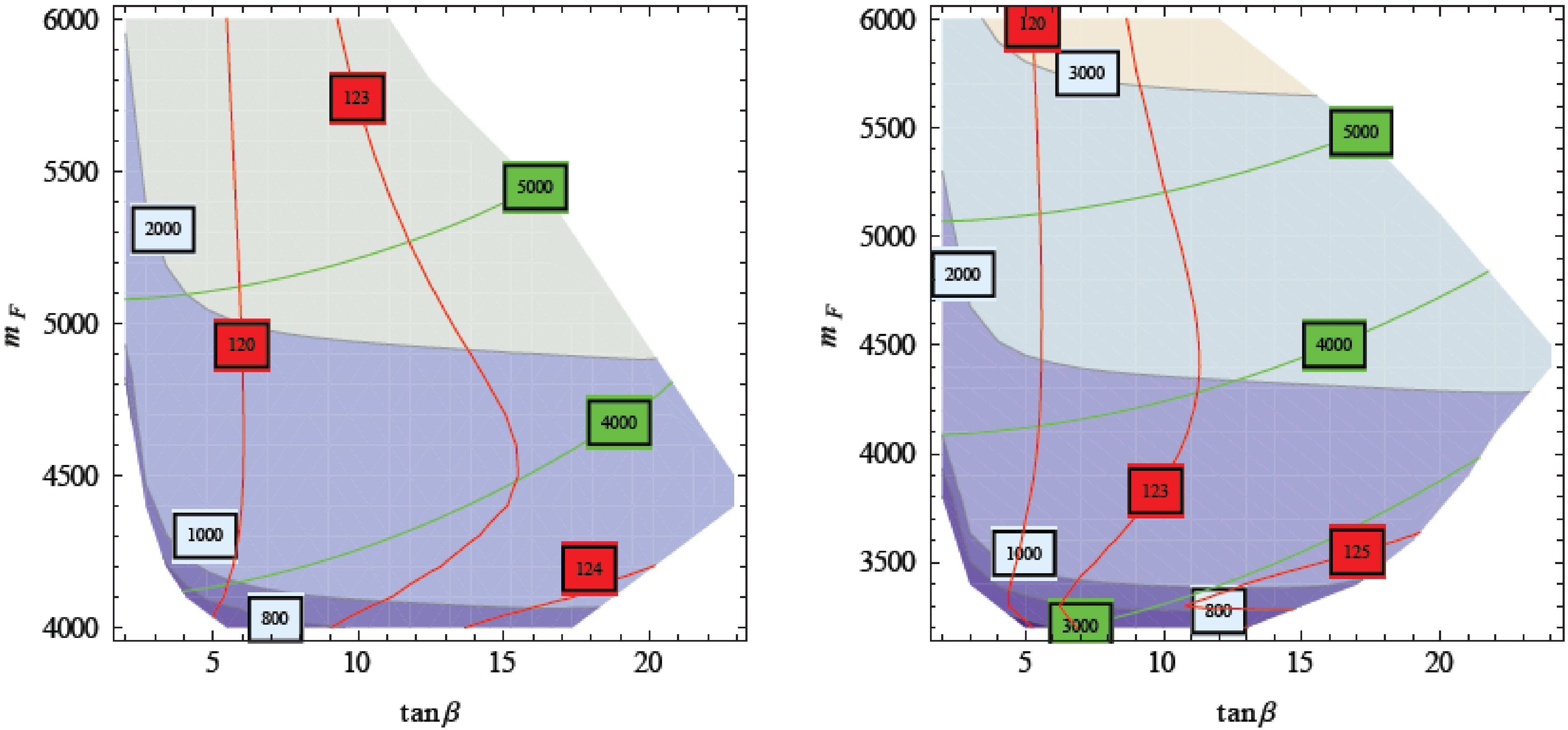
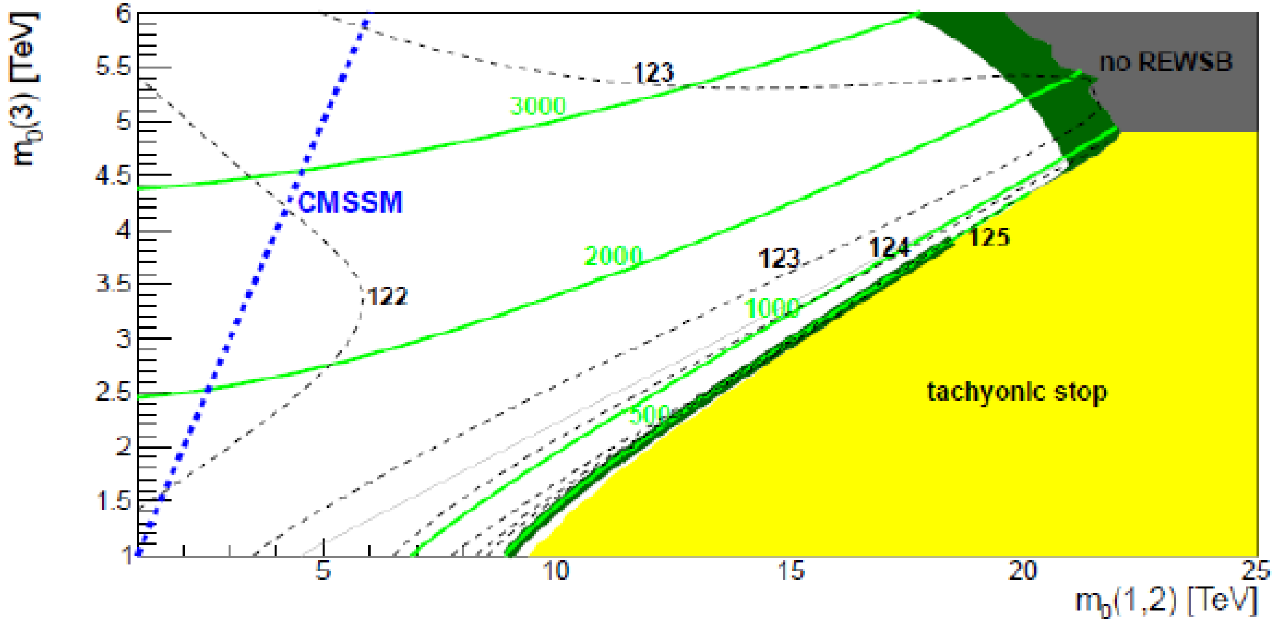


Figure 3: Parameter region in the $\tilde{m}_F/\tan\beta$ plane for fixed $\tilde{m}_D = 15\,\text{TeV}$ and $M_{1/2} = 0.6\,\text{TeV}$ (left panel) and $M_{1/2} = 1.0\,\text{TeV}$ (right panel). The contour lines correspond to the masses of $\tilde{t}_1$ (blue), $\tilde{\tau}_1$ (green) and h^0 (red).

(Courtesy of M. Badziak)

Large stop mixing can be generated from RG running (M. Badziak et al, 2012; see also Brummer et al, 2012.)



Inverted hierarchy example. Higgs mass (black dashed), stop mass (solid green) for $\mu > 0, \tan\beta = 10, M_{1/2} = 1, A_0 = -2$ (TeV). Yellow "tachyonic stop" and grey "no REWSB" ($\mu^2 < 0$) regions are excluded. Dark green region: $\Omega_{\rm DM} h^2 < 0.1288$.

Some issues model building: ::

- Discrete subgroups★ D'_n of U(2) avoid Goldstone bosons
- Simplest working example: D'_n with 12 elements generated by 2 generators with

$$A^6 = 1 \qquad B^4 = 1 \qquad ABA = B$$

On 2-dim. representations, they act as

$$\mathbf{2}_1 : \begin{pmatrix} e^{\pi i/3} & 0 \\ 0 & e^{-\pi i/3} \end{pmatrix}, \quad \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$$

$$\mathbf{2}_2 : \begin{pmatrix} e^{2\pi i/3} & 0 \\ 0 & e^{-2\pi i/3} \end{pmatrix}, \quad \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

- Operators breaking SU(2), invariant under D'_n appear usually at higher order in the lagrangian.

★Recent progress in string realization: Nilles et al, Camara et al…

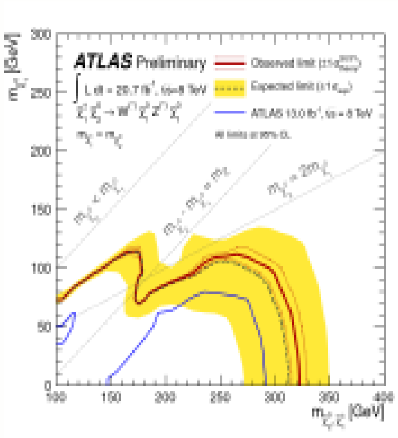
Natural SUSY/Inverted hierarchy in string theory ?

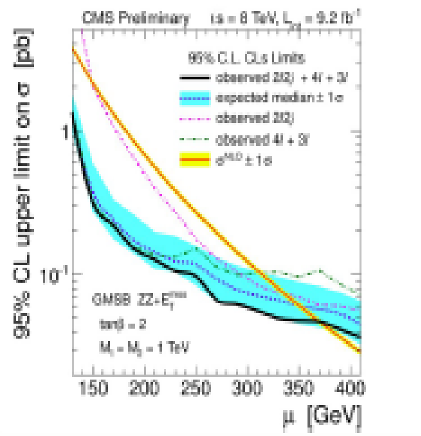
- Anomalous U(1)’s in all string theories and F-theory, flavor dependent + additional discrete symmetries
- Different localization of the third generation versus the first two ones: twisted/untwisted fields, varying fluxes

Inverted hierarchy can also be realized in:
- SUSY(SUGRA) RS 5d warped models
- flavored (higgsed) gauge mediation.

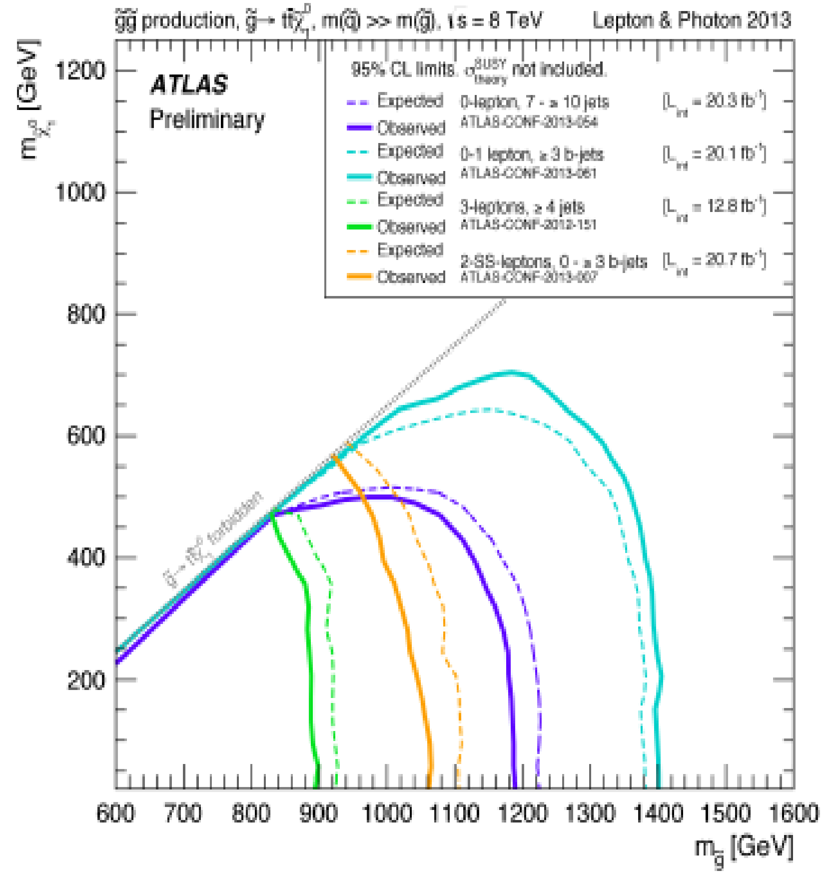
Bounds on « Natural SUSY » models

EWinos

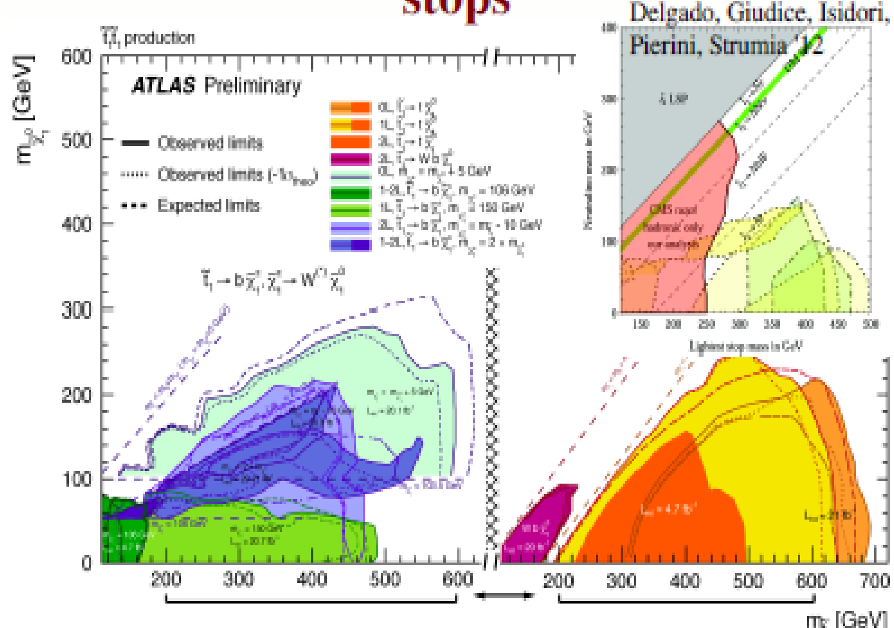




gluino



stops



Conclusions

- Popular SUSY models are more fine-tuned, more stringent limits on SUSY spectra from direct LHC searches and flavor physics constraints.
- But there is no reason to reduce low-energy SUSY to its simplest examples: mSUGRA,CMSSM, mGMSB.
- Most theories of fermion masses generate flavor-dependent soft terms. Inverted hierarchy/natural SUSY arises naturally in Xtra dims. and string theory constructions. Probably necessary to combine ingredients from abelian and non-abelian discrete flavor symmetries.
- Interesting to work out predictions: B, D physics.

- The mechanism and the scale of SUSY is THE big unknown: split or even high-energy SUSY possible in string theory.

THANK YOU

Backup slides

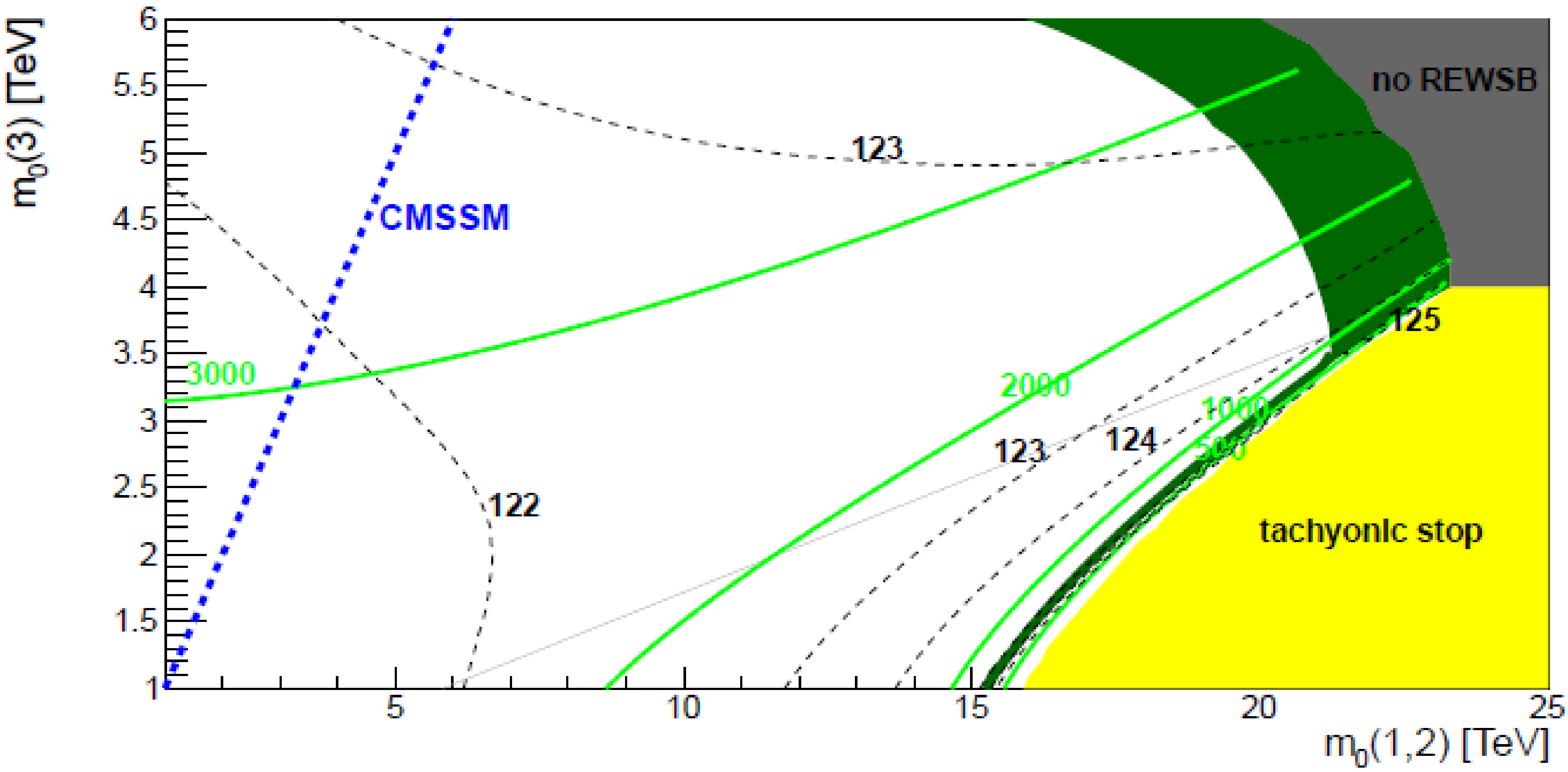


Figure 5: The same as in Figure 3 but for $M_{1/2} = 1.5$ TeV and $A_0 = 0$.

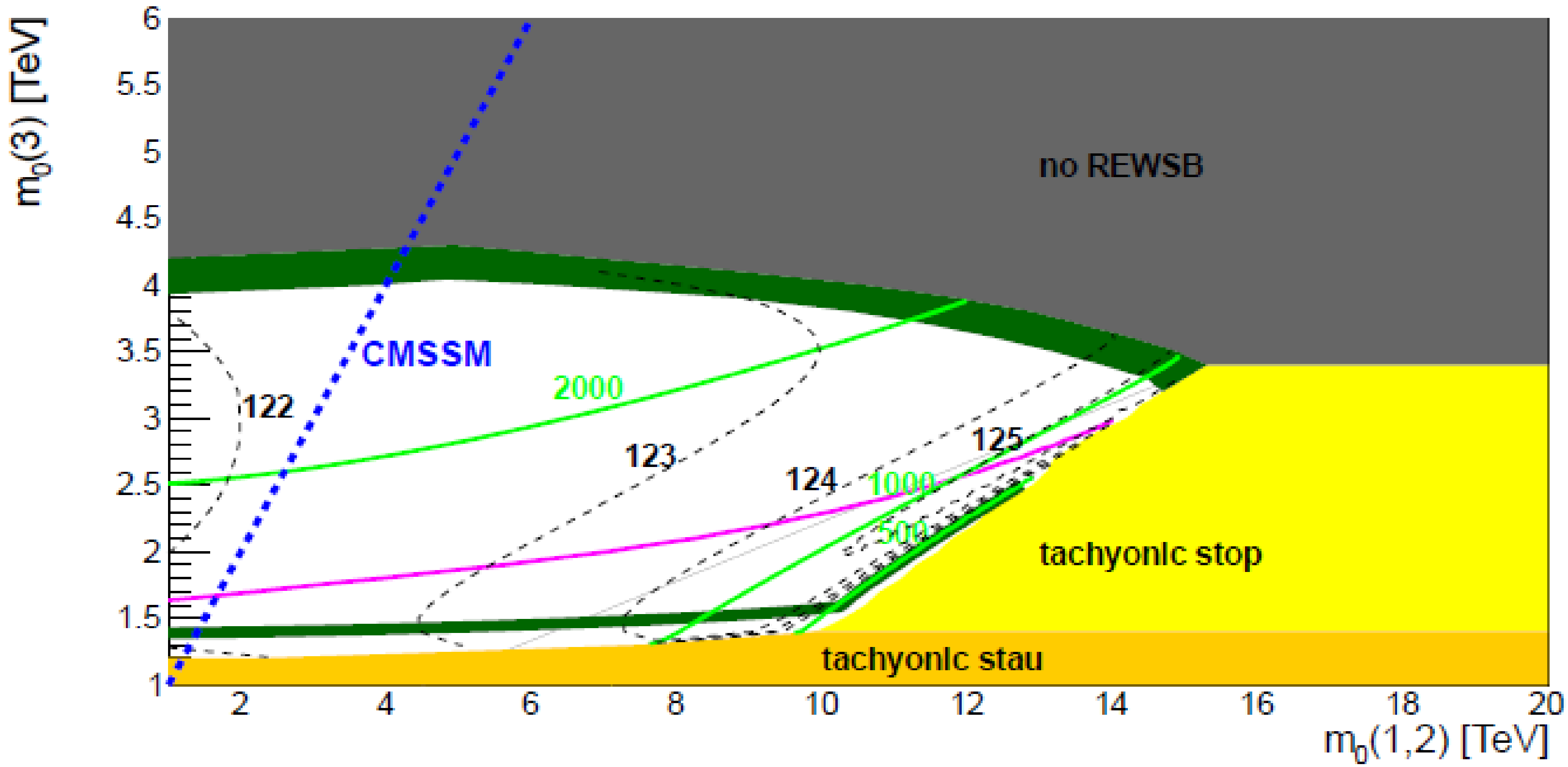
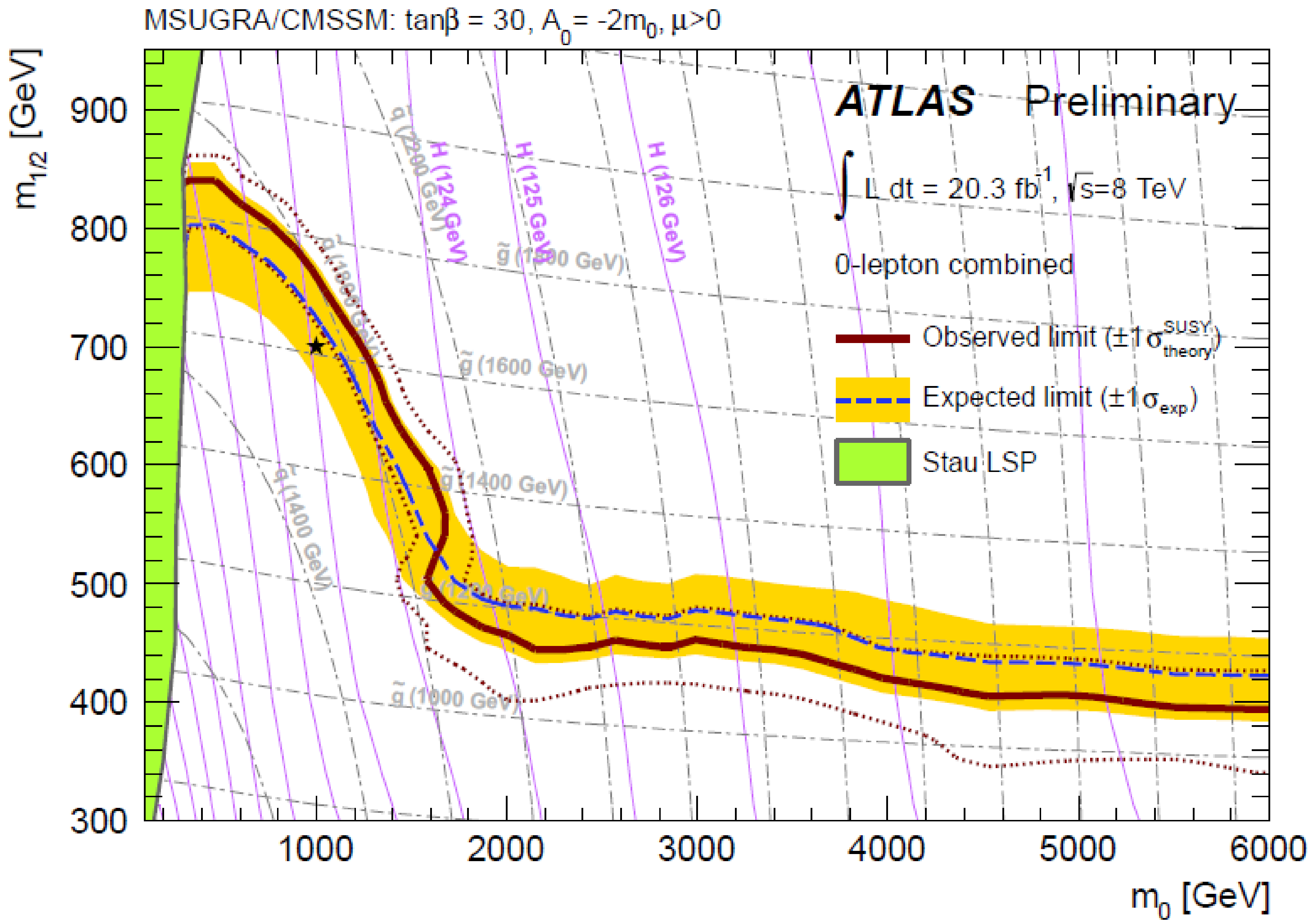


Figure 7: The same as in Figure 3 but for $\tan\beta = 50$ and $m_{H_d} = 1.6m_0(3)$. The region below the purple line is excluded by $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at 95% C.L. The orange region is excluded because it predicts a tachyonic stau.



MSUGRA/CMSSM: tanβ = 30, A0 = -2m0, μ>0
ATLAS Preliminary
∫ L dt = 20.3 fb-1, √s=8 TeV
0-lepton combined
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
Stau LSP
H (124 GeV)
H (125 GeV)
H (126 GeV)
g̃ (1800 GeV)
g̃ (1600 GeV)
g̃ (1400 GeV)
g̃ (1200 GeV)
g̃ (1000 GeV)
q̃ (2200 GeV)
q̃ (1800 GeV)
q̃ (1400 GeV)
m1/2 [GeV]
m0 [GeV]
300
400
500
600
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