FLAVOUR MODELS IN SUPERSYMMETRY

march 17, 2014

« Quantum Gravity in Paris »

LPT-Orsay

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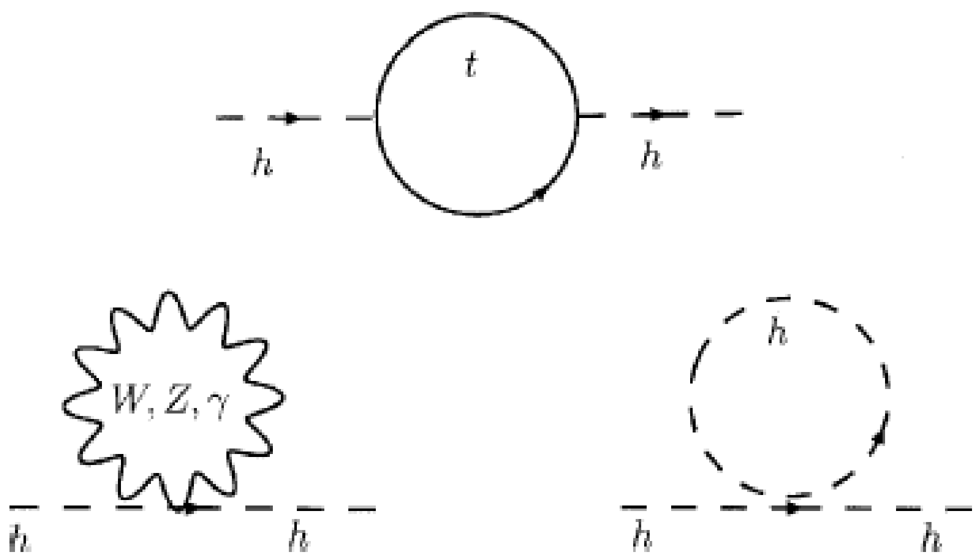
Outline

1) Low-energy Supersymmetry and its consequences
2) Naturalness and natural SUSY spectra
- SUSY constraints from LHC searches and Higgs mass
3) The supersymmetric flavor problem
- Flavor and inverted hierarchy/natural SUSY in MSSM
- U(1) and U(2) models
- Hybrid abelian/non-abelian models
4) Dirac gauginos, flavor and « fake gluino » models
- UV softness and flavor suppression with Dirac gauginos
- The « fake gluino » scenario
- Conclusions

1) Supersymmetry and its consequences

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

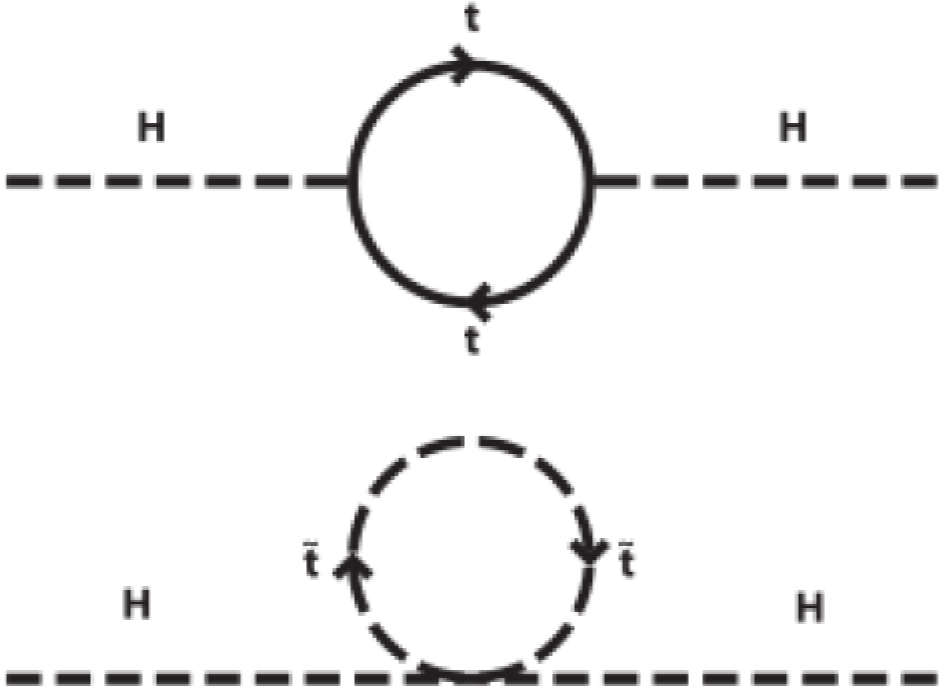
$$\delta m_h^2 \simeq \frac{3\Lambda^2}{8\pi^2 v^2}(4m_t^2 - 4M_W^2 - 2M_Z^2 - m_h^2)$$

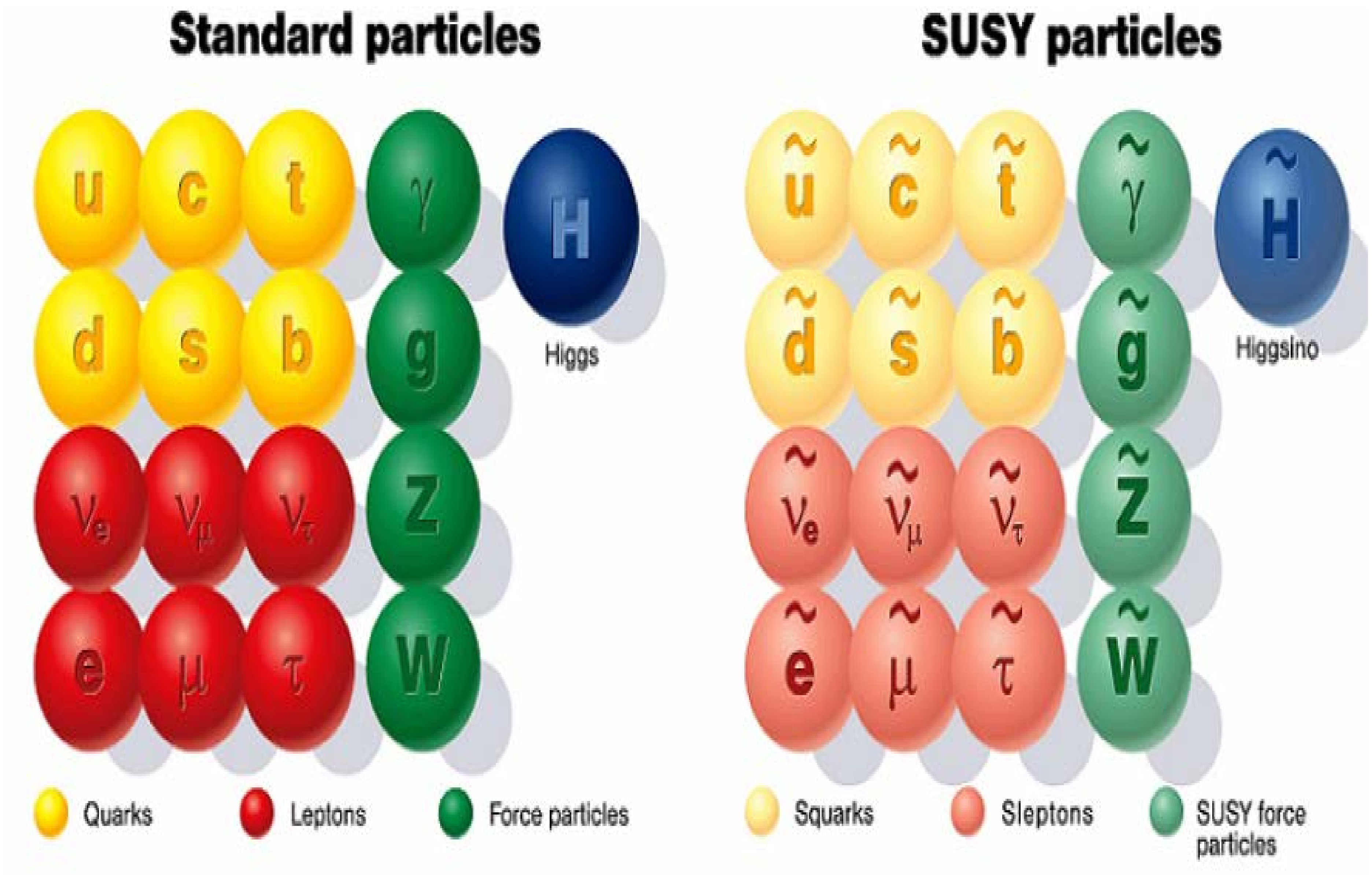


Supersymmetry naturally adresses:

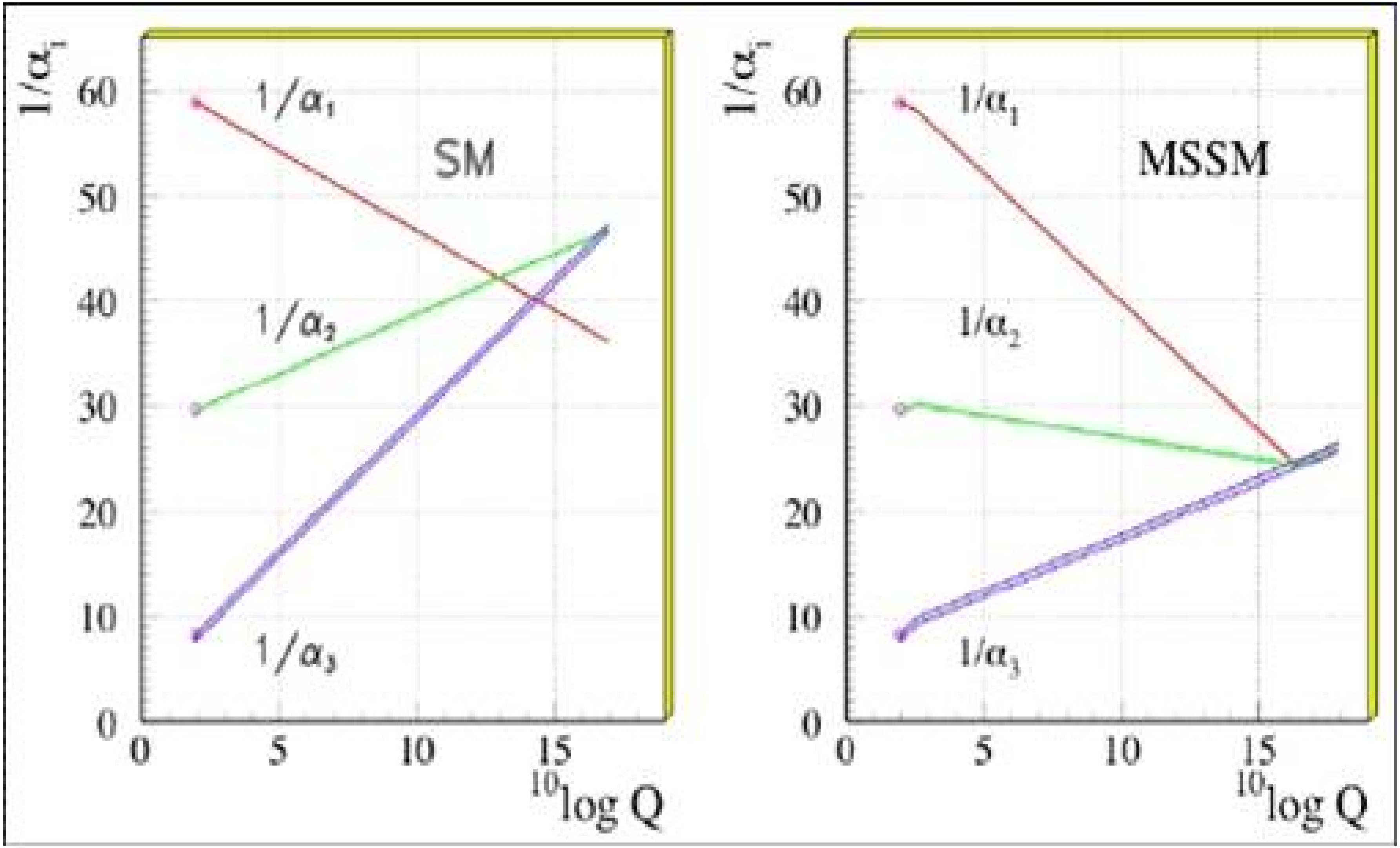
a) The hierarchy problem

$$\text{SM} \;:\; \Delta M_h^2 \sim \frac{\Lambda^2}{16\pi^2}\,, \quad \text{MSSM} \;:\; \Delta M_h^2 \sim \frac{m_t^2}{16\pi^2}\,\log\frac{m_{\tilde{t}}^2}{m_t^2}$$

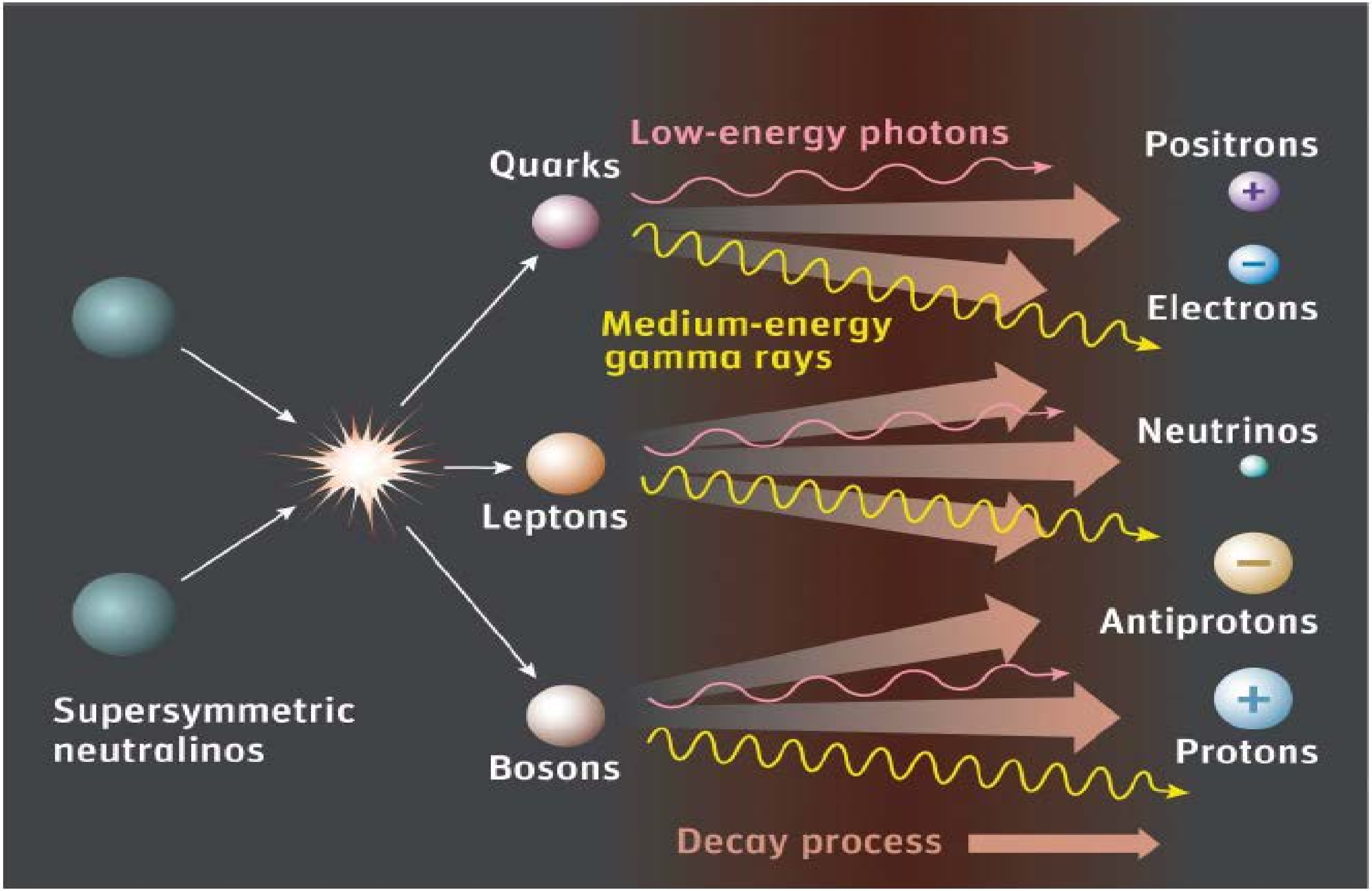



Standard particles
SUSY particles
u
c
t
γ
H
d
s
b
g
Higgs
νe
νμ
ντ
Z
e
μ
τ
W
Higgsino
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

b) Gauge coupling unification (Dimopoulos,Raby,Wilczek)



c) The missing Dark Matter Candidate: LSP (Ligthest Supersymmetric Particle), protected by R-parity ? (Fayet)



$$\mathcal{L}_{MSSM} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$$

where the SUSY part is

$$\mathcal{L}_{SUSY} = \int d^4\theta \, (\sum_{i=1,2} H_i^\dagger e^{V_i} H_i + \sum_{\Phi} \Phi^\dagger e^{V} \Phi)$$

$$+ \int d^2\theta \, (\mu H_1 H_2 + Q Y^U U_c H_2 + Q Y^D D_c H_1 + L Y^E E_c H_1)$$

$$+ \sum_{i=1}^{3} \frac{1}{4 g_i^2} \int d^2\theta \, \mathrm{Tr}\, [W^\alpha W_\alpha]_i + h.c.$$

The soft breaking terms are

$$-L_{soft} = \sum_{\Phi} m_\Phi |\Phi|^2 + m_i^2 |h_i|^2 + B\mu h_1 h_2$$

$$+ \tilde{q} A^U \tilde{u}_c h_2 + \tilde{q} A^D \tilde{d}_c h_1 + \tilde{l} A^E \tilde{e}_c h_1 + m_{\lambda_i} Tr(\lambda_i \lambda_i)$$

and do not introduce quadratic divergences.

Typical low-energy SUSY (MSSM) predictions:

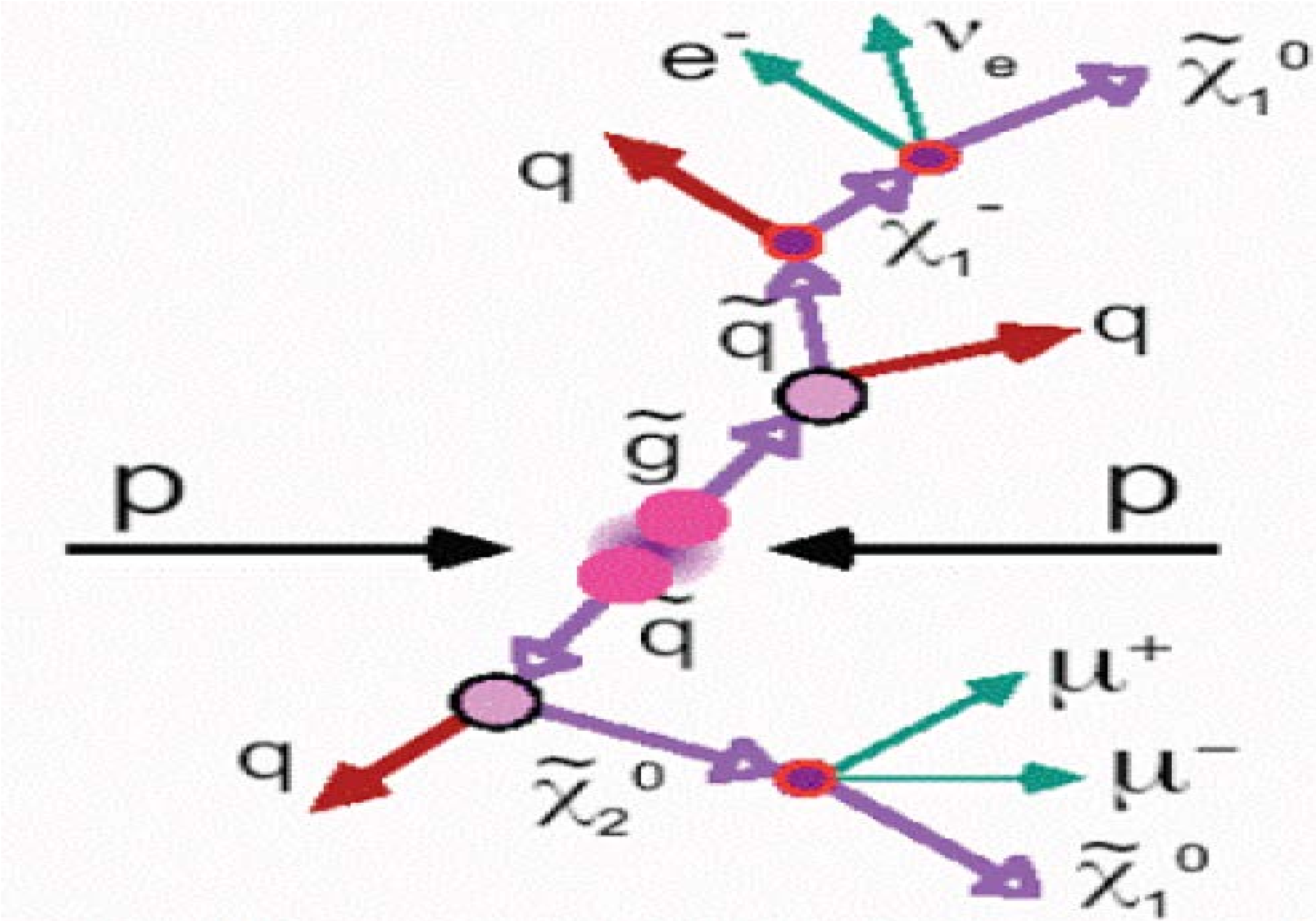
- Higgs mass < 130 GeV

$$V(h_i) = V_{mass} + \frac{g_1^2 + g_2^2}{8}\left(|h_1|^2 - |h_2|^2\right)^2$$

TeV-scale superpartners: squarks,sleptons,gluinos, higgsinos,neutralinos, 4 more Higgs scalars.

However, at tree level $M_h < M_Z$ $\Longrightarrow$ large radiative corrections : some superpartners maybe heavy.

- Missing energy signatures (LPS's)


e$^-$
ν_e
$\tilde{\chi}_1{}^0$
q
$\chi_1{}^-$
$\tilde{q}$
q
$\tilde{g}$
p
p
$\tilde{q}$
μ^+
q
$\tilde{\chi}_2{}^0$
μ^-
$\tilde{\chi}_1{}^0$

2) Naturalness, natural SUSY spectra

SUSY 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).

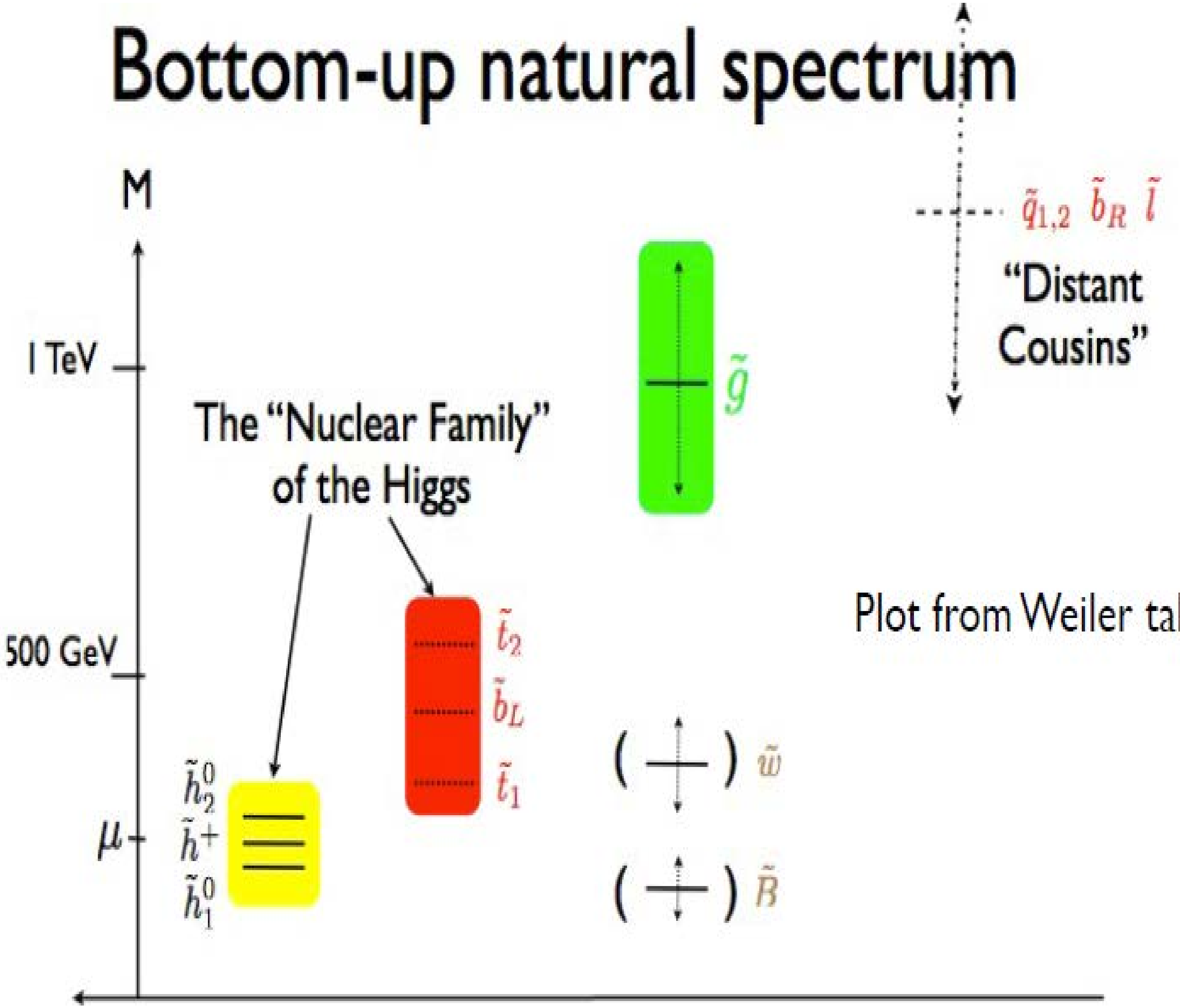
Electroweak scale natural for light higgsinos,gluinos,stops and L-handed sbottom:

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

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

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

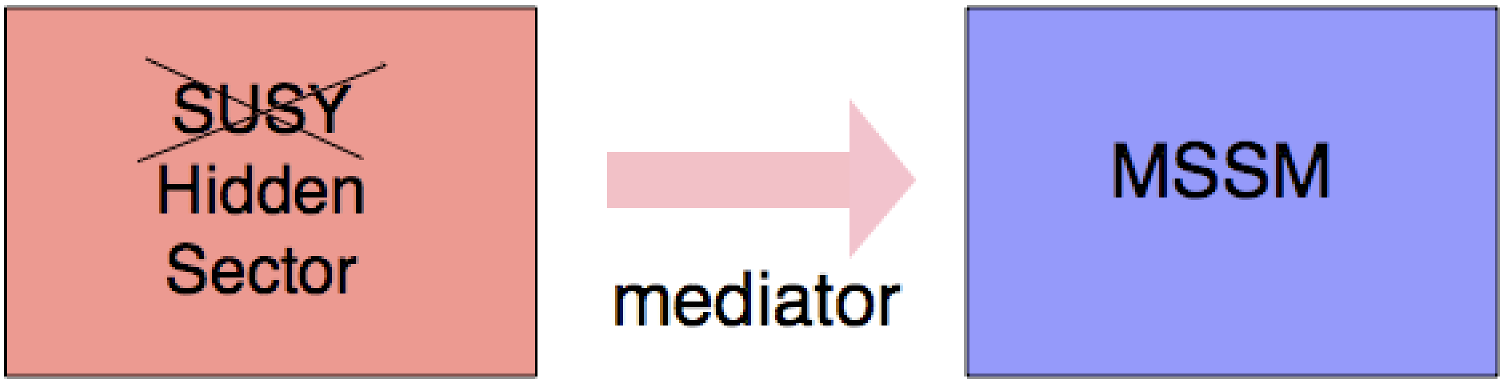
Bottom-up natural spectrum



Plot from Weiler talk on natural susy

Popular models:

- Gravity mediation: Planck-suppressed interactions between a hidden sector and the observable sector generate soft terms of order $m_{3/2}$



Simplest scenario: minimal Supergravity (mSUGRA) :

- all scalar masses equal $m_{\tilde{q}} = m_{\tilde{l}} = \cdots = m_0$
- all gaugino masses equal $m_{\lambda_3} = m_{\lambda_2} = m_{\lambda_1} = M_{1/2}$
- All trilinear terms = A_0

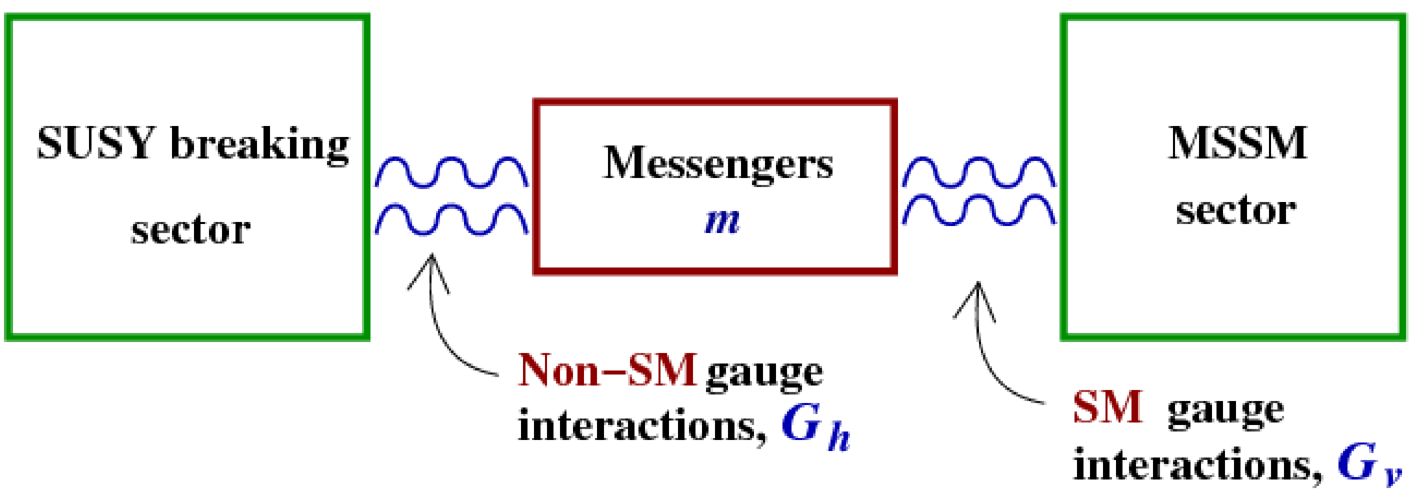
- Gauge mediation

Transmission of SUSY breaking through SM gauge loops

= gauge mediation

SUSY breaking sector $\leftrightarrow$ Messenger sector $\leftrightarrow$ MSSM

$$X = \langle X \rangle + \theta^2 F_X \quad \rightarrow \quad X\Phi\tilde{\Phi} \quad \rightarrow \quad \text{soft terms}$$



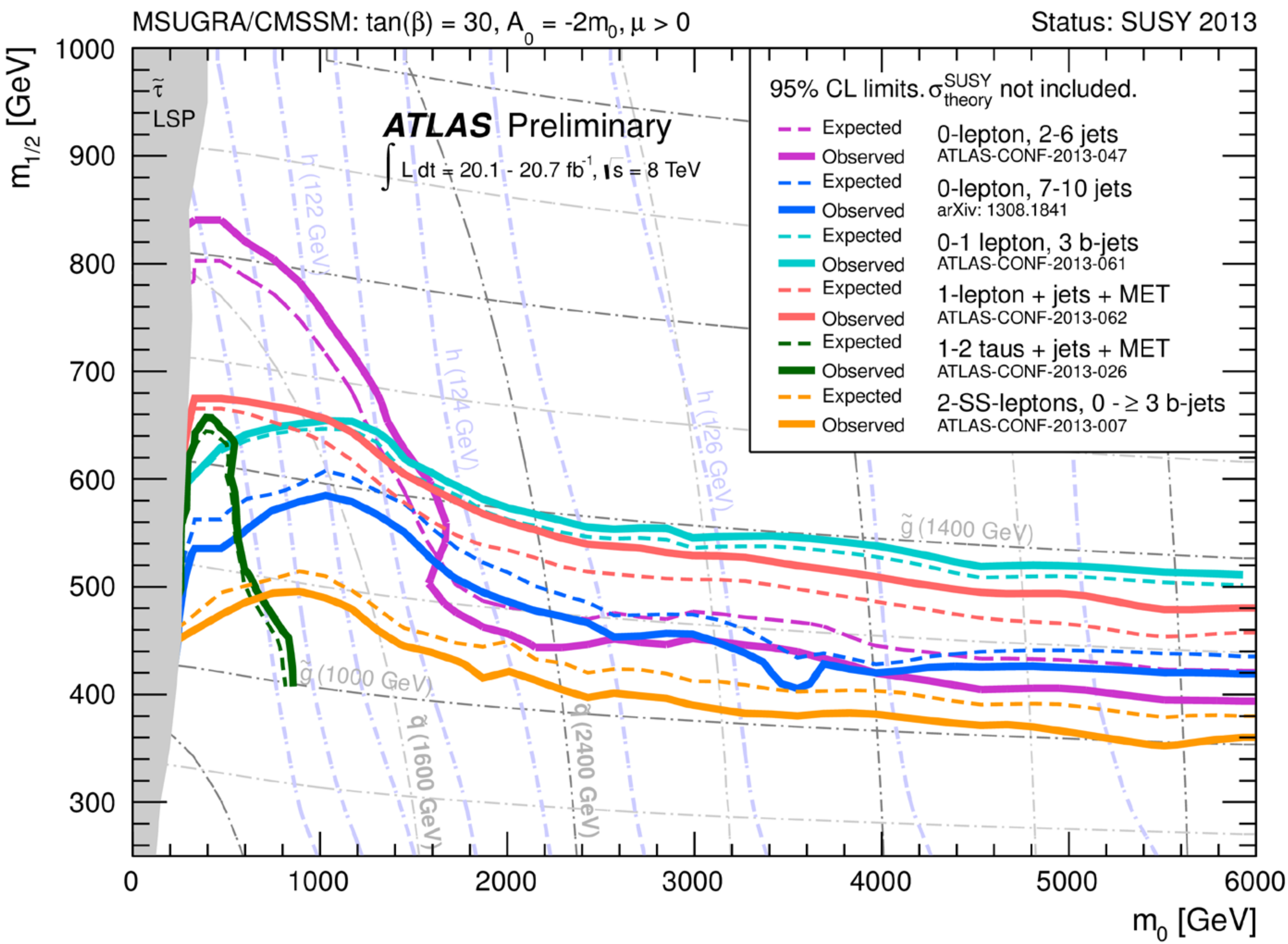
SUSY constraints from LHC searches and Higgs mass

- 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.

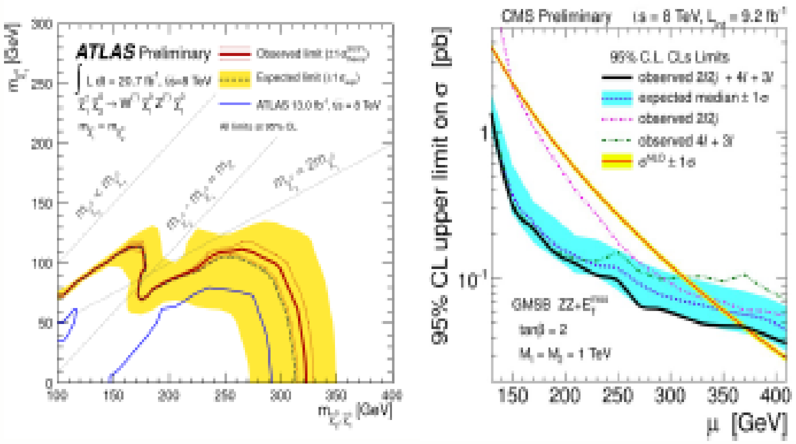
It is important to theoretically analyze and experimentally search for non-minimal SUSY models.



MSUGRA/CMSSM: tan(β) = 30, A_0 = -2m_0, 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
Expected
Observed
0-lepton, 7-10 jets
arXiv: 1308.1841
Expected
Observed
0-1 lepton, 3 b-jets
ATLAS-CONF-2013-061
Expected
Observed
1-lepton + jets + MET
ATLAS-CONF-2013-062
Expected
Observed
1-2 taus + jets + MET
ATLAS-CONF-2013-026
Expected
Observed
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 (2400 GeV)
m_1/2 [GeV]
m_0 [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000

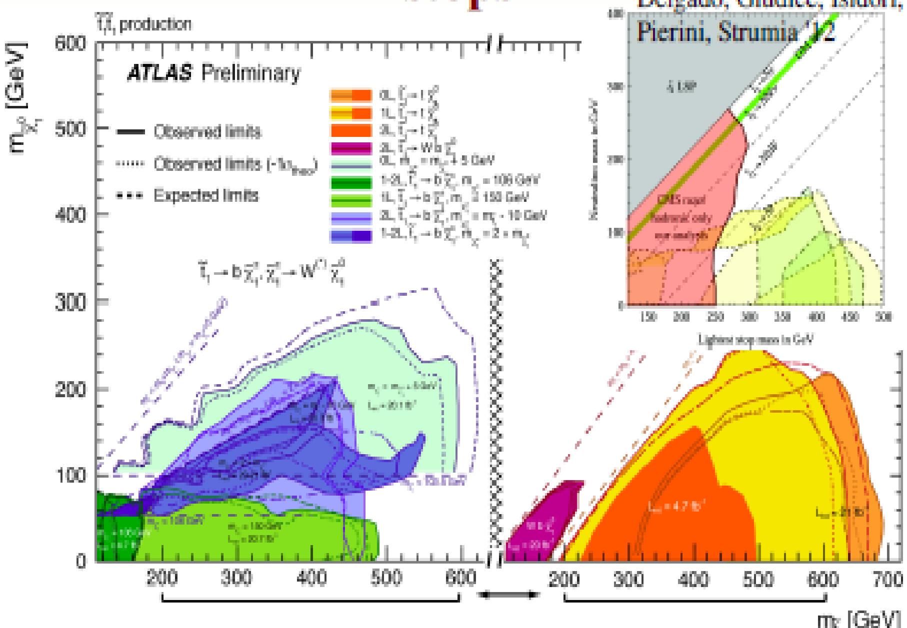
Bounds on « Natural SUSY » models

EWinos

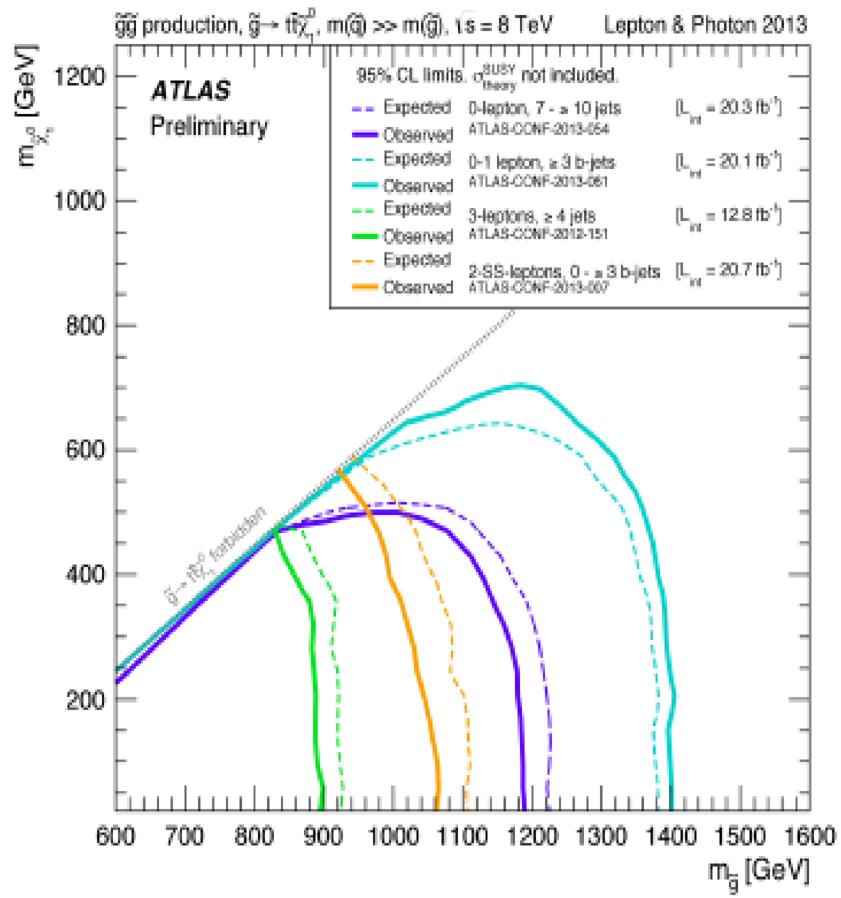


stops

Delgado, Giudice, Isidori, Pierini, Strumia '12



gluino



3) The SUSY Flavor Problem

Flavor transitions (FCNC) in the Standard Model are protected by the GIM mechanism ⇒

FCNC transitions $K^0 - \bar{K}^0$, $\mu \to e\gamma$, $b \to s\gamma$, etc
are very weak, protected by the :

- Unitarity of CKM matrix, GIM mechanism
- Hierarchical structure of $V_{\rm CKM}$
- Smallness of neutrino masses

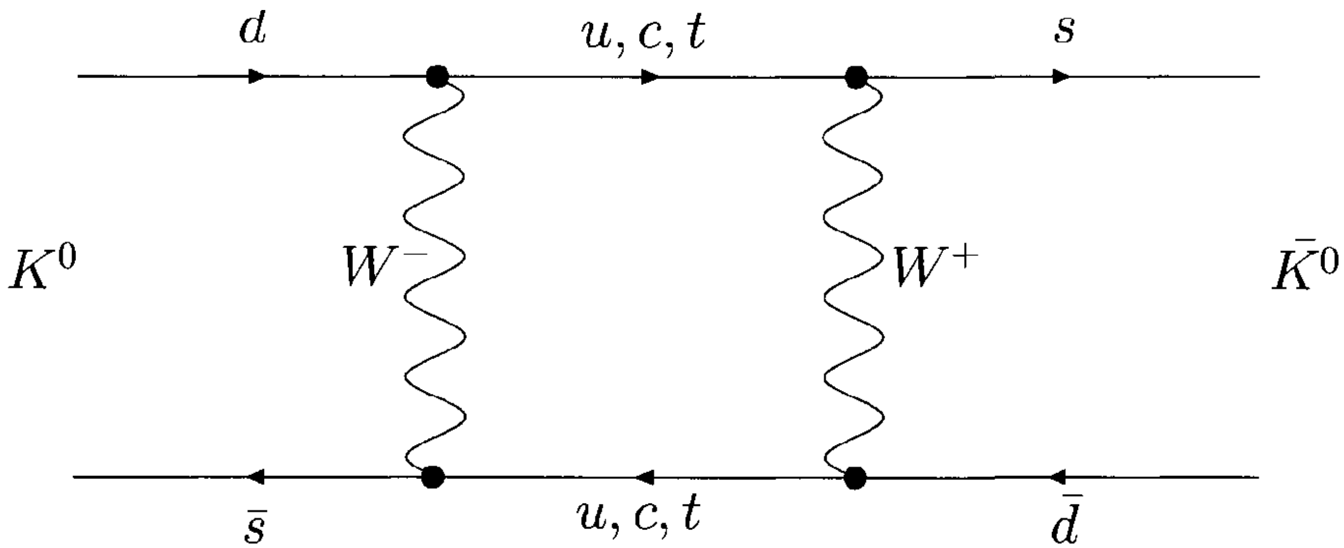
This protection is lost in most of extensions of the SM. In SUSY models, FCNC are suppressed if:

i) The three generations of squarks/sleptons are very degenerate

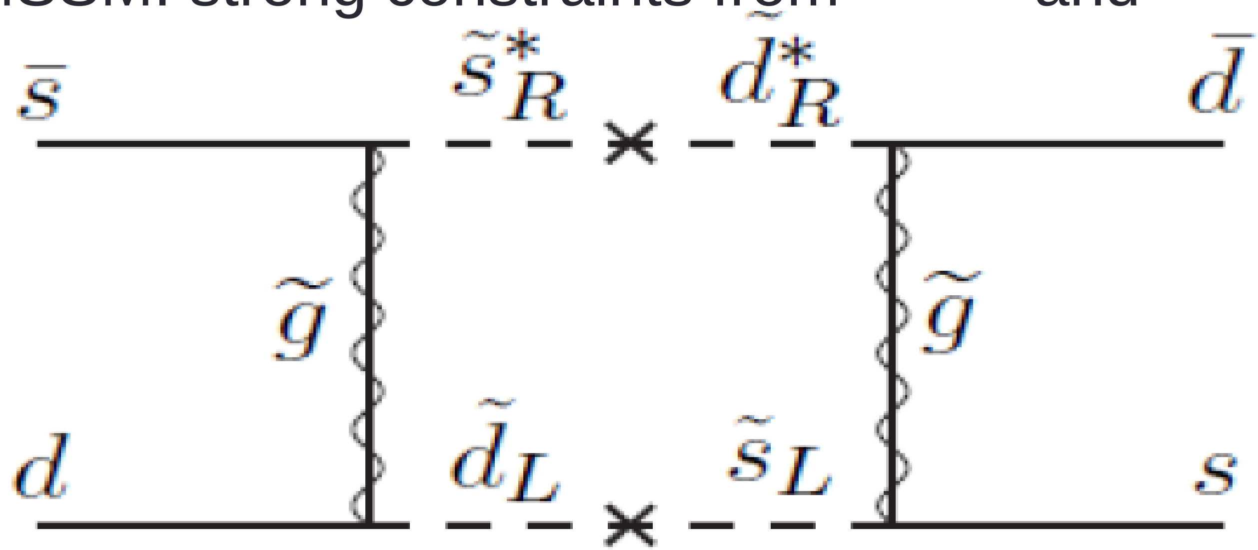
or

ii) Some squarks/sleptons are very heavy (> 10^4 TeV)

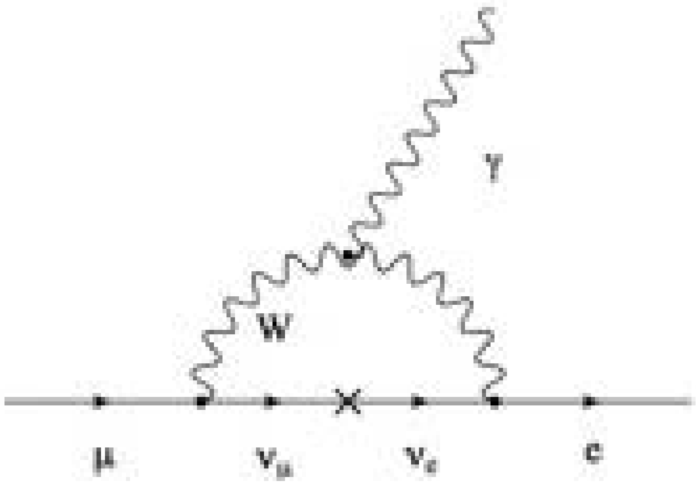
- $K^0 - K^0$ mixing in the SM

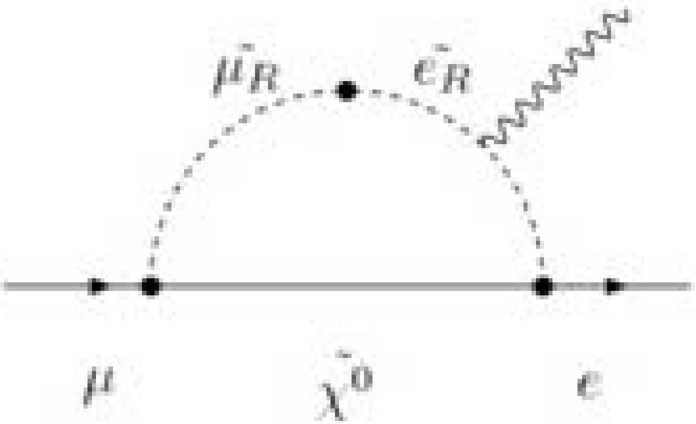


- In the MSSM: strong constraints from Δm_K and ϵ_K



$\mu \to e\gamma$ in the SM and MSSM





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}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	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].

Inverted hierarchy/Natural SUSY

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

- third generations squarks (light stops) and gluinos in the TeV range
- 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. Simplest constructions:

1) 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.

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

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

$m_t \sim 1$	$m_b \sim \epsilon^3$	$m_\tau \sim \epsilon^3$
$m_c \sim \epsilon^4$	$m_s \sim \epsilon^{5\div 6}$	$m_\mu \sim \epsilon^5$
$m_u \sim \epsilon^8$	$m_d \sim \epsilon^{7\div 8}$	$m_e \sim \epsilon^9$

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

Gauge anomalies $\Longrightarrow$ constraints on the charges, Green-Schwarz mechanism, anomalous U(1) (Ibanez-Ross…)

$$K \sim \frac{X^\dagger X}{\Lambda_S^2}\left(\frac{\phi}{\Lambda_F}\right)^{|q_i - q_j|} Q_i^\dagger Q_j$$

$\Longrightarrow$ F-term contributions to scalar masses.

Also D-term contributions; so scalar masses are of the form

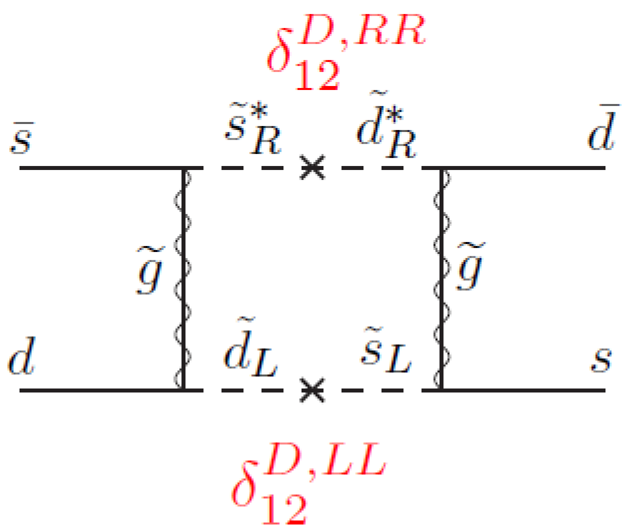
$$m_{ij}^2 \;=\; X_i \delta_{ij} \langle D \rangle \;+\; c_{ij} \epsilon^{|q_i - q_j|} (\tilde{m}_F)^2$$

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, otherwise tachyonic stops (Pomarol,Tommasini;Arkani-Hamed,Murayama)

Nowdays, FCNC constrain seriously these models;
need some degeneracy between first two generations.



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

⇨ $q_1 = q_2 \, , q_3 = 0$ 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 !

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 $x_i = \dfrac{m_i^2}{M_{\tilde{g}}^2}$ 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 : the minimal natural SUSY spectrum with heavy $\tilde{b}_R$ has difficulties with RG running from GUT to EW scale

Possible to combine abelian+non-abelian symmetries :
U(1) x D'_n, where D'_n is a discrete non-abelian subgroup of SU(2) (E.D.,Gersdorff, Pokorski, Ziegler, arXiv:1308.1090 [hep-ph])

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

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

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

Split spectrum from U(1) D-term

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

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

$\tilde{b}_R$ is necessarily heavy, since large right-handed rotations generate large FCNC.

4) Dirac gauginos, flavor and « fake gluino » models

SUSY with Dirac gauginos = MSSM + chiral adjoints χ

- Matter sector has N=1 spectrum
- Gauge sector is in N=2 multiplets
- Include Dirac masses for gauginos/gluinos

$$\int d^2\theta \; W'_\alpha Tr(W^\alpha \chi) \to m_D \; Tr(\lambda \Psi_\chi)$$

where $W'_\alpha = \theta_\alpha m_D$ is a fermionic spurion.

- UV softness and flavor suppression with Dirac gauginos

Squark/slepton masses generated at one-loop are UV finite

$$m_{\tilde{f}}^2 = \sum_a \frac{C_a(f)\alpha_a}{\pi} (m_D^a)^2 \ln \frac{\tilde{m}_i^2}{(m_D^a)^2})$$

where $\tilde{m}_i^2$ is the SUSY breaking mass of $Re\ O_\chi$

- Due to UV finiteness, quantum corrections to squarks are smaller than in MSSM. It is possible parametrically than $m_{\tilde{q}} < m_D$ at low energy.

- In MSSM, corrections to the Higgs soft terms are enhanced by a large factor $\ln \frac{\Lambda}{M_3}$. In purely Dirac MSSM case, the correction is softer

$$\delta m_{H_u}^2 = -\frac{3\lambda_t^2}{8\pi^2} m_{\tilde{t}}^2 \ln \frac{m_D^2}{m_{\tilde{t}}^2}$$

$\Rightarrow$ a 5 TeV Dirac gluino mass is as natural as a 900 GeV Majorana gluino in MSSM.

Dirac gluino models have several specific implications for colored sparticle production and flavor physics

In MSSM, the strongest FCNC constraint comes from the Kaon system (heavy gluino limit)

$$H_{\text{eff}} \sim \frac{\delta_{LL}^{d,12}\delta_{RR}^{d,12}}{M^2}(\bar{d}_R s_L)(\bar{d}_L s_R)$$

In the Dirac case, it was argued (Kribbs,Poppitz,Weiner) that there is an additional suppression due to R-symmetry

$$H_{\text{eff}} \sim \delta_{LL}^{d,12}\delta_{RR}^{d,12}\frac{m_{\tilde{q}}^2}{m_D^4}(\bar{d}_R s_L)(\bar{d}_L s_R)$$

⇒ if true, FCNC constraints can be relaxed significantly. However, in the hierarchical case, we didn't find such suppression (E.D,Goodsell, Heurtier and Tziveloglou, . arXiv:1312.2011 [hep-ph])

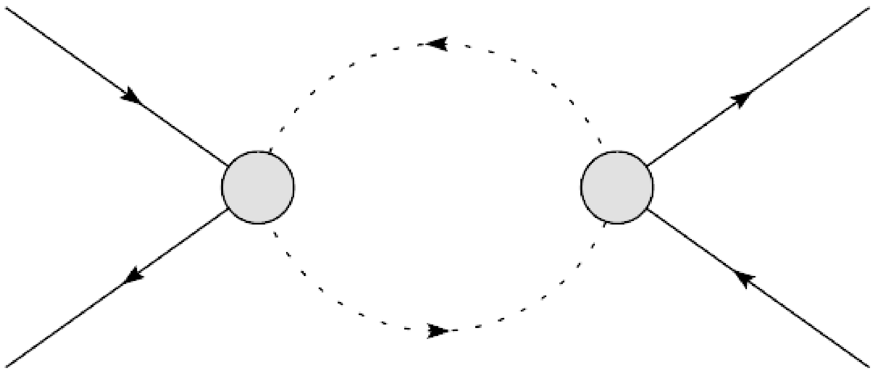
In order to solve the puzzle, go into details of the argument of KPW: integrate the (heavy) gluino ⇒

(Majorana) (Dirac)

$$\mathcal{L} \supset \frac{1}{m_{\tilde{g}}} \tilde{d}_R^* \tilde{s}_L^* \overline{d}_R s_L \,, \qquad \frac{1}{m_{\tilde{g}}^2} \tilde{d}_R \partial_\mu \tilde{s}_L^* \overline{d}_L \gamma^\mu s_L \,.$$

In the near-degeneracy/mass insertion approx., agreement with the FPW argument.

However , in the hierarchical case, the situation is different;



(Majorana)

$$\mathcal{L} \supset Q_i \frac{1}{m_{\tilde{g}}^2} W_{12}^2 \int^{m_{\tilde{g}}} d^4q \frac{1}{(q^2 - m_{\tilde{q}}^2)^2}$$

$$\sim Q_i W_{12}^2 \frac{1}{m_{\tilde{g}}^2} \log \frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}$$

(Dirac)

$$\mathcal{L} \supset Q_i \frac{1}{m_{\tilde{g}}^4} W_{12}^2 \int^{m_{\tilde{g}}} d^4q \frac{q^2}{(q^2 - m_{\tilde{q}}^2)^2}$$

$$\sim Q_i W_{12}^2 \frac{1}{m_{\tilde{g}}^2}$$

and the suppression is almost lost.

We considered a general lagrangian with:

- Majorana masses M (gluino) and M_χ (adjoint fermion)
- Dirac mass m_D
- General soft masses for scalar octet O : m_O, B_O

There are two cases with suppressed FCNC and production in colliders:

- Mostly Dirac case : $m_D >> M, M_\chi$

Protection guaranteed by R-symmetry (mass insertion approx) ; squarks naturally light for m_D around 5-10 TeV

- « Fake gluino » case : $M >> m_D, M_\chi$

Lightest adjoint fermion has a small coupling to quark/squarks $g\frac{m_D}{M}$. Squarks naturally heavier than Dirac case.

« Fake gluino » scenario

What if the lightest fermion adjoints are the « wrong » ones ? This happens if

$$M >> M_\chi , m_D$$

and leads to suppressed couplings to quarks.

Simple example: $$M > M_\chi \sim TeV \ , \ m_D/M << 1$$

« Fake gluino » and squarks in the TeV range, real gluino heavier ⇨ displaced vertices or long-lived « gluinos ». Suppression of both collider and FCNC effects.

There are large right-handed rotations ⇒ strongest constraints from $\tilde{Q}_1 = (\bar{d}_R \gamma_\mu s_R)^2$.

i) Pure Dirac case $m_D >> m_{\tilde{q}}$; we get

$$\frac{\langle K^0 | H_{eff} | \overline{K}^0 \rangle}{\Delta m(\exp)} \simeq 1 \times \left(\frac{\alpha_s}{0.1184}\right)^2 \left(\frac{15\ \mathrm{TeV}}{m_{D3}}\right)^2$$

which for ϵ_K would need $m_D > 350\ TeV$,
whereas for Δm_K we need $m_D > 15\ TeV$

⇒ still very constraining.

ii) « Fake gluino » case : for lightest octet of 5 TeV, we need Majorana gluino mass of about 150 TeV to satisfy Δm_K

In the U(1) x SU(2) model with pure Dirac gluinos, the flavor suppression is bigger than in the MSSM case, as expected.

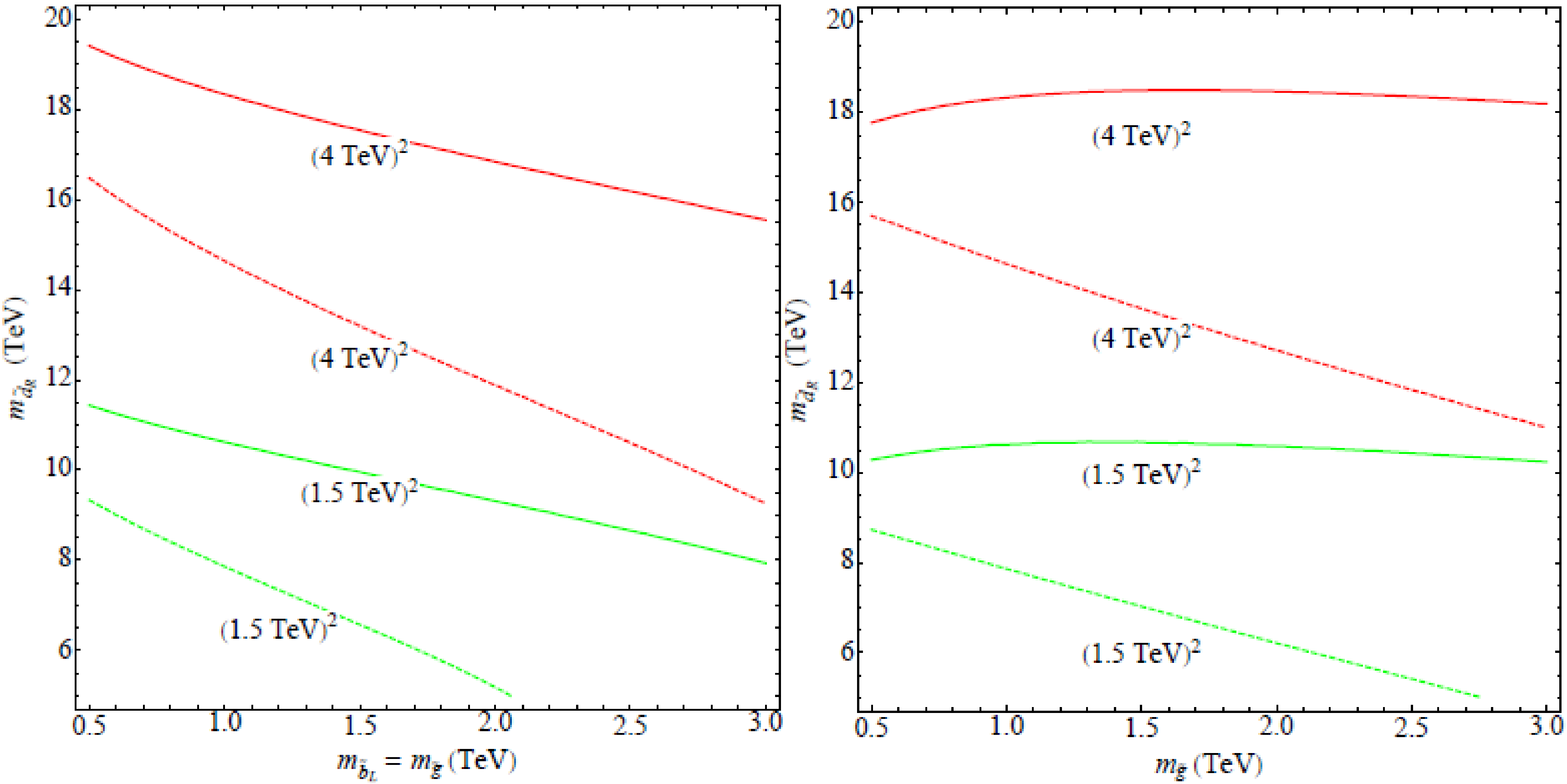


Figure 7: Constraints on the model of section 4.2.4. The dashed lines correspond to exactly Dirac gauginos, while the solid lines are purely Majorana, as in the original model of [15]. In the left plot, the left-handed sbottom mass is set equal to that of the gluino; in the right plot, the left-handed sbottom is fixed at 1 TeV.

Conclusions

- In my opinion, low-energy SUSY is still the best option nature has to address misteries of the Standard Model

- But popular SUSY models are more fine-tuned, more stringent limits from direct LHC searches and flavor physics constraints. However, 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.

- FCNC strongly constrain the flavor structure of soft terms. In MSSM, probably necessary to combine ingredients from abelian and non-abelian discrete flavor symmetries.

- Dirac gaugino models can suppress collider signatures and FCNC due to :

- R-symmetry in the pure Dirac gaugino mass case (only in the near-degeneracy case). Hierarchical case, still need to construct flavor models.

- suppressed « fake gluino » couplings to quarks/squarks in the large Majorana gluino (small Dirac) mass case.

- « Fake gluino » can easily be tested experimentally: ex. TeV squarks with long-lived gluinos.

- If no sign of SUSY at LHC14, maybe nature did chose other options:

- (mini)split SUSY, with very heavy scalars.
- high-scale SUSY or just SM until 10^{12} GeV or M_P , as suggested by the (meta)stability of the Higgs potential in SM.

THANK YOU

Backup slides

	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.

Main features of the model:

- Squark mass matrices essentially diagonal. Unitary rotations come entirely from quark masses.
- Due to non-abelian symmetry, first two generation (both L and R) squarks very degenerate, $m_1^2 = m_2^2$ 1-2 splittings negligeable compared to 1-3 , 2-3 splittings.
- For left squarks and right-handed up-squarks, there is an hierarchy, $m_1^2 >> m_3^2$ since

$$m_{1,2} = m_D \quad \text{and} \quad m_3 \sim m_F$$

- Right-handed down squarks are all charged under U(1), therefore heavy. Ex. in what follows

$$(m^d_{3,R})^2 = (m^d_{1,R})^2 + O(m_F^2)$$

- There are large right-rotations in the down-quark sector. This would force anyway R-handed sbottom to be heavy.

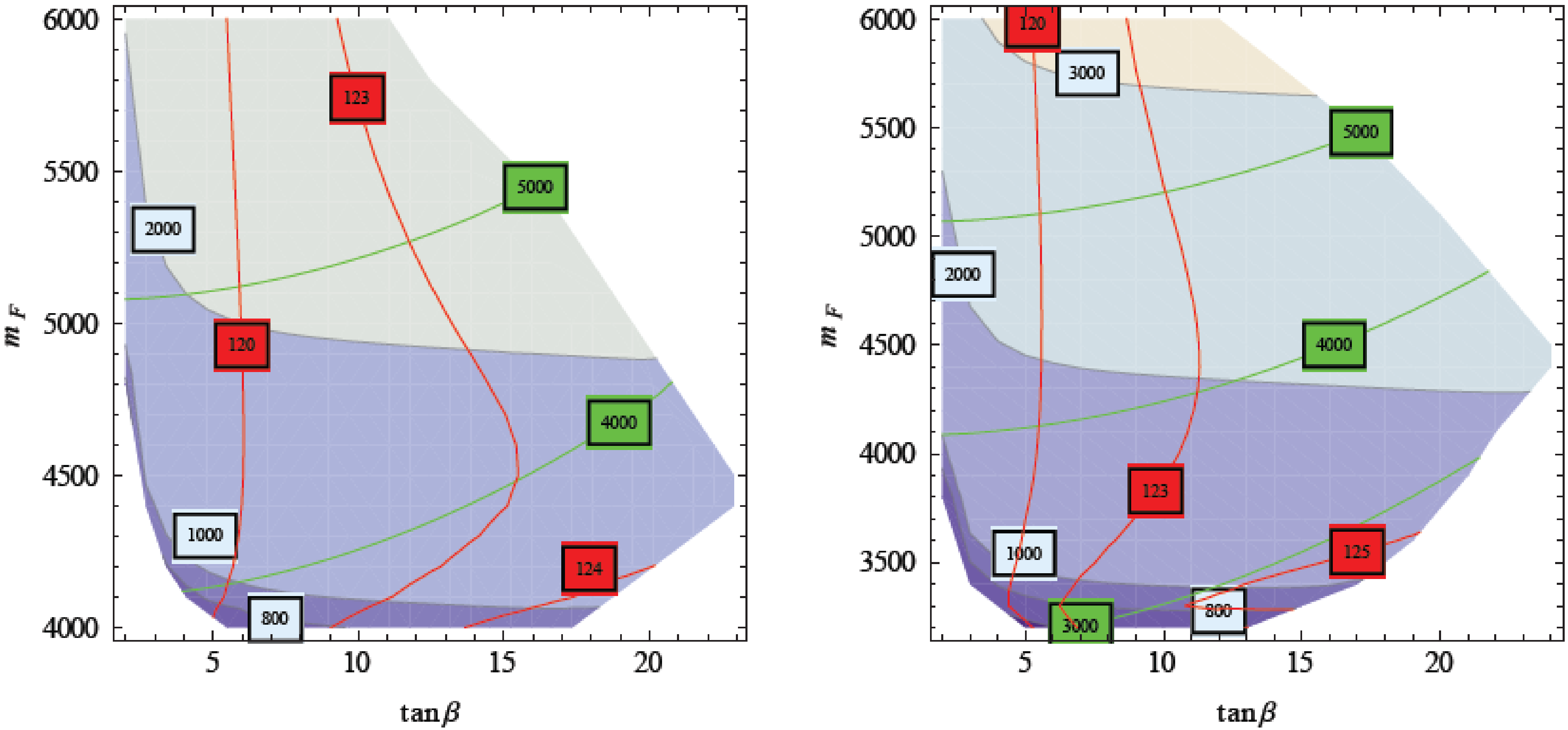


Figure 3: Parameter region in the $\tilde{m}_F/\tan\beta$ plane for fixed $\tilde{m}_D = 15\,\text{TeV}$ and $M_{1/2} = 0.6\,\text{TeV}$ (left panel) and $M_{1/2} = 1.0\,\text{TeV}$ (right panel). The contour lines correspond to the masses of $\tilde{t}_1$ (blue), $\tilde{\tau}_1$ (green) and h^0 (red).

(Courtesy of M. Badziak)

Some issues model building: ::

- Discrete subgroups★ D'_n of U(2) avoid Goldstone bosons
- Simplest working example: D'_3 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…

(More) Natural SUSY models:

- Natural SUSY/inverted hierarchy/split families :

light stops,gluinos,higgsinos (TeV)

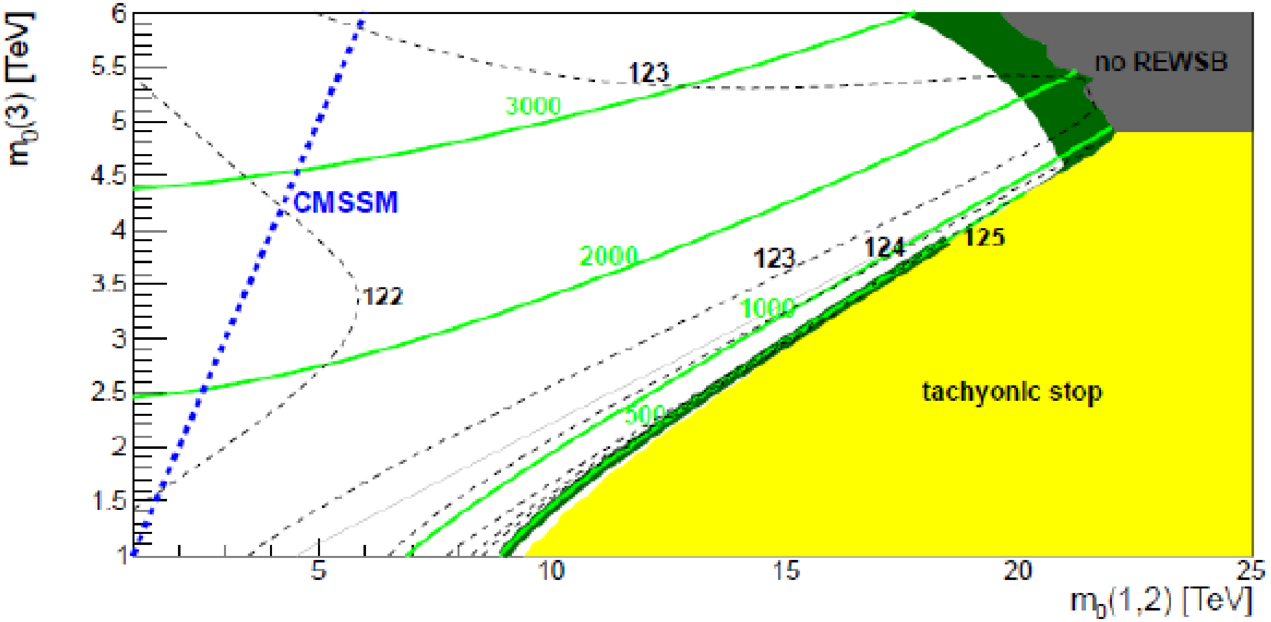
heavier 1,2 generations (10-15 TeV)

- 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: $m_{\rm scalars} >> m_{\rm fermions}$
- High-scale SUSY

Large stop mixing can be generated from RG running (M. Badziak et al, 2012; 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: $\Omega_{\mathrm{DM}} h^2 < 0.1288$.

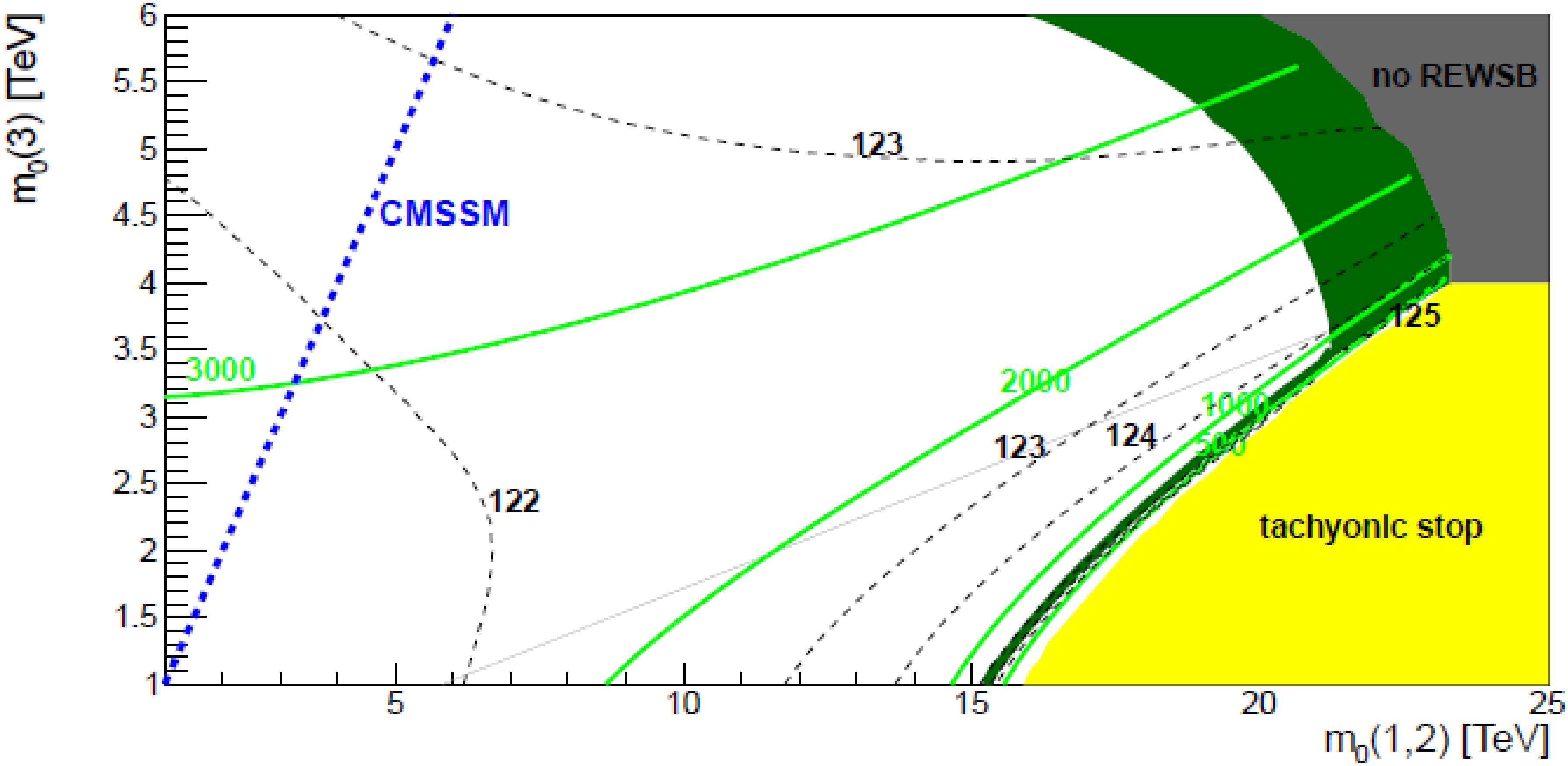


Figure 5: The same as in Figure 3 but for $M_{1/2} = 1.5$ TeV and $A_0 = 0$.

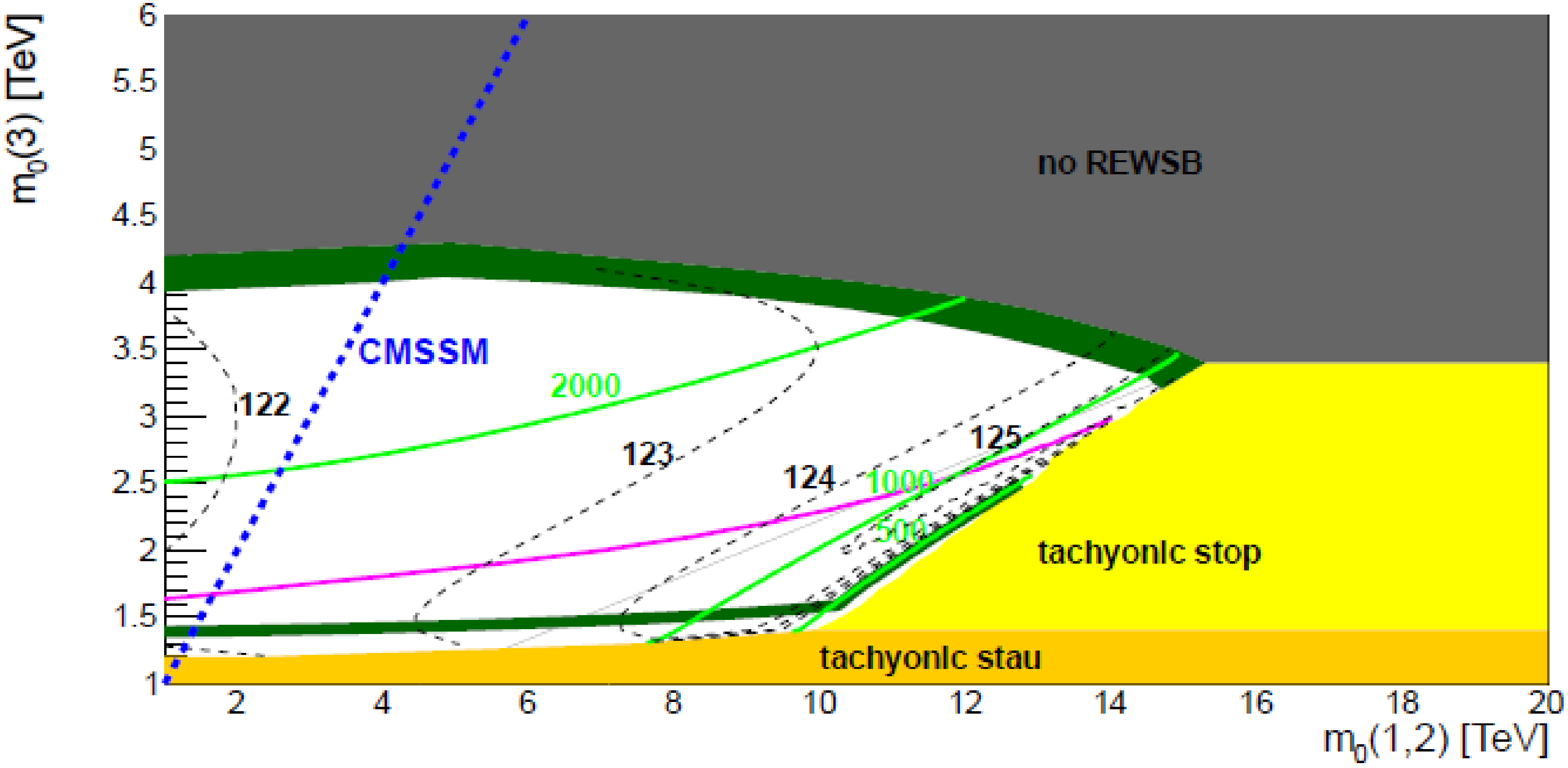


Figure 7: The same as in Figure 3 but for $\tan\beta = 50$ and $m_{H_d} = 1.6 m_0(3)$. The region below the purple line is excluded by $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at 95% C.L. The orange region is excluded because it predicts a tachyonic stau.

Some string comments:

- 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
- Some recent attempts to compute flavor structure of soft terms (Blumenhagen,Deser,Lust; Camara,E.D.,Palti; Camara,Ibanez,Valuenzuela).

- Dirac gauginos are natural in intersecting brane models (Antoniadis,Benakli,Delgado,Quiros and Tuckmantel)

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

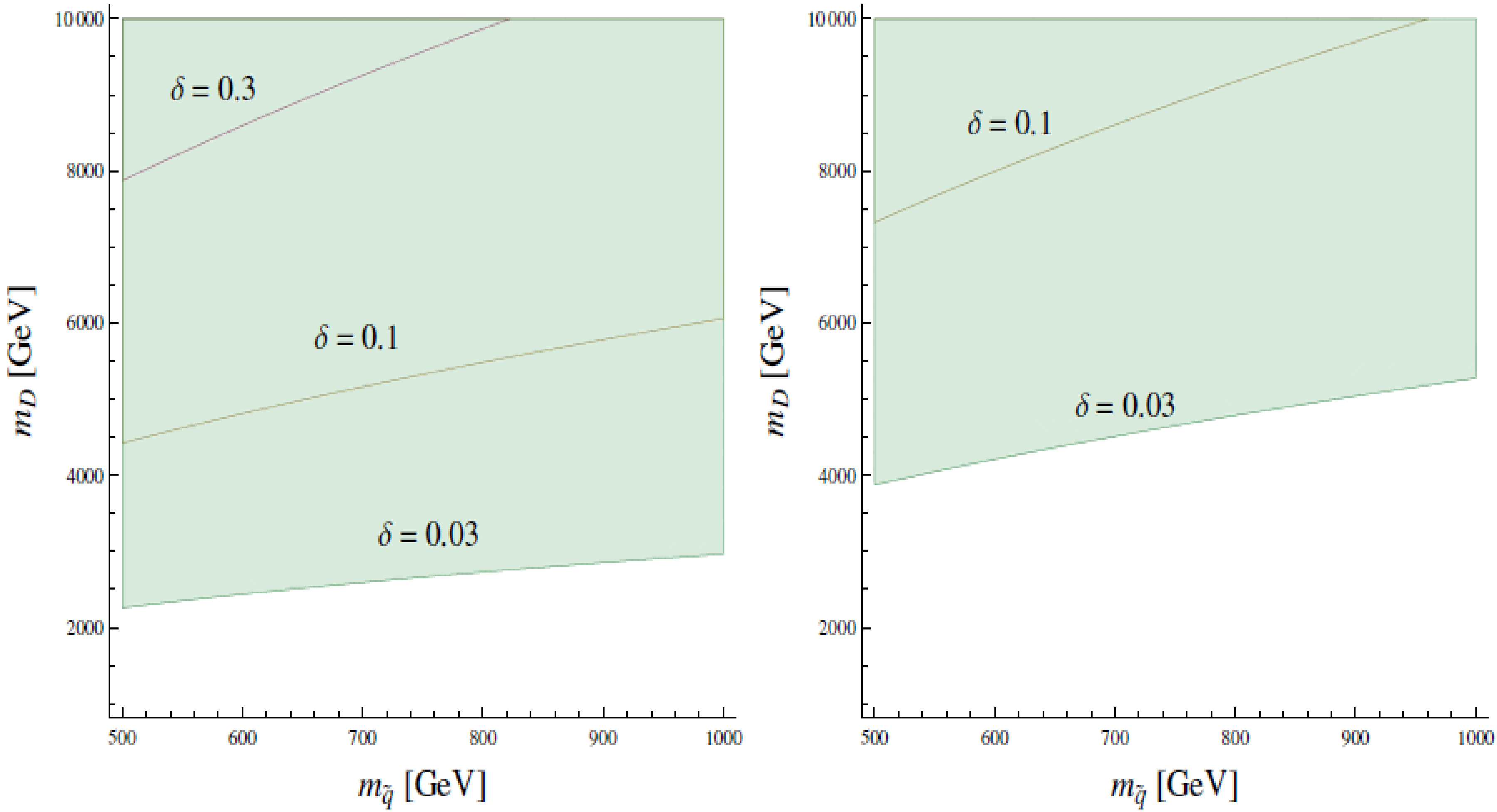
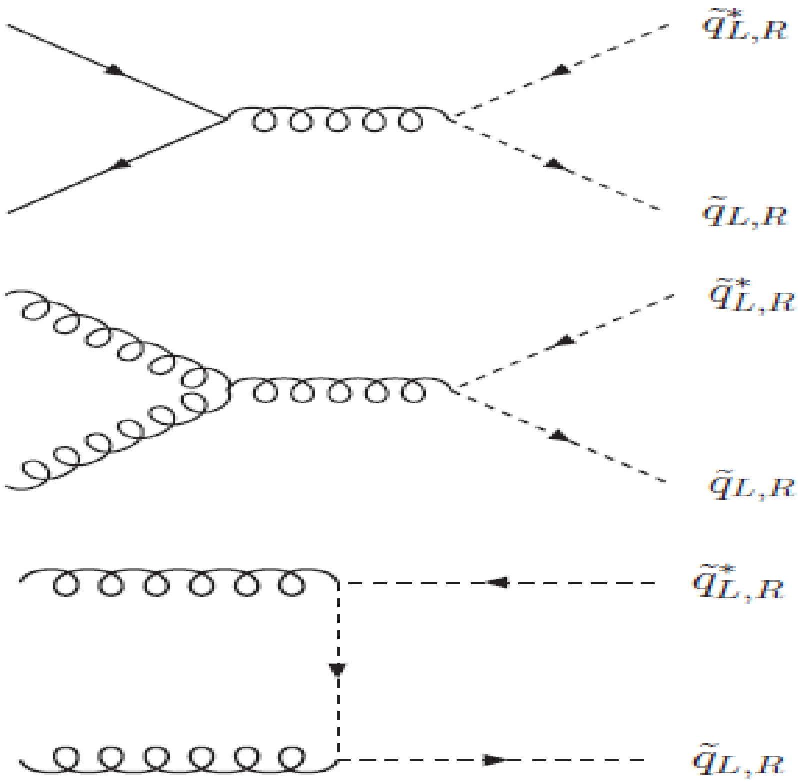


Figure 1: Contour plots in parameter space $m_{\tilde{q}}$ - m_D for purely Dirac gluino ($M = M_\chi = 0$). Left: $\delta_{LL} = \delta_{RR} = \delta$, $\delta_{LR} = \delta_{RL} = 0$. Right: $\delta_{LL} = \delta_{RR} = \delta_{LR} = \delta_{RL} = \delta$. Along the contours $\Delta M_K = \Delta M_K^{\text{exp}}$ (for $\delta_{IJ} = \sqrt{|\mathrm{Re}\,\delta_{12IJ}^2|}$) and $\epsilon_K = \epsilon_K^{\text{exp}}$ (for $\delta_{IJ} = \sqrt{c}\sqrt{|\mathrm{Im}\,\delta_{12IJ}^2|}$).

with c = 640

Colliders:

- Gluino pair production, gluino/squark production negligible.
- t-channel Dirac gluino exchanges are mass-suppressed.
- Processes like $pp \to \tilde{q}_L\tilde{q}_L, \tilde{q}_R\tilde{q}_R$ are absent in Dirac case



(from Kribs-Martin, arxiv:1203.4821[hep-ph])

FIG. 2. The dominant tree level Feynman diagrams for squark production at the LHC in the SSSM. Dirac gluino t-channel exchange diagrams (not shown) are suppressed by $1/M_3^2$ and thus negligible. In the MSSM, by contrast, Majorana gluino exchange is suppressed by $1/\tilde{M}_3$, and thus relevant even when $\tilde{M}_3$ is large, as shown in Fig. 3.

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

ii) Another case: « fake split SUSY scenario » with :

- Very heavy gluino, squarks and scalar octet + 1 Higgs

$$M, m_O, m_{\tilde{q}} \sim 10^{12}\ GeV$$

⇒ gauge coupling unification around $6 \times 10^{17}\ GeV$

(Bachas,Fabre,Yanagida)

- Light « fake gluinos » + higgsinos + SM Higgs +
  « fake electroweakinos »

- The outcome is similar to split SUSY, but the light adjoint fermions are not N=1 partners (but N=2) of gauge fields !

- Lifetime of the « fake gluinos » longer than in split SUSY.

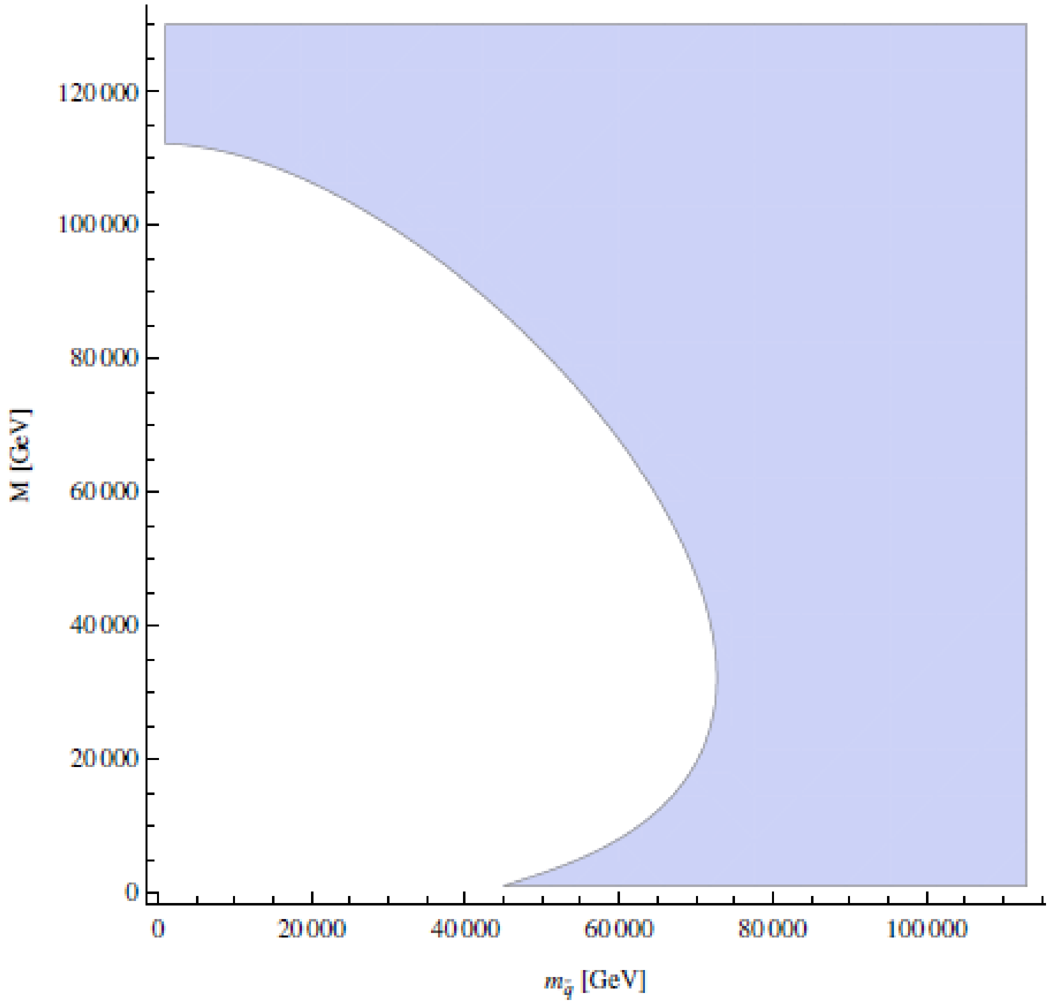


Figure 1: Contour plot in parameter space $m_{\tilde{q}}$ - M for purely Majorana gluino ($M_D = M_\chi = 0$). Along the contour $\Delta M_K = \Delta M_K^{exp} = 3.484 \times 10^{-15}$ GeV. $\sqrt{|\mathrm{Re}\,\delta^2_{12LL}|} = \sqrt{|\mathrm{Re}\,\delta^2_{12RR}|} = 0.22$.

- Different effective couplings: higgs-higgsinos-«fake winos » vertex not anymore a gauge coupling, multiplied by m_D/M

- If by accident/tuning, a squark is in the TeV range, its low-energy effects (FCNC,production) are still strongly suppressed due to its small coupling to the light fake gluino .

A numerical example of resulting masses is

$$M \sim 10^{12}\mathrm{GeV} \gtrsim m_{\mathcal{O}} \quad \gg \quad m_D,\ \sqrt{B_{\mathcal{O}}} \sim 10^{8}\mathrm{GeV} \quad \gg \quad M_{\chi} \sim 1\mathrm{TeV}$$

⇨ radiatively stable to have a very heavy gluino mass compared to the « fake gluino »

For Higgs mass analysis in such models, see
Benakli, Darmé, Goodsell and Slavich,
arXiv:1312.5220 [hep-ph].

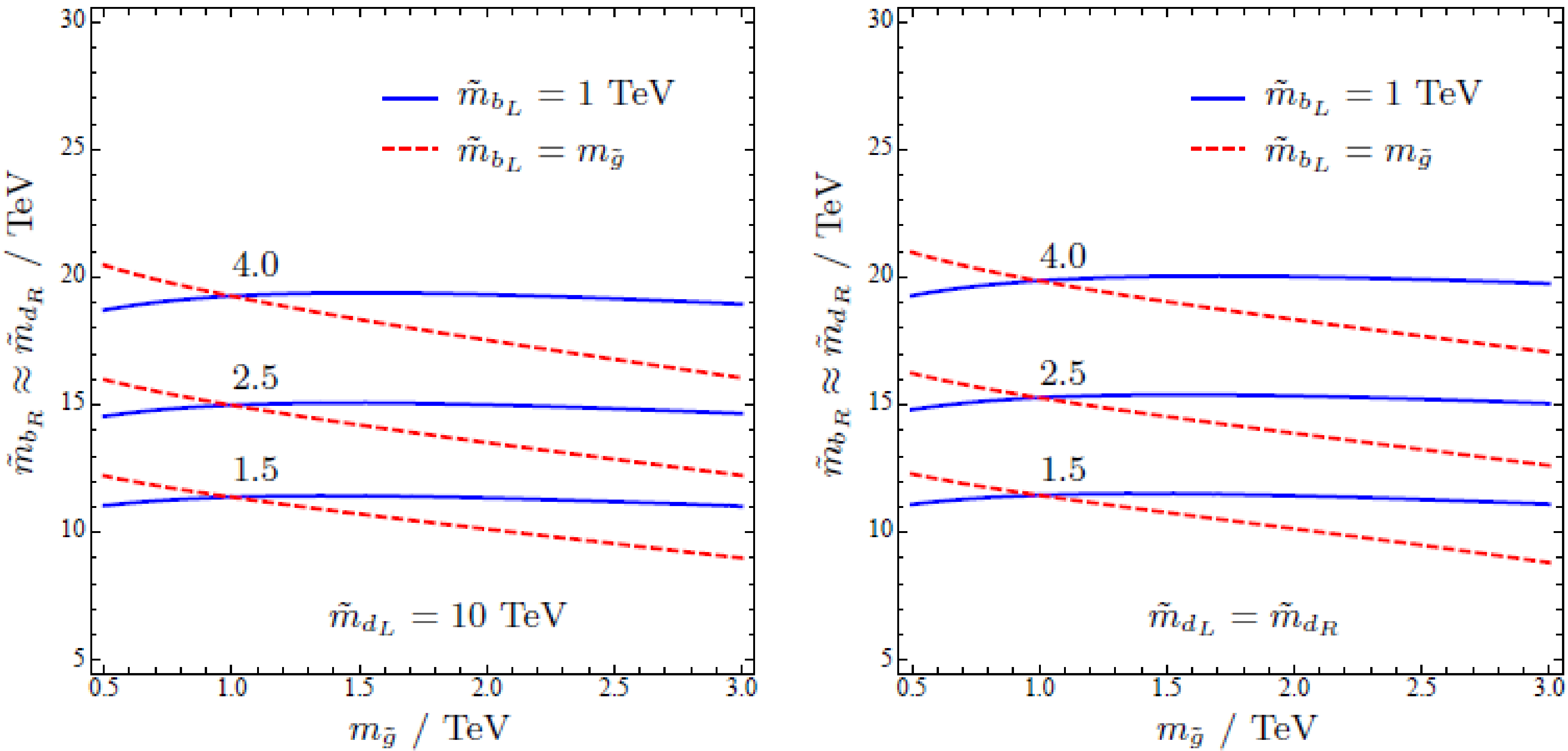


Figure 1: Bounds on the masses of the gluino and the approximately degenerate right handed down squark sector for various choices of the parameters. The region below each line is excluded. The three lines correspond to different choices of the dominant 3-1 splitting, namely $\tilde{m}^2_{d_R} - \tilde{m}^2_{b_R} = (1.5,\ 2.5,\ 4.0\ \text{TeV})^2$. 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.

Some simple flavor models we are considering:

- One U(1) models with alignment; ex. charges

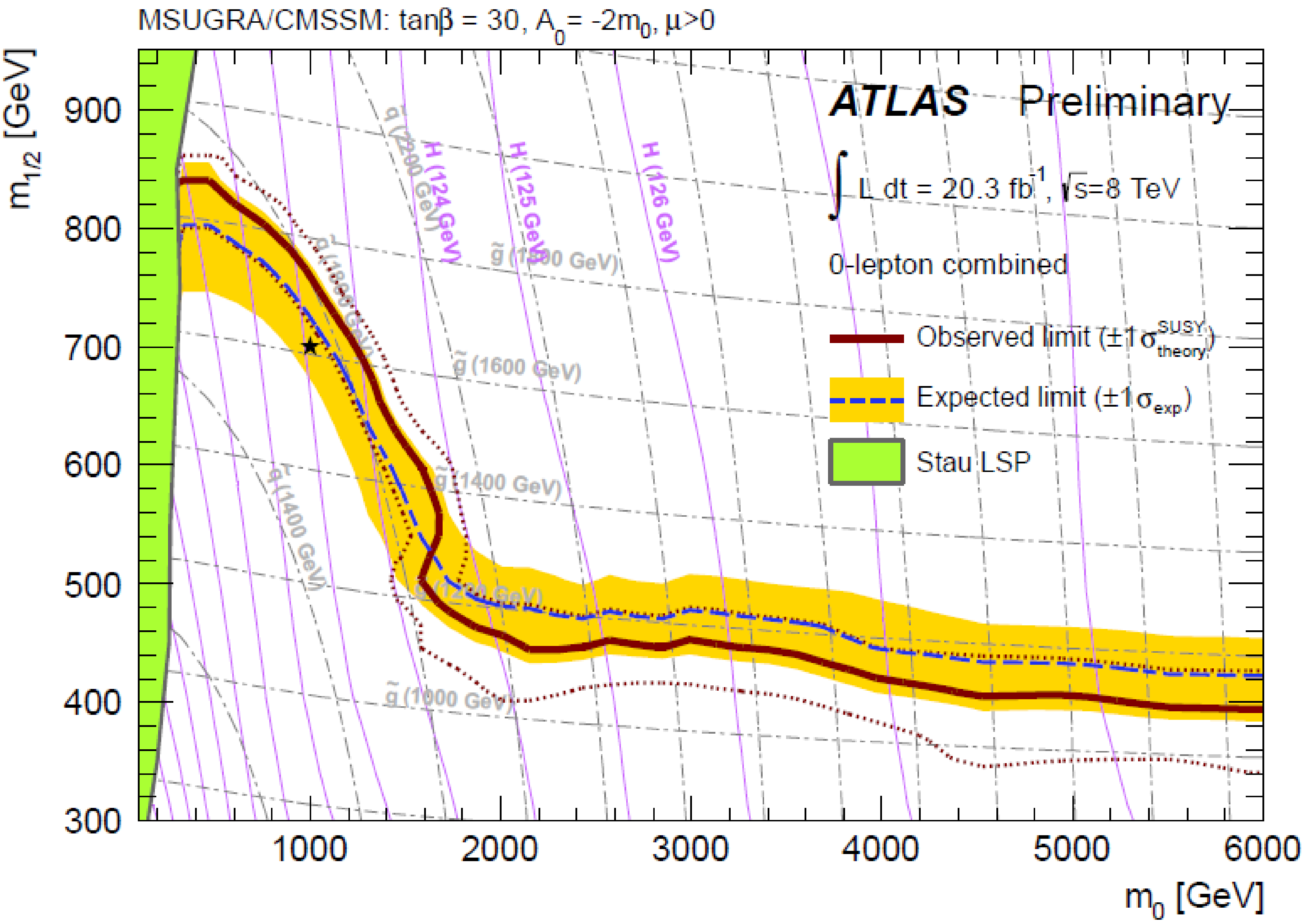
$$Q = (3,2,0) \qquad u = (3,1,0) \qquad d = (3,2,2)$$

Squark mass matrices are

$$\mathcal{M}^2_{d_L} \sim M_F^2 \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \qquad \mathcal{M}^2_{d_R} \sim M_F^2 \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

and quark rotations are

$$U_L^d \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \qquad U_R^d \sim \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$


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)
m1/2 [GeV]
m0 [GeV]
300
400
500
600
700
800
900
1000
2000
3000
4000
5000
6000

- MSSM soft terms, minimal gauge mediation:

- gaugino masses $\rightarrow$ 1-loop

$$M_{1/2} \sim N_m \frac{g^2}{16\pi^2} \left(\frac{F_X}{\langle X \rangle} \right) \sim N_m M_{GMSB}$$

- scalar (squarks,sleptons) masses : two-loops

$$m_0^2 \sim N_m \left(\frac{g^2}{16\pi^2} \right)^2 \left(\frac{F_X}{\langle X \rangle} \right)^2 \sim N_m M_{GMSB}^2$$

Typically $M_{GMSB} \gg m_{3/2}$, gravitino very light (LSP)