

Flavor violation and CP violation in BSM extensions

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Taller: “Más allá del Modelo Estándar y Astropartículas”

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Outline

① Flavor Violation BSM

- FV in Supersymmetry
- Phenomenological consequences on charged lepton sector.
 - $BR(\tau \rightarrow \mu\gamma)$.
 - $BR(h^0 \rightarrow \mu\tau)$.
 - EV contributions to $(g - 2)$.

② CP in extended Higgs sector.

- \rightsquigarrow 2HDM.
- \rightsquigarrow non-CP-MSSM.

Susy Flavor Violation Motivation

Eventhough the increment in particle spectrum, loop contributions to EW ρ parameter is safely achieved.

Search for possible **SUSY flavor structure** in low-energy SUSY model in order to test it in **EW precision data** results.

We may obtain **flavor non-conserving** 1-loop processes within an MSSM flavor extended model:

① Leptonic sector

- Susy loop contributions to lepton flavor violation processes $\tau \rightarrow \mu\gamma$, $\mu \rightarrow e\gamma$.
- EV extra contributions to muon's anomalous magnetic moment .
- neutrino mixing.

Hisano et. al. 95-96, Okada et. al. 00, Calvalho et.al. 01,

② Quark sector

- d-type quark FV as $b \rightarrow s\gamma$.
- u-type quark FV as $t \rightarrow c\gamma$.

Okomura and Roszkowski 03, K.Olive and L. Velasco-Sevilla 08

③ Higgs sector

- Sfermion FV leading to extra radiative corrections to Higgs mass.

Arana-Catania et.al 12, Bertuzzo 13

EW precision leptonic phenomenology effects

SUSY LFV contributions to EW precision data manifest at one-loop level



① The contribution to *Lepton Flavor Violation* from sleptons 1-loop diagram:

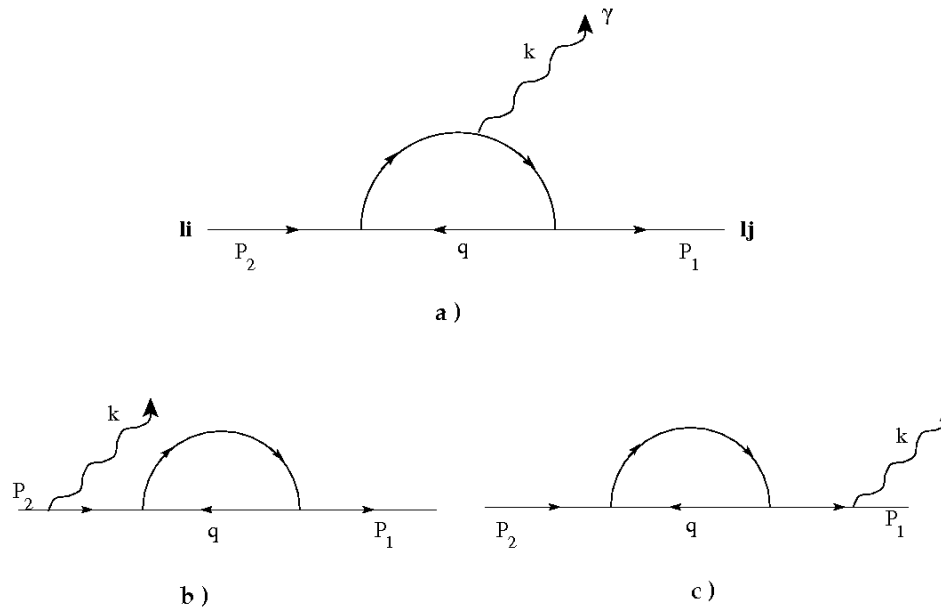


Figure 1: $\tau \rightarrow \mu \gamma$ *SUSY* contribution.

EW precision leptonic phenomenology effects

② LFV contribution to the anomalous magnetic moment of the muon:

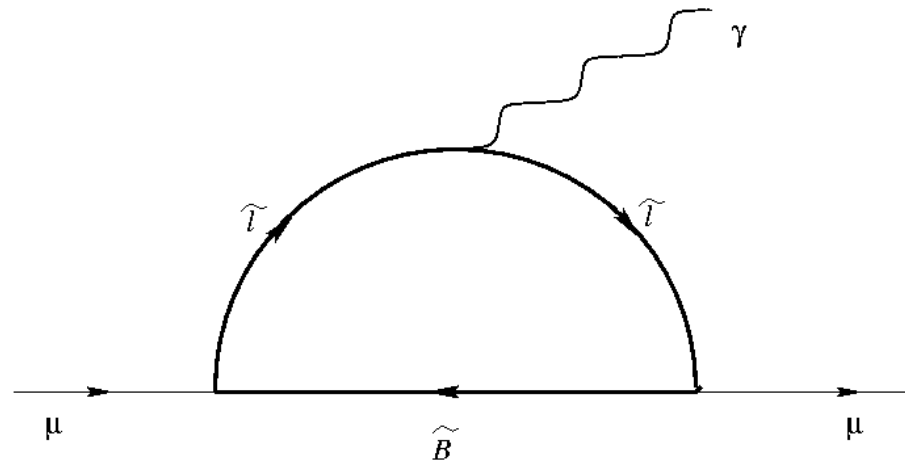


Figure 2: *muon's anomalous magnetic moment SUSY FV contribution.*



Supersymmetry

Symmetry relates fermions to bosons



SUSY uses superfields (chiral and vector) to describe all particles and interactions.

Straightforward phenomenological consequence



Duplicates the particle spectrum.

Superpartners for Standard Model particles

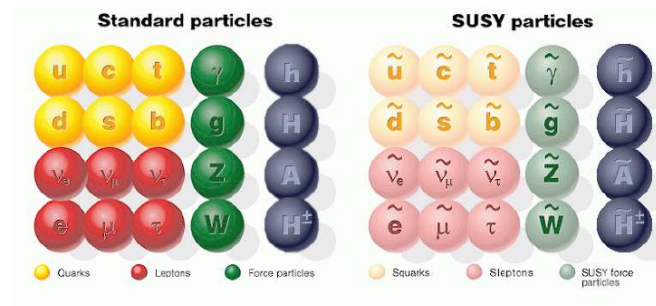


Figure 3: *Almost half of the Supersymmetry spectrum already found.*

~> **Susy must be broken introducing *Soft Susy Lagrangian.***

Supersymmetry field structure for fermions

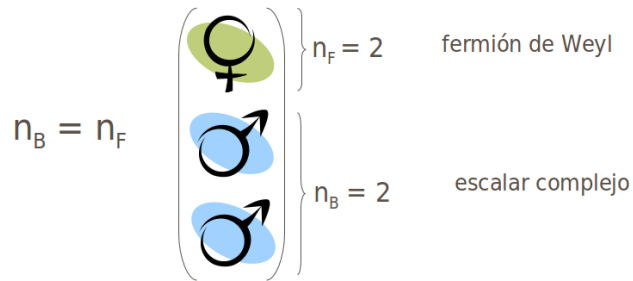
Supermultiplets:

Each of the fermion is accompanied by a complex scalar \rightarrow *chiral superfield*.

Supermultiplete quirral



fermions and sfermions



Higgsinos and Higgs

Figure 4: *Quiral supermultipletes: equal fermionic and bosonic d.o.f.*

And also each of the gauge boson fields is added by a fermionic field \rightarrow *vector superfield*.

Once SUSY is broken we need to add no-dynamical fields components F and D in order to conserved the fermionic-bosonic degrees of freedom.

Higgs sector of the MSSM

Two complex SU(2) Higgs doublets:

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

$H_1 \rightarrow d$ - type quarks

$H_2 \rightarrow u$ - type quarks

Physical Higgs particle spectrum :

ϕ_i , $CP = 1 \rightarrow$ two scalar fields: h^0, H^0 ,

χ_i , $CP = -1 \rightarrow$ one pseudoscalar field: A^0 .

and

ϕ^\pm , \rightarrow two charged fields: H^\pm

SSB: Assuming the scalar fields to develop nonzero vacuum expectation values

that break $SU(2)_L$

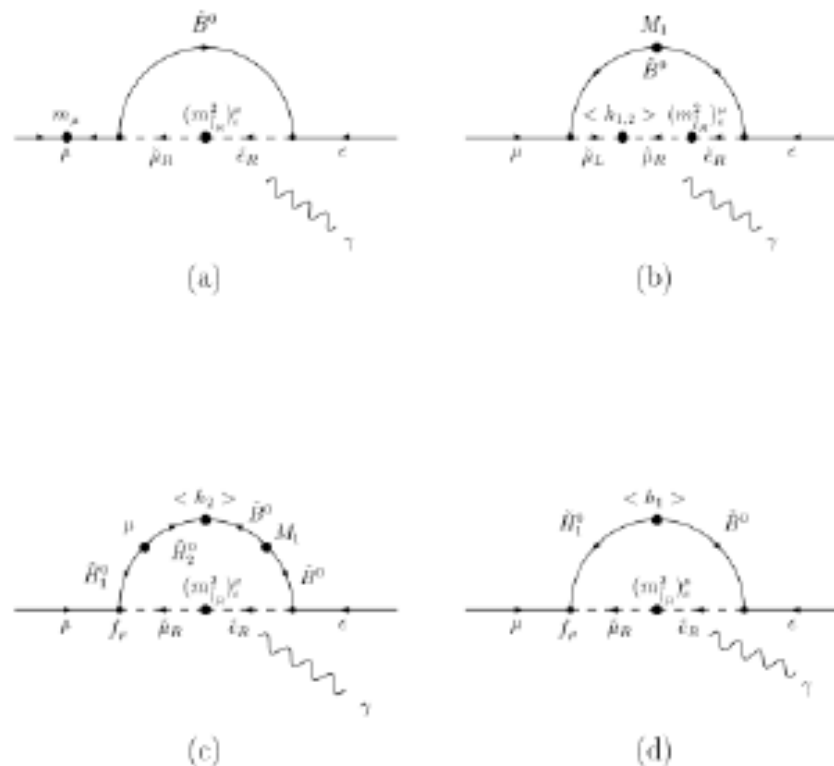
$$\langle H_1 \rangle = v_1 \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \langle H_2 \rangle = v_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (1)$$

Discrete symmetry is set to the Yukawa sector:

Pioneers on Lepton Flavor Violations in MSSM using MIA

Using a qualitative approximation in the flavor basis, known as *Mass Insertion Approximation (MIA)*,

J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B 391, 341 (1997)



Lepton Flavor Violations in MSSM using MIA

The MIA takes the diagonal part of the flavour mass matrix is absorbed into a definition on an unphysical massive propagator and the non-diagonal parts commonly refered to as mass insertions is treated perturbatively, as part of the interaction Lagrangian.

Dedes, Paraskevas, Rosiek, Suxho, Tamvakis 2015

"The MIA is a Taylor expansion only with respect ...(to) the mass-squared difference. A small off-diagonal element does not necessarily imply a small mass difference. Instead, it may be related to small mixing angles. But then the validity of the MIA is questionable."

Guy Raz 2002

SUSY \rightarrow Soft-terms of MSSM

Soft SUSY Lagrangian

Kuroda 99

$$\mathcal{L}_{soft}^{MSSM} = \mathcal{L}_{gauginogluino}^{mass} - \mathcal{L}_{sfermion}^{mass} - \mathcal{L}_{Higgs} - \mathcal{L}_{trilinear} \quad (2)$$

with

$$-\mathcal{L}_{gauginogluino}^{mass} = \frac{1}{2} \left[M_1 \tilde{B} \tilde{B} + M_2 \sum_{a=1}^3 \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^8 \tilde{G}^a \tilde{G}_a + h.c. \right] \quad (3)$$

$$-\mathcal{L}_{sfermion}^{mass} = \sum_{i=gen} m_{\tilde{Q}_i}^2 \tilde{Q}_i^\dagger \tilde{Q}_i + m_{\tilde{L}_i}^2 \tilde{L}_i^\dagger \tilde{L}_i + m_{\tilde{u}_i}^2 |\tilde{u}_{Ri}| + m_{\tilde{d}_i}^2 |\tilde{d}_{Ri}|^2 + m_{\tilde{l}_i}^2 |\tilde{l}_{Ri}|^2 \quad (4)$$

$$-\mathcal{L}_{Higgs} = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \mu B (H_2 \cdot H_1 + h.c.) \quad (5)$$

$$-\mathcal{L}_{trilinear} = \sum_{i,j=gen} \left[A_{ij}^u \tilde{Q}_i H_2 \tilde{u}_{Rj}^* + A_{ij}^d \tilde{Q}_i H_1 \tilde{d}_{Rj}^* + A_{ij}^l \tilde{L}_i H_1 \tilde{l}_{Rj}^* \right] \quad (6)$$

1. $BR(\tau \rightarrow \mu\gamma)$ *no-MIA*

The Lagrangian $\tilde{B}^0\tilde{l}l$ in mass eigenstate now is given by:

$$\begin{aligned} \mathcal{L}_{\tilde{B}\tilde{l}l} = & -\frac{g}{2\sqrt{2}} \tan \theta_W \bar{\tilde{B}} \left\{ [-P_L \tilde{e}_1 + 2P_R \tilde{e}_2] e + \right. \\ & -\frac{s_\varphi}{\sqrt{2}} [(1 + 3\gamma_5)\tilde{\mu}_1 + (3 + \gamma_5)\tilde{\mu}_2] \mu + \\ & +\frac{c_\varphi}{\sqrt{2}} [(1 + 3\gamma_5)\tilde{\mu}_1 + (3 + \gamma_5)\tilde{\mu}_2] \tau + \\ & +\frac{c_\varphi}{\sqrt{2}} [(3 + \gamma_5)\tilde{\tau}_1 + (1 + 3\gamma_5)\tilde{\tau}_2] \mu + \\ & \left. +\frac{s_\varphi}{\sqrt{2}} [(3 + \gamma_5)\tilde{\tau}_1 + (1 + 3\gamma_5)\tilde{\tau}_2] \tau \right\} \end{aligned}$$

(7)

We may write the coupling as

$$g_{l_i B \tilde{l}_r} = -\frac{g \tan \theta_W}{4} [S_{l_i, \tilde{l}_r} + P_{l_i, \tilde{l}_r} \gamma^5]$$

1. $BR(\tau \rightarrow \mu\gamma)$ gauge invariance

The total amplitude is written as follows:

$$\begin{aligned}\mathcal{M}_T &= \bar{u}(p_1)[iE_{ij}\sigma^{\mu\nu}k_\nu\epsilon_\mu + iF_{ij}\sigma^{\mu\nu}k_\nu\epsilon_\mu\gamma^5]u(p_2) \\ &= \bar{u}(p_1)\left[\frac{E_{ij}}{2} + \frac{F_{ij}}{2}\gamma^5\right][\not{k}, \not{\epsilon}]u(p_2) .\end{aligned}\tag{8}$$

The Branching Ratio will be given by

$$BR(\tau \rightarrow \mu\gamma) = \frac{(1-x^2)^3 m_\tau^3}{4\pi\Gamma_\tau} \left[\left| \sum_{\tilde{l}} E_{\tilde{l}}^{\tau\mu} \right|^2 + \left| \sum_{\tilde{l}} F_{\tilde{l}}^{\tau\mu} \right|^2 \right] ,\tag{9}$$

with $x = \frac{m_\mu}{m_\tau}$.

$(g - 2)$ from FV slepton loop.

$$\begin{aligned}
\bar{u}(p_1)\Gamma^\mu u(p_2) &= ig_c \bar{u}(p_1) \left[S_{\tilde{B}\mu, \tilde{l}} + P_{\tilde{B}\mu, \tilde{l}} \gamma^5 \right] \frac{1}{(2\pi)^4} \int dk^4 \frac{i[k\not{+} + m_{\tilde{B}}]}{D_t} i \frac{\tan\theta_w g_1}{4} \\
&\times \left[S_{\tilde{B}\mu, \tilde{l}} - P_{\tilde{B}\mu, \tilde{l}} \gamma^5 \right] \frac{i}{D_2} \frac{i}{D_1} [2k + p_1 + p_2]_\mu u(p_2) \\
&= ig_c^2 \left[S_{\tilde{B}\mu, \tilde{l}}^2 - P_{\tilde{B}\mu, \tilde{l}}^2 \right] m_{\tilde{B}} \bar{u}(p_1) \int \frac{dk^4}{(2\pi)^4} \frac{(2k + p_1 + p_2)^\mu}{D_t D_1 D_2} u(p_2) \\
&+ g_c^2 \bar{u}(p_1) \left[S_{\tilde{B}\mu, \tilde{l}}^2 + P_{\tilde{B}\mu, \tilde{l}}^2 \right] \int \frac{dk^4}{(2\pi)^4} \frac{(2k + p_1 + p_2)^\mu k\not{+}}{D_t D_1 D_2} u(p_2) + \dots \\
&= g_c^2 \bar{u}(p_1) \left[(S_{\tilde{B}\mu, \tilde{l}}^2 - P_{\tilde{B}\mu, \tilde{l}}^2) m_{\tilde{B}} B_1^\mu(q^2) \right] u(p_2) \\
&+ g_c^2 \bar{u}(p_1) \left[(S_{\tilde{B}\mu, \tilde{l}}^2 + P_{\tilde{B}\mu, \tilde{l}}^2) B_2^\mu(q^2) \right] u(p_2) + \dots, \tag{10}
\end{aligned}$$

where $q^2 = (p_2 - p_1)^2$ and the ellipsis means terms that are not involved in the determination of the anomaly contribution.

The propagators are given by

$$Dt = \frac{1}{k^2 - m_{\tilde{B}}^2}, \quad (11)$$

$$D_1 = \frac{1}{(p_1 + k)^2 - m_{\tilde{l}}^2}, \quad (12)$$

$$D_2 = \frac{1}{(p_2 + k)^2 - m_{\tilde{l}}^2}. \quad (13)$$

$$a_\mu = \frac{g_c^2 m_\mu}{(4\pi)^2} \left[(S_{\tilde{B}\mu, \tilde{l}}^2 + P_{\tilde{B}\mu, \tilde{l}}^2) \frac{m_\mu}{6m_{\tilde{l}}^2} F_1^N(x) - (S_{\tilde{B}\mu, \tilde{l}}^2 - P_{\tilde{B}\mu, \tilde{l}}^2) \frac{m_{\tilde{B}}}{3m_{\tilde{l}}^2} F_2^N(x) \right], \quad (14)$$

here $x = m_{\tilde{B}}^2/m_{\tilde{l}}^2$ and, for brevity we define $g_c^2 = \frac{\tan^2\theta_w g_1^2}{16}$. We have used the notation for the functions $F_{1,2}^N(x)$ given in Ref. [Stockinger:2006zn](#).

$$h^0 \rightarrow \tau\mu \text{ } FV \text{ slepton loop.}$$

the slepton which interacts with the muon (tau) is labeled with the index i (j), see Fig 1.

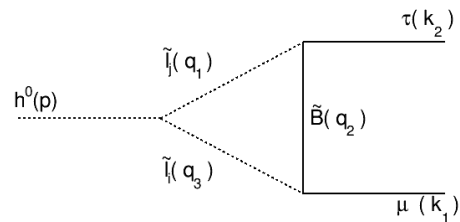
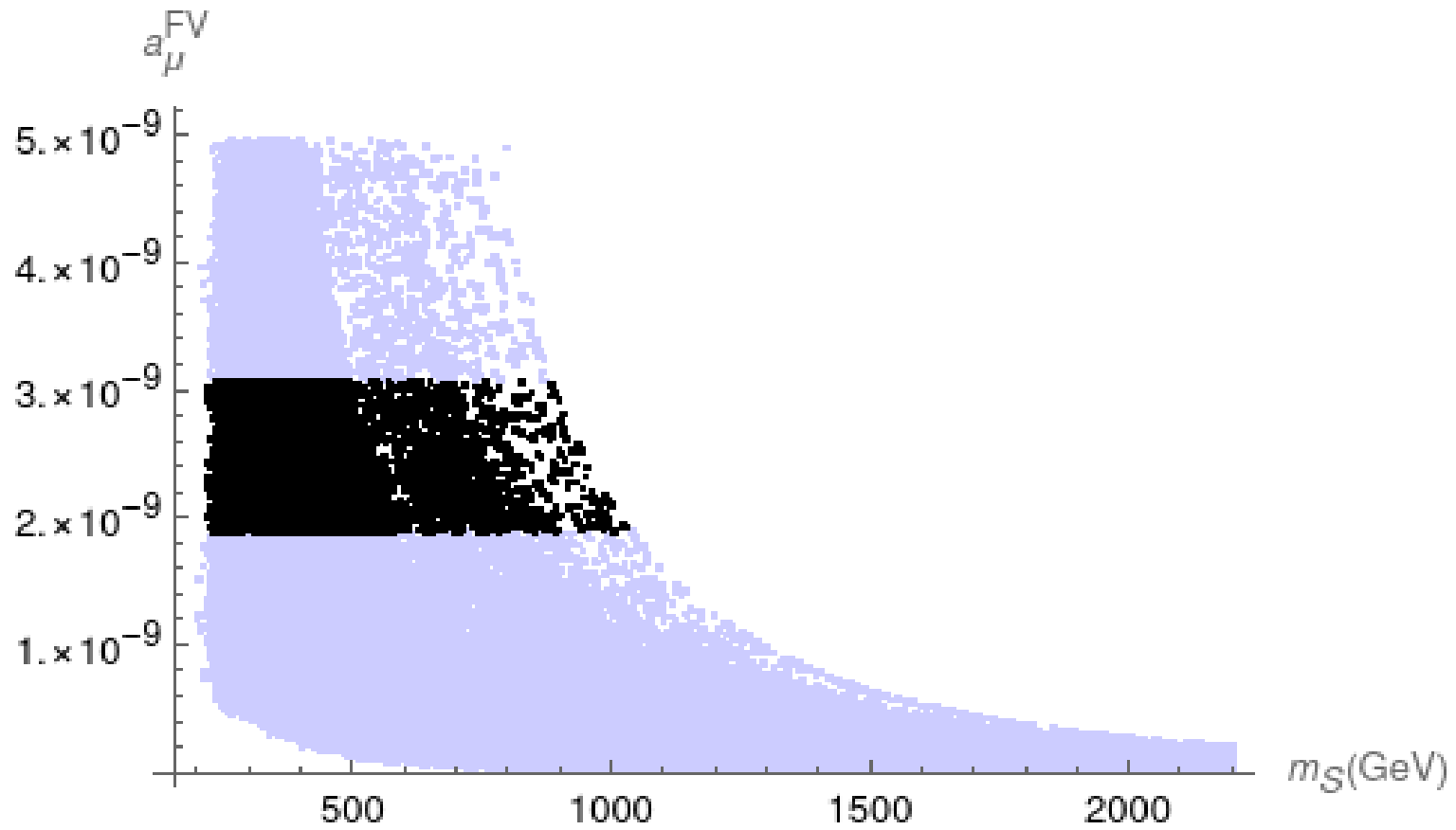


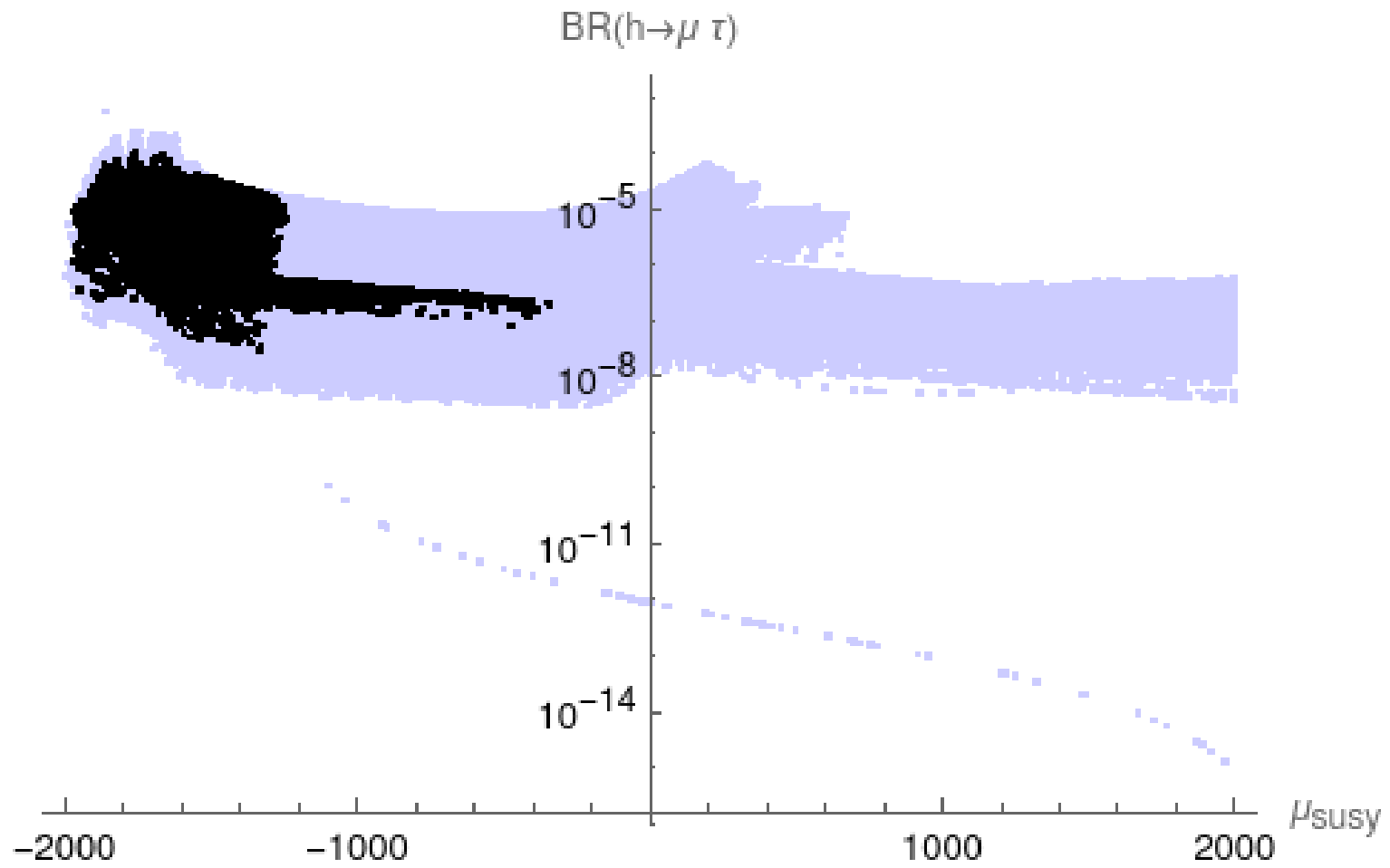
Figure 5: *1-loop SUSY slepton flavor mixing contribution to $h^0 \rightarrow \mu\tau$.*

The notation used for the coupling between the bino \tilde{B} , the slepton \tilde{l} and the lepton l , for $l = \mu, \tau$, which is denoted as $\tilde{B}\tilde{l}l$, can be written in terms of three types of coefficients for each lepton.

Preliminary Results $BR(h^0 \rightarrow \mu\tau)$



Preliminary Results $BR(h^0 \rightarrow \mu\tau)$



Preliminary Results: No-FV limit

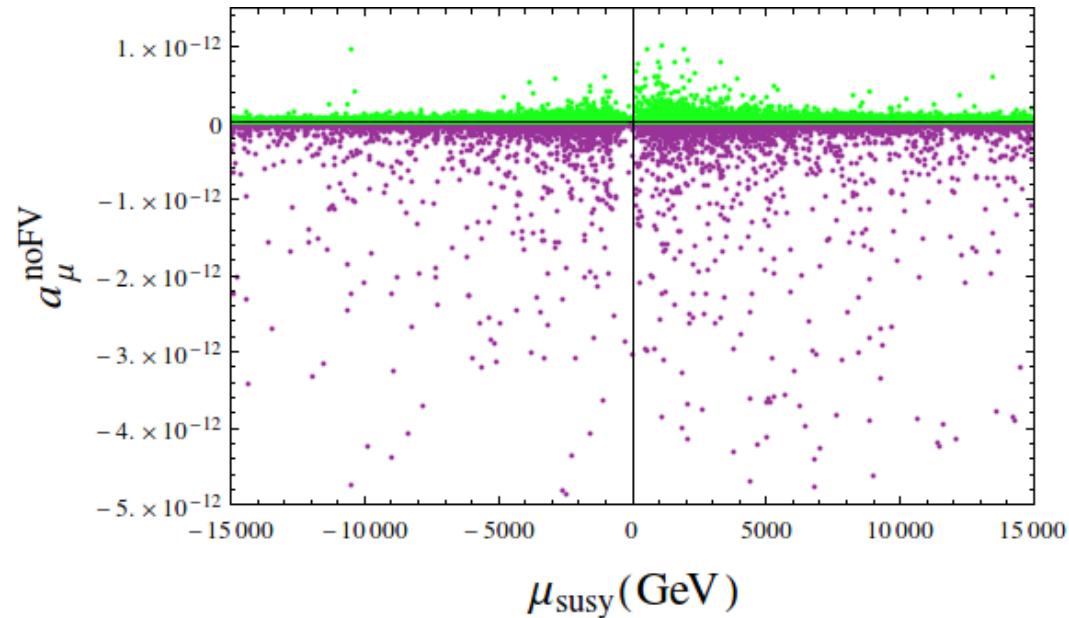


Figure 6: Complete Bino-smuon loop contribution on MSSM with no flavour violation to $g - 2$, considering $A_0 = 0$ green points (lighter), and running A_0 for $(50, 5000)$ GeV purple points (darker).

Higgs sector of the 2HDM with CP non-invariance I

The most general form of a two $SU(2)$ Higgs doublet model potential (2HDM) with CP violation is

$$\begin{aligned} \mathcal{L}_V = & \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) + m_{12}^2(\Phi_1^\dagger\Phi_2) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 \\ & + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + h.c. \end{aligned} \quad (15)$$

where $\Phi_{1,2}$ denote two complex $Y = 1$, $SU(2)_L$, iso-doublet scalar fields.

$\mathcal{CP} - 2HDM$ Higgs masses

Las segundas derivadas se obtiene la matriz de masa

$$M_{ij}^2 = \begin{pmatrix} M_{12} & M_{12} & M_{13} & M_{14} & 0 & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & M_{24} & 0 & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & M_{34} & 0 & 0 & 0 & 0 \\ M_{41} & M_{42} & M_{43} & M_{44} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & M_{56} & 0 & M_{58} \\ 0 & 0 & 0 & 0 & M_{65} & M_{66} & M_{67} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{76} & M_{77} & M_{78} \\ 0 & 0 & 0 & 0 & M_{85} & 0 & M_{87} & M_{88} \end{pmatrix}. \quad (16)$$

2HDM Elementos de la matriz de masa con CP

Los valores de los componentes de la matriz neutra son los siguientes:

$$\begin{aligned}M_{11} &= 12v_1^2\lambda_1 + v_2^2\lambda_R + 3v_1v_2(\lambda_6 + \lambda_6^*) + 2\mu_1^2 \\M_{12} &= \frac{1}{2}[4v_1v_2\lambda_R + 3v_1^2(\lambda_6 + \lambda_6^*) + 3v_2^2(\lambda_7 + \lambda_7^*) - 2(\mu_{12}^2 + \mu_{12}^{*2})] \\M_{13} &= -i(v_2^2(\lambda_5 - \lambda_5^*) + v_1v_2(\lambda_6 - \lambda_6^*)) \\M_{14} &= \frac{1}{2}i[(4v_1v_2(\lambda_5 - \lambda_5^*) + 3v_1^2(\lambda_6 - \lambda_6^*) + v_2^2(\lambda_7 - \lambda_7^*) - 2(\mu_{12} - \mu_{12}^{*2})] \\M_{22} &= 12v_2^2\lambda_2 + v_1^2\lambda_R + 3v_1v_2(\lambda_6 + \lambda_6^*) + 2\mu_2^2 \\M_{23} &= -\frac{1}{2}i[(4v_1v_2(\lambda_5 - \lambda_5^*) + v_1^2(\lambda_6 - \lambda_6^*) + 3v_2^2(\lambda_7 - \lambda_7^*) - 2(\mu_{12} - \mu_{12}^{*2})] \\M_{24} &= iv_1(v_1(\lambda_5 - \lambda_5^*) + v_2(\lambda_7 - \lambda_7^*)) \\M_{31} &= -iv_2(v_2(\lambda_5 - \lambda_5^*) + v_1(\lambda_7 - \lambda_7^*)) \\M_{33} &= 4v_1^2\lambda_1 + v_2^2(\lambda_R - 2(\lambda_5 + \lambda_5^*)) + v_1v_2(\lambda_6 + \lambda_6^*) + 2\mu_1^2 \\M_{34} &= \frac{1}{2}[(4v_1v_2(\lambda_5 + \lambda_5^*) + v_1^2(\lambda_6 + \lambda_6^*) + v_2^2(\lambda_7 + \lambda_7^*) - 2(\mu_{12} + \mu_{12}^{*2})] \\M_{44} &= 4v_2^2\lambda_2 + v_1^2(\lambda_R - 2(\lambda_5 + \lambda_5^*)) + v_1v_2(\lambda_7 + \lambda_7^*) + 2\mu_2^2\end{aligned}$$

Higgs sector in the Minimal Supersymmetric Extension of the Standard Model with CP

The radiative suppression establishes a hierarchy on the couplings. At tree level, without radiative corrections, the couplings have a discrete symmetry which gives the following values

$$\begin{aligned}\mu_1^2 &= -m_1^2 - |\mu|^2, & \mu_2^2 &= -m_2^2 - |\mu|^2, & \lambda_1 &= \lambda_2 = -\frac{1}{8}(g_w^2 + g'^2), \\ \lambda_3 &= -\frac{1}{4}(g_w^2 - g'^2), & \lambda_4 &= \frac{1}{2}g_w^2, & \lambda_5 &= \lambda_6 = \lambda_7 = 0.\end{aligned}$$

But we could have complex couplings in \mathcal{L}_V of the form

$$m_{12}^2 = m_{12}^{2R} + im_{12}^{2I} \quad \lambda_{5,6,7} = \lambda_{5,6,7}^R + i\lambda_{5,6,7}^I \quad (17)$$

At higher orders, the mixing of heavy neutral $H - A$ Higgses necessarily generates a new source of CP violation

The rotation to the known Higgs states would be given as CP-odd:

$$\begin{aligned}G^0 &= A_1 \cos \beta + A_2 \sin \beta \\A^0 &= -A_1 \sin \beta + A_2 \cos \beta\end{aligned}\tag{18}$$

CP-even:

$$\begin{aligned}h^0 &= -H_1 \sin \alpha + H_2 \cos \alpha \\H^0 &= H_1 \cos \alpha + H_2 \sin \alpha\end{aligned}\tag{19}$$

with $v = (v_1^2 + v_2^2)^{1/2} \approx 246 \text{ GeV}$.

Neutral Higgs bosons mass matrix $\mathcal{M}^2(s)$ in the \mathcal{CP} 2HDM

- The mass matrix \mathcal{M}_0^2 of neutral Higgs fields in the basis of h , H and A which is hermitian and symmetric by CPT invariance is readily derived from \mathcal{L}_V

$$\mathcal{M}_0^2 = v^2 \begin{pmatrix} \lambda & -\hat{\lambda} & -\hat{\lambda}_p \\ -\hat{\lambda} & \lambda - \lambda_A + \frac{1}{v^2} M_A^2 & -\lambda_p \\ -\hat{\lambda}_p & \lambda_p & \frac{1}{v^2} M \end{pmatrix} \quad (20)$$

The λ , $\hat{\lambda}$ and λ_A are functions of the $Re\lambda_i$ while λ_p and $\hat{\lambda}_p$ are functions of the $Im\lambda_i$ in \mathcal{L}_V

- For small mass differences, the mixing of the states is strongly affected by their widths. Therefore, the Hermitian matrix \mathcal{M}_0^2 has to be supplemented by the antihermitian part $-iM\Gamma(s)$ incorporating the decay matrix

$$\mathcal{M}^2(s) = \mathcal{M}_0^2 - iM \Gamma(s) \quad (21)$$

Higgs Masses in a CP Non-invariant Higgs Sector

- In a CP non-invariant Higgs sector of the THDM, the three neutral scalar bosons, H_1, H_2 and H_3 , mix and form a triplet with CP-even and CP-odd components in their wave functions.
- The 3×3 mass matrix, $\mathcal{M}^2 = \mathcal{M}_R^2 - iM\Gamma$ is non-Hermitian using the 2HDM notation for the mass matrix

$$\mathcal{M}_R^2 = v^2 \begin{pmatrix} \lambda & 0 & -\hat{\lambda}_p \\ 0 & m_A^2 - \lambda - \lambda_A & \lambda_p \\ -\hat{\lambda}_p & \lambda_p & m_A^2 \end{pmatrix}. \quad (22)$$

- In the decoupling limit,

$$M_A^2 \gg |\lambda_i|v^2, \quad (23)$$

mixing between the light state, H_1 , and the heavy Higgs states, H_2 and H_3 is small, compared with the mixing of the nearly degenerate heavy Higgs states H_2 and H_3 .

- By CPT-invariance, the mass matrix \mathcal{M}_{H_2, H_3}^2 is symmetric.
- In the basis of the $|H\rangle$ and $|A\rangle$ states, the 2×2 submatrix is

$$\mathcal{M}_{H,A}^2 = \begin{pmatrix} M_H^2 - iM_H\Gamma_H & \Delta_{HA}^2 \\ \Delta_{HA}^2 & M_A^2 - i\Gamma_A M_A \end{pmatrix} \quad (24)$$

..to be continued...

Thank you!

Muon magnetic moment anomaly a_μ

We know $\vec{\mu} = -g \frac{e}{2m} \vec{s}$. Which is corrected by 1-loop diagrams, for the muon

$$\vec{\mu}_\mu = \frac{e}{2m_\mu} (1 + a_\mu) \vec{\sigma}$$

The electron spin interacts with an external electromagnetic field. Using Gordon identity

$$\Gamma^\mu = A\gamma^\mu + B(p_1 + p_2)^\mu + \dots = F_1(q^2)\gamma^\mu + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)$$

F are called form factors and are functions depending on $q^2 = (p_2 - p_1)^2$. The magnetic moment anomaly is defined as

$$g = 2[F_1(0) + F_2(0)] = 2 + 2F_2(0) \rightarrow a_\mu \equiv F_2(0) = \frac{g - 2}{2}$$

At lowest order: $F_1 = 1, F_2 = 0$

$$a_{\mu}^{\text{SM}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{Had}} . \quad (4)$$

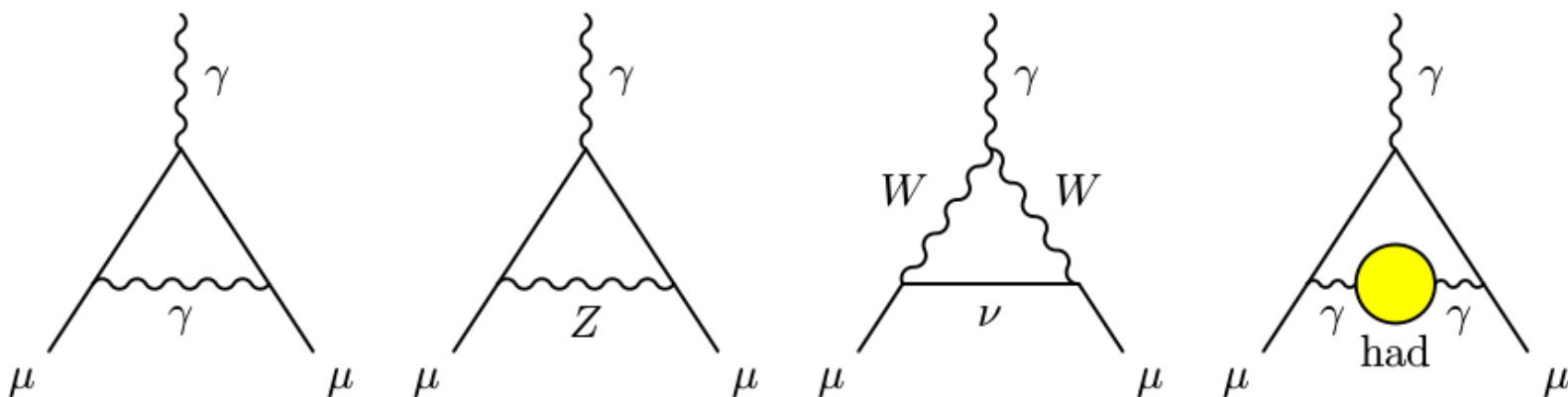
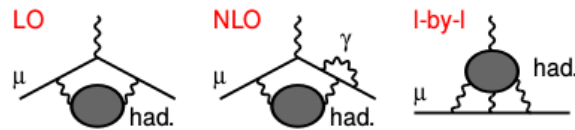


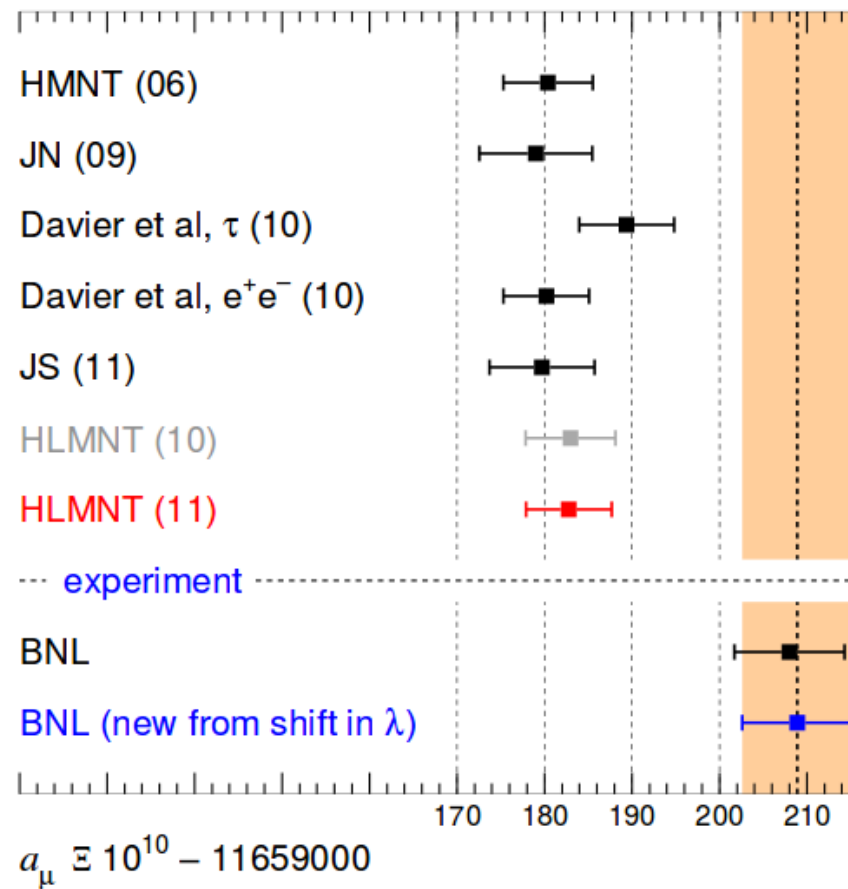
Figure 1: Representative diagrams contributing to a_{μ}^{SM} . From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.

Introduction: Standard Model prediction for muon $g - 2$

QED contribution	11 658 471.808 (0.015)	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2)	Czarnecki et al
Hadronic contributions		
LO hadronic	694.9 (4.3)	HLMNT11
NLO hadronic	-9.8 (0.1)	HLMNT11
light-by-light	10.5 (2.6)	Prades, de Rafael & Vainshtein
Theory TOTAL	11 659 182.8 (4.9)	
Experiment	11 659 208.9 (6.3)	world avg
Exp - Theory	26.1 (8.0)	3.3 σ discrepancy

(in units of 10^{-10} . Numbers taken from HLMNT11, arXiv:1105.3149)
n.b.: hadronic contributions:





HLMNT=K Hagiwara, R. Liao, D. Martin, D. Nomura and T. Teubner

Reducing MSSM parameters

At tree level, the MSSM parameters could be reduced to only 2: m_A and $\tan \beta$, CMSSM.

Once we calculate one-loop radiative corrections we must set values to other parameters.

Most scenarios were built in order to have the least free parameters.

phenomenological, pMSSM

- ① CP-conserving (no extra source)
- ② no FCNC
- ③ $m_{\tilde{f}_1} \approx m_{\tilde{f}_2}$ to accomplish $K^0 - \bar{K}^0$ mixing

phenomenological, pMSSM

22 input parameters:

$$\begin{aligned} & \tan \beta; \\ & m_1^2, m_2^2; \\ & M_1, M_2, M_3; \\ & \tilde{m}_q, \tilde{m}_{uR}, \tilde{m}_{dR}, \tilde{m}_l, \tilde{m}_{eR}; \\ & \tilde{m}_{Qt}, \tilde{m}_{tR}, \tilde{m}_{bR}, \tilde{m}_{L\tau}, \tilde{m}_{\tau R}; \\ & A_{u,c}, A_{d,s}, A_{e,\mu}; \quad A_t, A_b, A_\tau \end{aligned}$$

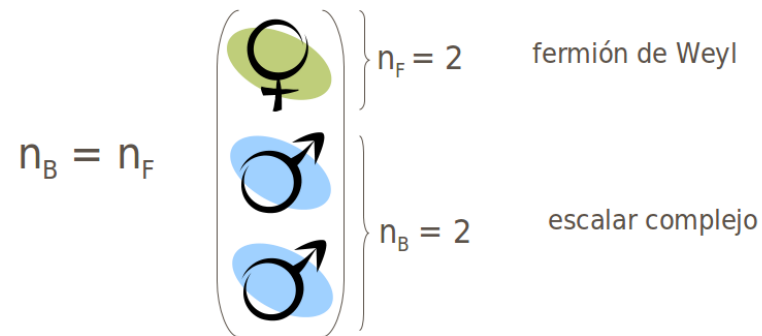
We propose a different consideration for trilinear couplings

$$A_u, A_d, A_e; \quad A_{c,t}, A_{s,b}, A_{\mu,\tau}$$

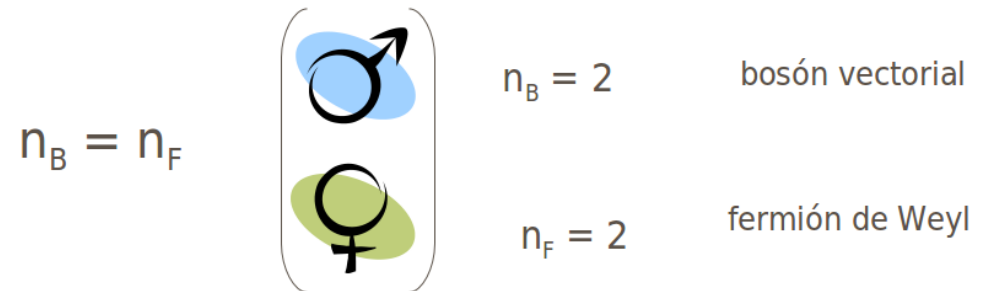
where the two families are mixed.

Supersymmetry

Supermultiplete quirral



Supermultiplete vectorial



Supersymmetry

In *MSSM* :

➤ EW scale is stabilized, with $\lambda_S = |\lambda_f|^2$ then the Λ_{UV}^2 will neatly cancel

for instance see [S.P. Martin 08, a SUSY Premier]

- Unification of gauge couplings.
- Generates DM candidates.
- Obtain FV couplings through *SUSY loops*
- Solution to hierarchy problem

H.Haber 95,
Low-energy Supersymmetry:Prospects and Challenges, Djouadi and Quevillon
13.

Supersymmetry experimental searches.

ATLAS SUSY Searches* - 95% CL Lower Limits
May 2017

ATLAS Preliminary
 $\sqrt{s} = 7, 8, 13$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu/1-2 \tau$	2-10 jets/3 b	Yes	20.3	\tilde{g}, \tilde{g}	1.85 TeV	$m(\tilde{g})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{q}	1.57 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(1^{\text{st}} \text{ gen. } \tilde{q}) = m(2^{\text{nd}} \text{ gen. } \tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{q}	608 GeV	$m(\tilde{q}) - m(\tilde{\chi}_1^0) < 5$ GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.02 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.01 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_2^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.825 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	\tilde{g}	1.8 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	\tilde{g}	1.65 TeV	$c\tau(\text{NLSP}) < 0.1$ mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g}	1.37 TeV	$m(\tilde{\chi}_1^0) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu < 0$	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	\tilde{g}	1.8 TeV	$m(\tilde{\chi}_1^0) > 680$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g}	900 GeV	$m(\text{NLSP}) > 430$ GeV	1503.03290
Gravitino LSP	0	mono-jet	Yes	20.3	\tilde{g}	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-1}$ eV, $m(\tilde{g}) = m(\tilde{q}) = 1.5$ TeV	1502.01518	
3 rd gen. \tilde{g} med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	\tilde{g}	1.92 TeV	$m(\tilde{\chi}_1^0) < 600$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	\tilde{g}	1.97 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.37 TeV	$m(\tilde{\chi}_1^0) < 300$ GeV	1407.0600
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	\tilde{b}_1	950 GeV	$m(\tilde{\chi}_1^0) < 420$ GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^+$	2 e, μ (SS)	1 b	Yes	36.1	\tilde{b}_1	275-700 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + 100$ GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	117-170 GeV	$m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^+), m(\tilde{\chi}_2^0) = 55$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{b}_1^0$ or $\tilde{t}_1\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	\tilde{t}_1	90-198 GeV	$m(\tilde{\chi}_1^0) = 1$ GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	\tilde{t}_1	90-323 GeV	$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 5$ GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{\chi}_1^0) > 150$ GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_2	290-790 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2017-019
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	320-880 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2017-019	
EW direct	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	\tilde{t}_1	90-440 GeV	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1\tilde{\chi}_1^+$	2 e, μ	0	Yes	36.1	\tilde{t}_1	710 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_2^0) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1\tilde{\chi}_1^0$	2 τ	-	Yes	36.1	\tilde{t}_1	760 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_2^0) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-035
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1\tilde{\chi}_1^0$	3 e, μ	0	Yes	36.1	\tilde{t}_1	580 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_2^0) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	\tilde{t}_1	580 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{\chi}_1^0\tilde{\chi}_1^0$	e, μ, γ	0-2 b	Yes	20.3	\tilde{t}_1	270 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	1501.07110
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{\chi}_1^0\tilde{\chi}_1^0$	4 e, μ	0	Yes	20.3	\tilde{t}_1	635 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	115-370 GeV	$m(\tilde{\chi}_2^0) = m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_2^0) = 0.5(m(\tilde{\chi}_2^+) + m(\tilde{\chi}_1^0))$	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	20.3	\tilde{W}	590 GeV	$c\tau < 1$ mm	1507.05493
	Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^+$	430 GeV	$m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^+) = 0.2$ ns
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$		dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^+$	495 GeV	$m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^+) < 15$ ns	1506.05332
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	$m(\tilde{\chi}_1^0) = 100$ GeV, $10 \mu\text{s} < \tau(\tilde{g}) < 1000$ s	1310.6584
Stable \tilde{g} R-hadron		trk	-	-	3.2	\tilde{g}	1.58 TeV		1606.05129
Metastable \tilde{g} R-hadron		dE/dx trk	-	-	3.2	\tilde{g}	1.57 TeV		1604.04520
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$		1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$m(\tilde{\chi}_1^0) = 100$ GeV, $\tau > 10$ ns	1411.8795
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model	1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}/\mu\tilde{\nu}/\mu\tilde{\nu}$		displ. $e\tilde{\nu}/\mu\tilde{\nu}$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740$ mm, $m(\tilde{g}) = 1.3$ TeV	1504.05162
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$		displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$6 < c\tau(\tilde{\chi}_1^0) < 480$ mm, $m(\tilde{g}) = 1.1$ TeV	1504.05162
RPV		LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, \tau\mu$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda_{311}^{\nu} = 0.11, \lambda_{132/133/233/233} = 0.07$
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.45 TeV	$m(\tilde{q}) = m(\tilde{g}), c\tau_{\text{LSP}} < 1$ mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}, \mu\tilde{\nu}, \mu\tilde{\nu}$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^0$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400$ GeV, $\lambda_{12k} \neq 0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}_\tau, e\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^0$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^+), \lambda_{133} \neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}$	0	4-5 large-R jets	-	14.8	\tilde{g}	1.08 TeV	$\text{BR}(\tilde{g}) \rightarrow \text{BR}(b) = \text{BR}(c) = 0\%$	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}, \tilde{q}^0 \rightarrow qq\tilde{q}$	0	4-5 large-R jets	-	14.8	\tilde{g}	1.55 TeV	$m(\tilde{\chi}_1^0) = 800$ GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}, \tilde{q}^0 \rightarrow qq\tilde{q}$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	2.1 TeV	$m(\tilde{\chi}_1^0) = 1$ TeV, $\lambda_{112} \neq 0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	1.65 TeV	$m(\tilde{t}_1) = 1$ TeV, $\lambda_{323} \neq 0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 b	-	15.4	\tilde{t}_1	410 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$	2 e, μ	2 b	-	36.1	\tilde{t}_1	0.4-1.45 TeV	$\text{BR}(\tilde{t}_1 \rightarrow b\tilde{\ell}/\mu) > 20\%$	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{z} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{z}	510 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹

1

Mass scale [TeV]

Supersymmetry at LHC.

In addition there are other SUSY models which may fit the current LHC data

- NUHM1 [Buchmueller et. al. 11]
 - NMSSM [Benbrik et. al. 12]
 - Split SUSY [Arkani-Hamed and S. Dimopoulos 05]
 - High-scale SUSY [L.J. Hall and Y. Nomura 10]
- ... we may even review H. Baer and J. List 13, *Post LHC8 SUSY benchmark points for ILC physics*