Muon g-2, DM, and lepton flavor violation in SUSY-GUT theories

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Colaboration with A. Tiwari, Q. Shafi, C. Ün, J. Ellis, S. Lola, Ruiz de Austri,JHEP 07 (2020) 07, 096 JHEP 09 (2020), Eur. Phys. J. C (2022) 82:561 + work in progress.

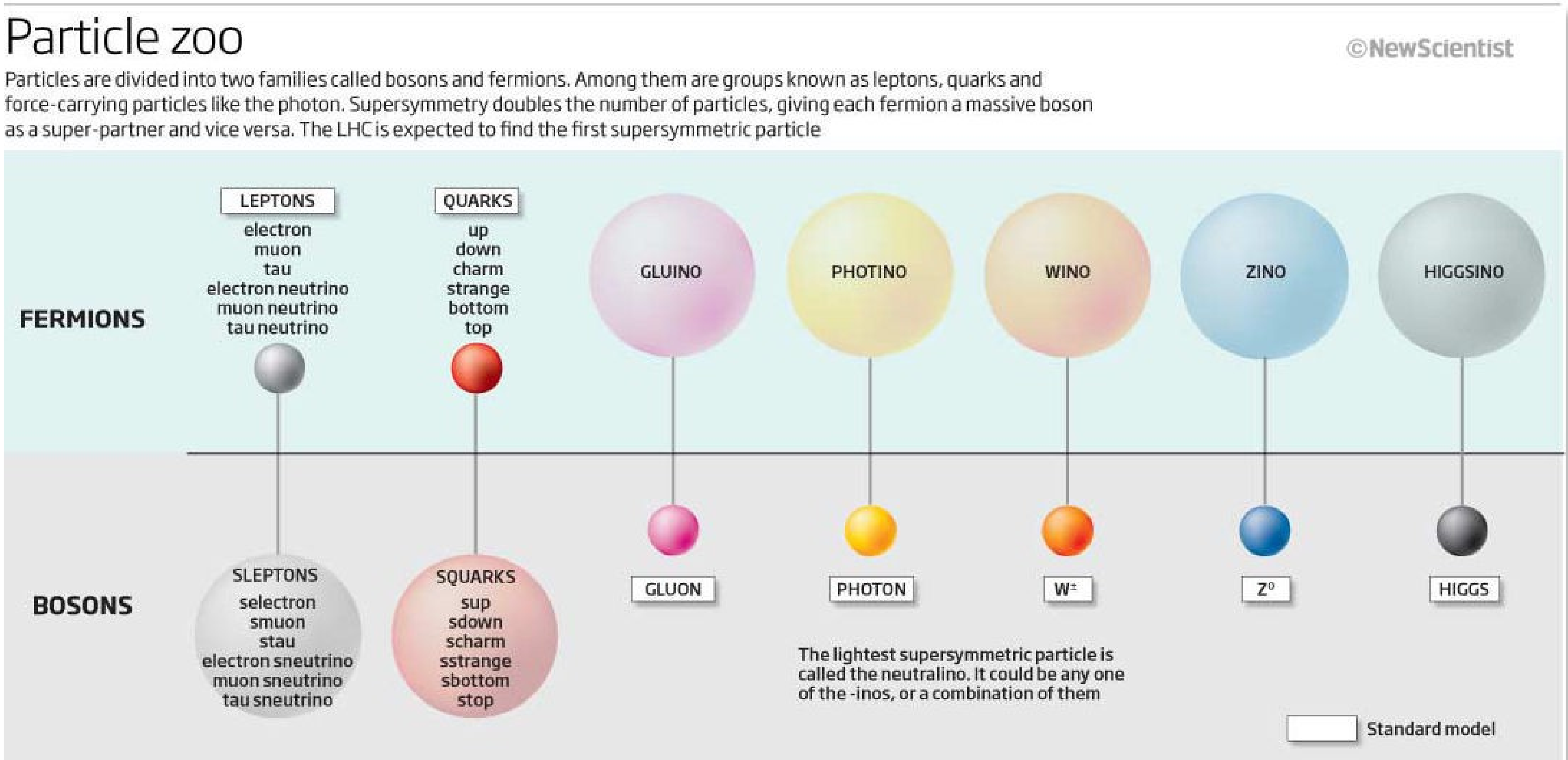
OUTLINE

-GUT's and SUSY.
-PS: SU(4)xSU(2)xSU(2)

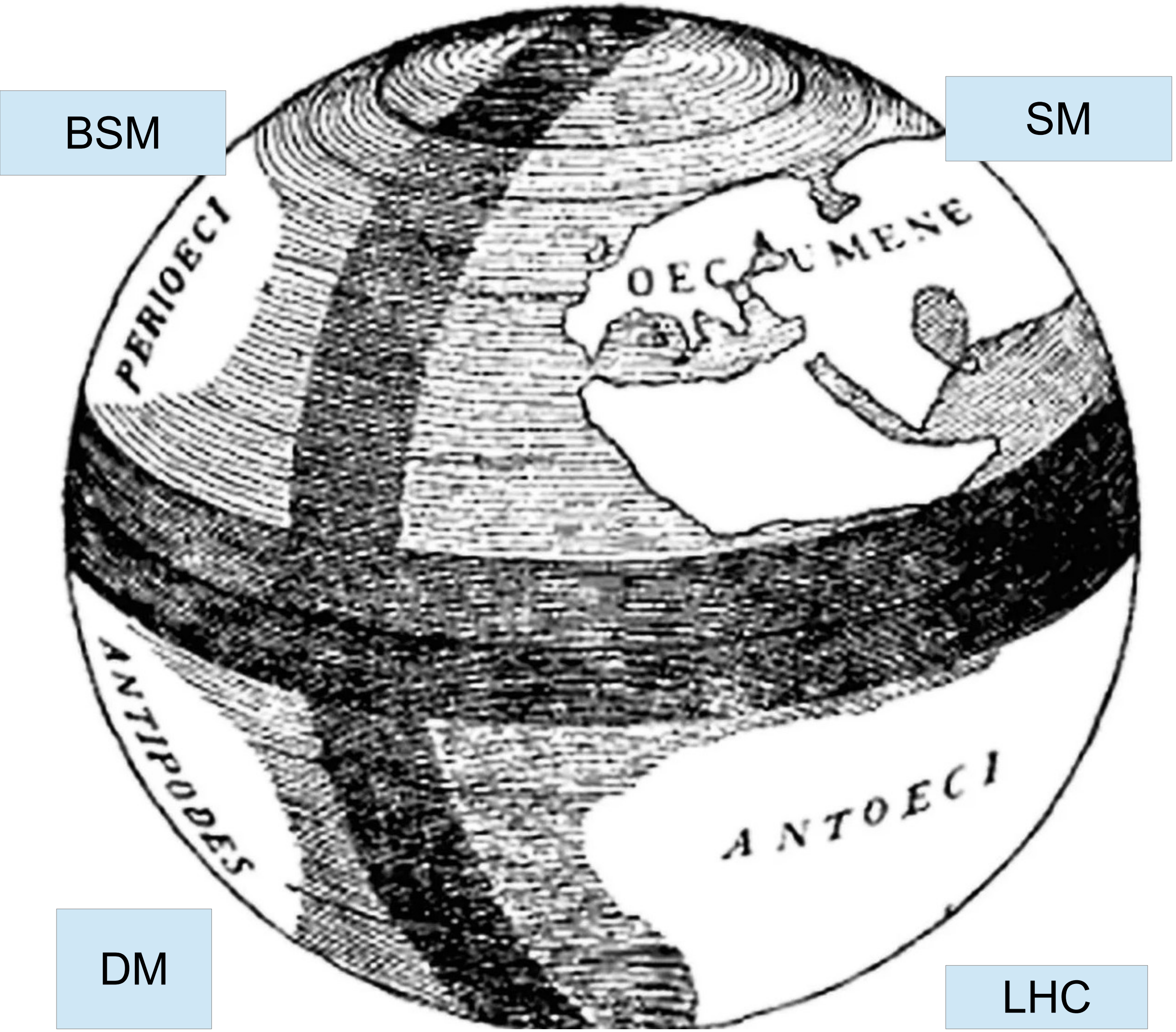
-Fitting muon (g-2) in SU(4)xSU(2)xSU(2) models

- LFV contraints and propects.
- Neutralino relic density .
- LHC vs LFV.

Conclusions.


Particle zoo
©NewScientist
Particles are divided into two families called bosons and fermions. Among them are groups known as leptons, quarks and force-carrying particles like the photon. Supersymmetry doubles the number of particles, giving each fermion a massive boson as a super-partner and vice versa. The LHC is expected to find the first supersymmetric particle
FERMIONS
LEPTONS
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino
QUARKS
up
down
charm
strange
bottom
top
GLUINO
PHOTINO
WINO
ZINO
HIGGSINO
BOSONS
SLEPTONS
selectron
smuon
stau
electron sneutrino
muon sneutrino
tau sneutrino
SQUARKS
sup
sdown
scharm
sstrange
sbottom
stop
GLUON
PHOTON
$W^{\pm}$
Z^0
HIGGS
The lightest supersymmetric particle is called the neutralino. It could be any one of the -inos, or a combination of them
Standard model

Crates of Mallus 150

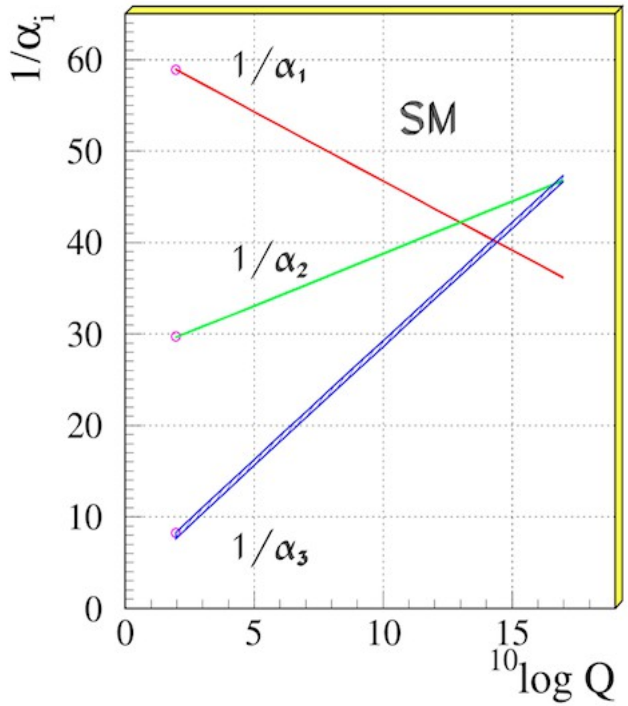


Antipodes theory:

Popular debate in the Middle age.

Probably referred in all explation trip proposals untill it was eliminated by direct observation.

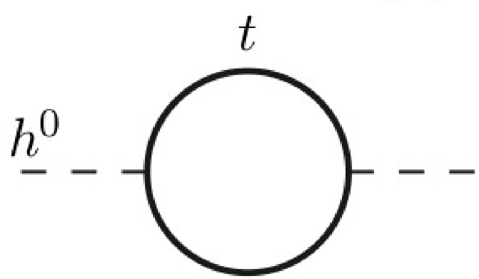
Hierarchy Problem



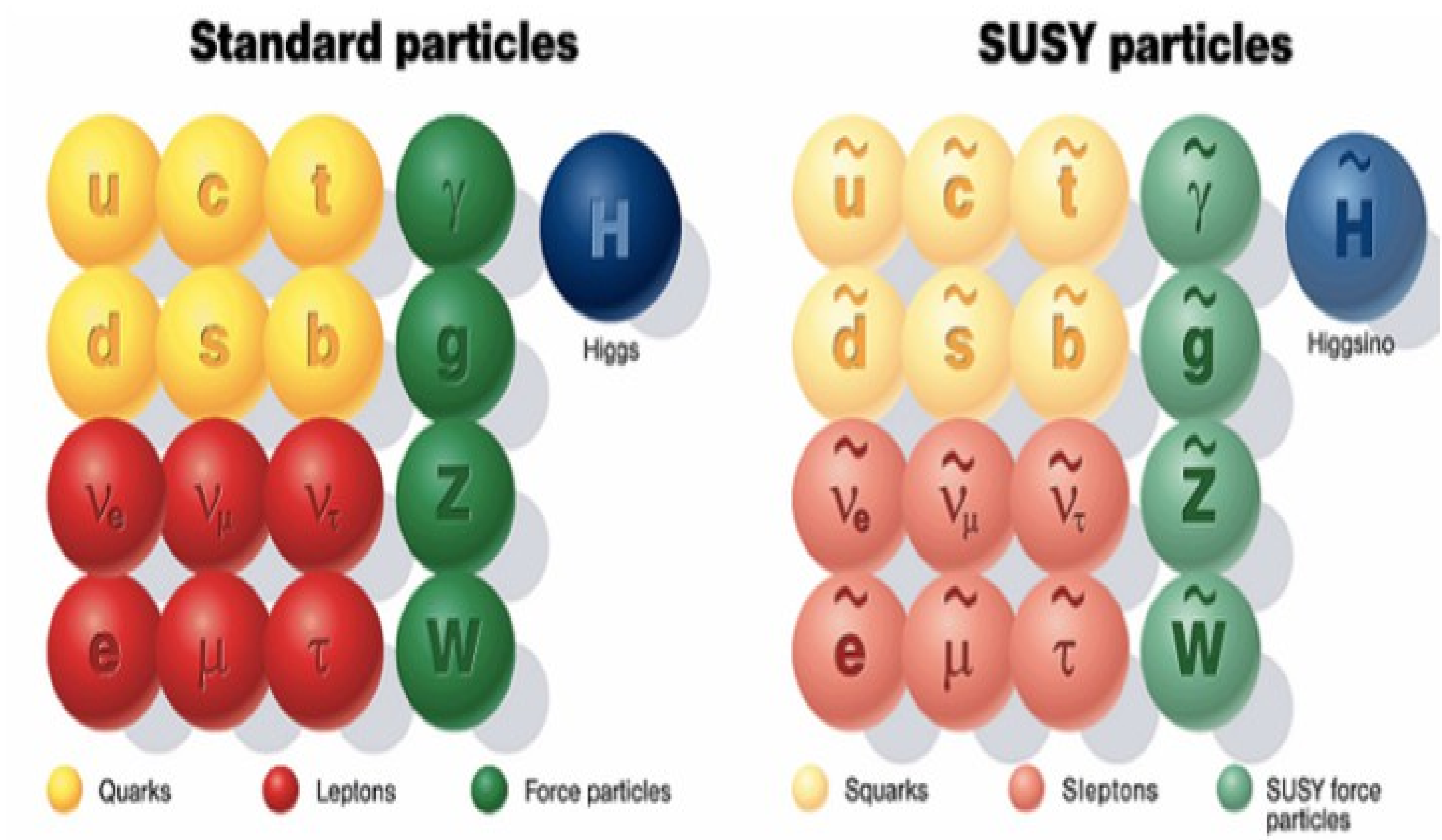
Almost unification at ~10^{14} GeV

$$\mu \frac{d\alpha_i(\mu)}{d\mu} = -\frac{1}{2\pi}\left[b_i + \frac{1}{4\pi}\sum b_{ij}\alpha_j(\mu)\right]\alpha_i^2(\mu)$$

$$b_i = (0, -22/3, -11) + N_F(4/3, 4/3, 4/3) + N_H(1/10, 1/6, 0)$$

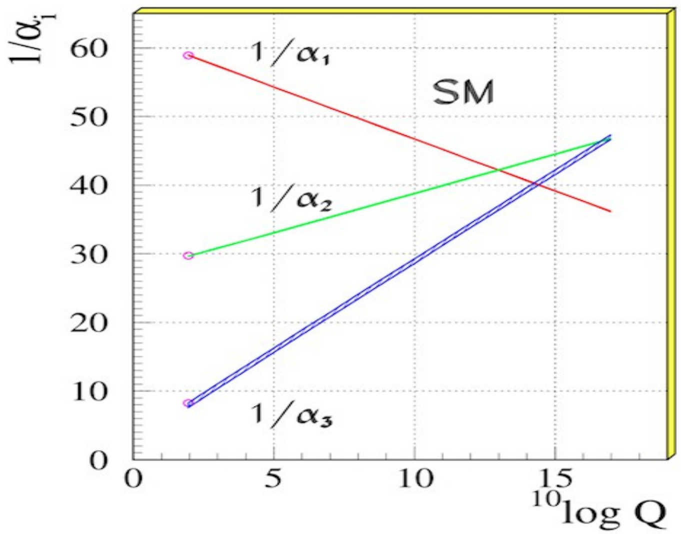


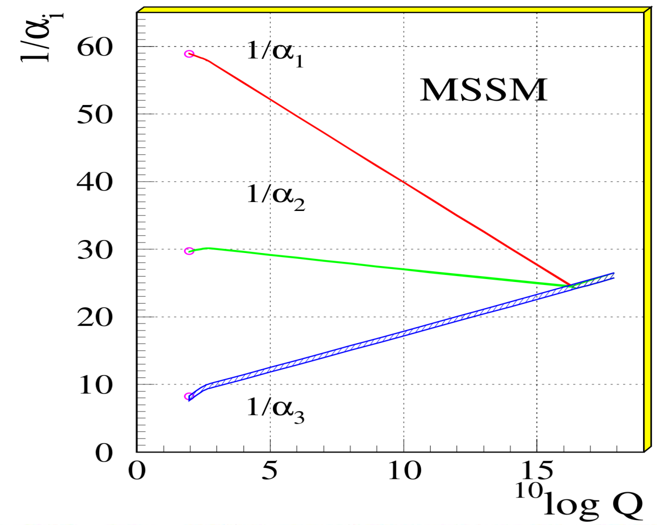
Divergent contribution to Higgs mass ↑ with $(m_{scale})^2$



Standard particles
SUSY particles
Higgs
Higgsino
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

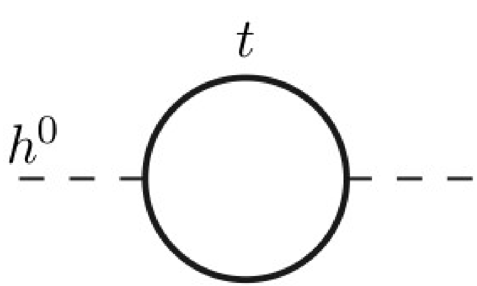
Hierarchy Problem





Unification at ~10^{16} GeV

$$b_i = (0,-6,-9) + N_F(2,2,2) + N_H(3/10,1/2,0)$$



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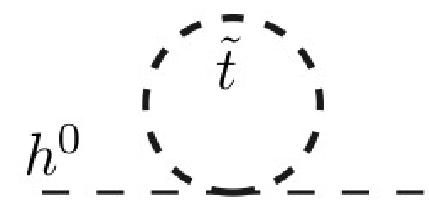
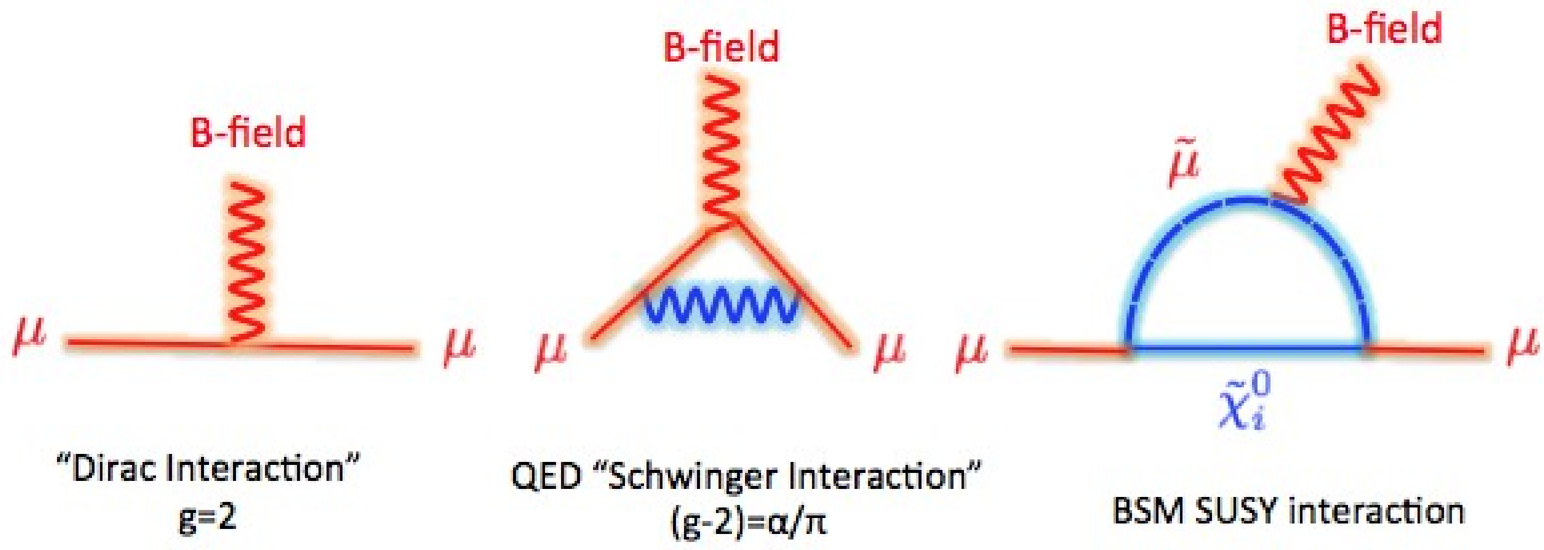


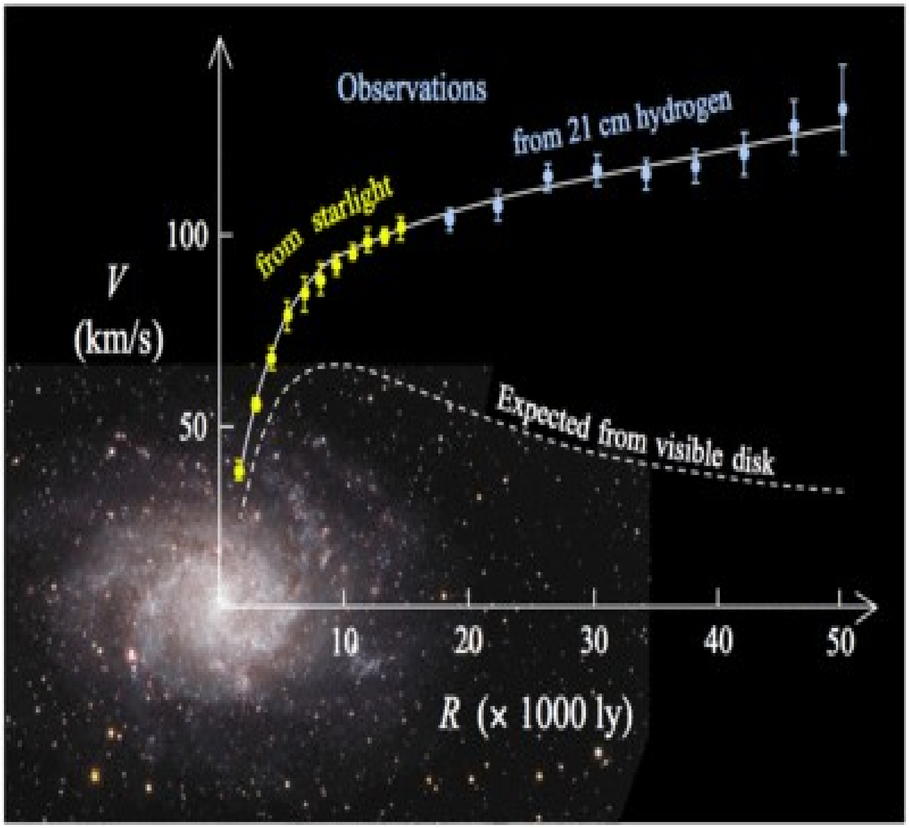
Cancelation of quadratic divergences

One loop contribution to SM proc.

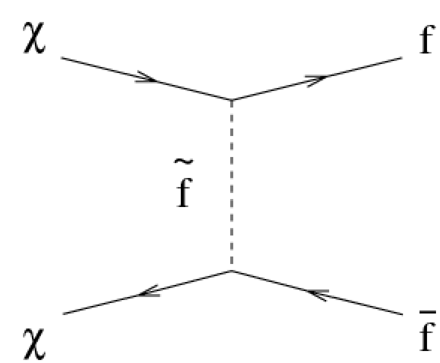


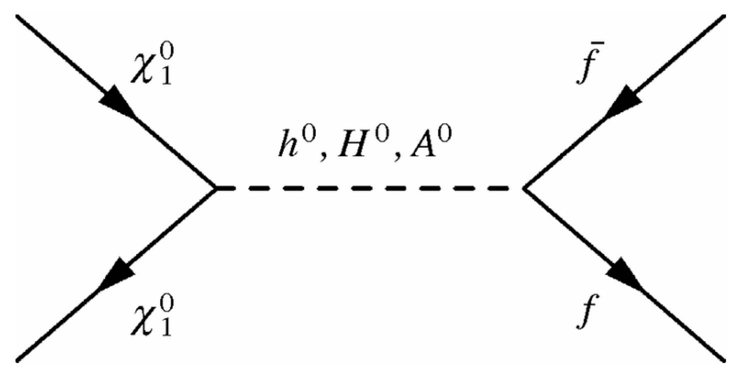
SM vs Experiment Discrepancies
anomalous magnetic dipole moment (g_μ-2)

Dark Matter problem



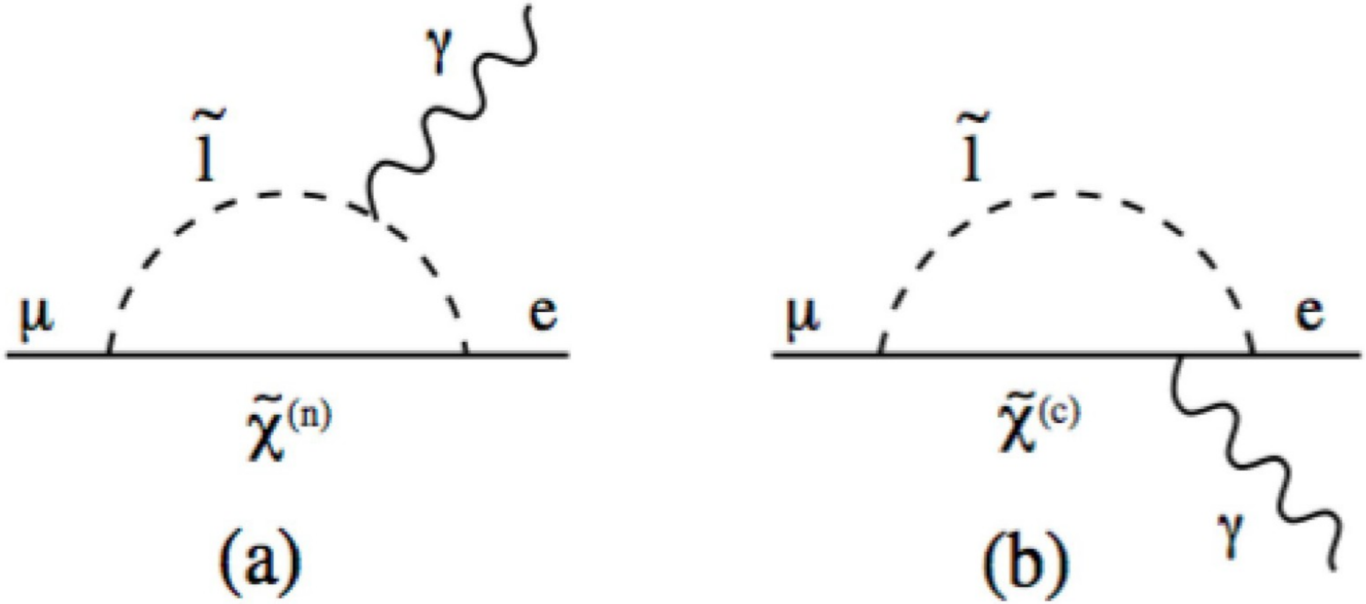
Rotation curve of spiral galaxy M 33 (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (white line). The discrepancy between the two curves can be accounted for by adding a dark matter halo surrounding the galaxy





$$\Omega h^2 \sim \frac{3\times 10^{-27}\,\mathrm{cm}^3 s^{-1}}{\langle \sigma_{\mathrm{ann}} v_{Mol} \rangle}$$

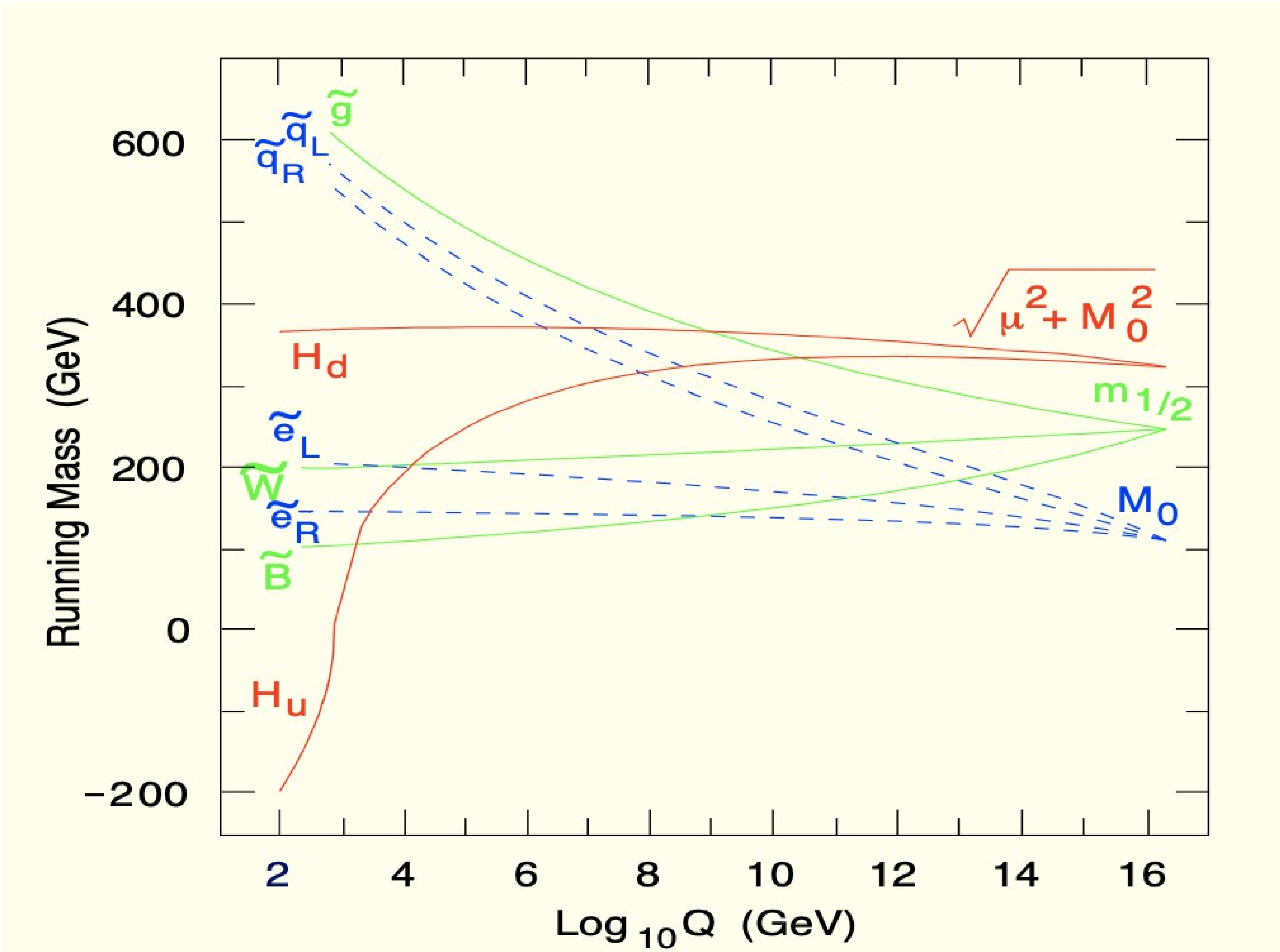
In SUSY flavor mixing lepton-slepton vertices can induce LFV diagrams:

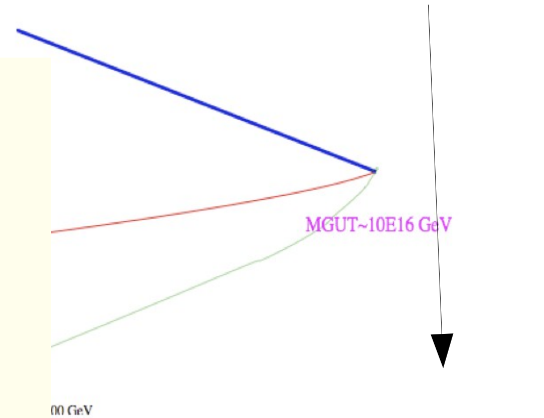


Lepton-slepton flavor mixing is very constrained by the experimental limits:

$$BR(\mu \rightarrow e\gamma) < 5.7\,x\,10^{-13}$$
$$BR(\tau \rightarrow \mu\gamma) < 4.4\,x\,10^{-8}$$
$$BR(\tau \rightarrow e\gamma) < 3.3\,x\,10^{-8}$$

GUT initial conditions

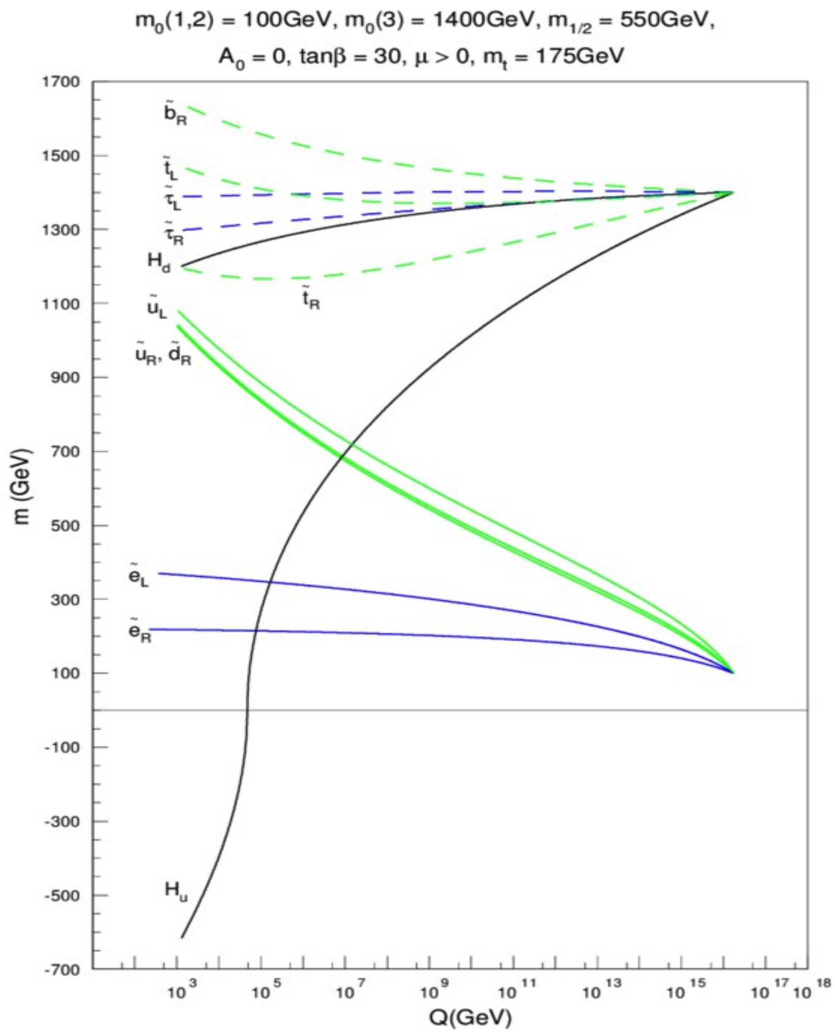




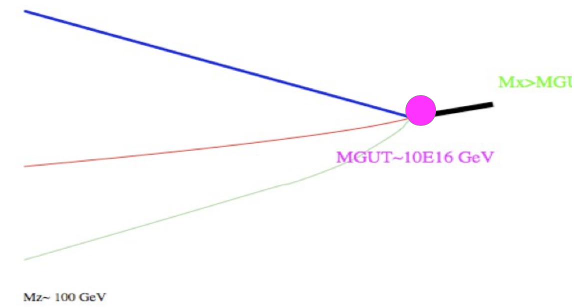
$m_0, m_{\frac{1}{2}}, A_0, \tan\beta, \mathrm{sign}(\mu)$

Gunion,
Int. J. Mod. Phys. A 2010

Non Universal scenarios



Baer et al., HEP 06 (2004) 044



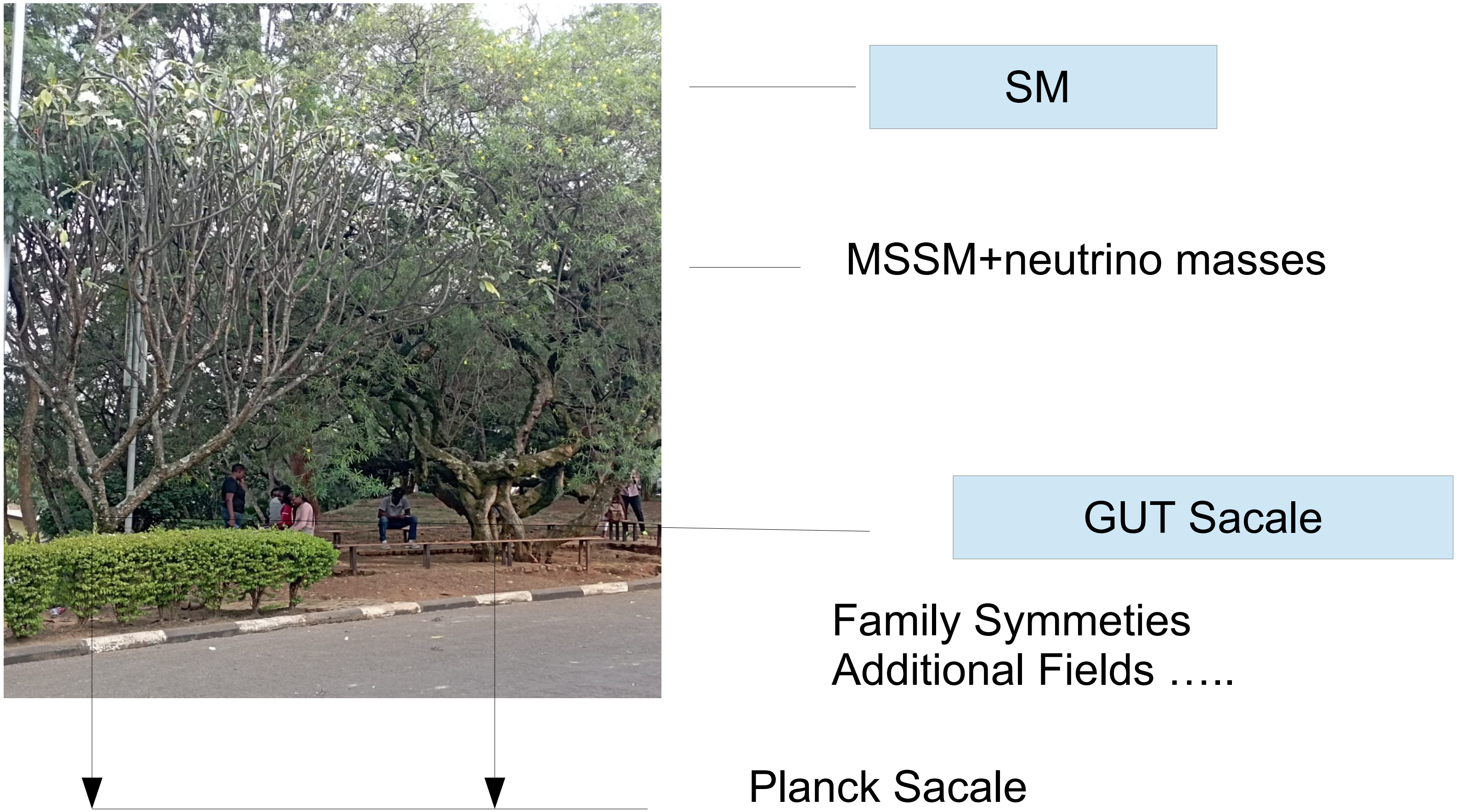
CMSSM choice:

- m0 *Universal soft masses.*
- m1/2 *Universal gaugino masses.*
- A0 *Universal Trilinear terms.*

Representation-dependent choice

$$m_r = x_r \, m_0$$

$$A_r = Y_r \, A_0 , \quad A_0 = a_0 \, m_0$$


SM
MSSM+neutrino masses
GUT Sacale
Family Symmeties
Additional Fields …..
Planck Sacale

PATI-SALAM Unification

$$G_{PS} \equiv SU(4) \times SU(2)_L \times SU(2)_R$$

Matter Fields		$\mathbf{4}_c\mathbf{2}_L\mathbf{2}_R$
F_r	$\begin{pmatrix} d_r & -u_r \end{pmatrix}$ $\begin{pmatrix} e_r & -\nu_r \end{pmatrix}$	$(\mathbf{4},\mathbf{2},\mathbf{1})$
F_r^c	$\begin{pmatrix} u_r^c \\ d_r^c \end{pmatrix}, \begin{pmatrix} \nu_r^c \\ e_r^c \end{pmatrix}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$

$$< \tilde{\nu_H^c} >=< \bar{\tilde{\nu_H^c}} >\sim M$$

Non universal Higgs Mass terms due to D- terms.

$$m^2_{H_{u,d}} = m^2_{10} \mp 2M_D^2$$

Higgs Fields		
H^c	$\begin{pmatrix} u_H^c \\ d_H^c \end{pmatrix}, \begin{pmatrix} \nu_H^c \\ e_H^c \end{pmatrix}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$
$\bar{H}^c$	$\begin{pmatrix} \bar{u}_H^c & \bar{d}_H^c \end{pmatrix}$ $\begin{pmatrix} \bar{\nu}_H^c & \bar{e}_H^c \end{pmatrix}$	$(\mathbf{4},\mathbf{1},\mathbf{2})$
h	$\begin{pmatrix} h_2^+ & h_1^0 \\ h_2^0 & h_1^- \end{pmatrix}$	$(\mathbf{1},\mathbf{2},\mathbf{2})$

$$G_{PS} \rightarrow \mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

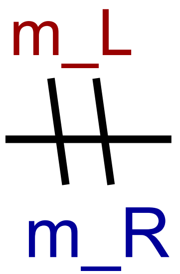
$$M_4 = M_3; M_2 = y_{LR} M_{2R}$$

$$M_4 = M_3; M_2 = y_{LR} M_{2R}$$

Condition for gaugino masses.

PS(4-2-1) ***LR Asymmetry***

Matter Fields		
F_r	$\begin{pmatrix} d_r & -u_r \end{pmatrix}$ $\begin{pmatrix} e_r & -\nu_r \end{pmatrix}$	$(\mathbf{4},\mathbf{2},\mathbf{1})$
F_r^c	$\begin{pmatrix} u_r^c \\ d_r^c \end{pmatrix}, \begin{pmatrix} \nu_r^c \\ e_r^c \end{pmatrix}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$



New Parameter

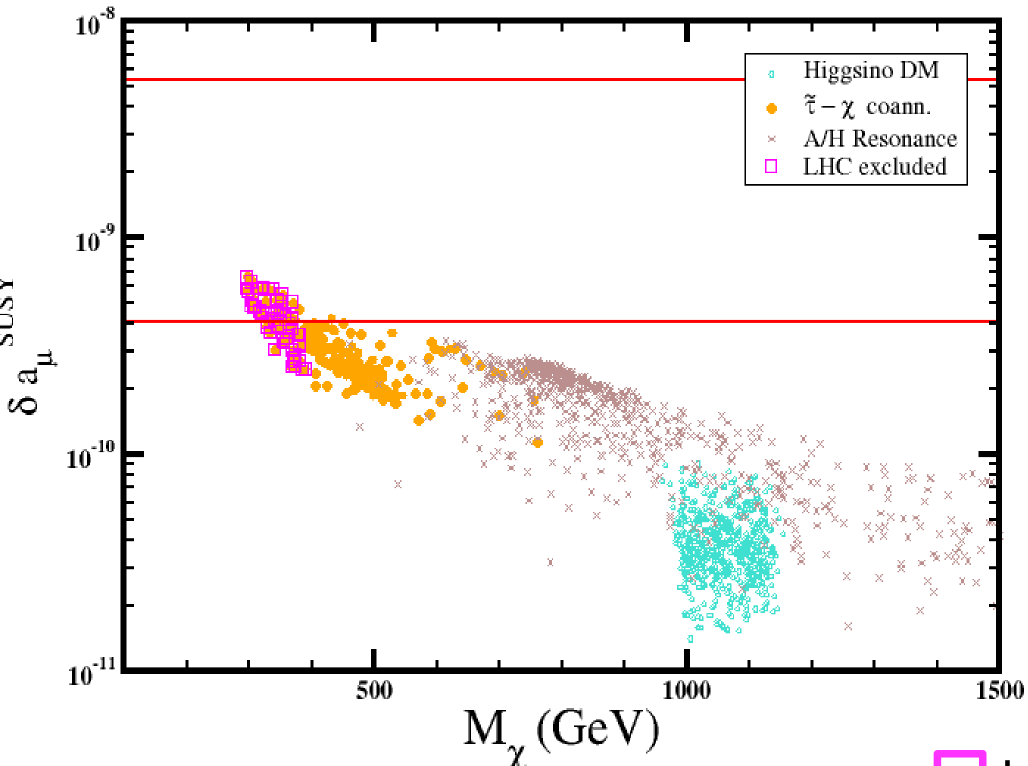
$$X_{LR}=\frac{m_R}{m_L}$$

Gaugino Masses

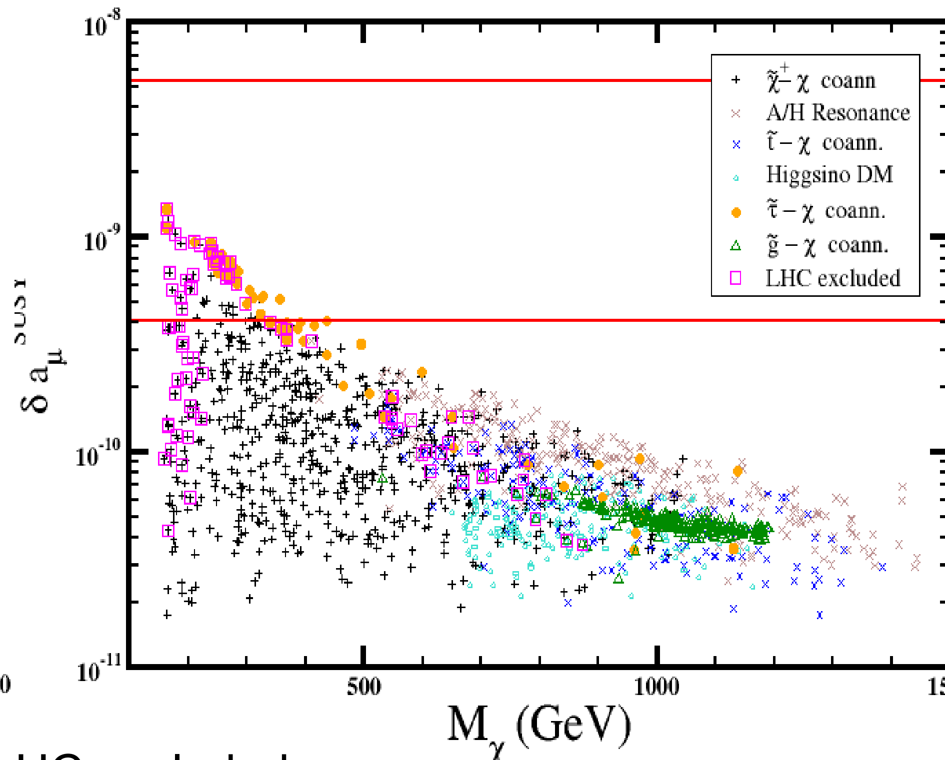
$$M_1 = \frac{3}{5}M_{2R} + \frac{2}{5}M_4 \ ,$$

$$M_4 = M_3 ;\ M_2 = y_{LR} M_{2R}$$

SO(10)



PS(4-2-2)



LHC excluded.

Higgsino DM

$$h_f > 0.1, \quad |m_A - 2m_\chi| > 0.1\, m_\chi.$$

$$h_f \equiv |N_{13}|^2 + |N_{14}|^2 ,$$

A/H Resonances

$$|m_A - 2m_\chi| \leq 0.1\, m_\chi$$

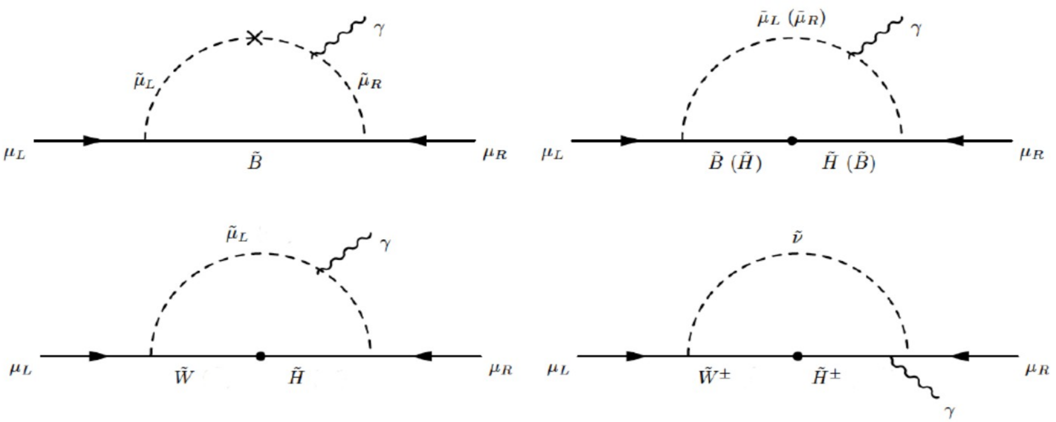
Coanihilations: $(m_z - m_{LSP}) < 0.1\, m_{LSP}$

$\tilde{\tau}$ $\tilde{\chi}^{+}$ Stop gluino

Muon g-2 combining Fermilab + BNL data

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (25.1 \pm 5.9) \times 10^{-10} \ .$$

SUSY Contribution to Muon g-2



Low Scale	GUT Scale
$m_{\tilde{\mu}_L}, m_{\tilde{\nu}}$	m_L
$m_{\tilde{\mu}_R}$	m_R
$M_{\tilde{B}}$	M_1
$M_{\tilde{W}}$	M_2
μ	m_{H_u}, m_{H_d}
A_μ	A_0
$\tan\beta$	$\tan\beta$

$$m_h = 123 - 127 \ {\rm GeV}$$

$$m_{\tilde{g}} \geq 2.1 \ {\rm TeV} \ (800 \ {\rm GeV \ if \ it \ is \ NLSP})$$

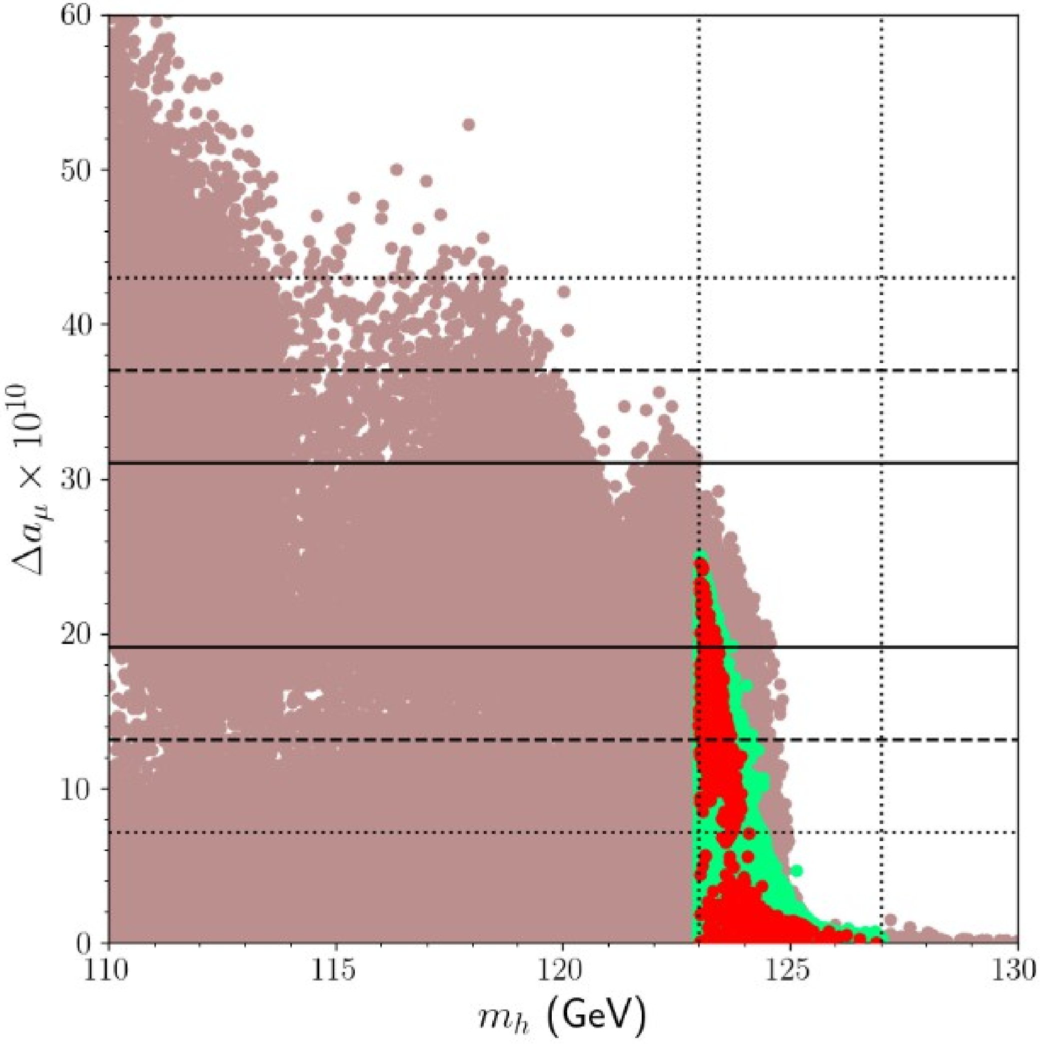
$$0.8 \times 10^{-9} \leq {\rm BR}(B_s \to \mu^+\mu^-) \leq 6.2 \times 10^{-9} \ (2\sigma)$$

$$2.99 \times 10^{-4} \leq {\rm BR}(B \to X_s\gamma) \leq 3.87 \times 10^{-4} \ (2\sigma)$$

$$0.114 \leq \Omega_{\rm CDM} h^2 \leq 0.126 \ .$$

$$\begin{array}{lll}
0 \leq & m_L & \leq 5 \ {\rm TeV} \\
0 \leq & M_{2L} & \leq 5 \ {\rm TeV} \\
-3 \leq & M_3 & \leq 5 \ {\rm TeV} \\
-3 \leq & A_0/m_L & \leq 3 \\
1.2 \leq & \tan\beta & \leq 60 \\
0 \leq & {\rm x_{LR}} & \leq 3 \\
-3 \leq & {\rm y_{LR}} & \leq 3 \\
0 \leq & {\rm x_d} & \leq 3 \\
-1 \leq & {\rm x_u} & \leq 2 \ .
\end{array}$$

Important contribution is in tension with the Higgs mass



$$\Delta a_\mu^{\tilde{B}\tilde{\mu}_L\tilde{\mu}_R} \simeq \frac{g_1^2}{16\pi^2} \frac{m_\mu^2 M_{\tilde{B}}(\mu \tan\beta - A_\mu)}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2} F_N\left(\frac{m_{\tilde{\mu}_L}^2}{M_{\tilde{B}}^2}, \frac{m_{\tilde{\mu}_R}^2}{M_{\tilde{B}}^2}\right)$$

$$\Delta m_h^2 \simeq \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta} \frac{\mu A_t}{M_{\rm SUSY}^2}\left[\frac{A_t^2}{M_{\rm SUSY}^2} - 6\right]$$

$$\frac{dm^2_{\tilde{l}_{R_i}}}{dt} = -\frac{1}{16\pi^2}\left[2(Y^i_l)^2 P^i_{\tilde{l}} + g_1^2 \mathrm{Tr}(Ym^2) - 4g_1^2 M_1^2\right]$$

$$\frac{dm^2_{\tilde{L}_i}}{dt} = -\frac{1}{16\pi^2}\left[(Y^i_l)^2 P^i_{\tilde{l}} - \frac{1}{2}g_1^2 \mathrm{Tr}(Ym^2) - (g_1^2 M_1^2 + 3g_2^2 M_2^2)\right]$$

$$\frac{dm^2_{\tilde{d}_{R_i}}}{dt} = -\frac{1}{16\pi^2}\left[2(Y^i_d)^2 P^i_{\tilde{d}} + \frac{1}{3}g_1^2 \mathrm{Tr}(Ym^2) - \left(\frac{4}{9}g_1^2 M_1^2 + \frac{16}{3}g_3^2 M_3^2\right)\right]$$

$$\frac{dm^2_{\tilde{u}_{R_i}}}{dt} = -\frac{1}{16\pi^2}\left[2(Y^i_u)^2 P^i_{\tilde{u}} - \frac{2}{3}g_1^2 \mathrm{Tr}(Ym^2) - \left(\frac{16}{9}g_1^2 M_1^2 + \frac{16}{3}g_3^2 M_3^2\right)\right]$$

$$\frac{dm^2_{\tilde{Q}_i}}{dt} = -\frac{1}{16\pi^2}\left[(Y^i_u)^2 P^i_{\tilde{u}} + (Y^i_d)^2 P^i_{\tilde{d}} + \frac{1}{6}g_1^2 \mathrm{Tr}(Ym^2) \ -\left(\frac{1}{9}g_1^2 M_1^2 + 3g_2^2 M_2^2 + \frac{16}{3}g_3^2 M_3^2\right)\right]$$

$$m^2_{\tilde{u}_{iL}} = m^2_{\tilde{q}_{i0}} + m^2_{u_i} + \tilde{\alpha}_G\left(\frac{8}{3}f_3 m_3^2 + \frac{3}{2}f_2 m_2^2 + \frac{1}{30}f_1 m_1^2\right)$$

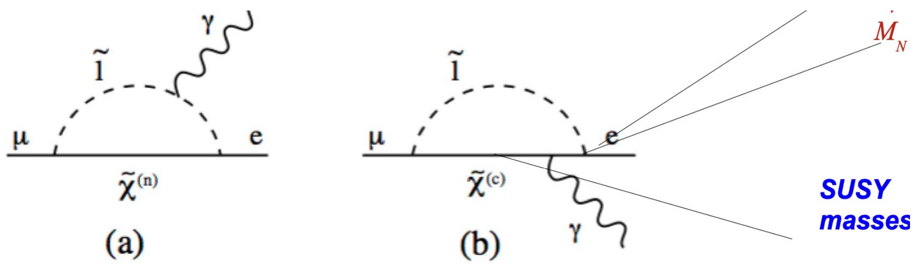
$$m^2_{\tilde{u}_{iR}} = m^2_{\tilde{u}_{i0}} + m^2_{u_i} + \tilde{\alpha}_G\left(\frac{8}{3}f_3 m_3^2 + \frac{8}{15}f_1 m_1^2\right)$$

$$m^2_{\tilde{e}_{iL}} = m^2_{\tilde{\ell}_{i0}} + m^2_{e_i} + \tilde{\alpha}_G\left(\frac{3}{2}f_2 m_2^2 + \frac{3}{10}f_1 m_1^2\right)$$

$$m^2_{\tilde{e}_{iR}} = m^2_{\tilde{e}_{i0}} + m^2_{e_i} + \tilde{\alpha}_G\frac{6}{5}f_1 m_1^2 \cdot$$

LFV violating through soft masses.

- LFV can be induced by a missalignement of leptosns and sleptons



- Flavor dependence on soft terms can be induced:
  - **Below GUT,** Radiatively generated by the same mechanism that explain neutrino oscilations.
  - **Above GUT,** by extra fields needed to explain fermion hierarchy.

MSSM extended by seesaw mechanism

- The superpotential for MSSM-Seesaw I can be written as

$$W = W_{\mathrm{MSSM}} + Y_\nu^{ij}\epsilon_{\alpha\beta}H_2^\alpha N_i^c L_j^\beta + \frac{1}{2}M_N^{ij}N_i^c N_j^c, \quad (5)$$

- The full set of soft SUSY-breaking terms is given by,

$$\begin{aligned} -\mathcal{L}_{\mathrm{soft,SI}} &= -\mathcal{L}_{\mathrm{soft}} + (m_{\tilde{\nu}}^2)^i_j \tilde{\nu}_{Ri}^* \tilde{\nu}_R^j + (\frac{1}{2}B_\nu^{ij} M_N^{ij} \tilde{\nu}_{Ri}^* \tilde{\nu}_{Rj}^* \\ &\quad + A_\nu^{ij} h_2 \tilde{\nu}_{Ri}^* \tilde{l}_{Lj} + \mathrm{h.c.})\ , \end{aligned} \quad (6)$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_\nu^D \\ m_\nu^{D^T} & M_R \end{pmatrix}$$

"See-Saw" explanation for tiny masses.

- The physical masses are:
  1. $m_1 \equiv m_{light} \simeq \frac{(m_\nu^D)^2}{M_R}$
  2. $m_2 \simeq M_R$
- For $(m_\nu^D)_{33} \approx (200 \text{ GeV})$ $(\lambda_\nu \approx \lambda_t)$ and $M_{N_3} \approx O(10^{14} \text{ GeV})$, $m_{eff} \approx 0.05$ eV

$$W = W_{\rm MSSM} + \frac{1}{2}(Y_\nu L H_2)^T M_N^{-1} (Y_\nu L H_2).$$

$$m_{\rm eff} = -\frac{1}{2} v_u^2 Y_\nu \cdot M_N^{-1} \cdot Y_\nu^T, \qquad m_\nu^\delta = U^T m_{\rm eff} U$$

Slepton flavor mixings

$$(m^2_{\tilde{L}})_{ij} \sim \frac{1}{16\pi^2}(6m_0^2 + 2A_0^2)\left(Y_\nu{}^\dagger Y_\nu\right)_{ij} \log\left(\frac{M_{\rm GUT}}{M_N}\right)$$

$$(m^2_{\tilde{e}})_{ij} \sim 0$$

$$(A_l)_{ij} \sim \frac{3}{8\pi^2} A_0 Y_{l\,i}\left(Y_\nu{}^\dagger Y_\nu\right)_{ij} \log\left(\frac{M_{\rm GUT}}{M_N}\right)$$

Orthogonal matrix

$$Y_\nu = \frac{\sqrt{2}}{v_u}\sqrt{M_R^\delta}R\sqrt{m_\nu^\delta}U^\dagger$$

Casas + Ibarra

Diagonal Universal 1E14 GeV

Limit case of degenerate MR

Order 1

$$Y_\nu^\dagger Y_\nu = \frac{2}{v_u^2} M_R U m_\nu^\delta U^\dagger$$

Using neutrino data LFV depends is controlled by MR

Slepton flavor mixing above GUT.

Generation of Yukawa textures using family symmetries, for example Abelian U(1)'s

$$\Phi_i \Phi^c_J h \, \frac{\theta^{(q_i - q_j + q_h)}}{M}, \qquad \epsilon = \frac{\langle \theta \rangle}{M} \longrightarrow Y_{IJ} \Phi_I \Phi^c_J h$$

$$Y_{IJ} \sim \epsilon^{(q_i - q_j + q_h)}$$

Froggatt-Nilsen 1979

Soft terms: In SUGRA models, redefiniton of fields due to flavons results in non universal soft masses.

$$m^2_f = \begin{pmatrix} 1 & \epsilon^{q^{12}} & \epsilon^{q^{13}} \\ \epsilon^{q^{12}} & 1 & \epsilon^{q^{23}} \\ \epsilon^{q^{12}} & \epsilon^{q^{23}} & 1 \end{pmatrix} \times m^2_{f0},$$

S. F. King et al 2005,
Olive+Velasco-Sevilla 2005
Das et al 2017

LFV depends on the value of ε

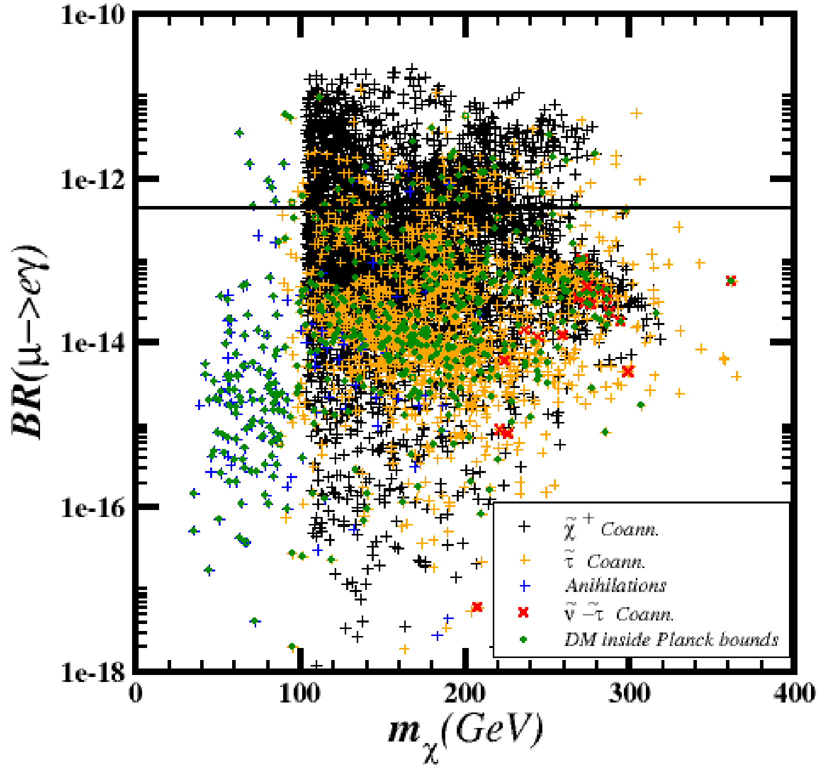
GUT

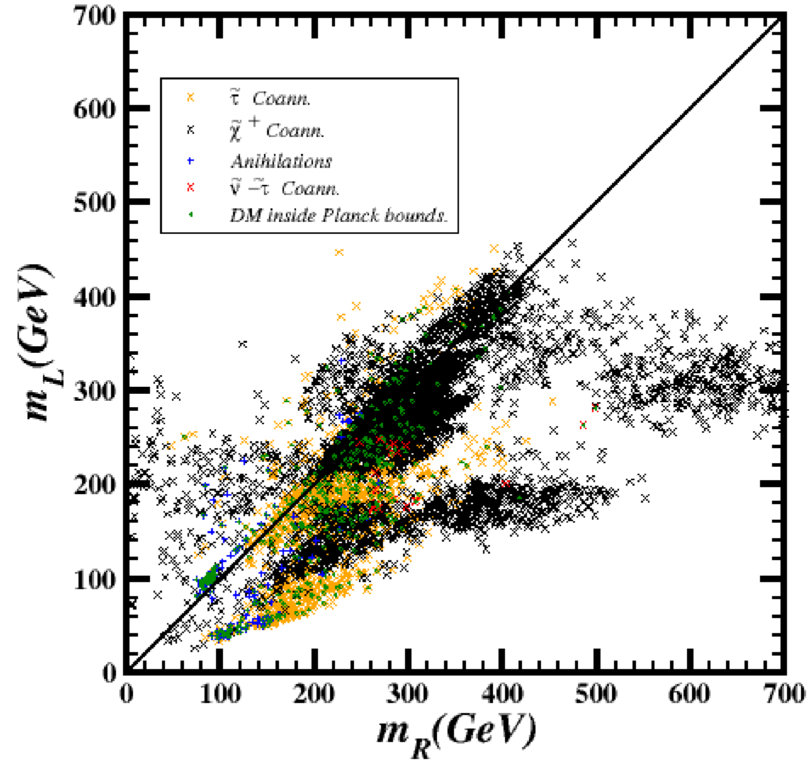
$$m_f^2 = \begin{pmatrix} 1 & \epsilon^{q_L^{12}} & \epsilon^{q_L^{13}} \\ \epsilon^{q_L^{12}} & 1 & \epsilon^{q_L^{23}} \\ \epsilon^{q_L^{12}} & \epsilon^{q_L^{23}} & 1 \end{pmatrix} \times m_L^2,$$

$$m_{f^c}^2 = \begin{pmatrix} 1 & \epsilon^{q_R^{12}} & \epsilon^{q_R^{13}} \\ \epsilon^{q_R^{12}} & 1 & \epsilon^{q_R^{23}} \\ \epsilon^{q_R^{12}} & \epsilon^{q_R^{23}} & 1 \end{pmatrix} \times m_R^2,$$

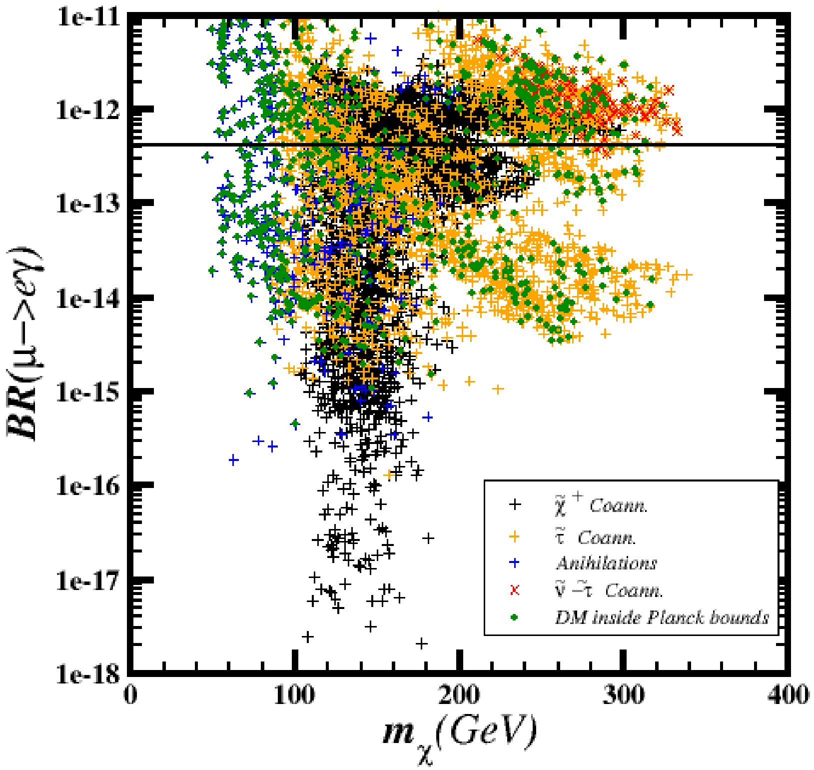
M_SUSY scale

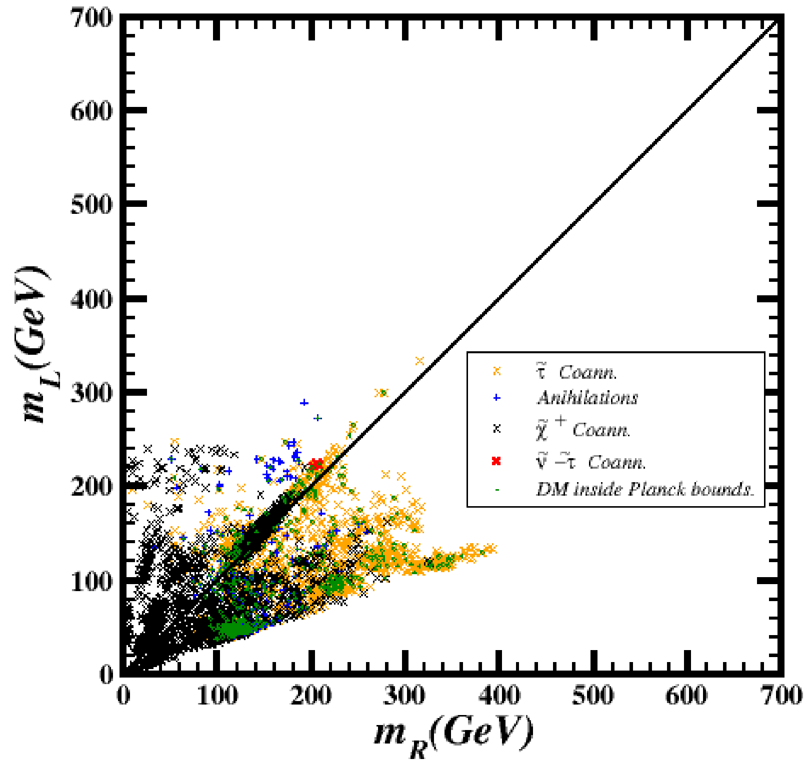
$$\begin{aligned}
m_{\tilde{Q}}^2 &\sim m_L^2 + (k_3 \cdot M_3^2 + k_2 \cdot M_1^2 + \frac{1}{36} k_1 \cdot M_1^2) \times I, \\
m_{\tilde{U}}^2 &\sim m_R^2 + (k_3 \cdot M_3^2 \qquad + \frac{4}{9} k_1 \cdot M_1^2) \times I, \\
m_{\tilde{D}}^2 &\sim m_R^2 + (k_3 \cdot M_3^2 \qquad + \frac{1}{9} k_1 \cdot M_1^2) \times I, \\
m_{\tilde{e}_L}^2 &\sim m_L^2 + (\qquad k_2 \cdot M_2^2 + \frac{1}{4} k_1 \cdot M_1^2) \times I, \\
m_{\tilde{e}_R}^2 &\sim m_R^2 + (\qquad k_1 \cdot M_1^2) \times I.
\end{aligned}$$





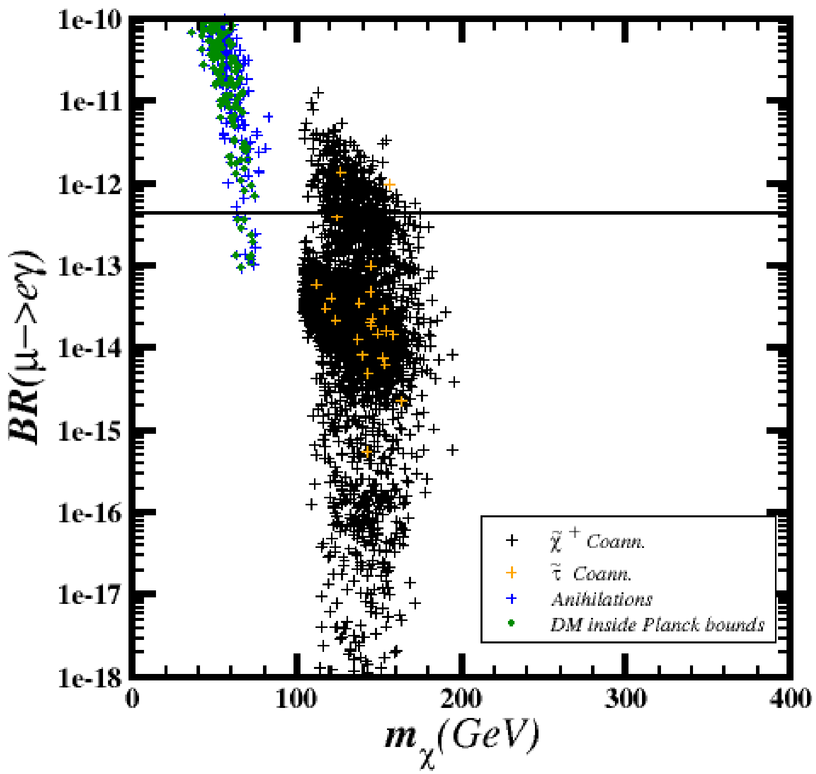
See-Saw with MR scale at 2.5 10^12 GeV

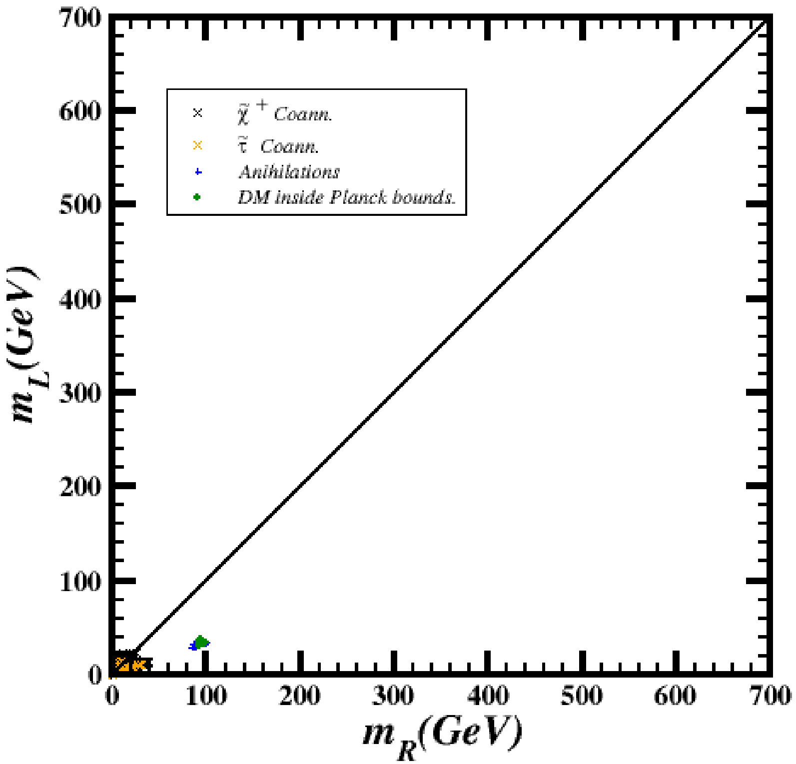




$$m_f^2 = \begin{pmatrix} 1 & \epsilon^{q_L^{12}} & \epsilon^{q_L^{13}} \\ \epsilon^{q_L^{12}} & 1 & \epsilon^{q_L^{23}} \\ \epsilon^{q_L^{12}} & \epsilon^{q_L^{23}} & 1 \end{pmatrix} \times m_L^2, \qquad m_{f^c}^2 = \begin{pmatrix} 1 & \epsilon^{q_R^{12}} & \epsilon^{q_R^{13}} \\ \epsilon^{q_R^{12}} & 1 & \epsilon^{q_R^{23}} \\ \epsilon^{q_R^{12}} & \epsilon^{q_R^{23}} & 1 \end{pmatrix} \times m_R^2,$$

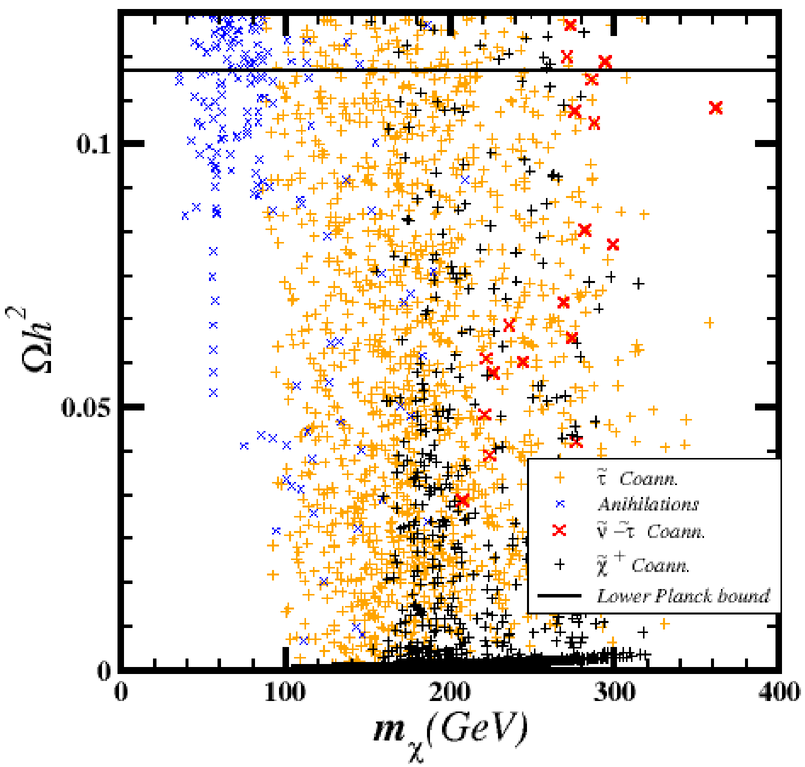
ε = 0.05



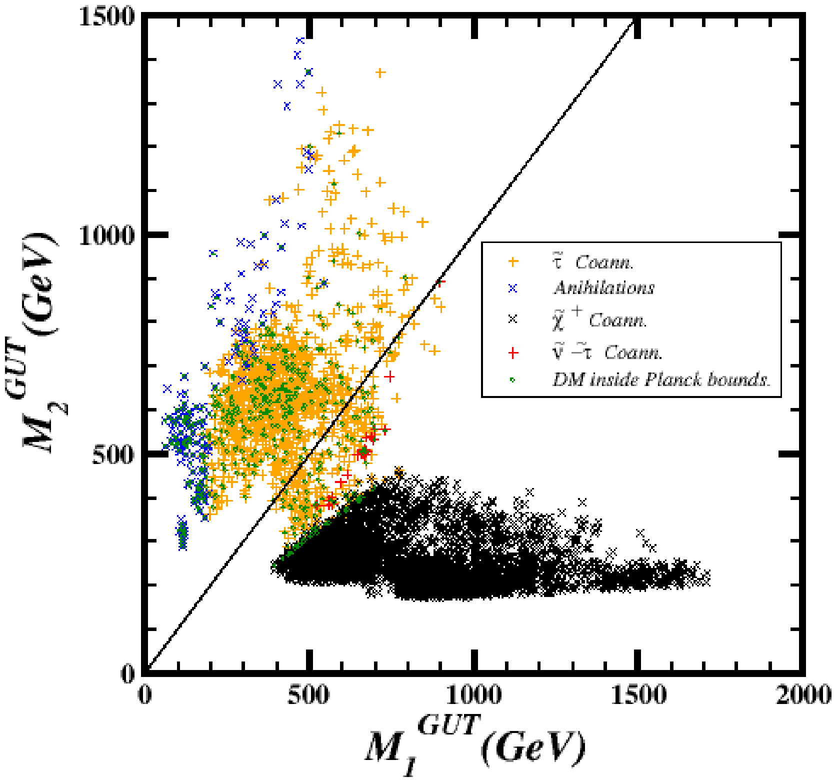


$$m_f^2 = \begin{pmatrix} 1 & \epsilon^{q_L^{12}} & \epsilon^{q_L^{13}} \\ \epsilon^{q_L^{12}} & 1 & \epsilon^{q_L^{23}} \\ \epsilon^{q_L^{12}} & \epsilon^{q_L^{23}} & 1 \end{pmatrix} \times m_L^2, \qquad m_{f^c}^2 = \begin{pmatrix} 1 & \epsilon^{q_R^{12}} & \epsilon^{q_R^{13}} \\ \epsilon^{q_R^{12}} & 1 & \epsilon^{q_R^{23}} \\ \epsilon^{q_R^{12}} & \epsilon^{q_R^{23}} & 1 \end{pmatrix} \times m_R^2,$$

ε = 0.2

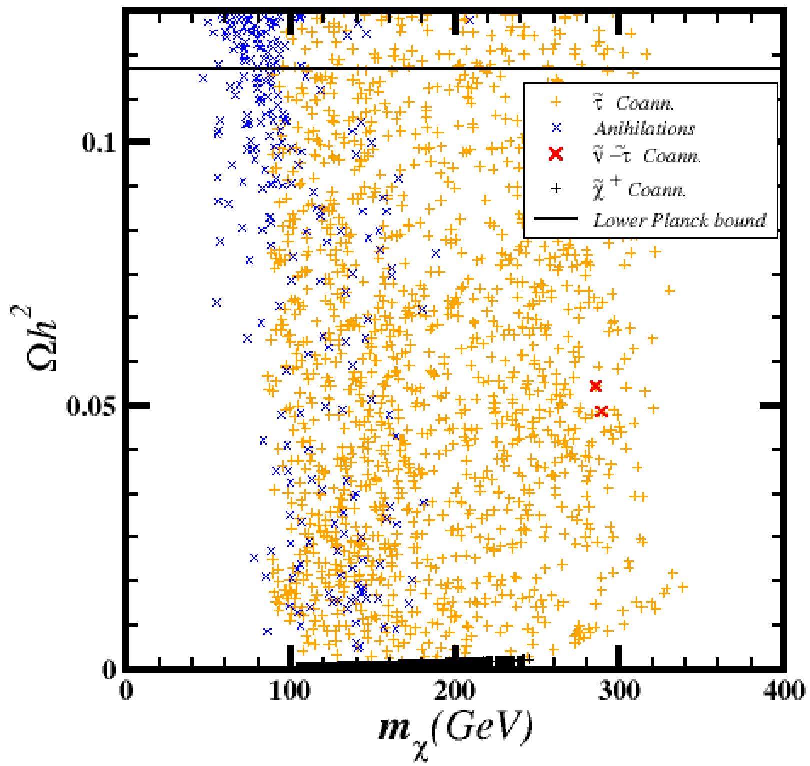


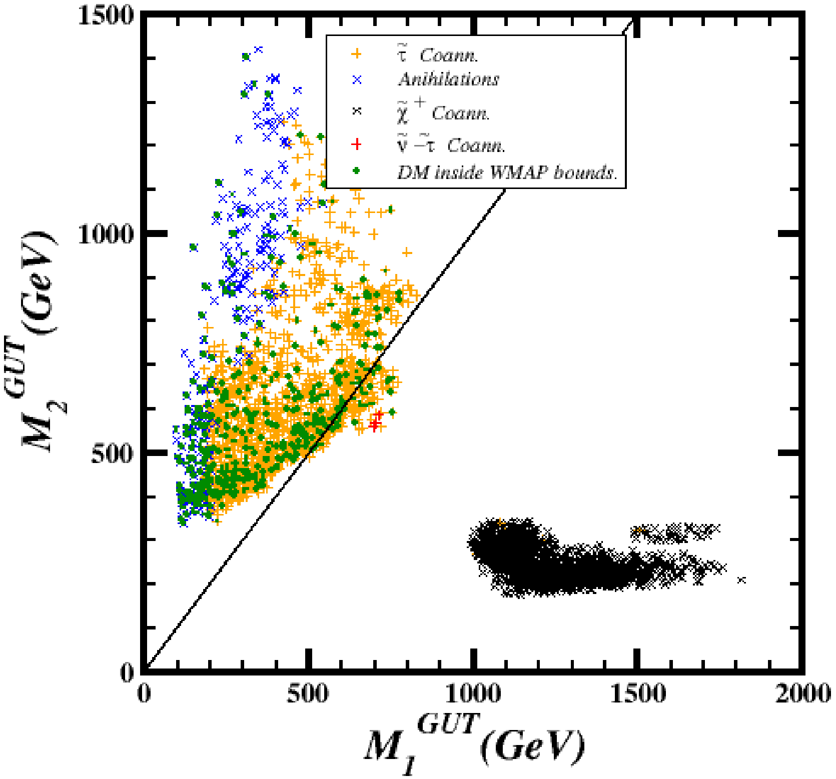
0.1
0.05
0
Ωh^2
0
100
200
300
400
$m_\chi (GeV)$
$\tilde{\tau}$ Coann.
Anihilations
$\tilde{\nu} - \tilde{\tau}$ Coann.
$\tilde{\chi}^+$ Coann.
Lower Planck bound



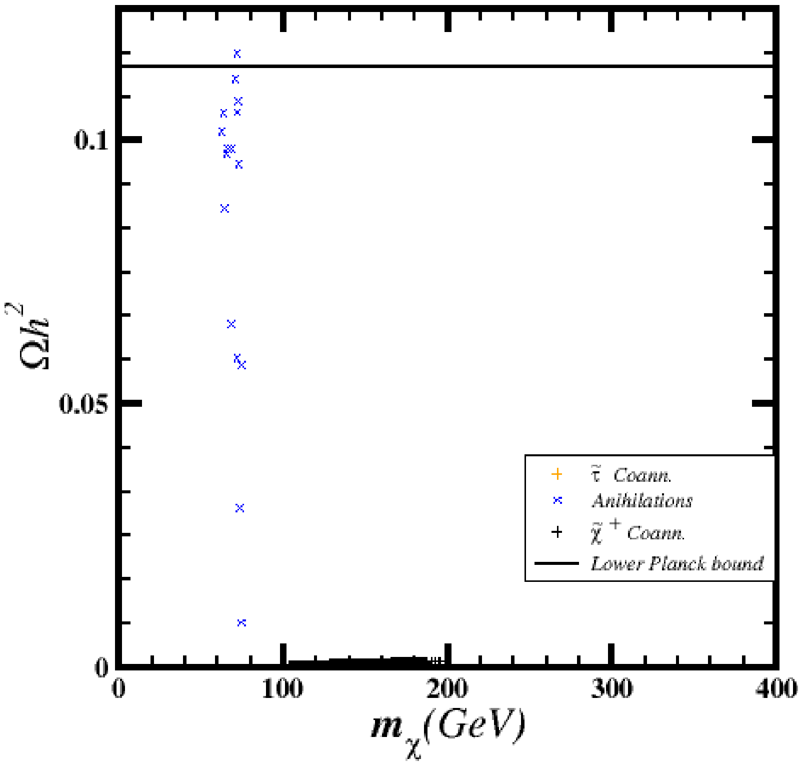
1500
1000
500
0
$M_2^{GUT} (GeV)$
0
500
1000
1500
2000
$M_1^{GUT} (GeV)$
$\tilde{\tau}$ Coann.
Anihilations
$\tilde{\chi}^+$ Coann.
$\tilde{\nu} - \tilde{\tau}$ Coann.
DM inside Planck bounds.

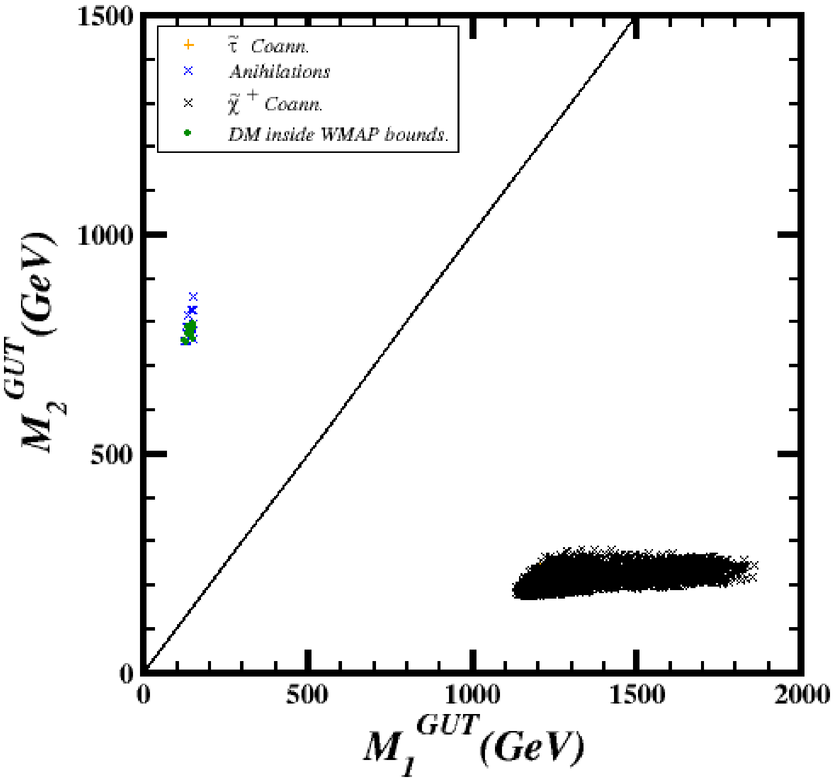
See-Saw



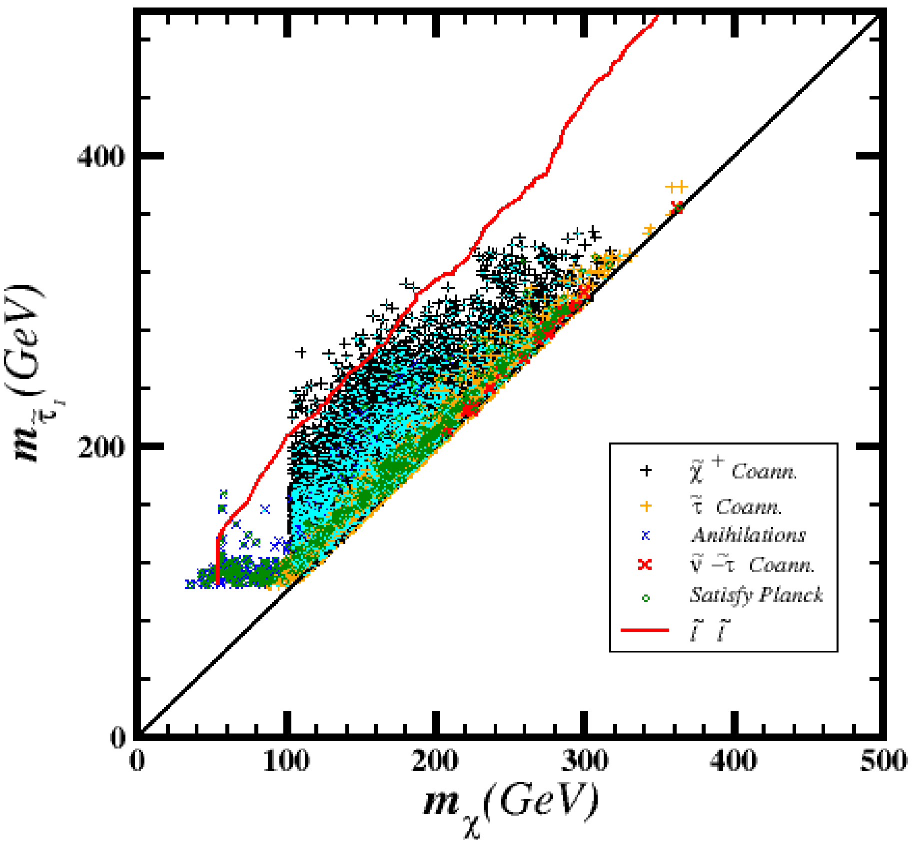


$\varepsilon = 0.05$

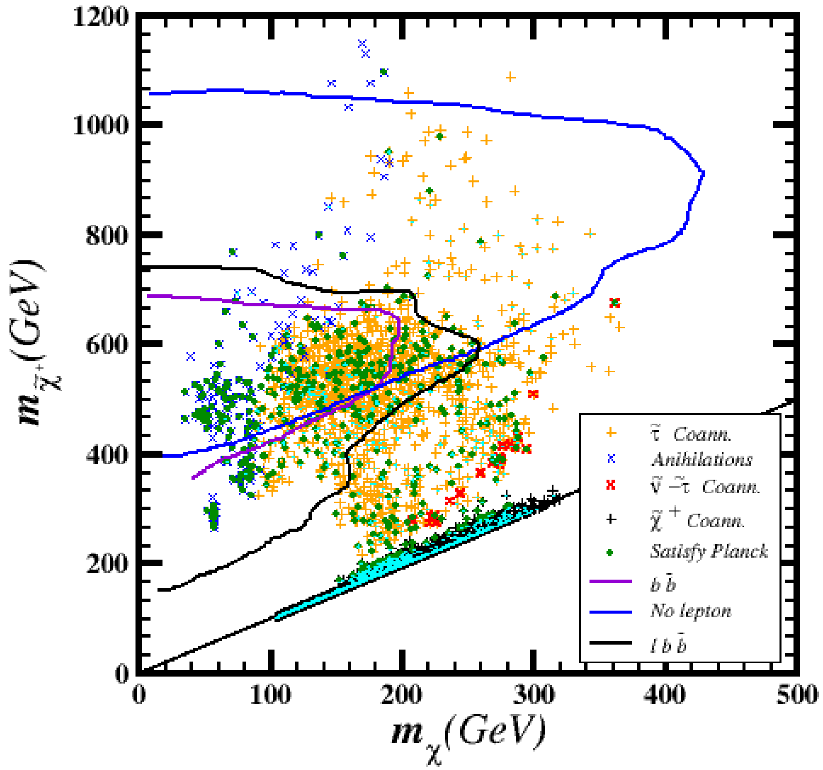




$\varepsilon = 0.2$

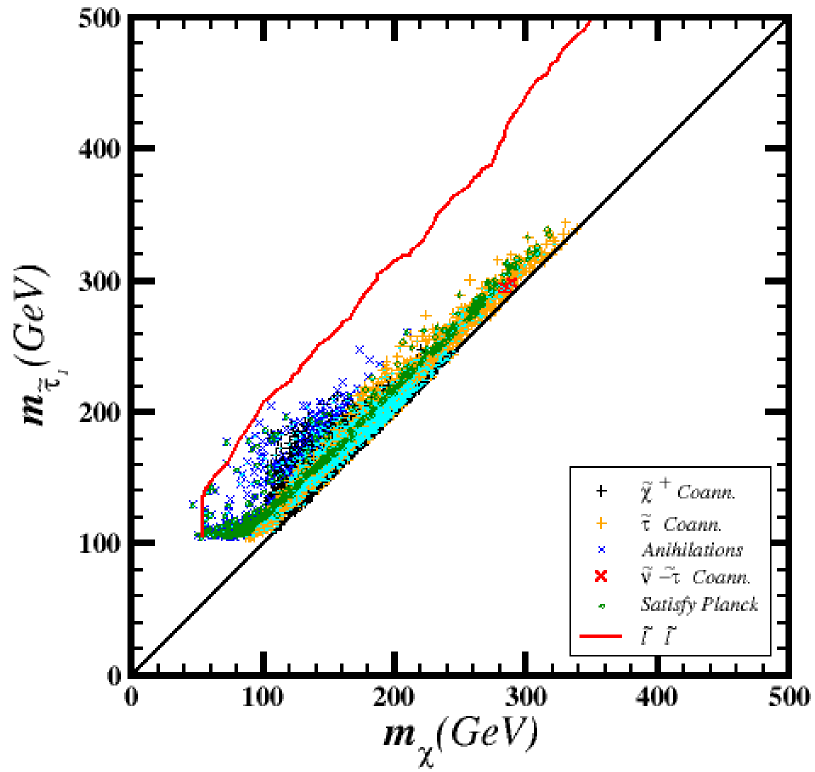


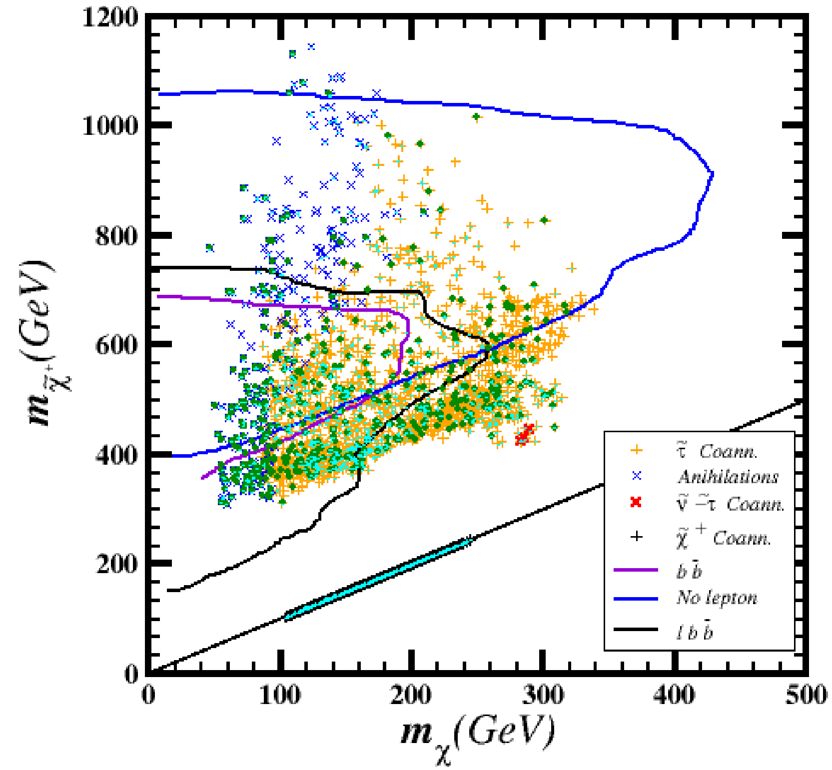
$m_{\tilde{\tau}_1}(GeV)$
$m_\chi(GeV)$
$\tilde{\chi}^+$ Coann.
$\tilde{\tau}$ Coann.
Anihilations
$\tilde{\nu}-\tilde{\tau}$ Coann.
Satisfy Planck
$\tilde{l}\ \tilde{l}$



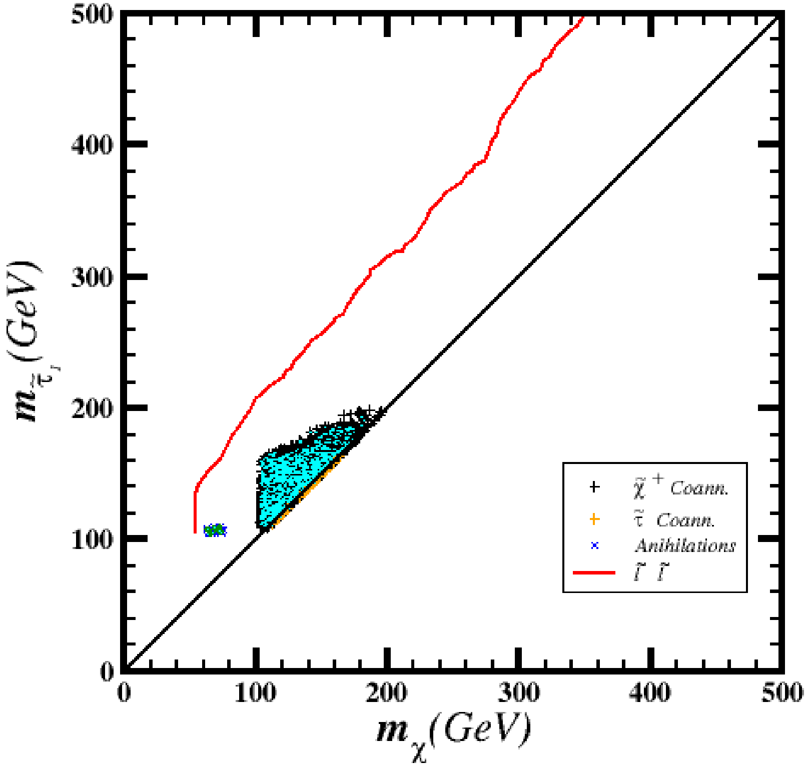
$m_{\tilde{\chi}^+}(GeV)$
$m_\chi(GeV)$
$\tilde{\tau}$ Coann.
Anihilations
$\tilde{\nu}-\tilde{\tau}$ Coann.
$\tilde{\chi}^+$ Coann.
Satisfy Planck
$b\,\bar{b}$
No lepton
$l\,b\,\bar{b}$

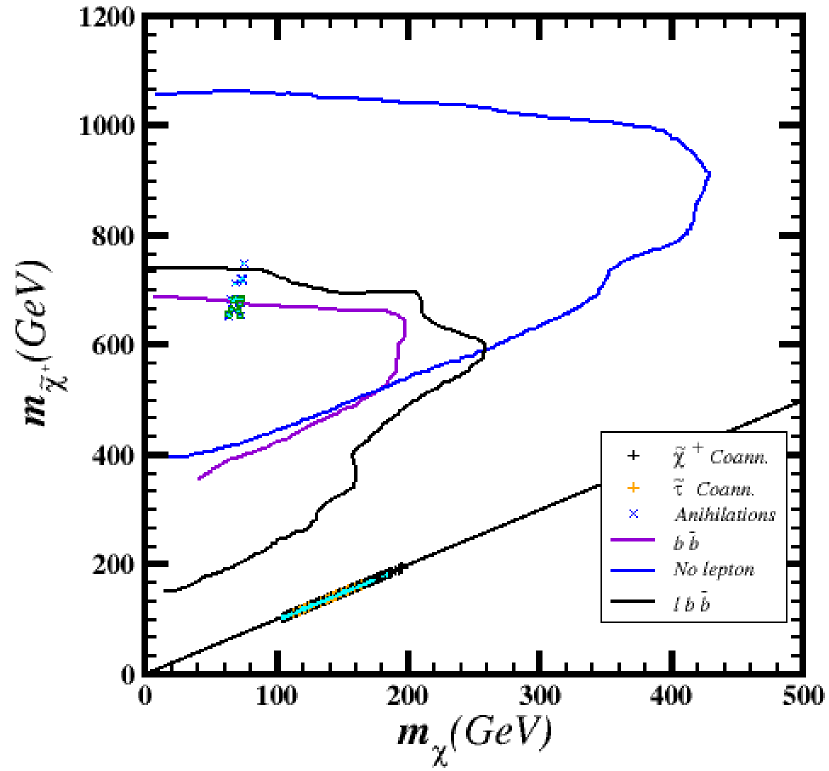
See-Saw





$\varepsilon = 0.05$





$\varepsilon = 0.2$

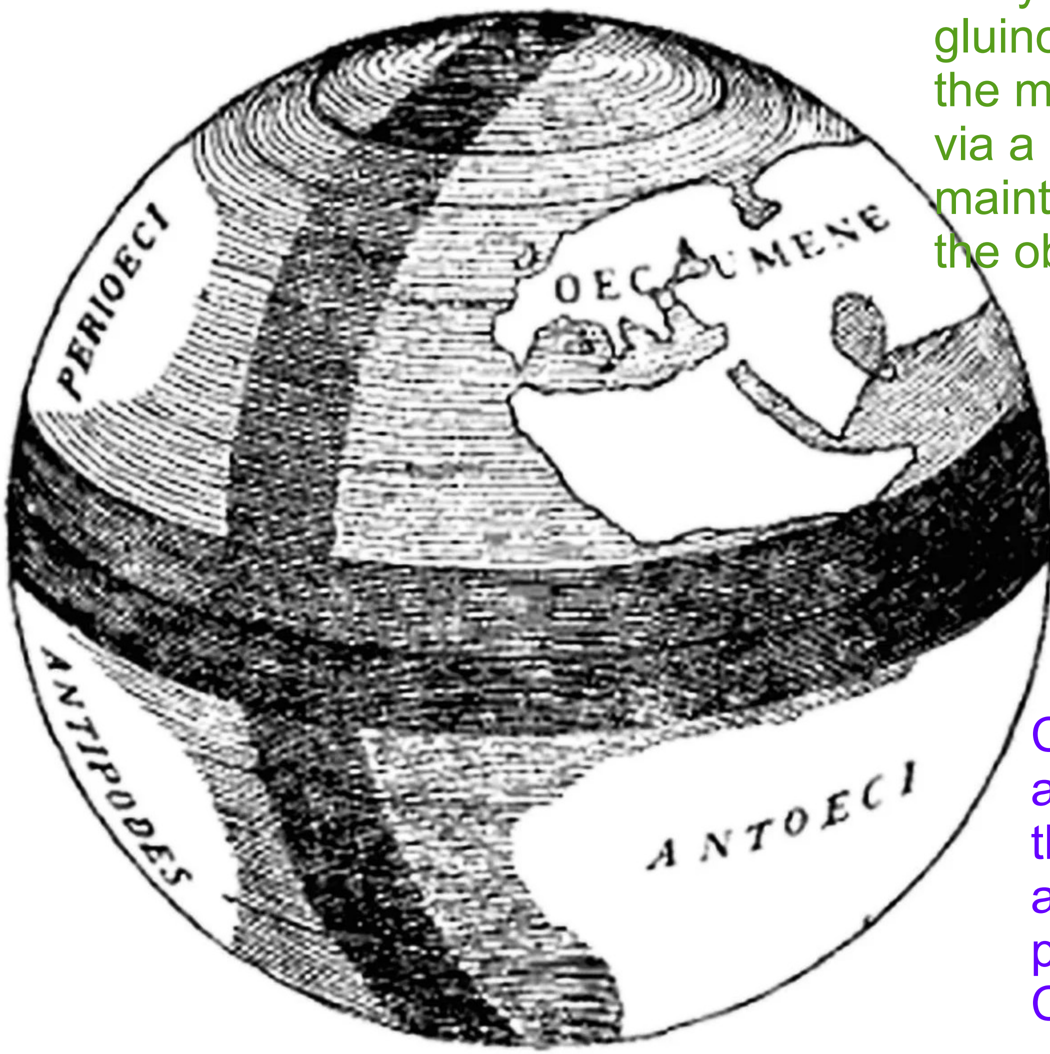
CONCLUSIONS

BSM

BR(μ-> e γ) falls in the experimental range (i.e. MEG projected bound).

SM

Susy Models with large gluino masses can explain the muon (g-2) discrepancy via a SUSY contribution mainting the prediction for the observed Higgs masses.



Accelerator

Charginos and staus are not so heavy but they can not be identify at the LHC. Good propects for Linear Collider..

Squarks are too heavy to be seen at the LHC

DM

Different kinds of LSP that satisfies the relic abundance condition.

murakoze!