Confronting Grand Unification with LFV Dark Matter and LHC data

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Colaboration with M. Canonni, J. Ellis, S. Lola, Ruiz de Austri Q. Shafi, C. Ün JHEP 1810 (2018) 062 Front.in Phys. 6 (2018), JHEP 09 (2020) 197, JHEP 07 (2020) 07, .

OUTLINE

.-GUT's and SUSY.

- SU(5), Flipped-SU(5) and SU(4)xSU(2)xSU(2)

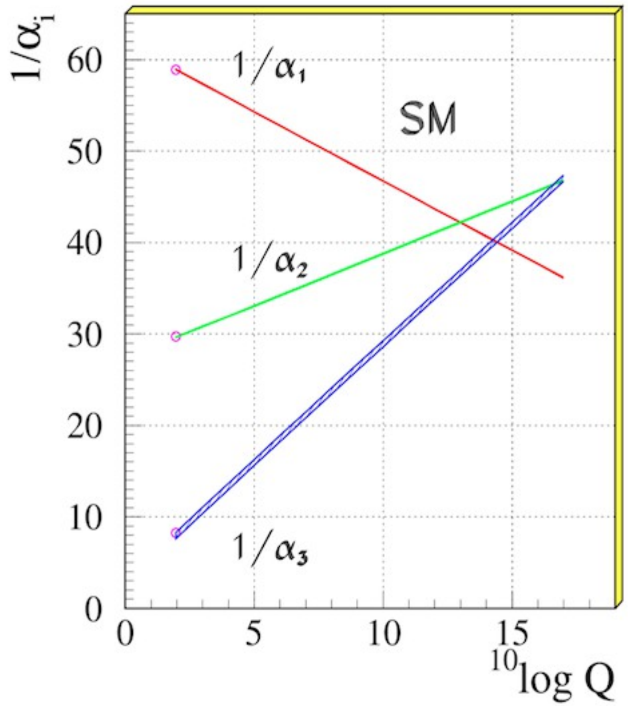
- Neutralino relic density and DM detection.

- Charged LFV in SUSY with a see-saw T1,

-SUSY Masses, LHC searches and rare lepton decays. .

Conclusions.

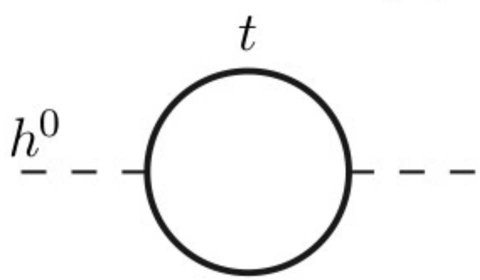
Unification & Hierarchy Problem



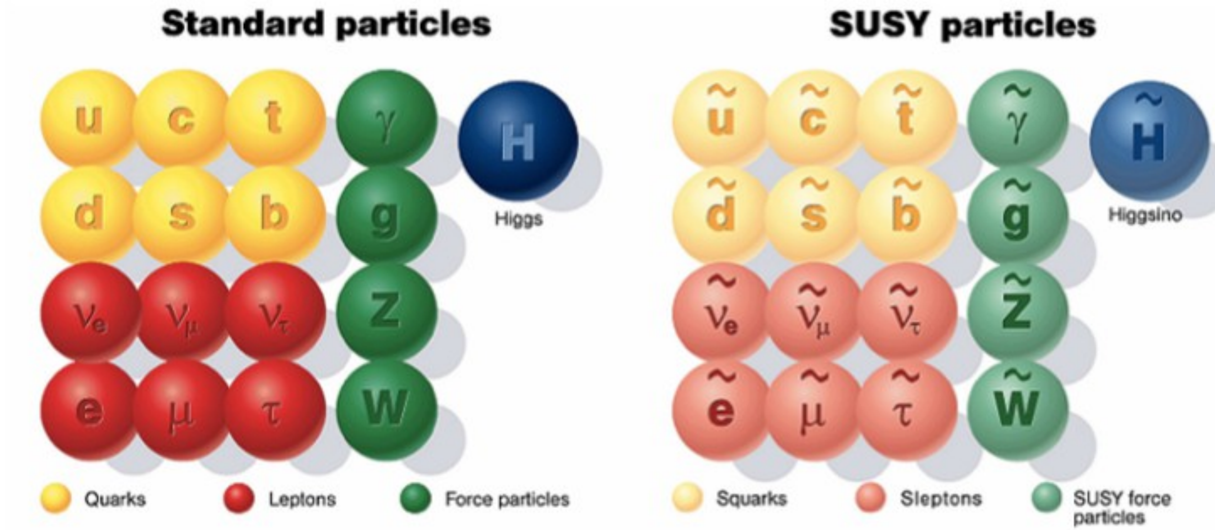
Almost unification at ~10^{14} GeV

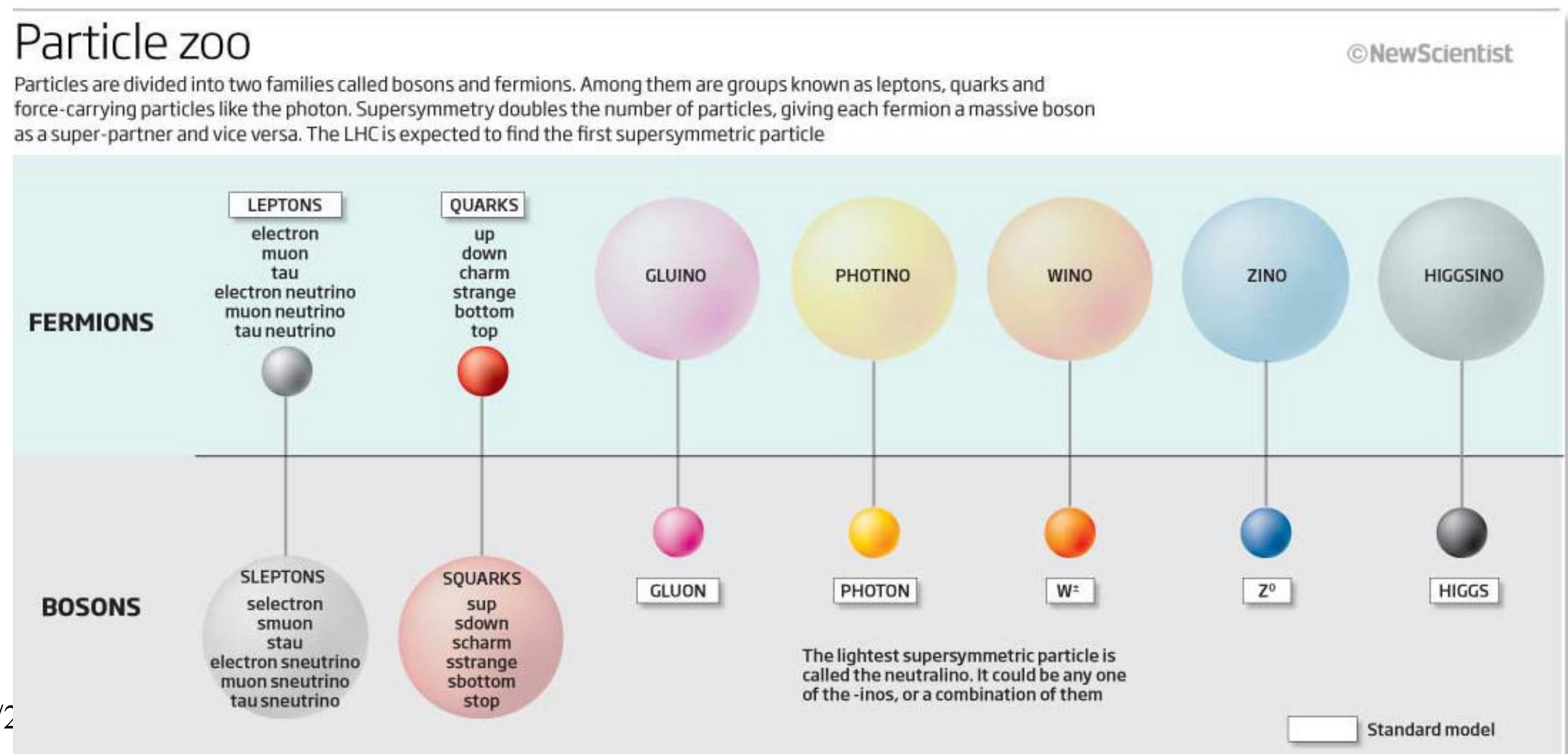
$$\mu \frac{d\alpha_i(\mu)}{d\mu} = -\frac{1}{2\pi}\left[b_i + \frac{1}{4\pi}\sum b_{ij}\alpha_j(\mu)\right]\alpha_i^2(\mu)$$

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

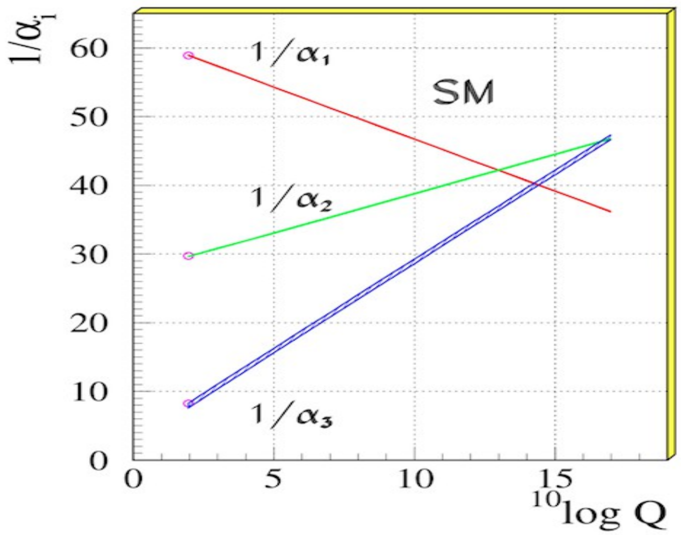


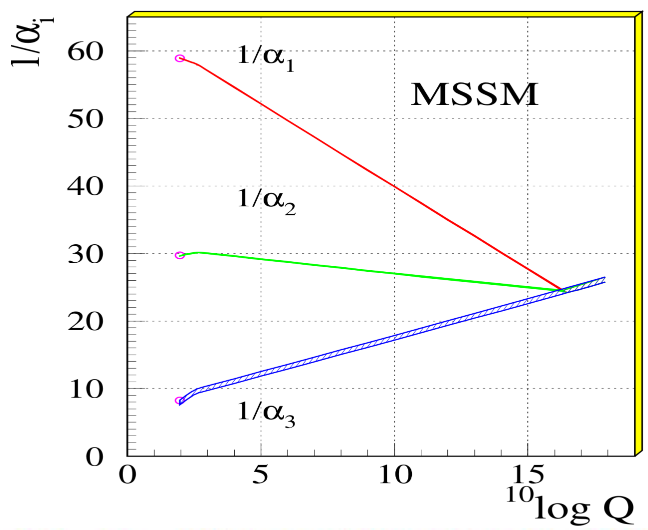
Divergent contribution to Higgs mass ↑ with $(m_{scale})^2$


Standard particles
SUSY particles
u c t γ H
d s b g
Higgs
ν_e ν_μ ν_τ Z
e μ τ W
Quarks
Leptons
Force particles
$\tilde{u}$ $\tilde{c}$ $\tilde{t}$ $\tilde{\gamma}$ $\tilde{H}$
$\tilde{d}$ $\tilde{s}$ $\tilde{b}$ $\tilde{g}$
Higgsino
$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$ $\tilde{Z}$
$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$ $\tilde{W}$
Squarks
Sleptons
SUSY force particles


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

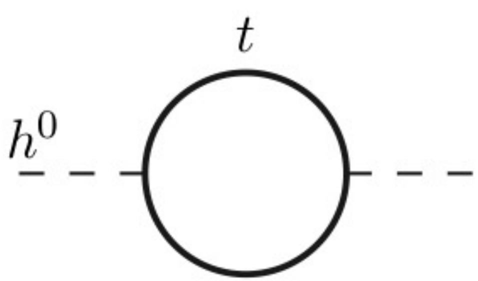
Unification & Hierarchy Problem



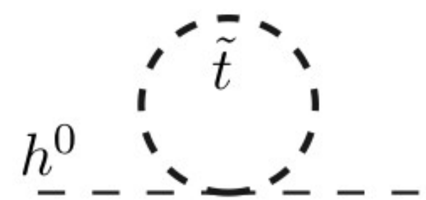


Unification at ~10^{16} GeV

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



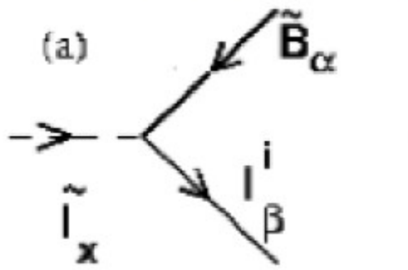
+



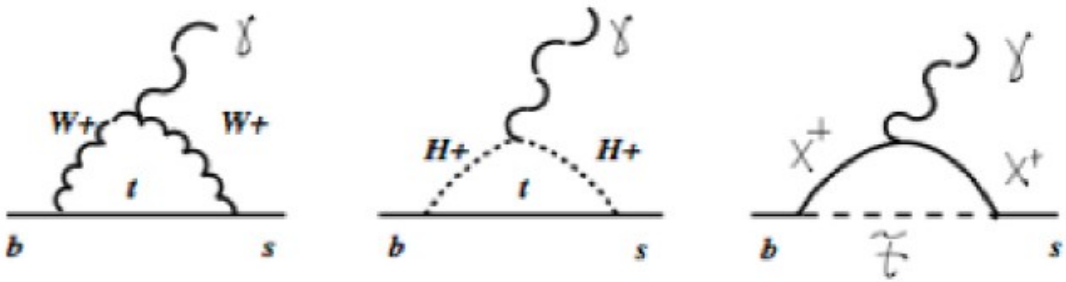
Cancelation of quadratic divergences

SUSY FLAVOR

R-parity warranties that SUSY particles only appear in pairs:



therefore SM model phenomenology is only modified at *loops level*:

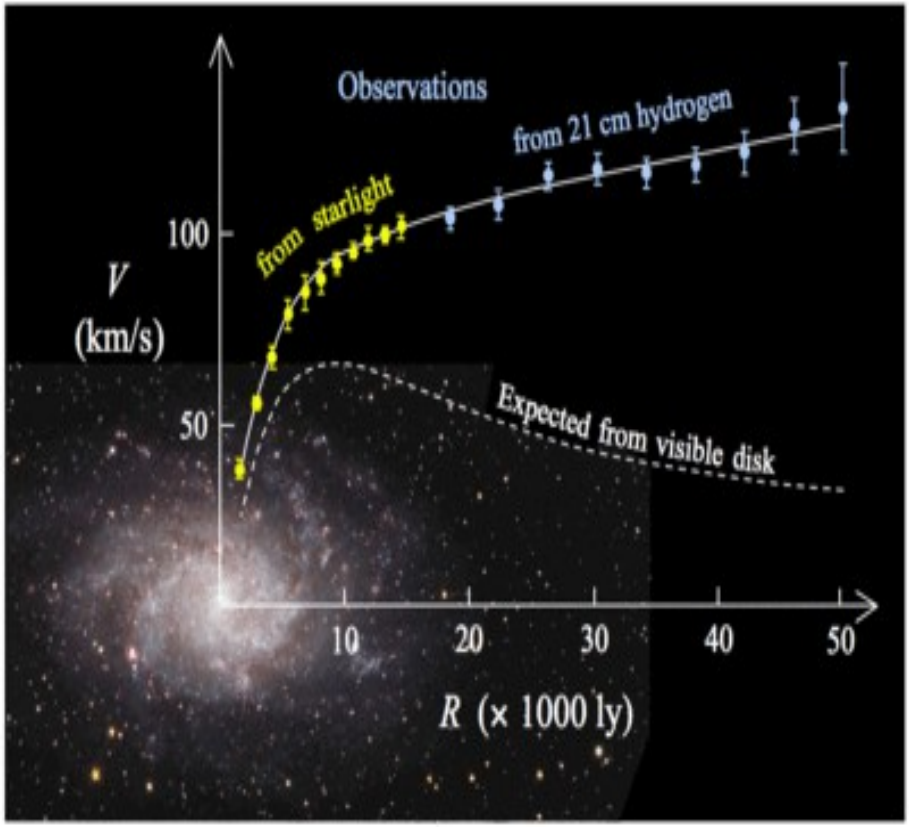


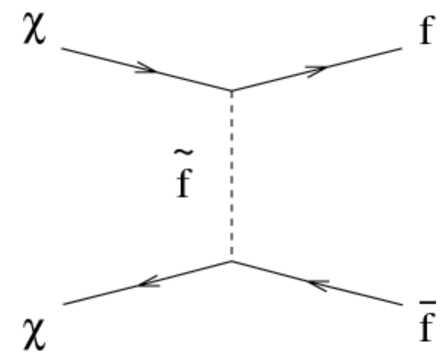
The present average given by the

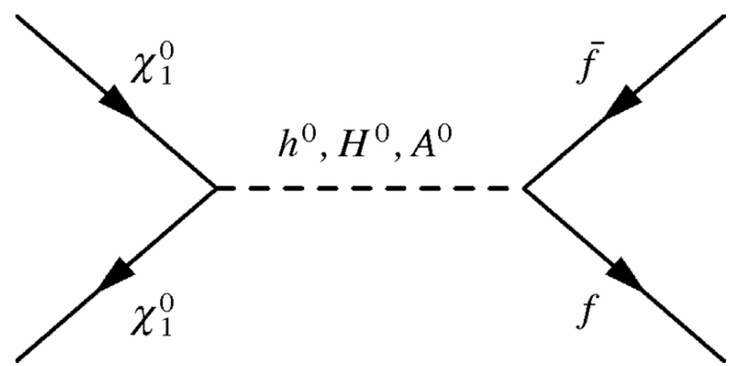
$$BR(b \to s\gamma) = (3.32 \pm 0.15) \times 10^{-4}$$

The SM prediction: $BR(b \to s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$

Dark Matter problem



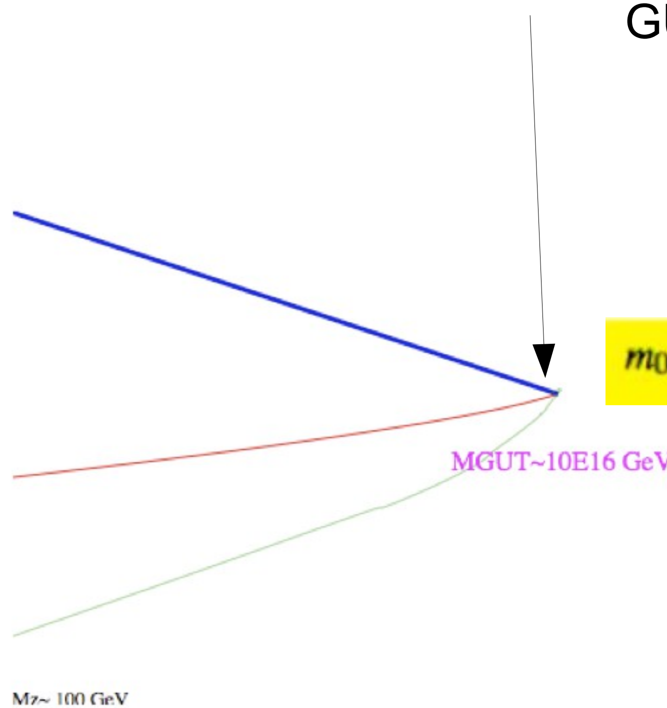




Rotation curve of spiral galaxy M 33 (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (white line). The discrepancy between the two curves can be accounted for by adding a dark matter halo surrounding the galaxy

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

GUT initial conditions

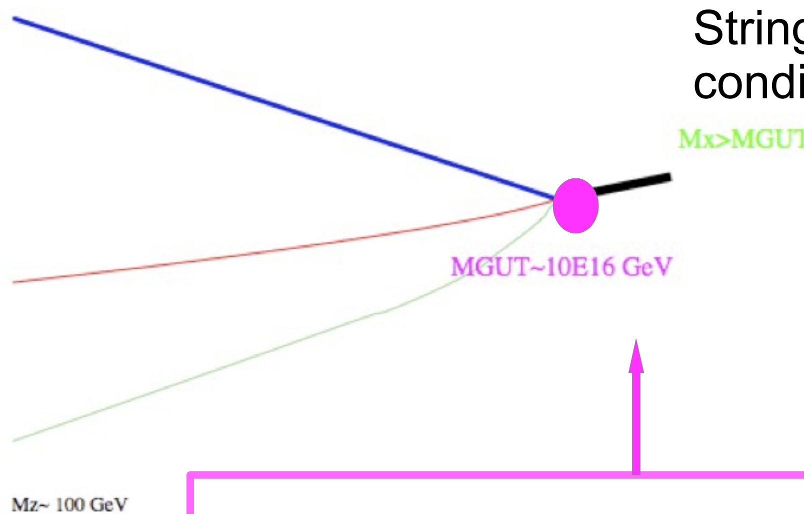


$m_0,\ m_{\frac{1}{2}},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)$

SU(3)xSU(2)XU(1) ← GUT

$$W_{SU(5)} = Y_u^{ij} 10_i 10_j 5^u + Y_d^{ij} 10_i \bar{5}_j \bar{5}^d$$

String scale Initial conditions



m_{10} $\quad$ m_5 $\quad$ m_u , m_d

$(Q_L, U, E) \subseteq 10$ $\quad$ $(D, L) \subseteq \bar{5}$ $\quad$ $H_u \subset 5^u ; H_d \subset \bar{5}^d$

Non Universal scenarios

CMSSM choice:

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

Representation-dependent choice

$$m_r = x_r \, m_0$$

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

Non Universal SU(5)

$$W_{SU(5)} = Y_u^{ij} 10_i 10_j 5^u + Y_d^{ij} 10_i \bar{5}_j \bar{5}^d$$

$$(Q_L, U, E) \subseteq 10$$

$$H_u \subset 5^u ; H_d \subset \bar{5}^d$$

$$(D, L) \subseteq \bar{5}$$

The soft terms are taken at GUT as:

$$m_{10} = m_0 ;$$

$$m_5 = x_5 \cdot m_{10} ;$$

$$m_u = x_u \cdot m_{10} ;$$

$$m_d = x_d \cdot m_{10.}$$

$$A_{10,5} = a_0 \cdot m_{0,}$$

Okada, Shafi, Raza

Phys.Rev. D90 (2014)

Flipped SU(5)

SU(5) $(Q, u^c, e^c)_i \in \mathbf{10}_i\,,\ (L, d^c)_i \in \overline{\mathbf{5}}_i\,,\ \nu_i^c \in \mathbf{1}_i\,.$

Flipped SU(5) $(Q, d^c, \nu^c)_i \in \mathbf{10}_i\,,\ (L, u^c)_i \in \overline{\mathbf{5}}_i\,,\ e_i^c \in \mathbf{1}_i\,.$

$$m_{10} = m_0, \quad m_5 = x_5 \cdot m_{10} \quad m_R = x_R \cdot m_{10}$$

$$m_{H_u} = x_u \cdot m_{10} \quad m_{H_d} = x_d \cdot m_{10}\,;$$

PATI-SALAM Unification

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

MATTER FIELDS		$\mathbf{4_c 2_L 2_R}$
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	$\begin{pmatrix} u_r^c \\ d_r^c \end{pmatrix}, \begin{pmatrix} \nu_r^c \\ e_r^c \end{pmatrix}$	$(\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})$

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

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	$\begin{pmatrix} h_2^+ & h_1^0 \\ h_2^0 & h_1^- \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, \mathbf{2})$

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

Non universal Higgs Mass terms due to D- terms.

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

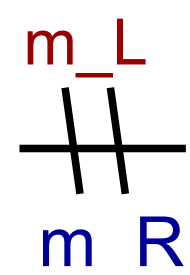
$$M_1 = \frac{3}{5} M_2 + \frac{2}{5} M_3.$$

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

$$x_{LR} = \frac{m_L}{m_R},$$

→ SUSY SEARCH: SuperBayeS, MultiNest

→ RGE's: SoftSusy

→ Relic Density: MicroOMEGAs

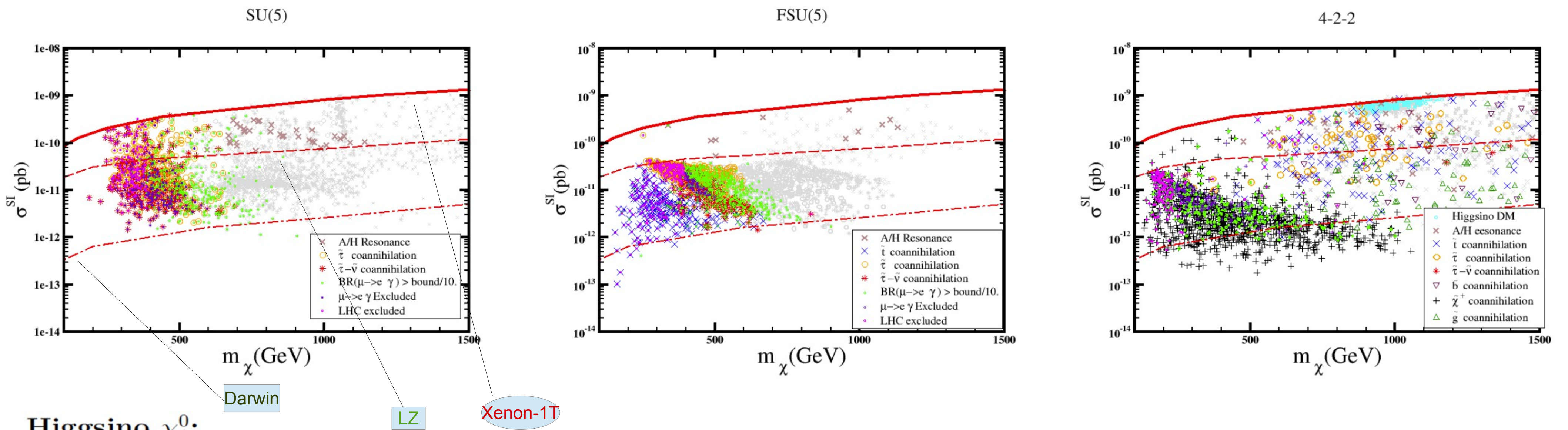
→ Direct DM detection: DarkSUSY

→ Super Iso: $\delta a_\mu^{\rm SUSY}$

→ SusyBSG: B-Physics.

Likelyhood function:

$$\begin{aligned}\ln \mathcal{L}_{\rm Joint} &= \ln \mathcal{L}_{\rm EW} + \ln \mathcal{L}_{\rm B} + \ln \mathcal{L}_{\Omega_\chi h^2} \\ &+ \ln \mathcal{L}_{\rm LUX} + \ln \mathcal{L}_{\rm Higgs} + \ln \mathcal{L}_{\rm SUSY} + \ln \mathcal{L}_{\rm g-2},\end{aligned}$$



Higgsino χ_1^0:

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

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

A/H resonances:

$$|m_A - 2m_\chi| \le 0.1\, m_\chi .$$

$\tilde{\tau}$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \le 0.1\, m_\chi$$

$\tilde{\tau} - \tilde{\nu}_\tau$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \le 0.1\, m_\chi, \quad (m_{\tilde{\mu}_1} - m_\chi) \le 0.1\, m$$

$\tilde{t}_1$ coannihilations:

$$h_f < 0.15, \quad (m_{\tilde{t}_1} - m_\chi) \le 0.1\, m_\chi .$$

$\tilde{\chi}^+ - \chi_1^0$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{\chi}^+} - m_\chi) \le 0.1\, m_\chi .$$

$\tilde{g} - \chi_1^0$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{g}} - m_\chi) \le 0.1\, m_\chi ,$$

$\tilde{b} - \chi_1^0$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{b}} - m_\chi) \le 0.1\, m_\chi ,$$

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

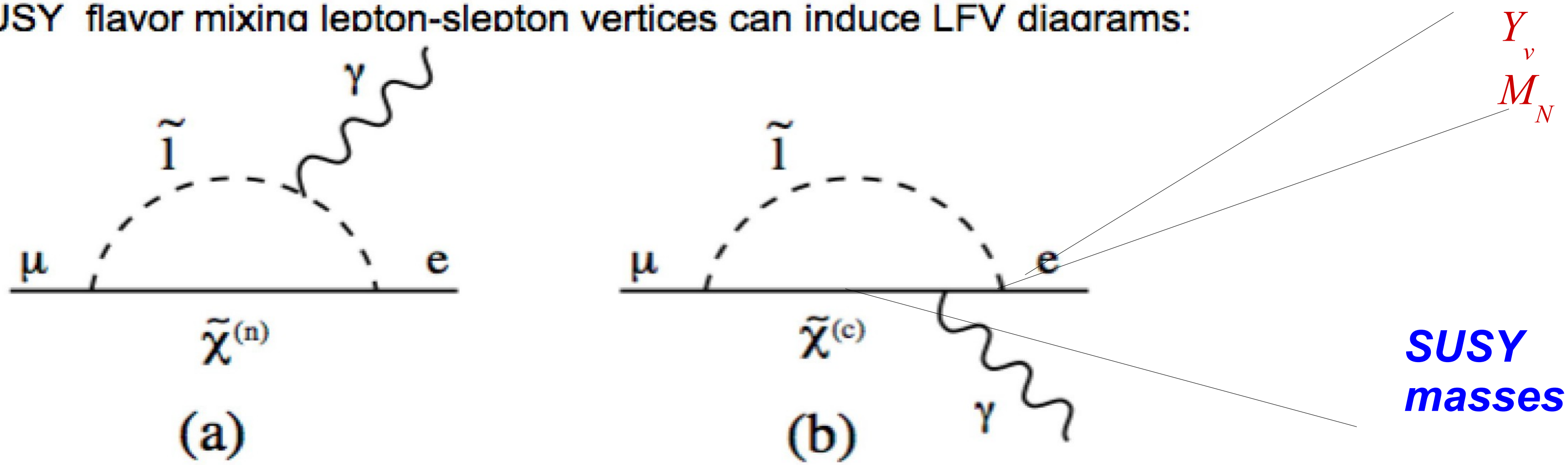
Diagonal Universal
1E14 GeV

Order 1

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

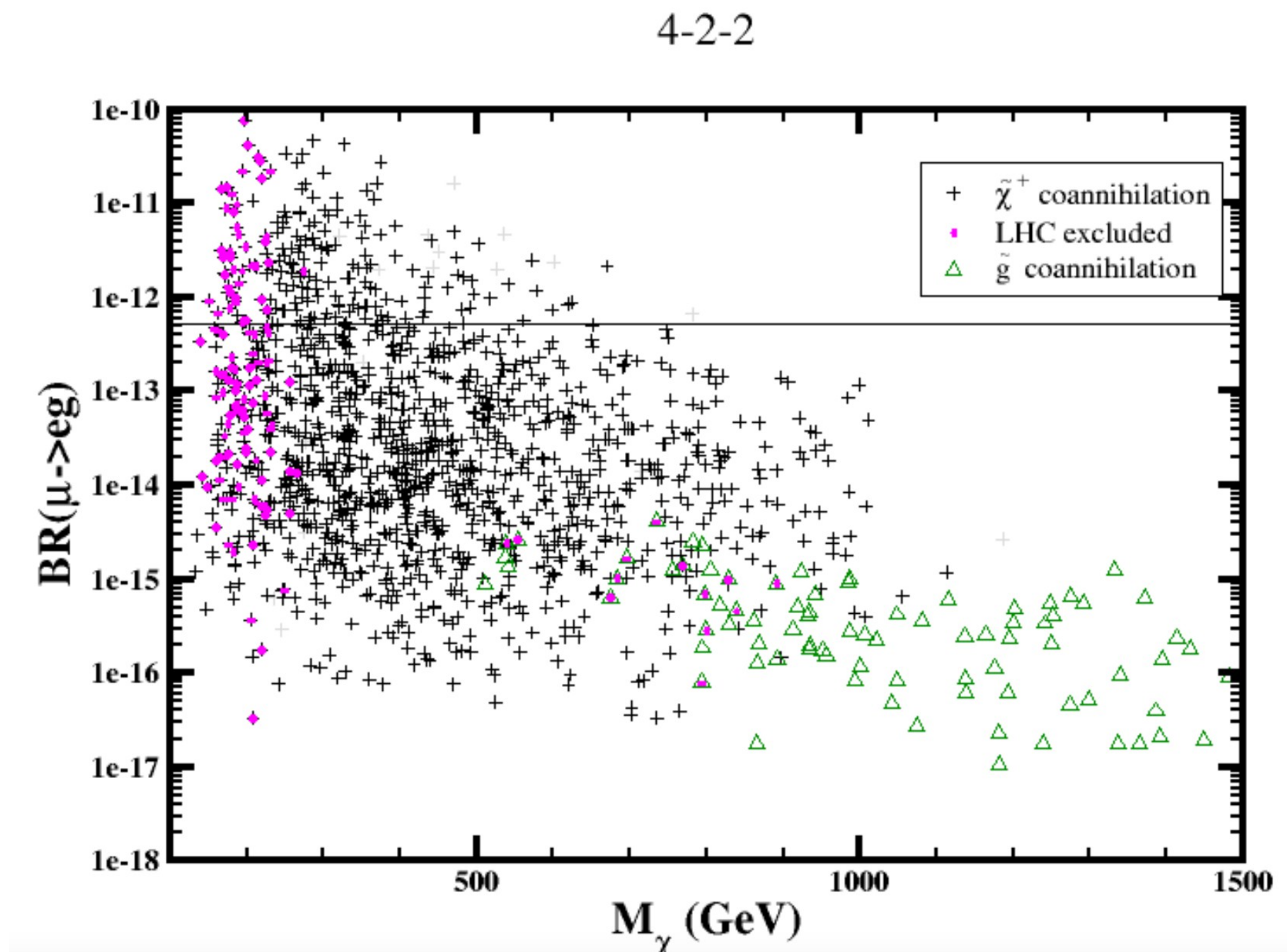
Limit case of degenerate MR

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

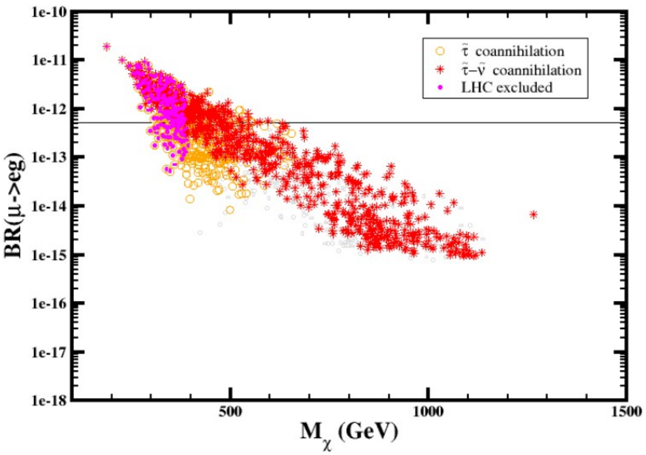


Lepton-slepton flavor mixing is very constrained by the experimental limits:

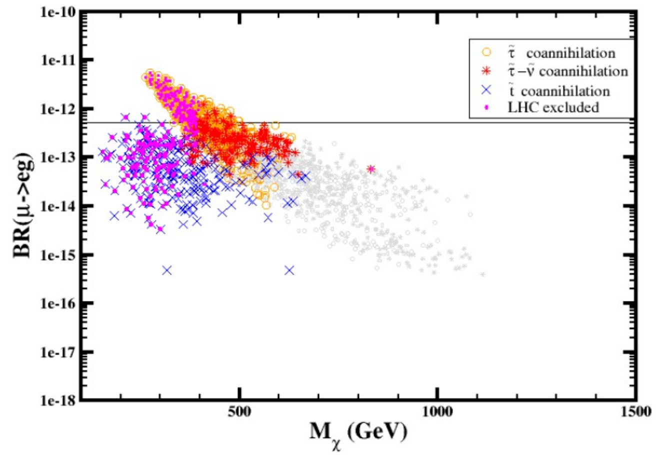
$$BR(\mu \rightarrow e\,\gamma) < 4.2\; x\, 10^{-13}$$
$$BR(\tau \rightarrow \mu\,\gamma) < 4.4\; x\, 10^{-8}$$
$$BR(\tau \rightarrow e\,\gamma) < 3.3\; x\, 10^{-8}$$


4-2-2
1e-10
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
500
1000
1500
BR(μ->eg)
Mχ (GeV)
χ̃+ coannihilation
LHC excluded
g̃ coannihilation

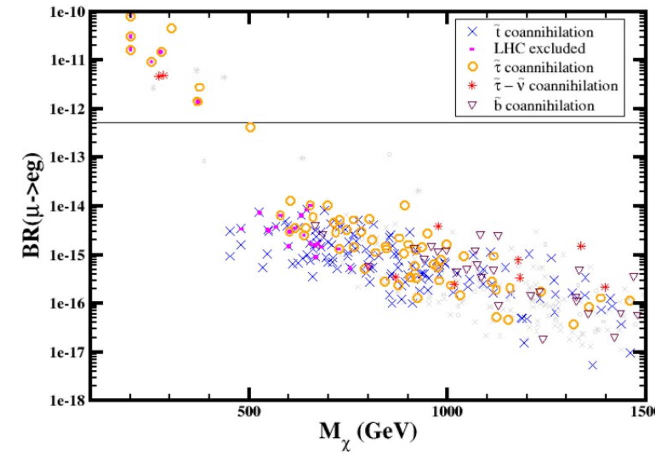
SU(5)



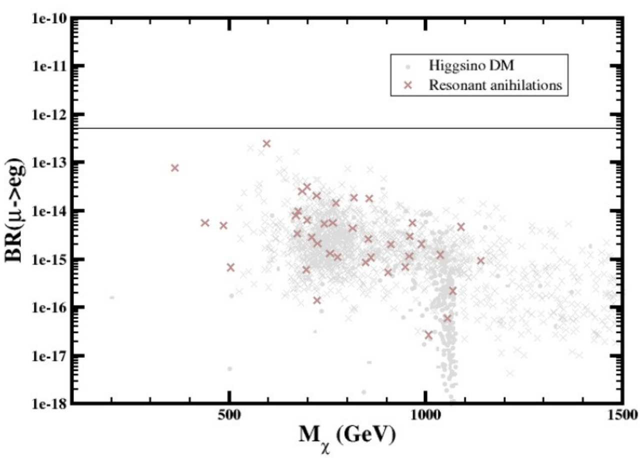
FSU(5)



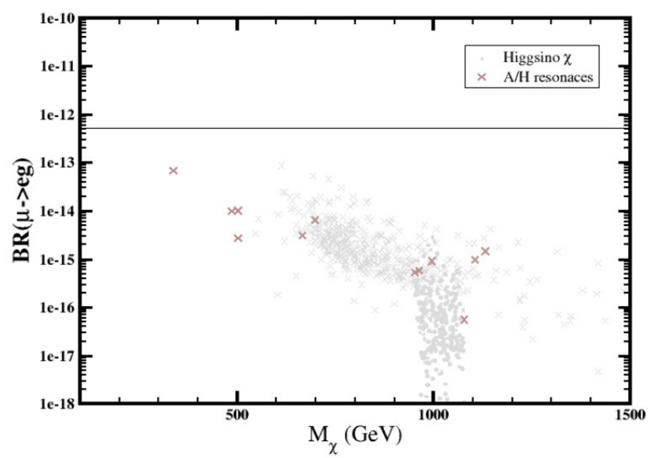
4-2-2



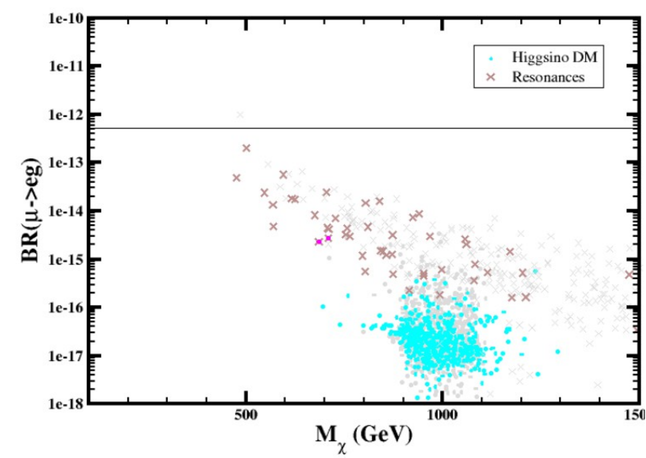
SU(5)



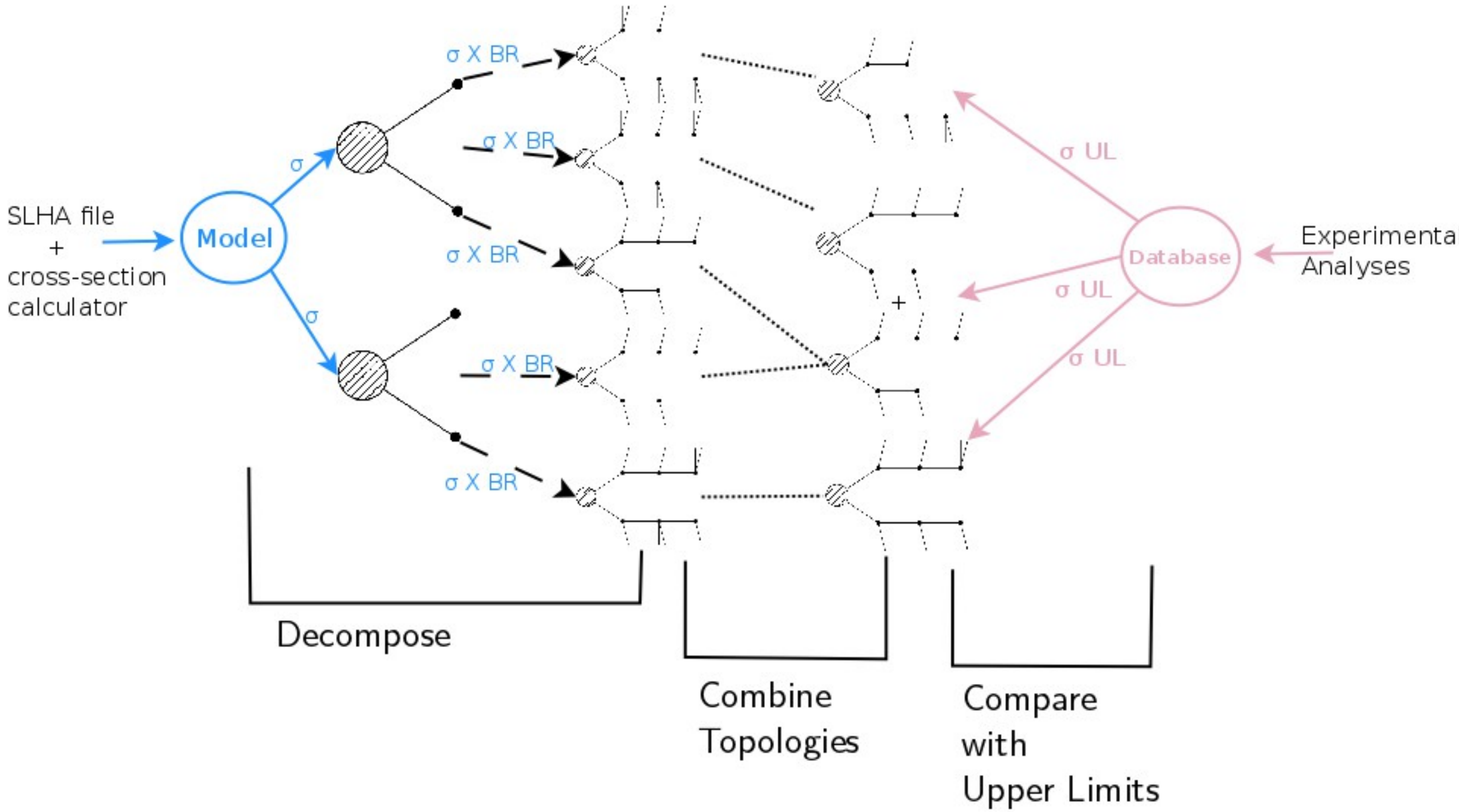
FSU(5)



4-2-2



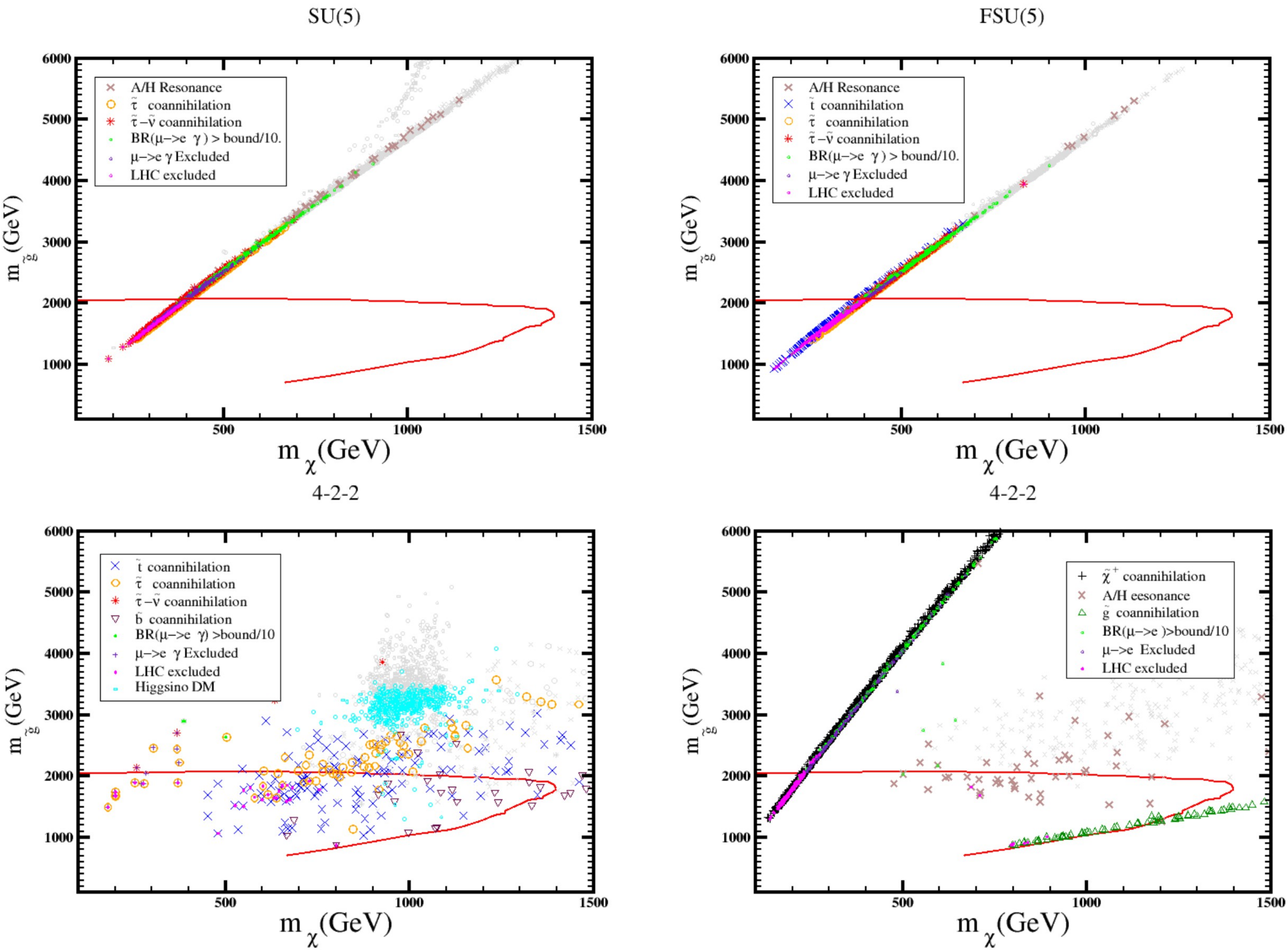
LHC analysis with Smodels, *http://smodels.hephy.at/wiki*



Analyzed points: Excluded

Allowed

Not analyzed.


SU(5)
A/H Resonance
τ̃ coannihilation
τ̃−ν̃ coannihilation
BR(μ−>e γ) > bound/10.
μ−>e γ Excluded
LHC excluded
FSU(5)
A/H Resonance
t̃ coannihilation
τ̃ coannihilation
τ̃−ν̃ coannihilation
BR(μ−>e γ) > bound/10.
μ−>e γ Excluded
LHC excluded
4-2-2
t̃ coannihilation
τ̃ coannihilation
τ̃−ν̃ coannihilation
b̃ coannihilation
BR(μ−>e γ) >bound/10
μ−>e γ Excluded
LHC excluded
Higgsino DM
4-2-2
χ̃+ coannihilation
A/H eesonance
g̃ coannihilation
BR(μ−>e)>bound/10
μ−>e Excluded
LHC excluded
$m_{\tilde{g}}$(GeV)
m_{χ}(GeV)

CONCLUSIONS

We have identified different patterns of soft SUSY-breaking terms at the GUT scale, with different dark matter predictions and the constraints from LHC searches.

We have calculated the SUSY spectra for the different gauge groups, finding that the models predict different spectra for the same LSP mass, connecting possible future observations with the structure of the underlying unified theory.

The see-saw mechanismto explain neutrino data may imply cLFV. The mu->e gamma prediction may be complementary (or alternative) signal to SUSY spectroscopy at the LHC.

We have found that SU(5) and FSU(5) GUT's (gaugino universality), PS (gaugino non universality) lead to very different predictions for dark matter LHC and cLFV experiments, and thus are distinguishable in future searches. PS predicts stop-LSP, gluino-LSP coannihilations that are absent in the other groups and can be explored by LHC searches.

The LHC searches for generic missing E_T, charginos and stops are quite complementary, and future LHC runs will be able to constrain the models in several different ways.

Models with compressed SUSY spectrum are difficult to test, however these are the natural scenarios with a suitable DM relic density. Furthermore, some of these scenarios also favor the detection of cLFV signals in the current experiments. The most promising one will be the chargino-LSP coannihilation class of models.