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 JCAP 1603 (2016) and Q. Shafi, JHEP 1810 (2018) 062 Front.in Phys. 6 (2018) and work in progress.

OUTLINE

-GUT's and SUSY.

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

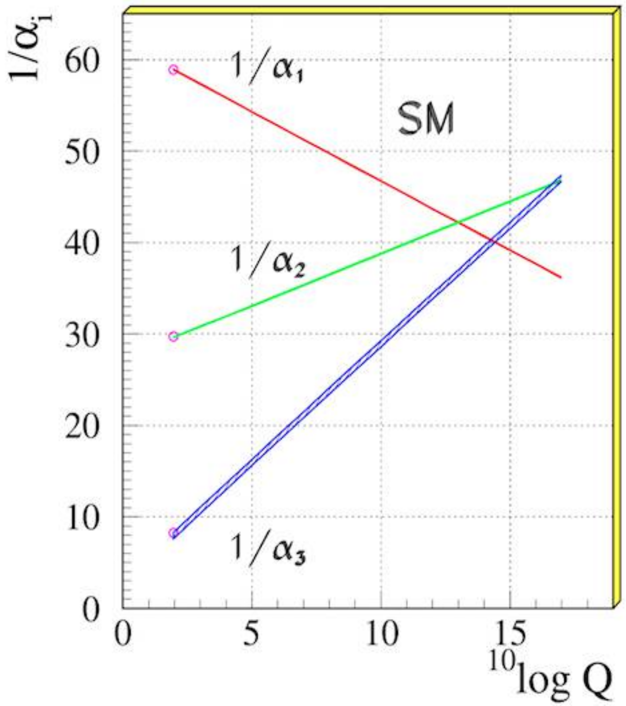
- Neutralino relic density and DM detection.
- Charged LFV in SUSY with a see-saw T1,
-SUSY Masses, LHC searches and rare lepton decays. .

Conclusions.

SUSY extension of SM

- Divergence cancellations
- Gauge unification
- Particles in the range of coming accelerators.
- DM candidate.
- Small but sizeable contribution to SM processes...

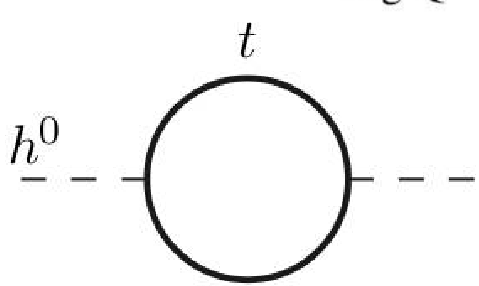
Unification & Hierarchy Problem



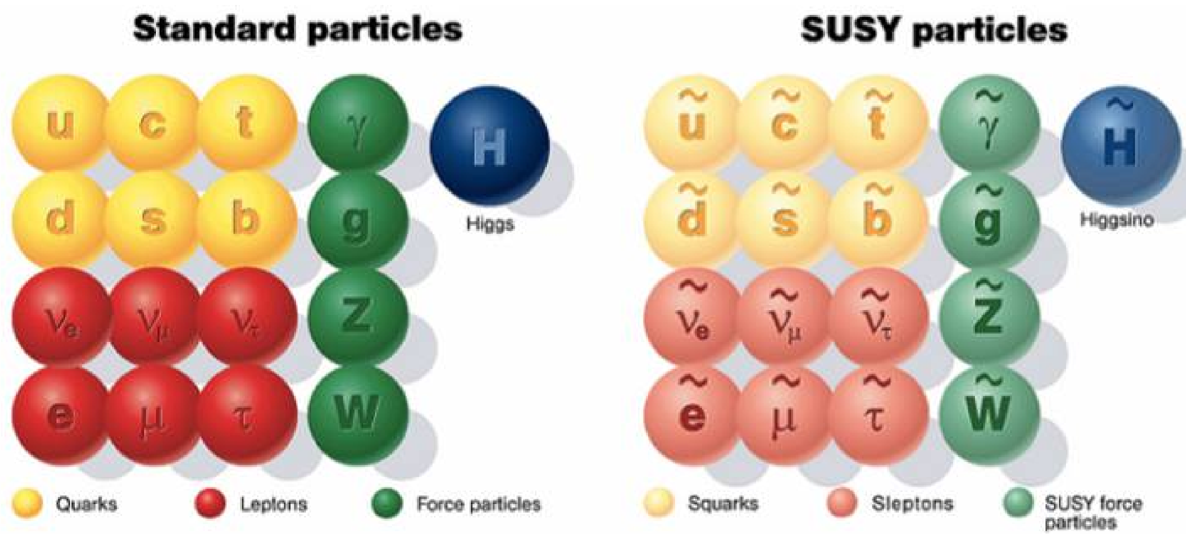
Almost unification at ~10^{14} GeV

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

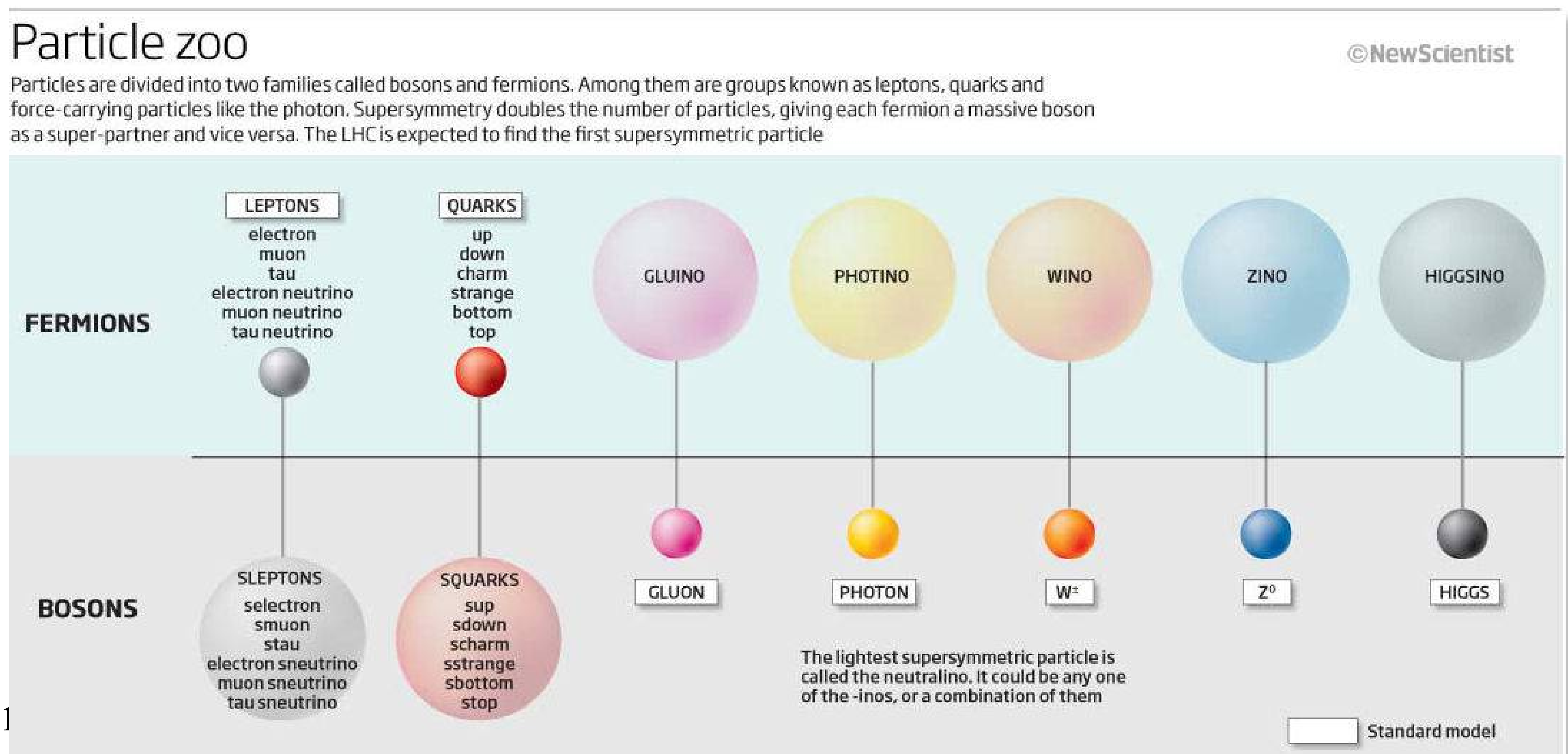
$$b_i = (0,-22/3,-11) + N_F(4/3,4/3,4/3) + N_H(1/10,1/6,0)$$



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

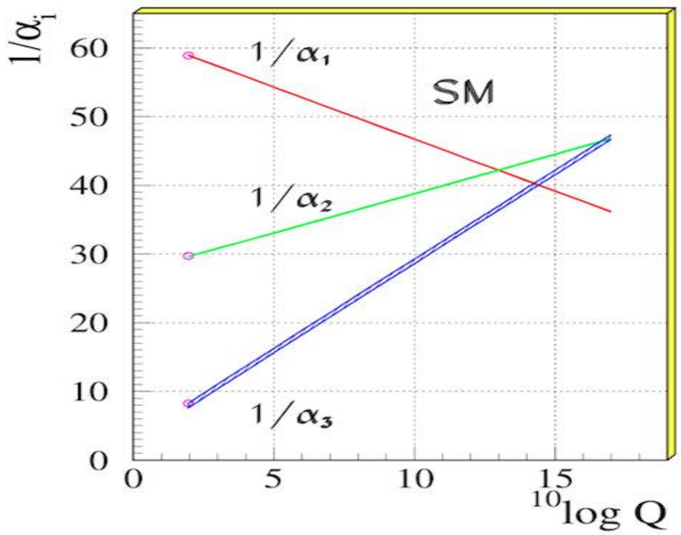


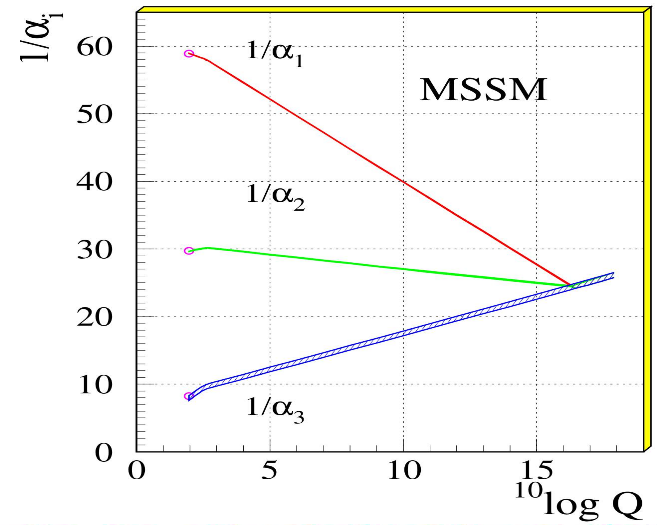
Standard particles
u c t γ
d s b g
Higgs
Z
W
e μ τ
Quarks
Leptons
Force particles
SUSY particles
Higgsino
Squarks
Sleptons
SUSY force particles



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±
Z0
HIGGS
The lightest supersymmetric particle is called the neutralino. It could be any one of the -inos, or a combination of them
Standard model

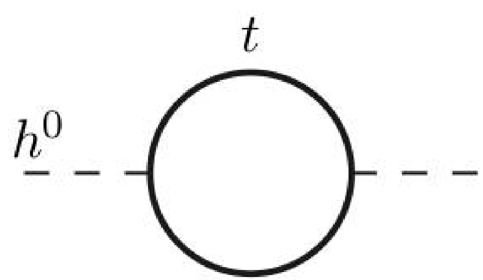
Unification & Hierarchy Problem



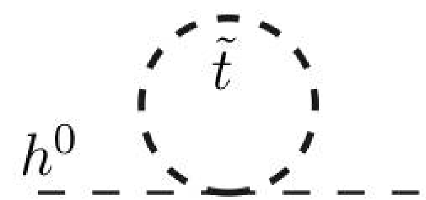


Unification at ~10^{16} GeV

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



+



Cancelation of quadratic divergences

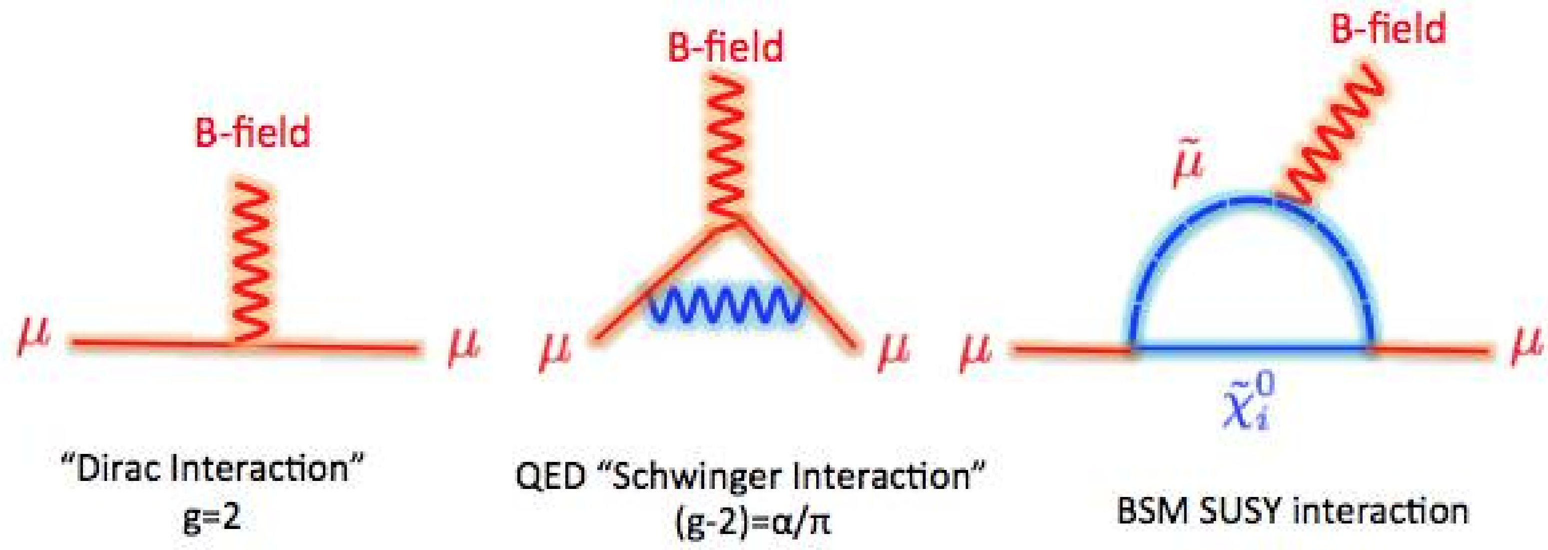
Crates of Mallus 150 B.C.

Antipodes theory:

Popular debate in the Midle ages.

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

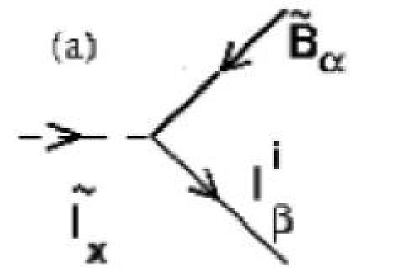
One loop contribution to SM proc.



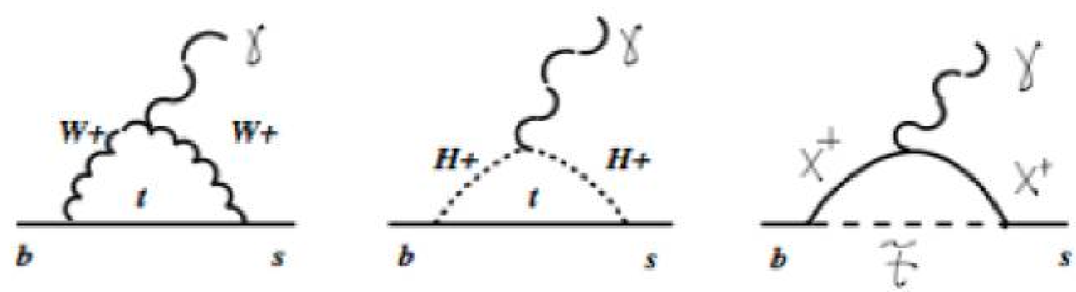
SM vs Experiment Discrepancies
anomalous magnetic dipole moment (g_μ-2)

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

Neutrino Oscillations

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} \sum_{l=e,\mu,\tau} \overline{l_L}(x)\,\gamma_\alpha\,\nu_{lL}(x)\,W^{\alpha\dagger}(x) + h.c.\,,$$

$$\nu_{l\rm L}(x) = \sum_{j=1}^{3} U_{lj}\,\nu_{j\rm L}(x),$$

EW interaction Mixes Lepton Flavor.

There is a matrix: PNMS=U Equivalent to CKM in the Quark sector.

$$P(\nu_{l(l')} \to \nu_{l'(l)}) \cong P(\bar{\nu}_{l(l')} \to \bar{\nu}_{l'(l)}) \cong \delta_{ll'} - 2|U_{ln}|^2 \left[\delta_{ll'} - |U_{l'n}|^2\right] \left(1 - \cos\frac{\Delta m^2_{n1}}{2p}\,L\right).$$

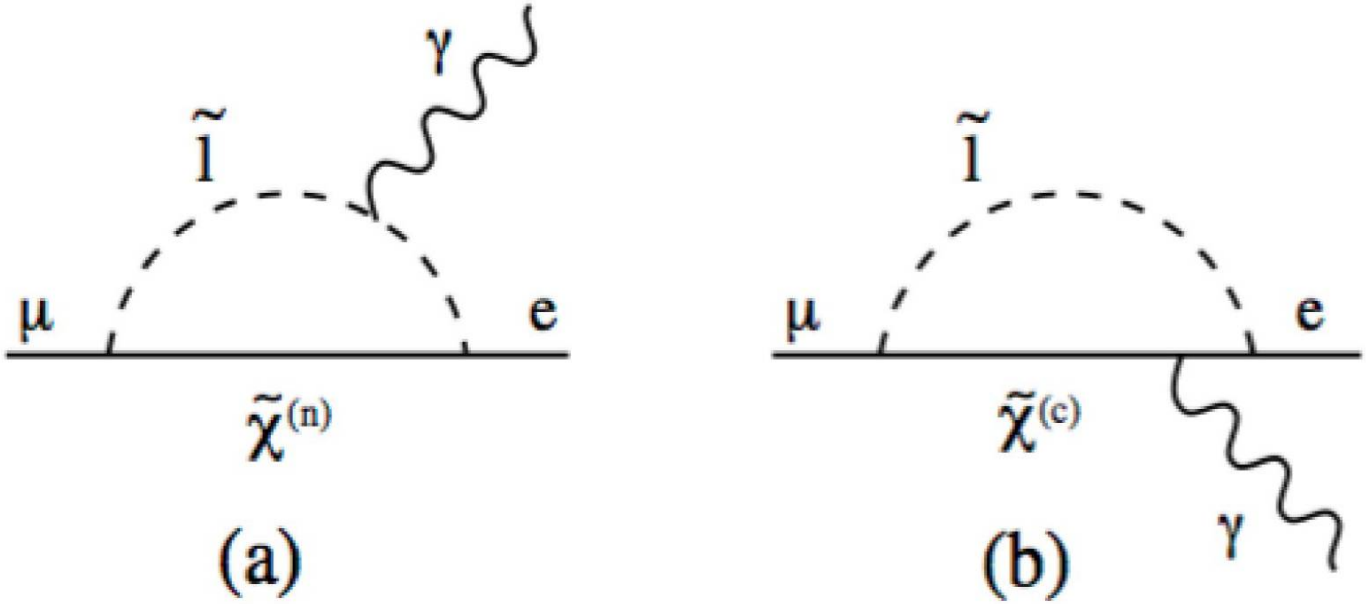
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

Atmospheric problem	Solar problem
$\Delta m^2_{atm} = \left(2.6^{+0.4}_{-0.7}\right) \times 10^{-3}$ eV^2 $\sin^2 2\theta_{atm} > 0.90$	$\Delta m^2_{sol} = \left(8.1^{+0.5}_{-0.5}\right) \times 10^{-5}$ eV^2 $\sin^2 2\theta_{sol} = \left(0.86^{+0.05}_{-0.06}\right)$

$0.06 < \sin^2 2\theta_{13} < 0.13$

Reactor data (RENO, Daya Bay).

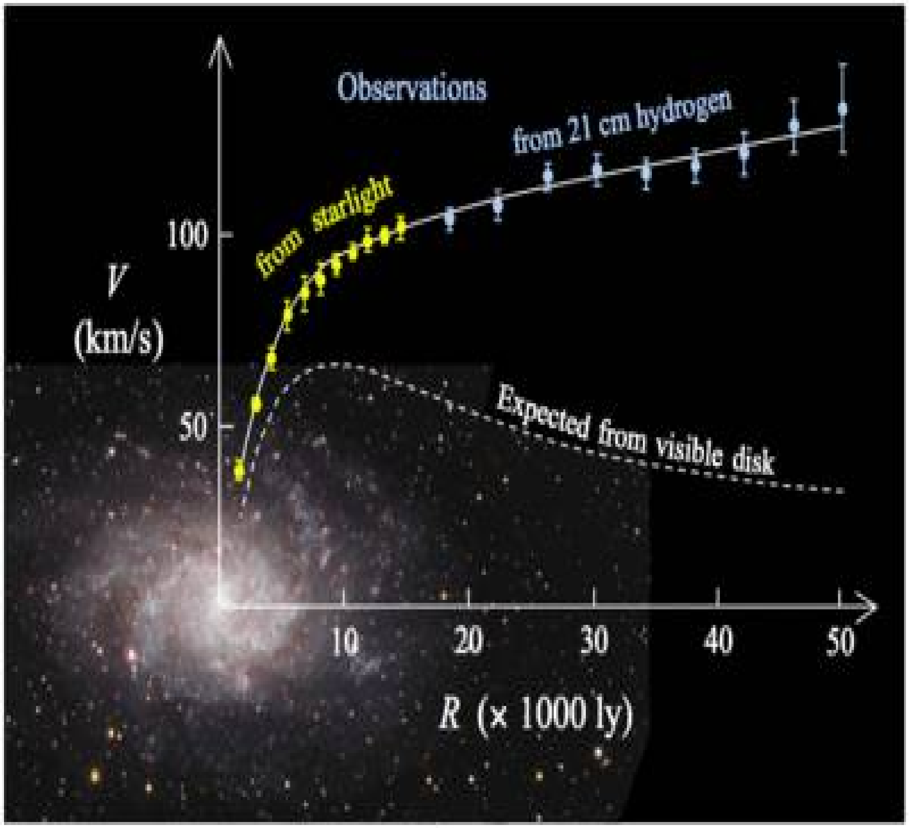
In SUSY flavor mixing lepton-slepton vertices can induce LFV diagrams:



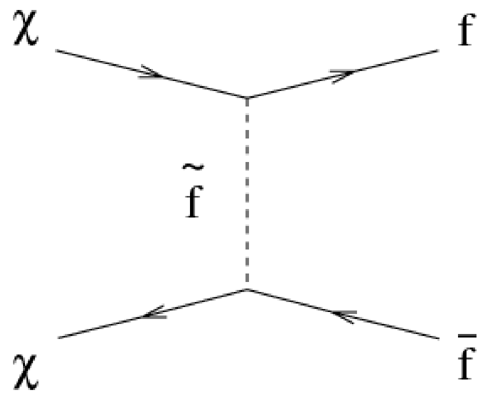
Lepton-slepton flavor mixing is very constrained by the experimental limits:

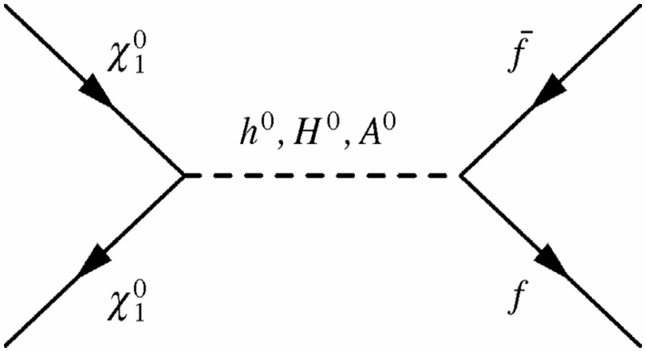
$$BR(\mu \to e\gamma) < 5.7\,x\,10^{-13}$$
$$BR(\tau \to \mu\gamma) < 4.4\,x\,10^{-8}$$
$$BR(\tau \to e\gamma) < 3.3\,x\,10^{-8}$$

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





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

Soft SUSY Breaking Terms

The soft SUSY breaking masses

$$
\begin{aligned}
-\mathcal{L}_{\rm soft} = & -\frac{1}{2}\left(M_3\,\lambda_{\tilde g}^a\lambda_{\tilde g}^a + M_2\,\lambda_{\widetilde W}^i\lambda_{\widetilde W}^i + M_1\,\lambda_{\widetilde B}\lambda_{\widetilde B} + \text{h.c.}\right) \\
& + M_L^2\,\widetilde L^\dagger\widetilde L + M_Q^2\,\widetilde Q^\dagger\widetilde Q + M_U^2\,\widetilde U^*\widetilde U + M_D^2\,\widetilde D^*\widetilde D + M_E^2\,\widetilde E^*\widetilde E + \\
& m_{H_d}^2\,\widetilde H_d^\dagger\widetilde H_d + m_{H_u}^2\,H_u^\dagger H_u - \left(B\mu\,\widetilde H_d^T H_u + \text{h.c.}\right) \\
& + \left(y_\ell A_\ell\,H_d^\dagger\widetilde L\widetilde E + y_d A_d\,H_d^\dagger\widetilde Q\widetilde D - y_u A_u\,H_u^T\,\widetilde Q\widetilde U\; + \;\text{h.c.}\right),
\end{aligned}
$$

Inspired from supergravity assume universal soft breaking, $\mathcal{L}_{\rm soft}$:

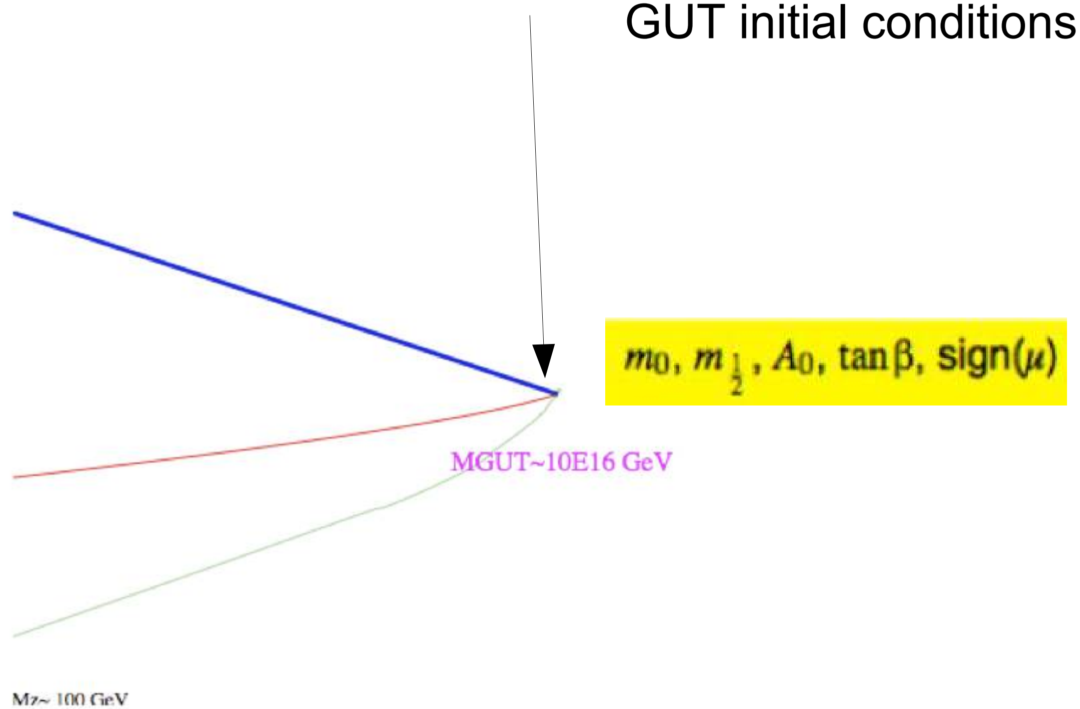
$$
\sum_{f,H} m_0^2\tilde f\tilde f + \sum_{\lambda} m_{\frac{1}{2}}\lambda\lambda + \sum_{f} A_0 Y_f\tilde f\tilde F H_f + B\mu H_u H_d
$$

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

μ and A_0 can be complex, however their phases contraint to be $< 0{,}2$ rad by the bounds c

the fermion EDM.

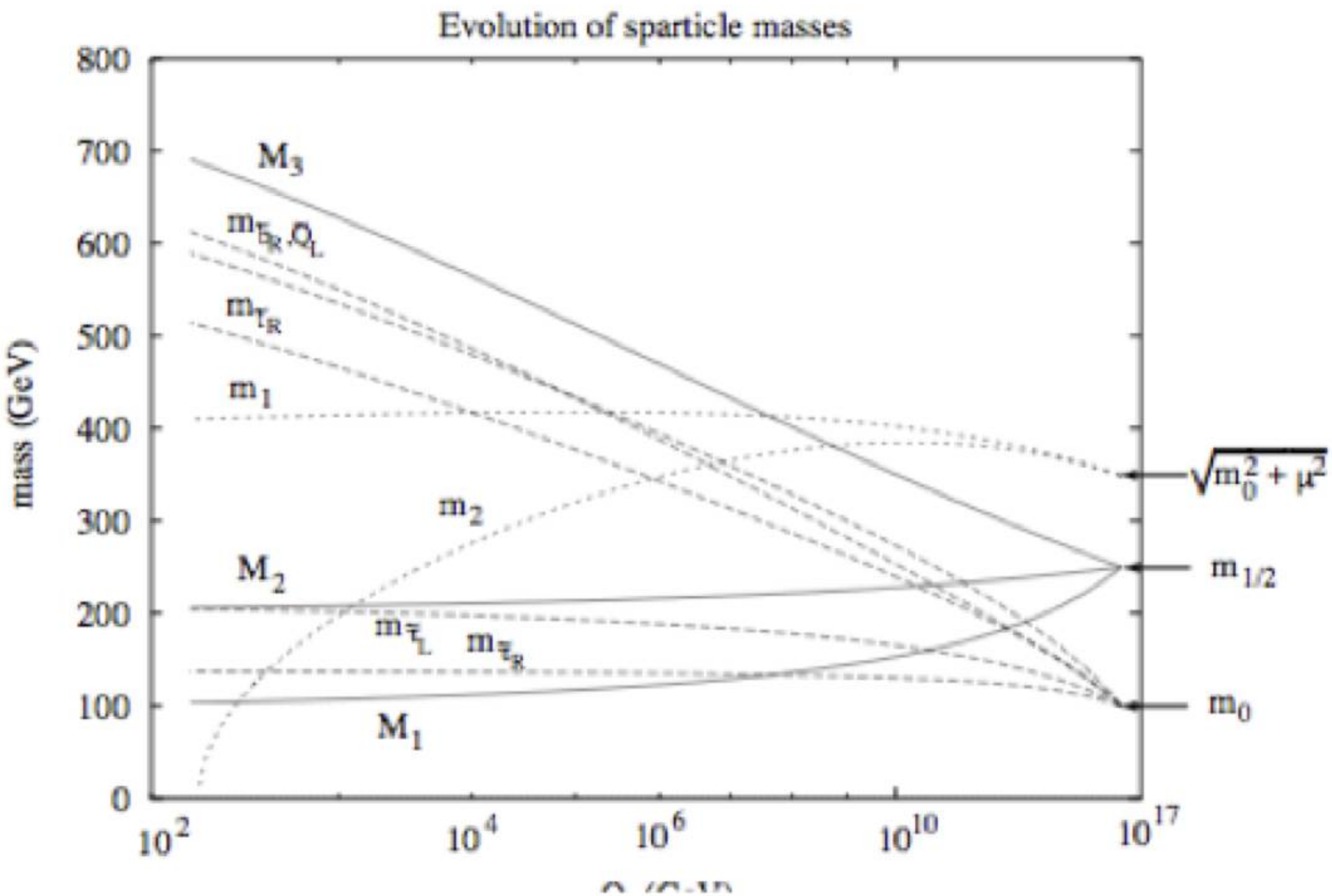
GUT initial conditions



SUSY spectrum

CMSSM, mSUGRA. Parametros de masa universales:

$$m_0,\ M_{1/2},\ A_0,\ \mu_0,\ \alpha_G,\ M_{GUT},\ \tan\beta\ .$$



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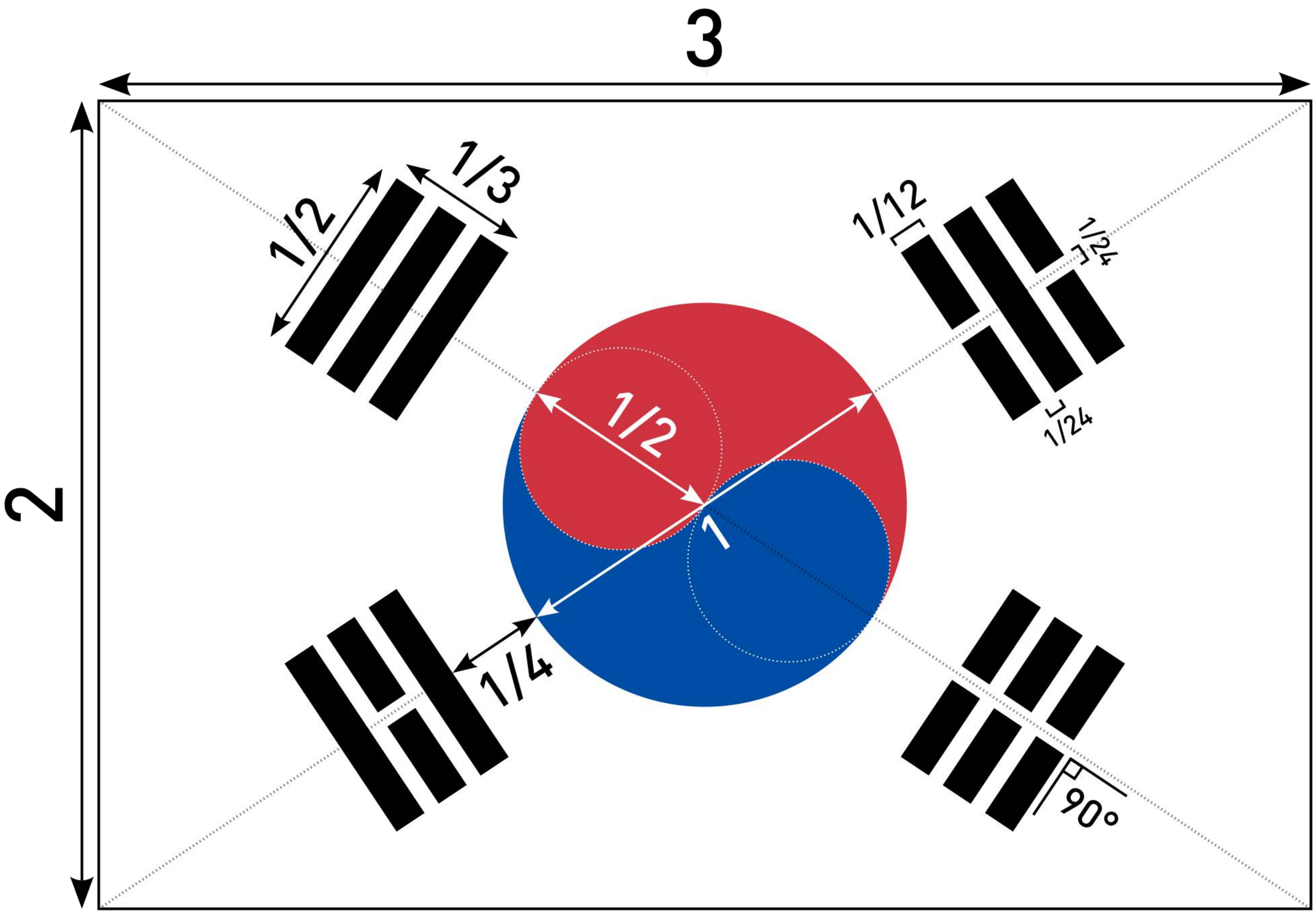
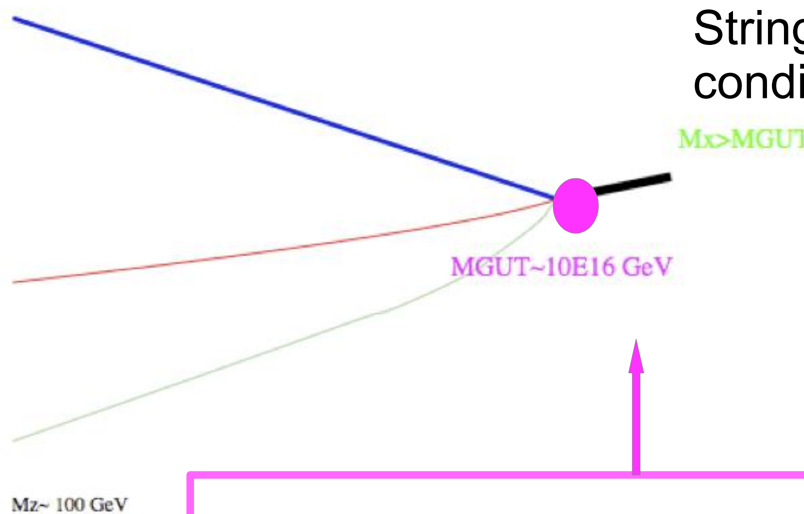
Symmetry



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} m_5 m_u , m_d

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

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

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

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

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

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.

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

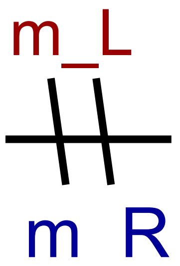
$$M_1 = \frac{3}{5} M_2 + \frac{2}{5} M_3.$$

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: $\delta a_{\mu}^{\mathrm{SUSY}}$

→ SusyBSG: B-Physics.

Likelyhood function:

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

Higgsino χ_1^0:

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

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

A/H resonances:

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

$\tilde{\tau}$ coannihilations:

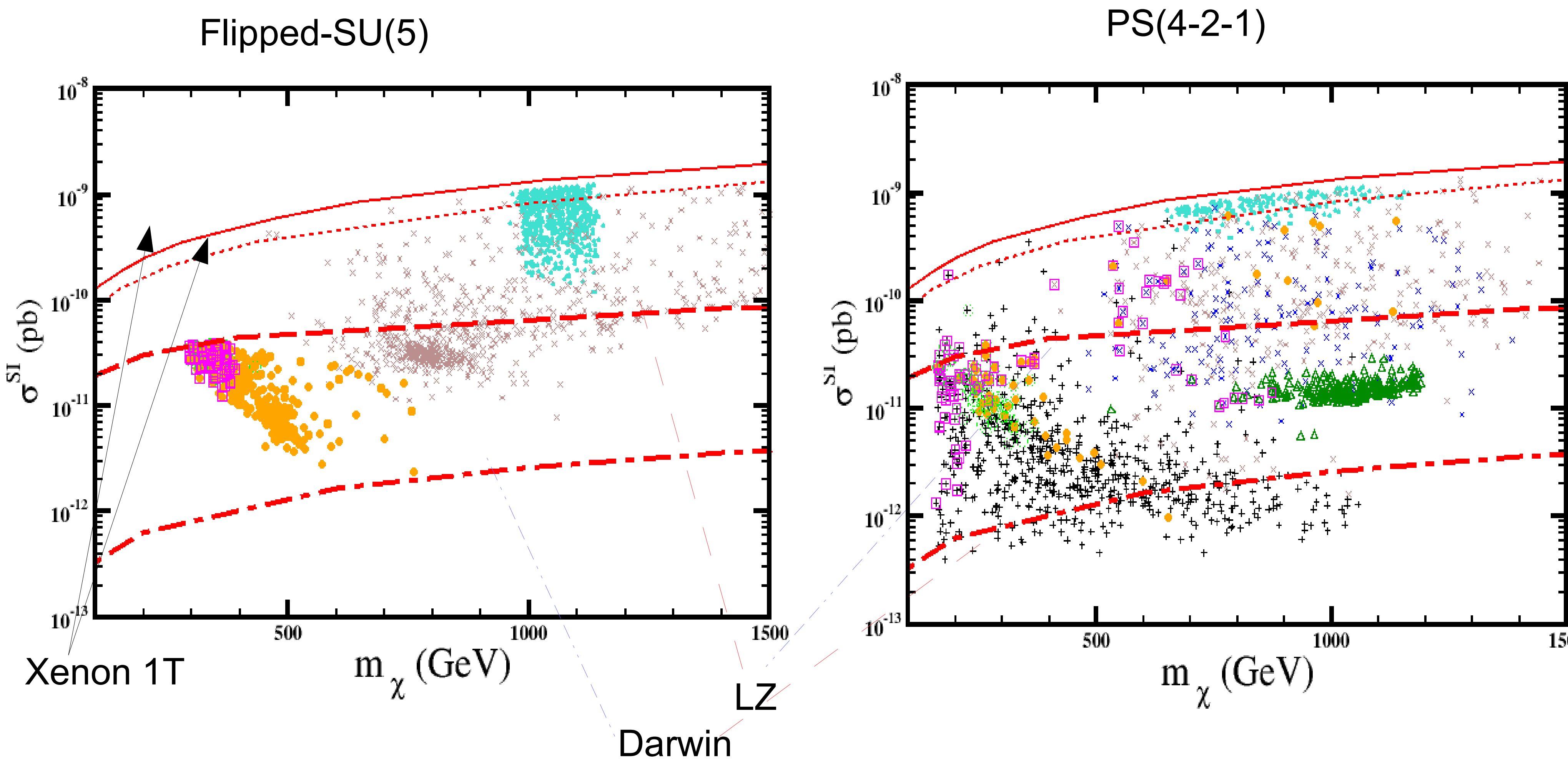
$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1\, m_\chi$$

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

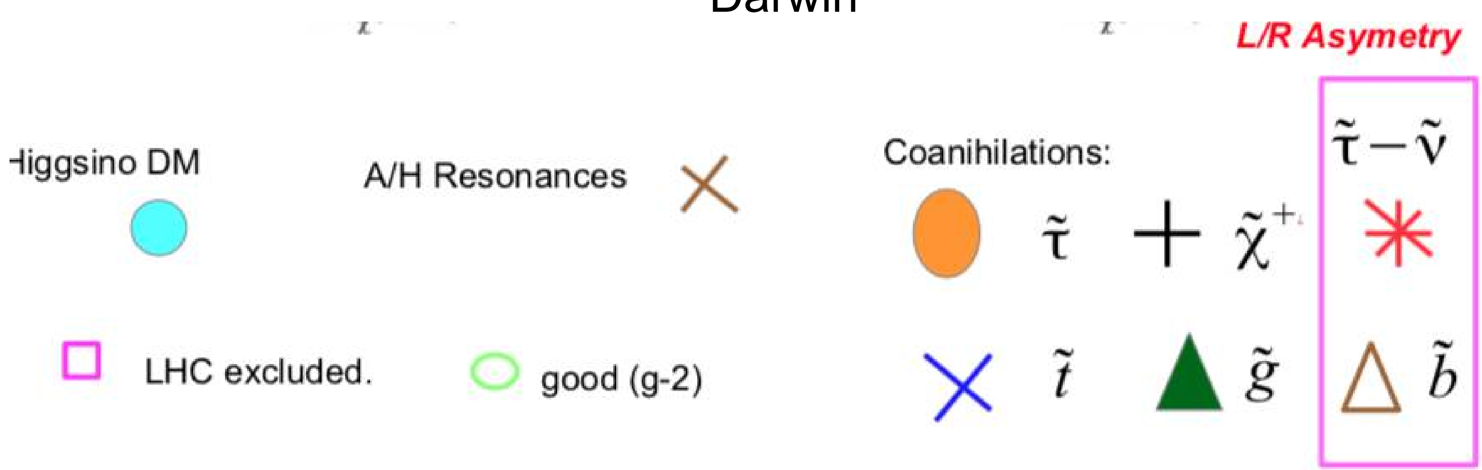
$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1\, m_\chi, \quad (m_{\tilde{\mu}_1} - m_\chi) \leq 0.1\, m_\chi .$$

$\tilde{t}_1$ coannihilations:

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



Flipped-SU(5)
PS(4-2-1)
σ^{SI} (pb)
m_χ (GeV)
Xenon 1T
LZ
Darwin



L/R Asymetry
Higgsino DM
A/H Resonances
Coanihilations:
$\tilde{\tau}$
$\tilde{\chi}^{+}$
$\tilde{\tau}-\tilde{\nu}$
LHC excluded.
good (g-2)
$\tilde{t}$
$\tilde{g}$
$\tilde{b}$

MSSM extended by seesaw mechanism

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

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

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

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

With $W_{\rm MSSM}$ and $\mathcal{L}_{\rm soft}$ given in Eq. 3 and 4 respectively.

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

"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 $(m_\nu^D)_{33} \approx (200\ \mathrm{GeV})$ $(\lambda_\nu \approx \lambda_t)$ and $M_{N_3} \approx O(10^{14}\ \mathrm{GeV})$, $m_{eff} \approx 0.05$ eV

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

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

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

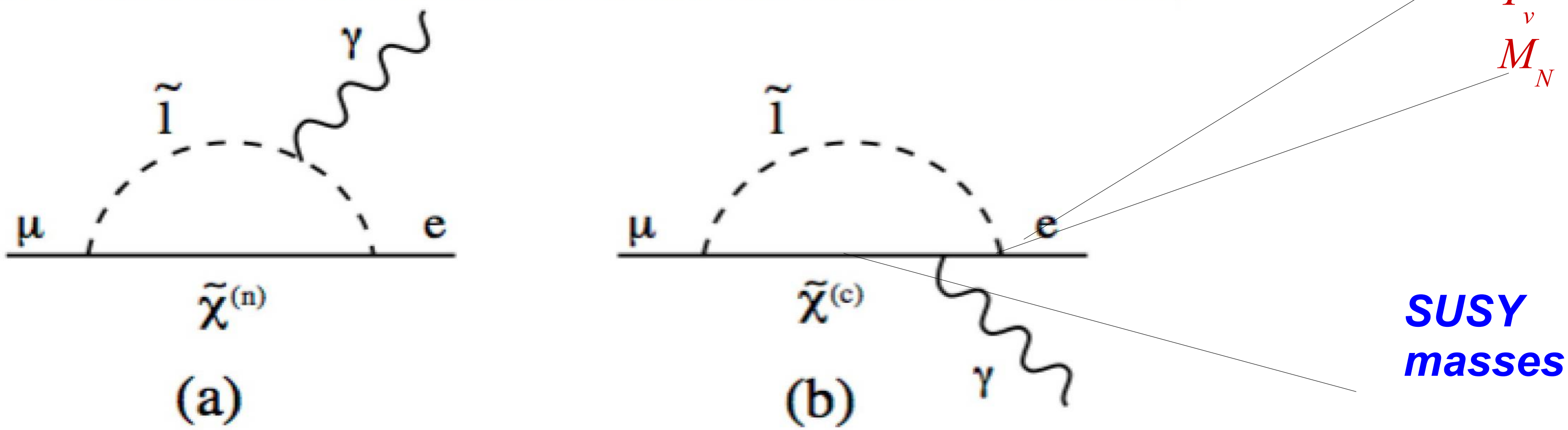
Diagonal Universal 1E14 GeV

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:

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

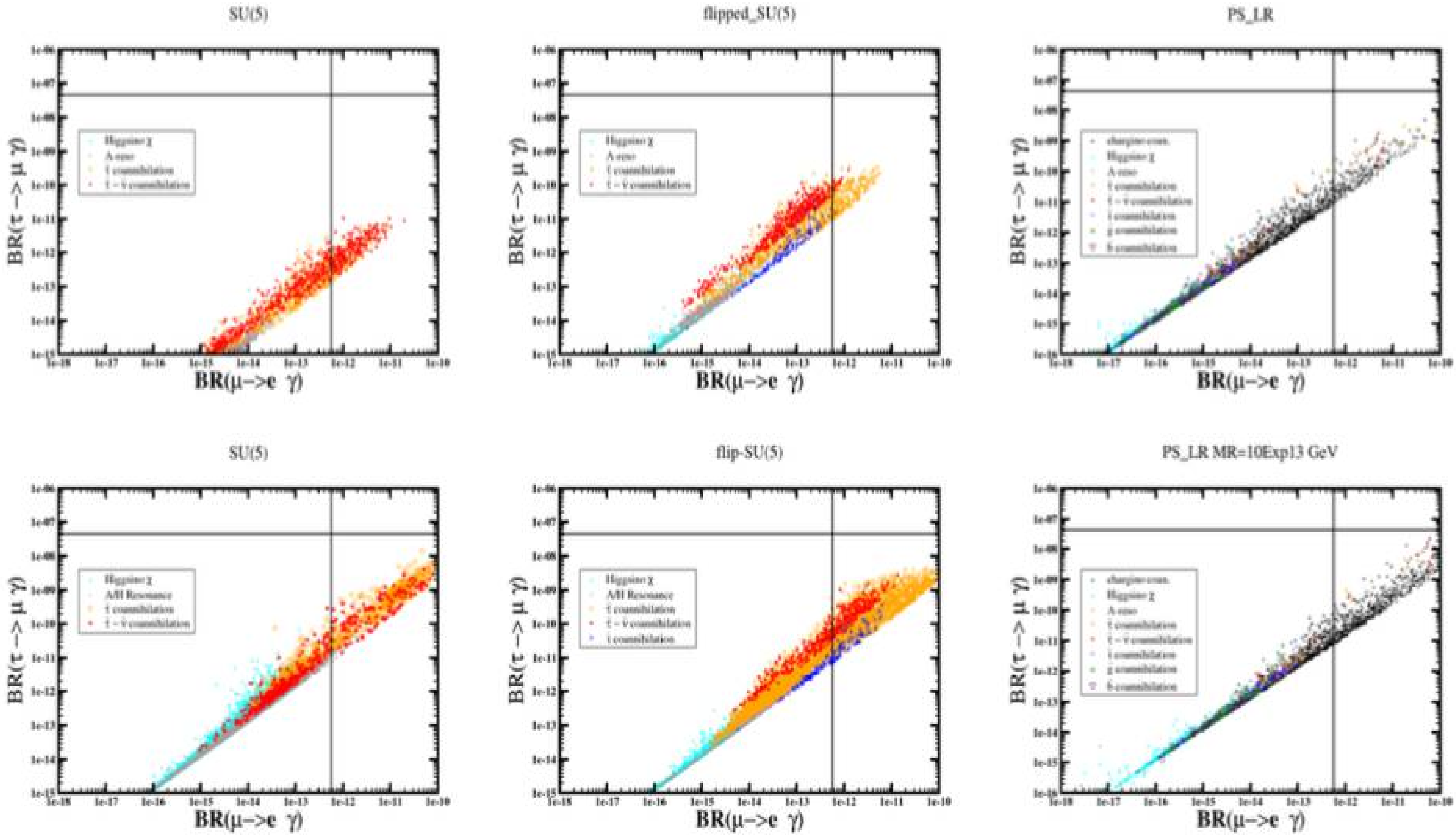
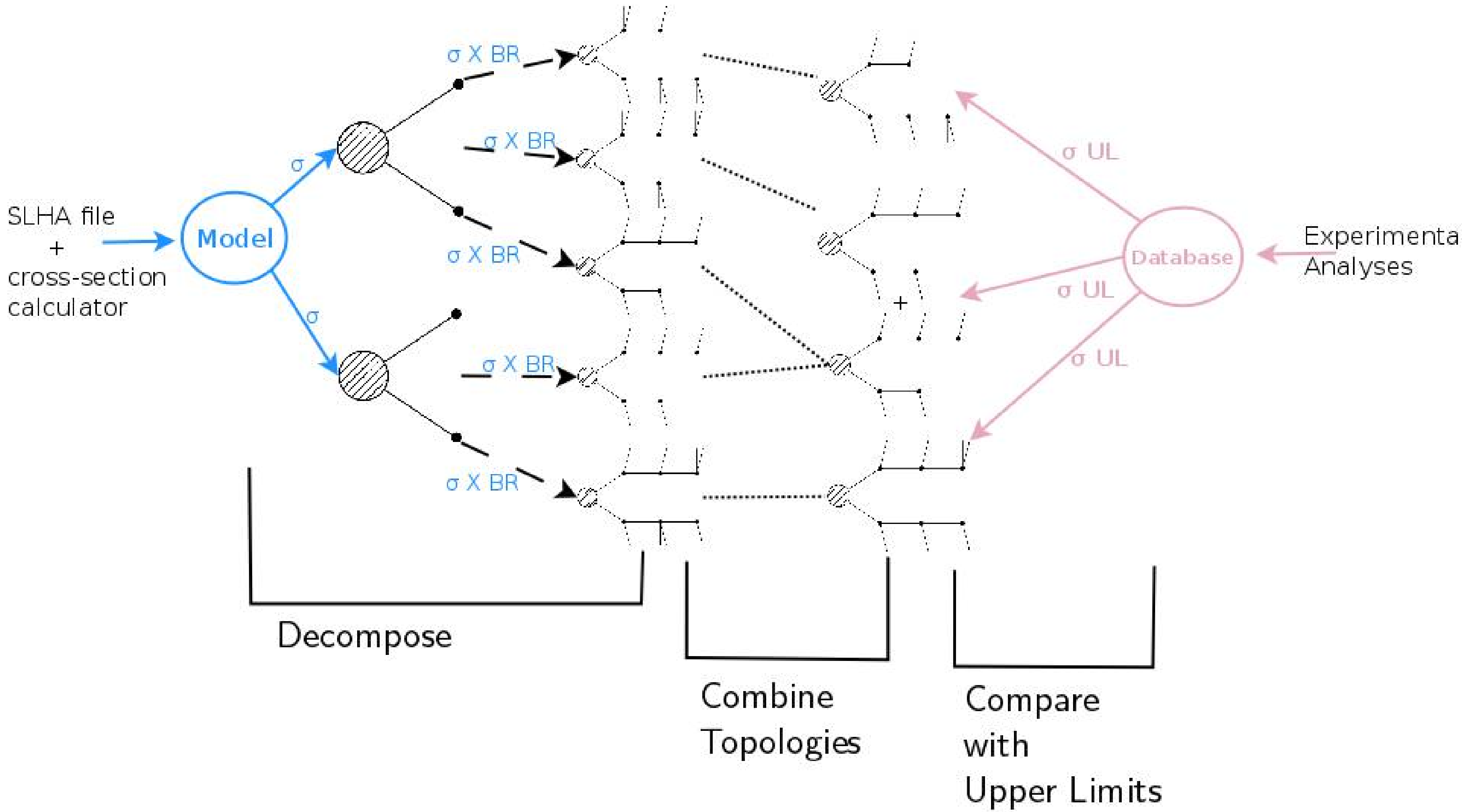


Figure 1: Prediction for $\mathrm{BR}(\tau \to \mu\gamma)$ vs $\mathrm{BR}(\mu \to e\gamma)$ for the SU(5), the f-SU(5) and the PS cases. The upper (lower) panels use $M_N = 2.5 \cdot 10^{12}$ ($M_N = 10^{13}$ GeV). The symbols correspond to the classes of models representing the DM scenarios descibed in the text: orange circles $\tilde{t} - \chi$ coannihilations ...

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

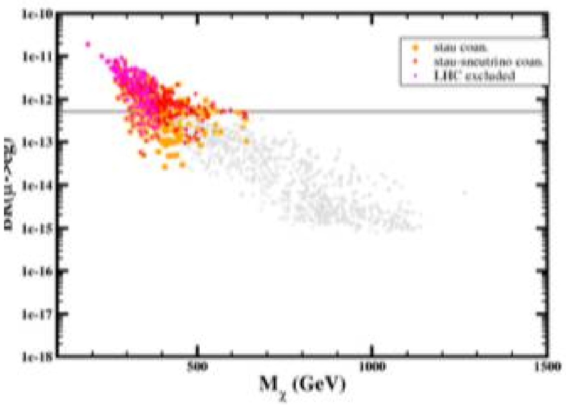


Analyzed points: Excluded

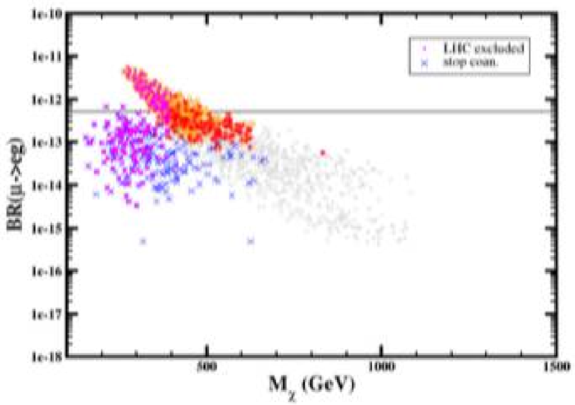
Allowed

Not analyzed.

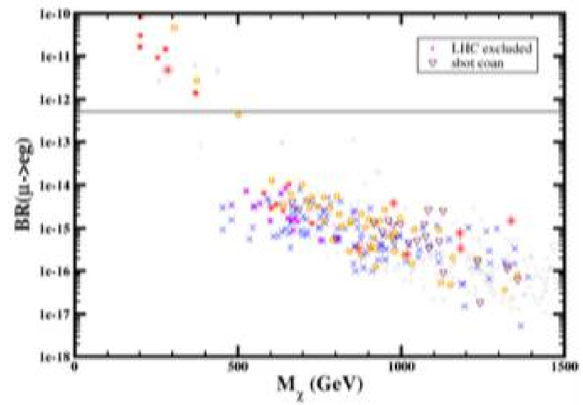
CRR MR 2.5 E12 SU5



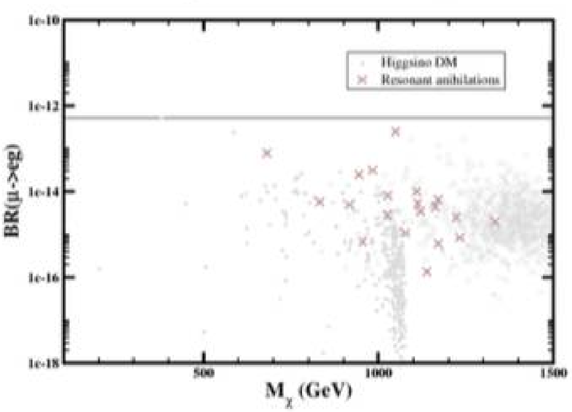
CRR MR 2.5 E12 FSU5



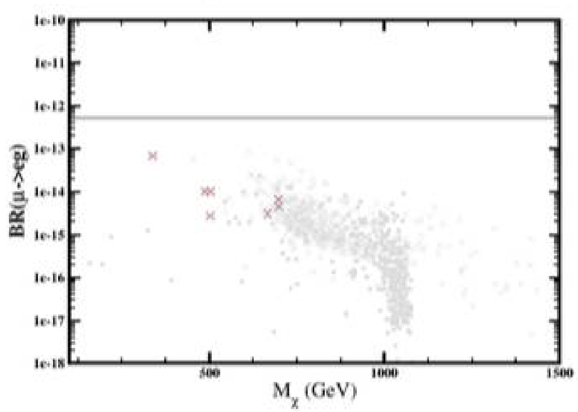
4-2-2 CSTOP MR 2.5 E12



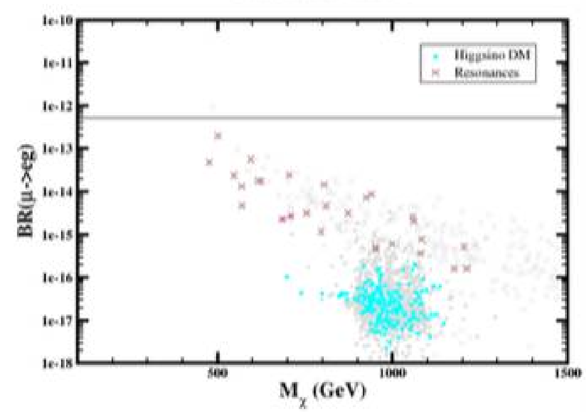
Higgsino-DM MR 2.5 E12 SU(5)

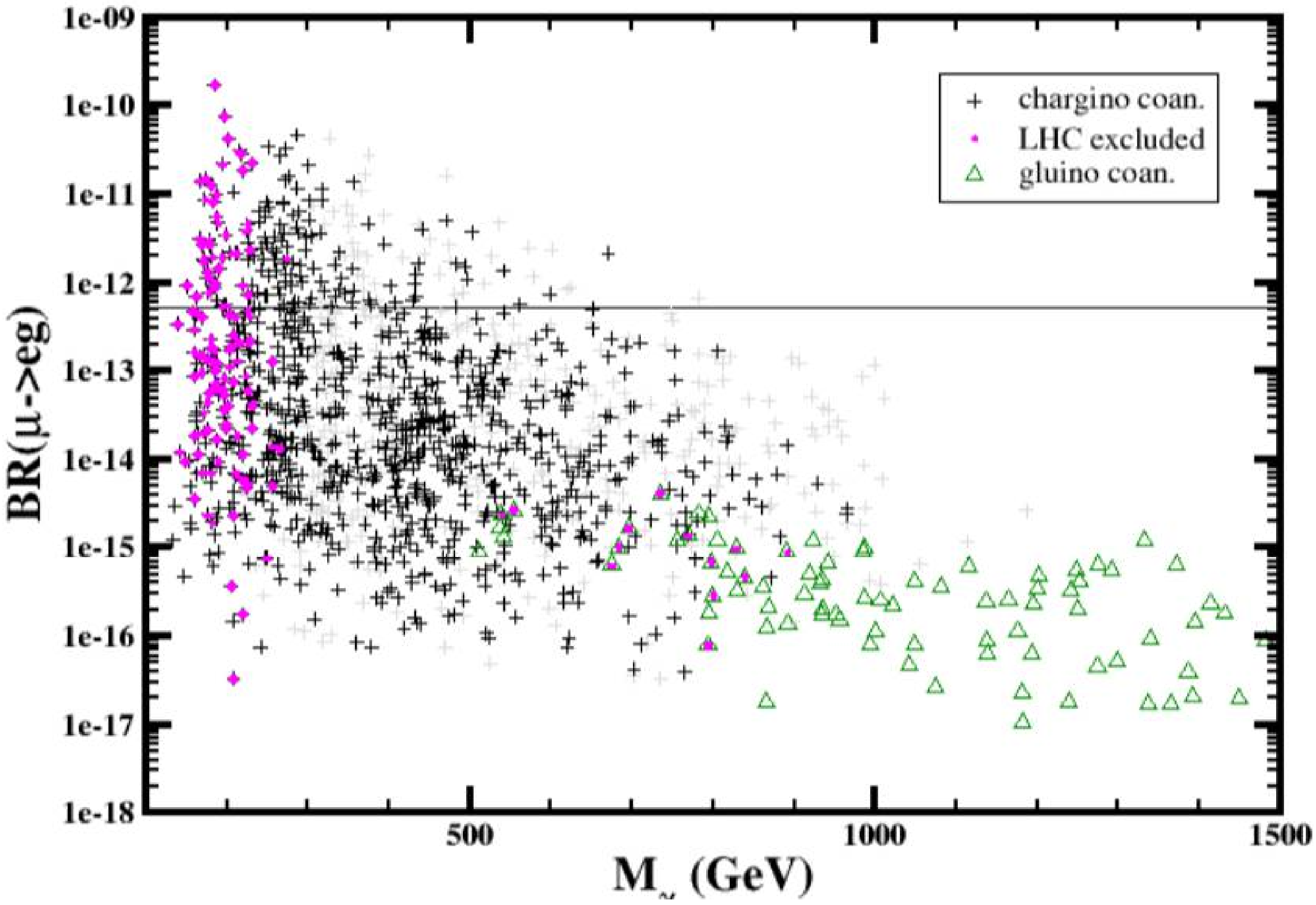


Higgsino DM MR=2.5 E12 FSU5



CRR MR 2.5 E12 PS



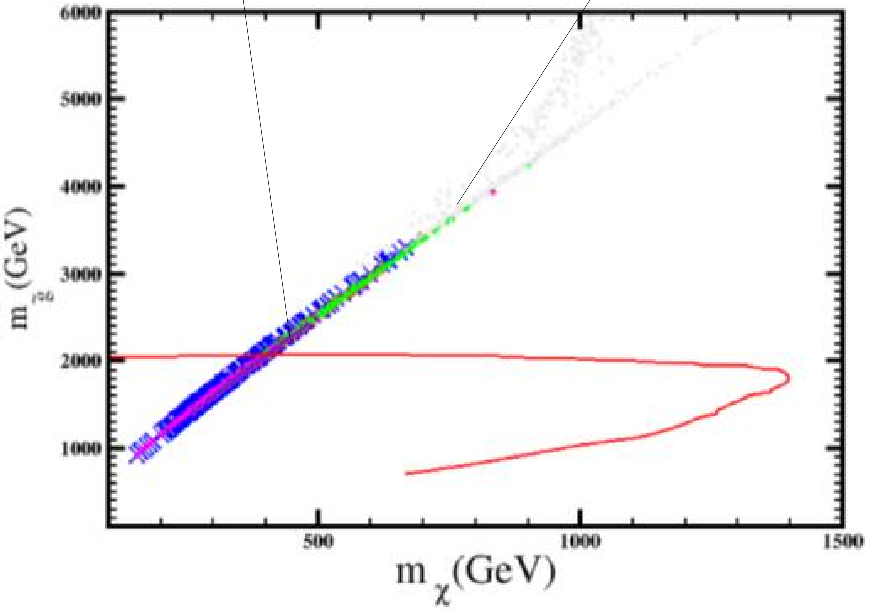


chargino coan.
LHC excluded
gluino coan.
BR(μ->eg)
1e-09
1e-10
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
500
1000
1500
M (GeV)

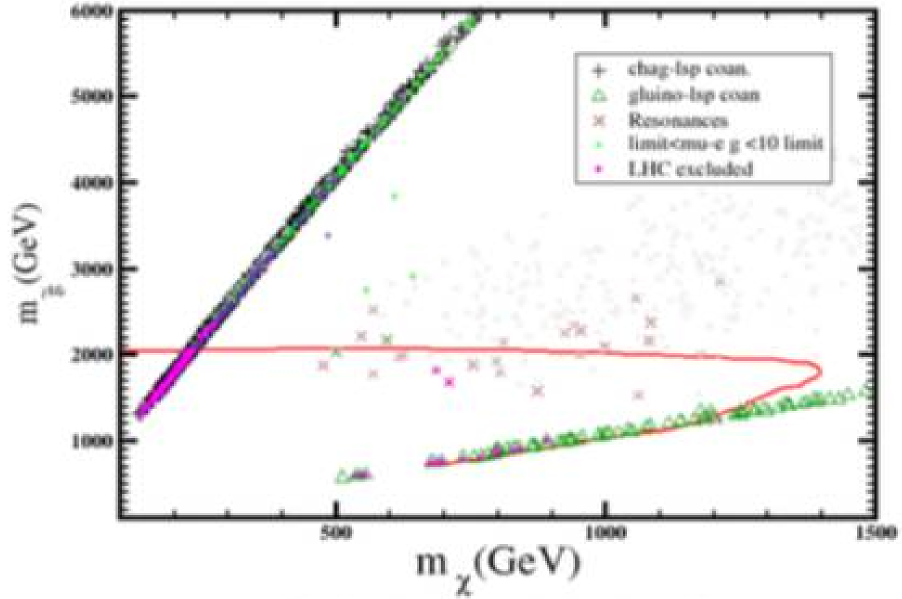
LFV excluded (indigo)

LFV prospect (green)

FSU5 all areas



PS Gauino and resonance areas



A/H Resonances

Higgsino DM

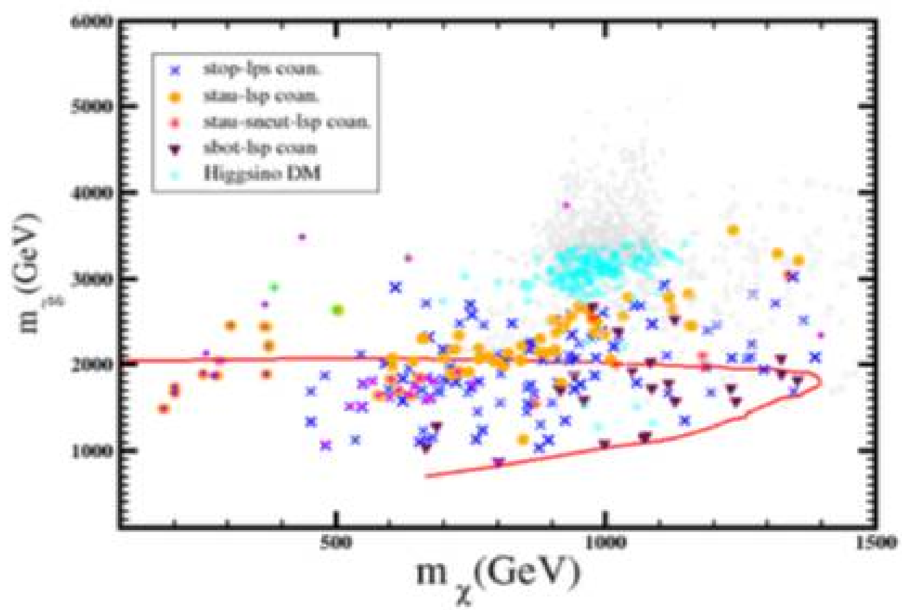
LHC excluded

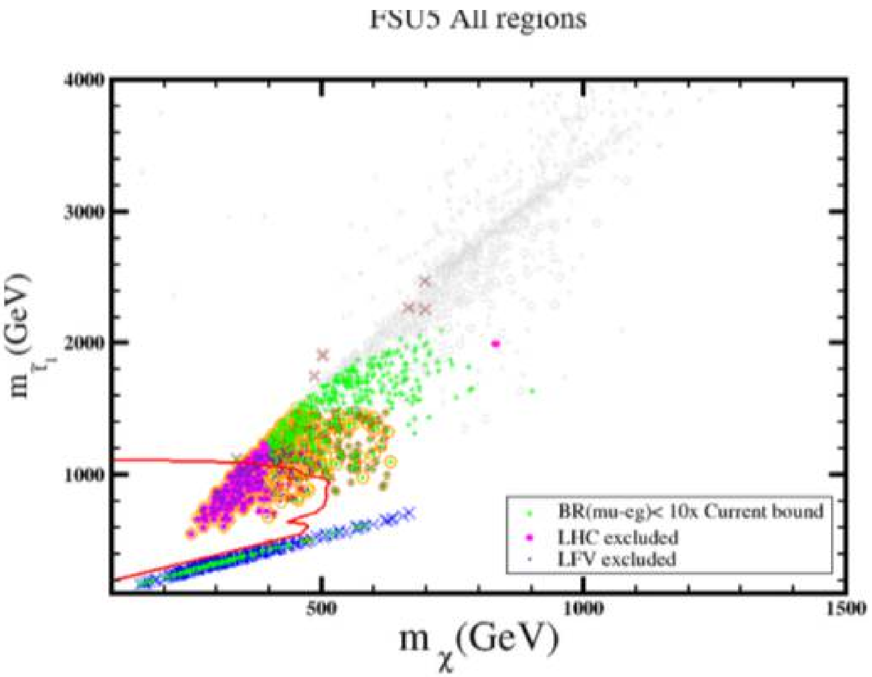
Coanihilations:

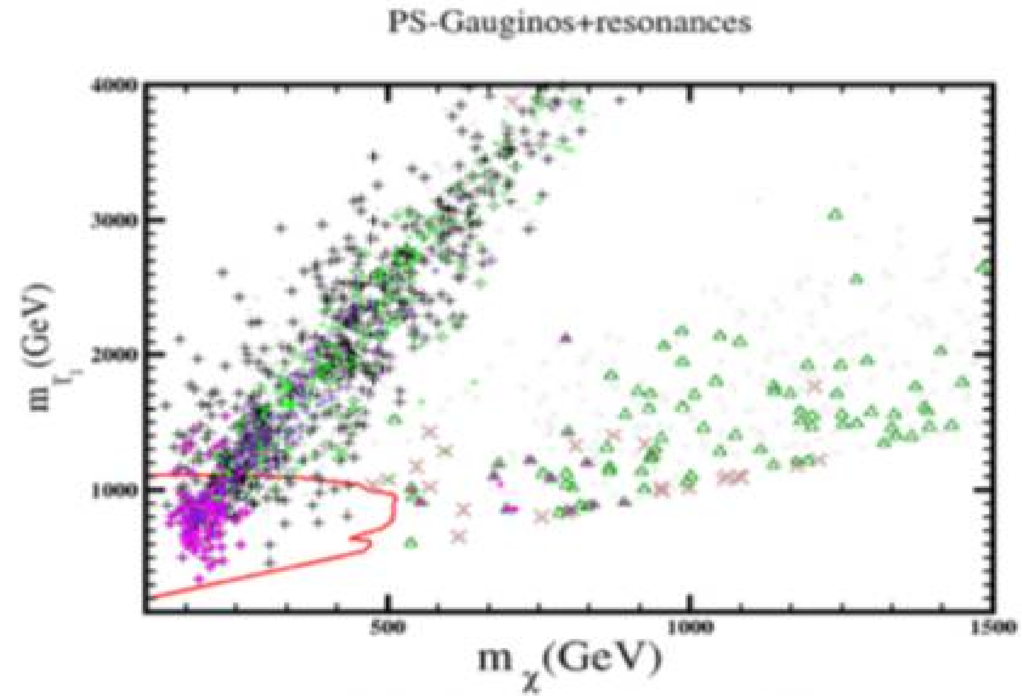
$\tilde{\tau}$ $\tilde{\tau}-\tilde{\nu}$ $\tilde{t}$

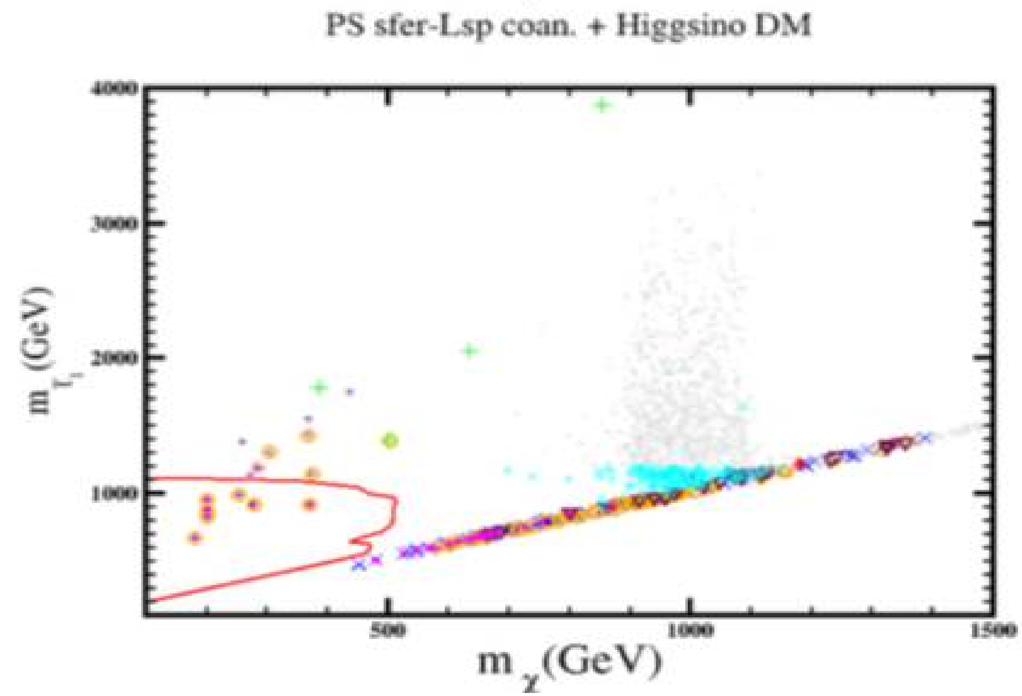
$\tilde{g}$ $\tilde{\chi}^{+¿}$ $\tilde{b}$

PS sfermions coan +Higgsino DM









A/H Resonances

Higgsino DM

LHC excluded

Coanihilations:

$\tilde{\tau}$ $\tilde{\tau}-\tilde{\nu}$ $\tilde{t}$

$\tilde{g}$ $\tilde{\chi}^{+}$¿ $\tilde{b}$

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.