Some aspects of SUSY

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Introduction

- Supersymmetry - one of the most attractive extensions of the SM

- Discovery of SUSY particles, their properties - among the main topics at the LHC

Supersymmetry

- What is supersymmetry ?

SUSY is a global symmetry that transforms fermions and bosons into each other by spin-1/2 carrying supercharges

- SUSY algebra — commutation and anticommutation

Particles (R-parity = +1)

Supermultiplets

Sparticles (R-parity = -1)

- Supersymmetry — a broken symmetry

$$M_{sparticles} - M_{particles} \sim M_s$$

MSSM

- What is MSSM ?

MSSM — a SUSY extension of the SM fields

(with two Higgs doublets)

+ a Higgs μ-term + SUSY breaking soft terms

+ R-parity conservation

$$\mathcal{L}_{\rm MSSM} = \mathcal{L}_{\rm SUPER-SM} + \mathcal{L}_{(\mu)} + \mathcal{L}_{\rm SOFT}$$

MSSM

- Why does one need SUSY and MSSM ?

Radiative corrections - Higgs mass and VEV run away to the next higher scale, $M_{\rm GUT}$

EW scale (M_W) - radiatively unstable

SUSY stabilises it - fermion boson cancellation

- MSSM - natural, radiatively stable theory ($M_s <$ a few TeV)

MSSM Superpotential

R-parity conserving

$$W = h_u Q U^c H_u + h_d Q D^c H_d + h_e L E^c H_d + \mu H_u H_d$$

R-parity violating

$$W = \lambda'' D^c U^c U^c + \lambda' Q D^c L + \lambda L L E^c + \mu_l H_u L$$

MSSM soft SUSY breaking terms

Scalar masses: $\tilde{m}^2 \tilde{q}^* \tilde{q}$

B-terms: $B_\mu H_u H_d$

Trilinear scalar couplings (A-terms): $A_{ij} H_{u/d} \tilde{q}^i_L \tilde{q}^j_R$

Majorana gaugino masses: $M_m \lambda\lambda$

SUSY breaking

- Why is the mechanism of SUSY breaking relevant to experiments ?
- Sparticle spectrum - nature of LSP
- No. of parameters can be reduced

SUSY breaking - theorists' approach

- explicitly add soft ~~SUSY~~ terms
- arbitrary, lacks any theoretical explanation

understand their origin in terms of some kind of spontaneous ~~SUSY~~

In terms of some high scale VEV $\sim \Lambda_{ss}$

$$M_s \sim \frac{\Lambda_{ss}^2}{M_{HS}}$$

Sum rule

- If spontaneous SUSY breaking arose from MSSM fields themselves-

- Dimopoulos-Georgi sum rule

$$\text{Str}\, M_u^2 + \text{Str}\, M_d^2 = 0$$

$$\text{Str}\, M_u^2 \rightarrow m_{\tilde{u}_1}^2 + m_{\tilde{u}_2}^2 - 2m_u^2 \qquad \text{Str}\, M_d^2 \rightarrow m_{\tilde{d}_1}^2 + m_{\tilde{d}_2}^2 - 2m_d^2$$

Disagrees with experiment!

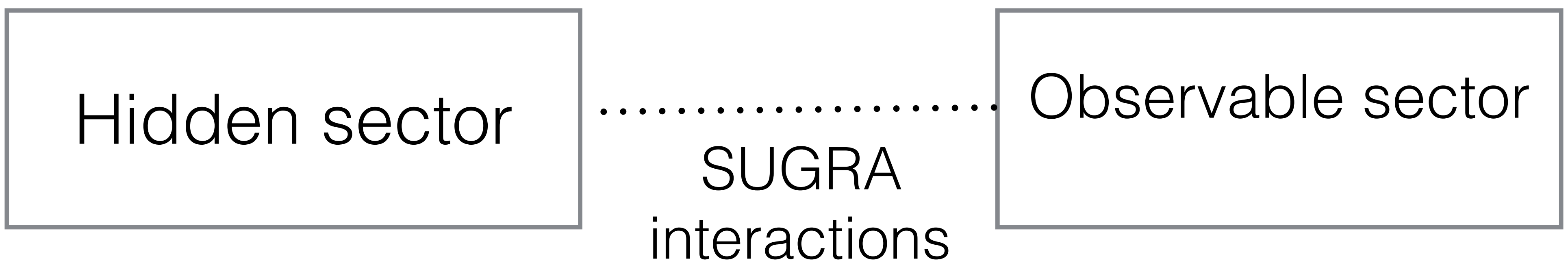
True for tree level renormalizable couplings

MSSM soft terms arise indirectly or radiatively

Need a hidden sector

SUSY breaking gets transmitted to the observable sector by some mediation mechanism (loops or non-renormalizable operators)

SUGRA



Consider SUGRA: $M_{HS} = M_{Pl}$

$$M_s \approx \Lambda_{ss}^2 M_{Pl}^{-1} \quad (< \text{a few TeV})$$

$\Lambda_{ss} \sim 10^{11}$ GeV does the job

mSUGRA

- Assume soft SUSY breaking universality

interpreted as the boundary condition on the running soft parameters at the scale M_{HS}

- RG-evolve down to EW scale

Entire MSSM spectrum - $m_{1/2}, m_0^2, A_0, sign(\mu), \tan\beta$

Minimal supergravity (mSUGRA)

Lightest neutralino $(\tilde{\chi}_1^0)$ is the LSP (dark matter)

Gravitino mass $m_{3/2} \sim \frac{\Lambda_{ss}^2}{M_{Pl}} \approx 100 \text{ GeV}$

mSUGRA is experimentally disfavoured due to the tension between the LHC lower bound on m_0 and the $(g-2)_\mu$ measurements

arXiv:1508.05951

Gauge mediated SUSY breaking

- Another possibility is that the mediating interactions for SUSY breaking are gauge interactions

- In GMSB scenario, the MSSM soft terms come from loop diagrams involving some messenger particles

- Messengers are chiral supermultiplets that couple to a SUSY breaking VEV (F) and have SM gauge interactions

MSSM soft masses $$M_s \sim \frac{\alpha_a}{4\pi} \frac{F}{M_{mess}}$$

If $M_{mess} \sim \sqrt{F},$ the scale of SUSY breaking

$(\sqrt{F}) \sim 10^5$ GeV for $M_S \sim$ a few TeV

GMSB Contd

Distinctive predictions: Gravitino is the LSP

$$m_{3/2} \sim 1 \text{ keV}$$

Important consequence for Cosmology

Talk by R. Rangarajan

and Collider Physics $\tilde{\chi}_1^0 \to \gamma \tilde{G}$

Other possibilities for mediating SUSY breaking

e.g. AMSB

Large gravitino mass (tens of TeV)

Neutrinos

- Experimental results on neutrino masses → non-zero neutrino masses and mixing angle

The data can be explained well with

$$6.80 \times 10^{-5}\mathrm{eV}^2 \leq \Delta m^2_{21} \leq 8.02 \times 10^{-5}\mathrm{eV}^2$$

$$2.399 \times 10^{-3}\mathrm{eV}^2 \leq \Delta m^2_{31} \leq 2.593 \times 10^{-3}\mathrm{eV}^2$$

$$0.27 \leq \sin^2\theta_{12} \leq 0.36,\ \ 0.39 \leq \sin^2\theta_{23} \leq 0.64,$$

$$0.01981 \leq \sin^2\theta_{13} \leq 0.02436 \qquad \Delta m^2_{ij} \equiv m^2_i - m^2_j$$

- One needs to go to a theory beyond the SM
- SUSY predicts new particles at the TeV scale
- Tempting to see whether TeV scale SUSY can explain the observed pattern of neutrino masses and mixing

SUSY and neutrinos

- Some of the ways in which SUSY can be of special significance to neutrino masses

- SUSY can provide new scales. Open up additional possibilities in the neutrino sector - helpful in explaining mass hierarchies

- Extended particle spectrum in SUSY can lead to mechanism for mass generation, e.g. through additional radiative effects

- Possibilities of low energy lepton number violation inbuilt in certain types of SUSY theories might lead to generation of Majorana masses

SUSY and neutrinos

- In the MSSM neutrinos are exactly massless
- Consider supersymmetric extension of an extended SM that contains Majorana neutrino masses
- In such models the lepton number violation can generate interesting phenomena in the sector of supersymmetric leptons
- The effect of $\Delta L = 2$ operators is to introduce a mass splitting and mixing into the sneutrino-antisneutrino system
- Or $\Delta L = 1$ operators (R-parity violating SUSY)
- LSP decays - interesting phenomenology at the LHC

$\Delta L = 2$ Majorana masses - seesaw mechanism

In the context of MSSM, supplement $\hat{\nu}_i$

(contained in $SU(2)_L$ doublet $\hat{L}_i$) with gauge singlet $\hat{\nu}_i^c$

$$\delta W = Y_\nu^{ij} \hat{H}_u \hat{L}_i \hat{\nu}_j^c + m_M^{ij} \hat{\nu}_i^c \hat{\nu}_j^c$$

Couplings Y_ν determine the Dirac masses for the neutrinos-

$m_D << m_M$ $\qquad (m_D \equiv Y_\nu v_u)$

m_M → Majorana masses

- light neutrino masses $\quad m_\nu \sim \dfrac{m_D^2}{m_M}$

$$Y_\nu \sim \mathcal{O}(1), m_M \sim 10^{15} \text{ GeV} \Longrightarrow m_\nu \sim 10^{-2} \text{ eV}$$

Sneutrino mixing phenomena

- The effect of $\Delta L = 2$ operators is to introduce a mass splitting and mixing into the sneutrino-antisneutrino system

- Neutrino mass and sneutrino mass splitting are related as a consequence of LNV interactions and SUSY breaking

Consider MSSM + one $\hat{\nu}^c$

$$\delta W = Y_\nu \hat{H}_u \hat{L} \hat{\nu}^c + \frac{1}{2} M \hat{\nu}^c \hat{\nu}^c - \mu \hat{H}_u \hat{H}_d$$

$$m_\nu \approx \frac{m_D^2}{M}$$

Grossman and Haber, PRL 79, 3438 (1997)
Davidson and King, PLB 445, (1998) 191

Sneutrino mixing phenomena

$$V_{soft} = m^2_{\tilde{L}}\tilde{\nu}^*\tilde{\nu} + m^2_{\tilde{\nu}^c}\tilde{\nu}^{c*}\tilde{\nu}^c + (Y_\nu A_\nu H_u^0\tilde{\nu}\tilde{\nu}^c + MB_N\tilde{\nu}^c\tilde{\nu}^c + H.c.)$$

Define $\tilde{\nu} = (\tilde{\nu}_1 + i\tilde{\nu}_2)/\sqrt{2}$ and $\tilde{\nu}^c = (\tilde{\nu}_1^c + i\tilde{\nu}_2^c)/\sqrt{2}$

- Two light neutrino mass eigenstates $\tilde{\nu}_1$ and $\tilde{\nu}_2$ are split

$$\frac{\Delta m_{\tilde{\nu}}}{m_\nu} \approx \frac{2(A_\nu - \mu\cot\beta - B_N)}{m_{\tilde{\nu}}} \qquad [m_{\tilde{\nu}} \equiv \frac{1}{2}(m_{\tilde{\nu}_1} + m_{\tilde{\nu}_2})]$$

Assume μ, A_ν and $m_{\tilde{\nu}}$ are all $\sim$ 100 GeV

If $B_N \sim \mathcal{O}(m_Z)$, then $\dfrac{\Delta m_{\tilde{\nu}}}{m_\nu} \sim \mathcal{O}(1)$

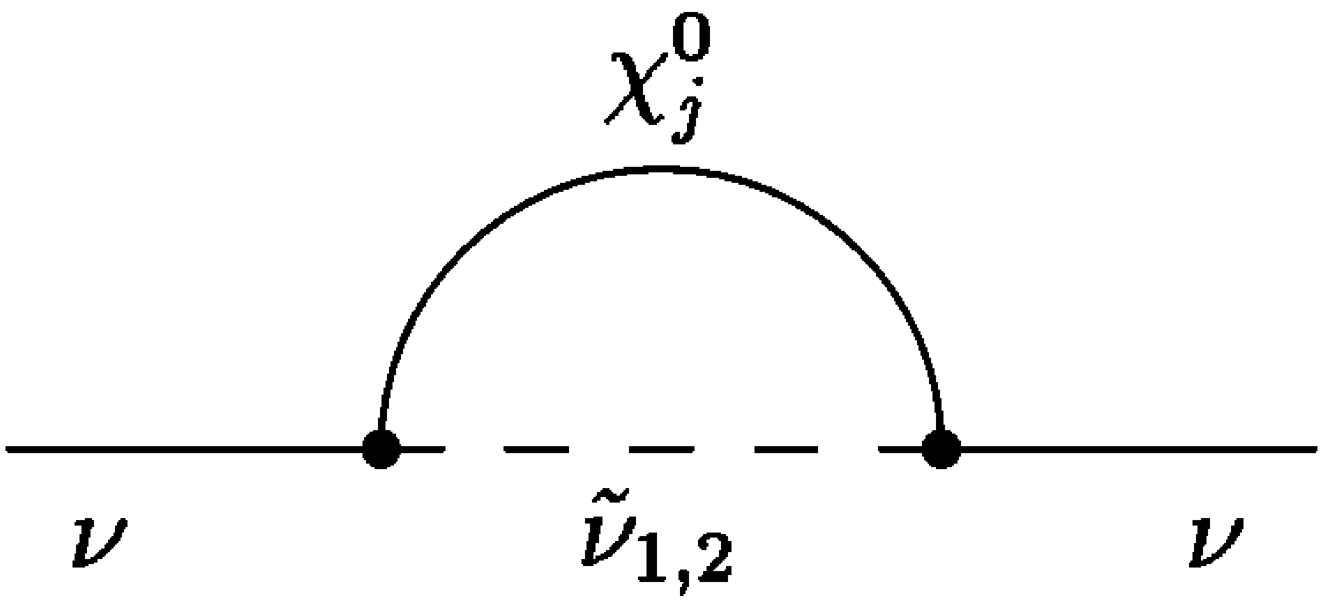
If $B_N \gg m_Z$, sneutrino mass splitting is significantly enhanced

Grossman and Haber, PRL 79, 3438 (1997)
Davidson and King, PLB 445 (1998)191

Loop effects

One loop contribution to the neutrino mass due to sneutrino mass splitting

Grossman, Haber (1997), Hirsch et al (1997)



Loop contribution $m_\nu^{(1)} \approx 10^{-3} \Delta m_{\tilde{\nu}}$

If $\Delta m_{\tilde{\nu}} / (m_\nu)^0 \gtrsim 10^3$,

one-loop correction to the neutrino mass cannot be neglected

Loop effects

Assuming no unnatural cancellation

$$m_\nu = (m_\nu)^0 + (m_\nu)^1$$

Radiative corrections to $m_\nu \Longrightarrow \Delta m_{\tilde{\nu}} / m_\nu \lesssim \mathcal{O}(10^3)$

$$m_\nu \sim 0.1 \text{ eV} \Longrightarrow \Delta m_{\tilde{\nu}} \lesssim 0.1 \text{ keV}$$

Sneutrino-antisneutrino oscillation

- $\Delta m_{\tilde{\nu}}$ induces sneutrino-antisneutrino oscillation
- lepton number can be tagged by the charge of the final state lepton

Similar behaviour in the flavour oscillation of B^0–$\bar{B}^0$ system

At t = 0

$$|\tilde{\nu}\rangle = \frac{1}{\sqrt{2}}[|\tilde{\nu}_1\rangle + i|\tilde{\nu}_2\rangle]$$

The state at time t is

$$|\tilde{\nu}(t)\rangle = \frac{1}{\sqrt{2}}[e^{-i(m_1 - i\Gamma_{\tilde{\nu}}/2)t}|\tilde{\nu}_1\rangle + ie^{-i(m_2 - i\Gamma_{\tilde{\nu}}/2)t}|\tilde{\nu}_2\rangle]$$

Oscillation probability contd

Probability of finding a ``wrong sign charged lepton"

$$P(\tilde{\nu} \to \ell^+) = \frac{x_{\tilde{\nu}}^2}{2(1+x_{\tilde{\nu}}^2)} \times B(\tilde{\nu}^* \to \ell^+)$$

$$P_{\tilde{\nu} \to \tilde{\nu}^*} = \frac{x_{\tilde{\nu}}^2}{2(1+x_{\tilde{\nu}}^2)}$$

$$x_{\tilde{\nu}} \equiv \frac{\Delta m_{\tilde{\nu}}}{\Gamma_{\tilde{\nu}}}$$

$$x_{\tilde{\nu}} \sim 1 \Longrightarrow \Gamma_{\tilde{\nu}} \sim 0.1 \text{ keV}$$

Two body decays- $\tilde{\nu} \to \nu \tilde{\chi}^0$ and/or $\tilde{\nu} \to \ell^- \tilde{\chi}^+$

Three body decays- $\tilde{\nu} \to \ell^- \tilde{\tau}_1^+ \nu_\tau$ and $\tilde{\nu} \to \nu \tilde{\tau}_1^\pm \tau^\mp$

$$m_{\tilde{\tau}_1} < m_{\tilde{\nu}} < m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}$$

Lepton charge asymmetry

- Number of negatively charged leptons (N_{l^-}) is proportional to $P(\tilde{\nu} \to \tilde{\nu})$
- Number of positively charged leptons (N_{l^+}) is proportional to $P(\tilde{\nu} \to \tilde{\nu}^*)$

$$A_{asym} \equiv \frac{N_{l^-} - N_{l^+}}{N_{l^-} + N_{l^+}}$$

- At the LHC one can study this asymmetry through

$$pp \longrightarrow \tilde{\nu}_\tau \tilde{\tau}_1^+$$

$$A_{asym} = P_{\tilde{\nu}_\tau \to \tilde{\nu}_\tau^*} - P_{\tilde{\nu}_\tau \to \tilde{\nu}_\tau}$$

Elsayed et al (2013)
Dedes, Haber, Rosiek (2008)
Ghosh, Honkavaara, Huitu, Roy (2008), (2010)

MSSM with R-parity violation

Neutrino masses in MSSM with RPV have been widely studied

$$R = (-1)^{3B+L+2s}$$

$$W = \epsilon_{ij}[-\mu_\alpha \hat{L}^i_\alpha \hat{H}^j_U + \frac{1}{2}\lambda_{\alpha\beta m}\hat{L}^i_\alpha \hat{L}^j_\beta \hat{E}_m + \lambda'_{\alpha nm}\hat{L}^i_\alpha \hat{Q}^j_n \hat{D}_m - h_{nm}\hat{H}^i_U \hat{Q}^j_n \hat{U}_m]$$

Four supermultiplets by one symbol $\hat{L}_\alpha (\alpha = 0, 1, 2, 3)$,
with $\hat{L}_0 \equiv \hat{H}_D$

It is not possible to distinguish between $\hat{H}_D$ and $\hat{L}_m$ $(m = 1, 2, 3)$

$$V_{\rm soft} = (M^2_{\widetilde{L}})_{\alpha\beta}\widetilde{L}^{i*}_\alpha \widetilde{L}^i_\beta - (\epsilon_{ij} B_\alpha \widetilde{L}^i_\alpha H^j_U + {\rm h.c.}) + \epsilon_{ij}[\frac{1}{2}A_{\alpha\beta m}\widetilde{L}^i_\alpha \widetilde{L}^j_\beta \widetilde{E}_m + A'_{\alpha nm}\widetilde{L}^i_\alpha \widetilde{Q}^j_n \widetilde{D}_m + {\rm h.c.}]$$

Hall, Suzuki (1984)

I.H. Lee (1984)

Decays of the LSP

- LSP decays because of the RPV

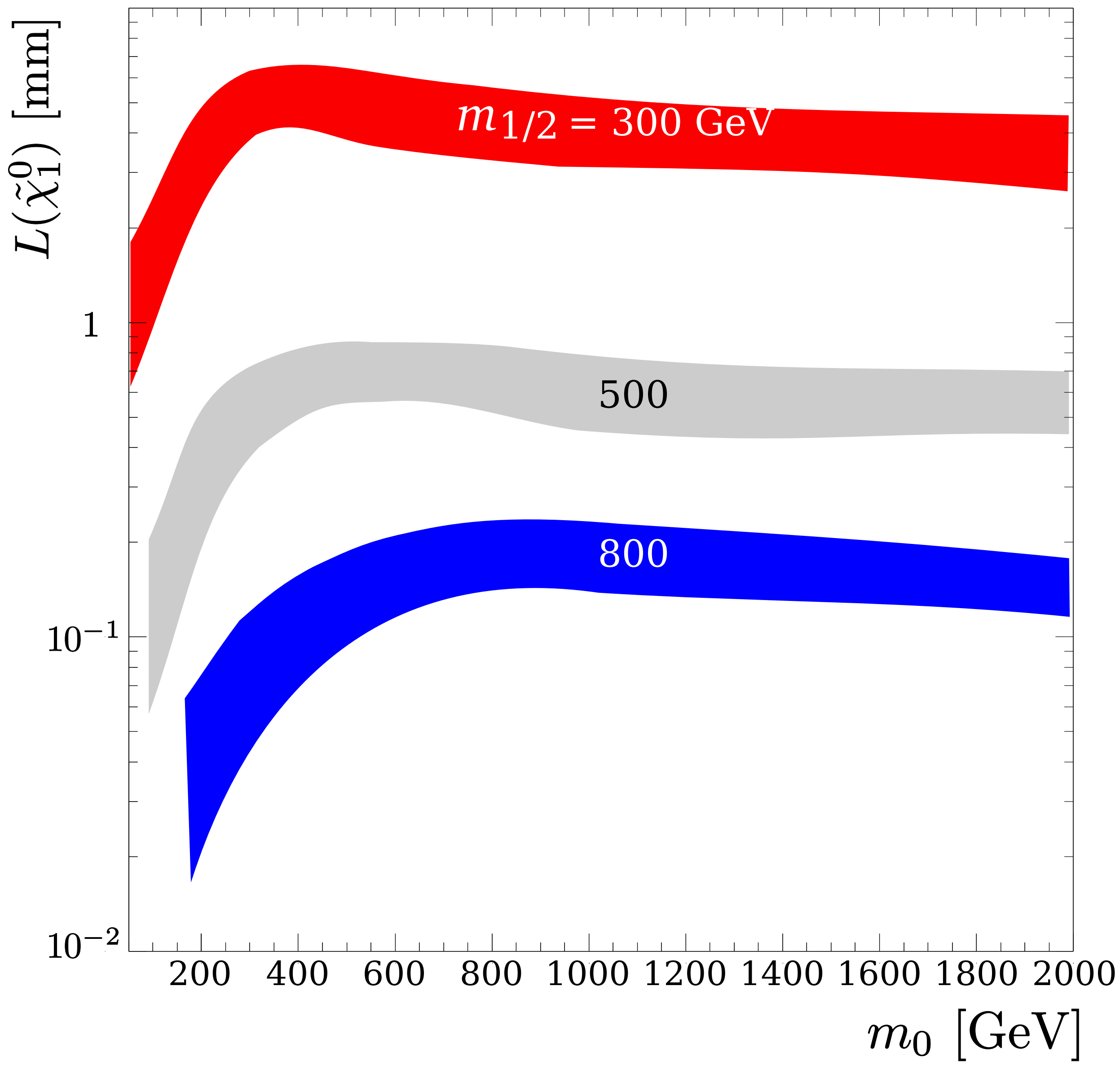
$\tilde{\chi}_1^0 - W^{\pm} - l_i^{\mp}$ and $\tilde{\chi}_1^0 - \nu_i - Z$ possible

- Possible decay modes are $\tilde{\chi}_1^0 \to W^{\pm} + l^{\mp}$ and $\tilde{\chi}_1^0 \to Z + \nu_i$

- One can find various correlations of these decay branching ratios with the neutrino data
- Measurable decay length of the LSP is another important consequence

Mukhopadhyaya, Roy, Vissani (1998)
Choi, Chun, Kang, Lee (1999)
Romao, Diaz, Hirsch, Porod, Valle (2000)
Porod, Hirsch, Romao, Valle (2001)

Decays of the LSP



F. de Campos et al (2008)

Decays of the LSP

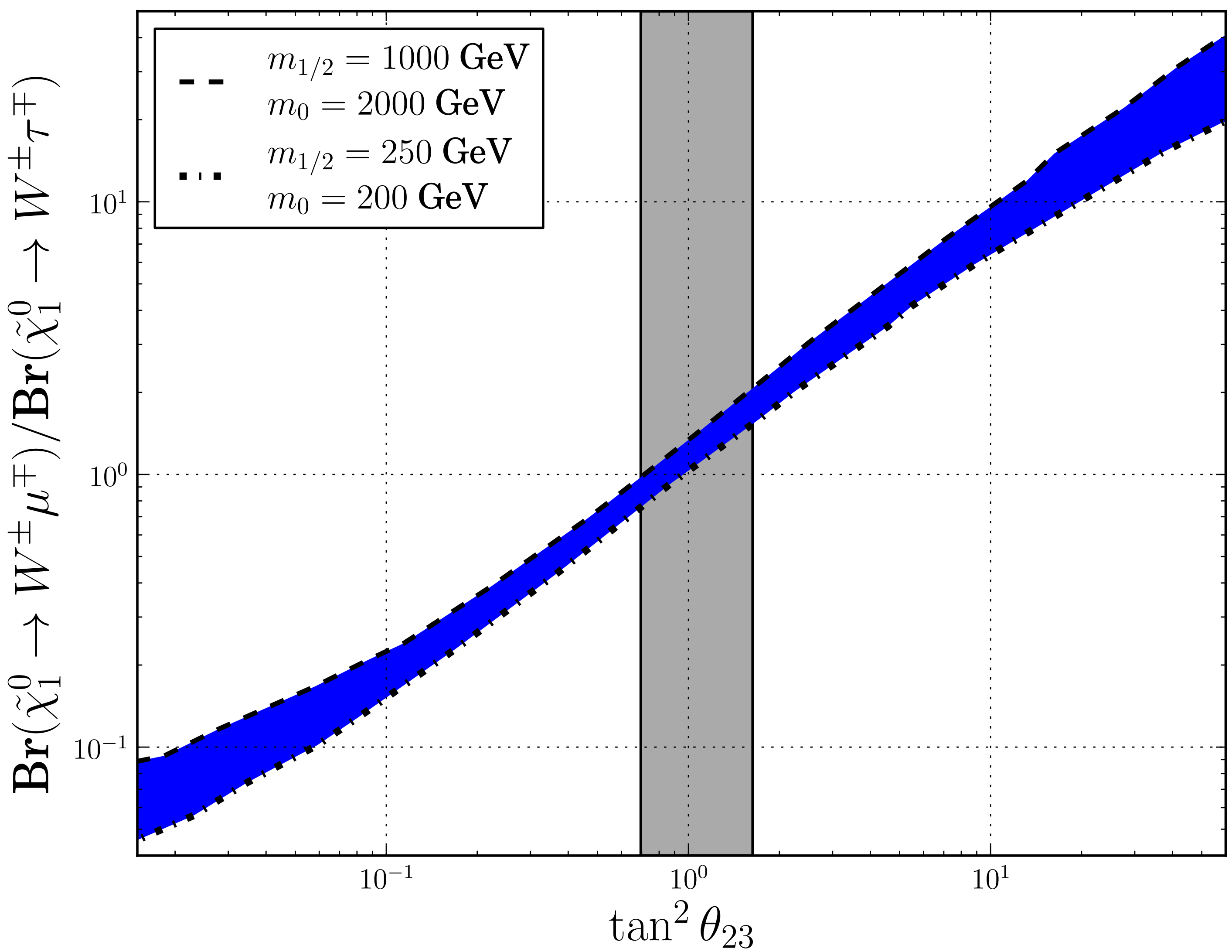
- Neutrino masses and mixing as well as the LSP decay properties are determined by the same interactions
- Connection between the high energy LSP physics at the LHC and the neutrino oscillation physics
- For instance, the ratio between the charged current decays

$$\frac{\mathrm{Br}(\tilde{\chi}_1^0 \to W^\pm \mu^\mp)}{\mathrm{Br}(\tilde{\chi}_1^0 \to W^\pm \tau^\mp)} \sim \tan^2\theta_{23}$$

Various collider studies (Multileptons, OSD, SSD)

Datta, Mukhopadhyaya, Vissani (2000)
F. de Campos et al (2008)
F. de Campos et al, 1206.3605

LSP decays and the atmospheric angle



F. de Campos et al, arXiv:1206.3605

Neutrino masses

We shall work in a basis spanned by $\hat{L}_\alpha$ such that

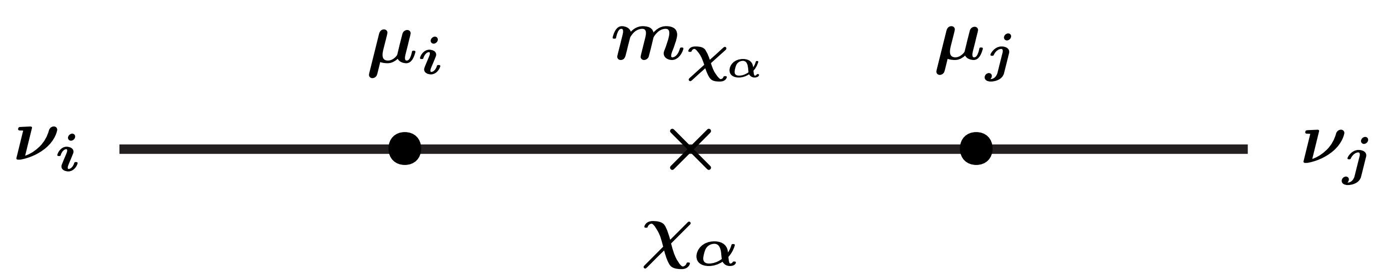
$$v_m = 0 \text{ and } v_0 = v_d$$

Neutralino neutrino mixing

In the basis $\{\widetilde{B}, \widetilde{W}^3, \widetilde{H}_U, \nu_\beta\}$

$$\begin{pmatrix}
M_1 & 0 & m_Z s_W v_u/v & -m_Z s_W v_d/v & 0 & 0 & 0 \\
0 & M_2 & -m_Z c_W v_u/v & m_Z c_W v_d/v & 0 & 0 & 0 \\
m_Z s_W v_u/v & -m_Z c_W v_u/v & 0 & \mu & \mu_1 & \mu_2 & \mu_3 \\
-m_Z s_W v_d/v & m_Z c_W v_d/v & \mu & 0 & 0 & 0 & 0 \\
0 & 0 & \mu_1 & 0 & 0 & 0 & 0 \\
0 & 0 & \mu_2 & 0 & 0 & 0 & 0 \\
0 & 0 & \mu_3 & 0 & 0 & 0 & 0
\end{pmatrix}$$

Tree level $(\mu\mu)$ masses



$$[m_\nu]_{ij}^{(\mu\mu)} = X_T \mu_i \mu_j \,,$$

$$X_T = \frac{m_Z^2 m_{\tilde{\gamma}} \cos^2\beta}{\mu(m_Z^2 m_{\tilde{\gamma}} \sin 2\beta - M_1 M_2 \mu)} \sim \frac{\cos^2\beta}{\tilde{m}}$$

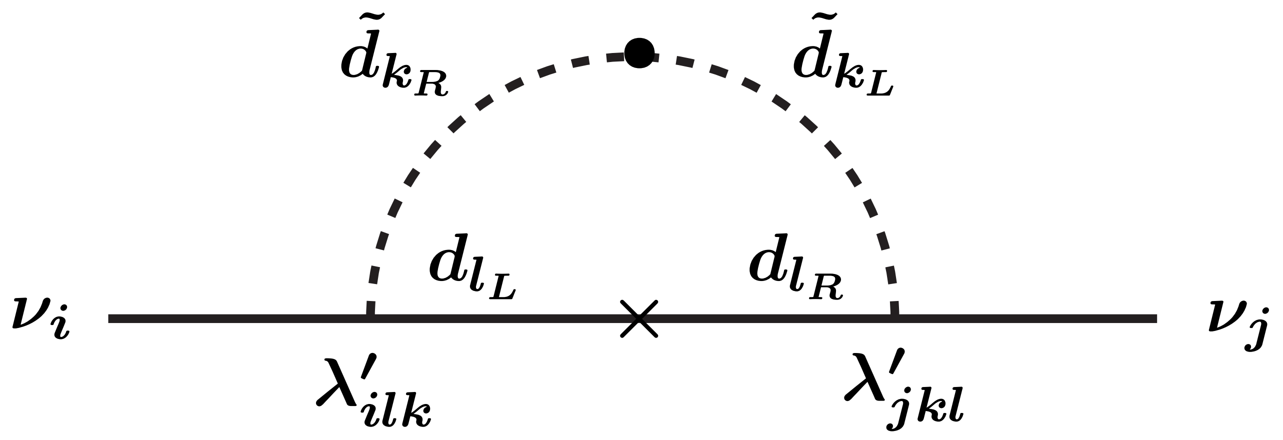
Tree level neutrino masses are eigenvalues of $[m_\nu]_{ij}^{(\mu\mu)}$

$$m_3^{(T)} = X_T(\mu_1^2 + \mu_2^2 + \mu_3^2)\,, \qquad m_1^{(T)} = m_2^{(T)} = 0$$

at the tree level only one neutrino is massive. Its mass is proportional to RPV parameter $\sum \mu_i^2$ and $\cos^2\beta$

Grossman, Rakshit (2004)
Valle et al (1997)
Mukhopadhyaya, Roy(1997)

Trilinear $(\lambda'\lambda' \text{ and } \lambda\lambda)$ loops

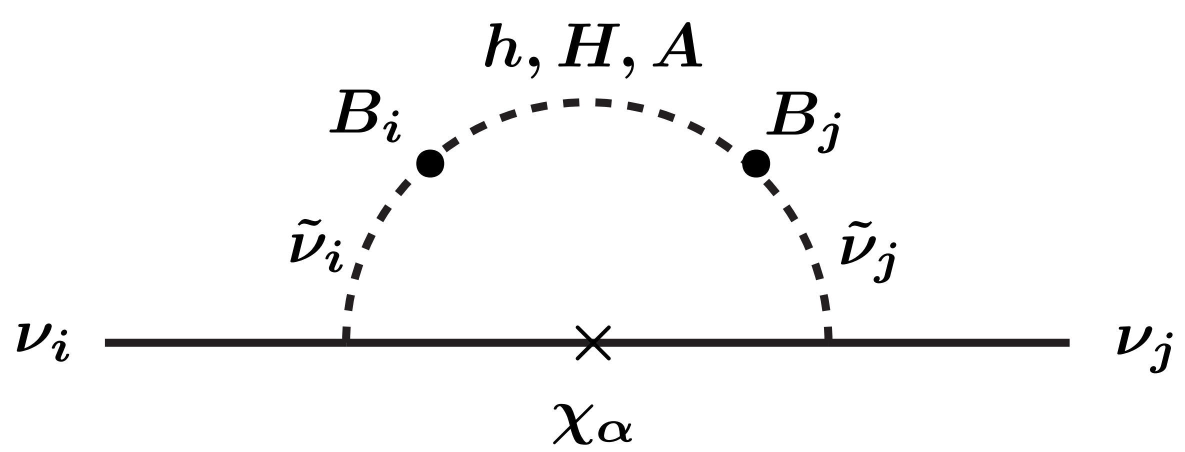


$$[m_\nu]_{ij}^{(\lambda'\lambda')} \approx \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{ilk}\, \lambda'_{jkl}\, \frac{m_{d_l}\, \Delta m^2_{\tilde{d}_k}}{m^2_{\tilde{d}_k}}$$

$$\sim \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{ilk} \lambda'_{jkl} \frac{m_{d_l} m_{d_k}}{\tilde{m}}$$

- Trilinear loop generated masses are suppressed by the RPV couplings $\lambda'^2[\lambda^2]$
- By a loop factor
- By two down type quark (charged lepton) masses

Bilinear (BB) loop induced masses



- Two insertions of RPV B_i parameters
- sneutrino splitting induced masses

Assuming that all masses are of the order weak scale

$$[m_\nu]_{ij}^{(BB)} \sim \frac{g^2}{64\pi^2 \cos^2\beta} \frac{B_i B_j}{\tilde{m}^3}$$

In general B_α is not proportional to μ_α

- In general one neutrino mass eigenstate acquires mass at tree level and the other from bilinear loops

Conclusions

- SUSY is still perhaps the most popular extension for physics beyond the SM
- A very interesting question is to understand ``How does the SM find about about SUSY breaking”.
- Sparticle spectrum, nature of LSP, phenomenology depend on this.
- Massive neutrinos suggests physics beyond the SM
- Various options - SUSY seesaw, MSSM with RPV
- Decays of LSP can show some correlations with neutrino data
- Signals of sneutrino oscillation.
- LHC data will restrict large portion of the parameter space