Working group report:

Neutrino Masses and Lepton Flavor Violation @ LHC

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Overview

- Workshop at DESY 4-6 May 2011
  (combined with LHC-D SUSY/BSM working group)
- topics in the last year
  - (Flavour-) Symmetries (Bonn, Dortmund)
  - R-parity violation (Bonn, Dortmund, Würzburg)
  - Seesaw models and SUSY (Würzburg), see also talk by M. Krauss
  - Models with extended gauge sector (Bonn, Würzburg), see also talks by F. Staub and A. Vicente
  - searches by ATLAS and CMS in the leptonic sector (Aachen, Bonn, Dortmund, Hamburg, Würzburg)
- Future directions

Flavour symmetries I

- general R-parity violation: e.g. allow only for L-violating couplings and reduce their number
- S_3 model for flavour symmetries $\rightarrow$ interesting Higgs phenomenology

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An exemplary S_3 model

Chen, Frigerio, Ma, *Phys. Rev.* **D70**, 073008 (2004)

Lepton doublets

RH singlets

$$(L_1, L_2) \propto \mathbf{2} \qquad L_3, \ell^c_3, \ell^c_1 \propto \mathbf{1} \qquad \ell^c_2 \propto \mathbf{1'}$$

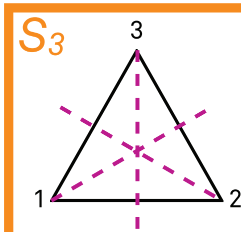
$$(Q_1, Q_2) \propto \mathbf{2} \qquad Q_3, u^c_3, u^c_1, d^c_3, d^c_1 \propto \mathbf{1} \qquad u^c_2, d^c_2 \propto \mathbf{1'}$$

$$(\phi_1, \phi_2) \propto \mathbf{2} \qquad \phi_3 \propto \mathbf{1}$$

Quark doublets

- Two generations $\rightarrow$ S_3 doublet; the other $\rightarrow$ S_3 singlet

S_3



6 elements
irreps: **1**,**1′**,**2**

Philipp Leser | DESY, 2011-05-05 6

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h_a is special, again

- The 3rd scalar ha **only couples off-diagonally,** always with 3rd generation:
  - $h_a \to e\tau(db, ut)$ $h_a \to \mu\tau(sb, ct)$
- FCNC couplings are numerically small and fixed by fermion masses

$$Y_{h_a} = \begin{pmatrix} 0 & 0 & Y^a_{e_L\tau_R} \\ 0 & 0 & Y^a_{\mu_L\tau_R} \\ Y^a_{\tau_L e_R} & Y^a_{\tau_L\mu_R} & 0 \end{pmatrix}, \quad Y_{h_b} = \begin{pmatrix} Y^b_{e_L e_R} & Y^b_{e_L\mu_R} & 0 \\ Y^b_{\mu_L e_R} & Y^b_{\mu_L\mu_R} & 0 \\ 0 & 0 & Y^b_{\tau_L\tau_R} \end{pmatrix}, \quad Y_{h_c} = \begin{pmatrix} Y^c_{e_L e_R} & Y^c_{e_L\mu_R} & 0 \\ Y^c_{\mu_L e_R} & Y^c_{\mu_L\mu_R} & 0 \\ 0 & 0 & Y^c_{\tau_L\tau_R} \end{pmatrix}$$

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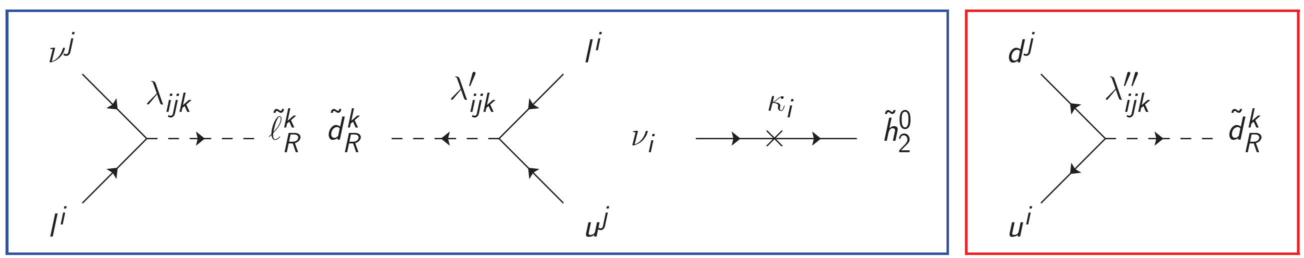
Summary

- Scalar sector is an interesting avenue to test flavor symmetries
- S_3 can **explain some mixing angles**, comes with an **enlarged scalar sector.**
- **Two SM-Higgs-like scalars** h_b and h_c**.** Decay dominantly into third scalar $h_a\, h_a$
- Scalar h_a has **limited gauge interactions**
- h_a has only off-diagonal Yukawa couplings, involving a lepton or quark from the third generation
- Scalars might already be buried in existing LEP or Tevatron data
- Currently expanding the analysis to include all scalar degrees of freedoms

Superpotential of the SSM

R-Parity violating operators in superpotential:

- $W \supset \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_2}_{\text{Lepton Number Violating}} \quad + \quad \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violating}}$

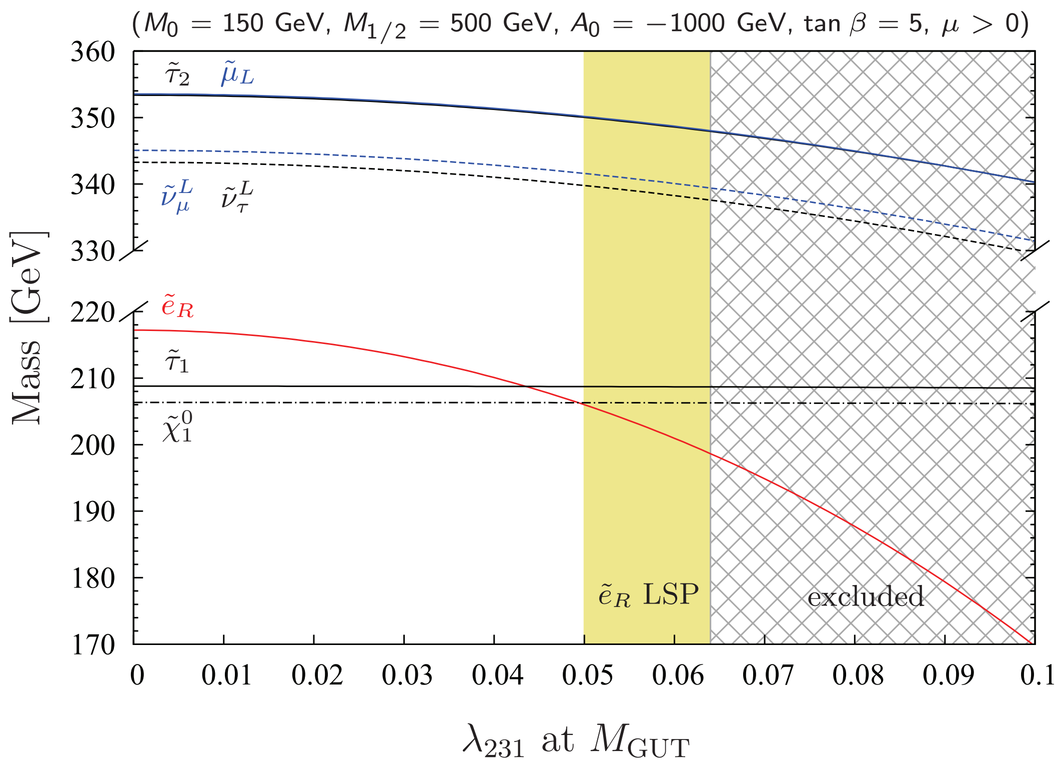


However: LNV + BNV lead to **proton decay!**

$\Rightarrow$ We will use a model which prohibits $\bar{U}\bar{D}\bar{D}$ (Baryon Triality)

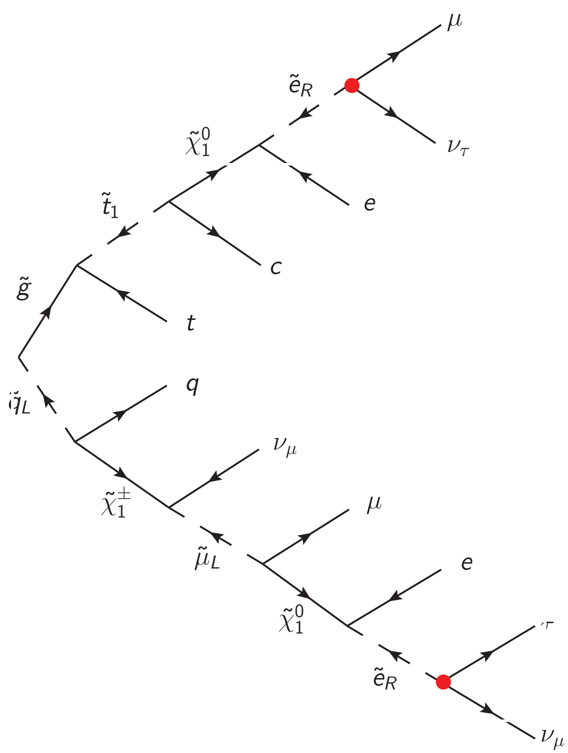
[Dreiner, Luhn, Thormeier, '06]

λ dependence of the $\tilde{e}_R$ mass



$\Rightarrow$ $\tilde{e}_R/\tilde{\mu}_R$ LSP with $\lambda \gtrsim \mathcal{O}(10^{-2})$ at M_{GUT}.

Signatures at hadron colliders



Example cascade decay with $\lambda_{231} \neq 0$

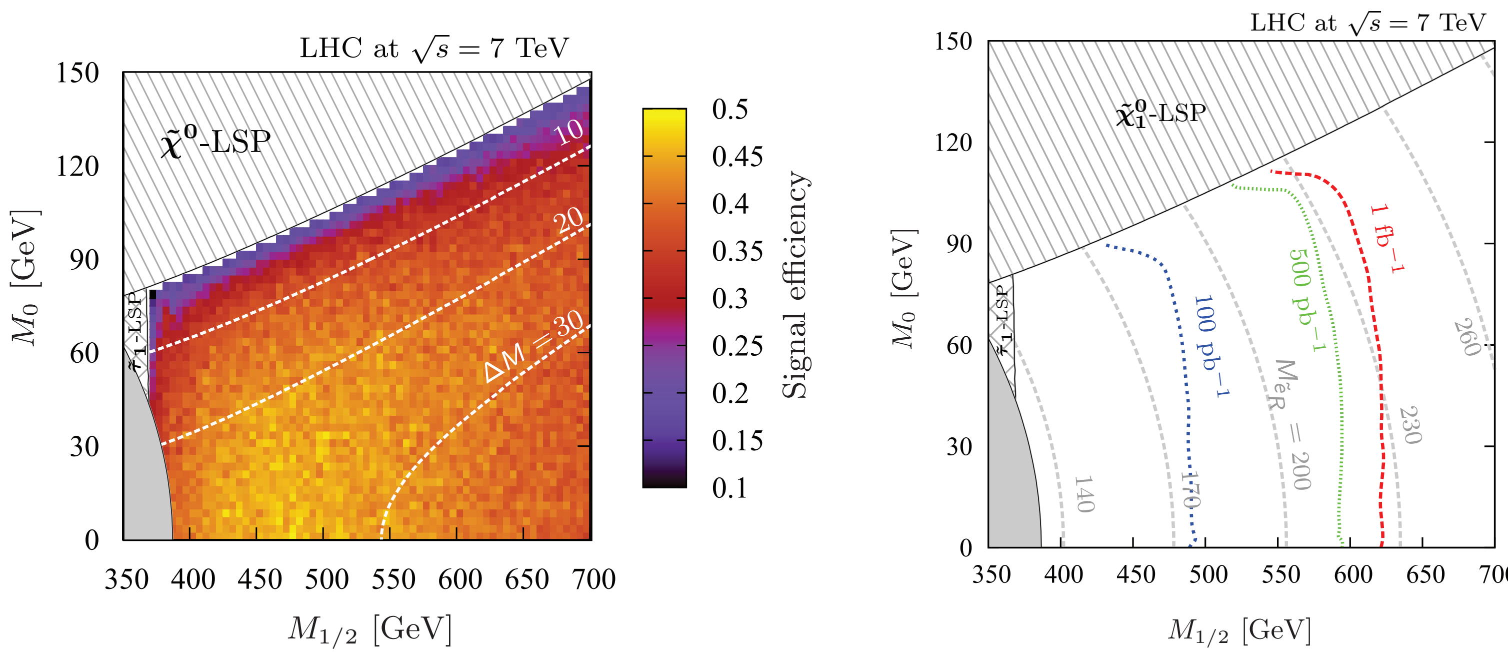
- Squark and gluino production dominant (at LHC)
- Mostly cascade decays into $\tilde{e}_R$-LSP
- $\tilde{e}_R$-LSP decays via λ_{231}:
  - $\tilde{e}_R \to \mu\nu_\tau,\ \tau\nu_\mu$
- Some other RPV decays via λ_{231}:
  - $\tilde{\nu}_\tau \to e^-\mu^+$
  - $\tilde{\tau}_1 \to e\nu_\mu$
- Typical signatures:

$$2e + 2\,\text{jets} + \not{E}_T + \begin{cases} 2\,\mu \\ \mu\,\tau \\ 2\,\tau \end{cases}$$

- Similar signatures for other λ_{ijk}-couplings

$\Rightarrow$ **Multi-leptonic events (plus jets)!**

Signal efficiency and discovery reach at LHC 7 TeV



- Signal efficiency decreases for small $\Delta M = M_{\tilde{\chi}^0_1} - M_{\tilde{e}_R}$.
- Signal is observable $\Leftrightarrow S \geq max\left[5\sqrt{B}, 5, 0.5B\right]$
- Scenarios with $M_{\tilde{q}} \leq 1.2$ TeV, $M_{\tilde{e}_R} \leq 230$ GeV can be tested with 1 fb^{-1}.
- Analysis is basically flavor independent $\Rightarrow$ same prospects for $\tilde{\mu}_R$ LSP.

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Generation of a Majorana mass term for ν_i via the L-violating terms

In the basis

$$\left(\psi^0\right)^T = \left(\tilde{B}, \tilde{W}_3^0, \tilde{H}_d^0, \tilde{H}_u^0, \nu_1, \nu_2, \nu_3\right)$$

one can write $\mathcal{L}_{\text{neutral}}^{\text{mass}} = -\frac{1}{2}\left(\psi^0\right)^T \mathcal{M}_n \psi^0 + h.c.$ with

$$\mathcal{M}_n = \begin{pmatrix} M_n & m \\ m^T & 0 \end{pmatrix}.$$

- M_n mixes the 4 heavy states
- m mixes the heavy states with the neutrinos

This leads to an effective neutrino mass matrix m_{eff}, which is at NLO given by

$$\left(m_{\text{eff}}\right)_{ij} = -\left(m^T M_n^{-1} m\right)_{ij} = a\Lambda_i\Lambda_j + b\left(\Lambda_i\epsilon_j + \epsilon_i\Lambda_j\right) + c\epsilon_i\epsilon_j$$

with $\Lambda_i = \mu v_i + v_d\epsilon_i$ and $\langle\tilde{\nu}_i\rangle = \frac{1}{\sqrt{2}}v_i$

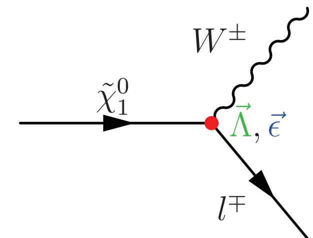
R-parity VI

Where does the correlation to neutrino physics come from?

Consider the lightest neutralino $\tilde{\chi}_1^0 = \tilde{W}_3^0$ as LSP in the $\mu\nu$SSM.
Two-body decay: At tree level the left-handed W-$\tilde{\chi}_1^0$-l_i-coupling reads:

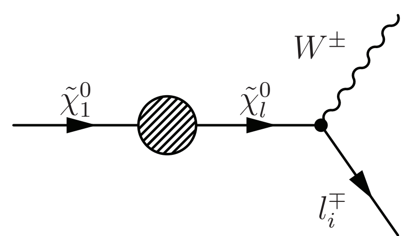
$$\mathcal{L} = \overline{l_i^-}\gamma^\mu \left(O_{Li}P_L + O_{Ri}P_R\right)\tilde{\chi}_1^0 W_\mu^- + h.c.$$

$$O_{Li} \approx \frac{g}{\sqrt{2}}\left[\frac{g\Lambda_i}{\det_+}N_{12} - \left(\frac{\epsilon_i}{\mu} + \frac{g^2 v_u \Lambda_i}{2\mu\det_+}\right)N_{13} - \sum_{j=1}^{5} N_{1j}\xi_{ij}\right]$$



$$\Longrightarrow \frac{Br\left(\tilde{\chi}_1^0 \to W^-\mu^+\right)}{Br\left(\tilde{\chi}_1^0 \to W^-\tau^+\right)} \propto \left|\frac{O_{L2}}{O_{L3}}\right|^2 = \left(\frac{\Lambda_2}{\Lambda_3}\right)^2 \approx \tan^2\theta_{atm}$$

However: We have to use a NLO neutralino mass matrix.
Problem: The branching ratios of $\tilde{\chi}_1^0 \to W^\pm l^\mp$ do not always show the tree-level prediction after the incomplete one-loop correction:

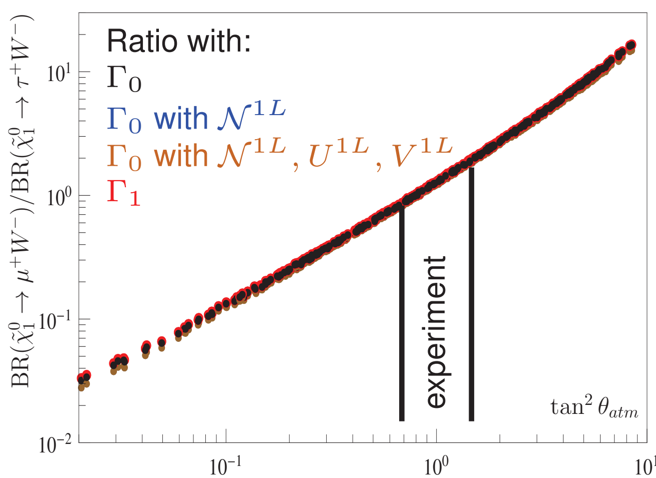


$\propto \Lambda_i, \epsilon_i$??

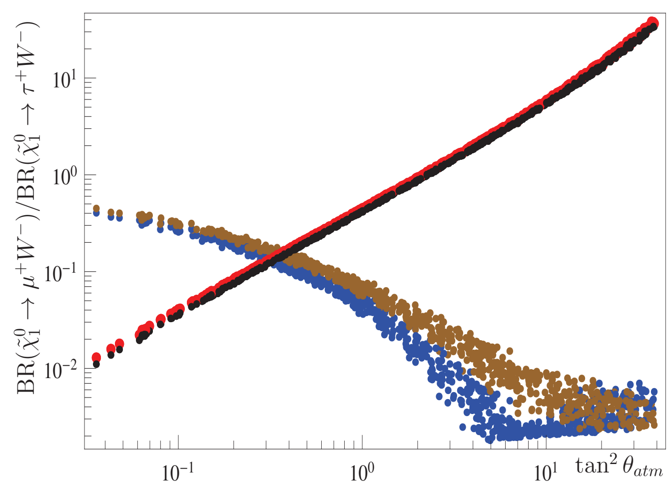
Correlations between neutrino mixing angles - $\tilde{\chi}_1^0 \to l^+W^-$

Finally we can compare the ratios of decay widths $\tilde{\chi}_1^0 \to l^+W^-$ with the neutrino mixing angles:

Bino $\tilde{\chi}_1^0 = \tilde{B}$



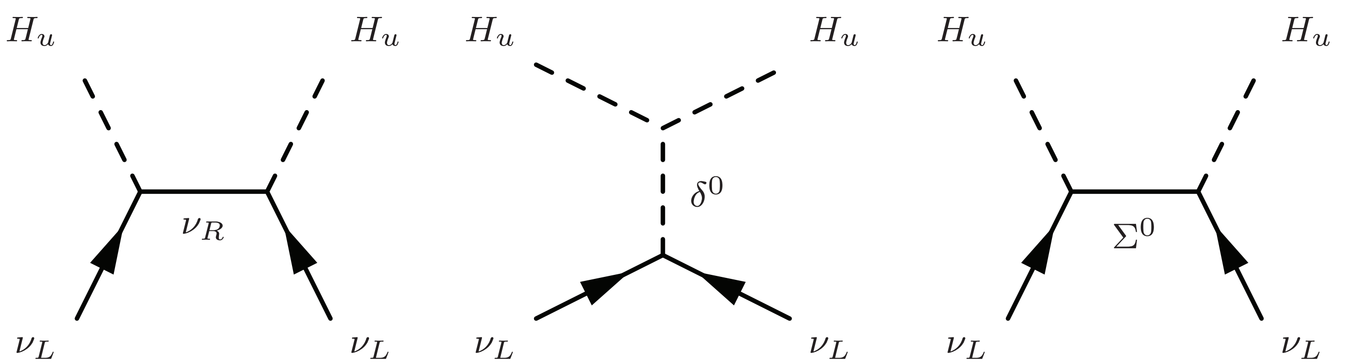
Higgsino with Singlino fraction $\tilde{\chi}_1^0 = \tilde{H}$



$\Longrightarrow$ The full NLO corrections show the behaviour predicted on tree-level!

Models

$$T_1 = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & \delta^+/\sqrt{2} \end{pmatrix} \qquad W_M = \begin{pmatrix} \Sigma^- & \Sigma^0/\sqrt{2} \\ \Sigma^0/\sqrt{2} & \Sigma^+ \end{pmatrix}$$



$$m_\nu = -\frac{v_u^2}{2} Y_\nu^T M_R^{-1} Y_\nu \qquad m_\nu = \frac{v_u^2}{2} \frac{\lambda_2}{M_T} Y_T \qquad m_\nu = -v_u^2 \frac{4}{10} Y_W^T M_W^{-1} Y_W$$

($M_R \simeq 10^{15}$ GeV) ($\frac{M_T}{\lambda_2} \simeq 10^{15}$ GeV) ($M_W \simeq 8 \times 10^{14}$ GeV)

(for Yukawas of $\mathcal{O}(1)$ and $m_\nu \sim \sqrt{\Delta m^2_{\mathrm{A}}} \sim 0.05$ eV)

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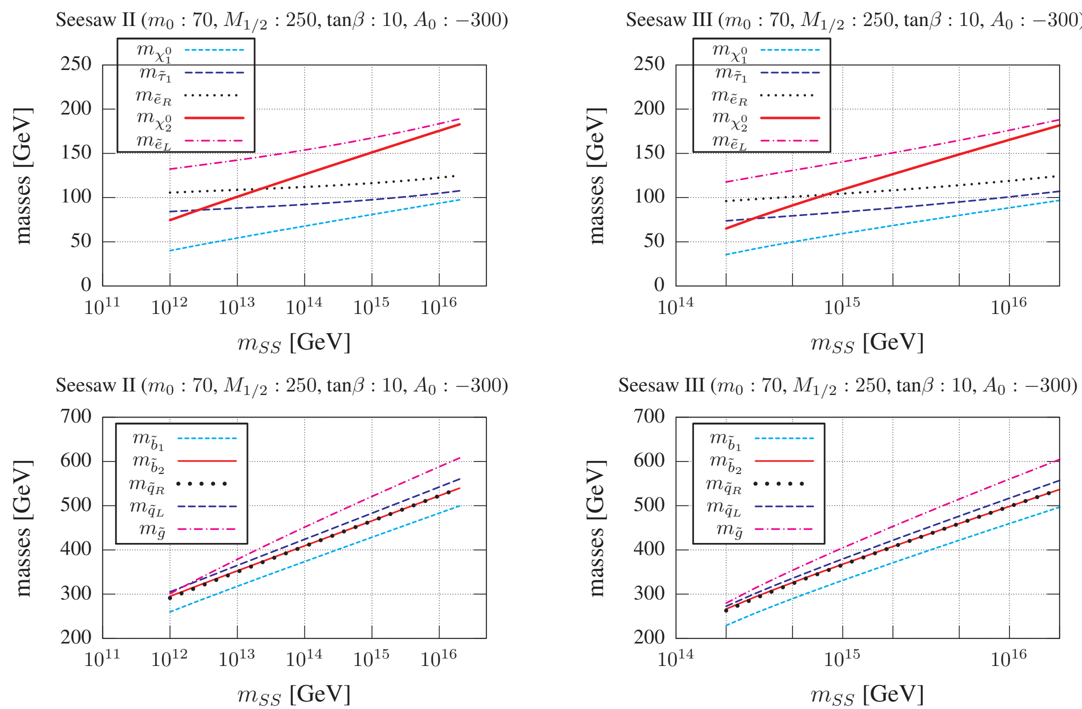
Observables

Dependence of slepton and squark masses on m_{SS}



$\longrightarrow$ Seesaw II and III pushes SUSY masses to smaller values!

$\longrightarrow$ MSP-1 $(70, 400, 10, -300)$, MSP-2 $(220, 700, 30, 0)$, MSP-3 $(120, 720, 10, 0)$

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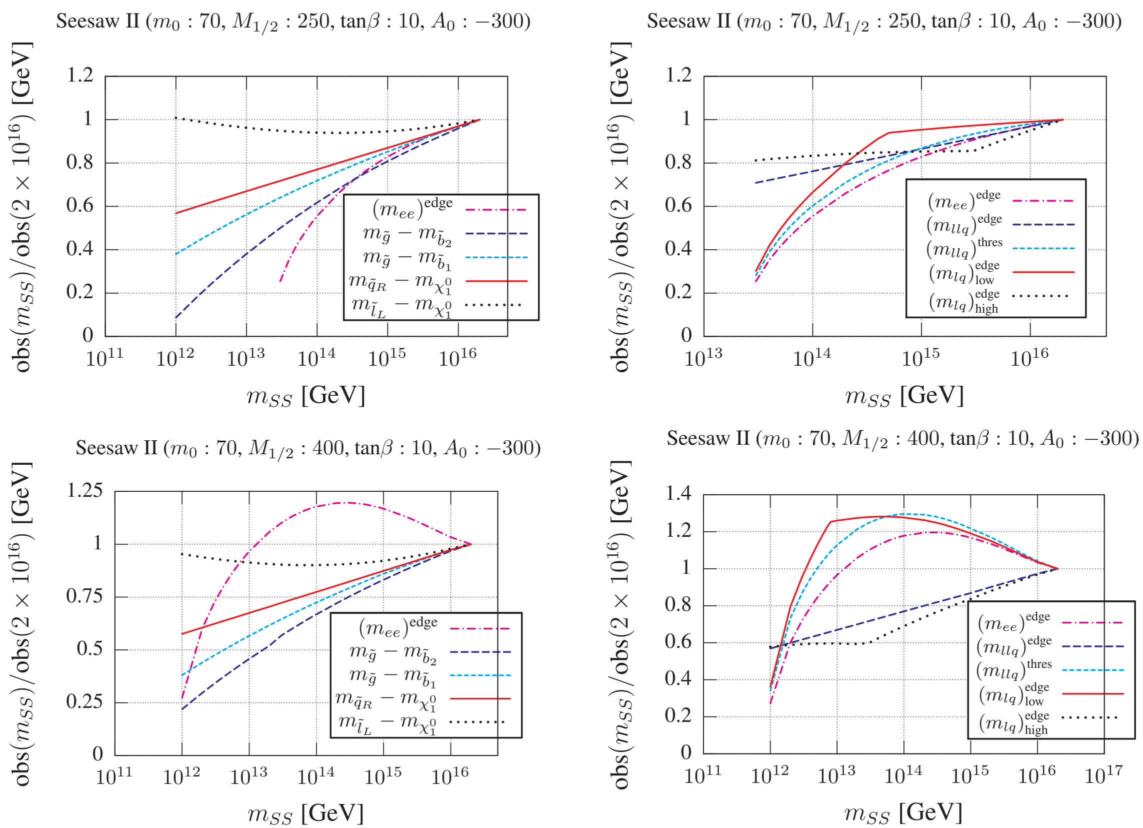
Observables

Dependence of LHC Observables on m_{SS}



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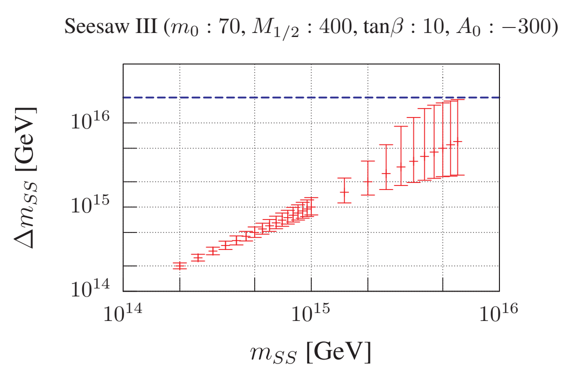
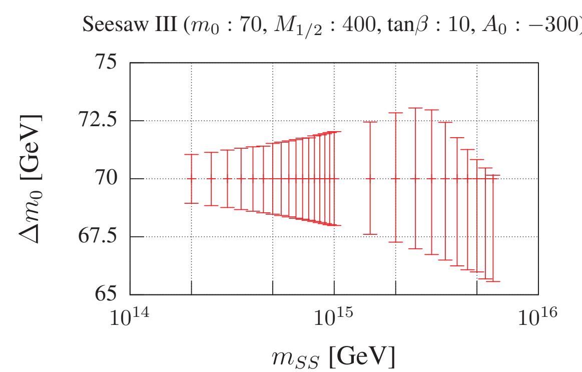
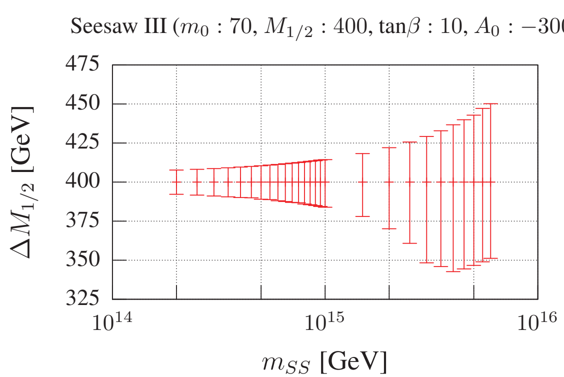
Results

Errors of m_0, $M_{1/2}$ and m_{SS} against m_{SS} for LHC + ILC (Seesaw III)







$\longrightarrow$ errors depend strongly on m_{SS}

$\longrightarrow$ distinguishable from mSUGRA for:

$m_{SS} \lesssim 6 - 7 \times 10^{15}$ GeV for 1σ c.f.

$\longrightarrow$ change in scale m_{SS}

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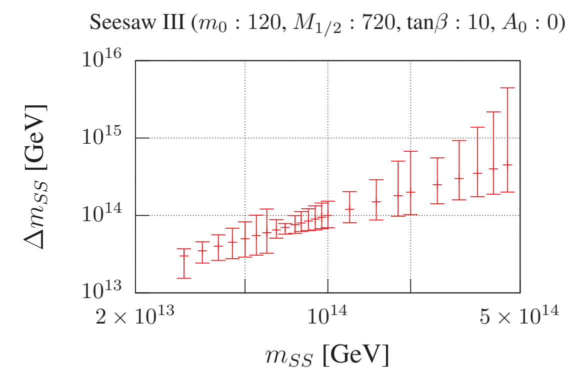
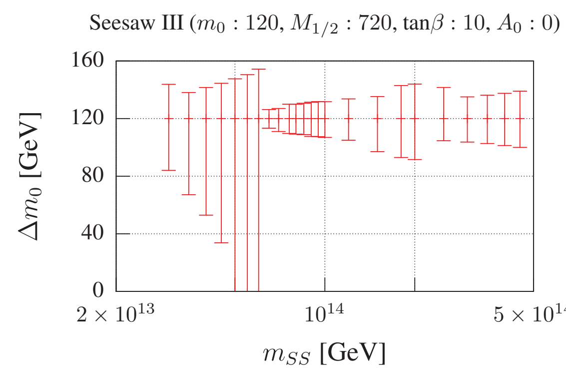
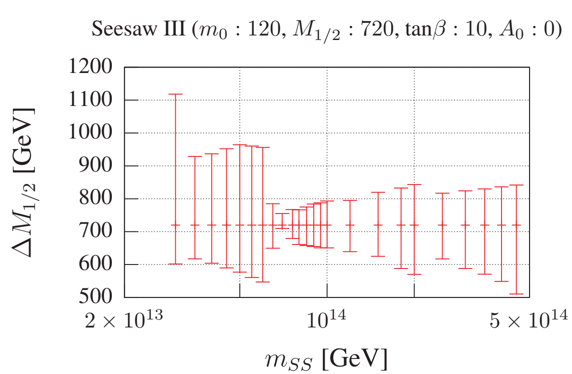
Results

Errors of $m_0, M_{1/2}$ and m_{SS} against m_{SS} for LHC obs. only (Seesaw III)







$\longrightarrow$ distinguishable from mSUGRA for:

$m_{SS} \lesssim 5 \times 10^{14}$ GeV for 1σ c.f.

$\longrightarrow$ All errors much larger than for LHC+ILC

Ongoing projects

- Detailed investigation of pseudoscalar Higgs bosons and charged Higgs bosons in S_3 models (Dortmund)
- Connections between $0\nu\beta\beta$ and LHC signals (Dortmund)
- Specific R-parity signals (Dortmund, Würzburg)
- SUSY models with additional $U(1)_{B-L}$: implications for LHC (Bonn, Würzburg)
- Experimental studies (Bonn, Würzburg)
  - search for R-parity violating signals at ATLAS
  - displaced vertices in case of R-parity violating
  - LSP mass reconstruction in case of R-parity violating
  - searches for lepto-quarks

More infos on (will be updated soon):
https://twiki.cern.ch/twiki/bin/view/Sandbox/NeutrinoMassesLFVatLHC