Supersymmetric mass spectra and the seesaw scale

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Planck

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based on: JHEP05(2011)086 (Martin Hirsch, Werner Porod)

Outline

- Models
- Observables (LHC and ILC)
- Results
- Yukawa couplings and LFV
- Conclusions

Models

Basic structure:

mSUGRA (m_0, $M_{1/2}$, A_0, tanβ, sign(μ)) "embedded" in SU(5) + Seesaw:

- **Seesaw I (Adding singlet)**

$$W_{SSI} = \widehat{N}^c Y_\nu \widehat{L} \cdot \widehat{H}_u + \frac{1}{2} \widehat{N}^c M_R \widehat{N}^c$$

- **Seesaw II (Adding 15-plet)**

$(15 = S(6,1,-2/3) + T(1,3,1) + Z(3,2,1/6))$

$$W_{SSII} = \frac{1}{\sqrt{2}}(Y_T \widehat{L}\widehat{T}_1\widehat{L} + Y_S \widehat{D}^c \widehat{S}_1 \widehat{D}^c) + Y_Z \widehat{D}^c \widehat{Z}_1 \widehat{L}$$
$$+ \frac{1}{\sqrt{2}}(\lambda_1 \widehat{H}_d \widehat{T}_1 \widehat{H}_d + \lambda_2 \widehat{H}_u \widehat{T}_2 \widehat{H}_u) + M_T \widehat{T}_1 \widehat{T}_2 + M_Z \widehat{Z}_1 \widehat{Z}_2 + M_S \widehat{S}_1 \widehat{S}_2$$

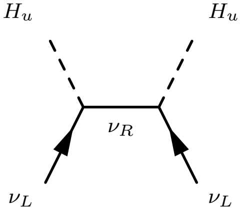
- **Seesaw III (Adding 24-plet)**

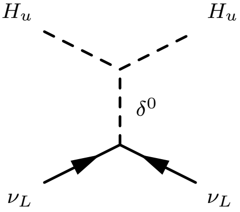
$(24 = B_M(1,1,0) + G_M(8,1,0) + W_M(1,3,0) + X_M(3,2,-5/6) + \bar{X}_M(\bar{3},2,5/6))$

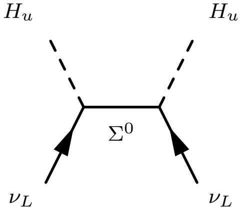
$$W_{SSIII} = \widehat{H}_u(\widehat{W}_M Y_W - \sqrt{\frac{3}{10}}\widehat{B}_M Y_B)\widehat{L} + \widehat{H}_u \widehat{\bar{X}}_M Y_X \widehat{D}^c$$
$$+ \frac{1}{2} M_B \widehat{B}_M \widehat{B}_M + \frac{1}{2} M_G \widehat{G}_M \widehat{G}_M + \frac{1}{2} M_W \widehat{W}_M \widehat{W}_M + M_X \widehat{X}_M \widehat{\bar{X}}_M .$$

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)

Models

1-loop RGEs for gauge couplings ($M_{\text{GUT}} \to m_{SS}$)

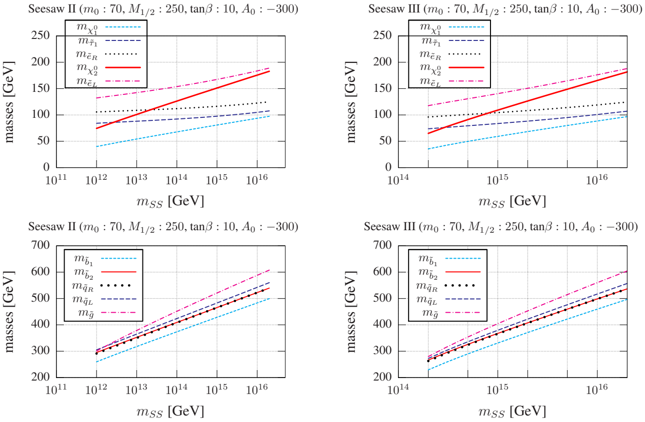
$$\alpha_i(M_G) = \frac{\alpha_i(m_{SS})}{1 - \frac{\alpha_i(m_{SS})}{4\pi}(b_i + \Delta b_i)\log\frac{M_{\text{GUT}}^2}{m_{SS}^2}}$$

$$b_i = (b_1, b_2, b_3)^{MSSM} = (\tfrac{33}{5}, 1, -3)$$

- Seesaw I $\Delta b_i = 0$
- Seesaw II $\Delta b_i = 7$ (one 15-plet/$\overline{15}$-plet)
- Seesaw III $\Delta b_i = 15$ (three 24-plets)

Observables

Dependence of slepton and squark masses on m_{SS}



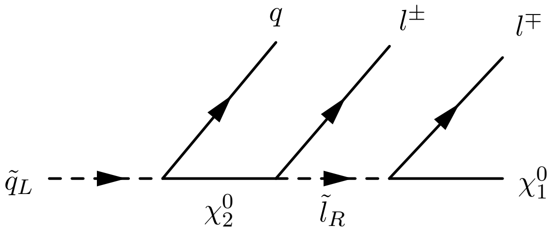
→ Seesaw II and III pushes SUSY masses to smaller values!

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

Observables

LHC Observables

→ In R_P LHC does not measure SUSY masses directly



→ Signal: Two opposite sign leptons + jets + missing energy

- Edges:
  $(m_{ll})^{\text{edge}}$, $(m_{lq})^{\text{edge}}_{\text{low}}$, $(m_{lq})^{\text{edge}}_{\text{high}}$, $(m_{llq})_{\text{edge}}$ and $(m_{llq})_{\text{thresh}}$
- Mass differences:
  $m_{\tilde{g}} - m_{\tilde{b}_i}$ with $i = 1, 2$, $m_{\tilde{q}_R} - m_{\chi_1^0}$ and $m_{\tilde{l}_L} - m_{\chi_1^0}$

Observables

ILC Observables

$\longrightarrow$ direct measurement of SUSY masses

$\longrightarrow$ much smaller erros on SUSY masses than at LHC

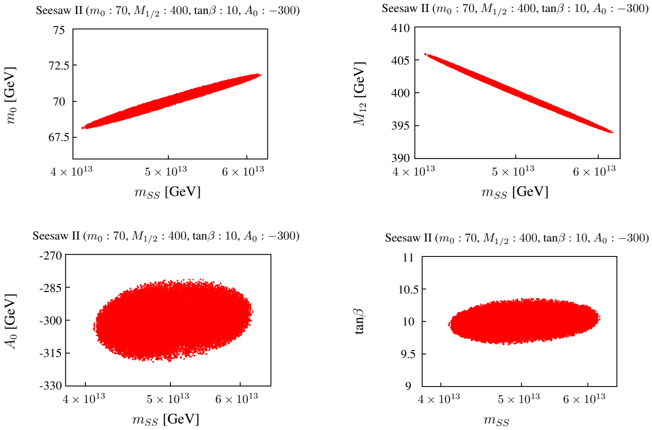
- We assume these masses accessible:
  $m_{\chi_1^0}, m_{\tilde{e}_R} \simeq m_{\tilde{\mu}_R}$ and $m_{\tilde{e}_L} \simeq m_{\tilde{\mu}_L}$
- Whenever within the reach of ILC also:
  $m_{\tilde{\tau}_1}, m_{\chi_2^0}, m_{\chi_1^+}$ and $m_{\tilde{t}_1}$

We assume for all the calculations that the lighter Higgs h_0 has been found.

Results

χ^2-distrib. for a random walk letting $m_0, M_{1/2}, \tan\beta, A_0$ and m_{SS} float freely

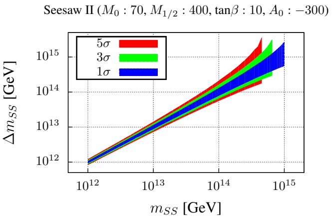
$(m_0 = 70,\ M_{1/2} = 400,\ \tan\beta = 10,\ A_0 = -300,\ m_{SS} = 5 \times 10^{13})$

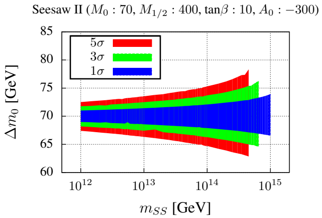


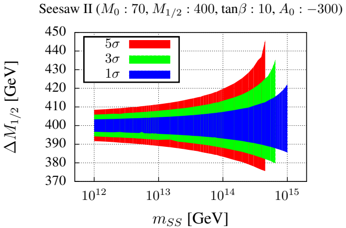
$\rightarrow m_0, M_{1/2}$ and m_{SS} are highly correlated among each other

Results

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







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

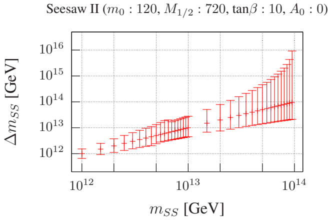
$\longrightarrow$ distinguishable from mSUGRA for:

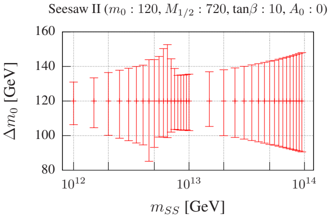
$m_{SS} \lesssim 8 \times 10^{14}$ GeV for 3σ c.f.

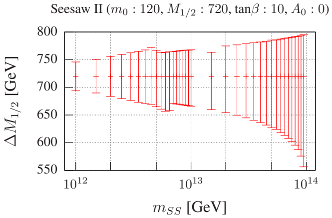
$m_{SS} \lesssim 5 - 6 \times 10^{14}$ GeV for 5σ c.f.

Results

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







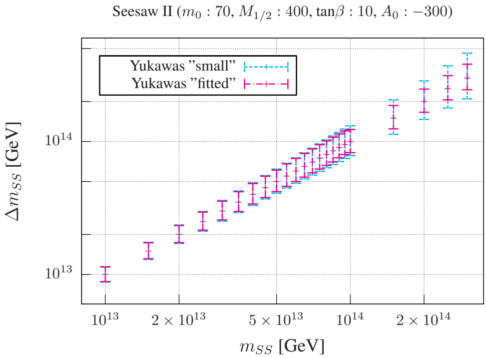
$\longrightarrow$ distinguishable from mSUGRA for:

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

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

Yukawa couplings and LFV

Yukawa couplings and type-II seesaw



$\rightarrow$ up to $m_{SS} \sim 10^{14}$ GeV Yukawa couplings can be neglected

Conclusions

LHC + ILC

- It is possible to distinguish pure mSUGRA from mSUGRA plus type-II/III seesaw for nearly any relevant value of the seesaw scale
- $\longrightarrow$ at least χ_1^0, $\tilde{e}_R$/ $\tilde{\mu}_R$ and $\tilde{e}_L$/ $\tilde{\mu}_L$ kinemetically accessible

LHC

- With LHC pure mSUGRA is only distinguishable from mSUGRA plus type-II/III seesaw in some favourable parts of parameter space
- $\longrightarrow$ small uncertainties of Edges and $m_{\tilde{g}} - m_{\tilde{b}_1}$ are very important

Thank you for your attention

- **Seesaw I (Adding singlet)**

$$W_{\rm RHN} = \mathbf{Y}_N^{\rm I} N^c \cdot \bar{5} \cdot 5_H + \frac{1}{2} M_R N^c N^c$$

- **Seesaw II (Adding 15-plet)**

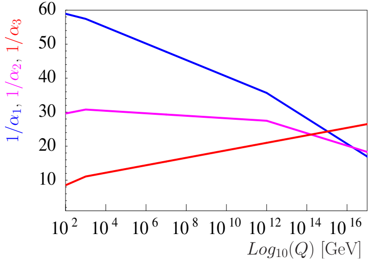
$$\begin{aligned} W_{15} =& \frac{1}{\sqrt{2}} \mathbf{Y}_N^{\rm II} \bar{5} \cdot 15 \cdot \bar{5} + \frac{1}{\sqrt{2}} \lambda_1 \bar{5}_H \cdot 15 \cdot \bar{5}_H + \frac{1}{\sqrt{2}} \lambda_2 5_H \cdot \overline{15} \cdot 5_H \\ &+ \mathbf{Y}_5 10 \cdot \bar{5} \cdot \bar{5}_H + \mathbf{Y}_{10} 10 \cdot 10 \cdot 5_H + M_{15} 15 \cdot \overline{15} + M_5 \bar{5}_H \cdot 5_H \end{aligned}$$

- **Seesaw III (Adding 24-plet)**

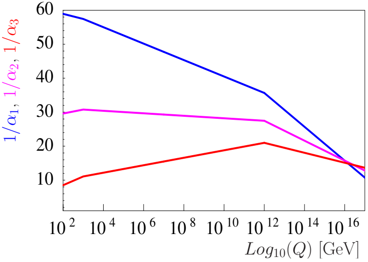
$$\begin{aligned} W_{24_{\rm M}} =& \sqrt{2}\, \mathbf{Y_5} \bar{5} \cdot 10 \cdot \bar{5}_H - \frac{1}{4} \mathbf{Y_{10}} 10 \cdot 10 \cdot 5_H + Y_N^{\rm III} 5_H \cdot 24_M \cdot \bar{5} \\ &+ \frac{1}{2} 24_M M_{24} 24_M \end{aligned}$$

Models

Running of $1/\alpha_1$, $1/\alpha_2$ and $1/\alpha_3$ for mSUGRA plus type-II seesaw



Adding Triplets only



Adding complete 15-plets

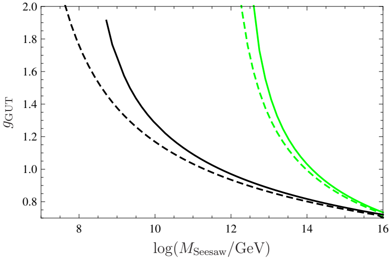
$\longrightarrow$ Adding complete $15/24$-plet maintains gauge coupling unification!

$\longrightarrow$ for $m_{SS} = M_{GUT}$ we recover usual “mSUGRA spectra”

Observables

- Lower bound on m_{SS}

  Dependence of $\alpha(M_{GUT})$ on m_{SS} for type-II and type-III seesaw



  $\longrightarrow$ Pertubativity of $\alpha(M_{GUT})$ gives lower limit on m_{SS}

- Upper bound on m_{SS}

  $\longrightarrow$ for $m_{SS} \gtrsim 10^{15}$ Yukawa couplings become non-perturbative

Variable	Value (GeV)	Error (GeV)
m_{ll}^{max}	77.07	0.08
m_{llq}^{max}	428.5	4.5
m_{lq}^{low}	300.3	3.1
m_{lq}^{high}	378.0	3.9
m_{llq}^{min}	201.9	2.6
m_{llb}^{min}	183.1	4.1
$m(\tilde{l}_L) - m(LSP)$	106.1	1.6
$m_{ll}^{max}(\chi_4^0)$	280.9	2.3
$m_{\tau\tau}^{max}$	80.6	5.1
$m(\tilde{g}) - 0.99 \times m(LSP)$	500.0	6.4
$m(\tilde{q}_R) - m(LSP)$	424.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.6

Particle	Mass	"LHC"	"ILC"	"LHC+ILC"
h^0	116.0	0.25	0.05	0.05
H^0	425.0		1.5	1.5
$\tilde{\chi}_1^0$	97.7	4.8	0.05	0.05
$\tilde{\chi}_2^0$	183.9	4.7	1.2	0.08
$\tilde{\chi}_4^0$	413.9	5.1	$3-5$	2.5
$\tilde{\chi}_1^\pm$	183.7		0.55	0.55
$\tilde{e}_R$	125.3	4.8	0.05	0.05
$\tilde{e}_L$	189.9	5.0	0.18	0.18
$\tilde{\tau}_1$	107.9	$5-8$	0.24	0.24
$\tilde{q}_R$	547.2	$7-12$	–	$5-11$
$\tilde{q}_L$	564.7	8.7	–	4.9
$\tilde{t}_1$	366.5		1.9	1.9
$\tilde{b}_1$	506.3	7.5	–	5.7
$\tilde{g}$	607.1	8.0	–	6.5

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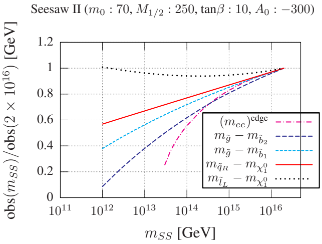
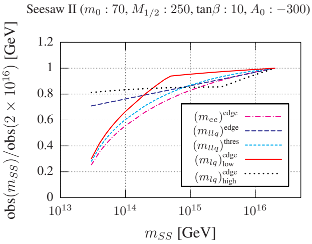
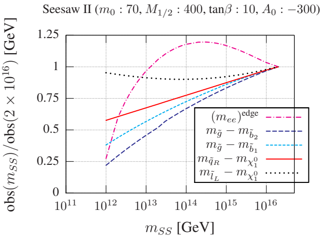
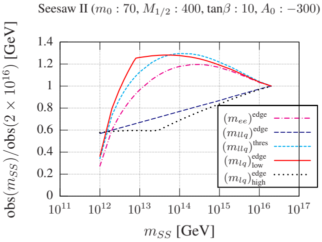
Observables

Dependence of LHC Observables on m_{SS}

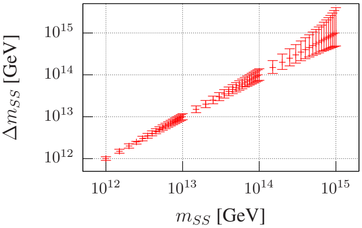




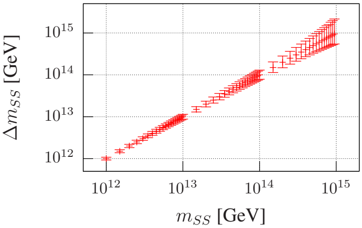




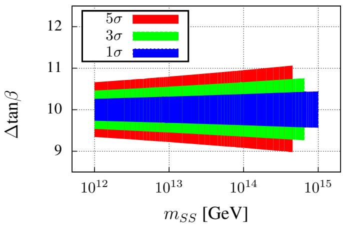
Seesaw II (m_0 : 220, $M_{1/2}$: 700, tanβ : 30, A_0 : 0)



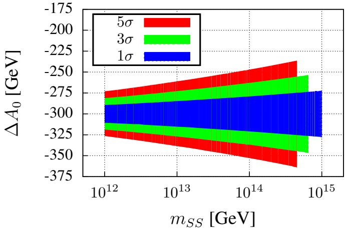
Seesaw II (m_0 : 120, $M_{1/2}$: 720, tanβ : 10, A_0 : 0)



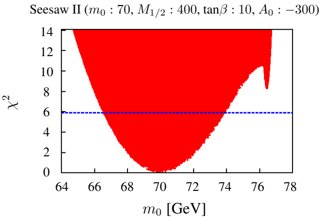
Seesaw II (M_0 : 70, $M_{1/2}$: 400, tanβ : 10, A_0 : -300)

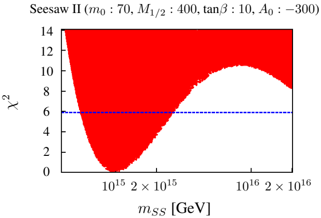


Seesaw II (M_0 : 70, $M_{1/2}$: 400, tanβ : 10, A_0 : -300)

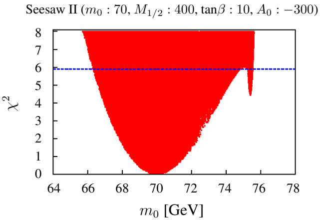


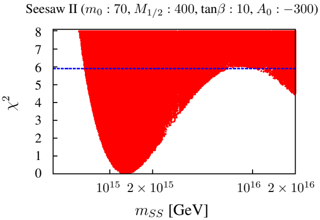
Results





$m_{SS} = 1 \times 10^{13}$ GeV

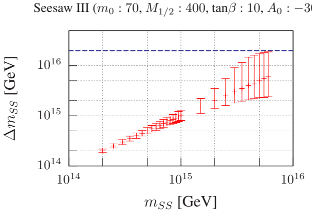


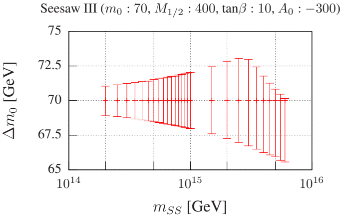


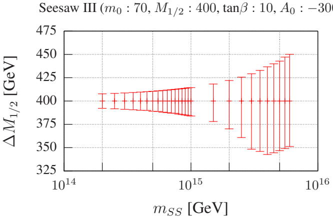
$m_{SS} = 1.3 \times 10^{13}$ GeV

Results

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





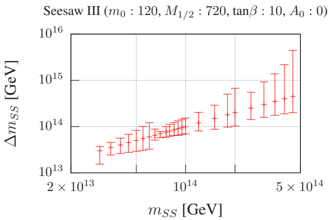


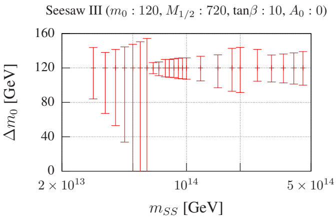
- $\longrightarrow$ errors depend strongly on m_{SS}
- $\longrightarrow$ distinguishable from mSUGRA for:

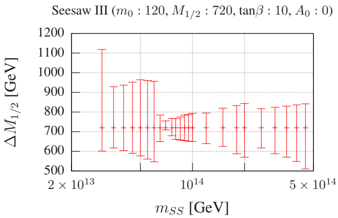
  $m_{SS} \lesssim 6 - 7 \times 10^{15}$ GeV for 1σ c.f.
- $\longrightarrow$ change in scale m_{SS}

Results

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







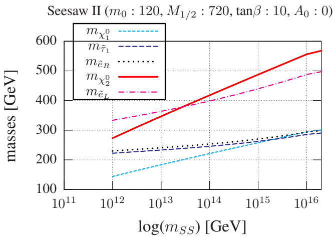
$\longrightarrow$ distinguishable from mSUGRA for:

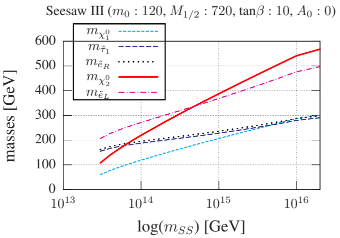
$m_{SS} \lesssim 5 \times 10^{14}$ GeV for 1σ c.f.

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

Results

Dependence of SUSY masses on m_{SS}

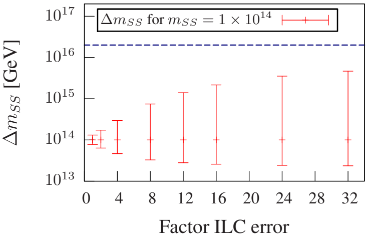




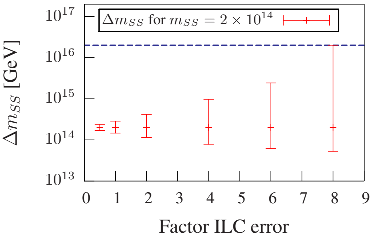
$\longrightarrow$ As function of m_{SS} mass ordering changed!

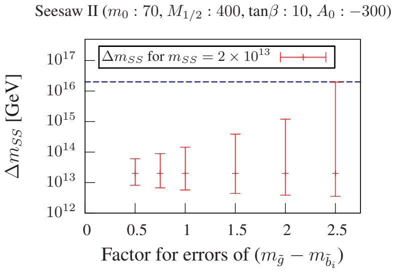
$\longrightarrow$ “Edge variables“ crucial for LHC

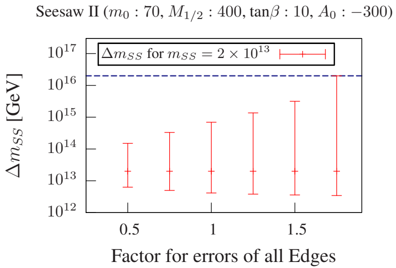
Seesaw II (m_0 : 70, $M_{1/2}$: 400, tanβ : 10, A_0 : −300)



Seesaw II (m_0 : 70, $M_{1/2}$: 400, tanβ : 10, A_0 : −300)

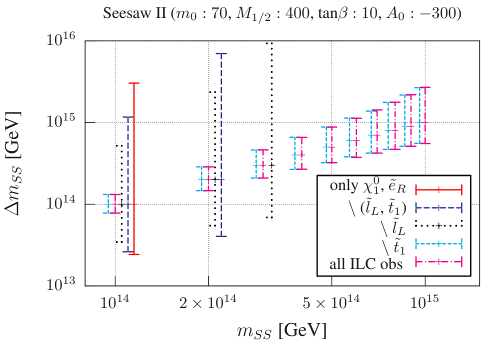



Seesaw II (m_0 : 70, $M_{1/2}$: 400, tanβ : 10, A_0 : -300)
Δm_{SS} for $m_{SS} = 2 \times 10^{13}$
Δm_{SS} [GeV]
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
0
0.5
1
1.5
2
2.5
Factor for errors of $(m_{\tilde{g}} - m_{\tilde{b}_i})$


Seesaw II (m_0 : 70, $M_{1/2}$: 400, tanβ : 10, A_0 : -300)
Δm_{SS} for $m_{SS} = 2 \times 10^{13}$
Δm_{SS} [GeV]
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
0.5
1
1.5
Factor for errors of all Edges

Observables and Uncertainties

Switching off different ILC observables (LHC + ILC obs.)



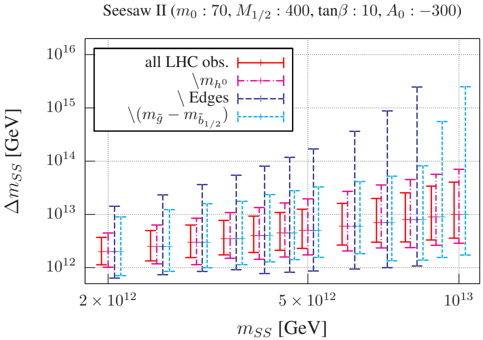
→ measuring left-slepton masses is highly important

→ for $m_{SS} \lesssim 10^{14}$ GeV χ_1^0 and $\tilde{l}_R$ are "sufficient"

→ $\tilde{t}_1$ has almost no influence on Δm_{SS}

Observables and Uncertainties

Switching off different LHC observables (LHC obs. only)

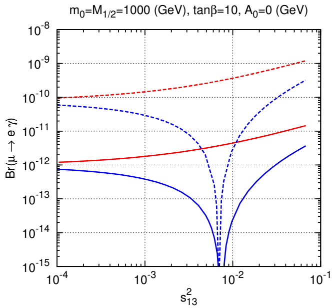


$\longrightarrow$ Edges and $m_{\tilde{g}} - m_{\tilde{b}_1}$ are the most important observables

$\longrightarrow$ but: Higgs mass is not negligible

Yukawa couplings and LFV

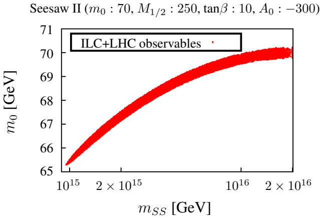
LFV in mSUGRA plus type-I and type-III seesaw

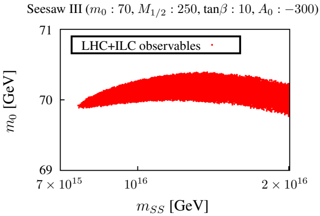


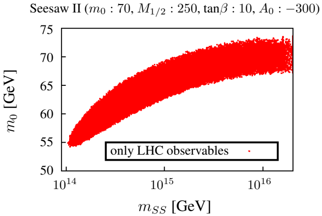
$\longrightarrow$ Note: Cancellations independent of any low-energy neutrino physics can be found

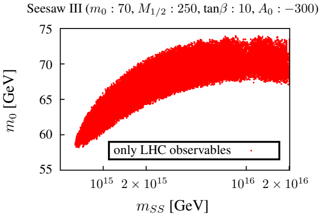
$\longrightarrow$ No predictions of LFV possible

$\longrightarrow$ but: Observation of LFV $\longrightarrow$ constraints on RH sector


Seesaw II (m_0 : 70, $M_{1/2}$: 250, tanβ : 10, A_0 : −300)
ILC+LHC observables
m_0 [GeV]
m_{SS} [GeV]
71
70
69
68
67
66
65
10^{15}
2×10^{15}
10^{16}
2×10^{16}


Seesaw III (m_0 : 70, $M_{1/2}$: 250, tanβ : 10, A_0 : −300)
LHC+ILC observables
m_0 [GeV]
m_{SS} [GeV]
71
70
69
7×10^{15}
10^{16}
2×10^{16}


Seesaw II (m_0 : 70, $M_{1/2}$: 250, tanβ : 10, A_0 : −300)
only LHC observables
m_0 [GeV]
m_{SS} [GeV]
75
70
65
60
55
50
10^{14}
10^{15}
10^{16}


Seesaw III (m_0 : 70, $M_{1/2}$: 250, tanβ : 10, A_0 : −300)
only LHC observables
m_0 [GeV]
m_{SS} [GeV]
75
70
65
60
55
10^{15}
2×10^{15}
10^{16}
2×10^{16}

Motivation

Neutrino oscillation experiments:

$\longrightarrow$ Neutrino masses are non-zero:

- $\Delta m^2_{\odot} \,:\, 7.59\,[10^{-5}\,\text{eV}^2],\ \Delta m^2_{\text{atm}} \,:\, 2.40\,[10^{-3}\,\text{eV}^2]$
- $\sin^2\theta_{\odot} \,:\, 0.318,\ \sin^2\theta_{\text{atm}} \,:\, 0.50,\ \sin^2\theta_{13} \,:\, 0.013$

If lepton number is violated:

$\longrightarrow$ Many possible models:

- Seesaw mechanism:
    - Type I: Exchange of fermion singlet
    - Type II: Exchange of scalar triplet
    - Type III: Exchange of fermion triplet
    - Inverse seesaw, ...
- Radiative models
- SUSY neutrino models: $\not{R}_P$
- ...

Motivation

- **SM + Seesaw:**
  - $\longrightarrow$ No experimental signal apart from the neutrino masses themselves
- **SUSY + Seesaw:**
  - $\longrightarrow$ Indirect information about seesaw parameters from:
    - Lepton flavor violating (LFV) decays
    - Superpartner mass measurements
- **SUSY "embedded" in SU(5) + Seesaw:**
  - $\longrightarrow$ Same features as in SUSY + Seesaw
  - $\longrightarrow$ Adding complete SU(5) representations maintains gauge coupling unification

Motivation

Is it possible to find signatures of Seesaw in SUSY spectra with mSUGRA boundary conditions?

$\longrightarrow$ How sensitive is the LHC?

$\longrightarrow$ ILC is needed?