LHC and lepton flavour violation phenomenology in Seesaw Models

Jorge C. Romão

Instituto Superior Técnico, Departamento de Física & CFTP

A. Rovisco Pais 1, 1049-001 Lisboa, Portugal

March 16^{th}, 2011

Outline

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions

- Motivation
- SUSY seesaw models for neutrino masses and mixings
- LFV observables and constraints from low-energy experiments
- LFV observables at LHC and interplay with low-energy experiments
- Conclusions: What can we learn?

Collaborators: A. Abada, J. N. Esteves, A. J. R. Figueiredo, M. Hirsch, S. Kaneko, W. Porod, F. Staub
A. M. Teixeira, A. Villanova del Moral

Papers:
arXiv:0903.1408 [JHEP05(2009)003], arXiv:0907.5090 [PRD80(2009)095003], arXiv:1007:4833 [JHEP10(2010)104]
arXiv:1010.6000 [PRD83(2011)013003] & ArXiv: 1011.0348 [JHEP12(2010)077]

Understanding lepton flavour mixing

Outline
Motivation
• cLFV
• Unique source
Models
Low-Energy Obs.
LHC Observables
Conclusions

- **Flavour violated** in neutral leptons ($\nu_i \leftrightarrow \nu_j$ oscillations)

  What about charged lepton flavour violation? $\ell_i \to \ell_j\gamma, \ell_i \to 3\ell_j, \ldots$

  - No evidence, so far
  - Huge experimental effort: **MEG, PRISM/PRIME, SuperB, ...**

- **Charged LFV:** complementary to LHC searches and ν experiments

  - Use low-energy LFV observables, like BR($\ell_i \to \ell_j\gamma$)

    and

  - high-energy data, like slepton mass splittings at LHC

- **Use cLFV** complementarity to **disentangle** model of New Physics

cLFV ↔

New Physics (beyond SM+ν_R)	+	Lepton Flavour Mixing
mSUGRA-like SUSY		seesaw mechanism
(testable at LHC)		(suggested by ν mixing)

A unique source of flavour violation

Outline
Motivation
• cLFV
• Unique source
Models
Low-Energy Obs.
LHC Observables
Conclusions

- mSUGRA-like SUSY seesaw: Y_ν **unique source of LFV**

  All **LFV** observables strongly related

  - **low-energies:** $\ell_i \to \ell_j \gamma, \ell_i \to 3\ell_j, \mu - e$ in Nuclei

    ➡ Large rates potentially observable (MEG, PRISM/PRIME, ...)

  - **high-energy:** look for charged slepton from $\chi_2^0 \to \ell^\pm \ell^\mp \chi_1^0$ decays

    ➡ Possibly sizable $\tilde{e} - \tilde{\mu}$ mass differences, multiple edges, and direct LFV decays $\chi_2^0 \to \ell_i \ell_j \chi_1^0$

- Interplay **low- high-energy:**

  Low-energy: LFV observable (large BRs & CR) ⟷ LHC: Interesting new phenomena

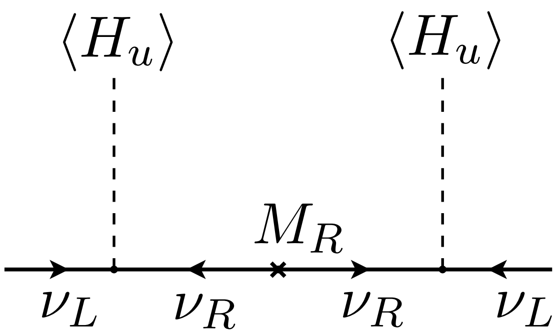
Seesaw models for neutrino masses: Type-I-II-III

$$\mathcal{L} = \cdots + H_u \overline{\nu_L}\, Y_\nu^{\rm I}\, \nu_R - \frac{1}{2}\nu_R^T\, C^{-1}\, M_R\, \nu_R$$

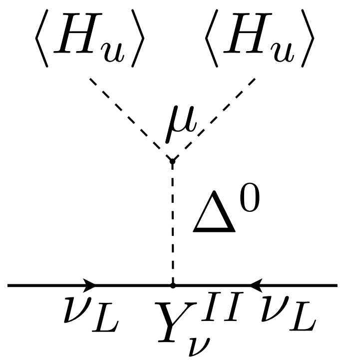
$$\mathcal{L} = \cdots - \frac{1}{2} Y_\nu^{\rm II} \overline{\nu_L^c} i\tau_2 \Delta_L \nu_L - \mu H_u^T \Delta_L H_u - M_\Delta^2 \Delta_L^\dagger \Delta_L$$

$$\mathcal{L} = \cdots + H_u \overline{W_M} Y_\nu^{\rm III} \nu_L - \frac{1}{2} W_M^T C^{-1} M_{W_M} W_M$$

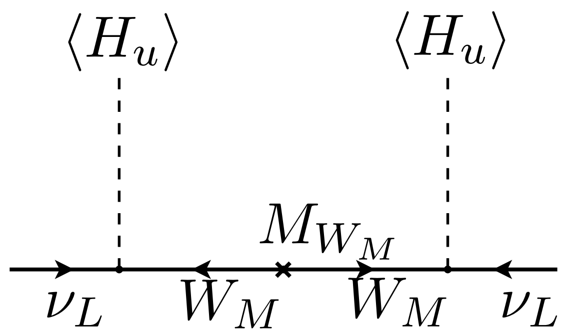
type-I



type-II



type-III



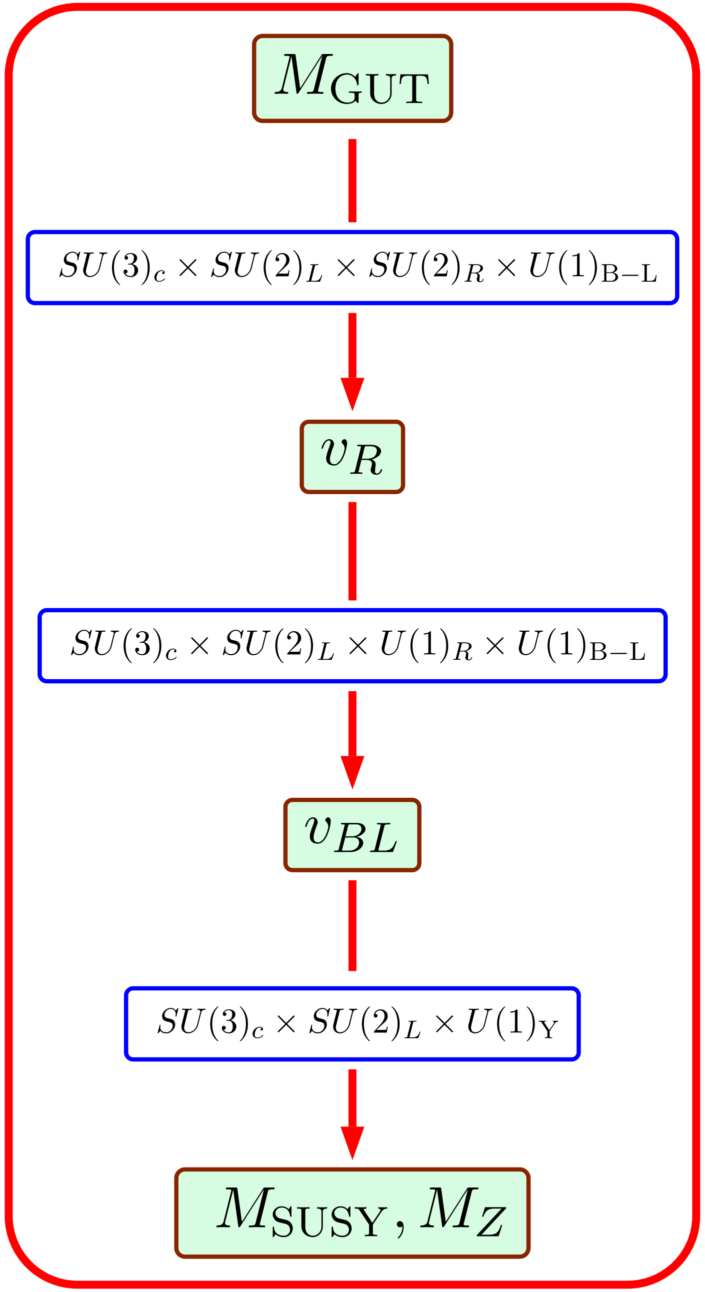
$$m_{\rm eff}^{\rm I} = -(vY_\nu) M_R^{-1} (vY_\nu)^T$$

$$m_{\rm eff}^{\rm II} = \frac{v^2 \mu Y_\nu^{\rm II}}{M_\Delta^2}$$

$$m_{\rm eff}^{\rm III} = -(vY_\nu^{\rm III}) M_{W_M}^{-1} (vY_\nu^{\rm III})^T$$

- Exchanged particle: Type-I-III: neutral fermion. Type-II: neutral scalar
- Type-I: gauge singlet. Type-II-III; gauge triplet ➡ Stronger running
- $m_\nu \sim 1$eV and $Y_\nu \sim \mathcal{O}(1)$ ➡ $M_{\rm Seesaw} \sim \mathcal{O}(10^{12-14})$GeV **Not directly observable**

Left-Right Model: breaking scales and neutrino mass



- Superpotential

$$\mathcal{W} = Y_L L \Phi L^c - f_c L^c \Delta^c L^c + \cdots$$

  - Y_L and f_c complex 3×3 matrices

- Lagrangian at $v_{BL} = \langle \Delta_c^0 \rangle$

$$\mathcal{L} = H_u \overline{\nu_L} Y_\nu^{\rm I} \nu_R - \frac{1}{2} \nu_R^T C^{-1} (f_c v_{BL}) \nu_R + \cdots$$

- Effective neutrino mass matrix (type-I)

$$m_{\rm eff}^{\rm LR} = -(v Y_\nu)(f_c v_{BL})^{-1} (v Y_\nu)^T$$

  - Y_ν fit $\to$ $f_c = \mathbb{1}$, Y_ν arbitrary
  - f fit $\to$ $Y_\nu = \mathbb{1}$, f_c arbitrary
  - Different imprints on RGE running

LFV in the slepton sector: Approximate formulas for $\Delta m_{L,E}$

Outline
Motivation
Models
• Type-I-II-III
• LR
• LFV
Low-Energy Obs.
LHC Observables
Conclusions

Starting with universal (mSUGRA) boundary conditions @ M_{GUT}:

❒ Seesaw type-I-II-III

$$\Delta m^2_{L,ij} \simeq -\frac{a_k}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(Y_N^{k,\dagger} L Y_N^k\right)_{ij}, \qquad L = \ln\left(\frac{M_{\text{GUT}}}{M_{\text{N}}}\right)$$

$$\Delta m^2_{E,ij} \simeq 0 \qquad\qquad a_{\text{I}} = 1\ ,\ a_{\text{II}} = 6 \text{ and } a_{\text{III}} = \frac{9}{5}$$

❒ Left-Right Model

M_{GUT} → v_R

$$\Delta m^2_L \simeq -\frac{1}{4\pi^2}\left(3 f f^\dagger + Y_L^{(k)} Y_L^{(k)\,\dagger}\right)\left(3m_0^2 + A_0^2\right)\ln\left(\frac{M_{\text{GUT}}}{v_R}\right)$$

$$\Delta m^2_E \simeq -\frac{1}{4\pi^2}\left(3 f^\dagger f + Y_L^{(k)\,\dagger} Y_L^{(k)}\right)\left(3m_0^2 + A_0^2\right)\ln\left(\frac{M_{\text{GUT}}}{v_R}\right)$$

v_R → v_{BL}

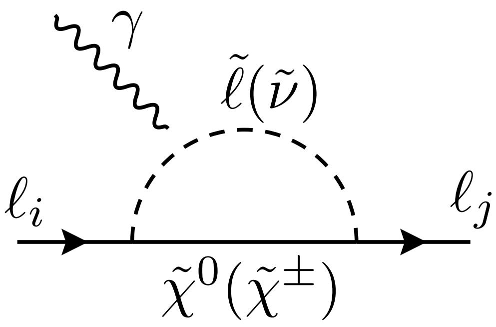
$$\Delta m^2_L \simeq -\frac{1}{8\pi^2} Y_\nu Y_\nu^\dagger \left(m_L^2|_{v_R} + A_e^2|_{v_R}\right)\ln\left(\frac{v_R}{v_{BL}}\right)$$

$$\Delta m^2_E \simeq 0$$

Radiative lepton decays $l_i \to l_j\gamma$: Approximate formulas

Outline
Motivation
Models
• Type-I-II-III
• LR
• LFV
Low-Energy Obs.
LHC Observables
Conclusions

- BR($l_i \to l_j\gamma$): (**MEG**...)



$$\mathcal{L}_{eff} = e\frac{m_i}{2}\bar{l}_i\sigma_{\mu\nu}F^{\mu\nu}(A_L^{ij}P_L + A_R^{ij}P_R)l_j + h.c.$$

$$\text{BR}(l_i \to l_j\gamma) = \frac{48\pi^3\alpha}{G_F^2}\left(|A_L^{ij}|^2 + |A_R^{ij}|^2\right)\text{BR}(l_i \to l_j\nu_i\bar{\nu}_j)$$

- For seesaw models: $A_L^{ij} \sim \frac{(\Delta m_L^2)_{ij}}{m_{SUSY}^4}, \quad A_R^{ij} \sim \frac{(\Delta m_E^2)_{ij}}{m_{SUSY}^4}$
  - type-I-II-III ➞ only A_L
  - Left-Right model: In principle **both** A_L and A_R
  - Distinguish models: ➞ Positron polarization asymmetry(**MEG**)

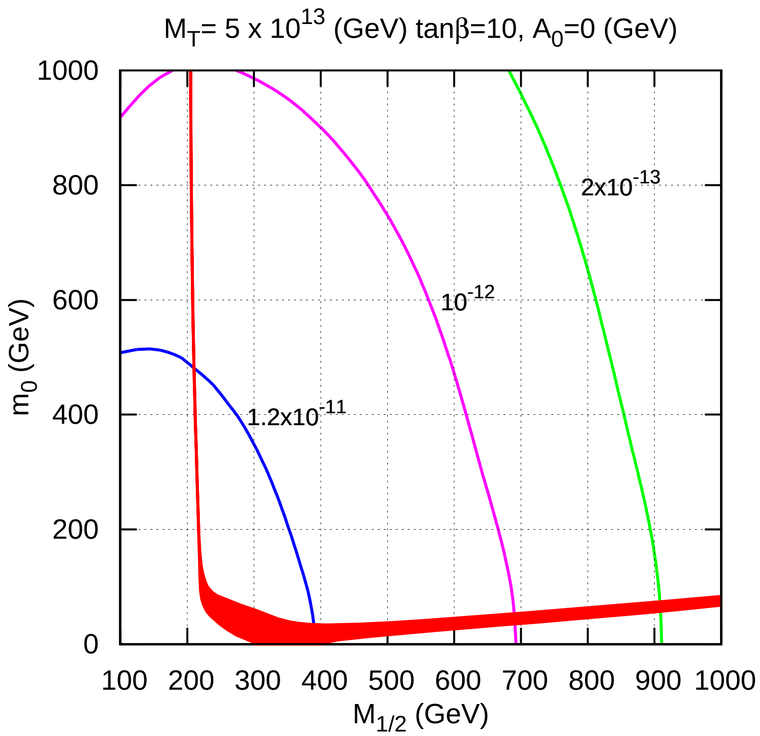
$$\mathcal{A}(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2} = \begin{cases} 1 & \text{type-I-II-III} \\ \neq 1 & \text{LR} \end{cases}$$

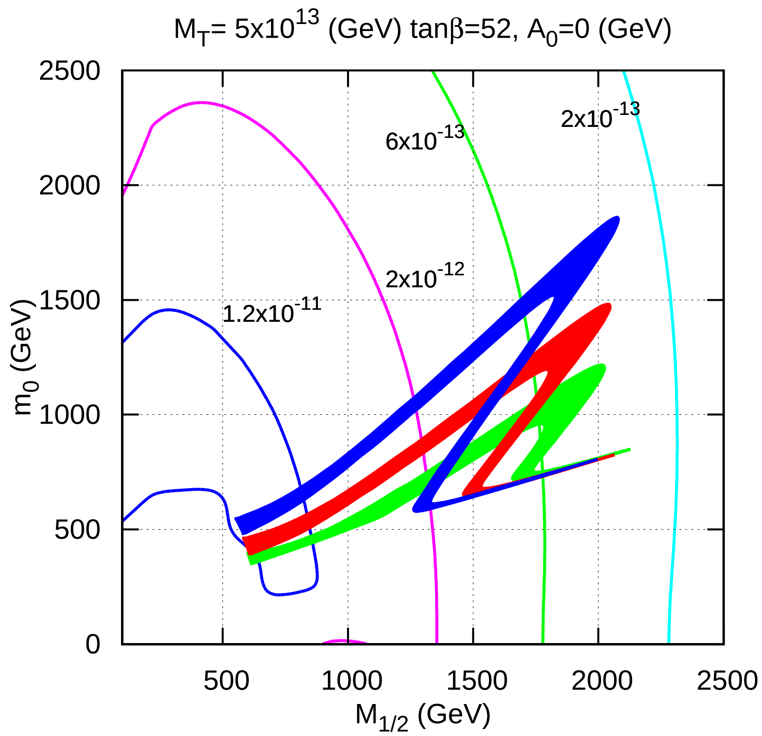
Low-Energy LFV constraints in SUSY seesaw models: type-II

Outline
Motivation
Models
Low-Energy Obs.
• DM & LFV
• $\mathcal{A}(\mu^+ \to e^+ \gamma)$
LHC Observables
Conclusions

- Parameters: SUSY: $\{m_0,\ M_{1/2},\ A_0 = 0,\ \tan\beta = 10, 52,\ \text{sign}(\mu) = +\}$
- Seesaw: $M_T = 5 \times 10^{13}$ GeV
- Dark matter region: WMAP (3σ), $0.081 \leq \Omega h^2 \leq 0.129$
- SPheno(W.Porod), SARAH(F.Staub)

Higgs funnel



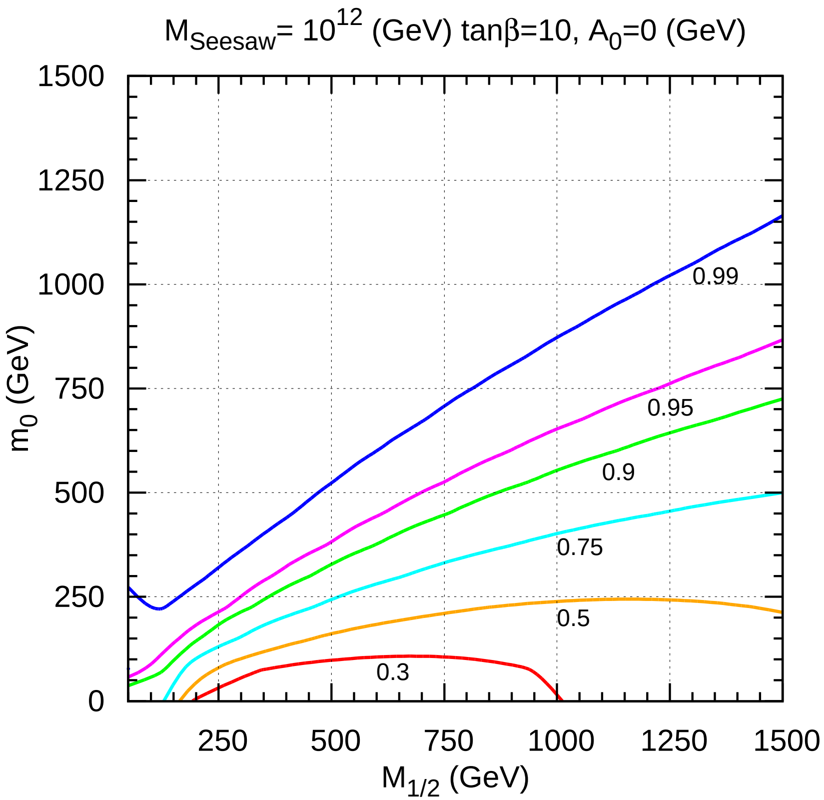


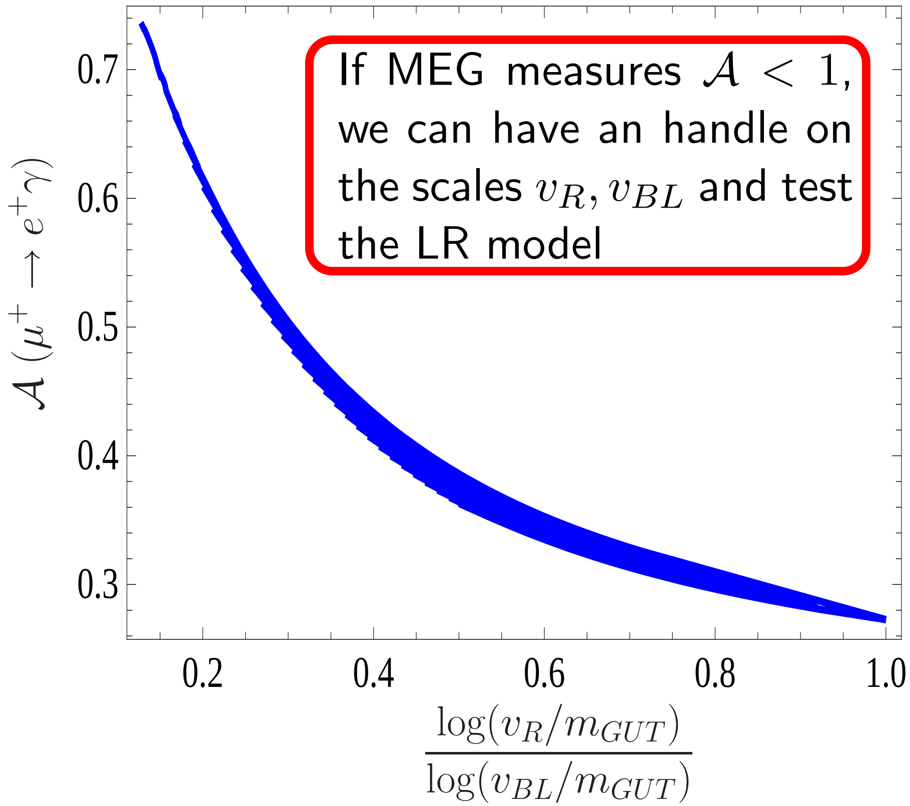
- $m_{top} = 169.1$ GeV (blue), 171.2 GeV (red), 173.3 GeV (green)
- Superimposed are the contour lines for the $Br(\mu \to e\gamma)$

A low-energy observable for Left-Right model: $\mathcal{A}(\mu^+ \to e^+\gamma)$

Outline
Motivation
Models
Low-Energy Obs.
• DM & LFV
• $\mathcal{A}(\mu^+ \to e^+\gamma)$
LHC Observables
Conclusions

- Positron polarization asymmetry: $\mathcal{A}(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}$
- In seesaw type-I-II-III: $\mathcal{A}(\mu^+ \to e^+\gamma) = 1$, as $A_R \simeq 0$
- Parameters:
  - SUSY: SPS3 $\{m_0 = 90, M_{1/2} = 400, A_0 = 0, \tan\beta = 10, \text{sign}(\mu) = +\}$
  - LR: $v_{BL} = 10^{15}$ GeV, $v_R \in [10^{14}, 10^{15}]$ GeV, Y_ν fit





If MEG measures $\mathcal{A} < 1$, we can have an handle on the scales v_R, v_{BL} and test the LR model

Slepton Mass reconstruction at the LHC

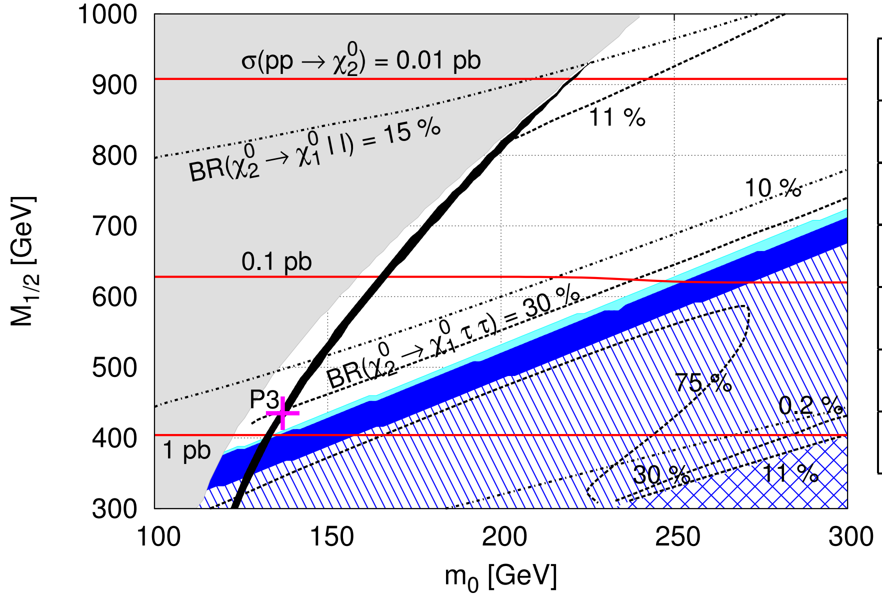
Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
• Slepton mass
• di-muon cMSSM
• di-lepton decays
• Low&High LFV
• $K_{e\mu}$ in LR
Conclusions

- Di-lepton invariant mass distributions from $\chi_2^0 \to \tilde{\ell}^i_{L,R}\ell \to \chi_1^0 \ell\ell$

  For on-shell sleptons & isolated leptons with large $p_T > 10$ GeV

  - $m_{\ell\ell} = \frac{1}{m_{\tilde{\ell}}}\sqrt{\left(m^2_{\chi_2^0} - m^2_{\tilde{\ell}}\right)\left(m^2_{\tilde{\ell}} - m^2_{\chi_1^0}\right)}$ (0.1% precision at LHC)
  - Infer $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j) = \frac{|m_{\tilde{\ell}_i} - m_{\tilde{\ell}_j}|}{<m_{\tilde{\ell}_{i,j}}>}$ @LHC: $\Delta m/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L) \to \mathcal{O}(0.1\%)$, $\Delta m/m_{\tilde{\ell}}(\tilde{\mu}_L, \tilde{\tau}_L) \to \mathcal{O}(1\%)$

- Standard window: Large χ_2^0 production, sizable BR($\chi_2^0 \to \chi_1^0 \ell\ell$), Ωh^2

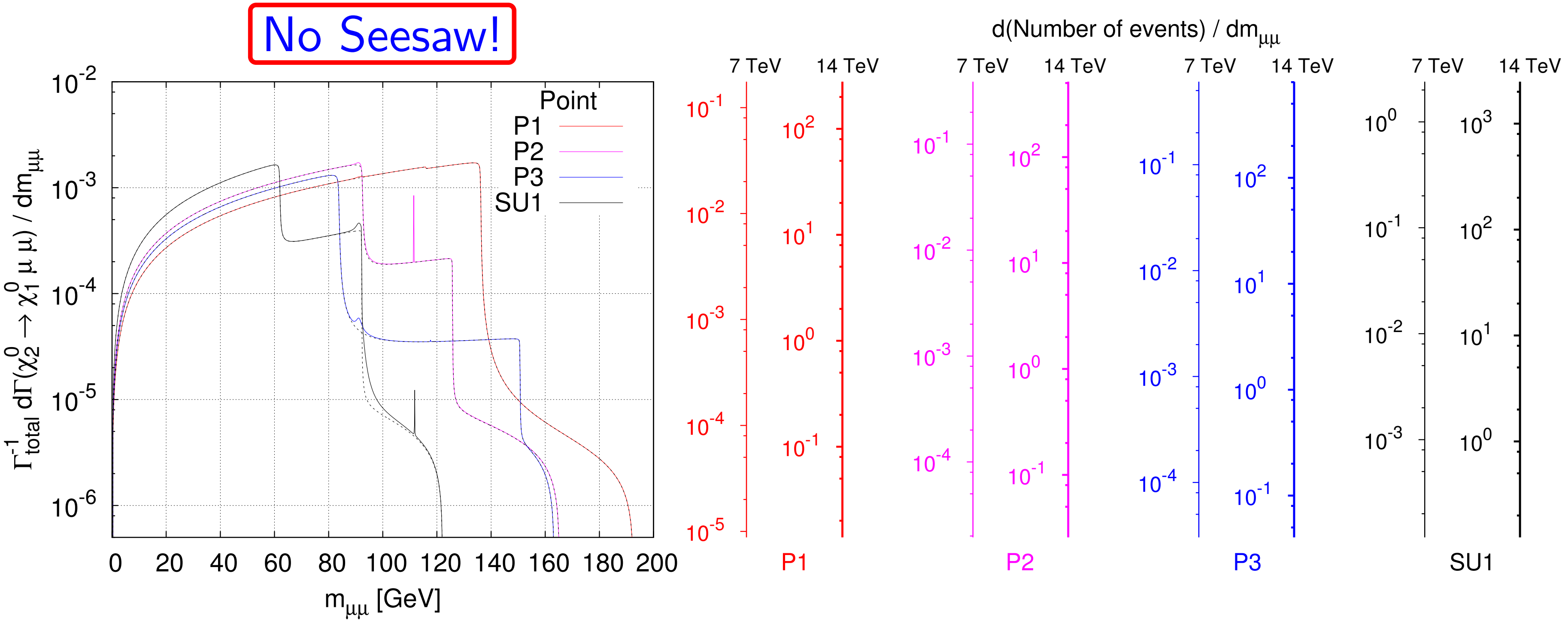


Point	m_0 (GeV)	$M_{1/2}$ (GeV)	A_0 (TeV)	$\tan\beta$
P1	110	528	0	10
P2	110	471	1	10
P3	137	435	-1	10
P4	490	1161	0	40
P5-HM1	180	850	0	10
P6-SU1	70	350	0	10

Proposed cMSSM study points

Di-muon invariant mass distributions in the cMSSM

No Seesaw!



Point	$m_{\chi^0_2}$	$m_{\chi^0_1}$	$m_{\tilde{\ell}_L}$	$m_{\tilde{\ell}_R}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\tau}_1}$	$< m_{\tilde{q}} >$	m_h
P1	410	217	374	231	375	224	1064	115.1
P2	356	191	338	212	335	198	963	111.4
P3	342	179	327	218	325	186	877	117.6
ATLAS-SU1	262	140	251	156	254	147	733	111.8

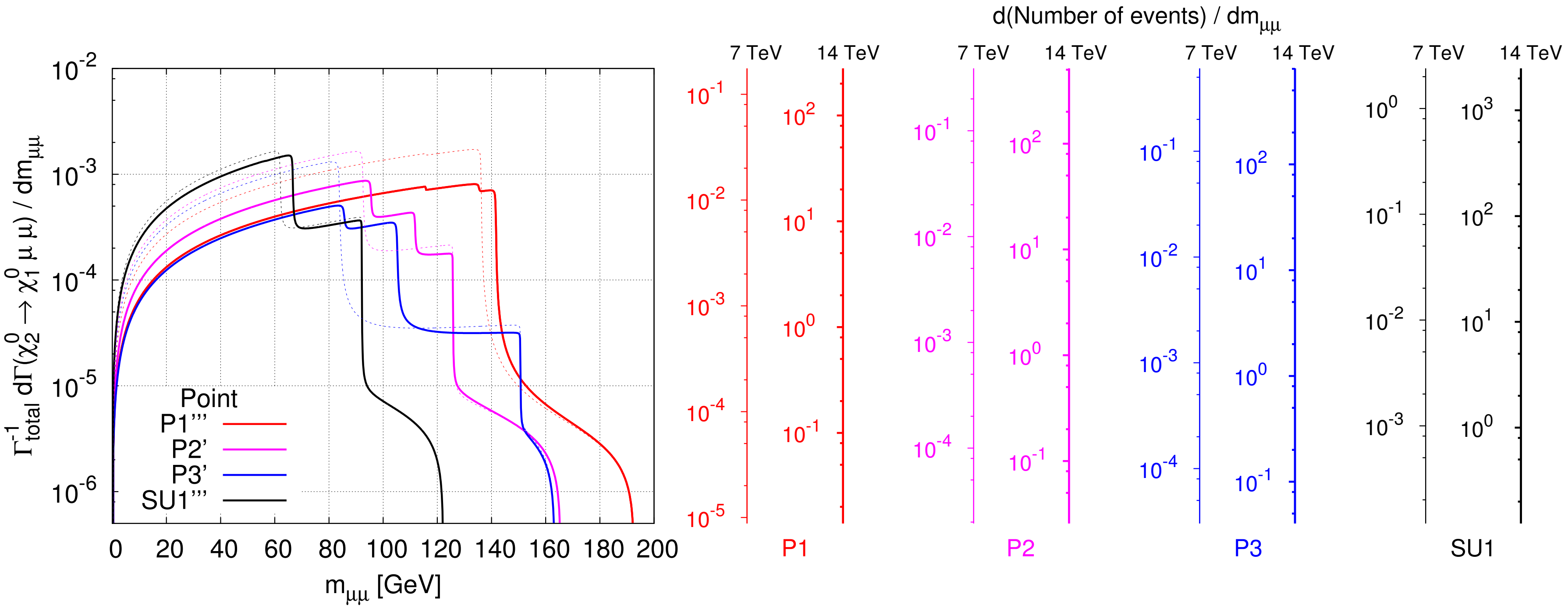
- Double-triangular distributions: intermediate $\tilde{\mu}_L$ and $\tilde{\mu}_R$ in $\chi^0_2 \to \chi^0_1 \mu\mu$
- cMSSM: Superimposed $\tilde{\ell}_{L,R}$ edges for $m_{\mu\mu}$ and m_{ee}: "degenerate" $\tilde{\mu}, \tilde{e}$

LFV at the LHC: di-lepton distributions in χ_2^0 decays (type-I)

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
- Slepton mass
- di-muon cMSSM
- di-lepton decays
- Low&High LFV
- $K_{e\mu}$ in LR
Conclusions

Impact for di-lepton distributions $\chi_2^0 \to \tilde{\ell}^i_{L,R}\ell_i \to \chi_1^0 \ell_i \ell_i$

Seesaw: $M_N = \{10^{10}, 5\times 10^{10}(10^{12}), 5\times 10^{13}(10^{15})\}$ GeV, $\theta_{13} = 0.1°$



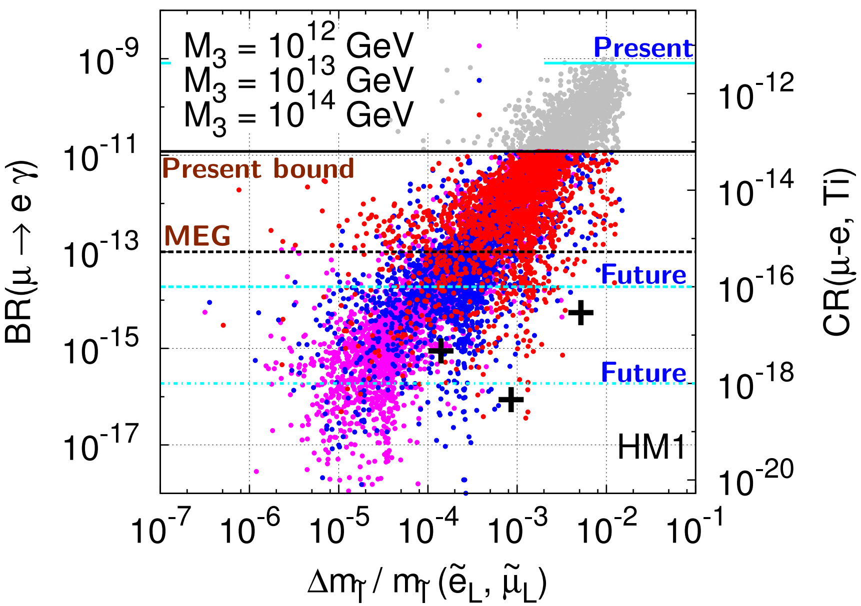
- ❐ Displaced $m_{\mu\mu}$ and m_{ee} edges (ℓ_L) ⇔ sizable $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$
- ❐ Appearance of new edge in $m_{\mu\mu}$: intermediate $\tilde{\tau}_2$
- ❐ LFV at the LHC: e.g $\chi_2^0 \to \tilde{\tau}_2 \mu \to \chi_1^0 \mu\mu$

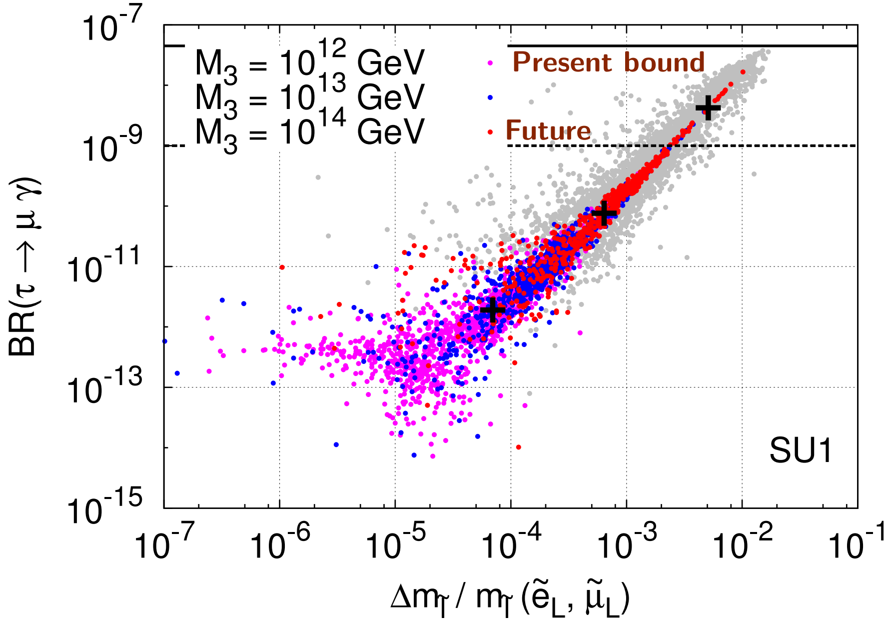
LFV at low- and high-energies: general results for type-I

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
• Slepton mass
• di-muon cMSSM
• di-lepton decays
• Low&High LFV
• $K_{e\mu}$ in LR
Conclusions

mSUGRA points: CMS HM1 {180,850,0,10,+1} & ATLAS SU1 {70,350,0,10,+1}

Seesaw: general scan with $M_{N_3} = 10^{12,13,14}$ GeV, $\theta_{13} = 0.1°$





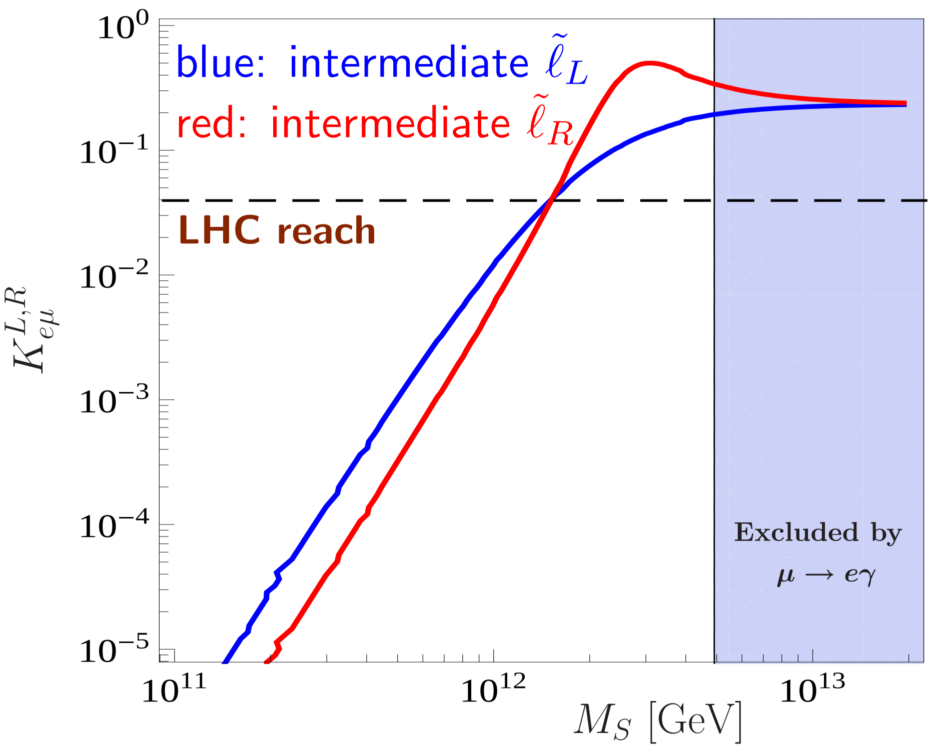
If SUSY observed (HM1, SU1) and type-I seesaw at work:

- LFV observables within experimental reach: $\Delta m|_{\mathrm{SU1}} \lesssim \Delta m|_{\mathrm{HM1}}$
- HM1: $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\mathrm{LHC}} \sim 0.1 - 1\% \to \mathrm{BR}(\mu \to e\gamma)|_{\mathrm{MEG}}$
- SU1: $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\mathrm{LHC}} \sim 0.1 - 1\% \to \mathrm{BR}(\tau \to e\gamma)|_{\mathrm{SuperB}}$

LFV in $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e\mu$: the $K_{e\mu}$ observable in LR Model

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
• Slepton mass
• di-muon cMSSM
• di-lepton decays
• Low&High LFV
• $K_{e\mu}$ in LR
Conclusions

- Observable $K_{e\mu} = \frac{Br(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e\mu)}{Br(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ee) + Br(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mu\mu)}$
- Study for CMS point LM1 {60, 250, 0, 10, +1}: LFV can be discovered @LHC with an integrated luminosity of $10 fb^{-1}$ if $K_{e\mu} \geq K_{e\mu}^{min} = 0.04$



Parameters

- SUSY: SPS3 {90, 400, 0, 10, +1}
- $v_{BL} = 10^{15}$ GeV
- $v_R = 5 \cdot 10^{15}$ GeV

- The SPS3 benchmark point satisfies $m(\tilde{\chi}_2^0) > m(\tilde{l}_i) > m(\tilde{\chi}_1^0)$, and thus the L and R sleptons can be produced on-shell

Conclusions: What can we learn?

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions

- **cMSSM:** no LFV, approximately degenerate $\tilde{e} - \tilde{\mu}$
- SUSY seesaw to account for neutrino masses and mixings:
  - $\dfrac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$ **within LHC sensitivity**
  - New edges in di-lepton distributions
  - Correlation of low- and high-energy LFV observables (e.g. **BR vs** $\Delta m_{\tilde{\ell}}$)
- Possible impact of experimental data:

BRs, CR and $\mathcal{A}(\mu^+ \to e^+\gamma)\vert_{\text{low-energy}}$	⟷	$\Delta m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L)$, $K_{e\mu}\vert_{\text{LHC}}$

  - Substantiate seesaw hypothesis getting hints of the new physics
  - Disfavour SUSY seesaw as the (only) source of flavour violation

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

Backup Slides

The Setup: GUT scale

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• $M_{\rm SS}$ Variation
• Funnel & $M_{\rm SS}$
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

At GUT scale the SU(5) invariant superpotentials are

- Type-I

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

- Type-II

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

- Type-III

$$W_{\rm 24H} = \sqrt{2}\,\bar{5}_M Y^5 10_M\bar{5}_H - \frac{1}{4}10_M Y^{10}10_M 5_H + 5_H 24_M Y_N^{III}\bar{5}_M$$
$$+\frac{1}{2}24_M M_{24}24_M$$

The $SU(5)$-broken phase

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

Under $SU(3) \times SU_L(2) \times U(1)_Y$

- The $\mathbf{5}$, $\mathbf{10}$ and $\mathbf{5}_H$ contain

$$\bar{5} = (d^c, L),\ \ 10 = (u^c, e^c, Q),\ \ 5_H = (H^c, H_u),\ \ \bar{5}_H = (\bar{H}^c, H_d)$$

- The $\mathbf{15}$ decomposes as

$$\mathbf{15} = S(6,1,-\frac{2}{3}) + T(1,3,1) + Z(3,2,\frac{1}{6})$$

- The $\mathbf{24}$ decomposes as

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

Supersymmetric seesaw type-I

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• $M_{\rm SS}$ Variation
• Funnel & $M_{\rm SS}$
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

In the case of seesaw type-I one postulates very heavy right-handed neutrinos yielding the following superpotential below M_{GUT}:

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

For the neutrino mass matrix one obtains the well-known formula

$$m_\nu = -\frac{v_u^2}{2} Y_\nu^T M_R^{-1} Y_\nu$$

Inverting the seesaw equation, allows to express Y_ν as (Casas & Ibarra)

$$Y_\nu = \sqrt{2}\frac{i}{v_u}\sqrt{\hat{M}_R} \cdot R \cdot \sqrt{\hat{m}_\nu} \cdot U^\dagger$$

where the $\hat{m}_\nu$ and $\hat{M}_R$ are diagonal matrices containing the corresponding eigenvalues. R is in general a complex orthogonal matrix.

IST

Supersymmetric seesaw type-II

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• $M_{\rm SS}$ Variation
• Funnel & $M_{\rm SS}$
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

Below M_{GUT} in the $SU(5)$-broken phase the superpotential reads

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

where fields with index 1 (2) originate from the 15-plet ($\overline{15}$-plet). The effective mass matrix is

$$m_\nu = -\frac{v_u^2}{2}\frac{\lambda_2}{M_T}Y_T.$$

Note that

$$\hat{Y}_T = U^T \cdot Y_T \cdot U \ ,$$

i.e. Y_T is diagonalized by the same matrix as m_ν. If all neutrino eigenvalues, angles and phases were known, Y_T would be fixed up to an overall constant.

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

Supersymmetric seesaw type-III

In the $SU(5)$ broken phase the superpotential becomes

$$\begin{aligned} W_{III} \;&=\; W_{MSSM} + \widehat{H}_u(\widehat{W}_M Y_N - \sqrt{\frac{3}{10}}\widehat{B}_M Y_B)\widehat{L} + \widehat{H}_u \widehat{\bar{X}}_M Y_X \widehat{D}^c \\ &+\frac{1}{2}\widehat{B}_M M_B \widehat{B}_M + \frac{1}{2}\widehat{G}_M M_G \widehat{G}_M + \frac{1}{2}\widehat{W}_M M_W \widehat{W}_M + \widehat{X}_M M_X \widehat{\bar{X}}_M \end{aligned}$$

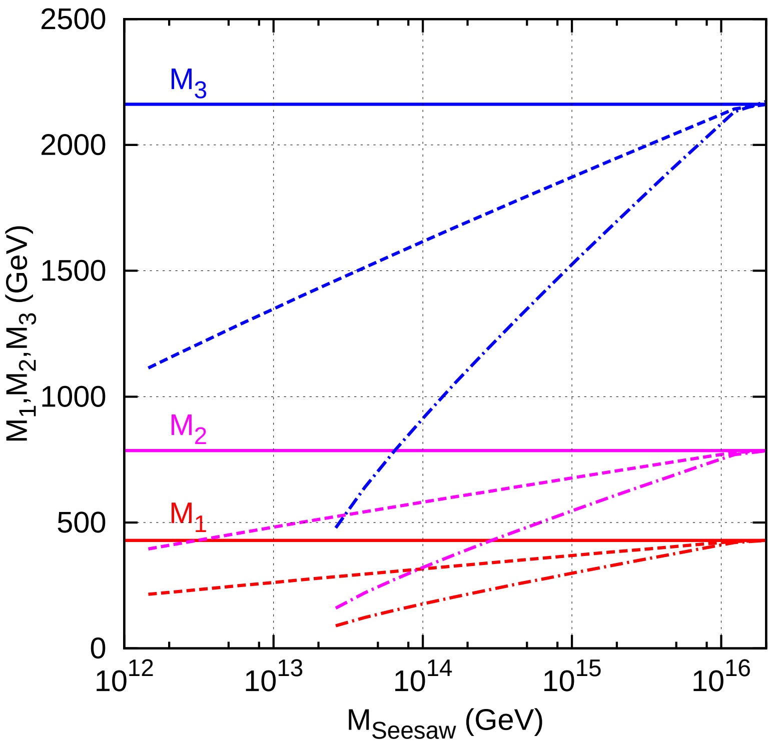
giving

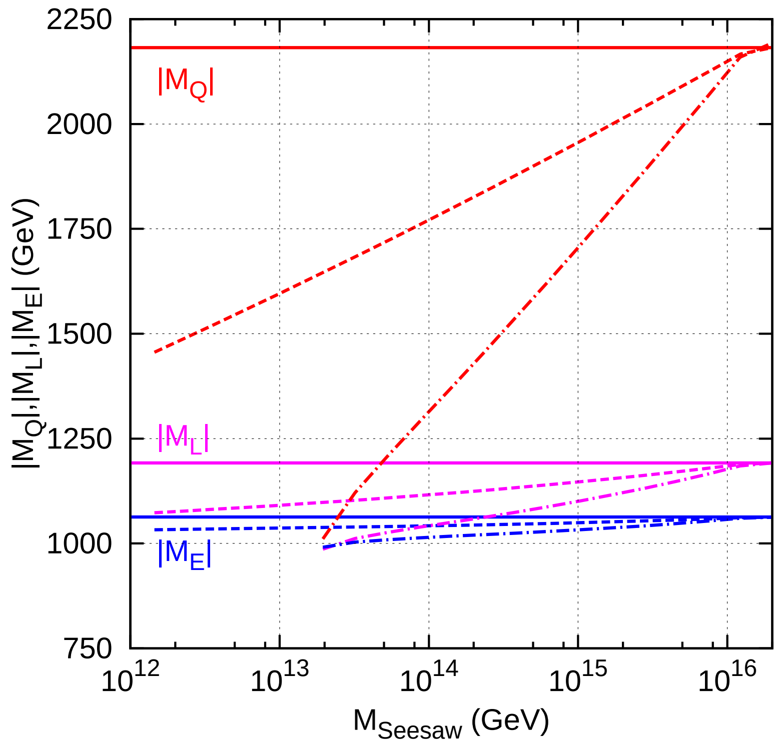
$$m_\nu = -\frac{v_u^2}{2}\left(\frac{3}{10}Y_B^T M_B^{-1} Y_B + \frac{1}{2}Y_W^T M_W^{-1} Y_W\right) \simeq -v_u^2 \frac{4}{10} Y_W^T M_W^{-1} Y_W$$

where the last step is justified as we start from universal couplings and masses at M_{GUT} we find that at the seesaw scale one still has $M_B \simeq M_W$ and $Y_B \simeq Y_W$. One can use the corresponding Casas-Ibarra decomposition for Y_W as in type-I up to the overall factor $4/5$.

Variation of the soft masses.

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR





Mass parameters at $Q = 1$ TeV versus the seesaw scale for fixed high scale parameters $m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. The full lines correspond to seesaw type-I, the dashed ones to type-II and the dash-dotted ones to type-III. In all cases a degenerate spectrum of the seesaw particles has been assumed.

IST

Variation on the Spectra

Outline

Motivation

Models

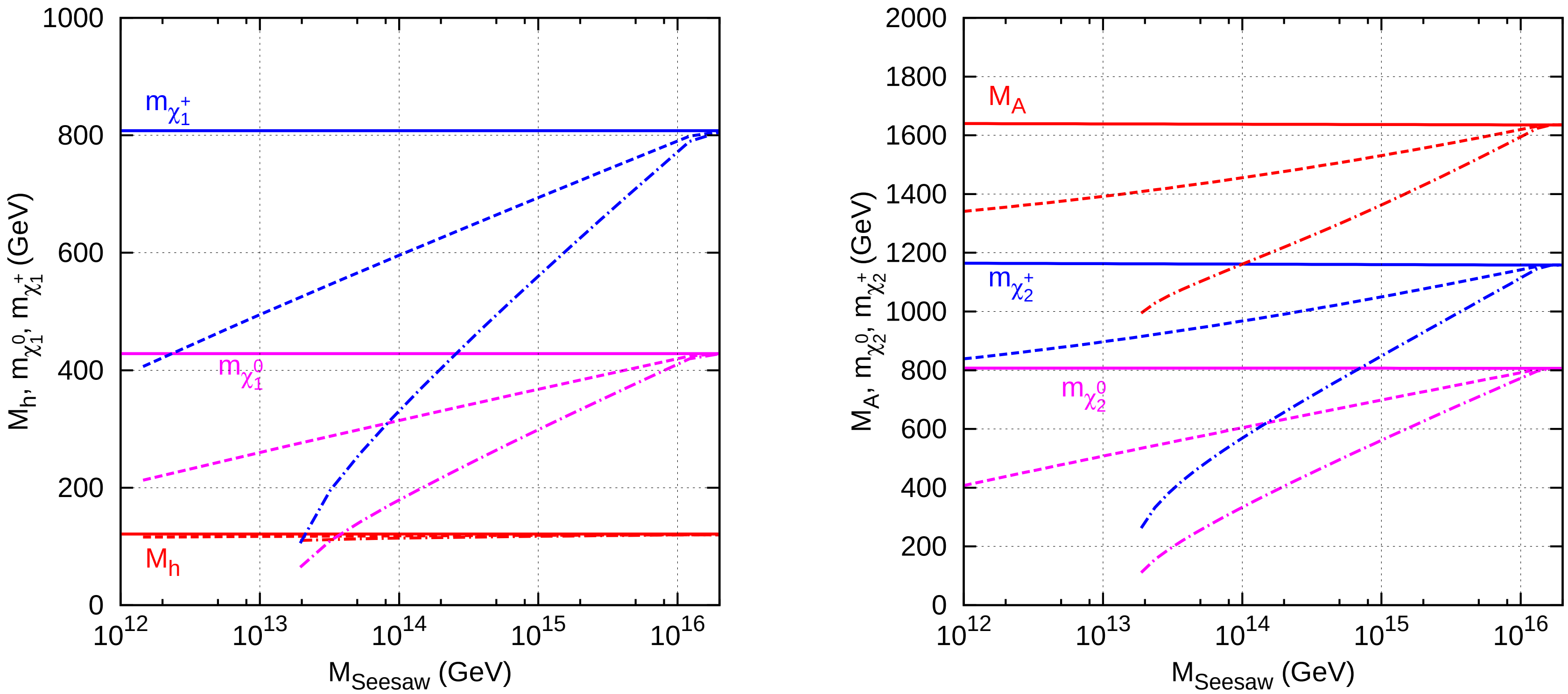
Low-Energy Obs.

LHC Observables

Conclusions

Backup Slides

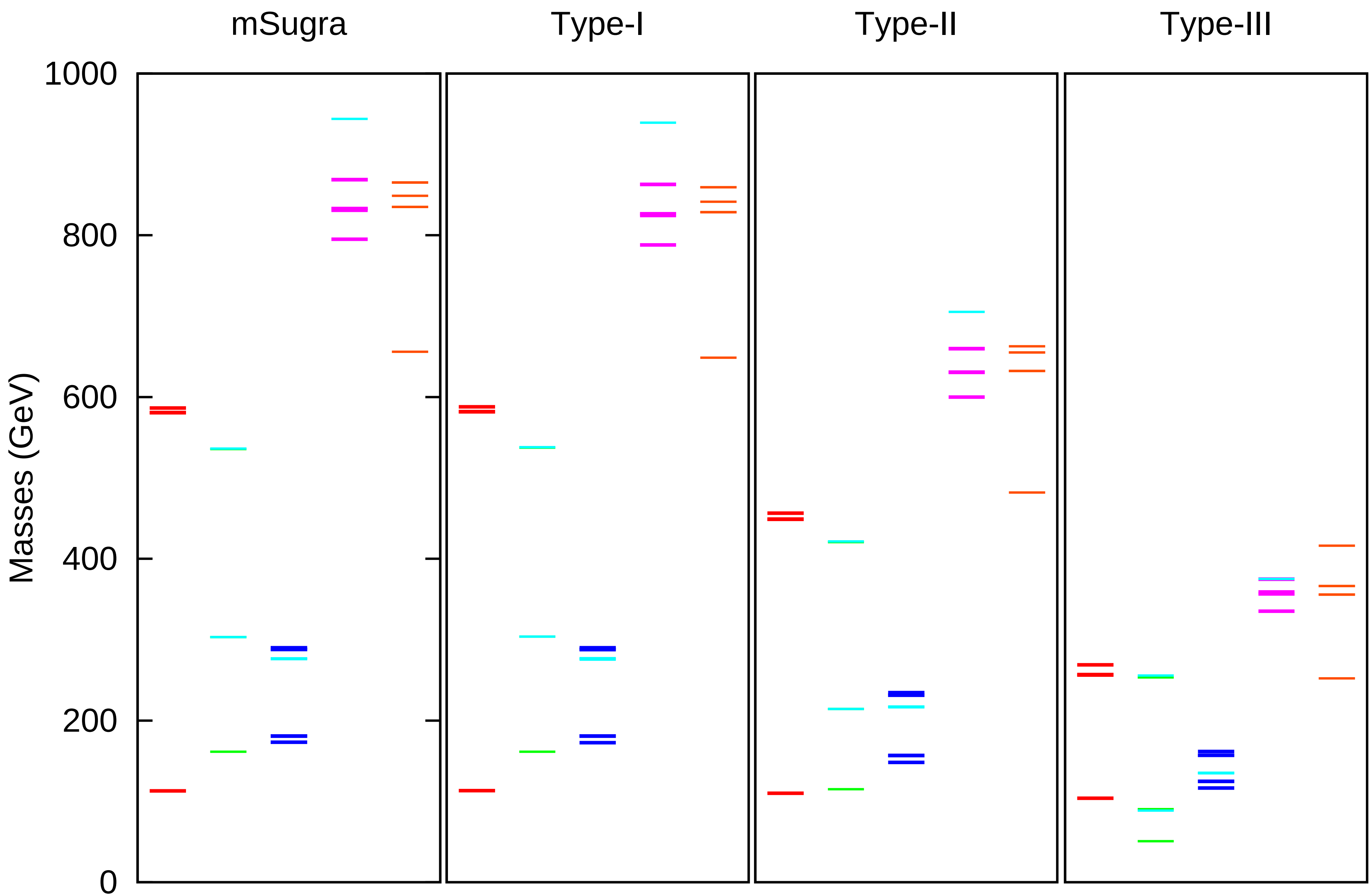
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- M_{SS} Variation
- Funnel & M_{SS}
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR



Example of spectra at $Q = 1$ TeV versus the seesaw scale for fixed high scale parameters $m_0 = M_{1/2} = 1$ TeV, $\tan\beta = 10$ and $\mu > 0$. On left panel $M_h, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^+}$ while on the right panel we have $M_A, m_{\chi_2^0}, m_{\tilde{\chi}_2^+}$.

Comparison for SPS3 ($M_{\text{Seesaw}} = 10^{14}$ GeV)

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- M_{SS} Variation
- Funnel & M_{SS}
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR



$m_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $\tan\beta = 10$, $A_0 = 0$ GeV, $\mu > 0$

Neutrino masses and mixings

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- Being complex symmetric, the light Majorana neutrino mass matrix is diagonalized by a unitary 3×3 matrix U

$$\hat{m}_\nu = U^T \cdot m_\nu \cdot U$$

- For U we will use the standard form

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

parameter	best fit	2-σ
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.59^{+0.23}_{-0.18}$	$7.22 - 8.03$
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	$2.18 - 2.64$
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	$0.29 - 0.36$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	$0.39 - 0.63$
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Lepton Flavour Violation (LFV) constraints

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- All these seesaw models have built in LFV, as they are models for neutrino masses. LFV is highly constrained
- We summarize the current bounds on the LFV observables, as well as the future sensitivity:

LFV process	Present bound	Future sensitivity
BR($\mu \to e\gamma$)	1.2×10^{-11}	10^{-13}
BR($\tau \to e\gamma$)	1.1×10^{-7}	10^{-9}
BR($\tau \to \mu\gamma$)	4.5×10^{-8}	10^{-9}
BR($\mu \to 3e$)	1.0×10^{-12}	
BR($\tau \to 3e$)	3.6×10^{-8}	2×10^{-10}
BR($\tau \to 3\mu$)	3.2×10^{-8}	2×10^{-10}
CR($\mu - e$, Ti)	4.3×10^{-12}	$\mathcal{O}(10^{-16})(\mathcal{O}(10^{-18}))$
CR($\mu - e$, Au)	7×10^{-13}	
CR($\mu - e$, Al)		$\mathcal{O}(10^{-16})$

Dark Matter

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- Standard cosmology requires the existence of a non-baryonic dark matter (DM) contribution to the total energy budget of the universe.
- In the past few years estimates of the DM abundance have become increasingly precise. The Particle Data Group now quotes at 1 σ c.l.

$$\Omega_{DM} h^2 = 0.110 \pm 0.006$$

- Since the data from the WMAP satellite and large scale structure formation is best fitted if the DM is cold, weakly interacting mass particles (WIMP) are currently the preferred explanation. While there is certainly no shortage of WIMP candidates, the literature is completely dominated by studies of the lightest neutralino.

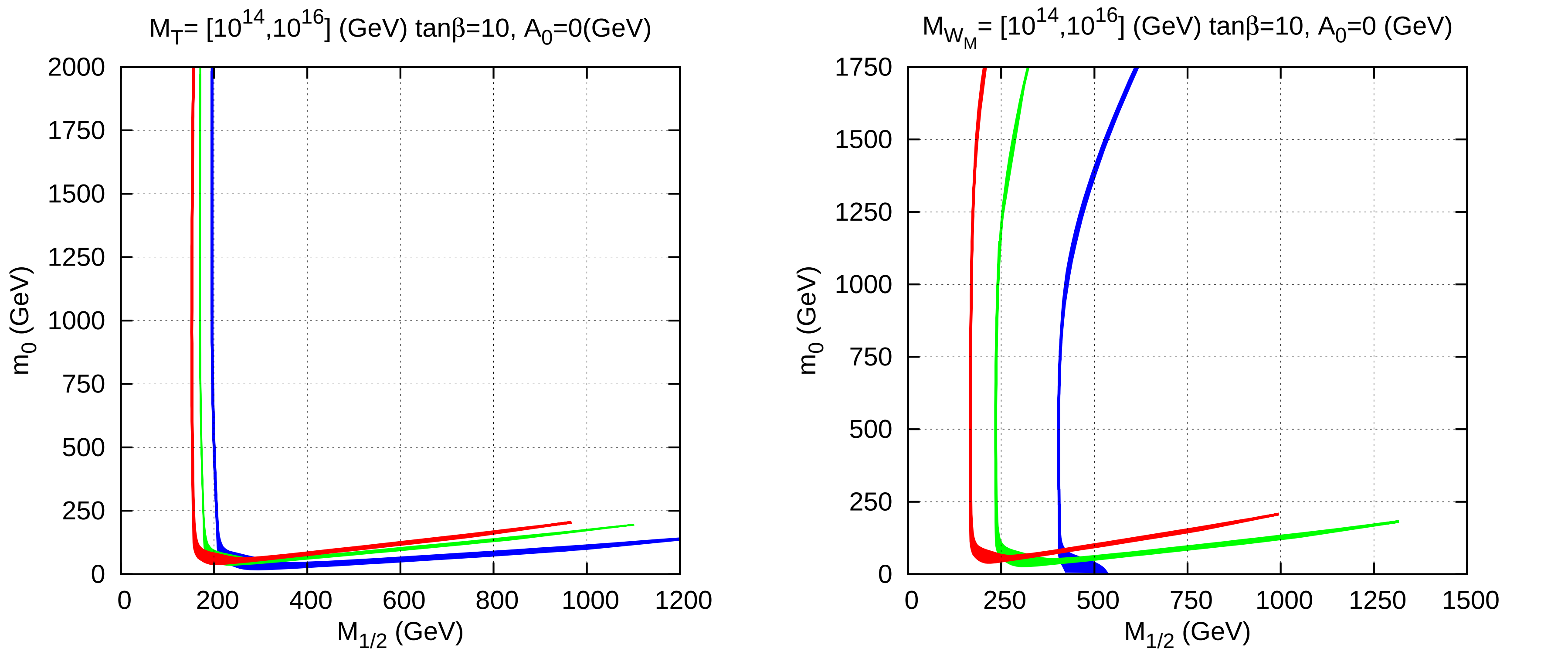
The Numerical Procedure

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- M_{SS} Variation
- Funnel & M_{SS}
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR

- All the plots shown below are based on the program packages `SPheno` and `micrOMEGAs`.
- We use `SPheno` version 3, including the RGEs for Seesaw Type I, II and III at the 2-loop level (calculated with `Sarah`).
- For any given set of mSugra and type-I, type-II or type-III parameters, SPheno calculates the supersymmetric particle spectrum at the electro-weak scale, which is then interfaced with micrOMEGAs2.4 to calculate the relic density of the lightest neutralino, $\Omega_{\chi_1^0} h^2$. All points satisfy neutrino data.
- For the standard model parameters we use the PDG 2008 values. As discussed below, especially important are the values (and errors) of the bottom and top quark masses, $m_b = 4.2 + 0.17 - 0.07$ GeV and $m_t = 171.2 \pm 2.1$ GeV. Note, the m_t is understood to be the pole-mass and $m_b(m_b)$ is the $\overline{MS}$ mass.
- For the allowed range for $\Omega_{DM} h^2$ we always use the 3 σ c.l. boundaries, i.e. $\Omega_{DM} h^2 = [0.081, 0.12.69]$. Note, however that the use of 1 σ contours results in very similar plots, due to the small error bars.
- We define our "standard choice" of mSugra parameters as $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ and use these values in all plots, unless specified otherwise.

Variation with the Seesaw Scale

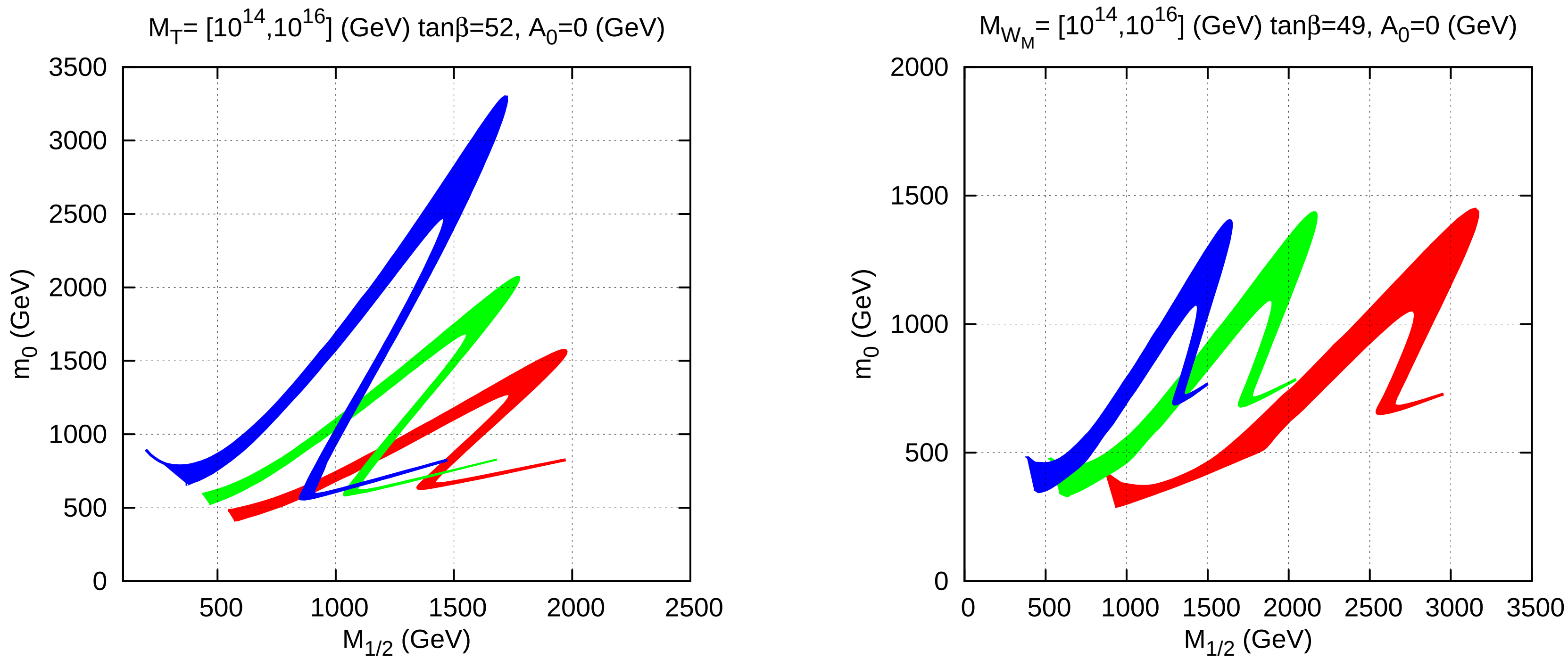
Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- M_{SS} Variation
- Funnel & M_{SS}
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR



Allowed region for dark matter density ($0.081 < \Omega_{\chi_1^0} h^2 < 0.129$) in the $(m_0, M_{1/2})$ plane for the "standard choice" $\tan\beta = 10$, $A_0 = 0$ and $\mu \geq 0$, for three values from M_T, $M_T = 10^{14}$ GeV (blue), to $M_T = 10^{16}$ GeV (red). Left (right) for panel type-II (type-III).

Variation of the Higgs Funnel with M_{Seesaw}

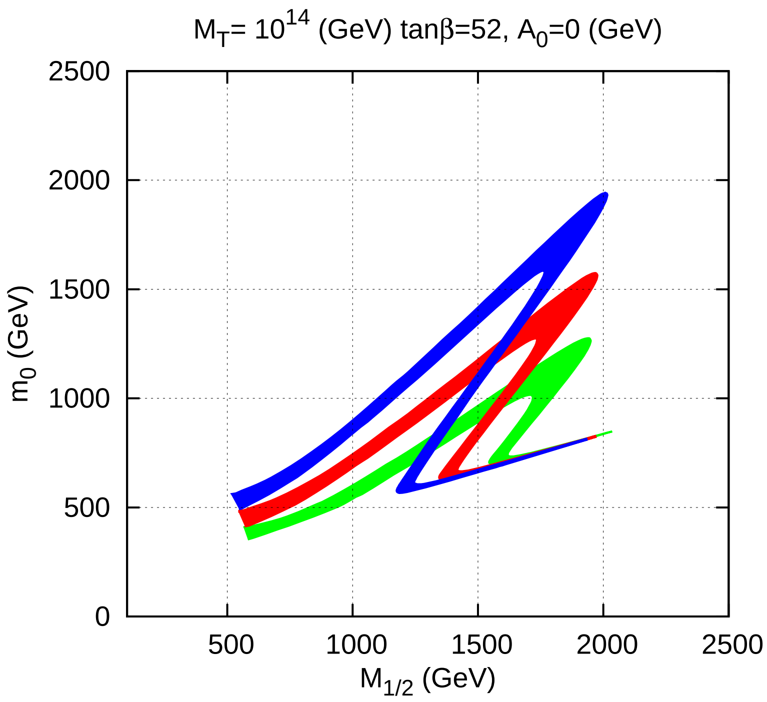
Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

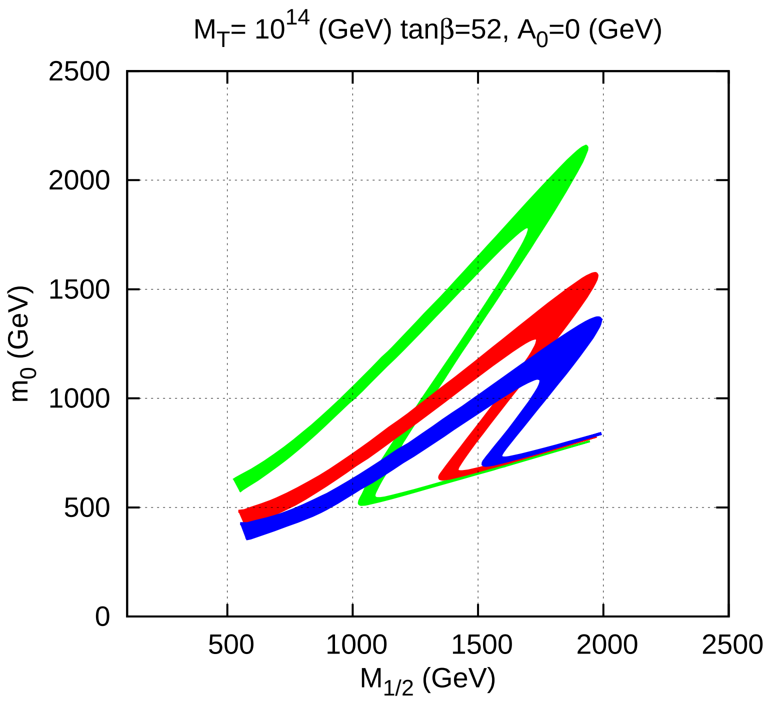


Allowed region for dark matter density in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$, for (from bottom to top) $M_T = 10^{14}$ GeV (red), $M_T = 10^{15}$(green) and $M_T = 10^{16}$ GeV (blue). Left panel for seesaw type-II with $\tan\beta = 52$ and right panel for seesaw type-III with $\tan\beta = 49$.

Variation of the Higgs Funnel with $m_{\rm top}$ & m_b (type-II)

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- $M_{\rm SS}$ Variation
- Funnel & $M_{\rm SS}$
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR

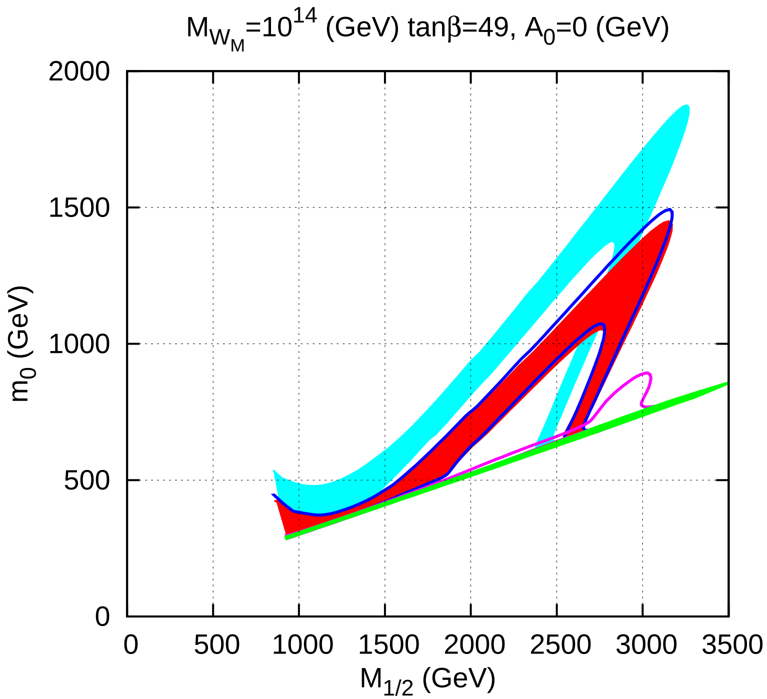


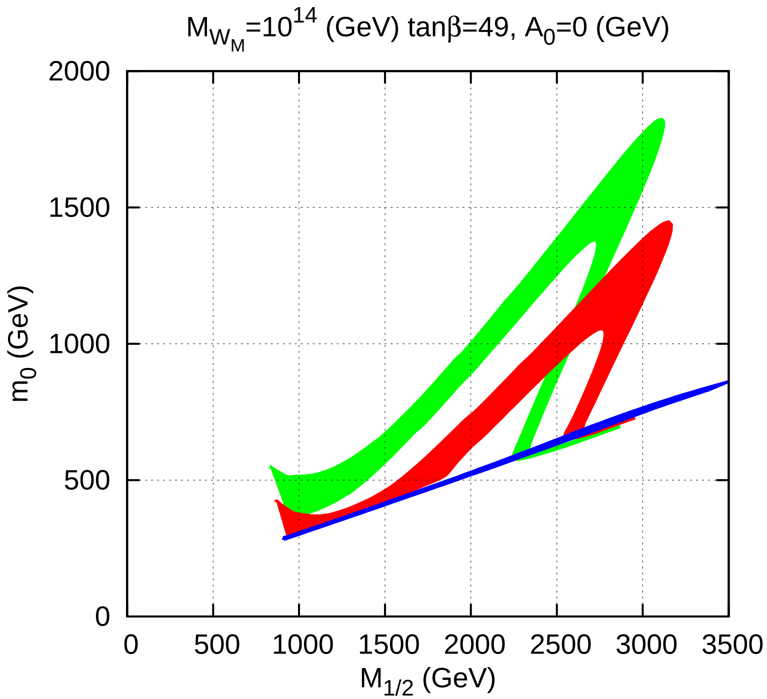


Allowed region for the dark matter density in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 52$, for $M_T = 10^{14}$ GeV and (to the left) for three values of $m_{top} = 169.1$GeV (blue), $m_{top} = 171.2$ GeV (red) and $m_{top} = 173.3$ GeV (green). To the right: The same, but varying m_b. $m_{bot} = 4.13$ GeV (blue), $m_{bot} = 4.2$ GeV (red) and $m_{bot} = 4.37$ GeV (green).

Variation of the Higgs Funnel with m_{top} & m_b (type-III)

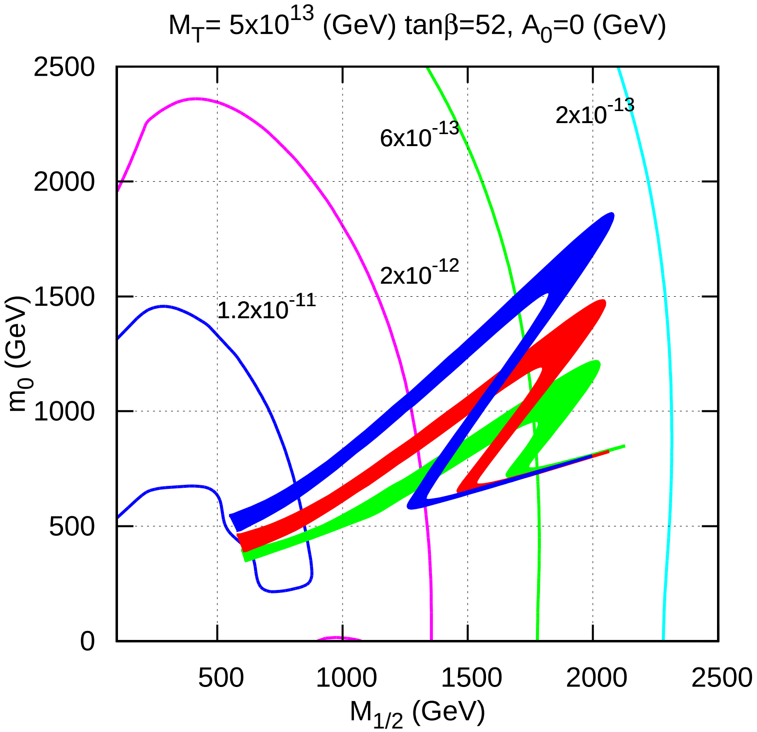
Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- M_{SS} Variation
- Funnel & M_{SS}
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR

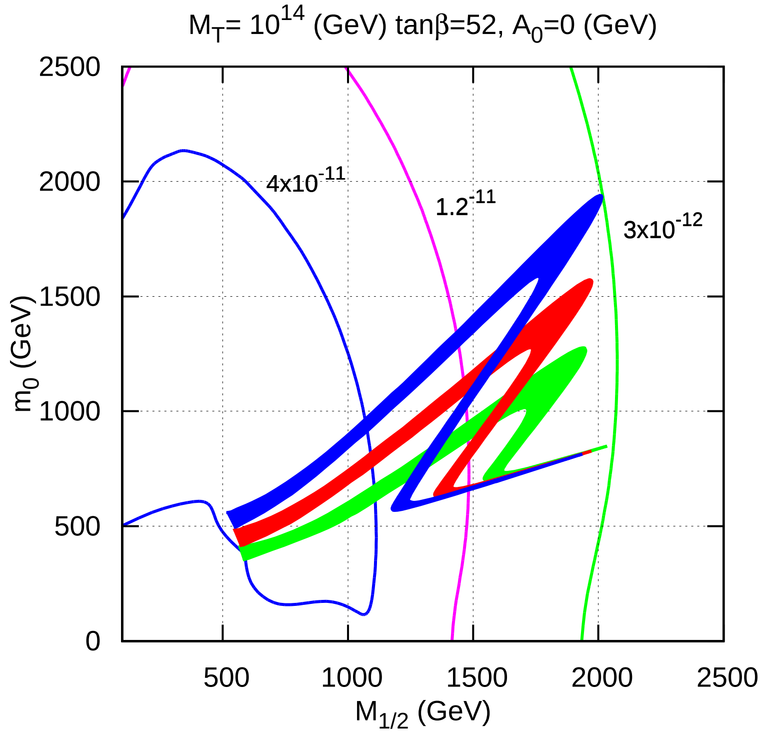




Allowed region for the dark matter density in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 52$, for $M_T = 10^{14}$ GeV and (to the left) for five values of $m_{top} = 168$GeV (cyan) $m_{top} = 169.1$GeV (blue), $m_{top} = 171.2$ GeV (red), $m_{top} = 171.4$ GeV (magenta) and $m_{top} = 173.3$ GeV (green). To the right: The same, but varying m_b. $m_{bot} = 4.13$ GeV (blue), $m_{bot} = 4.2$ GeV (red) and $m_{bot} = 4.37$ GeV (green).

DM & LFV: Seesaw type-II





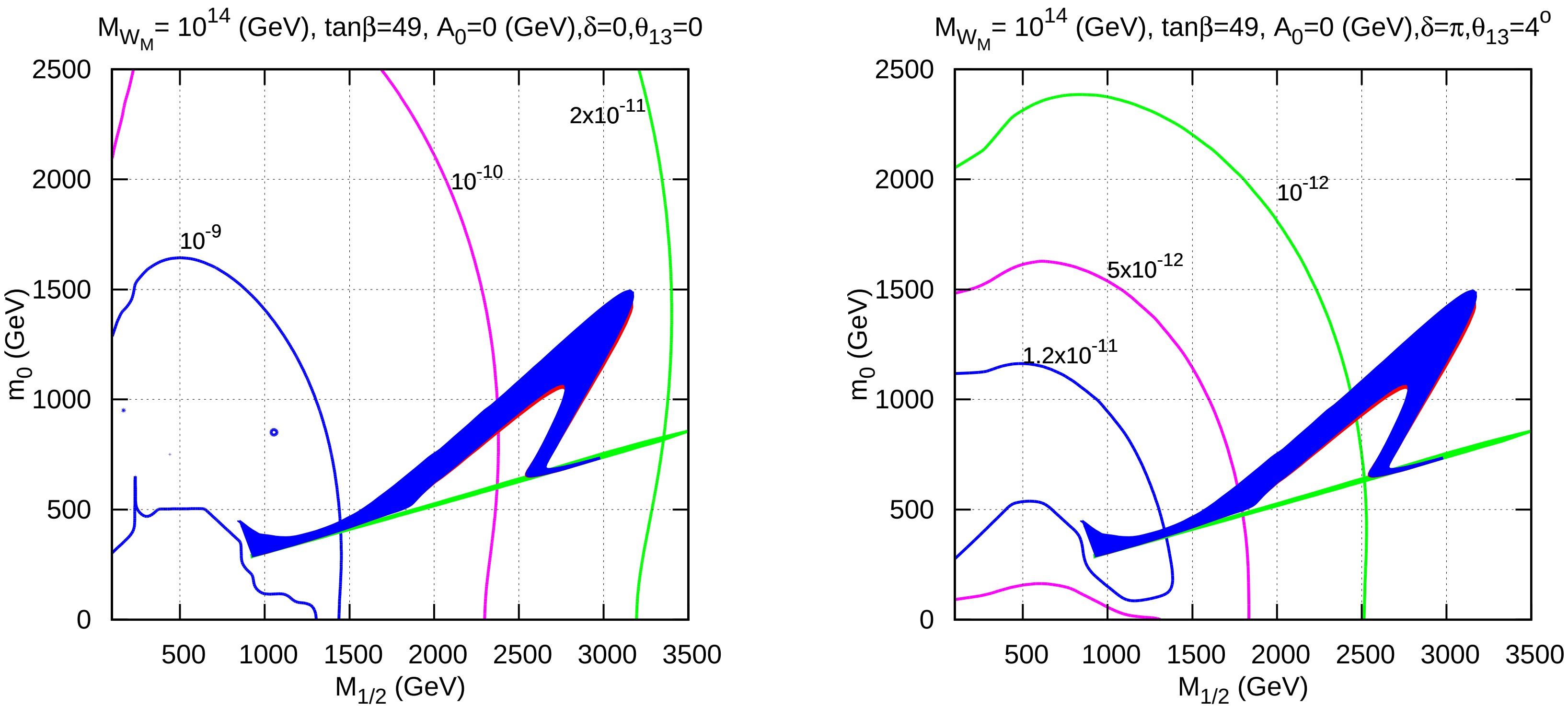
Allowed region for dark matter density $(0.081 < \Omega_{\chi_1^0} h^2 < 0.129)$ in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 52$, for three values of $m_{top} = 169.1$ GeV (blue), $m_{top} = 171.2$ GeV (red) and $m_{top} = 173.3$ GeV (green) for $M_T = 5 \times 10^{13}$ (left panel) and for $M_T = 10^{14}$ (right panel). Superimposed are the contour lines for the $Br(\mu \to e\gamma)$.

Dark Matter and Lepton Flavour Violation: Seesaw type-III

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- Parameters: SUSY: $\{m_0, M_{1/2}, A_0 = 0, \tan\beta = 49, \text{sign}(\mu) = +\}$
- Seesaw: $M_{W_M} = 10^{14}$ GeV. Neutrinos: $\{\delta, \theta_{13}\} = \{\{0, 0°\}, \{\pi, 4°\}\}$
- Dark matter region: WMAP (3σ), $0.081 \leq \Omega h^2 \leq 0.129$

Higgs funnel



- $m_{top} = 169.1$ GeV (blue), 171.2 GeV (red), 173.3 GeV (green)
- Superimposed are the contour lines for the $Br(\mu \to e\gamma)$

IST

Comparison of $\mu \to e\gamma$ for the three sessaw types

Outline

Motivation

Models

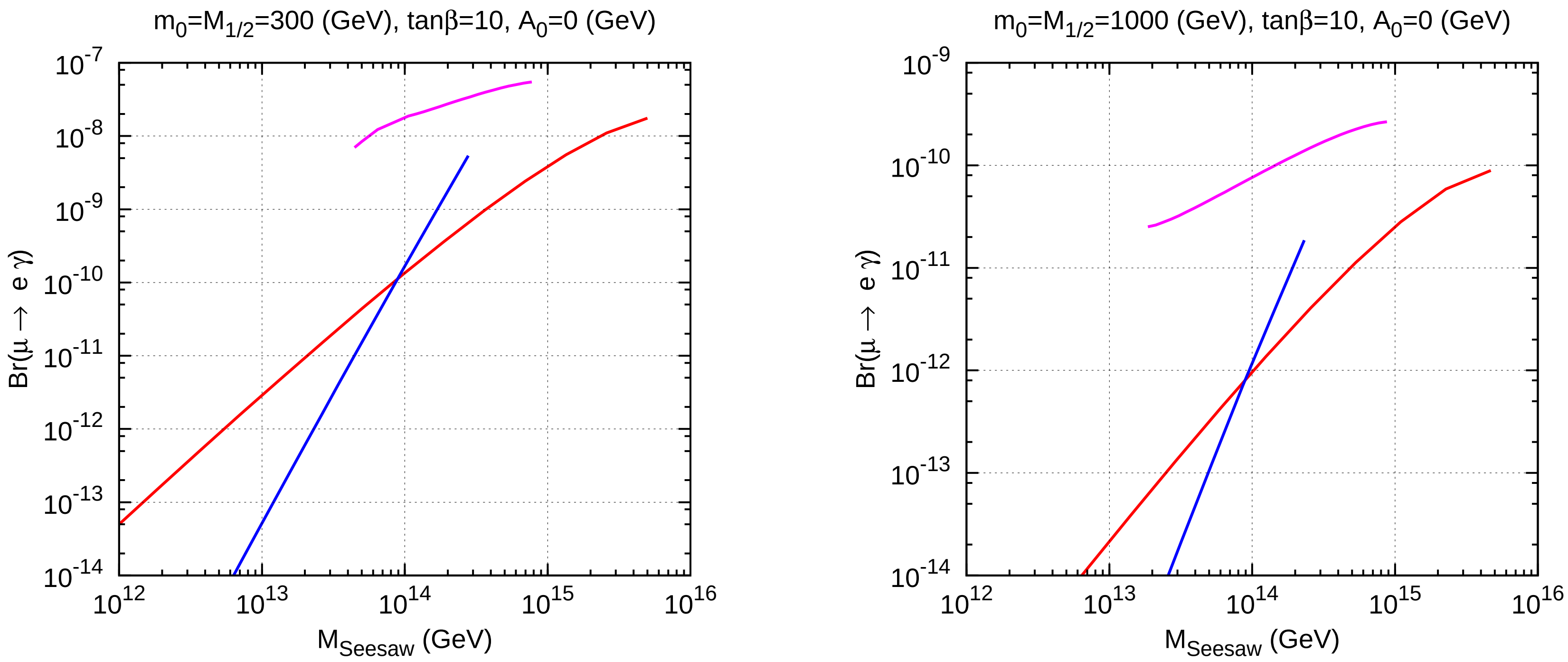
Low-Energy Obs.

LHC Observables

Conclusions

Backup Slides

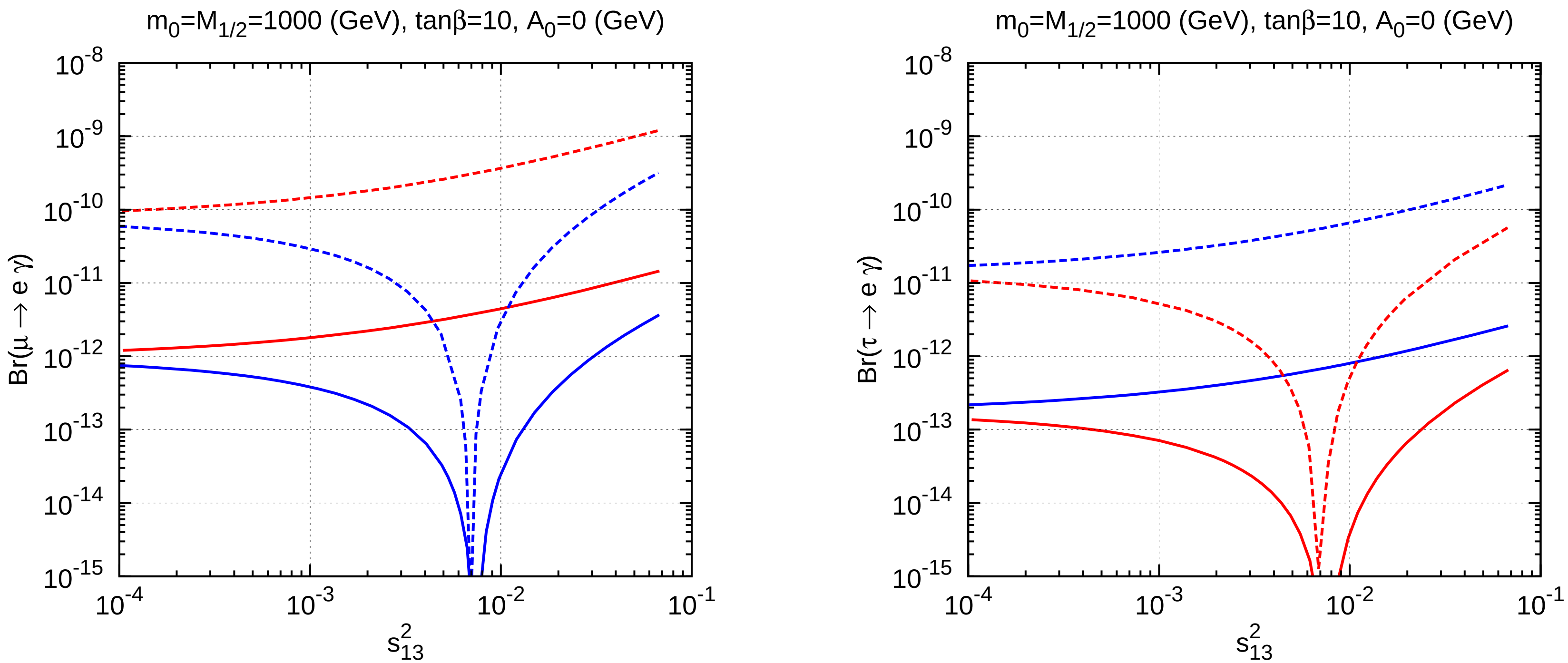
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- M_{SS} Variation
- Funnel & M_{SS}
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR



$Br(\mu \to e\gamma)$ as a function of the seesaw scale for seesaw type-I (red line), seesaw type-II (blue line) and seesaw type-III (magenta line). In case of type-I and type-III a degenerate spectrum has been assumed. On the left panel $m_0 = m_{1/2} = 300$ (GeV), on the right panel $m_0 = m_{1/2} = 1000$ (GeV). In both cases we take $\tan\beta = 10$, A_0=0 and $\mu > 0$.

Possible way out for type-III: Cancellations

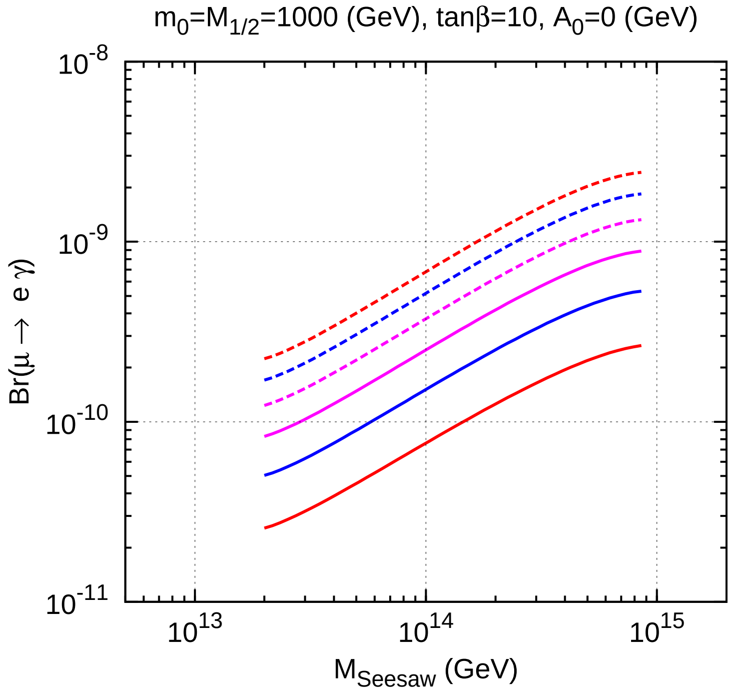
Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
- GUT scale
- Below GUT
- type-I
- type-II
- type-III
- Spectra
- Neutrino data
- LFV Constraints
- Dark Matter
- Procedure
- M_{SS} Variation
- Funnel & M_{SS}
- Funnel &mt mb
- LFV & type-III
- LFV in LR
- DM & LFV
- LFV decays
- MS in LR

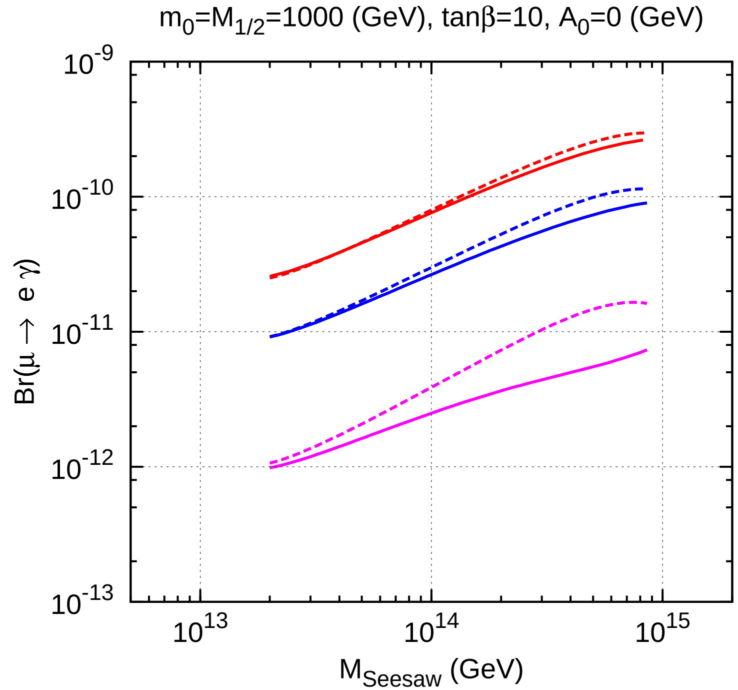


$Br(\mu \to e\gamma)$ (left) and $Br(\tau \to e\gamma)$ (right) versus s^2_{13} for $m_0 = M_{1/2} = 1000$ GeV, $\tan\beta = 10$, $A_0 = 0$ GeV and $\mu > 0$, for seesaw type-I (solid lines) and seesaw type-III (dashed lines), for $M_{\text{Seesaw}} = 10^{14}$ GeV. The curves shown are for 2 values of the Dirac phase: $\delta = 0$ (red) and $\delta = \pi$ (blue), both for normal hierarchy.

Possible way out for type-III: Cancellations

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR



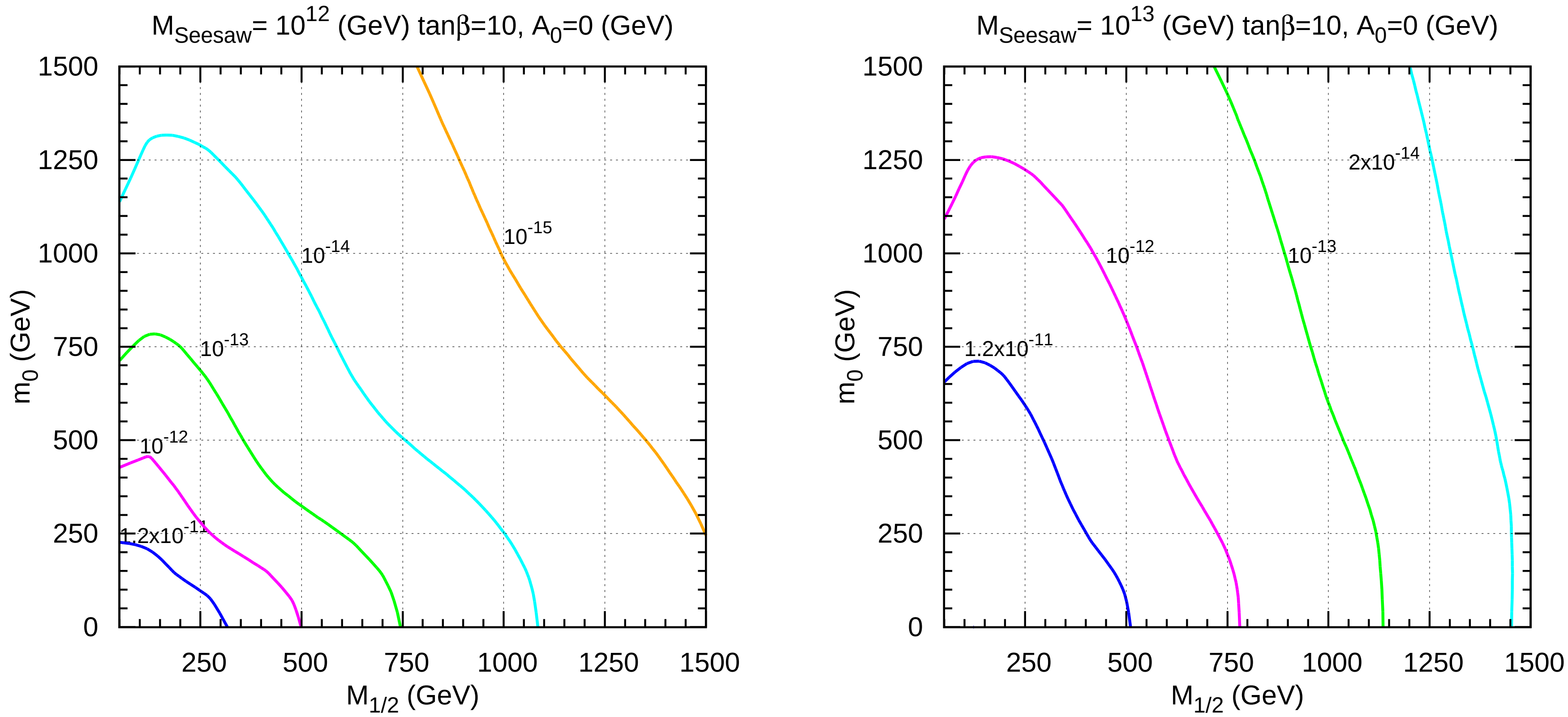


$\mu \to e\gamma$ versus M_{SS} for $m_0 = M_{1/2} = 1000$ GeV, $\tan\beta = 10$, $A_0 = 0$ GeV and $\mu > 0$, for seesaw type-III. On the left $\delta_{\rm Dirac} = 0$ and on the right $\delta_{\rm Dirac} = \pi$. The curves shown are for $\theta_{13} = 0$ (solid red), $\theta_{13} = 2$ (solid blue), $\theta_{13} = 4$ (solid magenta), $\theta_{13} = 6$ (dashed magenta), $\theta_{13} = 8$ (dashed blue), $\theta_{13} = 10$ (dashed red).

Lepton Flavour Violation: Left-Right model

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• $M_{\rm SS}$ Variation
• Funnel & $M_{\rm SS}$
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- Parameters: SUSY: $\{m_0,\, M_{1/2},\, A_0 = 0,\, \tan\beta = 10,\, \mathrm{sign}(\mu) = +\}$
- Seesaw: $v_{BL} = 10^{14}$ GeV, $v_R = 10^{15}$, $M_S = 10^{12}, 10^{13}$ GeV.
- Neutrinos: Y_ν fit

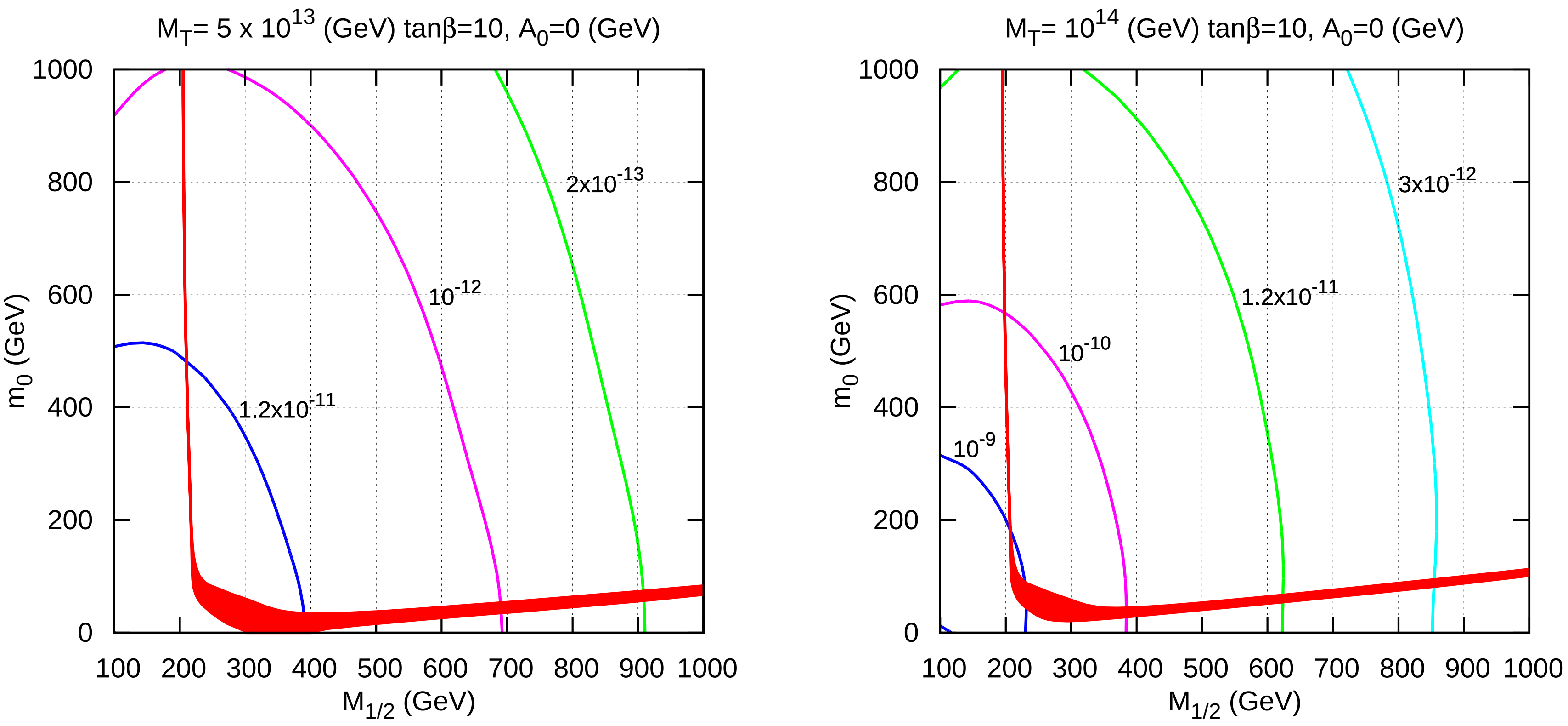


- Superimposed are the contour lines for the $Br(\mu \to e\gamma)$

Low-Energy LFV constraints in SUSY seesaw models: type-II

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- Parameters: SUSY: $\{m_0, M_{1/2}, A_0 = 0, \tan\beta = 10, \text{sign}(\mu) = +\}$
- Seesaw type-II: $M_T = 5 \times 10^{13}, 10^{14}$ GeV
- Dark matter region: WMAP (3σ), $0.081 \le \Omega h^2 \le 0.129$



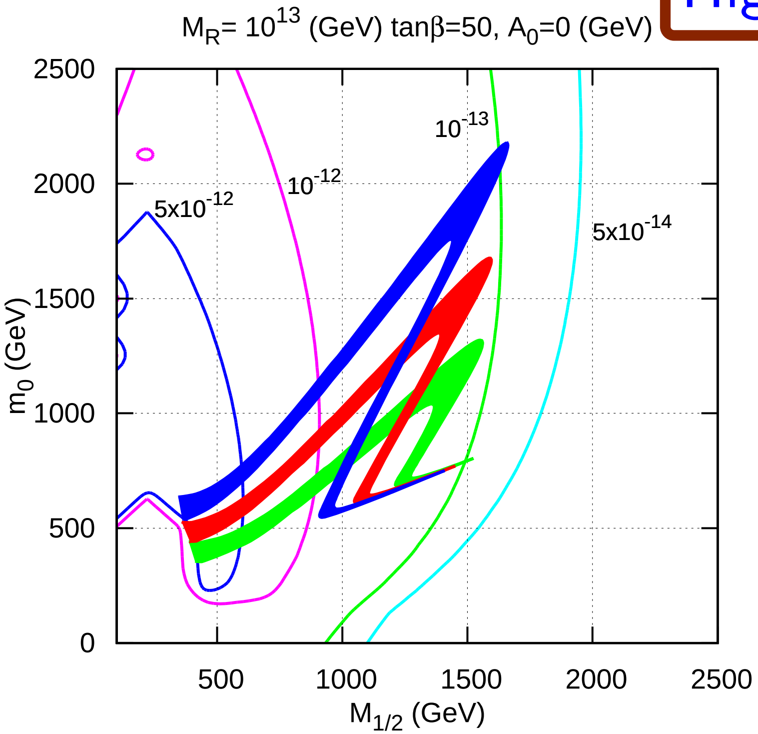
- Superimposed are the contour lines for the $Br(\mu \to e\gamma)$

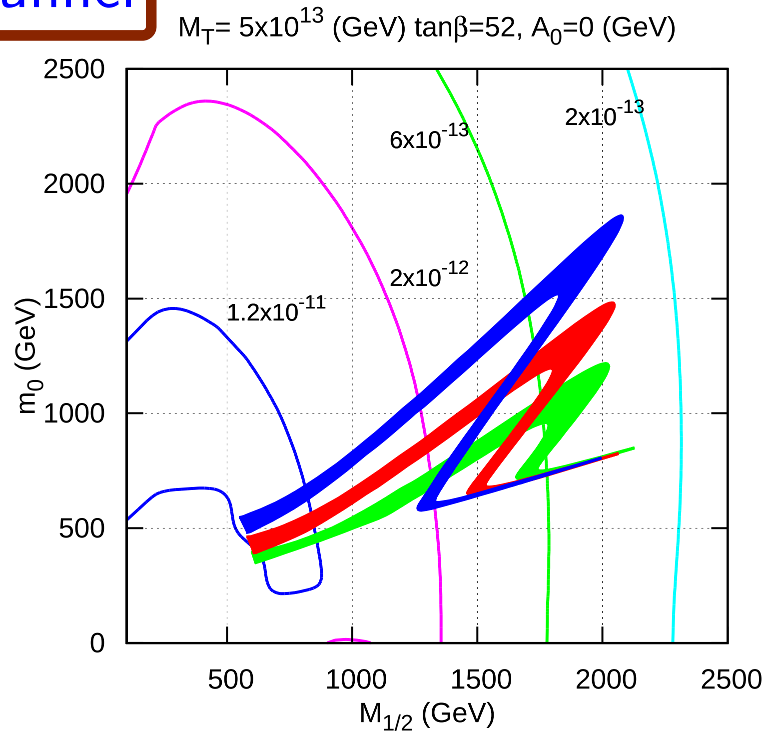
Dark Matter and LFV constraints: type-I and type-II

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- Parameters: SUSY: $\{m_0, M_{1/2}, A_0 = 0, \tan\beta = 50, 52, \text{sign}(\mu) = +\}$
- Seesaw: $M_R = 10^{13}, M_T = 5 \times 10^{13}$ GeV
- Dark matter region: WMAP (3σ), $0.081 \leq \Omega h^2 \leq 0.129$

Higgs funnel





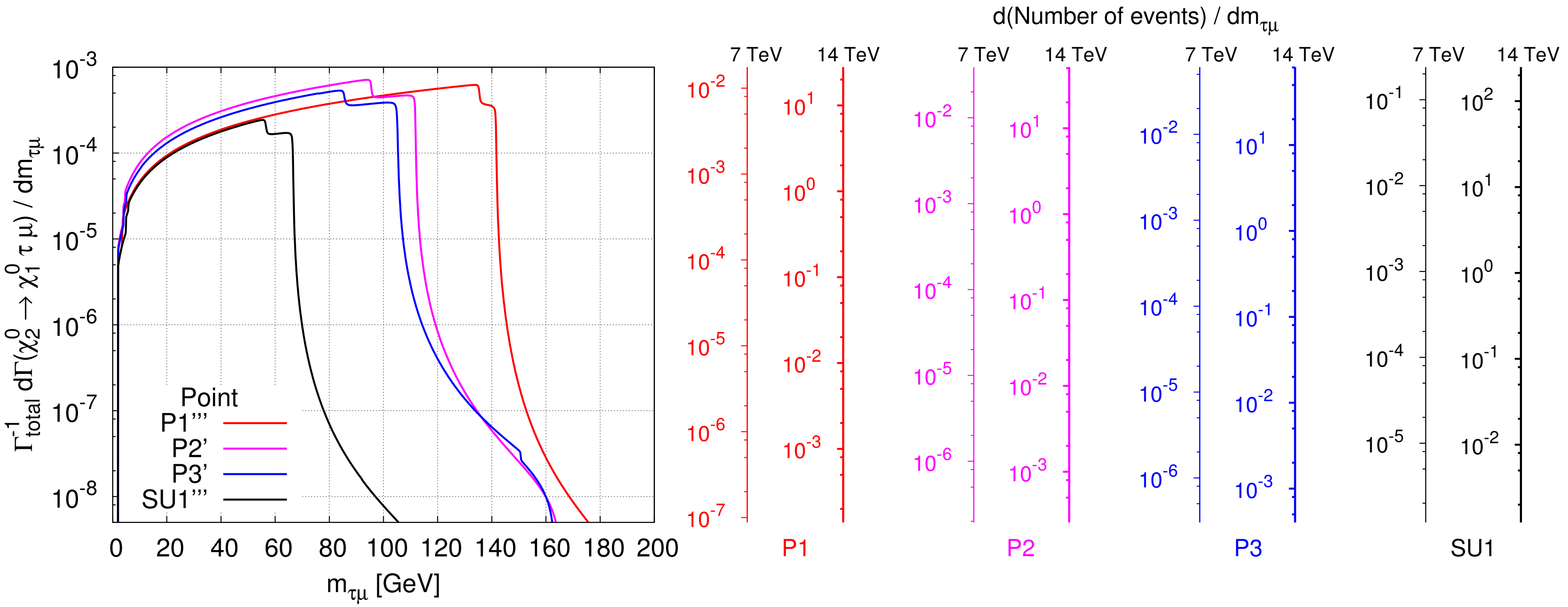
- $m_{top} = 169.1$ GeV (blue), 171.2 GeV (red), 173.3 GeV (green)
- Superimposed are the contour lines for the $Br(\mu \to e\gamma)$

LFV at the LHC: flavour violating χ_2^0 decays (type-I)

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

Impact for di-lepton distributions $\chi_2^0 \to \tilde{\ell}^j_{L,R}\ell_i \to \chi_1^0 \ell_i \ell_j$

Seesaw: M_N=$\{10^{10}, 5\times10^{10}(10^{12}), 5\times10^{13}(10^{15})\}$ GeV, $\theta_{13}=0.1^\circ$

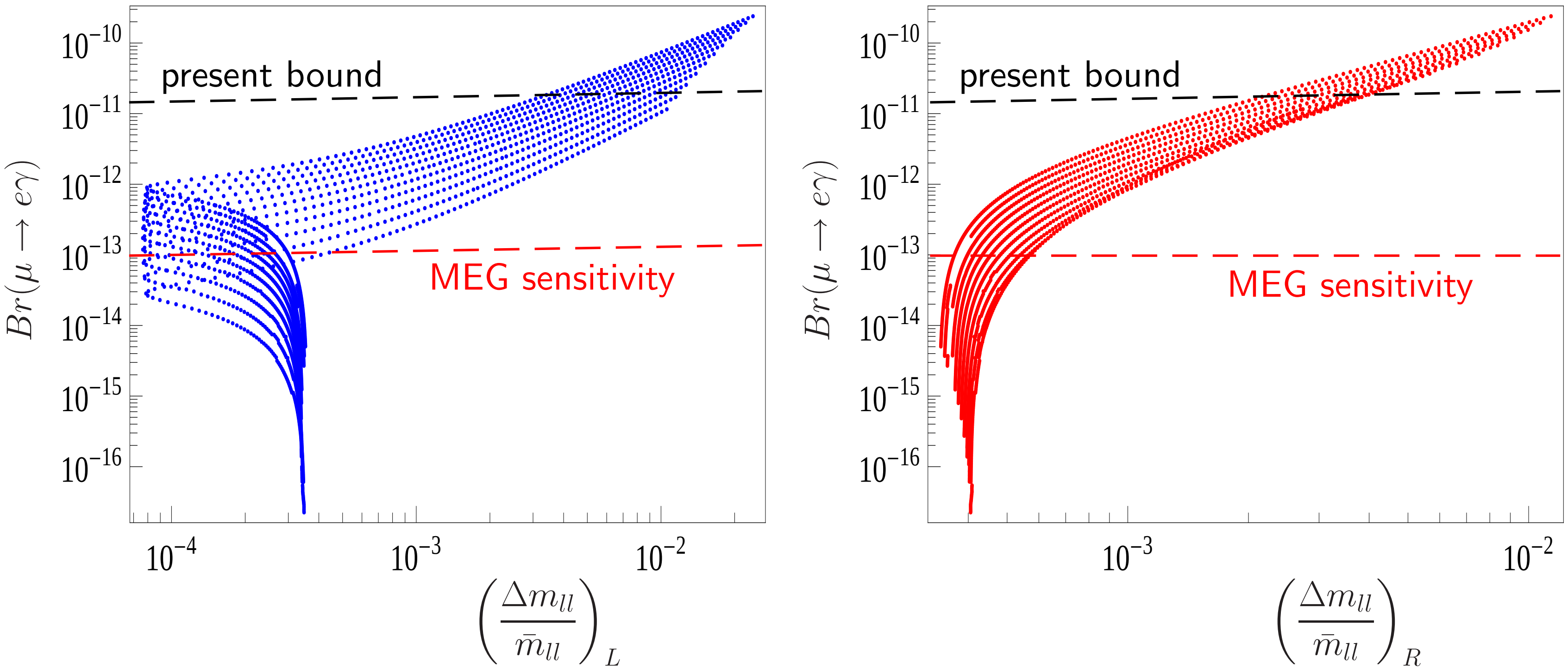


- ❐ Opposite-sign, different flavour final state leptons (τ, μ,etc)
- ❐ Lepton flavour violated in χ_2^0 and $\tilde{\ell}$ decays
- ❐ LFV at the LHC: e.g $\chi_2^0 \to \tilde{\tau}_2\mu \to \chi_1^0\tau\mu$, $\chi_2^0 \to \tilde{\mu}_L\tau \to \chi_1^0\tau\mu$

Mass Splittings in the LR Model

Outline
Motivation
Models
Low-Energy Obs.
LHC Observables
Conclusions
Backup Slides
• GUT scale
• Below GUT
• type-I
• type-II
• type-III
• Spectra
• Neutrino data
• LFV Constraints
• Dark Matter
• Procedure
• M_{SS} Variation
• Funnel & M_{SS}
• Funnel &mt mb
• LFV & type-III
• LFV in LR
• DM & LFV
• LFV decays
• MS in LR

- Parameters:
  - SUSY: SPS3 $\{90,400,0,10,+1\}$
  - LR: $v_{BL} = 10^{15}$ GeV, $v_R \in [10^{14}, 10^{15}]$ GeV
- $\frac{\Delta m_{ll}}{\bar{m}_{ll}} = \frac{\Delta m_{\tilde{l}}}{\bar{m}_{\tilde{l}}} \frac{m^2_{\tilde{\chi}^0_1} m^2_{\tilde{\chi}^0_2} - \bar{m}^4_{\tilde{l}}}{(\bar{m}^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1})(\bar{m}^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_2})}$ (0.1% precision at LHC)



- Interplay between LHC and low-energy experiments (MEG)