Testing neutrino mass models @ LHC

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Outline

$\mathcal{I}$. Introduction

$\mathcal{II}$. “Low-scale” seesaw

$\mathcal{III}$. Radiative neutrino mass models

$\mathcal{IV}$. $\not{R}_p$ Supersymmetric neutrino masses

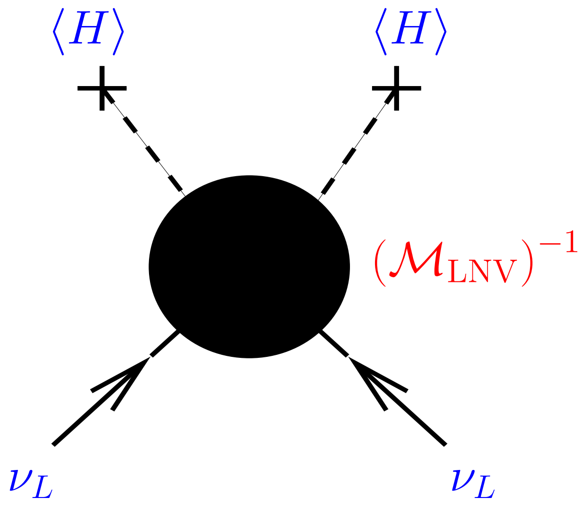
$\mathcal{V}$. High-scale Seesaw and SUSY

$\mathcal{I}.$

Introduction

Majorana $\mathcal{M}_\nu$

If Lepton Number is Violated:



Weinberg, 1979

$$(\mathcal{M}_\nu)_{\alpha\beta} = \frac{\kappa_{\alpha\beta}}{\mathcal{M}_{LNV}} (L_\alpha H)(L_\beta H)$$

Many realizations:

(i) Seesaw mechanism: Type-I, Type-II,
Type-III, Inverse seesaw, etc ...
(ii) Radiative models: Zee, Babu, LQs ...
(iii) SUSY neutrino masses: R-parity violation
(iv) $\cdots$

$\mathcal{II}.$

Non-supersymmetric

"Low-scale" seesaw

'Classical' Seesaw

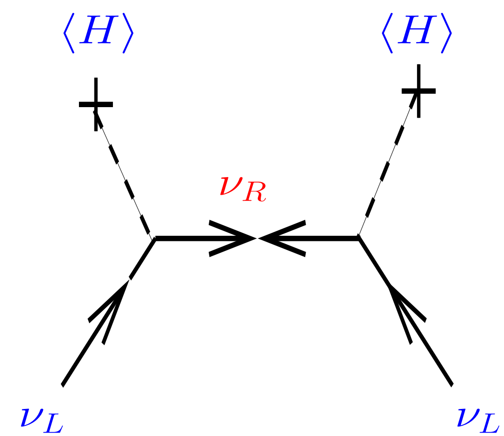
In the basis (ν_L, ν_R) write mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix}.$$

Minkowski, 1977
Yanagida, 1979
Gell-Mann, Ramond & Slansky, 1979
Mohapatra & Senjanovic, 1980
... ...

If $m_D \ll M_M$:

$$m_{1/2} \simeq (-\frac{m_D^2}{M_M}, M_M)$$

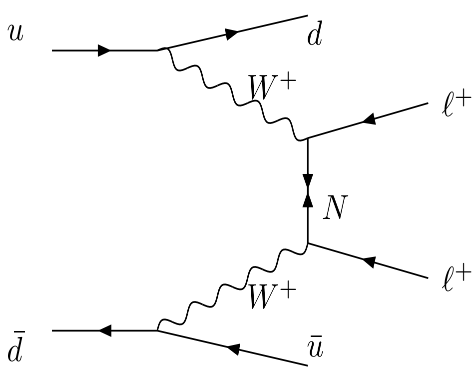


Santamaria, 1993

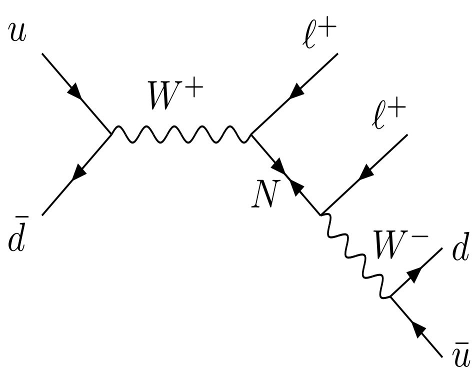
$\Rightarrow$ For 3 ν_R 21 parameters
$\Rightarrow$ At low energy 12 parameters measurable:
3 m_{l_i}, 3 m_{ν_i}, 3 angles & 3 phases

Seesaw type-I and LHC

Diagrams for N_R production at LHC:



$\sigma \propto |V_{lN}^4|$



$\sigma \propto |V_{lN}^2|$

del Aguila et al., 2008:

$$\sum_i |V_{eN_i}|^2 \leq 0.0030$$
$$\sum_i |V_{\mu N_i}|^2 \leq 0.0032$$
$$\sum_i |V_{\tau N_i}|^2 \leq 0.0062$$

From $0\nu\beta\beta$ decay:

$$\sum_i |V_{eN_i}^2 \frac{1}{m_{N_i}}| \leq 5 \times 10^{-8} \text{ GeV}^{-1}$$

del Aguila & Aguilar-Saavedra, 2009:

$\sigma(LHC) \leq 180$ fb^{-1} for $m_N = 100$ GeV

Han & Zhang, 2006:

$$\sum_i |V_{\mu N_i}|^2 \leq 10^{-4}\ (10^{-6})$$

for $m_N = 100$ GeV ($m_N = 50$ GeV)

Seesaw-I, LHC and $\mathcal{M}_\nu$

Estimate Yukawas:

$$h_\nu \sim \sqrt{\frac{m_\nu M_M}{v_U^2}} \sim \mathcal{O}(1)\left(\frac{m_\nu}{0.05\ \mathrm{eV}}\right)^{1/2}\left(\frac{M_M}{10^{15}\ \mathrm{GeV}}\right)^{1/2}$$

$$\sim \mathcal{O}(10^{-6})\left(\frac{m_\nu}{0.05\ \mathrm{eV}}\right)^{1/2}\left(\frac{M_M}{1\ \mathrm{TeV}}\right)^{1/2}$$

$\Rightarrow$ Recall:

$\sqrt{s} = 10\ (14)$ TeV @ LHC

EW cross sections @ LHC: $\sigma(W \to l\nu) = 15$ nb

Estimate: $\sigma(W \to lN) \leq \sigma(W \to l\nu) \times |V_{lN}|^2$

Luminosity: $\mathcal{L} = 10\ fb^{-1}$ per year (planned)

$\rightarrow$ less than 10^{-4} events/year for $h_\nu \sim 10^{-6}$

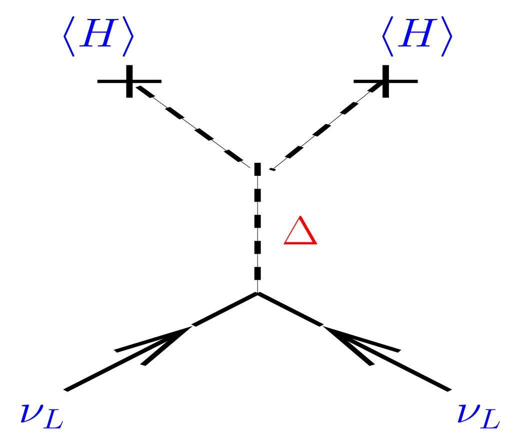
Possible exception: Inverse Seesaw — Mohapatra & Valle, 1986

Seesaw: Type II

Y=2 Scalar triplet: $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$

Schechter & Valle, 1980, 1982
Cheng & Li, 1980
Mohapatra, Senjanovic, 1981
...

$$\mathcal{M}_\nu = \begin{pmatrix} m_M & 0 \\ 0 & 0 \end{pmatrix}$$



with:

$$m_M \simeq Y^\nu \langle \Delta^0 \rangle$$

Example:

$SU(5)$ with $\mathbf{15}$:

$$\langle \Delta^0 \rangle \sim \frac{\langle h^0 \rangle^2}{m_{\mathbf{15}}}$$

$\Rightarrow$ With 2 triplets (SUSY) 15 parameters

Seesaw-II and LHC

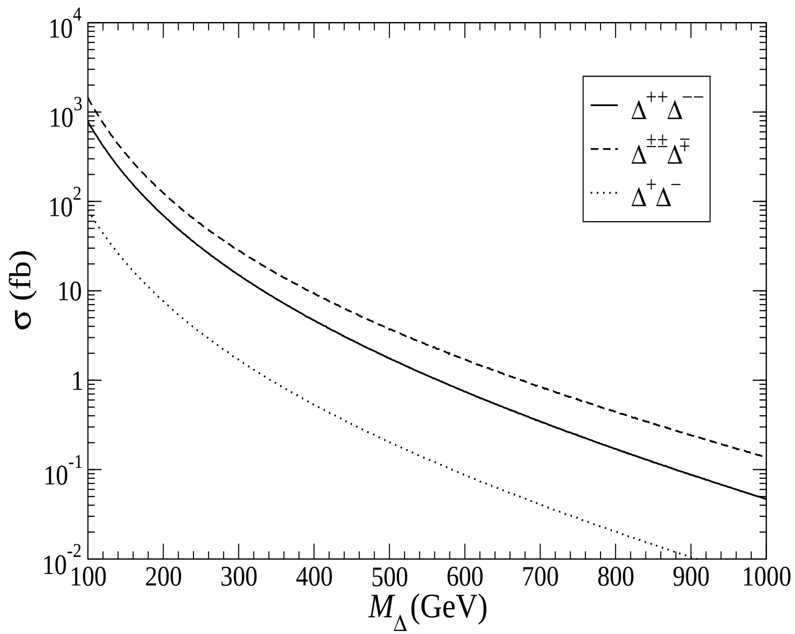
Production at LHC through gauge bosons:

$$q\bar{q} \to Z/\gamma \to \Delta^{++}\Delta^{--}$$
$$q\bar{q} \to Z/\gamma \to \Delta^{\pm}\Delta^{\mp}$$
$$q\bar{q}' \to W \to \Delta^{\pm\pm}\Delta^{\mp}$$

Gunion et al., 1996

$m_\Delta \leq 925$ GeV
with $\mathcal{L} = 100$ fb^{-1}

del Aguila & Aguilar-Saavedra, 2009:



Garayoa & Schwetz, 2008

Test neutrino mass hierarchy from:
Br($\Delta^{++} \to l_i^+ l_j^+$)

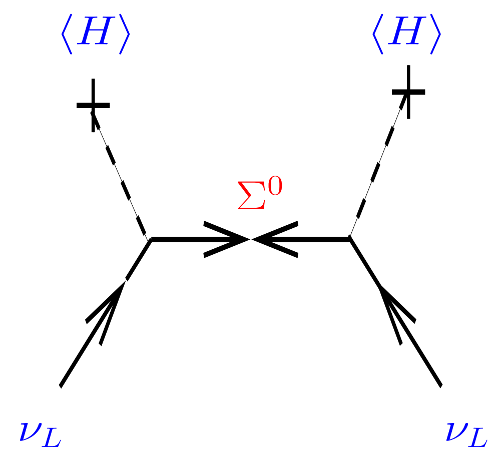
many others ...

Seesaw: Type-III

As in seesaw type-I. Replace ν_R by $\boldsymbol{\Sigma} = (\Sigma^+, \Sigma^0, \Sigma^-)$.
In the basis (ν_L, Σ) write mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_\Sigma \end{pmatrix}.$$

R. Foot et al., 1988
E. Ma, 1998



If $m_D \ll M_\Sigma$:

$$m_{1/2} \simeq \left(-\frac{m_D^2}{M_\Sigma}, M_\Sigma\right)$$

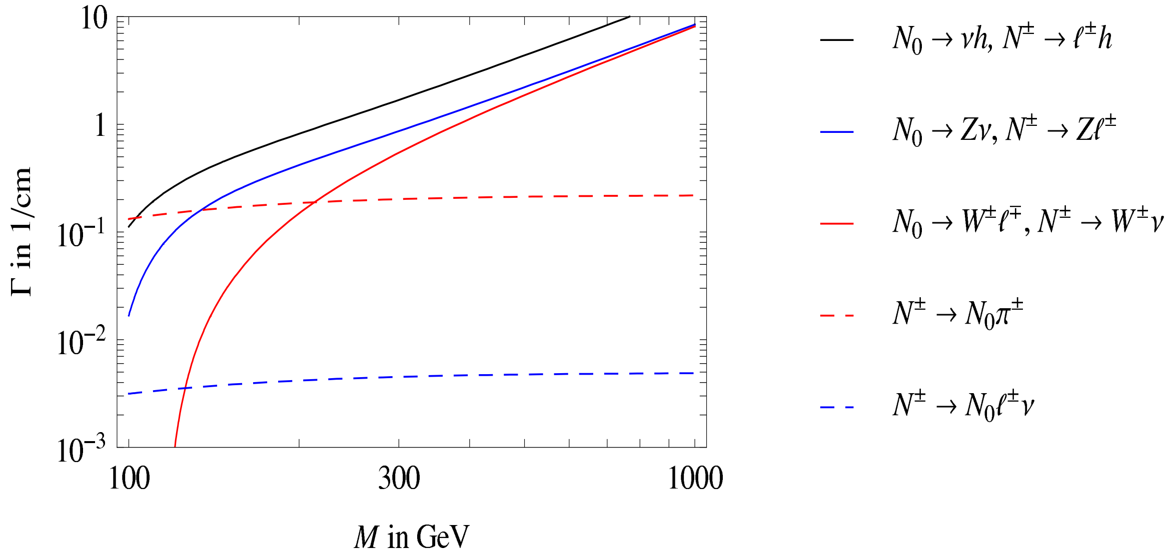
$\Rightarrow$ For 3 Σ 21 parameters

Seesaw-III and LHC

As in type-II: Production at LHC through gauge bosons, estimate:

Up to (roughly) $m_\Sigma \sim 1$ TeV

Franceschini et al., 2008



Displaced vertex!

$\Rightarrow$ For 3 generations of Σ no correlation of decays of Σ with neutrino angles

$\mathcal{III}.$

Radiative neutrino mass models

Only two examples!

Babu model

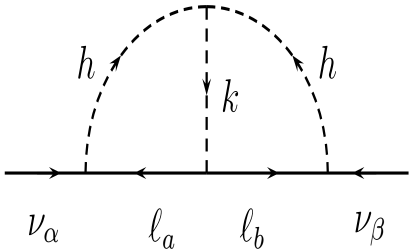
Cheng & Li, 1980; Zee, 1985; Babu, 1988:

$$\mathcal{L} = f_{\alpha\beta}(L^{Ti}_{\alpha L} C L^{j}_{\beta L})\epsilon_{ij} h^{+} + h'_{\alpha\beta}(e^{T}_{\alpha R} C e_{\beta R}) k^{++} + \mathrm{h.c.}$$

Scalar sector:

$$\mathcal{L} = -\mu h^{+} h^{+} k^{--} + \mathrm{h.c.}$$

$$\mathcal{M}_{\nu} = \left(\frac{1}{(16\pi^2)}\right)^2 (fhf)(m_l)^2 \times \mathcal{I} =$$



Babu & Macesanu, 2002 :

$m_{k^{++}}$ up to 800 GeV with 100 fb^{-1} at LHC

Aristizabal & Hirsch, 2006:

Decay branching ratios of new scalars fixed by neutrino angles

Leptoquarks

Hypothetical particles coupling to lepton-quark pairs:

Buchmüller et al., 1987

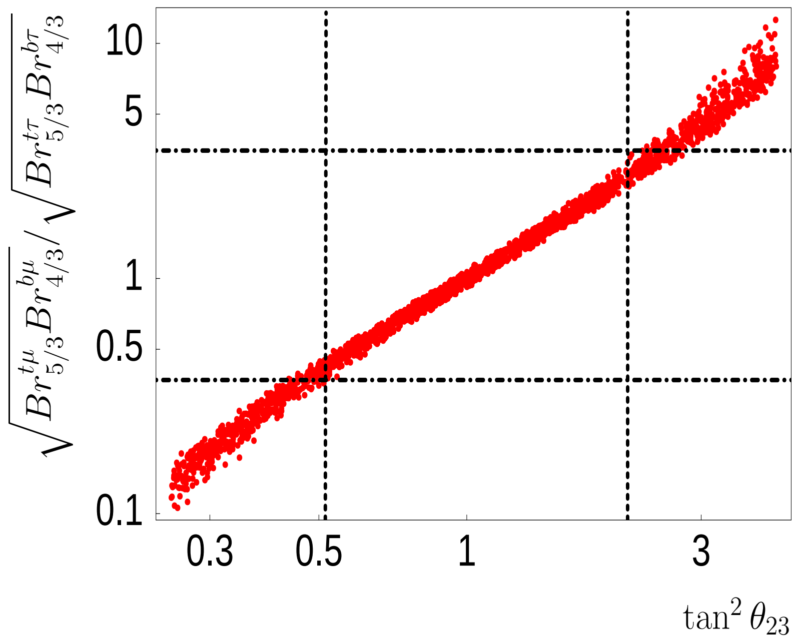
$$\mathcal{L}_{LQ-l-q} = +\lambda^{(R)}_{\tilde{S}_{1/2}} \overline{d} P_L l \, \tilde{S}^\dagger_{1/2} + \lambda^{(L)}_{S_{1/2}} \overline{q} P_R i\tau_2 e \, S^{L\dagger}_{1/2} + \cdots$$

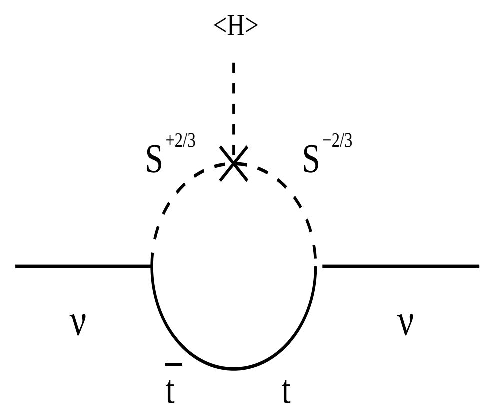
LQ-Higgs interaction mixies different LQ states:

Hirsch et al. 1996

$$V = Y^{(i)}_{S_{1/2}} \left(H i\tau_2 S^i_{1/2} \right) \left(\widetilde{S}^\dagger_{1/2} H \right) + \cdots$$

Aristizabal et al. 2008





Up to $m_{LQ} \leq (1.2 - 1.5)$ TeV @ LHC

Kramer et al., 2005

$\mathcal{IV}.$

Supersymmetric neutrino masses

R-parity violation

bilinear $R\!\!\!/_p$, spontaneous $R\!\!\!/_p$, $\mu\nu$SSM

Supersymmetric $\mathcal{M}_\nu$

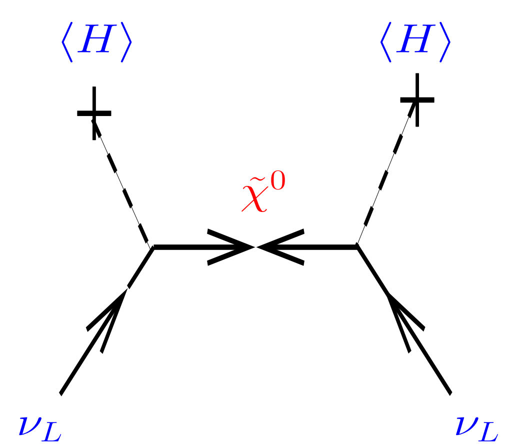
R-parity violation as origin of neutrino mass:

Aulakh & Mohapatra, 1982

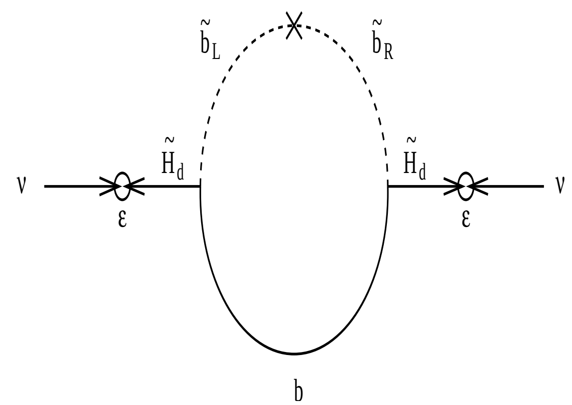
Hall & Suzuki, 1984

Ross & Valle, 1985

...



Tree-Level



+ 1-Loop

weak-scale Seesaw + radiative

Neutrino mass calculations after Super-K:

Drees et al., 1998

Chun et al., 1999

Hirsch et al., 2000, 2002

...

⇒ Easy to fit neutrino data, but no prediction for angles in general
... as in seesaw!

LHC and $R\!\!\!/_p$

With R-parity violated LSP decays, thus ...

... any superpartner can be the LSP!

$\Rightarrow$ Neutralino

$\Rightarrow$ Chargino

$\Rightarrow$ Gluino

$\Rightarrow$ Charged scalar

$\Rightarrow$ Scalar neutrino

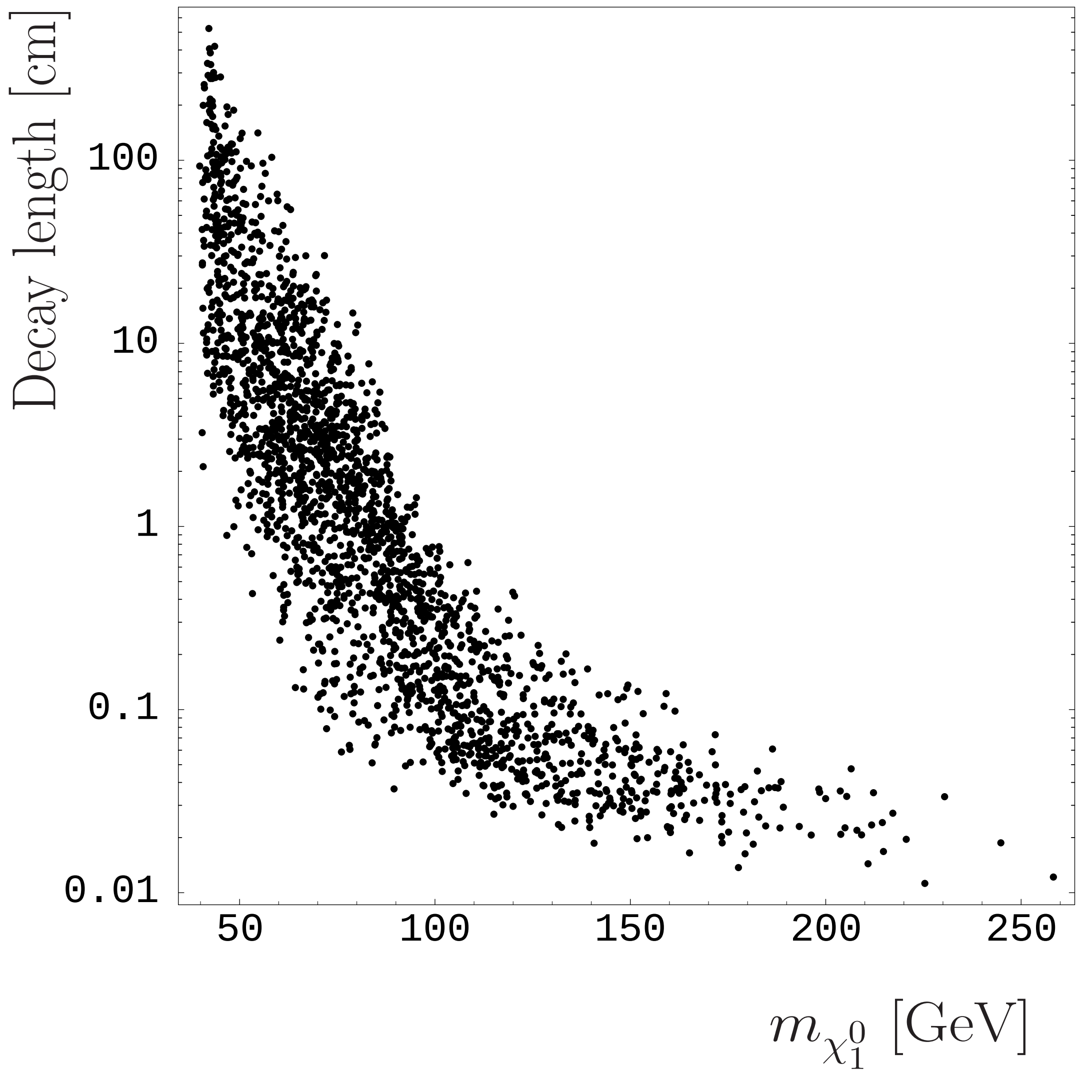
$\Rightarrow$ Scalar quark

Phenomenology depends on which is LSP, detailed studies so far only χ_1^0 and charged scalar

See, however: Hirsch & Porod 2003

Neutralino decay length

All Points with correct $\Delta m^2_{\mathrm{Atm}}$ and $\Delta m^2_{\odot}$:



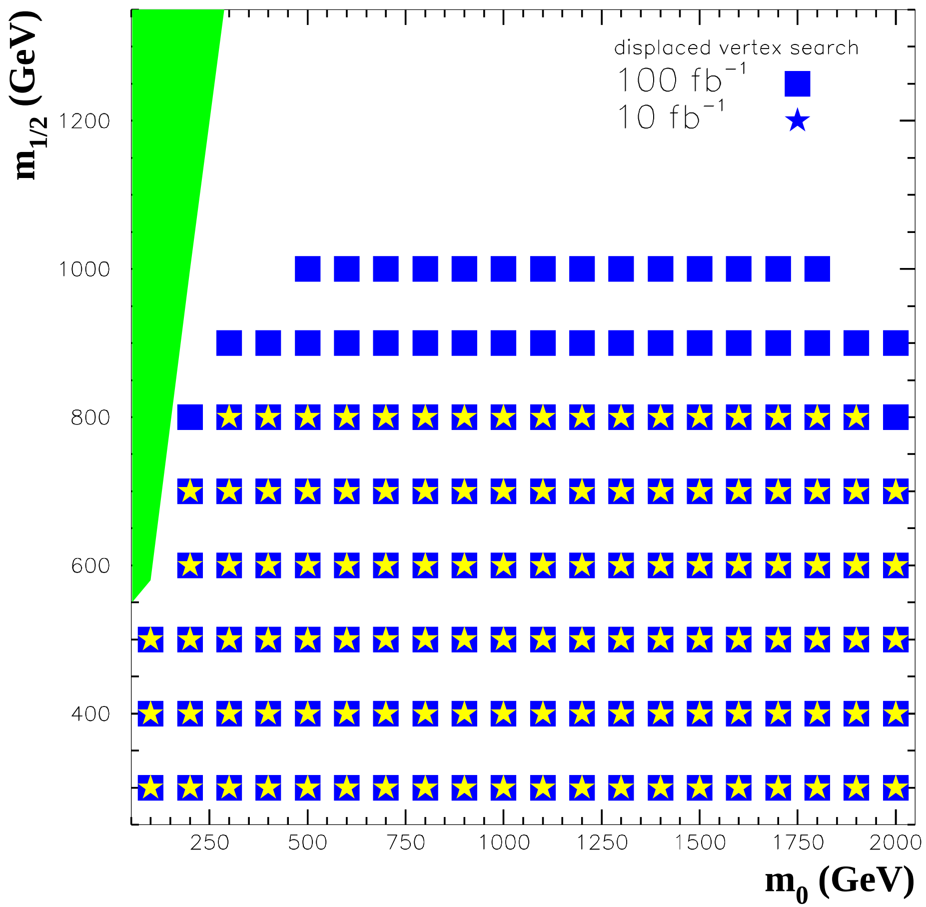
Porod et al., 2001

Displaced vertex!

No known SM background!

LHC reach

de Campos et al., 2008

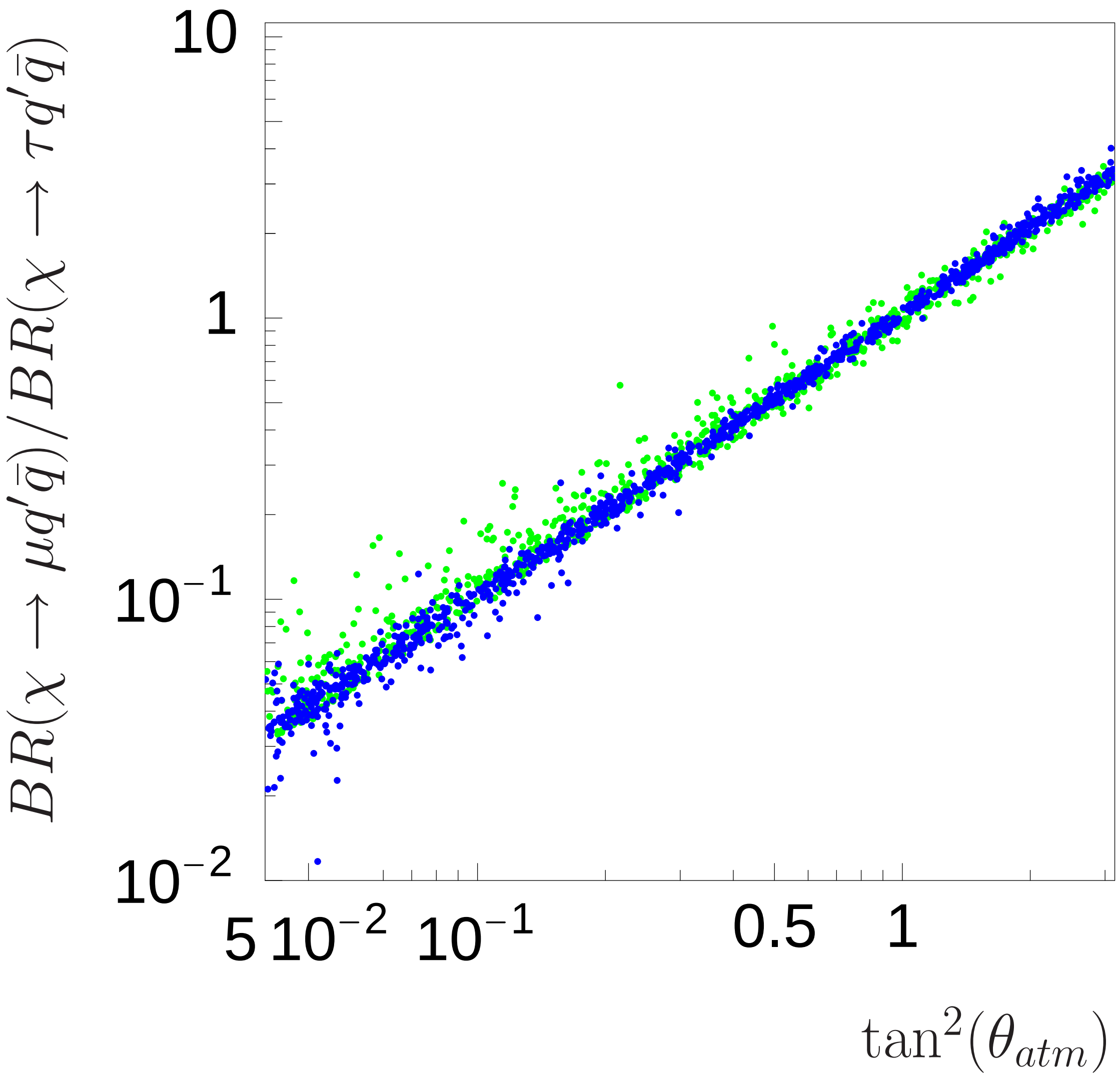


Displaced vertex search

$\sqrt{s} = 14$ TeV,

$\mathcal{L} = 10$ and 100 fb^{-1}

Neutralino decay and θ_{Atm}



Ratio of branching ratios predicted from atmospheric neutrino measurement

Porod et al., 2001

Spontaneous $\not{R}_p$

$$
\mathcal{W} = h_U^{ij}\widehat{Q}_i\widehat{U}_j\widehat{H}_u \;+\; h_D^{ij}\widehat{Q}_i\widehat{D}_j\widehat{H}_d + h_E^{ij}\widehat{L}_i\widehat{E}_j\widehat{H}_d
$$

$$
+h_\nu^{ij}\widehat{L}_i\widehat{\nu}^c_j\widehat{H}_u \;-\; h_0\widehat{H}_d\widehat{H}_u\widehat{\Phi} + h^{ij}\widehat{\Phi}\widehat{\nu}^c_i\widehat{S}_j
$$

- ⇒ Explains absence for trilinear terms
- ⇒ If scalar singlet gets vacuum expectation value: $\epsilon_i = h_i^\nu \langle \tilde{\nu}^c \rangle$
- ⇒ Spontaneous breaking of lepton number, Goldstone boson: Majoron
- ⇒ $\widehat{\Phi}$ potentially solves μ-problem á la NMSSM

Aulakh & Mohapatra, 1982
Ross & Valle 1985
Masiero & Valle 1990
...

Changes Pheno from explicit model due to:

- ⇒ Possibly invisible Higgs ($h^0 \to JJ$)
- ⇒ $\chi_1^0 \to J\nu$
- ⇒ $\mu \to eJ$ anticorrelates with $\chi_1^0 \to J\nu$

Hirsch et al., 2004, 2009

The $\mu\nu$SSM

$$\mathcal{W} = h_U^{ij}\widehat{Q}_i\widehat{U}_j\widehat{H}_u \;+\; h_D^{ij}\widehat{Q}_i\widehat{D}_j\widehat{H}_d + h_E^{ij}\widehat{L}_i\widehat{E}_j\widehat{H}_d$$
$$+h_\nu^{ij}\widehat{L}_i\widehat{\nu}_j^c\widehat{H}_u \;-\; \lambda_i\widehat{H}_d\widehat{H}_u\widehat{\nu}_i^c + \kappa_{ijk}\widehat{\nu}_i^c\widehat{\nu}_j^c\widehat{\nu}_k^c$$

As Next-to MSSM, but:

Lopez-Fogliani & Munoz, 2006
Escudero et al., 2008
Ghosh & Roy, 2009
Bartl et al., 2009

$\Rightarrow$ $\widehat{\Phi}$ identified as same field as ν^c
$\Rightarrow$ violates L explicitly
$\Rightarrow$ violates R_p explicitly
$\Rightarrow$ for heavy singlets approaches explicit bilinear model
$\Rightarrow$ For one $\widehat{\nu}^c$: m_ν = Tree + Loop
$\Rightarrow$ More than one $\widehat{\nu}^c$ all m_{ν_i} at tree-level

Distinguish $\not{R}_p$ models?

Bartl et al., 2009

	Displaced vertex	Comment	Br(invisible)	Higgs decays
b-$\not{R}_p$	Yes	Visible	≤ 10 %	standard
s-$\not{R}_p$	Yes/No (short)	anti-correlates with invisible	any	non-standard (invisible)
$\mu\nu$SSM	Yes/No (long)	anti-correlates with non-standard	≤ 10 %	non-standard

Note:

$\Rightarrow$ All models approach explicit $\not{R}_p$ if new singlet fields "heavy"

$\Rightarrow$ Correlation with neutrino angles lost if trilinear $\not{R}_p$ sizeable

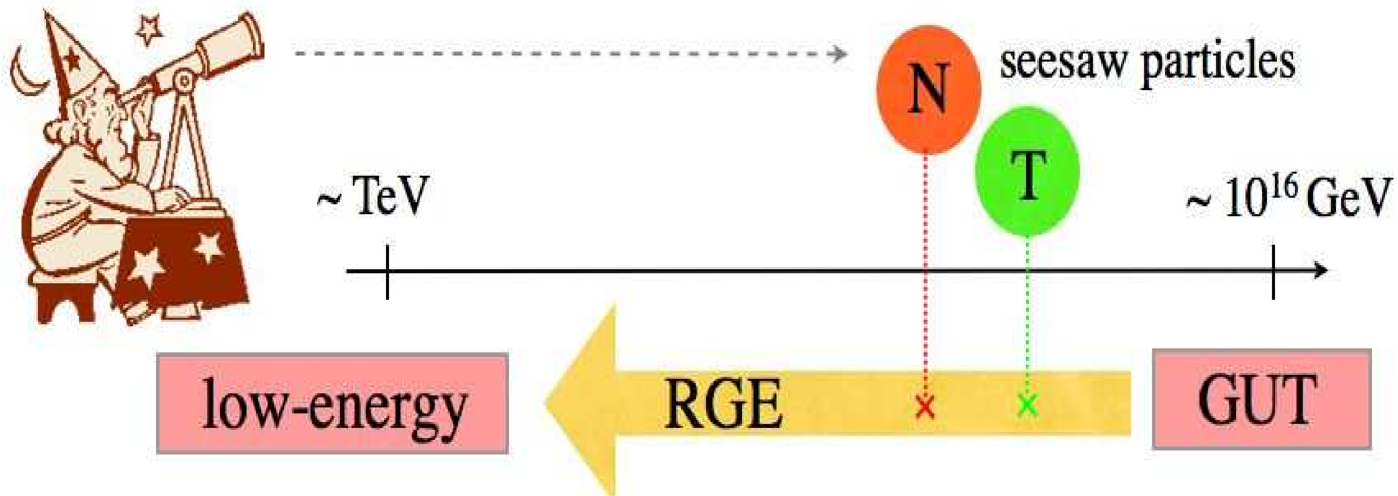
... unless $m_{\chi^0_1} > m_W$ + displaced vertex allows $m_{\chi^0_1}$ reconstruction

ν.

Supersymmetric Seesaw

(Indirect signals for seesaw)

Can we extrapolate from LHC to M_{GUT}?



mSugra and RGEs

mSugra defined by:

$$m_0, M_{1/2}, A_0, t_\beta, \text{sgn}(\mu)$$

$\Rightarrow$ No LFV in pure mSugra

Add Seesaw type-I: Borzumati & Masiero, 1986

$$(\Delta M^2_{\tilde{L}})_{ij} \sim -\frac{1}{8\pi^2} f(m_0, A_0, ...)(Y_\nu^\dagger L Y_\nu)_{ij}$$

$$(\Delta M^2_{\tilde{E}})_{ij} \simeq 0$$

Note: $L_i = \log[M_G/M_{R_i}]$.

Or Seesaw type-II: Rossi, 2002

$$(\Delta M^2_{\tilde{L}})_{ij} \sim -\frac{1}{8\pi^2} g(m_0, A_0, M_{1/2}, ...)(Y_T^\dagger Y_T)_{ij} \log(M_G/M_T)$$

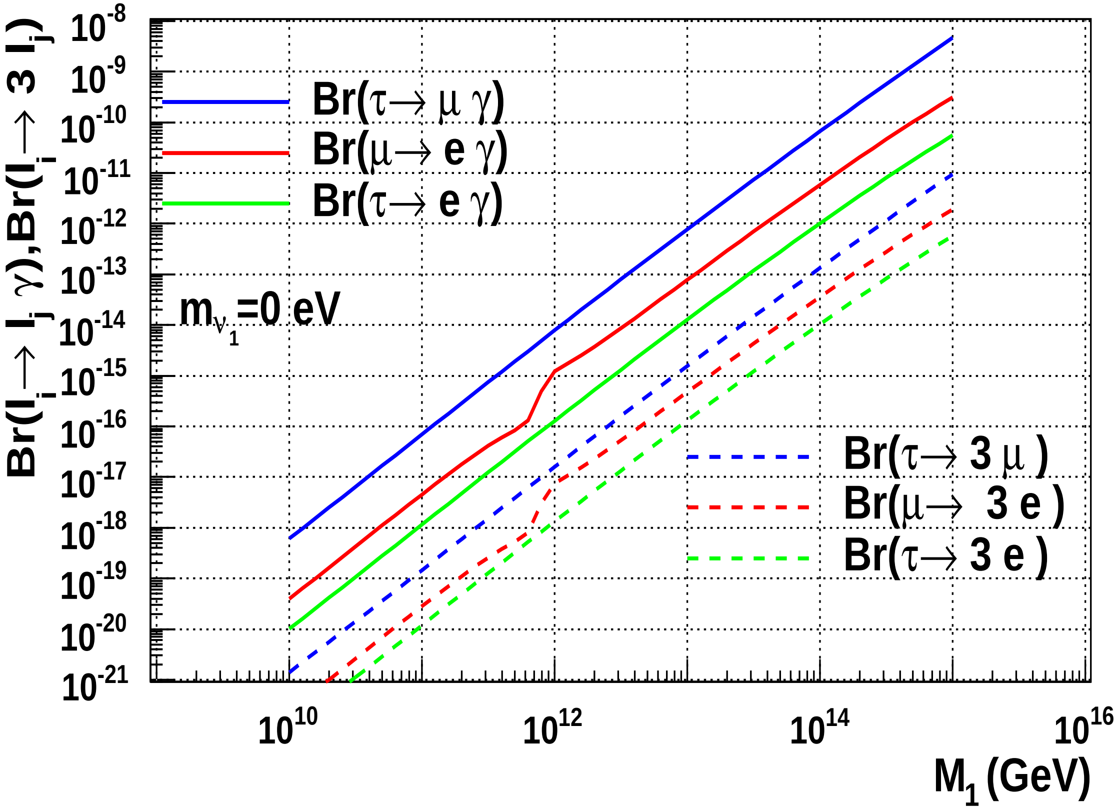
$$(\Delta M^2_{\tilde{E}})_{ij} = 0$$

$\Rightarrow$ Learn about $\hat{M}_R$ or M_T from $(\Delta M^2_{\tilde{L}})_{ij}$

Numerical results: SPheno3

Example: Seesaw-I, SPS3

Calculated assuming: (i) Degenerate N^c, (ii) TBM angles, (iii) best fit $\Delta m^2_{\rm A}$ and $\Delta m^2_{\odot}$, (iv) $m_{\nu_1} \equiv 0$:

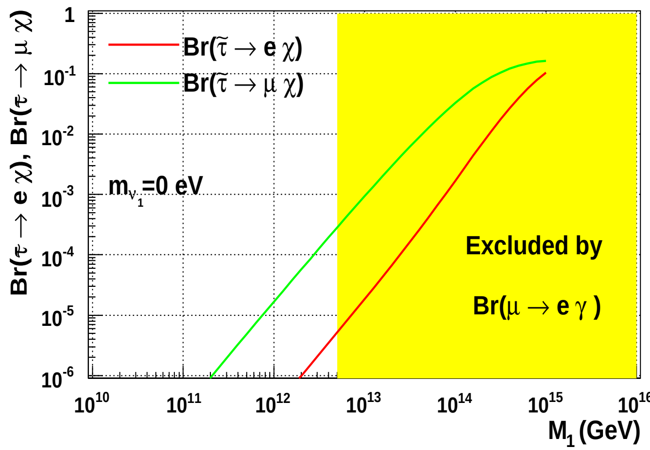


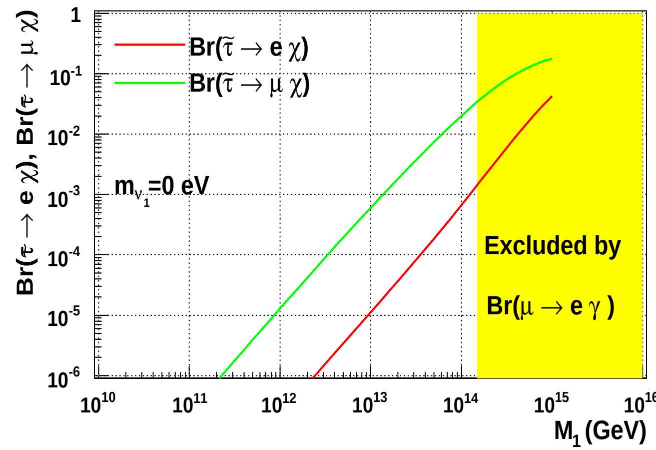
⇒ Ratios constant as function of seesaw scale!

Numerical results: LHC

Seesaw-I:

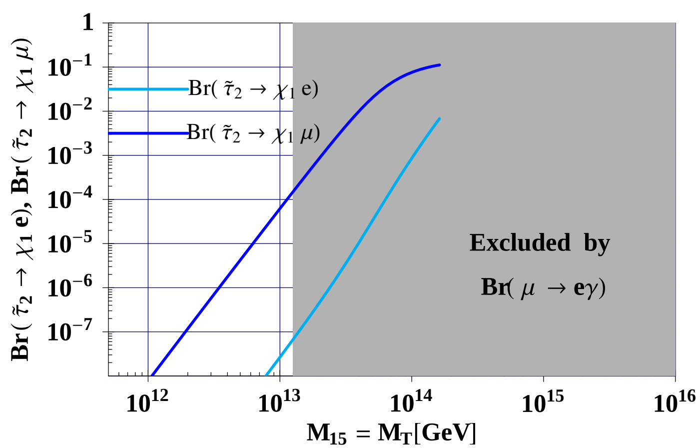
Left: SPS1a′ Right: SPS3

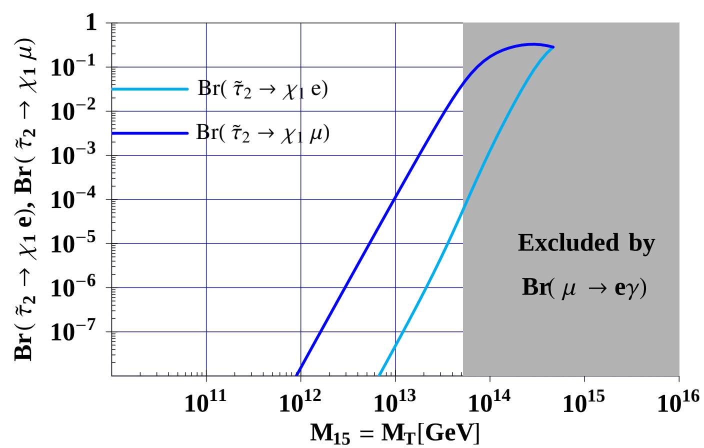




Seesaw-II:

Left: SPS1a′ Right: SPS3





$\Rightarrow$ LHC can see LFV (if SPS3-like ...)

Hirsch et al. 2008

V_{soft} & *the seesaw-II scale*

RGEs allow to calculate low-scale SUSY masses. Example:

$$
\begin{aligned}
m_{\tilde{L}}^2 &\simeq m_0^2 + 0.5 M_{1/2}^2 \\
m_{\tilde{E}}^2 &\simeq m_0^2 + 0.15 M_{1/2}^2 \\
M_1 &\simeq 0.45 M_{1/2}
\end{aligned}
$$

Blair, Porod & Zerwas, 2003

Buckley & Murayama, 2006

Form "invariants":

$$(m_{\tilde{L}}^2 - m_{\tilde{E}}^2)/M_1^2 \simeq 1.7$$

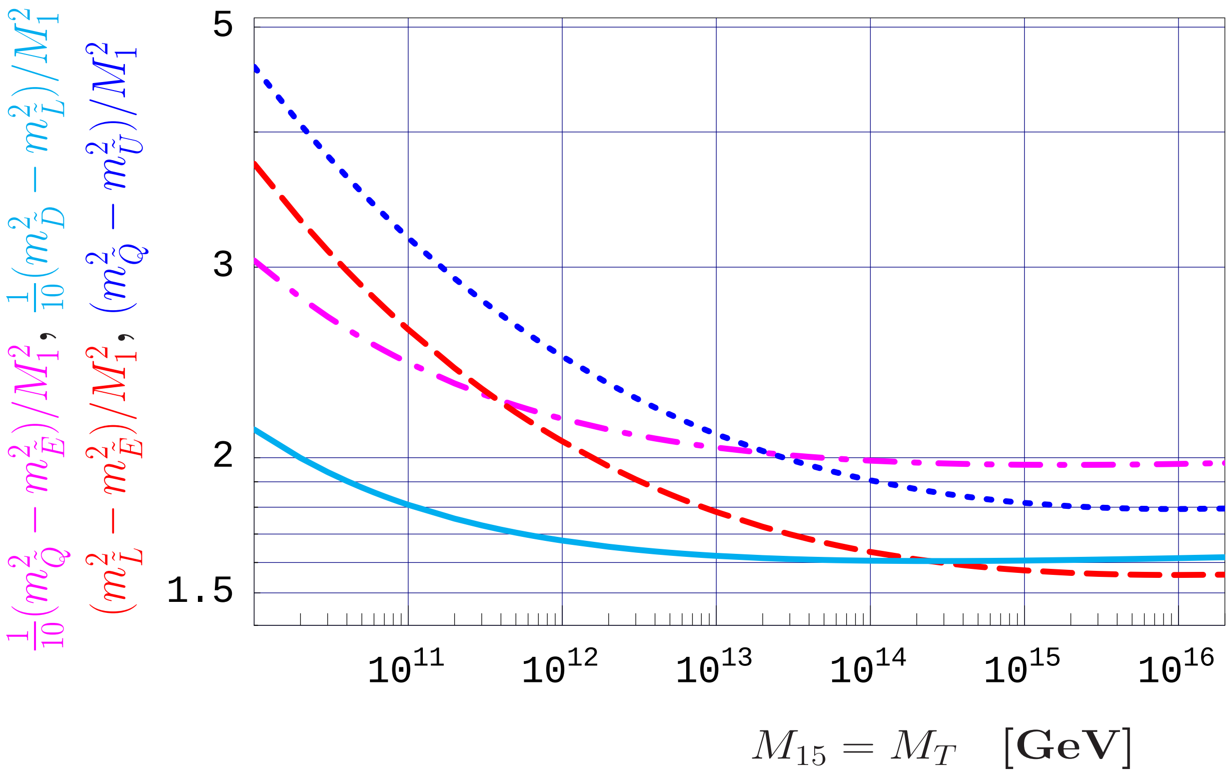
Idea!

⇒ To first approximation no dependence on m_0 and $M_{1/2}$

⇒ Departure from mSugra expecation contains info on high energy physics!

Soft masses and seesaw-II

Four examples of “invariants” as function of $M_{15} = M_T$:



Analytic
1-loop
leading-log
approximation

Hirsch et al., 2008

⇒ Consistent departures from mSugra point to M_T

⇒ Dependence on M_T only $\log(M_T)$

Conclusions

$\mathcal{II}$. "Low-scale" seesaw

Seesaw-I: (most probably) hopeless
Seesaw-II: LNV, up to $m_\Delta \sim 1$ TeV
Seesaw-III:Displaced vertex, up to $m_\Sigma \sim 1$ TeV

$\mathcal{III}$. Radiative neutrino mass models

LQs up to 1.5 TeV; k^{++} up to 800 GeV; h^+/S^0 (few) 100 GeV;
θ_ν correlate with decay properties

$\mathcal{IV}$. $\not{R}_p$ Supersymmetric neutrino masses

LSP decays; χ_1^0 with displaced vertex up to $M_{1/2} = 1$ TeV
θ_ν correlate with decay properties

$\mathcal{V}$. High-scale Seesaw and SUSY

LFV decays as indirect signals; precision measurements on masses for M_{LNV}