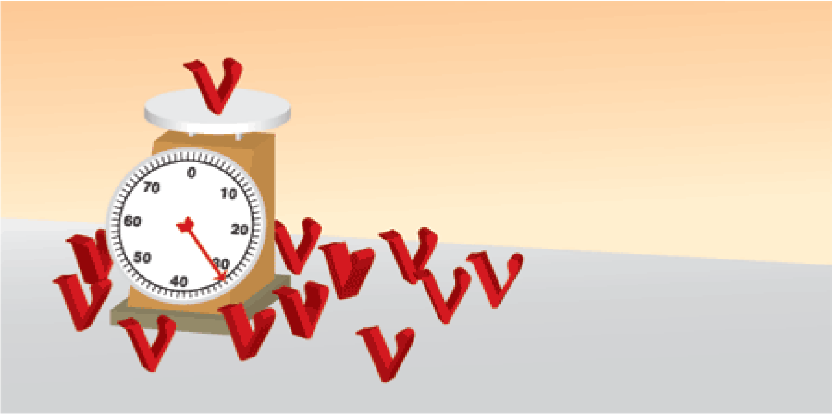
Neutrino masses in RPV models with extra pairs of Higgs doublets



arXiv:1401.1818

work in collaboration with Y. Grossman

Joint Particle Seminar, UC Irvine

Clara Peset

11th April, 2014

Outline

- Motivation for the model
  - why supersymmetry?
  - why RPV?
  - why neutrinos?
  - why extra pairs of Higgs doublets?
- Neutrinos in RPV models: tree level contribution
  - bounds on small RPV
  - contributions to the mass matrix
- Neutrinos in RPV models: loop level
  - small RPV
  - possible new effects
- Conclusions

NEUTRINO MASSES

SUSY
with
R-parity violation
and
extra pairs of Higgs doublets

Why SUSY?

Standard model is NOT the theory of everything

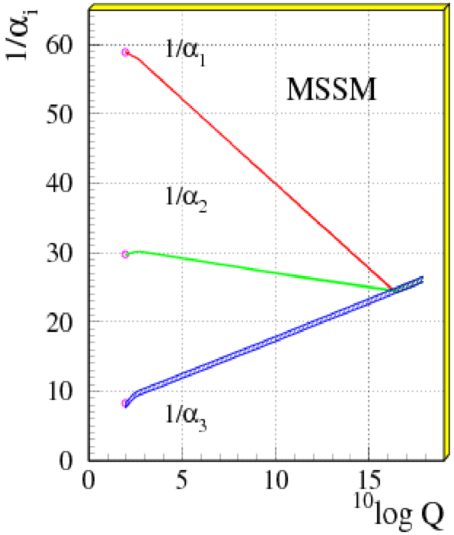
Cannot account for gravity, neutrino masses...

The mass of the Higgs is UV sensitive: $m_H^2 \approx \frac{\Lambda_{NP}^2}{16\pi^2}$

SUPERSYMMETRY

no UV sensitivity → scalar masses protected
mass of the Higgs boson arises naturally

Other benefits: unification of couplings, string theory...



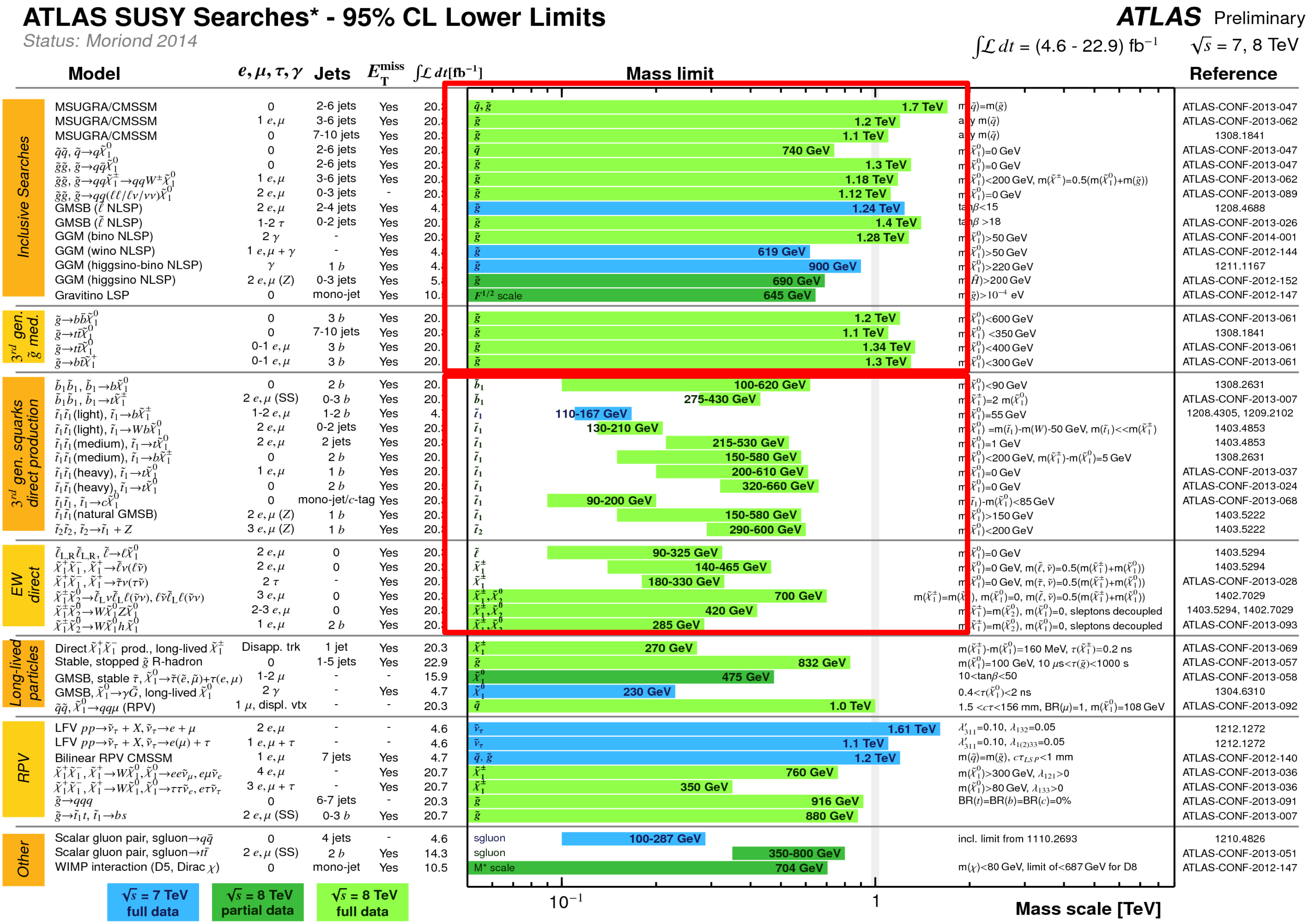
Simplest models should have been/be detected at LHC!

SUSY @ LHC

MSSM: $m_H^2 \approx m_Z^2$ +loop corrections $m_{\tilde{t}} \approx 400\,GeV\ ,\ m_{\tilde{g}} \approx 800\,GeV\ ,\ m_{\tilde{W}} \approx 1\,TeV$

size of tree level!

SUSY @ LHC



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.	$\tilde{q},\tilde{g}$	1.7 TeV	m $\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.	$\tilde{g}$	1.2 TeV	a y m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.	$\tilde{g}$	1.1 TeV	a y m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.	$\tilde{q}$	740 GeV	m $\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.	$\tilde{g}$	1.3 TeV	m $\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.	$\tilde{g}$	1.18 TeV	m $\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.	$\tilde{g}$	1.12 TeV	m $\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.	$\tilde{g}$	1.24 TeV	ta β<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.	$\tilde{g}$	1.4 TeV	ta β >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	20.	$\tilde{g}$	1.28 TeV	m $\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.	$\tilde{g}$	619 GeV	m $\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.	$\tilde{g}$	900 GeV	m $\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.	$\tilde{g}$	690 GeV	m $\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.	$F^{1/2}$ scale	645 GeV	m $\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.	$\tilde{g}$	1.2 TeV	m $\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.	$\tilde{g}$	1.1 TeV	m $\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.	$\tilde{g}$	1.34 TeV	m $\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.	$\tilde{g}$	1.3 TeV	m $\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.	$\tilde{b}_1$	100-620 GeV	m $\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.	$\tilde{b}_1$	275-430 GeV	m $\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.	$\tilde{t}_1$	110-167 GeV	m $\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.	$\tilde{t}_1$	130-210 GeV	m $\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.	$\tilde{t}_1$	215-530 GeV	m $\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.	$\tilde{t}_1$	150-580 GeV	m $\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.	$\tilde{t}_1$	200-610 GeV	m $\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.	$\tilde{t}_1$	320-660 GeV	m $\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.	$\tilde{t}_1$	90-200 GeV	m $\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.	$\tilde{t}_1$	150-580 GeV	m $\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.	$\tilde{t}_2$	290-600 GeV	m $\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.	$\tilde{\ell}$	90-325 GeV	m $\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.	$\tilde{\chi}_1^{\pm}$	140-465 GeV	m $\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.	$\tilde{\chi}_1^{\pm}$	180-330 GeV	m $\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	420 GeV	m $\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	285 GeV	m $\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q},\tilde{g}$	1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

SUSY @ LHC

MSSM: $m_H^2 \approx m_Z^2$ +loop corrections

$$m_{\tilde{t}} \approx 400\,GeV\ ,\ m_{\tilde{g}} \approx 800\,GeV\ ,\ m_{\tilde{W}} \approx 1\,TeV$$

size of tree level!

No panic!

still large amount of data to analyze

&

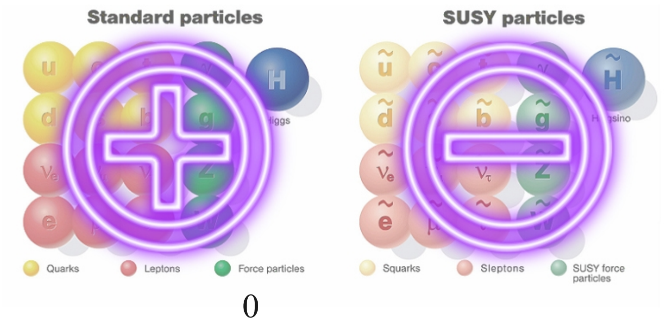
second round of LHC

&

other models to explore

(RPV, non-minimal models...)

Why RPV?



R-Parity: $(-1)^R$, $R = 2S+3B+L$

- Proton decay @ dim 5
- Neutral stabe fermion ⇒ cold DM candidate χ^0

NOT NECESSARY FOR NATURALNESS!

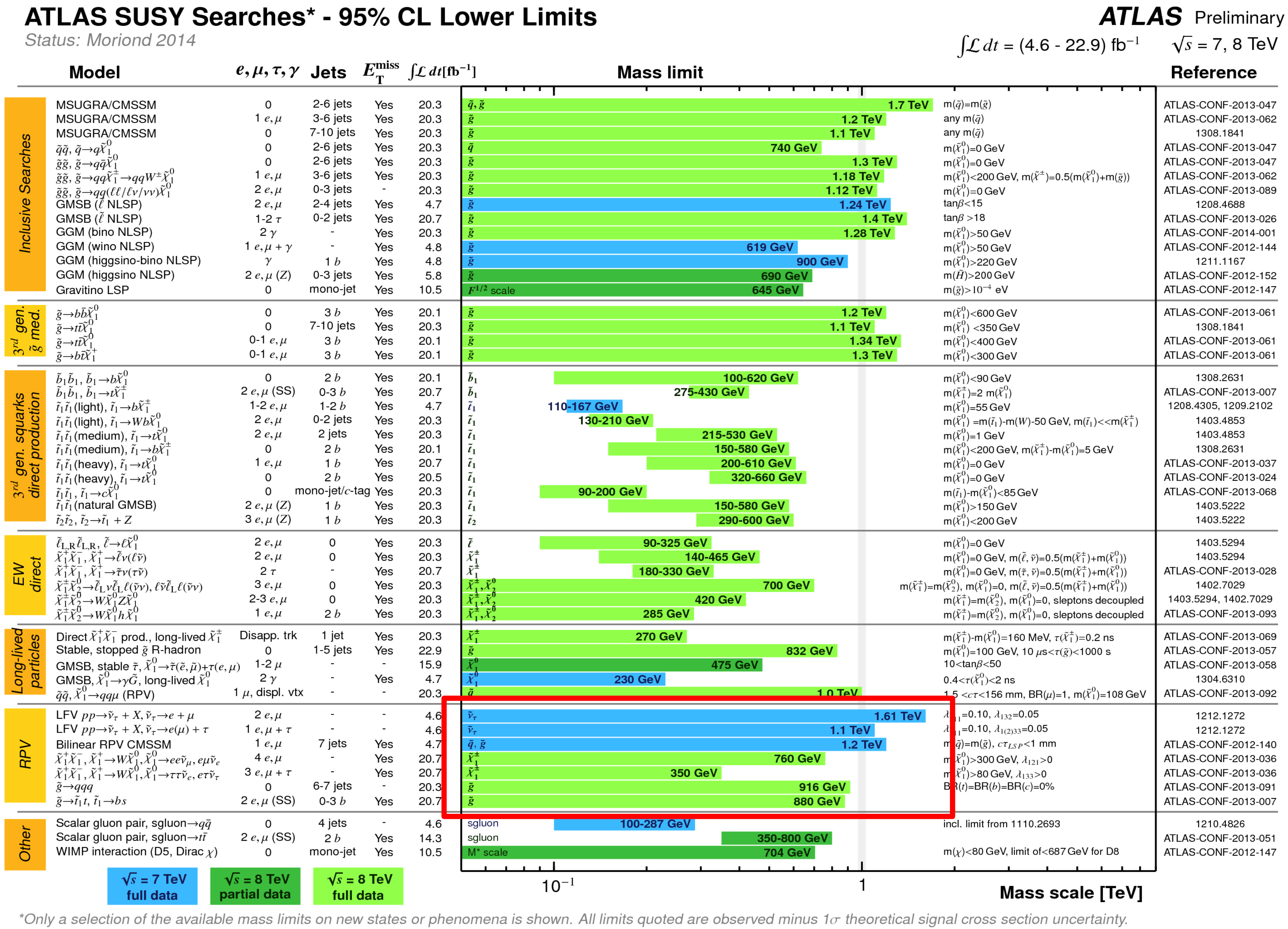
R-Parity violation:

$\chi^0 \longrightarrow$ SM particles NO need for MET @ LHC searches!

RPV searches: distinctive final states with many particle states

high jet or lepton activity

RPV SUSY @ LHC



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int \mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	$E_T^{\rm miss}$	$\int \mathcal{L}\,dt$[fb^{-1}]	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_{\rm L}\nu\tilde{\ell}_{\rm L}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\rm L}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda_{\;11}$=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda_{\;11}$=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q},\tilde{g}$ 1.2 TeV	m $\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	m $\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	m $\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

🟦 $\sqrt{s}$ = 7 TeV full data
🟩 $\sqrt{s}$ = 8 TeV partial data
🟩 $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Why RPV?

New RPV terms in the superpotential:

$$W = \underbrace{-\mu\hat{L}_I\hat{H}_U + \frac{1}{2}\lambda_{IJm}\hat{L}_I\hat{L}_J\hat{E}_m + \lambda'_{Inm}\hat{L}_I\hat{Q}_n\hat{D}_m}_{\text{L-number violation}} + \xcancel{\underbrace{\frac{1}{2}\lambda''_{lmn}\hat{D}_l\hat{D}_m\hat{Q}_n}_{\text{B-number violation}}}$$

Plus soft SUSY breaking

Lots of new parameters! general predictions become difficult

Generally allows for proton decay! ONLY lepton RPV or ONLY baryon RPV

Other constrains from constrains from:

- $n-\bar{n}$
- $\mu \rightarrow e$

→ Small RPV parameters

Leptonic RPV → majorana neutrino masses arise naturally! $\Delta L = 2$

Why neutrinos?

Neutrinos' small masses

are a BIG enigma

Cowen, Reines '56

- Sun neutrinos reaching the Eatth

$7\times10^9\,cm^{-2}\,s^{-1}$

- Contribute to the total energy of the universe as much as all the stars combined

Neutrino masses **not** within SM

Neutrinos oscillate:

Flavor basis $\neq$ mass basis

Majorana neutrinos: $\bar{\nu}\equiv\nu$

- dim 5 op in SM ► probe for GUT scales
- leptogenesis...
- detection double β-decays

yet to be achieved

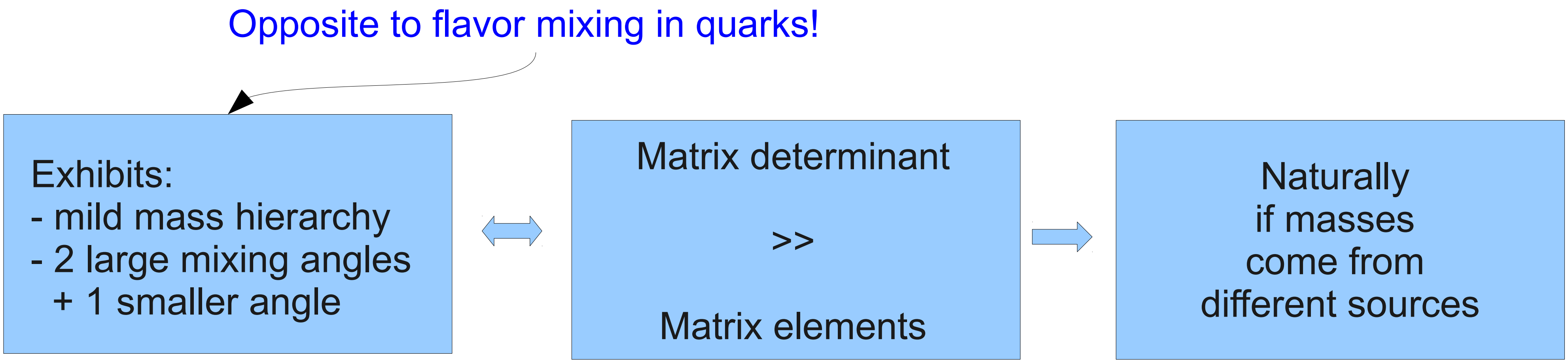
Why neutrinos?

Neutrino experimental data:

$$\Delta m^2_{32} = \left(2.32^{+0.12}_{-0.08}\right) \times 10^{-3}\,\mathrm{eV}^2, \qquad \Delta m^2_{21} = (7.5 \pm 0.20) \times 10^{-5}\,\mathrm{eV}^2,$$

$$\sin^2(2\theta_{32}) > 0.95, \quad \sin^2(2\theta_{12}) = 0.857 \pm 0.024, \quad \sin^2(2\theta_{13}) = 0.095 \pm 0.010$$

From: solar, detector & atmospheric neutrino experiments



Opposite to flavor mixing in quarks!

Exhibits:
- mild mass hierarchy
- 2 large mixing angles
  + 1 smaller angle

⟺

Matrix determinant

>>

Matrix elements

⟹

Naturally
if masses
come from
different sources

Extra Higgs doublets

Breaking the spectrum:

- more possibilities for s-partners mass spectrum → detection @ LHC

- rise Higgs mass without fine tuning → Sister Higgs

D. Alves '12

General Issues:

- FCNC arise $\xcancel{\lambda'_{Inm}\hat{L}^i_I\hat{Q}^j_n\hat{D}_m}$

- New RPV term $$\boxed{\frac{\tilde{\lambda}_m}{2}\epsilon_{ij}\left(\hat{H}^i_{D_1}\hat{H}^j_{D_2}-\hat{H}^i_{D_2}\hat{H}^j_{D_1}\right)\hat{E}_m}$$

Neutrinos in RPV SUSY

Higgs down has the same quantum numbers as leptons → Indistinguishable!

MSSM:

$$\hat{L}_\mu = (\hat{H}_D, \hat{L}_1, \hat{L}_2, \hat{L}_3)$$

RPV terms:

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

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

EWSB characterized by:

$$v_u, \qquad v_d = \left(\sum v_\alpha^2\right)^{1/2}, \qquad \mu = \left(\sum \mu_\alpha^2\right)^{1/2}$$

$$v \equiv \left(|v_u|^2 + |v_d|^2\right)^{1/2} = \frac{2m_W}{g} = 246\,\text{GeV}$$

Neutrinos in RPV SUSY

Higgs down has the same quantum numbers as leptons → Indistinguishable!

SUSY with extra pair of Higgses: $\hat{L}_I = (\hat{H}_{D_1}, \hat{H}_{D_2}, \hat{L}_1, \hat{L}_2, \hat{L}_3)$

RPV terms:

$$W = \epsilon_{ij}\left[-\mu_{1I}\hat{L}^i_I\hat{H}^j_{U_1} - \mu_{2I}\hat{L}^i_I\hat{H}^j_{U_2} + \frac{1}{2}\lambda_{IJm}\hat{L}^i_I\hat{L}^j_J\hat{E}_m + \lambda'_{Inm}\hat{L}^i_I\hat{Q}^j_n\hat{D}_m\right]$$

$$V_{\text{soft}} = \left(M^2_{\tilde{L}}\right)_{IJ}\tilde{L}^{i*}_I\tilde{L}^i_J - \left(\epsilon_{ij}B_{1I}\tilde{L}^i_I H^j_{U_1} + \text{h.c.}\right) - \left(\epsilon_{ij}B_{2I}\tilde{L}^i_I H^j_{U_2} + \text{h.c.}\right)$$
$$+\epsilon_{ij}\left[\frac{1}{2}A_{IJm}\tilde{L}^i_I\tilde{L}^j_J\tilde{E}_m + A'_{Inm}\tilde{L}^i_I\tilde{Q}^j_n\tilde{D}_m + \text{h.c.}\right]$$

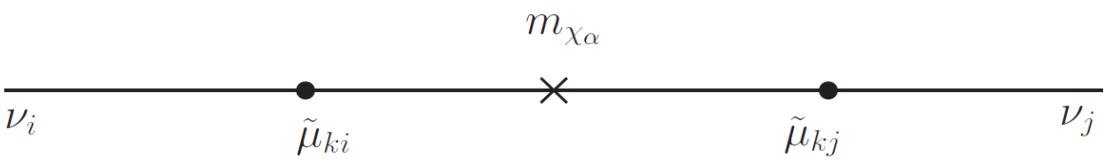
EWSB characterized by:

$$v_u = \left(v^2_{u_1} + v^2_{u_2}\right)^{1/2}, \qquad v_d = \left(\sum v^2_I\right)^{1/2}, \qquad \mu_1 = \left(\sum \mu^2_{1I}\right)^{1/2}, \qquad \mu_2 = \left(\sum \mu^2_{2I}\right)^{1/2}$$

$$v \equiv \left(|v_u|^2 + |v_d|^2\right)^{1/2} = \frac{2m_W}{g} = 246\,\text{GeV}$$

TL Neutrino mixing matrix

Neutrino – neutralino mixing



MSSM:

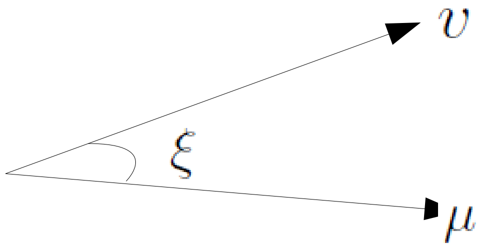
Mixing matrix

$$M^N = \begin{pmatrix} M_1 & 0 & m_Z s_W \hat{v}_u & -m_Z s_W \hat{v}_\alpha \\ 0 & M_2 & -m_Z c_W \hat{v}_u & m_Z c_W \hat{v}_\alpha \\ m_Z s_W \hat{v}_u & -m_Z c_W \hat{v}_u & 0 & \mu_\alpha \\ -m_Z s_W \hat{v}_\alpha^T & m_Z c_W \hat{v}_\alpha^T & \mu_\alpha^T & 0_{3\times 3} \end{pmatrix}$$

Basis: $\{\tilde{B}, \tilde{W}^3, \tilde{H}_U, \nu_\alpha\}$

Product of non-zero eigenvalues

$$\boxed{\det{}' M^N = \mu^2 v_d^2 \sin^2 \xi}$$



4D-vectors

$$\boxed{\xi^2 \lesssim \frac{m_3}{\tilde{m}}}$$

small RPV

TL Neutrino masses

Diagoalize M to obtain the neutrino mass matrix:

Seesaw mechanism

MSSM:

$$M^N = \begin{pmatrix} M_{4\times 4} & \mu_{4\times 3} \\ \mu^T_{3\times 4} & 0_{3\times 3} \end{pmatrix} \Longrightarrow U M^N U^+ = \begin{pmatrix} M'_{4\times 4} & 0_{4\times 3} \\ 0_{3\times 4} & m_{\nu\ 3\times 3} \end{pmatrix}$$

$$\boxed{m_{\nu\ 3\times 3} = \mu^T M^{-1} \mu}$$

$$(m_\nu)_{ij} = X \mu_i \mu_j$$

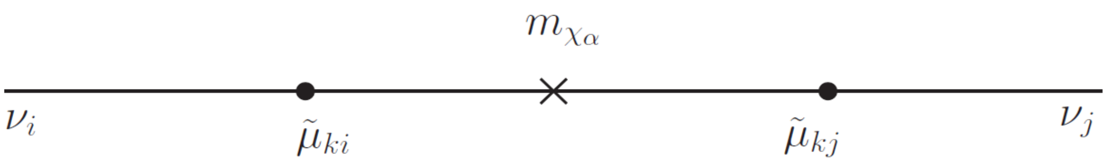
rank 1 matrix

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

$$\boxed{m_3 = X\vec{\mu}^2, \qquad m_1 = m_2 = 0}$$

TL Neutrinos mixing matrix

Neutrino – neutralino mixing



SUSY with extra
pair of Higgses:

Mixing matrix

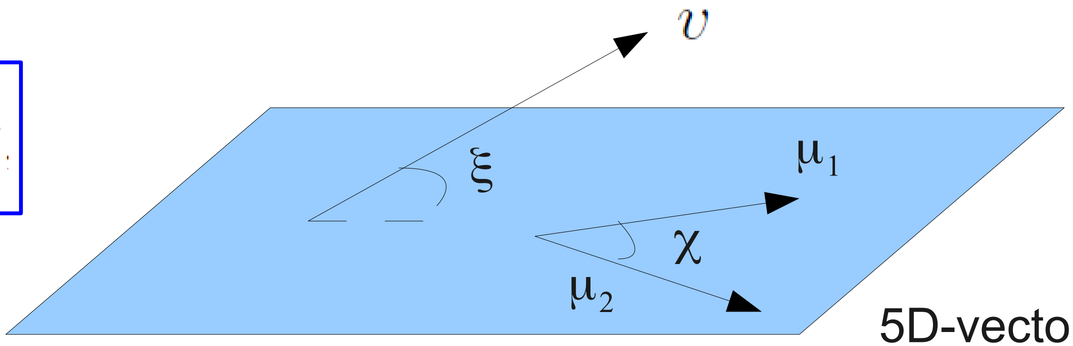
Basis: $\{\tilde{B}, \tilde{W}^3, \tilde{H}_{U_1}, \tilde{H}_{U_2}, \nu_I\}$

$$M^N = \begin{pmatrix} M_1 & 0 & m_Z s_W \hat{v}_{u_1} & m_Z s_W \hat{v}_{u_2} & -m_Z s_W \hat{v}_I \\ 0 & M_2 & -m_Z c_W \hat{v}_{u_1} & -m_Z c_W \hat{v}_{u_2} & m_Z c_W \hat{v}_I \\ m_Z s_W \hat{v}_{u_1} & -m_Z c_W \hat{v}_{u_1} & 0 & 0 & \mu_{1I} \\ m_Z s_W \hat{v}_{u_2} & -m_Z c_W \hat{v}_{u_2} & 0 & 0 & \mu_{2I} \\ -m_Z s_W \hat{v}_I^T & m_Z c_W \hat{v}_I^T & \mu_{1I}^T & \mu_{2I}^T & 0_{5\times 5} \end{pmatrix}$$

Product of non-zero eigenvalues

$$\boxed{\det{}' M^N = 2\frac{m_Z^2\, m_{\tilde{\gamma}}}{v^2}\, v_d^2\, \mu_1^2\, \mu_2^2 \sin^2\chi \sin^2\xi}$$

$$\boxed{\xi^2 \lesssim \frac{m_3}{\tilde{m}}}$$



5D-vectors

TL Neutrino masses

Diagoalize M to obtain the neutrino mass matrix:

Seesaw mechanism

light neutrinos

SUSY with extra
pair of Higgses:

heavy neutralinos

$$M^N = \begin{pmatrix} M_{6\times 6} & \mu_{6\times 3} \\ \mu^T_{3\times 6} & 0_{3\times 3} \end{pmatrix} \Longrightarrow U M^N U^+ = \begin{pmatrix} M'_{6\times 6} & 0_{6\times 3} \\ 0_{3\times 6} & m_{\nu\ 3\times 3} \end{pmatrix}$$

$$\boxed{m_{\nu\ 3\times 3} = \mu^T M^{-1} \mu}$$

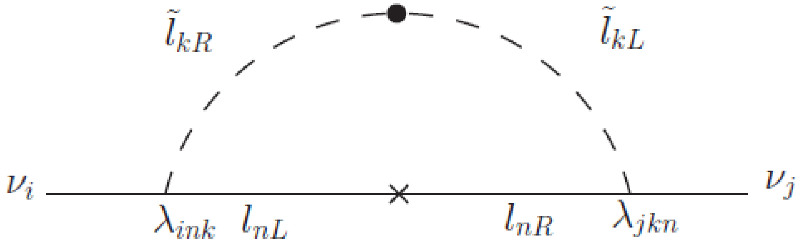
$$(m_\nu)_{ij} = \frac{X}{\Delta\mu^2} \left[\mu_{1i}\tilde{\mu}_2 - \mu_{2i}\tilde{\mu}_1\right] \left[\mu_{1j}\tilde{\mu}_2 - \mu_{2j}\tilde{\mu}_1\right]$$

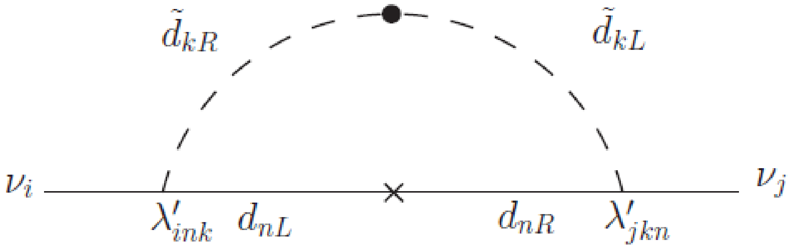
$$X \equiv \frac{m_{\tilde{\gamma}} m_Z^2 \cos^2\beta}{M_1 M_2 \Delta\mu^2 + m_{\tilde{\gamma}} m_Z^2 \sin(2\beta)(\tilde{\mu}_1 \sin\beta_2 - \tilde{\mu}_2 \cos\beta_2)} \sim \frac{\cos^2\beta}{\tilde{m}}$$

rank 1 matrix

$$\boxed{m_3 = \frac{X}{\Delta\mu^2}\mu_1^2\mu_2^2 \sin^2\chi \sin^2\xi, \qquad m_1 = m_2 = 0}$$

Loop contributions: λλ loops





MSSM:

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

Grossman, Rakshit '04

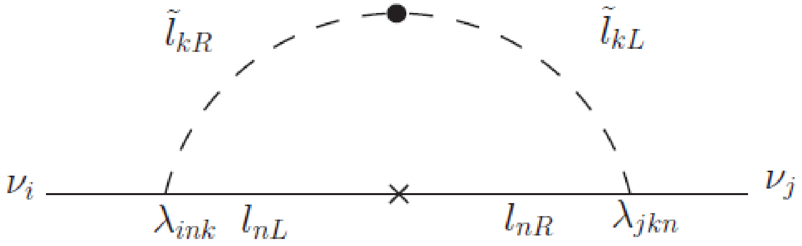
neglecting quark/lepton mixings

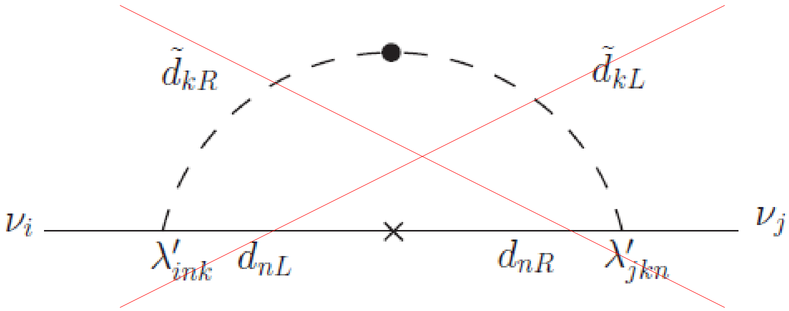
Supression factors:

2RPV COUPLINGS+LOOP FACTOR+2 QUARK MASSES

Irrelevant in most cases

Loop contributions: λλ loops





SUSY with extra
pair of Higgses:

$$\delta m_{\nu_{ij}}^{\lambda\lambda} \approx \frac{1}{8\pi^2} \sum_{n,k} \lambda_{ink}\lambda_{jkn} \frac{\boxed{m_{l_n} \Delta m^2_{\tilde{l}_k}}}{m^2_{\tilde{l}_k}}$$

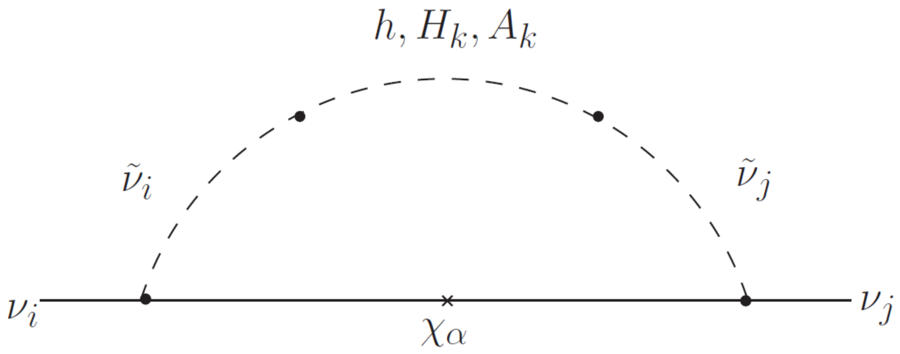
neglecting quark/lepton mixings

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+2 LEPTON MASSES

Irrelevant in most cases

Loop contributions: BB loops



MSSM:

$$[m_\nu]_{ij}^{(BB)} = \sum_{\alpha,i,j} \frac{g^2 B_i B_j}{4\cos^2\beta} (Z_{\alpha 2} - Z_{\alpha 1} g'/g)^2 m_{\chi_\alpha} \Big\{ I_4(m_h, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \cos^2(\alpha - \beta)$$
$$+ I_4(m_H, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \sin^2(\alpha - \beta) - I_4(m_A, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \Big\} ,$$

Supression factors:

Grossman, Rakshit '04

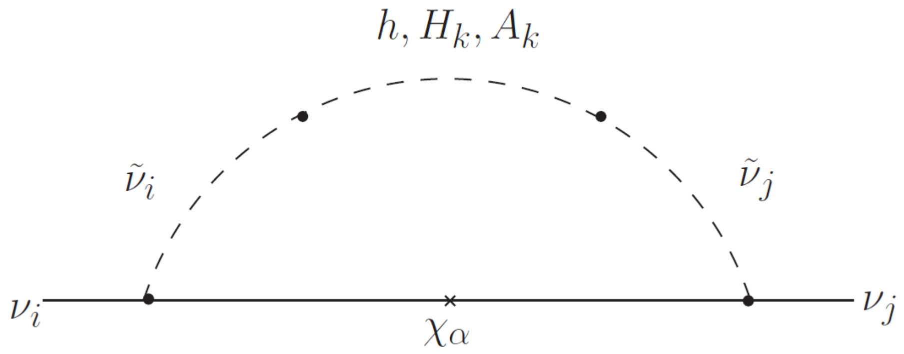
2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

$$\cos^2(\alpha - \beta) = \frac{m_h^2 (m_Z^2 - m_h^2)}{m_A^2 (m_H^2 - m_h^2)}$$

$$m_Z^2 - m_h^2 = m_H^2 - m_A^2$$

Loop contributions: BB loops

SUSY with extra pair of Higgses:



$$\delta m_{\nu_{ij}}^{BB} = \sum_\alpha \frac{g^2}{4}\left(Z_N^{0\alpha} - \frac{g'}{g} Z_N^{1\alpha}\right)^2 \Big[\tilde{B}_{ih}\tilde{B}_{jh} I_4(m_h, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha})$$

$$+ \sum_k \tilde{B}_{iH_k}\tilde{B}_{jH_k} I_4(m_{H_k}, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) + \sum_k \tilde{B}_{iA_k}\tilde{B}_{jA_k} I_4(m_{A_k}, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha})\Big]$$

Enlarged Higgs-like spectrum:

$$\frac{i}{\sqrt{2}}\tilde{B}_{i\{h,H_j,A_j\}} \equiv \frac{i}{\sqrt{2}}\Big[B_{1i}\{Z_R^{00}, Z_R^{0j}, iZ_H^{0j}\} + B_{2i}\{Z_R^{10}, Z_R^{1j}, iZ_H^{1j}\}$$

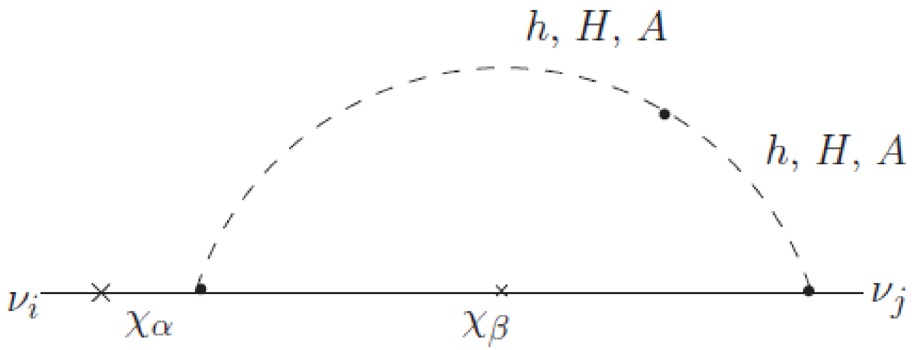
$$+(M_{\tilde{L}}^2)_{0(1+i)}\{Z_R^{20}, Z_R^{2j}, iZ_H^{2j}\} + (M_{\tilde{L}}^2)_{1(1+i)}\{Z_R^{30}, Z_R^{3j}, iZ_H^{3j}\}\Big]$$

larger number of diagrams!

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

Loop contributions: μB loops



MSSM:

$$[m_\nu]_{ij}^{(\mu B)} \sim \frac{g^2}{64\pi^2 \cos\beta} \frac{\mu_i B_j + \mu_j B_i}{\tilde{m}^2}$$

(approximate expression)

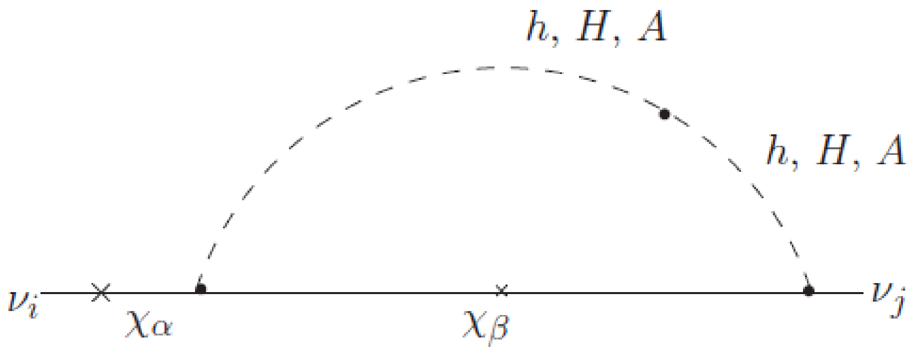
- subleading in μ with respect to the tree level (if tree level is dominant)

$$\begin{tikzcd}
 & {[m_\nu]_{ij}^{(V\mu)} = C\varepsilon_L(\mu_i V_j + \mu_j V_i)} \arrow[r] & \frac{m_1}{m_2} \sim O\left(\varepsilon_L^2\right) \\
{[m_\nu]_{ij}^{(\mu\mu)} = C\mu_i\mu_j} \arrow[ur] \arrow[dr] & & \\
 & {[m_\nu]_{ij}^{(VU)} = C_{ij}^{VU}\varepsilon_L(V_i U_j + V_j U_i)} \arrow[r] & \frac{m_1}{m_2} \sim O(\varepsilon_L)
\end{tikzcd}$$

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

Loop contributions: μB loops



SUSY with extra pair of Higgses:

$$\delta m_{\nu_{ij}}^{\mu B} \sim \sum_{\alpha,\beta} \frac{g^2}{16\pi^2} \left(\tilde{\mu}_{i\alpha}\tilde{B}_{jh} + \sum_k \tilde{\mu}_{i\alpha}\tilde{B}_{jH_k} + \sum_k \tilde{\mu}_{i\alpha}\tilde{B}_{jA_k} \right. \\ \left. + \tilde{\mu}_{j\alpha}\tilde{B}_{ih} + \sum_k \tilde{\mu}_{j\alpha}\tilde{B}_{iH_k} + \sum_k \tilde{\mu}_{j\alpha}\tilde{B}_{iA_k} \right)$$

- subleading in μ with respect to the tree level
(if tree level is dominant)

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

Contributions from new term

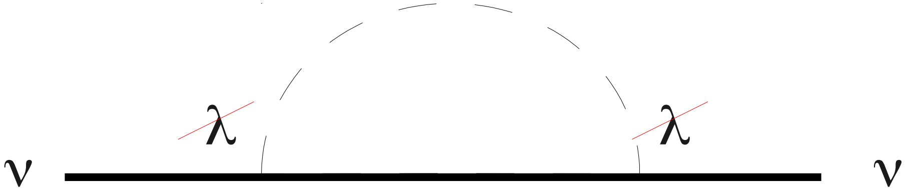
$$\boxed{\frac{\tilde{\lambda}_m}{2}\epsilon_{ij}\left(\hat{H}^i_{D_1}\hat{H}^j_{D_2}-\hat{H}^i_{D_2}\hat{H}^j_{D_1}\right)\hat{E}_m}$$

less constrained than usual RPV couplings

NO ONE LOOP EFFECTS

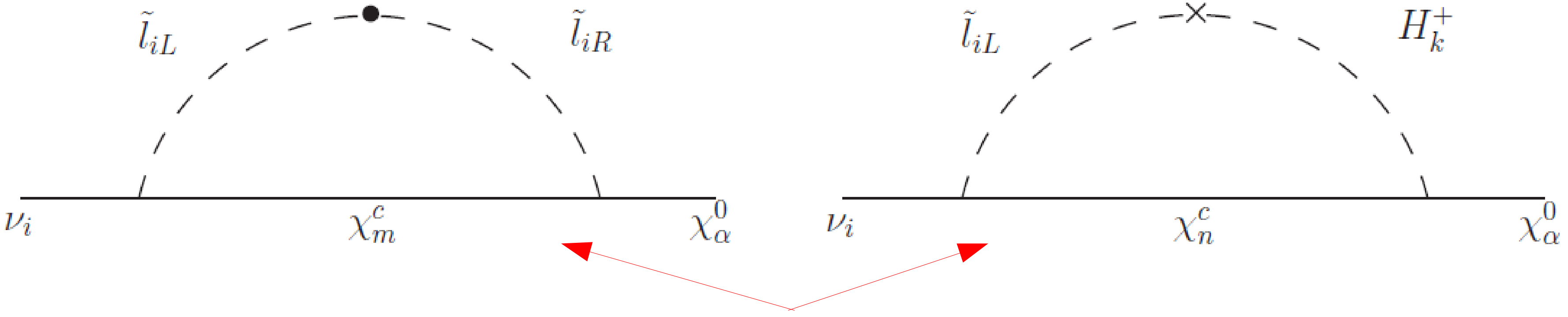
No neutrinos involved in the vertex
RPV in charged sector

Topological argument:



Contributions from new term

SEPARABLE TWO LOOP DIAGRAMS



effective μ couplings

$$[m_\nu]^{S,\tilde{\lambda}\tilde{\lambda}}_{ij} = \sum_\alpha \frac{\mu^{\tilde{\lambda}}_{i\alpha}\mu^{\tilde{\lambda}}_{j\alpha}}{m_{\chi^0_\alpha}} \approx \frac{27}{32\pi^4} g^2 \tilde{\lambda}_i \tilde{\lambda}_j \frac{m_{l_i} m_{l_j}}{\tilde{m}}$$

$$[m_\nu]^{S,\tilde{\lambda}\tilde{B}}_{ij} = \sum_\alpha \frac{\mu^{\tilde{\lambda}}_{i\alpha}\mu^{\tilde{B}}_{j\alpha} + \mu^{\tilde{B}}_{i\alpha}\mu^{\tilde{\lambda}}_{j\alpha}}{m_{\chi^0_\alpha}} \approx \sum_k \frac{27}{128\pi^4} g^3 \frac{\tilde{\lambda}_i \tilde{B}_{jk} m_{l_i} + \tilde{\lambda}_j \tilde{B}_{ik} m_{l_j}}{\tilde{m}^2}$$

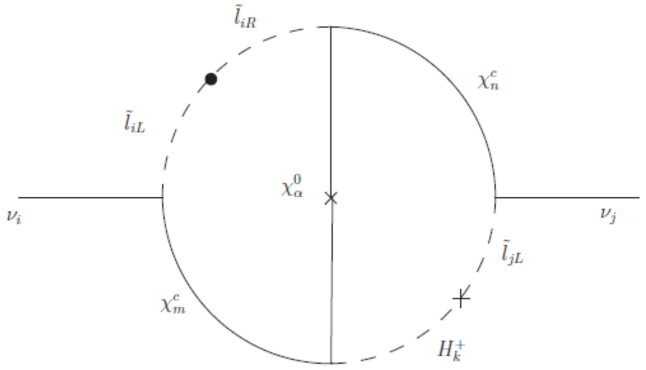
$$[m_\nu]^{S,\tilde{B}\tilde{B}}_{ij} = \sum_\alpha \frac{\mu^{\tilde{B}}_{i\alpha}\mu^{\tilde{B}}_{j\alpha}}{m_{\chi^0_\alpha}} \approx \sum_{k,k'} \frac{27}{512\pi^4} g^4 \frac{\tilde{B}_{ik} \tilde{B}_{jk'}}{\tilde{m}^3}$$

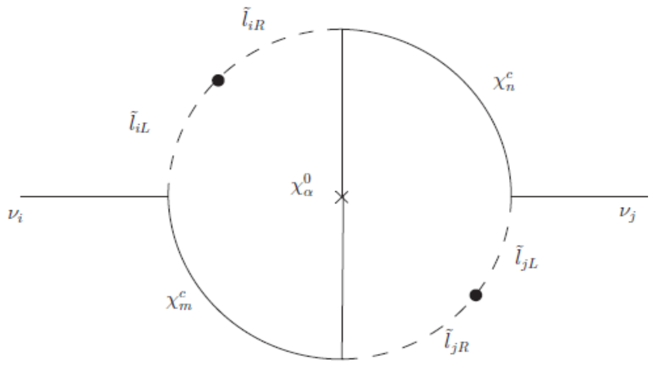
Supression factors:

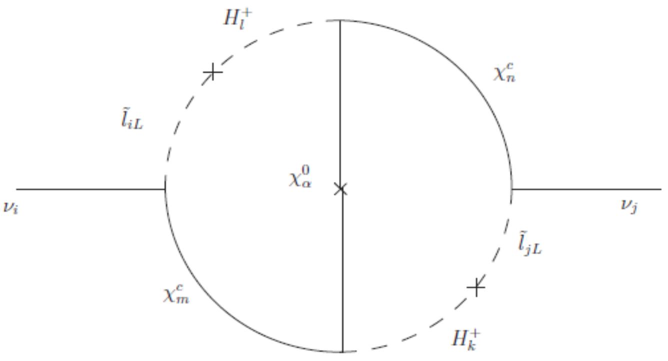
2RPV COUPLINGS+2LOOP FACTOR+
2 lepton Yukawas
1 lepton Yukawa
0 lepton Yukawa

Contributions from new term

NON- SEPARABLE TWO LOOP DIAGRAMS







Complicated loop functions involving fermionic propagators → solved numerically

$$[m_\nu]^{\mathrm{NS},\tilde{\lambda}\tilde{\lambda}}_{ij} \approx \frac{60.48}{256\pi^4} g^2 \tilde{\lambda}^*_i \tilde{\lambda}^*_j \frac{m_{l_i} m_{l_j}}{\tilde{m}}$$

$$[m_\nu]^{\mathrm{NS},\tilde{\lambda}\tilde{B}}_{ij} \approx -\sum_k \frac{15.12}{256\pi^4} g^3 \tilde{\lambda}^*_i \tilde{B}_{jk} \frac{m_{l_i}}{\tilde{m}^2}$$

$$[m_\nu]^{\mathrm{NS},\tilde{B}\tilde{B}}_{ij} \approx \sum_{k,l} \frac{3.80}{256\pi^4} g^2 \frac{\tilde{B}_{il}\tilde{B}_{jk}}{\tilde{m}^3}$$

Supression factors:

2RPV COUPLINGS+2LOOP FACTOR+
2 lepton Yukawas
1 lepton Yukawa
0 lepton Yukawa

Conclusions: neutrino masses in RPV MSSM

- RPV SUSY models provide an alternative to usual seesaw mechanism

- Naturally generate mild hierarchichal masses with large mixing angles

- Need small RPV couplings

- One neutrino has a tree level mass, while the other two just from loop effects

- Several suppression factors
    relative importance is model dependent

Conclusions: neutrino masses in RPV extra HD

- Adding pairs of Higgs doublets makes a new term HHE, which is forbidden in the MSSM arise in the superpotential

- The extra pairs of Higgs doublets do not change the fact that only one neutrino gets mass at tree level

- The new term containing two Higgses starts contributing at two loops

- We find that there is a new parameter that controls the suppression, the lepton Yukawa coupling

  If the couplings are of the same order, it governs the suppression
  If λ is the only significant coupling, it always comes with a Yukawa

Furture perspectives

- SUSY needs to be further tested before it can be “ruled out”
need to analyze more data, more processes, more models...

- Neutrino masses are still one of the most interesting enigmas in particle physics
their small masses can constrain the parameters of different models

- The results here exposed can be extended to similar models, and are not only valid when the doublet is just a copy of the MSSM one
for example, they could be relevant in the case of dRPV

THANK YOU!

IV. Future prospectives