Probing R-Parity Violating ~l_4 Resonance at The LHC

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Outline

- 4^{th} Generation Facts
- SUSY
- R-Parity Violation
- RPV Production of $\sim L_4$
- RPV Production of $\sim v_4$
- Searches at LHC
- Conclusion

4th Generation Facts

- SM cannot predict **the number of families**, their **masses** and **mixing patterns** for fermions.
- Bounds for number of families, $N \geq 3$ from LEP Data,

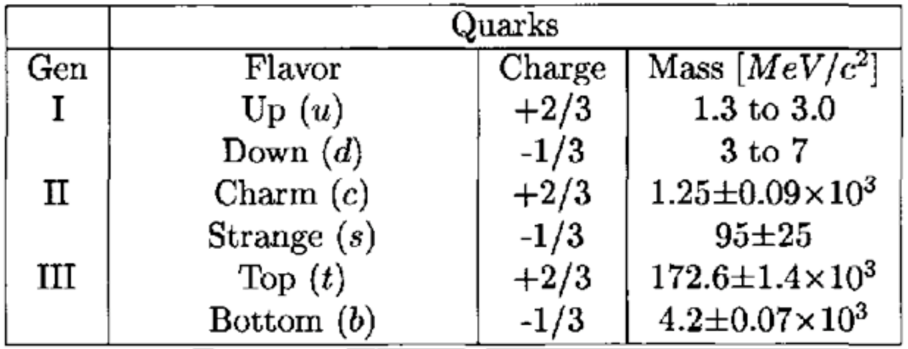
  $N < 9$ from asymptotic freedom
- EW Precision Data Measurements allow 4th SM families for Higgs masses between 115 – 750 GeV and for **massive neutrinos.** For massless neutrinos, one can calculate the number of families as 3.
- Partial-wave unitarity leads to $m_Q \leq 700$ GeV $\approx 4m_t$ and in general we expect $m_t << m_4 << m_5$.
- According to LEP results, there are only 3 *"light"* ($2m_\nu < m_Z$) non -sterile neutrinos, whereas in the case of "5" SM families "*4 light neutrinos*" are expected.
- **Fifth SM family** is excluded at more than **5σ** level by EW precision data.

4th Generation Facts

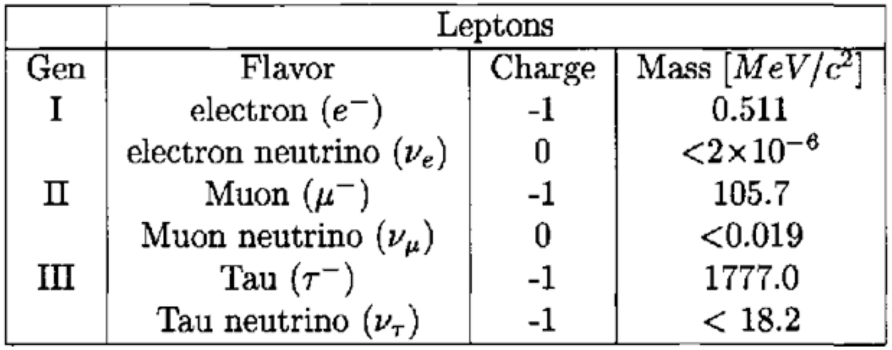
- **In the SM**, the masses and mixings of quarks arise from the Yukawa interactions with the Higgs condensate.

$$L_Y = -Y_{ij}^{d}\bar{Q}_{Li}^{I}\phi d_{Rj}^{I} - Y_{ij}^{u}\bar{Q}_{Li}^{I}\varepsilon\phi^{*}u_{Rj}^{I} + h.c.$$

- When *Φ* acquires a vev after Spontaneous Sym. Breaking, mass terms appear in above equation and physical mass states are obtained by diagonalizing $Y^{u,d}$ by four unitary matrices, $V_{L,R}^{u,d} \rightarrow M_{diag}^{f} = V_L^f Y^f (V_R^f)^{\dagger}(v/\sqrt{2})$
- As a result, $W^{\pm}$ interactions couple to physical u_{Lj}, d_{Lk} quarks with couplings given by $V_{CKM} \equiv V_L^u (V_L^d)^{\dagger}$ and we have the mass matrices.
- Note that since we have **Hierarchy problem in the SM**, we can not explain why fermions have so different mass values at the end **???**



	Quarks		
Gen	Flavor	Charge	Mass $[MeV/c^2]$
I	Up (u)	+2/3	1.3 to 3.0
	Down (d)	-1/3	3 to 7
II	Charm (c)	+2/3	1.25±0.09×10^3
	Strange (s)	-1/3	95±25
III	Top (t)	+2/3	172.6±1.4×10^3
	Bottom (b)	-1/3	4.2±0.07×10^3



	Leptons		
Gen	Flavor	Charge	Mass $[MeV/c^2]$
I	electron (e^-)	-1	0.511
	electron neutrino (ν_e)	0	<2×10^{-6}
II	Muon (μ^-)	-1	105.7
	Muon neutrino (ν_μ)	0	<0.019
III	Tau (τ^-)	-1	1777.0
	Tau neutrino (ν_τ)	-1	< 18.2

4th Generation Facts

- One way to overcome **Hierarchy problem in the SM4** may be **Flavour Democratic Approach.**
- **Flavour Democracy** offers that SM masses are equal before Spontaneous Symmetry Breaking. (*)

$$m_{u_4} > 335 \text{ GeV} \;\; 95\% \text{ CL.} \qquad \mathrm{m}_{l_4} > 100 \text{ GeV}$$

$$m_{d_4} > 338 \text{ GeV} \;\; 95\% \text{ CL.} \qquad \mathrm{m}_{\nu_4} > 90 \;\; (80) \text{ for Dirac (Majorana)}$$

700 GeV
(Partial Wave Unitarity)

We can generalize 4th family case to SUSY in order to find RPV couplings of 4th family sfermions !!

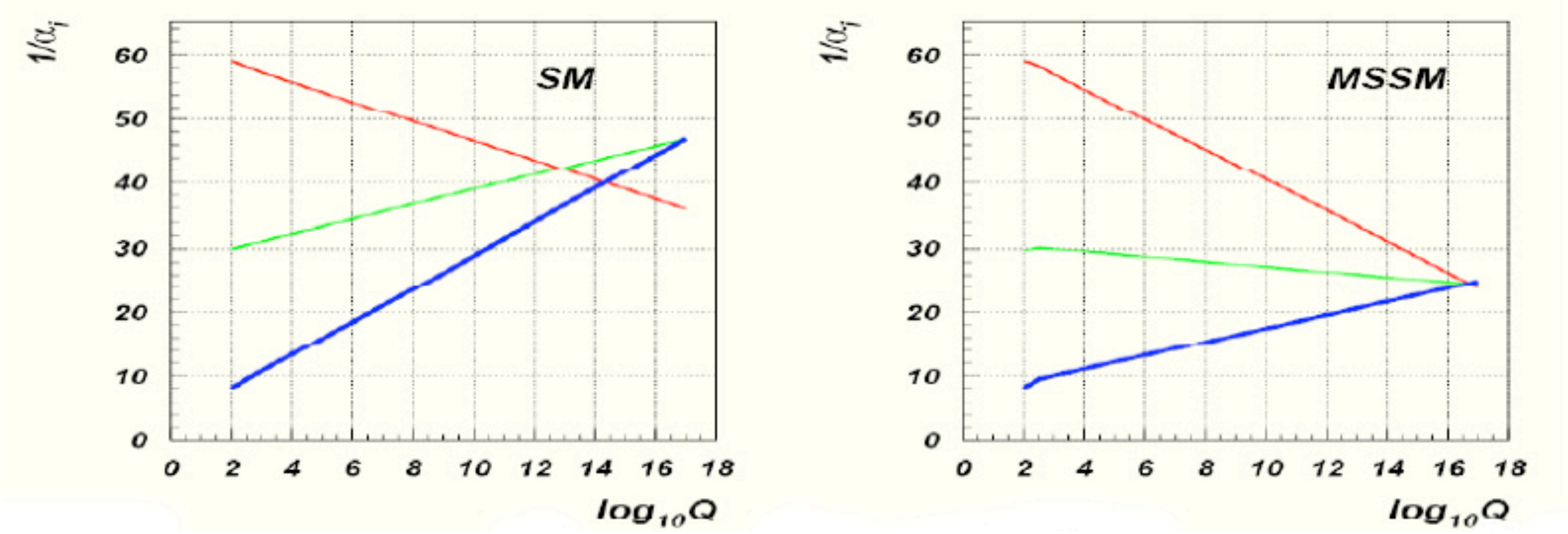
(*) H.Fritches *et al.* Physics Letters B, Volume 237, Issue 3-4.
S.Sultansoy *et al.* arxiv.org/abs/hep-ph/0610279.

SUSY

“Supersymmetry is a space-time symmetry which is defined by the transformations between fermion and boson states using an operator Q.” (Martin F. Sohnius, 1985) $n_B = n_F$

$$Q|Fermion\rangle = |Boson\rangle \qquad Q^\dagger|Boson\rangle = |Fermion\rangle$$

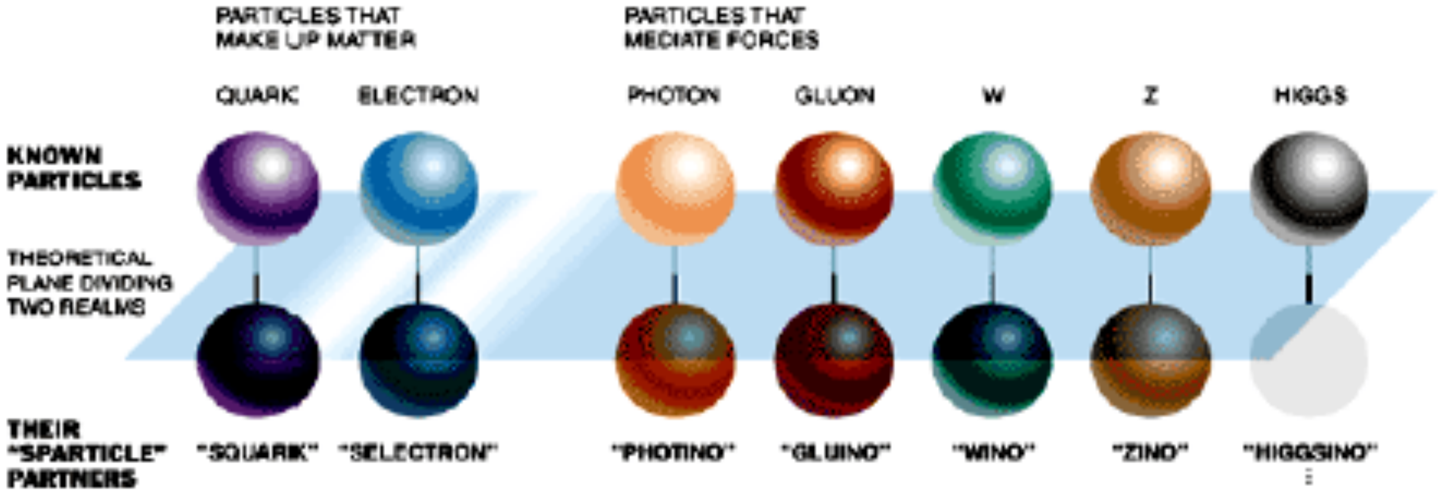
$$\{Q,Q^\dagger\} \approx P^\mu \qquad \{Q,Q\} = \{Q^\dagger,Q^\dagger\} = 0 \qquad [P^\mu,Q] = [P^\mu,Q^\dagger] = 0$$



SUSY

supersymmetry

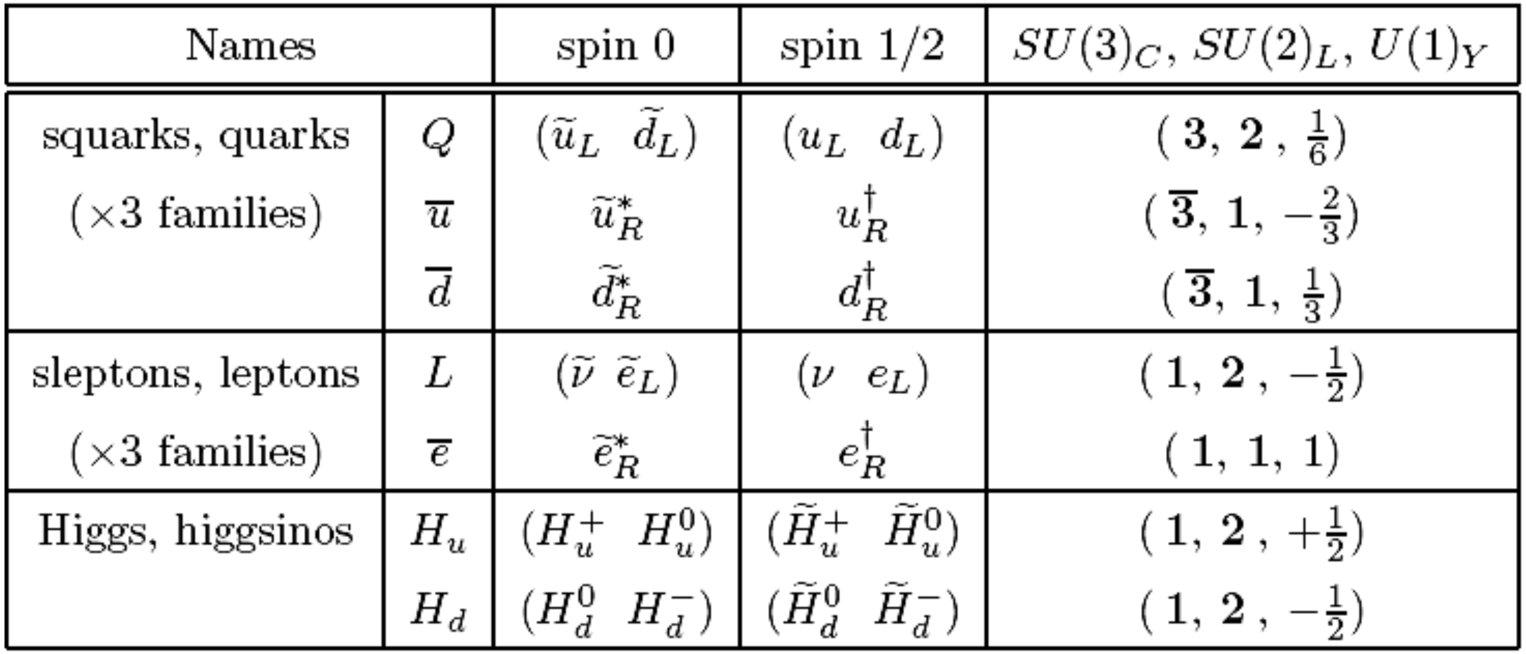
fermions ⟷ **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

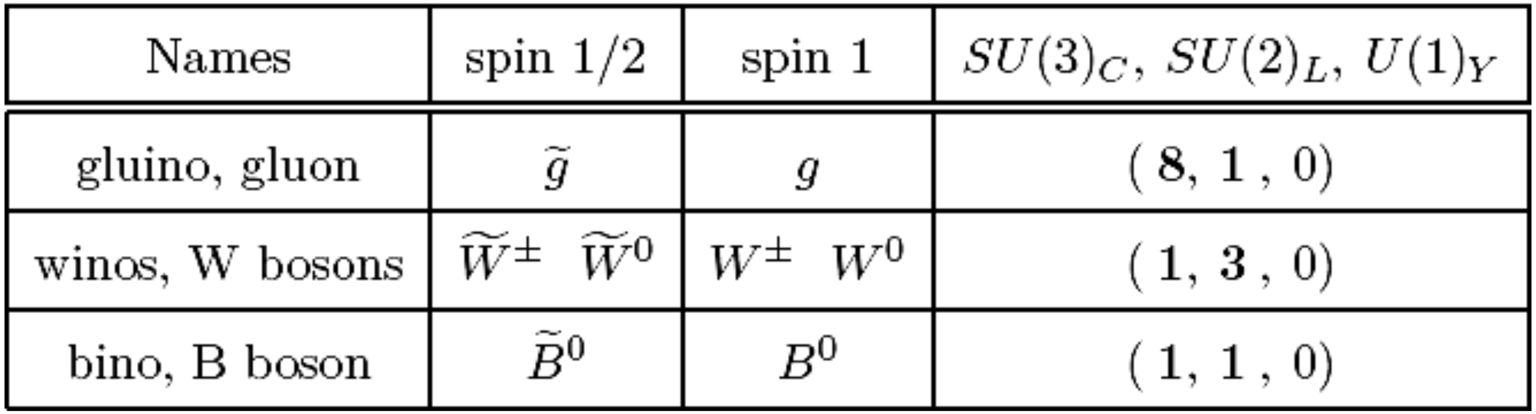
Charged Wino, charged Higgsino: Charginos

Sparticle Pool



Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\ \mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

Chiral supermultiplets



Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

Gauge supermultiplets

MSSM Superpotential

- **MSSM** extension of SM is specified by the superpotential choice of the form:

$$W_{\rm MSSM} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_uH_d\,.$$

- However, one can find other gauge invariant and renormalizable terms which violate ***L*** and ***B*** numbers in the total superpotential, namely:

$$\begin{aligned} W_{\Delta \rm L=1} &= \frac{1}{2}\lambda^{ijk}L_iL_j\overline{e}_k + \lambda'^{ijk}L_iQ_j\overline{d}_k + \mu'^{i}L_iH_u \\ W_{\Delta \rm B=1} &= \frac{1}{2}\lambda''^{ijk}\overline{u}_i\overline{d}_j\overline{d}_k \end{aligned}$$

- *B*- and *L*- violating above processes have never seen experimentally. But we cannot forbid them since both of them are produced by **non-perturbative electroweak effects.**

- Non-perturbative electroweak effects are negligible at ordinary energies but may be relevant in the early universe.

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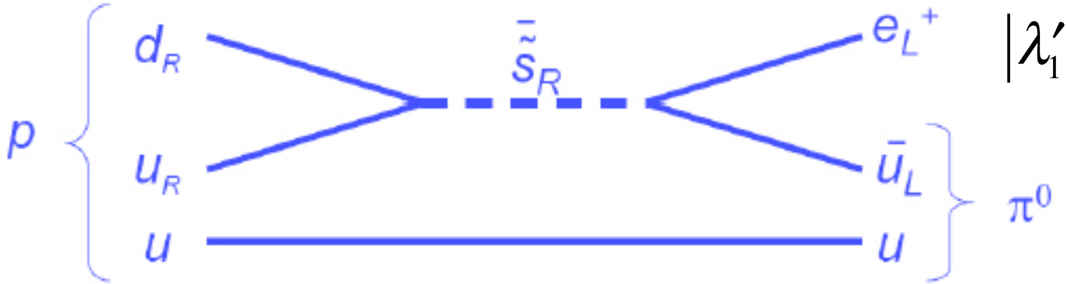
R-Parity Violation

- We can define S,B and L conservation together with **R-parity** as:

$$R = (-1)^{3(B-L)+2S} \begin{cases} +1 \text{ for all matter particles (even R state)} \\ -1 \text{ for all sparticles (odd R state)} \end{cases}$$

- If ***B*** or ***L*** number is violating at a vertex, it is a matter violation even if **R-parity** is conserving.
- Multiplication of particle R-states violates **R-parity** if multiplication is equal to -1 (odd).
- **In the MSSM**, R-parity violation can only come from R-odd, B - and L -violating terms in the superpotential.
- On the other hand, proton should decay immediately via **R-parity** violating processes. A solution to this problem taking:



$$\left|\lambda'_{11k}\lambda''_{11k}\right| \le 8\times10^{-27}\times\left(\frac{m_{\tilde{\bar{s}}}}{100GeV}\right)^2$$

Super Kamiokande Result

R-Parity Violation

If R-parity violating exists;

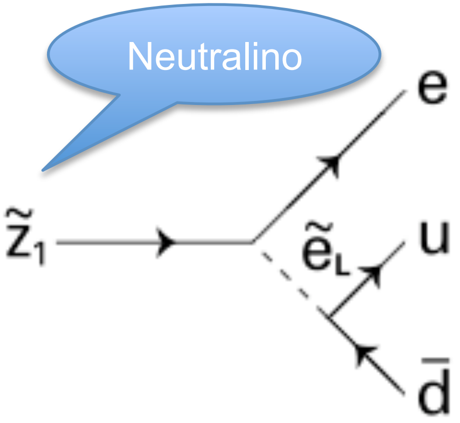
1. The lightest sparticle can not be stable and should decay into some SM particles.
2. Decay products of all other sparticles must contain **odd** and **even** R states which can mix to form mass eigenstates. But we can assume one of the states are dominant.
3. Sparticles can be produced in pairs as well as **in resonances.**

$$\Gamma(\tilde{Z}_1 \to eu\bar{d}) \sim \frac{3\alpha\lambda'^{2}_{111}}{128\pi^2}\frac{m^5_{\tilde{Z}_1}}{M^4_{SUSY}}$$

If we cannot observe in 1m long detector:

$$c.\gamma.\tau(\tilde{Z}_1) \le 1 \qquad LorentzFactor = \gamma = \frac{E_{\tilde{Z}_1}}{m_{\tilde{Z}_1}}$$

$$\lambda'_{111} > 1.4\times 10^{-6}\sqrt{\gamma}\left(\frac{M_{SUSY}}{200GeV}\right)^2\left(\frac{100GeV}{m_{\tilde{Z}_1}}\right)^{5/2}$$



RPV-4 Model

The RPV supersymmetric trilinear interaction terms for the charged fourth family slepton can be written as

$$L_{RPV} = \lambda_{i4k}\tilde{l}_{4L}\bar{l}_{kR}\nu_i + \lambda_{ij4}\tilde{l}^*_{4R}\bar{\nu}^c_i l_{jL} - \lambda_{4jk}\tilde{l}_{4L}\bar{l}_{kR}\nu_j - \lambda_{ij4}\tilde{l}^*_{4R}\bar{\nu}^c_j l_{iL} - \lambda'_{4jk}\tilde{l}_{4L}\bar{q}_{kR}q_{jL} + h.c.$$

$$M^2_{\tilde{l}_4} = \begin{pmatrix} m^2_{\tilde{l}_{4L}} & a_{l_4} m_{l_4} \\ a_{l_4} m_{l_4} & m^2_{\tilde{l}_{4R}} \end{pmatrix} \quad \left\{ \begin{aligned} m^2_{\tilde{l}_{4L}} &= M^2_{\tilde{L}_4} + m^2_{l_4} - m^2_Z \cos 2\beta \left(\frac{1}{2} - \sin^2\theta_W\right) \\ m^2_{\tilde{l}_{4R}} &= M^2_{\tilde{E}_4} + m^2_{l_4} - m^2_Z \cos 2\beta \sin^2\theta_W \\ a_{l_4} &= A_{l_4} - \mu \tan\beta \end{aligned} \right.$$

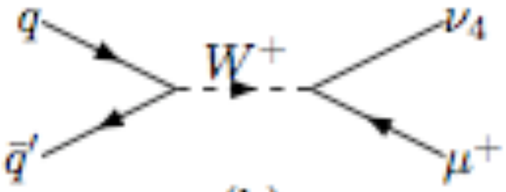
$$\begin{pmatrix} \tilde{l}_{4l} \\ \tilde{l}_{4h} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{l}_4} & \sin\theta_{\tilde{l}_4} \\ -\sin\theta_{\tilde{l}_4} & \cos\theta_{\tilde{l}_4} \end{pmatrix} \begin{pmatrix} \tilde{l}_{4L} \\ \tilde{l}_{4R} \end{pmatrix}$$

$$\cos\theta_{\tilde{l}_4} = \frac{-a_{l_4} m_{l_4}}{\sqrt{(m^2_{\tilde{l}_{4L}} - m^2_{\tilde{l}_{4l}})^2 + a^2_{l_4} m^2_{l_4}}}$$

$$m^2_{\tilde{l}_{4(l,h)}} = \frac{1}{2}(m^2_{\tilde{l}_{4L}} + m^2_{\tilde{l}_{4R}}) \mp \frac{1}{2}\sqrt{(m^2_{\tilde{l}_{4L}} - m^2_{\tilde{l}_{4R}})^2 + 4a^2_{l_4} m^2_{l_4}}$$

RPV Production of ~L_4

(a)



(b)

- Resonant production of ~l_4 is possible via R-parity violating interactions of SUSY as shown in figure (a).
- Dominant background process will be resonant W^+ production of SM4 as shown in figure (b).
- SUSY backgrounds (pair production of ~l_4) will be negligibly low after applying P_T cuts for high-energetic jets.
- Allowed parameter space by PEW Data is large enough if we consider neutrinos as Majorana.

RPV Production of ~L_4

For Signal: “Process (a)” one can calculate partonic cross section as:

$$\hat{\sigma}_{part}(\hat{s}) = \sum_{jk} \frac{C_F(\lambda'^{eff}_{4jk}\lambda^{eff}_{442})^2(\hat{s} - m^2_{\nu_4})^2}{16\pi\hat{s}[(\hat{s} - m^2_{\tilde{l}_{4l}})^2 + m^2_{\tilde{l}_{4l}}\Gamma^2_{\tilde{l}_{4l}})]}$$

$$where \quad \lambda^{eff}(\lambda'^{eff}) = \cos\theta_{\tilde{l}_4}\lambda(\lambda')$$

$$m_{\nu_4} = 100\ GeV, \quad m_{\tilde{l}_4} = 300\ GeV$$

C_F: Color Factor

In calculations of total cross section, we implemented interactions into CompHEP with CTEQ6M PDF data.

For Background: “Process (b)”

Cross section of SM4 background is proportional to $|U_{\nu 4\mu}|^2$

Analysis of PMNS matrix elements showed that $|U_{\nu 4\mu}| < 0.115$

0.016 pb for $\sqrt{s} = 7$ TeV

0.024 pb for $\sqrt{s} = 10$ TeV

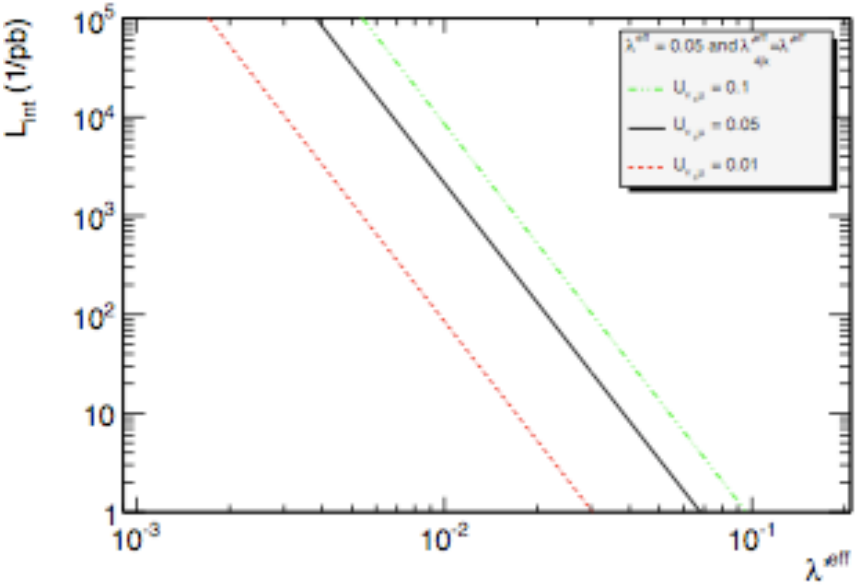
0.035 pb for $\sqrt{s} = 14$ TeV

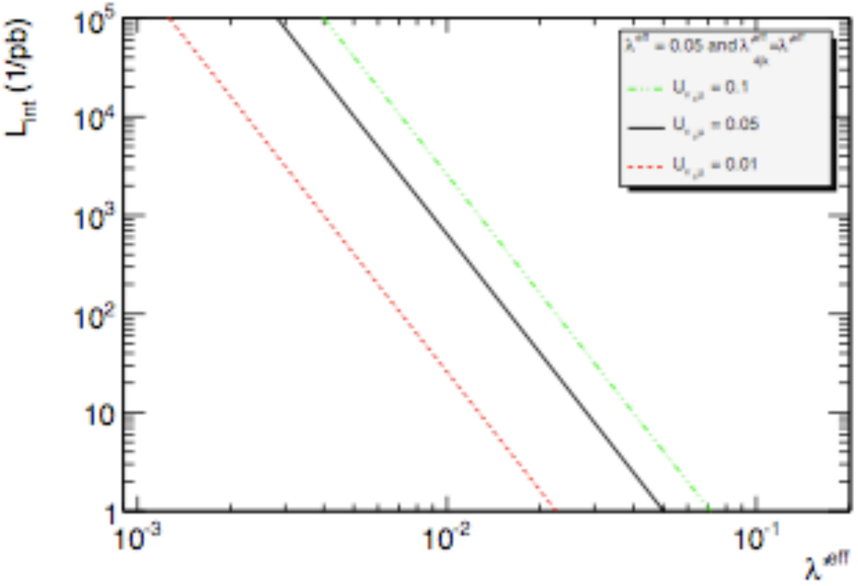
Calculated by CompHEP using $|U_{\nu 4\mu}| = 0.05$

RPV Production of ~L_4

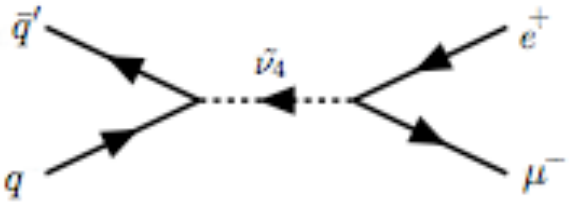
Achievable values of λ'^{eff} for 3σ observation and L vs. λ'^{eff} for 7, 14 TeV:

$\lvert U_{\nu_4\mu}\rvert$	$\sqrt{s} = 7$ TeV, $L_{int} = 1\ fb^{-1}$	$\sqrt{s} = 10$ TeV, $L_{int} = 100\ fb^{-1}$	$\sqrt{s} = 14$ TeV, $L_{int} = 100\ fb^{-1}$
0.1	0.017	0.0048	0.0040
0.05	0.010	0.0032	0.0028
0.01	0.0045	0.0015	0.0012





RPV Production of ~v_4



- **For Signal**: Partonic cross section;

C$_F$: Color Factor

$$\hat{\sigma}_{par}(\hat{s}) = \sum_{jk} \frac{C_F(\lambda'_{4jk}\lambda_{412})^2 \hat{s}^2}{16\pi\left[(\hat{s}-m^2_{\tilde{\upsilon}_4})^2 + m^2_{\tilde{\upsilon}_4}\Gamma^2_{\tilde{\upsilon}_4}\right]}$$

$$where\ m_{\tilde{\upsilon}_4} = 300\ GeV$$

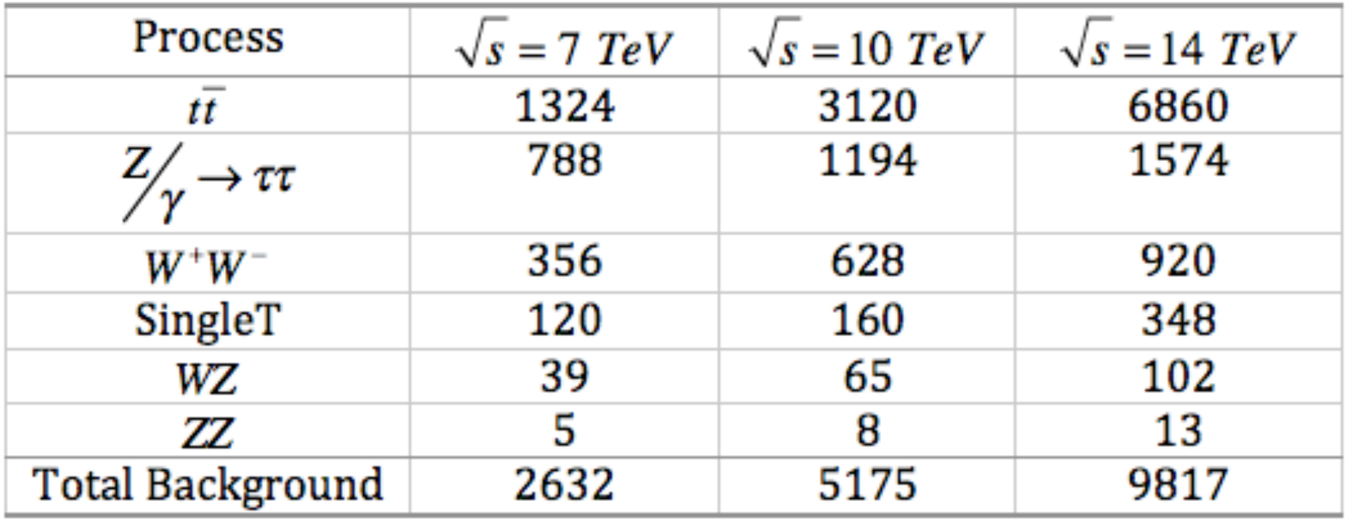
$$\lambda' = \lambda = 0.05$$

- We make *"one coupling dominance assumption"* which helps us in total cross section calculations using CTEQ6m PDF data with CompHEP-v4-5-1.

Events for *L=1 fb^{-1}*	7 TeV	10 TeV	14 TeV
pp ➔sn4➔ eμ	490	335	253

RPV Production of $\sim v_4$

- **For Background:** We estimated total **SM background events** which will contribute the *eμ* final state for the total integrated luminosity 1 fb^{-1}



Process	$\sqrt{s} = 7\ TeV$	$\sqrt{s} = 10\ TeV$	$\sqrt{s} = 14\ TeV$
$t\bar{t}$	1324	3120	6860
$Z/\gamma \rightarrow \tau\tau$	788	1194	1574
W^+W^-	356	628	920
SingleT	120	160	348
WZ	39	65	102
ZZ	5	8	13
Total Background	2632	5175	9817

Simulation tools like CompHEP, Pythia, Hathor, Jimmy, Herwig, PowHEG are useful to cross check above results.

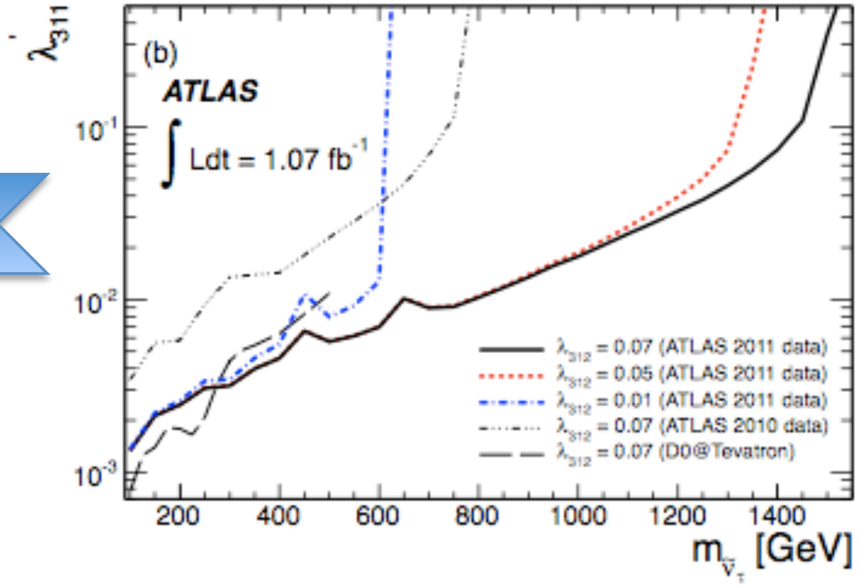
RPV Production of $\sim\upsilon_4$

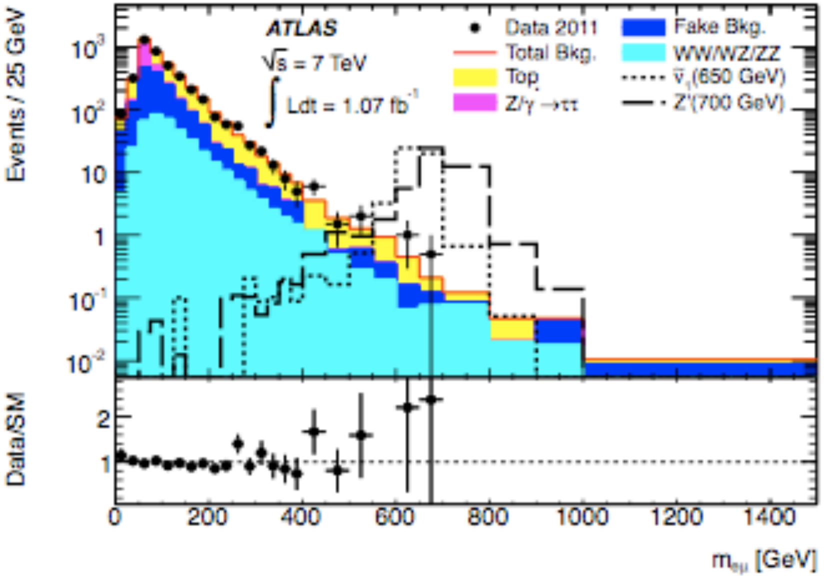
- Achievable values of λ'_{4jk} for 3σ observation:

λ	**7 TeV, L_{int}=1 fb $^{-1}$**	**10 TeV, L_{int}=100 fb $^{-1}$**	**14 TeV, L_{int}=100 fb $^{-1}$**
0,1	0,015	$1,2\text{x}10^{-3}$	$9\text{x}10^{-4}$
0.05	0.03	$2,5\text{x}10^{-3}$	$1,5\text{x}10^{-3}$
0.01	0.13	0,014	0.011

Searches at LHC

The 95% C.L. upper limits on the λ'_{311} Coupling as a function of $m^{\sim}_{\nu\tau}$ for three values of λ_{312} . The regions above the three curves represent ranges of λ'_{311} values that are excluded. (*)





Observed and predicted eμ invariant mass distributions. The couplings taken as $\lambda'_{311} = 0.1$ and $\lambda_{312} = 0.05$. The ratio plot at the bottom includes statistical uncertainties. (*)

* ATLAS Collaboration, arxiv.org/abs/hep-ph/1109.3089v1

Conclusion

- We have studied the resonance production of sleptons through R-parity violating couplings at LHC energies. This could be the first manifestation of 4th family for SUSY.
- One can see that LHC has a potential to exclude R-parity couplings about the order of 10^{-4}. Here we present the exact values of λ_{412} and λ'_{4jk} with respect the LHC energies and luminosities.
- R-parity violating terms are relevant at high energies and luminosities so that they are important to understand early universe.