Bounds and LHC Implications for R-Parity Violation

Based on work with Tao Han

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   - R-parity
   - R-parity Violation
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   - Low-energy effects
   - Numerical Technique
3. LHC Signals
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R-parity

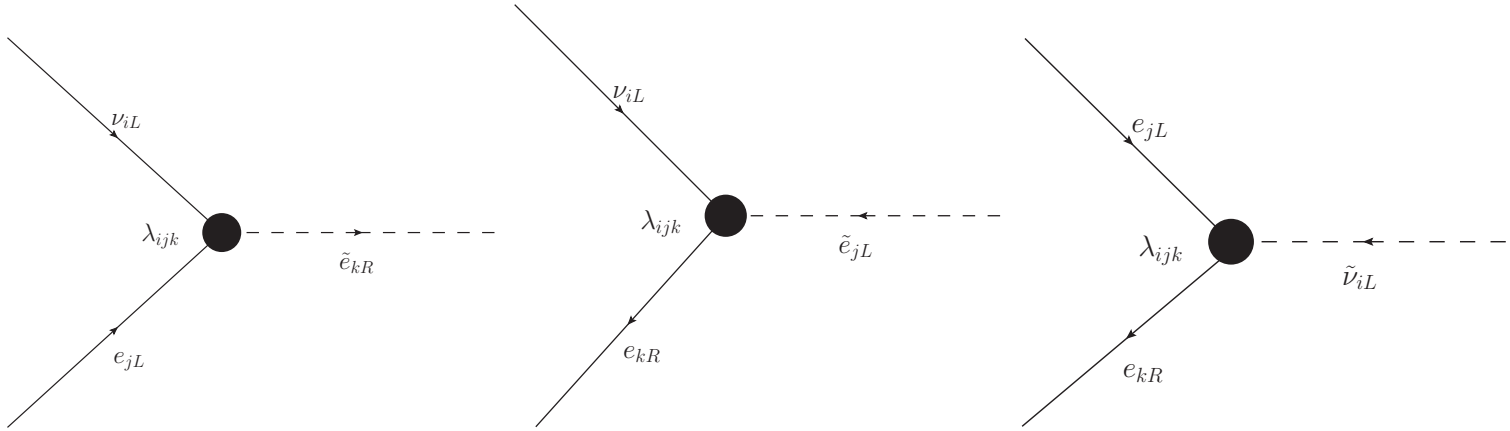
- In the Standard model, $L = n_l - n_{\bar{l}}$ and $B = \frac{1}{3}(n_q - n_{\bar{q}})$ are naturally conserved
- Supersymmetry adds new bosons that carry B and L
- We need a new discrete symmetry, $R = (-1)^{2S+3B+L} = (-1)^{2S+3(B-L)}$
- R=1 for all SM particles and R=-1 for superpartners
- R-parity forbids direct interaction between SM particles and odd numbers of sparticles are forbidden

R-parity Violation

- When supersymmetric particles are included, it is possible to write renormalizeable terms that violate R-parity
- We have the R-violating superpotential
  $W_{RPV} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_i D^c_k$
- The terms proportional to λ and λ' violate L while those proportional to λ'' violate B
- From gauge invariance, $\lambda_{ijk} = -\lambda_{jik}$, $\lambda''_{ijk} = -\lambda''_{ikj}$
- Total of 45 independent parameters

R-parity-vioatling Interactions

- These parameters allow couplings between SM fermions and sfermions
- R-parity violation opens a rich new phenomenology at both high and low energies



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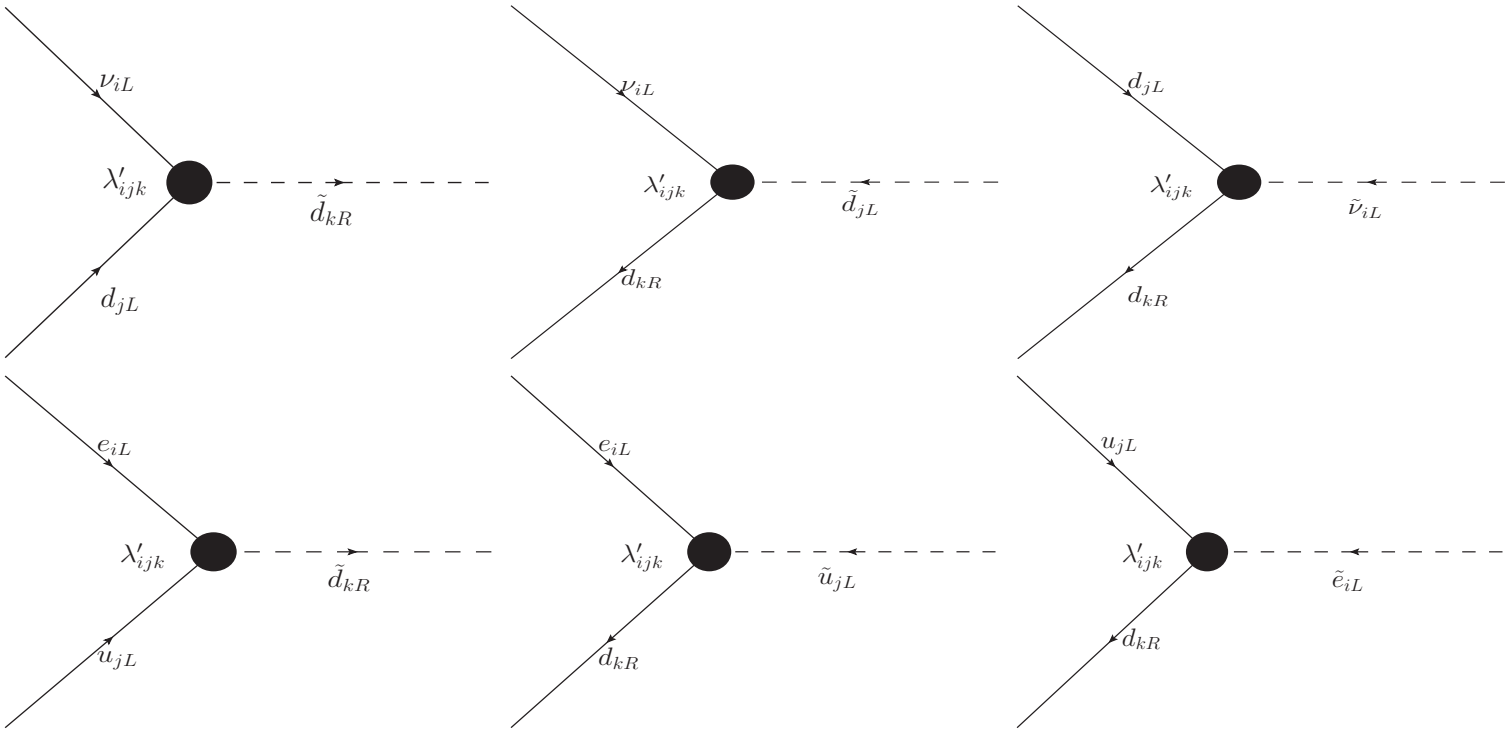

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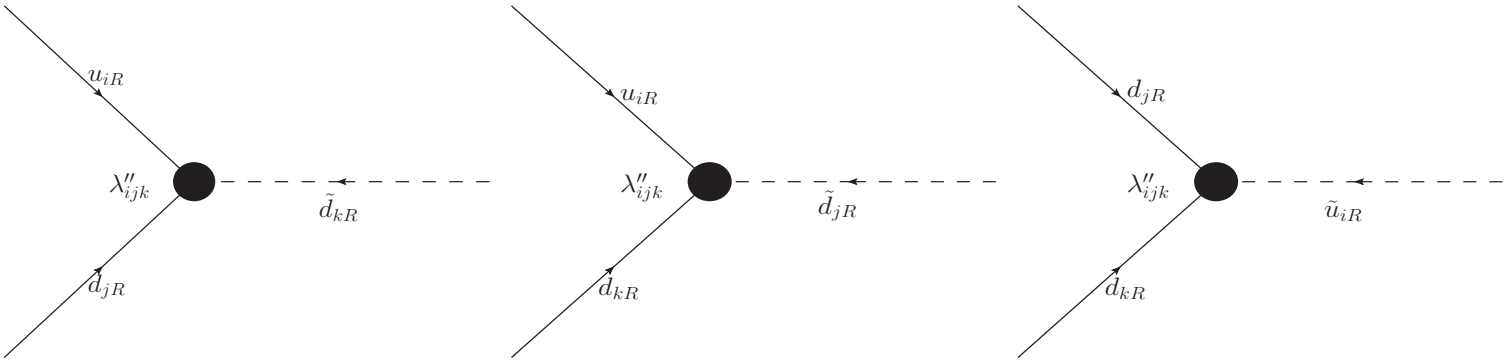
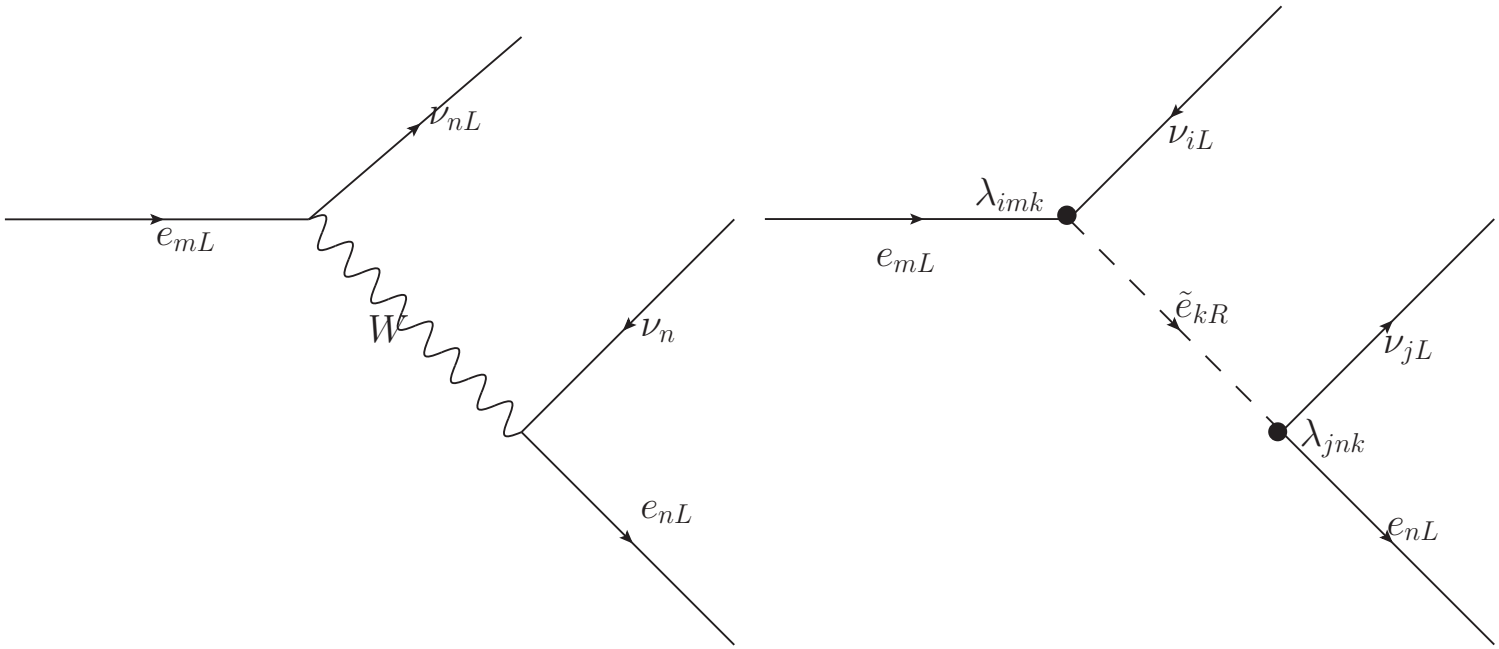


Low-energy Effects

- At low energies, new interactions can be seen through virtual sparticles in intermediate states
- These new interactions contribute additional contributions to SM processes that can be used to set bounds on the strengths of couplings
- Limits on λ, λ', λ'' can be derived from existing measurements

Example: Lepton Universality

- We have a new contribution to leptonic decays $e_m \to e_n \nu\nu$ through a virtual $\tilde{e}$



Lepton Universality

- This alters the expected decay ratios

$$R_{\tau\mu} = \frac{\Gamma(\tau\to\mu\bar{\nu}\nu)}{\Gamma(\mu\to e\bar{\nu}\nu)} = R^{SM}_{\tau\mu}\frac{(1+\sum\frac{\sqrt{2}|\lambda_{3ik}\lambda_{2jk}|}{8G_F m^2_{\tilde{e}_{kR}}})^2}{(1+\sum\frac{\sqrt{2}|\lambda_{3ik}\lambda_{1jk}|}{8G_F m^2_{\tilde{e}_{kR}}})^2}$$

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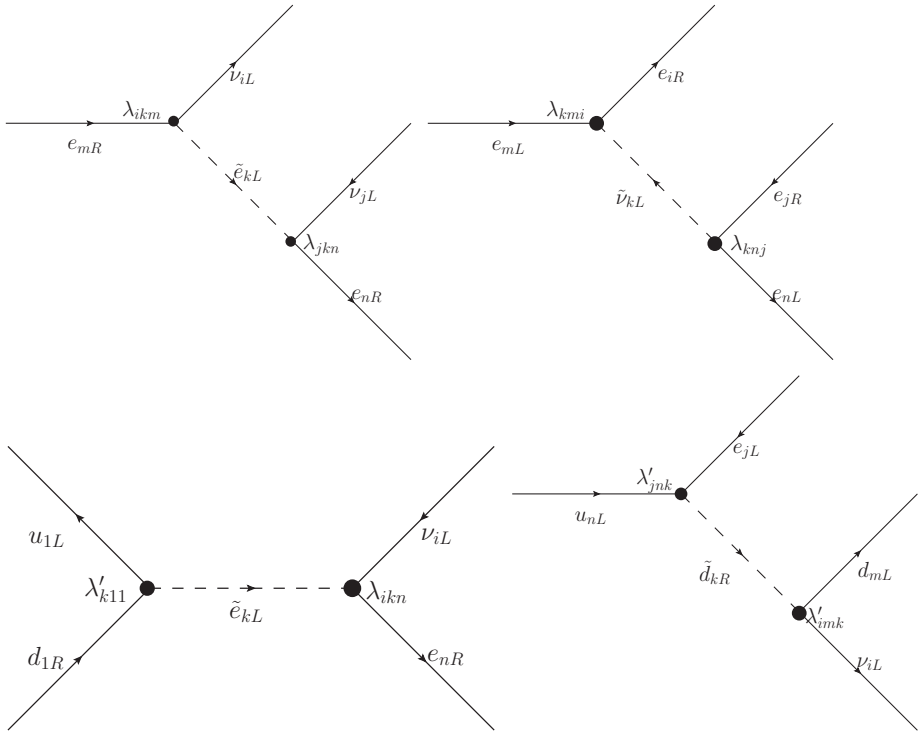
- Both additive and canceling effects are observed from different couplings

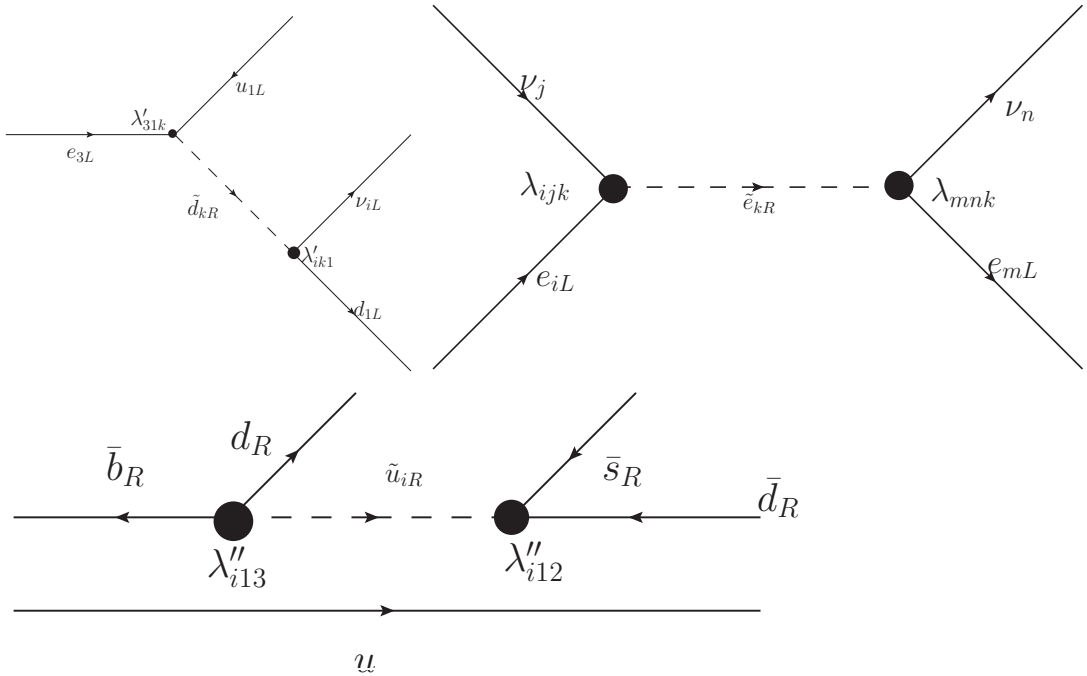
Other Processes

- Many other processes result from allowing R-parity violation
- Right-handed lepton decay, $l^- \to l^- l^- l^+$ decays, pion decays, quark flavor changing...



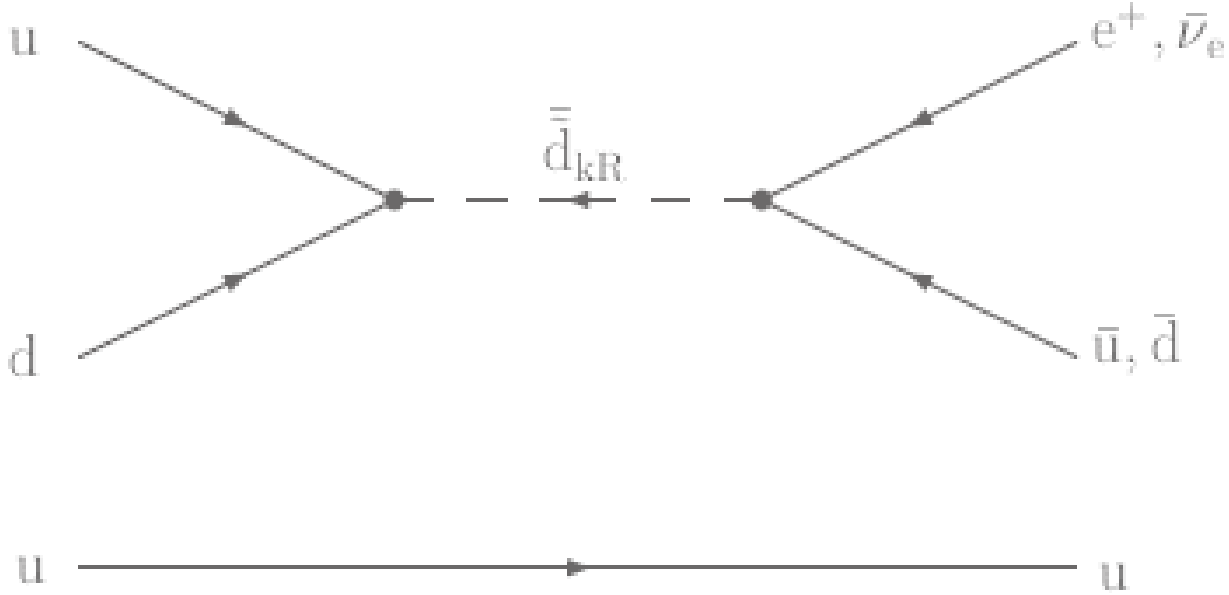
Other Processes

- Many other processes result from allowing R-parity violation
- semilepton τ decays, neutrino-electron scattering, B decays...



Other Processes

- Many other processes result from allowing R-parity violation
- Proton decay :(



- And more!

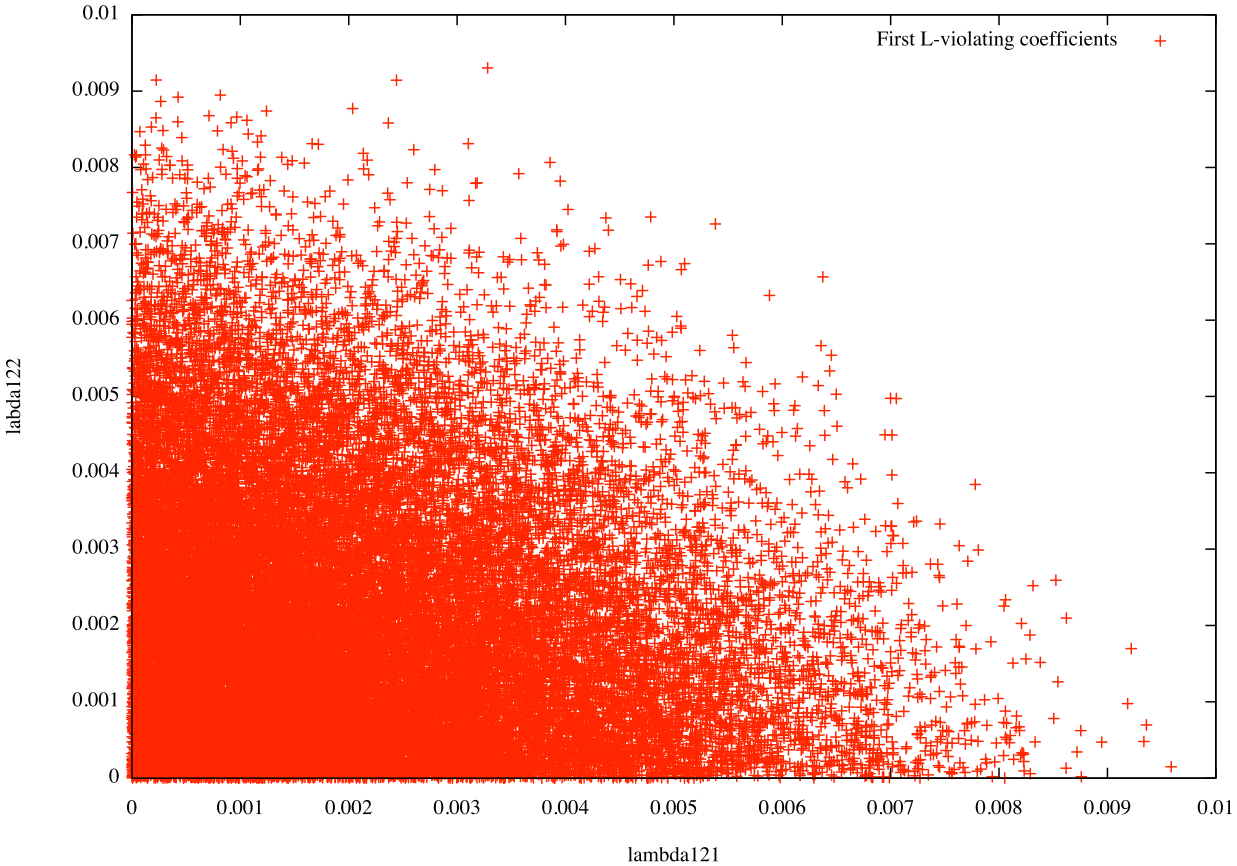
Numerical Technique

- Analytic bounds on individual couplings can be computed only if we assume single coupling dominance - not theoretically well-motivated
- Using numerical methods we can set bounds on all couplings (from many different experiments) simultaneously
- Use a Monte Carlo technique to test points from the full 45-dimensional parameter space, keeping only parameter sets that do not violate experimental constraints
- We can see relationships between all sets of parameters

Bounds

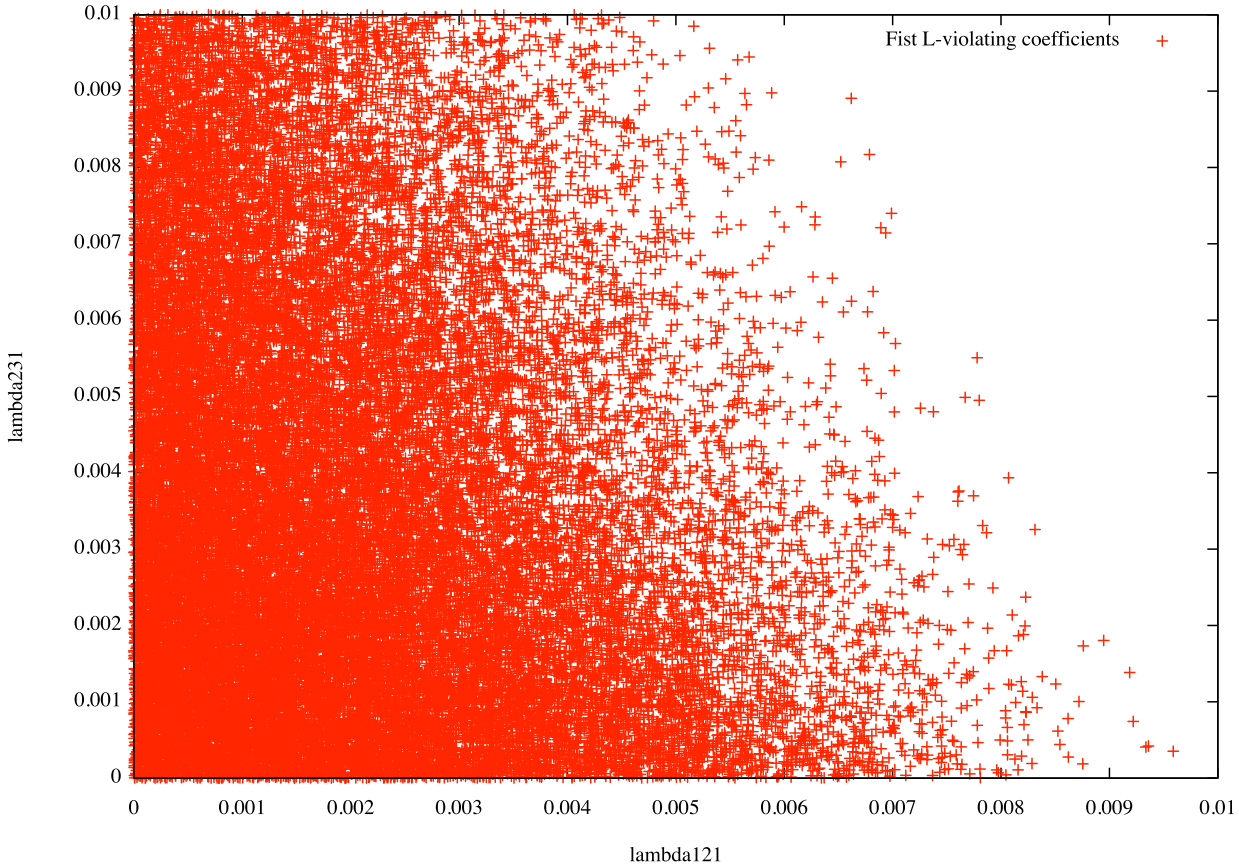
- Since bounds on any individual coupling can depend on any or all of the others, we give bounds as slices of the full parameter space
- Some examples...

Bounds



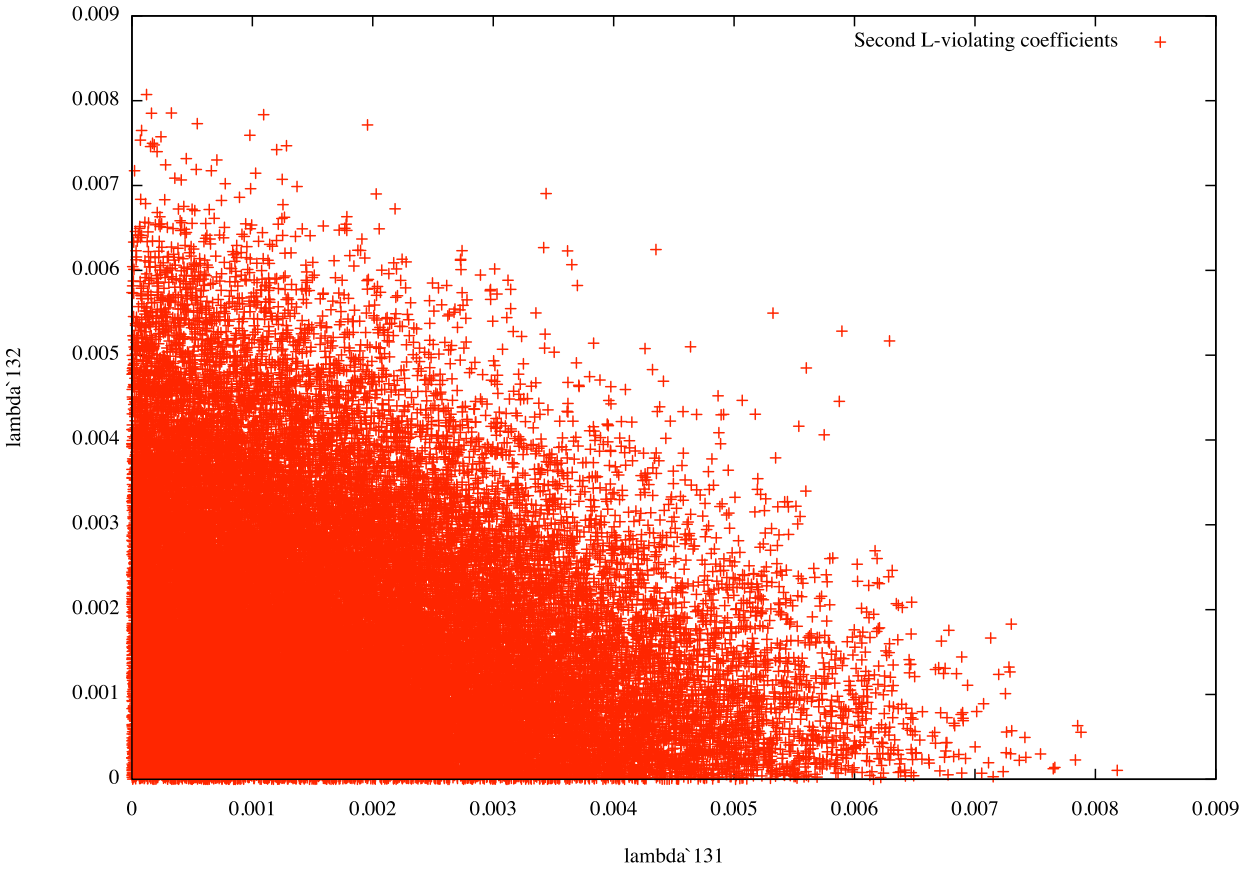
λ_{121} v λ_{122} (related though right-handed decays, $R_{\tau\mu}$ and $\mu \to 3e$)

Bounds



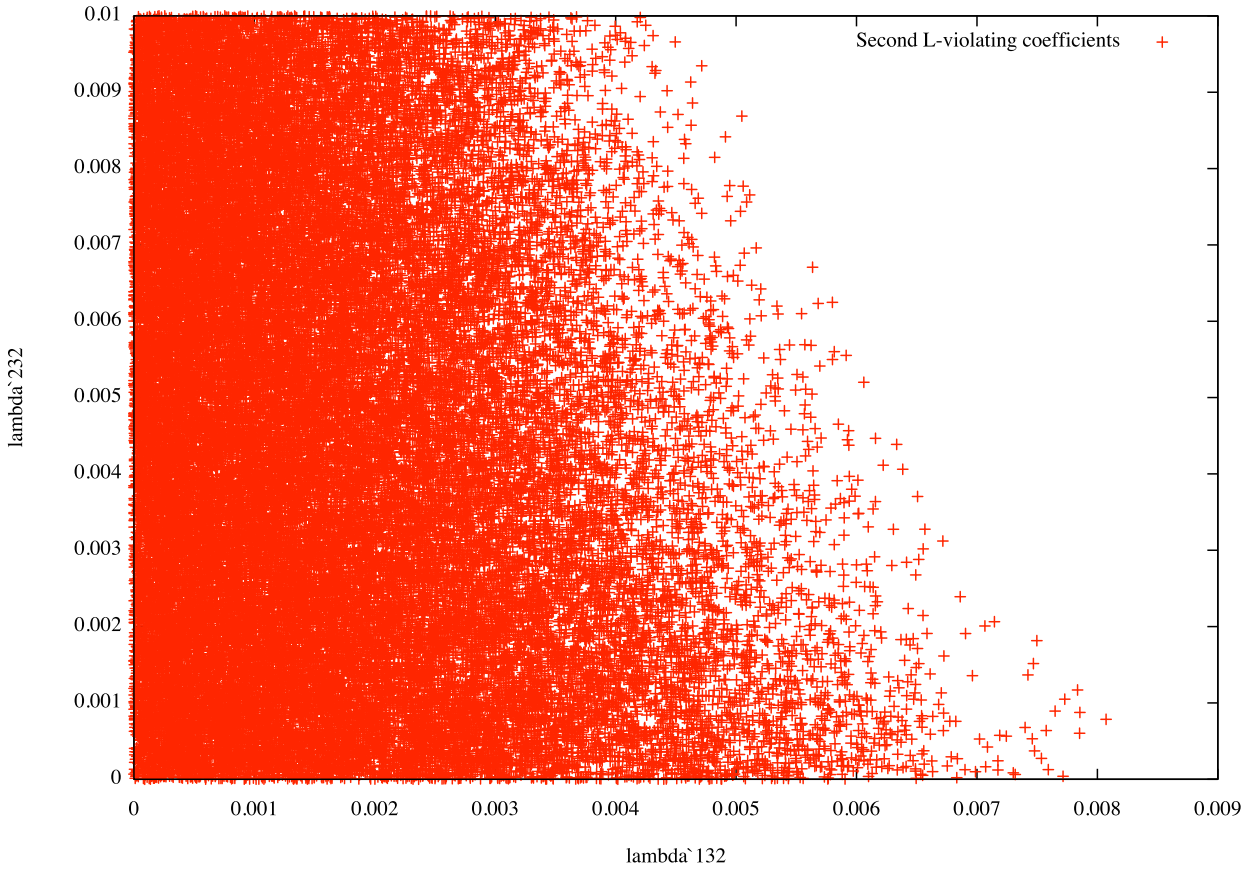
λ_{121} v. λ_{231} (related through $R_{\tau\mu}$ and $\tau \to 3e$)

Bounds



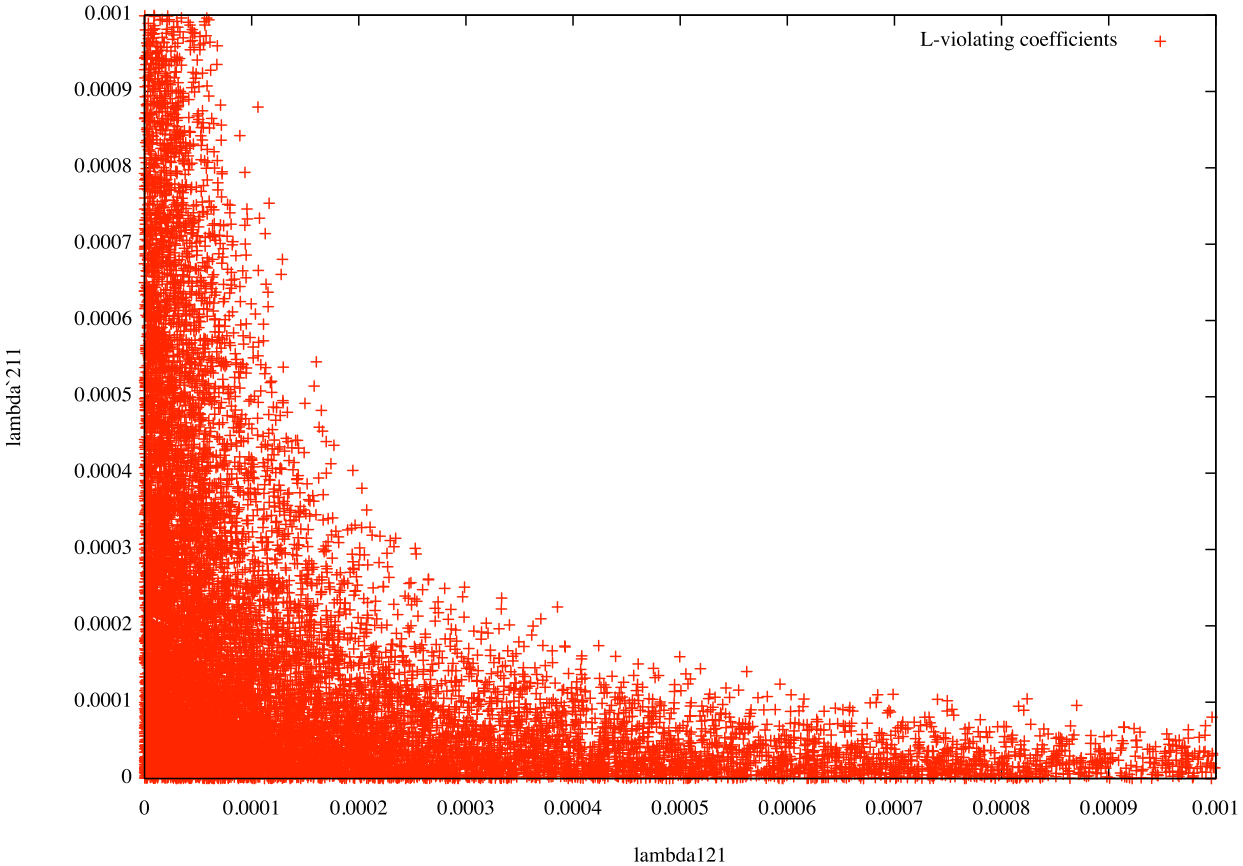
λ'_{131} v. λ'_{132} (related through $D \to l$ decays, neutrino-nucleon scattering , quark flavor changing)

Bounds



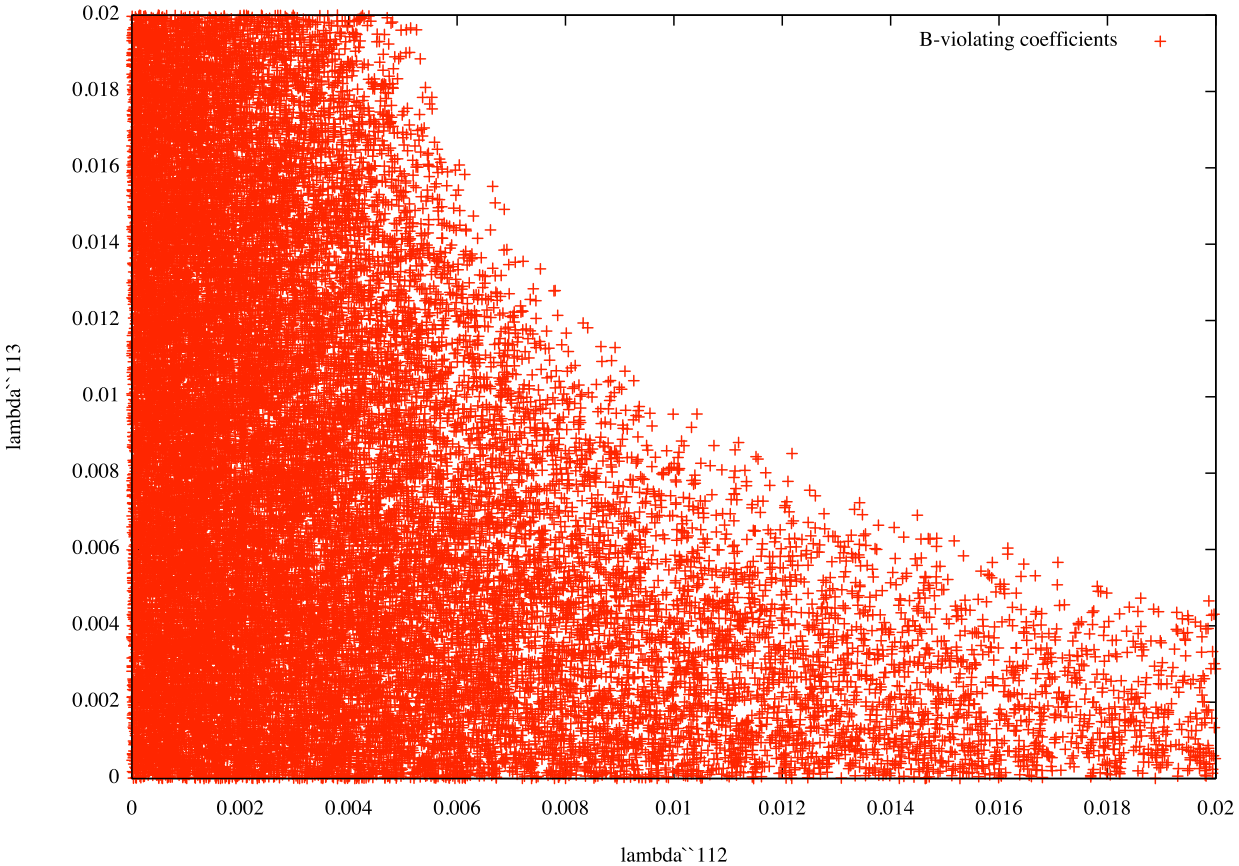
λ'_{132} v. λ'_{232} (related through $K \to \pi$ decays, neutrino-nucleon scattering)

Bounds



λ_{121} v. λ'_{111} (related through quark flavor changing, pion decays)

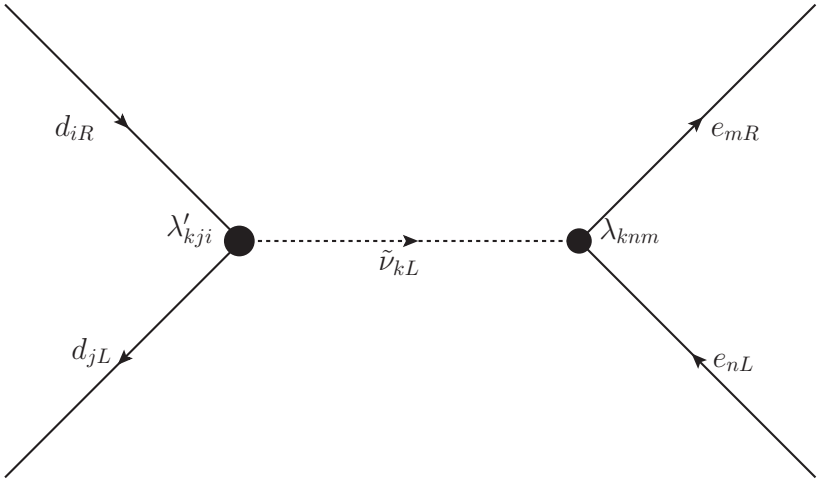
Bounds



λ''_{112} v. λ''_{113} (related through $B \to \pi K$ decay)

Single Sparticle Production

- R-parity violation allows a single sfermion to be produced from two SM Fermions
- These sfermions can then decay via R-parity violating interactions into 2 final-state fermions



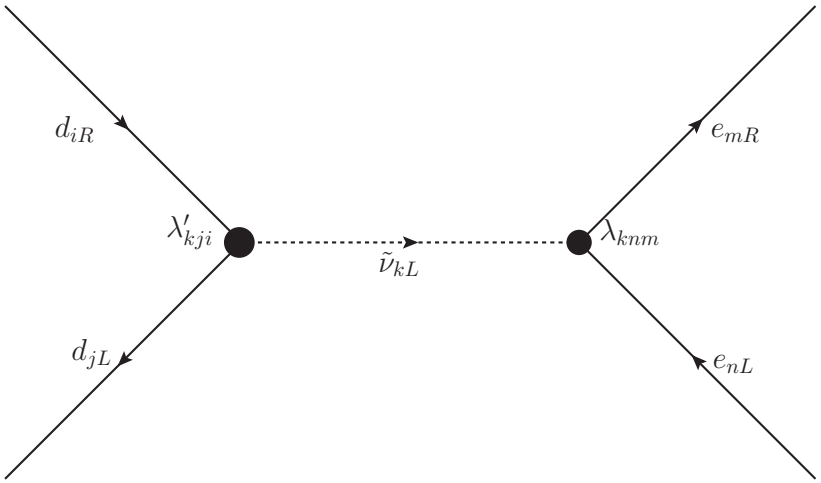
Single Sparticle Production

- The production cross-section will be given by

$$\sigma_{q_1 q_2} = \sum \frac{4\pi \hat{s} \Gamma(\tilde{f} \to q_1 q_2)\Gamma(\tilde{f} \to ab)}{9 m_{\tilde{f}}((\hat{s} - m_{\tilde{f}}^2)^2 - m_{\tilde{f}}^2)\Gamma_{\tilde{f}}^2}$$

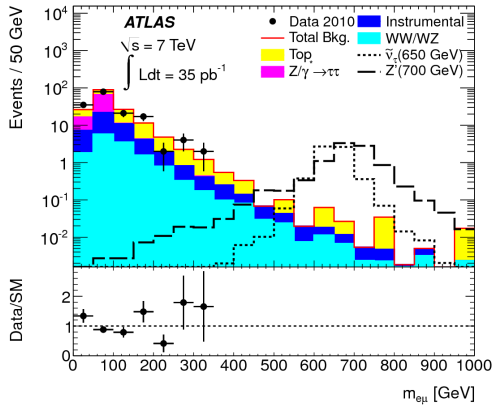
$$\Gamma(\tilde{f} \to f_1 f_2) = \frac{N_C \lambda^2 m_{\tilde{f}}}{16\pi}$$

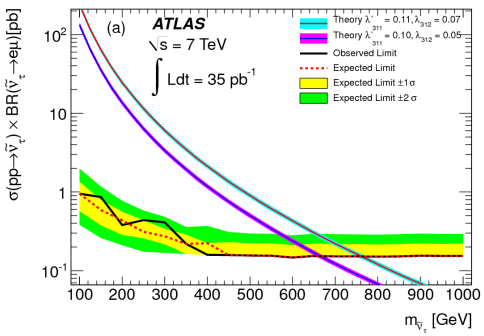
$$\sigma_{pp} = \sum \int \int dx_1 dx_2 f_{q_1}(x_1) f_{q_2}(x_2) \sigma_{q_1 q_2}$$

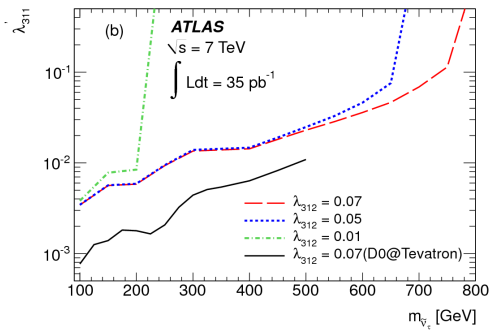


Bounds from Single Sparticle Resonances

- These new processes should have a distinctive signature with a peak at the superpartner mass
- As we obtain new data from the LHC, we can update our bounds from high-energy process
- Example: recent ATLAS paper on $e\mu$ production (1103.5559)



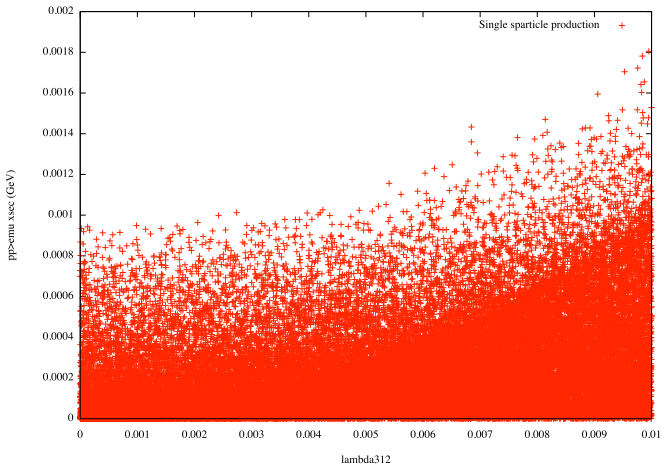


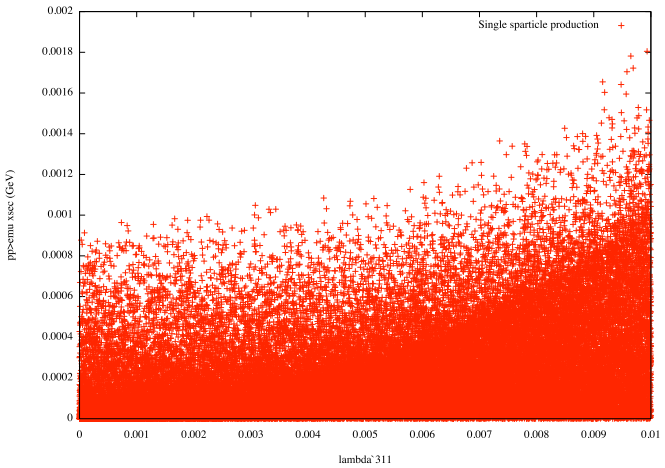


- Bounds continue to be updated as new results come in...

Bounds from Single Sparticle Resonances

- ... but this numerical technique already gives a stronger constraint on the $\lambda\lambda'$ couplings



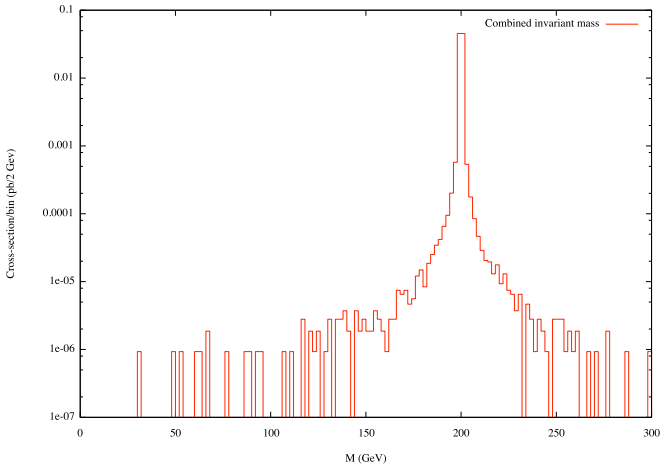


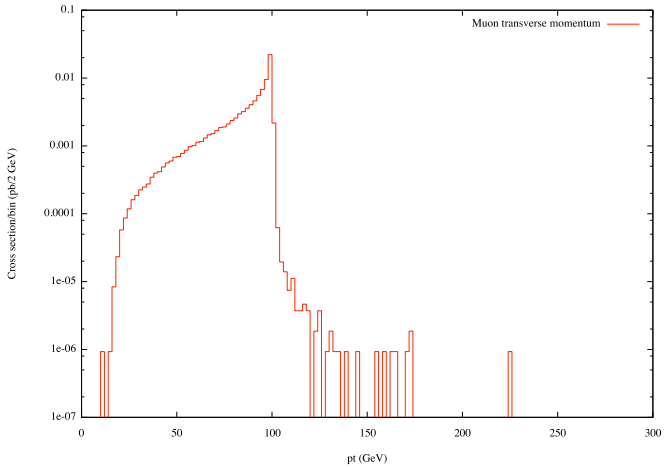
Resonant Sparticle Production

- But we can use our limits to predict new signals
- Examination of these signals is in progress....

Resonant Sparticle Production

- But we can use our limits to predict new signals
- Examination of these signals is in progress....
- Preliminary signal with a toy model ($m_{\tilde{\nu}} = 200$ GeV):





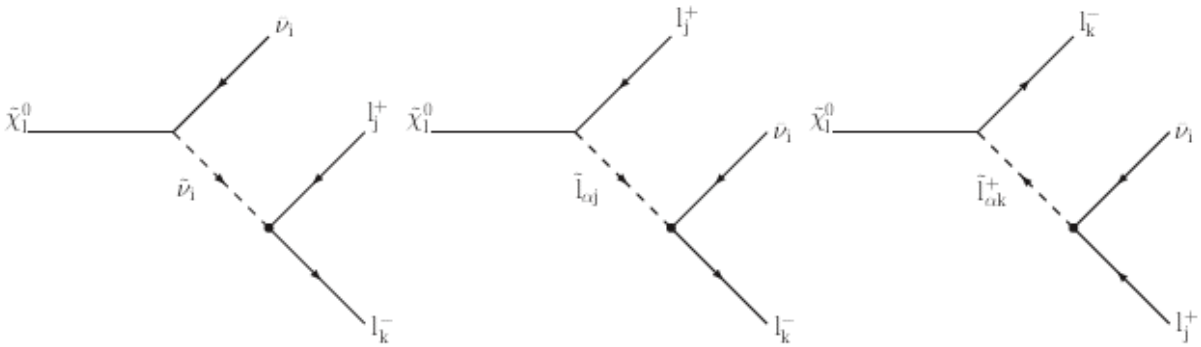
Summary

- R-parity violation introduces 45 new parameters and a large number of new physical processes
- With numerical testing, we can place bounds on all couplings from all possible tests simultaneously
- These bounds can be applied to predict possible new signals at the LHC
- We have many possible interesting effects and new signals to look for
- Thank You!

Extra Slides

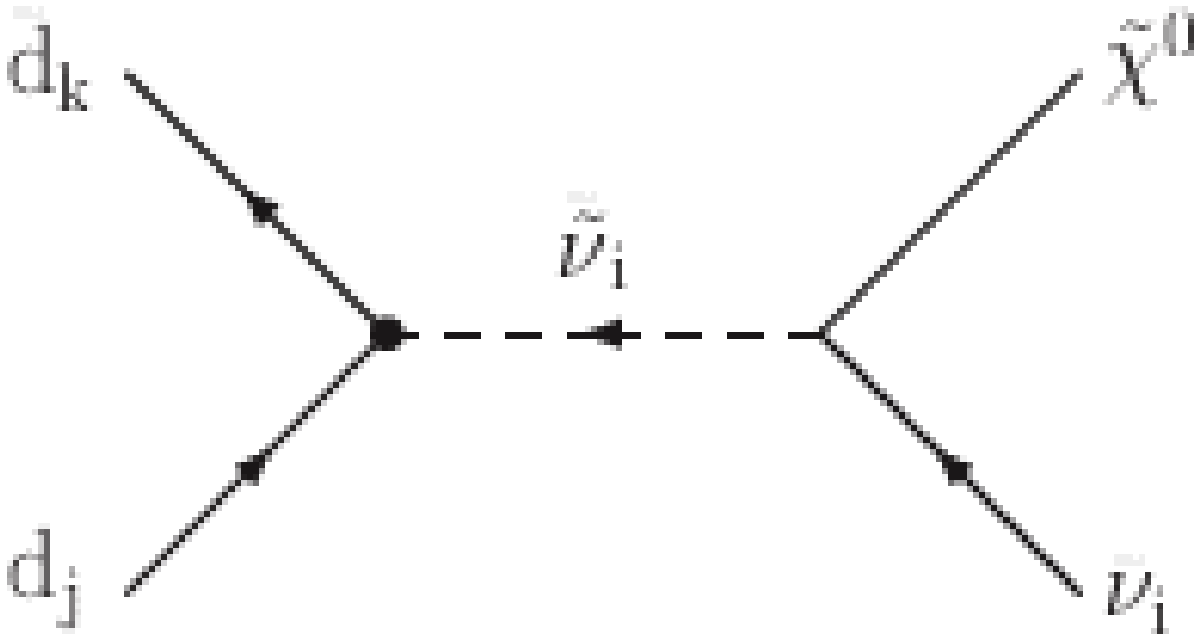
Decay Chains

- SUSY with R-parity Violation allows the LSP to decay into SM particles
- This model lacks the large missing energy signals that characterize most SUSY models
- Instead we have decay chains to the LSP, which then decays via RPV couplings, e.g. $\tilde{\chi} \to l^+ l^- \nu$



Single Sparticle Signals

- Instead of an immediate R-parity violating decay, singly produced sparticles can initially decay through standard SUSY interactions
- e.g. $pp \to \tilde{\nu} \to \nu^+(\tilde{\chi} \to l^+ l^- \nu)$



Sparticle Pair Production

- We still have standard pair production of sparticles in the MSSM
- These particles will eventually decay to a SM state
- We have many possible final states from RPV decays - $4l2\nu, l\nu4j, 2l4j, 2\nu4j, 6j$
- Many different signals are possible if all couplings are allowed - examining these signals is a future goal