 Searches for Signatures of R-Parity Violating (RPV) Supersymmetry Models in ATLAS

SUSY 2014, Manchester, UK

David W. Miller, on behalf of the ATLAS Collaboration

THE UNIVERSITY OF CHICAGO

Monday, July 21st, 2014
New Perspectives: SUSY is not just around the corner

Buchmuller (2008) [1]

“No reasonable person could view these figures together without concluding that we need to change our perspective. But, what new perspective is called for?”

– M. E. Peskin, Lepton-Photon 2011 [3]
Hiding Supersymmetry through R-Parity Violation

The RPV superpotential

Direct decay of sparticles to SM particles can occur in R-parity violating (RPV) SUSY via three general terms:

- **Lepton number violating (LNV) term:** \( LLE \) via \( \lambda_{ijk} \) (multileptons)

\[
W_{RP} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2
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- **LNV term**: $LQD$ via $\lambda'_{ijk}$ (leptons+jets)

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- **LNV term:** \( LQD \) via \( \lambda'_{ijk} \) (leptons+jets)
- **Baryon number violating (BNV) term:** \( UDD \) via \( \lambda''_{ijk} \) (multijets)

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$$W_{R_p} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa L_i H_2$$
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- **Baryon number violating (BNV) term:** $UDD$ via $\lambda''_{ijk}$ (multijets)
- **Bilinear lepton-gaugino mixing term:** $LH$ via $\kappa$

The $UDD$ term ($\lambda''_{ijk}$) is generally least constrained via collider experiments, in part because the all-hadronic decays are hard to constrain.
Hunting for RPV SUSY: the signals that we’re after

- **Multilepton production from neutralino $LLE (\lambda_{ijk})$ LNV decays**
  - Prompt production of many leptons and large $E_T^{miss}$ and $M_{eff}$
- **Multijet production from gluino $UDD (\lambda''_{ijk})$ BNV decays**
  - Massive multijet final states, very tough background estimation
Multilepton search

4-lepton RPV+RPC SUSY search (arXiv:1405.5086)

Concept: Look for events with 4 leptons (at least 2 e or μ) and significant $E_T^{\text{miss}}$ from $\nu$'s. Separately consider $\geq 0, 1, 2\tau$ events.

- Veto low mass ($m_{\ell\ell} < 12$ GeV) or $m_{\ell\ell} \approx m_Z$ events for same-flavor, opposite sign (SFOS) lepton pairs
- Estimate reducible backgrounds ($\geq 1$ fake) from data
- Estimate irreducible (mostly SM) backgrounds from Monte Carlo (MC)

Higher $E_T^{\text{miss}}$ selection ($E_T^{\text{miss}} > 100$ GeV vs. 50 GeV) for events required to have 1 $\tau$.

Signal regions for RPV signals add $M_{\text{eff}} > 400, 600$ GeV selection
### Background estimation and validation

#### 4-lepton RPV+RPC SUSY search (arXiv:1405.5086)

**ATLAS**

$\sqrt{s} = 8$ TeV \ \ \ \int L \ dt = 20.3 \ fb^{-1}

<table>
<thead>
<tr>
<th>N(\ell)</th>
<th>N(\tau)</th>
<th>Z\text{-requirement}</th>
<th>E_T^{miss} [\text{GeV}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR0Z</td>
<td>$\geq 4$</td>
<td>$\geq 0$</td>
<td>SFOS $&lt;50$</td>
</tr>
<tr>
<td>VR1Z</td>
<td>$= 3$</td>
<td>$\geq 1$</td>
<td>SFOS $&lt;50$</td>
</tr>
<tr>
<td>VR2Z</td>
<td>$= 2$</td>
<td>$\geq 2$</td>
<td>SFOS $&lt;50$</td>
</tr>
</tbody>
</table>

- **(Left):** Validation of the MC estimates for the irreducible backgrounds
- **(Right):** Validation of the data-driven estimates for the reducible backgrounds

D. W. Miller (EFI, Chicago)  
SUSY 2014 – ATLAS RPV SUSY Results
Signal region observations

4-lepton RPV+RPC SUSY search (arXiv:1405.5086)

<table>
<thead>
<tr>
<th>(N(\ell))</th>
<th>(N(\tau))</th>
<th>(Z)-veto</th>
<th>(E_T^{\text{miss}} ) [GeV]</th>
<th>(m_{\text{eff}} ) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR0noZa</td>
<td>(\geq 4)</td>
<td>(\geq 0)</td>
<td>SFOS, SFOS+(\ell), SFOS+SFOS</td>
<td>(\geq 50)</td>
</tr>
<tr>
<td>SR1noZa</td>
<td>=3</td>
<td>(\geq 1)</td>
<td>SFOS, SFOS+(\ell)</td>
<td>(\geq 50)</td>
</tr>
<tr>
<td>SR2noZa</td>
<td>=2</td>
<td>(\geq 2)</td>
<td>SFOS</td>
<td>(\geq 75)</td>
</tr>
<tr>
<td>SR0noZb</td>
<td>(\geq 4)</td>
<td>(\geq 0)</td>
<td>SFOS, SFOS+(\ell), SFOS+SFOS</td>
<td>(\geq 75) or (\geq 600)</td>
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<tr>
<td>SR1noZb</td>
<td>=3</td>
<td>(\geq 1)</td>
<td>SFOS, SFOS+(\ell)</td>
<td>(\geq 100) or (\geq 400)</td>
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</tbody>
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Benchmark model limits: strong production

4-lepton RPV+RPC SUSY search (arXiv:1405.5086)

Significant sensitivity due to unique final state and high production cross section.

- Multiple couplings explored independently
- Similar sensitivity for different light flavor couplings, or heavy flavor combinations
- Heavy flavor ($\tau$) cross section limits are significantly weaker

Reconstruction efficiency drops significantly when the $\tilde{\chi}_1^0$ is significantly less massive than the $\tilde{g}$ and becomes boosted.
Benchmark model limits: weak production

4-lepton RPV+RPC SUSY search (arXiv:1405.5086)

Sensitivity drops for lower cross-section weak production scenarios.

- If $m_{\tilde{\chi}^0} > 0.2 m_{\tilde{\chi}^\pm}$ then a lower limit on wino-like charginos of 450 GeV is observed.
- Similar sensitivity for different light flavor couplings, or heavy flavor combinations.
- Heavy flavor ($\tau$) cross section limits are significantly weaker.

A limit of 400 GeV can be placed on sneutrino masses for RPV models with electron and muon decays of the LSP.


Looking for SUSY in multijet events

RPV gluino $2 \times 3$ jet search (arXiv:1210.4813)

Two approaches to background discrimination:

- Resolved jet counting method
- Merged jet resonance method

Singe jet mass from merged gluino ($\tilde{g}$) quark decay products
**Background discrimination**

**RPV gluino** $2 \times 3$ jet search (*arXiv:1210.4813*)

- **Merged – Left:** In addition to jet mass (previous slide) use shape observable called “$\tau_{32}$” (estimates subjets in jet) to select signal
- **Resolved – Right:** Focus only on jet multiplicity (no 3-body mass) and estimate by projecting from lower jet multiplicity bins
RPV gluino limits: boosted + jet counting

Boosted RPV gluino search (*arXiv:1210.4813*)

- Both analyses exclude top-mass region (non-trivial!)
- Resolved analysis uses very tight selections and relies on MC to model jet multiplicity $\Rightarrow$ excludes up to $m_{\tilde{g}} > 666$ GeV
Extending the search at 8 TeV

Gluino ($\tilde{g}$) pair production, decaying with $\tilde{g} \rightarrow \tilde{q} q$, $\tilde{q} \rightarrow \tilde{\chi}_1^0 q$, $\tilde{\chi}_1^0 \rightarrow 3q$

A natural, UDD RPV model: final state characterized by many partons
- Between 10 (light quarks) and 22 (tops) partons in final state
- Very challenging environment!
**Updated multijet search for 8 TeV**

**ATLAS-CONF-2013-091**

- **New for 8 TeV:** use $b$-tagging information to estimate branching ratios of various RPV decays to different flavors
Multijet search results for 8 TeV

**ATLAS-CONF-2013-091**

- **Set limits in the branching ratio plane:** BR($t$) vs. BR($b$)
- **Constrain the gluino masses** for given neutralino masses and branching ratio assumptions
Many other searches done and underway!

Keep an eye out for new results over the next few months

Work proceeding towards Run II
**Early Run II Expectations**

Early 2015 LHC Program:
- **May:** Stable beams operation with 50ns bunch spacing after intensity ramp-up
- **June:** Stable beams operation with 25ns bunch spacing after intensity ramp-up

**Outlook for 2015:**
- Huge increase in discovery potential
- Suggests a strong focus on targeted searches very early
- Both short-term and longer-term efforts will depend on detector performance
- With $3 \text{ fb}^{-1}$ many searches reach or surpass current sensitivity

**Strong production processes see biggest increase!**

- Process
  - $H(ggF)$
  - $H(VBF)$
  - $t\bar{t}$,
  - $t\bar{t}, M=0.5 \text{ TeV}$
  - $t\bar{t}, M=0.6 \text{ TeV}$
  - $t\bar{t}$,
  - $gg, M=1.6 \text{ TeV}$
  - $gg, M=2.0 \text{ TeV}$

$\sigma(14 \text{ TeV}) / \sigma(8 \text{ TeV})$

$LHC \text{ Run II}$

Cross-section ratios: $14 \text{ TeV} / 8 \text{ TeV}$
A rich program in RPV SUSY searches

- A well motivated alternative avenue compared to the standard jet+$E_T^{\text{miss}}$ searches
  - Performance of novel techniques demonstrated at $\sqrt{s} = 7$ TeV and ongoing at $\sqrt{s} = 8$ TeV
  - Challenging background estimations but very sensitive searches
  - Limits are approaching the 1 TeV range for RPV hadronic final states

- Extending and enhancing the interpretations of results
  - Increasing the phase space of interpretations by considering mixed branching ratios and additional couplings

- Focus shifting to Run II searches
  - Center-of-mass energy increase dramatically enhances strong production processes and the potential for discovery of new resonances
  - Expect RPV searches to play significant role in initial physics program of Run II
Additional Material
**Control region definitions**

*Boosted RPV gluino search (arXiv:1210.4813)*

<table>
<thead>
<tr>
<th>Region</th>
<th>Jet ($J_1$) selections</th>
<th>Jet ($J_2$) selections</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CR-A</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>Low-mass jets, to validate $\tau_{32}$ shape</td>
</tr>
<tr>
<td>CR-B</td>
<td>$m_{\text{jet}} &gt; M_{\text{threshold}}$</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>Signal-like leading jet, $\tau_{32} &lt; 0.7$ to validate $m_{\text{jet}}$</td>
</tr>
<tr>
<td>CR-C</td>
<td>$m_{\text{jet}} &lt; M_{\text{threshold}}$</td>
<td>$m_{\text{jet}} &gt; M_{\text{threshold}}$</td>
<td>Signal-like subleading jet, $\tau_{32} &lt; 0.7$, to validate $m_{\text{jet}}$</td>
</tr>
</tbody>
</table>

**Accounting for correlations between control regions:**

\[
N_{SR} = N_{\text{CR-C}} \times \left( \frac{N_{\text{CR-B}}}{N_{\text{CR-A}}} \right) \times \alpha_{MC} 
\]  

\[
\alpha = \left( \frac{N_{SR}/N_{\text{CR-C}}}{N_{\text{CR-B}}/N_{\text{CR-A}}} \right) \bigg|_{\text{POWHEG MC}}
\]

- **Syst:** jet kinematic and tagging systematics in each signal and control region separately
- **MC Syst:** difference between POWHEG and PYTHIA is taken as an additional systematic uncertainty
Trimmed jet mass correlations \((m_{\text{jet}} > 100 \text{ GeV})\)

**Boosted RPV gluino search** (arXiv:1210.4813)

- Correlations between leading and subleading (in \(p_T\)) jet masses

**ATLAS**

Data \(\sqrt{s} = 7 \text{ TeV}\)

\begin{align*}
\text{Leading jet mass, } m^1_{\text{jet}} & \quad \text{[GeV]} \\
100 & \quad 150 & \quad 200 & \quad 250 & \quad 300 & \quad 350 & \quad 400 \\
\text{Sub-leading jet mass, } m^2_{\text{jet}} & \quad \text{[GeV]} \\
100 & \quad 150 & \quad 200 & \quad 250 & \quad 300 & \quad 350 & \quad 400
\end{align*}

- **Data**: 10.1\%
- **POWHEG**: 10.9\% (trimmed)

Excellent agreement between data and **POWHEG** at high leading-jet mass
**Boosted gluino mass distributions**

*Boosted RPV gluino search (arXiv:1210.4813)*

- **Distinct signature of RPV \( \tilde{g} \)**
- Incomplete “merging” of \( \tilde{g} \) decay products for \( m_{\tilde{g}} = 300 \) GeV, but still good discrimination (peak at \( m_{\text{jet}} \approx 275 \) GeV)

---

*ATLAS* SR1 \( m_{\text{jet}} > 60 \) GeV, \( \tau_{32} < 0.7 \)

- Data, \( \sqrt{s} = 7 \) TeV
- Multijet (Pythia)
- Multijet (POWHEG+Pythia)
- RPV gluino (\( m_{\tilde{g}} = 100 \) GeV)

*ATLAS* SR2 \( m_{\text{jet}} > 140 \) GeV, \( \tau_{32} < 0.7 \)

- Data, \( \sqrt{s} = 7 \) TeV
- Multijet (Pythia)
- Multijet (POWHEG+Pythia)
- RPV gluino (\( m_{\tilde{g}} = 300 \) GeV)
Attractive “Answer” to some of the open questions: SUSY

Supersymmetry (SUSY) provides not only an attractive, and seemingly natural symmetry, by relating fermions to bosons, but also hopes to solve a few of the problems mentioned above.

- A potential Dark Matter candidate
- If $R$-parity is conserved
- The potential for unifying the Strong, electromagnetic, and weak forces
- Stabilizing the Higgs mass
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R-Parity Violating (RPV)

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$R_p = (-1)^R = (-1)^{2S}(-1)^{3B+L}$
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(Arkani-Hamed and Dimopoulos, 2004 [4])
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\[
m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2
\]

(Hewitt, SSI 2012)
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(Hewitt, SSI 2012)

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(Hewitt, SSI 2012)
The Ingredients of a SUSY Search

A decades-old approach using jets+$E_T^{\text{miss}}$

- **Squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) are strongly produced in pairs**
  - Dominant production mode
  - Preference for $\tilde{q}$ vs. $\tilde{g}$ depends on $m_{\tilde{q}}$ vs. $m_{\tilde{g}}$

- **Decay chain leads to many jets and $E_T^{\text{miss}}$**
  - Frequent assumption: Neutralino ($\tilde{\chi}_1^0$) is the lightest super symmetric particle and escapes detection, creating $E_T^{\text{miss}}$
  - Leptons also possible

- **Search strategies so far have relied on number of jets and $E_T^{\text{miss}}$**
  - $H_T = \sum_{\text{jets}} p_T^{\text{jet}} + \left( \sum_{\text{leptons}} p_T^{\text{leptons}} + \ldots \right)$
  - $M_{\text{eff}} = E_T^{\text{miss}} + H_T$

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\[
M_{\text{eff}} = E_T^{\text{miss}} + H_T
\]
### ATLAS SUSY Searches* - 95% CL Lower Limits

*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.

<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>$E_{\text{min}}^{\text{jet}}$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>$0, 2-6$ jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$\sqrt{s}$ = 7, 8 TeV</td>
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<tr>
<td>MSUGRA/CMSSM</td>
<td>$1, \mu, 3-6$ jets</td>
<td>Yes</td>
<td>20.3</td>
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<tr>
<td>MSUGRA/CMSSM</td>
<td>$0, 7-10$ jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$\sqrt{s}$ = 7, 8 TeV</td>
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<tr>
<td>Staus</td>
<td>$\tilde{q}s$, $\tilde{g}$-squarks</td>
<td>Yes</td>
<td>20.3</td>
<td>$\sqrt{s}$ = 7, 8 TeV</td>
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<tr>
<td>Staus</td>
<td>$\tilde{q}_2 \rightarrow q \tilde{\chi}^0_1$, $\tilde{q}_1 \rightarrow q \tilde{\chi}^0_1$</td>
<td>Yes</td>
<td>20.3</td>
<td>$\sqrt{s}$ = 7, 8 TeV</td>
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<tr>
<td>Staus</td>
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<td>$\tilde{g} \rightarrow q \tilde{\chi}^0_1$, $\tilde{g} \rightarrow q \tilde{\chi}^0_1$</td>
<td>Yes</td>
<td>20.3</td>
<td>$\sqrt{s}$ = 7, 8 TeV</td>
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<td>Staus</td>
<td>$\tilde{q}_1 \rightarrow q \tilde{\chi}^0_1$, $\tilde{q}_2 \rightarrow q \tilde{\chi}^0_1$</td>
<td>Yes</td>
<td>20.3</td>
<td>$\sqrt{s}$ = 7, 8 TeV</td>
</tr>
<tr>
<td>Staus</td>
<td>$\tilde{g} \rightarrow q \tilde{\chi}^0_1$, $\tilde{g} \rightarrow q \tilde{\chi}^0_1$</td>
<td>Yes</td>
<td>20.3</td>
<td>$\sqrt{s}$ = 7, 8 TeV</td>
</tr>
</tbody>
</table>

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**D. W. Miller**  
**SUSY 2014 – ATLAS RPV SUSY Results**  
**Monday, July 21st, 2014**  
**7 / 13**
Direct Stop ($\tilde{t}$) Search Summary

**ATLAS** Preliminary

- $\tilde{t}\rightarrow t\tilde{\chi}_1^0$
- $\tilde{t}\rightarrow t\tilde{\chi}_2^0$
- $\tilde{t}\rightarrow t\tilde{\chi}_1^-$
- $\tilde{t}\rightarrow b\tilde{\chi}_1^0$
- $\tilde{t}\rightarrow c\tilde{\chi}_1^0$
- $Wb\tilde{\chi}_1^0$

**Observed limits**

**Expected limits**

All limits at 95% CL

**Status:** ICHEP 2014

**Backup slides and additional information**

SUSY Search Summary

**ATLAS Preliminary.** $L_{\text{int}} = 20 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

**Status:** ICHEP 2014

**Observed limits**

**Expected limits**

All limits at 95% CL

**Observed limits**

**Expected limits**

**Status:** ICHEP 2014

**Observed limits**

**Expected limits**

All limits at 95% CL
The RPV superpotential

Direct decay of sparticles to SM particles can occur via the R-parity violation (RPV) superpotential, $W_{R_p}$, via three general terms:

$$W_{R_p} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \chi'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \chi''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2$$

- **Trilinear baryon number violating term:** $UDD$

The $UDD$ term is generally least constrained via collider experiments, in part because the all-hadronic decays are hard to constrain.
Luminosity in 2011 and 2012

**ATLAS Online Luminosity**
- 2010 pp $\sqrt{s} = 7$ TeV
- 2011 pp $\sqrt{s} = 7$ TeV
- 2012 pp $\sqrt{s} = 8$ TeV

**Recorded Luminosity**
- $\sqrt{s} = 8$ TeV, $L_{dt} = 20.8$ fb, $<\eta> = 20.7$
- $\sqrt{s} = 7$ TeV, $L_{dt} = 5.2$ fb, $<\eta> = 9.1$

**Peak interactions per crossing**

D. W. Miller (EFI, Chicago)  
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**Bunch structure information**

- The possibility of offset collisions in LHCb
- The LHC injection kicker flat top cannot exceed 7.86 µs
- Optimization of the pattern to minimize pacman bunches – essentially by attempting to generate four-fold symmetry.
- Additional constraints on the bunch structure coming from the injector chain also exist.
  
  It should be noted that in each case the particularities of the scheme determines the number of bunches in each LHC ring. However for each scheme the bunch characteristics, such as intensity and emittance, can be varied within the limits imposed by the LHC and its injector chain. For example, the intensity per bunch can be varied in all cases from a minimum of around $5 \times 10^{13}$ protons to a maximum presently limited by the stored beam power in the machine.

2. The 25 ns Scheme

This is the principal scheme that will be used for high luminosity operation. The beam is arranged in the form of 39 batches of 72 bunches. The bunches in each batch are spaced at 25 ns. Between the batches are gaps to allow for the SPS and LHC kicker rise times. This makes a total of 2808 bunches per LHC ring.

The scheme is illustrated in Figure 1. As with all the schemes described here, bunch 1 is defined to be the first bunch after the beam dump gap. The filling scheme can be described in the following form:

\[
3564 = 2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) + 31e + 3x (2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e ) + 80e
\]

**Figure 1: Schematic of the Bunch Disposition around an LHC Ring**
Limits on $\lambda''$

From Barbier, et al. [5]

Table 6.1 (continued)

<table>
<thead>
<tr>
<th>$\lambda''_{ij}$</th>
<th>Charged current</th>
<th>Neutral current</th>
<th>Other processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda''_{122}$</td>
<td>$10^{-2} \tilde{s} \tilde{m}^{-1/2}$ [$m_s &lt; 1$ eV]</td>
<td>($\tilde{m}<em>{L22}^2 = \tilde{m}</em>{R22}$) (5.12)</td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{433}$</td>
<td>$4 \times 10^{-4} \tilde{b} \tilde{m}^{-1/2}$ [$m_l &lt; 1$ eV]</td>
<td>($\tilde{m}<em>{L33}^2 = \tilde{m}</em>{R33}$) (5.12)</td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{11k}$</td>
<td>$(10^{-8} \ldots 10^{-7})(10^8 s/\text{osc}) \tilde{m}^{5/2}$</td>
<td>[$\tilde{m}$] (6.128)</td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{112}$</td>
<td>$10^{-9} [VN]$ ($\tilde{m} = 300$ GeV) (6.131)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{113}$</td>
<td>$6 \times 10^{-17} \tilde{z}<em>{22}^2 (m</em>{33}/1$ eV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[$p \rightarrow K^+ G$] (6.121)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$8 \times 10^{-17} C_{\beta\gamma}^{m} \tilde{z}_{22}^2 (F_a/10^{10}$ GeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[$p \rightarrow K^+ a$] (6.122)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{113}$</td>
<td>$10^{-3} [VN]$ ($\tilde{m} = 300$ GeV) (6.131)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{123}$</td>
<td>1.25 [$RG$]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{212}$</td>
<td>1.25 [$RG$]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{213}$</td>
<td>1.25 [$RG$]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{223}$</td>
<td>1.25 [$RG$]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{312}$</td>
<td>1.45 [$R_l$] (6.41)</td>
<td>4.28 [$RG$]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>($\tilde{m} = 100$ GeV)</td>
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<td></td>
</tr>
<tr>
<td>$\lambda''_{313}$</td>
<td>1.46 [$R_l$] (6.41)</td>
<td>1.12 [$RG$]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>($\tilde{m} = 100$ GeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{323}$</td>
<td>1.46 [$R_l$] (6.41)</td>
<td>1.12 [$RG$]</td>
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</tr>
<tr>
<td></td>
<td>($\tilde{m} = 100$ GeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda''_{4jk}$</td>
<td>$(10^{-11} \tilde{m}^3 \ldots 10^{-8} \tilde{m}^2)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\times (m_{33}/1$ eV) [$p \rightarrow K^+ G$] (6.123)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\times (F_a/10^{10}$ GeV) [$p \rightarrow K^+ a$] (6.124)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We use the notation $V_{ij}$ for the CKM matrix, $R_{lj}$, $R_{lj}'$, $R_D$, $R_D'$ for various branching fractions or ratios of branching fractions as defined in the text, $Q_W$ for the weak charge, $\nu_l$ for the neutrino elastic scattering on quarks and leptons, $m_s$ for the neutrino Majorana mass, RG for the renormalization group, $A_{FB}$ for forward–backward asymmetry, $Q_W$ (Cs) for atomic physics parity violation, $\tilde{n}$ for neutron–antineutron oscillation and $N$ for two nucleon nuclear decay, $[K \bar{K}]$, for $K^0 - \bar{K}^0$ mixing. The generation indices denoted $i, j, k$ run over the three generations while those denoted $l, m, n$ run over the first two generations. The dependence on the superpartner mass follows the notational convention $\tilde{m}^P = (\tilde{m}/100$ GeV)$^P$. Aside from a few cases associated with one-loop effects, we use the reference value $\tilde{m} = 100$ GeV. The quoted equation labels refer to equations in the text.
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