**Reminder: Supersymmetry (SUSY)**

**Idea:** Introduce a new symmetry transformation 'Q' with the following property:

\[ Q |\text{fermion}\rangle = |\text{boson}\rangle; \quad Q |\text{boson}\rangle = |\text{fermion}\rangle \]

Assign each particle in the standard model a supersymmetric partner

→ Spin different by 1/2, all other properties identical

- SUSY can provide a solution to the **Hierarchy Problem**
- No Superpartners observed so far - if it exists, SUSY must be a broken symmetry
- SUSY breaking introduces new parameters - rich parameter space
Writing down all the allowed interaction terms in a (minimal) supersymmetric standard model, we get something new:

\[ W_{\Delta B,L} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u \]

- \( L, Q \): left-handed lepton/quark superfields (contain leptons and sleptons / quarks and squarks)
- \( E, D, U \): right handed lepton/ up-type quark / down-type quark superfields
- \( H_u \): Higgs superfield coupling to up-type fermions
- Baryon and Lepton number (accidentally conserved in SM) violated
- \( \lambda' \) and \( \lambda'' \) can mediate rapid proton decay

\[ p \rightarrow e^+ \pi^0 \]

\[ \mathcal{L} \supset \lambda''_{112} u_L d_L \bar{s}_R \]

\[ \mathcal{L} \supset \lambda'_{112} e_L u_L \bar{s}_R^* \]
One way out: **R-Parity**

\[ R_P = (-1)^{2s+3B+L} = \begin{cases} +1 & (\text{particles}) \\ -1 & (\text{sparticles}) \end{cases} \]

**R-Parity Conservation** (RPC): Frequent assumption in SUSY models

- Forbids the bi/trilinear \( W_{\Delta B,L} \) terms
- SUSY particles only produced in pairs
- **Lightest SUSY particle** (LSP): cannot decay
  \( \rightarrow \) dark matter candidate

Consequences for **collider searches**:

- Pair production of SUSY particles
- Decay cascades until 2 LSP are left
- LSPs escape the detector

**Resulting search strategy:**

Signs of escaping, undetected particles (**Missing transverse momentum**)
This session: Drop the assumption of R-Parity conservation

R-Parity Violation (RPV)

Trilinear $W_{\Delta B, L}$ terms allowed (possibly only some of them $\rightarrow$ Proton)

- Decays of SUSY particles to SM particles
- Lepton and Baryon number violation
- No dark matter candidate

Why would we want to do this?

- R-Parity Violation may significantly alter collider signatures
  - No escaping LSP - no missing transverse momentum!
- Potential generation of neutrino masses (Neutralino-Neutrino mixing)
- B and/or L violation: matter/antimatter imbalance
- Several other ways of stabilizing the proton exist

Dedicated searches are starting to fill this gap
Phenomenology of R-Parity violation (RPV)

New superpotential terms:

\[ W_{RPV} = \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \tilde{D}_k + \kappa_i L_i H_2 \]

Consequences of a nonzero \( \lambda_{ijk} \):

- \( \tilde{\ell} \ell/\tilde{\nu} \ell \ell \) coupling - flavours determined by i,j,k
- Lepton number and flavour violation
- Neutralino LSP: Opens dilepton decay mode

\[ \lambda_{121} \neq 0 \Rightarrow \chi_1^0 \rightarrow e^- \mu^+ \bar{\nu}_e \]

Turn \( \lambda \) RPV on

\[ p \tilde{g} \tilde{\chi}_1^0 \rightarrow p \tilde{g} \tilde{\chi}_1^0 \]

\[ q \tilde{g} \tilde{\chi}_1^0 \rightarrow q \tilde{g} \tilde{\chi}_1^0 \]

\[ e^+ / \mu^+ \]

\[ \tilde{\nu}_\mu / \tilde{\nu}_e \]

\[ \lambda_{121} \]

\[ \chi_1^0 \]

\[ p \tilde{g} \tilde{\chi}_1^0 \rightarrow p \tilde{g} \tilde{\chi}_1^0 \]

\[ q \tilde{g} \tilde{\chi}_1^0 \rightarrow q \tilde{g} \tilde{\chi}_1^0 \]

\[ \ell \lambda \nu \]

\[ \ell \lambda \nu \]

\[ \tilde{\nu}_\mu / \tilde{\nu}_e \]

\[ e^- \]

\[ \ell \lambda \nu \]

\[ \ell \lambda \nu \]
The ATLAS 4-Lepton search

- Consider events with at least **4 charged leptons**
  → include hadronic decay modes of the \( \tau \)-lepton

Look for an excess in the number of events over the **standard model background**:

**Irreducible Backgrounds:**
- at least four prompt charged leptons
- main sources: \( ZZ, t\bar{t}Z, tWZ, VV, Higgs \)
- estimate using **MC simulation**

| Dominant uncertainty: Theory (cross-sections, differential shapes) |

**Reducible Backgrounds:**
- fewer than four prompt charged leptons
  → at least one non-prompt / fake
- main sources: \( WZ, Z+\text{jets}, t\bar{t} \)
- estimate using **data-driven method**

| Dominant uncertainty: estimation of non-prompt / fake leptons |

Exploit **properties of SUSY signal** to suppress background and gain sensitivity

- Presence of **Neutrinos** - moderate **Missing Transverse Momentum**
- **Cascade decays** - additional SM particles (leptons, jets) with high momenta
- Leptons do not originate from \( Z \rightarrow \ell\ell \) decays
  → reject events with lepton pairs of \( |m_{\ell\ell} - m_Z| < 10 \text{ GeV} \) (**'Z veto'**)
Cascade decays: Typically, high final state particle multiplicities

Sensitive quantity: Effective mass: $M_{\text{eff}} := \sum_{\text{leptons, Jets}} p_T + E_T^{\text{Miss}}$

(a) low $M_{\text{eff}}$

(b) high $M_{\text{eff}}$

4-Lepton analysis: $M_{\text{eff}}$ requirement powerful tool for signal/background discrimination
**Observation on Data**

<table>
<thead>
<tr>
<th>Event Category</th>
<th>SM Data</th>
<th>Data</th>
<th>$p_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4 \ (e,\mu)$</td>
<td>$1.4 \pm 0.4$</td>
<td>1</td>
<td>0.50</td>
</tr>
<tr>
<td>$3 \ (e,\mu) + 1 , \tau$</td>
<td>$2.9^{+1.0}_{-0.9}$</td>
<td>1</td>
<td>0.50</td>
</tr>
<tr>
<td>$2 \ (e,\mu) + 2 , \tau$</td>
<td>$3.0 \pm 1.0$</td>
<td>6</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*Note: simplified overview*

- Observation in solid agreement with SM expectation
- → Translate into **exclusion limits** in the SUSY parameter space

**3 \ (e,\mu) + 1 \, \tau**

**2 \ (e,\mu) + 2 \, \tau**
Exclusion Limits

Example 1: Strong production of Gluino pairs

\[ pp \rightarrow \tilde{g} \tilde{g} \rightarrow q \bar{q} \tilde{\chi}^0_1, q \bar{q} \tilde{\chi}^0_1, \tilde{\chi}^0_1 \rightarrow \ell^+ \ell^- \]

Investigate 4 \( \lambda \) Couplings (only turn one on at a time):

1. (e,\( \mu \))-rich \( \lambda_{121}, \lambda_{122} \) - LSP decays to \( e\nu e\nu \) and \( e\mu \nu \), or \( \mu\mu \nu \) and \( e\mu \nu \)
2. Tau-rich \( \lambda_{133}, \lambda_{233} \) - LSP decays to \( e\tau \nu \) and \( \tau\tau \nu \), or \( \mu\tau \nu \) and \( \tau\tau \nu \)

Stronger exclusion for (e,\( \mu \))-rich couplings - reconstruction efficiency

Close to the X axis: collimated leptons \( \rightarrow \) lose efficiency

High cross sections - strong limits up to \( m(\tilde{g}) = 1400/950 \text{ GeV} \)
Example 2: Electroweak production of Sneutrino pairs

$p p \to \tilde{\nu} \tilde{\nu} \to \nu \tilde{\chi}^0_1 \tilde{\chi}^0_1 \nu \ell^+ \ell^-$

No visible particles from the cascade - challenging signature
Cross-sections lower than for strong production
Limits up to $m(\tilde{\nu}) = 400$ GeV (light leptons)
Tau-rich couplings: exclude region at $m(\tilde{\nu}) \sim m(\tilde{\chi}^0_1) = 100$ GeV
A look at the lifetime

So far: assumed prompt LSP decays
What if we play with the **LSP lifetime** (i.e. change $|\lambda|$)?

$0 \lesssim \tau(\tilde{\chi}^0_1) \lesssim 10^{-1}$ ps:
- Decay length **below detector resolution**
- 4 prompt leptons, 4 jets,
- low $E_T^{\text{Miss}}$ (Neutrinos)
- →4-Lepton results apply

100 ns $\lesssim \tau(\tilde{\chi}^0_1)$:
- LSP decays **outside the detector**
- zero leptons, 4 jets,
- high $E_T^{\text{Miss}}$ (LSPs)
- →covered by existing RPC searches
Medium lifetimes

Interesting case: \(10^{-1}\, \text{ps} \lesssim \tau(\tilde{\chi}_1^0) \lesssim 100\, \text{ns}\)

- Decays in the detector, but outside the primary vertex

- Signature: displaced lepton pairs

- 4-lepton search: restricted sensitivity → new search channel
Displaced Dileptons - a short overview

Ongoing effort - the analysis so far

Key ingredient: **Retracking**
- Issue: Highly displaced tracks are missed by conventional ATLAS track reconstruction
- Solution: Rerun track reconstruction and vertex finding with special algorithms

Look for a **displaced vertex** in the tracker volume of $|r| < 30\text{cm}$, $|z| < 30\text{cm}$
- Should contain two oppositely charged leptons
- Invariant mass: Require more than 10 GeV to suppress light resonances
- Reject any vertices in regions with detector material

Expect very **low background** ($< 1$ event)

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ATLAS Work in Progress

- Both lepton tracks reconstructed
- Dilepton Vertex reconstructed

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Signal Region
$m_\ell > 10\text{ GeV}$

$m(\tilde{\chi}_1^0) = 50\text{ GeV}$

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Max Goblirsch (MPI)

Searches for RPV SUSY with ATLAS

19.9.2014 13 / 16
Displaced Dileptons - the background

- Study potential background using MC simulation and low mass data

1. resonances - At low masses (delayed J/\(\Psi\), \(K_S \rightarrow \pi\pi\) with 2 fakes)
2. random crossings - Random crossing of two tracks to form a vertex.
3. cosmic muons - might be interpreted as back-to-back dilepton vertex
4. conversions/bremsstrahlung - \(ee/e\mu\) vertex

random crossings appear dominant

- Invariant mass:
  \[ m_{12} \approx 2E_1E_2(1 - \cos(\phi_{12})) \]
  - determined by (random) momenta and crossing angle
- Estimation technique: Random combination of tracks

![Graph showing vertex mass after track/lepton pt cuts](image-url)
R-Parity violation (RPV): Interesting class of supersymmetric models
- Collider signatures may evade conventional searches
- B and L violation, potential for Neutrino masses
- No SUSY dark matter candidate

ATLAS: Probe $\lambda$ RPV with a 4-Lepton search
- Low background, sensitive up to high masses (low cross-sections)
- Final run 1 results: No signs of SUSY yet
- Further ATLAS RPV analyses: also see next talk!

Another loophole: Long-lived signatures
- RPC decays may occur with long lifetimes
- Not covered by existing searches
- Dedicated displaced vertex search in progress
One more thing...