Searches for RPV SUSY with ATLAS

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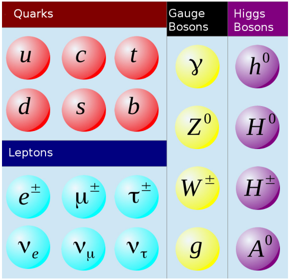
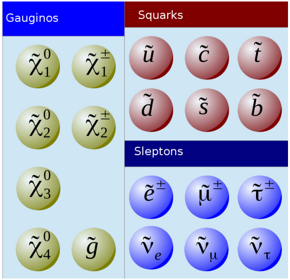
Idea: Introduce a new symmetry transformation 'Q' with the following property:

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

Assign each particle in the standard model a supersymmetric partner

$\rightarrow$ 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

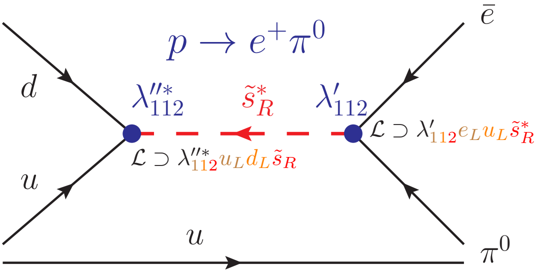
- Writing down all the allowed interaction terms in a (minimal) supersymmetric standard model, we get something new:

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

→ 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

- λ' and λ'' can mediate rapid **proton decay**



One way out: R-Parity

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

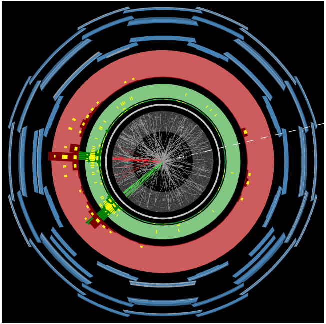
R-Parity Conservation (RPC): Frequent assumption in SUSY models

- 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**

$\rightarrow$ 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

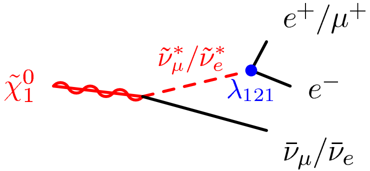
New superpotential terms:

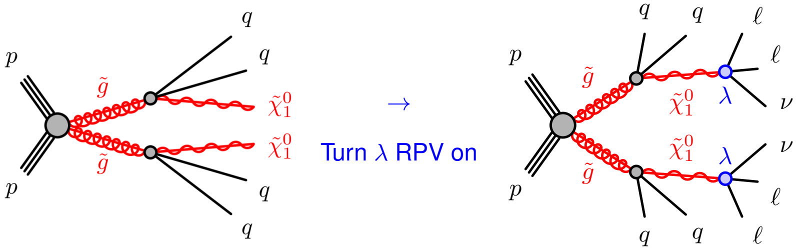
$$W_{RPV} = \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k}_{\text{this talk}} + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2$$

Consequences of a nonzero λ_{ijk}:

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

$\rightarrow$ Example: $\lambda_{121} != 0 \Rightarrow \chi_1^0 \rightarrow e^- \mu^+ \bar{\nu}_e$





The ATLAS 4-Lepton search

- Consider events with at least **4 charged leptons**

$\rightarrow$ include hadronic decay modes of the τ-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, VVV, Higgs**

estimate using **MC simulation**

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

Reducible Backgrounds:

fewer than four prompt charged leptons

$\rightarrow$ at least one non-prompt / fake

main sources: **WZ, Z+jets, $t\bar{t}$**

estimate using **data-driven method**

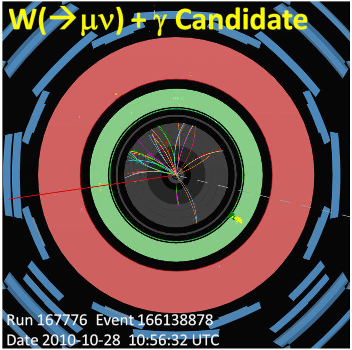
Dominant **uncertainty:** estimation of non-prompt / fake leptons

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

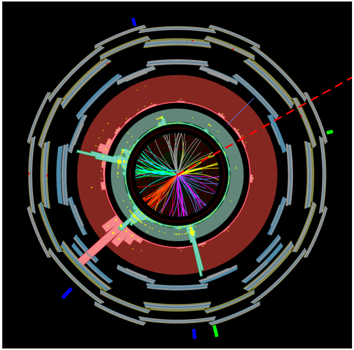
- Presence of **Neutrinos** - moderate **Missing Transverse Momentum**
- **Cascade decays** - additional SM particles (leptons, jets) with high momenta
- Leptons do not originate from $Z \rightarrow \ell\ell$ decays

$\rightarrow$ reject events with lepton pairs of $|m_{\ell\ell} - m_Z| < 10$ GeV (' **Z veto**')

- **Cascade decays:** Typically, high final state particle multiplicities
- Sensitive quantity: **Effective mass**: $M_{eff} := \sum_{\text{leptons, Jets}} p_T + E_T^{Miss}$



(a) low M_{eff}



(b) high M_{eff}

4-Lepton analysis: M_{eff} requirement powerful tool for signal/background discrimination

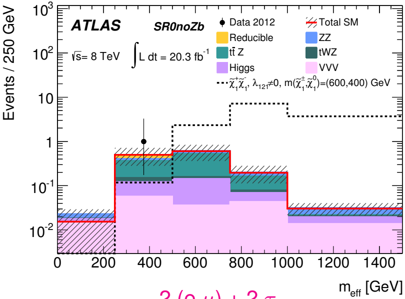
Event Category	Σ SM	Data	p_0
4 (e,μ)	1.4 ± 0.4	1	0.50
3 (e,μ) + 1 τ	$2.9^{+1.0}_{-0.9}$	1	0.50
2 (e,μ) + 2 τ	3.0 ± 1.0	6	0.10

Note: simplified overview

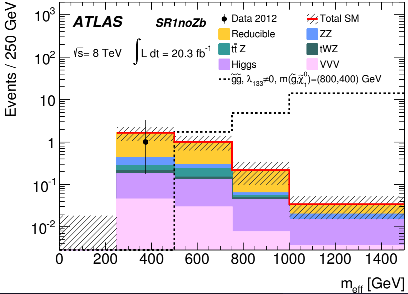
- Observation in solid agreement with SM expectation

→ Translate into **exclusion limits** in the SUSY parameter space

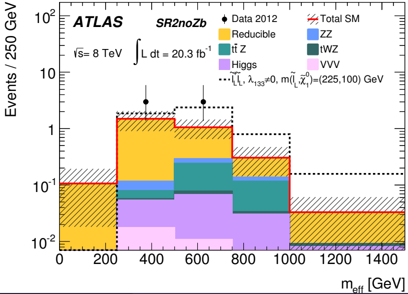
4 (e,μ)



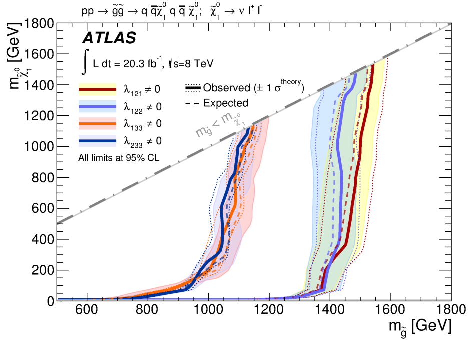
3 (e,μ) + 1 τ

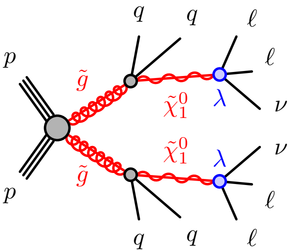


2 (e,μ) + 2 τ



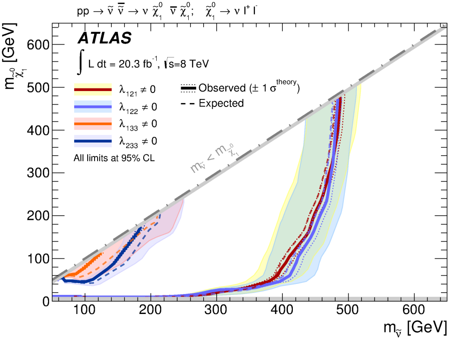
Example 1: Strong production of Gluino pairs

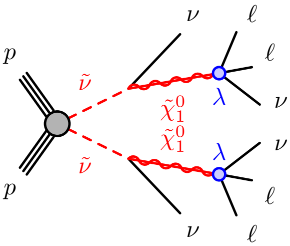




- Investigate 4 λ Couplings (only turn one on at a time):
  1. (e,μ)-rich λ_{121}, λ_{122} - LSP decays to $ee\nu$ and $e\mu\nu$, or $\mu\mu\nu$ and $e\mu\nu$
  2. Tau-rich λ_{133}, λ_{233} - LSP decays to $e\tau\nu$ and $\tau\tau\nu$, or $\mu\tau\nu$ and $\tau\tau\nu$
- Stronger exclusion for (e,μ)-rich couplings - reconstruction efficiency
- Close to the X axis: collimated leptons $\rightarrow$lose efficiency
- High cross sections - strong limits up to $m(\tilde{g}) = 1400/950$ GeV

Example 2: Electroweak production of Sneutrino pairs





- 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 $m(\tilde{\nu}) \sim m(\tilde{\chi}_1^0) = 100$ GeV

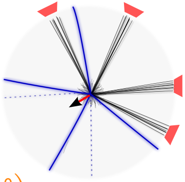
So far: assumed prompt LSP decays

What if we play with the **LSP lifetime**(i.e. change $|\lambda|$)?

0

$\tau\left(\tilde{\chi}_1^0\right)$

∞



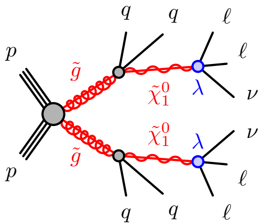
$0 \lesssim \tau\left(\tilde{\chi}_1^0\right) \lesssim 10^{-1} ps$:

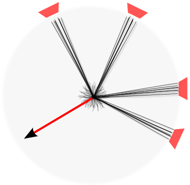
Decay length **below detector resolution**

4 prompt leptons, 4 jets,

low E_T^{Miss} (Neutrinos)

$\rightarrow$**4-Lepton results apply**





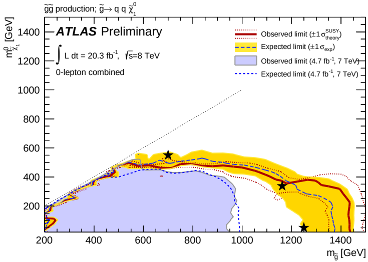
$100ns \lesssim \tau\left(\tilde{\chi}_1^0\right)$:

LSP decays **outside the detector**

zero leptons, 4 jets,

high E_T^{Miss} (LSPs)

$\rightarrow$**covered by existing RPC searches**



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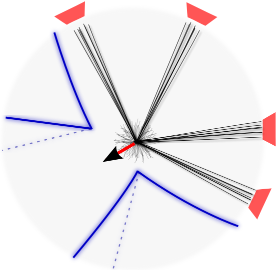
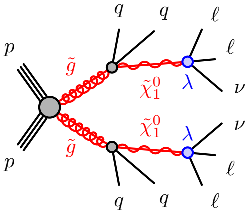
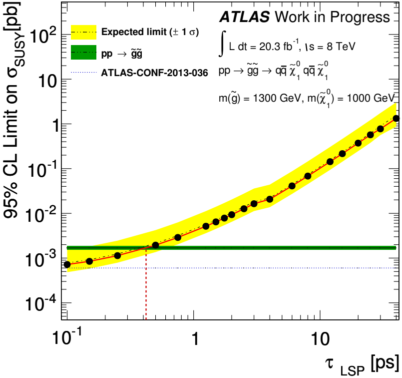
Interesting case: $10^{-1} ps \lesssim \tau\left(\tilde{\chi}_1^0\right) \lesssim 100 ns$

- Decays in the detector, but **outside the primary vertex**







- Signature: displaced lepton pairs
- 4-lepton search: restricted sensitivity

→ **new search channel**

Ongoing effort - the analysis so far

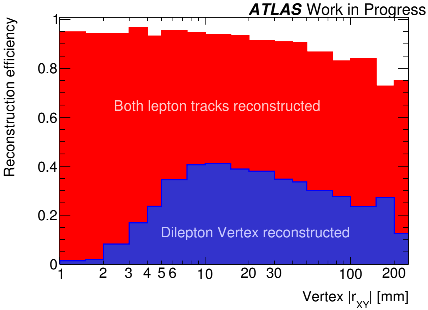
Key ingredient: **Retracking**

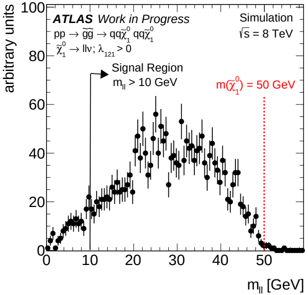
- Issue: Highly displaced tracks are missed by conventional ATLAS track reconstruction
- Solution: Rerun track reconstruction and vertex finding with special algorithms

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

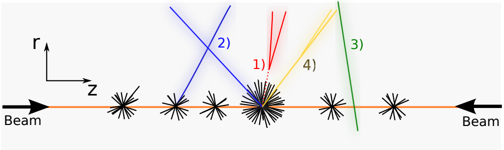
Expect very **low background** (< 1 event)





Displaced Dileptons - the background

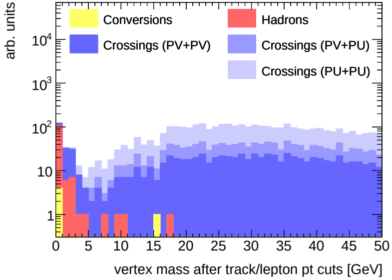
- Study potential background using MC simulation and low mass data



1. resonances - At low masses (delayed J/Ψ, $K_S \to \pi\pi$ 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: $m_{12} \simeq 2E_1E_2(1 - cos(\phi_{12}))$ - determined by (random) momenta and crossing angle
- Estimation technique: Random combination of tracks



Summary, Outlook

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 λ 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…

ATLAS
EXPERIMENT

http://atlas.ch