Search for Signs of R-Parity Violating Supersymmetry in Multilepton Events with the ATLAS Detector

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(One) Motivation: The Hierarchy Problem

- Higgs vacuum mass receives loop corrections from possible high-scale new physics

→ corrections scale $\propto \Lambda_{UV}^2$ with the cutoff scale

→ corrections scale $\propto m^2$ with masses of particles

- Recently, the Higgs[1] mass was measured to be $m_H \sim 125\ \mathrm{GeV}$
- Planck-scale new physics: M_{Pl}^2 contributions fine-tuned down by 34 orders of magnitude?

Possible Solution: Symmetry

- Find a symmetry that automatically leads to cancellation of the loop terms
- Corrections from Bosons and Fermions have opposite signs

→ Idea of a symmetry assigning a matching boson to every fermion

→Supersymmetry

[1] *pending sudden experimental evidence on the contrary*

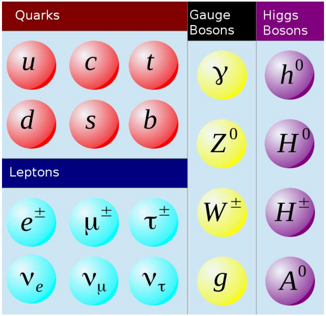
Supersymmetry (SUSY) as an extension of the standard model

Introduce a new symmetry transformation Q:

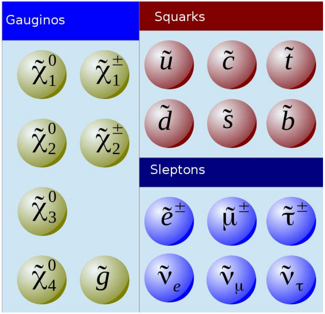
$$Q|\text{fermion}\rangle = |\text{boson}\rangle; \quad Q|\text{boson}\rangle = |\text{fermion}\rangle$$

$\rightarrow$ Assign each particle in the standard model a supersymmetric partner

- spins differ by $\frac{1}{2}$
- all other properties unchanged



Experimentally Observed ✓



Not Observed so far

$\rightarrow$If there is SUSY, it must be a **broken** symmetry.

R-Parity

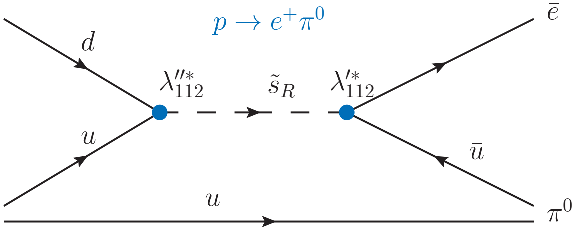
- Writing down the allowed interaction terms in a (minimal) supersymmetric standard model, something interesting appears:

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

  - → i,j,k: generation indices
  - → $\lambda, \lambda', \lambda'', \kappa$: couplings.
  - → 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_d: Higgs superfield coupling to down-type fermions

→ Baryon and Lepton number (accidentally conserved in SM) violated

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



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

- What can we do about these terms?
- **Minimal supersymmetric standard model** (MSSM): Impose conservation of a new quantum number, **R-Parity**

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

Consequences of R-Parity Conservation (RPC)

- B/L violating terms forbidden
- SUSY particles can only be created in pairs
- the lightest SUSY particle (LSP) is **stable** and electrically neutral

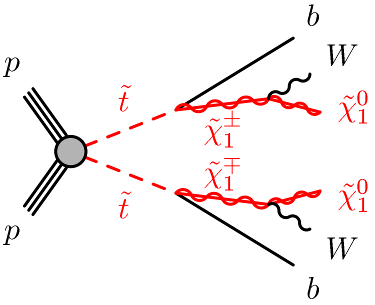
$\rightarrow$ dark matter candidate!

Typical MSSM SUSY searches

- Conserved R-Parity: SUSY Particles produced in **pairs**
- Cascade decays to the LSP and standard model particles
- finally, the LSPs escape the detector

$\rightarrow$ apparent non-conservation of transverse momentum: $E_T^{Miss} = |\sum \vec{p_T}| > 0$

- Typical **Search strategy**: Cascade particles and high E_T^{Miss}



- 2 years of searches at $\sqrt{s} = 7\,/\,8$ TeV
- Wide variety of search channels
- common result: everything **consistent with standard model**

$\longrightarrow$

- Many popular models almost completely excluded
- No SUSY (within our reach)?
- Or is it **cleverly hidden**?

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LP 2013

ATLAS Preliminary

$\int\mathcal{L}\,dt = (4.4 - 22.9)$ fb^{-1} $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e,μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$>18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	0	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	$m(\tilde{\chi}_1^0)$ <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 150-440 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^\pm)$=10 GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0Z^*\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035

R-Parity violation

Subject of growing interest: R-Parity violation (RPV)

- Drop the assumption of R-Parity conservation, allow (some of) the terms we encountered earlier
- proton stabilized in other ways (no fundamental problems)

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

Consequences of R-Parity violation

- The LSP no longer needs to be stable and neutral

$\rightarrow$ lose dark matter candidate

- SUSY particles can decay into standard model particles

$\rightarrow$ could escape traditional, E_T^{Miss} based searches

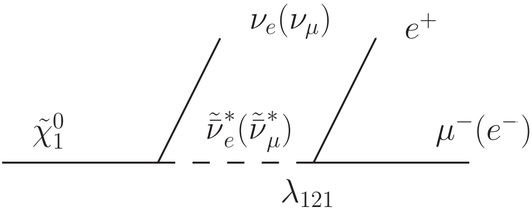
One promising search channel: Multileptons

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \ldots$$

- λ_{ijk} terms: L-violating slepton-lepton-neutrino vertex

$\rightarrow$ allow for the LSP to decay into leptons and neutrinos!

- example: $\lambda_{121} > 0$: $\chi_1^0 \rightarrow e^+ \mu^- \nu_e$
- lower $E_{\mathrm{T}}^{\mathrm{miss}}$ compared to 'conventional' SUSY scenarios, as LSP decays produce visible particles, but **at least 4 leptons**



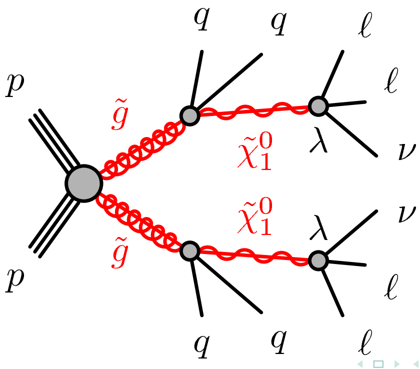
Study **Simplified RPV models**

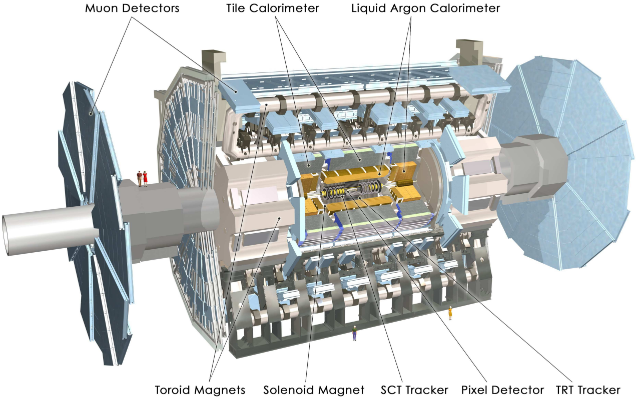
→ simplified: only 2 SUSY particles contribute

- Bino-like **neutralino ($\tilde{\chi}_1^0$) LSP**
- One next-to-lightest SUSY particle (NLSP) (several choices)
- all other sparticles **decoupled** to very high masses (4.5 TeV)
- Choose a **single** λ_{ijk} parameter to be non zero

→ study λ_{121},λ_{122},λ_{133},λ_{233} as representative sample

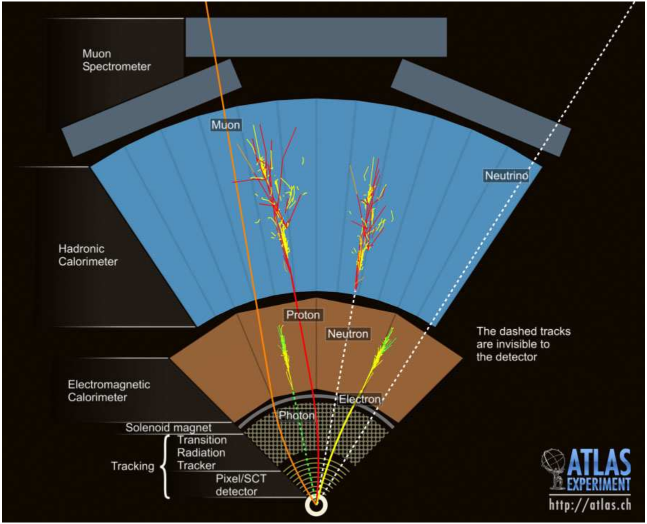
- expect at least 4 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$





- High Luminosity, multi purpose detector at the Large Hadron Collider in Geneva
- Record p-p-collisions at $\sqrt{s} = 7(2011)/8(2012)\ \mathrm{TeV}$
- Total dataset: 4.7fb^{-1} (2011) / 20.4fb^{-1} (2012)

The ATLAS detector



- High Luminosity, multi purpose detector at the Large Hadron Collider in Geneva
- Record p-p-collisions at $\sqrt{s} = 7(2011)/8(2012)\ \mathrm{TeV}$

Backgrounds

Which **Standard Model processes** do we need to consider as backgrounds?

$\rightarrow$ separate based on number of **prompt** (from the primary interaction) leptons

4 prompt leptons

- Di- and Triboson production (ZZ, WWZ)
- Higgs decays ($H \rightarrow 4\ell$, $ZH \rightarrow WWZ \rightarrow 4\ell 2\nu$
- Estimate contributions using Monte-Carlo simulation

fewer than 4 prompt leptons

- Z+jets (secondary leptons from jets)
- Top quark pairs (secondary leptons from $b \rightarrow c\ell\nu$)
- Di/Triboson processes (WW,WZ,WWW)
- Estimate contributions using data-driven techniques

Challenge: Suppress background as much as possible while avoiding rejection of signal events

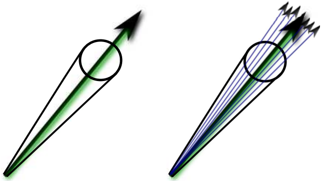
Event Selection

Main requirement:

- At least 4 isolated leptons

$\rightarrow$ isolated leptons: not surrounded by further activity (jets)

$\rightarrow$ effect: separate prompt from secondary leptons



hadronic tau decays

- 7 out of 9 possible λ_{ijk} indices contain third generation ($i/j/k = 3$) indices
- to be sensitive, need to take **tau lepton** decays into account

$\rightarrow$ allow a hadronic tau decay ($\tau \rightarrow W^*\nu$; $W^* \rightarrow$ hadrons) to replace one lepton

- challenging **separation from jets** - multivariate techniques

$\rightarrow$ 2 event categories: 4ℓ, $3\ell 1\tau$ $(\ell = e, \mu)$

RPV decays of a $\tilde{\chi}_1^0$ LSP via a non-zero λ_{ijk} parameter.

	$ij = 12$	$ij = 13$	$ij = 23$
$k = 1$	$ee\nu/e\mu\nu$	$ee\nu/e\tau\nu$	$e\mu\nu/e\tau\nu$
$k = 2$	$e\mu\nu/\mu\mu\nu$	$e\mu\nu/\mu\tau\nu$	$\mu\mu\nu/\mu\tau\nu$
$k = 3$	$e\tau\nu/\mu\tau\nu$	$e\tau\nu/\tau\tau\nu$	$\mu\tau\nu/\tau\tau\nu$

Veto of Z bosons

- Many backgrounds contain lepton pairs from $Z \to \ell\ell$ decays
- Apply a **Z veto**: Reject events containing a lepton pair with invariant mass within 10 GeV of the Z resonance
- no significant effect on signal, powerful suppression of background

Final selection

- Use properties of SUSY events

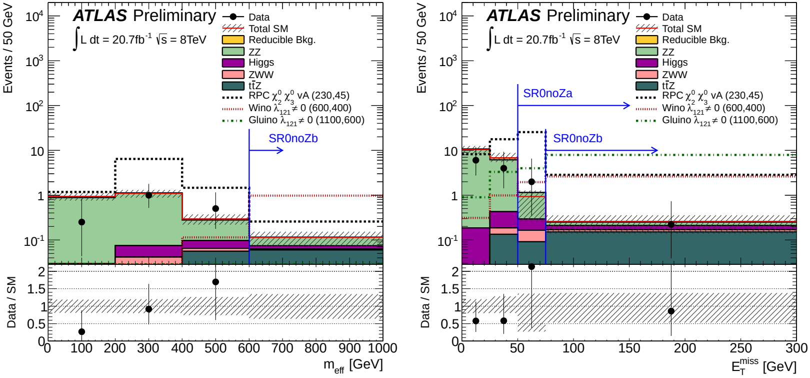
→ neutrinos from LSP decay: moderate E_T^{Miss}

→ cascade activity: many high momentum objects

- useful quantity: **effective mass** - $m_{eff} = \sum_{leptons} |\vec{p_T}| + \sum_{jets} |\vec{p_T}| + E_T^{Miss}$
- require E_T^{Miss} or m_{eff} to pass a certain threshold

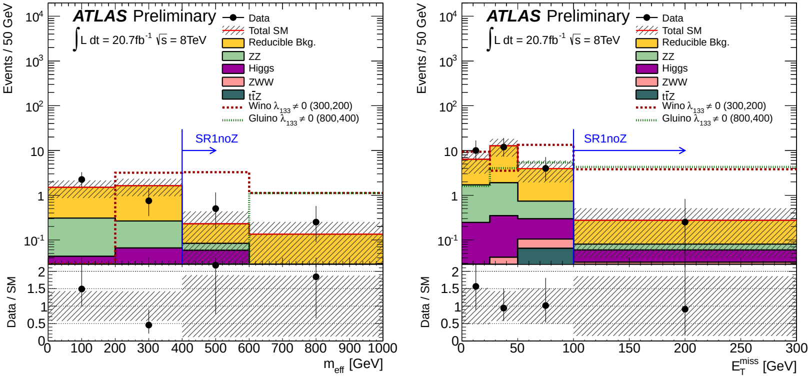
→ almost complete suppression of standard model processes, high efficiency on signal

Results



$\underline{4\ell 0\tau}$ event category:

- main surviving background: 4 prompt leptons
- very low background expectation - expect 1.6 SM events
- observe 1 event - in agreement with SM



$\underline{3\ell 1\tau}$ event category:

- events with non-prompt leptons become important background

$\rightarrow$ jets misidentified as hadronic taus

- overall background level again very low (2 events)
- observe 4 events
- well within uncertainty of the background estimation ($p_0 = 0.13$)

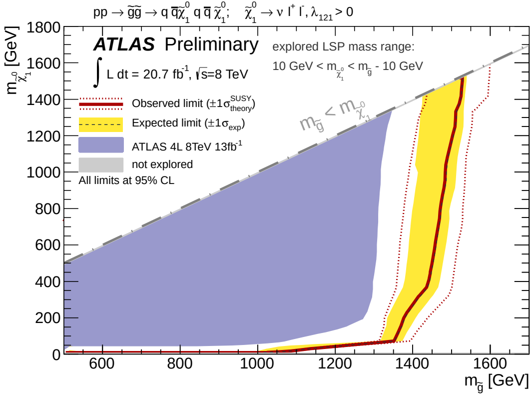
2012 Exclusion Limits - examples

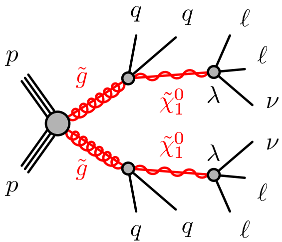
- No excess over SM observed, place upper limits on possible signal
- exclusion plot: region excluded within the model at 95%CL

$\rightarrow$ area to the left of the red band is **excluded**

- for $\lambda_{121} > 0$: strongest exclusion.

$\rightarrow$ Only e, μ in final states, high acceptance and efficiency

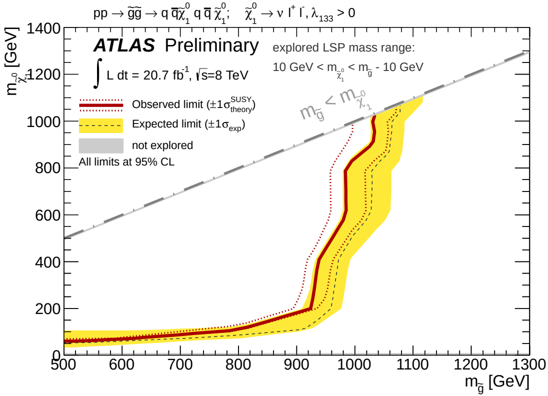


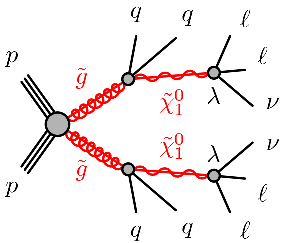


2012 Exclusion Limits - examples

- for $\lambda_{133} > 0$: weaker limits
- tau decays in all possible final states

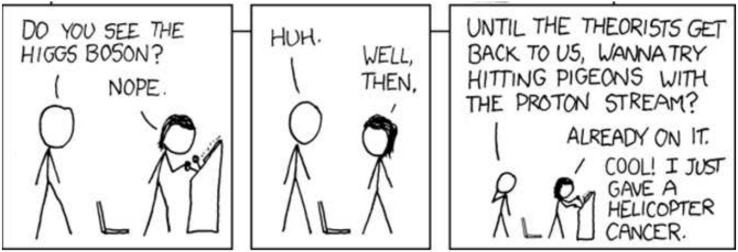
$\rightarrow$ more challenging, reduced selection efficiency





The story so far

- Conventional RPC SUSY searches at the LHC observe no deviation from the SM
- Non-observation is starting to exclude the most popular models
- Searches have been extended into the realm of R-Parity violation
- and again, no signs of SUSY
- Are we done until 2015?



Long-lived RPV

One more loophole!

- So far, we considered the case where λ is of a sufficient magnitude for prompt LSP decays

$\rightarrow$ what happens when we go to lower values?

- study **finite LSP lifetimes**
- main concept: finite lifetime $\rightarrow$decay vertex is spatially displaced from the interaction point
- How far does the sensitivity of the 4-lepton search reach?

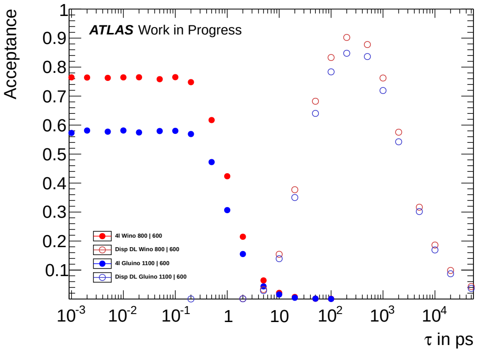
$\rightarrow$ requirements that reject displaced leptons from b decays and cosmic muons will then reject signal

- If our sensitivity runs out, can we complement it somehow?
- what is our maximum reach?

Preliminary study

- Simulate LSP lifetimes from 0.001 to 10000 ps
- study acceptance of the 4l analysis
- also study acceptance of a potential complementary analysis

→ **displaced lepton pairs**: look for two leptons coming from a displaced vertex



- 4 leptons lose sensitivity at 1 ps
- displaced lepton pairs become sensitive above 20 ps
- total reach: up to 10^4ps - LSPs start to decay outside the tracking volume

Conclusions, Outlook

- **SUSY** is a hot topic for LHC searches

$\rightarrow$ possible solution to the **Hierarchy problem**

$\rightarrow$ most natural models (low fine tuning) expect masses in the TeV range or below

- Recent searches have set **strong limits** on conventional, R-Parity conserving SUSY

$\rightarrow$ already straining the boundaries of natural SUSY

- Extend scope of searches - **R-Parity violation**

$\rightarrow$ New signatures, including **Multilepton** events

$\rightarrow$ could have been missed by conventional searches

- Next step - **Long lived signatures**

$\rightarrow$ can be caused by a weak RPV coupling

$\rightarrow$ could have been missed by **all** previous ATLAS analyses . . .

$\rightarrow$ SUSY could still be hiding in plain sight