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

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Outline

Supersymmetry (SUSY) as an extension of the standard model

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

$$Q|fermion\rangle = |boson\rangle$$
$$Q|boson\rangle = |fermion\rangle$$

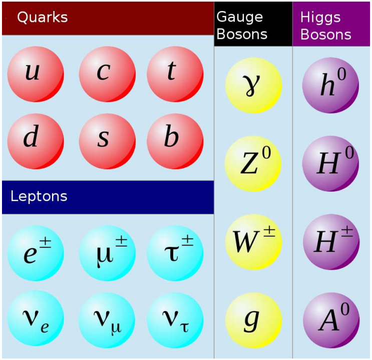
→ Assign each particle in the standard model a supersymmetric partner

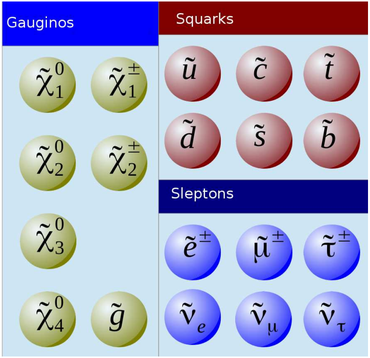
- spins differ by $\frac{1}{2}$
  (boson ↔ fermion)

- Motivation:
  - stabilize Higgs vacuum mass against loop corrections
  - convergence of fundamental interactions' coupling strenghts (→ GUT's)
  - obtain a dark matter candidate

Multilepton signatures in SUSY

Overview: Minimal SUSY particle content





(mostly) experimentally observed

not observed so far! May be shifted to higher masses (broken SUSY)

Important concept: R-Parity

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

Motivation:

- protection against rapid proton decay
- stable, neutral LSP (lightest supersymmetric particle) $\rightarrow$dark matter candidate

Consequences:

- SUSY particles can only occur in even numbers at vertices
- SUSY decay chains end at the LSP, which escapes the detector

$\rightarrow$ visible to the analyser as a non-conservation of the transverse momentum

$\rightarrow$ quantitatively: expect high $E_{\mathrm{T}}^{\mathrm{miss}} = |\sum_{\text{Objects}} \vec{p_T}|$

R-Parity Violation:

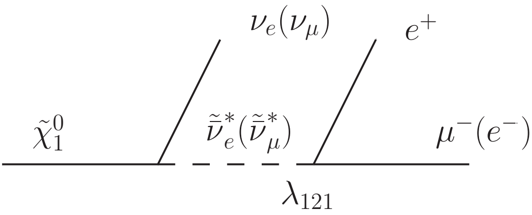
- RPV superpotential terms:

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

- non-zero λ_{ijk}: lepton flavour violating LSP decay

$\rightarrow$ example: $\lambda_{121} > 0$: $\chi_1^0 \rightarrow e^+ \mu^- \nu_e$

- reduced E_T^{miss} compared to 'conventional' SUSY scenarios, as LSP decays produce visible particles, but **high lepton multiplicities**



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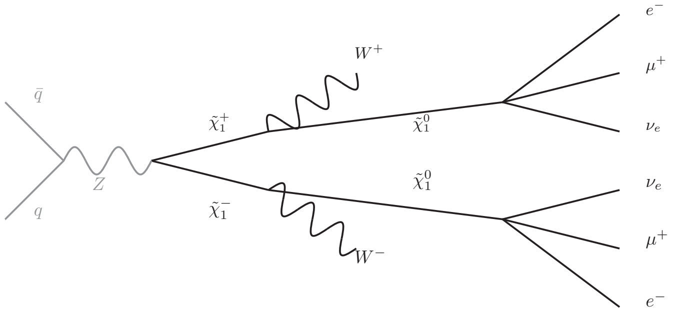
Overview: RPV decays of a $\tilde{\chi}_1^0$ LSP via a non-zero λ_{ijk} parameter.

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

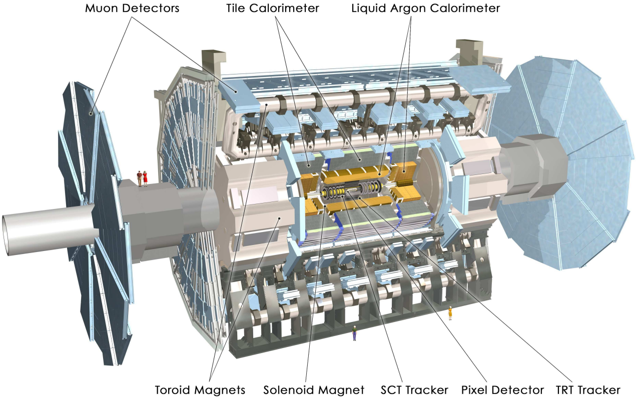
Signal models for the RPV analysis

Study **Simplified RPV models**

- Bino-like **neutralino ($\tilde{\chi}_1^0$) LSP**
- several next-to-lightest SUSY particle (NLSP) choices (Winos, Gluinos, Sleptons, Sneutrinos)
- all other sparticles **decoupled** to very high masses (4.5 TeV)
- generate sets of samples (grids) in the $m_{\tilde{\chi}_1^0}/m_{NLSP}$ plane
- expect at least 4 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$



The ATLAS detector



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

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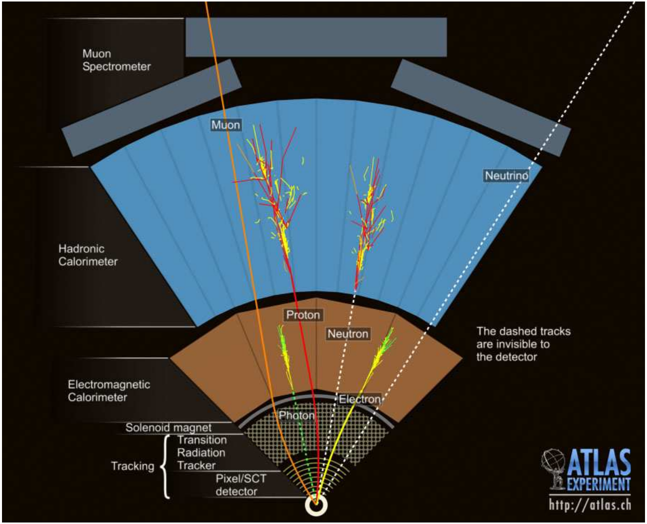

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- Record p-p-collisions at $\sqrt{s} = 7(2011)/8(2012)$ TeV

Backgrounds

Which **Standard Model processes** can yield 4 leptons in the final state?

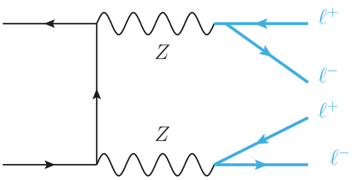
- Irreducible backgrounds - 4 prompt leptons similiar to those from signal

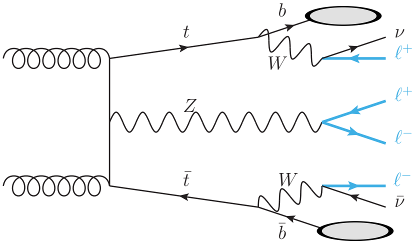
$\rightarrow$ ZZ diboson production (and $H \rightarrow ZZ^* \rightarrow 4\ell$)

$\rightarrow$ top quark pairs in association with vector bosons ($t\bar{t} + WW/Z$)

$\rightarrow$ ZWW triboson production

- low cross-sections, but hard to suppress!





Backgrounds

- Reducible backgrounds, with leptons from secondary decays or fakes

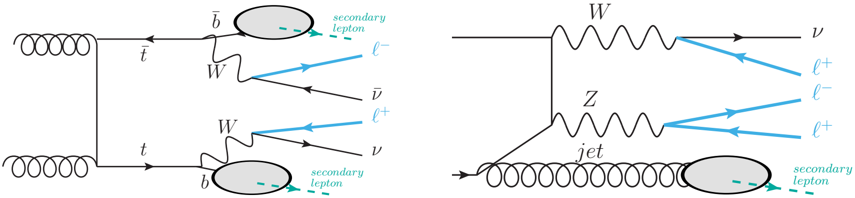
→ $Z \rightarrow \ell\ell$

→ WZ, WW, WWW di/triboson processes

→ top quark pairs ($t\bar{t}$/$t\bar{t}$+W)

→ Z+γ

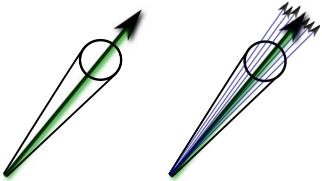
- can be suppressed more easily, but high cross-sections



Main requirement:

- At least 4 signal leptons

→ Signal leptons: Appear **isolated** in the detector, not surrounded by further activity (jets etc)



Suppression of Z backgrounds:

- reject events with a dilepton pair with an invariant mass in the region $|M_{ll} - M_Z| < 10$

→ powerful suppression of ZZ, WZ, Z+jets, ttZ

Selection of SUSY candidates

- neutrinos from the LSP decays →look for $E_{\mathrm{T}}^{\mathrm{miss}}$

→ First signal event category (Signal region 1, SR1): $E_{\mathrm{T}}^{\mathrm{miss}} > 50\ \mathrm{GeV}$

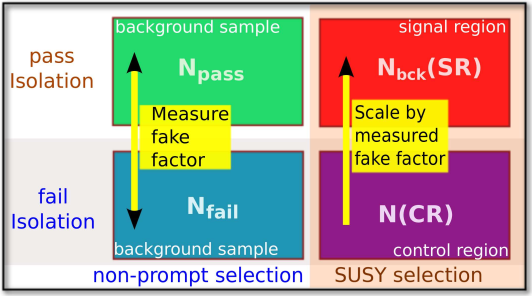
- another sensitive variable: Effective mass: $m_{eff} = \sum_{leptons} p_T + \sum_{jets} p_T + E_{\mathrm{T}}^{\mathrm{miss}}$

→ Second signal event category (Signal region 2, SR2): $m_{eff} > 300\ \mathrm{GeV}$

Goal: Estimate the background from reducible processes using data

1. Define a **control region** - signal selection, but require one lepton to fail the isolation cuts
2. Define a **background sample** of events with non-prompt leptons (example: $b\bar{b}$)
3. Measure propability f of a non prompt lepton to appear isolated in the background sample
4. Use this to scale counts in the control region to expected signal region background

$$N_{bck}(SR) = \frac{\mathbf{f}}{1-\mathbf{f}} \cdot N(CR) = \frac{N_{pass}}{N_{fail}} \cdot N(CR)$$



Background estimation - 2012 results

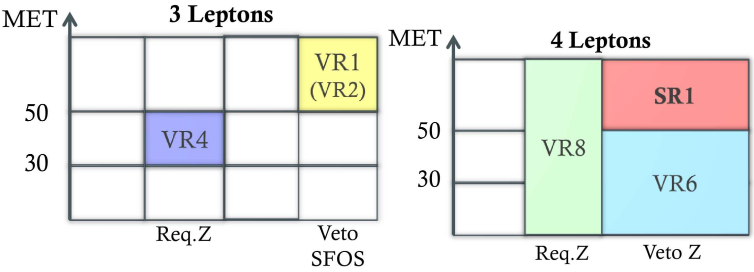
Selection	SR1	SR2
ZZ	$0.07^{+0.18}_{-0.08}$	$0.99^{+0.66}_{-0.63}$
triboson	$0.10^{+0.01}_{-0.01}$	$0.08^{+0.01}_{-0.01}$
$t\bar{t}Z$	$0.04^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$
$t\bar{t}WW$	$0.01^{+0.01}_{-0.00}$	$0.00^{+0.00}_{-0.00}$
Σ Irreducible	$0.22^{+0.20}_{-0.08}$	$1.14^{+0.67}_{-0.63}$
Fakes	$-0.01^{+0.14}_{-0.19}$	$0.09^{+0.17}_{-0.17}$
Σ SM	$0.21^{+0.24}_{-0.21}$	$1.23^{+0.66}_{-0.63}$

- Background expectation dominated by irreducible processes
- reducible contributions: dominated by WZ (according to MC)
- SM background almost completely suppressed!

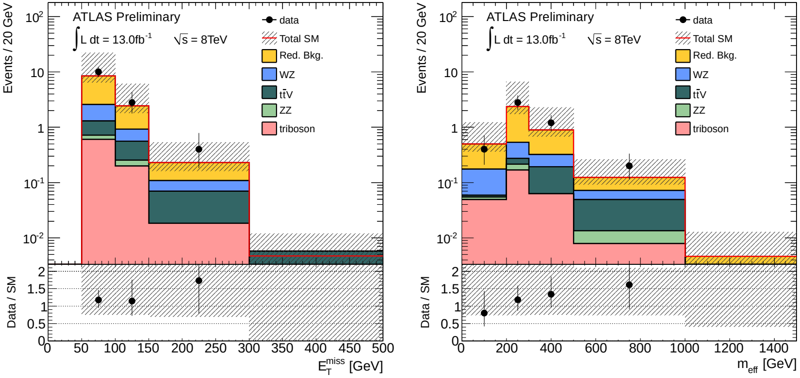
Define **Validation Regions** enriched with certain backgrounds to validate our description

- Test background modelling for the different contributions
- can be checked before looking at signal regions, keeping the analysis 'blinded'

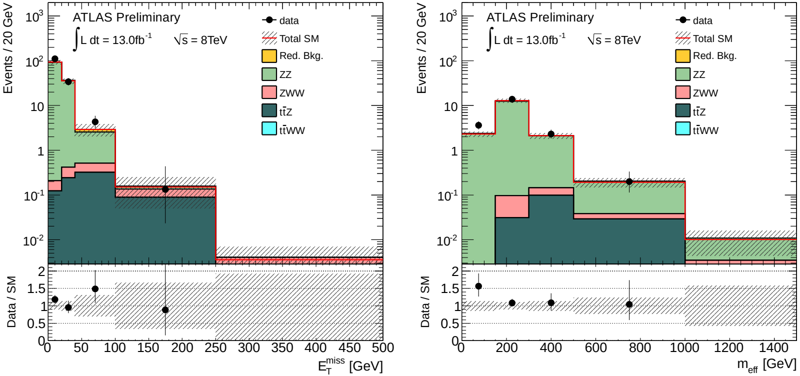
Name	Selection
VR1-3LTop	3 signal leptons, no SFOS pair, $E_T^{miss} > 50$ GeV
VR2-3LTop	3 signal leptons, no SFOS pair, $E_T^{miss} > 50$ GeV, *b*-jet request
VR4-3LZ	3 signal leptons, *Z* request, $30 < E_T^{miss} < 50$ GeV
VR6-4LnoZ	4 signal leptons, *Z* veto, $E_T^{miss} < 50$ GeV, $m_{eff} < 300$ GeV
VR8-4LZZ	4 signal leptons, *Z* request



top validation regions - 3 signal leptons, no same-flavour opposite-charge pair, high $E_{\mathrm{T}}^{\mathrm{miss}}$.
$E_{\mathrm{T}}^{\mathrm{miss}}$ left, m_eff right



ZZ validation region - 4 signal leptons, Z request



Observed events on Data

- Data in agreement with background expectation

$\rightarrow$ confidence in our understanding of backgrounds

$\rightarrow$ but no signs of RPV SUSY!

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Data	1	2
p0-value (σ)	0.14 (1.1)	0.31 (0.5)

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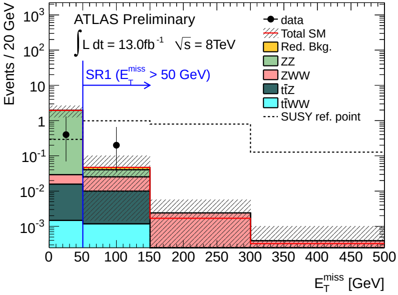
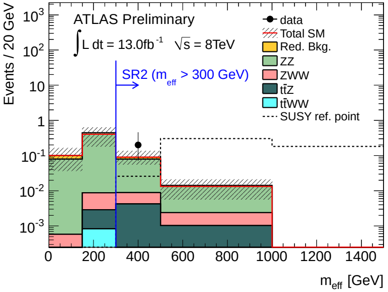
Distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$(left) and m_{eff}(right) in agreement with SM background



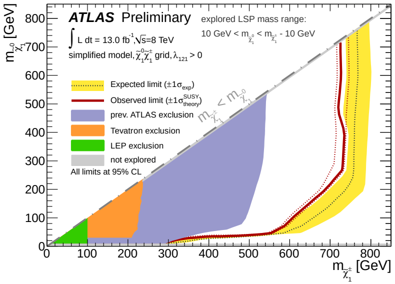


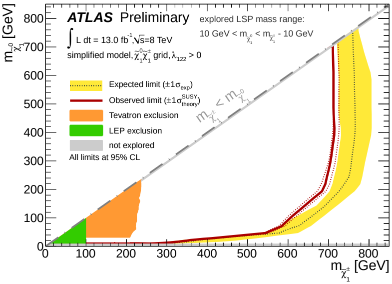
2012 Exclusion Limits - Wino grids

- test expectations for the points in a grid against the observation
- exclude grid points at 95% Confidence level

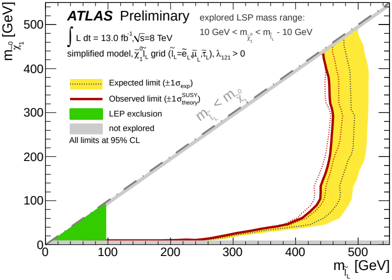
→ 2D exclusion contours

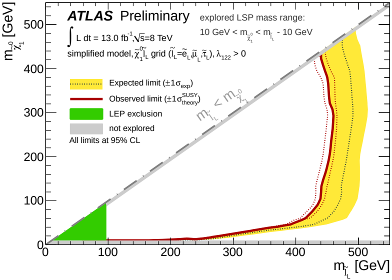
- Exclude Wino masses up to 700 GeV
- results comparable between λ_{121}(left) and λ_{122}(right)





- Exclude Slepton masses up to 450 GeV
- results again comparable between λ_{121}(left) and λ_{122}(right)

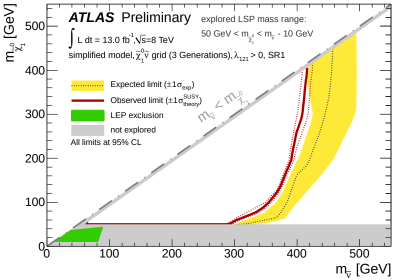


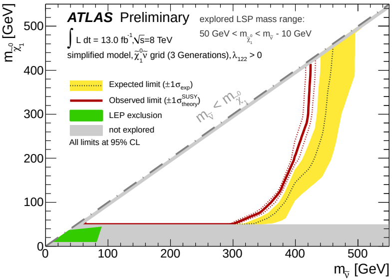


- Sneutrinos: Very pronounced loss of efficiency at low LSP masses

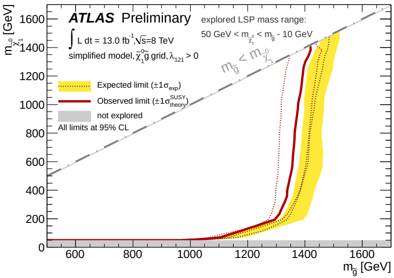
→ no cascade leptons, rely completely on LSP decay

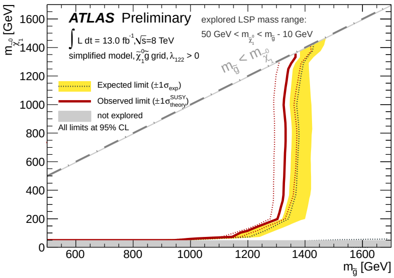
- to be improved for Moriond
- Analysis restricted to $m_{LSP} > 50\ \mathrm{GeV}$,
- exclude Sneutrino masses up to 400 GeV





- Analysis restricted to $m_{LSP} > 50$ GeV
- high production cross-sections due to QCD couplings allow for strong exclusions
- exclude Gluino masses up to 1.3 TeV

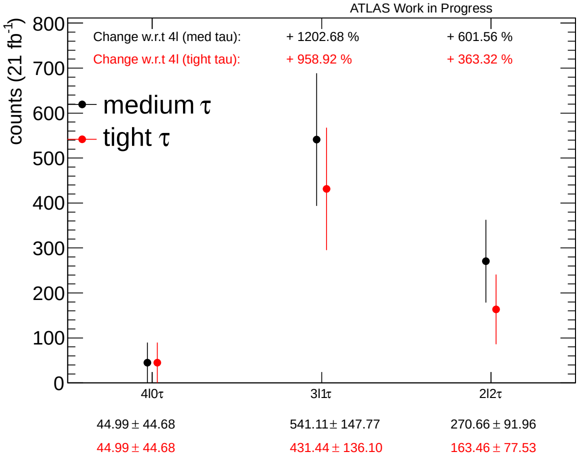




Outlook: Inclusion of semileptonic of τ decays

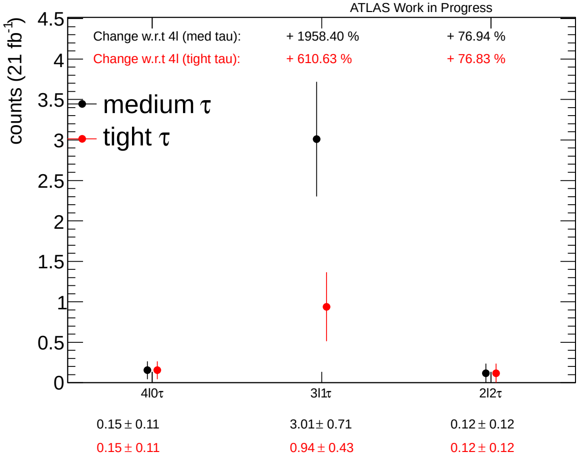
- 7 out of 9 allowed leptonic RPV parameters lead to τ in final states
- currently, weak sensitivity - we only pick up the leptonic decays

$\rightarrow$ next step for the analysis: inclusion of τ jets



Outlook: Inclusion of semileptonic of τ decays

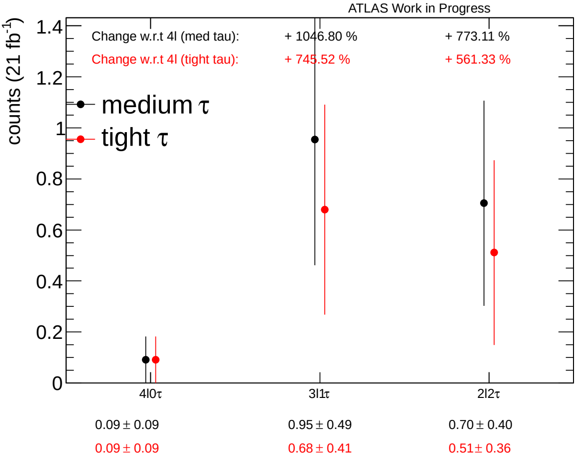
- challenging: want to keep a low background level



- with τ, will be able to cover the entire range of leptonic RPV with short-lived signatures

$\rightarrow$ fit into evolving systematic scan of RPV SUSY at ATLAS

- first results: Moriond 2013



Conclusions

- RPV SUSY may yield striking multilepton signatures
- ATLAS search performed using $\int Ldt = 13\text{fb}^{-1}$ of data at $\sqrt{s} = 8$ TeV
- interpretation in the scope of simplified models

$\rightarrow$ publication of detailed results allow for easy reinterpretation by theoreticians

- no signs of SUSY so far, we keep looking...

Thank you for your attention!

Backup

Background estimation - weighting method

Use lepton quality to estimate the background in the SR:

- define the **Fake Ratio** F for a fake lepton:

$$F = \frac{P(\text{reco as 'signal lepton'})}{P(\text{reco as 'loose lepton'})}$$

- then we can estimate the number of events with one or two fakes:

$$N_{red} = \left(N_{data}(\text{3Signal1Loose}) - N_{MC}^{irred}\cdot(\text{3Signal1Loose})\right)\cdot F$$
$$- \left(N_{data}(\text{2Signal2Loose}) - N_{MC}^{irred}\cdot(\text{2Signal2Loose})\right)\cdot F_1 \cdot F_2$$

- The fake ratio depends on
  - fake type (conversion / jet)
  - production process (top / boson)
  - signal region (SR1 / SR2)

Background estimation - fake ratio determination

Reminder - Fake categories

- Types: conversion / jet - use index i
- Processes: top / boson - use index j

Use a weighted average:

- introduce scale factors $sf(i)$ for each fake type i to relate fake ratios in data and MC, measured in a control region:

$$sf(i) = \frac{F^{Data}(i)}{F^{MC}(i)}$$

→ assume constant between regions and processes

- define fake fraction $R(i,j)$ as the fraction of fakes in a given region with type i and process category j from MC
- Then, we can average over the individual fake ratios $F(i,j)$ for each fake type i and process j:

$$F = \sum_{i,j} sf(i) R(i,j) F(i,j)$$

Object selection

Leptons above $p_T > 10$ GeV

- Medium++ electrons within $|\eta| < 2.47$
- STACO loose muons within $|\eta| < 2.4$

AntiKt4 **jets** above $p_T > 20$ GeV

- 2011: AntiKt4TopoEMJets within $|\eta| < 4.9$
- 2012: AntiKt4LCTopoJets within $|\eta| < 4.5$

Overlap removal between identified objects:

- Discard softer electron if $\Delta R(e,e) < 0.1$
- Discard jet if $\Delta R(e,j) < 0.2$
- Discard electron if $\Delta R(j,e) < 0.4$
- Discard muon if $\Delta R(j,\mu) < 0.4$
- Discard electron and muon if $\Delta R(e,\mu) < 0.1$
- Discard low mass SFOS pairs with $m_{\ell\ell} < 12$ GeV

Event selection

separate **signal** leptons and **loose** leptons

	2011	2012
Signal μ	$p_T^{cone20} > 1.6$ GeV	$p_T^{cone30} > 0.11 \cdot p_T$ $\left\lvert \frac{d_0}{\sigma(d_0)} \right\rvert < 3$ $\lvert z_0 sin(\theta) \rvert < 1mm$
Loose μ	fail any cut	
Signal e	$p_T^{cone20} > 0.1 p_T$ Tight++	$p_T^{cone30} > 0.16 \cdot p_T$ $E_T^{cone30} > 0.18 \cdot p_T$ $\left\lvert \frac{d_0}{\sigma(d_0)} \right\rvert < 5$ $\lvert z_0 sin(\theta) \rvert < 0.4mm$ Tight++
Loose e	fail any cut	

- 2012 isolation includes 'custom' SUSY 2nd order pileup correction
- leptons passing all cuts are regarded as signal
- all other leptons are labeled as loose.

Trigger

- 2011: unprescaled single- and dilepton triggers, apply trigger efficiencies on MC
- 2012: 'OR' of unprescaled dilepton triggers, use MC trigger simulation + systematic