SUSY searches in multi-lepton final states

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On behalf of the ATLAS collaboration

Les Rencontres de Physique de la Valle d'Aoste

ATLAS EXPERIMENT

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Introduction

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- Present two SUSY searches with multiple (≥ 3) leptons ($\ell = e/\mu$)
  - $=3$ leptons: Gaugino production
  - ≥ 4 leptons: R-parity violating SUSY
- 2012 ATLAS data ($\sqrt{s} = 8$ TeV, 13 fb^{-1})
- Similar backgrounds $\rightarrow$ similar background estimation/analysis strategy

3 leptons

Search for weak gaugino production
ATLAS-CONF-2012-154

≥ 4 **leptons**

Search for R-parity violating SUSY
ATLAS-CONF-2012-153

Gaugino searches: motivation

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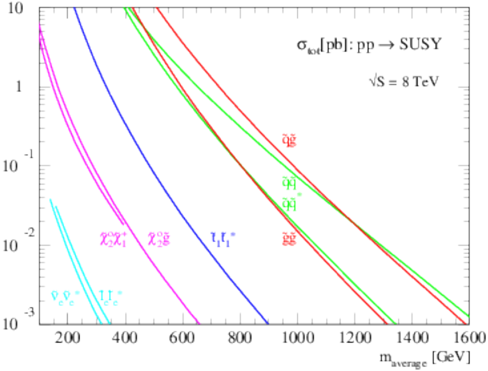
- Gauginos = linear combination of higgsinos, winos and binos
  - Charginos ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$) or neutralinos ($\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$)
- Limits on coloured SUSY particle ($\tilde{q}$, $\tilde{g}$) masses **much higher** than on uncoloured SUSY particles (sleptons, gauginos)

- Weak production of gauginos and sleptons could dominate at LHC
- Search for events with multiple leptons, missing energy and few jets



Simplified models

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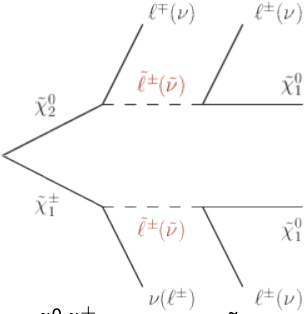
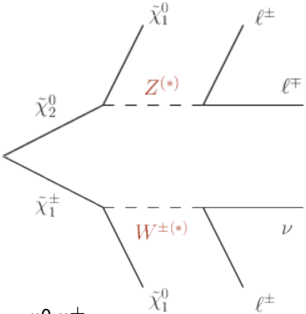
- Simulate a single process/diagram
- Simplified phenomenology (set most particle masses to > 1 TeV: effective theory)
- Reasonable assumptions about branching ratios
- Can translate into realistic model results
- Used for all results shown here

$$qq' \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow 3\ell + \not{E}_T$$



1) $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ decay via $\tilde{\ell}/\tilde{\nu}$



2) $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ decay via W/Z

- Simplified models **1** and **2** have different kinematics
- Distinct background compositions
- Different signal regions required

3 lepton signal regions (SRs)

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Selection	SR1a	SR1b	SR2
Targeted $\tilde{\chi}_2^0$ decay	$\tilde{l}^{(*)}$ or Z^*		on-shell Z
$Z \to \ell\ell$ candidate[1]	veto		requirement
Number of b-jets	0		any
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 75 GeV		> 120 GeV
m_{T}	any	> 110 GeV	> 110 GeV
p_{T} of leptons	> 10 GeV	> 30 GeV	> 10 GeV

- Different signal regions target distinct $\tilde{\chi}_2^0$ decays
- SR1a/b vetoes $Z \to \ell\ell$ production
- SR1b = SR1a + additional selection for large mass splittings between sparticles
- SR2 targets $Z \to \ell\ell$ production

[1] Z candidate: $m_{\ell\ell}$ within 10 GeV of m_Z

3 lepton analysis background estimation

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Matrix method

- Data made up of "**real**" (**R**) leptons (Z/γ^*, SUSY decays) and "**fake**" (**F**) leptons (conversions, light and heavy flavour decays): $N(R, F)$
- Only observe "**tight**" (**T**: high efficiency, low purity) and "**loose**" (**L**: low efficiency, high purity) leptons: $N(T, L)$

$$N(L, T) = \mathbf{M} \quad N(R, F)$$
$$\rightarrow N(R, F) = \mathbf{M}^{-1} N(T, L)$$

- **M** = matrix of lepton efficiencies and mis-identification rates
- Control regions used to measure terms in **M**

3 lepton analysis background estimation

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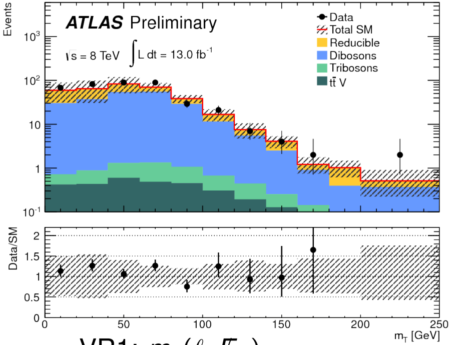
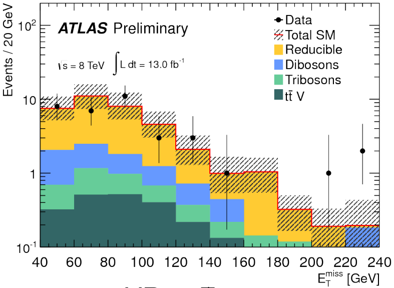
- Irreducible backgrounds = ≥ 3 "**real**" leptons $\rightarrow$ MC prediction
- Reducible backgrounds = ≤ 2 "**real**" leptons $\rightarrow$ matrix method estimation

- *WZ* is largest irreducible background
  - Normalise to data in control region
- Background validation regions (VRs):
  - VR1: $Z^* + X, WZ^*$
  - VR2: $t\bar{t}$/reducible
  - VR3: WZ



VR1: $m_{\mathrm{T}}(\ell, \not{E}_T)$



VR2: $\not{E}_T$

3 lepton analysis results

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- $\sqrt{s} = 8$ TeV, 13 fb^{-1}
- Visible cross section limit = $\sigma \times$ acceptance $\times$ efficiency at 95% CL

	SR1a	SR1b	SR2
$t\bar{t}$+V	0.62 ± 0.28	0.13 ± 0.07	0.9 ± 0.4
triboson	3.0 ± 3.0	0.7 ± 0.7	0.34 ± 0.34
ZZ	2.0 ± 0.7	0.30 ± 0.23	0.10 ± 0.10
WZ (normalised)	34 ± 4	1.2 ± 0.6	4.7 ± 0.8
Reducible	10 ± 6	0.8 ± 0.4	$0.012^{+1.6}_{-0.012}$
Total expected events (stat. + syst. combined)	50 ± 8	3.1 ± 1.0	$6.1^{+2.0}_{-1.2}$
Observed number of events	48	4	4
Observed (expected) vis. cross section limit	1.3 (1.5) fb	0.5 (0.4) fb	0.4 (0.5) fb

- SR1a: 3 ℓ + $\not\!\!E_T > 75$ GeV + Z veto + b-jet veto
  - SR1b: SR1a + $m_T > 110$ GeV + $p_T^{\ell} > 30$ GeV
- SR2: 3 ℓ + $\not\!\!E_T > 110$ GeV + Z request + $m_T > 110$ GeV

3 lepton analysis results

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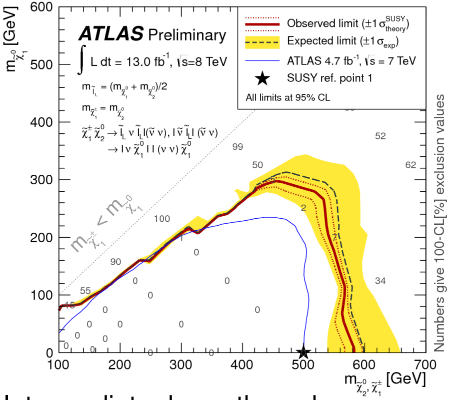
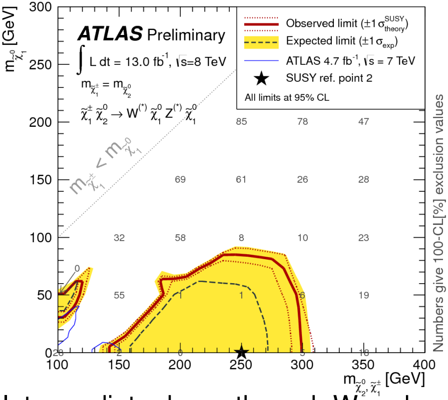
- Simplified models of chargino-neutralino ($\tilde{\chi}_2^0\tilde{\chi}_1^\pm$) production
- Other interpretations in backup



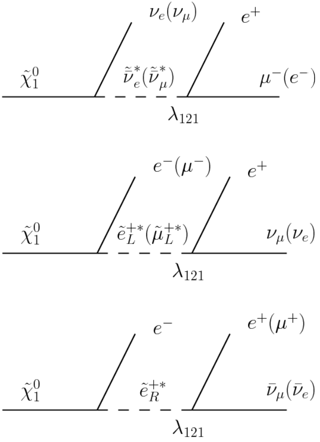
Intermediate decay through sleptons/sneutrinos



Intermediate decay through W and Z bosons

R-parity violation

- Most general formulation of SUSY has *B*- and/or *L*-violating couplings $\lambda_{ijk} \neq 0$
  - No stable LSP
- Here assume $\tilde{\chi}_1^0$ LSP with decays
  - $\tilde{\chi}_1^0 \rightarrow \nu_{i/j} \ell^{\pm}_{j/i} \ell^{\mp}_{k}$ at rate $\propto \lambda_{ijk}$



- Final states with multiple leptons and $\not{E}_T$
- Search for $\geq$ 4 leptons and one of
  - High $\not{E}_T$
  - High effective mass, m_{eff} ($m_{\text{eff}} = \not{E}_T + \sum(p_T^{\text{lepton}} + p_T^{\text{jet}})$)

4 lepton analysis background estimation

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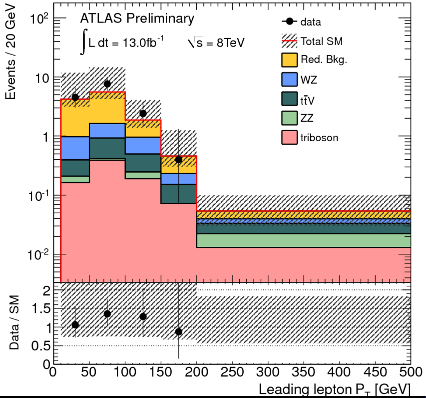
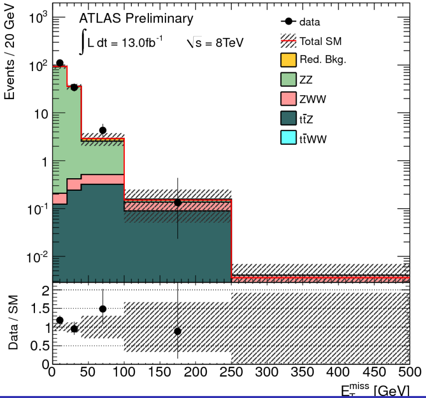
- Irreducible backgrounds = $\geq$ 4 "**real**" leptons $\rightarrow$ MC prediction
- Reducible backgrounds = $\leq$ 3 "**real**" leptons $\rightarrow$ simplified matrix method
- Background modelling checked in 4 validation regions (VRs)





4 lepton analysis results

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- $\sqrt{s} = 8$ TeV, 13 fb^{-1}
- Select 4 ℓ + no Z candidate[2] and then
  - Signal Region 1: $E\!\!\!/_T > 50$ GeV
  - Signal Region 2: $m_{\text{eff}} > 300$ GeV

	SR1	SR2
ZZ	$0.07^{+0.18}_{-0.08}$	$0.99^{+0.66}_{-0.63}$
triboson	$0.10^{+0.01}_{-0.01}$	$0.08^{+0.01}_{-0.01}$
$t\bar{t}Z$	$0.04^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$
$t\bar{t}WW$	$0.01^{+0.01}_{-0.00}$	$0.00^{+0.00}_{-0.00}$
Reducible	$-0.01^{+0.14}_{-0.19}$	$0.09^{+0.17}_{-0.17}$
Total expected events (stat. + syst. combined)	$0.25^{+0.29}_{-0.25}$	$1.2^{+0.5}_{-0.4}$
Observed number of events	1	2
Observed (expected) vis. cross section limit	$<$ 0.34 (0.28) fb	$<$ 0.28 (0.38) fb

- Visible cross section limit = σ × acceptance × efficiency at 95% CL

[2] all lepton invariant mass combinations ($m_{\ell\ell}, m_{3\ell}, m_{4\ell}$) 10 GeV from m_Z

4 lepton analysis results

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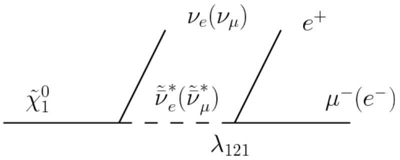
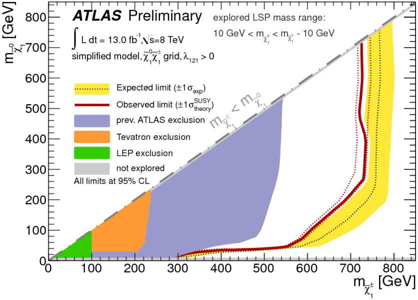
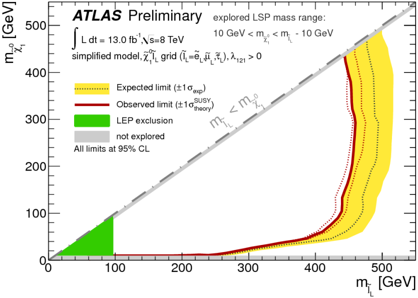
- 4 RPV simplified models with $\lambda_{121} \neq 0$
- Different NLSP decays (assume 100% branching ratio)
  - Wino: $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$
  - Left-handed slepton: $\tilde{\ell}_L \to \ell \tilde{\chi}_1^0$
  - Sneutrino: $\tilde{\nu}_\ell \to \nu_\ell \tilde{\chi}_1^0$
  - Gluino: $\tilde{g} \to q\bar{q}' \tilde{\chi}_1^0$
- $\lambda_{122} \neq 0$ in backup



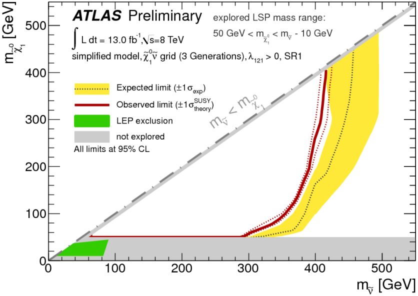
Example $\tilde{\chi}_1^0$ decay



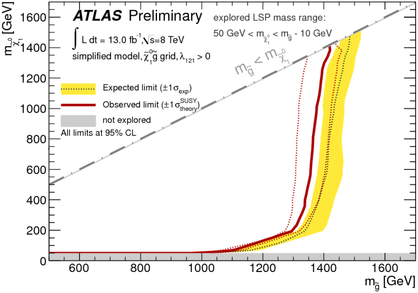
RPV Wino NLSP ($\lambda_{121} \neq 0$)



RPV L-slepton NLSP ($\lambda_{121} \neq 0$)



RPV Sneutrino NLSP ($\lambda_{121} \neq 0$)



RPV Gluino NLSP ($\lambda_{121} \neq 0$)

Conclusions

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- 13.0 fb^{-1} of 8 TeV *pp* data analysed
- Two analyses (3 and $\geq$ 4 lepton final states)
- No significant excesses observed
- Limits set in a variety of different SUSY scenarios
- Analyses of full 2012 dataset underway now!

More information:

3 leptons

Search for weak gaugino production
ATLAS-CONF-2012-154

$\geq$ 4 **leptons**

Search for R-parity violating SUSY
ATLAS-CONF-2012-153

Backup

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- Supersymmetry
- m_{eff}, m_T
- Background estimation details
  - Matrix method (3 lepton)
  - Weighting method (4 lepton)
- Extra interpretations
- Photo credit:
  - Aosta valley - www.stevehuffphoto.com
  - Spherical cow - Ingrid Kallick, Wikipedia

Supersymmetry

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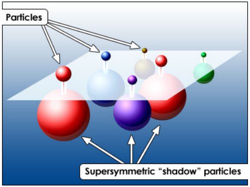
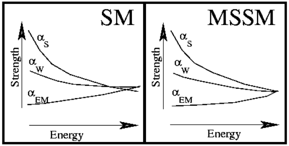
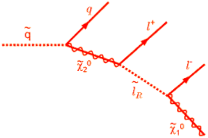
- Symmetry between fermions and bosons
  - Entirely new spectrum of “superpartners”
  - Solution to hierarchy problem
  - Dark matter candidate (lightest supersymmetric particle (LSP) stable, weakly interacting)
  - Unification of gauge couplings at GUT scale



- Phenomenology
  - “Cascade” decays $\rightarrow$ multiple jets and leptons
  - Significant missing energy from LSP





m_{eff}, m_T

Transverse mass of 4-vectors L_1, L_2

- $m_T = 2\sqrt{p_T^{L_1} p_T^{L_2}(1 - \cos\phi(L_1, L_2)}$
  - Here, always referring to $m_T(\ell, \not{E}_T)$

Effective mass of an event

- $m_{\text{eff}} = \not{E}_T + \sum(p_T^{\text{lepton}} + p_T^{\text{jet}})$
- Jet p_T above 40 GeV, lepton p_T above 10 GeV
- Scalar sum

3 leptons: matrix method: extra details

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- Highest p_T lepton is real in 99% of cases (from MC)
- Always treating it as real reduces matrix dimension from 8×8 to 4×4
- Final matrix equation:

$$\begin{pmatrix} N_{TT} \\ N_{TL'} \\ N_{L'T} \\ N_{L'L'} \end{pmatrix} = \begin{pmatrix} \epsilon_1 \epsilon_2 & \epsilon_1 f_2 & f_1 \epsilon_2 & f_1 f_2 \\ \epsilon_1 (1-\epsilon_2) & \epsilon_1 (1-f_2) & f_1 (1-\epsilon_2) & f_1 (1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1) f_2 & (1-f_1)\epsilon_2 & (1-f_1) f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix} \cdot \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

4 leptons: weighting method: extra details

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- Total reducible background estimated by:

$$\begin{aligned} N_{\text{red}} &= [N_{\text{data}}(3\ell_T + \ell_L) - N_{\text{MCirr}}(3\ell_T + \ell_L)] \times F(\ell_L) \\ &- [N_{\text{data}}(2\ell_T + \ell_{L_1} + \ell_{L_2}) - N_{\text{MCirr}}(2\ell_T + \ell_{L_1} + \ell_{L_2})] \times F(\ell_{L_1}) \times F(\ell_{L_2}) \end{aligned}$$

- Definitions:
  - $N_{\text{data}}(3\ell_T + \ell_L)$: number of events in data with 3 tight leptons and 1 loose lepton
  - $N_{\text{MCirr}}(3\ell_T + \ell_L)$: number of events in MC with 3 tight leptons and 1 loose lepton
  - $F(\ell_L)$: “Fake factor” similar to usual definition of fake rate
- Use of loose leptons allows for higher statistics
- Contributions from events with > 2 fake leptons found to be negligible
- Similar to matrix method, but only using one linear equation

Phenomenological MSSM (pMSSM)

The pMSSM is a general framework for exploring SUSY parameter space

- Gluinos, squarks and left-handed sleptons set to have masses > 2 TeV
- Use $\tan\beta = 6 \rightarrow$: good branching ratios into all slepton types
- M_1, M_2 and μ define mixing of $\tilde{\chi}_i^{\pm}$ and $\tilde{\chi}_j^{0}$
- 2 lepton final state: mainly $\tilde{\ell}^{\pm}\tilde{\ell}^{\mp}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$
- 3 lepton final state: mainly $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ production

pMSSM $M_1 = 100$

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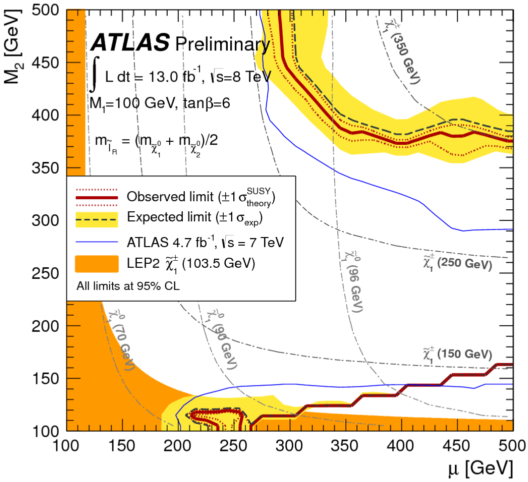

3 lepton pMSSM $M_1 = 100$ limit (blue lines from 2/3 lepton analysis combination)

pMSSM $M_1 = 140$

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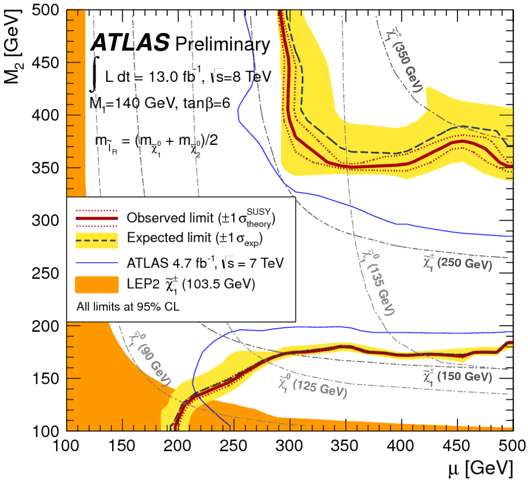
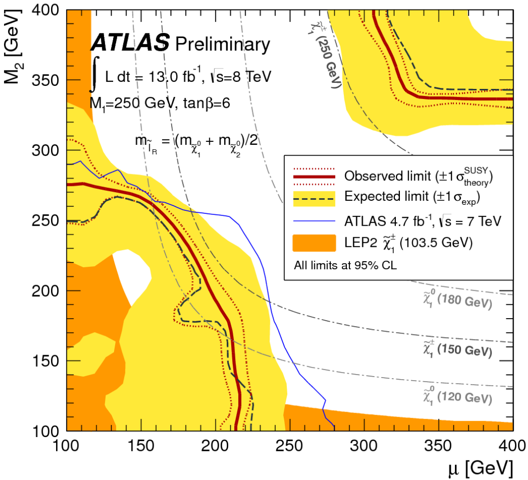


3 lepton pMSSM $M_1 = 140$ limit (blue lines from 2/3 lepton analysis combination)

pMSSM $M_1 = 250$



3 lepton pMSSM $M_1 = 250$ limit (blue lines from 2/3 lepton analysis combination)

4 lepton analysis results

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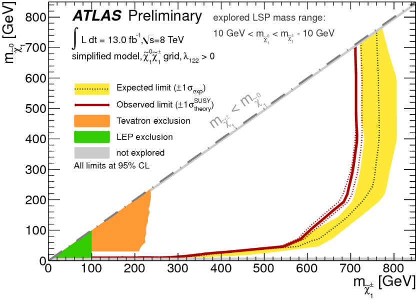
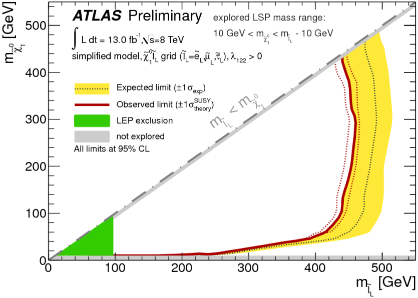
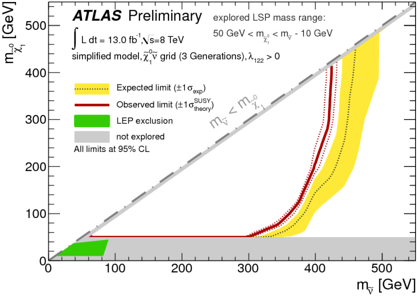
- Extra grids with $\lambda_{122} \neq 0$ instead of $\lambda_{121} \neq 0$ on next slide



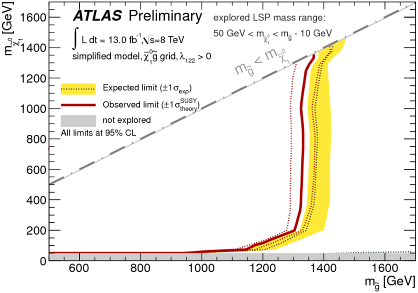
RPV Wino NLSP ($\lambda_{122} \neq 0$)



RPV L-slepton NLSP ($\lambda_{122} \neq 0$)



RPV Sneutrino NLSP ($\lambda_{122} \neq 0$)



RPV Gluino NLSP ($\lambda_{122} \neq 0$)