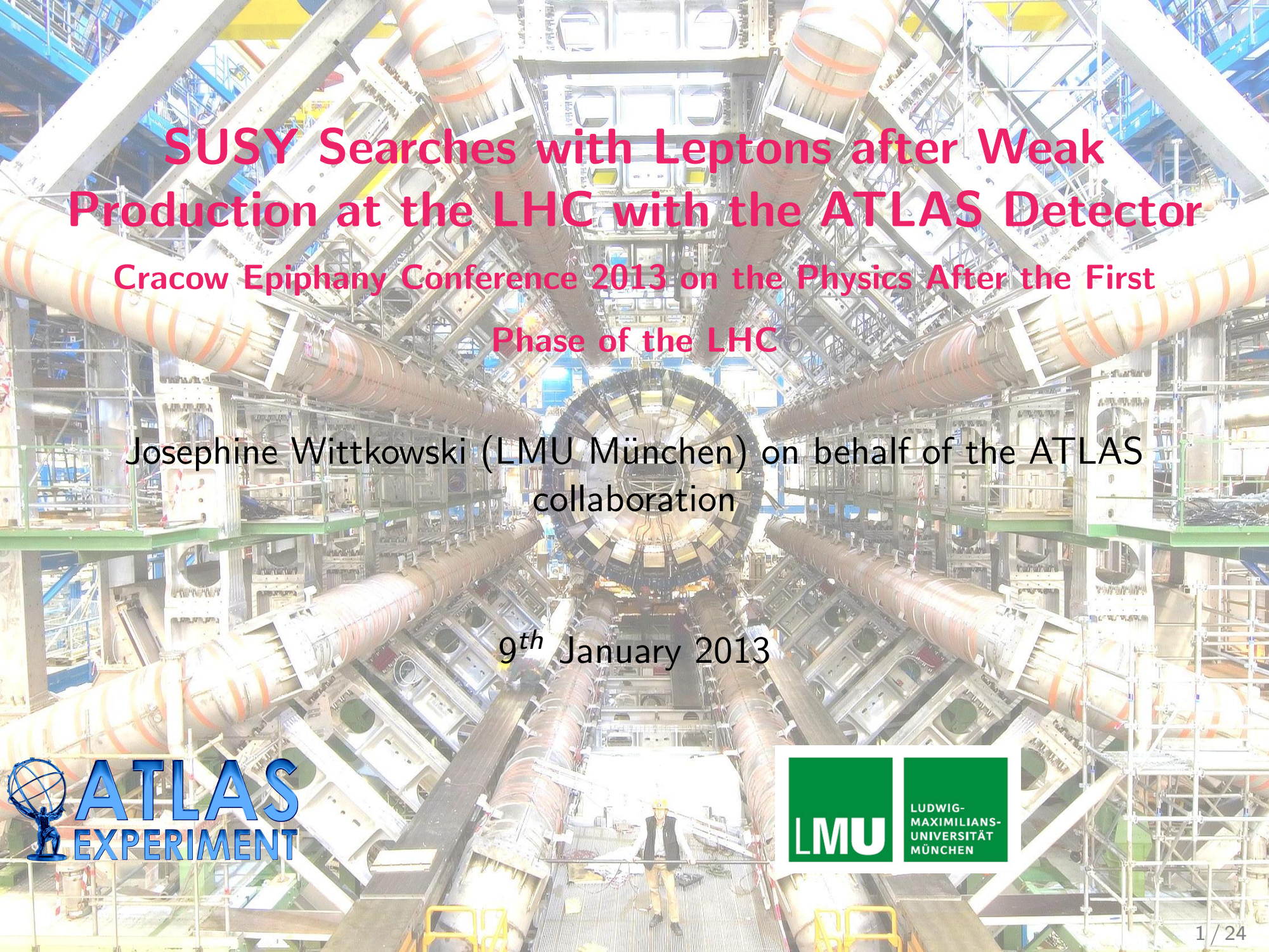


SUSY Searches with Leptons after Weak Production at the LHC with the ATLAS Detector

Cracow Epiphany Conference 2013 on the Physics After the First Phase of the LHC

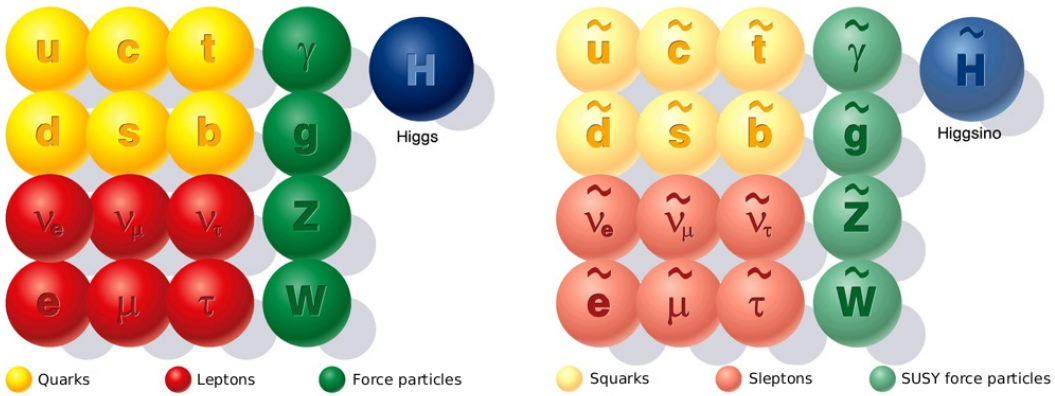
Josephine Wittkowski (LMU München) on behalf of the ATLAS collaboration

9^{th} January 2013

ATLAS EXPERIMENT

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Supersymmetry

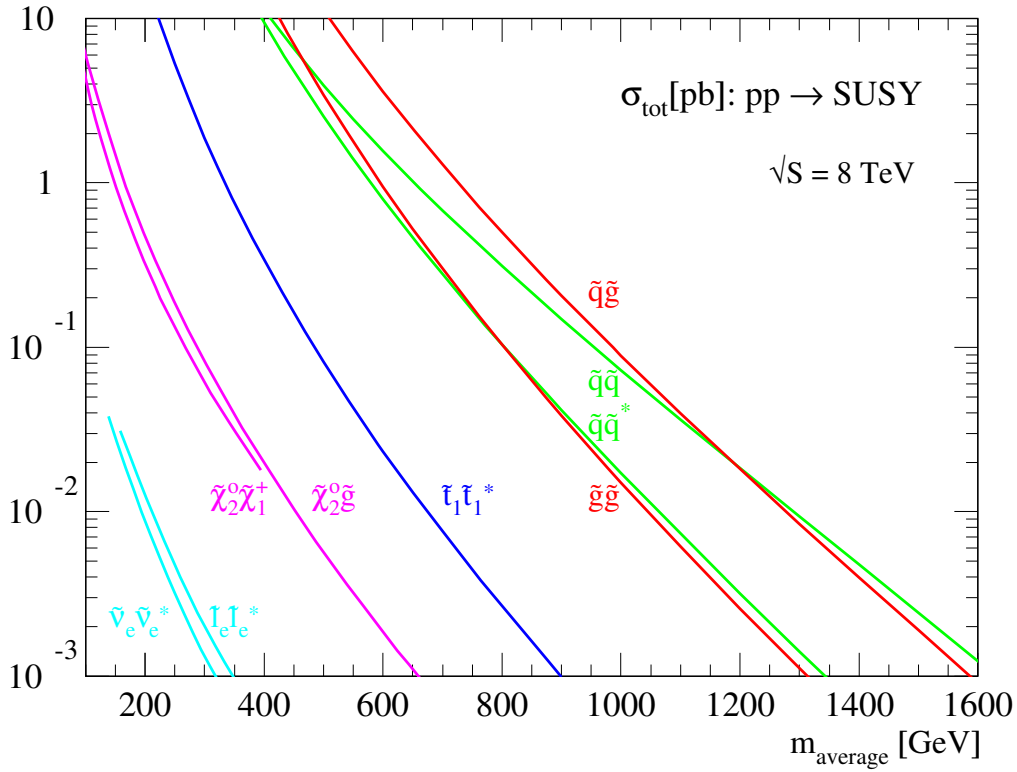


Every particle d.o.f. gets a superpartner d.o.f. with same quantum numbers but different spin.
fermions $\rightarrow$ bosons and v.v.

Supersymmetry extends the Standard Model:

- Provides a candidate for Dark Matter
- Solution for hierarchy problem and unification of the forces

Looking for SUSY @ LHC: Strong and Electroweak Production



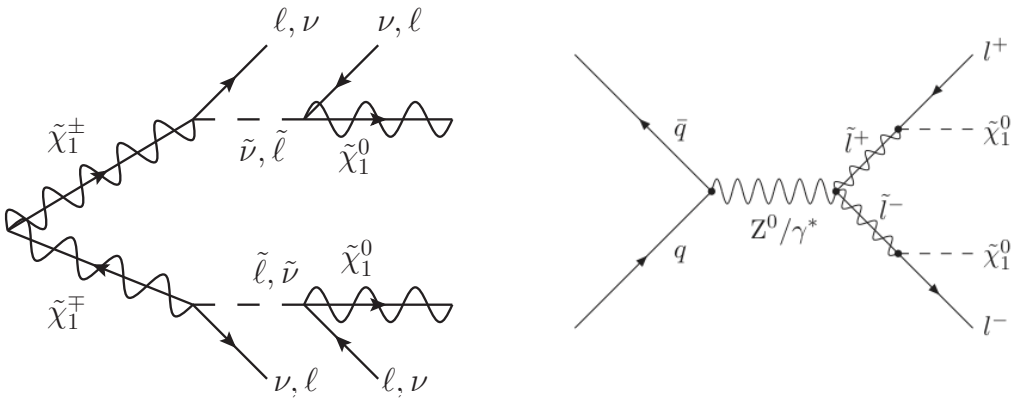
Naturalness prefers light mass neutralinos and charginos at $\mathcal{O}(100\,\text{GeV})$.

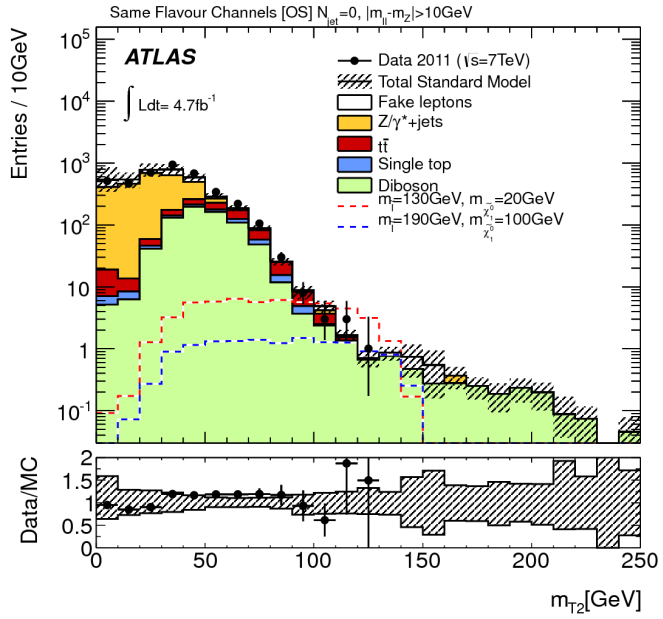
- **Strong production:** Gluino and squark pairs decay into final states with jets and high E_T^{miss} (and leptons)
- **Electroweak production:** Charginos, neutralinos and sleptons: decay into final states with multiple leptons and high E_T^{miss}

The analyses presented in this talk are **separated depending on the number of leptons** (electrons and muons) in the final state.

The methods used for background estimation are described in more detail e.g. in talk by Vu Anh Tuan ('SUSY searches in ATLAS')

2 Leptons, $\sqrt{s} = 7\,TeV$, $\int \mathcal{L}\,dt$ =4.7fb^{-1}, CERN-PH-EP-2012-216





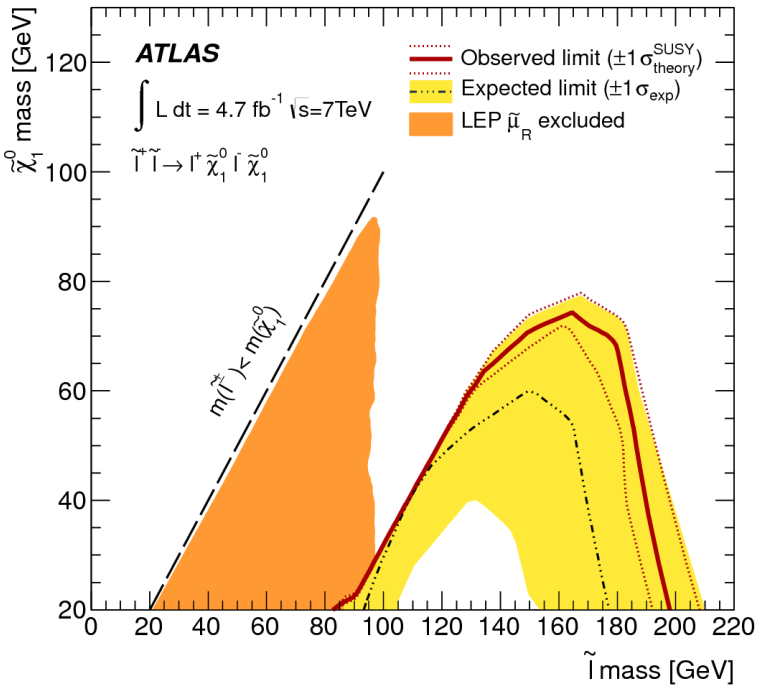
Four Signal Regions requiring exactly two leptons were designed.

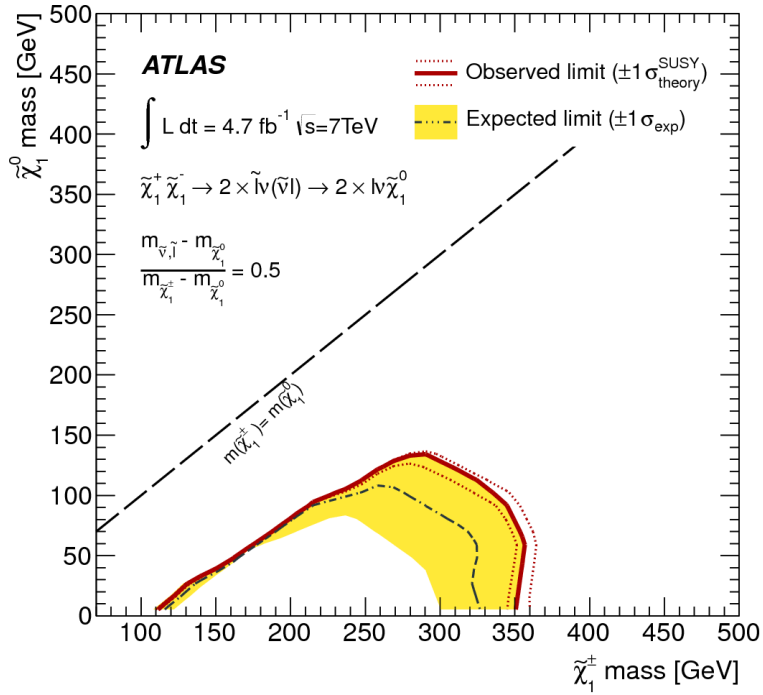
E.g. SR-m_{T2}. Sensitive to **sleptons and charginos**.

$p_T > 10\,\text{GeV}$ for leptons, $E_T^{miss,rel} > 40\,\text{GeV}$.

m_{T2}: for events with pair-produced identical particles. Based on transverse mass. Bound by $m_{\tilde{l}}$ or $m_{\tilde{\chi}_1^{\pm}}$.

$m_{T2} > 90\,\text{GeV}$ suppresses $t\bar{t}$ and diboson background.





No significant excess is observed in data.

- Slepton pair production in Simplified Model. SR m_{T2} used (most sensitive for all models).
- Common $m_{\tilde{e}_L}$ and $m_{\tilde{\mu}_L}$ between 85 and 195 GeV excluded.

- $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production in Simplified Model.
- Chargino masses between 110 and 340 GeV excluded at 95 % CL

3 Leptons, $\sqrt{s} = 8\,TeV$, $\int \mathcal{L}\,dt$ =13.0fb^{-1}, ATLAS-CONF-2012-154

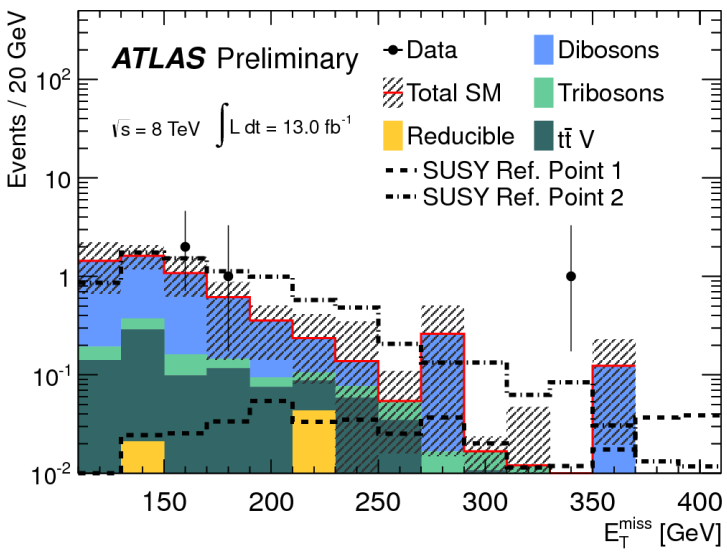
Three Signal Regions were designed, requiring exactly three leptons.

SR1a and SR1b: Neutralino decays **via intermediate sleptons**

- Veto events with Z candidates, E_T^{miss} >75 GeV, no b-tagged jets (SR1a).
- Additionally: p_T^l >30 GeV, m_T >110 GeV (SR1b).

SR2: Neutralino decays **via** Z^0

- Select events with a Z candidate.
- m_T >110 GeV to suppress WZ background.
- E_T^{miss} > 120 GeV



Plot: SR2

SUSY reference point 1:

$m_{\tilde{\chi}_1^\pm} = 500$ GeV, $m_{\tilde{\chi}_2^0} = 500$ GeV,

$m_{\tilde{l}_L} = 250$ GeV, $m_{\tilde{\chi}_1^0} = 0$ GeV.

SUSY reference point 2:

$m_{\tilde{\chi}_1^\pm} = 250$ GeV, $m_{\tilde{\chi}_2^0} = 250$ GeV,

$m_{\tilde{\chi}_1^0} = 0$ GeV.

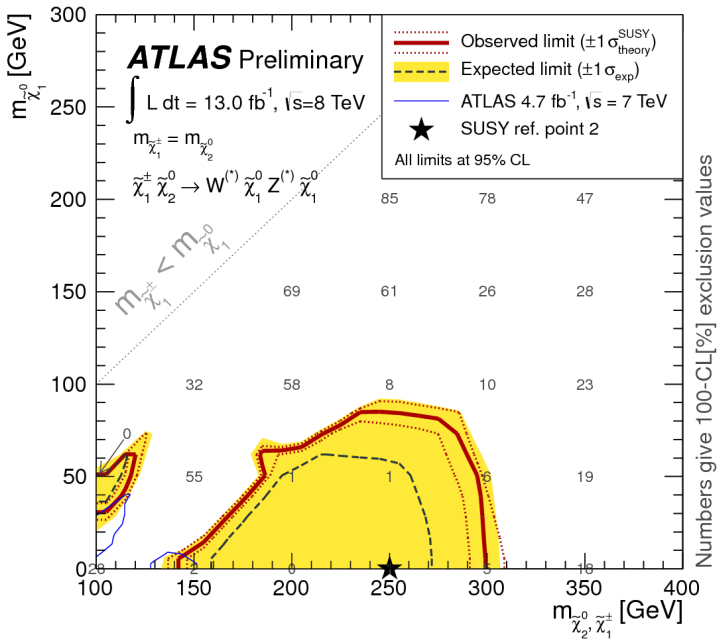
3 Leptons, $\sqrt{s} = 8\,TeV$, $\int \mathcal{L}\,dt$ =13.0fb^{-1}

Largest irreducible background: WZ

Background is fit to data in CR: 3 leptons w/ $p_T > 20$ GeV, 1 SFOS lepton pair, Z candidate, $50 < E_T^{miss} < 75$ GeV, b-veto, $50 < m_T < 110$ GeV.

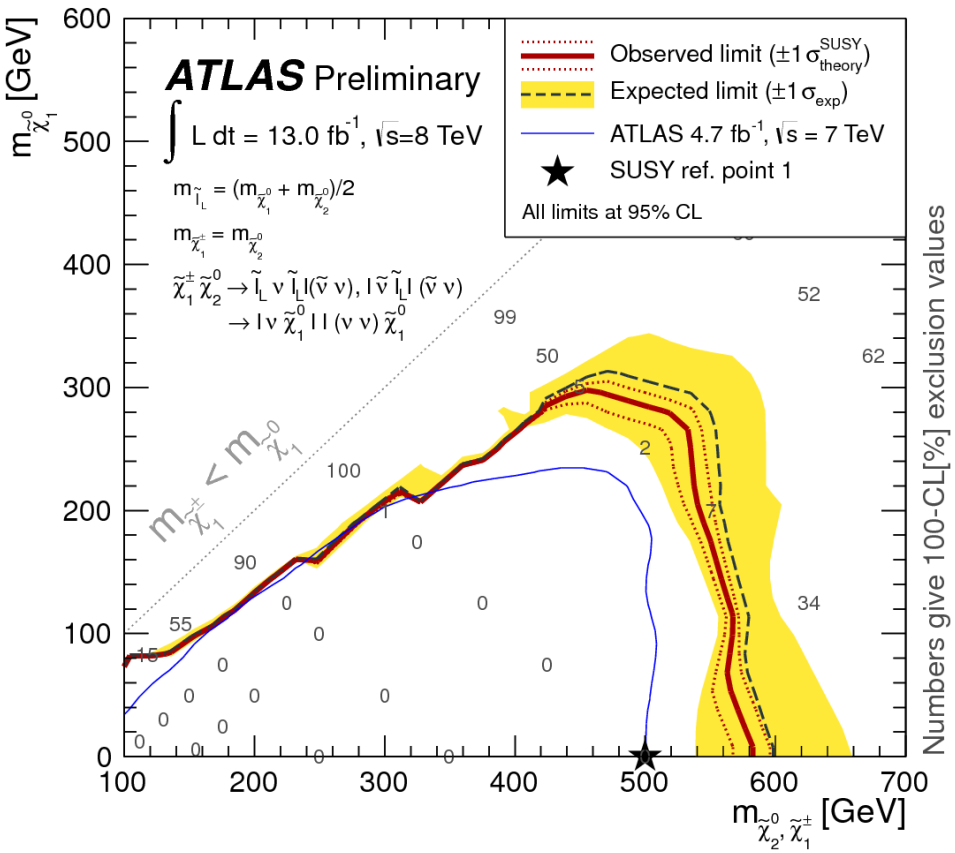
No significant excess is observed in data.

Simplified Model: neutralino decays via gauge bosons



- SR2 responsible for larger exclusion area.
- Z-depleted SR1a wo/ additional m_T requirement best sensitive for small mass differences between the lightest neutralinos.

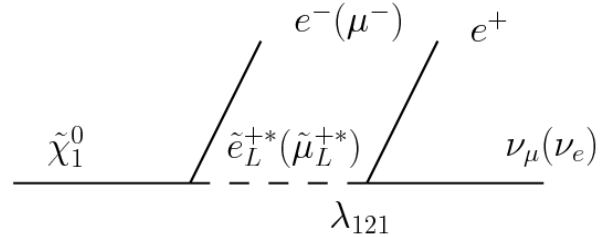
3 Leptons, $\sqrt{s} = 8\,TeV$, $\int \mathcal{L}\,dt$ =13.0fb^{-1}



- Simplified Model with intermediate slepton decay
- Z-depleted SR1b with additional m_T requirement is best sensitive.
- degenerate chargino and $\tilde{\chi}_2^0$ masses up to 580 GeV excluded for large mass differences from the $\tilde{\chi}_1^0$

Violating the R-parity

- **R-p**arity $P_R = (-1)^{2s+3B+L}$ may be **v**iolated: RPV
- corresponding superpotential terms $W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2$ (new Yukawa couplings λ_{ijk}, λ'_{ijk}, λ''_{ijk})
- **Proton decay is prevented** under special assumptions concerning the RPV couplings ($\lambda_{121} \neq 0$ or $\lambda_{122} \neq 0$).
- Lightest Supersymmetric Particle **LSP may be unstable**
- E.g. here LSP promptly decaying $\tilde{\chi}_1^0 \to \nu l^{\pm} l^{\mp}$ $\to$ **high lepton multiplicities, low** E_T^{miss}.



Two Signal Regions with $\geq$4 leptons. Veto events w/ Z-candidate.

SR (1): $E_T^{miss} > 50\,\text{GeV}$

SR (2): Effective mass $m_{eff} > 300\,\text{GeV}$

$m_{eff} = E_T^{miss} + \sum_\mu p_T^\mu + \sum_e E_T^e + \sum_j E_T^j$

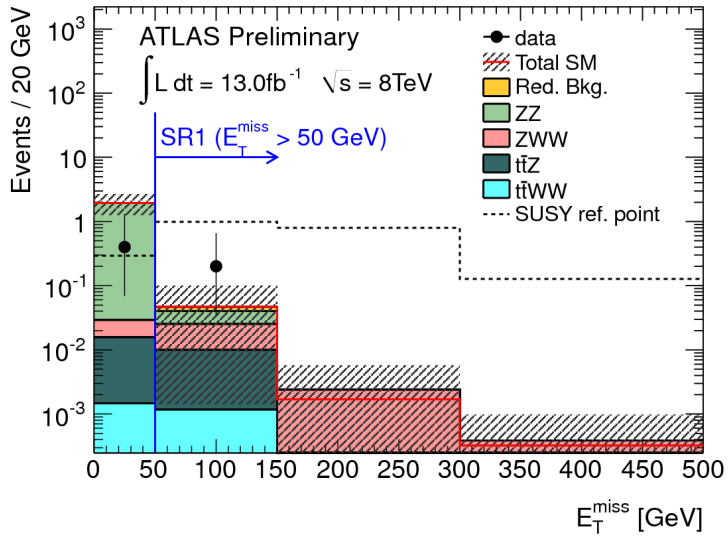
$\geq$4 Leptons, $\sqrt{s} = 8\,TeV$, $\int \mathcal{L}\,dt$ =13.0fb^{-1}

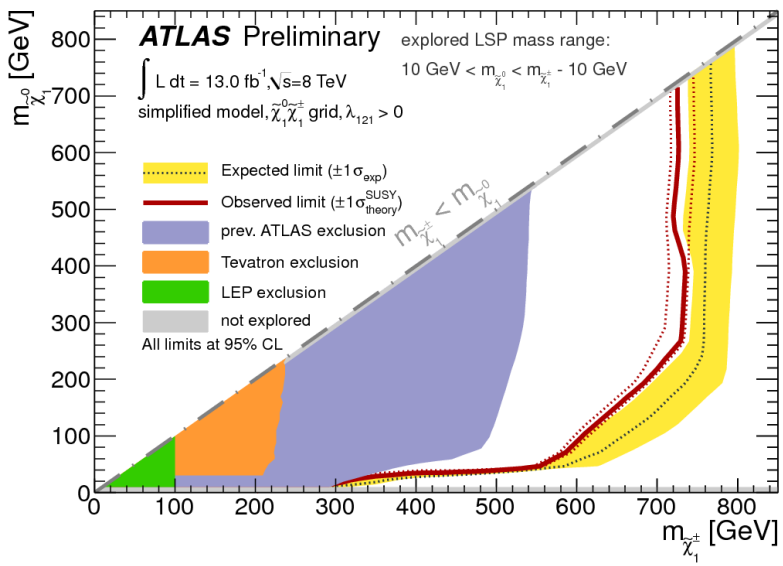
ATLAS-CONF-2012-153

No significant excess is observed in data.

Six RPV Simplified Models for electroweak produced SUSY.
E.g. NLSP is a wino-like $\tilde{\chi}_1^{\pm}$

$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$ ($W^{\pm}$ may be virtual). More sensitive: SR1.
Chargino masses up to 710 GeV excluded.
(Also considered but not shown: $\tilde{l}_L \to l\tilde{\chi}_1^0$ and $\tilde{\nu}_l \to \nu_l\tilde{\chi}_1^0$)





Summary & Outlook

- Several analyses looking for SUSY with leptons were presented.
- Naturalness may lead to the existence of light charginos and neutralinos
- Searches are **sensitive to electroweak production.**
- Limits on slepton, neutralino and chargino masses have been derived using simplified models.
- In **R-parity conserving models**, slepton masses between 85 and 195 GeV and chargino masses up to 580 GeV can be excluded for specific models.
- In **RPV models**, slepton masses until 430 GeV and chargino masses until 710 GeV can be excluded under special assumptions.

Spare Slides

Supersymmetric Particles

- Squarks $\tilde{q}$, sleptons $\tilde{l}$ and sneutrinos $\tilde{\nu}$:
  superpartners to quarks, leptons and neutrinos.
- Higgs sector: charged $\tilde{H}^{\pm}$, CP-even and neutral h^0, H^0 ($m_h \leq m_H$), CP-odd A^0
- Charginos $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$: physical states for mixing $\tilde{W}^{\pm}$ and $\tilde{H}_u^+$, $\tilde{H}_d^-$ (couple exclusively to up- resp. down-type quarks)
- Neutralinos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$: physical states for mixing $\tilde{B}$, $\tilde{W}^0$ and $\tilde{H}_u^0$, $\tilde{H}_d^0$

masses of the sparticles should be equal to masses of their SM superpartners. But: no sparticles observed $\rightarrow$ SUSY is a broken symmetry

2 Leptons in Final State:

SR-m_{T2}					
	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	all	SF
Z+X	$3.2 \pm 1.1 \pm 1.7$	$0.3 \pm 0.1 \pm 0.2$	$3.6 \pm 1.3 \pm 1.7$	$7.1 \pm 1.7 \pm 2.1$	$6.8 \pm 1.7 \pm 2.1$
WW	$2.3 \pm 0.3 \pm 0.4$	$4.8 \pm 0.4 \pm 0.7$	$3.5 \pm 0.3 \pm 0.5$	$10.6 \pm 0.6 \pm 1.5$	$5.8 \pm 0.4 \pm 0.9$
$t\bar{t}$, single top	$2.6 \pm 1.2 \pm 1.3$	$6.2 \pm 1.6 \pm 2.9$	$4.1 \pm 1.3 \pm 1.6$	$12.9 \pm 2.4 \pm 4.6$	$6.8 \pm 1.8 \pm 2.3$
Fake leptons	$1.0 \pm 0.6 \pm 0.6$	$1.1 \pm 0.6 \pm 0.8$	$-0.02 \pm 0.01 \pm 0.05$	$2.2 \pm 0.9 \pm 1.4$	$1.0 \pm 0.6 \pm 0.6$
Total	$9.2 \pm 1.8 \pm 2.5$	$12.4 \pm 1.7 \pm 3.1$	$11.2 \pm 1.9 \pm 3.0$	$32.8 \pm 3.2 \pm 6.3$	$20.4 \pm 2.6 \pm 3.9$
Data	7	9	8	24	15
$\sigma_{\mathrm{vis}}^{\mathrm{obs(exp)}}$ (fb)	1.5 (1.8)	1.6 (2.0)	1.6 (1.9)	2.5 (3.3)	1.9 (2.5)

No significant excess is observed in data.

2 Leptons in Final State:

SR-	m_{T2}	OSjveto	SSjveto	2jets
charge	OS	OS	SS	OS
flavour	any	any		SF
$m_{\ell\ell}$	Z-veto	Z-veto	-	Z-veto
signal jets	$= 0$	$= 0$		≥ 2
signal b-jets	-	-		$= 0$
$E_{\mathrm{T}}^{\mathrm{miss,rel.}}$	> 40	> 100		> 50
other	$m_{T2} > 90$	-		m_{CT}-veto

Figure: Signal regions. OS (SS) denotes two opposite-sign (same-sign) signal leptons, of same (SF) or different (DF) flavour.

	top	WW	$Z + X$
$m_{\ell\ell}$	Z-veto	Z-veto	Z-window
signal jets	≥ 2	$=0$	$= 0, \geq 2, \geq 0$
signal b-jets	≥ 1	$=0$	$\geq 0, = 0, \geq 0$
$E_{\mathrm{T}}^{\mathrm{miss,rel.}}$	$> 100, 50, 40$	70–100	$> 100, 50, 40$
other	-	-	-, m_{CT}-veto, -

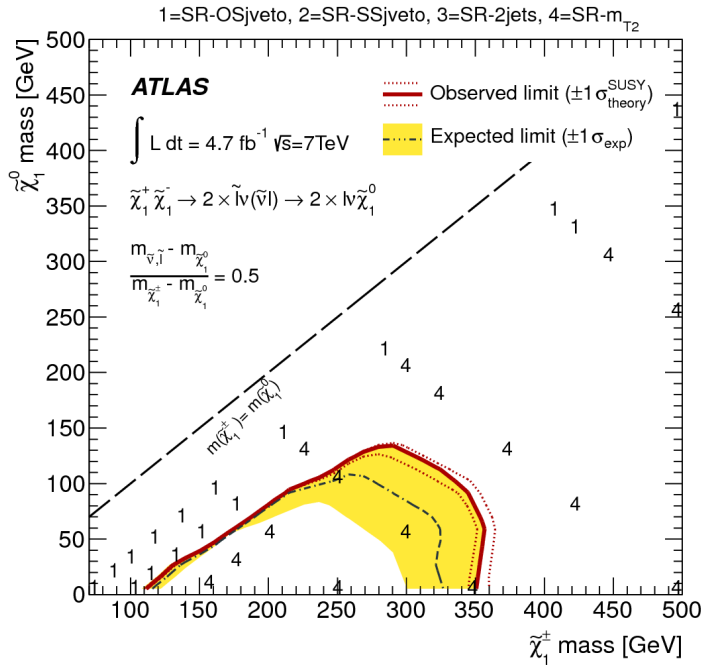
Figure: Requirements for entering each CR for top, W W and Z +X background estimation in the OS SR.

- transverse mass $m_T =$

$$\sqrt{2 \cdot E_T^{miss} p_T^l \cdot (1 - \cos \Delta\phi_{l, E_T^{miss}})}$$

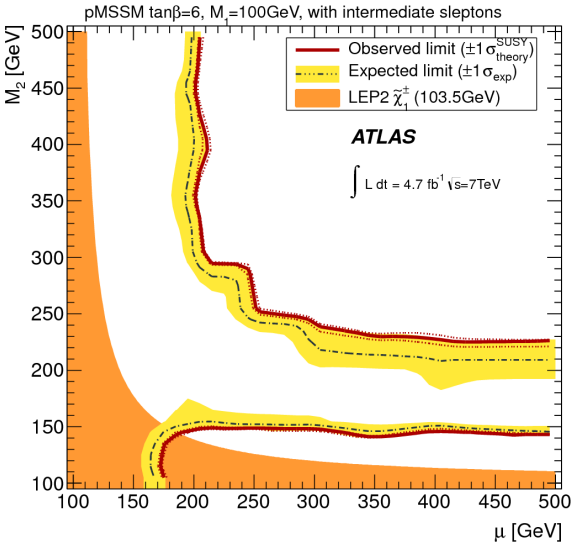
- stransverse mass m_{T2} :
take maximum value of m_T (two leptons!) and minimize with respect to the possible decompositions of $\vec{p}_T^{miss} = \vec{q}_T + \vec{r}_T$

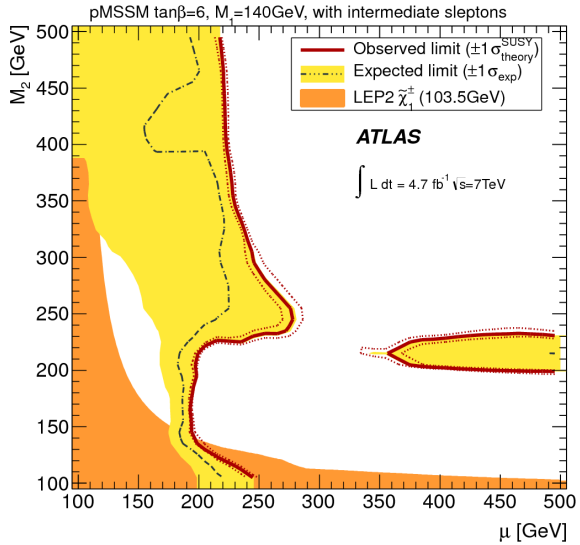
2 Leptons in Final State:



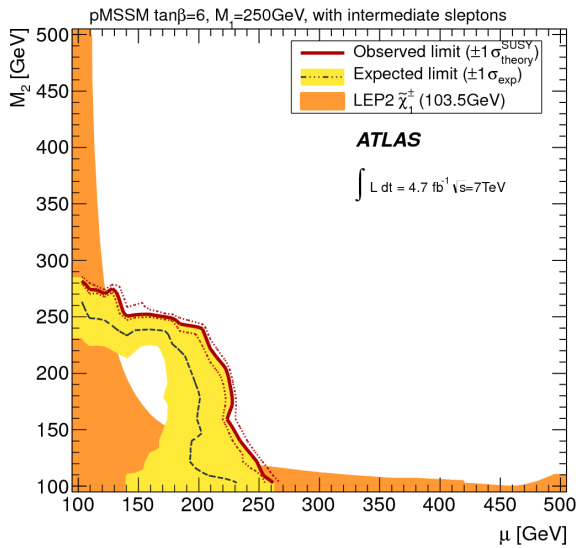
- $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production in Simplified Model.
- Chargino masses between 110 and 340 GeV excluded at 95 %CL for neutralino masses larger than 10 GeV.

2 Leptons in Final State:





- Signal regions are combined to derive exclusion limits in the pMSSM μ-M_2 plane for $\tan\beta = 6$ by selecting for each signal point the SR which provides the best expected p-value.



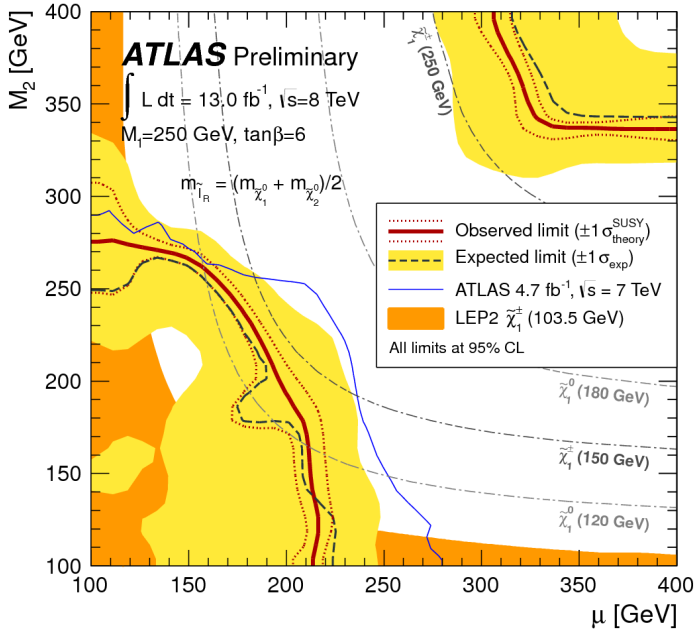
3 Leptons in the Final State

Expected numbers of events from SM backgrounds an observed numbers of events in data in SR1a, SR1b and SR2:

Selection	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 Bkg.	10 ± 6	0.8 ± 0.4	$0.012^{+1.6}_{-0.012}$
Total Bkg.	50 ± 8	3.1 ± 1.0	$6.1^{+2.0}_{-1.2}$
Data	48	4	4
SUSY Ref. Point 1	13.9 ± 1.0	11.4 ± 0.9	0.5 ± 0.1
SUSY Ref. Point 2	0.9 ± 0.1	0.3 ± 0.1	8.0 ± 0.6
Visible σ (exp)	< 1.5 fb	< 0.4 fb	< 0.5 fb
Visible σ (obs)	< 1.3 fb	< 0.5 fb	< 0.4 fb

No significant excess is observed in data.

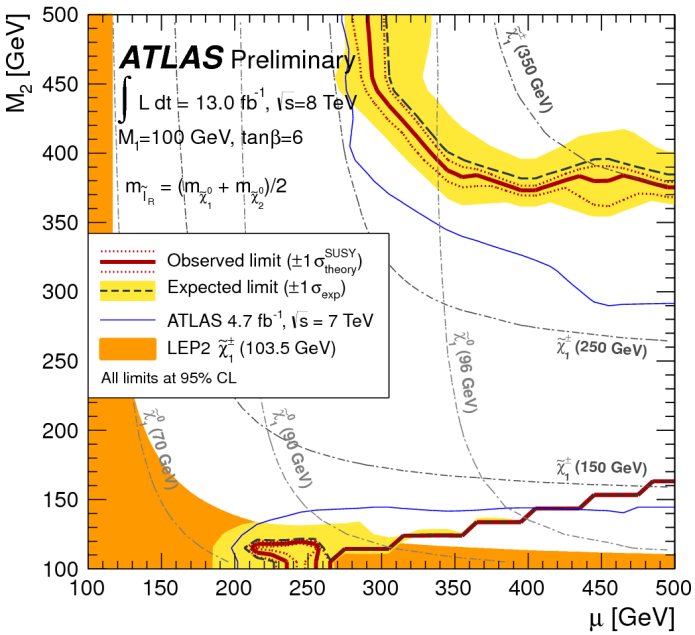
3 Leptons in the Final State

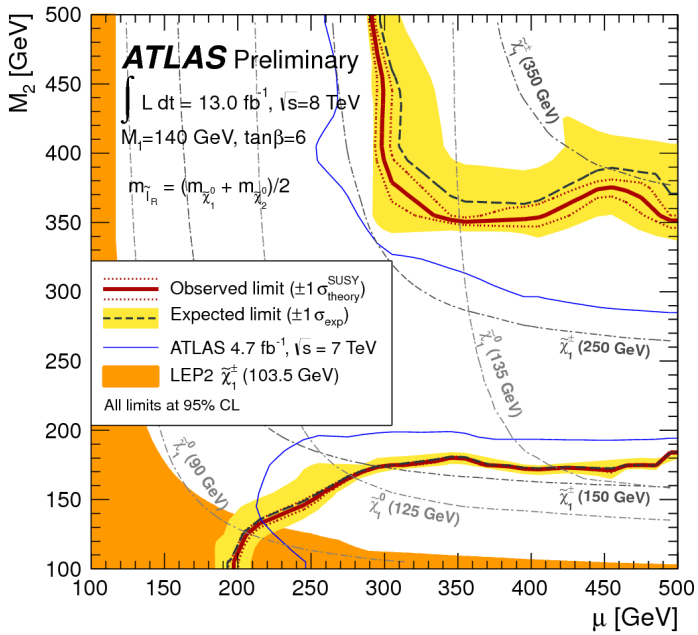


pMSSM Direct Gaugino Production

- Best sensitivity: Z-depleted SR 1 A, B. Two regions of exclusion in μ-M_2 plane with $\tan\beta = 6$.
- left lower corner: high cross section.
- upper right corner: large mass splitting between neutralinos $\tilde{\chi}_1^0$,$\tilde{\chi}_2^0$ (no dependence on μ).

3 Leptons in the Final State
pMSSM Direct Gaugino Production





- Best sensitivity: Z-depleted SR 1 A, B. Two regions of exclusion in μ-M_2 plane with $\tan\beta = 6$.
- right lower corner: reduced sensitivity due to small mass splitting between the neutralinos 1 and 2.
- When μ is greater than M_1 and M_2, the mass of the gauginos does not depend on μ and the sensitivity remains constant as a function of μ (corner on top).

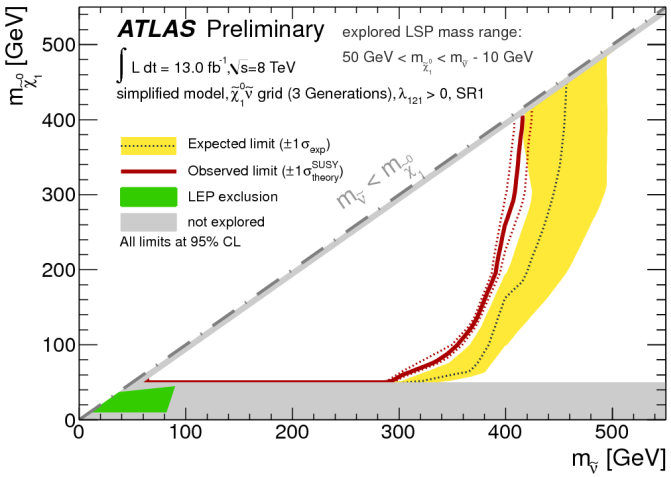
4 Leptons in the Final State, RPV

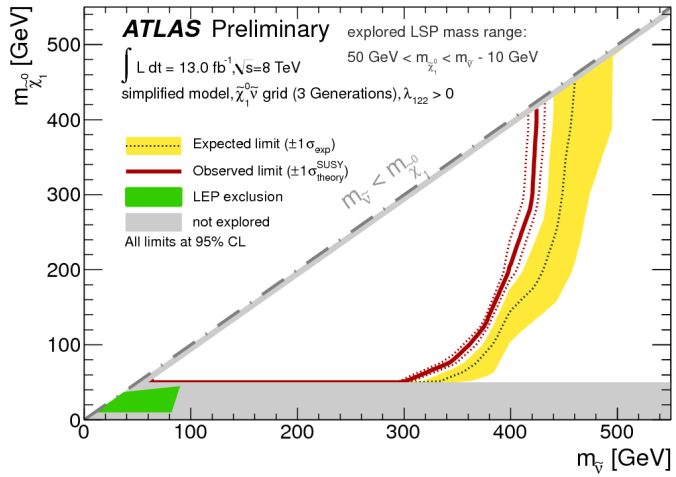
Expected number of events from SM backgrounds and observed number of events in data in the two SR's:

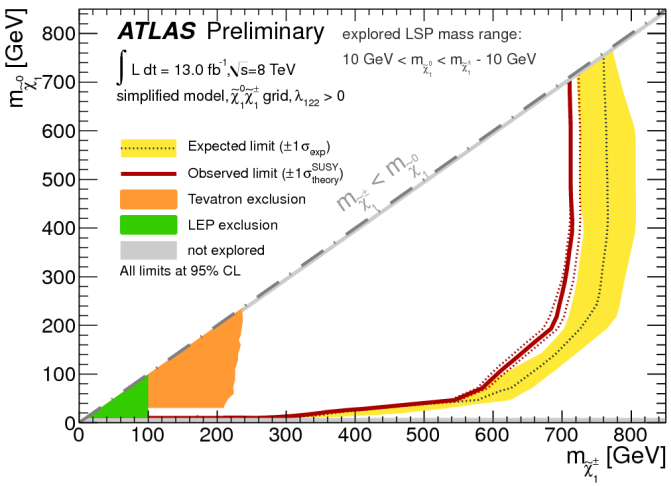
Selection	SR1	SR2
ZZ	$0.07^{+0.22}_{-0.07}$	$1.0^{+0.4}_{-0.4}$
ZWW	$0.10^{+0.10}_{-0.10}$	$0.09^{+0.09}_{-0.09}$
$t\bar{t}Z$	$0.045^{+0.028}_{-0.028}$	$0.06^{+0.04}_{-0.04}$
$t\bar{t}WW$	$(6^{+6}_{-5})\times10^{-3}$	$(3.3^{+4.8}_{-3.3})\times10^{-3}$
Irreducible Bkg.	$0.22^{+0.27}_{-0.21}$	$1.1^{+0.5}_{-0.4}$
Reducible Bkg.	$0.028^{+0.107}_{-0.028}$	$0.10^{+0.14}_{-0.10}$
Total Bkg.	$0.25^{+0.29}_{-0.25}$	$1.2^{+0.5}_{-0.4}$
Data	1	2
p_0-value (σ)	0.037 (1.8)	0.16 (1.0)
σ_{vis} (exp)	< 0.28 fb	< 0.28 fb
σ_{vis} (obs)	< 0.34 fb	< 0.38 fb

No significant excess is observed in data.

4 Leptons in the Final State, RPV



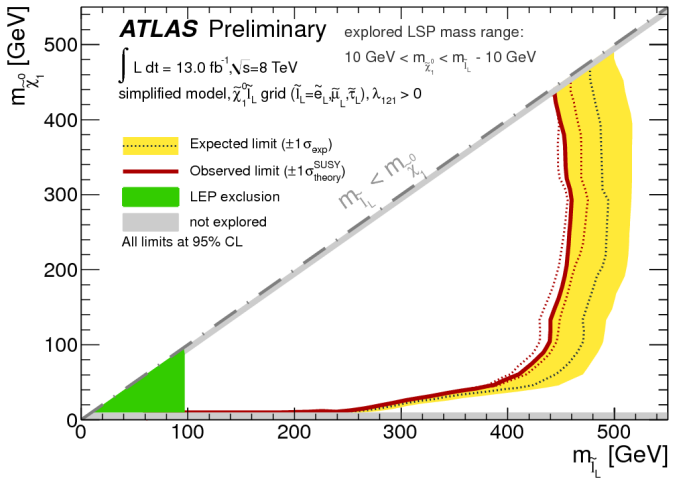


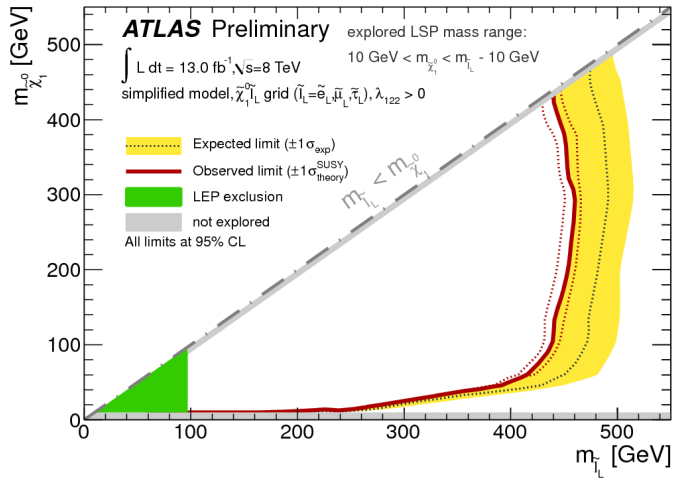


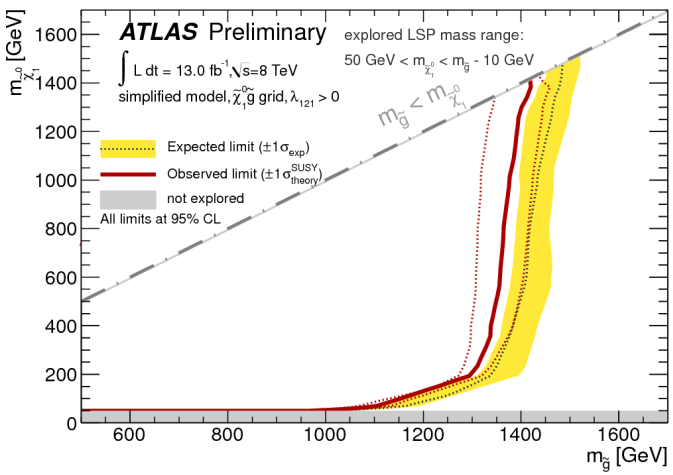
- Top: $\tilde{\nu}_l \rightarrow \nu_l \tilde{\chi}_1^0$. equal masses: ν_e, ν_μ, ν_τ. Sneutrino masses are excluded until 410 GeV.
- Bottom: When the NLSP is a wino-like chargino, chargino masses until 710 GeV are excluded.

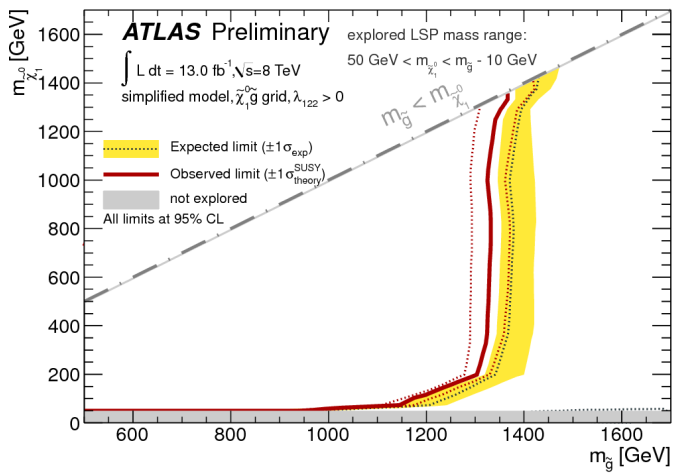
not explored regions: $\tilde{\chi}_1^0$ masses above 10 resp. 50 GeV considered because of requirements concerning minimum value of SFOS dilepton mass and lepton-lepton separation.

4 Leptons in the Final State, RPV









- Top: In a simplified model with left-handed sleptons of equal mass, $\tilde{l} \rightarrow l\tilde{\chi}_1^0$, slepton masses until 450 GeV can be excluded.
- Bottom: When the NLSP is a gluino, $\tilde{g} \rightarrow q\bar{q}^{'}\tilde{\chi}_1^0$, the gluino mass can be excluded until 1300 GeV.