EW SUSY production in ATLAS

Implications of LHC results for TeV-scale physics

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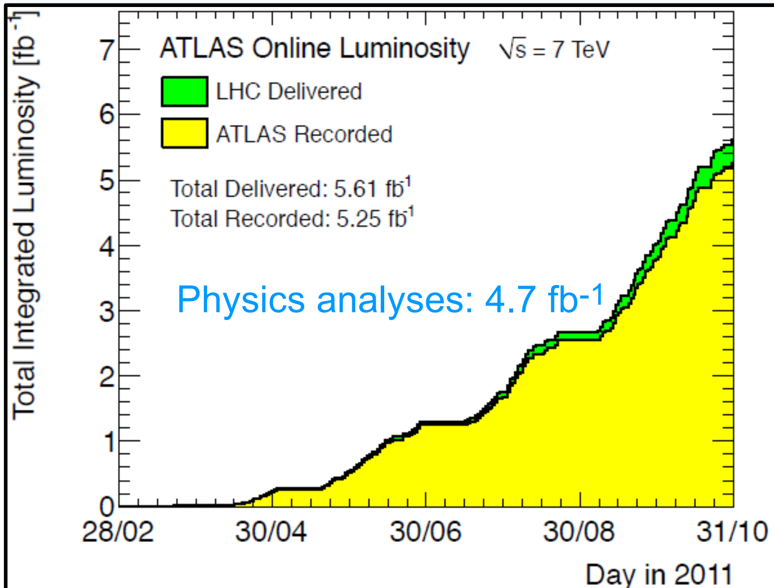
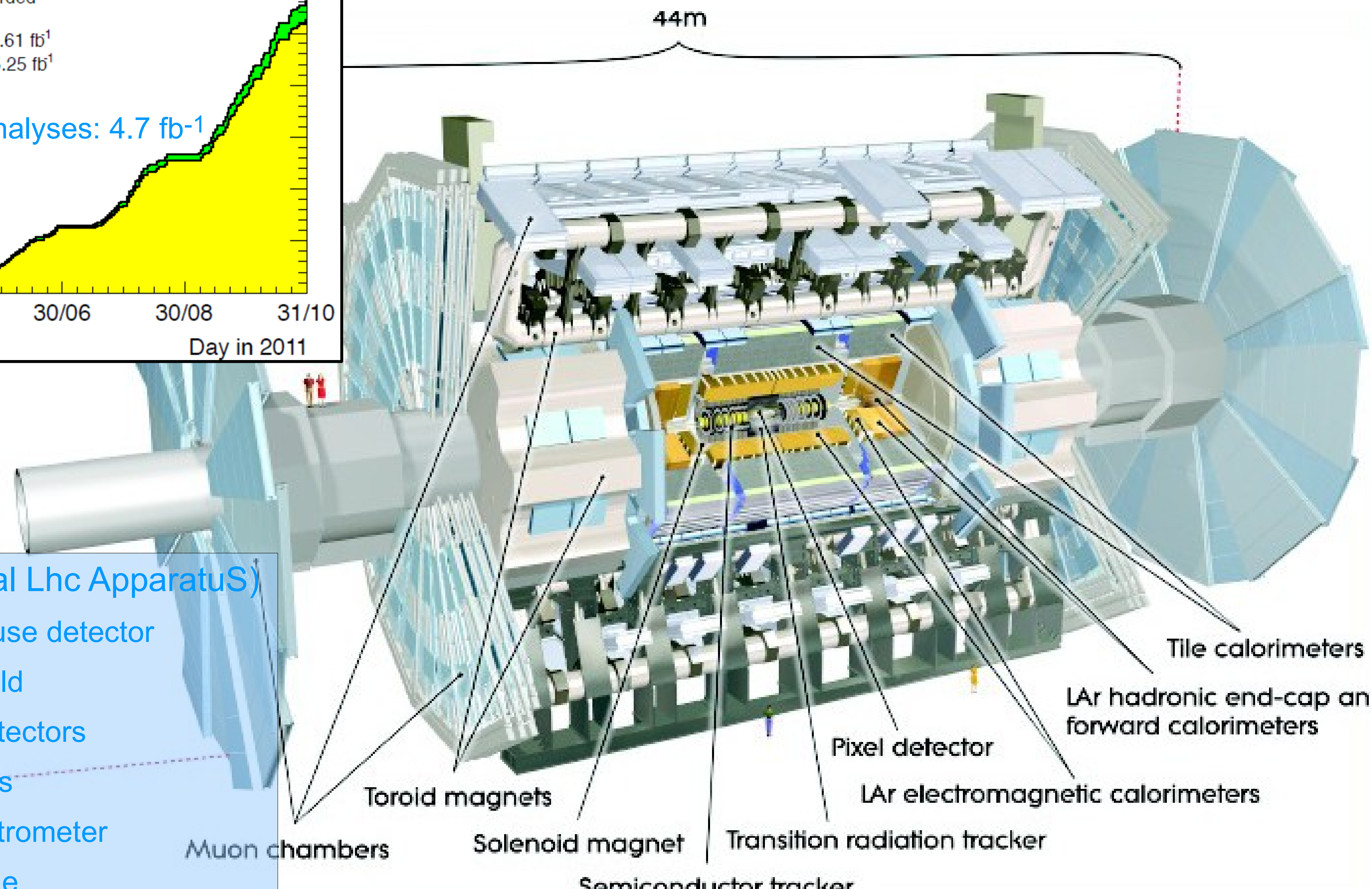
on behalf of the ATLAS collaboration

Outline

- Intro:
  - current limits, weak vs strong production,
    neutralino/chargino sector
    slepton sector
    EW search channels
- Analyses:
  - cuts, backgrounds, methods, results
- Interpretations
  - Direct sleptons, simplified models, pMSSM

ATLAS, datataking 2011





ATLAS (A Toroidal Lhc ApparatuS)

- General-purpuse detector
- Traditional build
  - tracking detectors
  - calorimeters
  - muon spectrometer
- Good coverage

SUSY limits, strong vs weak prod

- **Current limits on squarks and gluinos are already rather strong**, ATLAS ex.:
  - 0-lepton exclude
    $m_{\tilde{g}}, m_{\tilde{q}} \lesssim 1400 \text{ GeV for } m_{\tilde{\chi}_1^0} = 0$

    [ATLAS-CONF-2012-033]
  - 1-lepton exclude
    $m_{\tilde{g}} \lesssim 900 \text{ GeV for } m_{\tilde{\chi}_1^0} \lesssim 300 \text{ GeV}$

    $(\text{with } m_{\tilde{\chi}_1^\pm} = (m_{\tilde{\chi}_1^0} + m_{\tilde{g}})/2)$

    [ATLAS-CONF-2012-041]

  (though still many regions with softer limits, e.g. more compressed scenarios + softer limits on third generation)

- **LEP limits**

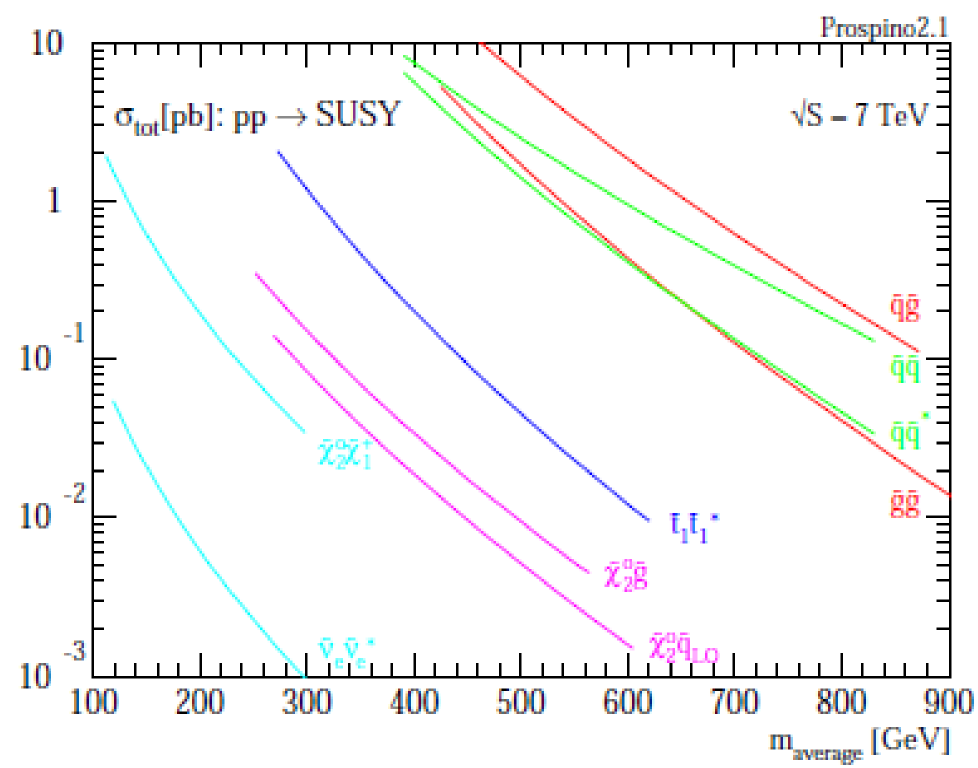
  $m_{\tilde{\chi}_1^0} \gtrsim \frac{1}{2} m_Z \text{ (roughly)}$

  $m_{\tilde{\chi}_1^\pm} > 103.5 \text{ GeV}$

  $m_{\tilde{e}_R}, m_{\tilde{\mu}_R}, m_{\tilde{\tau}_R} \gtrsim 100, 95, 90 \text{ GeV}$

  (in fairly general model setups)
  [at least as strong limits on left-handed slep]

- With gluinos and squarks heavy, EW production processes may be more relevant
  - direct neutralinos/charginos
  - direct sleptons



Neutralinos, charginos

Neutralino/Chargino Sector:

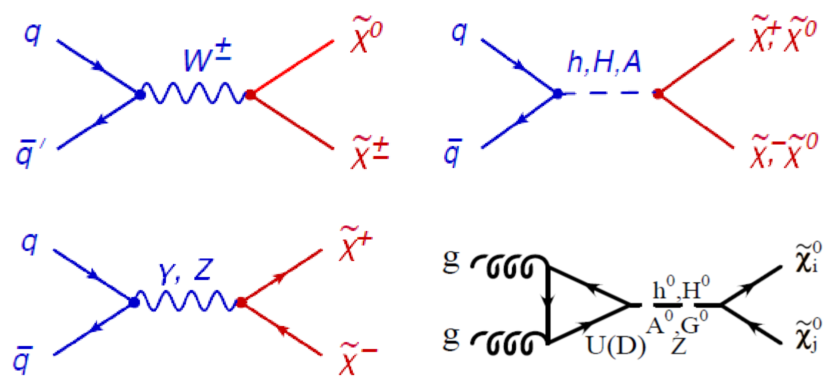
- In a minimal setup (MSSM) six neutralinos/charginos,
  - N_1,N_2,N_3,N_4 / C_1,C_2

  are governed by 4 parameters,
  - $M_1,M_2,\mu,\tan\beta$
- N_i are in general mixtures of bino (M_1), wino (M_2) and higgsino (μ)
  C_j are mixtures of wino and higgsino
- The mixture affects their masses and decay preferences

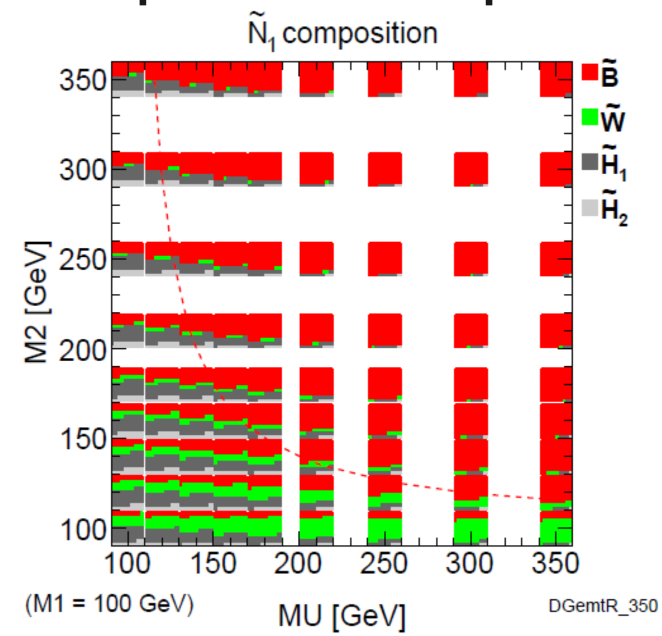
$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

$s_\beta = \sin\beta,\ c_\beta = \cos\beta,\ s_W = \sin\theta_W$, and $c_W = \cos\theta_W$

Some production diagrams



Example of LSP composition



Sleptons

Slepton sector

- In minimal setup (MSSM) we have six charged sleptons :
  - $\tilde{e}_R, \tilde{e}_L, \tilde{\mu}_R, \tilde{\mu}_L, \tilde{\tau}_1, \tilde{\tau}_2$
    (staus are mixtures of the left and right-handed components)

  controlled by one parameter each
  (plus one additional mixing parameter for stau)

- and neutral sneutrinos :
  - $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$

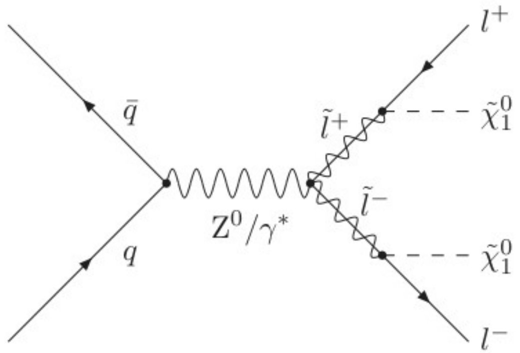
  whose masses are connected to (and close to) the mass of their left-handed charged partner

Full slepton sector adds 7 parameters to handle

(i) Direct slepton production

- Sleptons can be directly pair-produced:
  $\tilde{e}_L^+\tilde{e}_L^-, \ \tilde{e}_R^+\tilde{e}_R^-, \ \tilde{e}_L^\pm\tilde{\nu}_e, \ \tilde{\nu}_e\tilde{\nu}_e, \quad \tilde{\tau}_1^+\tilde{\tau}_1^+, \ \tilde{\tau}_2^+\tilde{\tau}_2^-, \ \tilde{\tau}_1^\pm\tilde{\tau}_2^\mp, \ \ldots$

Ex:



- Final states will have 0,1,2 (charged) leptons
- Cross-section is small, but we have sensitivity

(ii) Intermediate sleptons:

Sleptons are very relevant for the decay preferences of neutralinos and charginos

Neutralino/Chargino decays

- Many possible decays (mini-cascades):

Without sleptons:

$$\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z^{(*)}/h$$
$$\tilde{\chi}_1^\pm \to \tilde{\chi}_2^\pm Z^{(*)}/h$$
$$\tilde{\chi}_i^0 \to \tilde{\chi}_j^\pm W^{(*)}$$
$$\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^{(*)}$$

With sleptons we also get:

$$\tilde{\chi}_i^0 \to \tilde{\ell}^{(*)}\ell, \tilde{\nu}^{(*)}\nu$$
$$\tilde{\chi}_i^\pm \to \tilde{\ell}_L^{(*)}\nu, \tilde{\nu}^{(*)}\ell$$
$$\tilde{\ell} \to \tilde{\chi}_1^0\ell,\ \tilde{\nu} \to \tilde{\chi}_1^0\nu$$

- The full decay picture depends strongly on the composition of N_i and C_j (given by M_1,M_2,μ,tanβ) as well as the whereabouts of the (many) sleptons.
- This is to be folded with O(30) subprocesses whose cross-sections also depend on M_1,M_2,μ,tanβ
- Not easy to make very general claims (theoretically and exclusion-wise)

- Final states include 0-4(+) leptons
  - 0 leptons: hard (impossible?)
  - 1 leptons: hard
  - ≥2 leptons: ok

  (In extended scenarios, e.g. RPV-MSSM or NMSSM can have many more leptons)

- ATLAS 7 TeV search channels:
  - 2L (OS, SS, 0/2 jets)
  - 3L (N2C1,..)
  - 4L (N2N2,N2N3,..)

ANALYSES

2-lepton (4.7 fb^{-1}): OS+0jets+mT2, OS+2jets, OS+0jets, SS+0jets
ATLAS-CONF-2012-076 (http://cdsweb.cern.ch/record/1460273)

3-lepton (4.7 fb^{-1}): Z-veto, Z-veto (w/harder cuts), Z-requirement
ATLAS-CONF-2012-076 (http://cdsweb.cern.ch/record/1460273)

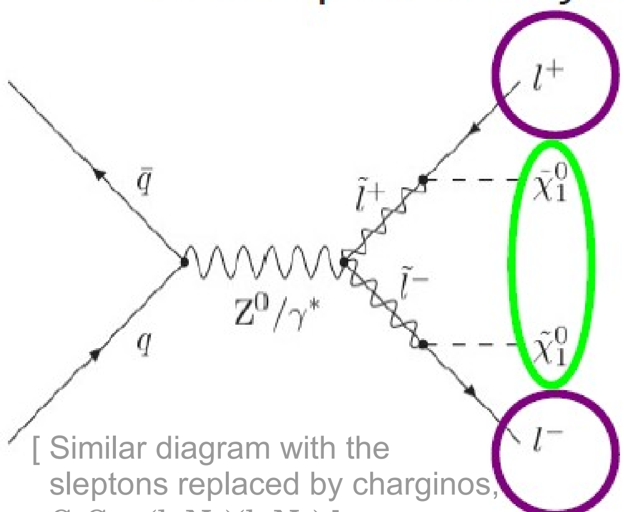
≥4-lepton (2.1 fb^{-1}): inclusive, Z-veto
ATLAS-CONF-2012-001 (https://cdsweb.cern.ch/record/1418920)

Note: In the following “lepton” refers to e and μ. There is no ATLAS analysis on 2011 data with taus targetting EW produced SUSY

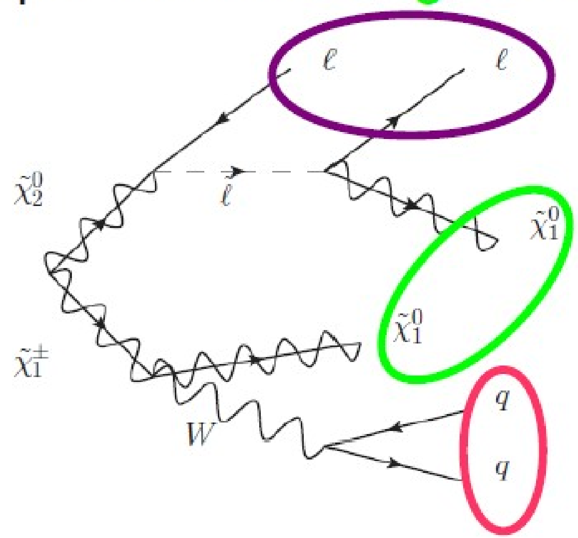
2-lepton signal regions

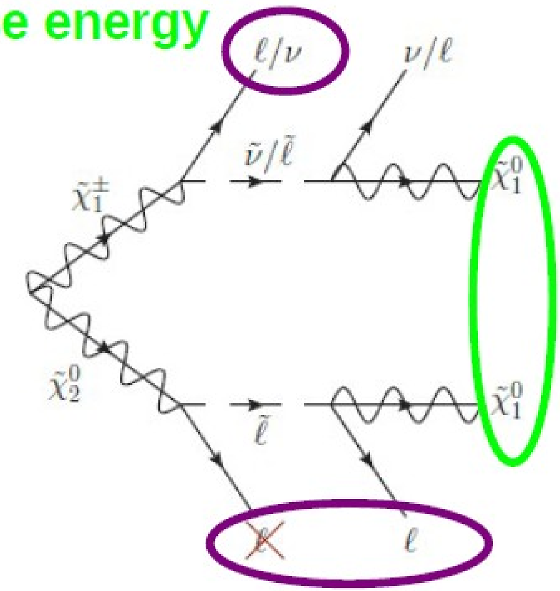
Four **signal regions (SRs)** motivated by direct slepton and various neutralino/chargino processes *(the canonical ones shown)*

- All require exactly 2 leptons and **missing transverse energy**



[Similar diagram with the sleptons replaced by charginos, $C_1C_1 \rightarrow (l\nu N_1)(l\nu N_1)$]





[For OS also $C_1C_1 \rightarrow (l\nu N_1)(l\nu N_1)$]

(True 2-lepton final state)

SR-mT2-jetveto
- OS
- mT2 > 90 GeV
- METrel > 40 GeV
- Z-veto

(True 2-lepton final state)

SR-2jets
- OS SF
- 2 jets, no b-jets
- METrel > 50 GeV
- Z-veto, mCT-veto

(3-lepton final state with 1 lepton lost)

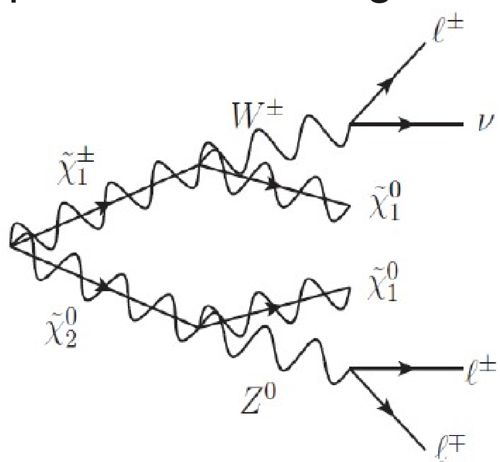
SR-OS-jetveto
- OS
- METrel > 100 GeV
- Z-veto

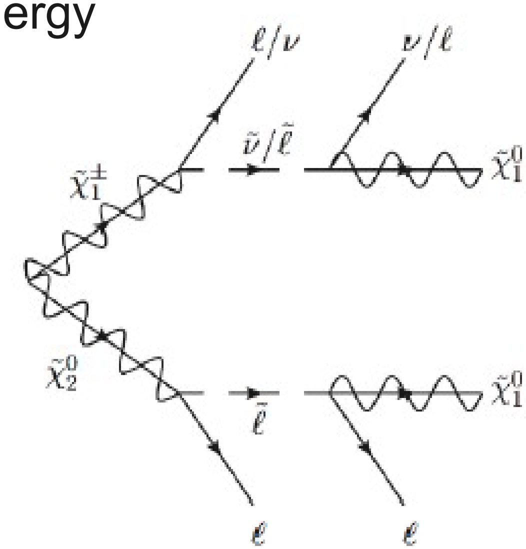
SR-SS-jetveto
- SS
- METrel > 100 GeV

3-lepton signal regions

Three **signal regions (SRs)**, all targeting N_2C_1 production (or higher):

All require exactly 3 leptons and missing transverse energy





SR2
- at least one OSSF
- MET > 75 GeV
- Z-requirement
- mT > 90 GeV

SR1a
- at least on OSSF
- MET > 75 GeV
- Z-veto
- 0 b-jets

SR1b: SR1a plus
- mT > 90 GeV
- harder lepton pt

(for larger mass splittings)

Backgrounds

2-lepton

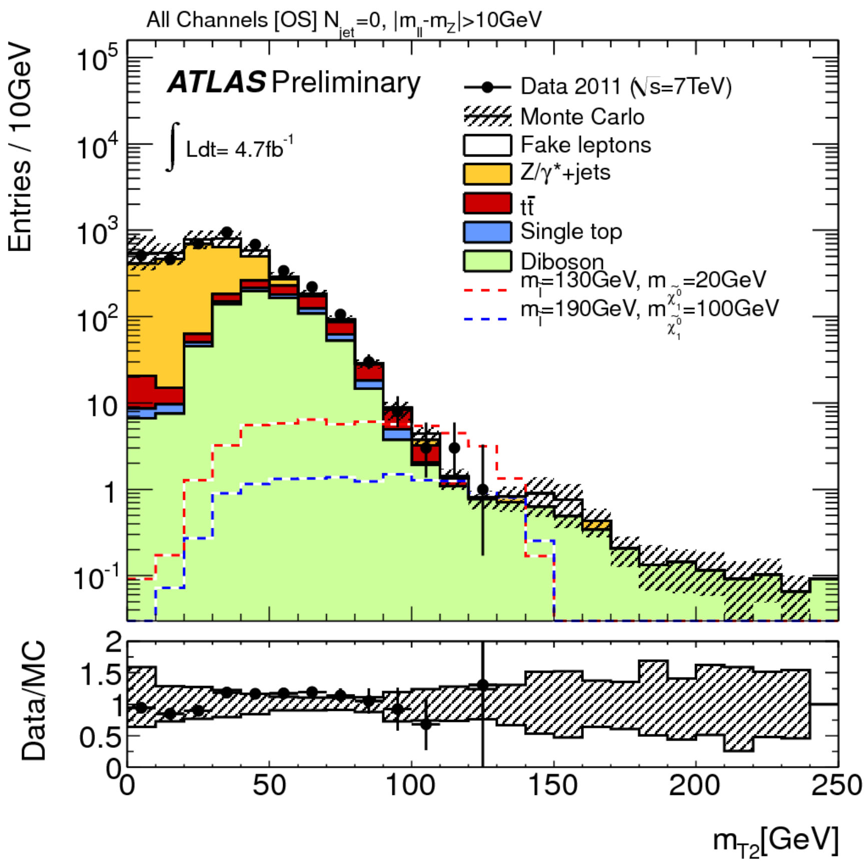
- Irreducible (two prompt leptons):
  - **Top, Z+jets, ZW, ZZ:** *MC normalised to data in dedicated CRs*
  - **WW**: *MC / datadriven (SR-dep.)*
- Reducible:
  - **W+jets, multijets** with one or two fake leptons: *Matrix Method*
  - **Charge-flip ($e\gamma^*$, $\gamma^* \rightarrow e^+e^-$)** [in SS channel]: *measured in Z-peak*

3-lepton

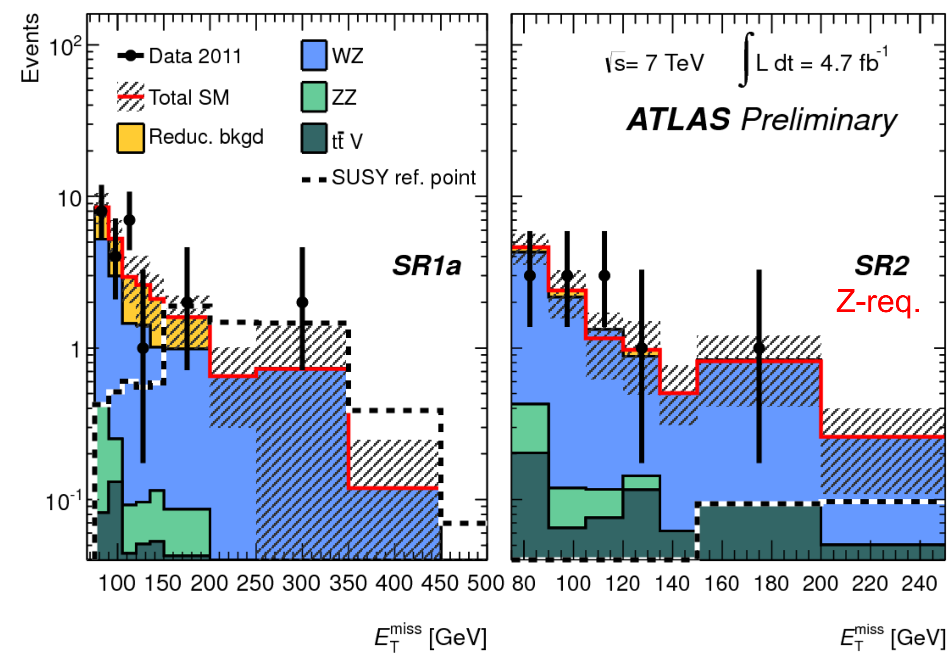
- Irreducible (three prompt leptons):
  - **WZ**: *MC normalised to data in dedicated CR*
  - **ZZ, ttbar+W/Z**: *MC*
- Reducible:
  - **top, WW, W/Z+jets/gamma** with one or two fake leptons: *Matrix Method*

Some SR plots

2-lepton



3-lepton



Data points consistent with Standard Model estimates

Results

2-lepton

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
$\sigma_{\text{vis}}^{\text{obs(exp)}}$ (fb)	1.6 (1.9)	1.7 (2.2)	1.7 (2.1)	2.6 (3.8)	2.0 (2.7)

SR-OSjveto	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	all
Z+X	$4.5 \pm 1.2 \pm 1.2$	$3.0 \pm 0.9 \pm 0.5$	$4.7 \pm 1.1 \pm 1.2$	$12.2 \pm 1.8 \pm 1.8$
WW	$8.8 \pm 1.8 \pm 4.4$	$20.9 \pm 2.6 \pm 6.2$	$13.3 \pm 1.9 \pm 3.5$	$43.0 \pm 3.7 \pm 12.2$
$t\bar{t}$, single top	$21.1 \pm 2.3 \pm 4.2$	$47.7 \pm 3.4 \pm 20.5$	$27.5 \pm 2.5 \pm 9.0$	$96.2 \pm 4.8 \pm 29.5$
Fake leptons	$2.9 \pm 1.2 \pm 1.2$	$6.9 \pm 1.8 \pm 2.6$	$0.4 \pm 0.6 \pm 0.3$	$10.3 \pm 2.2 \pm 4.1$
Total	$37.2 \pm 3.3 \pm 6.4$	$78.5 \pm 4.7 \pm 20.9$	$45.9 \pm 3.4 \pm 9.4$	$161.7 \pm 6.7 \pm 30.8$
Data	33	66	40	139
$\sigma_{\text{vis}}^{\text{obs(exp)}}$ (fb)	3.5 (4.0)	8.1 (9.6)	4.3 (5.1)	11.4 (14.1)

SR-2jets	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	SF
Z+X	$3.8 \pm 1.3 \pm 2.7$	—	$5.8 \pm 1.6 \pm 3.9$	$9.6 \pm 2.0 \pm 5.1$
WW	$6.4 \pm 0.5 \pm 4.3$	—	$8.4 \pm 0.6 \pm 5.7$	$14.8 \pm 0.7 \pm 9.9$
$t\bar{t}$, single top	$14.8 \pm 1.9 \pm 9.2$	—	$22.1 \pm 2.1 \pm 20.7$	$36.9 \pm 2.9 \pm 29.6$
Fake leptons	$2.5 \pm 1.2 \pm 1.5$	—	$1.7 \pm 1.3 \pm 0.8$	$4.2 \pm 1.8 \pm 2.3$
Total	$27.5 \pm 2.6 \pm 10.6$	—	$37.9 \pm 3.0 \pm 21.0$	$65.5 \pm 4.0 \pm 31.8$
Data	39	—	39	78
$\sigma_{\text{vis}}^{\text{obs(exp)}}$ (fb)	7.1 (5.1)	—	9.7 (9.6)	15.6 (13.9)

SR-SSjveto	$e^\pm e^\pm$	$e^\pm\mu^\pm$	$\mu^\pm\mu^\pm$	all
Charge flip	$0.49 \pm 0.03 \pm 0.17$	$0.34 \pm 0.02 \pm 0.11$	—	$0.83 \pm 0.04 \pm 0.18$
Dibosons	$0.62 \pm 0.13 \pm 0.18$	$1.93 \pm 0.23 \pm 0.36$	$0.94 \pm 0.16 \pm 0.26$	$3.50 \pm 0.31 \pm 0.54$
Fake leptons	$3.2 \pm 0.9 \pm 1.7$	$2.9 \pm 0.9 \pm 1.9$	$0.6 \pm 0.6 \pm 0.3$	$6.6 \pm 1.4 \pm 3.8$
Total	$4.3 \pm 0.9 \pm 1.7$	$5.1 \pm 1.0 \pm 1.9$	$1.5 \pm 0.6 \pm 0.4$	$11.0 \pm 1.5 \pm 3.9$
Data	1	5	3	9
$\sigma_{\text{vis}}^{\text{obs(exp)}}$ (fb)	0.8 (1.2)	1.5 (1.5)	1.3 (0.8)	2.0 (2.3)

3-lepton

Selection	SR1a	SR1b	SR2
SUSY ref. point	8.0±0.8	6.5±0.6	0.46±0.05
$t\bar{t}Z$	0.06±0.05	0.025±0.023	0.6±0.5
$t\bar{t}W$	0.36±0.29	0.10±0.08	0.09±0.08
$t\bar{t}WW$	0.010±0.008	0.0023±0.0019	0.004±0.004
ZZ	0.67±0.21	0.09±0.08	0.34±0.17
WZ	13.5±3.2	1.1±0.28	9.3±2.2
Reducible Bkg.	10±5	0.35±0.34	$0.5^{+1.0}_{-0.5}$
Total Bkg.	25±6	1.6±0.5	10.9±2.4
Data	24	0	11
Visible σ (exp)	< 3.0 fb	< 0.8 fb	< 2.0 fb
Visible σ (obs)	< 3.0 fb	< 0.7 fb	< 2.0 fb

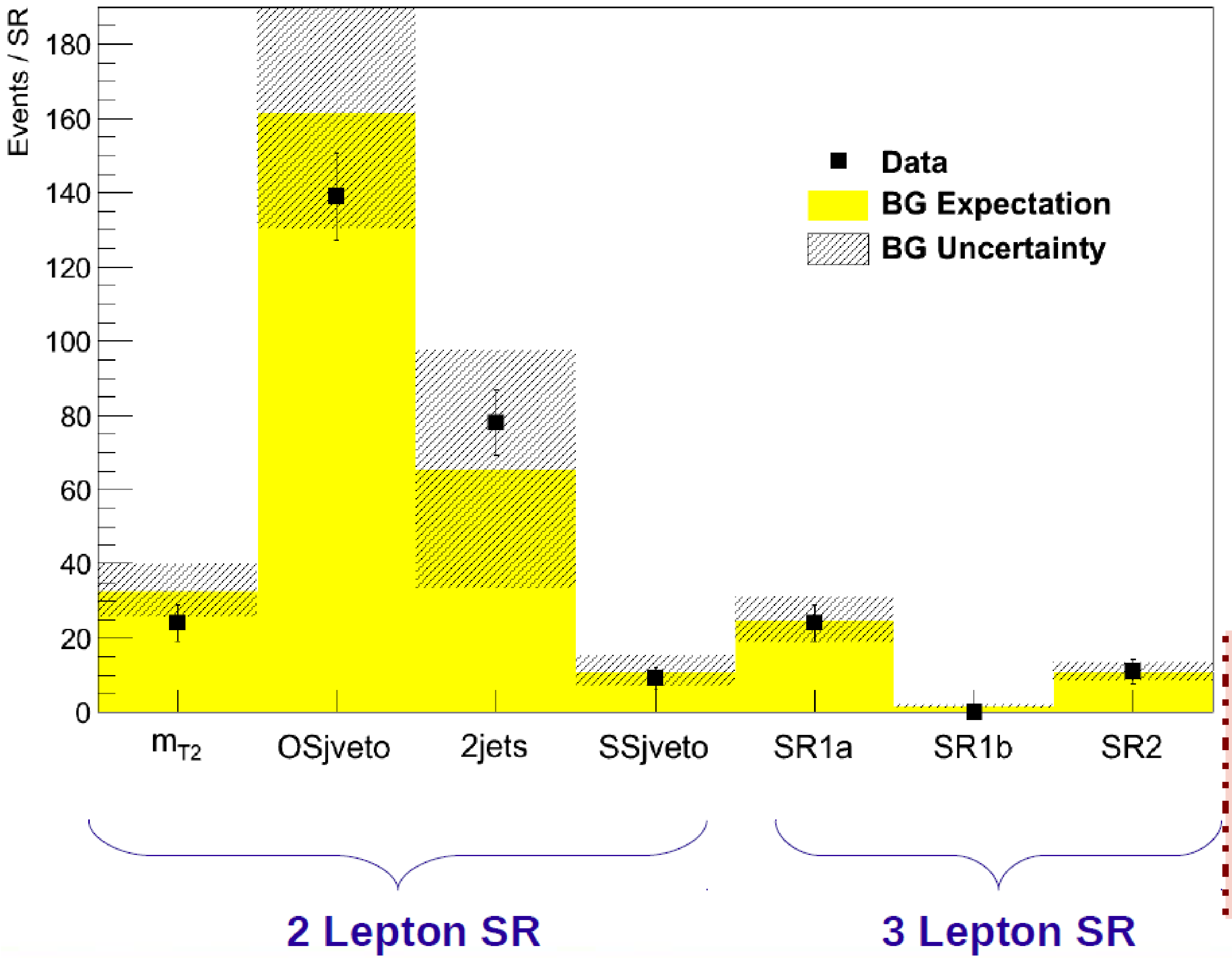
"SUSY ref. point"
$(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_L}, m_{\tilde{\chi}_1^0}) = 425,\ 425,\ 250,\ 75$ GeV)

No excess in 2/3-lepton channels

Upper limits on the cross-section of new physics is set in the various SRs (using CLs method)

Interpretation: exclude parameter regions in various SUSY models

Results #2



No excess in 2/3-lepton channels

Upper limits on the cross-section of new physics is set in the various SRs (using CLs method)

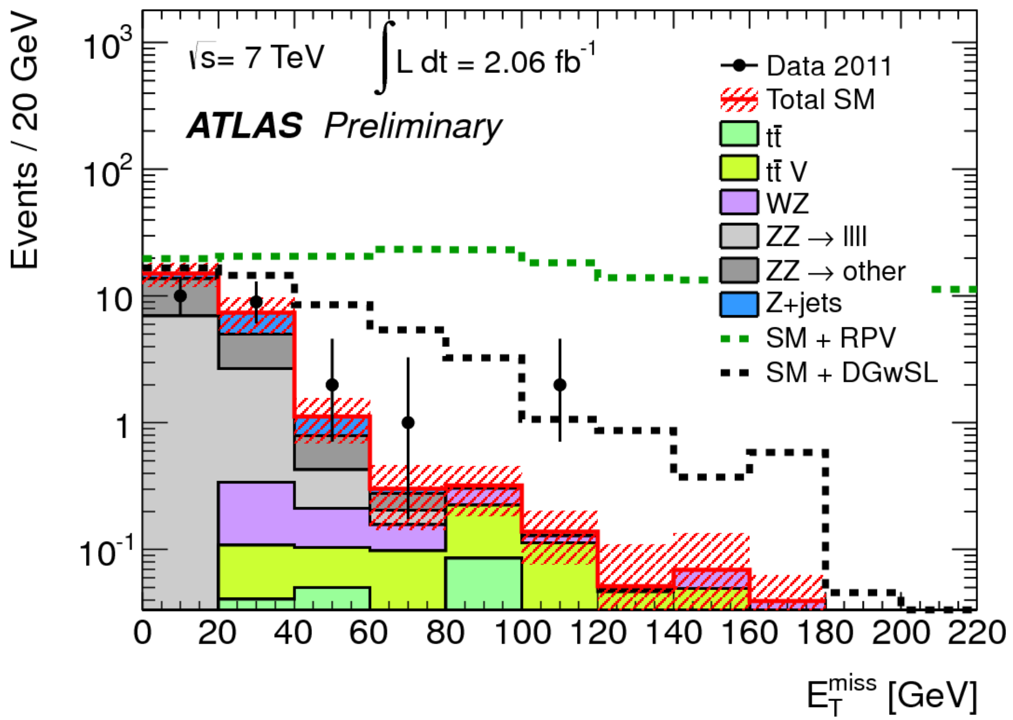
Interpretation: exclude parameter regions in various SUSY models

≥4-lepton analysis

SR1: MET > 50 GeV
SR2: add Z-veto

Background estimation

- Irreducible:
  - **ZZ, ttbar+Z:**
    MC (validated in CR)
- Reducible:
  - Z → llγ* → llll:
    Conversion ratio measured in CR



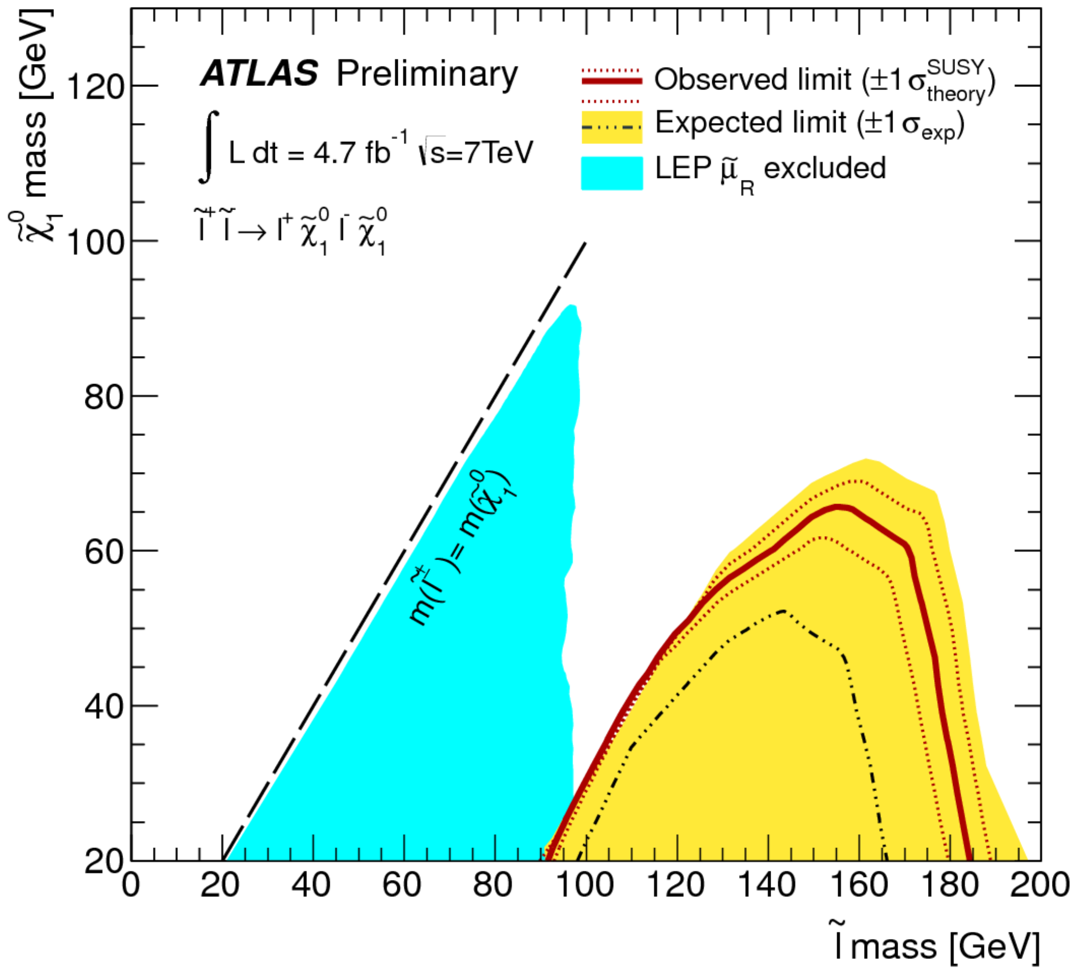
	Background	Observed	95% CL
E_T^{miss} > 50 GeV	1.7±0.9	4	3.5 fb
E_T^{miss} > 50 GeV, Z-veto	0.7±0.8	0	1.5 fb

No significant excess observed
Can set limit on new physics

Not (yet) interpreted in the context of EW SUSY production

INTERPRETATIONS

Interpretation: Direct Sleptons



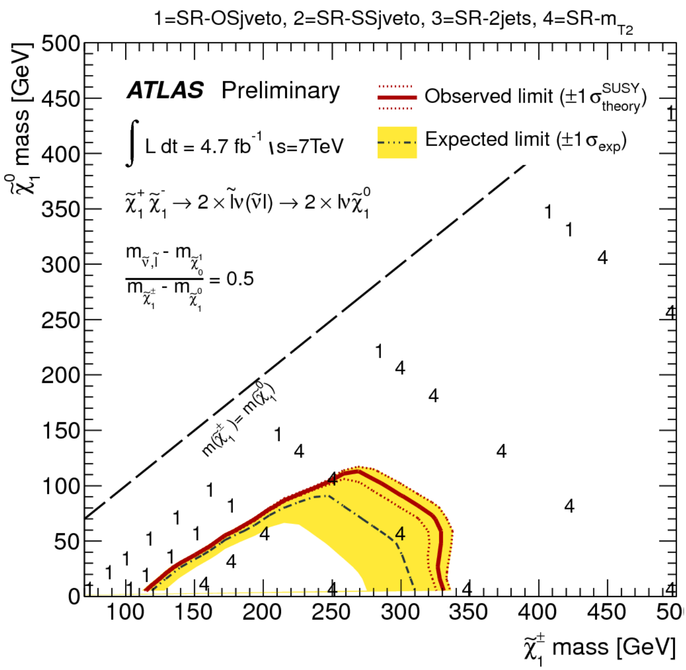
Model setup:

- degenerate 1st and 2nd slepton generations
- bino-LSP
- (all the rest heavy)

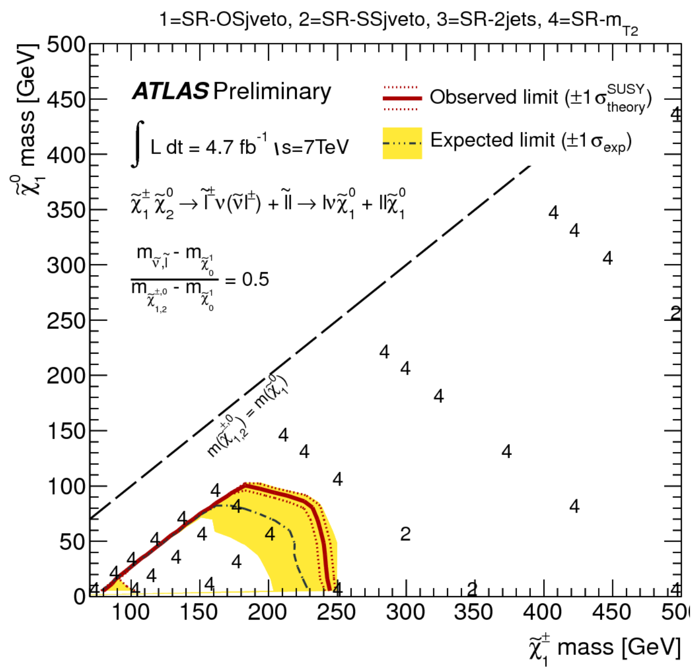
Limits:

- Extend the LEP exclusion
- Need considerable mass gap down to the LSP

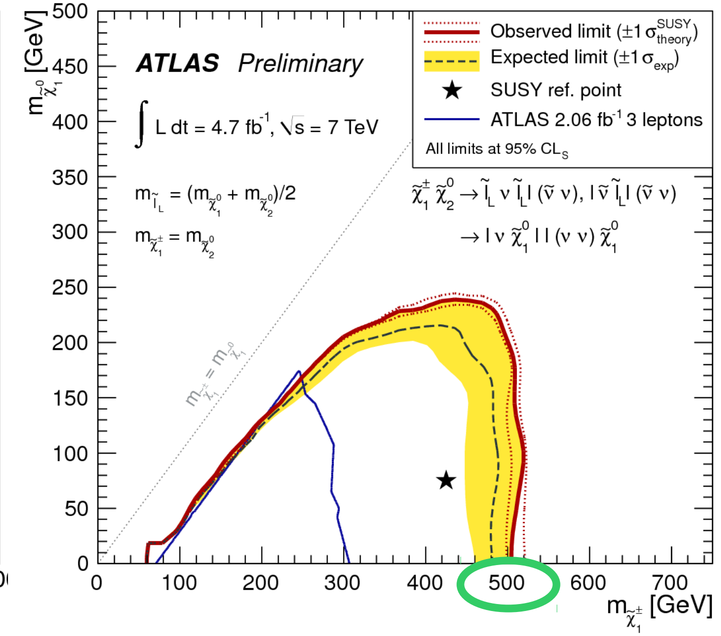
Interpretation: Simplified Model



2L C_1C_1



2L N_2C_1



3L N_2C_1

Simplified model setup:

- N_2,C_1 pure wino & degenerate; N_1 pure bino
- Left-handed 1. and 2. generation sleptons inserted midway between C_1/N_2 and N_1
- BR($N_2 \to$ charged slepton) = 50%
- BR($C_1 \to$ charged slepton) = 50%

Note: *C_1C_1 and N_2C_1 samples are analysed separately; there is no combination*
Note: *Charged slepton and sneutrino are set degenerate*

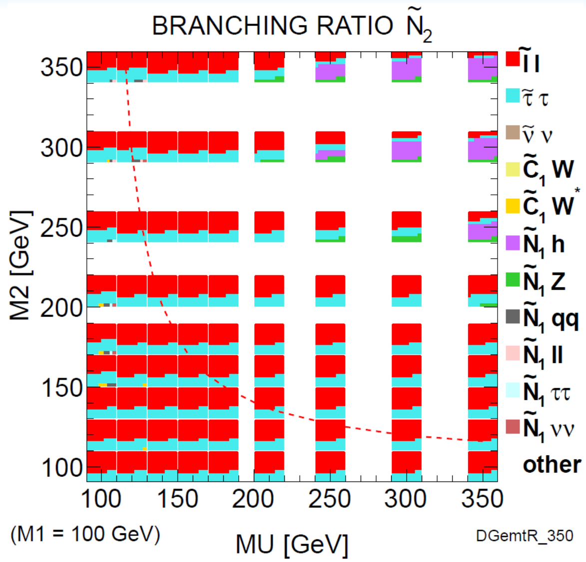
3L analysis very strong:

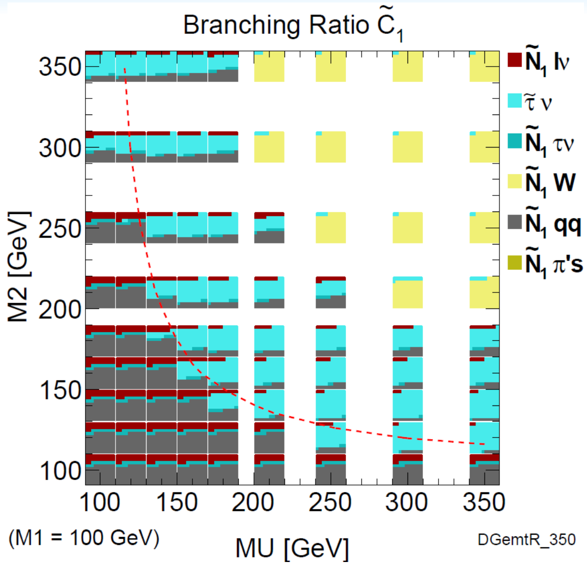
- exclude wino C_1=N_2 between 80 and 500 GeV for bino N_1 < 225 GeV provided C_1-N_1 > 75 GeV (approx.)

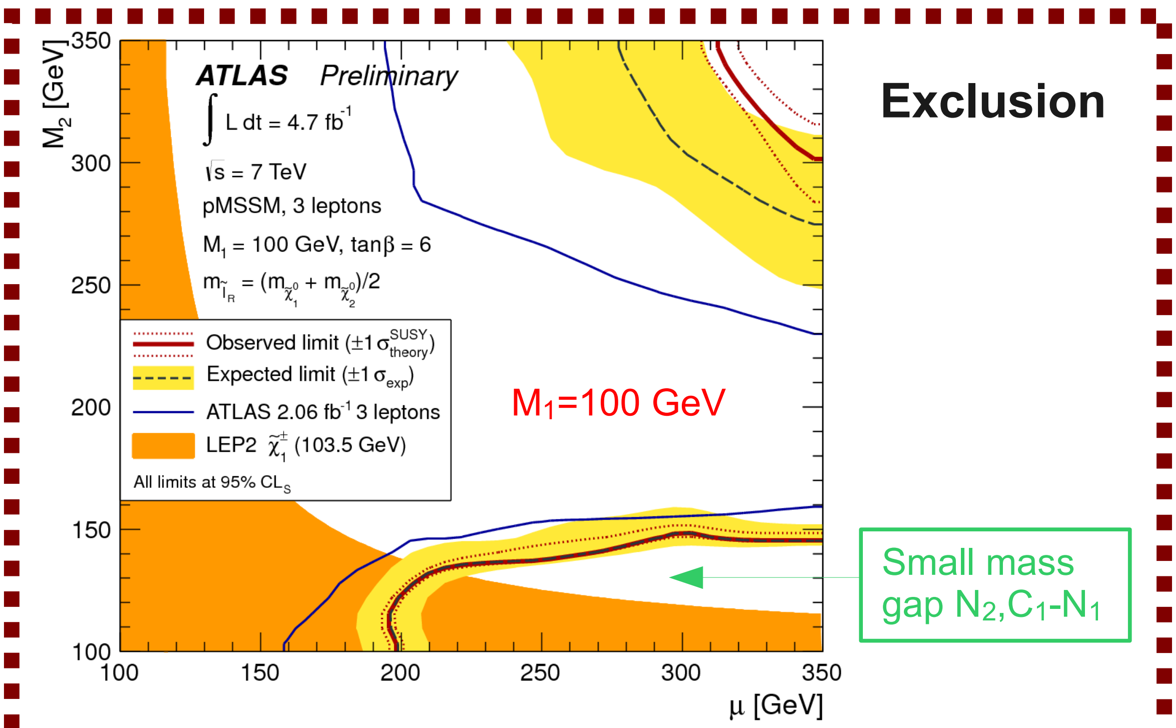
Near future:

- Interpretation without intermediate sleptons

Interpretation: pMSSM slices







Motivation:

- Want a general physics model
- Want results as generic as possible [not easy]

pMSSM model setup:

- Scan in μ and M_2 at fixed M_1 values
- tanβ = 6
- right-handed sleptons at $(N_1+N_2)/2$ (all three flavours)
- mA = 500 GeV, max stop mixing, remaining sparticles at 2 TeV
- [gives Higgs at 119 GeV]

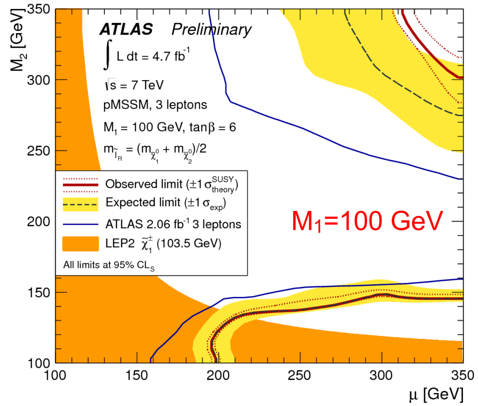
Sleptons:

- In general difficult to be very general
- Left-handed sleptons left out:
  - no sneutrino (take BR and can become LSP)
  - no Ci decay to selectron/smuon
  - Z,W,h take large share when on-shell
- Exclusion would go higher if staus left out

Variation:

- Results fairly stable w.r.t. slepton mass
- Only small changes with tanβ = 10

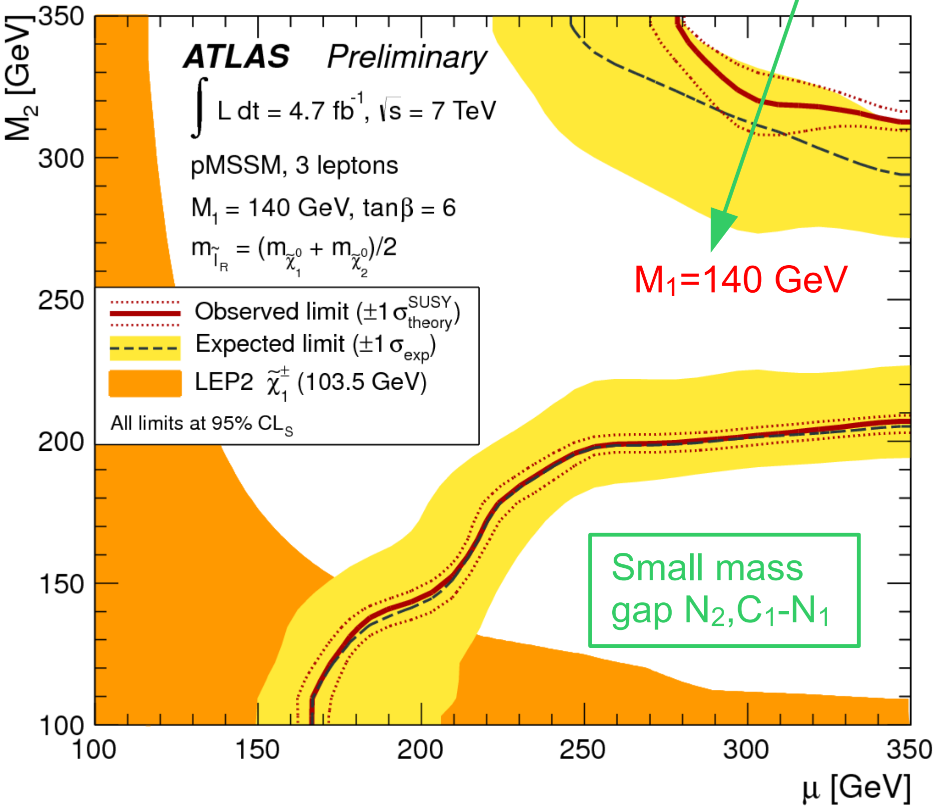
Interpretation pMSSM slices #2

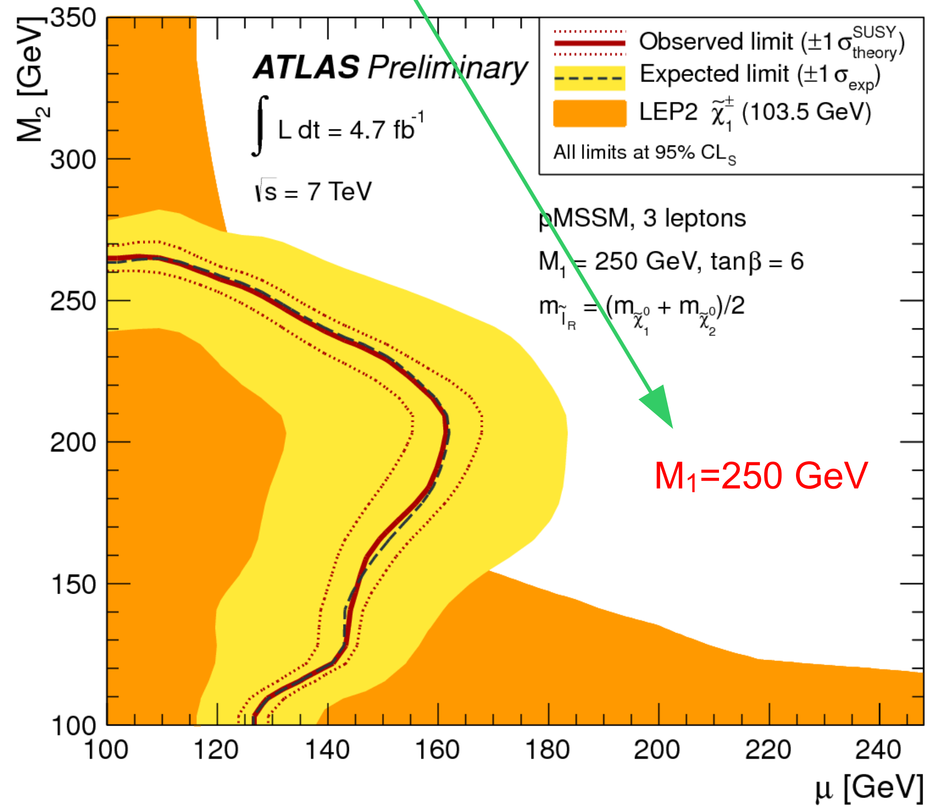


Combination of 2 and 3-lepton nearly ready, will move exclusion lines

Similar to M_1=100 GeV

Bino-component heavier, different neutralino layout





SUMMARY

- ATLAS has searched for directly produced neutralinos/charginos and sleptons with 4.7 fb^{-1} of 2011 data
- No excess observed
- Limits have been set in
  - l_L-N_1 plane (pMSSM, direct sleptons)
  - C_1-N_1 plane (simplified models with gaugino content)
  - μ-M_2 plane (pMSSM, tanβ=6, M_1=100,140,250 GeV, right-handed sleptons all flavours midway between N_1 and N_2)
- 2012: more data, more channels, more interpretations

BACKUP

BACKUP

BACKUP

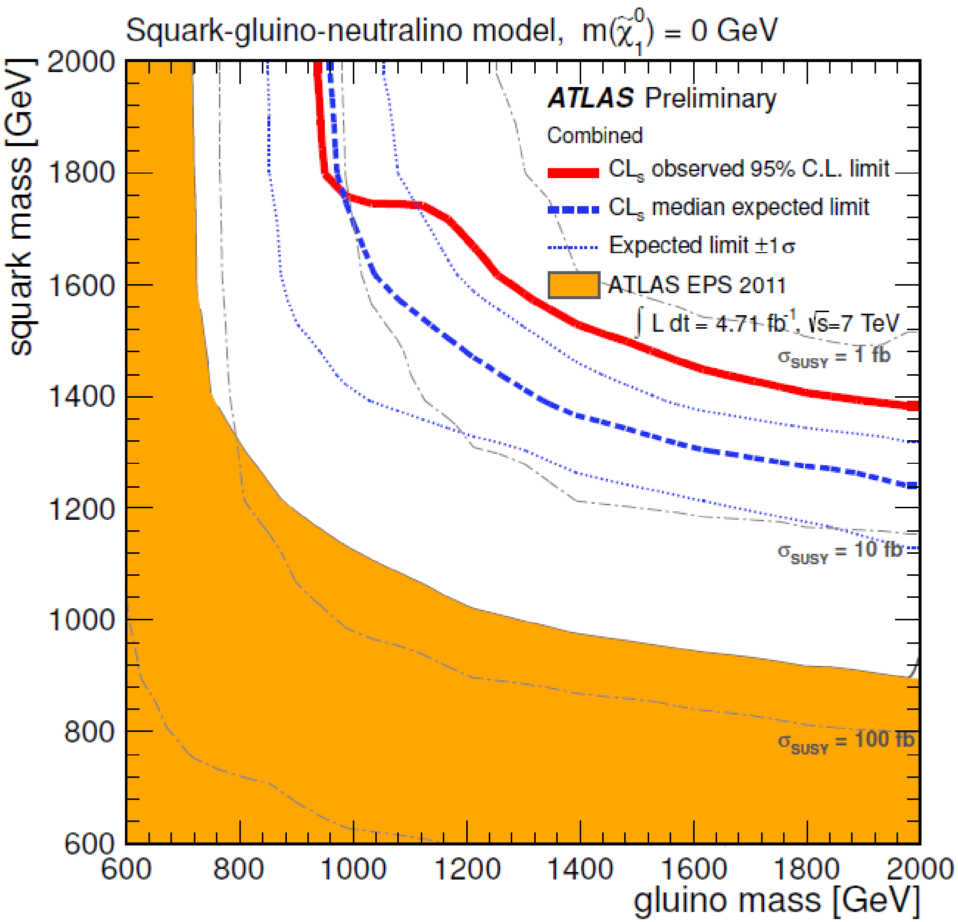
BACKUP

BACKUP

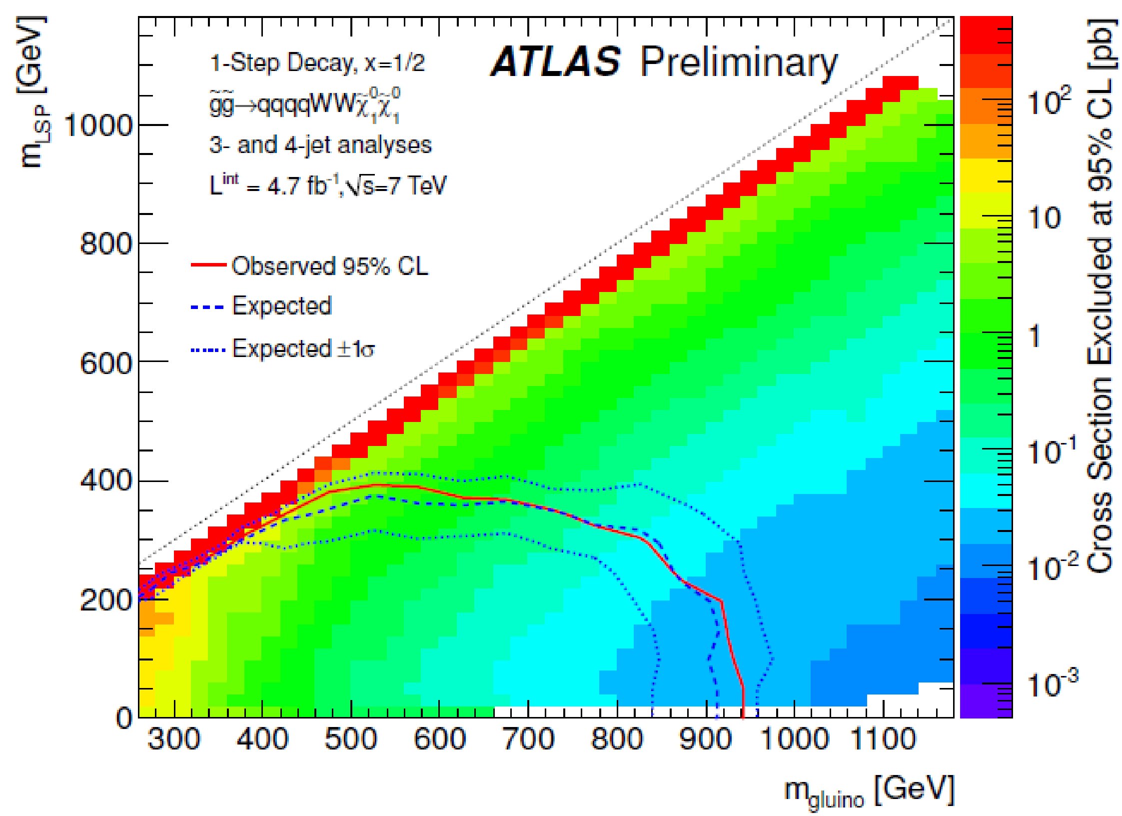
BACKUP

Some limit plots for gluinos and squarks

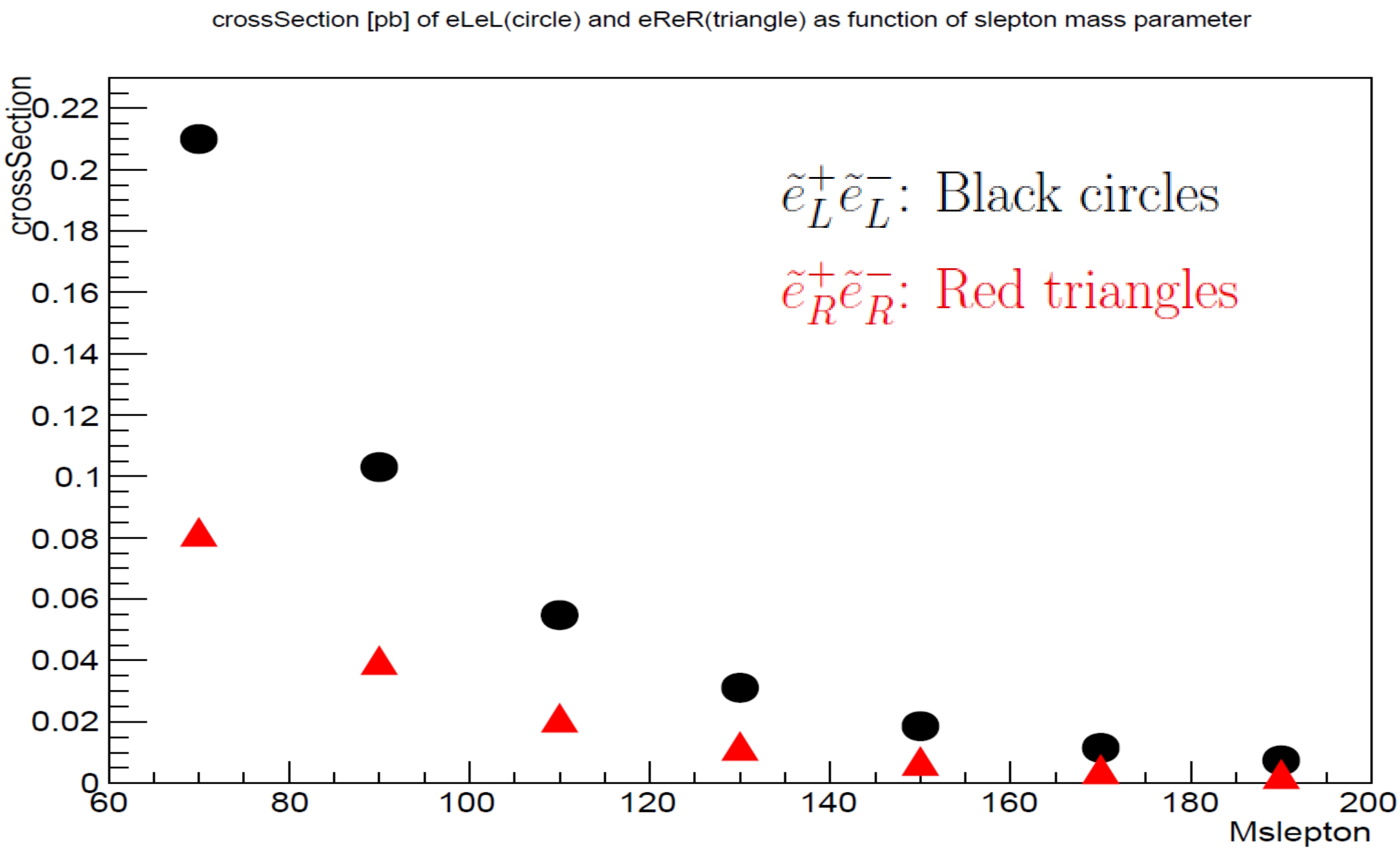
0-lepton, 2-4 jets, 4.7/fb:
ATLAS-CONF-2012-033



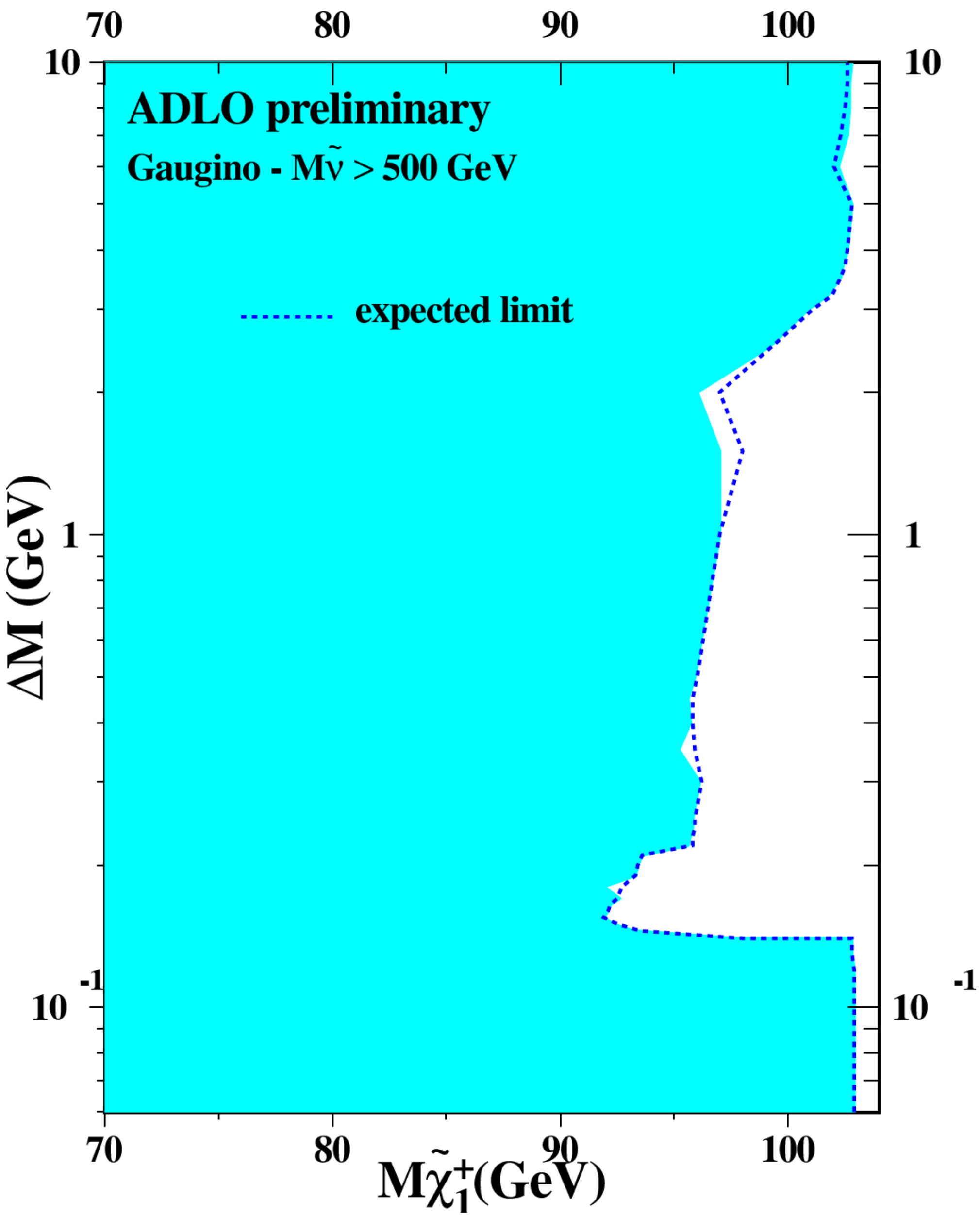
1-lepton, 3-4 jets, 4.7/fb
ATLAS-CONF-2012-041

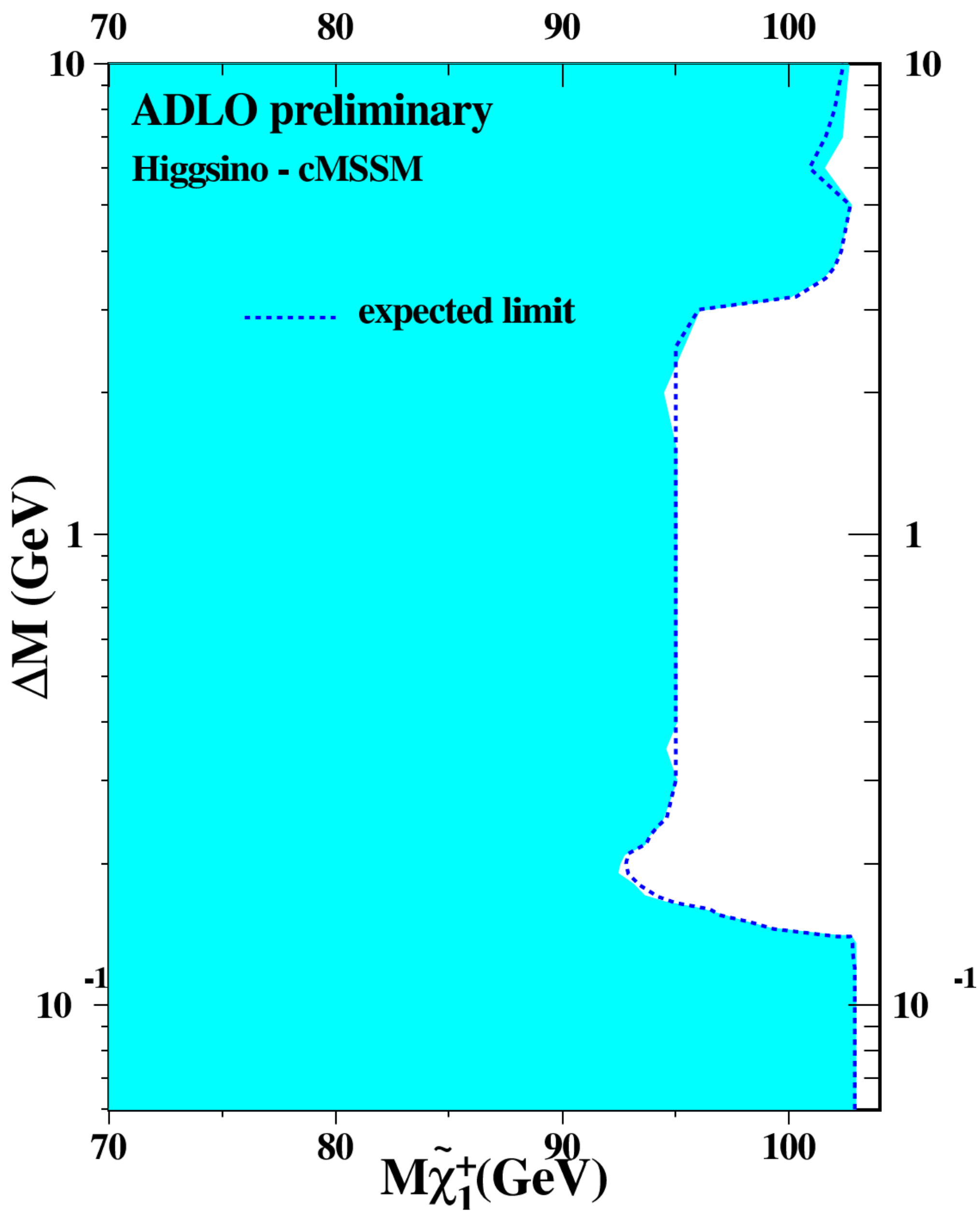


Cross-section of direct slepton prod.

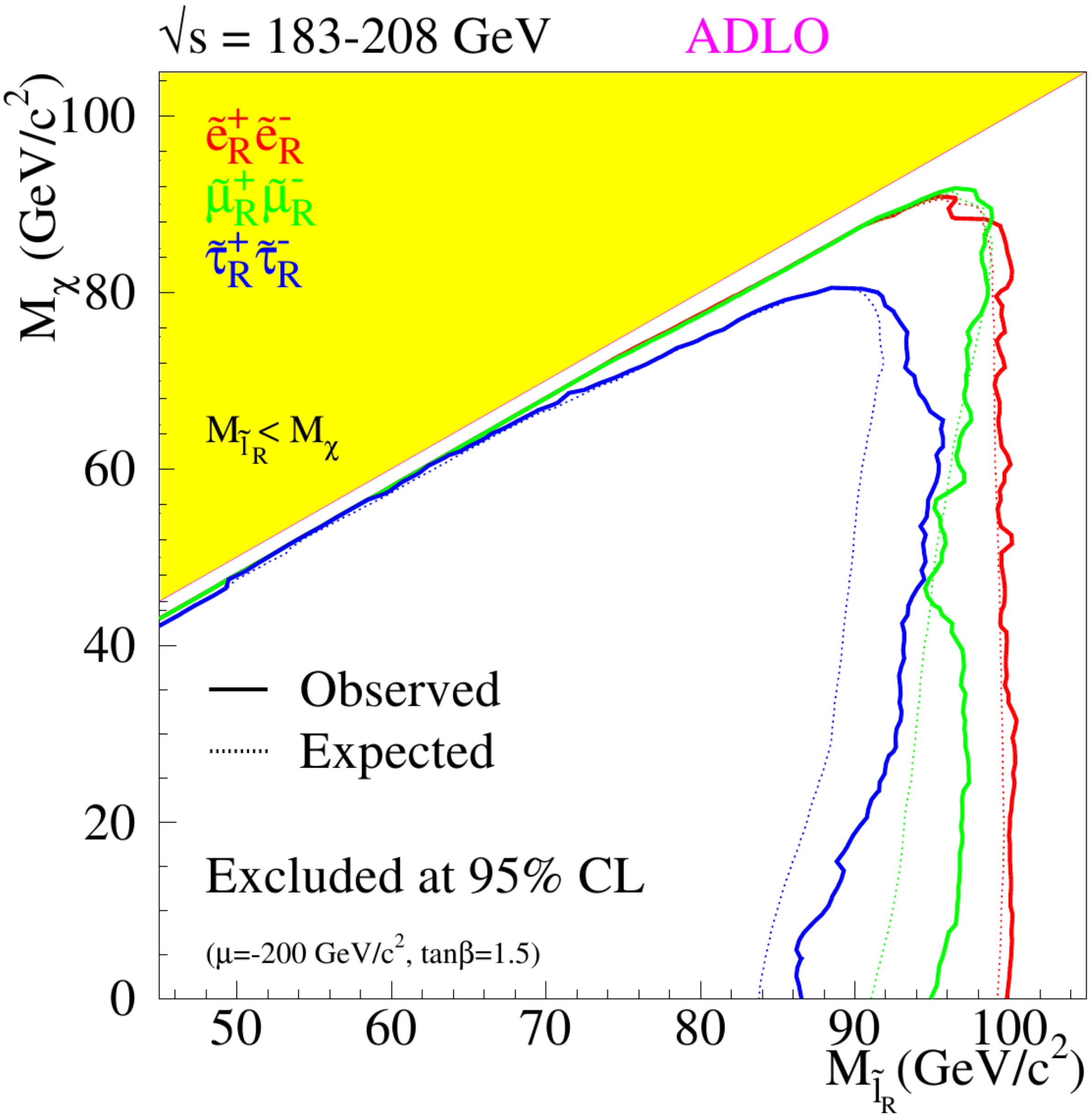


LEP limits on chargino mass





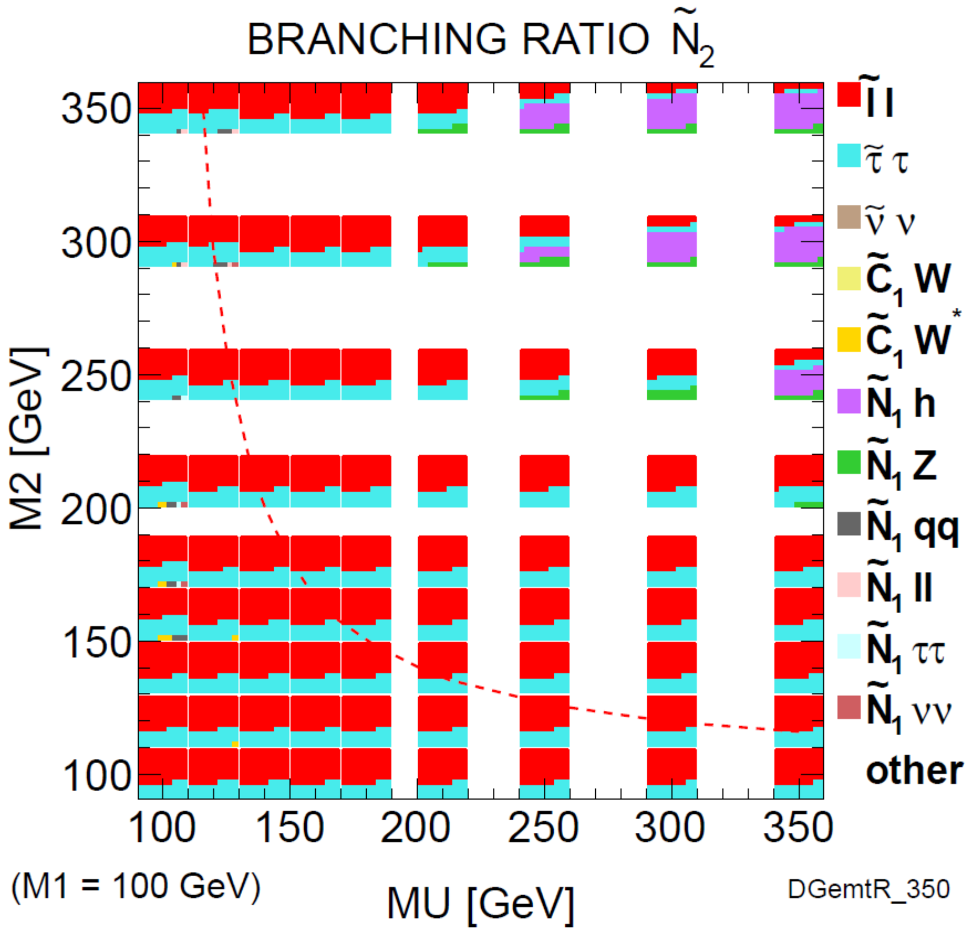
LEP limits on slepton masses

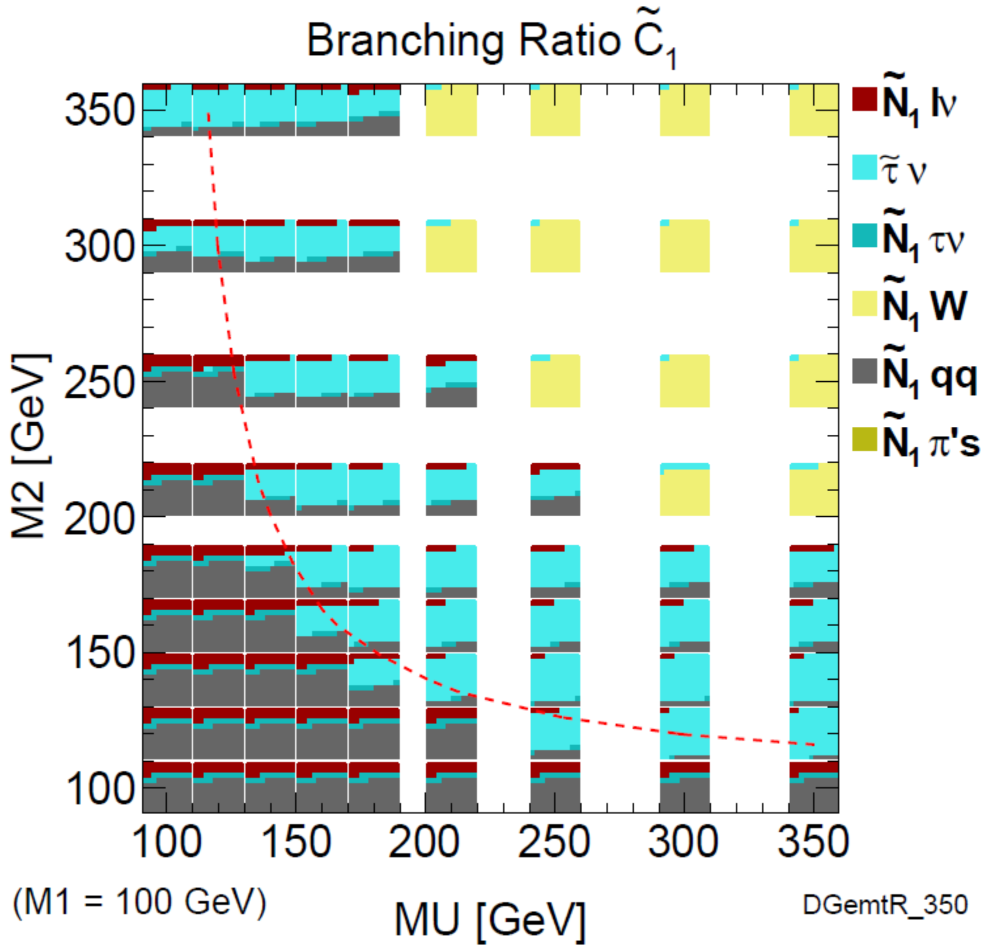


Some definitions

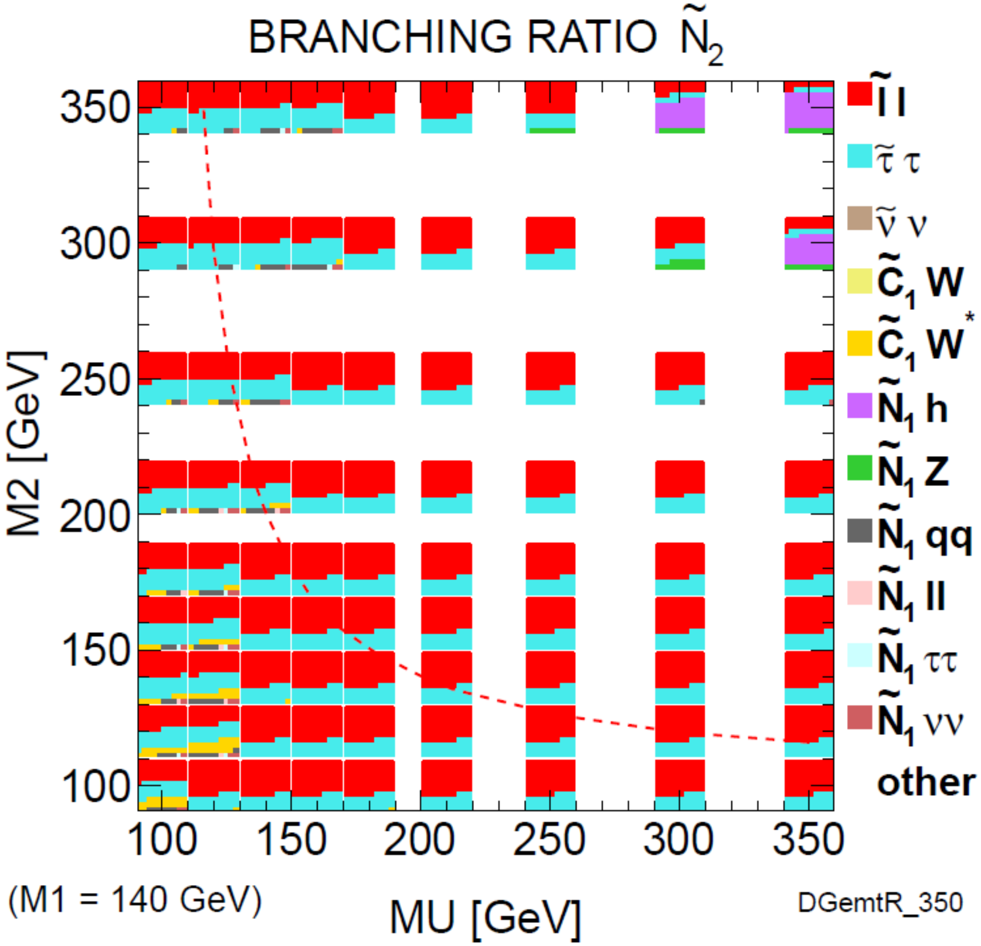
- METrel: $E_{\mathrm{T}}^{\mathrm{miss,rel.}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \times \sin\Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases}$
- mCT: $m_{\mathrm{CT}}^2(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\mathbf{p}_{\mathrm{T}}(v_1) - \mathbf{p}_{\mathrm{T}}(v_2)]^2$
- mT2: stransverse mass, relates to endpoint in processes with missing particles in the decay, *J.Phys. G29 (2003) 2343-2363, Phys.Lett. B463 (1999) 99-103*
- Notation: $(\mathrm{N}_1,\mathrm{N}_2,\mathrm{N}_3,\mathrm{N}_4) = (\tilde{\chi}_1^0, \tilde{\chi}_2^0\, \tilde{\chi}_3^0, \tilde{\chi}_4^0), \quad (\mathrm{C}_1,\mathrm{C}_2) = (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$

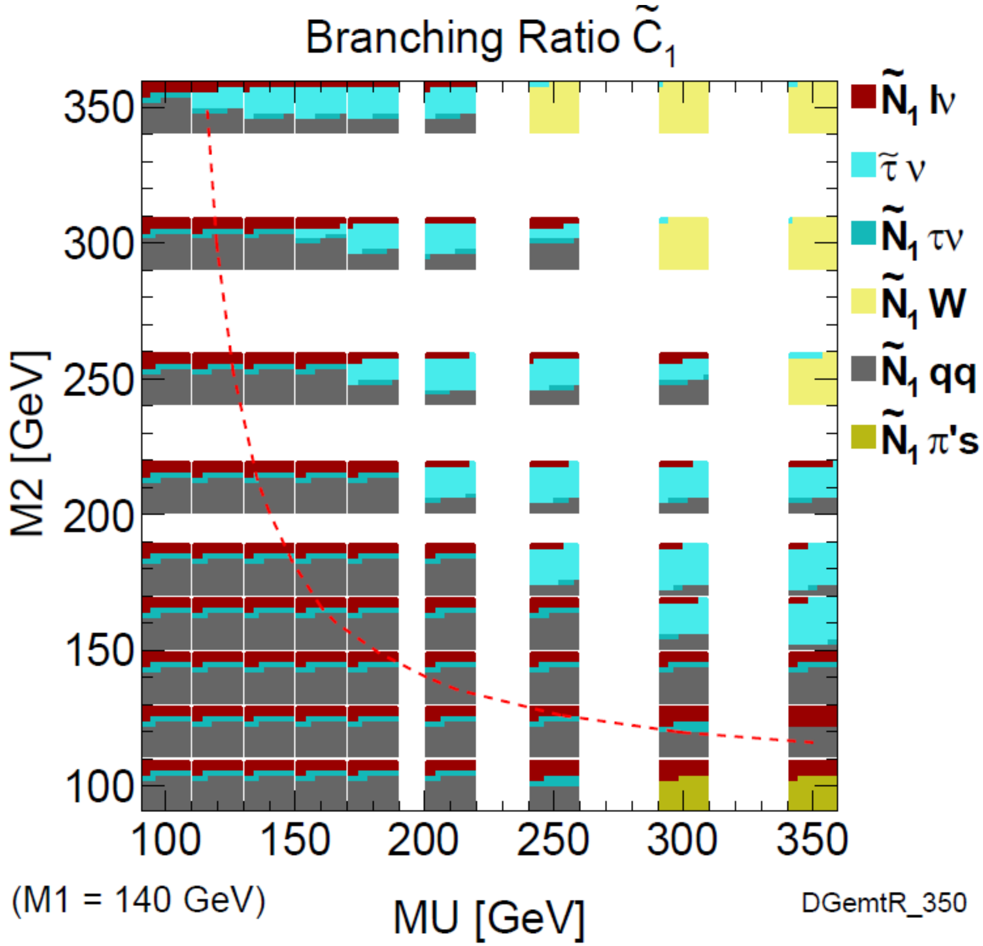
pMSSM BR of N_2 and C_1, M_1=100 GeV



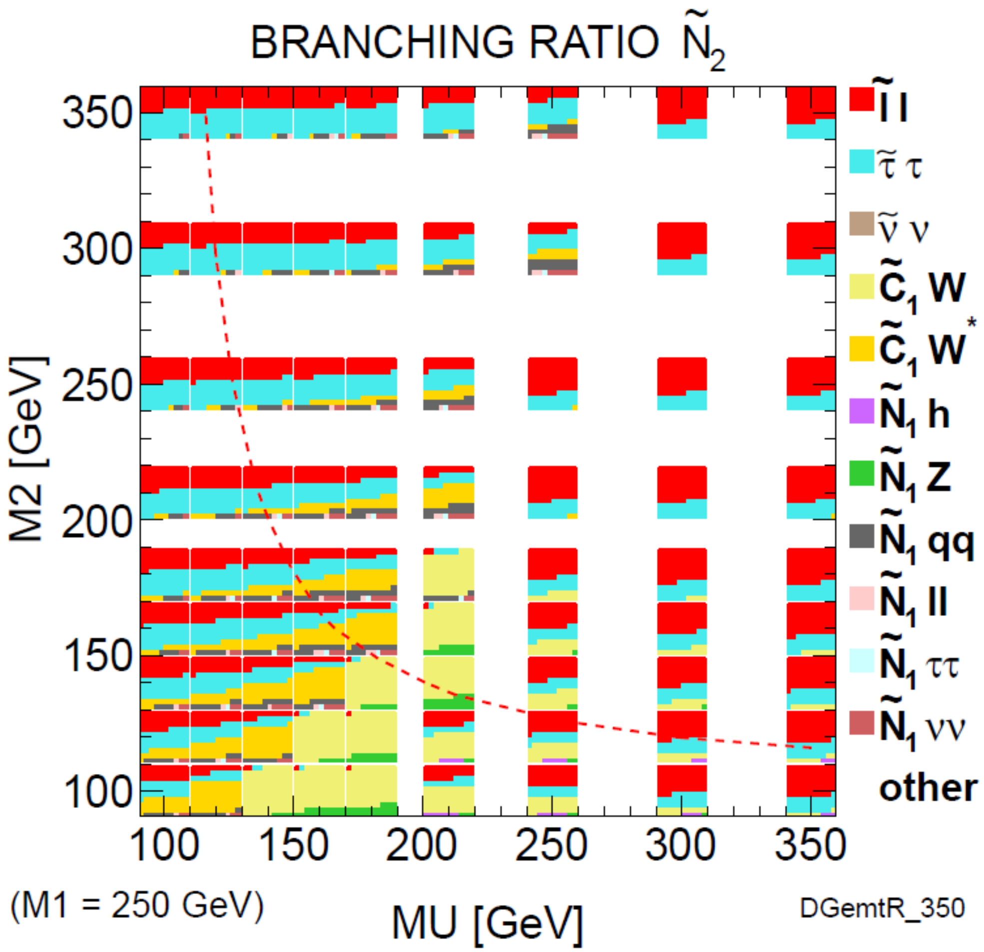


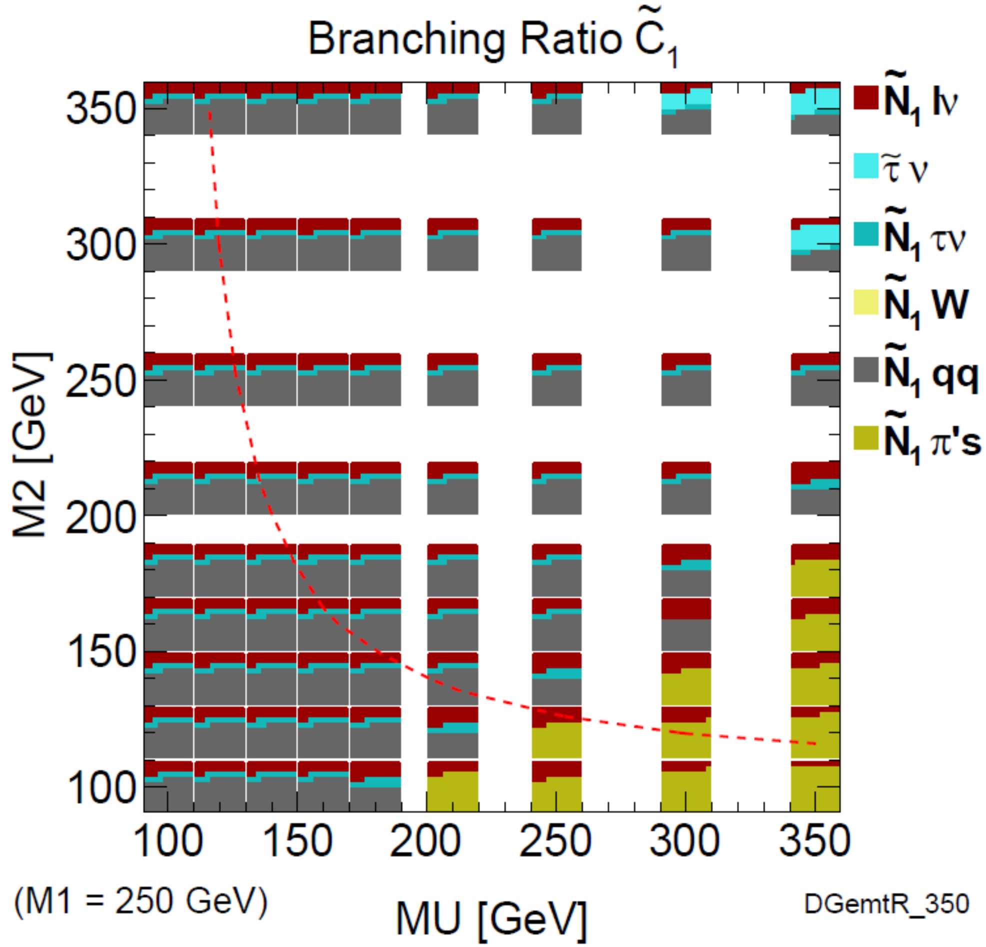
pMSSM BR of N_2 and C_1, M_1=140 GeV



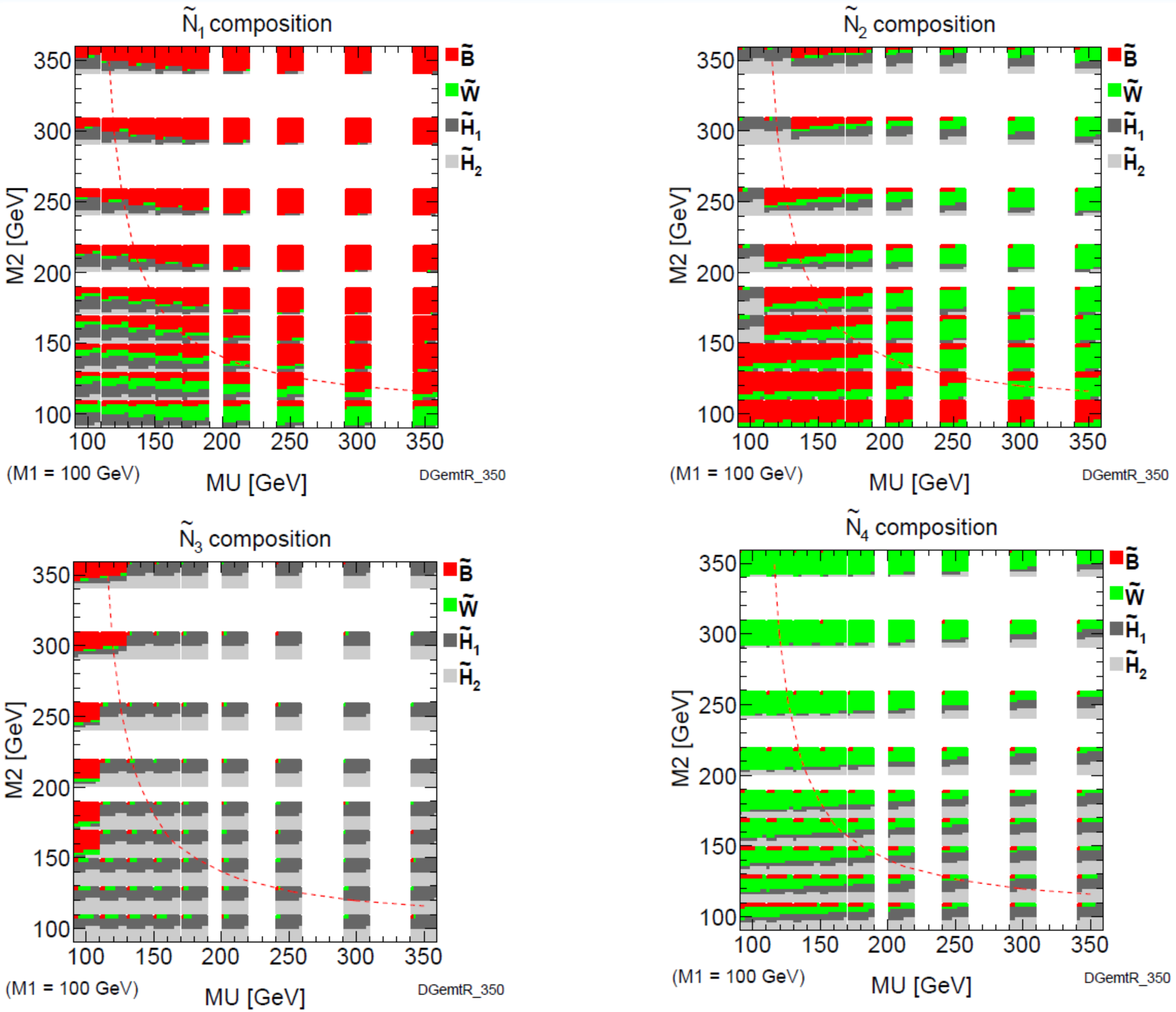


pMSSM BR of N_2 and C_1, M_1=250 GeV

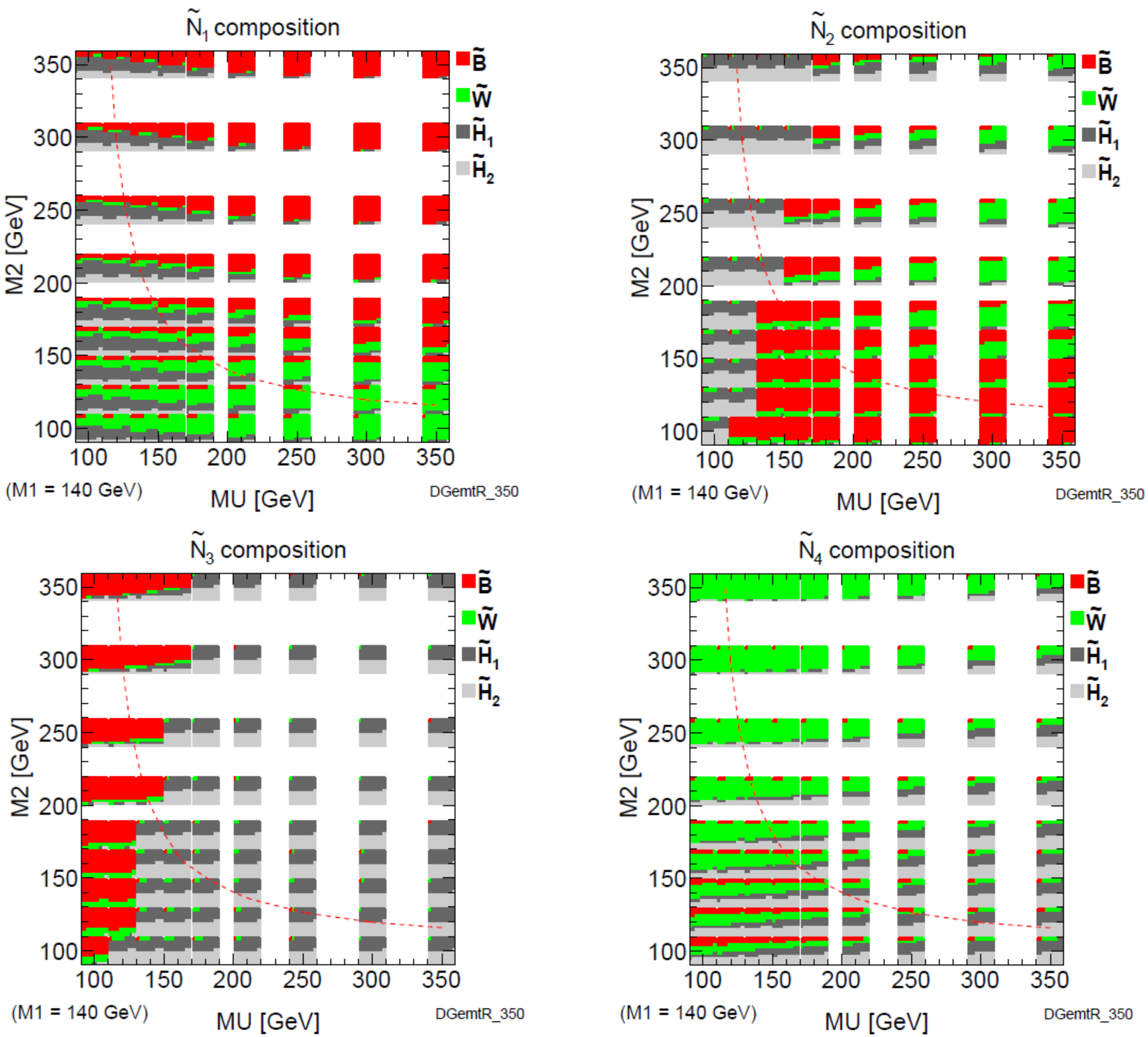




pMSSM neutralino comp. M_1=100 GeV



pMSSM neutralino comp. M_1=140 GeV



pMSSM neutralino comp. M_1=250 GeV