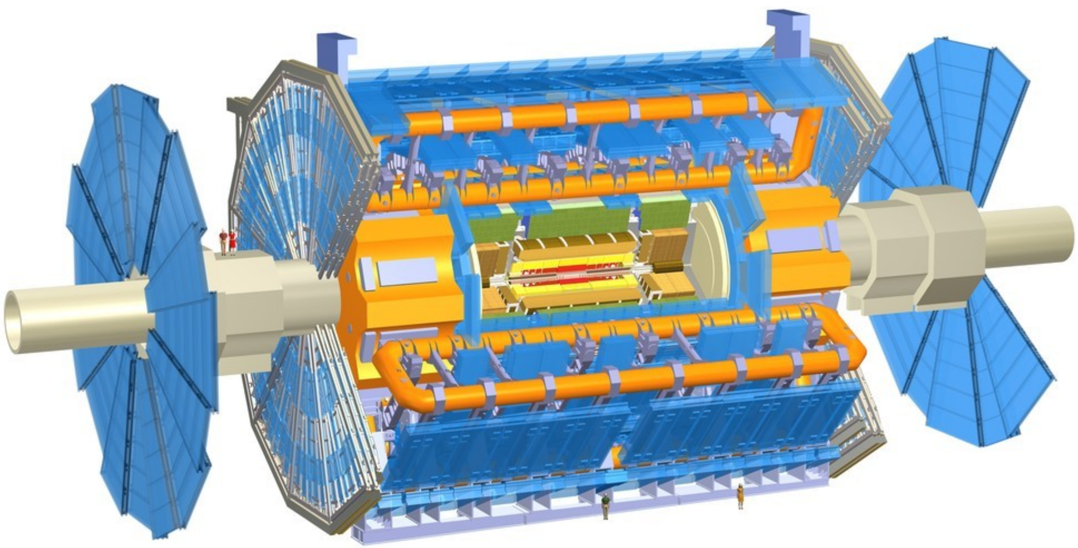
Search for Supersymmetric Partners of the Top Quark at the LHC



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Outline

Introduction to SUSY

- What is it?
- Why SUSY?
- Different models
- The stop quark

Search for the stop at the LHC

- Stop decays
- How can it be detected?
- Experimental results

The Standard Model

The SM explains so far all the experimental results.

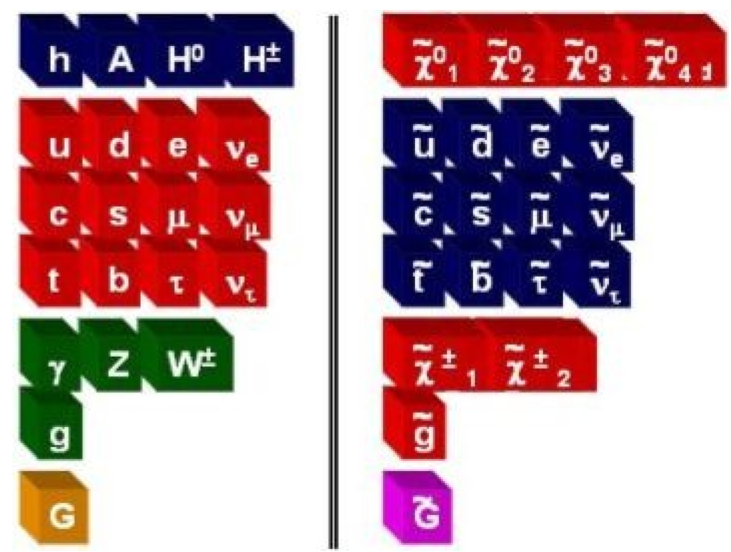
But...

- Gravity is not included
- Many input parameters
- Hierarchy problem
- Lots of unanswered questions: dark matter, three families, matter/antimatter asymmetry...

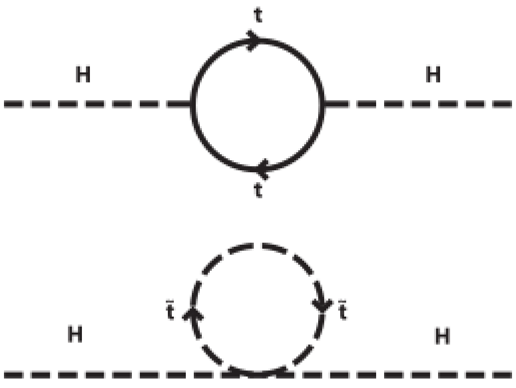
What's Supersymmetry?

- Extension of the Standard Model
- New fundamental symmetry between fermions and bosons
- New partner particles of the SM, differing by ½ in spin
- Broken symmetry

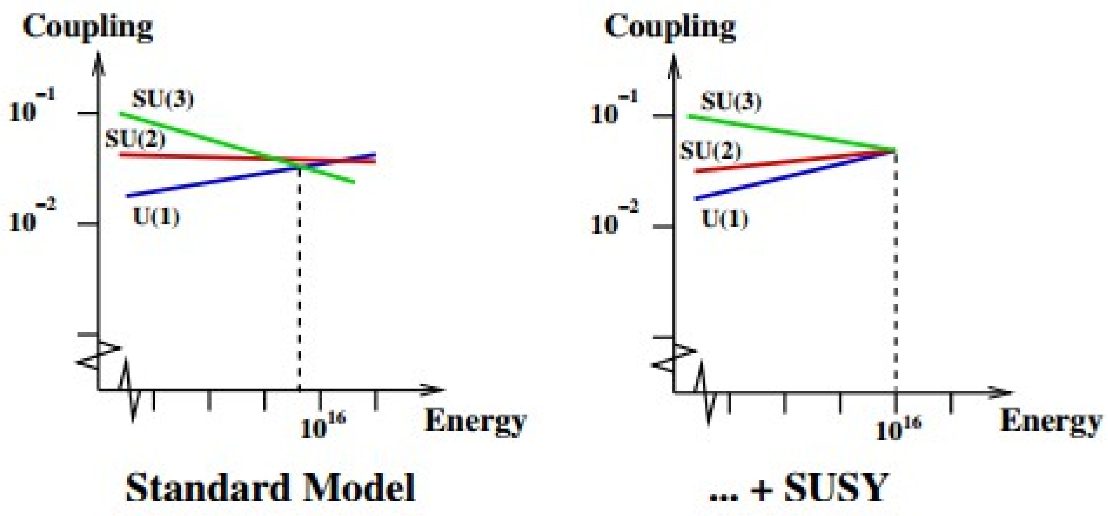
$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$



Why SUSY?



- Hierarchy problem: natural explanation of the Higgs mass, less fine tuning.
- Gauge-coupling unification
- Dark matter



SUSY models

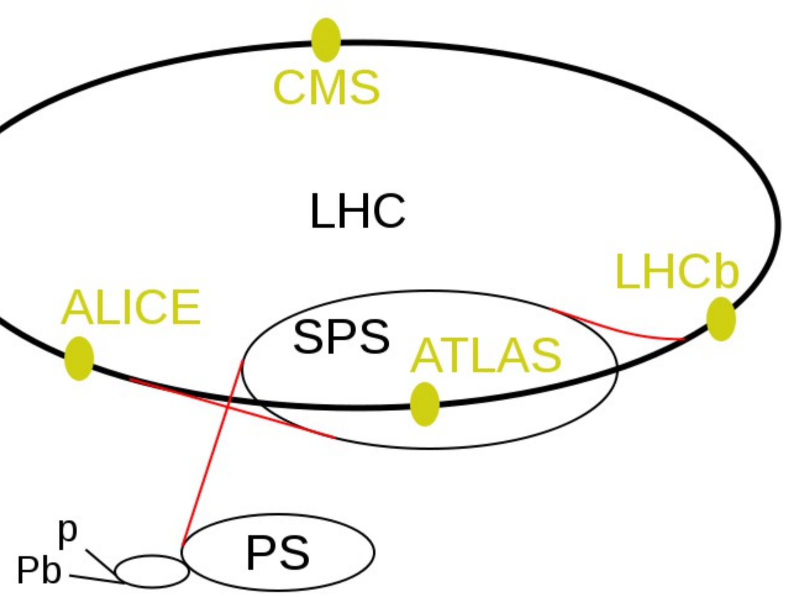
Wide variety of models, e.g.

- MSSM: most direct extension, more than 100 parameters
- mSUGRA: constrained MSSM model, gravity SUSY-breaking, 5 parameters
- Varying the parameters can still change the experimental signatures substantially

Search for the stop at the LHC

Motivation:

- The stop-top loop diagrams are the main contribution to the Higgs mass
- If the stop is light → less fine tuning necessary
- A light stop could be produced at the LHC



Particle Mixing

- Gauginos and higgsinos have the same quantum numbers → they mix

Name	Spin	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ A^0\ H^0\ H^\pm$
squarks	0	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	same
		$\tilde{c}_L\ \tilde{c}_R\ \tilde{s}_L\ \tilde{s}_R$	same
		$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	same
		$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	same
		$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	$\frac{1}{2}$	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$
charginos	$\frac{1}{2}$	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{\chi}_1^\pm\ \tilde{\chi}_2^\pm$
gluino	$\frac{1}{2}$	$\tilde{g}$	same

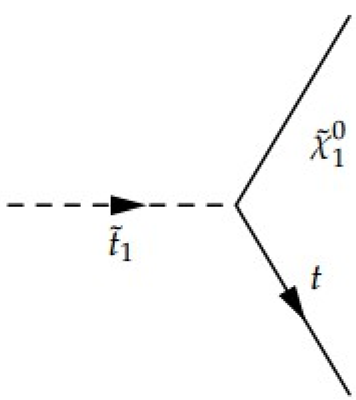
Decays

Depend on the sparticle mass spectrum and assumptions made on the SUSY model.

Try to select the ones with a higher branching ratio.

- Two body decays:

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t$$



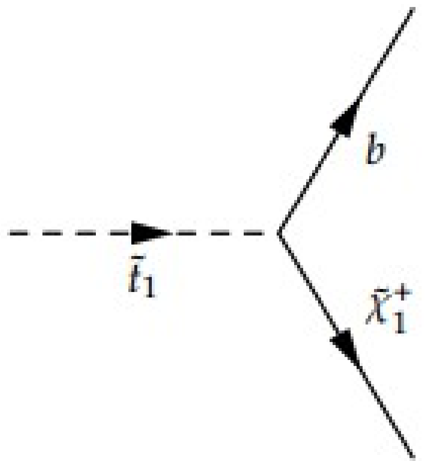
If $m_{\tilde{t}_1} > m_t + m_{\tilde{\chi}_1^0}$

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 c$$

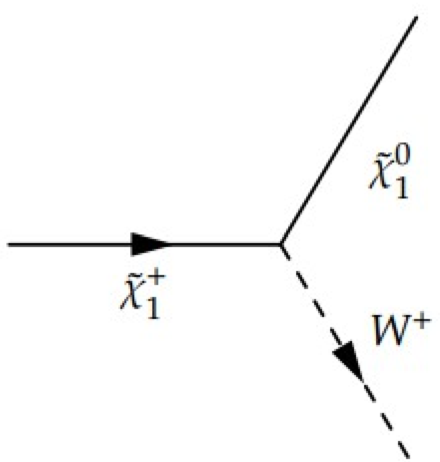
For $m_{\tilde{t}_1} < m_t$ and $m_{\tilde{t}_1} < m_{\tilde{\chi}_1^\pm} + m_b$ the only two body decay available

Decays

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$$

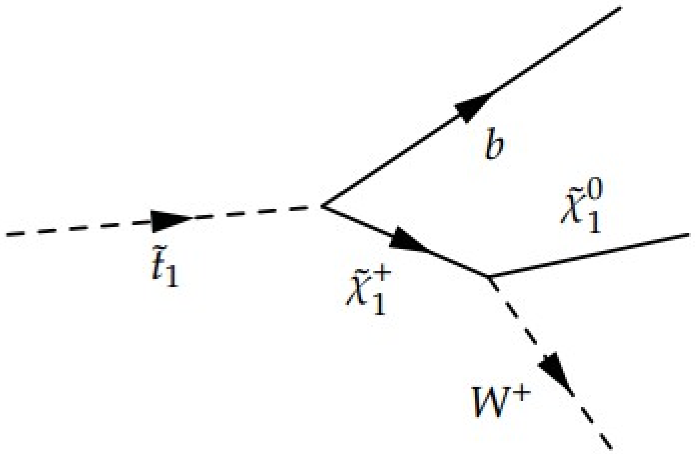


If $\quad m_{\tilde{t}_1} > m_{\tilde{\chi}_1^\pm} + m_b$



- Three-body decay:

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 W^+ b$$



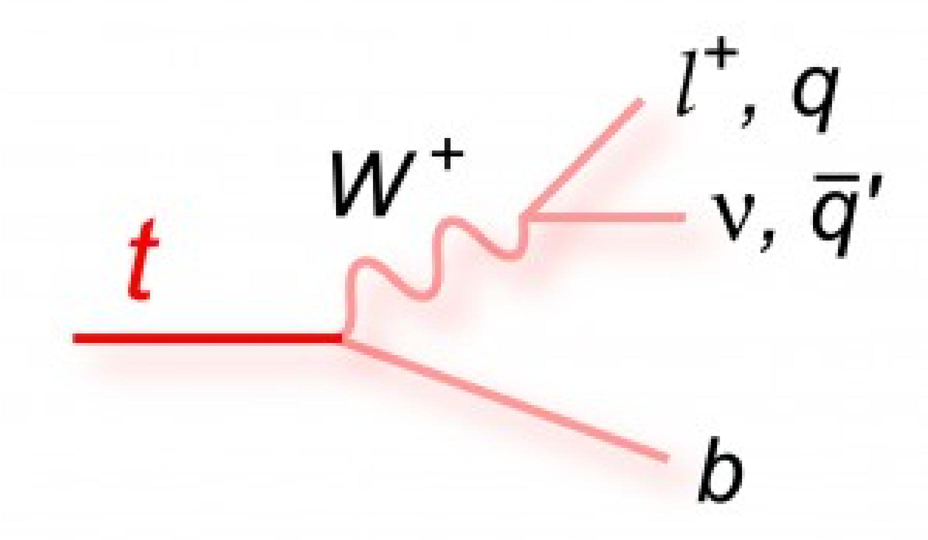
If the chargino is heavier than the stop and

$$m(W) + m(b) < m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < m(t)$$

becomes dominant

What are we looking for?

- Isolated leptons with high transverse momentum in leptonic decay channels
- Large missing transverse energy
- Jets from b-quarks



Search in final states with one isolated lepton, jets, and missing transverse momentum (ATLAS-CONF-2013-037)

- Decays considered: $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t$ and $\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$

  Chargino decays into LSP and W boson (on- or off-shell)

- Event selection:

  exactly one muon $|\eta|<2.4$ and $p_T>25$ GeV or

  one electron $|\eta|<2.47$ and $p_T>25$ GeV (isolated)

  four or more jets satisfying $|\eta|<2.5$ and $p_T>80,60,40,25$ GeV

  at least one is a b-jet

- 6 Signal regions sensitive to different stop scenarios

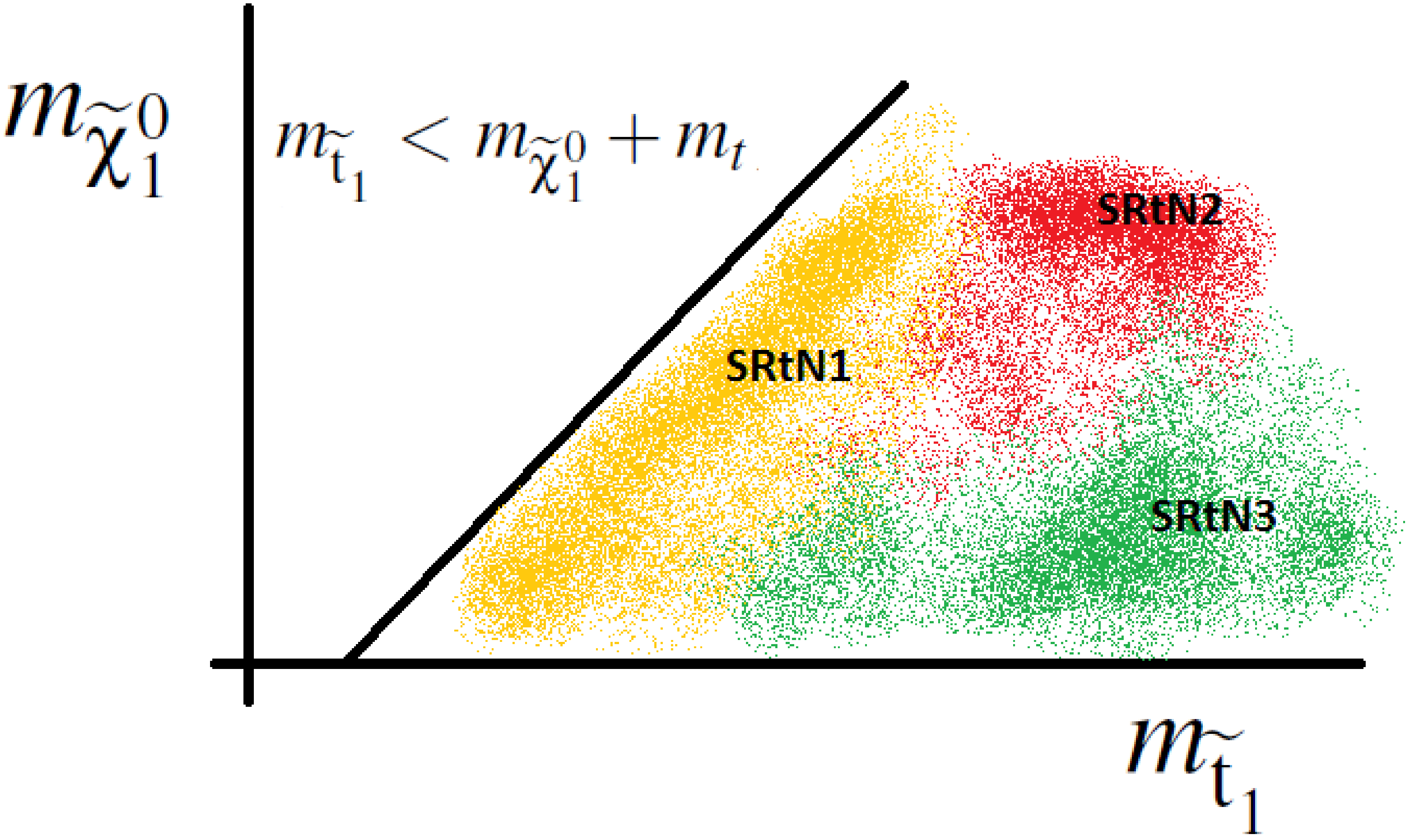
$$\eta = -ln\left[tan\left(\frac{\theta}{2}\right)\right]$$

Signal regions selection requirements

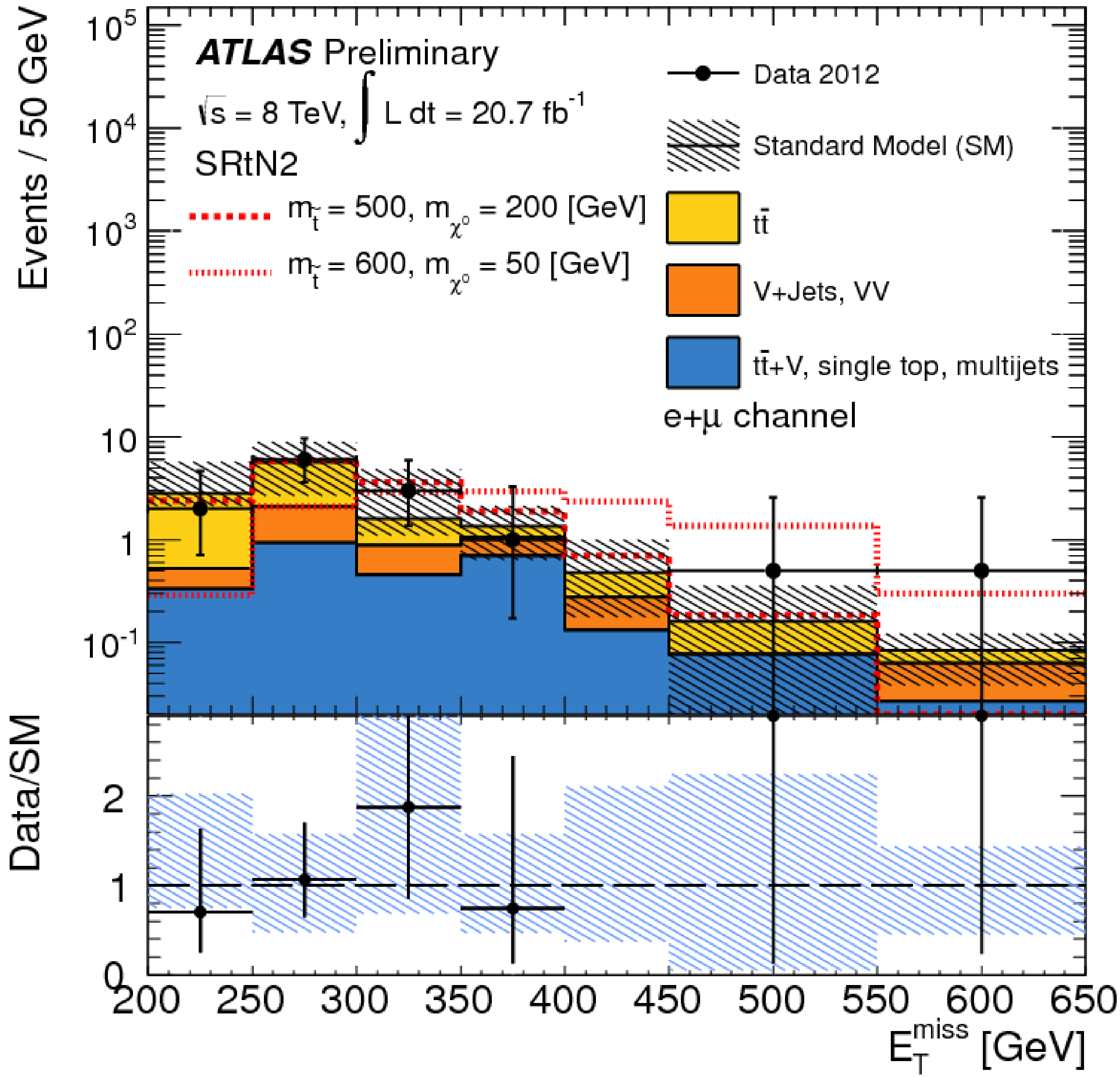
Requirement	SRtN1_shape	SRtN2	SRtN3	SRbC1	SRbC2	SRbC3
$\Delta\varphi(\text{jet}_1, \vec{p}_{\mathrm{T}}^{\text{miss}}) >$	0.8	-	0.8	0.8	0.8	0.8
$\Delta\varphi(\text{jet}_2, \vec{p}_{\mathrm{T}}^{\text{miss}}) >$	0.8	0.8	0.8	0.8	0.8	0.8
$E_{\mathrm{T}}^{\text{miss}}$ [GeV] >	$100^{(\star)}$	200	275	150	160	160
$E_{\mathrm{T}}^{\text{miss}} / \sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] >	5	13	11	7	8	8
m_{T} [GeV] >	$60^{(\star)}$	140	200	120	120	120
$\mathrm{m_{eff}}$ [GeV] >	-	-	-	-	550	700
am_{T2} [GeV] >	-	170	175	-	175	200
m_{T2}^{τ} [GeV] >	-	-	80	-	-	-
m_{jjj}	Yes	Yes	Yes	-	-	-
$N^{\text{iso-trk}} = 0$	-	-	-	Yes	Yes	Yes
Number of b-jets ≥	1	1	1	1	2	2
p_{T} (leading b-jet) [GeV] >	25	25	25	25	100	120
p_{T} (second b-jet) [GeV] >	-	-	-	-	50	90

$$m_T^2 = 2\, p_T^{lep} E_T^{miss} \left(1 - cos\left(\Delta\varphi\right)\right)$$

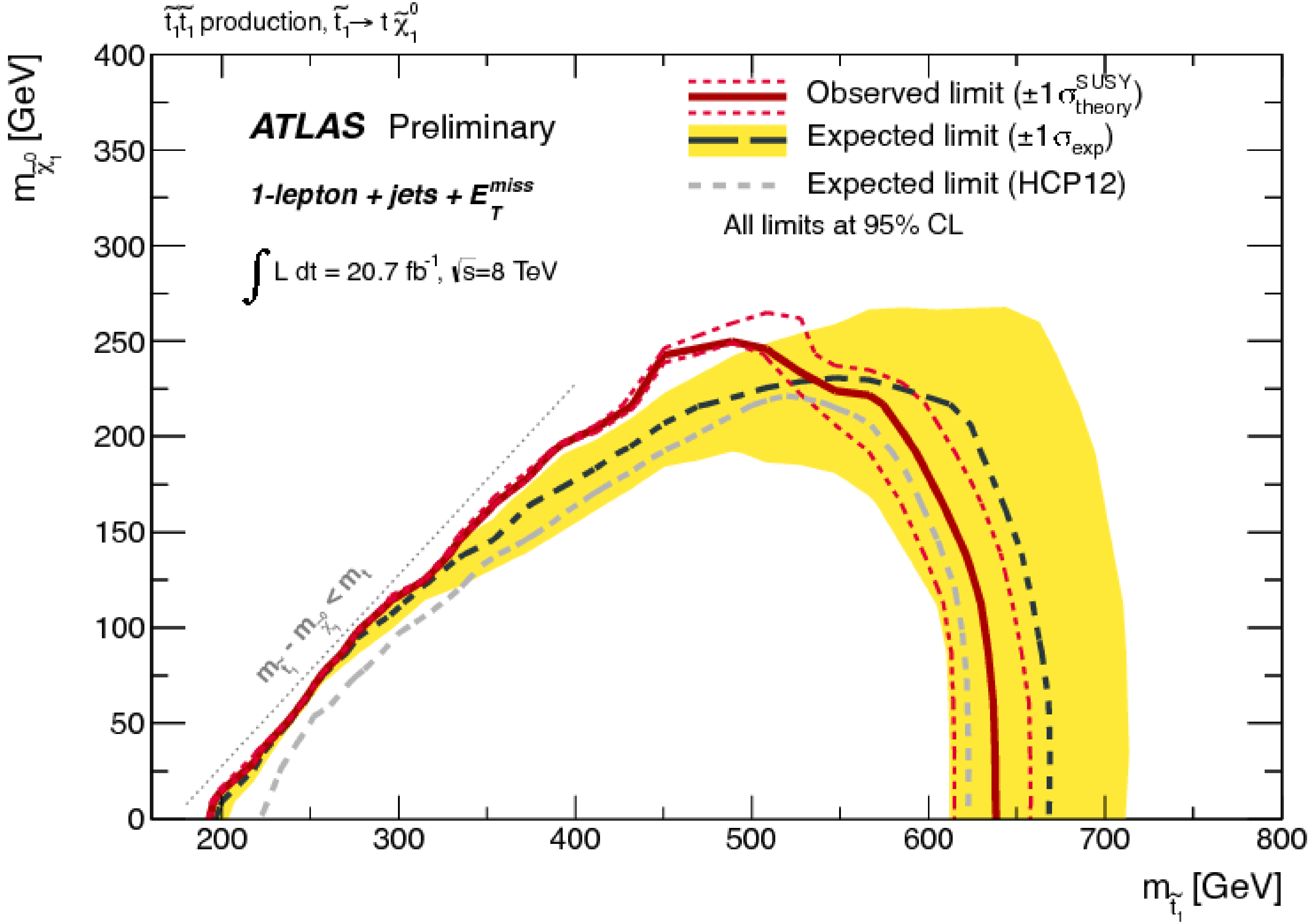
$$m_T^2 = (E_{T1} + E_{T2})^2 - (p_{T1} + p_{T2})^2$$



$m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_t$
SRtN2
SRtN1
SRtN3
$m_{\tilde{t}_1}$



ATLAS Preliminary
√s = 8 TeV, ∫ L dt = 20.7 fb-1
SRtN2
m t̃ = 500, m χ° = 200 [GeV]
m t̃ = 600, m χ° = 50 [GeV]
Data 2012
Standard Model (SM)
tt̄
V+Jets, VV
tt̄+V, single top, multijets
e+μ channel
Events / 50 GeV
Data/SM
E T miss [GeV]



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to t\,\tilde{\chi}^0_1$
ATLAS Preliminary
1-lepton + jets + E_T^{miss}
$\int L\,dt = 20.7\ fb^{-1}$, $\sqrt{s}$=8 TeV
Observed limit ($\pm 1\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\sigma_{exp}$)
Expected limit (HCP12)
All limits at 95% CL
$m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1} < m_t$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
400
200
300
400
500
600
700
800

Search in final states with two leptons
(ATLAS-CONF-2013-048)

- Decays considered:

  $\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$ with the subsequent decay $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W$

  $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 W^+ b$ if the chargino is heavier than the stop

- Requirments:

  Electrons and muons p_T>10 GeV and $|\eta|<2.47$ / $|\eta|<2.4$ respectively

  Exactly two leptons, at least one p_T>25 GeV, invariant mass of both >20 GeV

  Opposite charge
  Jets p_T>20 GeV and $|\eta|<2.5$

- Background:

  Z boson → invariant mass of SF lepton pairs outside 71-111 GeV
  Z/γ^* + jets → m_{T2} > 40 GeV
  top-antitop → m_{T2} distribution endpoint at the W boson mass

Signal regions

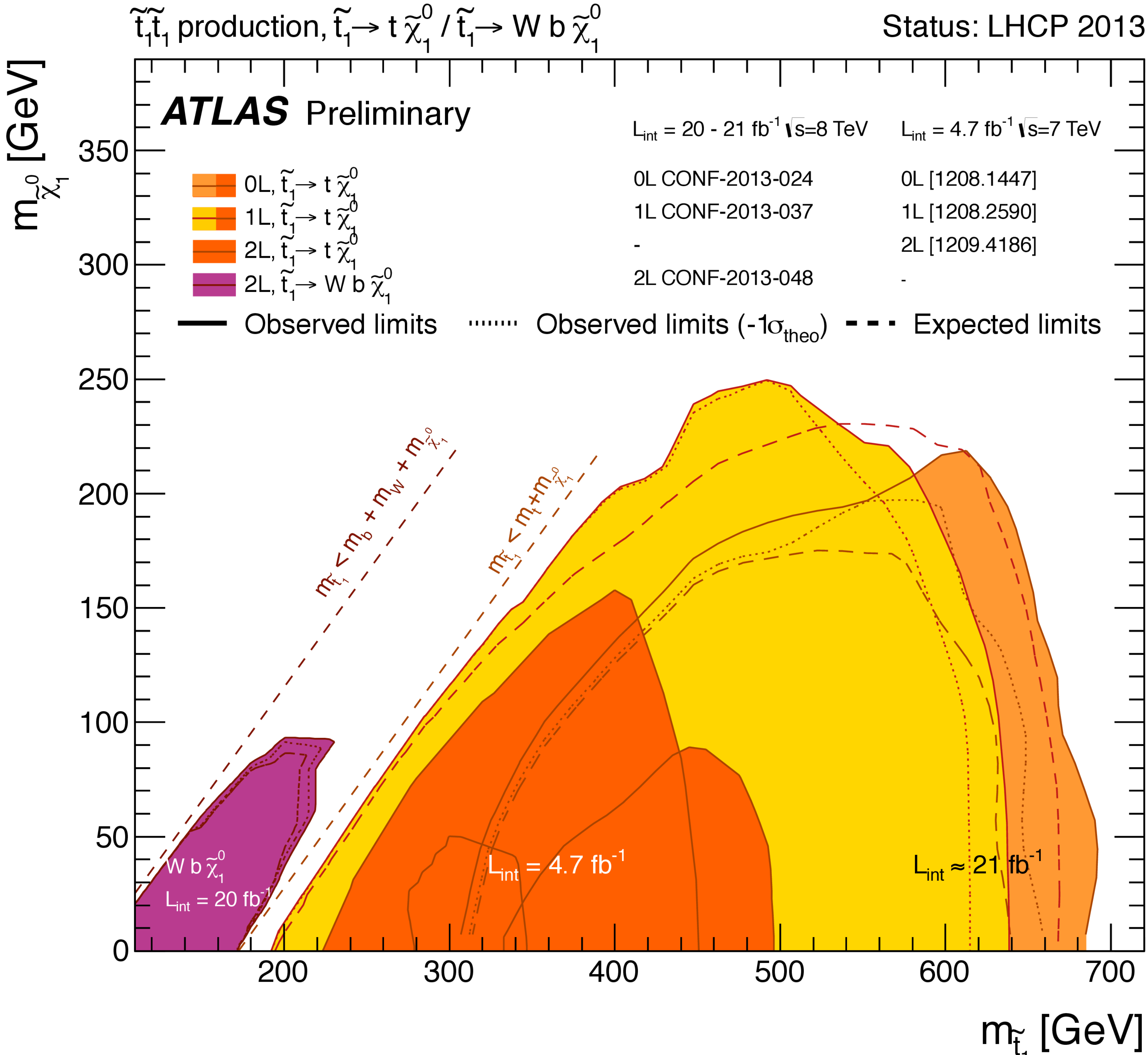
- 4 signal regions defined:

  M90: small $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^+}$, no high p_T jets expected

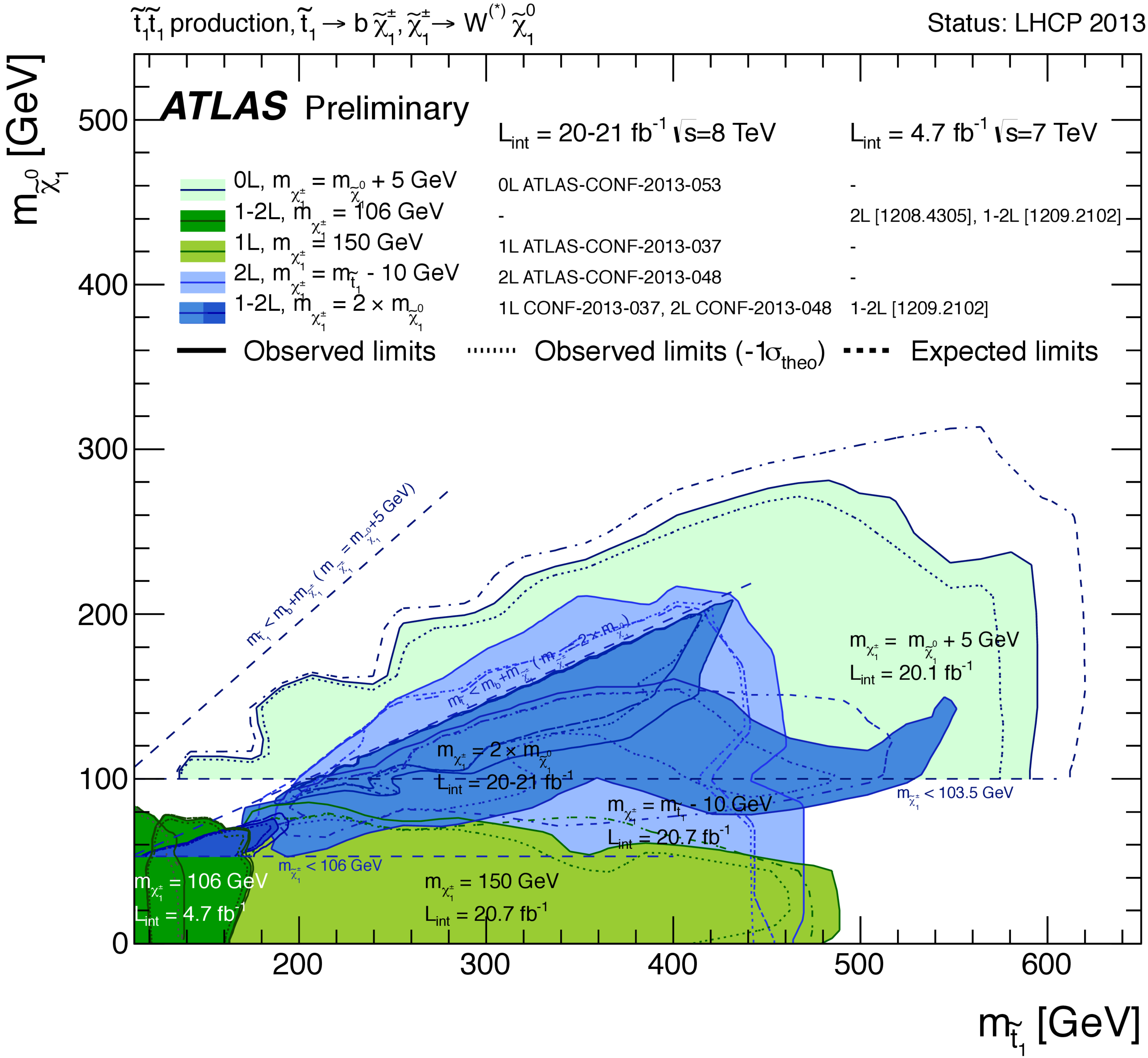
  M100: large $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^+}$ and $m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}$

  M110 and 120: small/moderate $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^+}$

SR	M90	M100	M110	M120
p_T leading lepton	> 25 GeV			
$\Delta\phi(E_T^{miss}$, closest jet) $\Delta\phi(E_T^{miss}$, $p_{Tb}^{\ell\ell})$	> 1.0 < 1.5			
m_{T2}	> 90 GeV	> 100 GeV	> 110 GeV	> 120 GeV
p_T leading jet p_T second jet	no selection no selection	> 100 GeV > 50 GeV	> 20 GeV > 20 GeV	> 20 GeV > 20 GeV

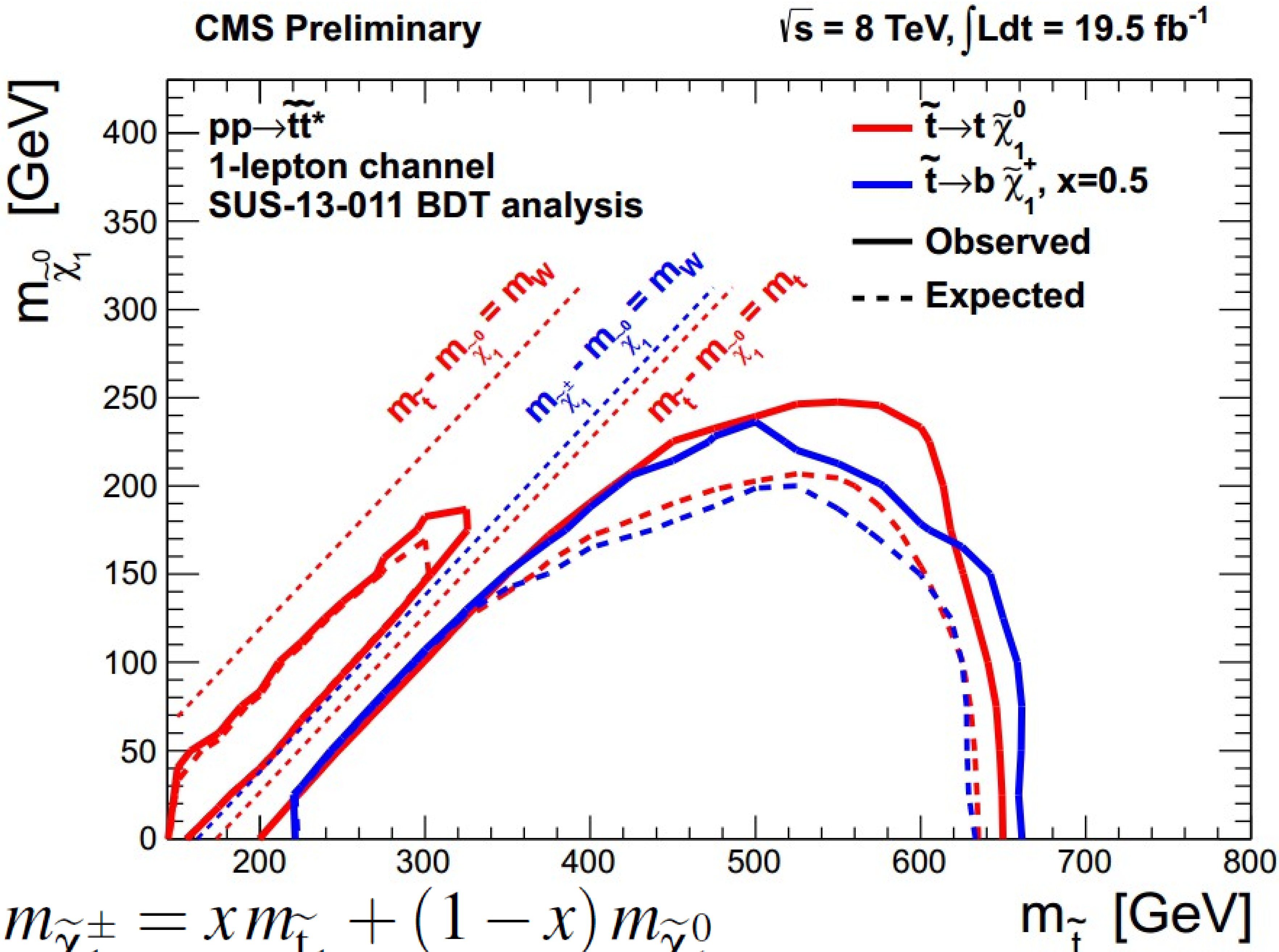


$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$
Status: LHCP 2013
ATLAS Preliminary
L_{int} = 20 - 21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
1L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
2L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
2L, $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$
0L CONF-2013-024
1L CONF-2013-037
-
2L CONF-2013-048
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
-
Observed limits
Observed limits (-1σ_{theo})
Expected limits
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$W\,b\,\tilde{\chi}_1^0$
L_{int} = 20 fb^{-1}
L_{int} = 4.7 fb^{-1}
$L_{int} \approx$ 21 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
200
300
400
500
600
700



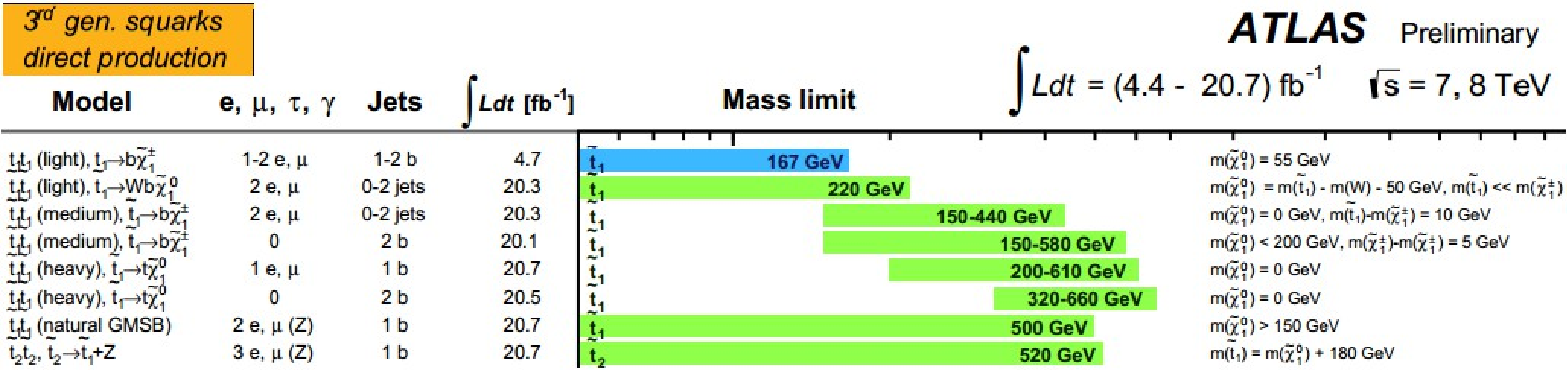
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \rightarrow W^{(*)}\,\tilde{\chi}_1^0$
Status: LHCP 2013
ATLAS Preliminary
L_{int} = 20-21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L, $m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_1^0}$ + 5 GeV
0L ATLAS-CONF-2013-053
-
1-2L, $m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV
-
2L [1208.4305], 1-2L [1209.2102]
1L, $m_{\tilde{\chi}_1^{\pm}}$ = 150 GeV
1L ATLAS-CONF-2013-037
-
2L, $m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{t}_1}$ - 10 GeV
2L ATLAS-CONF-2013-048
-
1-2L, $m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$
1L CONF-2013-037, 2L CONF-2013-048
1-2L [1209.2102]
Observed limits
Observed limits (-1σ_{theo})
Expected limits
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^{\pm}}$ ($m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_1^0}$+5 GeV)
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^{\pm}}$ ($m_{\tilde{\chi}_1^{\pm}}$ = 2 × $m_{\tilde{\chi}_1^0}$)
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_1^0}$ + 5 GeV
L_{int} = 20.1 fb^{-1}
$m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 20-21 fb^{-1}
$m_{\tilde{\chi}_1^{\pm}}$ < 103.5 GeV
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{t}_1}$ - 10 GeV
L_{int} = 20.7 fb^{-1}
$m_{\tilde{\chi}_1^{\pm}}$ < 106 GeV
$m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV
L_{int} = 4.7 fb^{-1}
$m_{\tilde{\chi}_1^{\pm}}$ = 150 GeV
L_{int} = 20.7 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
500
200
300
400
500
600
$m_{\tilde{t}_1}$ [GeV]

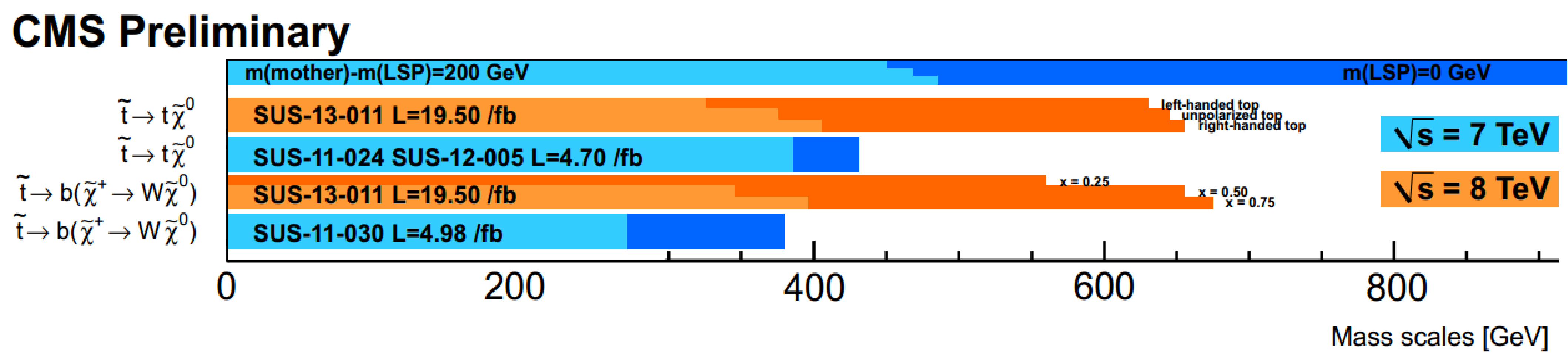
CMS Results



$$m_{\tilde{\chi}_1^{\pm}} = x\, m_{\tilde{t}_1} + (1-x)\, m_{\tilde{\chi}_1^0}$$

Conclusions





Next pp collisions at 14 TeV scheduled for the beginning of 2015...