ATLAS 3rd Generation $\tilde{q}$ searches

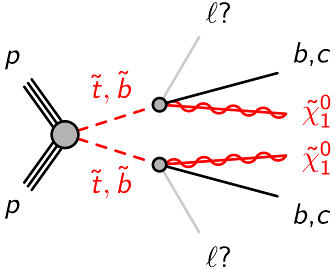
Dan Guest

Atlas Collaboration

November 19, 2013

Introduction

- Light $\tilde{t}$, $\tilde{b}$ cancel m_H t corrections, needed for naturalness
- No need for all SUSY particles to be light
- Dark Matter candidate provided by LSP ($\tilde{\chi}_1^0$ or $\tilde{G}$)
- Focuses on simplified direct production here (see Alexandra's talk for $\tilde{g}$-mediated)

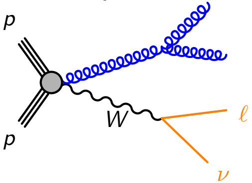


- Typical 3rd generation SUSY searches look for:
  - jets, usually heavy-flavor (can b- or c-tag)
  - invisible particles (large $E_{\mathrm{T}}^{\mathrm{miss}}$)
  - (sometimes) leptons

Backgrounds

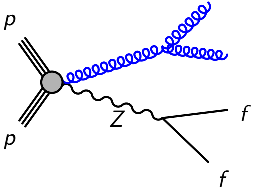
- Many SM processes look similar to $E_{\mathrm{T}}^{\mathrm{miss}} + b\text{-jets} + \{0, 1, 2\}\ell$
- Some can be reduced:

$W + \text{jets}$



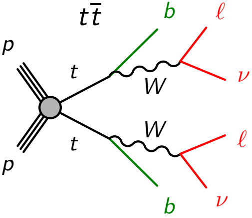
- tagging
- m_{T}

$Z + \text{jets}$



- tagging

$t\bar{t}$



- m_{T2}
- c-tagging

- Also more difficult combinations: VV, VVV, Vt, $t\bar{t}V$

$\tilde{t}$ vs. $\tilde{\chi}_1^0$ mass plane

Assuming $m_{\tilde{\chi}_1^\pm} > m_{\tilde{t}_1}$, 3 decays:

- High $\Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$: t onshell
  $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$
- Medium Δm: W onshell
  3-body decay, to $b + W + E_{\mathrm{T}}^{\mathrm{miss}}$
- Low Δm: W offshell
  decay to c jets $+ E_{\mathrm{T}}^{\mathrm{miss}}$ or via 4-body $\tilde{t} \to bff\tilde{\chi}_1^0$

For $m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}}$, $\tilde{\chi}_1^\pm$ is on-shell:

- $\tilde{t} \to b + \tilde{\chi}_1^\pm \quad \tilde{\chi}_1^\pm \to W + \tilde{\chi}_1^0$ is also possible
- Final objects similar, different kinematics.

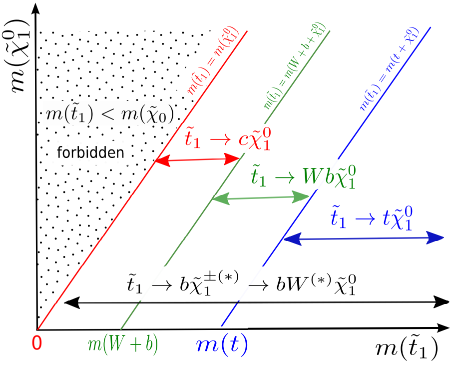
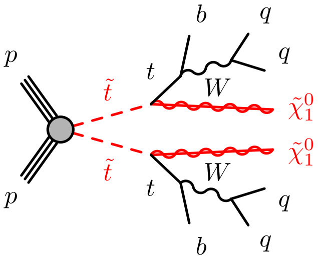
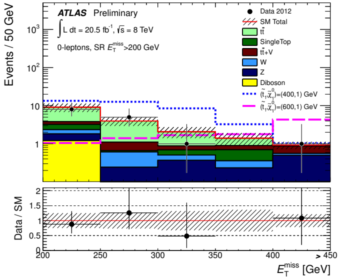
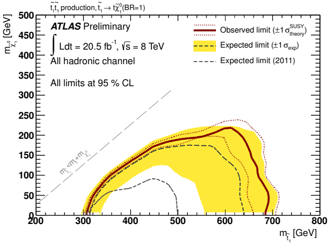


Fig Credit: Antoine Marzin

High Δm: $\tilde{t} \to t + \tilde{\chi}_1^0$ (0 lepton) ATLAS-CONF-2013-024

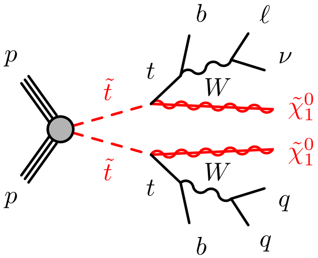


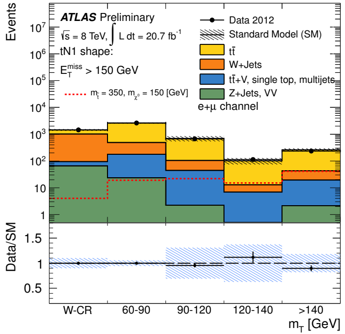


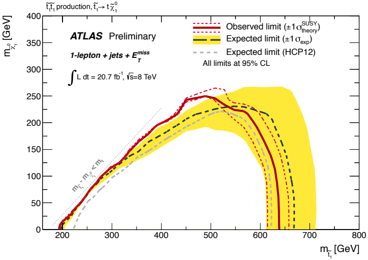


- Hadronic $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ selection:
  - 6 or more jets
  - 2 b-tags
  - both t: $|m_{jjj} - m_t| < 95$ GeV
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
- Main background: one hadronic t, one $t \to b + \tau + \nu$ where τ fakes jet

High Δm: $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ (1 lepton) ATLAS-CONF-2013-037

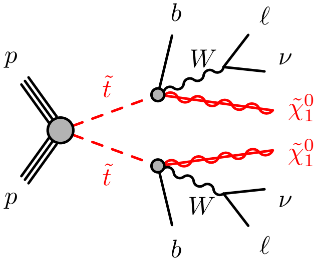


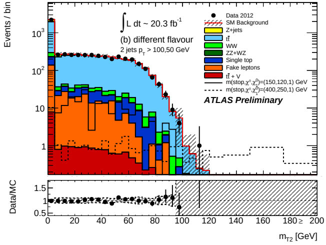


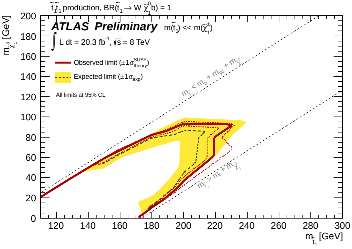


- Semi-leptonic $t\bar{t}$ + $E_{\mathrm{T}}^{\mathrm{miss}}$ selection:
  - 4 or more jets
  - 1 b-tag
  - 130 GeV $< m_{jjj} <$ 205 GeV
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV or "shape fit"
  - $m_{\mathrm{T}} > 140$ or shape fit
  - m_{T2} (many variants)
- exc depends on $\tilde{t}_{\mathrm{L}}$ vs. $\tilde{t}_{\mathrm{R}}$ (see slide 24)

Medium Δm, 3-body decay (2 lepton)

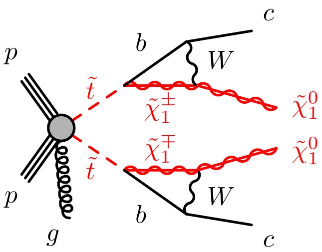


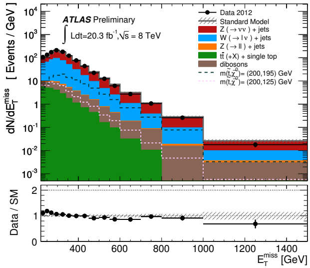


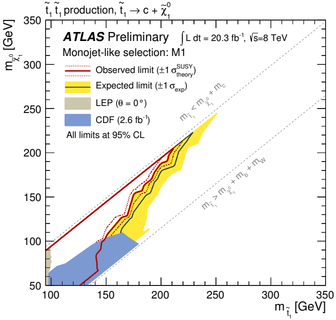


- $\tilde{t} \to t$ no longer allowed
- Select high m_{T2} to cut out $t\bar{t}$ background.
- ATLAS-CONF-2013-048
- Search mainly focused on models with light $\tilde{\chi}_1^{\pm}$ (more later)

Low Δm: "Monojet-like": ATLAS-CONF-2013-068

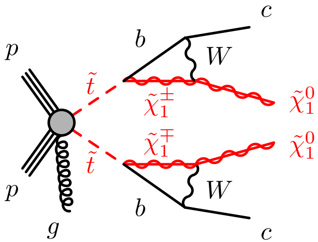


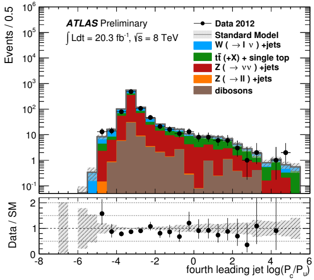


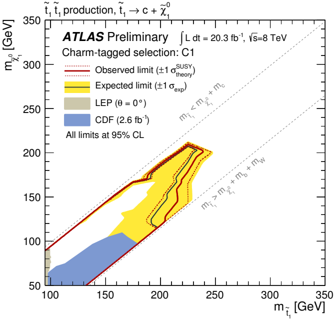


- Very little $E_{\mathrm{T}}^{\text{miss}}$ without ISR
- $p_{\mathrm{T}}^{\text{ISR}} > 280\,\text{GeV}$
- Balanced by large $E_{\mathrm{T}}^{\text{miss}}$:
  - Require $E_{\mathrm{T}}^{\text{miss}} > 220\,\text{GeV}$
  - $p_{\mathrm{T}}^{\text{ISR}}$ doesn't exactly balance $E_{\mathrm{T}}^{\text{miss}}$ because of *c*-jets

Low Δm: c-tagged







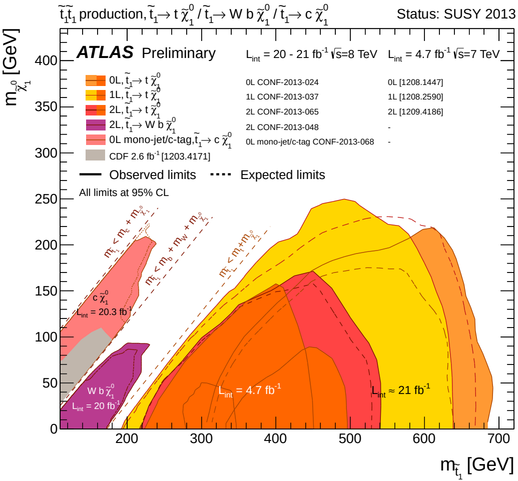
- For $\Delta m \gtrsim 20\,\text{GeV}$, c-jets are tagged
- Conceptually very similar to b-tagging:
  - Neural net gives P_b,P_c, $P_{u\in\{u,d,s,g\}}$
  - anti-b selection: $P_c/P_b > X$
  - anti-light selection: $P_c/P_u > Y$

medium OP: $\epsilon_c \approx 0.2$, $1/\epsilon_b \approx 8$, $1/\epsilon_u \approx 200$

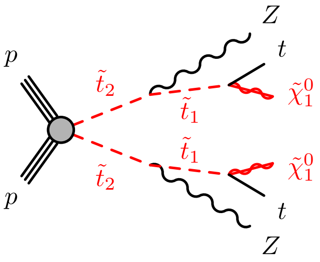
Part 1 Summary: $m_{\tilde{t}} < m_{\tilde{\chi}_1^{\pm}}$ results

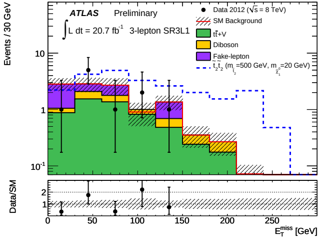
- ATLAS excludes large piece of (simplified model) $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{t}}$ plane
- most of $m_{\tilde{\chi}_1^0} < 200\,\text{GeV}$, $m_{\tilde{t}} < 650\,\text{GeV}$ excluded (assuming 100% BR)

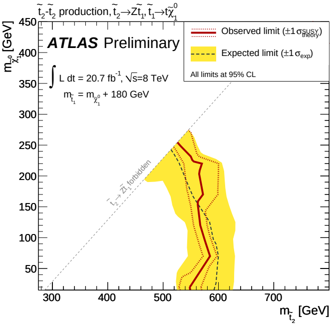
- Gaps around $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \approx m_t$: signal nearly identical to $t\bar{t}$
- Region can be covered by $\tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ (see slide 12)



$\tilde{t}_2 \to t + Z + \tilde{\chi}_1^0$: ATLAS-CONF-2013-025



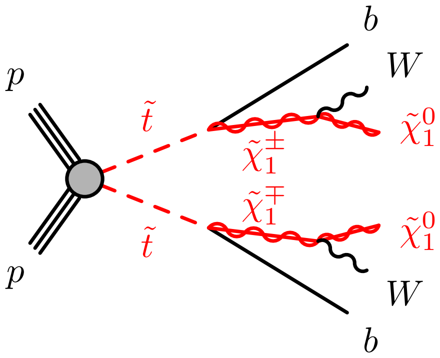




- Designed to fill the $\Delta m \approx m_t$ "gap"
- High p_{T} Z required:
  $|m_{\ell\ell} - m_Z| < 10\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\ell\ell} > 75\,\mathrm{GeV}$
- Also interpretted in a GMSB stop scenario (see slide 25).

Light $\tilde{\chi}_1^\pm$ models

- $m_{\tilde{t}} > m_{\tilde{\chi}_1^\pm} > m_{\tilde{\chi}_1^0}$ allows $\tilde{t} \to b + \tilde{\chi}_1^\pm$
- Final states share objects (but not always kinematics) with $\tilde{t} \to t + \tilde{\chi}_1^0$
- Signal grids also become 3d, thus much more expensive



- In practice, we slice through $(m_{\tilde{t}}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$ space in a few ways:
  - Fix $m_{\tilde{\chi}_1^\pm} = X$ ($X \sim 200$, GeV)
  - Set $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
  - Set $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + X$ ($X \sim 5$ GeV)
  - Fix $m_{\tilde{t}} \sim 300$ GeV, plot $m_{\tilde{\chi}_1^\pm}$ vs. $m_{\tilde{\chi}_1^0}$
  - etc.

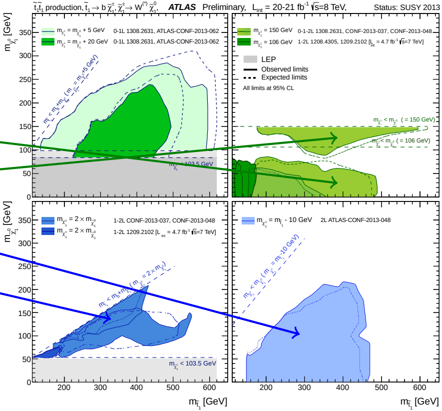
$\tilde{t} \to \tilde{\chi}_1^\pm + b$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + W$

Many of the analyses already shown also give limits in this scenario:

- 1L: $m_{\tilde{\chi}_1^\pm} = 150$ GeV upper right, see slide 7
- 3-body: see slide 8
  - $m_{\tilde{\chi}_1^\pm} = 150$ GeV
  - $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}} - 10$ GeV
  - $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$

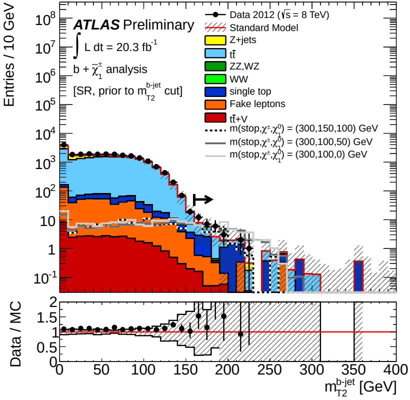
Also some earlier results:

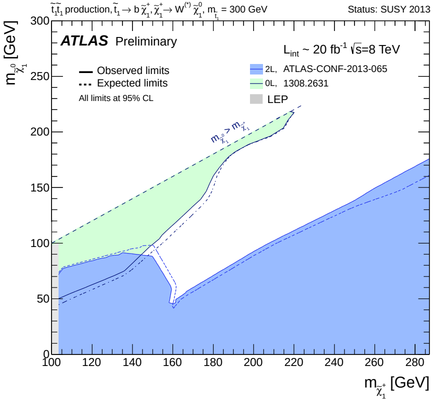
- 0L: arXiv:1308.2631 see slide 16
- 1–2L: arXiv:1208.4305 arXiv:1209.2102



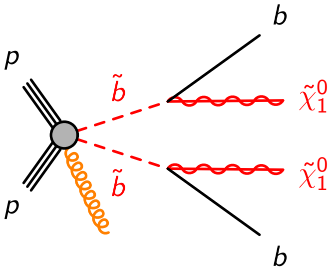
$\tilde{t} \to \tilde{\chi}_1^\pm + b$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + W$: $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{\chi}_1^\pm}$ plane

- $\tilde{t} \to b + \tilde{\chi}_1^\pm$ version of 2 lepton search (see slide 8)
  - Select events with high $m_{T2}^{b\text{-jet}}$ (no BDT)





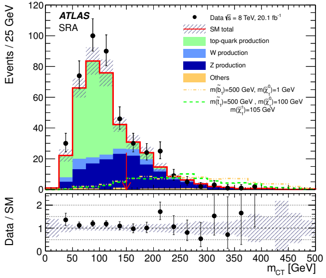
$\tilde{b} \to b + \tilde{\chi}_1^0$: arXiv:1308.2631

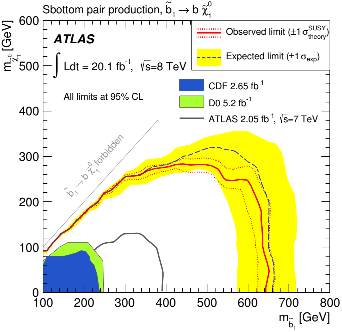


- Two signal regions:

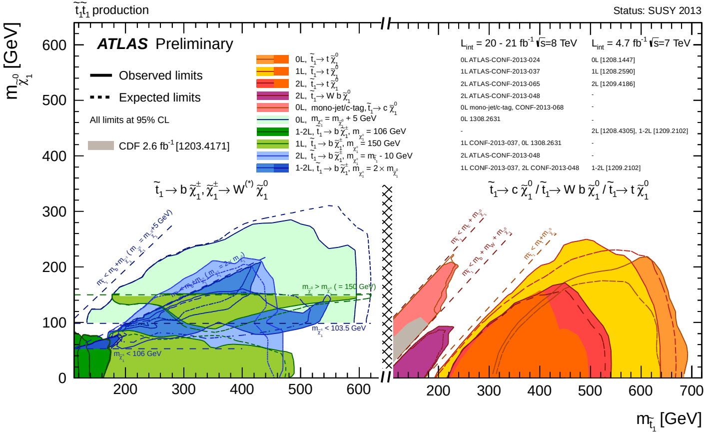
	$E_{\mathrm{T}}^{\mathrm{miss}}$	b-tags	$p_{\mathrm{T}}^{j_1}$
high Δm	150	j_1, j_2	130
low Δm	250	j_2, j_3	150

- unboosted region cuts on m_{CT}, removes t background.





Summary



- ATLAS excludes lots of simplified SUSY space where $m_{\tilde{\chi}_1^0} < 250\,\text{GeV}$ and $m_{\tilde{t}} < 700\,\text{GeV}$
- Still work to do and holes to fill!

BACKUP

The 4-vector tricks: m_{T} and m_{T2}

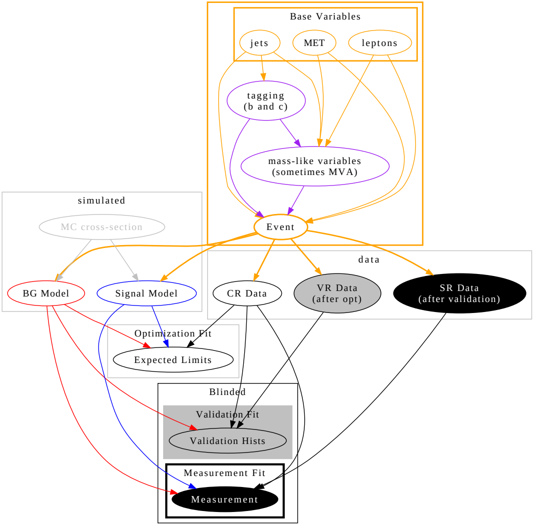
- Use kinematic variables to place background below some bound
- $m_{\mathrm{T}}(\mathbf{p}_1, \mathbf{p}_2)^2 \equiv (p_{\mathrm{T},1} + p_{\mathrm{T},2})^2 - |\mathbf{p}_{\mathrm{T},1} + \mathbf{p}_{\mathrm{T},2}|^2$
- For a 2-body decay (i.e. $W \to \ell + \nu$), $m_{\mathrm{T}} < m_{\text{parent}}$
- m_{T2} extends this to two particles, each decaying semi-invisibly:

$$m_{\mathrm{T2}}(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{p}_{\mathrm{T}}^{\ell_2}, \mathbf{p}_{\mathrm{T}}^{\text{miss}}) \equiv \min_{\mathbf{q}_{\mathrm{T}}+\mathbf{r}_{\mathrm{T}}=\mathbf{p}_{\mathrm{T}}^{\text{miss}}} \left\{ \max[m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{q}_{\mathrm{T}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell_2}, \mathbf{r}_{\mathrm{T}})] \right\}$$

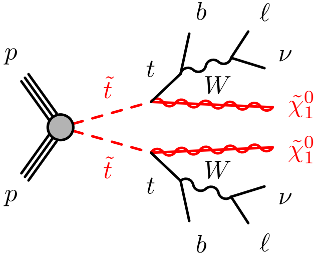
- Several instances will appear:
  - $m_{\mathrm{T2}}^{\ell\ell} \equiv m_{\mathrm{T2}}(\ell_1, \ell_2, E_{\mathrm{T}}^{\text{miss}})$: bounded by W mass for WW, Wt, $t\bar{t}$
  - $m_{\mathrm{T2}}^{b\text{-jet}} \equiv m_{\mathrm{T2}}(b_1, b_2, \ell_1 + \ell_2 + E_{\mathrm{T}}^{\text{miss}})$: bounded by top mass in $t\bar{t}$
- arXiv:hep-ph/9906349
- arXiv:0711.4526
- arXiv:0810.5576

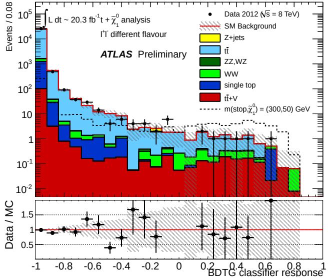
Blinding and Fitting: How we search for SUSY

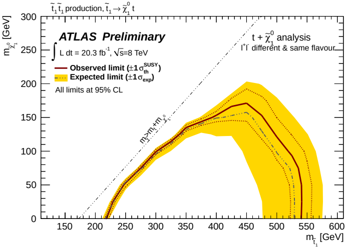
1. Pick a signal model
2. Simulate events,
   - signal
   - SM background
3. Find or invent variables
   - b-tagging, c-tagging
   - m_{T}, m_{T2}, $m_{\mathrm{T2}}^{b\text{-jet}}$, m_{CT}
4. pick SRs and go blind
5. Control backgrounds
   - use CR for larger ones
   - **backgrounds are most of the work!**
6. check validation region
7. **Unblind / Fit Signal Region**



High Δm: $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ (2 lepton) ATLAS-CONF-2013-065

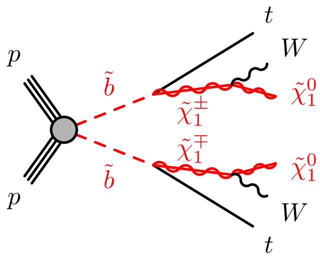


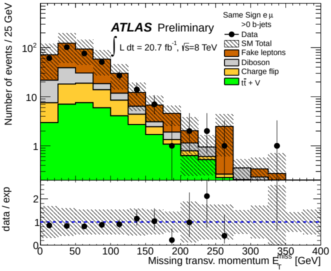


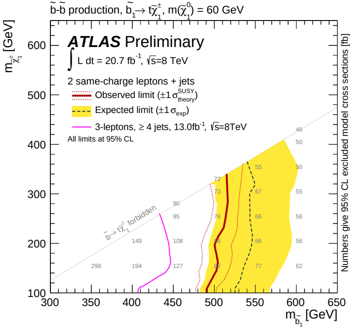


- Relation between E_T^{miss} and other kinematics more complicated with 4 invisible particles.
- Use a boosted decision tree. Variables:
  - E_T^{miss}, m_{T2}, $m_{\ell\ell}$
  - lepton $\Delta\phi$, $\Delta\theta$
  - $\Delta\phi(\ell_{leading}, E_T^{miss})$, $\Delta\phi(\ell_{leading}, j_{leading})$

Direct $\tilde{b}$: $\tilde{b} \to t + \tilde{\chi}_1^0$: ATLAS-CONF-2013-007







- Same-sign leptons + b-jets
- Major backgrounds from fake leptons and "charge flip"

	jets	b-tags	E_T^{miss}	m_T
low Δm	≥ 3	≥ 1	> 150	> 100
high Δm	≥ 5	≥ 3	< 150	< 100

c-tagging

- Neural net transforms vertex and track-based information into three posterior probabilities (P_b, P_c, P_u, where $u = \{u, d, s, g\}$)
- Calibrated with $D^{*+} \to D^0 + \pi^+$, $D^0 \to K^- \pi^+$ ATLAS-CONF-2012-039

- Select jets based on ratios:
  - anti-b selection: $P_c/P_b > X$
  - anti-light selection: $P_c/P_u > Y$

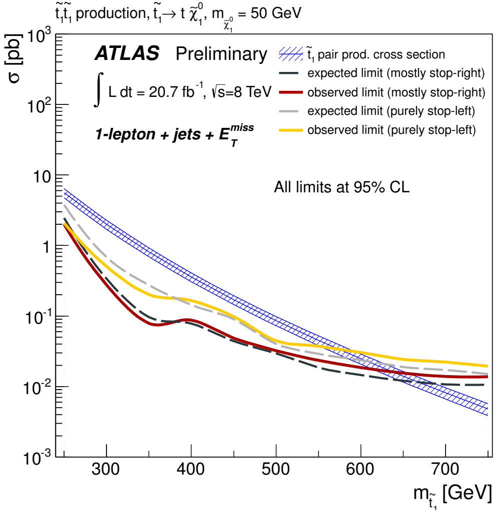
c-tagging

Operating Point	ϵ_c	$1/\epsilon_b$	$1/\epsilon_u$
loose	0.95	2.5	1.0043
medium	0.19	8.0	200

b-tagging

Operating Point	ϵ_b	$1/\epsilon_c$	$1/\epsilon_u$
anti-loose	0.60	21	230

$\tilde{t}_{\mathrm{L}}$ limits from 1 lepton



GMSB from $\tilde{t}_2 \to Z + t_1$