Searches for direct pair production of stops and sbottoms with the ATLAS detector

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on behalf of the ATLAS collaboration

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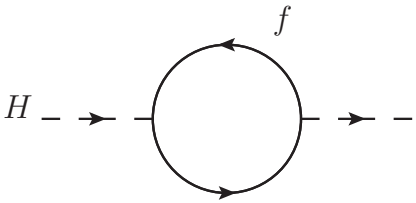
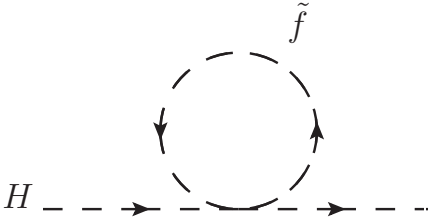
Third generation squarks

- Important in addressing the hierarchy problem

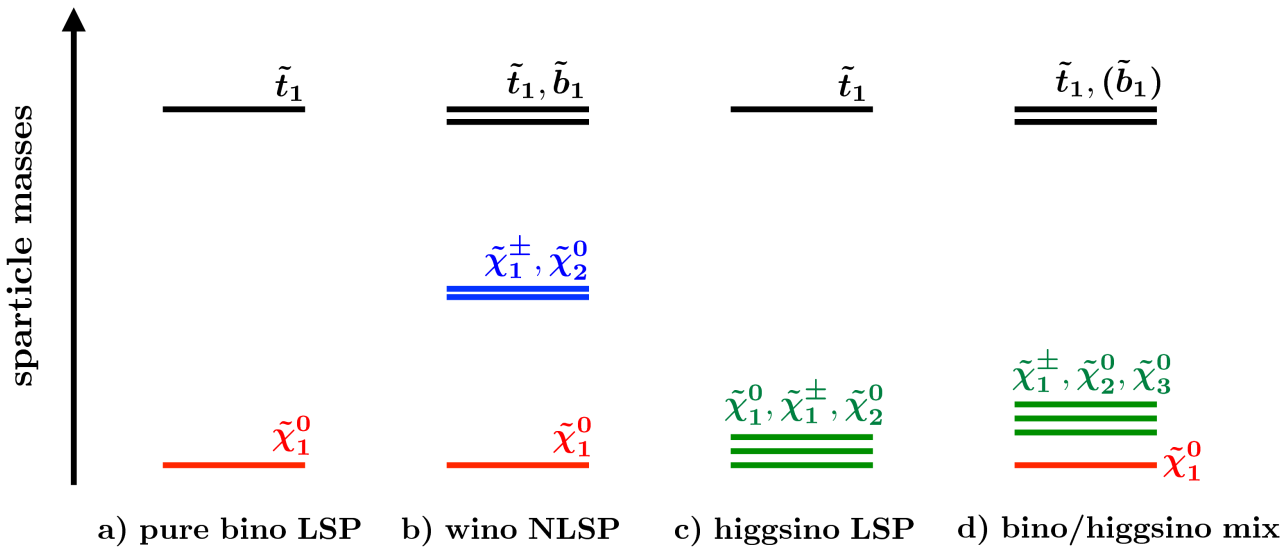




$\rightarrow$ Light $\tilde{t}$ is favoured

- Mass eigenstates $\tilde{t}_{1/2}$ and $\tilde{b}_{1/2}$ are composed of $\tilde{t}_{\mathrm{L/R}}$, $\tilde{b}_{\mathrm{L/R}}$
  - Large $\tilde{t}$ mixing possible due to large Yukawa coupling

Stop scenarios



- Different final state for each scenario
- pMSSM models allow to consider both stop and sbottom production: larger signal acceptance

Analysis overview

Analyses are classified by 3rd gen. squark flavour and final state

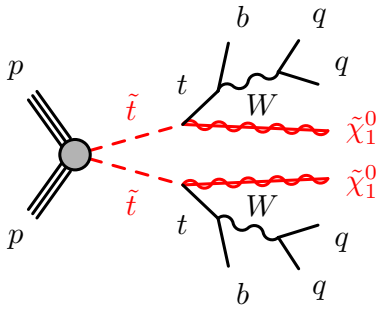
Channel	Publication
Stop 0L	JHEP 12 (2017) 085
Stop 1L	JHEP 06 (2018) 108
Stop 2L	EPJC 77 (2017) 898
Stop Z/h	JHEP 08 (2017) 006
Stop to charm	arXiv:1805.01649 (to JHEP)
Stop to stau	arXiv:1803.10178 (to PRD)
Sbottom $b\tilde{\chi}_1^0$	JHEP 11 (2017) 195
Sbottom multi-b	ATLAS-CONF-2018-040

New result!

- All analyses use data collected in 2015+2016 ($\mathcal{L}_{\mathrm{int}} = 36.1\ \mathrm{fb}^{-1}$)
- Sbottom multi-b first ATLAS 3rd gen. analysis to include also 2017 data ($\mathcal{L}_{\mathrm{int}} = 79.8\ \mathrm{fb}^{-1}$)

Stop 0L [JHEP 12 (2017) 085]

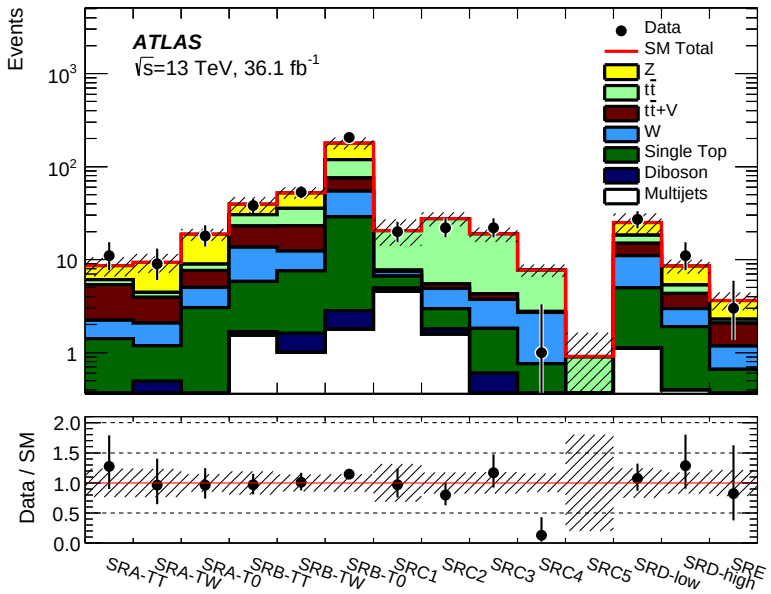
- Event selection: Lepton veto, ≥ 4 jets, ≥ 2 b-tags, $E_{\mathrm{T}}^{\mathrm{miss}}$
- Top reconstruction by reclustering jets into large-R jets
  - Categorize events w.r.t. large-R jet mass



Background rejection by stransverse mass (m_{T2})

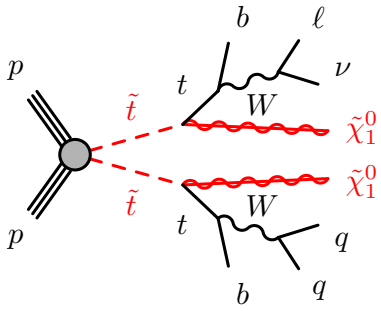
- Reconstruct two top candidates with $\boldsymbol{p}_{\mathrm{T},i}^{\mathrm{top}}$
- Assume, that $\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$ is result of two neutralinos' transverse momenta $\boldsymbol{q}_{\mathrm{T},i}$
- $m_{\mathrm{T2}}^2(\boldsymbol{p}_{\mathrm{T},1}^{\mathrm{top}}, \boldsymbol{p}_{\mathrm{T},2}^{\mathrm{top}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) = \min\left[\max\left[m_{\mathrm{T}}^2(\boldsymbol{p}_{\mathrm{T},1}^{\mathrm{top}}, \boldsymbol{q}_{\mathrm{T},1}), m_T^2(\boldsymbol{p}_{\mathrm{T},2}^{\mathrm{top}}, \boldsymbol{q}_{\mathrm{T},2})\right]\right]$
  under condition $\boldsymbol{q}_{\mathrm{T},1} + \boldsymbol{q}_{\mathrm{T},2} = \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$

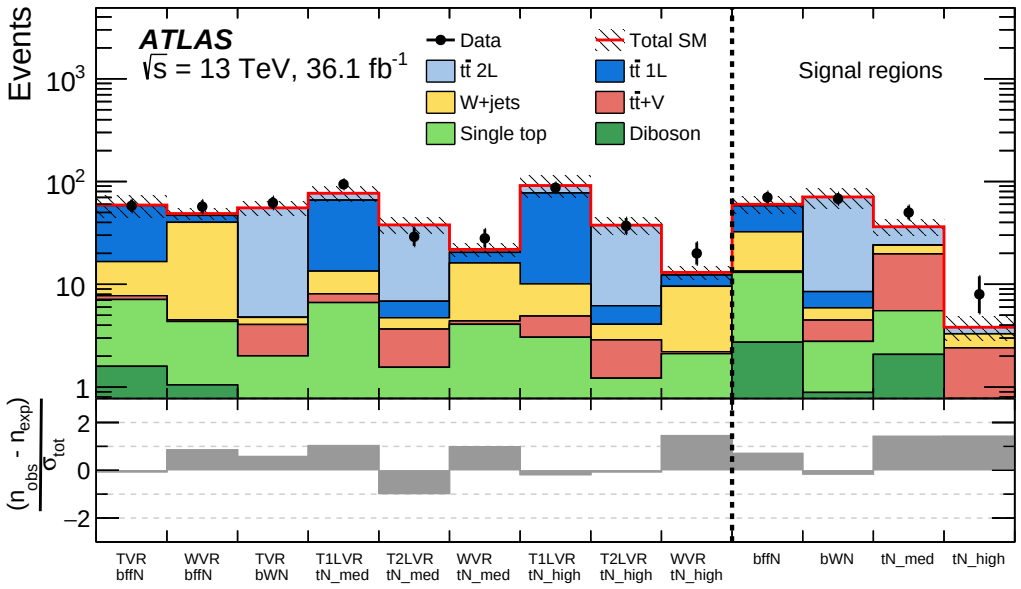
$\Rightarrow$ $m_{\mathrm{T2}} \leq m_{\tilde{t}_1}$



Stop 1L [JHEP 06 (2018) 108]

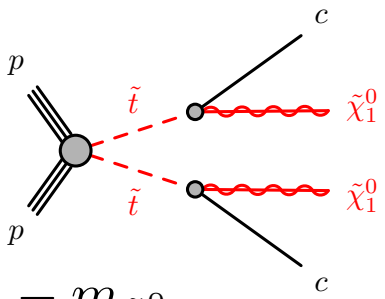
- Event selection: 1 e/μ
- Top reconstruction by reclustering
- Reject dileptonic $t\bar{t}$ by asymmetric stransverse mass (am_{T2})

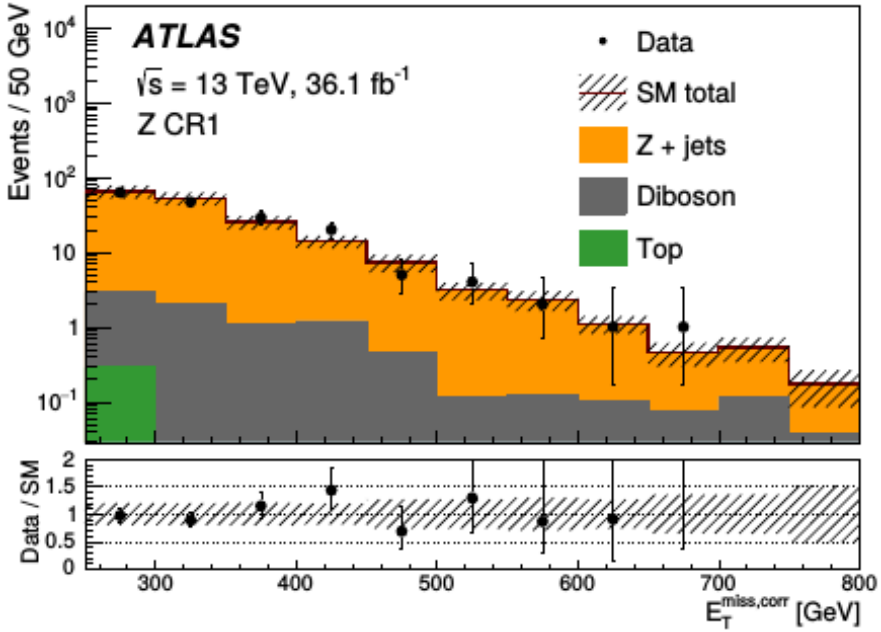


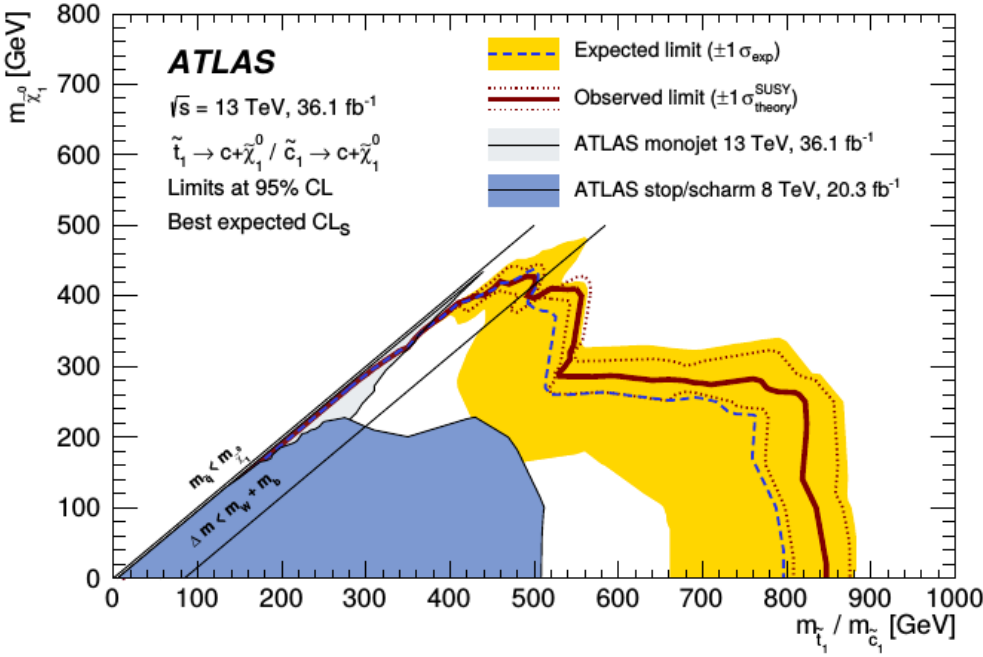


Stop to charm [arXiv:1805.01649]

- Flavour violation: $\tilde{t}_1 \to c\tilde{\chi}_1^0$
- Event selection: Lepton veto, ≥ 2 jets, ≥ 1 c-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $p_{\mathrm{T}}^{\mathrm{lead.\ jet}} > 250\ \mathrm{GeV}$ from ISR required
- Five signal regions to address different mass splittings $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$
- Reject had. τ background by
  $m_{\mathrm{T}}^{c-\mathrm{jets}} = \min_{c-\mathrm{jets}} \sqrt{2E_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{c} \cdot (1 - \cos\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{c}))}$
- Main background: $Z(\to \nu\nu) + c/l$, estimated via $Z \to e^+e^-/\mu^+\mu^-$

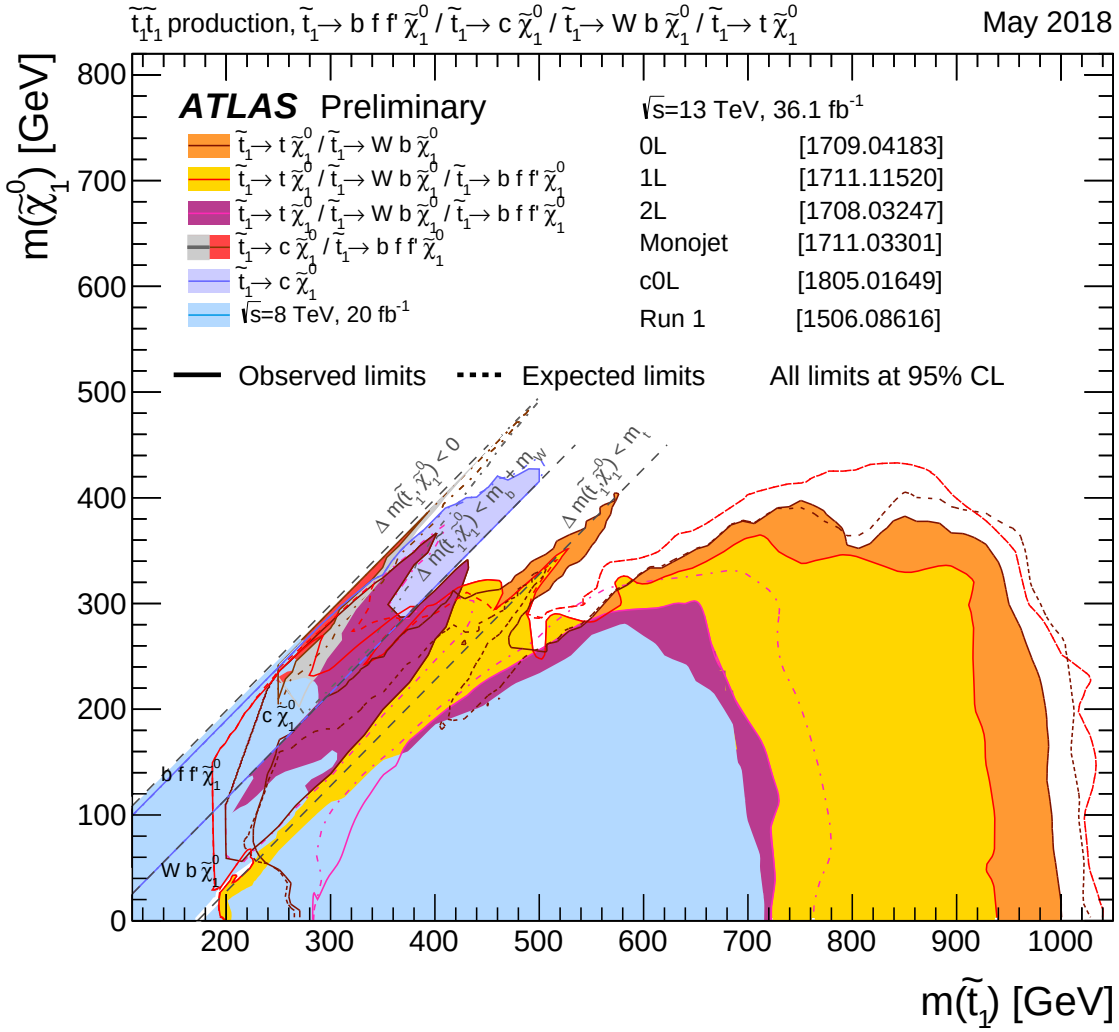






Results: $\tilde{B}$ LSP

[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/]



- Exclusion limits touch stop mass of $1\ \mathrm{TeV}$ for light $\tilde{\chi}_1^0$
- Run 2 analyses cover large area of 3-body and 4-body parameter space

Results: $\tilde{B}/\tilde{H}$ LSP

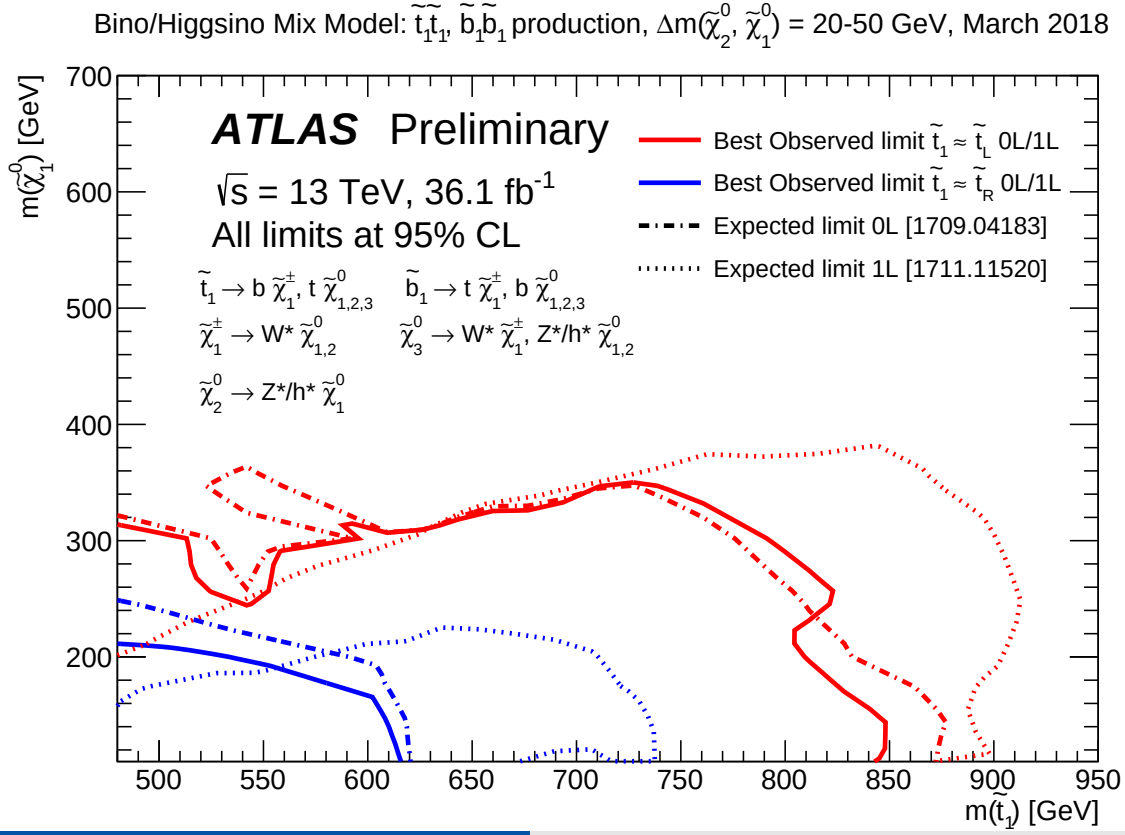
[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/]

$\tilde{t}_1, (\tilde{b}_1)$

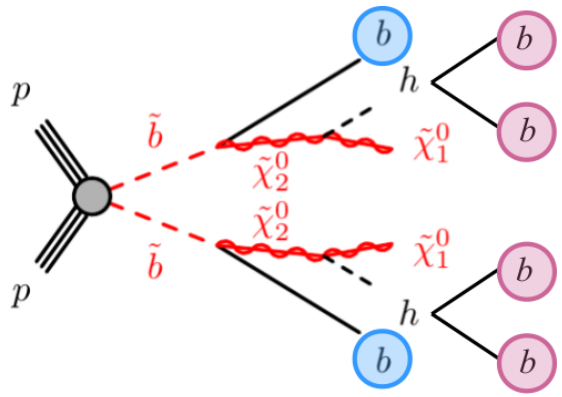
$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0, \tilde{\chi}_3^0$

$\tilde{\chi}_1^0$

- Preserves $\Omega h^2 \approx 0.12$
- $m(\tilde{\chi}_2^0/\tilde{\chi}_3^0/\tilde{\chi}_1^{\pm}) \approx m(\tilde{\chi}_1^0) + (20 \ldots 50)\ \mathrm{GeV}$
- Consider stop and sbottom production for $\tilde{t}_1 \approx \tilde{t}_\mathrm{L}$

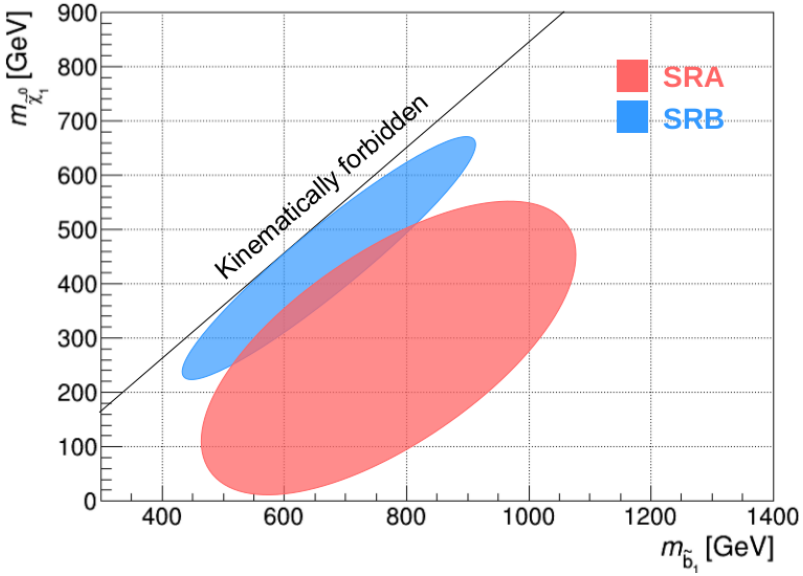


Sbottom multi-b [ATLAS-CONF-2018-040]

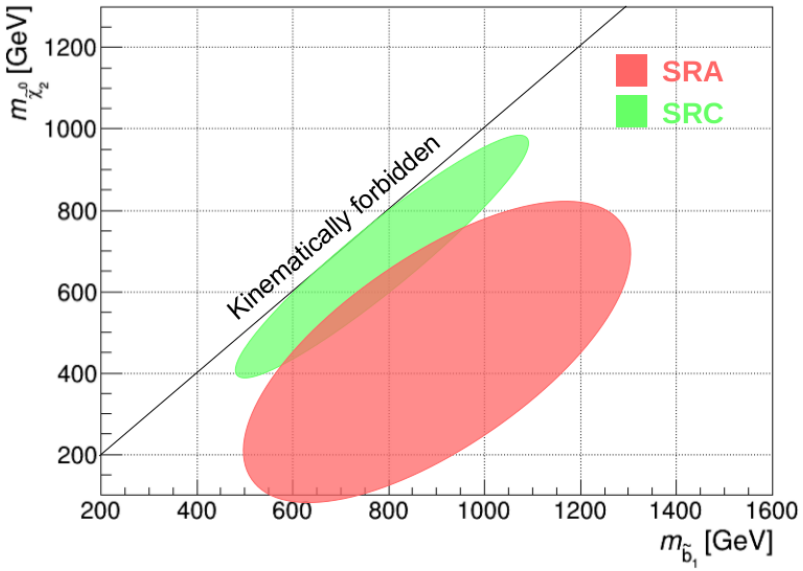


- Target: $\tilde{b}_1 \to b\tilde{\chi}_2^0$, where $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$
  - All BR's = 1, except $\mathrm{BR}(h \to bb) = 0.58$ (SM-like)

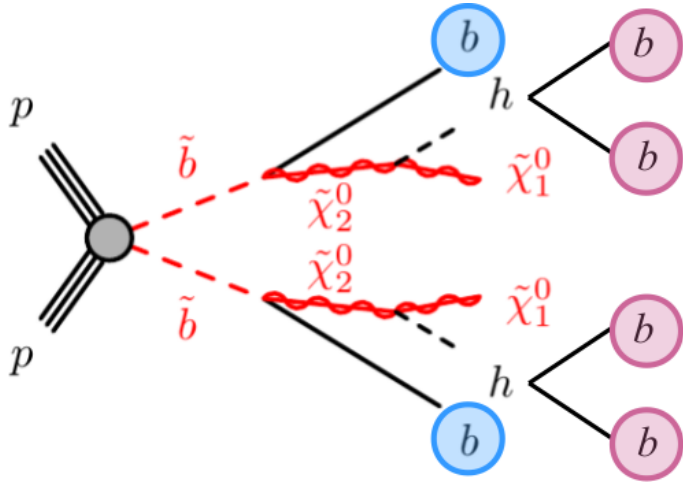
$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV



$m(\tilde{\chi}_1^0) = 60$ GeV

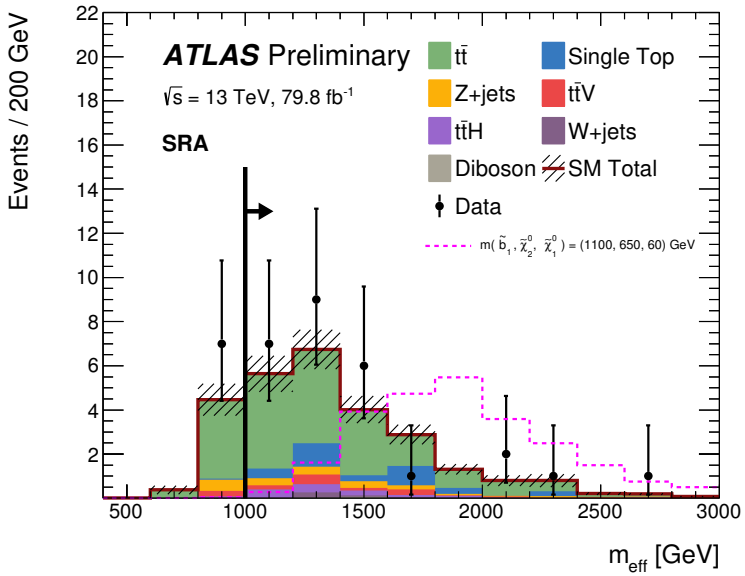


Sbottom multi-b: Signal Region A



- ≥ 6 jets, ≥ 4 b-tags, $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV
- Higgs-boson reconstruction
  - Remove pair of b-jets with maximum $\Delta R \leftarrow$ **Sbottom decay**
  - Select pair of b-jets with minimum $\Delta R \leftarrow$ **Higgs decay**
  - Accept, if $m(b, b) > 80$ GeV

- 3 statistically independent bins in m_{eff}: SRA-L/M/H
  - $m_{\mathrm{eff}} = \sum_{i=1}^{N_{\mathrm{jets}}} p_{\mathrm{T},i} + E_{\mathrm{T}}^{\mathrm{miss}}$, main discriminating variable



Sbottom multi-b: Signal Regions B & C

SRB

- Optimised for small $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$ and $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130\ \mathrm{GeV}$
- ≥ 5 jets, ≥ 4 b-tags, $E_{\mathrm{T}}^{\mathrm{miss}} > 300\ \mathrm{GeV}$
- Require ISR jet
- Higgs candidate reconstruction
  - Find combination, that minimizes $\max[\Delta R(b_1, b_2), \Delta R(b_3, b_4)]$
  - Take average mass of both candidates $m(h_1, h_2)_{\mathrm{avg}}$
  - Accept, if $50 < m(h_1, h_2)_{\mathrm{avg}} < 140\ \mathrm{GeV}$
- $m_{\mathrm{eff}} > 1\ \mathrm{TeV}$

SRC

- Optimised for small $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$ and $m(\tilde{\chi}_1^0) = 60\ \mathrm{GeV}$
- ≥ 4 jets, ≥ 3 b-tags, $E_{\mathrm{T}}^{\mathrm{miss}} > 250\ \mathrm{GeV}$
- Use object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance

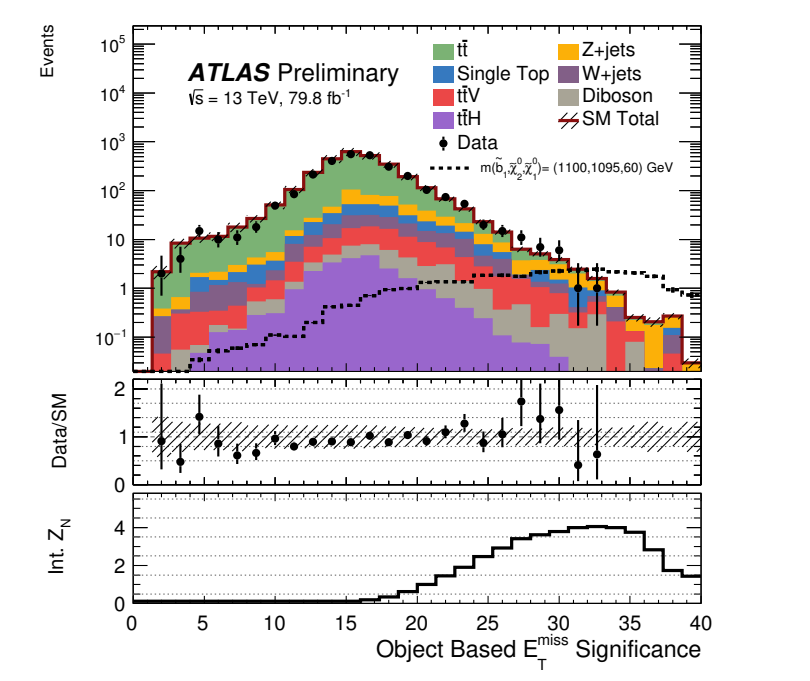
Variable	SRC25	SRC27	SRC30	SRC32
N_{leptons} (baseline)		$= 0$		
N_{jets}		≥ 4		
$N_{\mathrm{b-jets}}$		≥ 3		
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]		> 250		
$\min \Delta\phi(\mathrm{jet}_{1-4}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ [rad]		> 0.4		
$\mathcal{S}$	> 25	> 27	> 30	> 32

Sbottom multi-b: $\mathcal{S}$ ($E_{\mathrm{T}}^{\mathrm{miss}}$ significance)

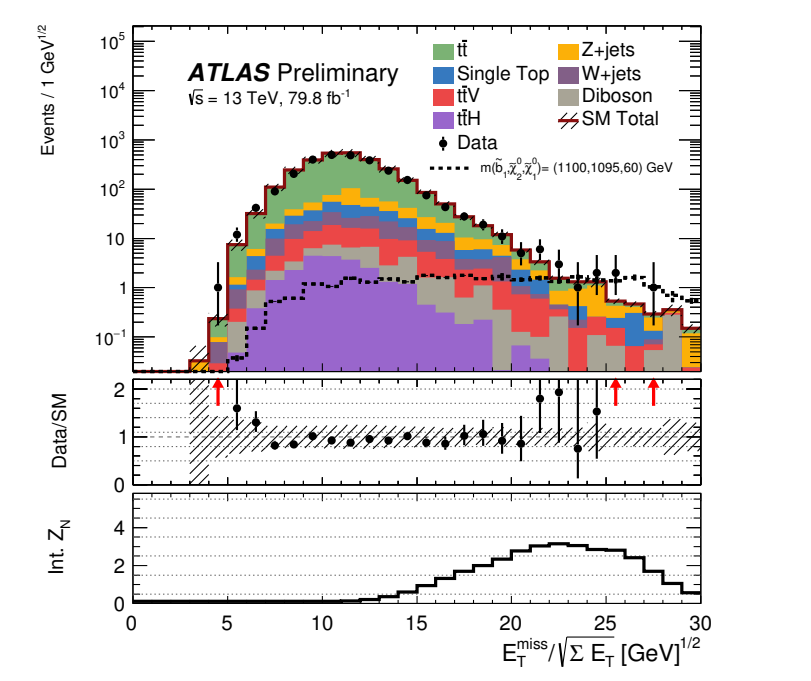
- Previously: $\mathcal{S} = E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{\sum E_{\mathrm{T}}}$ or $E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{H_{\mathrm{T}}}$
- New in ATLAS: Determine $\mathcal{S}$ based on expected resolution of each object
- $\mathcal{S}$: Defined by $\mathcal{S}^2 = 2 \ln \frac{\max_{\boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}} \neq \mathbf{0}} \mathcal{L}(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}})}{\max_{\boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}} = \mathbf{0}} \mathcal{L}(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}})}$

Details in:
ATLAS-CONF-2018-038

Object-based $\mathcal{S}$

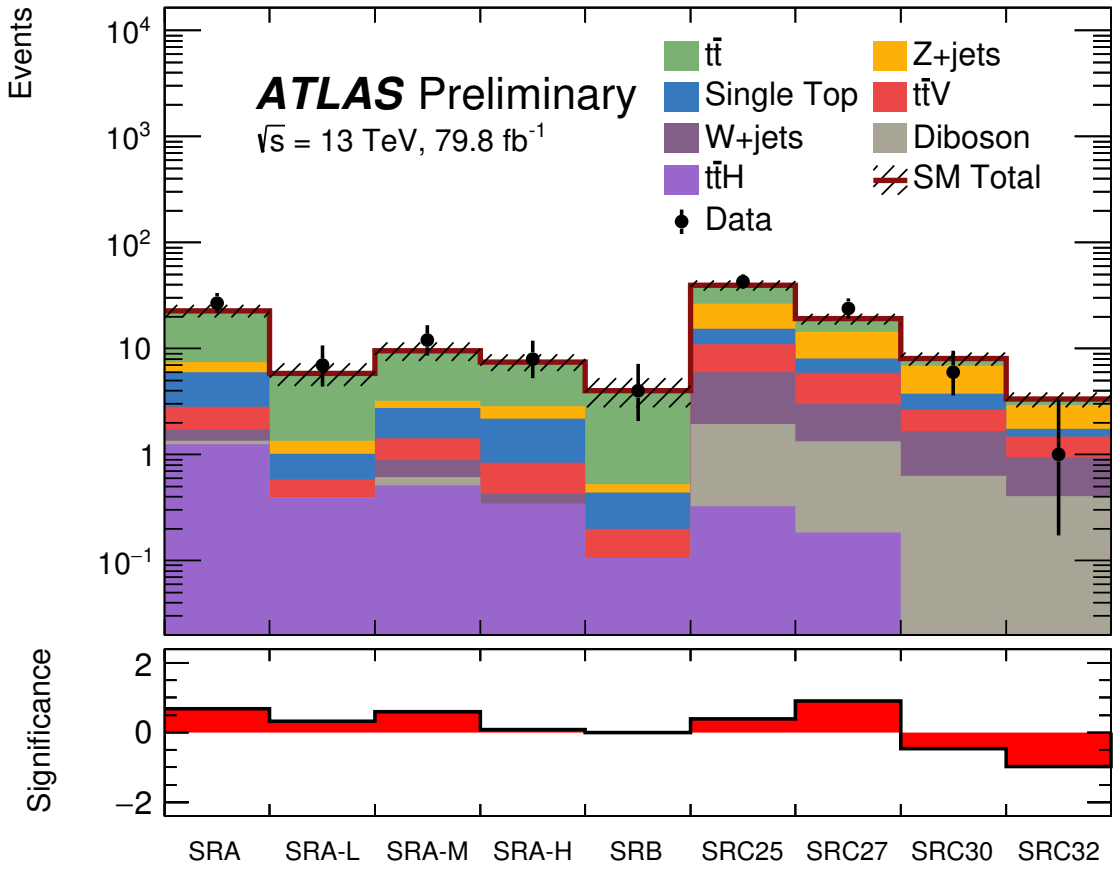


$E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{E_{\mathrm{T}}}$



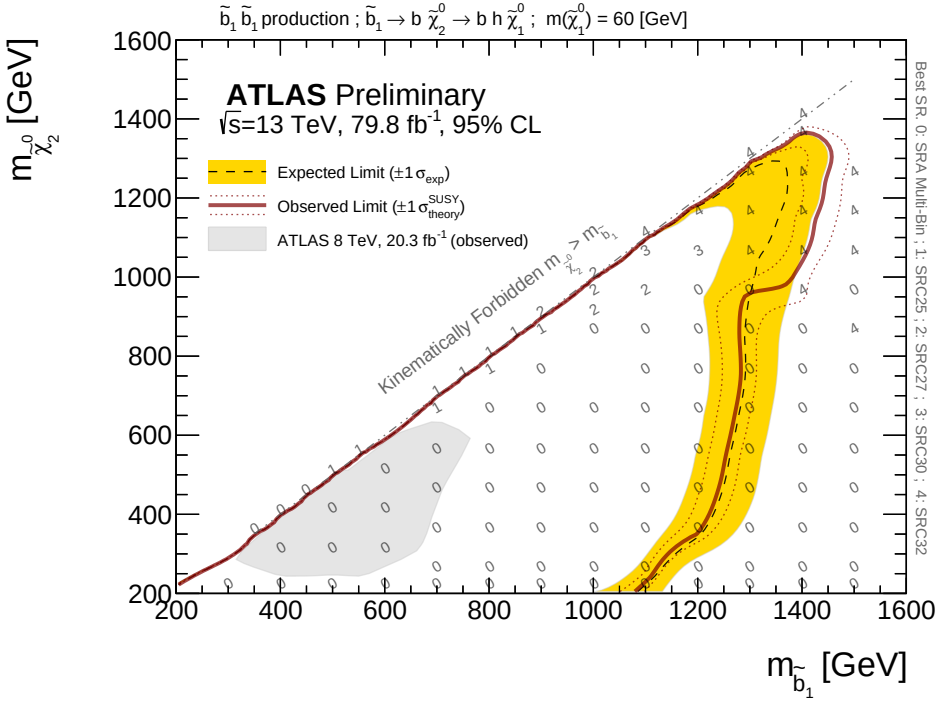
For more information, see Marco Valente's talk on Thursday

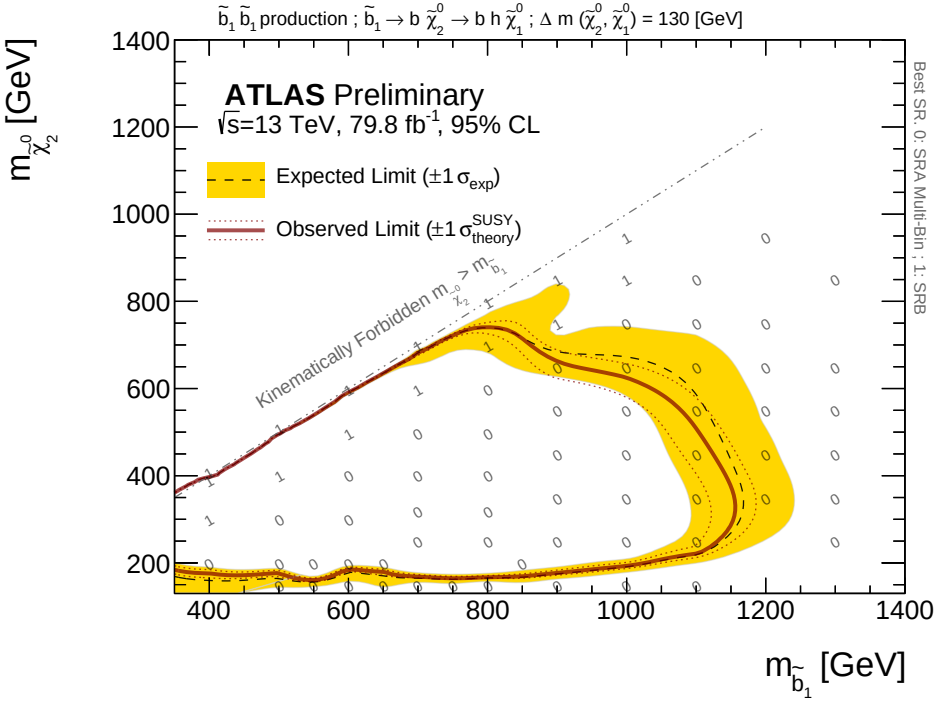
Sbottom multi-b: Results



No significant excess observed

Sbottom multi-b: Interpretations





- Significant improvement of constraints on $\tilde{b}_1$ mass

Conclusions

- Broad search programme carried out with $36\ \mathrm{fb}^{-1}$
- New sbottom search with $80\ \mathrm{fb}^{-1}$
- No significant excess observed so far
- Severly tightened constraints on sbottom masses
- Interpretation of stop search results in pMSSM models

3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2 \times M_1$		Multiple		36.1	$\tilde{t}_1$	0.7	m($\tilde{\chi}_1^0$)=60 GeV
			Multiple		36.1	$\tilde{t}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}_1^0$)=1 GeV
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$	0.4-0.9	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$
			Multiple		36.1	$\tilde{t}_1$	Forbidden 0.6-0.8	m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$	0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c} \to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$	0.85	m($\tilde{\chi}_1^0$)=0 GeV
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV
		0	mono-jet	Yes	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2 \to \tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV

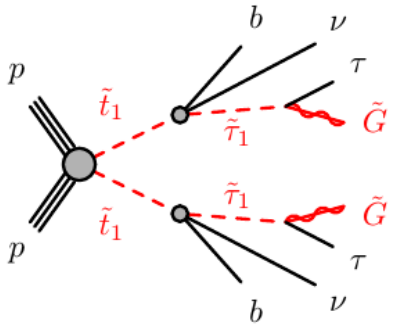
Backup

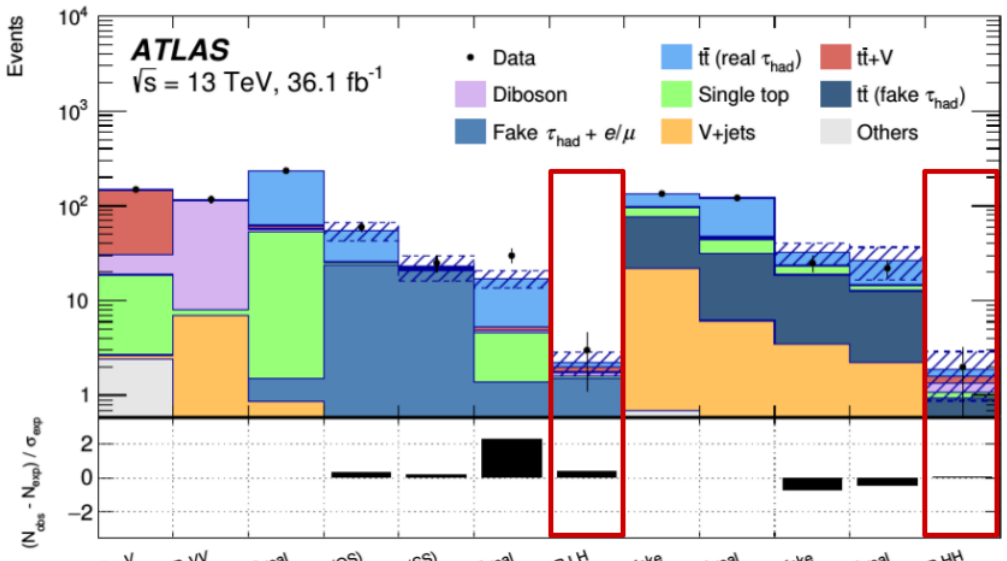
Stop to stau [arXiv:1803.10178]

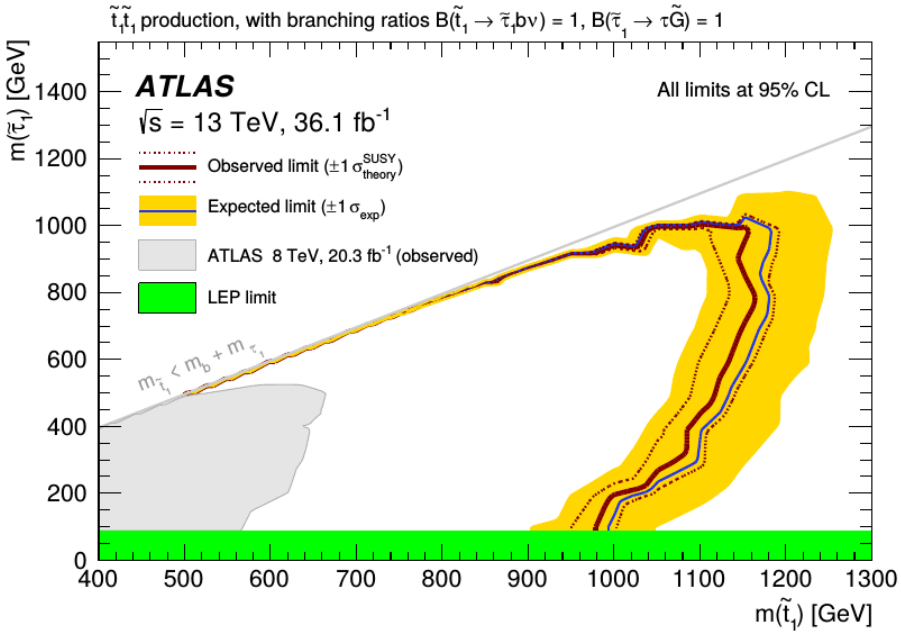
- Sparticles: $\tilde{t}_1$, $\tilde{\tau}$ (even mix of $\tilde{\tau}_\mathrm{L}$, $\tilde{\tau}_\mathrm{R}$), $\tilde{G}$ (massless)
- Event selection: 2 $\tau_\mathrm{had.}$ (HH) or 1 e/μ + 1 $\tau_\mathrm{had.}$ (LH)
- Reject $t\bar{t}$ by using m_{T2}
- Main backgrounds

  HH: Fake τ, estimated in control region

  LH: Fake τ, data-driven estimate (*fake factor method*)



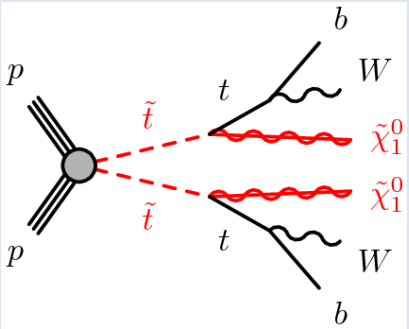


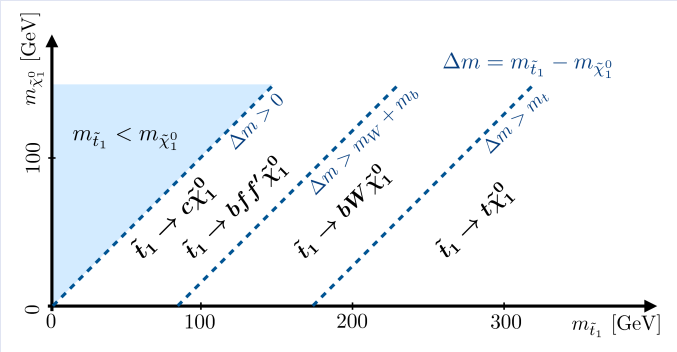


Stop scenarios: $\tilde{B}$ LSP & $\tilde{B}/\tilde{H}$ LSP

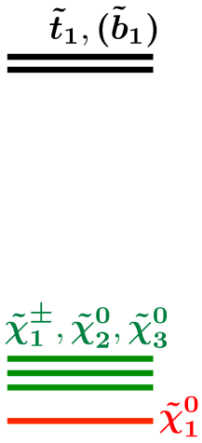
$\tilde{B}$ LSP scenario

- $\tilde{\chi}_1^0 = \tilde{B}$
- $M_2,\ M_3 \gg M_1$, other sparticles decoupled
- $\mathrm{BR}(\tilde{t}_1 \to t\tilde{\chi}_1^0) = 1 \Rightarrow \tilde{t}_1 \approx \tilde{t}_\mathrm{L}$





$\tilde{B}/\tilde{H}$ LSP



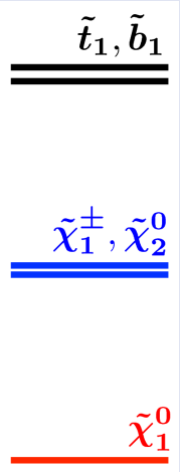
- pMSSM model
- Motivated by DM relic density
- $M_1 \approx -\mu$, satisfies $0.10 < \Omega h^2 < 0.12$
- $M_{Q_3\mathrm{L}}$ vs. M_1
  - Mostly $\tilde{t}_1 \to t\tilde{\chi}_{1/2/3}^0$ and $\tilde{b}_1 \to b\tilde{\chi}_1^0$
- M_{t_R} vs. M_1
  - Mostly $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$

Stop scenarios: $\tilde{H}$ LSP & $\tilde{W}$ NLSP

$\tilde{H}$ LSP

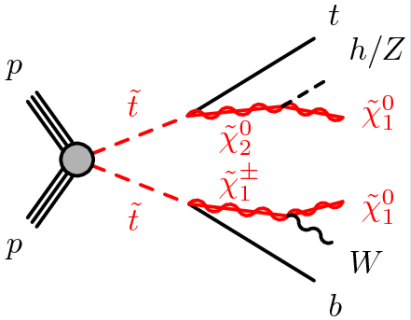
- Motivated by naturalness
- $M_1,\ M_2 \gg \mu$
- $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 5\ \mathrm{GeV}$
  $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + 10\ \mathrm{GeV}$
- Three scenarios addressing varying left-right mixing
- Event signatures involve soft leptons from $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ decays

$\tilde{W}$ NLSP scenario

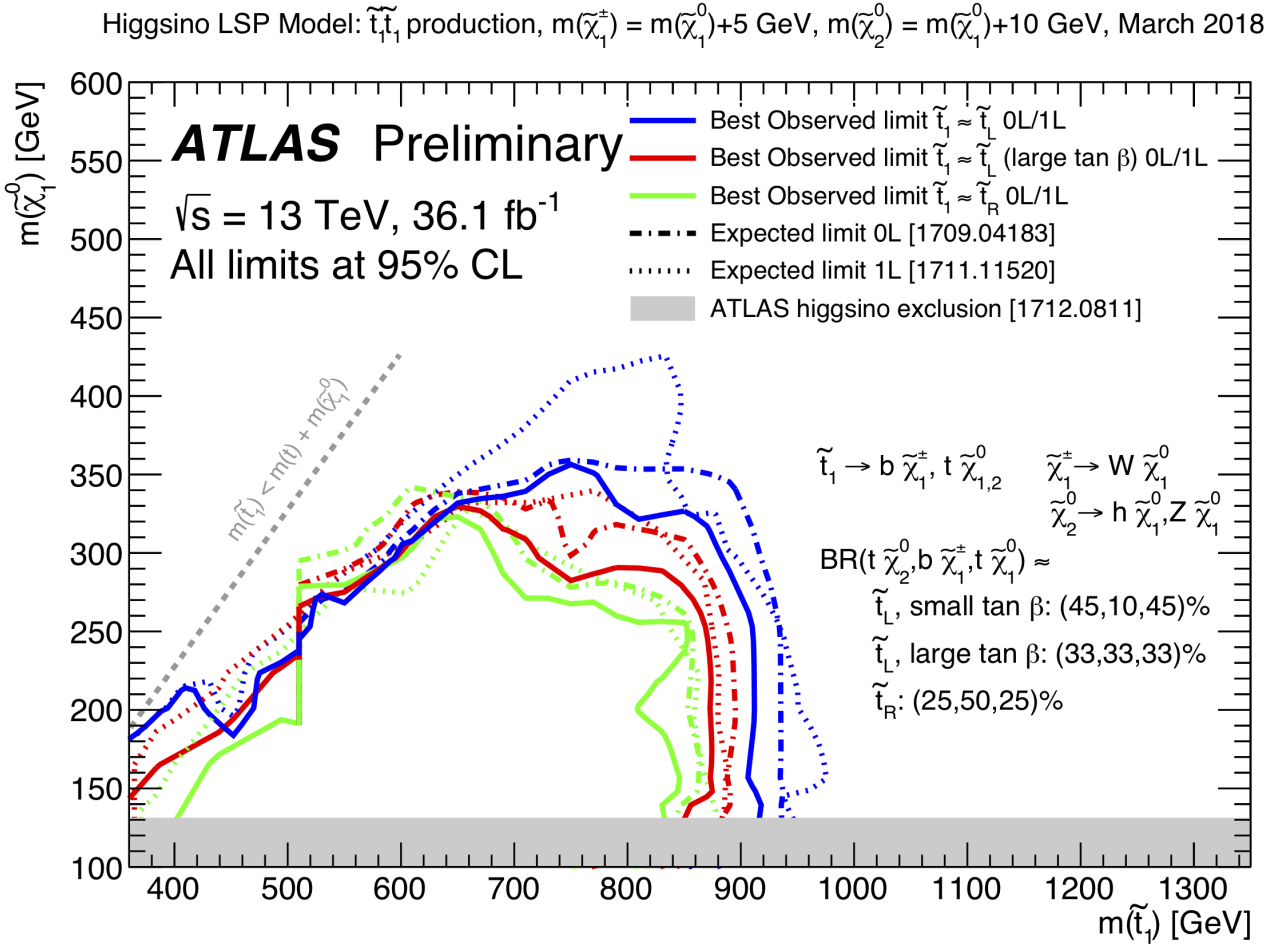


- Motivated by grand unification
- pMSSM model
- $M_2 = 2 \cdot M_1$
- Distinguish $\mu < 0$ and $\mu > 0$
- Event signatures involve strongly boosted b-jets

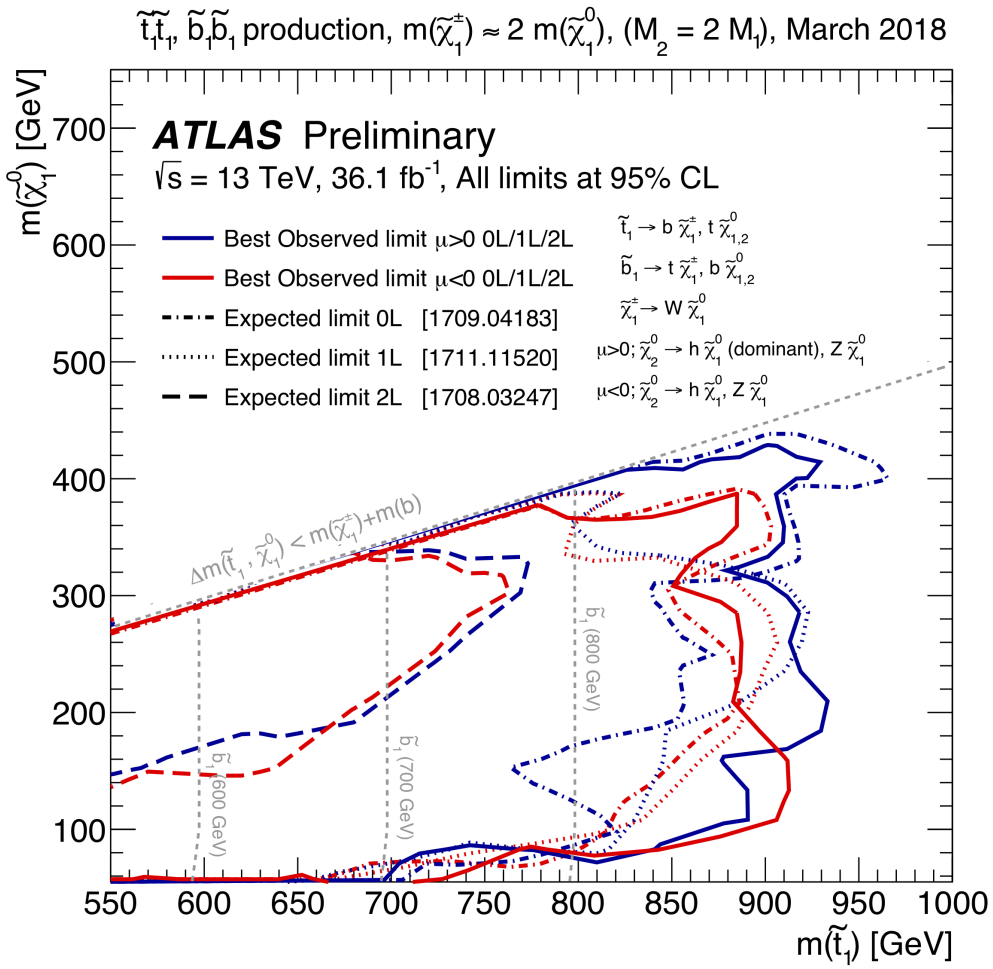
Example



$\tilde{H}$ LSP exclusion limit



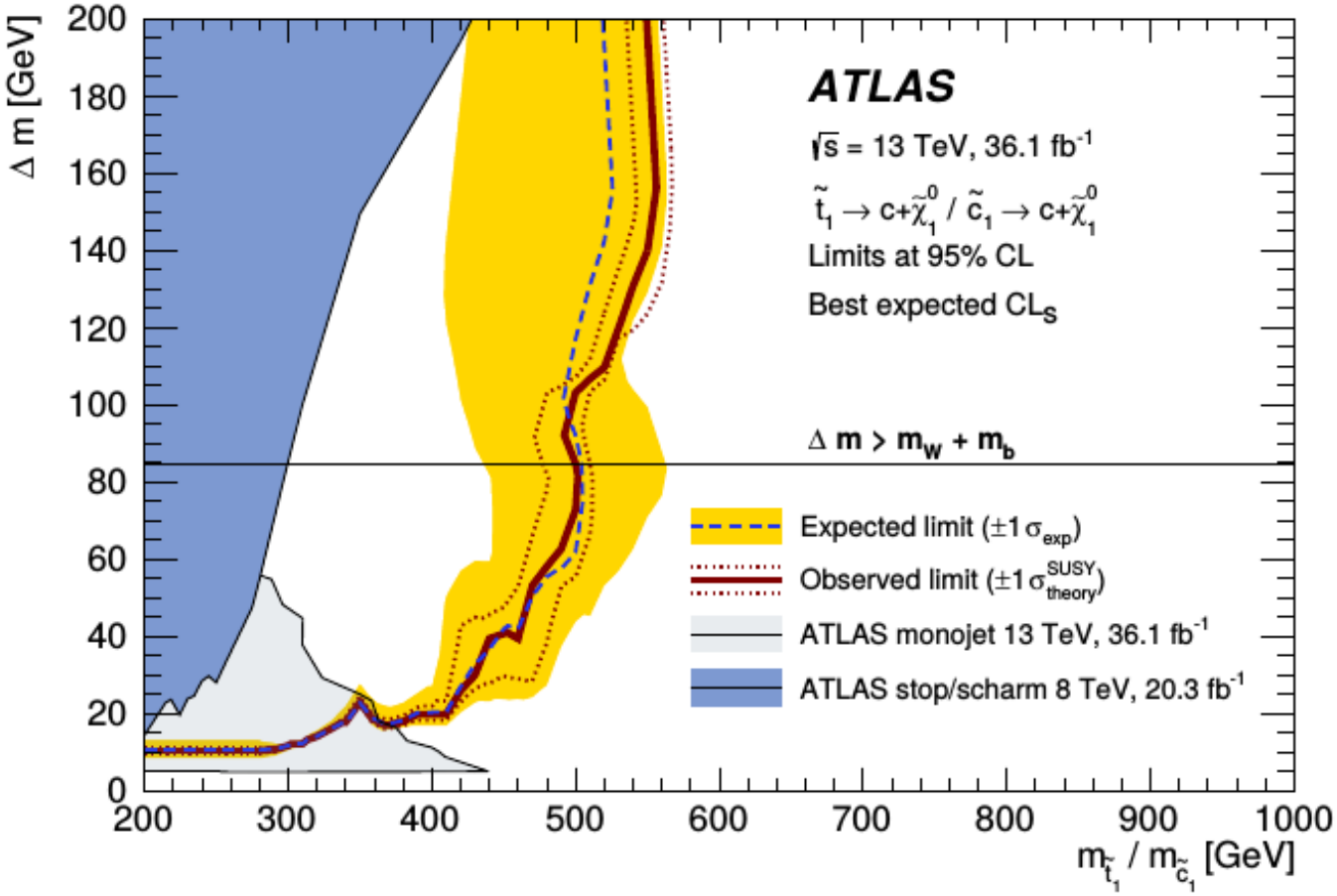
$\tilde{W}$ NLSP exclusion limit



Stop to charm: signal region definitions

	SR1	SR2	SR3	SR4	SR5
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers				
Leptons	0 e AND 0 μ				
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 500				
$\Delta\phi_{\mathrm{min}}(\mathrm{jet}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})$ [rad]	> 0.4				
$N_{c-\mathrm{jets}}$	≥ 1				
N_{jets}	≥ 2	≥ 3	≥ 3	≥ 3	≥ 3
Leading jet c-tag veto	yes	yes	yes	yes	no
$p_{\mathrm{T}}^{j_1}$ [GeV]	> 250	> 250	> 250	> 250	> 300
$p_{\mathrm{T}}^{j_2}$ [GeV]	–	–	> 100	> 140	> 200
$p_{\mathrm{T}}^{j_3}$ [GeV]	–	–	> 80	> 120	> 150
$p_{\mathrm{T}}^{c_1}$ [GeV]	< 100	> 60	> 80	> 100	> 150
m_{T}^{c} [GeV]	$\in (120, 250)$	$\in (120, 250)$	$\in (175, 400)$	> 200	> 400

Stop to charm: interpretation in low Δm



Sbottom multi-b: SRA cuts

Variable	SRA	SRA-L	SRA-M	SRA-H
N_{leptons} (baseline)		$= 0$		
N_{jets}		≥ 6		
$N_{\text{b-jets}}$		≥ 4		
$E_{\text{T}}^{\text{miss}}$ [GeV]		> 250		
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]		> 0.4		
τ veto		Yes		
$p_{\text{T}}(b_1)$ [GeV]		> 200		
$\Delta R_{\text{max}}(b, b)$		¿ 2.5		
$\Delta R_{\text{max-min}}(b, b)$		¡ 2.5		
$m(h_{\text{cand}})$ [GeV]		> 80		
m_{eff} [TeV]	> 1.0	$\in [1.0, 1.2]$	$\in [1.2, 1.5]$	> 1.5

Sbottom multi-b: SR yields

	SRA	SRA-L	SRA-M	SRA-H	SRB
Observed events	27	7	12	8	4
Fitted SM bkg events	22.8 ± 3.2	5.8 ± 1.5	9.5 ± 2.0	7.5 ± 1.4	4.0 ± 1.1
$t\bar{t}$	15.3 ± 2.7	4.5 ± 1.4	6.3 ± 1.7	4.7 ± 1.3	3.5 ± 1.2
Z+jets	1.5 ± 0.9	0.3 ± 0.2	0.5 ± 0.2	0.7 ± 0.4	0.09 ± 0.08
Single-top	3.1 ± 0.8	0.4 ± 0.3	1.4 ± 0.5	1.3 ± 0.3	$0.24^{+0.26}_{-0.24}$
$t\bar{t}$ $+W/Z$	1.1 ± 0.2	0.2 ± 0.1	0.5 ± 0.2	0.4 ± 0.2	0.09 ± 0.07
$t\bar{t}$ $+h$	1.3 ± 0.2	0.4 ± 0.1	0.5 ± 0.1	0.3 ± 0.1	0.11 ± 0.03
W+jets	0.4 ± 0.3	–	$0.28^{+0.33}_{-0.28}$	0.09 ± 0.02	–
Diboson	0.10 ± 0.05	$0.00^{+0.02}_{-0.00}$	0.10 ± 0.04	–	–

	SRC25	SRC27	SRC30	SRC32
Observed events	43	24	6	1
Fitted SM bkg events	39.8 ± 3.9	19.1 ± 2.3	8.1 ± 1.5	3.3 ± 0.7
$t\bar{t}$	13.1 ± 2.6	4.7 ± 0.9	1.2 ± 0.3	0.4 ± 0.1
Z+jets	11.3 ± 3.0	6.3 ± 1.8	3.1 ± 0.9	1.2 ± 0.4
Single-top	4.3 ± 0.5	2.2 ± 0.2	1.1 ± 0.3	0.3 ± 0.1
$t\bar{t}$ $+W/Z$	5.0 ± 1.6	2.9 ± 0.9	1.0 ± 0.4	0.5 ± 0.2
$t\bar{t}$ $+h$	0.33 ± 0.05	0.18 ± 0.03	$0.01^{+0.02}_{-0.01}$	$0.01^{+0.01}_{-0.01}$
W+jets	4.1 ± 0.4	1.7 ± 0.3	1.0 ± 0.3	0.5 ± 0.1
Diboson	1.6 ± 0.4	1.2 ± 0.2	0.6 ± 0.2	0.4 ± 0.3

Sbottom multi-b: background validation