ATLAS EXPERIMENT

UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

Searches for direct pair production of third generation squarks with the ATLAS detector

September 3rd 2017

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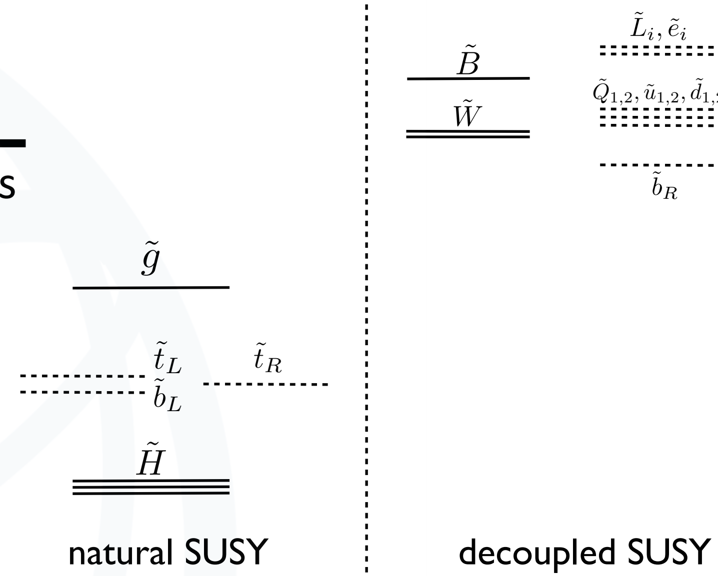
on behalf of the ATLAS Collaboration

LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN

3rd generation SUSY and naturalness

$\Delta m^2(h) \propto \Lambda^2_{cutoff}$



M.Papucci, J.Ruderman, A. Weiler
hep-ph:1110.6926

- **Higgs mass²**
  - Quadratic loop corrections
  - In SM natural scale
    - $\Lambda_{cutoff} \sim M_{planck}$
  - Need m(h) at 125 GeV

- The SUSY solution
  - 2 x top squarks
  - Factor of -1 from Feynman rules
  - Same coupling, λ
  - Quadratic corrections cancel

Top and bottom squarks are key ingredients for SUSY and the solution to the SM hierarchy problem.

3rd generation squarks outlook

A wide search program to cover all possible decay modes and mass hierarchy scenarios.

ATLAS SUSY results webpage

conference notes with full 2015+2016 dataset

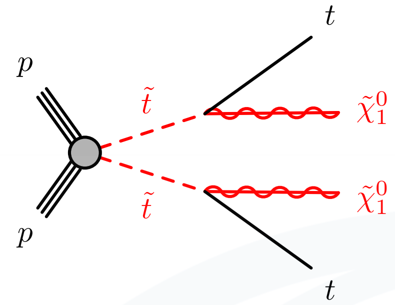
Short Title of preliminary conference note/paper	Date	√s (TeV)	L (fb^{-1})	Document	Plots
stop B-L (RPV) NEW	5/2017	13	36	ATLAS-CONF-2017-036	Link
stop 1L with DM+HF NEW	5/2017	13	36	ATLAS-CONF-2017-037	Link
stop 2x2	3/2017	13	36	ATLAS-CONF-2017-025	Link
stop 0L	3/2017	13	36	ATLAS-CONF-2017-020	Link

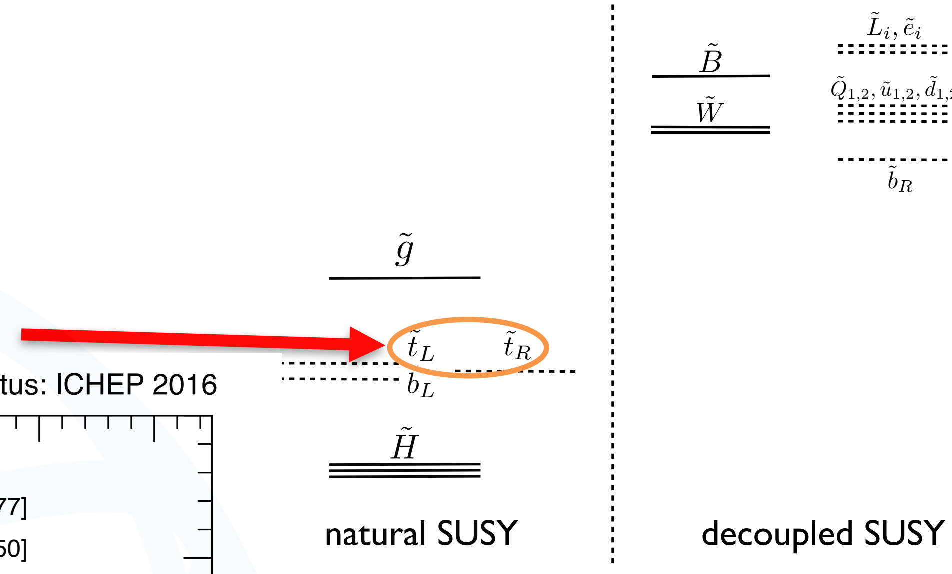
papers

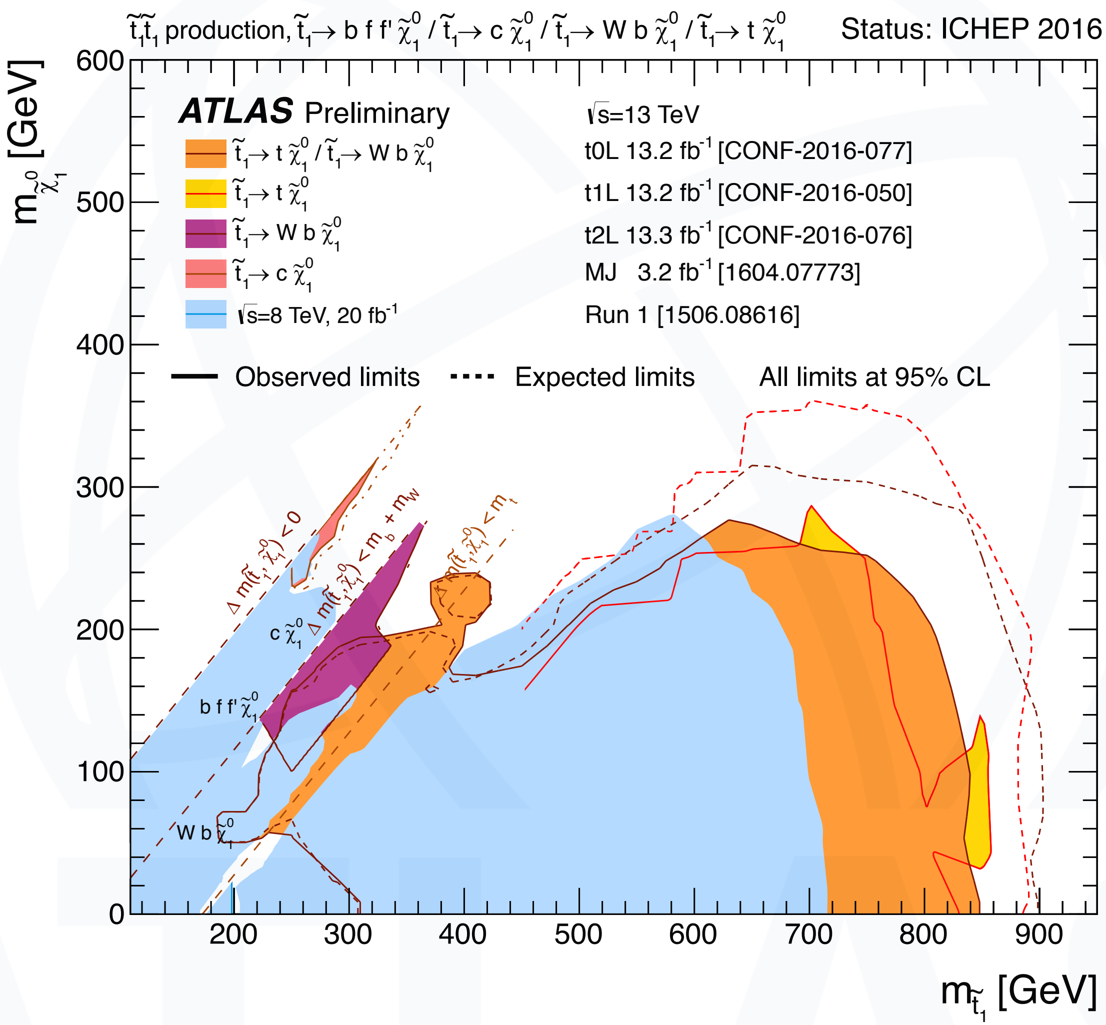
Short Title of Paper	Date	√s (TeV)	L (fb^{-1})	Document	Plots+Aux. Material	Journal
2b+MET (sbottom) NEW	8/2017	13	36	1708.09266	Link	submitted to JHEP
stop 2L NEW	8/2017	13	36	1708.03247	Link (+data)	submitted to EPJC
stop in Z/h	6/2017	13	36	1706.03986	Link (+data)	JHEP08 (2017) 006

In this talk I will highlight a personal selection of recent results.

STOP

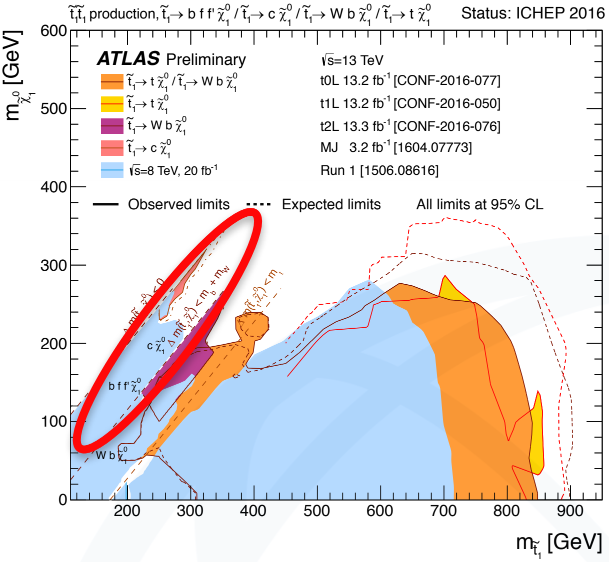






Start the search with simplified models

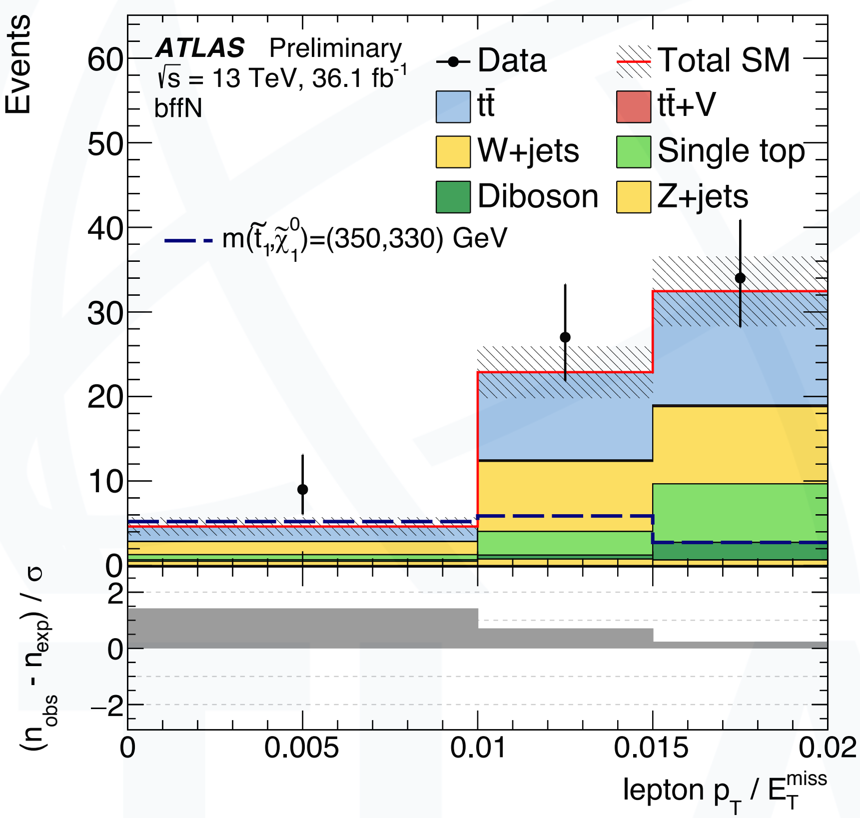
- Only t_1 and χ_1 accessible
- Mostly right-handed t_1
- χ_1 is B-ino like



Four-body decays

Target a single soft isolated lepton

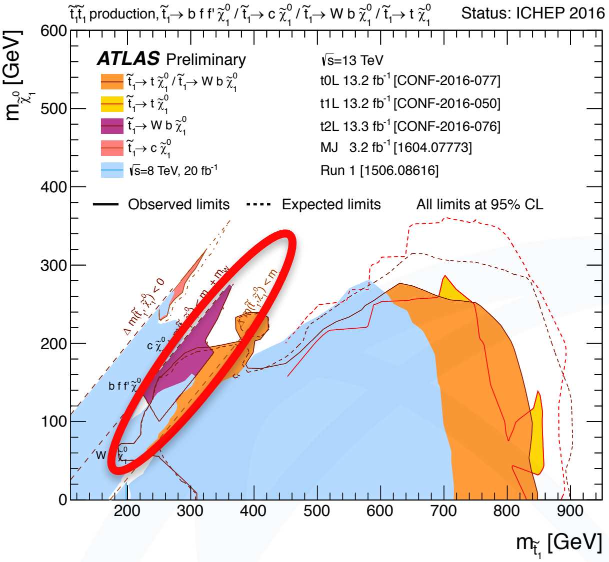
- Perform a shape fit of p_T(lep)/E_T^{miss}
- Major SM backgrounds (tt and W+jets) from CR fit



Signal region	bffN
Preselection	soft-lepton
Number of (jets, b-tags)	$(\geq 2, \geq 1)$
Jet p_{T} [GeV]	$>(400,\ 25)$
b-tagged jet p_{T} [GeV]	≥ 25
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>300
m_{T} [GeV]	<160
am_{T2} [GeV]	–
$m_{\mathrm{top}}^{\mathrm{reclustered}}$ [GeV]	top veto
$p_{\mathrm{T}}^{\ell}/E_{\mathrm{T}}^{\mathrm{miss}}$	<0.02
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\ell)$	–
$\min(\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, b\text{-jet}_i))$	<1.5
$\lvert\Delta\phi(j_{1,2},\vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$	>0.4
m_{T2}^{τ} based τ-veto [GeV]	–

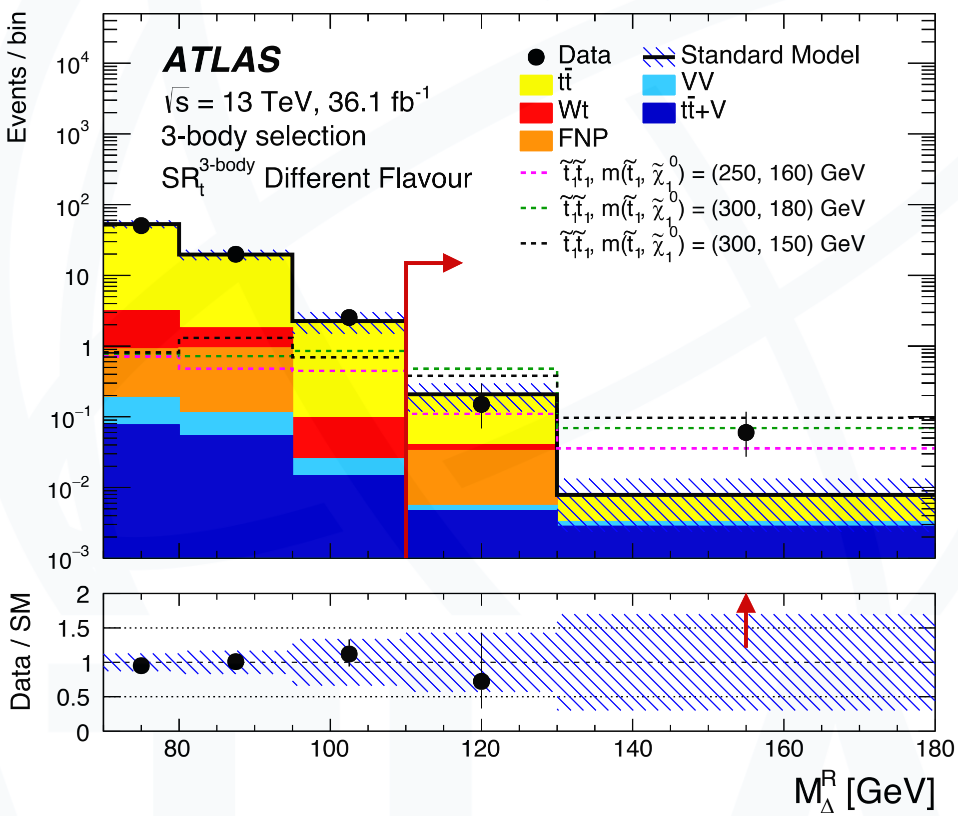
arXiv: 1708.03247

Three-body decays

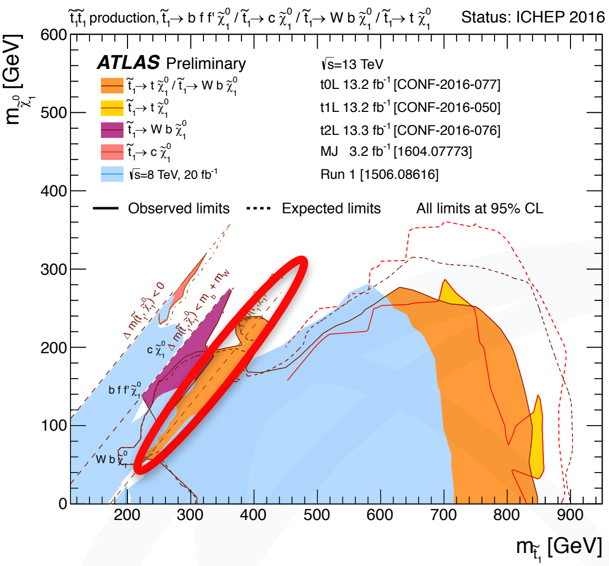


Target two opposite charge leptons

- Exploit recursive jigsaw (razor) variables
- Major SM backgrounds (tt and VV) from CR fit, fake leptons data-driven



	$SR_W^{3\text{-body}}$	
Lepton flavour	SF	DF
$p_T(\ell_1), p_T(\ell_2)$ [GeV]	> 25, > 20	
$m_{\ell\ell}$ [GeV]	[20, 71.2] or > 111.2	> 20
$n_{b\text{-jets}}$	= 0	
M_Δ^R [GeV]	> 95	
R_{p_T}	> 0.7	
$1/\gamma_{R+1}$	> 0.7	
$\Delta\phi_\beta^R$	$> 0.9\lvert\cos\theta_b\rvert + 1.6$	



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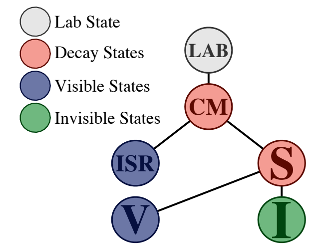
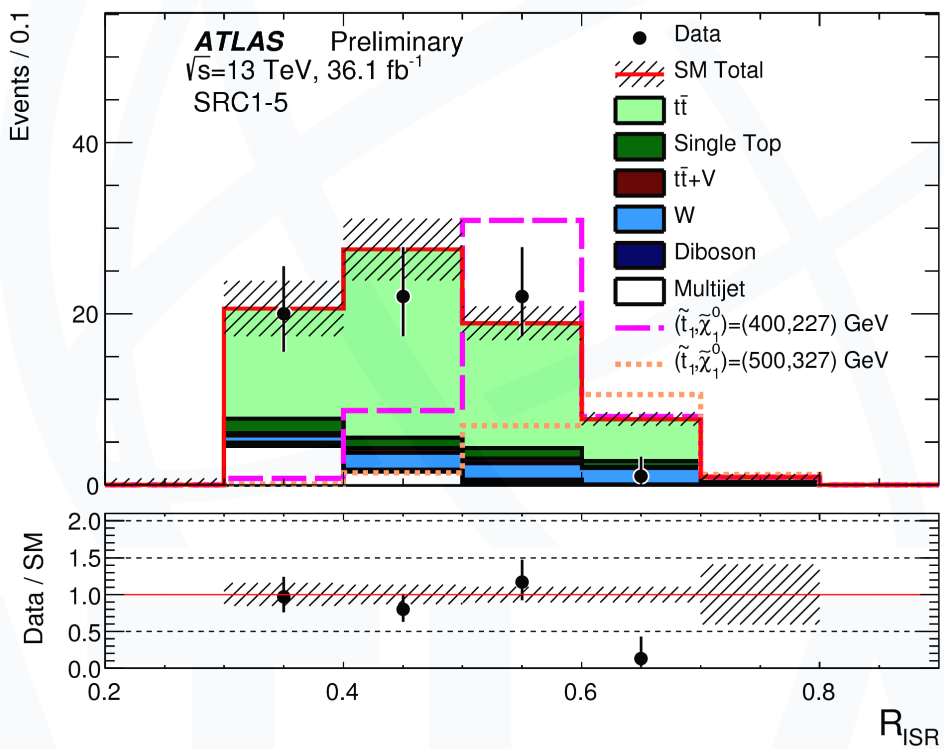
tt-like decays



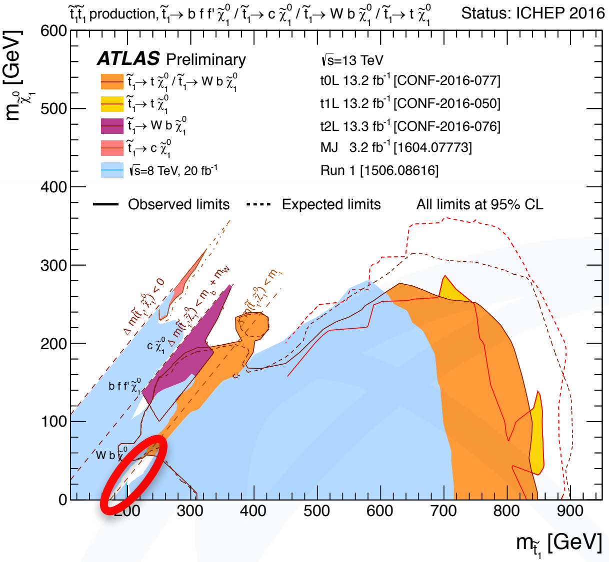
Target fully hadronic events

- Exploit recursive jigsaw variables
- Major SM background (tt with hadronic tau) from CR fit



$$R_{\mathrm{ISR}} \equiv \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\mathrm{ISR}}} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}}$$

Variable	SRC1	SRC2	SRC3	SRC4	SRC5
$N_{b-\mathrm{jet}}$	≥ 1				
$N_{b-\mathrm{jet}}^{\mathrm{S}}$	≥ 1				
$N_{\mathrm{jet}}^{\mathrm{S}}$	≥ 5				
$p_{\mathrm{T},b}^{0,\mathrm{S}}$	> 40 GeV				
m_{S}	> 300 GeV				
$\Delta\phi_{\mathrm{ISR},E_{\mathrm{T}}^{\mathrm{miss}}}$	> 3.0				
$p_{\mathrm{T}}^{\mathrm{ISR}}$	> 400 GeV				
$p_{\mathrm{T}}^{4,\mathrm{S}}$	> 50 GeV				
R_{ISR}	0.30-0.40	0.40-0.50	0.50-0.60	0.60-0.70	0.70-0.80

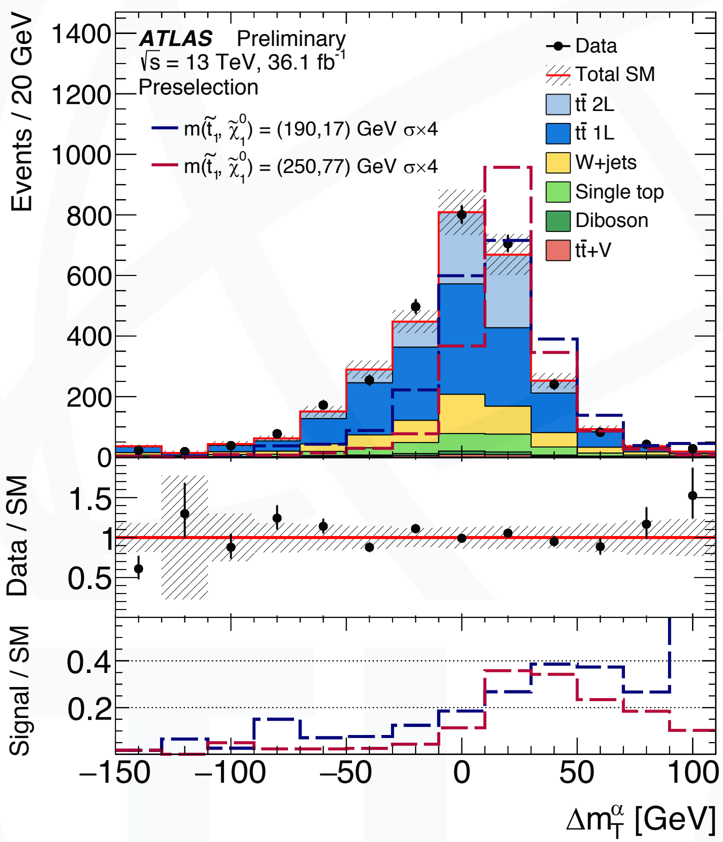


ATLAS-CONF-2017-037

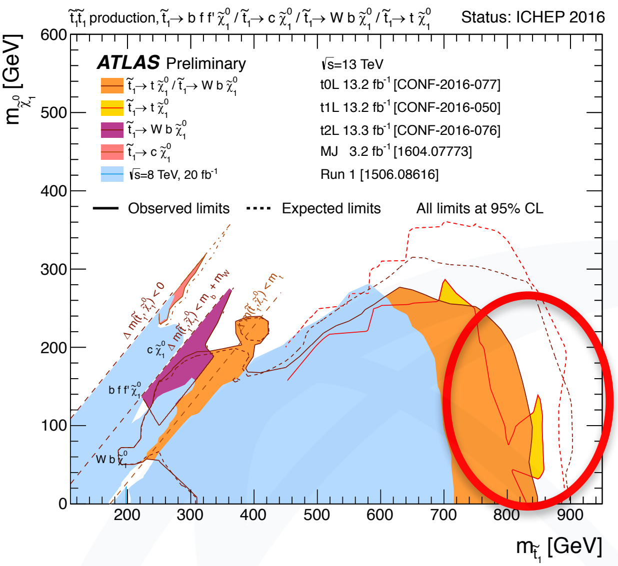
tt-like decays

Target a single isolated lepton

- Exploit multivariate discriminant
- Reconstruct neutrino p_T and lepton's m_T shift (Δm_T) for a given signal
  - Major SM background (tt) from CR fit



Variable	tN_diag_low
Preselection	low-E_T^{miss}
Number of (jets, b-tags)	$(\geq 4, \geq 1)$
Jet p_T [GeV]	$> (120, 25, 25, 25)$
E_T^{miss} [GeV]	> 100
m_T [GeV]	> 90
R_{ISR}	–
$p_T(t\bar{t})$ [GeV]	> 400
$\lvert\Delta\phi(l, t\bar{t})\rvert$	> 1.0
$\lvert\Delta\phi(j_{1,2}, \vec{p}_T^{miss})\rvert$	> 0.4
m_{T2}^{τ} based τ-veto [GeV]	–
BDT score	BDT_low ≥ 0.55



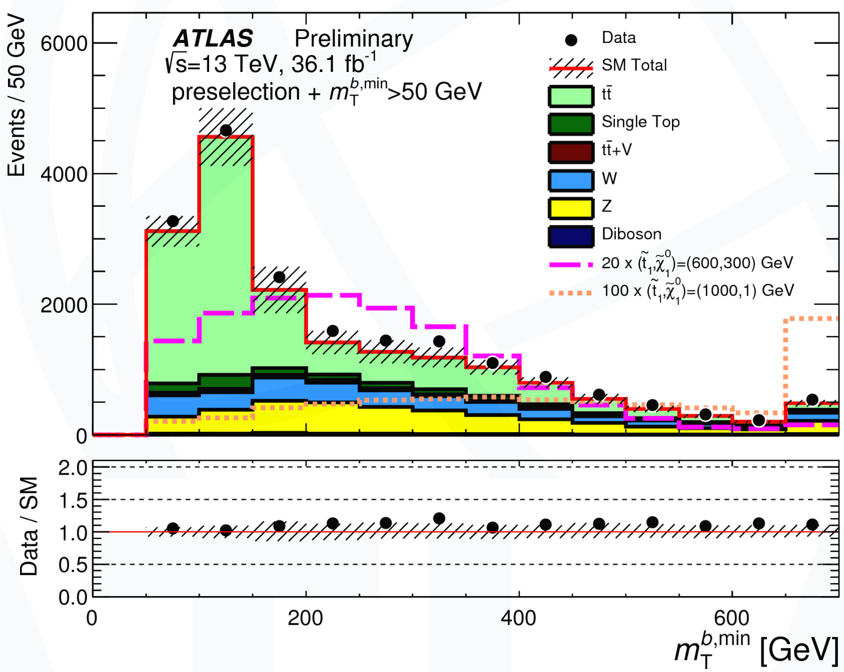
ATLAS-CONF-2017-020

Two-body decays

Target fully hadronic events

- Reconstruct top candidates with reclustered jets
- Major SM background (Z+jets,tt/Wt/W+jets,ttZ) from CR fit

$$m_T^{b,\min} = \sqrt{2\, p_T^b\, E_T^{\text{miss}} \left[1 - \cos\Delta\phi\left(\mathbf{p}_T^b, \mathbf{p}_T^{\text{miss}}\right)\right]}$$



Signal Region		TT	TW	T0
	$m^0_{\text{jet},R=1.2}$	> 120 GeV		
	$m^1_{\text{jet},R=1.2}$	> 120 GeV	$[60, 120]$ GeV	< 60 GeV
	$m_T^{b,\min}$	> 200 GeV		
	$N_{b-\text{jet}}$	≥ 2		
	τ-veto	yes		
	$\left\lvert\Delta\phi\left(\text{jet}^{0,1,2}, \mathbf{p}_T^{\text{miss}}\right)\right\rvert$	> 0.4		
A	$m^0_{\text{jet},R=0.8}$	> 60 GeV		
	$\Delta R\,(b,b)$	> 1	-	
	$m_{T2}^{\chi^2}$	> 400 GeV	> 400 GeV	> 500 GeV
	E_T^{miss}	> 400 GeV	> 500 GeV	> 550 GeV
B	$m_T^{b,\max}$	> 200 GeV		
	$\Delta R\,(b,b)$	> 1.2		

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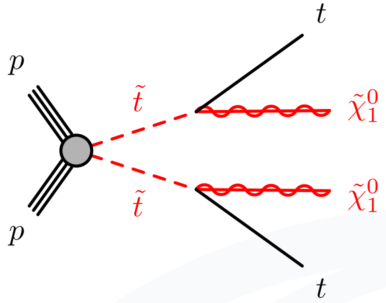
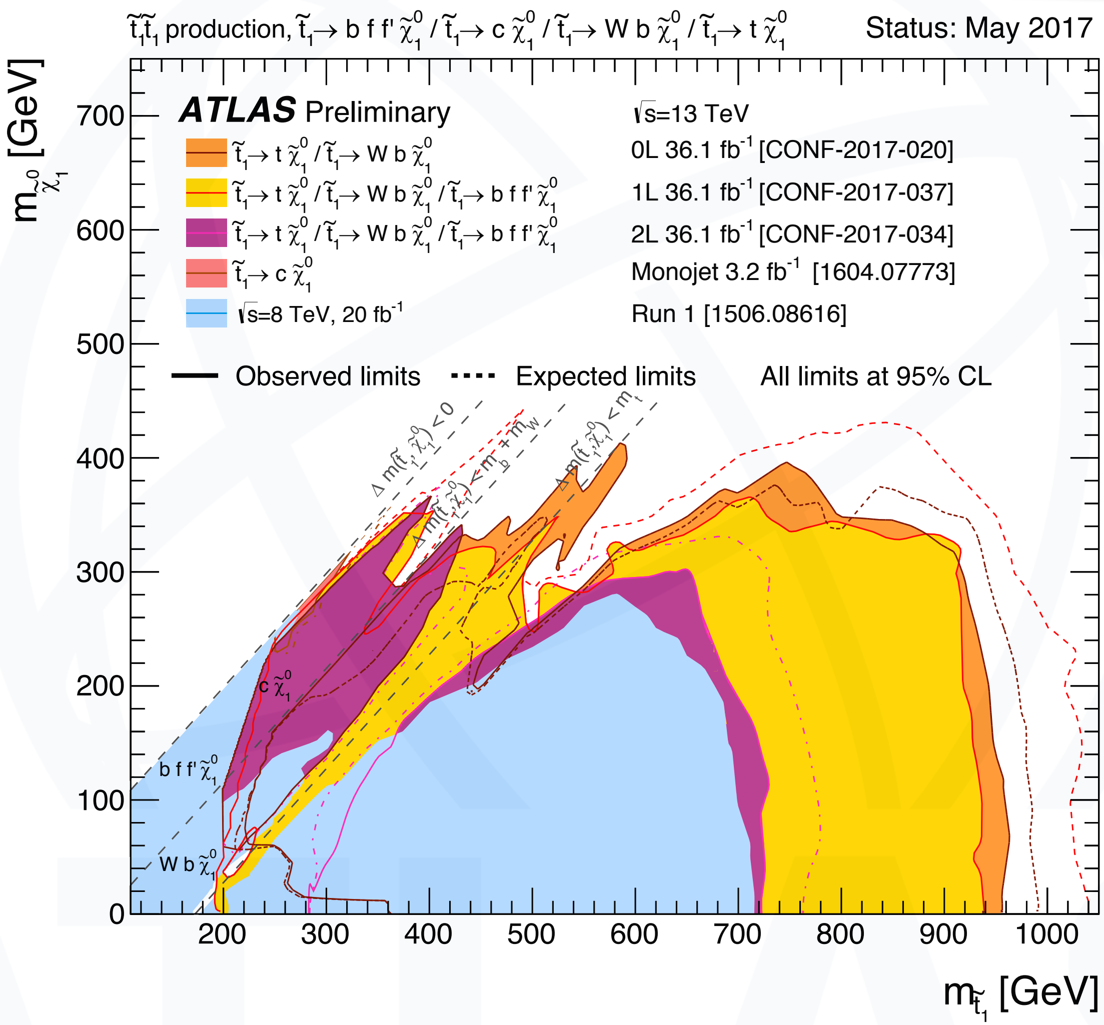
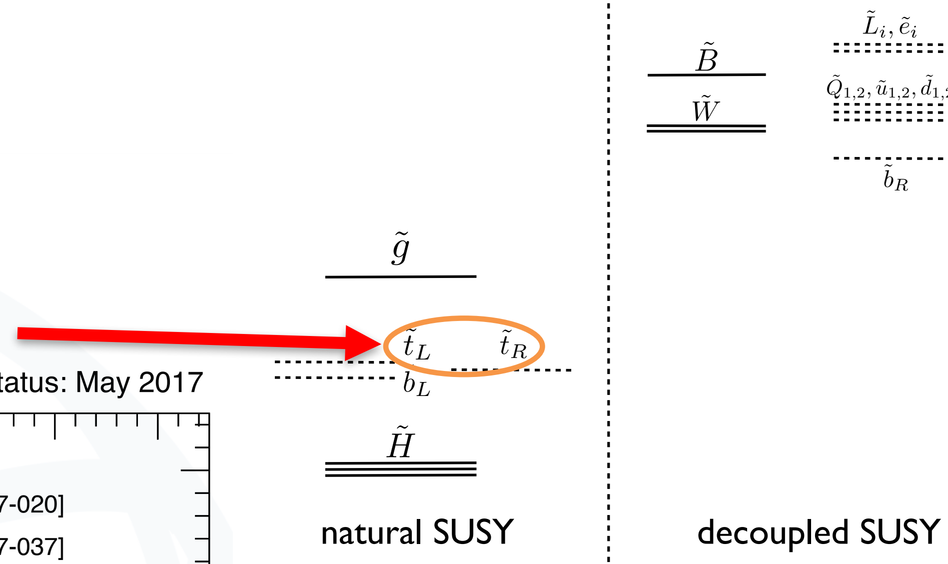
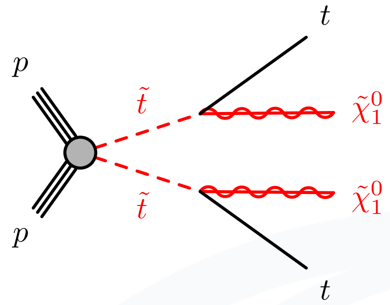


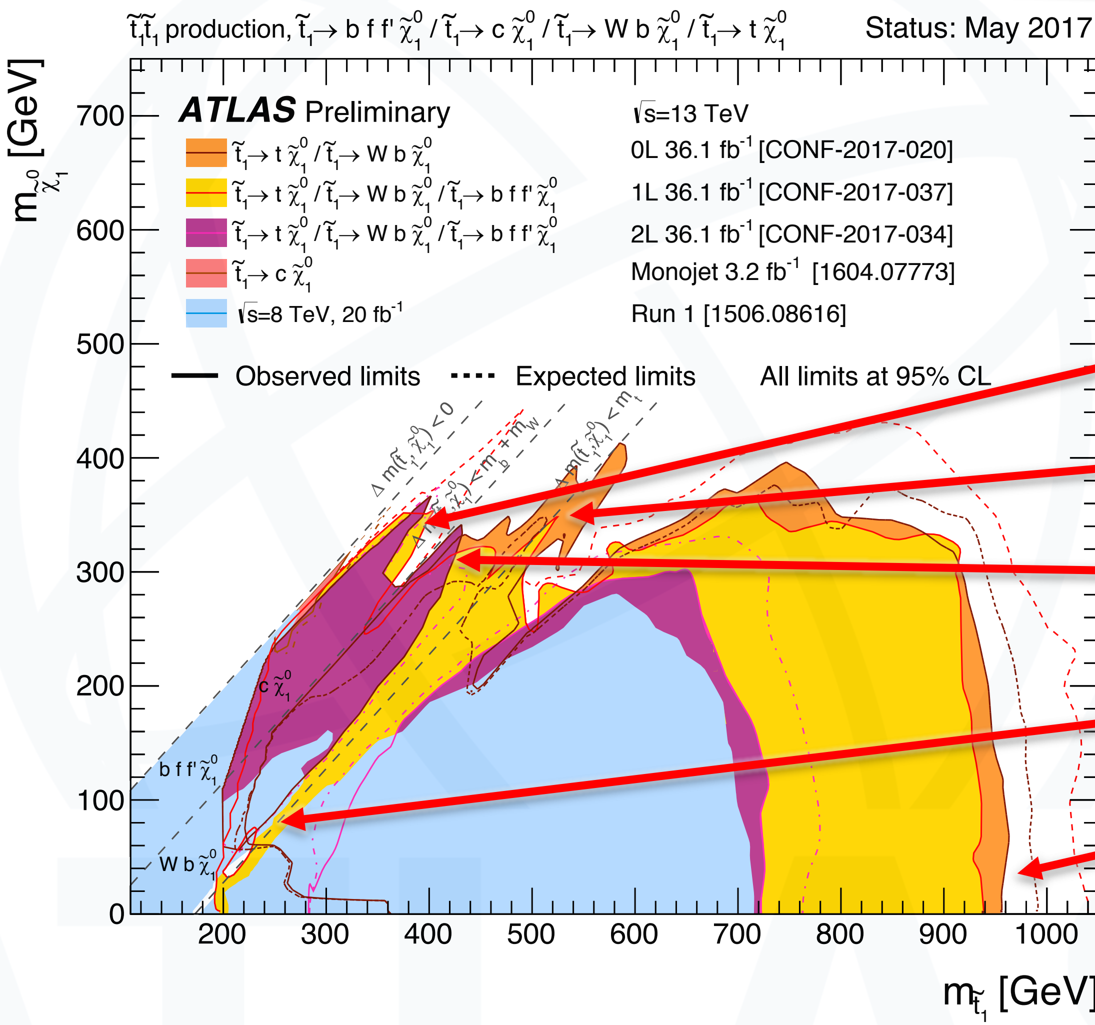


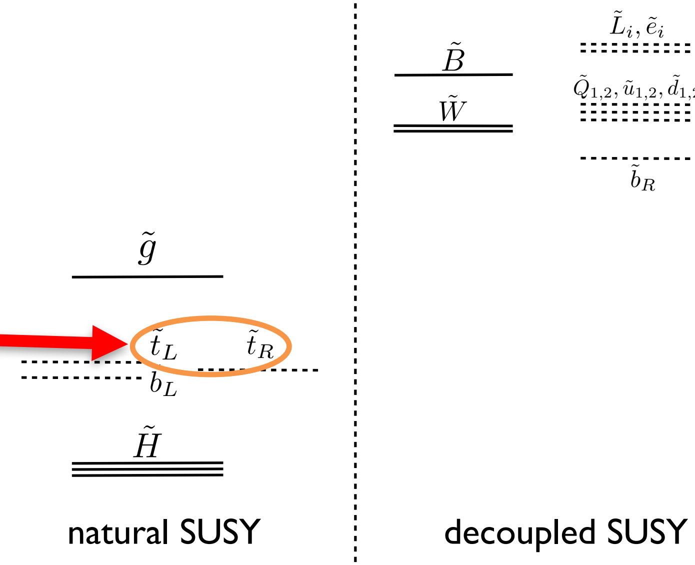


- Sensitivity **exceeds 1 TeV** in favourable scenarios.
- (Almost) no gaps left behind.

STOP







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[CONF-2017-020]

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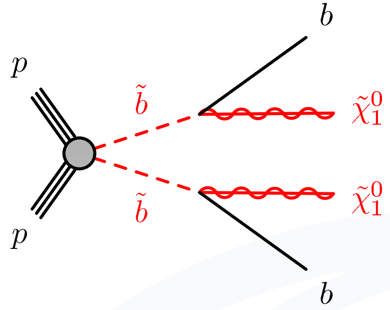
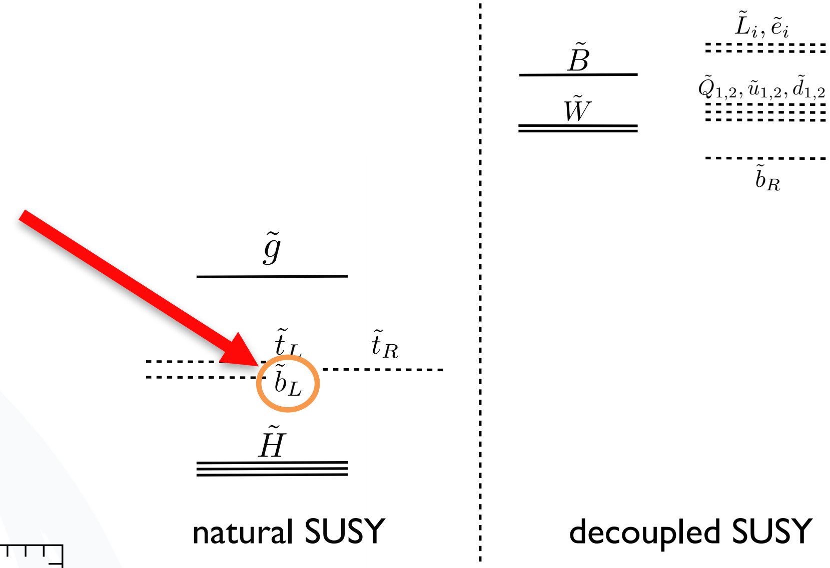
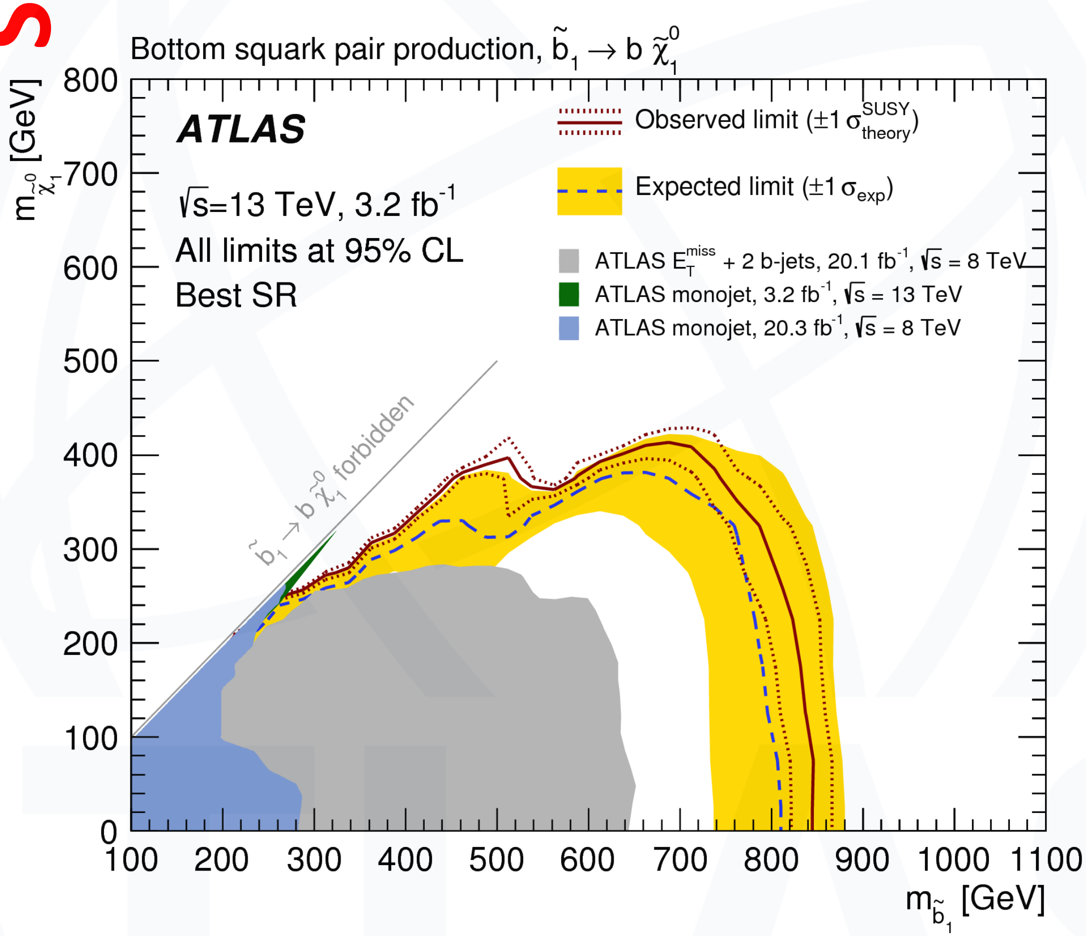
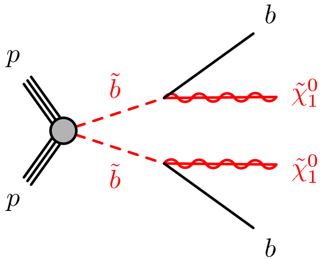






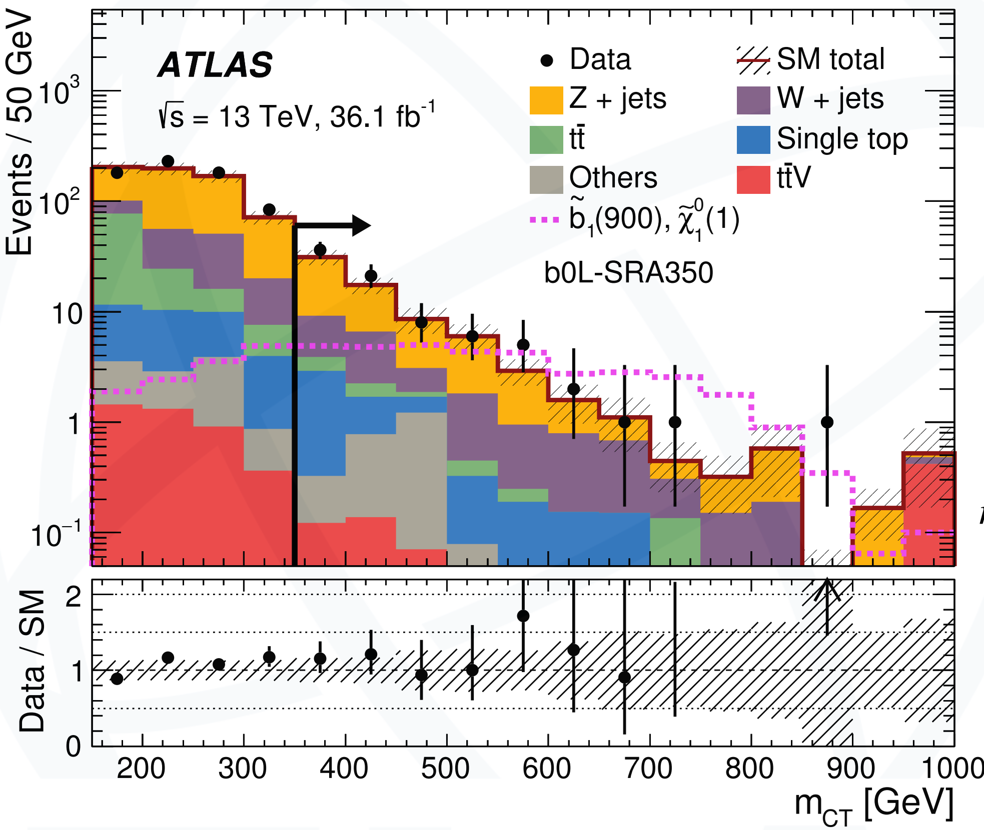
Start the search with simplified models

- Only b_1 and χ_1 accessible
- χ_1 is b-ino like



arXiv: 1708.09266

Fully hadronic search



Simple final state with a clear detector signature.

Selects events with **two** energetic *b*-jets and missing momentum

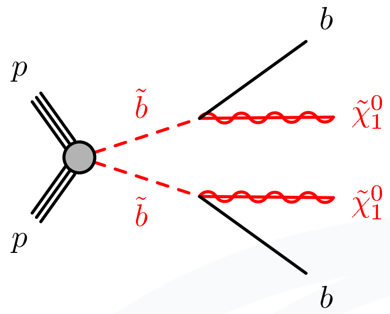
- E_T^{miss}> 250 GeV
- m_{CT}> 350, 450, 550 GeV

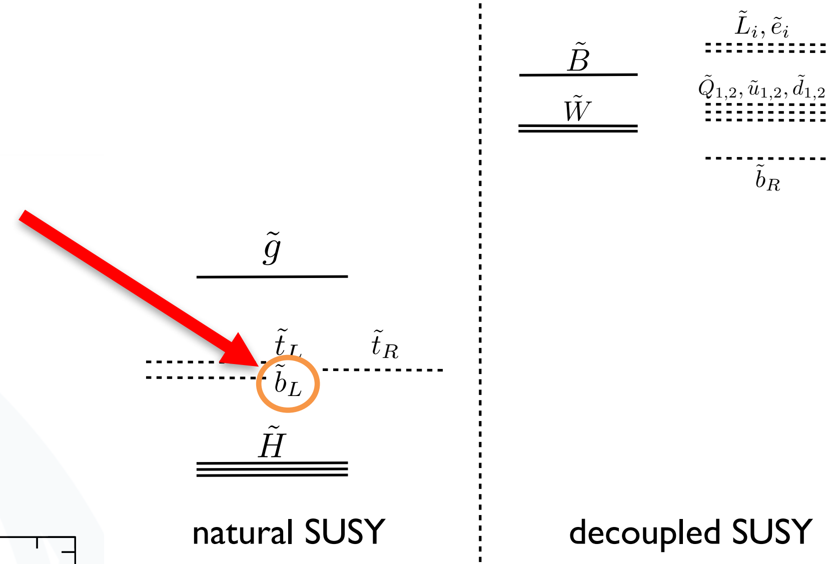
$$m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2$$

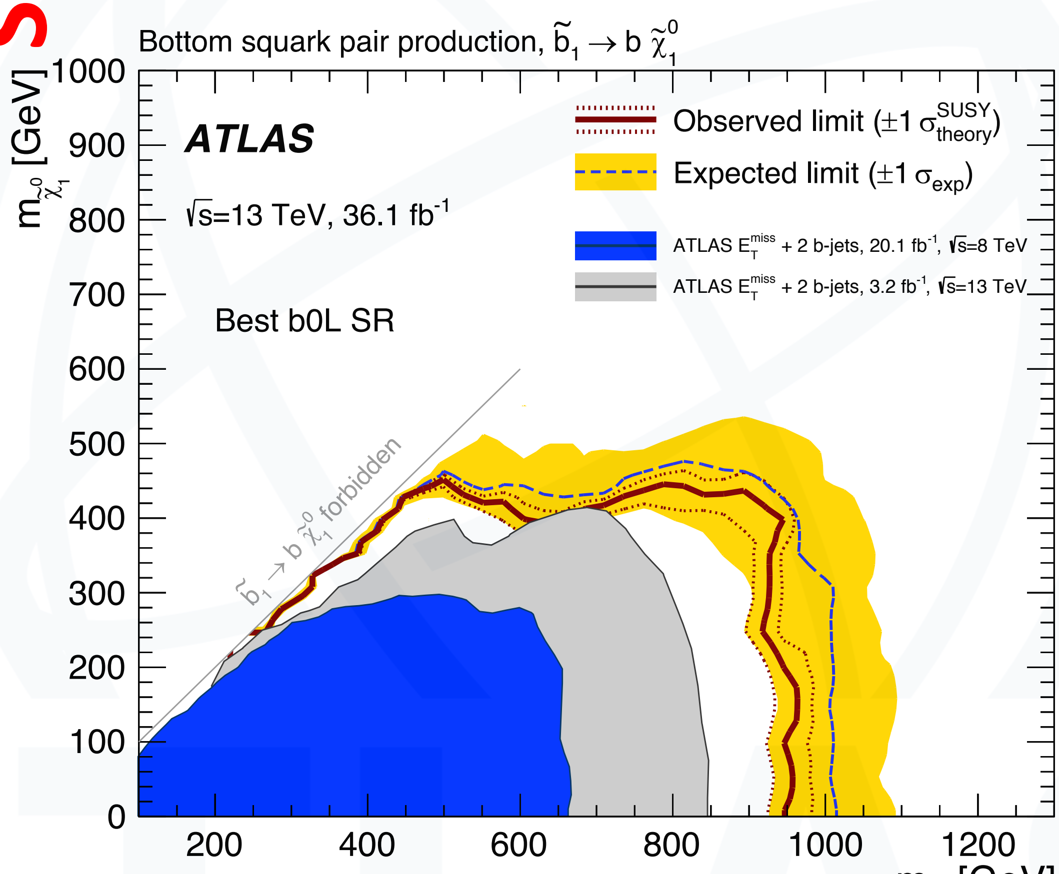
m_{CT} is used to measure the masses of pair-produced semi-invisibly decaying heavy particles.

$$m_{CT}^{max} = \frac{m_i^2 - m_X^2}{m_i}$$

SBOTTOM

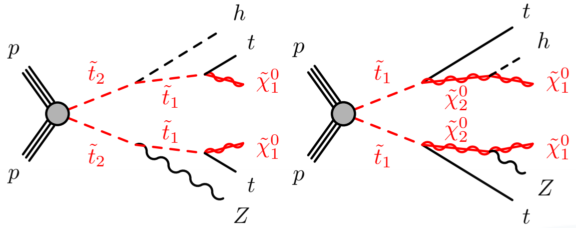






arXiv: 1708.09266

- Sensitivity **exceeds 1 TeV** in favourable scenarios.
- No gaps left behind.



JHEP08 (2017) 006

More complex decays

The phenomenology changes if more particles are accessible.

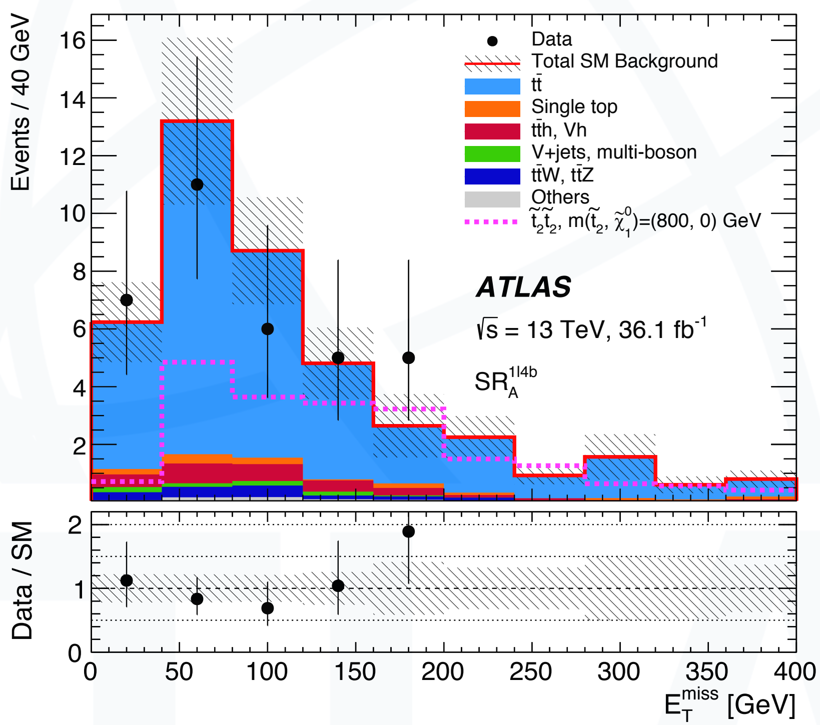
- Decays via Z and Higgs bosons can provide additional sensitivity.

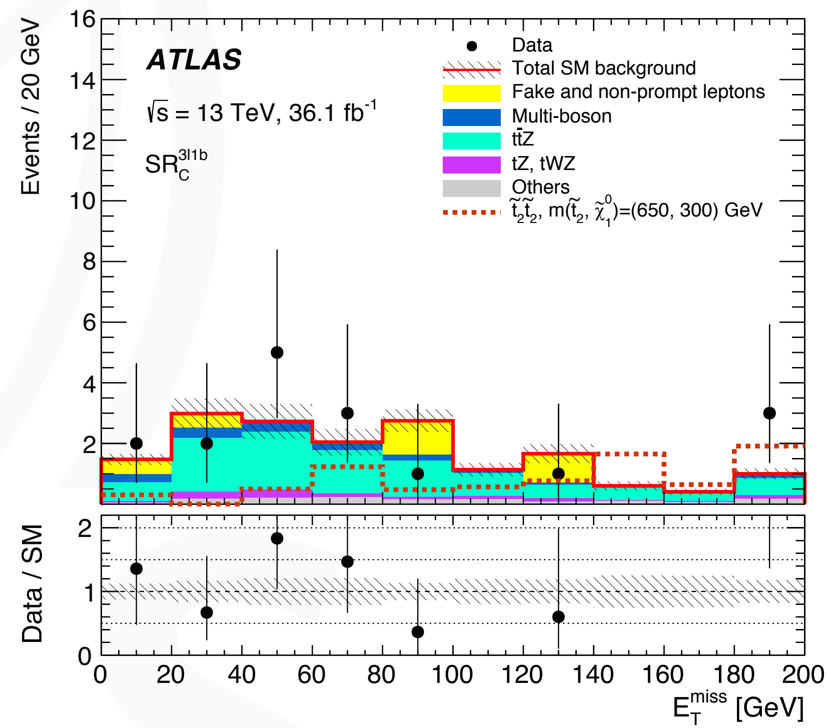
1 lepton + 4 b-jets (1l4b)

- Targets Higgs boson hadronic decays (bb)
- Major SM background (ttbb) from CR fit

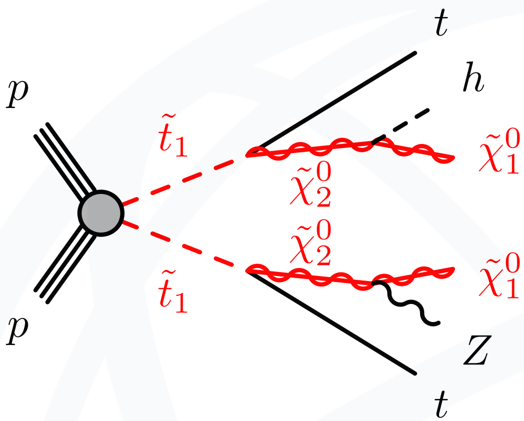
3 leptons + 1 b-jets (3l1b)

- Targets Z boson decays to charged leptons
- Major SM backgrounds (ttZ, VV) from CR fit, data-driven fakes





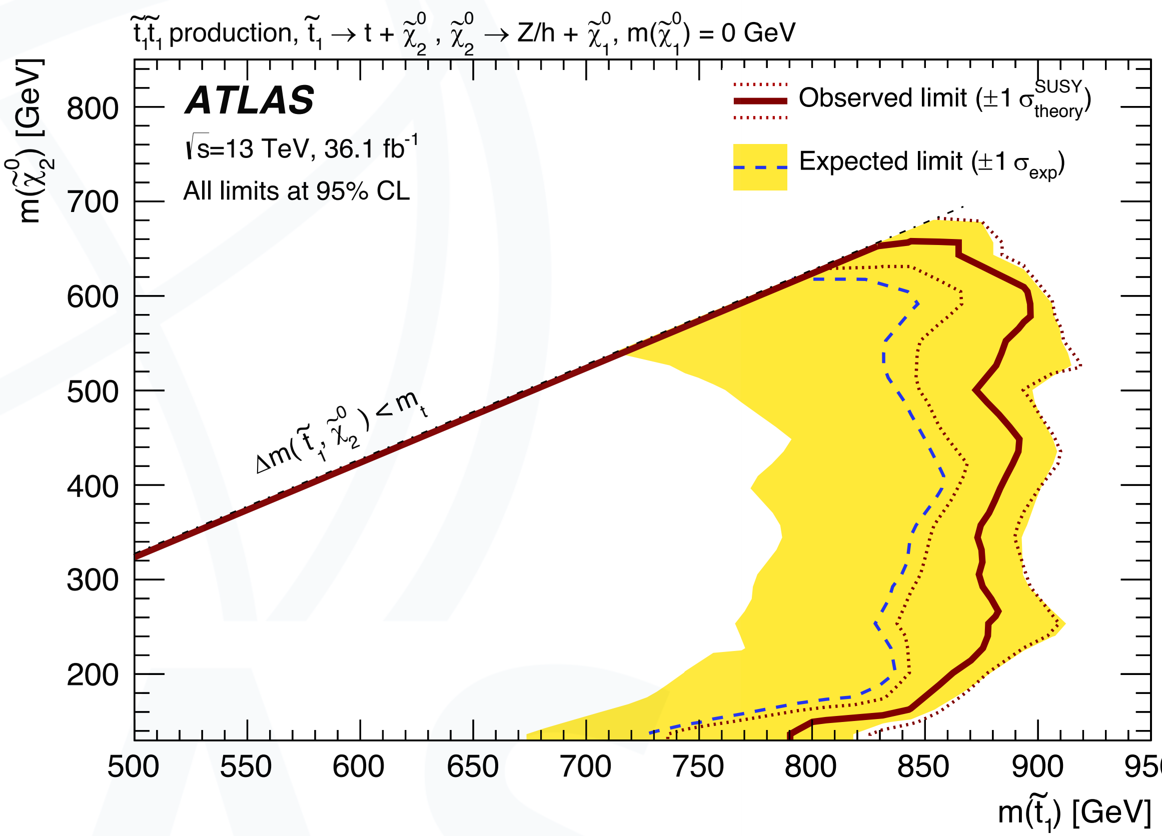
More complex decays



- χ_1 is assumed to be massless
- $\Delta m(\chi_2,\chi_1) > m(h)$
- 50% BR of χ_2 to Z and h bosons

Statistical combination of 3l1b and 1l4b selections

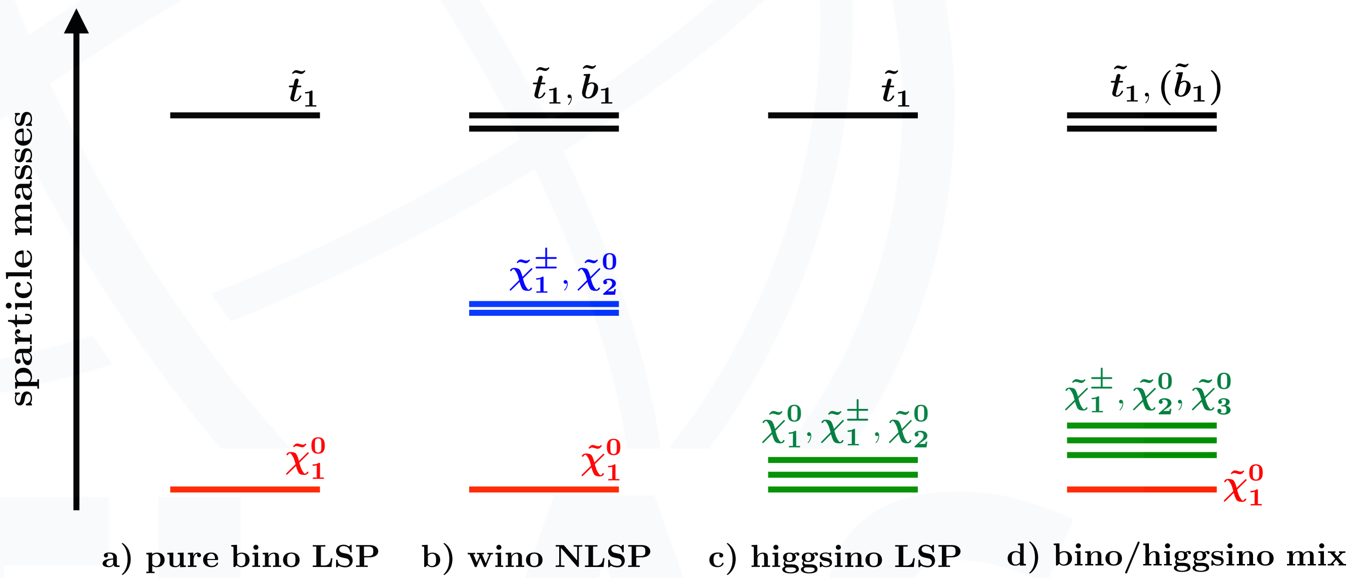
- Sensitivity up to about 900 GeV



More realistic models

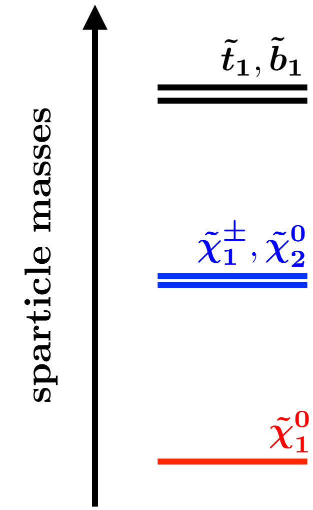
What if the top squark - neutralino model is too simple?

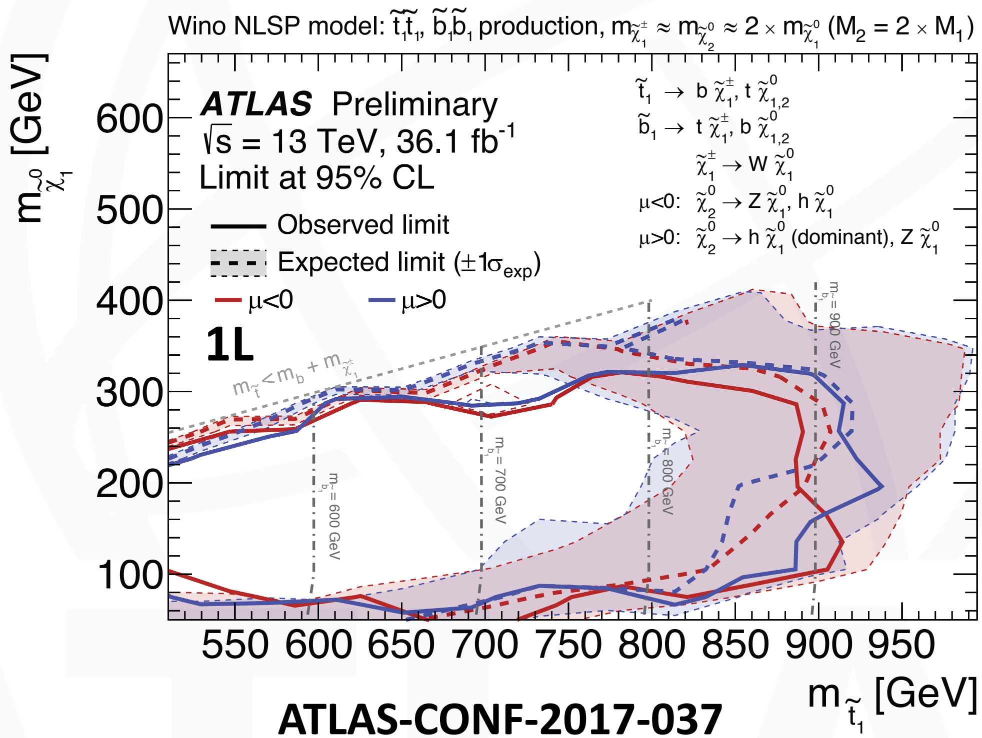
- Set of pMSSM-inspired models with a non-minimal ewk-ino sector
- More complex decay chains than Run 1 benchmarks



Wino-Bino scenario

- Consider both top and bottom squark pair production.
- More complex phenomenology, **reduced sensitivity.**
- **Complementarity between 1L and 2L searches**





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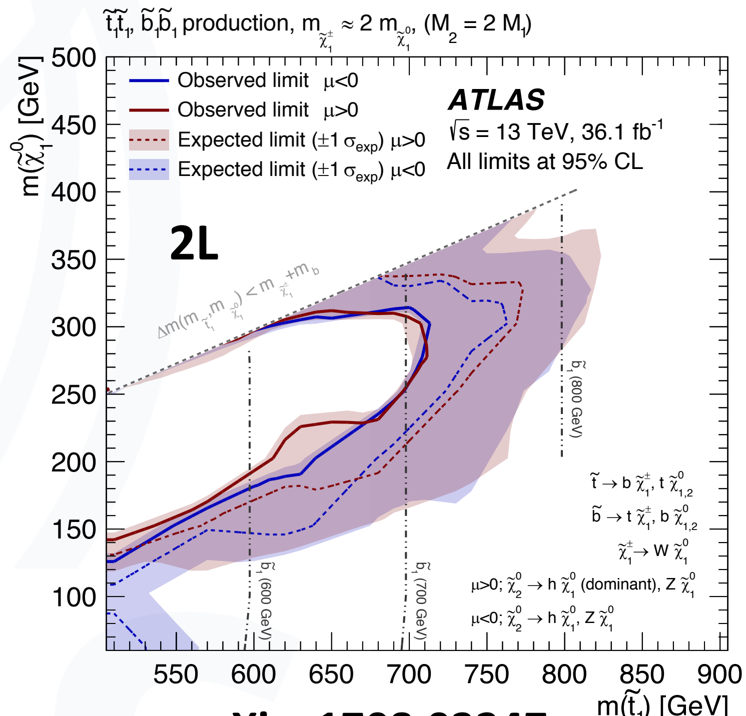
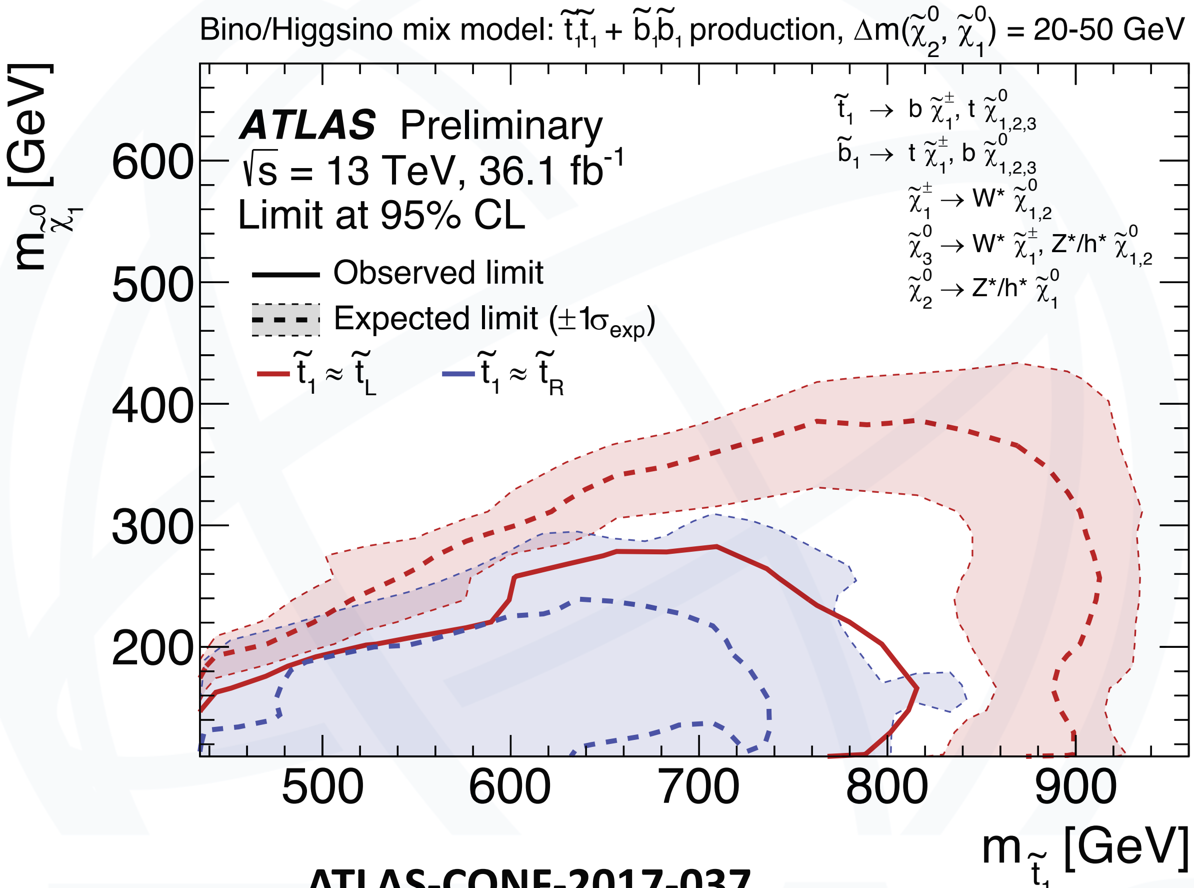


arXiv: 1708.03247

Bino/Higgsino scenario



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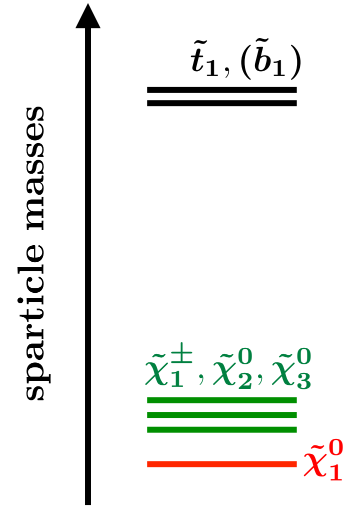


$0.10 < \Omega h^2 < 0.12$

“Well-tempered neutralino”: satisfy naturalness and DM relic density constraints

- Reduced sensitivity

R-Parity Violating models

R-parity R = $(-1)^{3B+L+2S}$ is a discrete multiplicative symmetry.

- **SUSY particles must be produced in pairs**
- The Lightest Supersymmetric Particle (LSP) is stable (dark matter)

L-number violating terms

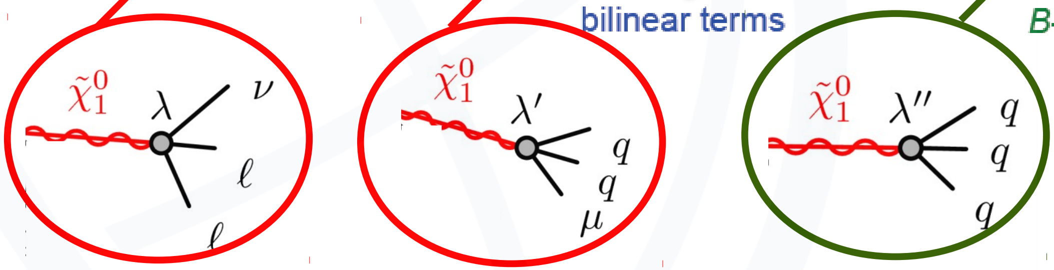
The MSSM potential

$$W_{\not{R}p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

bilinear terms

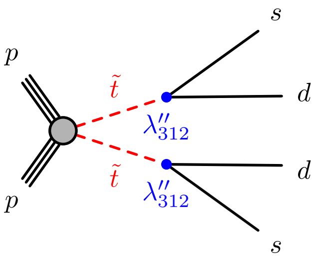
B-number violating terms

RPV couplings $\lambda, \lambda', \lambda''$



No reason to assume conservation of R-parity

- Can constrain proton decay with lepton or baryon violating SUSY, but not both



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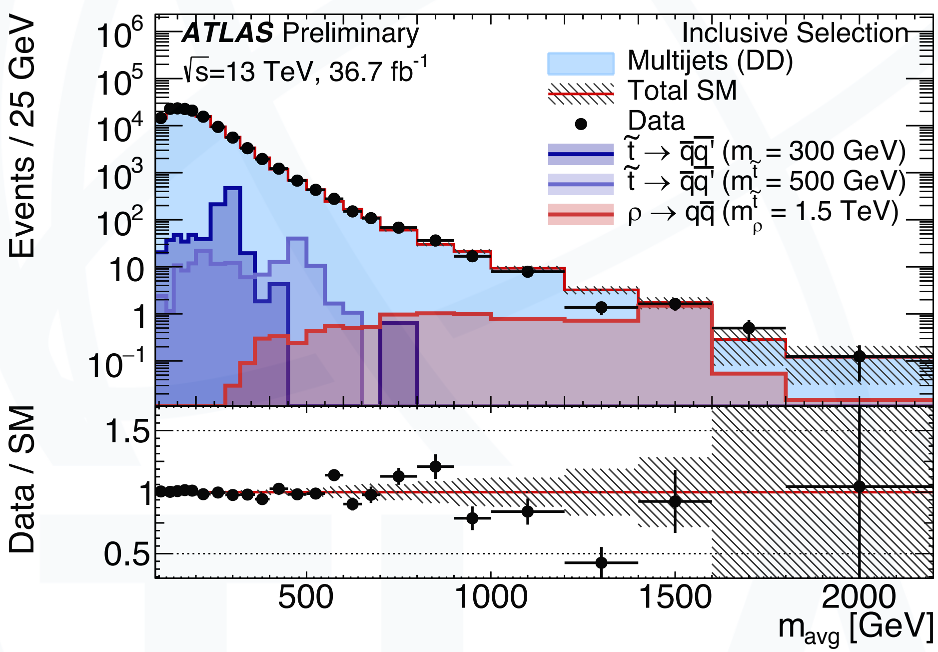
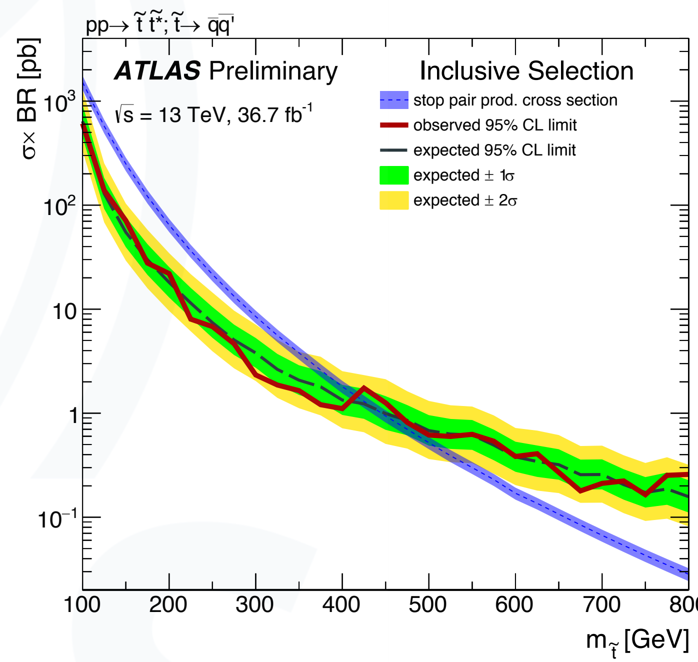
Fully hadronic RPV stops

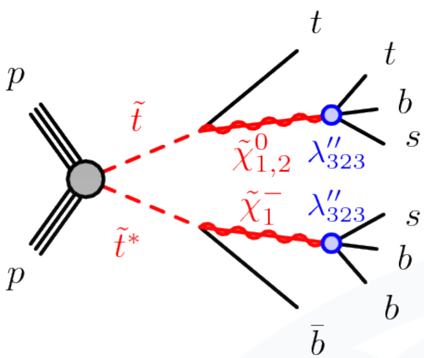
Targets final states with at least **four jets**

$$\Delta R_{\min} = \sum_{i=1,2} |\Delta R_i - 1|$$

- Look at jet pairs that minimise $\Delta R_{\min}$
- Major SM backgrounds (QCD multi-jet) from data-driven ABCD method





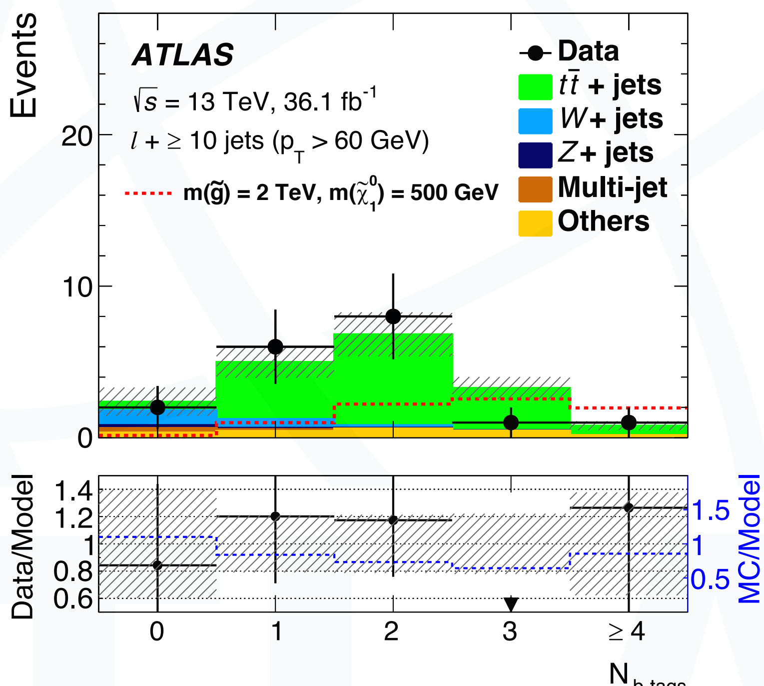


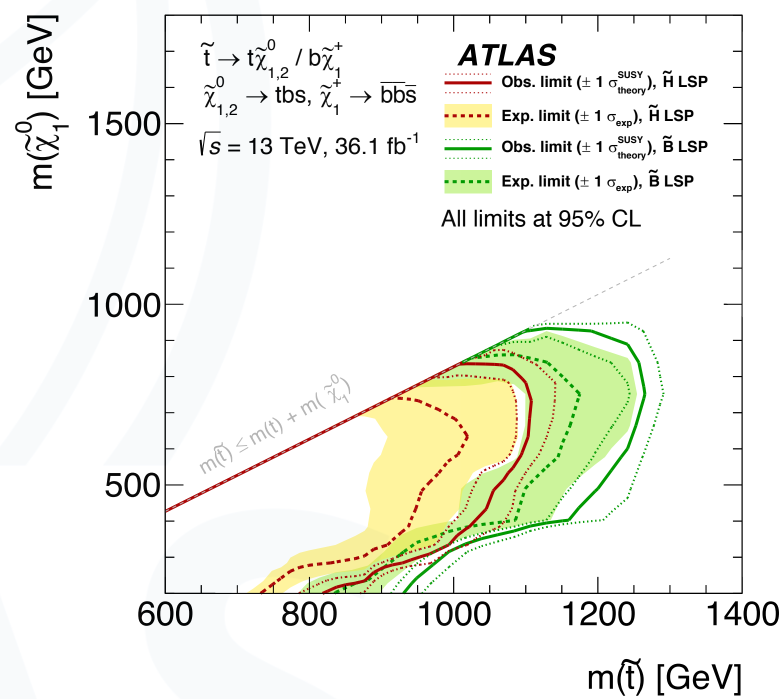
arXiv: 1704.08493

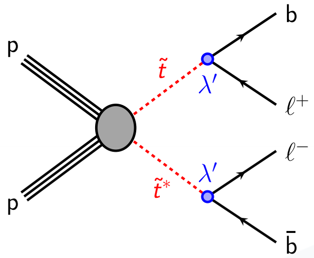
Single-lepton RPV stops

Targets final states with **one lepton and N_{jet} > 8**

- Sensitive to a wide range of BSM physics (not just stops)
- Major SM backgrounds (tt, *W*/*Z*+jets) suffers from large theoretical uncertainties, from data-driven template fit





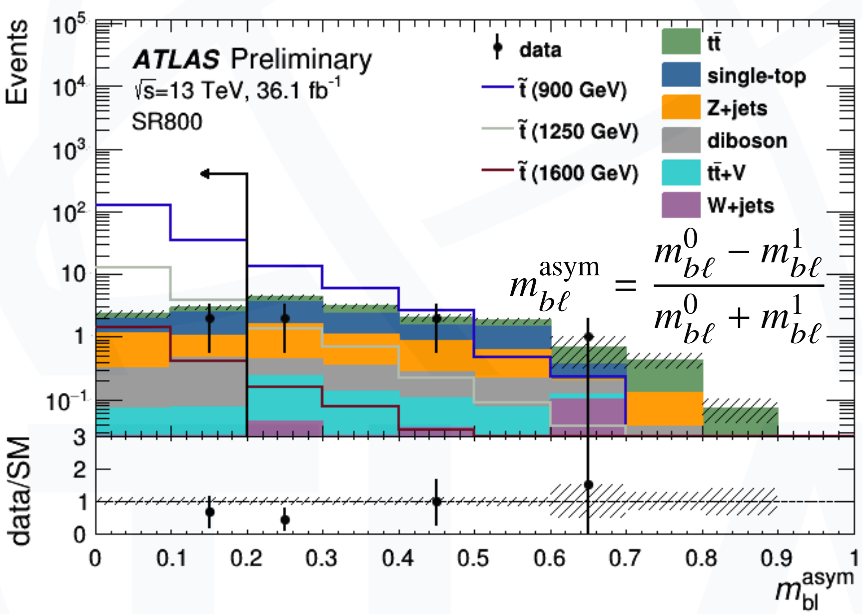


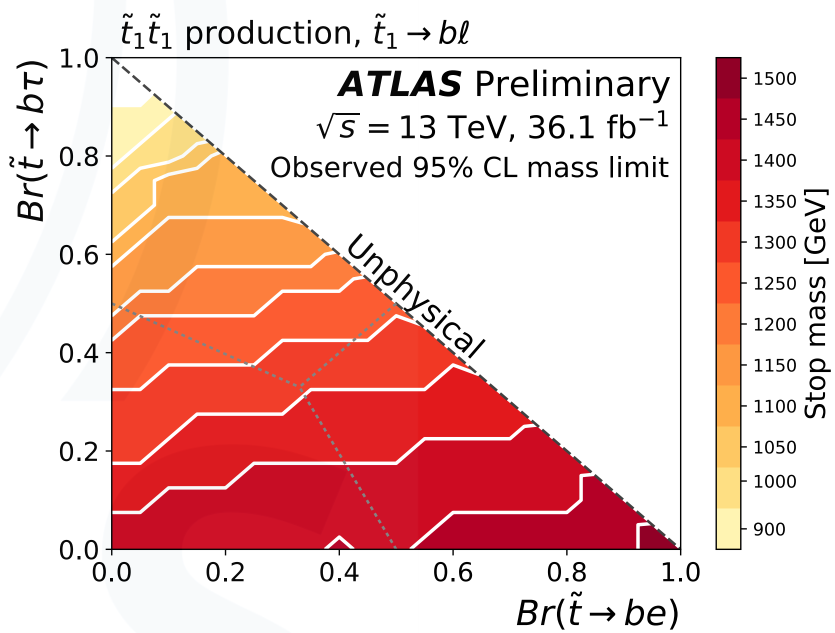
Di-lepton RPV stops

Target events with **2 leptons and 2 jets** (at least one b-tag)

- Look at bl pairs that minimise m_{bl} asymmetry
- BR to lepton flavours ∝ to neutrino mass hierarchy

Region	N_b	$m^0_{b\ell}$ [GeV]	$m^1_{b\ell}$(rej)[GeV]	H_T [GeV]	$m_{\ell\ell}$ [GeV]
SR800	≥ 1	> 800	> 150	> 1000	> 300
SR1100	≥ 1	> 1100	> 150	> 1000	> 300





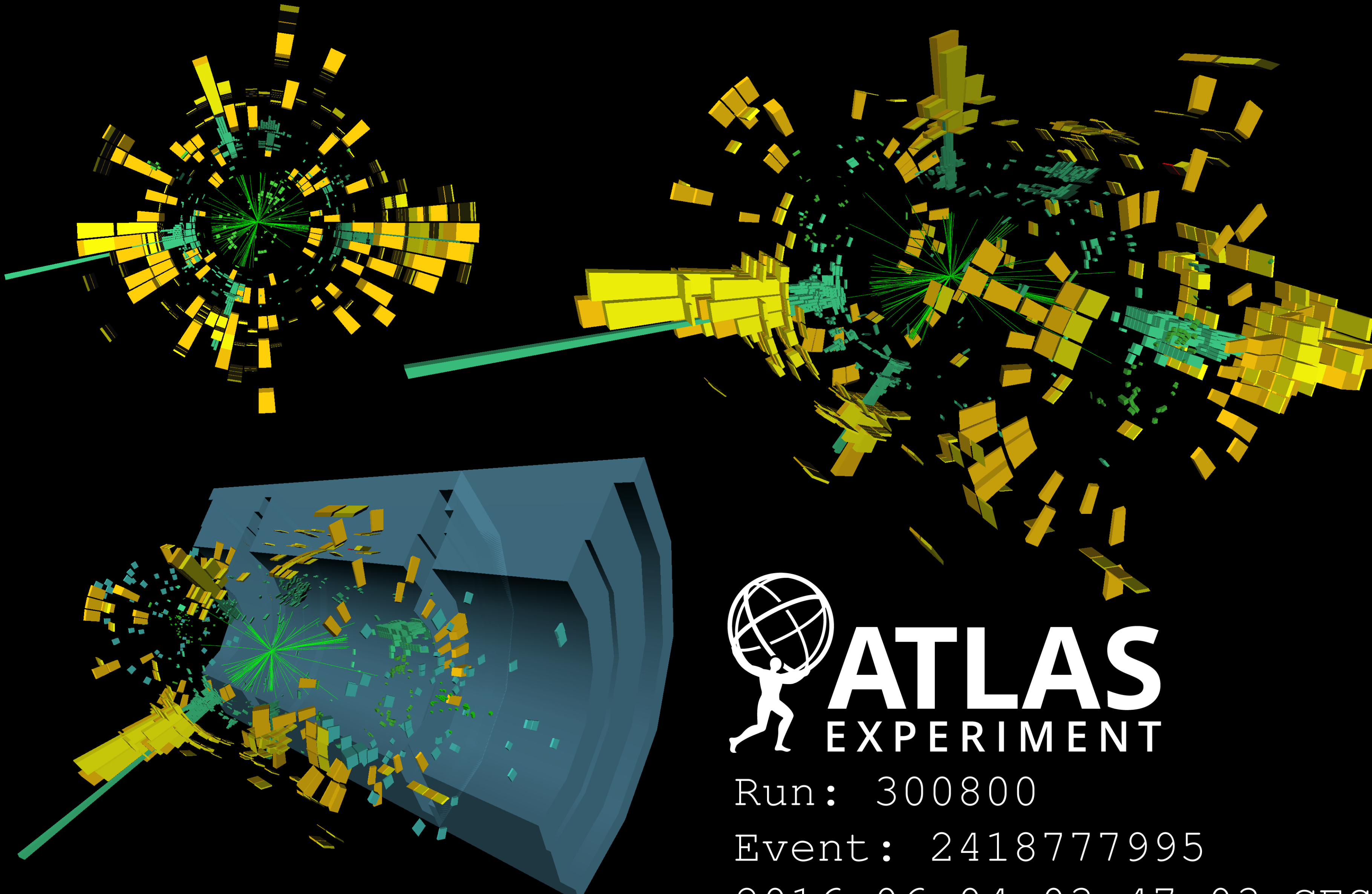
Summary

- Searches for sbottom and stops based on full 2015+2016 data ($36\ fb^{-1}$) have given **results consistent with the SM expectations**.
- Limits on the 3rd generation squark masses close to 1 TeV for the most favourable scenarios
- Stringent limits obtained in pMSSM inspired models, yet **some part of the parameter space is still uncovered**.

The search for SUSY continues!

- **Exciting results ahead with the full Run 2 dataset**

Thanks for your attention

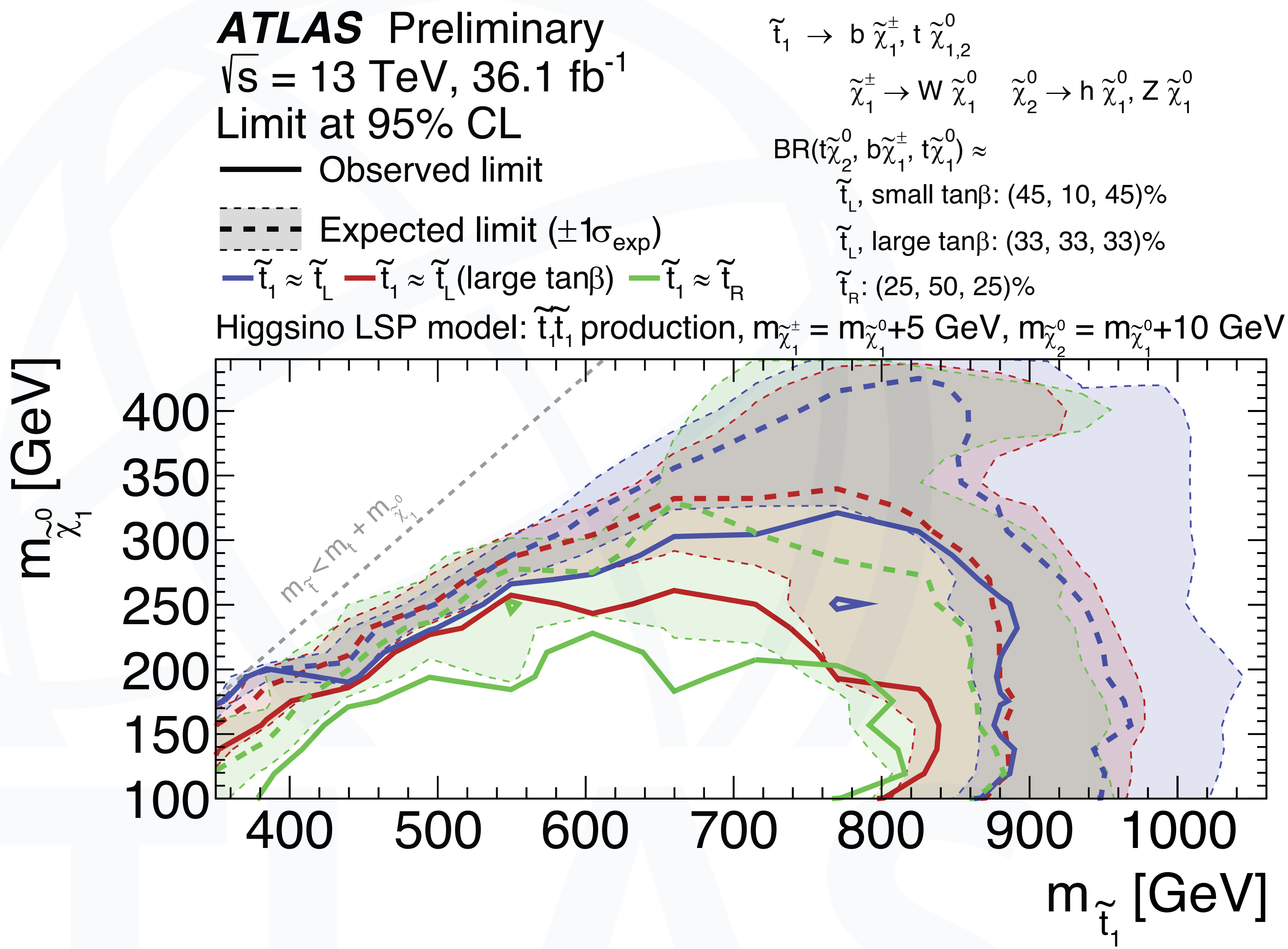


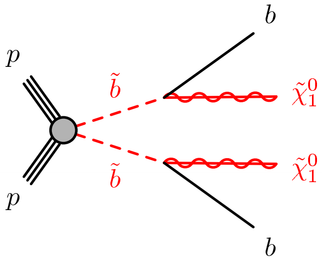
ATLAS
EXPERIMENT

Run: 300800
Event: 2418777995
2016-06-04 03:47:03 CEST

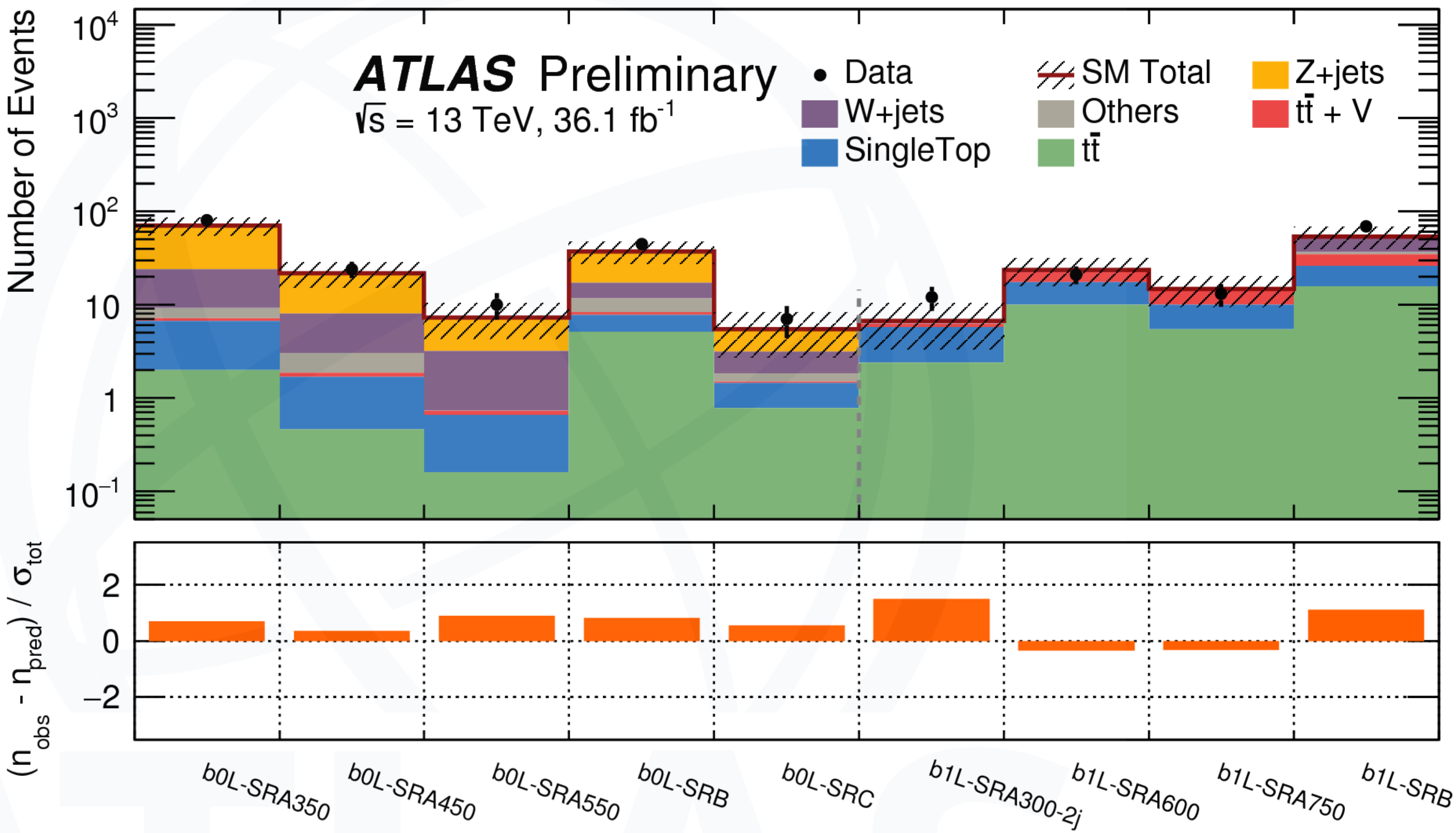
BACKUP

Higgsino scenario

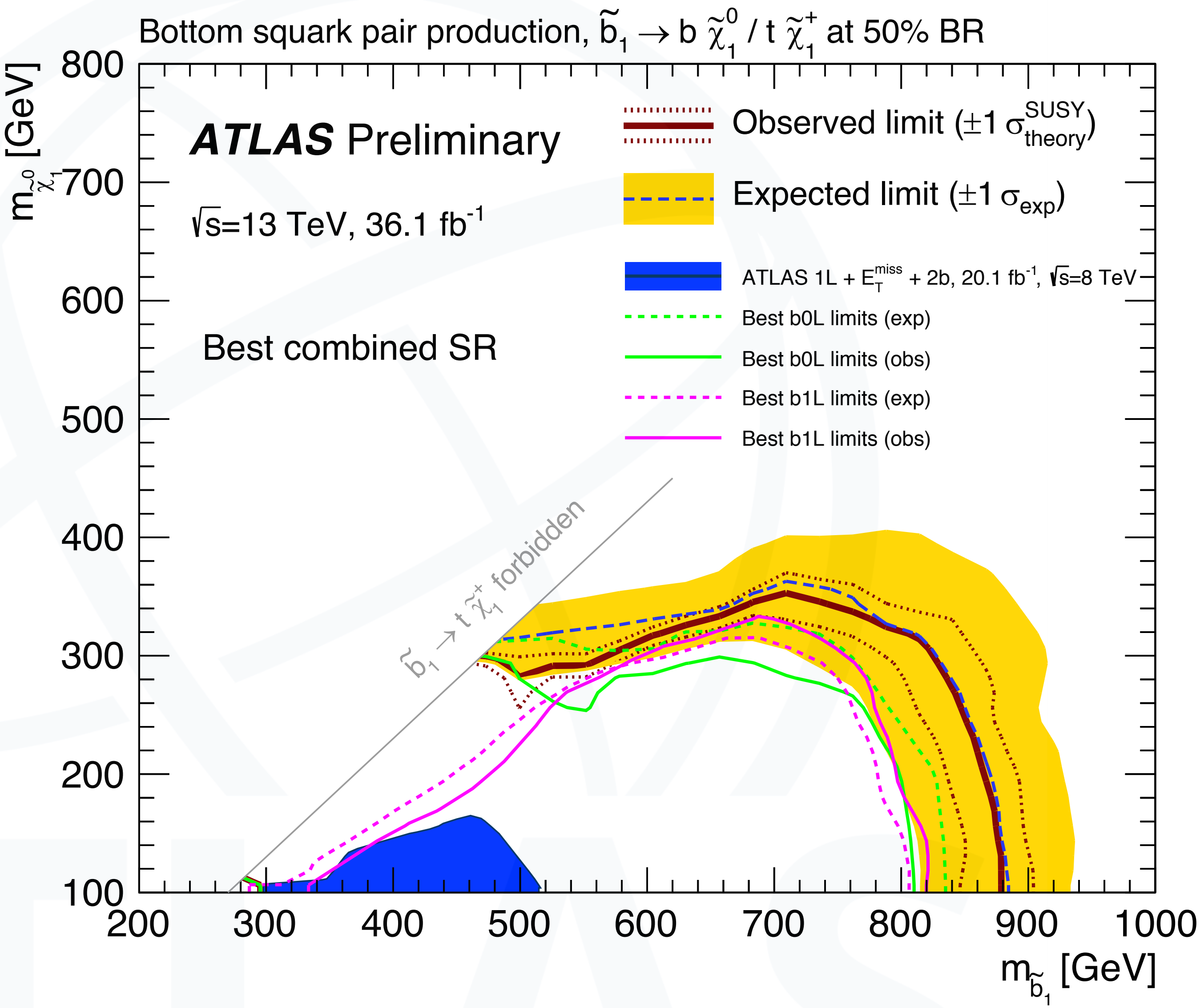


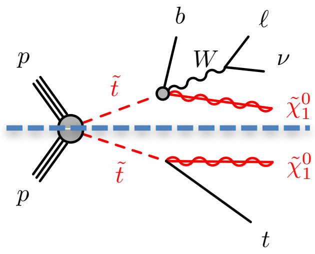


Sbottom results

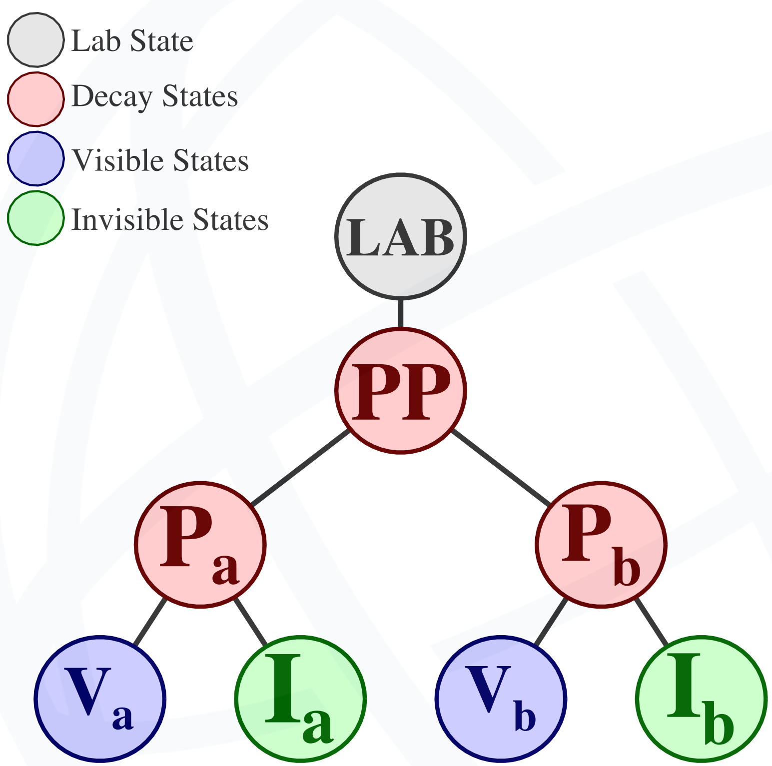


~Higgsino scenario (sbottom)



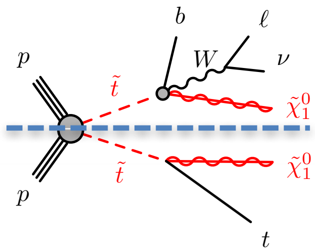


The Recursive Jigsaw

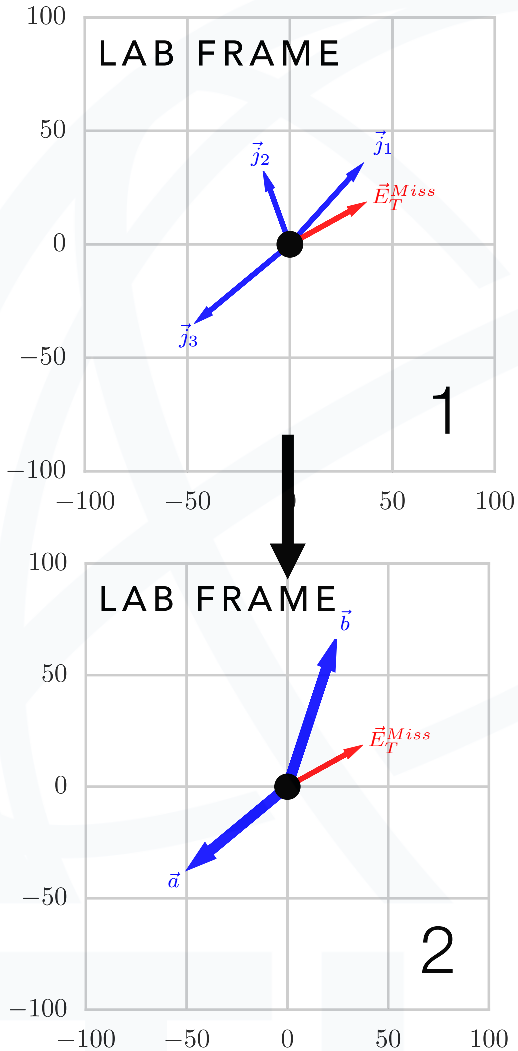


The Recursive Jigsaw Reconstruction provides an approximate way to solve kinematic ambiguities, **assuming a known decay tree**.

- unknown longitudinal momenta
- combinatorial ambiguities
- kinematic ambiguities (from multiple invisible objects)



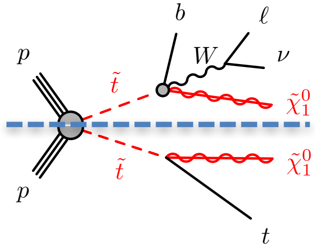
The Recursive Jigsaw



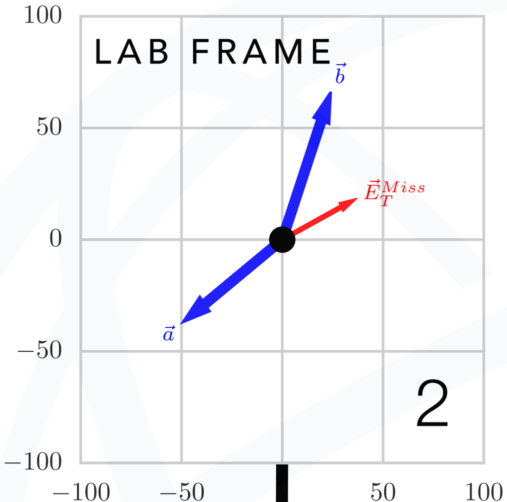
Figures by L.Lee

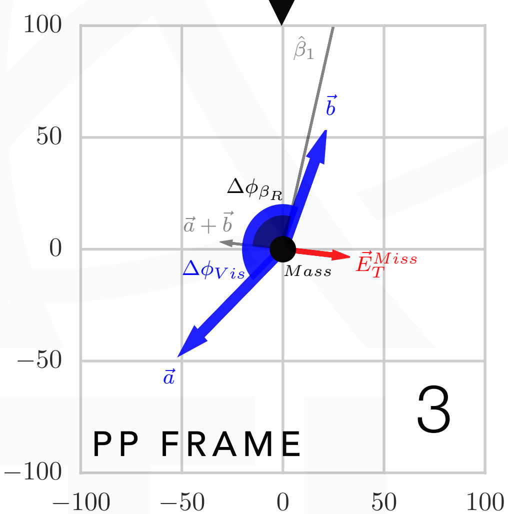
- Each decay step is solved by simultaneously **minimizing the masses of two daughter systems**
- Boost into the new reference frame
- Split the invisible momentum between the two

Kinematic variables are built to be invariant for longitudinal boosts



The Recursive Jigsaw





Figures by L.Lee

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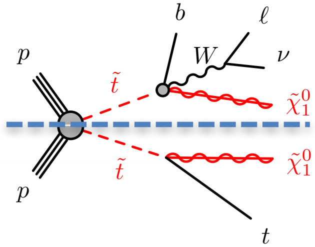
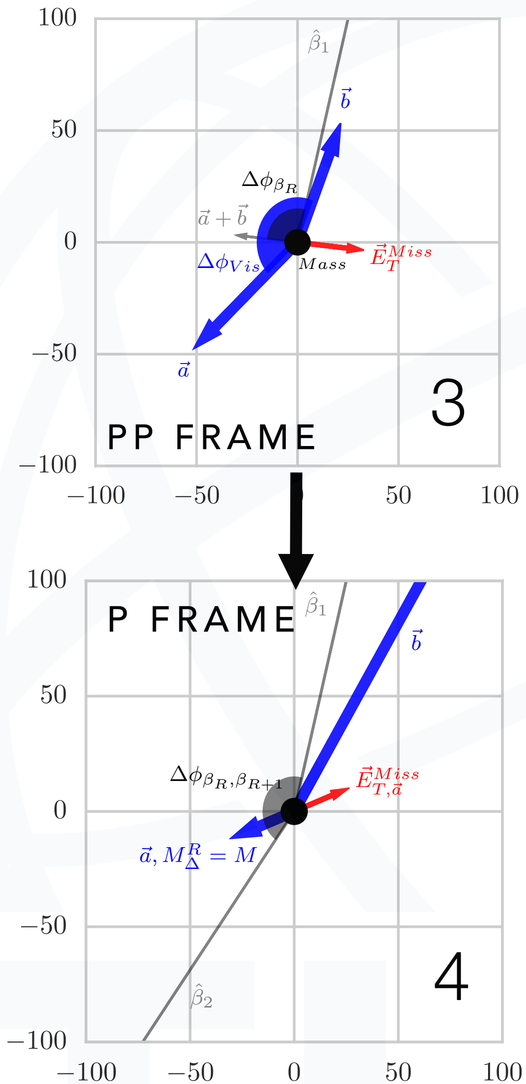


The Recursive Jigsaw



Figures by L.Lee

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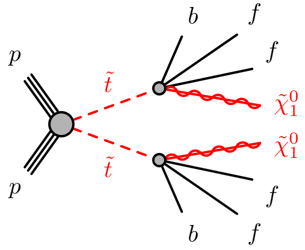
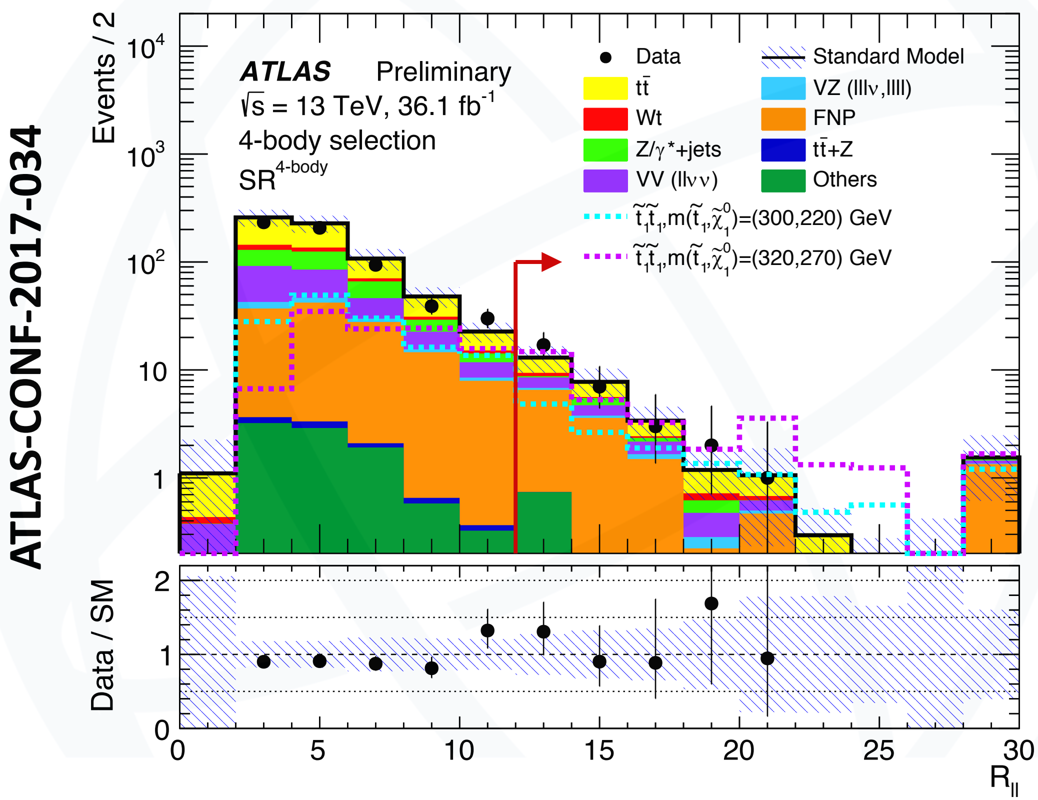
Kinematic variables are built to be **invariant for longitudinal boosts**



Two leptons search



Compressed spectrum

- **Select t_1 pairs recoiling against initial-state radiation** (ISR)

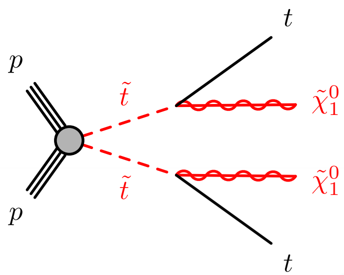
Selects events with **two** isolated soft **leptons**

- E_T^{miss}> 200 GeV
- p_T^{ISR}> 150 GeV

$$R_{\ell\ell} = E_{\mathrm{T}}^{\mathrm{miss}} / (p_{\mathrm{T}}(\ell_1) + p_{\mathrm{T}}(\ell_2))$$

Exploit ratios to suppress hard processes.

- Challenging estimation of fake and non-prompt leptons



Single lepton search

Complex search targeting many different signal scenarios

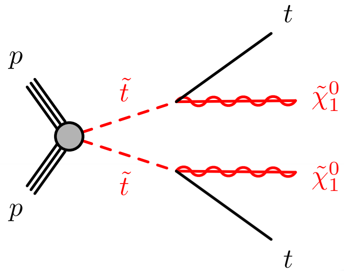
- Baseline selection requires 1 lepton, 4 jets, *b*-jets, high m_T

ATLAS-CONF-2017-037

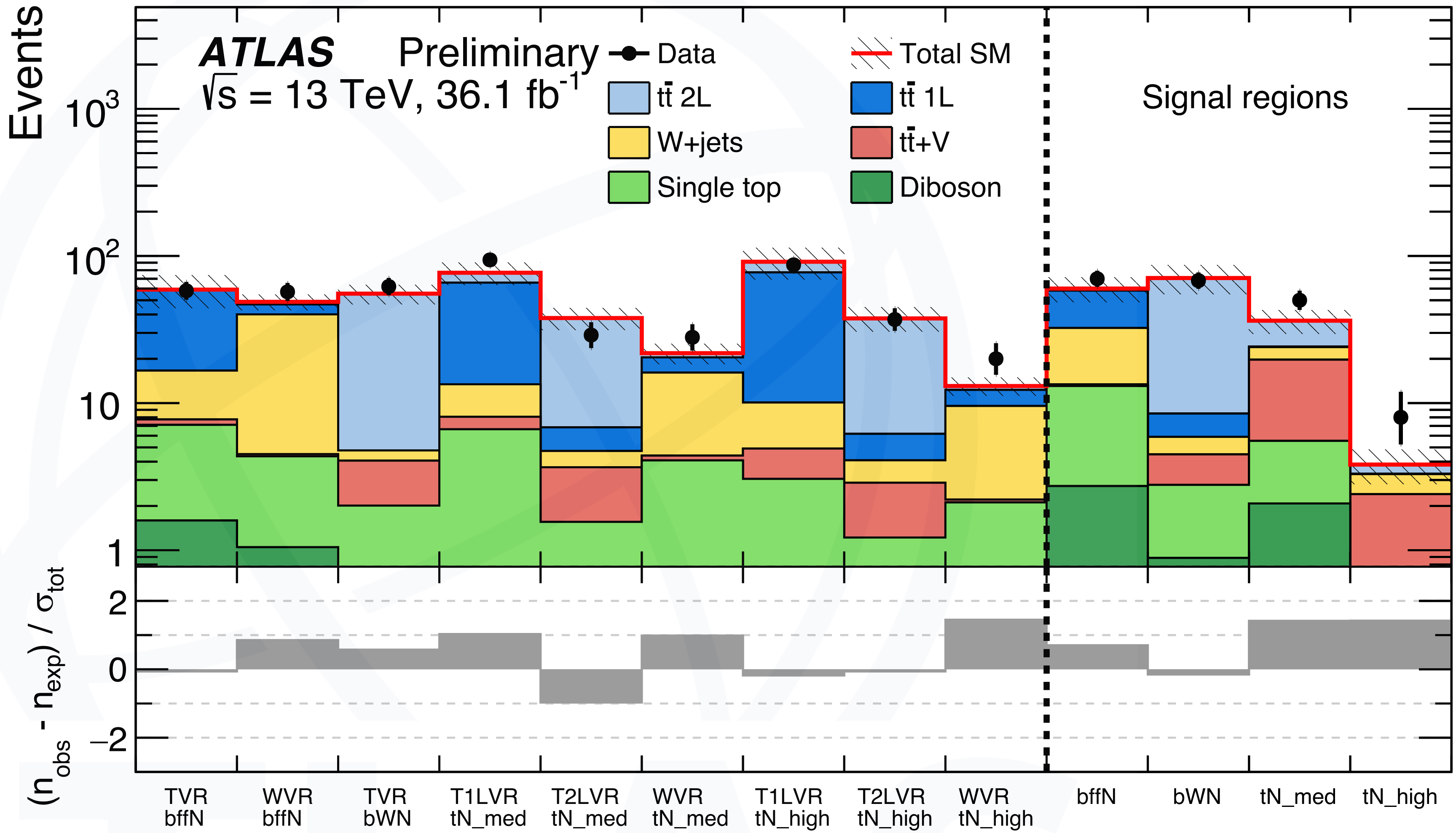
SR	Signal scenario	benchmark	Exclusion technique	Table
tN_med	Pure bino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^0$)=(600,300)	shape-fit (E_T^{miss})	6
tN_high	Pure bino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^0$)=(1000,1)	cut-and-count	6
tN_diag_low	Pure bino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^0$)=(190,17)	BDT cut-and-count	7
tN_diag_med	Pure bino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^0$)=(250,62)	BDT shape-fit	7
tN_diag_high	Pure bino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^0$)=(450,277)	BDT shape-fit	7
bWN	Pure bino LSP ($\tilde{t}_1 \to bW\tilde{\chi}_1^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^0$)=(350,230)	shape-fit (am_{T2})	8
bffN	Pure bino LSP ($\tilde{t}_1 \to bff'\tilde{\chi}_1^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^0$)=(400,350)	shape-fit (p_T^{ℓ}/E_T^{miss})	8
bC2x_med	Wino NLSP ($\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}, \tilde{t}_1 \to t\tilde{\chi}_2^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$)=(750,300,150)	cut-and-count	9
bC2x_diag	Wino NLSP ($\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}, \tilde{t}_1 \to t\tilde{\chi}_2^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$)=(650,500,250)	cut-and-count	9
bCbv	Wino NLSP ($\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}, \tilde{t}_1 \to t\tilde{\chi}_2^0$)	m($\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$)=(700,690,1)	cut-and-count	9
bCsoft_diag	Higgsino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0, \tilde{t}_1 \to t\tilde{\chi}_2^0, \tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$)	m($\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$)=(400,355,350)	shape-fit (p_T^{ℓ}/E_T^{miss})	10
bCsoft_med	Higgsino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0, \tilde{t}_1 \to t\tilde{\chi}_2^0, \tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$)	m($\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$)=(600,205,200)	shape-fit (p_T^{ℓ}/E_T^{miss})	10
bCsoft_high	Higgsino LSP ($\tilde{t}_1 \to t\tilde{\chi}_1^0, \tilde{t}_1 \to t\tilde{\chi}_2^0, \tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$)	m($\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$)=(800,155,150)	shape-fit (p_T^{ℓ}/E_T^{miss})	10
DM_low_loose	spin-0 mediator (DM+$t\bar{t}$)	m(Φ/a, χ)=(20,1)	cut-and-count	11
DM_low	spin-0 mediator (DM+$t\bar{t}$)	m(Φ/a, χ)=(20,1)	cut-and-count	11
DM_high	spin-0 mediator (DM+$t\bar{t}$)	m(Φ/a, χ)=(300,1)	cut-and-count	11

Dedicated CRs for:

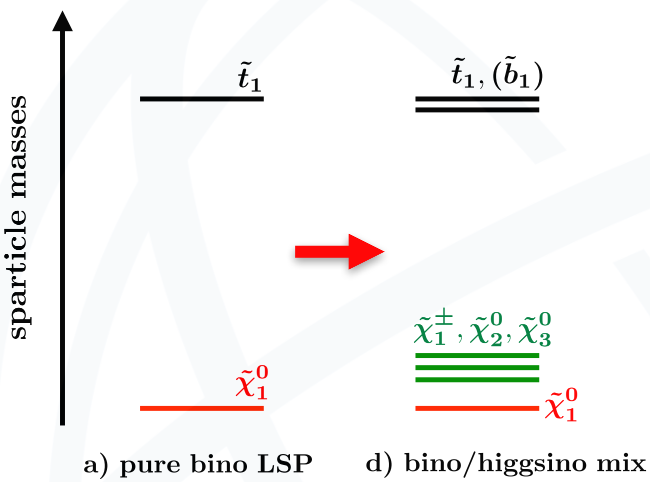
- W+jets
- tt pairs
- single top
- tt + V

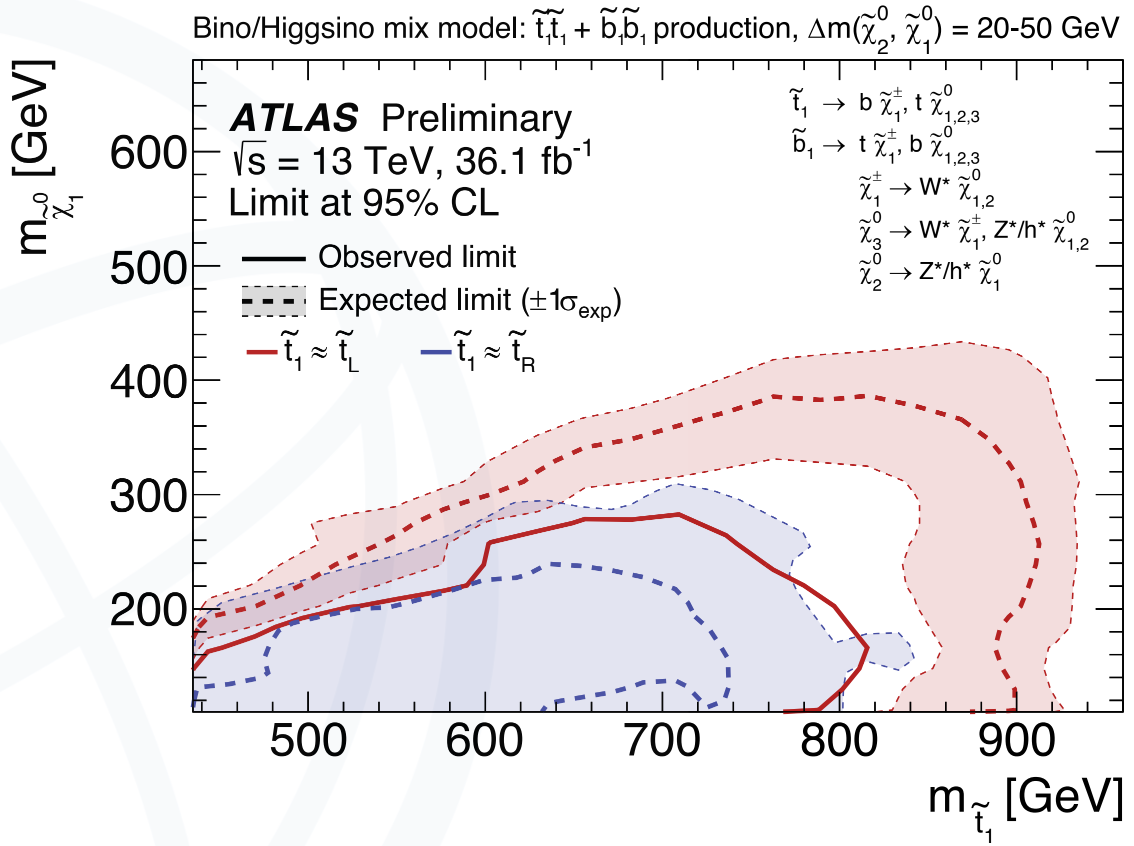

p
p
t
t
$\tilde{t}$
$\tilde{t}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$

Results


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Data
Total SM
$t\bar{t}$ 2L
$t\bar{t}$ 1L
W+jets
$t\bar{t}$+V
Single top
Diboson
Signal regions
Events
$(n_{obs} - n_{exp}) / \sigma_{tot}$
TVR bffN
WVR bffN
TVR bWN
T1LVR tN_med
T2LVR tN_med
WVR tN_med
T1LVR tN_high
T2LVR tN_high
WVR tN_high
bffN
bWN
tN_med
tN_high

Beyond Simplified Models





Results are also interpreted in more realistic models.

- pMSSM models that include more complex decay chains
- Bino/higgsino -> satisfy naturalness and DM relic density