EW SUSY production at the LHC

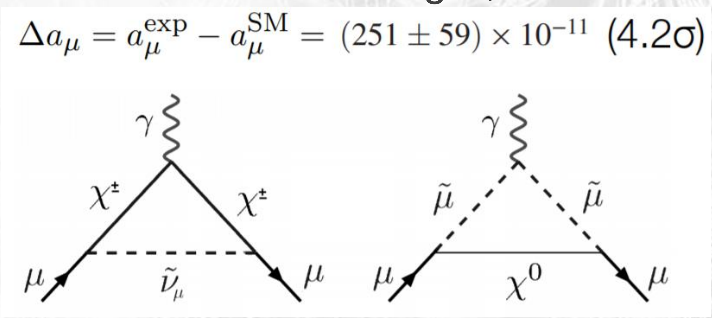
05/09/21

Holly Pacey
obo the ATLAS & CMS Collaborations

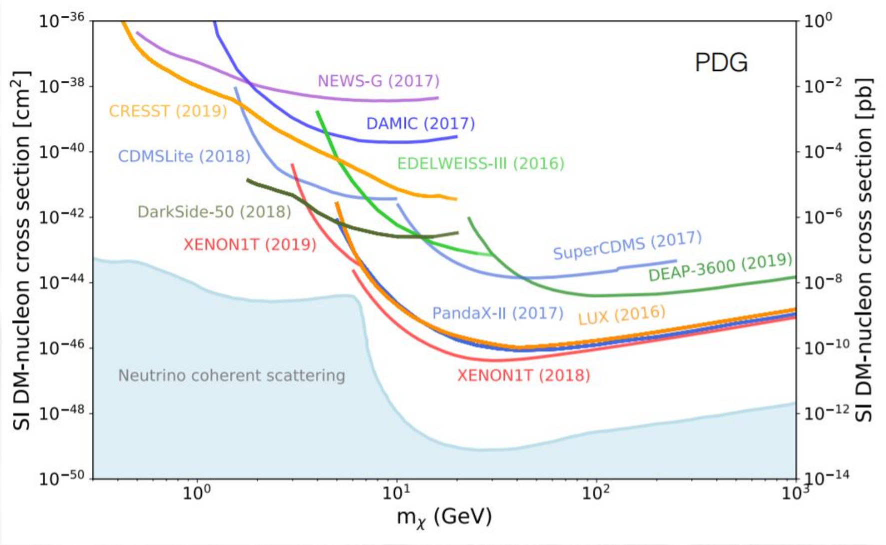
Motivation

Rare but clean signatures, less well-constrained than Strong SUSY

- Light Higgsinos favoured by naturalness arguments.
- Sleptons/Neutralinos affect g-2, favour $0.2 < M < 1$ TeV



- Dark matter relic density favours light gauginos/sleptons
- R-Parity conserving models: LSP as dark matter candidate



In this talk?

Gauge-mediated SUSY breaking (GMSB) models giving gravitino/goldstino stable lightest sparticle (LSP) + light higgsinos (NLSPs)

Simplified models with wino/bino gauginos fitting with MSSM parameter space for g-2

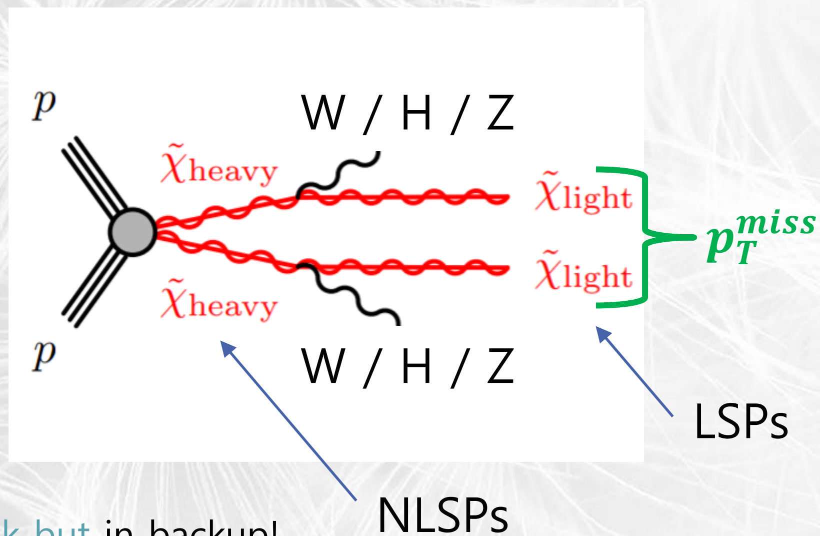
LSP is Axino: SUSY partner of Axion – a light DM candidate

This talk

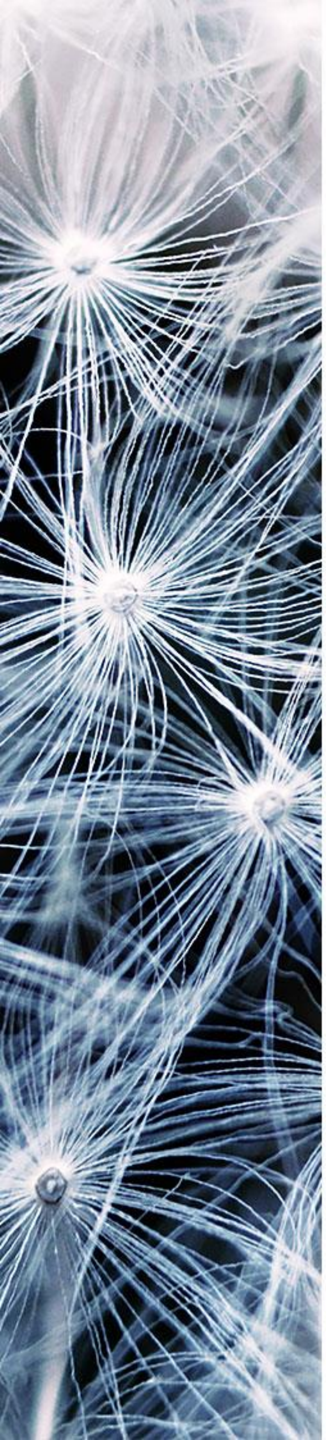
Latest CMS and ATLAS EW SUSY results

- Gaugino searches with differing final states and interpretations.
- Full Run-2 LHC dataset 2015-2018, $\sim 140 fb^{-1}$
- Final states: $\mathbf{X} + \boldsymbol{p_T^{miss}}$, exploiting p_T^{miss} triggers $\rightarrow$ looser requirements on X
- Sophisticated object/event reconstruction improves sensitivity e.g.
  - Large radius jets: ↑ acceptance for boosted topologies = sensitivity to rarer, heavy sparticles
  - Machine learning to tag specific processes better and reduce mis-tag rates

(1) First! Fully-hadronic @ATLAS
(2) First! Fully-hadronic @ CMS
(3) 3 leptons @ATLAS
(4) diHiggs to 4b @ CMS



Other recent direct stau @ CMS search not in this talk but in backup!
Also see Strong + 3rd Gen SUSY talk next!

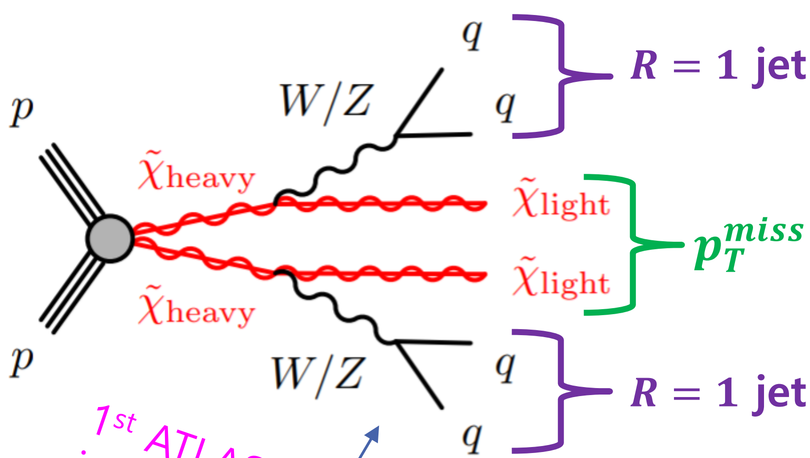


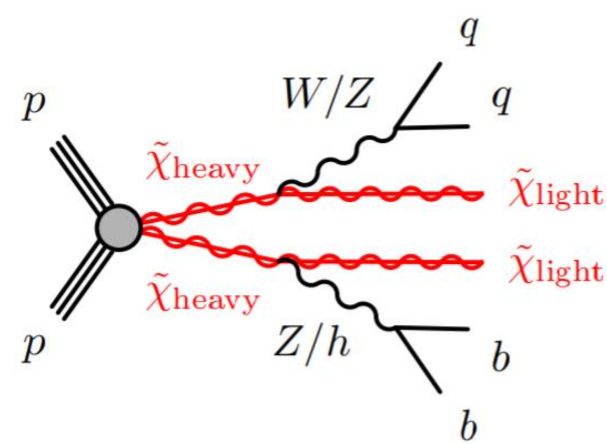
Fully-Hadronic @ ATLAS

CMS version next

Signature: 2 **boosted** bosons decaying hadronically + p_T^{miss}

- Extensive interpretations:
  - *Baseline* MSSM: Wino ($\tilde{W}$), Bino ($\tilde{B}$), Higgsino ($\tilde{H}$) pairs
    $(\tilde{\chi}_{Heavy}, \tilde{\chi}_{Light}) = (\tilde{W}, \tilde{H}), (\tilde{W}, \tilde{B}), (\tilde{H}, \tilde{B}), \ldots$
  - Gauge Mediated: light $\tilde{H}$ and gravitino LSP: $(\tilde{\chi}_{Heavy}, \tilde{\chi}_{Light}) = (\tilde{H}, \tilde{G})$
  - Axion: light $\tilde{H}$ and axino LSP: $(\tilde{\chi}_{Heavy}, \tilde{\chi}_{Light}) = (\tilde{H}, \tilde{a})$





1st ATLAS SUSY search in this final state!

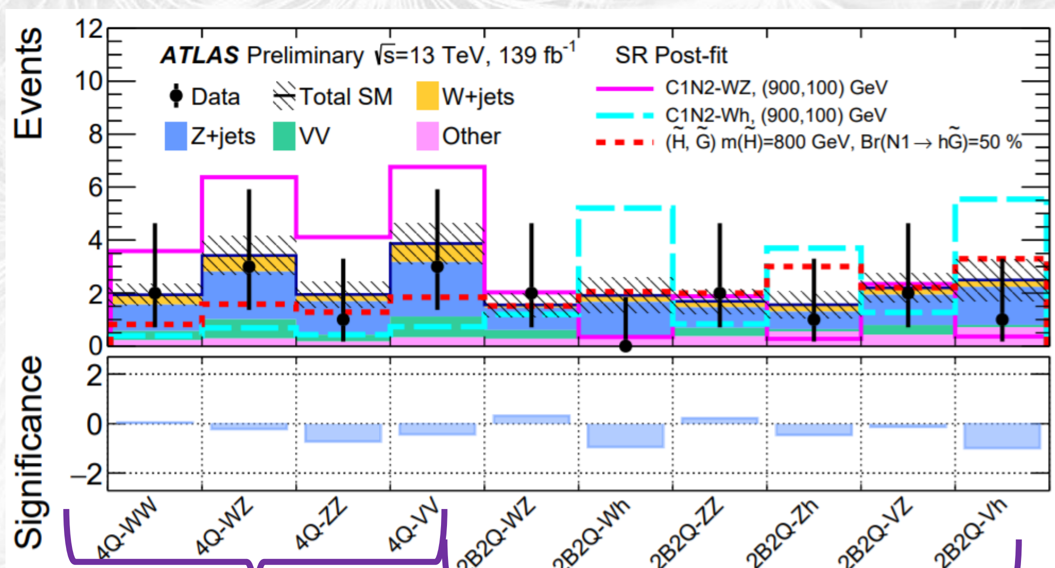
ATLAS SUSY-2018-41, arXiv:2108.07586

Fully-Hadronic ATLAS Analysis

Boosted $W/Z \rightarrow qq$ taggers are basis for region definitions

- p_T^{miss} triggers, >200 GeV
- Taggers use m_j, N_{tracks} & energy correlation function (targets 2-prong jets)
  - **50%** signal efficiency, **<93%** bg rejection
  - Specifically re-optimised for this search!

- M_{bb} cuts for $\mathbf{Z/H} \rightarrow \boldsymbol{bb}$, tag small-R b-jets.
- Main Z+jets, W+jets, VV bgs: normalise MC using data in orthogonal control regions.
- Dominant uncertainties: MC stats.



qq qq

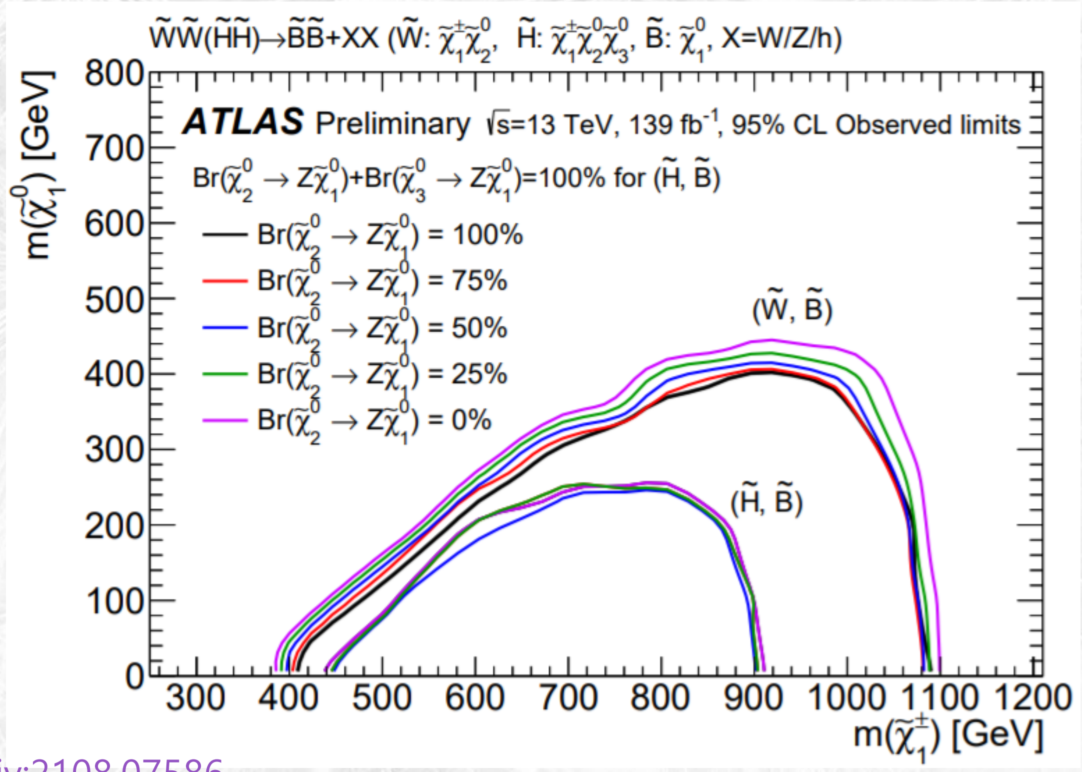
qq bb

ATLAS SUSY-2018-41, arXiv:2108.07586

Fully-Hadronic ATLAS Results

Excellent exclusion power, complementing previous ATLAS searches.

- NLSP mass on x-axis, LSP mass on y-axis.
- Wino limits stronger than Higgsino.
- Br to Z decay has small effect on limits.



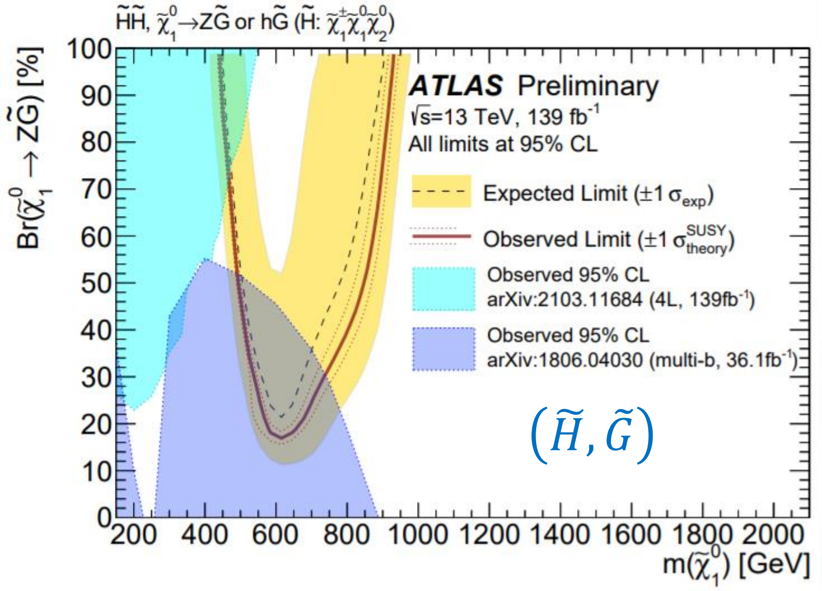
Baseline MSSM
$(\tilde{\chi}_{Heavy}, \tilde{\chi}_{Light})$

ATLAS SUSY-2018-41, arXiv:2108.07586

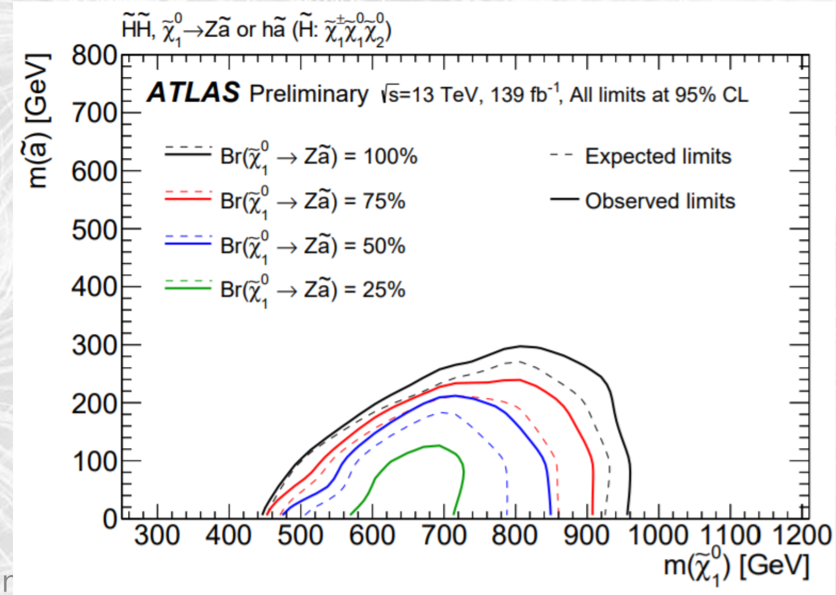
Fully-Hadronic ATLAS Results

Excellent exclusion power, complementing previous ATLAS searches.

- Gauge-Mediated results complement previous ATLAS searches in different final states.
- Axino results stronger with higher Br for Z decay.

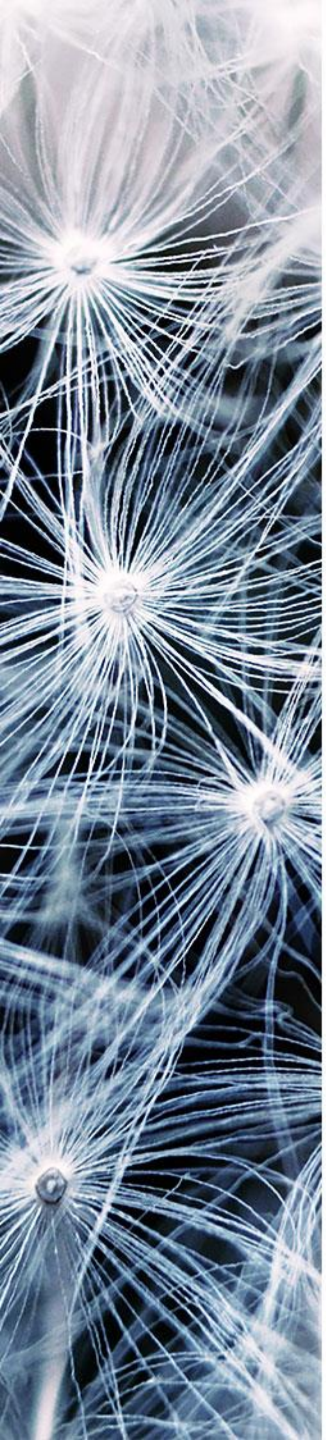


Gauge-Mediated



Axion+Naturalness

[ATLAS SUSY-2018-41](), [arXiv:2108.07586]()



Fully-Hadronic @ CMS

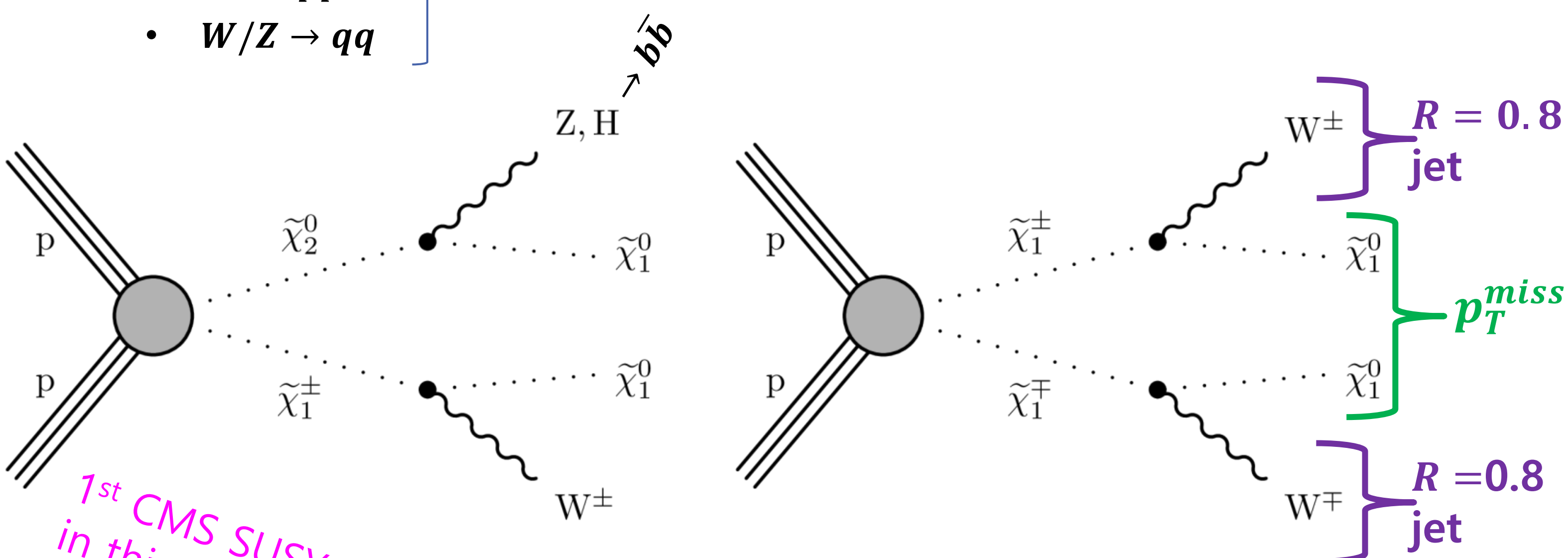
ATLAS version prev. slides

Brand new!

Signature: 2 **boosted** bosons decaying hadronically + p_T^{miss}

- Interpretation in Simplified model:
  - $\tilde{W}$ degenerate $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$, $\tilde{B}$ $\tilde{\chi}_1^0$ - eqv. to $(\tilde{W}, \tilde{B})$ interpretation from ATLAS hadronic search.
- p_T^{miss} triggers, >200 GeV
- Main region definition again using DNN + m_j based taggers :
  - $H/Z \to b\bar{b}$
  - $W \to qq$
  - $W/Z \to qq$

Signal efficiency **45%-54%**
Mis-ID rates of only **1-2.5%**



1st CMS SUSY search in this final state!

CMS SUS-21-002

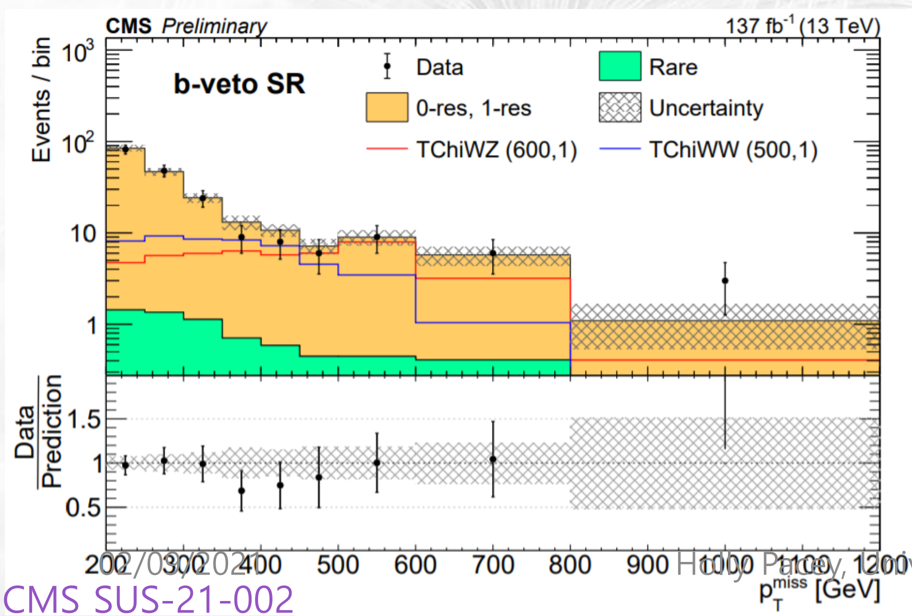
Fully-Hadronic CMS Analysis

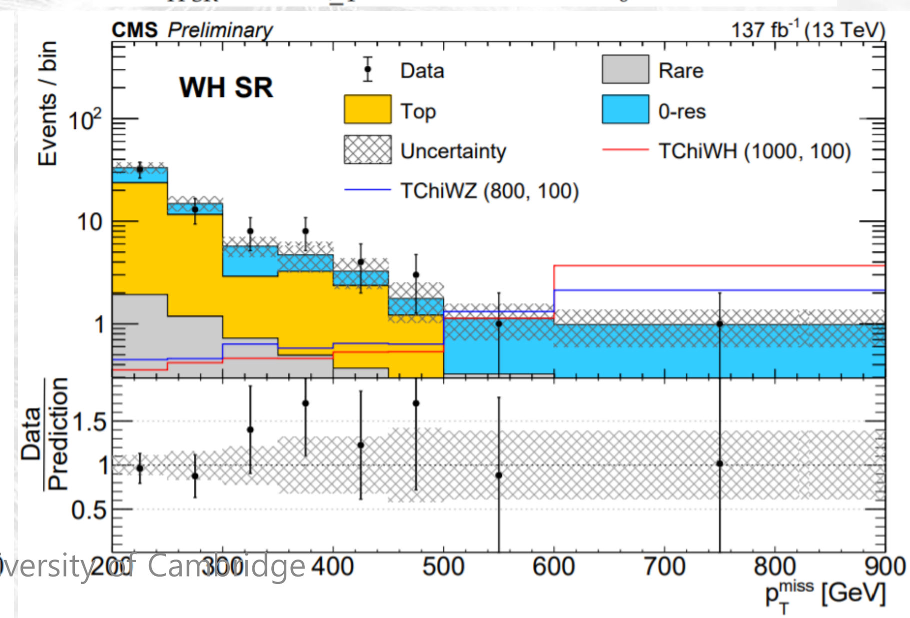
Boosted jet taggers and b-jet tagging are basis for region definitions

- SRs with **0 b-jets** (WW/WZ/ZZ), or **>0 b-jets** (WH/WZ), each binned in p_T^{miss}.
- Shrink QCD bg by requiring large phi between p_T^{miss} and 4 leading small-radius jets.
- Main bgs estimated by normalising MC using data in orthogonal control regions :
  - '0-res': fakes from Z/W+jets, QCD
  - '1-res': ttbar, Wt, VV
- Dominant uncertainties: MC stats, then $W \rightarrow qq$ tagger systs.

Region	Requirements
b-veto SR	$\geq$1 V-tagged jet $\geq$1 W-tagged jet $\geq$2 V- or W-tagged jets

	Higgs boson candidate		W boson candidate	
	$b\bar{b}$ tagged	not $b\bar{b}$ tagged	W tagged	not W tagged
WH SR	$\geq$1	—	$\geq$1	—
W SR	0	—	$\geq$1	—
H SR	$\geq$1	—	0	—





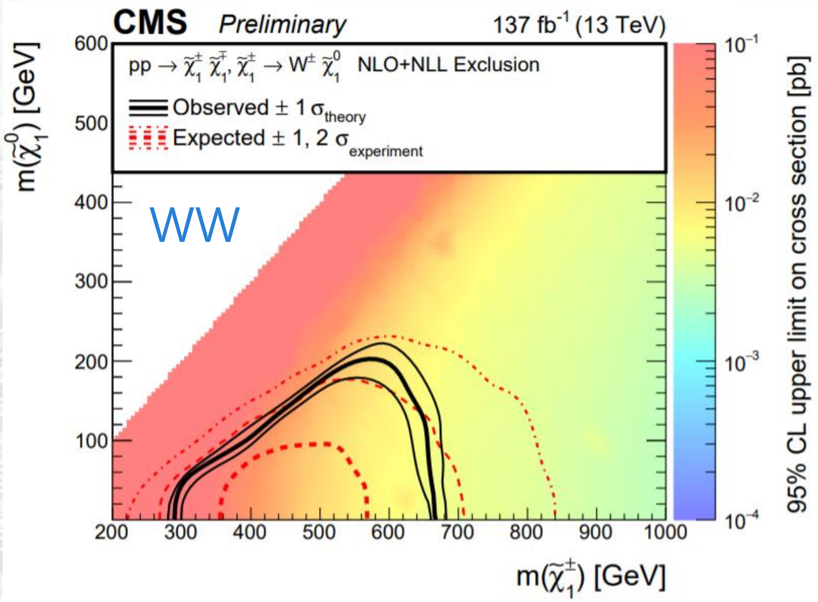
CMS SUS-21-002

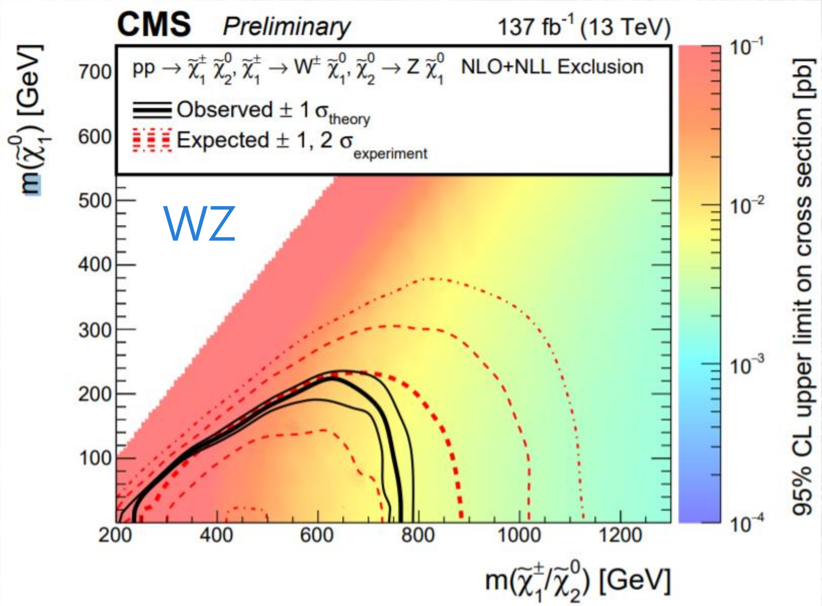
Fully-Hadronic CMS results

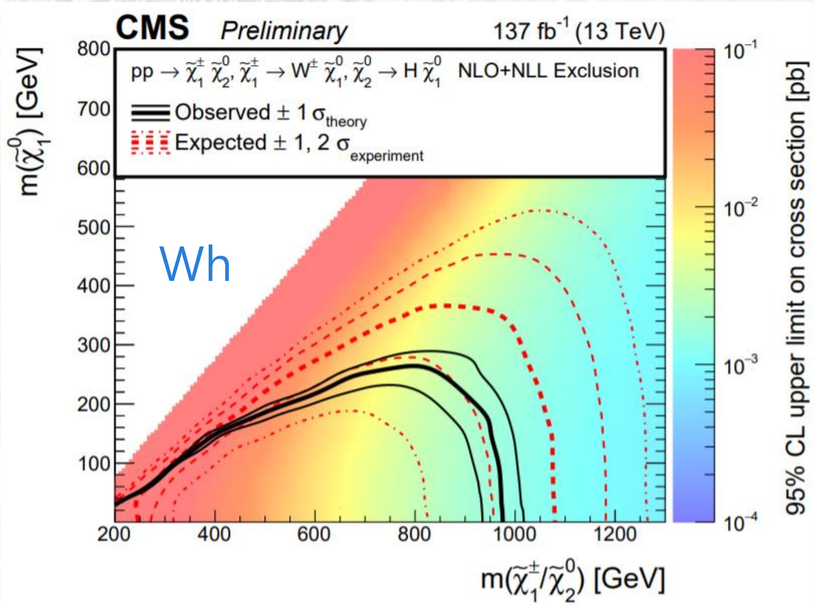
Good exclusion power fitting all SRs together, beating previous CMS searches.

Tiny deficit in b-veto SR cause obs > exp for WW

Tiny excess in Wh SR causes obs < exp in WH





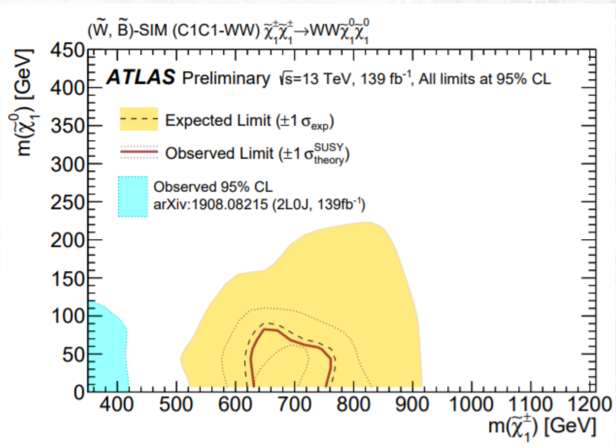


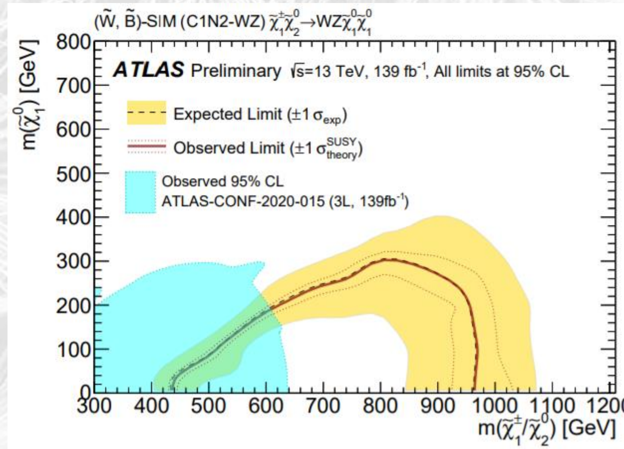
Fully-Hadronic ATLAS vs CMS

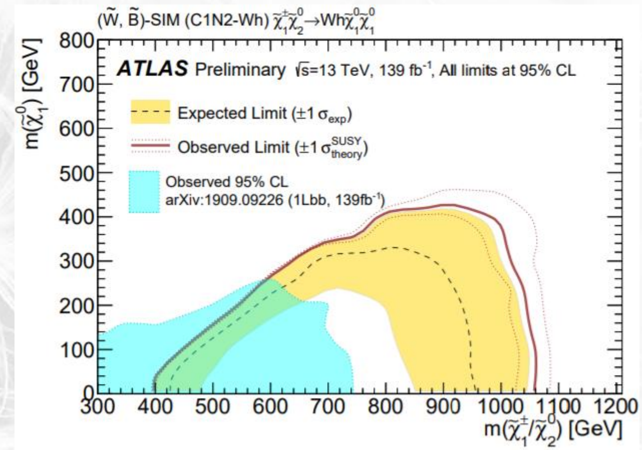
WW
good complementarity

WZ
exp. similar

WH
very similar



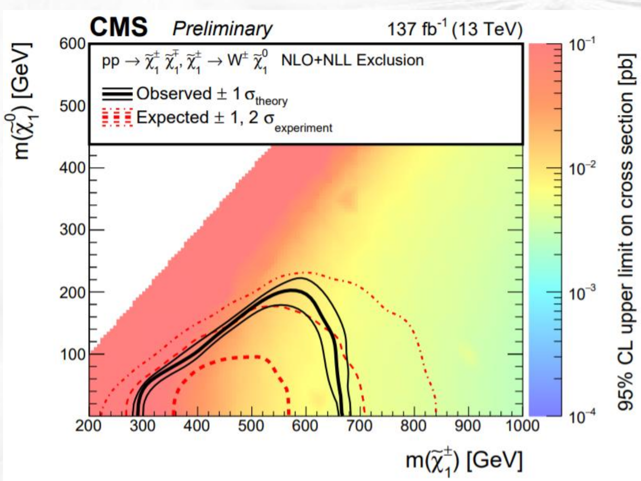


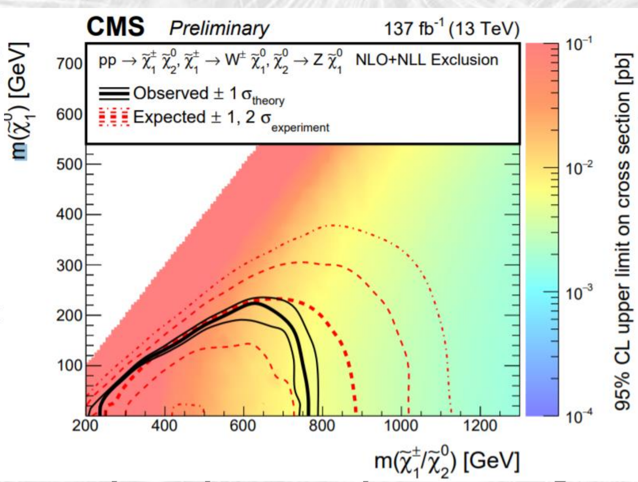


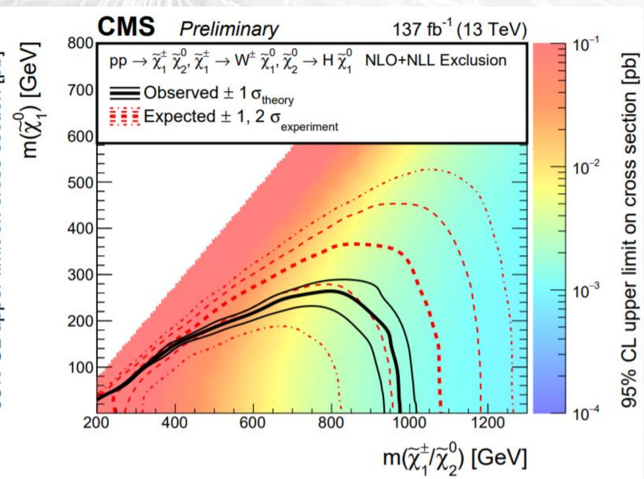
WW

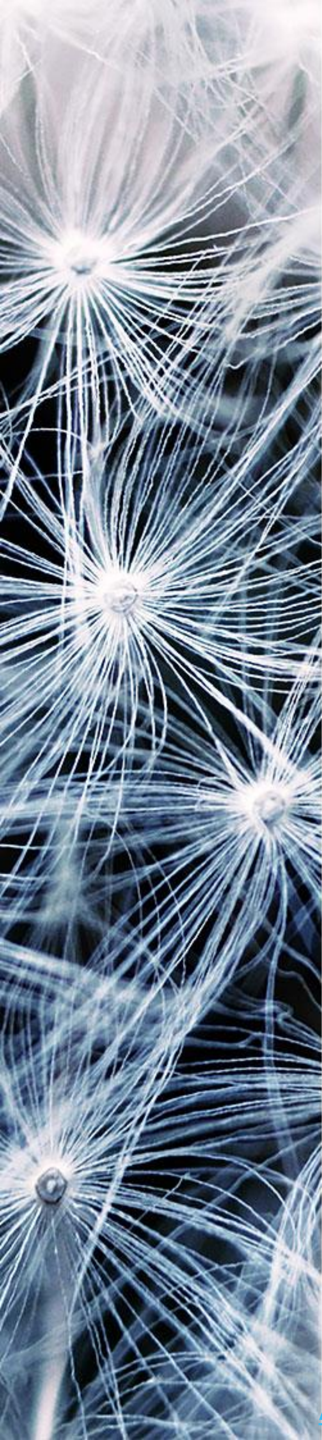
WZ

Wh









3 Leptons @ ATLAS

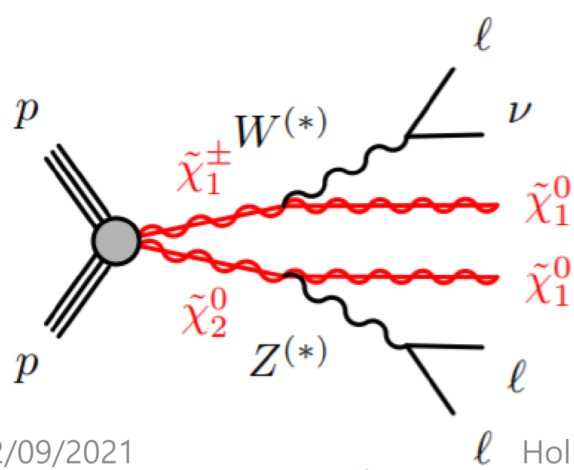
CMS version:
CMS SUS-19-012

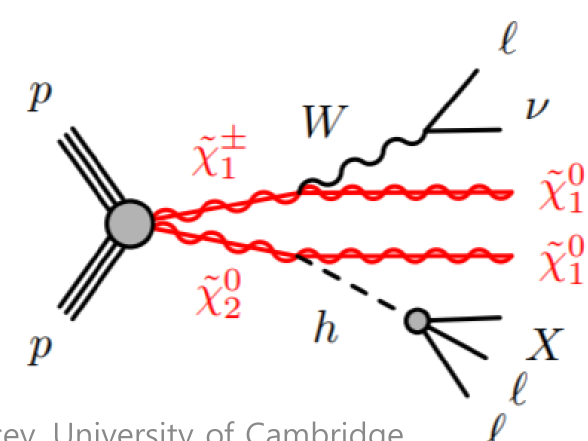
Signature: 3 leptons + p_T^{miss}

- Interpretations in MSSM:
  - $\tilde{W}$ degenerate $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$, $\tilde{B}$ $\tilde{\chi}_1^0$ (same as CMS hadronic search)
  - $\tilde{H}$ triplet $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$, $\tilde{\chi}_1^0$
- 3 selections:
  - Wh – large ΔM
  - On-shell WZ – large ΔM
  - Off-shell WZ - small ΔM

Wh and on-shell WZ: Lepton triggers
Off-shell WZ: p_T^{miss} triggers

- BDT used to reduce fake-lepton bg – uses Iso, track, b-tagging info.
  - Reducing large fake bg at low p_T crucial for compressed region
  - Retain 70-90% real lepton, fake lepton rejection factor 2-3





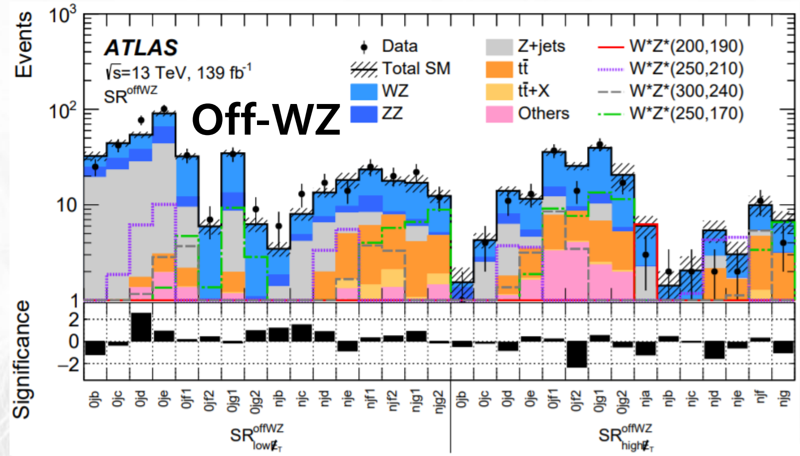
ATLAS-SUSY-2019-09, arXiv:2106.01676

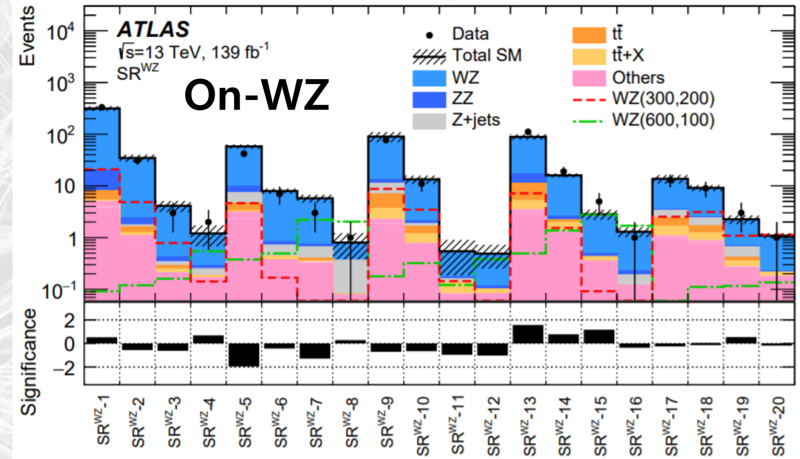
3 Leptons Analysis

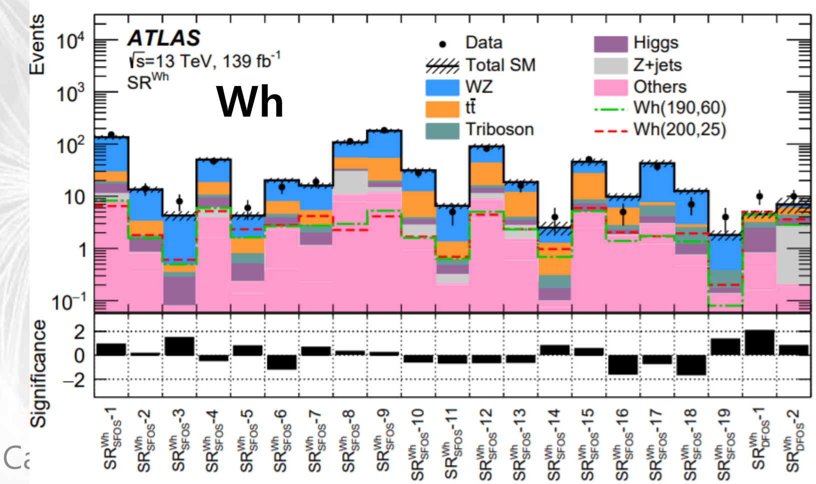
Complex set of binned SRs

- Off-Shell: Split high / low p_T^{miss} and $\mathbf{0}, > \mathbf{0}$ jets
- On-Shell: Bin p_T^{miss} and m_T , Z-mass selection
- Wh: Z veto, both different/same flavour lepton pairs considered.

- Main WZ bg: normalise MC using data in orthogonal control region
- ttbar bg: MC validated in orthogonal region
- Z+jets bg: data-driven Fake Factor method





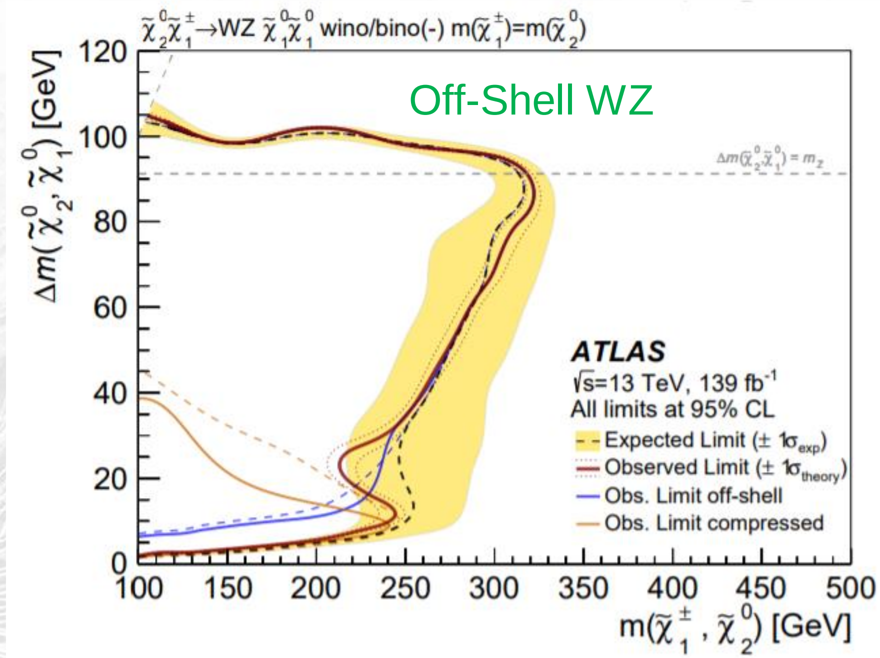


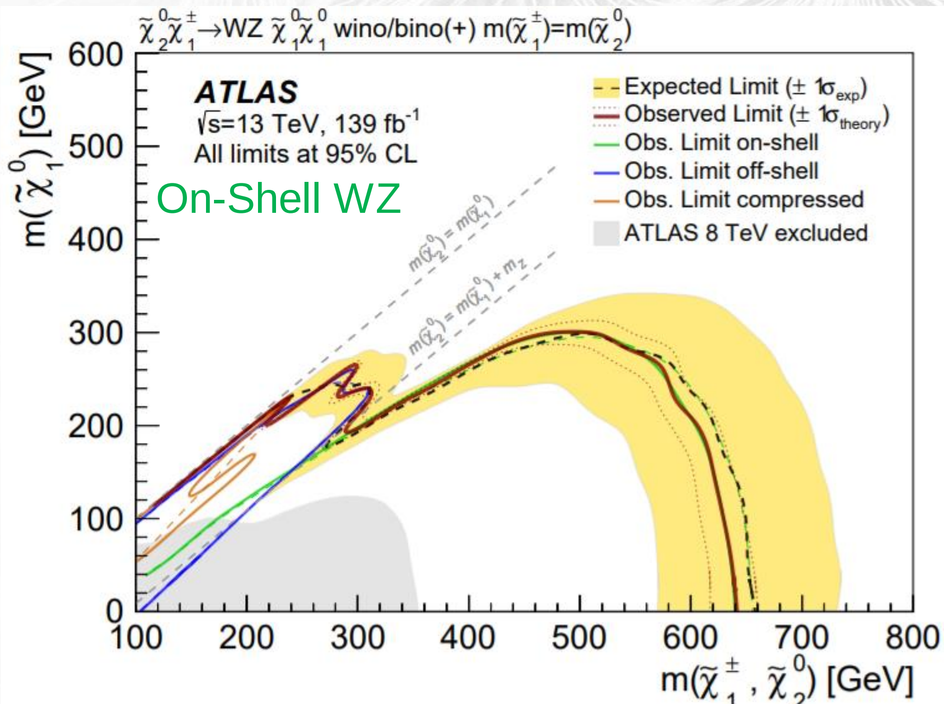
ATLAS-SUSY-2019-09, arXiv:2106.01676

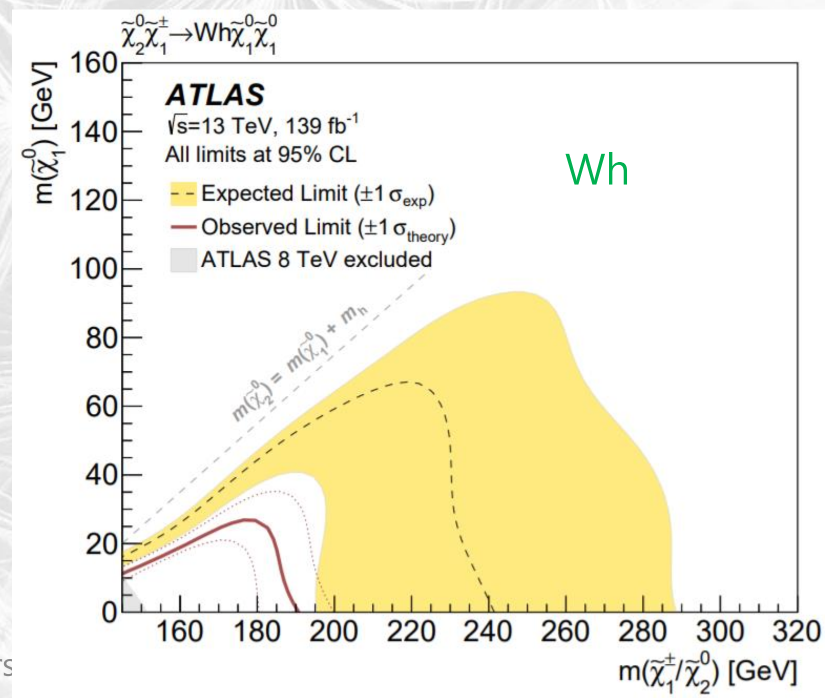
3 Leptons Results

Great improvement to limits

- WZ: Combines this analysis SRs with previous [2-lepton compressed analysis]
- For wino/bino: $sign(M(\tilde{\chi}_2^0) * M(\tilde{\chi}_1^0)) = \pm 1$





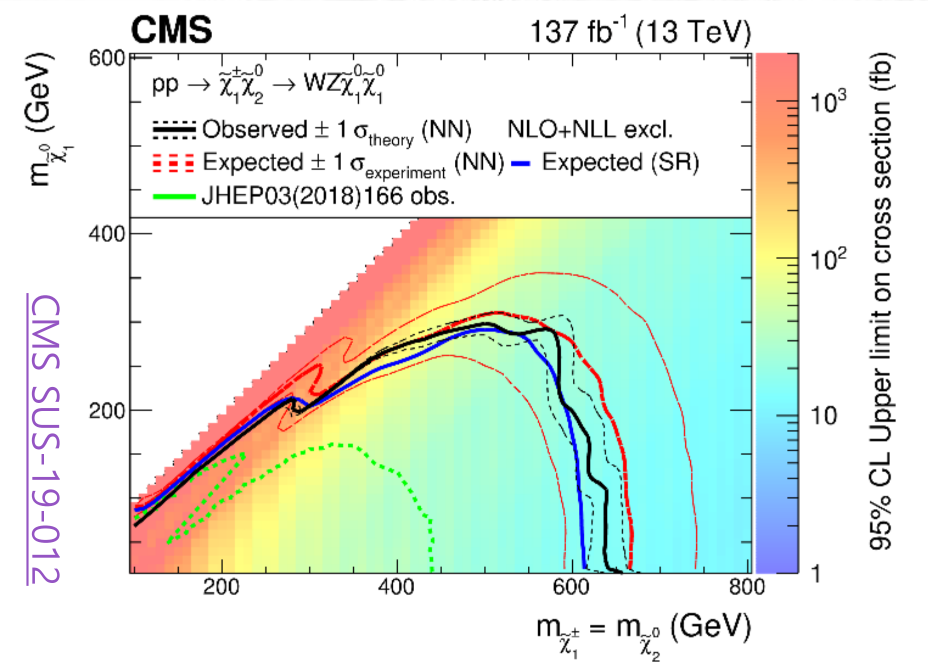


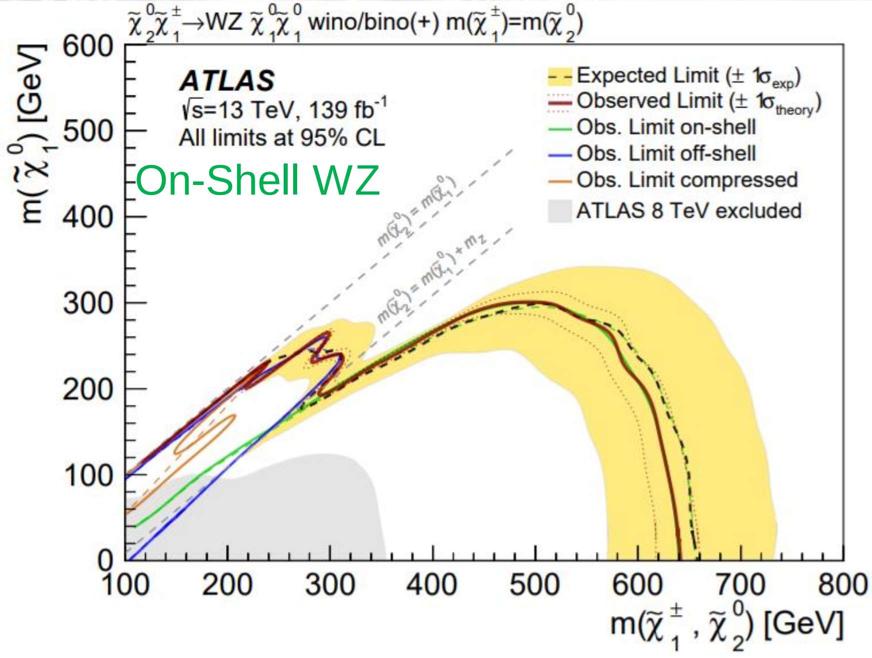
ATLAS-SUSY-2019-09, arXiv:2106.01676

3 Leptons Results – compare to CMS

WZ comparable for ATLAS and CMS

CMS SUS-19-012

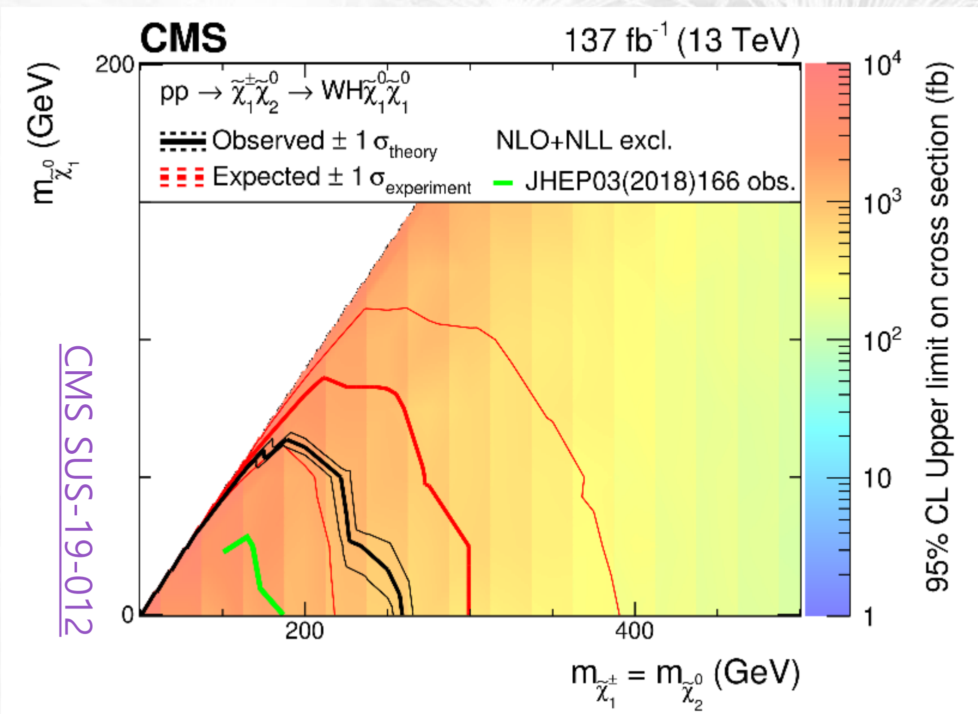


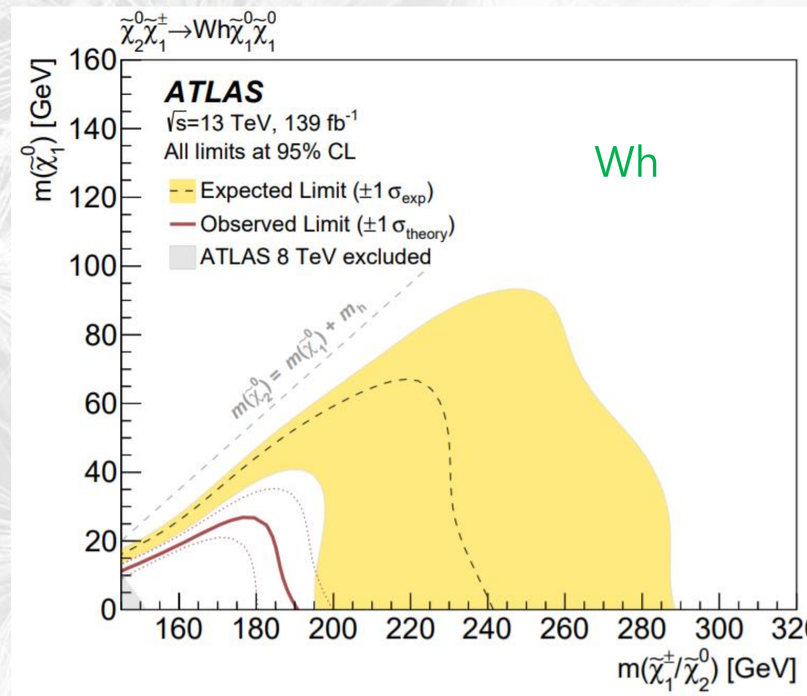


ATLAS-SUSY-2019-09, arXiv:2106.01676

3 Leptons Results – compare to CMS

CMS exclusion stronger ATLAS for Wh





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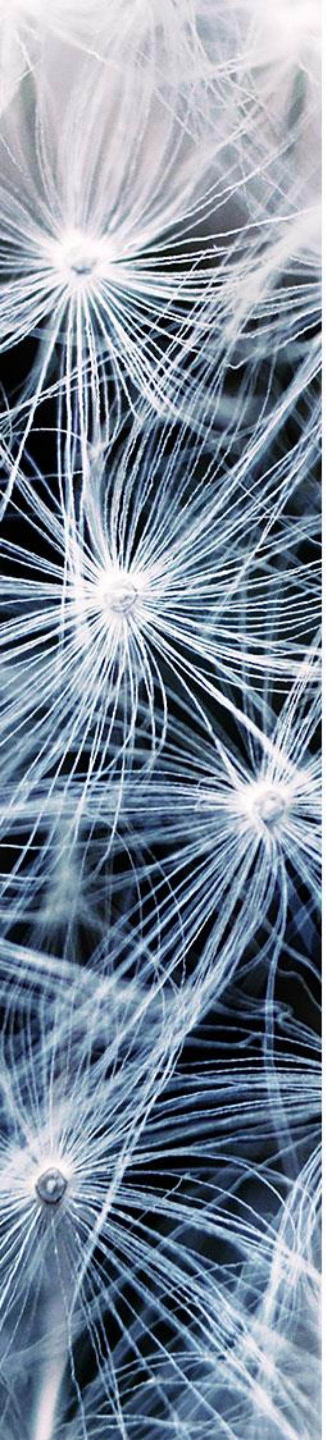
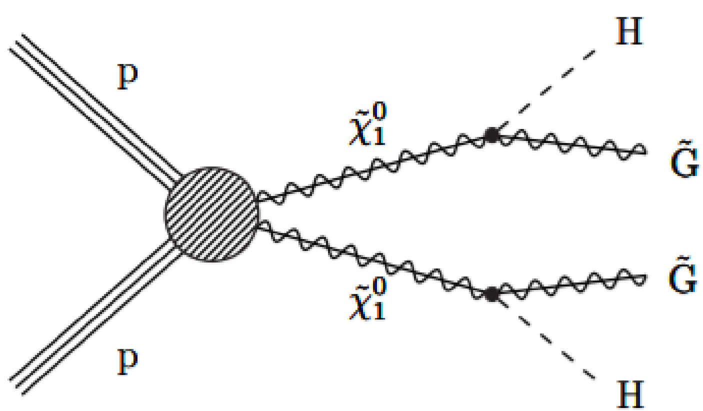


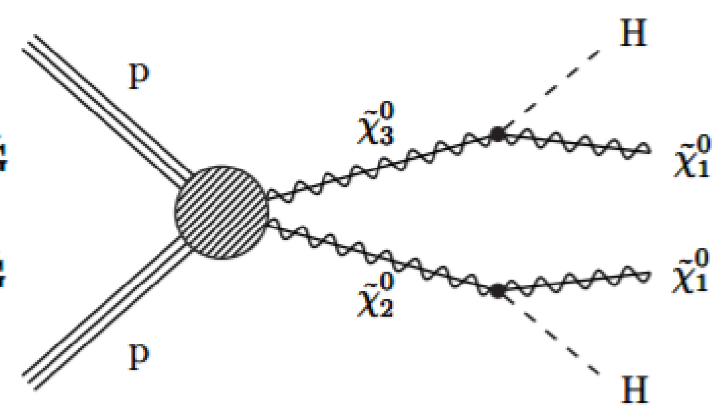
4b @ CMS

ATLAS version (only 36 fb^{-1})
CERN-EP-2018-050

Signature: 2h->bbbb + p_T^{miss}

- Interpretations with $\widetilde{H}$:
  - GMSB, Goldstino LSP: $\tilde{G}$, NLSP $\tilde{\chi}_1^0$
  - Simplified model, degenerate $\tilde{\chi}_3^0, \tilde{\chi}_2^0$ $\tilde{B}$ $\tilde{\chi}_1^0$
  - Strong (gluino) production mode – see paper, not discussed here.
- Each h decays to bb (highest BR), considering either
  - 1 R =0.8 jet per h - **boosted!** Sensitive to larger M($\widetilde{H}$)
  - 2 $R = 0.4$ jets per h: Sensitive to more compressed regions.
- Crucial: b-tagging using Deep Neural Networks:
  - 2b/large-R jet. **90%** efficiency to find H->bb! Counts= Nh
  - 1b/small-R jet. 3 WPs with efficiencies **<85%.** Counts= Nb



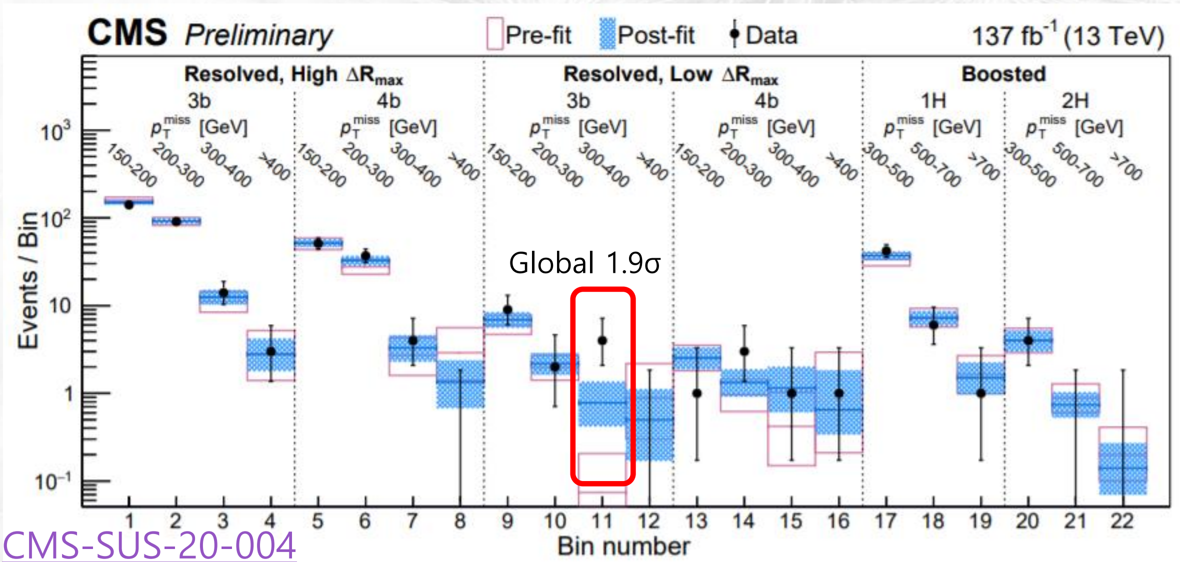


4b Analysis

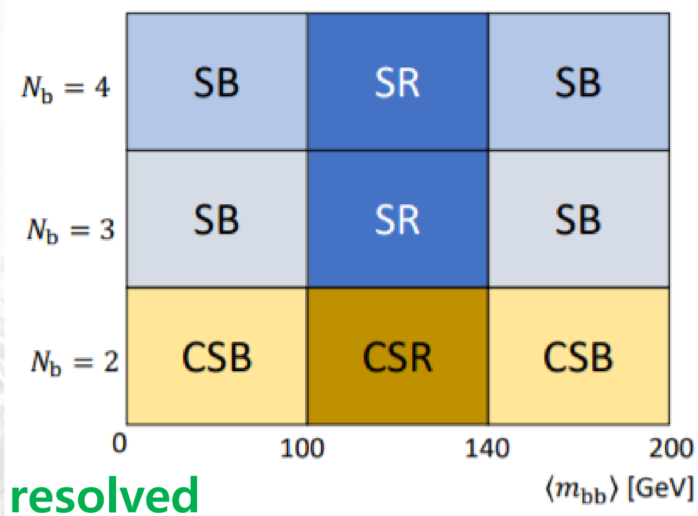
Multibin fit with ABCD bg estimate

- p_T^{miss} triggers: >150/300 GeV for resolved/boosted
- Assign jet pairs to h, minimising: $|m(b_i b_j) - m(b_k b_l)|$
- Resolved SRs: binned in p_T^{miss} & max, angle between 2 b-jets in a higgs.
- Boosted SRs: binned in p_T^{miss}
- Data-driven ABCD bg estimate: with κ for var. correlation
- Dominant uncertainties: stats.

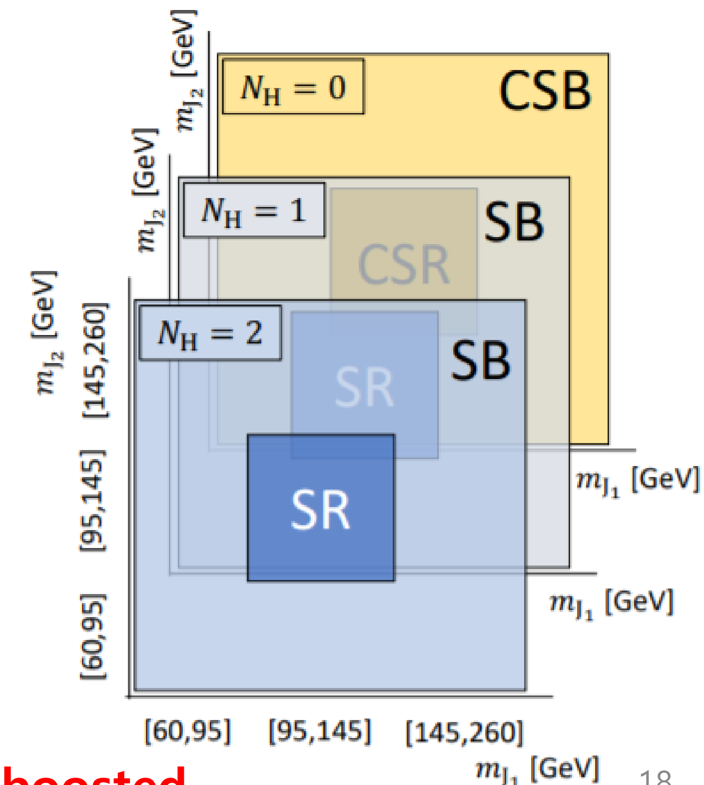
$$N_{\mathrm{SR}} = \kappa \frac{N_{\mathrm{CSR}}}{N_{\mathrm{CSB}}} N_{\mathrm{SB}},$$



CMS-SUS-20-004

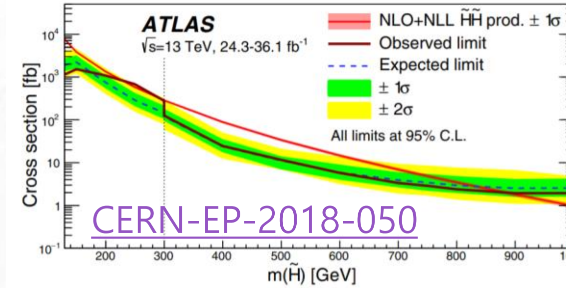


resolved



boosted

4b Results

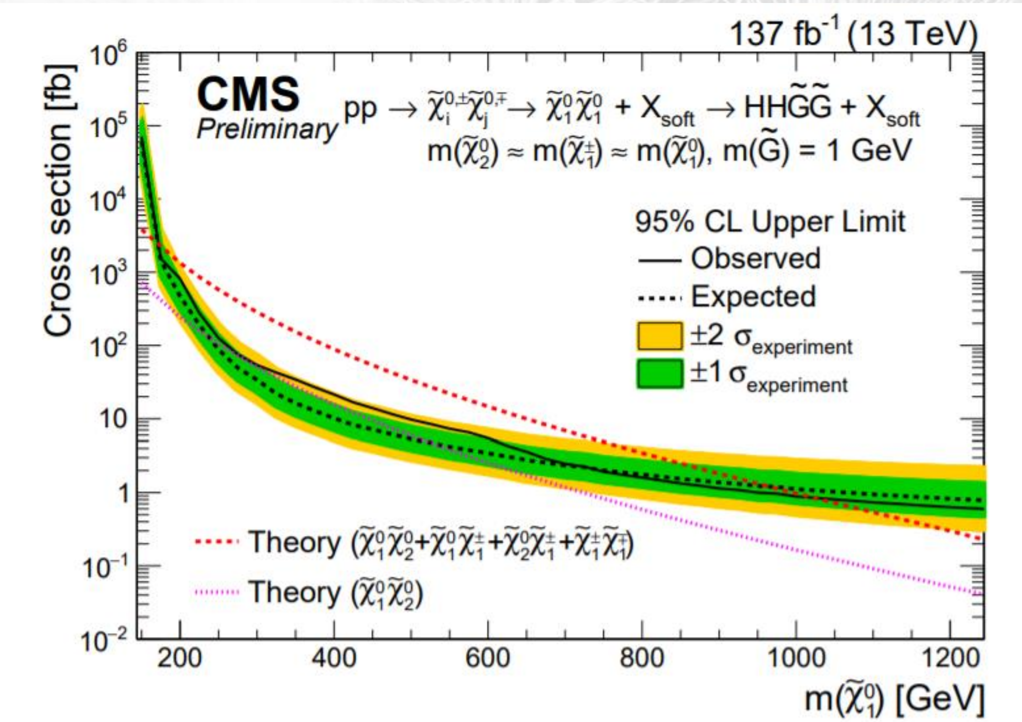


CERN-EP-2018-050

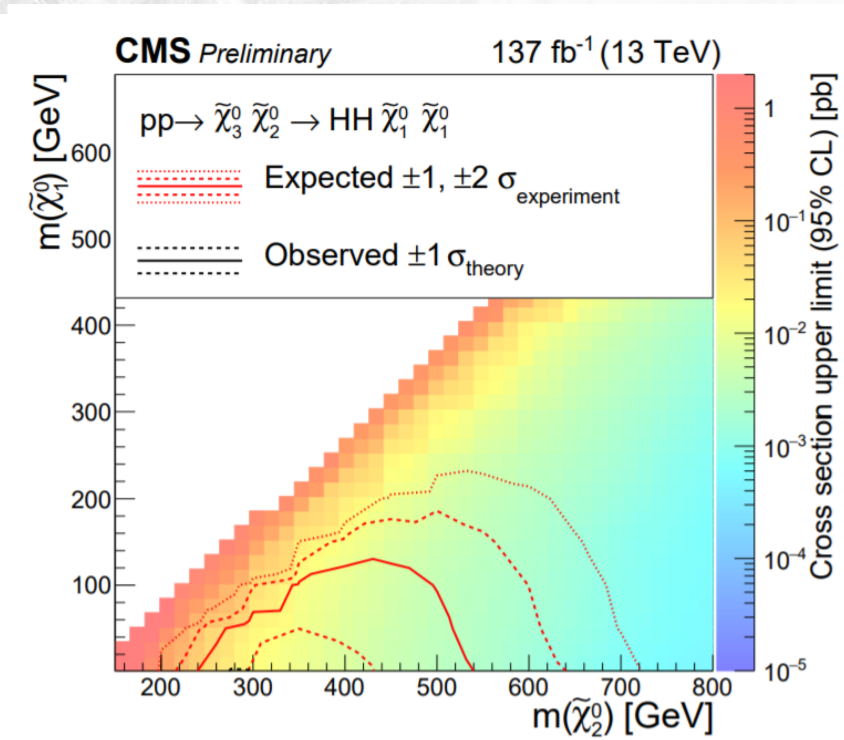
ATLAS excluded 290-890 GeV $\tilde{H}$

Combine boosted and resolved channels for best results Obs. Limit small due to small data excess.

GMSB



Simplified



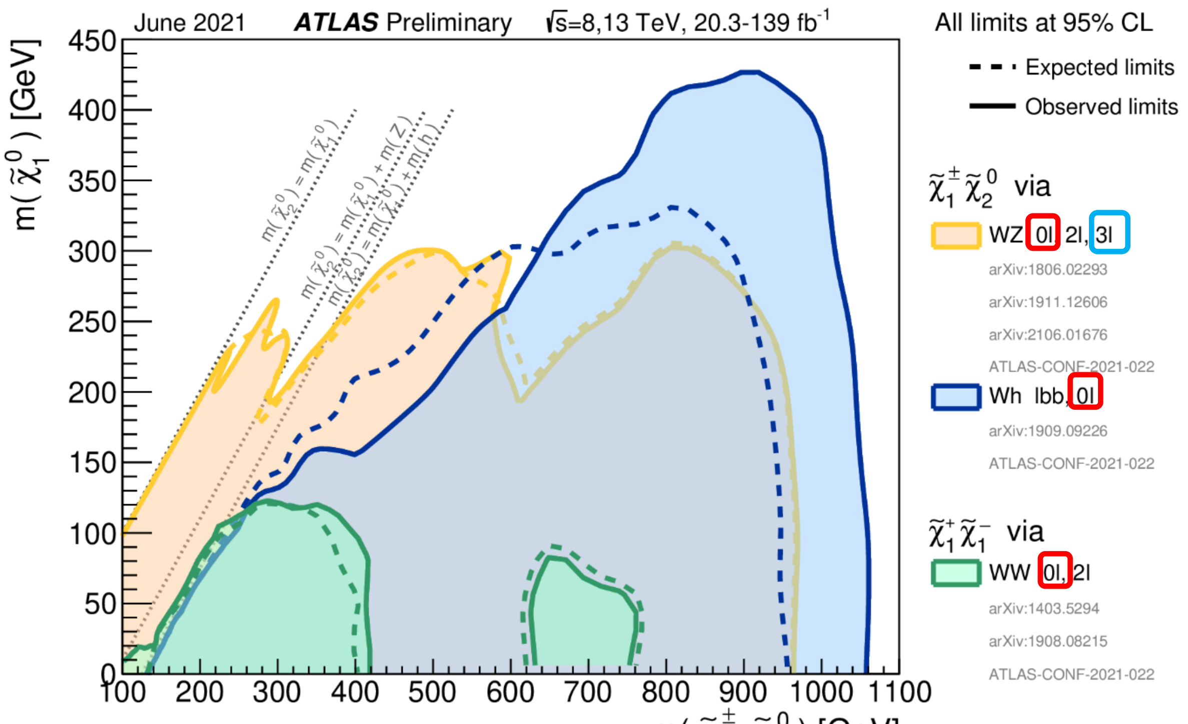
CMS excluded 175-1025 GeV $\tilde{H}$

Summary

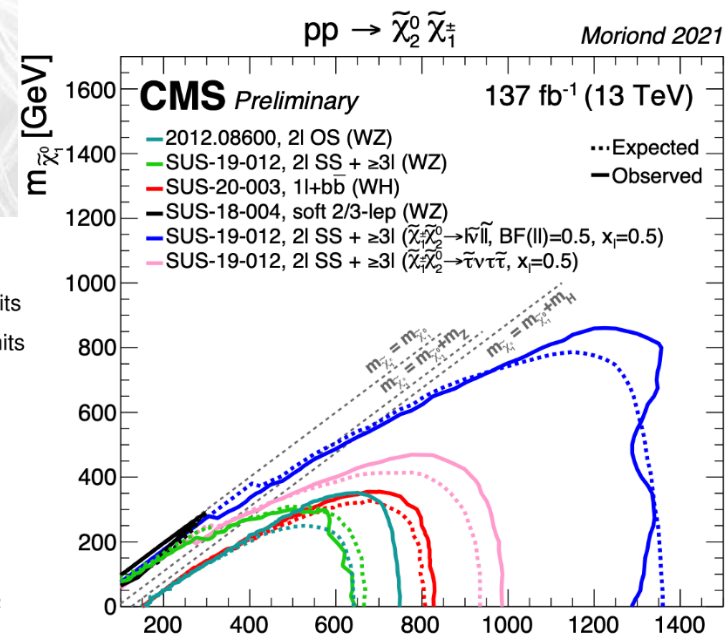
not in this talk but take a look! →

- CMS SUS-19-012 3/4lepton FS
- ATLAS SUSY-2018-02 4+lepton FS
- CMS SUS-20-003 1lepton+bb FS
- CMS SUS-18-004 2/3 soft lepton FS
- ATLAS SUSY-2018-23 H->γγ FS

Latest searches expand excluded gaugino phase space ever further for many final states (FS)



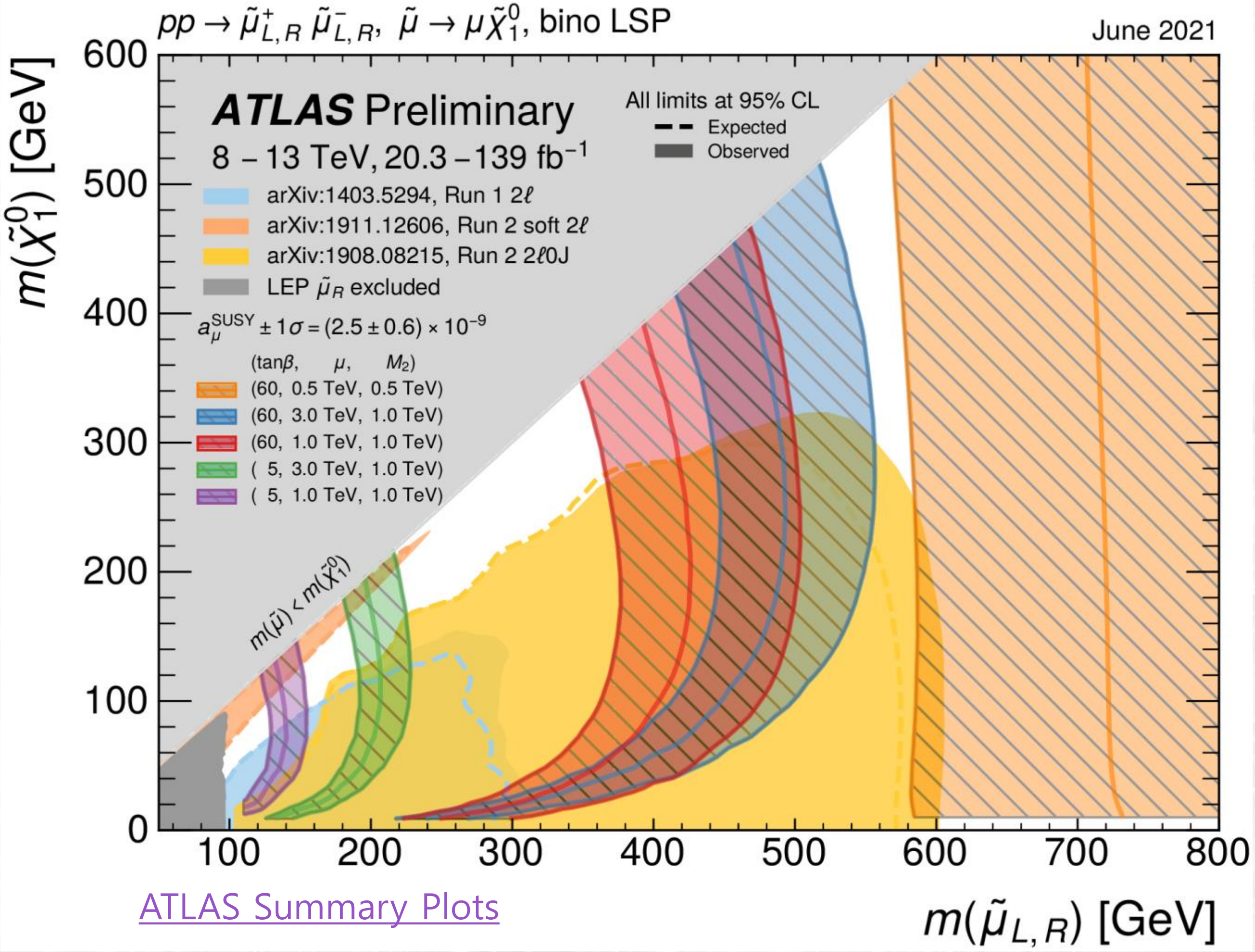
ATLAS Summary Plots



CMS Summary Plots

Summary

But still lots of well-motivated phase space to explore, e.g. models consistent with g-2 anomaly and slepton searches.



[ATLAS Summary Plots]

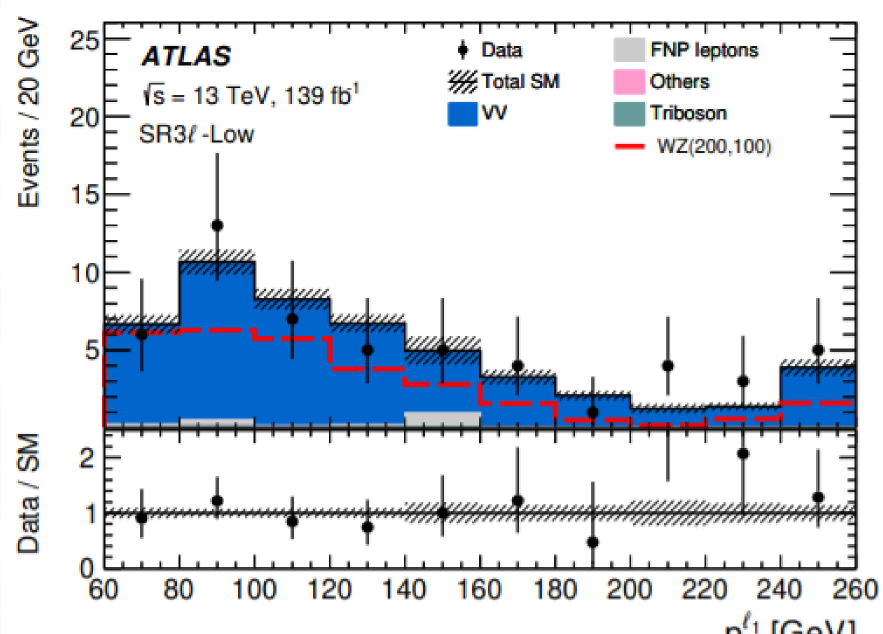
BACKUP

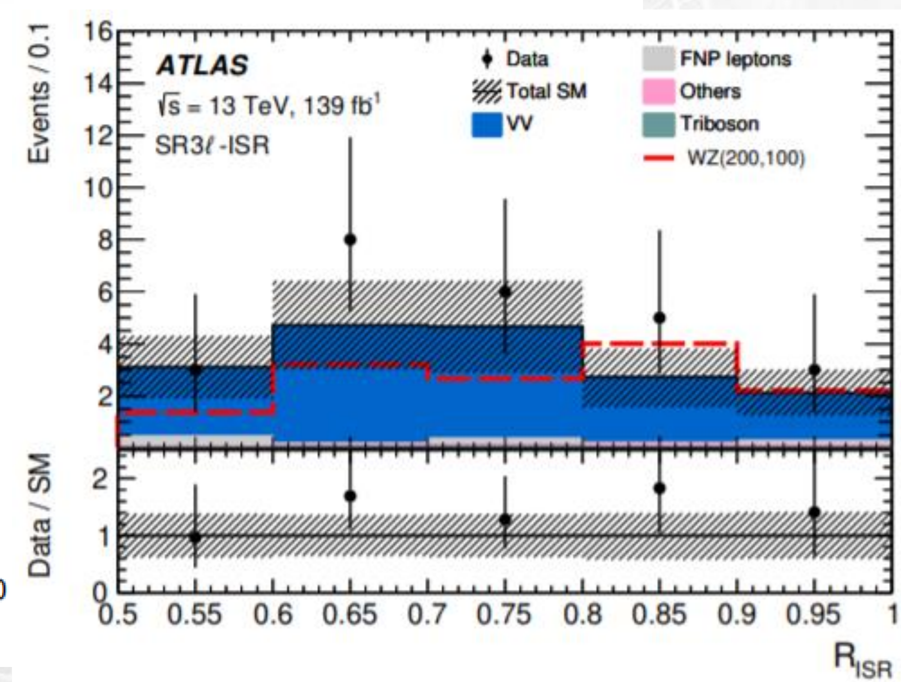
3 Leptons – RJR follow-up

$2.1/3\sigma$ Excess @ $36fb^{-1}$ gone with $139fb^{-1}$ data

- arXiv:1806.02293 used recursive-jigsaw technique to reconstruct $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ decays by b oosting into their rest-frames.
- Redo analysis with 2017+2018 datasets, find excess no longer persists.

SR	$\sigma_{\mathrm{vis}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	$\mathrm{CL_b}$	$p(s=0)$ (Z)
SR3ℓ-Low	0.24	33	30^{+10}_{-8}	0.61	0.39 (0.28)
SR3ℓ-ISR	0.14	19	12^{+5}_{-4}	0.89	0.09 (1.32)





ATLAS-SUSY-2019-09

Fully Hadronic Regions ATLAS

Table 3: Summary of selection for the SRs, CRs, and VRs. $n(V_{qq})$ ($n(!V_{qq})$) represents the number of large-R jets passing (failing) the V_{qq}-tagging between the two highest-p_{T} large-R jets. The same selection is applied between the SR (VR) and CR in the same category except for the V_{qq}-tagging and some kinematic selections that are explicitly indicated by the parentheses. The trigger selection and event cleaning described in Section 5 is applied additionally. VRTTX is a validation region for verify the $t\bar{t}+X$ modeling as described in Section 7.1. $p_{\mathrm{T}}(W)$ is the vector sum of the p_{T} of lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ in the 1L regions. In the 1L (1Y) regions, $E_{\mathrm{T}}^{\mathrm{miss}}$ is replaced by $p_{\mathrm{T}}(W)$ ($p_{\mathrm{T}}(\gamma)$) when calculating the kinematic variables m_{eff}, min $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j)$ and m_{T2}. Details are described in Section 7.2.

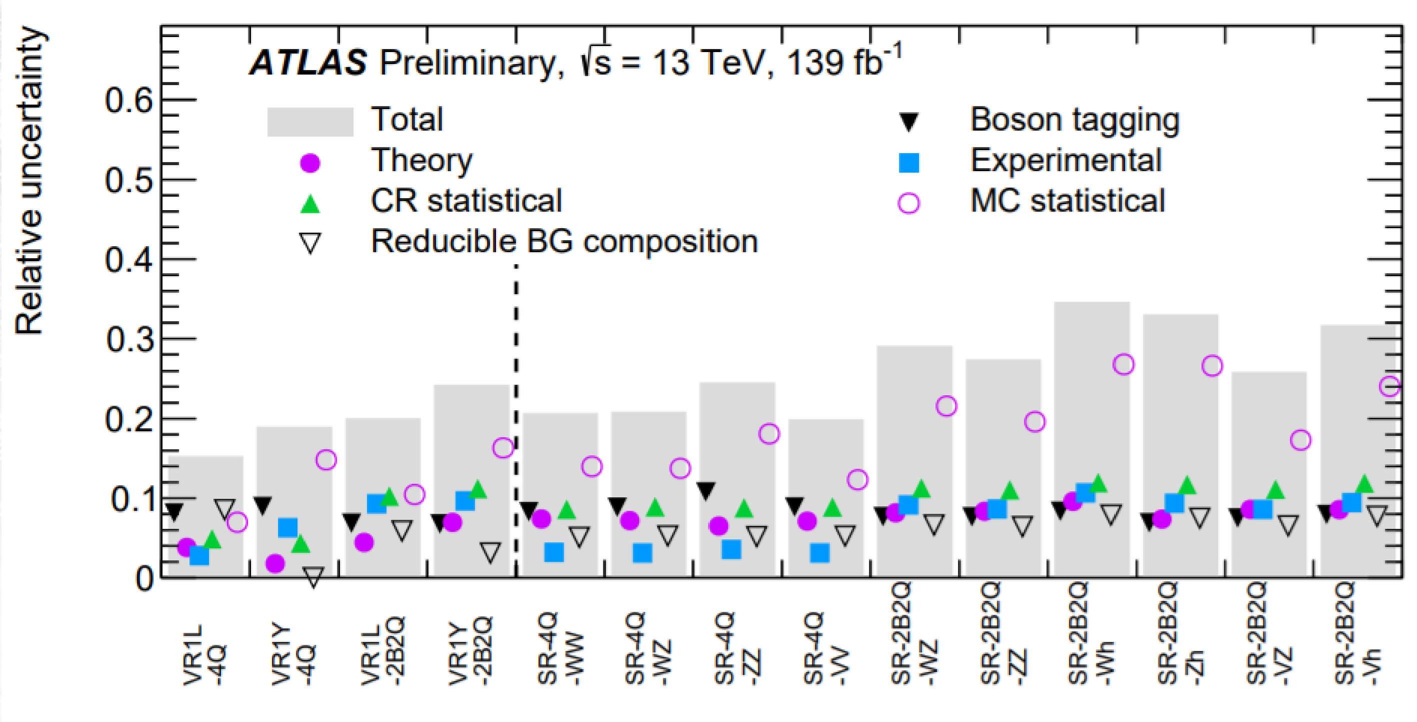
	SR(CR0L)		VR(CR)1L		VR(CR)1Y		VRTTX
	4Q	2B2Q	4Q	2B2Q	4Q	2B2Q	
$n_{\mathrm{Large-}R\ \mathrm{jets}}$	≥ 2		≥ 2		≥ 2		$= 1$
n_{lepton}	$= 0$		$= 1$		$= 0$		$= 3$
$p_{\mathrm{T}}(\ell_1)$ [GeV]	-		> 30		-		> 30
n_{photon}	-		-		$= 1$		-
$n(V_{qq})$	$= 2\ (= 1)$	$= 1\ (= 0)$	$= 2\ (= 1)$	$= 1\ (= 0)$	$= 2\ (= 1)$	$= 1\ (= 0)$	-
$n(!V_{qq})$	$= 0\ (= 1)$	$= 0\ (= 1)$	$= 0\ (= 1)$	$= 0\ (= 1)$	$= 0\ (= 1)$	$= 0\ (= 1)$	-
$n(J_{bb})$	$= 0$	$= 1$	$= 0$	$= 1$	$= 0$	$= 1$	$= 1$
$m(J_{bb})$ [GeV]	-	$\in [70, 135\ (150)]$	-	$\in [70, 150]$	-	$\in [70, 150]$	-
$n_{b\mathrm{-jet}}^{\mathrm{unmatched}}$	$= 0$		$= 0$		$= 0$		-
$n_{b\mathrm{-jet}}$	≤ 1	-	$= 0$	-	≤ 1	-	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 300	> 200	> 50		< 200		-
$p_{\mathrm{T}}(W)$ [GeV]	-		> 200		-		-
$p_{\mathrm{T}}(\gamma)$ [GeV]	-		-		> 200		-
m_{eff} [GeV]	> 1300	$> 1000\ (> 900)$	> 1000	> 900	> 1000	> 900	-
min $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j)$	> 1.0		> 1.0		> 1.0		-
m_{T2} [GeV]	-	> 250	-	> 250	-	> 250	-

	$n(W_{qq})$	$n(Z_{qq})$	$n(V_{qq})$	$n(Z_{bb})$	$n(h_{bb})$
4Q-WW	$= 2$	-	$= 2$	$= 0$	$= 0$
4Q-WZ	≥ 1	≥ 1	$= 2$	$= 0$	$= 0$
4Q-ZZ	-	$= 2$	$= 2$	$= 0$	$= 0$
4Q-VV	-	-	$= 2$	$= 0$	$= 0$
2B2Q-WZ	$= 1$	-	$= 1$	$= 1$	$= 0$
2B2Q-ZZ	-	$= 1$	$= 1$	$= 1$	$= 0$
2B2Q-Wh	$= 1$	-	$= 1$	$= 0$	$= 1$
2B2Q-Zh	-	$= 1$	$= 1$	$= 0$	$= 1$
2B2Q-VZ	-	-	$= 1$	$= 1$	$= 0$
2B2Q-Vh	-	-	$= 1$	$= 0$	$= 1$

ATLAS-CONF-2021-022

Fully-Hadronic systs ATLAS

Uncertainty contributions: stats. dominate everywhere



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Fully-Hadronic upper limits ATLAS

Model-independent upper limits set in SRs + added ‘discovery’ SRs wit h looser selections

Table 6: Left to right: 95% CL upper limits on the visible cross section ($\langle\epsilon\sigma\rangle^{95}_{obs}$). S^{95}_{obs} (S^{95}_{exp}) shows the 95% CL upper limit on the number of signal events, given the observed number (expected number and $\pm 1\sigma$ excursions) of background events. The last two columns indicate the CL_B value and the discovery p-value ($p(s) = 0$) with the corresponding gaussian significance (Z). CL_B provides a measure of the disagreement of the observation with the background-only hypothesis by quantifying how frequently a measurement suggesting a higher signal contribution than the best fit signal strength would occur due to background fluctuations, whilst the p_0 value instead quantifies the excess of data given the null hypothesis of background only. By convention, the quoted p-value is truncated at 0.5 in the case of a data deficit.

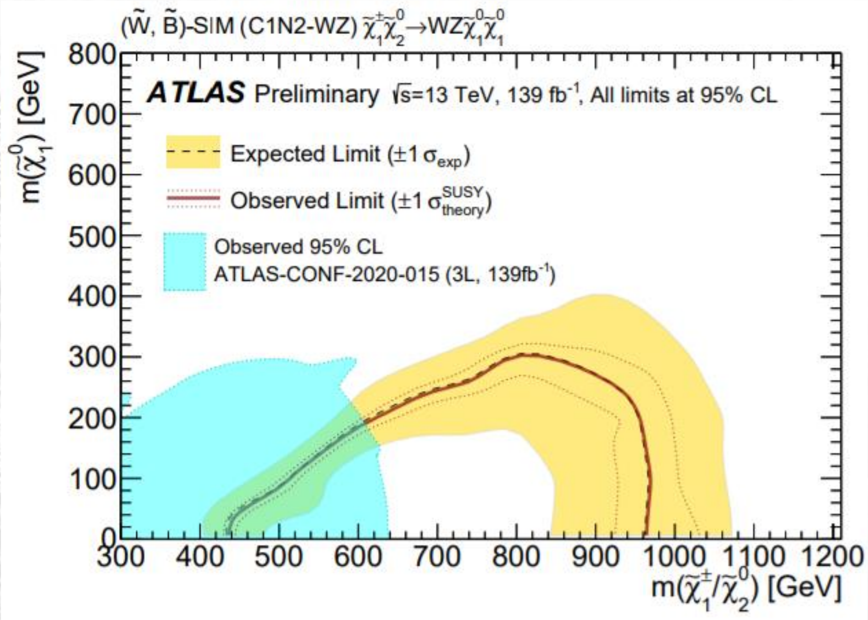
Signal region	$\langle\epsilon\sigma\rangle^{95}_{obs}$[fb]	S^{95}_{obs}	S^{95}_{exp} ($\pm 1\sigma$)	CL_B	$p(s=0)$ (Z)
SR-4Q-WW	0.032	4.5	$4.2^{+1.8}_{-1.0}$	0.55	0.44 (0.15)
SR-4Q-WZ	0.036	5.0	$5.1^{+2.1}_{-1.3}$	0.46	0.50 (0.00)
SR-4Q-ZZ	0.025	3.6	$4.1^{+1.8}_{-1.0}$	0.30	0.50 (0.00)
SR-4Q-VV	0.034	4.7	$5.3^{+2.3}_{-1.5}$	0.38	0.50 (0.00)
SR-2B2Q-WZ	0.033	4.7	$4.0^{+1.7}_{-0.7}$	0.66	0.33 (0.44)
SR-2B2Q-Wh	0.022	3.1	$3.9^{+1.3}_{-0.7}$	0.28	0.50 (0.00)
SR-2B2Q-ZZ	0.033	4.5	$4.1^{+1.7}_{-0.9}$	0.63	0.37 (0.32)
SR-2B2Q-Zh	0.026	3.6	$3.9^{+1.4}_{-0.7}$	0.38	0.50 (0.00)
SR-2B2Q-VZ	0.032	4.4	$4.4^{+1.8}_{-1.0}$	0.50	0.50 (0.00)
SR-2B2Q-Vh	0.026	3.6	$4.4^{+1.7}_{-1.0}$	0.24	0.50 (0.00)
Disc-SR-2B2Q	0.034	4.8	$5.6^{+2.4}_{-1.6}$	0.30	0.50 (0.00)
Disc-SR-Incl	0.042	5.9	$7.2^{+2.2}_{-2.0}$	0.27	0.50 (0.00)

+
+
+

ATLAS-CONF-2021-022

Fully-Hadronic results ATLAS

Simplified model interpretations allow comparison with existing searches



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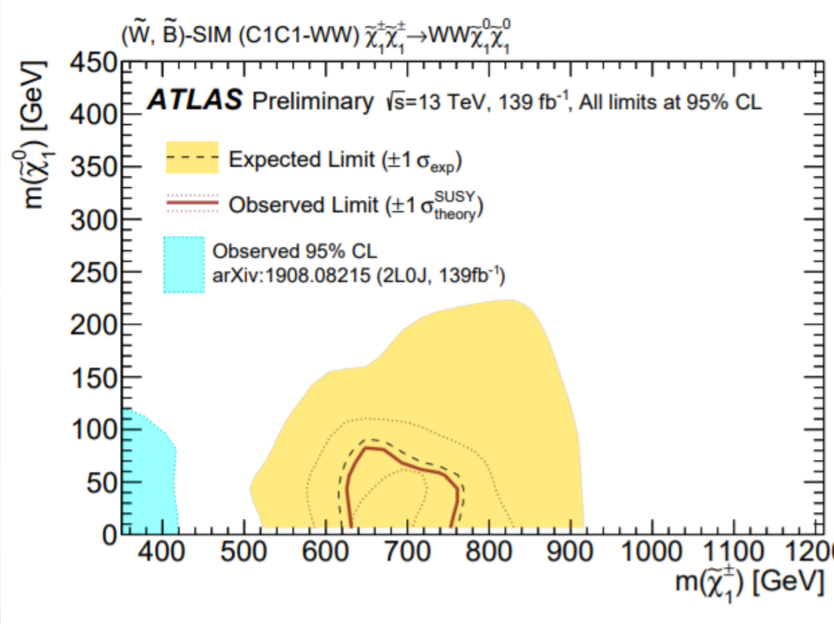
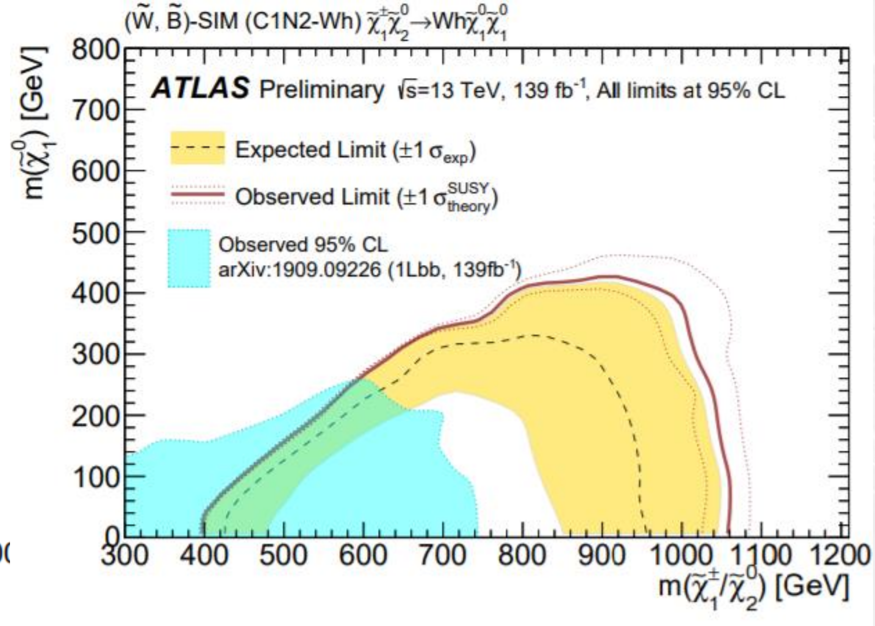




Fully-Hadronic regions CMS

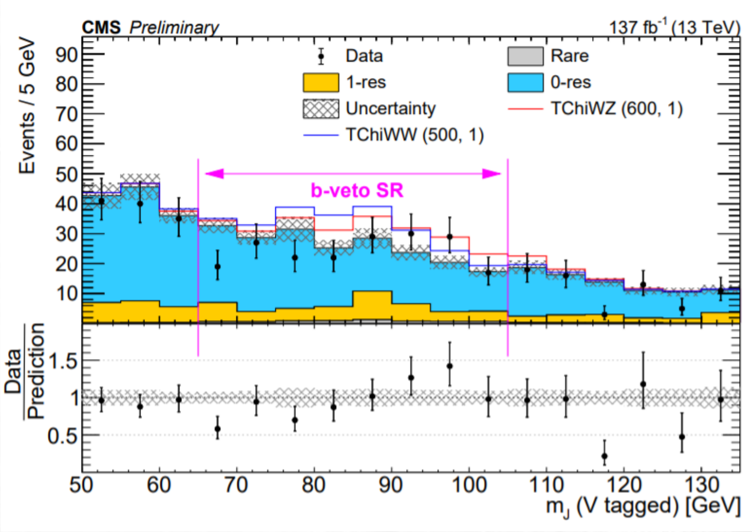
Table 1: Summary of tagging requirements for the b-veto SR and CRs. Each of these regions includes the baseline requirements described in Section 4, as well as requiring zero b-tagged AK4 jets and requiring at least two AK8 jets satisfying $65 < m_J < 105$ GeV. The SR and CRs are described in detail in Sections 4.1 and 5.1, respectively. The W and V taggers are described in Section 3.

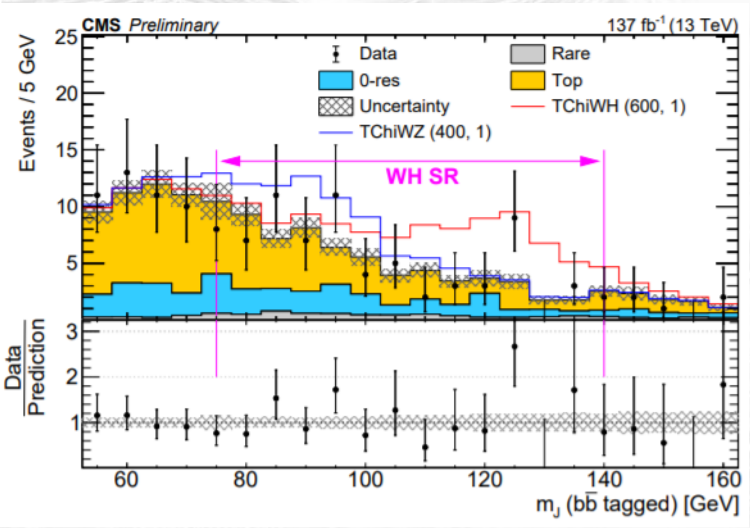
Region	Requirements
b-veto SR	≥1 V-tagged jet ≥1 W-tagged jet ≥2 V- or W-tagged jets
b-veto zero-tag CR	0 V-tagged jets 0 W-tagged jets
b-veto one-tag CR	1 V-tagged jet 0 other W-tagged jets

Table 2: Summary of tagging requirements for the b-tag SRs and CRs. Each of these regions includes the baseline requirements described in Section 4, as well as requiring at least one b-tagged AK4 jet and at least two AK8 jets. The SRs and CRs are described in detail in Sections 4.2 and 5.2, respectively. The $b\bar{b}$ and W taggers are described in Section 3, and the definitions of W and Higgs boson candidates are given in Section 4.2. In addition to the six regions described in this table, the b-tag predictions also use six single-lepton CRs that are identical except that exactly one charged lepton is required. A dash (—) indicates that no requirement is imposed.

	Higgs boson candidate		W boson candidate	
	$b\bar{b}$ tagged	not $b\bar{b}$ tagged	W tagged	not W tagged
WH SR	≥1	—	≥1	—
W SR	0	—	≥1	—
H SR	≥1	—	0	—
WH antitag CR	0	≥1	0	≥1
W antitag CR	0	0	0	≥1
H antitag CR	0	≥1	0	0

Fully-Hadronic N-1 plots CMS





Fully-Hadronic systs CMS

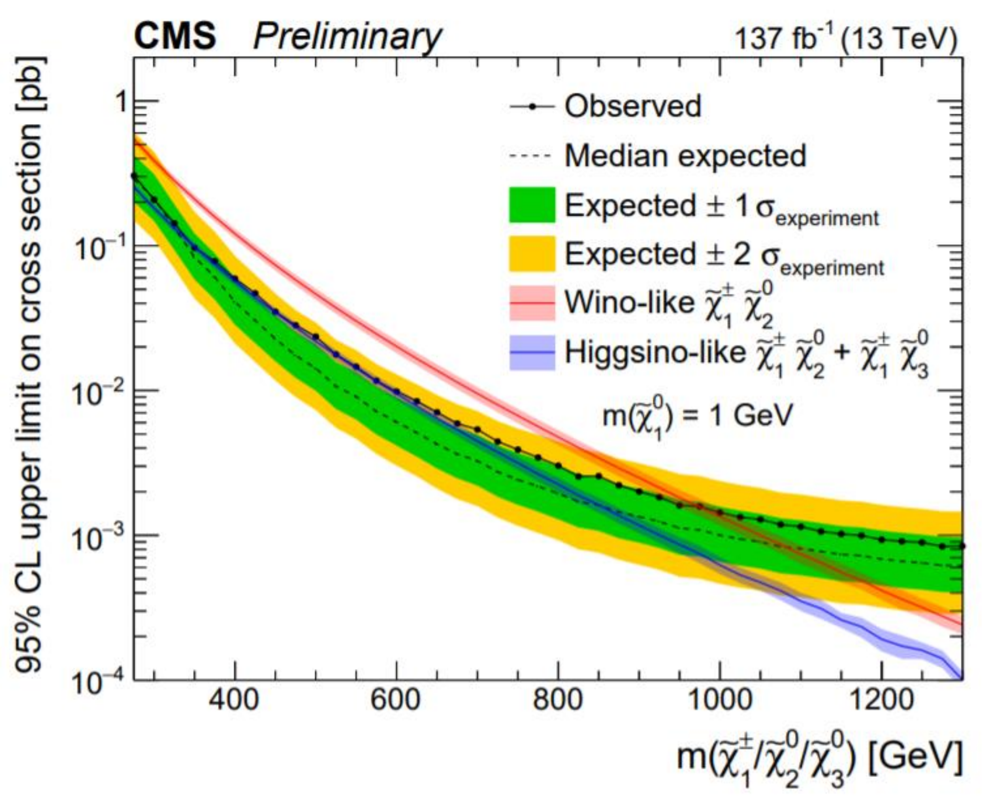
Stats dominate generally, followed by systs on the W->qq taggers and signal cross section

Table 3: Summary of the dominant systematic uncertainties (in %) in various analysis regions. For the 0- and 1-res backgrounds in the b-veto SR, uncertainties are presented separately depending on the CR region used for the estimation. A dash (—) indicates that the source of uncertainty is not applicable.

Source	b veto				b tag			
	0- and 1-res bkg.		Rare	Signal	Top	0-res	Rare	Signal
	0-tag CR	1-tag CR						
Luminosity	—	—	1.6	1.6	—	—	1.6	1.6
CR data size	6–71	5–50	—	—	3–100	2–35	—	—
MC sample size	8–25	8–30	14–24	2–5	2–28	3–40	4–27	2–5
μ_R, μ_F scales	1.2	0.4	8	< 5	2–10	0.5	11	< 5
Trigger efficiency	—	—	2–3	2–3	—	—	2–3	2–3
b-tag correction	< 1	< 1	< 1	1	1	< 3	< 3	2–3
$b\bar{b}$-tag correction	—	—	—	—	—	4	2–7	4
W-tag correction	12–28	6–22	11–15	15	1	9	7	9
V-tag correction	7–15	2–10	1–4	2	—	—	—	—
W-tag non-closure	3–48	3–48	—	—	—	—	—	—
V-tag non-closure	1–27	—	—	—	—	—	—	—
Fast-simulation	—	—	—	5	—	—	—	8

Fully-Hadronic results CMS

Adding Higgsino interpretation (mass degenerate gauginos)



3 lepton regions – on shell WZ

Variable	Preselection requirements $\mathrm{SR}^{\mathrm{WZ}}$	$\mathrm{SR}^{\mathrm{Wh}}_{\mathrm{SFOS}}$	$\mathrm{SR}^{\mathrm{Wh}}_{\mathrm{DFOS}}$
$n^{\mathrm{baseline}}_{\mathrm{lep}}, n^{\mathrm{signal}}_{\mathrm{lep}}$		$= 3$	
Trigger		dilepton	
$p_{\mathrm{T}}^{\ell_1}, p_{\mathrm{T}}^{\ell_2}, p_{\mathrm{T}}^{\ell_3}$ [GeV]		$> 25, 20, 10$	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]		> 50	
$n_{b\text{-jets}}$		$= 0$	
Resonance veto $m_{\ell\ell}$ [GeV]	> 12	> 12	-
n_{SFOS}	≥ 1	≥ 1	$= 0$
$m_{\ell\ell}$ [GeV]	$\in [75, 105]$	$\notin [75, 105]$	-
$\lvert m_{3\ell} - m_Z \rvert$ [GeV]	> 15	> 15	-

Selection requirements				
		$n_{\mathrm{jets}} = 0$		
m_{T} [GeV]		$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]		
[100, 160]	$\mathrm{SR}^{\mathrm{WZ}}$-1: [50, 100]	$\mathrm{SR}^{\mathrm{WZ}}$-2: [100, 150]	$\mathrm{SR}^{\mathrm{WZ}}$-3: [150, 200]	$\mathrm{SR}^{\mathrm{WZ}}$-4: > 200
> 160	$\mathrm{SR}^{\mathrm{WZ}}$-5: [50, 150]	$\mathrm{SR}^{\mathrm{WZ}}$-6: [150, 200]	$\mathrm{SR}^{\mathrm{WZ}}$-7: [200, 350]	$\mathrm{SR}^{\mathrm{WZ}}$-8: > 350
		$n_{\mathrm{jets}} > 0$, $H_{\mathrm{T}} < 200$ GeV		
m_{T} [GeV]		$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]		
[100, 160]	$\mathrm{SR}^{\mathrm{WZ}}$-9: [100, 150]	$\mathrm{SR}^{\mathrm{WZ}}$-10: [150, 250]	$\mathrm{SR}^{\mathrm{WZ}}$-11: [250, 300]	$\mathrm{SR}^{\mathrm{WZ}}$-12: > 300
> 160	$\mathrm{SR}^{\mathrm{WZ}}$-13: [50, 150]	$\mathrm{SR}^{\mathrm{WZ}}$-14: [150, 250]	$\mathrm{SR}^{\mathrm{WZ}}$-15: [250, 400]	$\mathrm{SR}^{\mathrm{WZ}}$-16: > 400
		$n_{\mathrm{jets}} > 0$, $H_{\mathrm{T}} > 200$ GeV, $H_{\mathrm{T}}^{\mathrm{lep}} < 350$ GeV		
m_{T} [GeV]		$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]		
> 100	$\mathrm{SR}^{\mathrm{WZ}}$-17: [150, 200]	$\mathrm{SR}^{\mathrm{WZ}}$-18: [200, 300]	$\mathrm{SR}^{\mathrm{WZ}}$-19: [300, 400]	$\mathrm{SR}^{\mathrm{WZ}}$-20: > 400

3 lepton regions - Wh

Selection requirements			
$m_{\ell\ell} \leq 75$ GeV, $n_{\text{jets}} = 0$			
m_T [GeV]	E_T^{miss} [GeV]		
[0, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-1: [50, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-2: [100, 150]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-3 > 150
[100, 160]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-4: [50, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-5: > 100	
> 160	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-6: [50, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-7: > 100	
$m_{\ell\ell} \leq 75$ GeV, $n_{\text{jets}} > 0$, $H_T < 200$ GeV			
m_T [GeV]	E_T^{miss} [GeV]		
[0, 50]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-8: [50, 100]		
[50, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-9: [50, 100]		
[0, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-10: [100, 150]		$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-11: > 150
[100, 160]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-12: [50, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-13: [100, 150]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-14: > 150
> 160	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-15: [50, 150]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-16: > 150	
$m_{\ell\ell} \geq 105$ GeV, $n_{\text{jets}} = 0$			
m_T [GeV]	E_T^{miss} [GeV]		
> 100	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-17: [50, 100]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-18: [100, 200]	$\text{SR}^{\text{Wh}}_{\text{SFOS}}$-19: > 200

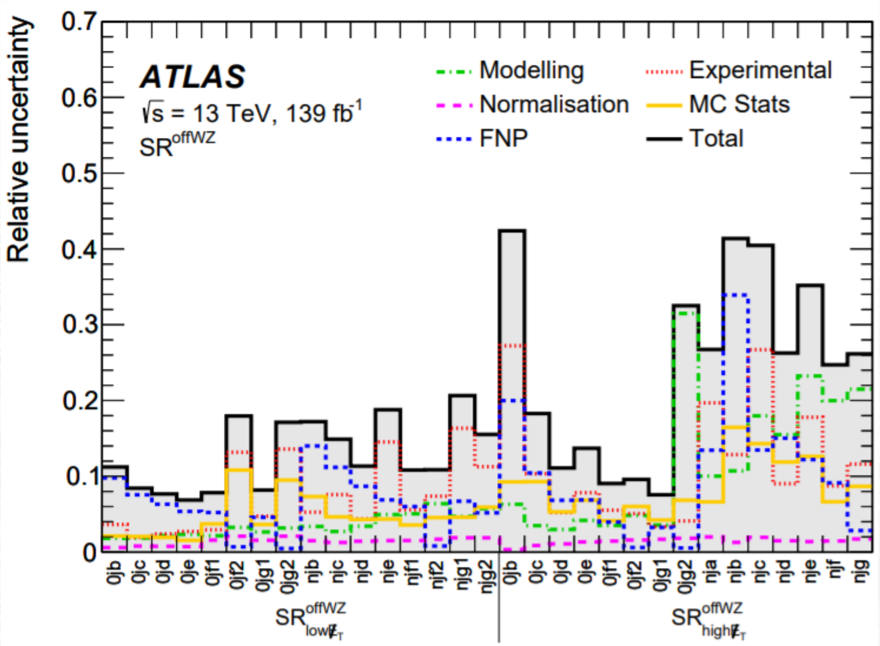
	Selection requirements	
Variable	$\text{SR}^{\text{Wh}}_{\text{DFOS}}$-1	$\text{SR}^{\text{Wh}}_{\text{DFOS}}$-2
n_{jets}	$= 0$	$\in [1, 2]$
E_T^{miss} significance	> 8	> 8
$p_T^{\ell_3}$ [GeV]	> 15	> 20
$\Delta R_{\text{OS,near}}$	< 1.2	< 1.0

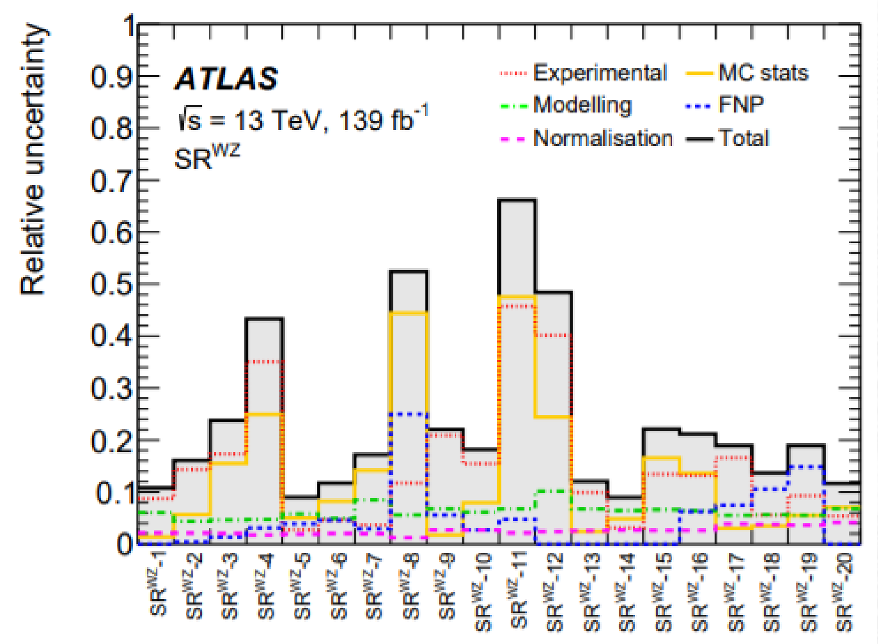
3 Lepton regions – off shell WZ

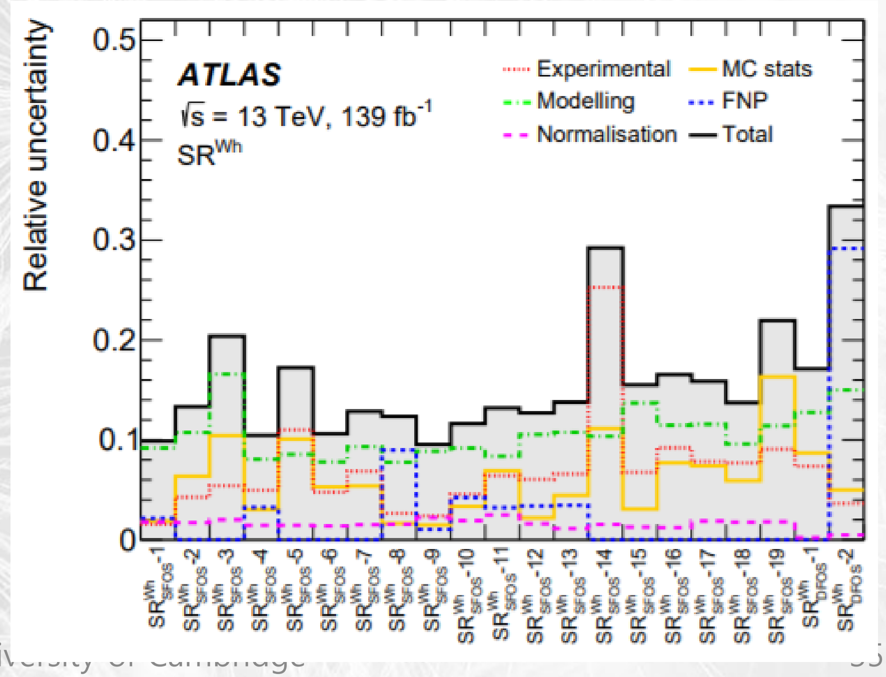
Variable	Preselection requirements: $\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_T}$-$\mathtt{0j}$	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_T}$-$\mathtt{nj}$	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_T}$-$\mathtt{0j}$	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_T}$-$\mathtt{nj}$
$n_{\mathrm{lep}}^{\mathrm{baseline}}, n_{\mathrm{lep}}^{\mathrm{signal}}$	$= 3$			
n_{SFOS}	≥ 1			
$m_{\ell\ell}^{\mathrm{max}}$ [GeV]	< 75			
$m_{\ell\ell}^{\mathrm{min}}$ [GeV]	$\in [1, 75]$			
$n_{b\text{-jets}}$	$= 0$			
$\min \Delta R_{3\ell}$	> 0.4			
Resonance veto $m_{\ell\ell}^{\mathrm{min}}$ [GeV]	$\notin [3, 3.2], \notin [9, 12]$			-
Trigger	(multi-)lepton		((multi-)lepton $\|\|$ $E_{\mathrm{T}}^{\mathrm{miss}}$)	
$n_{\mathrm{jets}}^{30\ \mathrm{GeV}}$	$= 0$	≥ 1	$= 0$	≥ 1
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	< 50	< 200	> 50	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	> 1.5	> 3.0	> 3.0	> 3.0
$p_{\mathrm{T}}^{\ell_1}, p_{\mathrm{T}}^{\ell_2}, p_{\mathrm{T}}^{\ell_3}$ [GeV]	> 10			$> 4.5(3.0)$ for $e(\mu)$
$\|m_{3\ell} - m_Z\|$ [GeV]	> 20 ($\ell_W = e$ only)		-	
$\min \Delta R_{\mathrm{SFOS}}$	$[0.6, 2.4]$ ($\ell_W = e$ only)		-	

Variable	Selection requirements: a	b	c	d	e	f1	f2	g1	g2
$m_{\ell\ell}^{\mathrm{min}}$ [GeV]	[1, 12]	[12, 15]	[15, 20]	[20, 30]	[30, 40]	[40, 60]		[60, 75]	
	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_T}$ common								
$m_{\ell\ell}^{\mathrm{max}}$ [GeV]	×	< 60	< 60	< 60	< 60	-	-	-	-
$m_{\mathrm{T}}^{\mathrm{mllmin}}$ [GeV]	×	< 50	< 50	< 50	< 60	< 60	> 90	< 60	> 90
m_{T2}^{100} [GeV]	×	< 115	< 120	< 130	-	-	-	-	-
$\min \Delta R_{\mathrm{SFOS}}$	×	< 1.6	< 1.6	< 1.6	-	-	-	-	-
$p_{\mathrm{T}}^{\ell_1}, p_{\mathrm{T}}^{\ell_2}, p_{\mathrm{T}}^{\ell_3}$ [GeV]	×	> 10	> 10	> 10	> 10	> 15	> 15	> 15	> 15
	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_T}$-$\mathtt{0j}$								
$\|\mathbf{p}_{\mathrm{T}}^{\mathrm{lep}}\| / E_{\mathrm{T}}^{\mathrm{miss}}$	×	< 1.1	< 1.1	< 1.1	< 1.3	< 1.4	< 1.4	< 1.4	< 1.4
$m_{3\ell}$ [GeV]	×	-	-	-	-	> 100	> 100	> 100	> 100
	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_T}$-$\mathtt{nj}$								
$\|\mathbf{p}_{\mathrm{T}}^{\mathrm{lep}}\| / E_{\mathrm{T}}^{\mathrm{miss}}$	×	< 1.0	< 1.0	< 1.0	< 1.0	< 1.2	< 1.2	< 1.2	< 1.2
	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_T}$ common								
m_{T2}^{100} [GeV]	< 112	< 115	< 120	< 130	< 140	< 160	< 160	< 175	< 175
	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_T}$-$\mathtt{0j}$								
$p_{\mathrm{T}}^{\ell_1}, p_{\mathrm{T}}^{\ell_2}, p_{\mathrm{T}}^{\ell_3}$ [GeV]	×	$> 25, > 15, > 10$							
$m_{\mathrm{T}}^{\mathrm{mllmin}}$ [GeV]	×	< 50	< 50	< 60	< 60	< 70	> 90	< 70	> 90
	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_T}$-$\mathtt{nj}$								
						f		g	
$p_{\mathrm{T}}^{\ell_1}, p_{\mathrm{T}}^{\ell_2}, p_{\mathrm{T}}^{\ell_3}$ [GeV]	> 4.5 (3.0) for e (μ)								
$\|\mathbf{p}_{\mathrm{T}}^{\mathrm{lep}}\| / E_{\mathrm{T}}^{\mathrm{miss}}$	< 0.2	< 0.2	< 0.3	< 0.3	< 0.3	< 1.0		< 1.0	

3 Lepton uncertainties



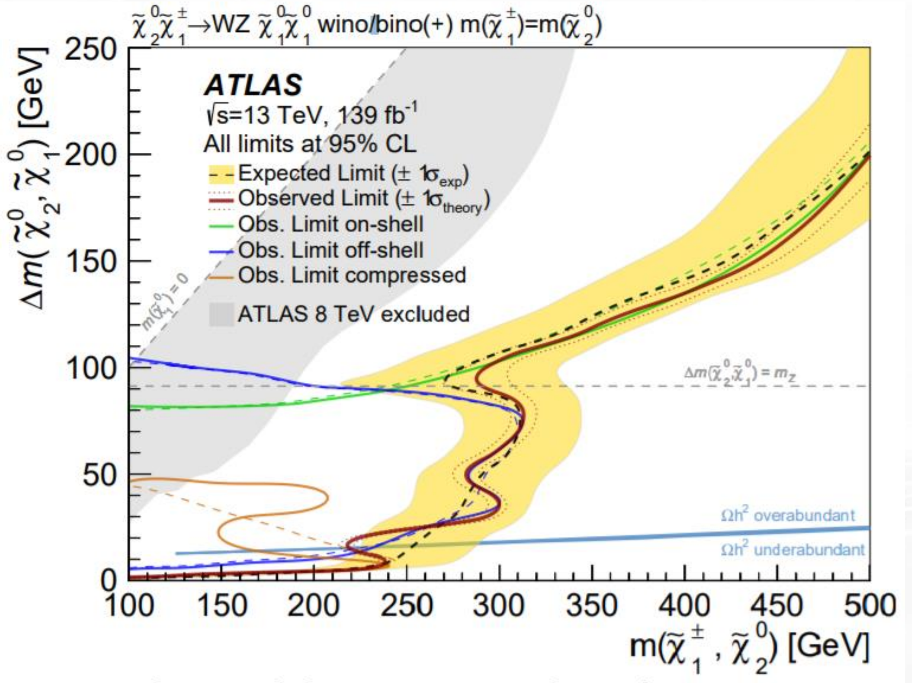


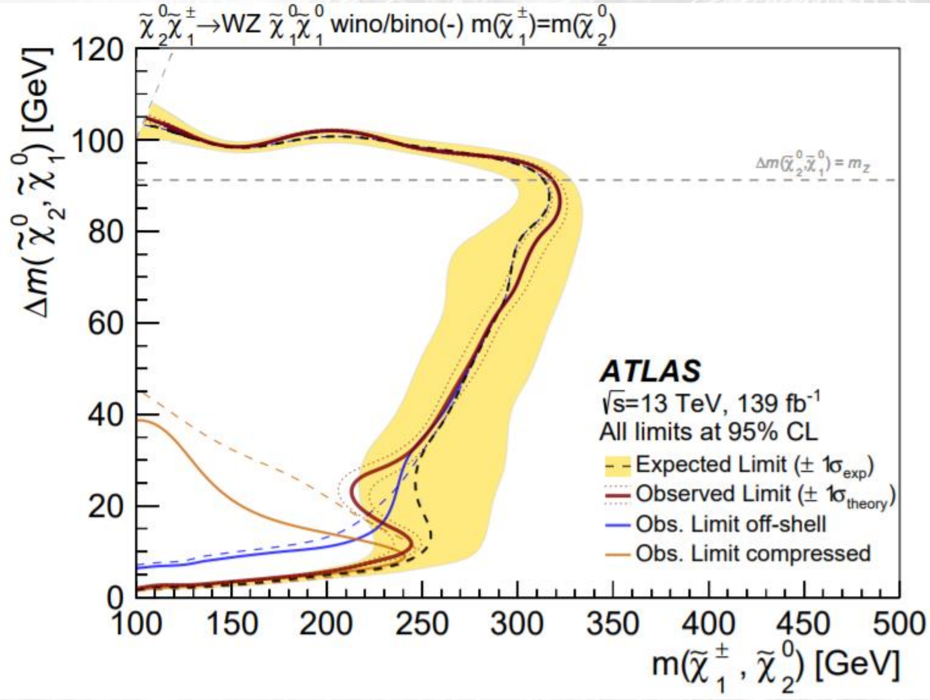


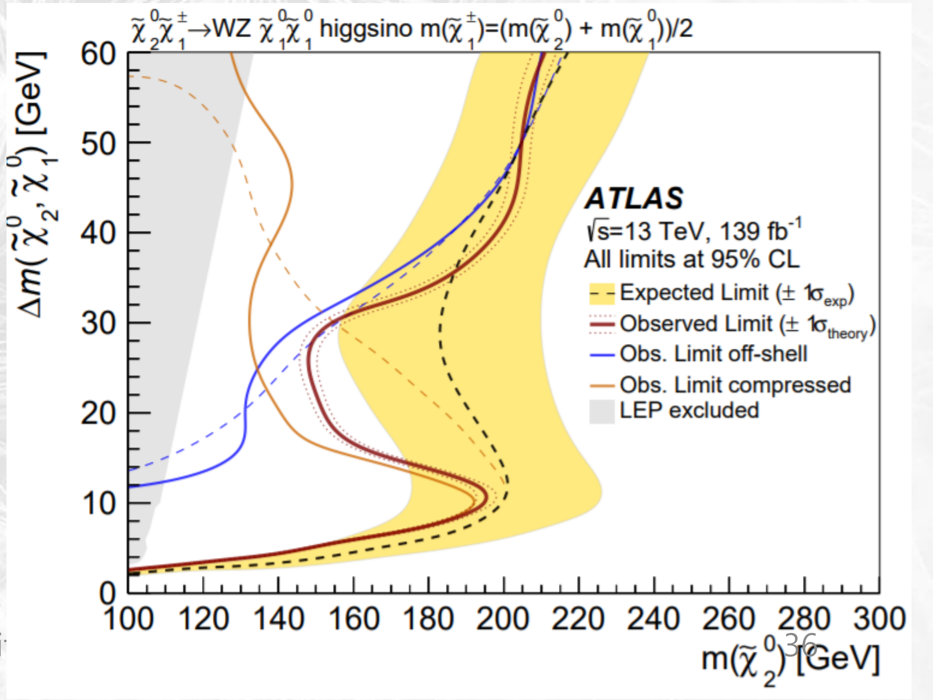
3 Lepton WZ Limits

Combines this analysis' SRs with previous 2 lepton compressed search: [arXiv:1911.12606]

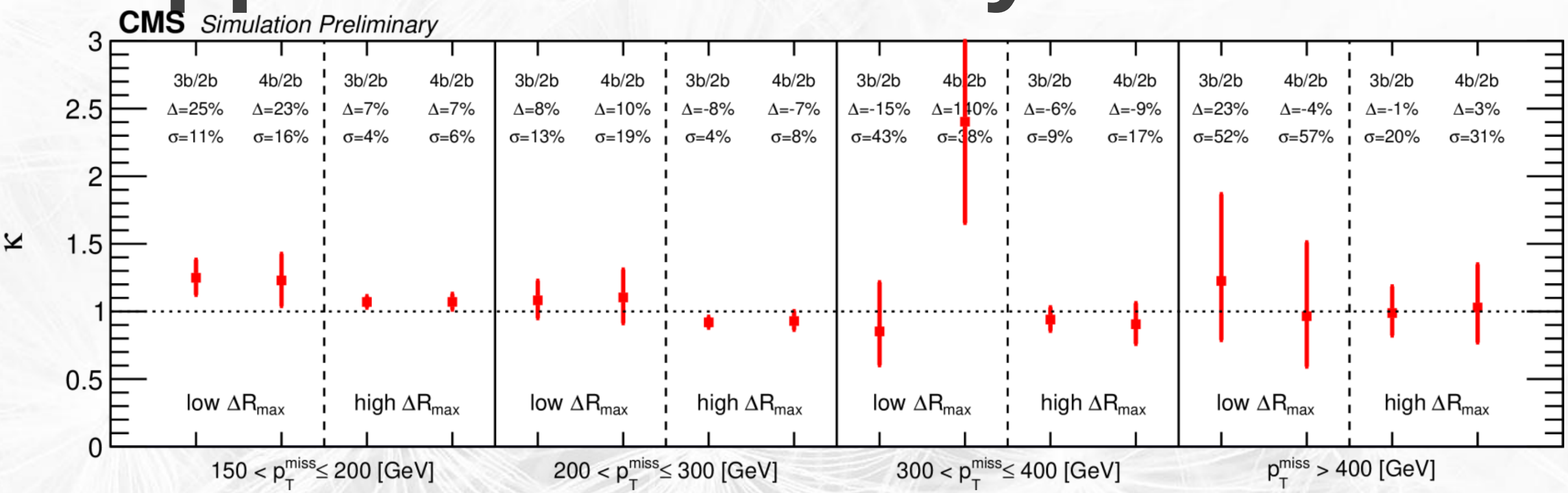
Excellent exclusion improvement







4b kappa values and systs.



Source	Relative uncertainty (%) Resolved	Boosted
MC sample statistics	0–18	1–15
ISR modeling	0–2	0–18
Renormalization and factorization scales μ_R and μ_F	0–2	0–7
Pileup corrections	0–2	0–9
Integrated luminosity	1.6	
Jet energy scale	0–7	0–12
Jet energy resolution	0–7	0–7
Trigger efficiency	1-13	0–4
Wide-angle jet mass resolution	—	0–9
b tagging efficiency	2–7	—
b mis-tagging	1–3	—
bb tagging efficiency	—	6–15
Uncertainties attributable to the fast simulation		
Jet quality requirements	1	
p_T^{miss} modeling	0–13	0–12
Wide-angle jet mass resolution	—	2–4
b tagging efficiency	0–1	—
b mis-tagging	0–1	—
bb tagging efficiency	—	< 1

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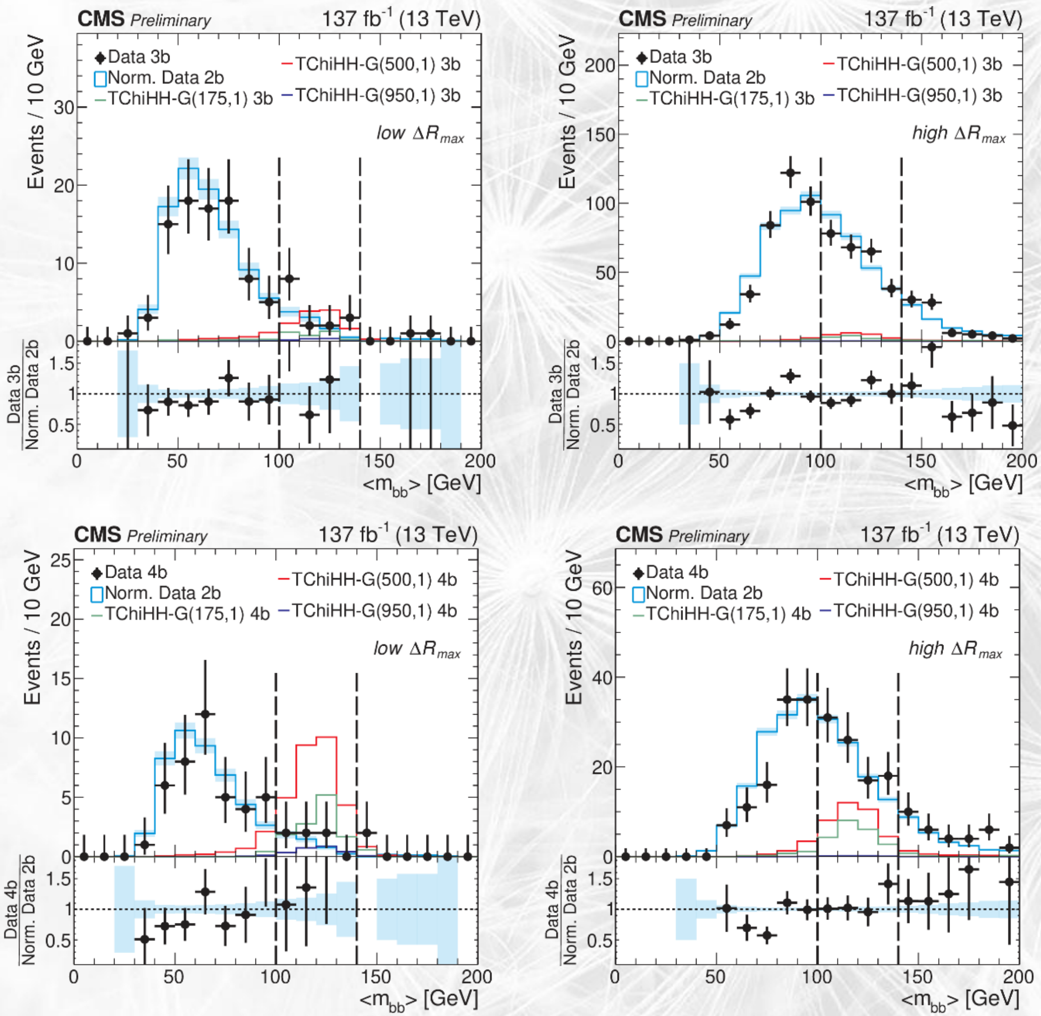
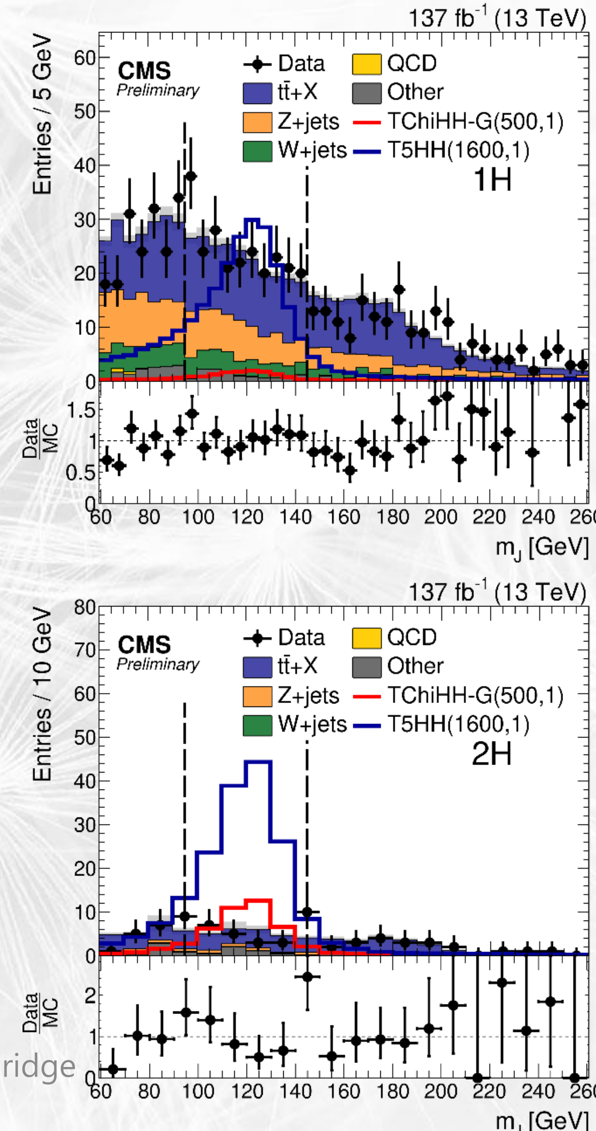
4b SR Distributions

Resolved DeltaR bins:

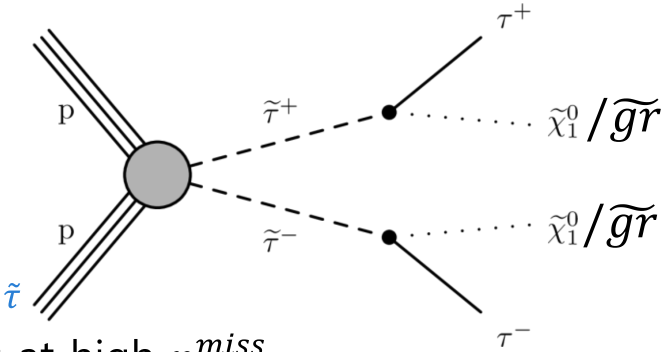


Boosted, largeR jet mass:

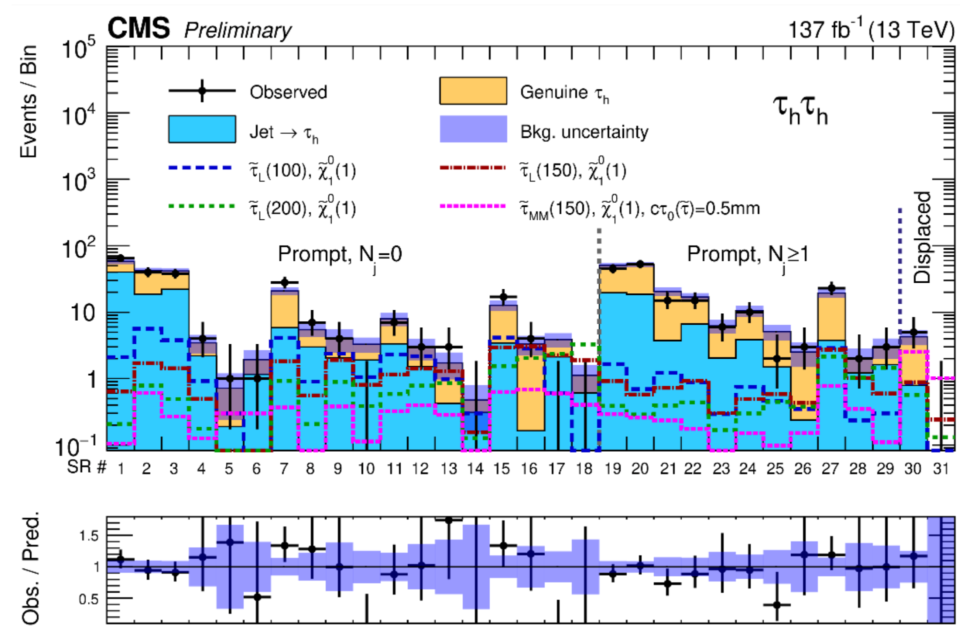


Hadronic taus @ CMS

Signature: 2 hadronic $\boldsymbol{\tau} + \boldsymbol{p_T^{miss}}$



- Interpretations:
  - Simplified model – LSP: $\tilde{\chi}_1^0$, LH/RH/mixture $\tilde{\tau}$
  - GMSB: Gravitino LSP: $\widetilde{gr}$, **long-lived** NLSP $\tilde{\tau}$
- Di-τ triggers @ low p_T^{miss}, p_T^{miss} triggers at high p_T^{miss}.
- 2τ passing DNN tau-ID, 0.06% mis-tag rate.
- Main 'real' bgs ($Z \to \tau\tau$) estimated with data-driven 'embedding':
  - Take 2μ data events -> replace μs with simulated τs.
  - Only need to consider τ syst. uncertainties ☺
- 'fake' bgs extrapolate from data in loose τ-ID region.
- Prompt-τ SRs binned in m_{T2}, $\sum m_T$, number of jets.
- Displaced- τ SRs require large impact-parameters



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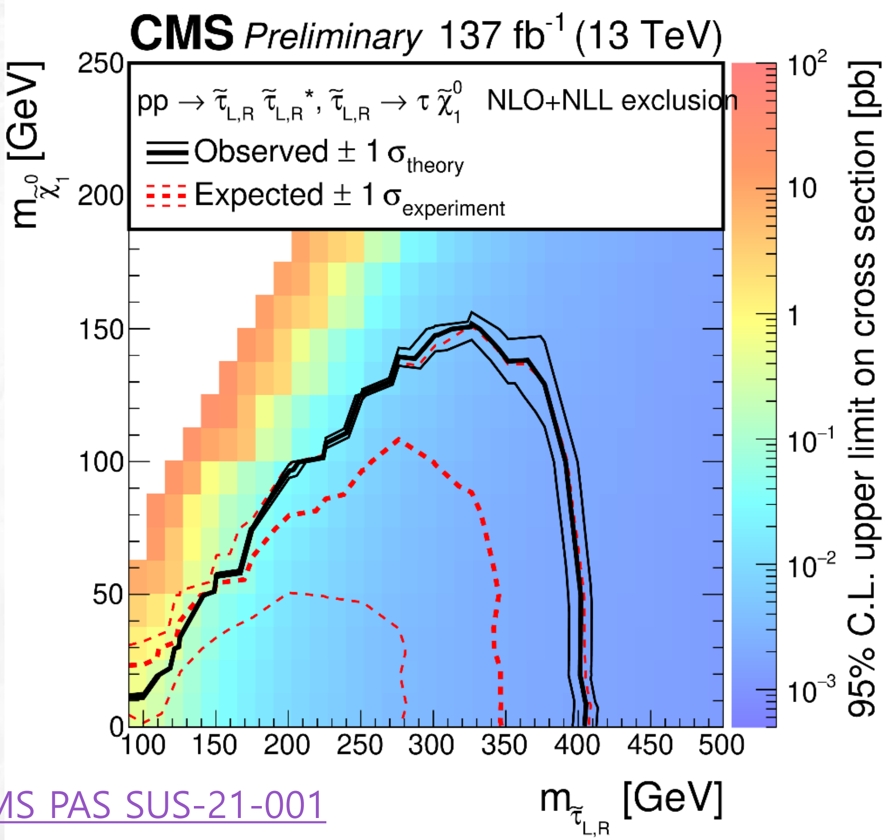
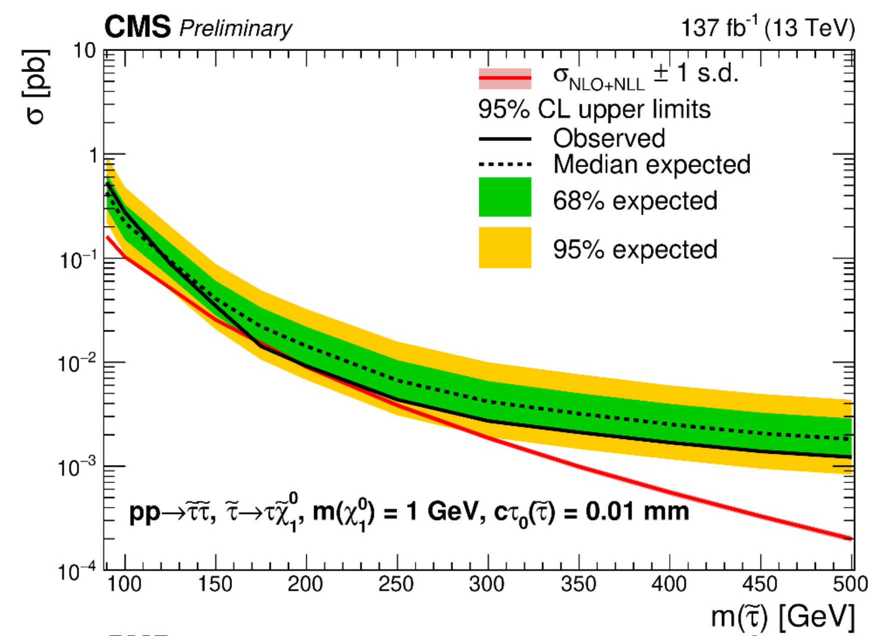
Hadronic taus Results

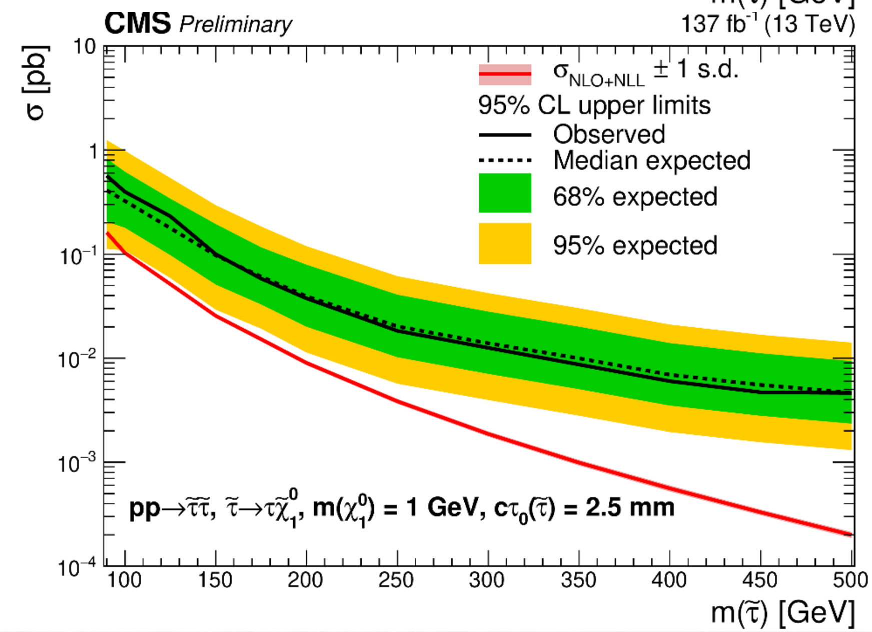
Corresponding ATLAS search

Limits on degenerate LH/RH staus here, LH or RH separately in paper

Long-lived stau limits set for different lifetimes @ $M(\tilde{\chi}_1^0) = 1$ GeV







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Hadronic taus regions and systs.

	Uncertainty [%]		
Source	Genuine τ_h	Misidentified τ_h	Signal
Statistical	8.3–141	5.0–100	6.3–52
τ_h ID efficiency	7.2–7.8	—	6.2–6.4
τ_h ID vs displacement	—	—	3.0
τ_h trigger efficiency	3.1–4.2	—	6.9–14
τ_h energy scale	0.1–35	—	1.6–44
τ_h misidentification rate	—	30–56	—
p_T^{miss} trigger efficiency	1.0	—	1.5
Embedded normalization	19	—	—
Embedded top quark fraction	1.0–3.8	—	—
Jet energy scale	—	—	0.7–32
Jet energy resolution	—	—	1.3–55
Unclustered energy	—	—	0.5–32
B–tagging	—	—	0.2–1.1
Pileup	—	—	1.0–28
Pre-fire	—	—	0.1–0.4
Integrated luminosity	—	—	1.8
ISR	—	—	0.1–16
Renormalization/factorization scale	—	—	0.4–3.6

Prompt SRs			
SR bin	Σm_T [GeV]	m_{T2} [GeV]	$p_T^{\tau_h 1}$ [GeV]
$N_j = 0$			
1	$200 - 250$	$25 - 50$	< 90
2	$200 - 250$	$25 - 50$	> 90
3	$200 - 250$	$50 - 75$	< 90
4	$200 - 250$	$50 - 75$	> 90
5	$200 - 250$	> 75	—
6	$250 - 300$	$25 - 50$	< 90
7	$250 - 300$	$25 - 50$	> 90
8	$250 - 300$	$50 - 75$	< 90
9	$250 - 300$	$50 - 75$	> 90
10	$250 - 300$	> 75	—
11	$300 - 350$	$25 - 50$	—
12	$300 - 350$	$50 - 75$	—
13	$300 - 350$	$75 - 100$	—
14	$300 - 350$	> 100	—
15	> 350	$25 - 50$	—
16	> 350	$50 - 75$	—
17	> 350	$75 - 100$	—
18	> 350	> 100	—
$N_j \geq 1$			
19	$200 - 250$	$25 - 50$	—
20	$200 - 250$	> 50	—
21	$250 - 300$	$25 - 50$	—
22	$250 - 300$	$50 - 75$	—
23	$250 - 300$	> 75	—
24	$300 - 350$	$25 - 50$	—
25	$300 - 350$	$50 - 75$	—
26	$300 - 350$	> 75	—
27	> 350	$25 - 75$	—
28	> 350	$75 - 100$	—
29	> 350	> 100	—
Displaced SRs			
SR bin	$p_T^{\tau_h 2}$ [GeV]		
30	< 110		
31	> 110		

Hadronic taus results