Searches for electroweak SUSY production with the full CMS Run II sample

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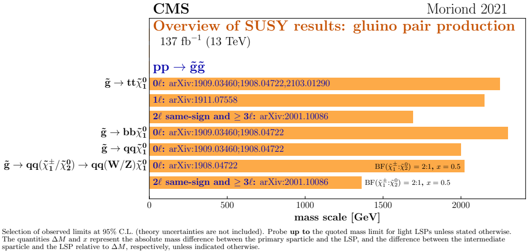
Electroweak SUSY introduction

- Why should SUSY be electroweak?
  - Limits on coloured gauginos and sparticles stringent
  - Coannihilation scenarios of EW gauginos or sleptons cosmologically tempting, though often compressed



- General motivations for SUSY:
  - Lightest stable particle (LSP) consistent with observed relic dark matter when R-parity conserved
  - Amendments to the hierarchy problem
- All analyses covered use $\mathcal{L}^{-1}$ =137 fb^{-1} corresponding to the full Run 2 sample at $\sqrt{s} = 13$ TeV

Electroweak Run 2 combination

CMS Run2 electroweak combination SUS-21-008		
Compressed	Intermediate	High mass
SUS-18-004 2 or 3 ℓ (soft)	SUS-20-001 2 ℓ on-Z & 2 ℓ non-resonant	SUS-21-002 W+[W,Z,H] hadronic (boosted)
SUS-19-012 2 ℓ (SS) & $\geq 3\ell$	SUS-20-003 1 ℓ and 2b (resolved or boosted)	SUS-20-004 4b (resolved or boosted)

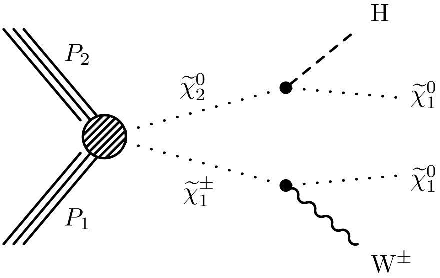
- Table summarizes channels of the combination paper relevant to EW parameter space, only
- Overlaps between signal regions have been accounted for
- Improvements on the parametric signal extraction have been made
- 2 or 3 ℓ (soft) optimized binning for each compressed scenario

Combination signal contribution overview

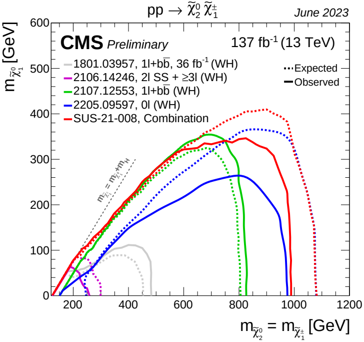
	gaugino		GMSB			higgsino-bino			sleptons
Search	WZ	WH	ZZ	HZ	HH	WW	HH	WH	$\ell^+\ell^-$
$2/3\ell$ soft [17]	all								2ℓ soft
2ℓ on-Z [15]	EW		EW	EW					
2ℓ non-res. [15]									Slepton
$\geq 3\ell$ [18]	SS, A(NN)	SS, A–F	all	all	all			SS, A–F	
1ℓ2b [16]		all						all	
4b [19]					all		3-b, 4-b, 2-bb		
Hadr. WX [20]	all	b-tag				b-veto		b-tag	

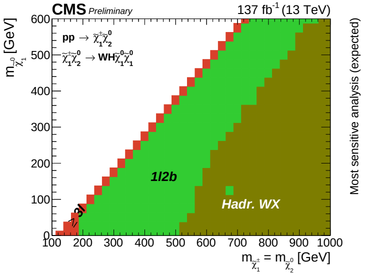
- Various models considered for interpretation
- Individual channels assigned for combination to where they have reach
- When possible, highest contributing channel per parameter space point will be indicated

Gaugino WH: $\tilde{\chi}_1^\pm \rightarrow W^\pm$ and $\tilde{\chi}_2^0 \rightarrow H$

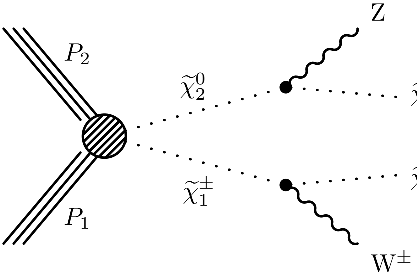


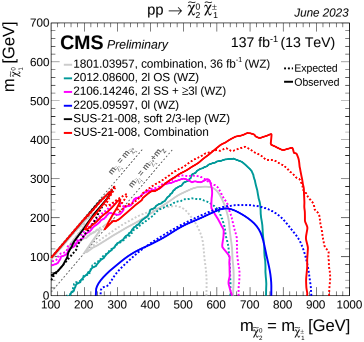
- Complementarity of decay channels improves reach
- WH and later WZ model are of the Wino-Bino type
- Boosted hadronic channels dominate high-mass exclusion

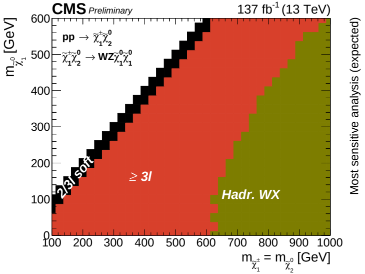




Gaugino WZ: $\tilde{\chi}_1^\pm \to W^\pm$ and $\tilde{\chi}_2^0 \to Z$

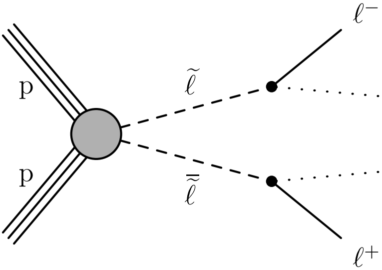


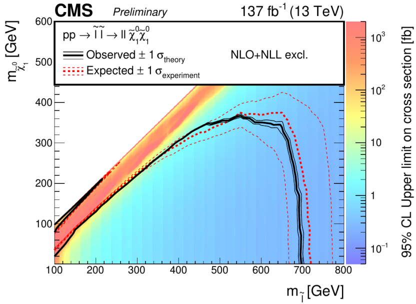


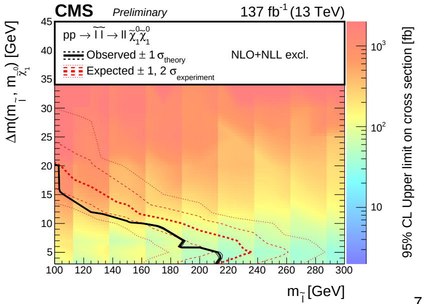


- Soft lepton reconstruction challenging
- 2/3l soft: dedicated soft multilepton trigger
- Combining SS+OS and ℓ multiplicities improves mass reach and off-shell Z corridor

Direct slepton pair production

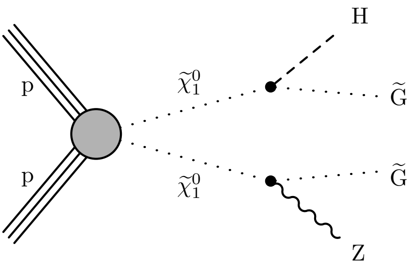


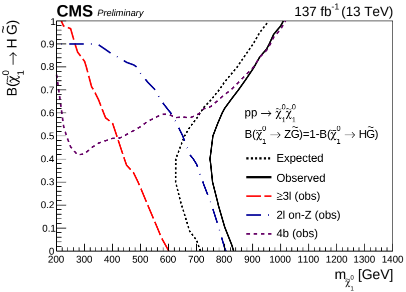


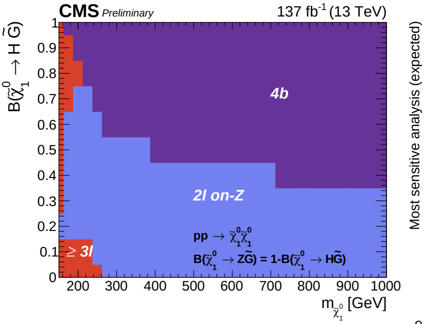


- Slepton masses of 210 GeV at mass splittings of 3 GeV can be achieved in the compressed edge in the combination
- 2 ℓ soft dominates compressed section
- 2 ℓ non-resonant drives high mass exclusion power

GMSB neutralino pair production

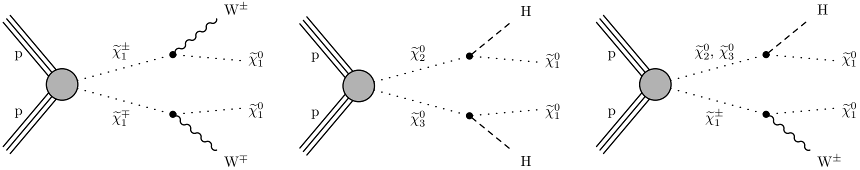




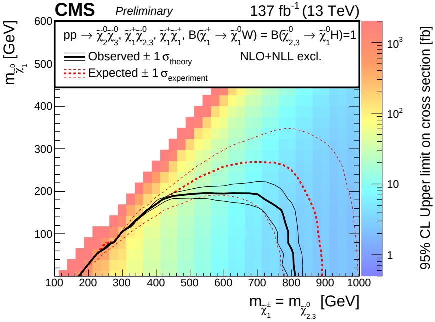


- In case the Gravitino is the LSP in GMSB models, direct neutralino production can be probed
- Sensitivity depends here on the Higgsino vs Bino nature
- Combination improves the equal branching ratios scenario

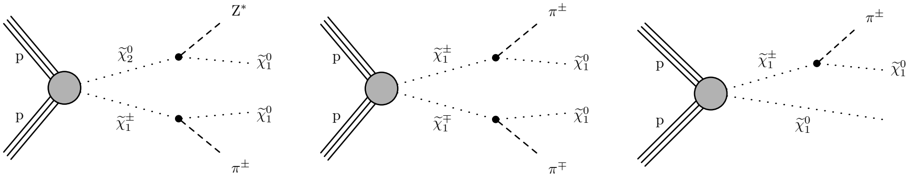
Higgsino-bino interpretation



- χ_1^0 stays LSP, but in context of mass-degenerate Higgsino triplet
- Considering WW, HH, and WH final states
- $\geq 3\ell$, $1\ell 2b$, 4b, and W+[W,Z,H] contribute
- Best reach towards higher mass splittings

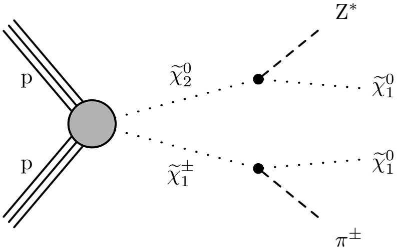


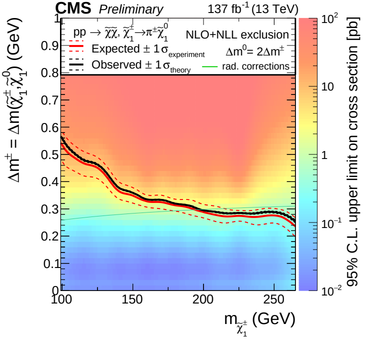
Disappearing track search - electroweak results



- PAS-SUS-21-006 uses disappearing tracks of long-lived charginos with Δ m of $\mathcal{O}$(100 MeV)
- This leads to decays into pions or an off-shell Z boson inside of the tracker
- Search for one ($\geq$ two) disappearing track(s), at least one jet
- Aided by machine-learning-based classifier for genuine disappearing tracks
- Conducted in hadronic and leptonic search categories

Very compressed EW limits from disappearing tracks

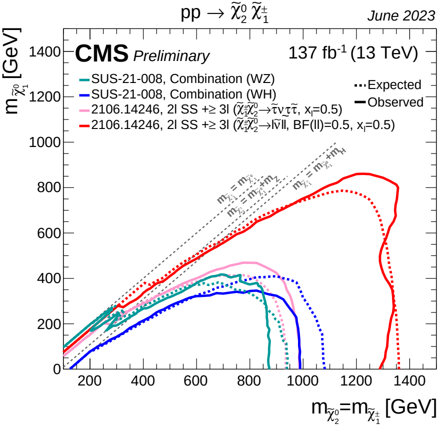




- Limits set on pure Higgsino dark matter model (predictions indicated by green line)
- Mass splitting given by radiative corrections only
- Chargino and LSP masses can be excluded up to 200 GeV

Summary

- Electroweak SUSY is being hunted in every corner CMS can access
- A combination of electroweak analyses and their combined results for winos, binos, higgsinos, and sleptons was presented. The complimentarity between search channels and their parameter spaces drives improvements in limit setting, even without new data
- Results on Higgsino dark matter in disappearing tracks was presented, setting limits in extremely compressed scenarios



SUS-18-004 SR definitions

Variable	2ℓ-Ewk		2ℓ-Stop		3ℓ-Ewk	
	Low-MET	Higher-MET	Low-MET	Higher-MET	Low-MET	Higher-MET
N_{lep}	2	2	2	2	3	3
$p_{\text{T}}(\ell_1)$ [GeV] for e(μ)	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$
$p_{\text{T}}(\ell_2)$ [GeV] for e(μ)	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$
$p_{\text{T}}(\ell_3)$ [GeV] for e(μ)	—	—	—	—	$(5, 30)$	$(5(3.5), 30)$
1 OS pair	✓	✓	✓	✓	✓	✓
1 OSSF pair	✓	✓	✓	—	✓	✓
$\Delta R(\ell_i \ell_j)$ $(i, j = 1, 2, 3, i \neq j)$	—	> 0.3	—	> 0.3	—	> 0.3
$M_{\text{SFOS}}(\ell\ell)$ ($M^{\text{min}}_{\text{SFOS}}(\ell\ell)$ in 3ℓ) [GeV]	$(4, 50)$	$(1, 50)$	$(4, 50)$	$(1, 50)$	$(4, 50)$	$(1, 50)$
$M^{\text{max}}_{\text{SFAS}}(\ell\ell)$ (AS=any sign) [GeV]	—	—	—	—	< 60	—
$M_{\text{SFOS}}(\ell\ell)$ ($M^{\text{min}}_{\text{SFOS}}(\ell\ell)$ in 3ℓ) [GeV]	veto $(3, 3.2)$ and $(9, 10.5)$					
$p_{\text{T}}(\ell\ell)$ [GeV]	> 3		> 3		—	
Leading jet "Tight lepton veto"	✓		✓		—	
$m_{\text{T}}(\ell_i, p_{\text{T}}^{\text{miss}})$ [GeV] $(i = 1, 2)$	< 70		—		—	
H_{T} [GeV]	> 100					
$p_{\text{T}}^{\text{miss}} / H_{\text{T}}$	$(2/3, 1.4)$		$(2/3, 1.4)$		—	
$\text{N}_b(p_{\text{T}} > 25\,\text{GeV})$	$= 0$					
$M_{\tau\tau}$ [GeV]	veto $(0, 160)$		veto $(0, 160)$		—	

SUS-19-012 SR definitions Part 1

Category	Requirements
2ℓSS	Two light leptons with the same sign
3ℓA	Three light leptons including one or more OSSF pairs
3ℓB	Three light leptons including no OSSF pairs
3ℓC	A pair of light leptons forming an OSSF pair and a τ_h candidate
3ℓD	A pair of light leptons of different flavor and opposite sign and a τ_h candidate
3ℓE	A pair of light leptons of same sign and a τ_h candidate
3ℓF	A light lepton and two τ_h candidates
4ℓG	Four light leptons including two independent OSSF pairs
4ℓH	Four light leptons including one or less OSSF pairs
4ℓI	Three light leptons and a τ_h candidate
4ℓJ	Two light leptons and two τ_h candidates, including two OSSF pairs
4ℓK	Two light leptons and two τ_h candidates, including one or no OSSF pair

3ℓA : three light leptons with at least one OSSF pair, $75 < M_{\ell\ell} < 105$ **GeV**

M_T (GeV)	$p_\mathrm{T}^\mathrm{miss}$ (GeV)	$H_\mathrm{T} < 100$ GeV	$100 \leq H_\mathrm{T} < 200$ GeV	$H_\mathrm{T} \geq 200$ GeV
0–100	50–100	A23	A36	A49
	100–150	A24	A37	
	150–200	A25	A38	A50
	200–250	A26	A39	
	250–350	A27	A40	A51
	≥350			A52
100–160	50–100	A28	A41	A53
	100–150	A29	A42	A54
	150–200	A30	A43	A55
	200–250	A31	A44	A56
	250–300			A57
	≥300			A58
≥160	50–100	A32	A45	A59
	100–150	A33	A46	A60
	150–200	A34	A47	A61
	200–250	A35	A48	A62
	250–300			A63
	≥300			A64

2ℓSS : two light leptons of the same sign

$M_\mathrm{T2}(\ell\ell)$ (GeV)	$p_\mathrm{T}(\ell\ell)$ (GeV)	$60 < p_\mathrm{T}^\mathrm{miss} < 100$ GeV	$100 \leq p_\mathrm{T}^\mathrm{miss} < 200$ GeV	$p_\mathrm{T}^\mathrm{miss} \geq 200$ GeV
0	<70	SS01		
	≥70	SS02	SS03 (++)	SS05 (++)
			SS04 (−−)	SS06 (−−)
0–80	<30	SS07 (++)		SS09
		SS08 (−−)		
	≥30	SS10		
> 80	<200	SS11	SS12 (++)	SS14 (++)
			SS13 (−−)	SS15 (−−)
	≥200	SS16	SS17 (++)	SS19 (++)
			SS18 (−−)	SS20 (−−)

3ℓB: three light leptons without an OSSF pair

$\min(\Delta R(\ell,\ell)) < 0.4$	$0.4 \leq \min(\Delta R(\ell,\ell)) < 1$	$\min(\Delta R(\ell,\ell)) \geq 1$
B01	B02	B03

3ℓC: $\mu^+\mu^-$ **or** e^+e^- **+** τ_h

$p_\mathrm{T}^\mathrm{miss}$ (GeV)	$M_\mathrm{T}^{2\ell}$ (GeV)	$M_\mathrm{T2} < 80$ GeV	$80 \leq M_\mathrm{T2} < 120$ GeV	$M_\mathrm{T2} \geq 120$ GeV
50–200	≥0	C01	C02	C03
200–300	≥0	C04	C05	C06
≥300	0–250	C07		
	250–500	C08		
	≥500	C09		

3ℓD: $e^\pm\mu^\mp$ **+** τ_h

$M_\mathrm{T2}(\ell\ell)$ (GeV)	$p_\mathrm{T}^\mathrm{miss}$ (GeV)	$M_{\ell\ell} < 60$ GeV	$60 \leq M_{\ell\ell} < 100$ GeV	$M_{\ell\ell} \geq 100$ GeV
0–100	50–100	D01	D06	D11
	100–150	D02	D07	D12
	150–200	D03	D08	D13
	200–250	D04	D09	D14
	≥250	D05	D10	
≥100	50–200	D15		
	≥200	D16		

SUS-19-012 SR definitions Part 2

3ℓE: same-sign light lepton pair + τ_h

<table>
<tr><th>$M_{T2}(\ell, \tau_h)$ (GeV)</th><th>p_T^{miss} (GeV)</th><th>$M_{\ell\tau_h} \leq 50$ GeV</th><th>$50 < M_{\ell\tau_h} \leq 100$ GeV</th><th>$M_{\ell\tau_h} > 100$ GeV</th></tr>
<tr><td rowspan="3">0–80</td><td>50–100</td><td>E01</td><td colspan="2">E04</td></tr>
<tr><td>100–250</td><td>E02</td><td colspan="2" rowspan="2">E05</td></tr>
<tr><td>≥250</td><td>E03</td></tr>
<tr><td rowspan="3">≥80</td><td>50–150</td><td colspan="2">E06</td><td rowspan="2">E08</td></tr>
<tr><td>150–200</td><td colspan="2" rowspan="2">E07</td></tr>
<tr><td>≥200</td><td>E09</td></tr>
</table>

4ℓG: 4 light leptons with 2 separate OSSF pairs

<table>
<tr><th>$M_{T2}(ZZ)$ (GeV)</th><th>$M_{Z2} \geq 60$ GeV</th><th>$M_{Z2} < 60$ GeV</th></tr>
<tr><td>0–150</td><td colspan="2">G01</td></tr>
<tr><td>150–250</td><td>G02</td><td>G03</td></tr>
<tr><td>250–400</td><td colspan="2">G04</td></tr>
<tr><td>≥400</td><td colspan="2">G05</td></tr>
</table>

3ℓF: $2\tau_h$ + light lepton

<table>
<tr><th>$M_{T2}(\ell, \tau_h)$ (GeV)</th><th>p_T^{miss} (GeV)</th><th>$M_{\ell\tau_h} < 100$ GeV</th><th>$M_{\ell\tau_h} \geq 100$ GeV</th></tr>
<tr><td rowspan="6">0–100</td><td>50–100</td><td>F01</td><td>F07</td></tr>
<tr><td>100–150</td><td>F02</td><td>F08</td></tr>
<tr><td>150–200</td><td>F03</td><td>F09</td></tr>
<tr><td>200–250</td><td>F04</td><td rowspan="3">F10</td></tr>
<tr><td>250–300</td><td>F05</td></tr>
<tr><td>≥300</td><td>F06</td></tr>
<tr><td rowspan="2">≥100</td><td>50–200</td><td colspan="2">F11</td></tr>
<tr><td>≥200</td><td colspan="2">F12</td></tr>
</table>

4ℓH-K : 4 leptons with one or more τ_h or without two light-lepton OSSF pairs

<table>
<tr><th>M_{Z1} (GeV)</th><th>$\Delta R^H < 0.8$</th><th>$\Delta R^H \geq 0.8$</th></tr>
<tr><td>0–60</td><td rowspan="2">X03</td><td>X02</td></tr>
<tr><td>>60</td><td>X01</td></tr>
</table>

SUS-20-001 SR definitions

Strong-production on-Z search sample ($86 < m_{\ell\ell} < 96$ GeV)

Region	n_{j}	n_{b}	H_{T} [GeV]	$M_{T2}(\ell\ell)$ [GeV]	p_{T}^{miss} bins [GeV]
SRA b veto	2–3	$=0$	>500	>80	$[100, 150, 230, 300, \infty)$
SRB b veto	4–5	$=0$	>500	>80	$[100, 150, 230, 300, \infty)$
SRC b veto	>5	$=0$	—	>80	$[100, 150, 250, \infty)$
SRA b tag	2–3	>0	>200	>100	$[100, 150, 230, 300, \infty)$
SRB b tag	4–5	>0	>200	>100	$[100, 150, 230, 300, \infty)$
SRC b tag	>5	>0	—	>100	$[100, 150, 250, \infty)$

EW-production on-Z search sample ($86 < m_{\ell\ell} < 96$ GeV)

Region	n_{j} ($n_{V}^{boosted}$)	n_{b}	Dijet mass [GeV]	M_{T2} [GeV]	p_{T}^{miss} bins [GeV]
Boosted VZ	<2 (>0)	$=0$	—	—	$[100, 200, 300, 400, 500, \infty)$
Resolved VZ	>1	$=0$	$m_{jj} < 110$	$M_{T2}(\ell\ell) > 80$	$[100, 150, 250, 350, \infty)$
HZ	>1	$=2$	$m_{bb} < 150$	$M_{T2}(\ell b \ell b) > 200$	$[100, 150, 250, \infty)$

Edge search sample ($20 < m_{\ell\ell} < 86$ or $m_{\ell\ell} > 96$ GeV)

Region	n_{j}	n_{b}	$M_{T2}(\ell\ell)$ [GeV]	p_{T}^{miss} [GeV]	$m_{\ell\ell}$ bins [GeV]
Edge fit	> 1	—	>80	>200	>20
b veto	> 1	$=0$	>80	>150	$[20, 60, 86]+[96, 150, 200, 300, 400, \infty)$
b tag	> 1	>0	>80	>150	$[20, 60, 86]+[96, 150, 200, 300, 400, \infty)$

Slepton search sample ($20 < m_{\ell\ell} < 65$ or $m_{\ell\ell} > 120$ GeV)

Region	n_{j}	n_{b}	$p_{T}^{\ell_2} / p_{T}^{j_1}$	M_{T2} [GeV]	p_{T}^{miss} bins [GeV]
Slepton jet-less	$=0$	$=0$	—	$M_{T2}(\ell\ell) >100$	$[100, 150, 225, 300, \infty)$
Slepton with jets	>0	$=0$	>1.2	$M_{T2}(\ell\ell) >100$	$[100, 150, 225, 300, \infty)$

SUS-20-003 SR definitions

Lepton	$\ell = \mu(\mathrm{e})$ with $p_T^\ell > 25(30)$ GeV, $\lvert\eta^\ell\rvert < 2.1$ (1.44)
	$p_T^{sum} < 0.1\, p_T^\ell$, $p_T^{sum} < 5$ GeV
Veto lepton	μ or e with $p_T^\ell > 5$ GeV, $\lvert\eta^\ell\rvert < 2.4$
	$p_T^{sum} < 0.2\, p_T^\ell$
Veto track	charged PF candidate, $p_T > 10$ GeV, $\lvert\eta\rvert < 2.4$
	$p_T^{sum} < 0.1\, p_T$, $p_T^{sum} < 6$ GeV
Veto τ_h	hadronic τ_h with $p_T > 10$ GeV, $\lvert\eta\rvert < 2.4$
	τ_h MVA isolation
Jets	anti-k_T jets, $R = 0.4$, $p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$
	anti-k_T jets, $R = 0.8$, $p_T > 250$ GeV, $\lvert\eta\rvert < 2.4$
b tagging	DEEPCSV algorithm (1% misidentification rate)
H tagging	mass-decorrelated H tagging discriminator
p_T^{sum} cone size	ℓ relative isolation: $\Delta R = \min[\max(0.05, 10\,\mathrm{GeV}/p_T^\ell), 0.2]$
	veto track, and ℓ absolute isolation: $\Delta R = 0.3$

$p_T^{miss} > 120$ GeV and $H_T^{miss} > 120$ GeV (2016–2018)

$p_T^{miss} > 170$ GeV (2016)

Isolated $\mu(\mathrm{e})$ with $p_T^\ell > 24\,(25)$ GeV (2016)

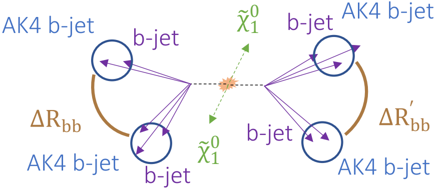
Isolated $\mu(\mathrm{e})$ with $p_T^\ell > 24\,(35)$ GeV (2017–2018)

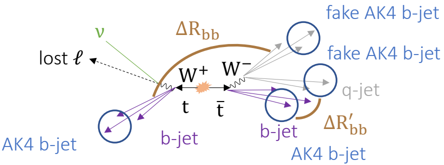
Lepton	Single e or μ and no additional veto lepton, track or tau
Small-R jets	$2 \le N_{jets} \le 3$, $N_b = 2$, $p_T^{non\text{-}b} < 300$ GeV
p_T^{miss}	>125 GeV
$m_{b\bar{b}}$	90–150 GeV
m_T	>150 GeV
m_{CT}	>200 GeV

N_H	N_{jets}	p_T^{miss} [GeV]
0	2, 3	[125, 200), [200, 300), [300, 400), [400, ∞)
1	2, 3	[125, 300), [300, ∞)

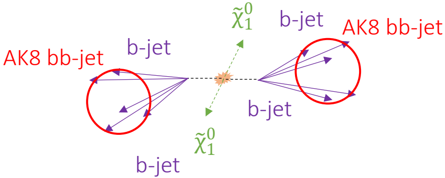
SUS-20-004 signal topologies

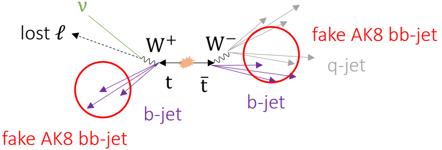
resolved topology





boosted topology





SUS-21-002 SR definitions

Region	Requirements
b-veto SR	$\geq$1 V-tagged jet $\geq$1 W-tagged jet $\geq$2 V- or W-tagged jets
b-veto 0-tag CR	0 V-tagged jets 0 W-tagged jets
b-veto 1-tag CR	1 V-tagged jet 0 other W-tagged jets

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