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Search for Electroweak SUSY in Hadronic Final States with the CMS Detector

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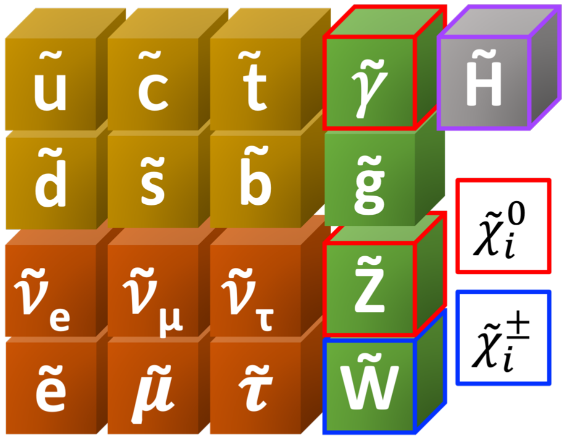
Overview

- Electroweak SUSY
- Hadronic Final States
- Heavy Flavor Tagging
- WX + MET Search
- HH + MET Search
- WH + MET Search
- Conclusions & Outlook

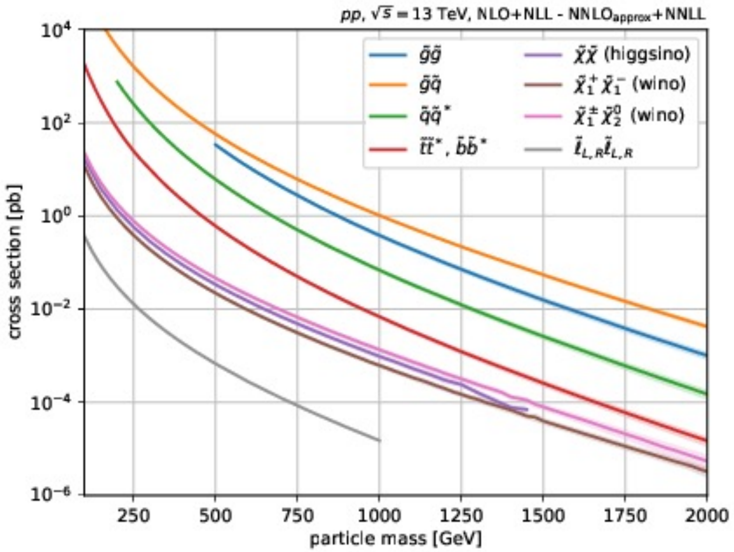
Electroweak Supersymmetry

Motivation: Sensitivity to electroweakino production can offer valuable insight in key search regions left for testing natural SUSY



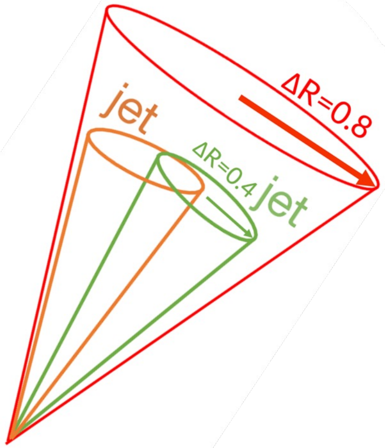
chargino and neutralino:
mixed states of higgsino and EW gauginos

- Smaller cross-sections for electroweak (EW) SUSY have led to less exploration of this phase space
- Stringent limits on strong production at TeV scale leave open promising unconstrained regions for EW searches
- Full CMS Run 2 dataset with 137 fb^{-1} at 13 TeV can significantly extend previous reach



Hadronic Final States

- Detector signature of signal decay is identified jet objects from bosons + missing energy (MET or p_T^{miss}) from neutralinos
- Improvements in heavy flavor tagging improve EW search sensitivity – new ML algorithms have great performance
  - DeepCSV identifies b-tagged single-parton (AK4) jets
  - DeepAK8 and DeepDoubleB identify large-radius (AK8) jets from merged-jet daughters for H / W / Z bosons



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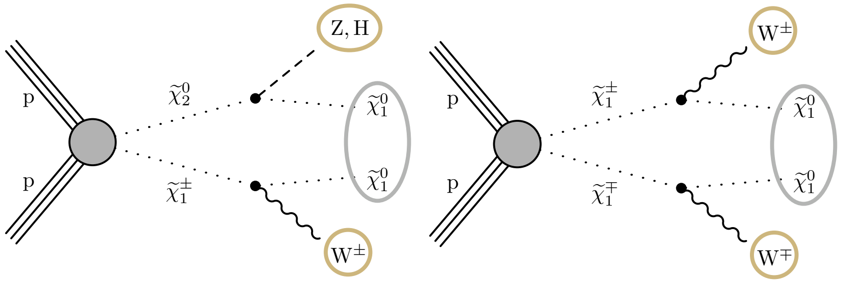

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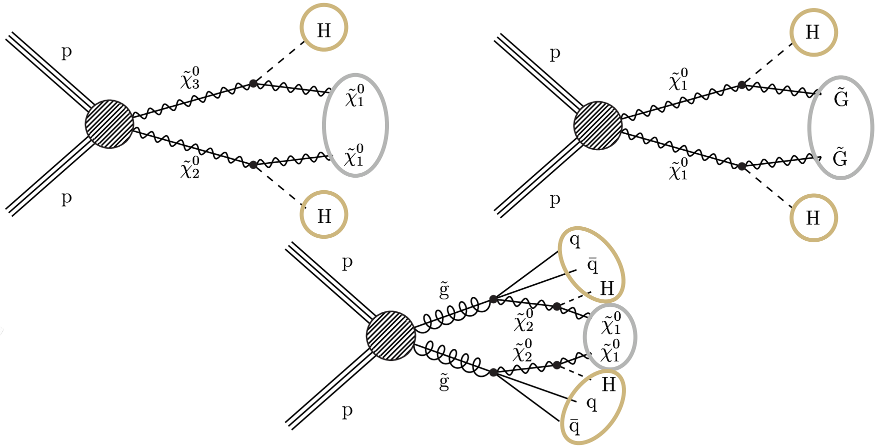

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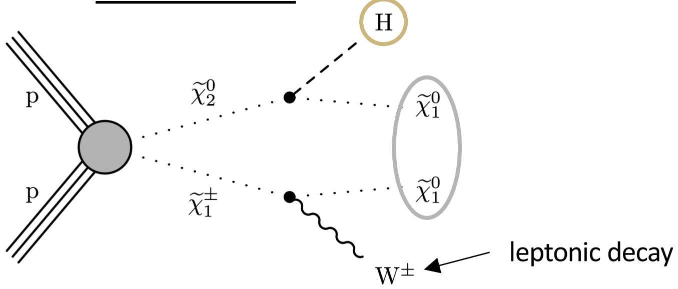
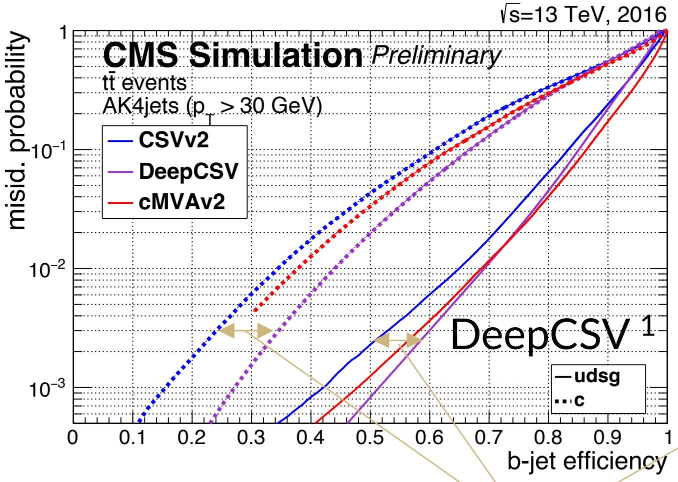
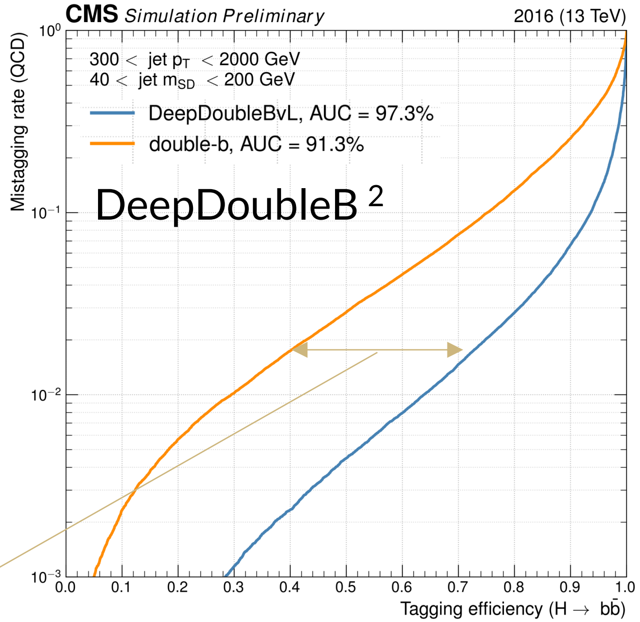


Heavy Flavor Tagging

- DeepCSV Algorithm – b-tagging
  - 6-layer, 100-node DNN
  - Extension of CSVv2 tagger
  - Additional charged particle tracks - NEW
- DeepDoubleB (DDBvL) – H-tagging
  - Inputs:
    - 27 from jet objects
    - 8 from charged Particle Flow (PF) constituents + 2 from associated Secondary Vertices (SVs) - NEW
  - PF and vertex inputs handled separately, then fed through 50 dense layers with track inputs
- DeepAK8 (+ Mass Decorrelation) – H/W/Z-tagging
  - Use of jet substructure and flavor signatures - NEW
  - Inputs: up to 100 PF candidates + up to 5 SVs
  - PFs and SVs processed in separate 1D CNNs, then combined in fully connected layer
  - Adversarial training used to decorrelate mass



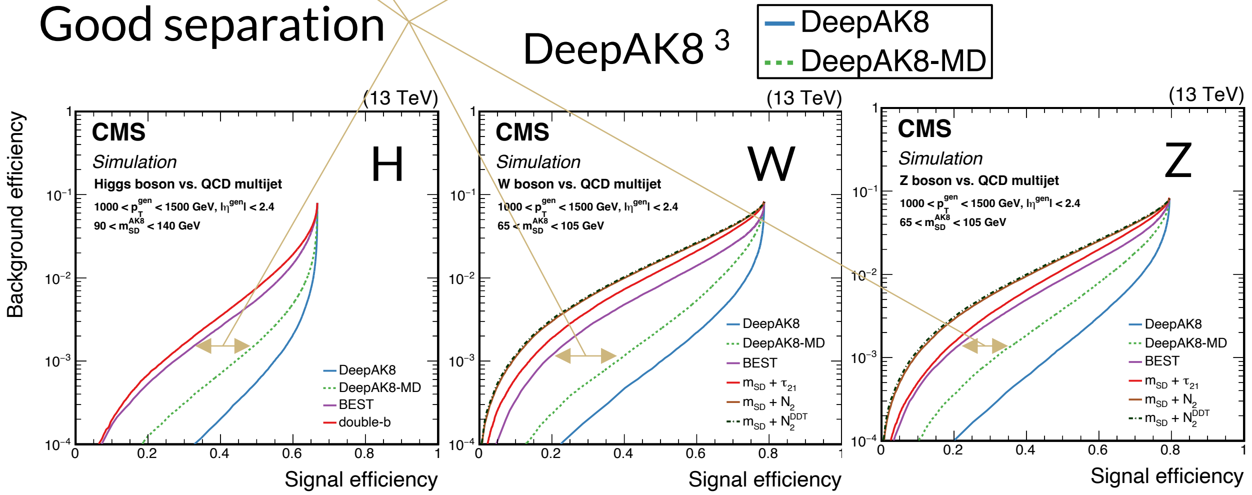
DeepCSV [1]



DeepDoubleB [2]

Good separation

DeepAK8 [3]



1) https://twiki.cern.ch/twiki/bin/view/CMSPublic/BTV13TeVDPDeepCSV

2) http://cms-results.web.cern.ch/cms-results/public-results/publications/JME-18-002/

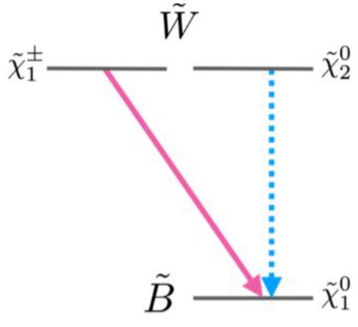
3) https://twiki.cern.ch/twiki/bin/view/CMSPublic/BTV13TeVDDBDDC

WX + MET Search [1]

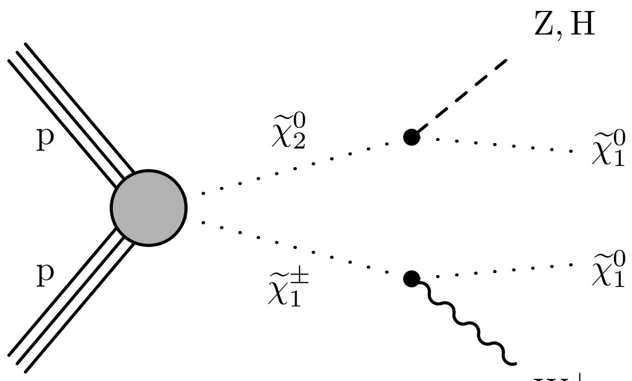
WX Search: Signal Models

- Direct Electroweakino Production
  - Wino-like ($\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\widetilde{W}$) or higgsino-like ($\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ /$\tilde{\chi}_3^0$) NLSP, bino-like LSP ($\tilde{\chi}_1^0/\tilde{B}$)
  - Larger NLSP-LSP mass difference ⇒ high p_T LSP ⇒ high p_T^{miss}
  - Larger m_{NLSP} ⇒ high p_T H/W/Z ⇒ taggable boosted AK8 jets
  - Extends leptonic search phase space

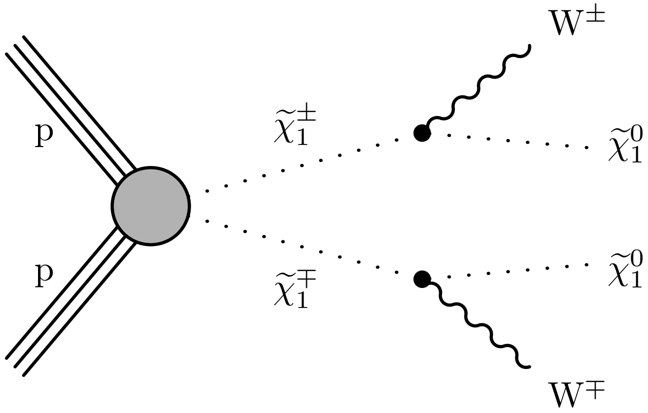
Wino-like Interpretation



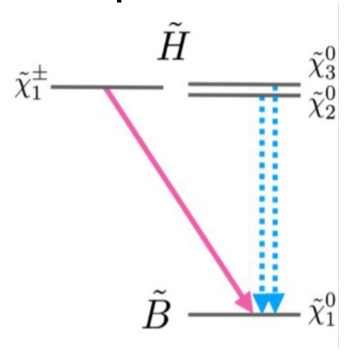
TChiWZ, TChiWH



TChiWW



Higgsino-like Interpretation



WX Search: Event Selection

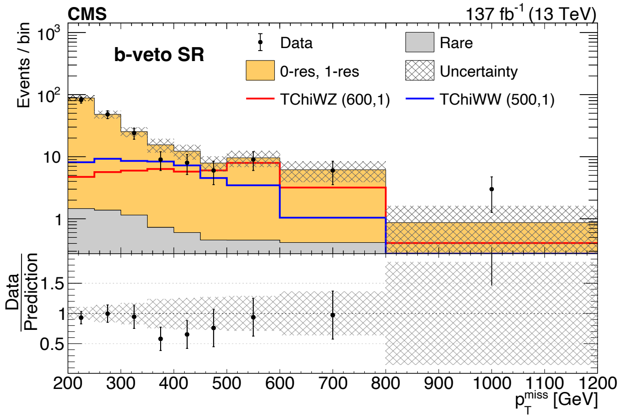
- Baseline Selection
  - High p_T^{miss} and H_T required for desired phase space
  - Lepton vetos reject major leptonic W decay background
  - DeepAK8 and DeepCSV tagger cuts on AK8 and AK4 jets

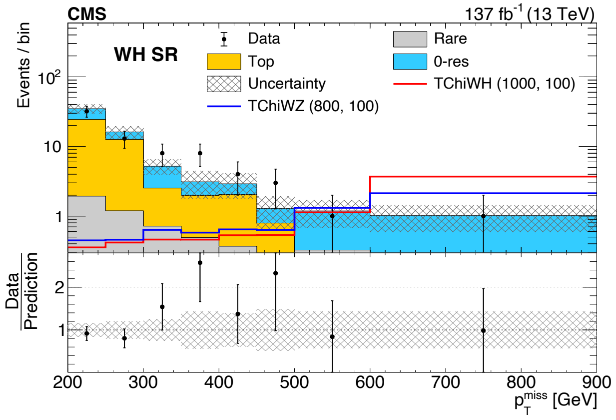
Baseline Event Selection

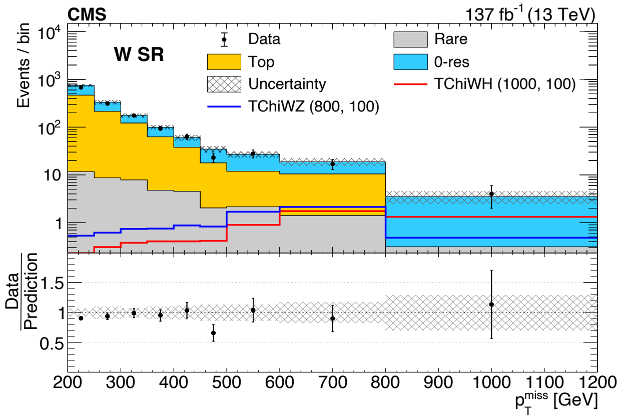
Lepton	Iso lepton veto + iso photon veto + iso track veto
p_T^{miss}	> 200 GeV
H_T	> 300 GeV
N_{AK8}	≥ 2, ($p_T > 300$ GeV, $\lvert\eta\rvert < 2.0$)
N_{AK4}	2 - 4 ($p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$, med. WP DeepCSV b-tag)

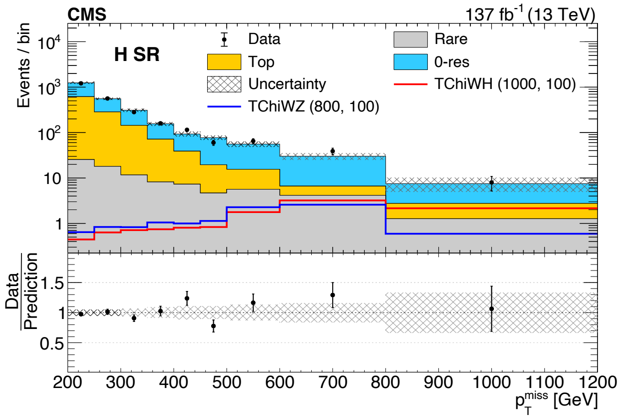
Signal Regions

Region	Requirements*
b-veto SR (TChiWW & TChiWZ)	≥ 1 V-tagged jet & ≥ 1 W-tagged jet & ≥ 2 V- or W-tagged jets
b-tag WH SR (TChiWH & TChiWZ)	≥ 1 W-tagged jet & ≥ 1 bb-tagged jet
b-tag W SR (TChiWH & TChiWZ)	≥ 1 W-tagged jet & 0 bb-tagged jet
b-tag H SR (TChiWH & TChiWZ)	0 W-tagged jet & ≥ 1 bb-tagged jet





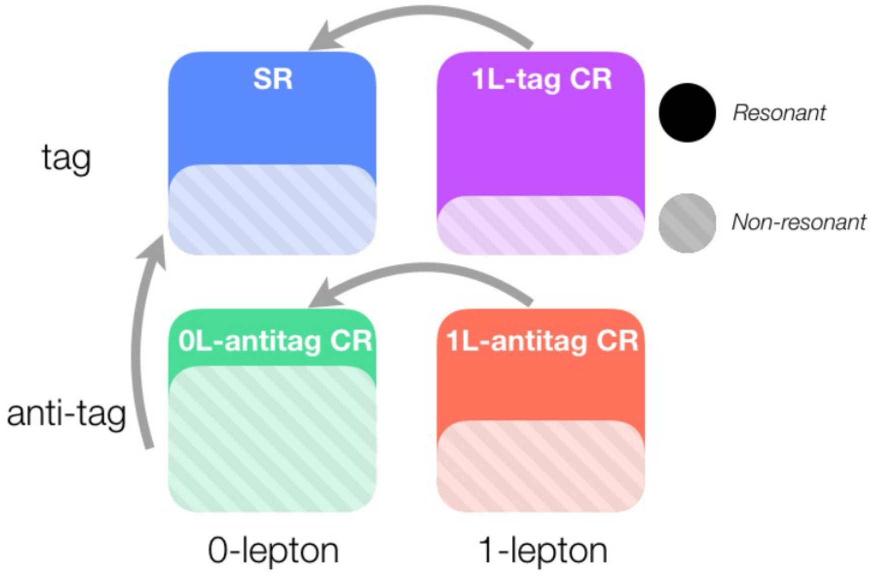




* tagged jets also require soft-drop mass window

WX Search: Search Strategy

- Data-driven background estimation split into 2 categories for b-tag signals
  - Resonant Hadronic W Background
    - $t\bar{t}$, single t, and $t\bar{t}H$ - contains real signal-like W peak
    - Derived in 1ℓ data CR due to missed-ℓ W decays in SR
  - Non-Resonant Background
    - $W\rightarrow\ell\nu$, $Z\rightarrow\nu\nu$, and QCD - BG from fake W-tagged objects
    - Derived in anti-tag data CR, using known fake W-tag rate
- 2 categories for b-veto SR prediction
  - Fake Hadronic W background (0+1 resonance) estimated from 0-tag and 1-tag CR
  - 2 real Hadronic boson background from tri-boson events derived from MC



In b-tag region, resonant BG (solid) in SR estimated from 1ℓ CR, non-resonant BG (hashed) in SR estimated from 0ℓ anti-tag CR

<u>b-tag SRs</u>

$$N^{\mathrm{data}}_{0\ell,\mathrm{res}} = \left(N^{\mathrm{MC}}_{0\ell,\mathrm{res}}/N^{\mathrm{MC}}_{1\ell,\mathrm{all}}\right) \times N^{\mathrm{data}}_{1\ell}$$

$$N^{\mathrm{pred}}_{\mathrm{non-res}} = \frac{N^{\mathrm{MC}}_{\mathrm{tag}}}{N^{\mathrm{MC}}_{\mathrm{!tag}}}\left(N^{\mathrm{data},0\ell}_{\mathrm{!tag}} - N^{\mathrm{pred}}_{\mathrm{!tag,res}} - N^{\mathrm{MC}}_{\mathrm{!tag,rare}}\right) \times \mathrm{SF}_{\mathrm{pass/fail}}$$

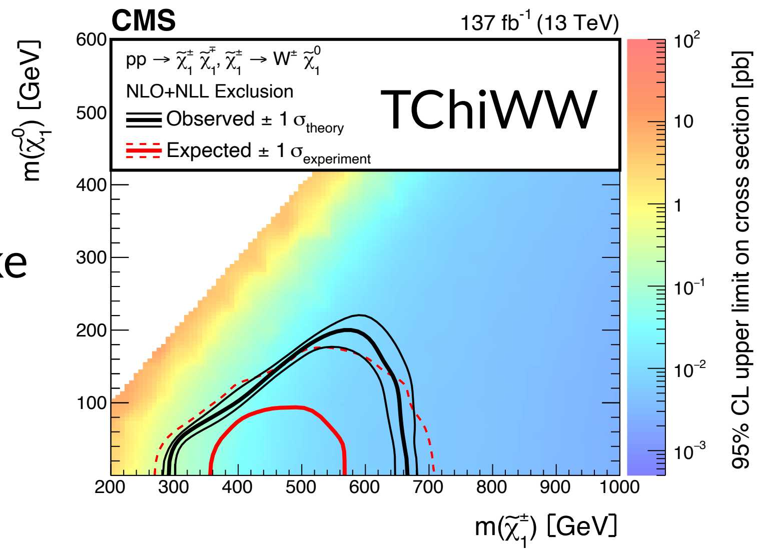
<u>b-veto SR</u>

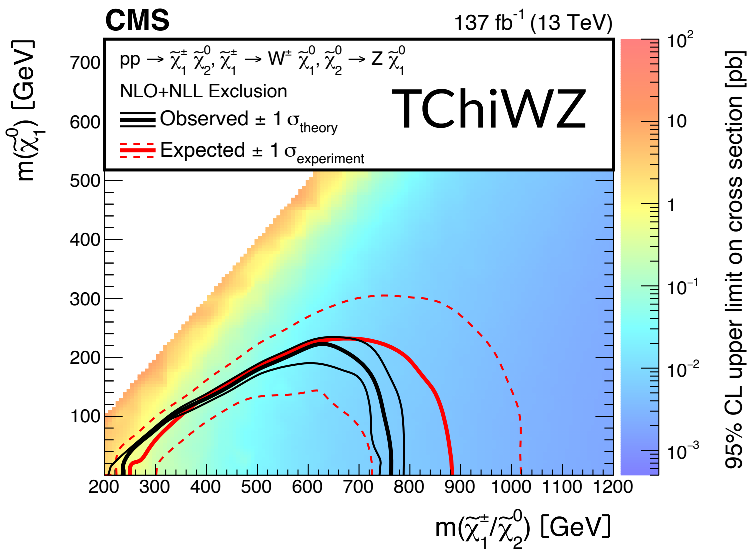
$$N^{\mathrm{data}}_{SR} = \frac{N^{\mathrm{MC}}_{SR,0\&1-\mathrm{res}}}{N^{\mathrm{MC}}_{CR,0\&1-\mathrm{res}}}\left(N^{\mathrm{data}}_{\mathrm{CR}}/N^{\mathrm{MC}}_{\mathrm{CR,2-res}}\right) + N^{\mathrm{MC}}_{\mathrm{SR,2-res}}$$

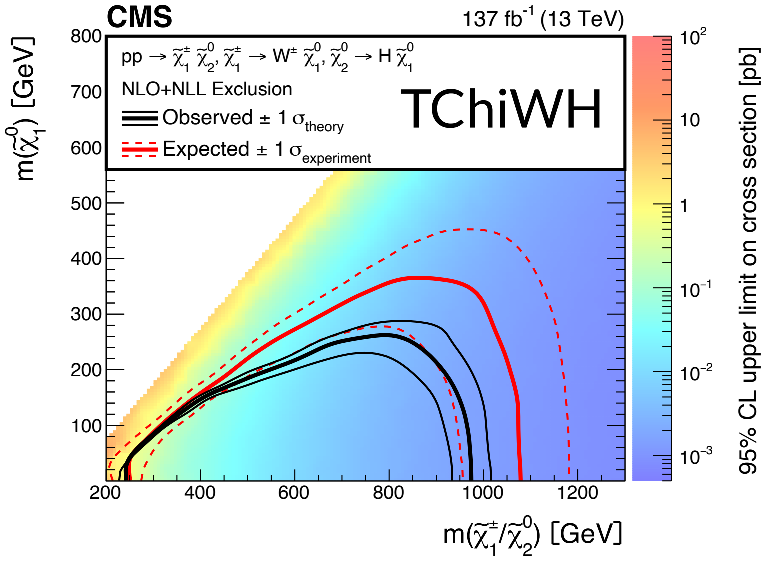
Antitag (!tag) regions:
All H/W/Z candidates are not tagged

WX Search: Results

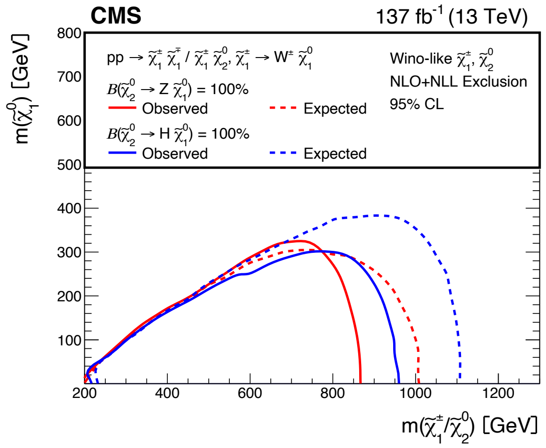
Wino-like



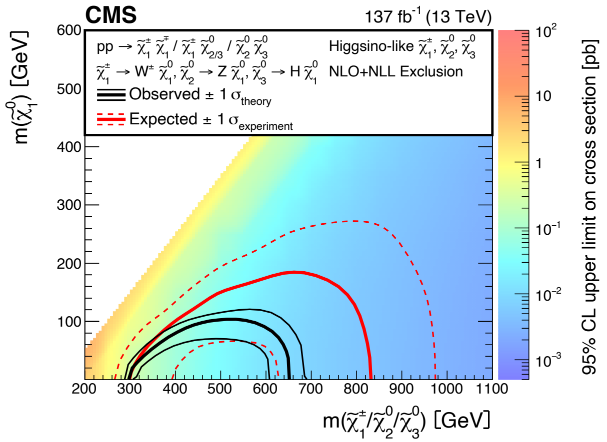




"Realistic Wino"



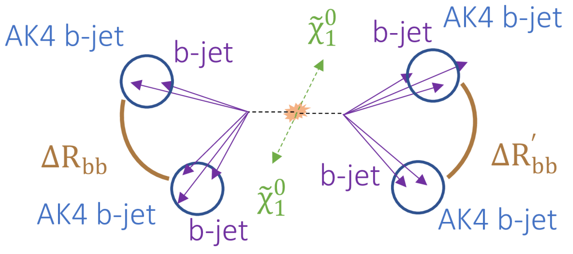
Higgsino-like



- Most stringent limits placed on phase space by CMS
- "Realistic Wino" Interpretations
  - Assume Br($\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$)=100% or Br($\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$)=100%
  - Pushes exclusion up to 870 and 960 GeV, respectively
- Higgsino-like Interpretation
  - **First significant phase space exclusion of higgsino-bino MSSM scenario for CMS - exclusion of 300-650 GeV**

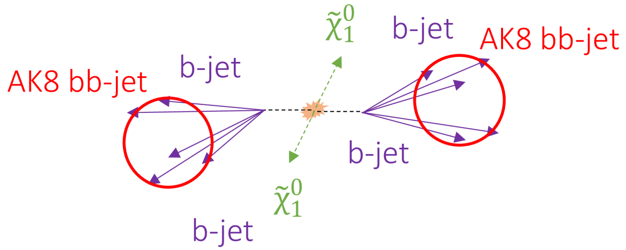
HH + MET Search[2]

HH Search: Signal Models



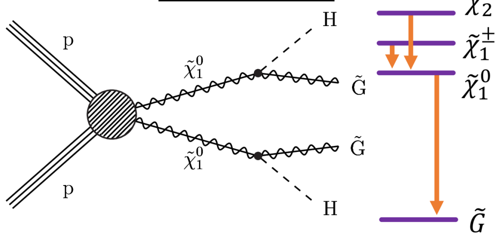
resolved

boosted

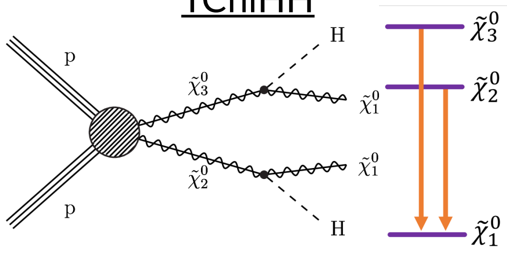


- 2 signatures of HH + p_T^{miss}
  - Resolved: b-jets from H decay independently resolved
  - Boosted: b-jets merged into single wider jet
- Gauge Mediated Symmetry Breaking (GMSB)
  - Goldstino ($\tilde{G}$) LSP, $\tilde{\chi}_1^0$ NLSP (BR($\tilde{\chi}_1^0 \to H\tilde{G}$) ~ 100%)
  - High $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production due to $\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ mass degeneracy
- Simplified SUSY Model
  - $\tilde{\chi}_1^0$ LSP, $\tilde{\chi}_2^0$/ $\tilde{\chi}_3^0$ NLSP
  - Only $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ (nearly mass-degenerate) may decay to LSP
- T5HH Model
  - High H production rate from gluino cascade decays
  - $\tilde{\chi}_1^0$ LSP, $\tilde{\chi}_2^0$ NLSP ($\tilde{\chi}_3^0$ NLSP in newer dark matter models)

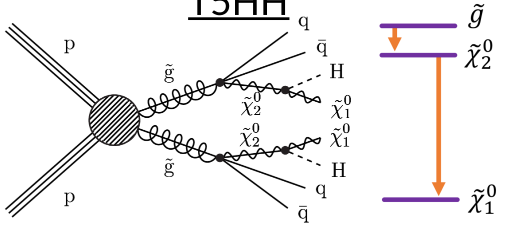
TChiHH-G



TChiHH



T5HH



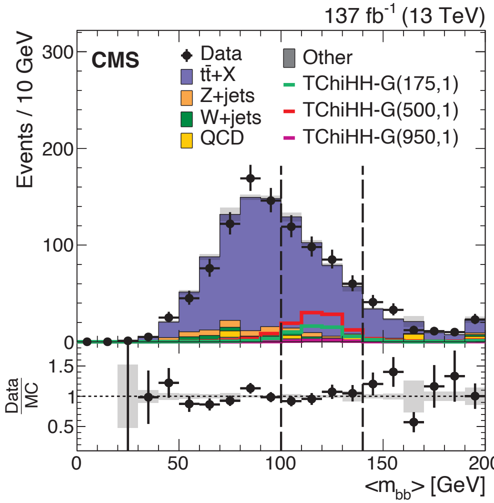
HH Search: Event Selection

- Baseline selection
  - QCD background reduced by $\Delta\phi$ cut on p_T^{miss}-aligned b-jets
  - Higgs mass reconstructed from jets by AK4 mass selection (resolved) and Soft-Drop algorithm (boosted)
  - Suppress $t\bar{t}$ lost-lepton background with ΔR cut on b-jets
  - N_b (resolved) and N_H (boosted) use working point cuts from DeepCSV and DeepDoubleB taggers

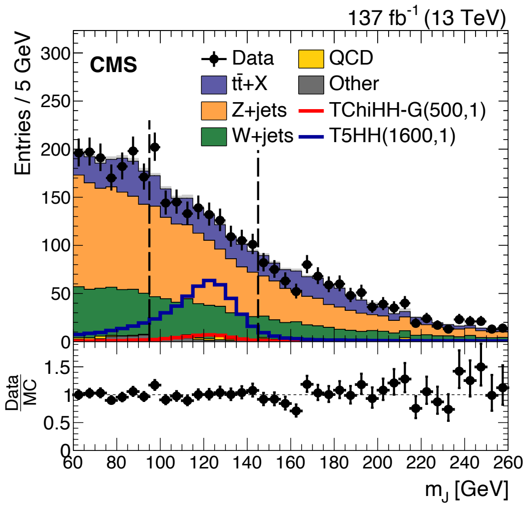
Baseline Event Selection

	Resolved	Boosted
Lepton	Lepton vetoes & Charged particle track veto	
p_T^{miss}	> 150 GeV	> 300 GeV
N_jets	$4 \leq N_\mathrm{AK4} \leq 5$	$N_\mathrm{AK8} \geq 2$ ($p_\mathrm{T} > 300$ GeV)
m_jets	$\langle m_\mathrm{bb} \rangle < 200$ GeV & $\Delta m_\mathrm{bb} < 40$ GeV	$60 \leq m_\mathrm{J} \leq 260$ GeV for $\mathrm{J_1}$, $\mathrm{J_2}$
ΔR_max	< 2.2	
N_b	≥ 2	
N_H		0, 1 or 2

N_b = 3 or 4
resolved signal region



Baseline
boosted signal region

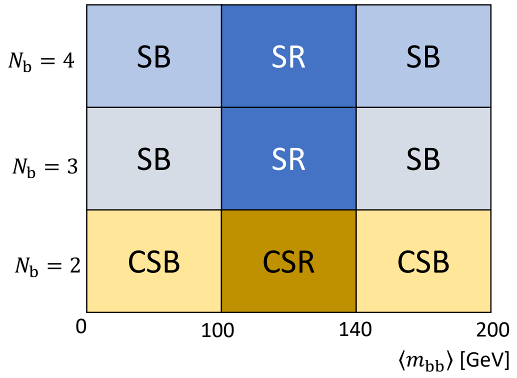


HH Search: Search Strategy

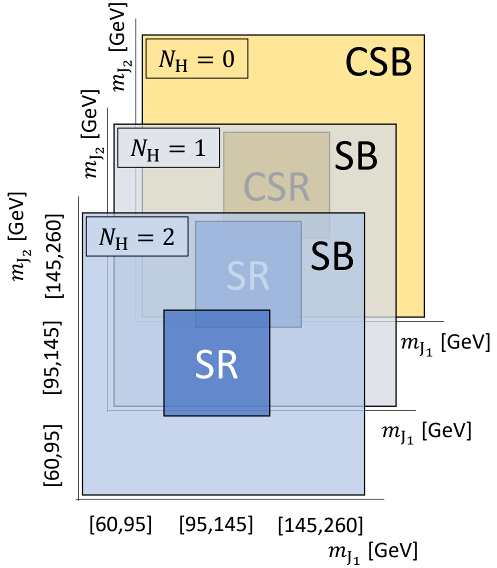
- Background estimation - ABCD Method
  - For given SR, estimate comes from background yield in Sideband Region (SB), Control Sideband Region (CSB), and Control Signal Region (CSR)
    - Regions defined by H boson mass ($\langle m_{\mathrm{bb}} \rangle / m_{\mathrm{J}_{1,2}}$) and jet tagging count ($N_{\mathrm{b}}/N_{\mathrm{H}}$) variables
    - κ taken from MC and validated in data CRs
- Resolved
  - Sorted into 16 bins in p_T^{miss}, $\Delta R_{\max}$, and N_b and calculated individually bin-by-bin
- Boosted
  - Sorted into 6 bins in p_T^{miss} and N_{H}

$$N_{\mathrm{SR}}^{\mathrm{pred}} = \kappa \frac{N_{\mathrm{CSR}}}{N_{\mathrm{CSB}}} N_{\mathrm{SB}}, \quad \kappa = \frac{N_{SR}/N_{SB}}{N_{CSR}/N_{CSB}}\Bigg|_{MC}$$

Signal Regions



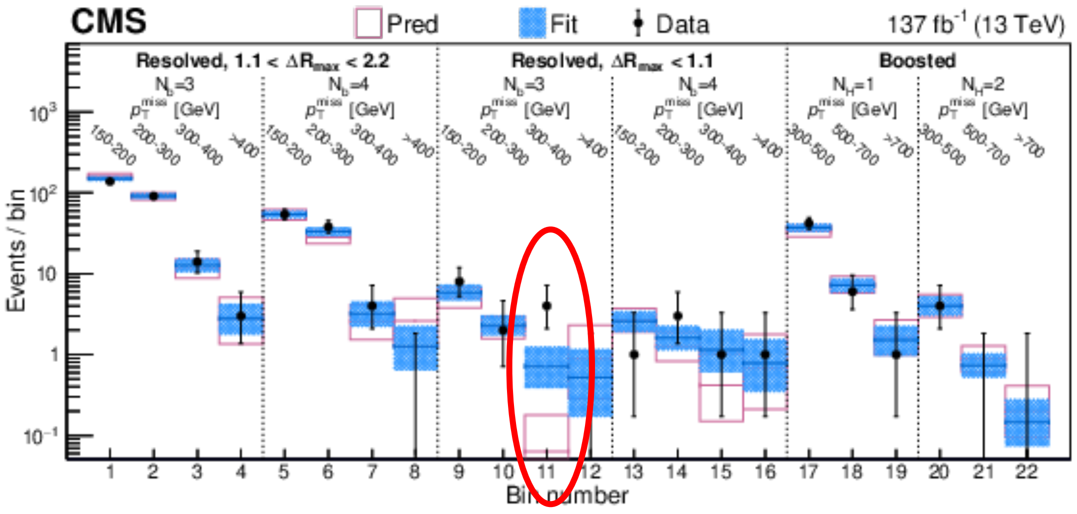
resolved

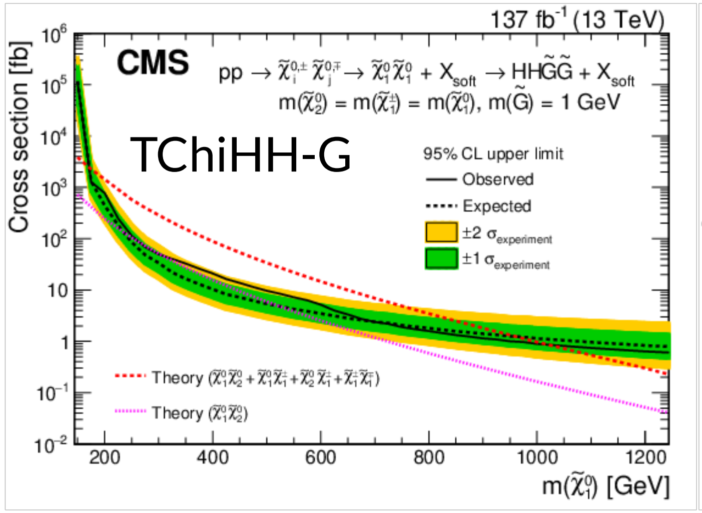


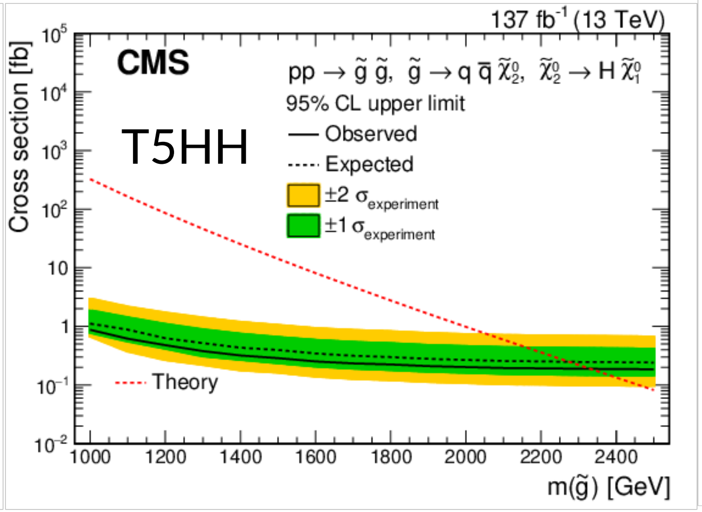
boosted

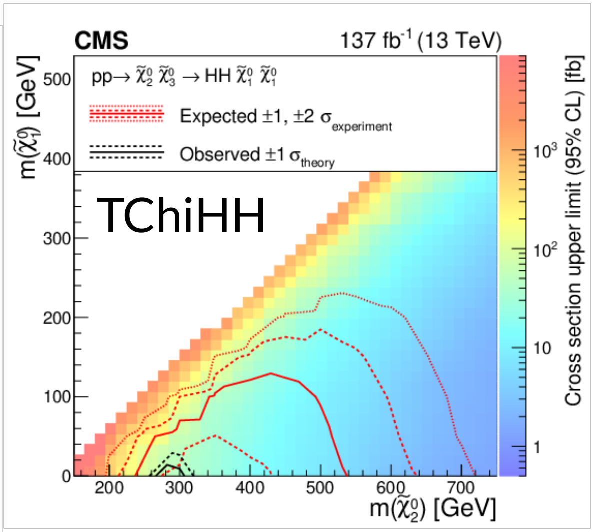
HH Search: Results

- Bin 11 for resolved signature sees local ~3.3σ significance
  - Unphysical shape in single bin ⇒ **unlikely signal**
- TChiHH Model limited to smaller observed exclusion due to 1-bin excess
  - expected exclusion shows solid sensitivity to higgsino







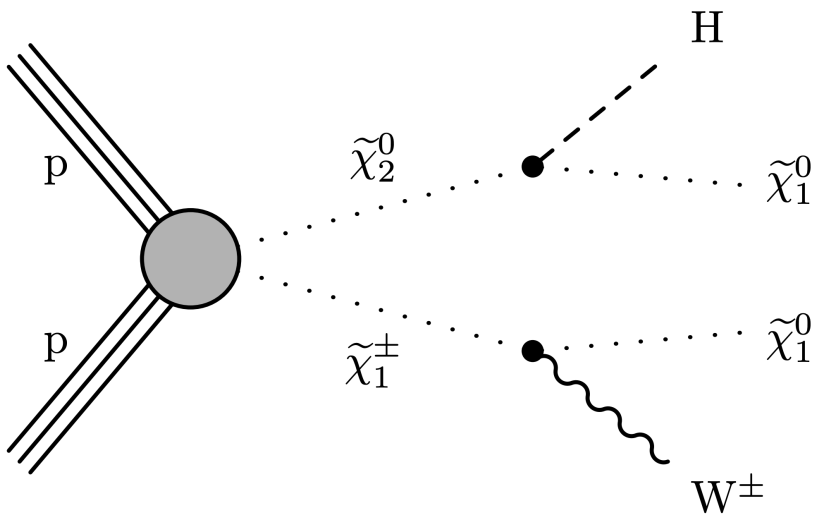


- Largest exclusions set for TChiHH-G and T5HH Models

WH + MET Search [3]

WH Search: Signal Model

- Target simplified SUSY model final states with
  - Charged lepton produced in the W boson decay
  - Two jets reconstructed from the H→bb decay
  - Large p_T^{miss} resulting from the LSPs and neutrino*



- $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ assumed wino-like and nearly mass-degenerate, $\tilde{\chi}_1^0$ assumed to be stable LSP
  - Simplified model further to two mass parameters ($m_{\tilde{\chi}_2^0/\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$)

WH Search: Event Selection

- Baseline event selection
  - W background suppressed by transverse mass (m_T) requirement and lepton selection
  - Cotranverse mass (m_{CT}) rejects $t\bar{t}$ and tW
  - SM Higgs boson mass window requirement
  - Jet multiplicity requirement to suppress $t\bar{t}$

- 12 non-overlapping signal regions (SRs) defined w.r.t. N_H, N_{jets}, and p_T^{miss}

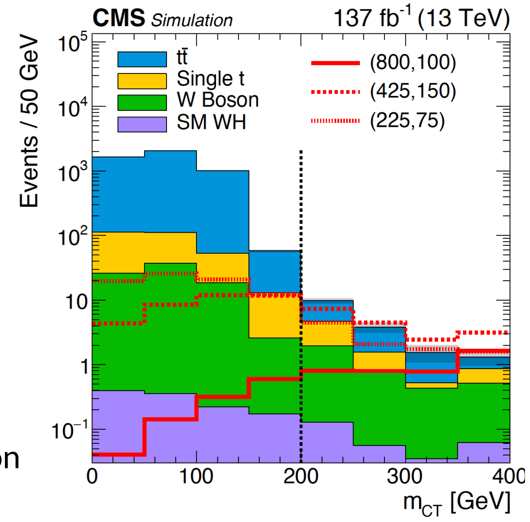
Baseline Event Selection

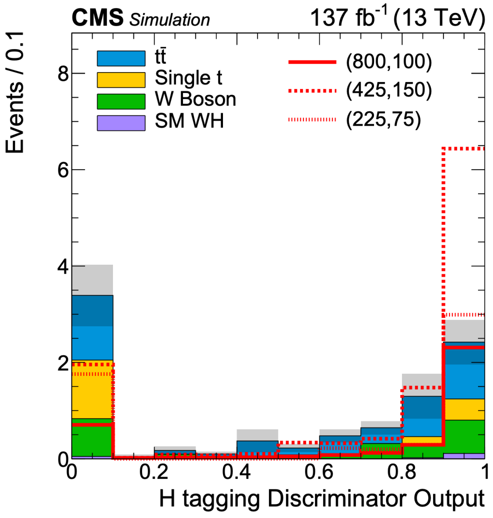
Lepton	Single e or μ and no additional veto lepton, track or tau
Small-R jets	$2 \leq N_{\text{jets}} \leq 3$, $N_b = 2$, $p_T^{\text{non-b}} < 300$ GeV
p_T^{miss}	>125 GeV
$m_{b\bar{b}}$	90–150 GeV
m_T	>150 GeV
m_{CT}	>200 GeV

Signal Regions

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

N_{jets} = 2 + p_T^{miss}>125 signal region





WH Search: Search Strategy

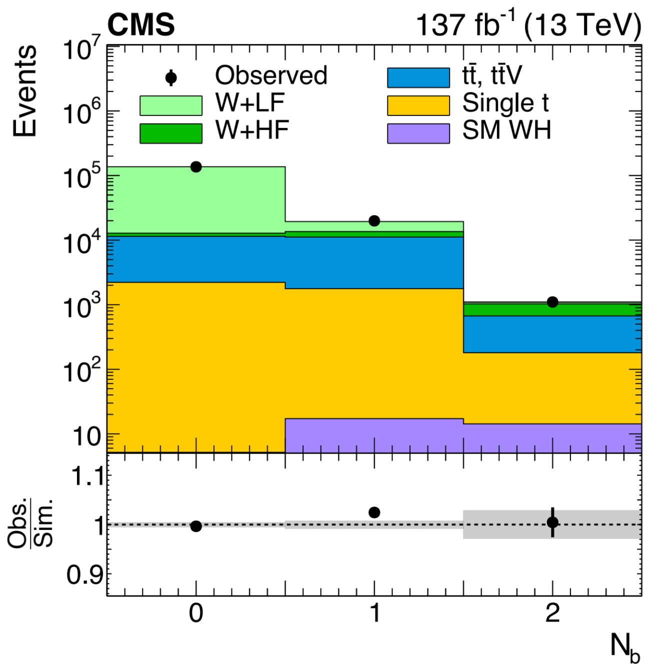
- Background estimation – observed yields estimated in control regions (CRs), transfer factors derived from SM MC
  - Low-p_T^{miss}: top quark-dominant

$$N_{\mathrm{SR}}^{\mathrm{top}}(p_{\mathrm{T}}^{\mathrm{miss}}, N_{\mathrm{jets}}, N_{\mathrm{H}}) = R_{\mathrm{top}}(p_{\mathrm{T}}^{\mathrm{miss}}, N_{\mathrm{jets}}, N_{\mathrm{H}}) N_{\mathrm{CR}}^{\mathrm{obs.}}(p_{\mathrm{T}}^{\mathrm{miss}}, N_{\mathrm{jets}}, N_{\mathrm{H}})$$

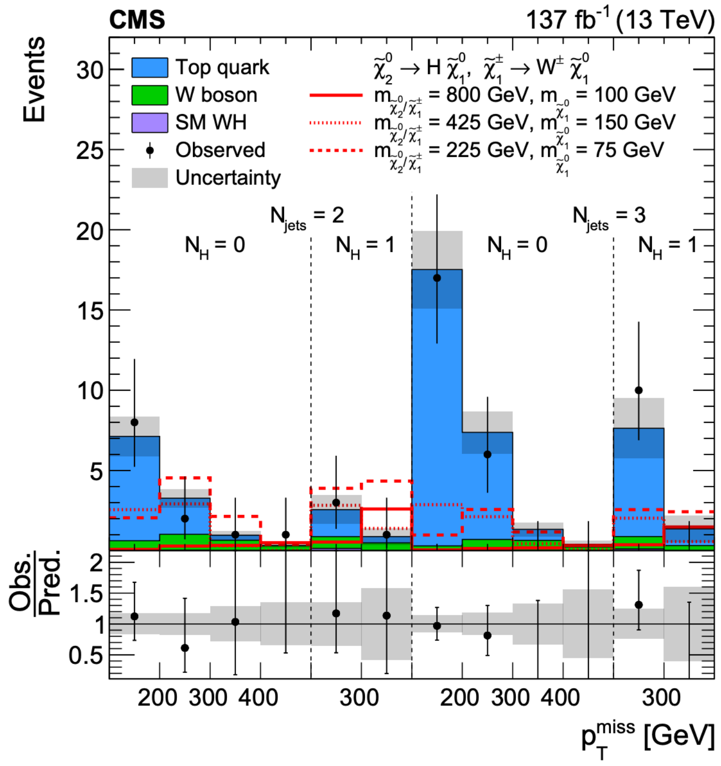
  - High-p_T^{miss}: W-dominant

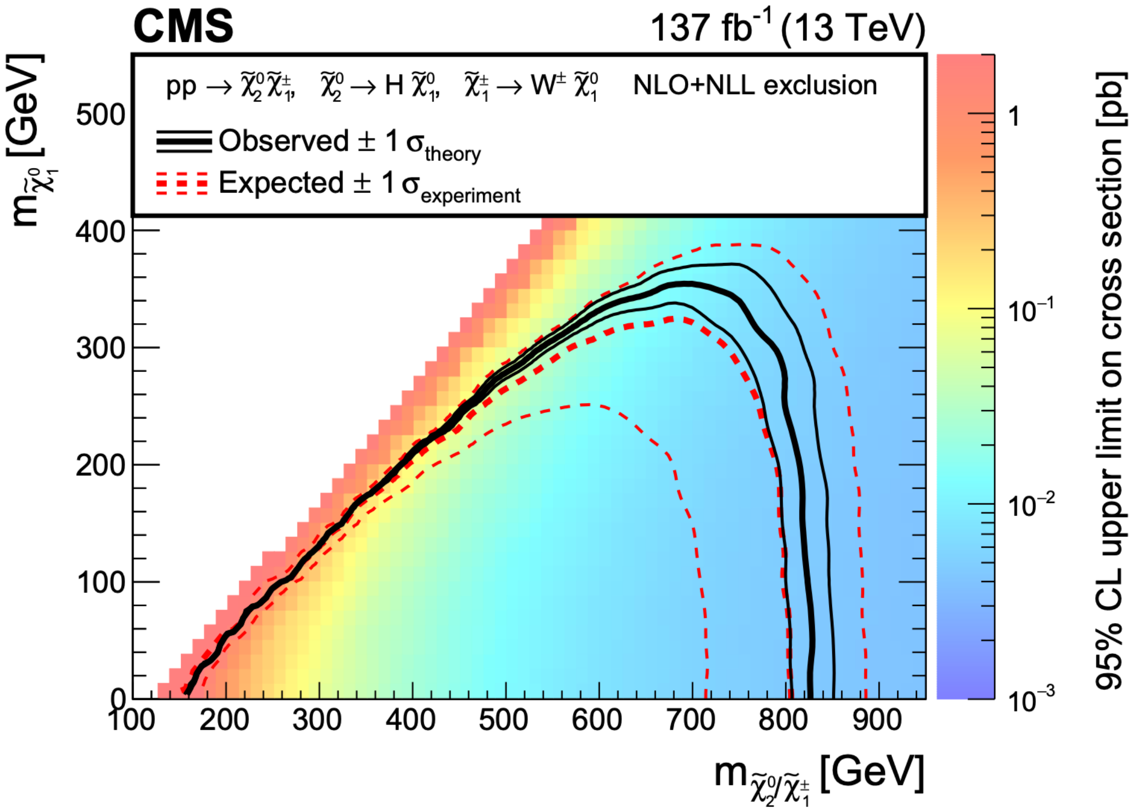
$$N_{\mathrm{SR}}^{\mathrm{W}}(p_{\mathrm{T}}^{\mathrm{miss}}, N_{\mathrm{jets}}, N_{\mathrm{H}}) = N_{\mathrm{CR}}^{\mathrm{W}}(p_{\mathrm{T}}^{\mathrm{miss}}, N_{\mathrm{jets}}) R_{\mathrm{W}}(p_{\mathrm{T}}^{\mathrm{miss}}, N_{\mathrm{jets}}, N_{\mathrm{H}})$$

Data-MC validation in low-m_T CR



WH Search: Results





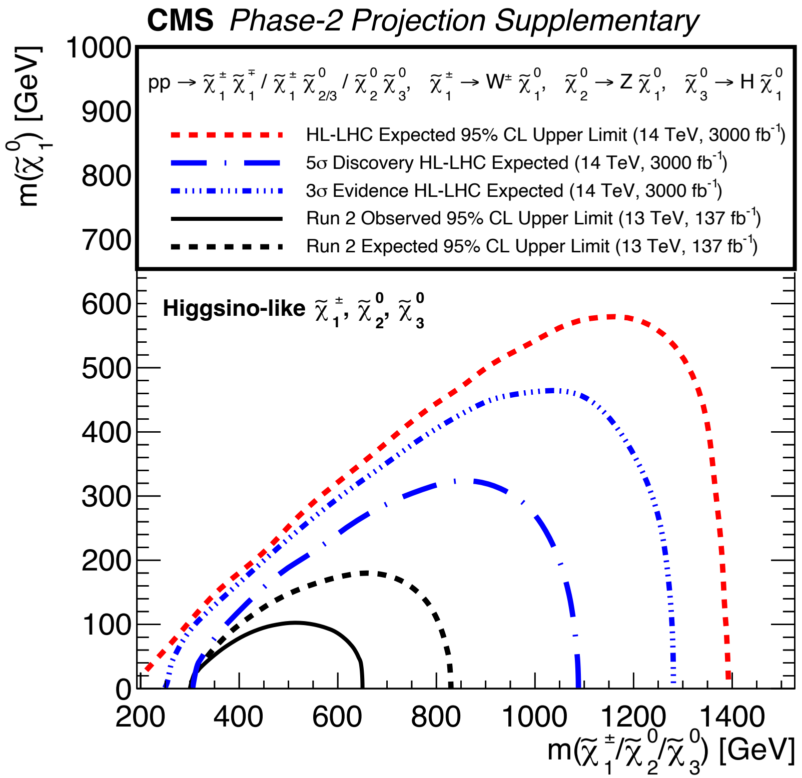
- Likelihood for SUSY signal strength and yield of backgrounds + nuisance parameters performed shows agreement with SM prediction
  - **Chargino (Neutralino) exclusion for mass up to ~820 (~340) GeV**
- WH sensitivity is complementary to WX + MET search, can be combined for greater reach

Conclusions & Outlook

- Several new stringent limits placed on EWKino masses in multiple searches

- New higgsino interpretation explored in phase space

- Hadronic analyses **show promise to push discovery reach further in HL-LHC era**



Higgsino-like WX Search reach projected to HL-LHC luminosity

References

1. The CMS collaboration., Tumasyan, A., Adam, W. *et al.* Search for electroweak production of charginos and neutralinos at √s = 13 TeV in final states containing hadronic decays of WW, WZ, or WH and missing transverse momentum. Tech. rep., CERN, Geneva, May 2022. Submitted to Physics Letters B. All figures and tables can be found at http://cms-results.web.cern.ch/cms-results/publicresults/publications/SUS-21-002 (CMS Public Pages).
2. The CMS collaboration., Tumasyan, A., Adam, W. *et al.* Search for higgsinos decaying to two Higgs bosons and missing transverse momentum in proton-proton collisions at √s = 13 TeV. *J. High Energ. Phys.* **2022,** 14 (2022). https://doi.org/10.1007/JHEP05(2022)014
3. The CMS collaboration., Tumasyan, A., Adam, W. *et al.* Search for chargino-neutralino production in events with Higgs and W bosons using 137 fb^{-1} of proton-proton collisions at √s = 13 TeV. *J. High Energ. Phys.* **2021,** 45 (2021). https://doi.org/10.1007/JHEP10(2021)045

Backup

WX Search Cont.

- MET trigger
  - 74-95% trigger efficiency at p_T^{miss}= 200 GeV, >98% for p_T^{miss}>270 GeV (year-dependent at low p_T^{miss})

Sources of Systematic Uncertainty

Source	b veto: 0- and 1-res bkg. 0-tag CR	b veto: 0- and 1-res bkg. 1-tag CR	b veto: Rare	b veto: Signal	b tag: Top quark	b tag: 0-res	b tag: Rare	b tag: Signal
Integr. 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 and μ_F	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 nonclosure	3–48	3–48	—	—	—	—	—	—
V-tag nonclosure	1–27	—	—	—	—	—	—	—
Fast simulation	—	—	—	5	—	—	—	8

HH Search Cont.

- MET trigger used for signal region
  - 30–70% trigger efficiency for p_T^{miss} = 150 GeV, >99% for p_T^{miss} > 260 GeV
  - Control samples from single- and di- lepton + MET triggers

Sources of Systematic Uncertainty

Source	Relative uncertainty [%] Resolved	Boosted
MC sample size	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	0–3	0–9
Integrated luminosity	1.6	
Jet energy scale	0–7	0–12
Jet energy resolution	0–7	0–7
Isolated track veto	2–9	1–8
Trigger efficiency	1–12	0–4
m_J resolution	—	0–9
b tagging efficiency	2–6	—
b mistagging	0–1	—
bb tagging efficiency	—	6–15
Uncertainties attributable to the fast simulation		
Jet quality requirements	1	
p_T^{miss} modeling	0–14	0–12
m_J resolution	—	2–4
b tagging efficiency	0–1	—
b mistagging	0–1	—
bb tagging efficiency	—	0–1

WH Search Cont.

- Combination of MET and lepton trigger
  - 99% trigger efficiency achieved for events with p_T^{miss} > 225 GeV and $p_T(\ell)$>20 GeV

- Cotranverse Mass
  - Discriminates $t\bar{t}$ and tW events which peak at m_{CT}~150 when bs are correctly identified from higher- m_{CT} signal

$$m_{CT} = \sqrt{2p_T^{b_1}p_T^{b_2}(1 + \cos(\Delta\phi_{b\bar{b}}))}$$

Sources of Systematic Uncertainty

Source	Typical values
Simulation statistical uncertainty	1–10%
Lepton efficiency	$<$1%
b tagging efficiency	$<$4%
H tagging efficiency	7–20%
Trigger efficiency	$<$5%
Jet energy scale	1–7%
Jet energy resolution	1–7%
b jet energy scale	1–10%
μ_R and μ_F	$<$1%
Initial-state radiation	1%
Integrated luminosity	1.8%
Pileup	$<$2%