



# Searches for electroweak production of SUSY particles with the CMS experiment

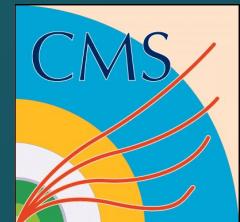
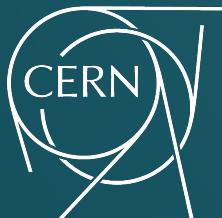
PABLO MATORRAS-CUEVAS

*Instituto de Física de Cantabria (CSIC-Universidad de Cantabria)*

*On behalf of the CMS collaboration*

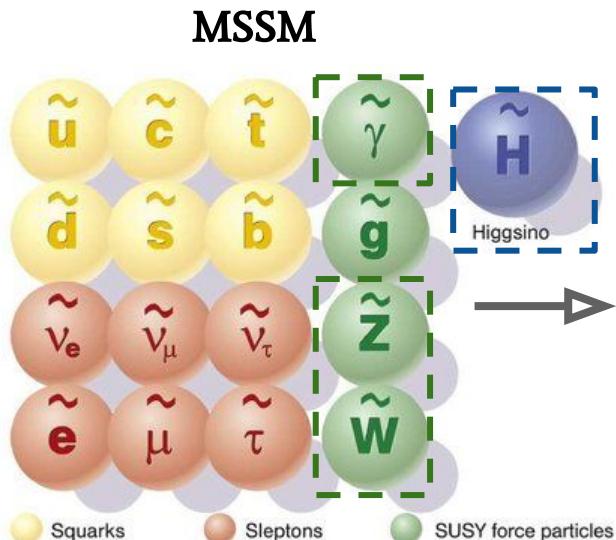
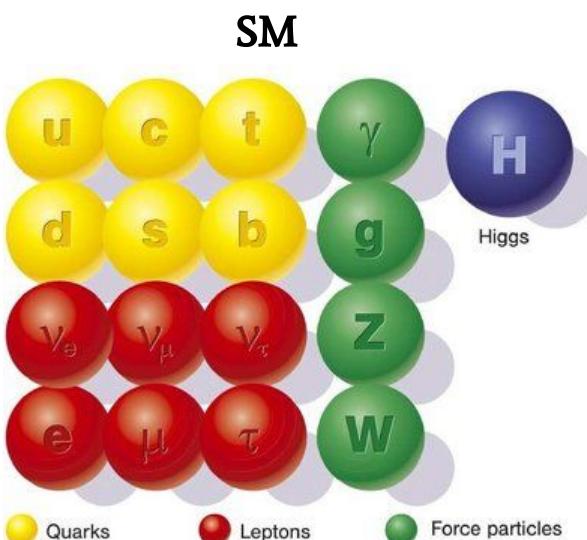
*30th International Conference on Supersymmetry and Unification of Fundamental Interactions*

Southampton, United Kingdom, 18<sup>th</sup> July, 2023

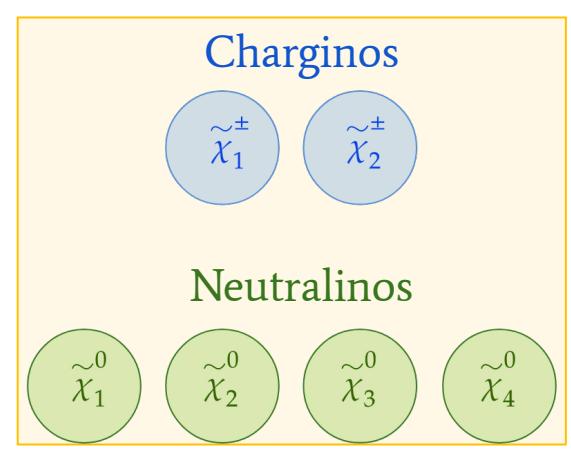


# Electroweak SUSY in a nutshell

- ▶ In general SUSY is constructed as an extension of the standard model (SM)
  - Electroweakinos are mixtures of **Winos**, **Zinos**, **photinos** and **higgsinos**, whose mass eigenstates are **charginos** and **neutralinos**
- ▶ Relevant due to:
  - Contribute to large corrections of the Higgs mass
  - Its lightest supersymmetric particle (LSP), typically the neutralino, is a good dark matter candidate
  - Masses accessible by the LHC ( $\sim$ order of the TeV)



## Electroweakinos



# Electroweak SUSY: Challenges

Multiple SUSY models:

- Particles' masses unknown and large parameter space to cover

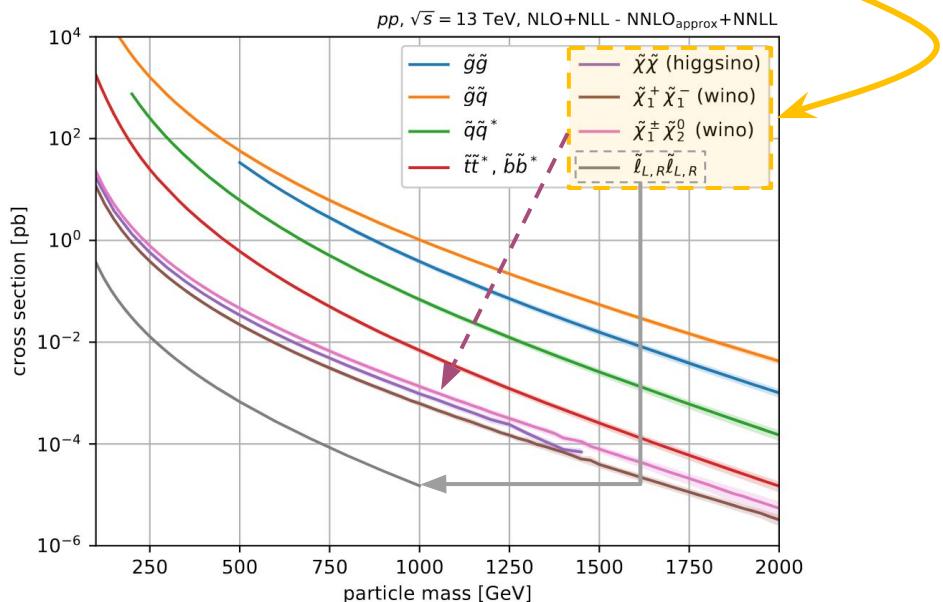
## Challenges

- Several SM processes with similar kinematics and large cross-sections (e.g. Drell-Yan, boson, diboson or ttbar production, also including jets)
  - Compressed scenarios: Difficult signal to background separation
- Electroweak (EWK) SUSY has small cross section, especially sleptons

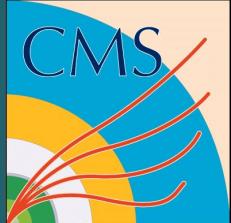
Several interesting Run-2 results address these difficulties:

- Exploiting the additional data and novel analysis techniques
- Combining analyses probing complementary phase spaces:

→ [CMS PAS SUS-21-008](#)

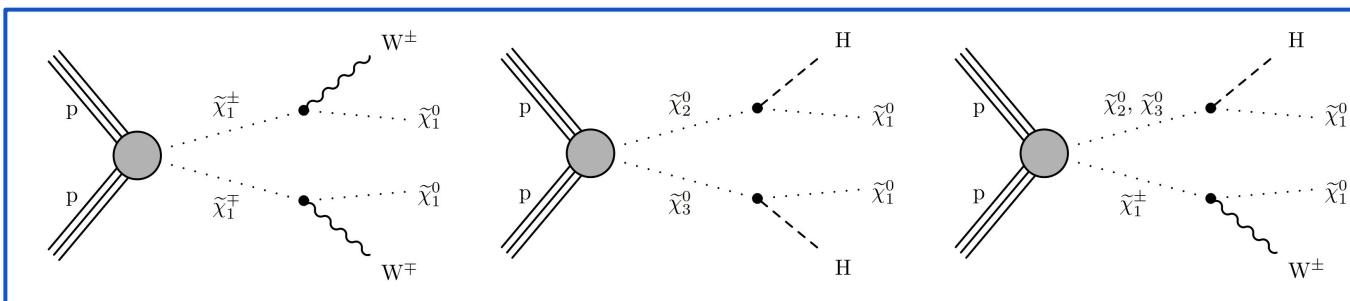
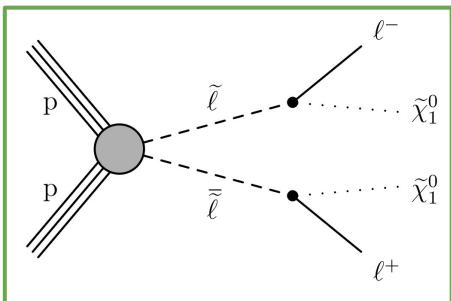
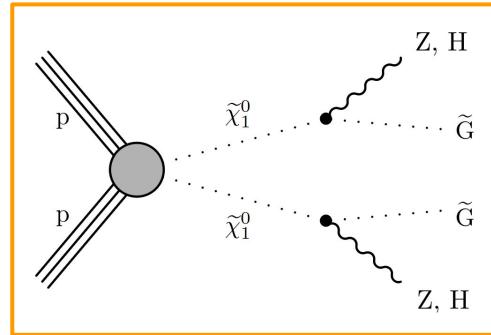
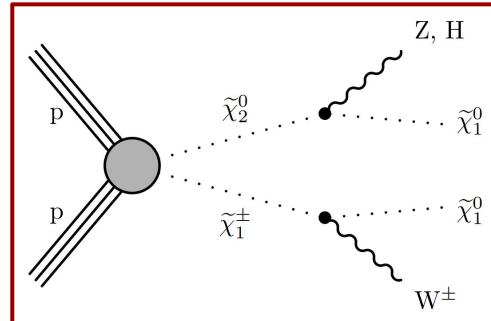


# Electroweakino Combination: Considered Models



- ▶ An improvement respect the previous Electroweakino Combination ([JHEP03\(2018\)160](#)) using 2016 data that targeted the production of:
  - Wino-like chargino and neutralino, decaying via a bino like LSP neutralino
  - Neutralino pair production in Gauge-Mediated SUSY breaking (GMSB), quasi degenerate Higgsinos
- ▶ Revisit the same interpretation with Run 2 data, including some improvements
- ▶ New interpretations also considered:
  - Chargino/neutralino production in a Higgsino-bino interpretation.
  - Slepton pair production

**CMS PAS SUS-21-008**



# Combination strategy

## Leptonic analyses:

- 2/3 $\ell$  soft: [JHEP04\(2022\)091](#)
- 2 $\ell$  on-Z/non res: [JHEP04\(2021\)123](#)
- $\geq 3\ell$ : [JHEP04\(2022\)147](#)

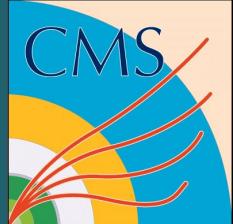
## Hadronic/Semihadronic analyses:

- 1 $\ell$  2b: [JHEP10\(2021\)045](#)
- 4b: [JHEP05\(2022\)014](#)
- Hadr. WX: [Phys.Lett.B 842 \(2023\) 137460](#)

Search	Gaugino		GMSB			Higgsino-bino			Sleptons
	WZ	WH	ZZ	ZH	HH	WW	HH	WH	$\ell^+\ell^-$
2/3 $\ell$ soft	✓								✓
2 $\ell$ on-Z	✓		✓	✓					
2 $\ell$ non-res.									✓
$\geq 3\ell$	✓	✓	✓	✓	✓			✓	
1 $\ell$ 2b		✓						✓	
4b				✓			✓		
Hadr. WX	✓	✓				✓		✓	

n.b. Overlaps between analyses' Signal Regions (SR) accounted for in combination

# Leptonic input analyses



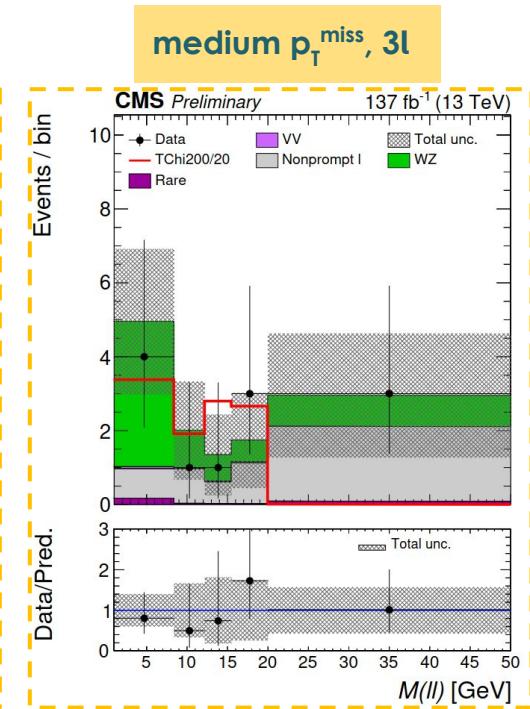
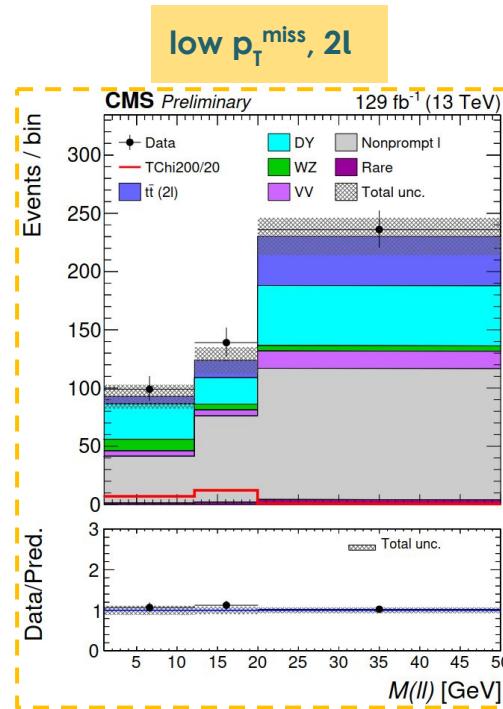
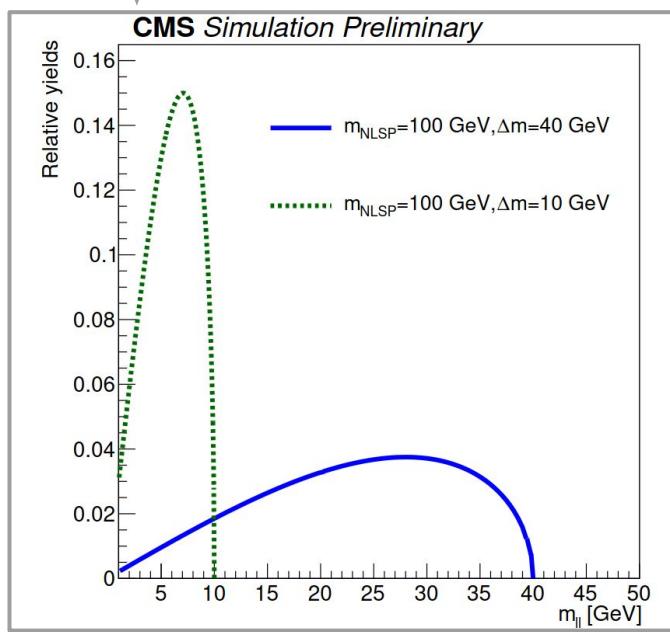
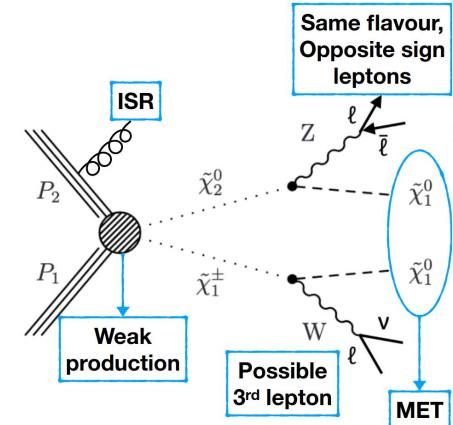
## Leptonic analyses:

- ▶ **2/3l soft:** [JHEP04\(2022\)09](#) (Compressed)
  - “2l bin”: Two opposite sign (OS) same flavour (SF) lepton pair,
  - “3l bin”: One additional SF lepton ( $e, \mu$ )
  - $3.5 (5) < p_T(\text{lep}) < 30$  GeV for 2l (3l) bins and an ISR jet.
  - Further binned in terms of  $p_T^{\text{miss}}$  and  $m_{\parallel}$
  - New parametric signal extraction to improve sensitivity
- ▶ **2l on-Z/non res:** [JHEP04\(2021\)123](#) (Boosted)
  - Two OS SF leptons ( $ee/\mu\mu$ ), with SR split in terms of  $p_T^{\text{miss}}$ .
  - on Z analysis:  $86 < m_{\parallel} < 96$  GeV, using standard jet (AK4) & wider (AK8) jet reconstructions, further splitting in terms of b-jet content.
  - off Z analysis:  $20 < m_{\parallel} < 65$  GeV &  $m_{\parallel} > 120$  GeV
- ▶  **$\geq 3l$ :** [JHEP04\(2022\)147](#) (Intermediate)
  - $ee/\mu\mu$  or 3/4l with up to 2 hadronic taus ( $\tau_h$ ).
  - $p_T^{l1} > 25$  GeV,  $p_T^{l2} > 20$  GeV

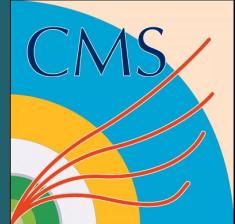
Search	Gaugino		GMSB			Higgsino-bino		
	WZ	WH	ZZ	ZH	HH	WW	HH	WH
2/3 $\ell$ soft	✓							
2 $\ell$ on-Z	✓		✓	✓				
2 $\ell$ non-res.								
$\geq 3\ell$	✓	✓	✓	✓	✓			✓

# Optimisation of 2/3l soft analysis

- Each mass hypothesis has different kinematics
  - Optimise binnings per each mass splitting wrt [JHEP04\(2022\)09](#)
  - Use  $m_{\parallel}$  as discriminating variable  
→ Individual binning for each  $\Delta m$  and SR.
  - Expected exclusion of Next to LSP improved by ~5-25 GeV



# Hadronic & semihadronic input analyses



Hadronic & Semihadronic analyses:

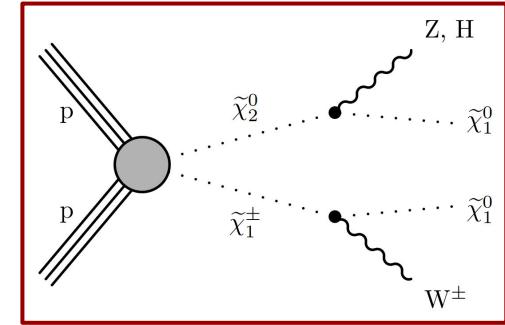
- ▶ **1ℓ 2b:** [JHEP10\(2021\)045](#)
  - $p_T^{miss} > 30 \text{ GeV}$ , 2 b-tagged jets consistent with the Higgs boson mass, and large  $p_T^{miss}$ .
- ▶ **4b:** [JHEP05\(2022\)014](#)
  - No leptons. Two Higgs boson, each  $H \rightarrow bb$
  - SRs based on  $N_{b\text{-jets}}$ .
  - Also considering boosted topologies (with AK8 jets)
- ▶ **Hadr. WX:** [Phys.Lett.B 842 \(2023\) 137460](#)
  - At least 2 AK8 jets, compatible with W, Z and H bosons.
  - 2-6 AK4 jets
  - New for Run 2 combination
- Additional sensitivity in the uncompressed spectra

Search	Gaugino		GMSB			Higgsino-bino		
	WZ	WH	ZZ	ZH	HH	WW	HH	WH
1ℓ2b		✓						✓
4b					✓		✓	
Hadr. WX	✓	✓			✓	✓	✓	✓

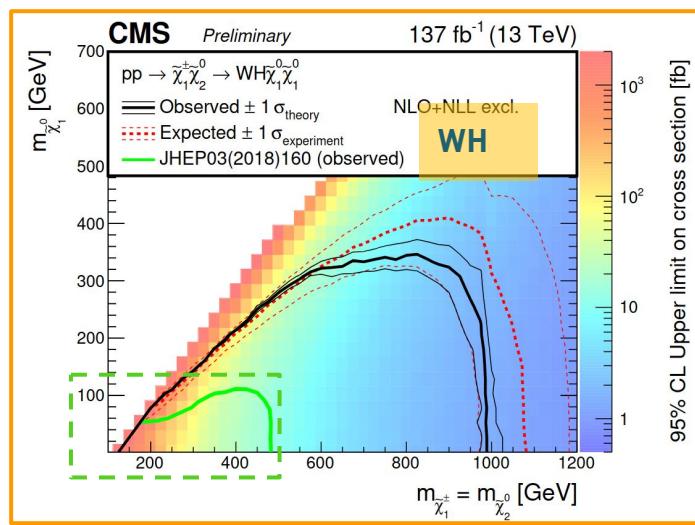
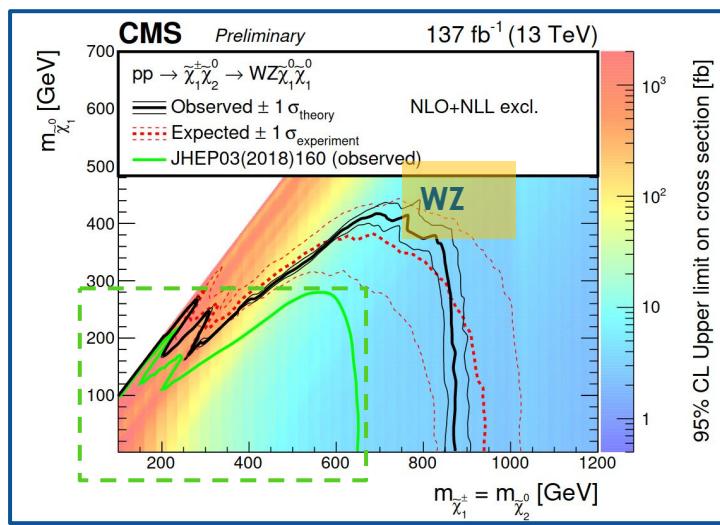
# Chargino/neutralino production in WZ/WH final states

Several analyses contribute to the combined limit (more information in backup):

- Uncompressed region: dominated by Hadr WX analysis.
- Compressed region: 2/3 $\ell$  soft analysis ( $\geq 3\ell$ ) in the **WZ** (**WH**) models.
- Expected limit significantly improved with respect to the **2016 combination**

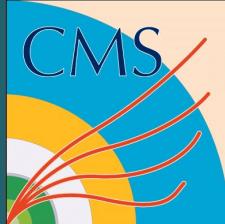


Search	Gaugino	
	WZ	WH
2/3 $\ell$ soft	✓	
2 $\ell$ on-Z		✓
2 $\ell$ non-res.		
$\geq 3\ell$	✓	✓
1 $\ell$ 2b		✓
4b		
Hadr. WX	✓	✓



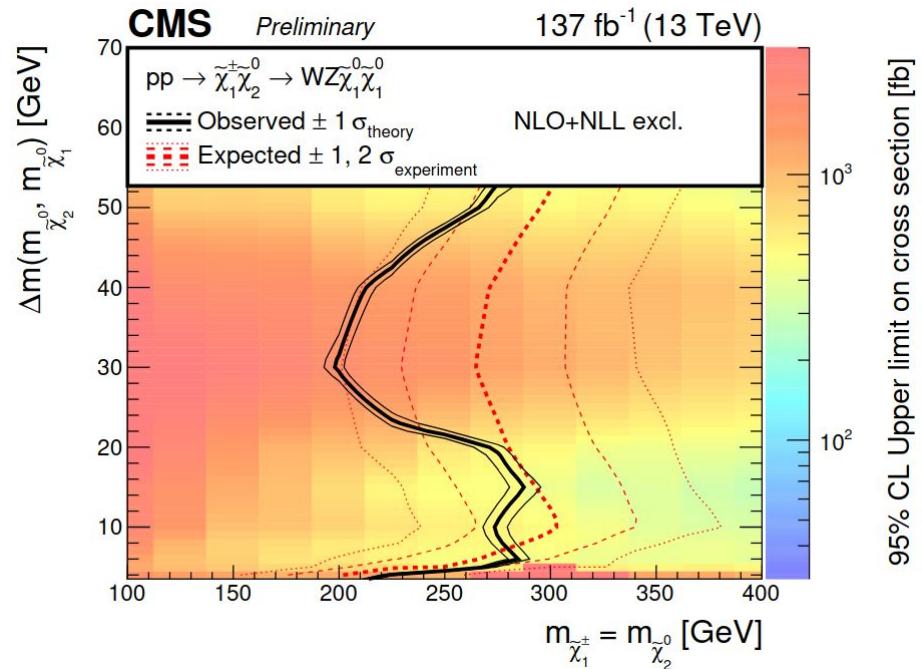
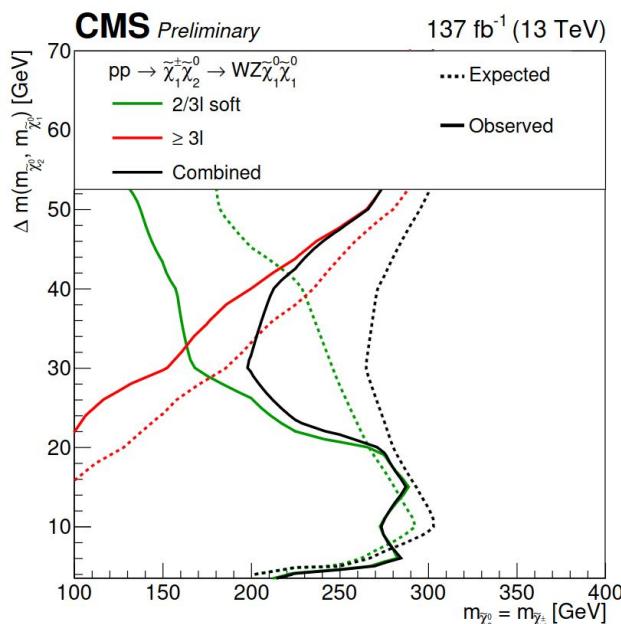
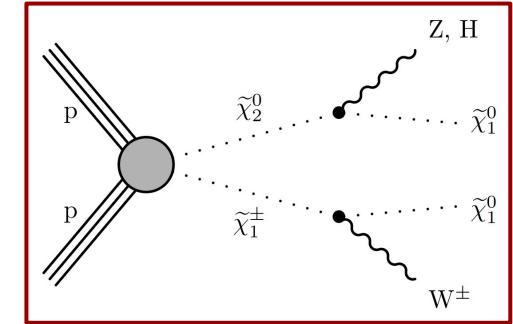
# Chargino/neutralino production in WZ/WH final states

## Compressed



More challenging → Required full Run2 data as well as novel techniques

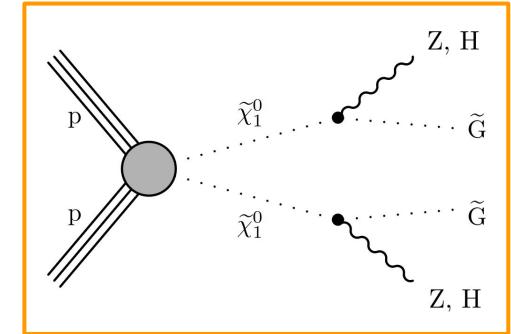
- **2/3l soft** and  **$\geq 3l$**  analyses complement each other.
  - Orthogonal lepton  $p_T$
  - Different discriminant variables
- Expected limits close gap at  $\Delta m \sim 40$  GeV, where a mild ( $2\sigma$ ) excess is found



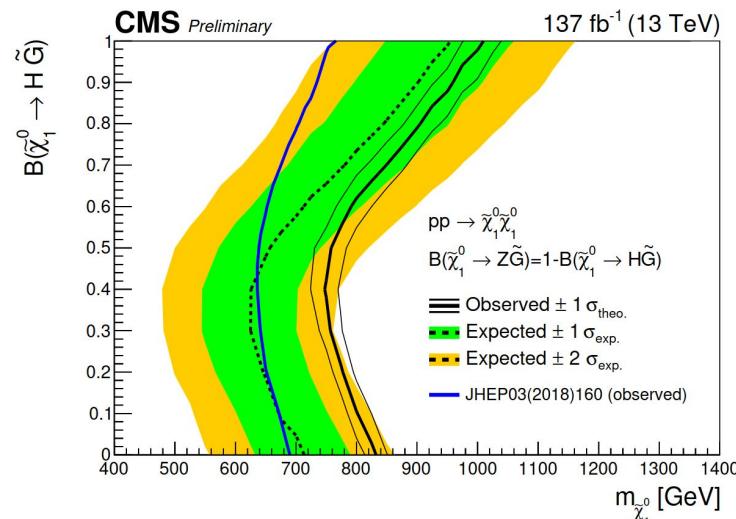
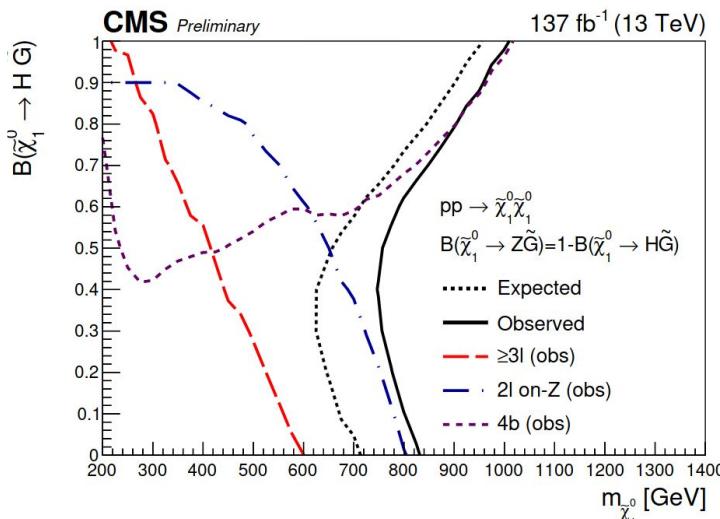
# Chargino/neutralino production in GMSB models

In GMSB models,  $\chi_1^\pm$ ,  $\chi_1^0$  and  $\chi_2^0$  have minimal mass splitting:

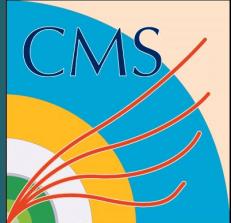
- Models can be reduced to  $\chi_1^0$  pair production, decaying to:
  - Gravitino  $\tilde{G}$  with  $m_{\tilde{G}}=1$  GeV (LSP)
  - SM neutral boson ( $Z$  or  $H$ )
- Exclusion limits in terms of  $B(\chi_1^0 \rightarrow H\tilde{G})$ :
  - **4b** analysis more sensitive at large  $B(\chi_1^0 \rightarrow H\tilde{G})$
  - Small  $B(\chi_1^0 \rightarrow H\tilde{G})$  dominated by **2l on Z** analysis



Search	GMSB		
	ZZ	ZH	HH
2/3ℓ soft	✓	✓	
2ℓ on-Z		✓	
2ℓ non-res.			✓
≥ 3ℓ	✓	✓	✓
1ℓ 2b			
4b			✓
Hadr. WX			

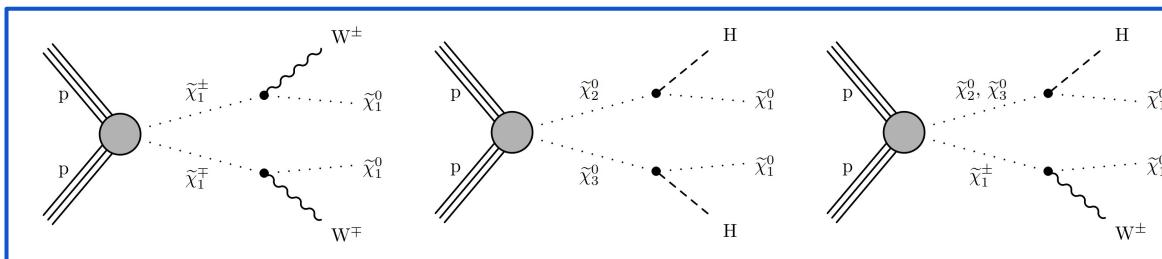
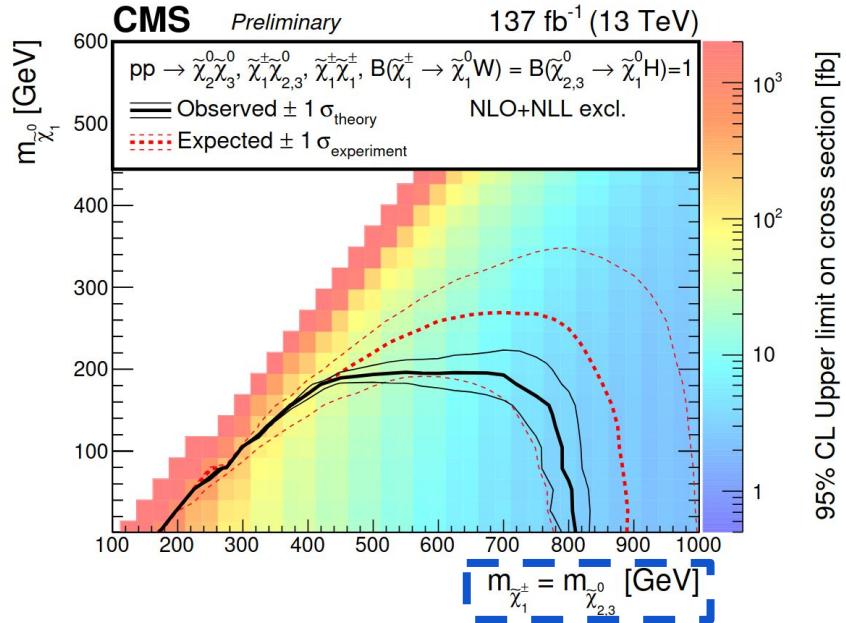


# Chargino/neutralino production in Higgsino-bino models



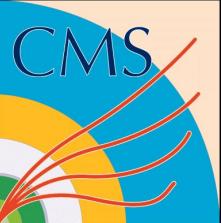
New interpretation wrt [JHEP04\(2022\)09](#)

- $\tilde{\chi}_1^0$  as LSP, and a **mass degenerate Higgsino triplet**:
- Target either WW, HH or WH final states with:
  - $B(\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0) = 100\%$
  - $B(\tilde{\chi}_{2,3}^0 \rightarrow H\tilde{\chi}_1^0) = 100\%$
- More sensitive to the uncompressed phase space



Search	Higgsino-bino		
	WW	HH	WH
2/3ℓ soft			
2ℓ on-Z			
2ℓ non-res.			
≥ 3ℓ			✓
1ℓ 2b			✓
4b			✓
Hadr. WX	✓		✓

# Slepton production

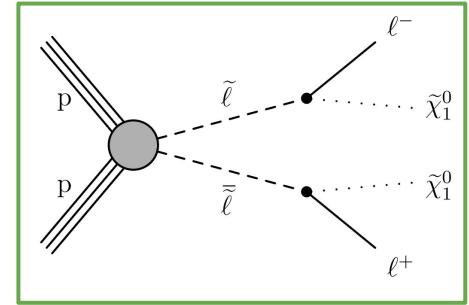


Particularly difficult due to their small cross sections.

- Slepton as Next to LSP with lightest neutralino as LSP
- 1<sup>st</sup> & 2<sup>nd</sup> generation (3<sup>rd</sup> covered in [CMS-PAS-SUS-21-001](#))

2/3l soft analysis targeting compressed signatures:

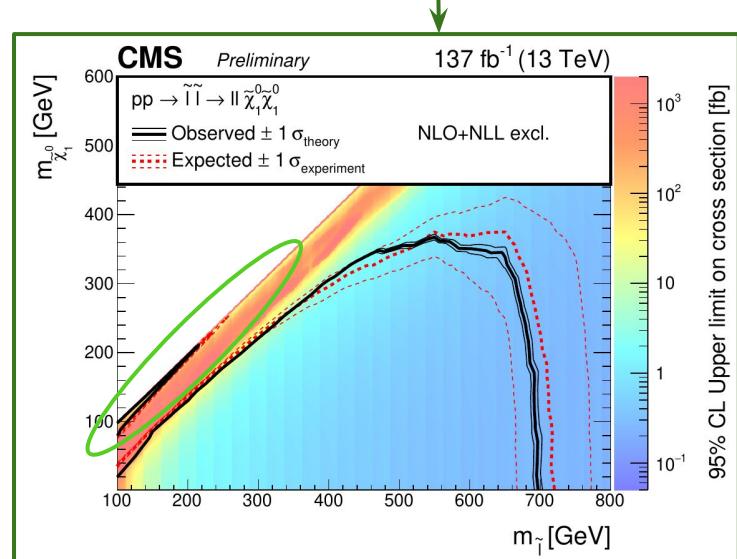
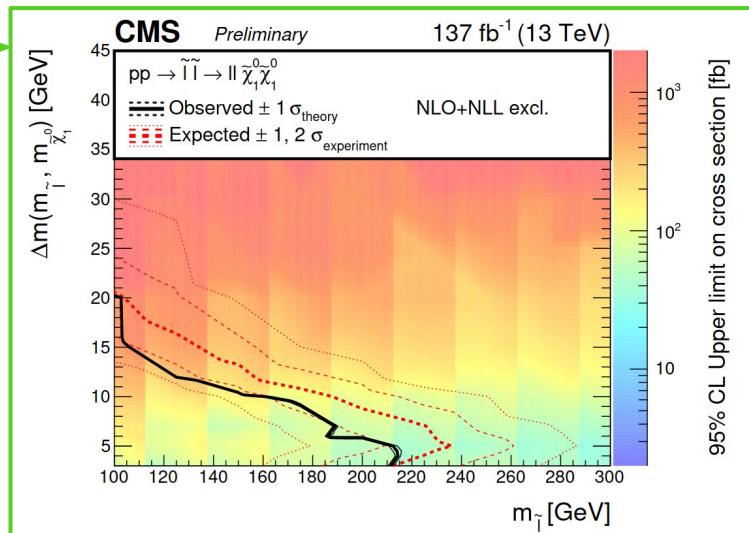
- Similar SR as for Wino-bino interpretation
- $m_{T2}(\ell\ell, \chi)$  as discriminant variable:



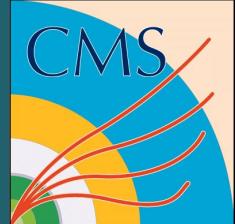
$$m_{T2}(\ell\ell, \chi) = \min_{\vec{p}_T^{\text{miss}(1)} + \vec{p}_T^{\text{miss}(2)} = \vec{p}_T^{\text{miss}}} \left[ \max \left( M_T^1(m_\chi), M_T^2(m_\chi) \right) \right]$$

2l non resonant used for non compressed scenario:

- Equivalent SR as before

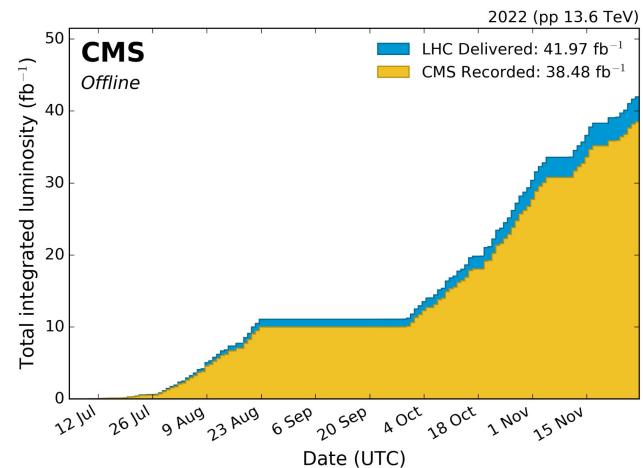


# Summary and future prospects



A combination of several EWK SUSY processes have been made.

- ★ Both leptonic and hadronic signatures considered
- ★ Various phase spaces probed, ranging from compressed to high mass splittings.
- ★ More sensitivity and new models considered wrt previous combination
- ★ **No significant deviations** from expectation found
- ★ **Chargino** excluded up to **1 TeV**, and **Higgsino** to **990 GeV**
- ★ **Slepton** mass excluded up to **215 GeV** for  $\Delta m=5 \text{ GeV}$  and **110-720 GeV** for  $\Delta m=50 \text{ GeV}$
- But there always is hope!
  - Current exclusions come under assumptions that could be proven wrong.
  - Currently on Run-3 data taking period
    - (Expect **~3x more luminosity** than Run-2!)
  - New phase spaces will become available (compressed area, even more boosted scenarios...).



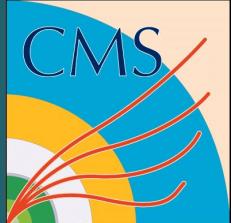
# Thanks for your attention



# BACKUP



# Search targeting final states with a photon, jets and large MET

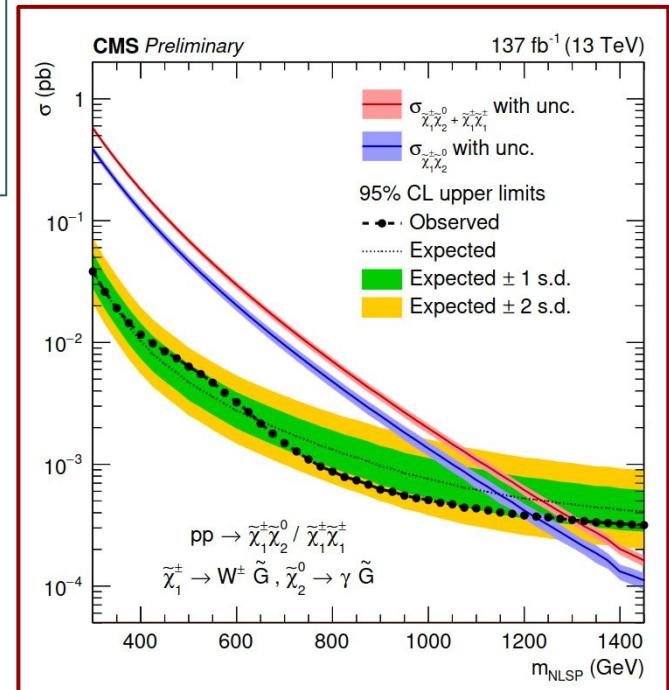
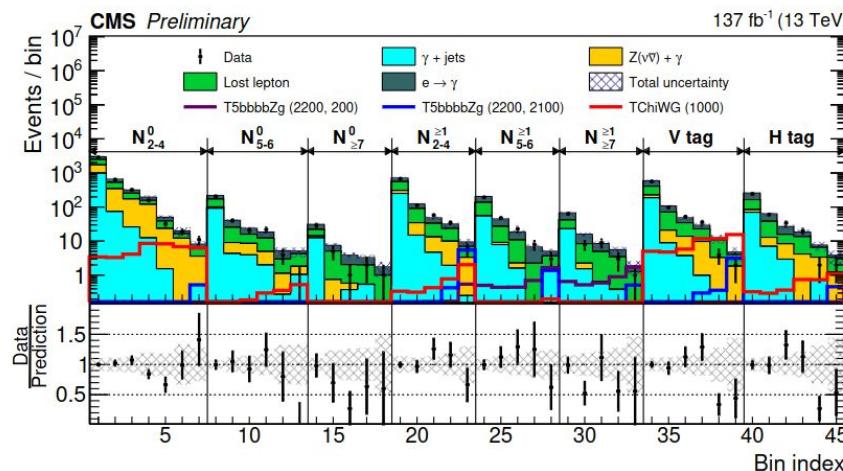
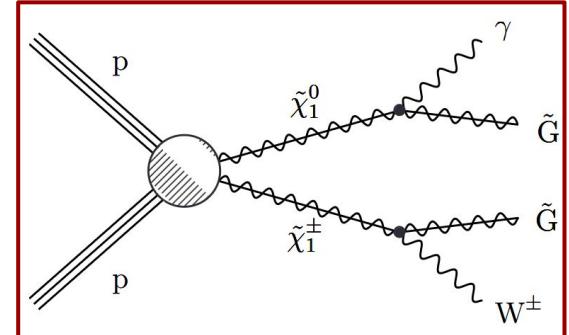


Analysis exploring gauge-mediated SUSY breaking (GMSB)

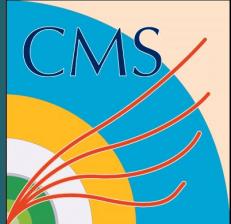
- Several EWK SUSY models considered, in final states with the gravitino as the LSP .
- Events selected with no leptons and at least 1 photon, two jets, large  $p_T^{\text{miss}}$  and large  $S_T$ :  

$$S_T = \sum_{\text{jets}} p_T + p_T^\gamma$$
- Split in Signal Region (SRs) depending on the tagging of W/Z/H bosons, and further split in terms of  $p_T^{\text{miss}}$  and  $N_{\text{jets}}$ .
- Main backgrounds:  $W\gamma + \text{jets}$ ,  $t\bar{t}\gamma + \text{jets}$ 
  - Estimated via data driven methods
- Chargino/neutralino masses excluded up to 1.3 TeV for the **TChiWG** model (more models in the [backup](#))

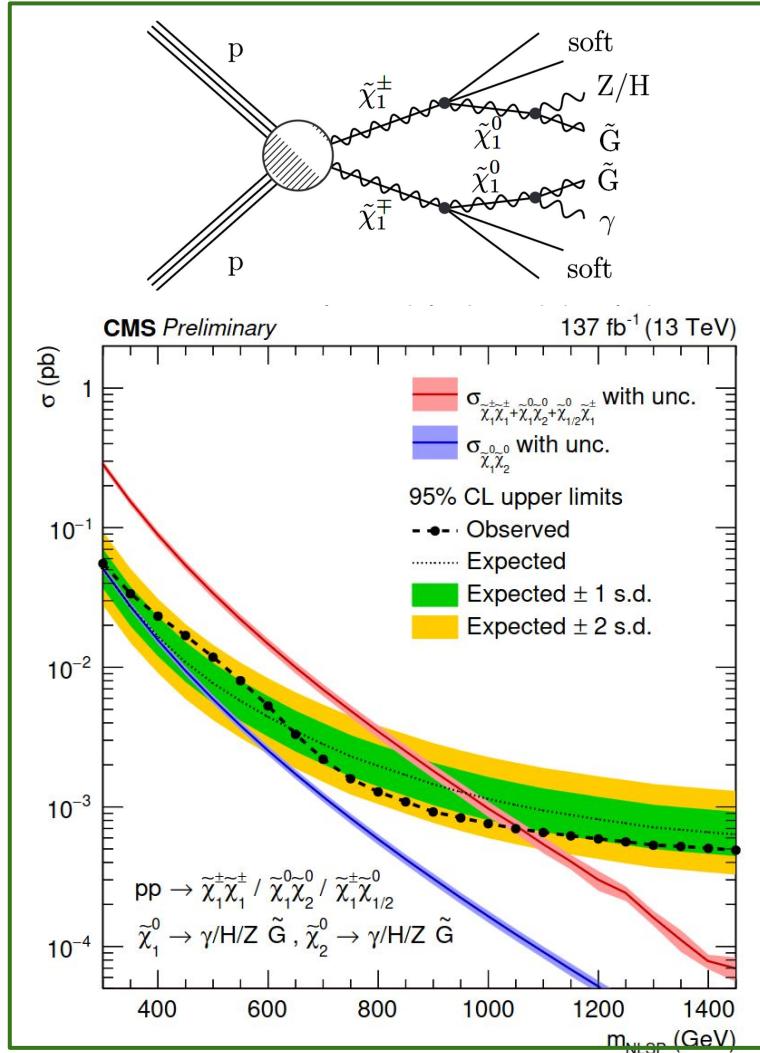
CMS-PAS-SUS-21-009



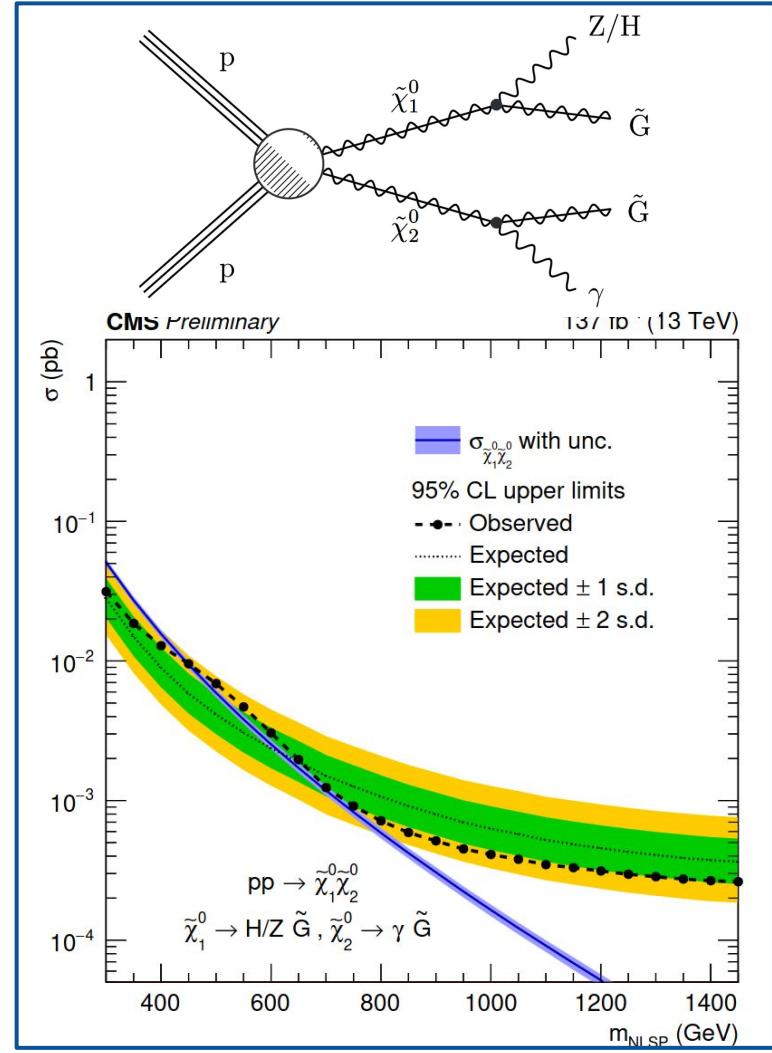
# Search targeting final states with a photon, jets and large MET: Other models



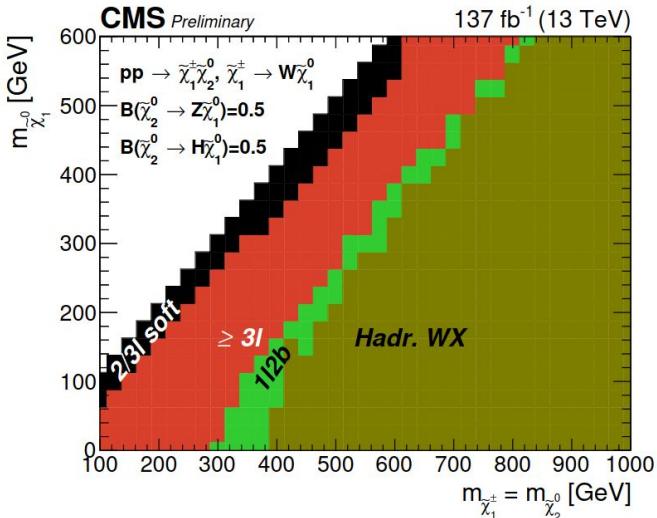
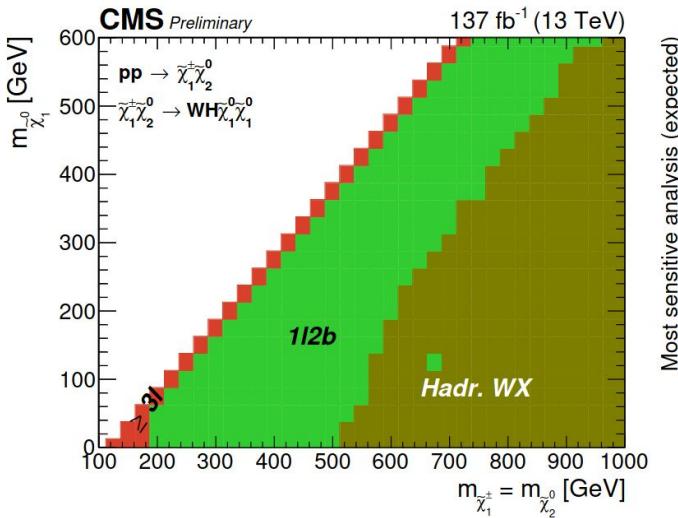
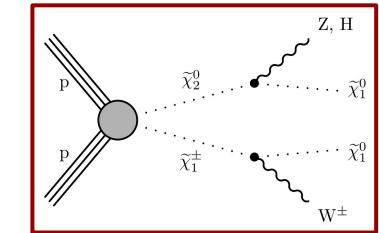
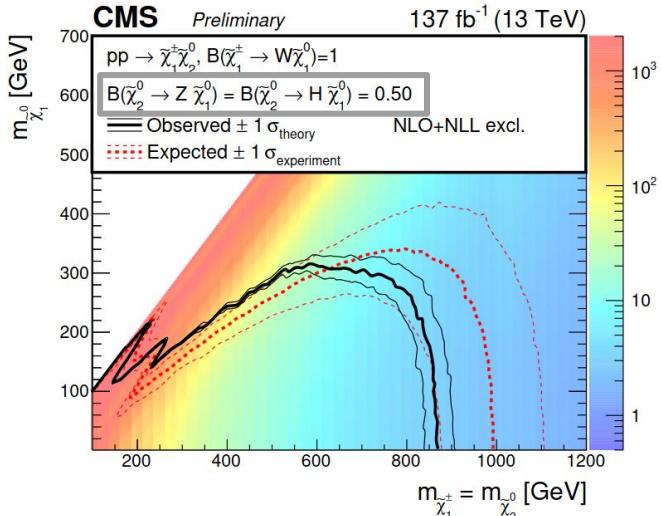
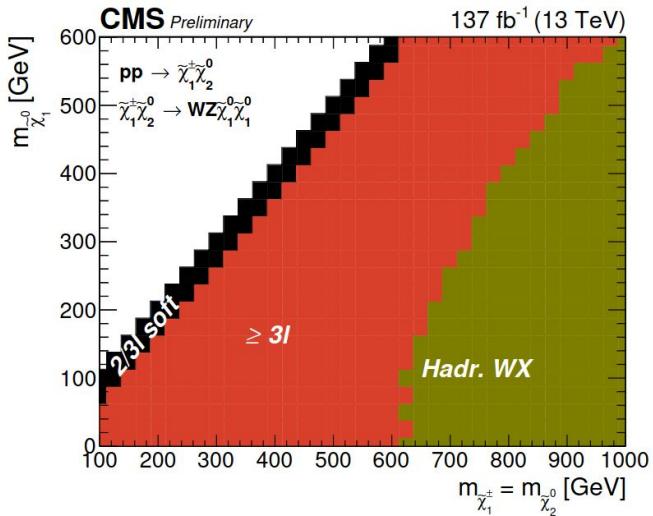
**TChiNG model**



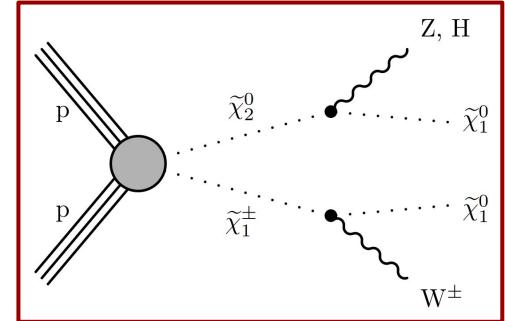
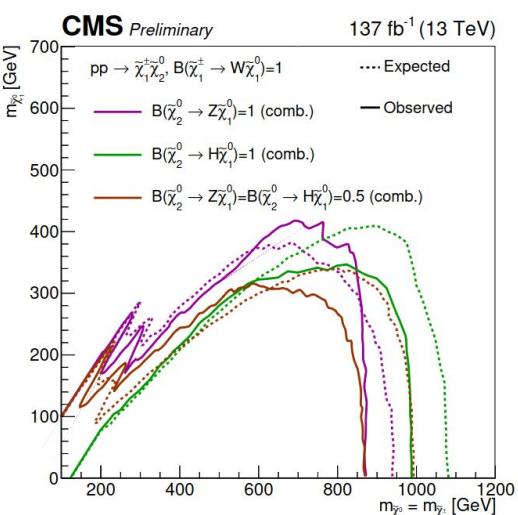
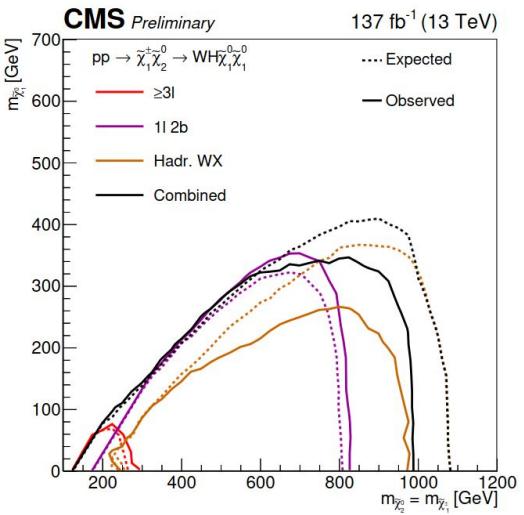
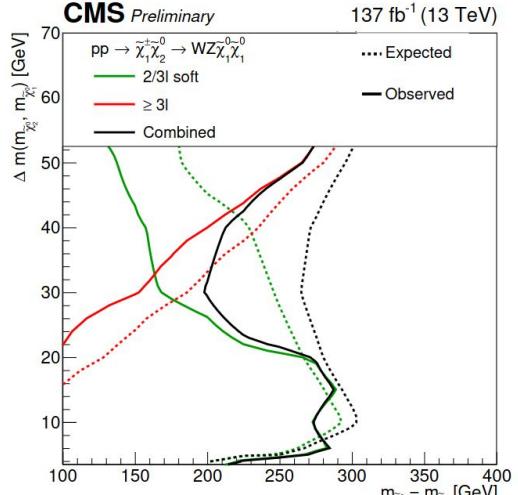
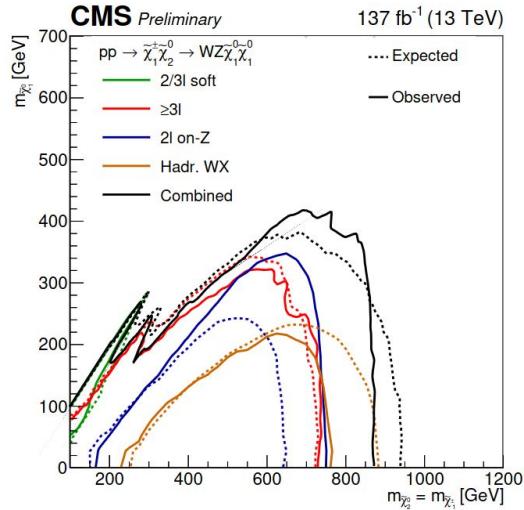
**TChiNGnn model**



# Chargino/neutralino production in WZ/WH final states: Best exclusion limit per mass point + additional interpretations



# Chargino/neutralino production in WZ/WH final states: Exclusion contours



Search	Gaugino	
	WZ	WH
2/3 $\ell$ soft	✓	
2 $\ell$ on-Z	✓	
2 $\ell$ non-res.		
$\geq 3\ell$	✓	✓
1 $\ell$ 2b		✓
4b		
Hadr. WX	✓	✓

# Event variables' definition

- $H_T$ : scalar  $p_T$  sum of all jets.

- Transverse mass:

$$m_T = \sqrt{2 p_T p_T^{\text{miss}} (1 - \cos \Delta\phi)}$$

- $m_{T2}$ : Stransverse mass

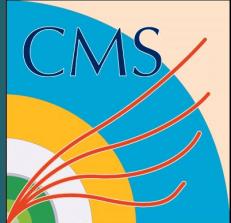
$$m_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{\text{miss}}} \left[ \max \left( m_T^{(1)}, m_T^{(2)} \right) \right]$$

- $m_{T2}(\ell\ell, \chi)$  (slepton production in Z/SM SOT leptons):

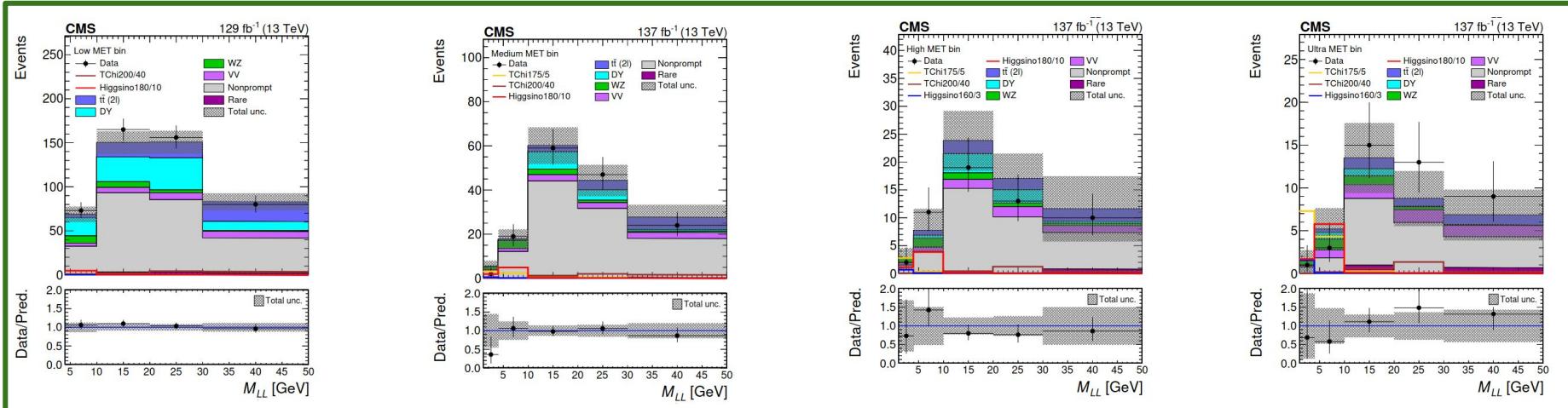
- $d_0$ : the distance of the transverse plane of the helical trajectory of the track with respect to the beam axis. +info [here](#)

# EWK SUSY Combination Input analyses

# 2/3l soft search: Binning change in 2l soft SR



JHEP04(2022)091



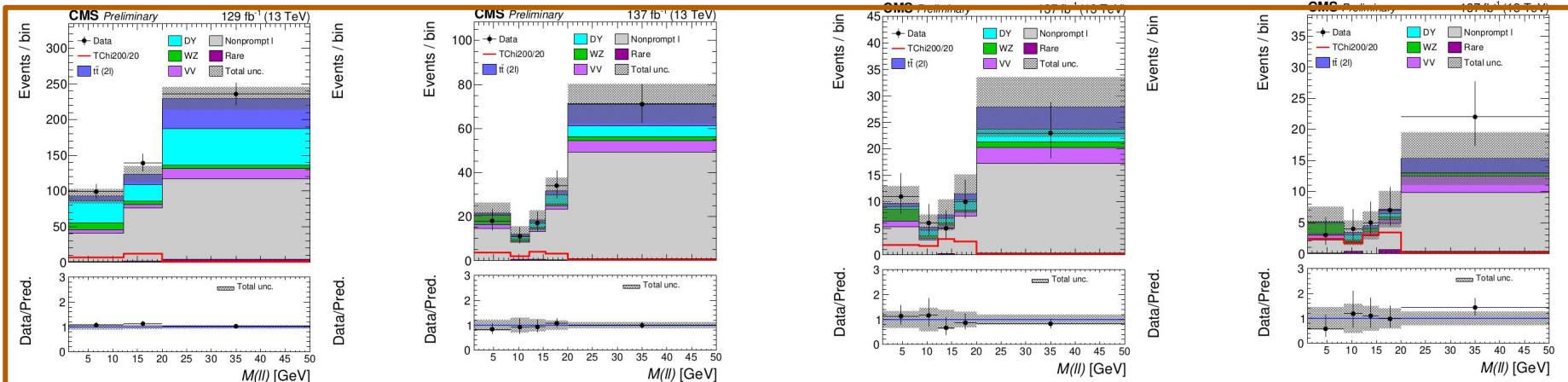
2l Low MET

2l med MET

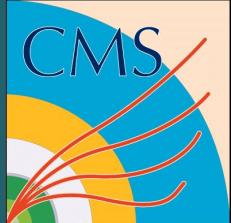
2l high MET

2l ultra MET

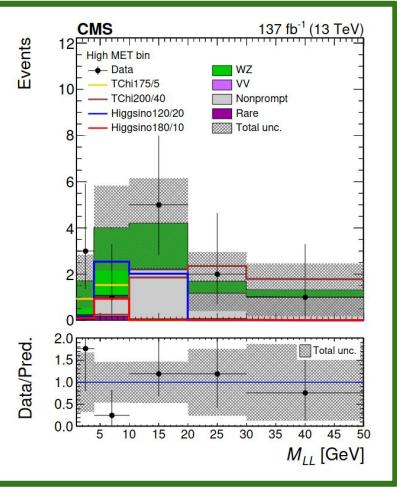
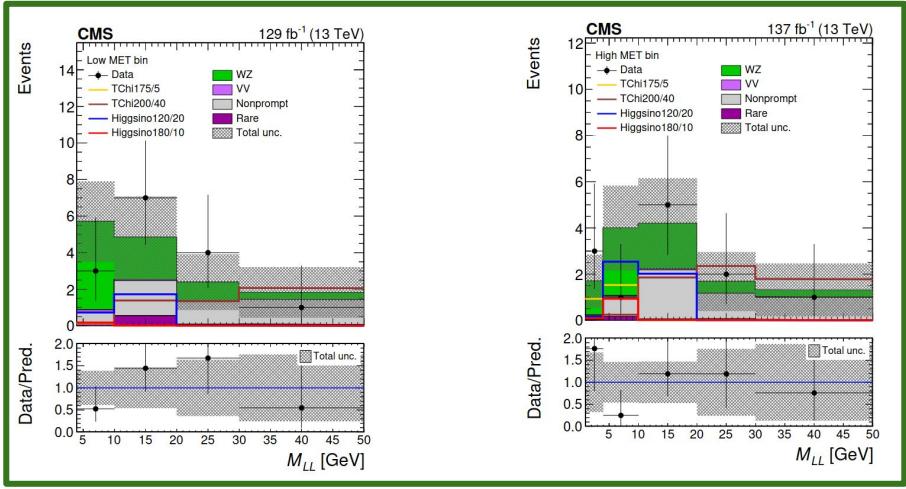
Updated binning



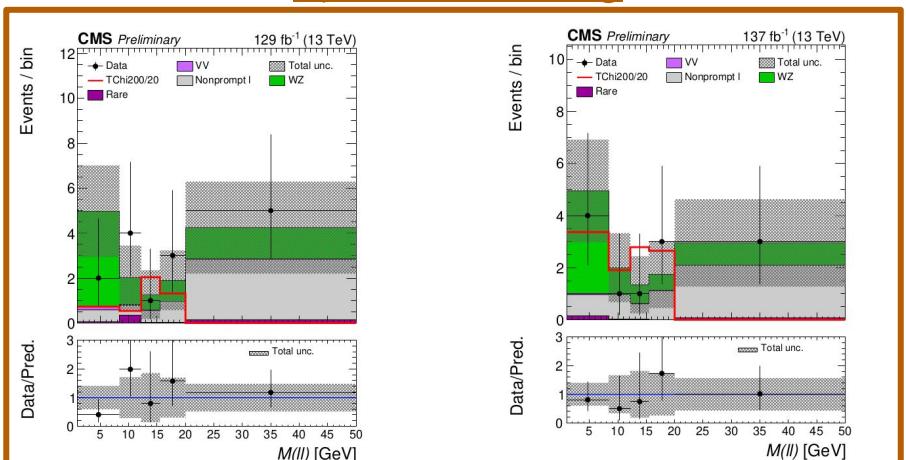
# 2/3l soft search: Binning change in 3l soft SR and binning for slepton production



JHEP04(2022)091

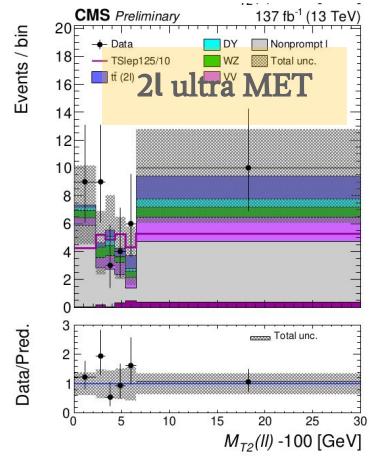
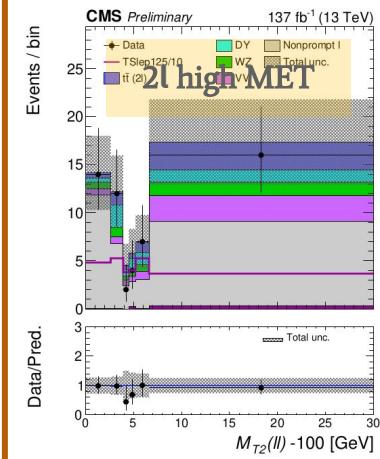
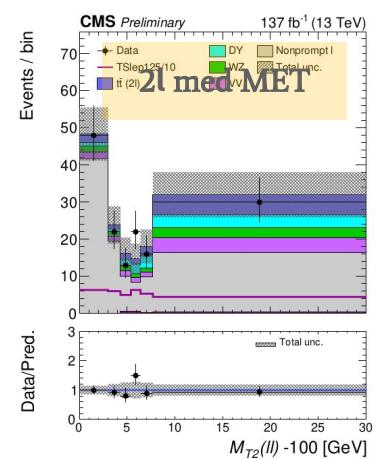
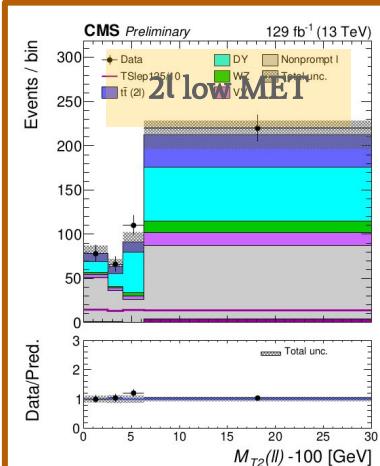


Updated binning

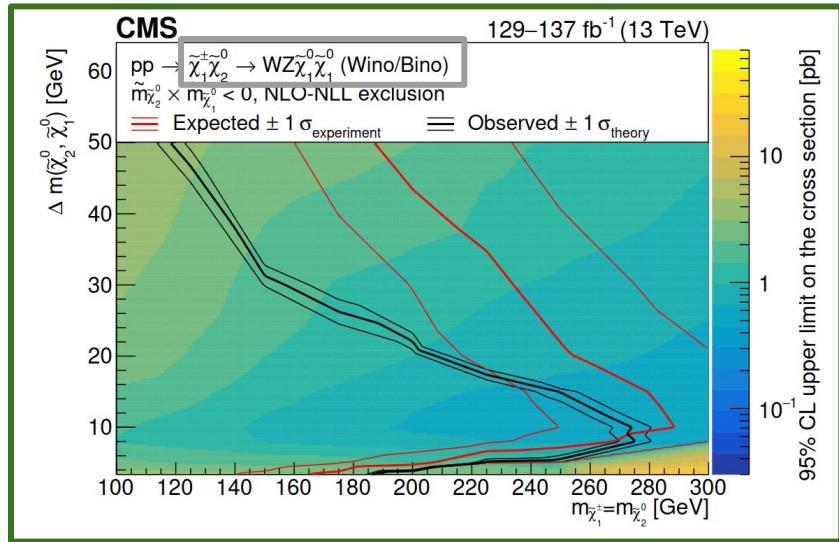
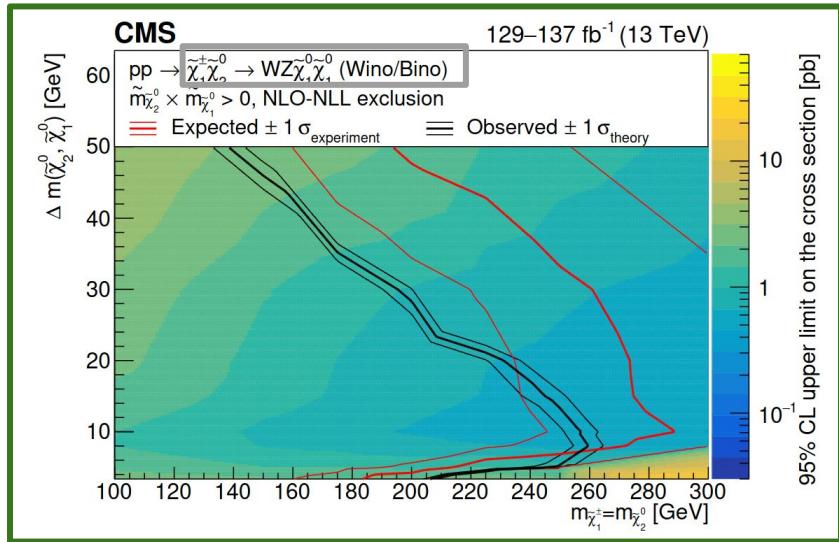
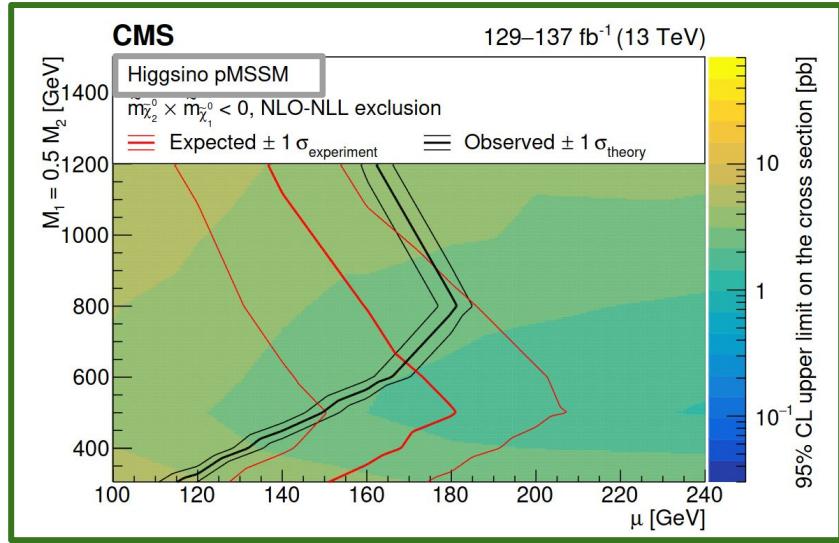
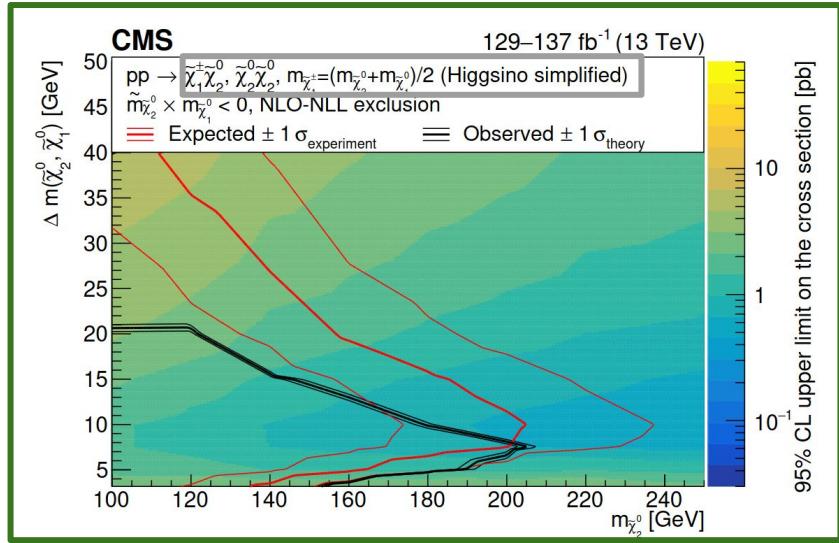
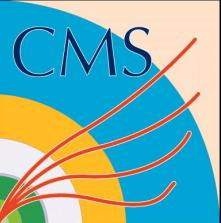


Binning for slepton production:

$M_{ll}$  not meaningful: use  $M_{T2}$  with  $M_X = 100$  GeV



# 2/3L soft search: Expected & Observed limits ([JHEP04\(2022\)091](#))

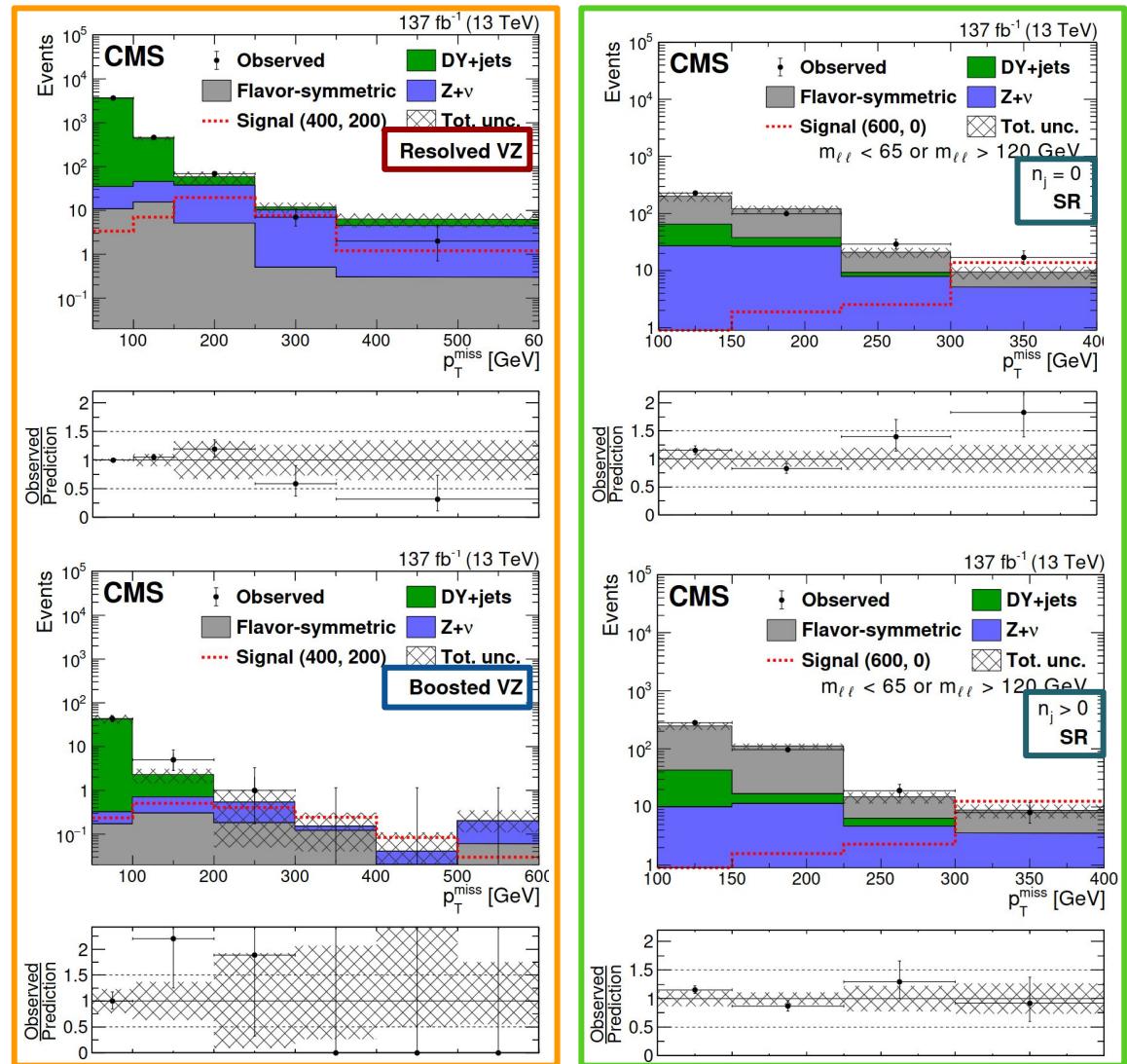


# 2l on Z/non resonant search: Signal region strategy (JHEP04(2021)123)



## 2l on-Z/non res: (Boosted)

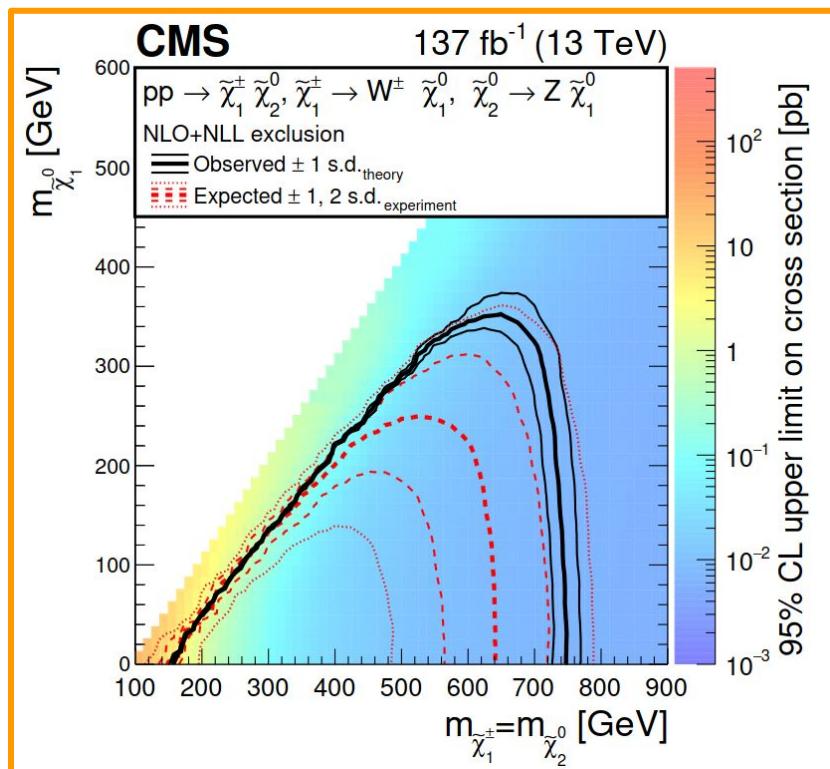
- ▶ Two OS SF leptons ( $ee/\mu\mu$ ), with SR split in terms of  $p_T^{\text{miss}}$ .
- ▶ on Z analysis (slepton production):  
 $86 < m_{ll} < 96 \text{ GeV}$ , standard (AK4) & wider (AK8) jet reconstructions, further splitting in terms of **jet content**.
- ▶ off Z analysis (GMSB models):  $20 < m_{ll} < 65 \text{ GeV}$  &  $m_{ll} > 120 \text{ GeV}$ . SR split in **resolved** and boosted topologies



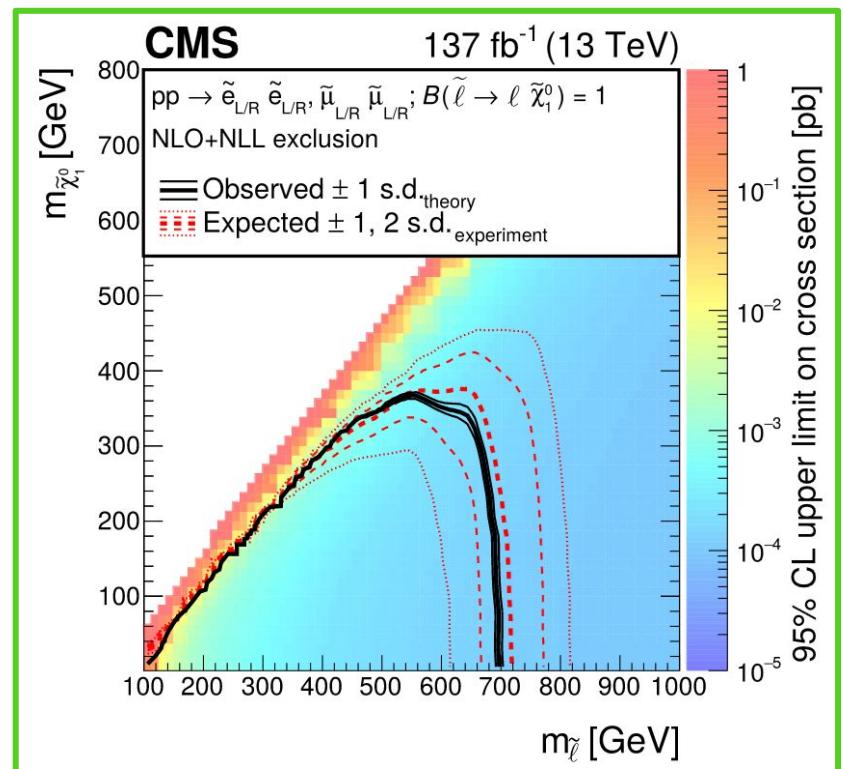
# 2l on Z/non resonant search: Expected & Observed limits ([JHEP04\(2021\)123](#))



## GMSB models

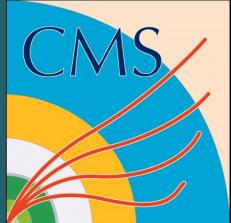


## Slepton production



# 1l 2b search:

Signal selection and observed/expected limits ([JHEP10\(2021\)045](#))



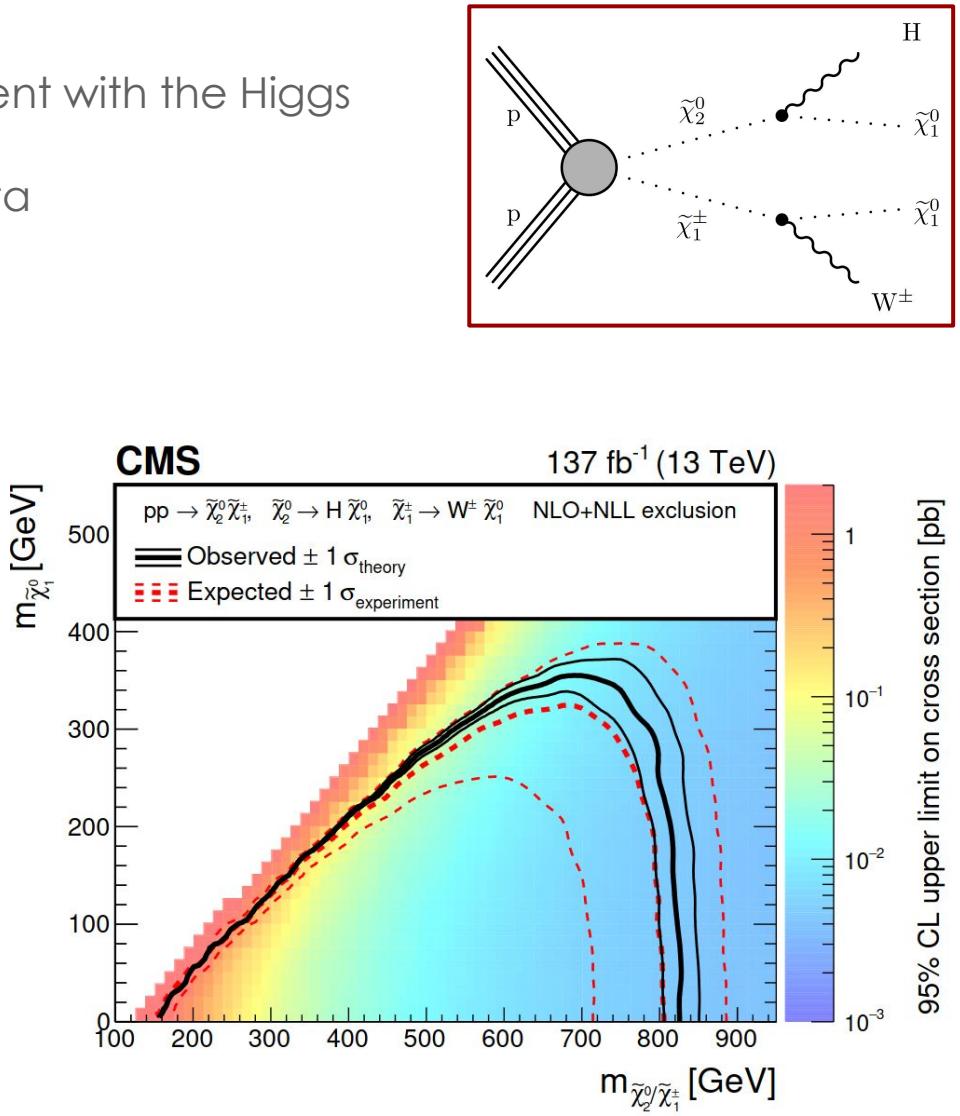
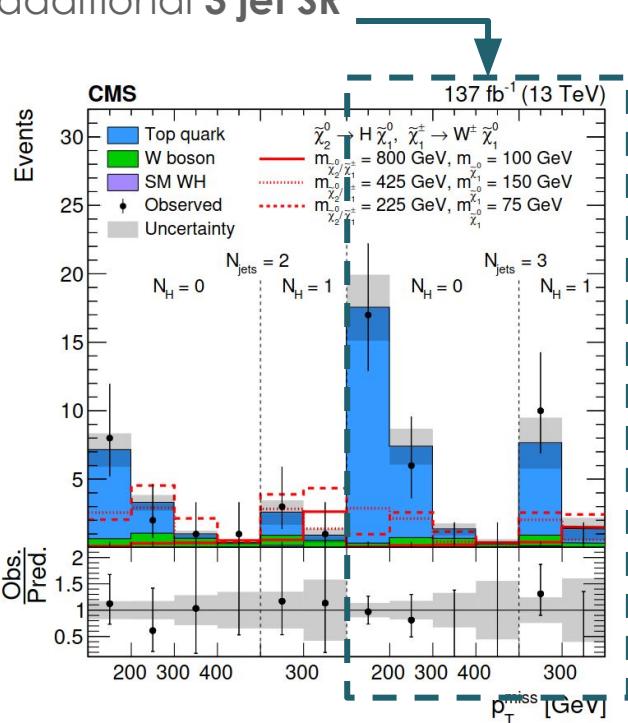
Targeting **WH final states** by selecting:

- $p_T^{l^1} > 30$  GeV, 2 b-tagged jets consistent with the Higgs boson mass, and large  $p_T^{\text{miss}}$ .

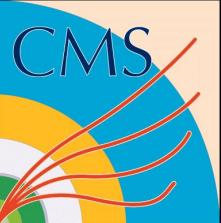
Improvements wrt analysis using 2016 data

([JHEP11\(2017\)029](#)):

- Use of a booster tagger
- Higher  $p_T^{\text{miss}}$  binning
- An additional **3 jet SR**

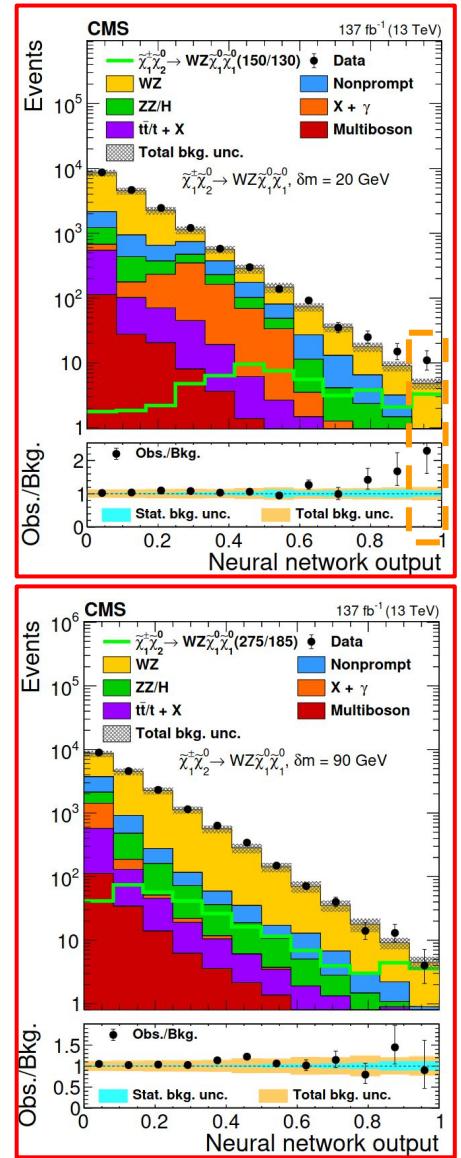
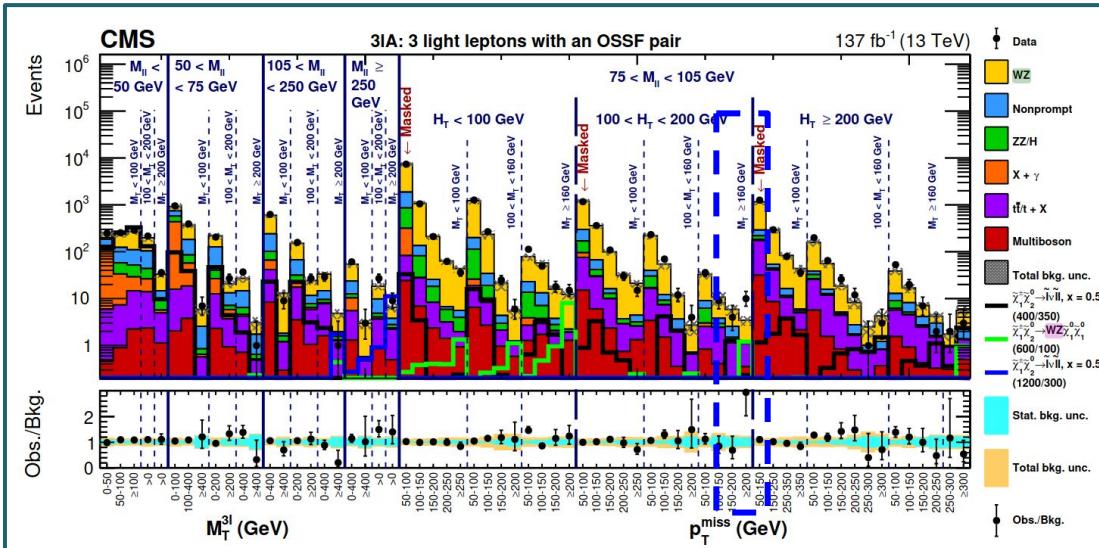


# >3l search: Signal selection (JHEP04(2022)147)

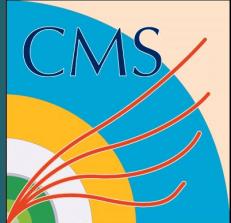


A search that targets neutralino production in diboson final states:

- 2l SS leptons (compressed region)
- 3l and 4l: up to 2 hadronic taus  $\tau_h$ .
  - $p_T^{l1} > 25 \text{ GeV}$ ,  $p_T^{l2} > 20 \text{ GeV}$
- Uses parametric neural networks (NN) with the mass splitting ( $\Delta m = m_{\text{NLSP}} - m_{\text{LSP}}$ ) as variable, trained per each signal hypothesis.
  - Gaining  $\sim 50 \text{ GeV}$  wrt SR analysis
  - Mild excesses found at low  $\Delta m$  in the NN case and in bins of high  $p_T^{\text{miss}}$  and  $100 < H_T < 200 \text{ GeV}$  in the SR case

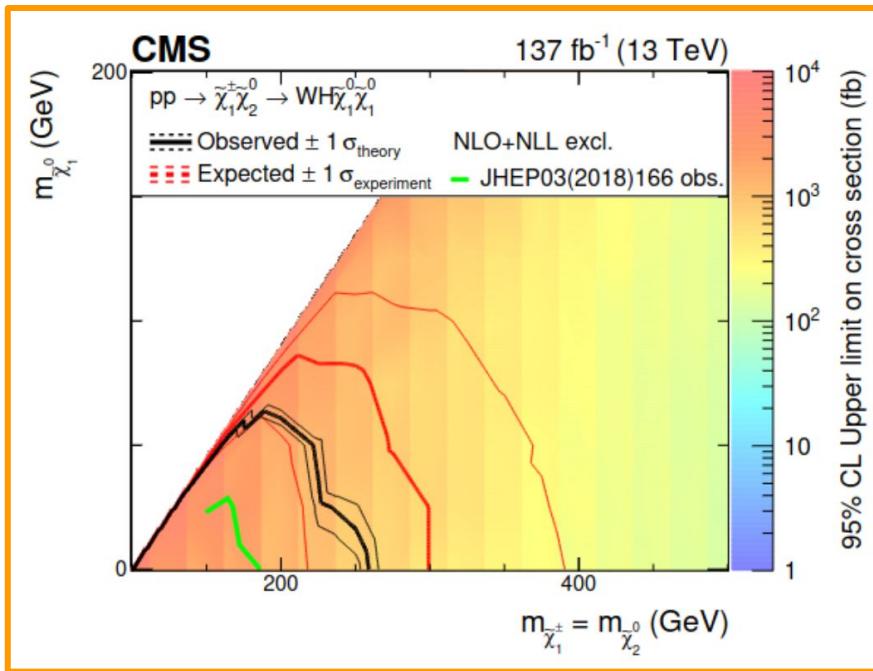


# $\geq 3l$ search: Observed/expected limits (JHEP04(2022)147)

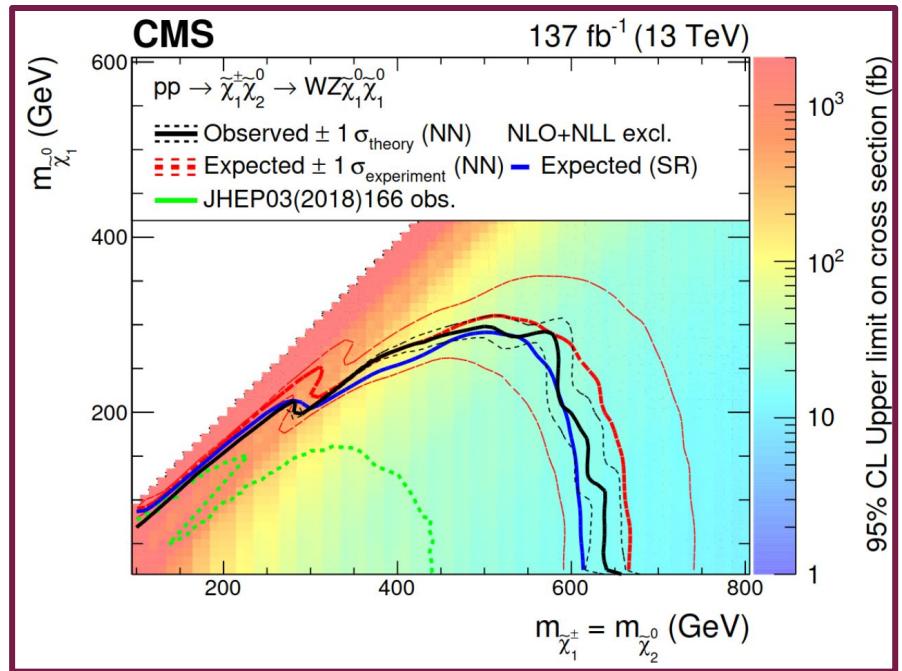


$\chi_1^\pm \chi_2^0$  production in:

WH mediated decays



WZ mediated decays



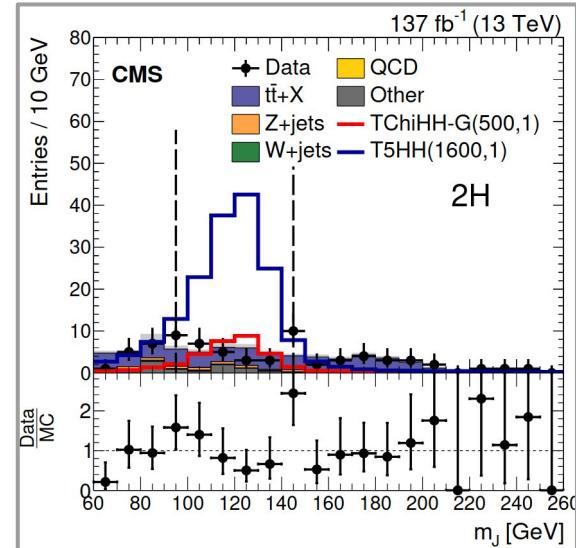
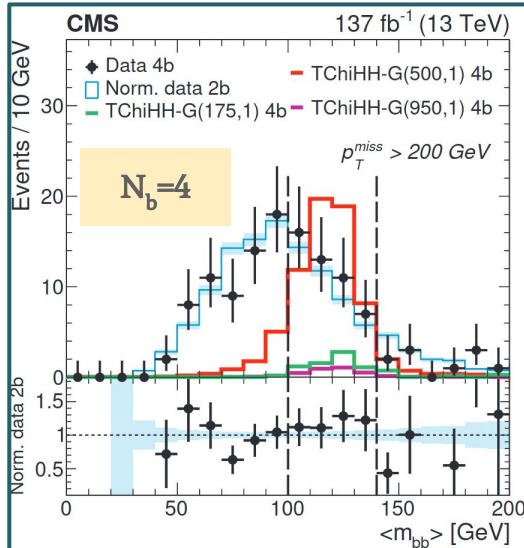
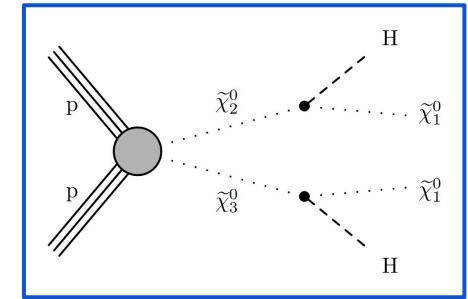
# 4b search:

## Signal selection (JHEP05(2022)014)



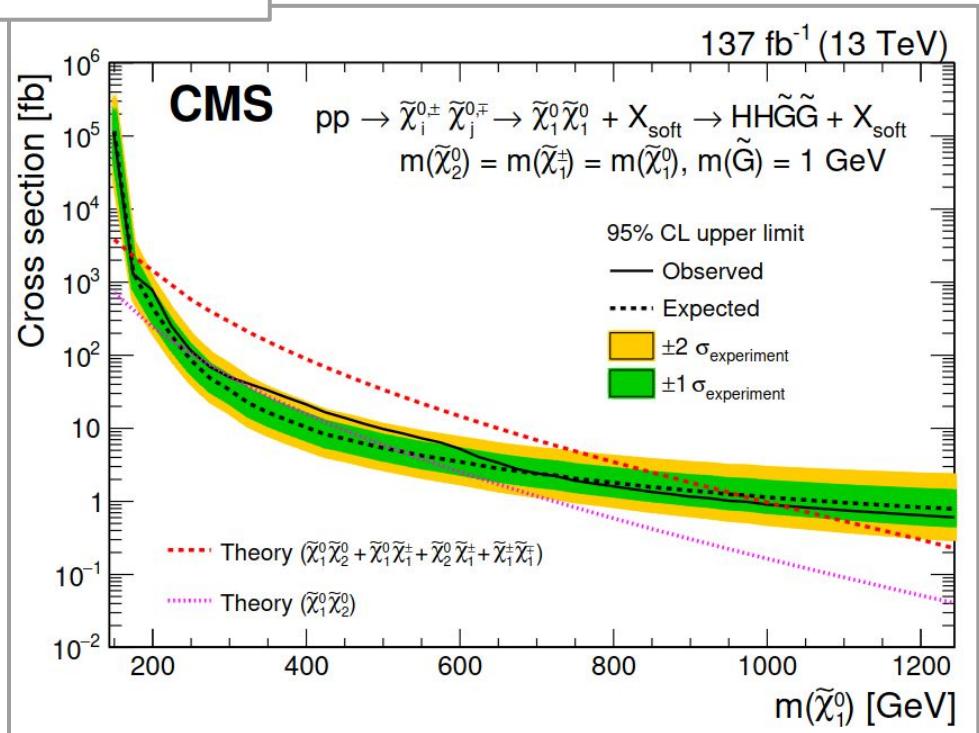
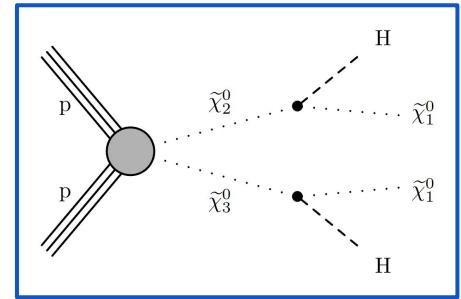
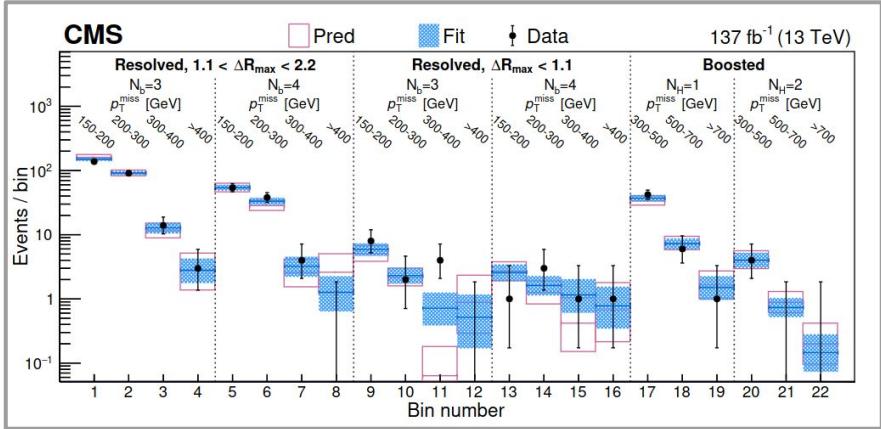
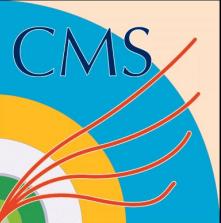
Targeting **HH final states** that considers both resolved and boosted scenarios, with no leptons

- ▶ **Resolved** scenario: 2 separate AK4 b-tagged jets.
  - Signal extracted in terms of the  $\langle m_{bb} \rangle$  of the two b jets and  $N_{b\text{-jets}}$
- ▶ **Boosted** scenario: 2b jets into an AK8 jet
  - Signal extracted in terms of the AK8 mass  $m_j$  and its  $n_H$
- ▶ Main background,  $t\bar{t}+X$  estimated with data driven ABCD method.



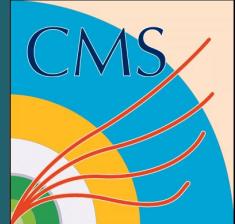
# 4b search:

Observed/expected yields and limits (JHEP05(2022)014)



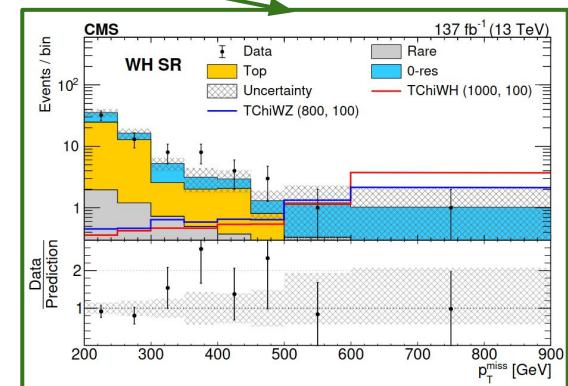
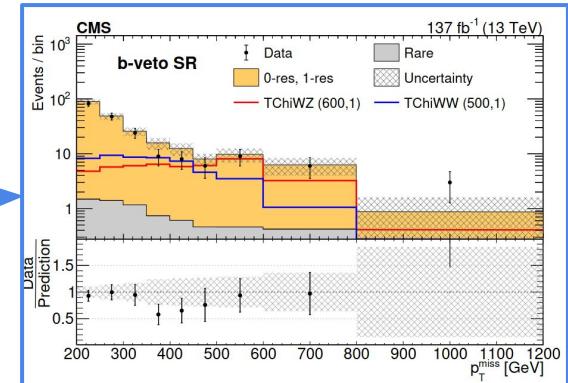
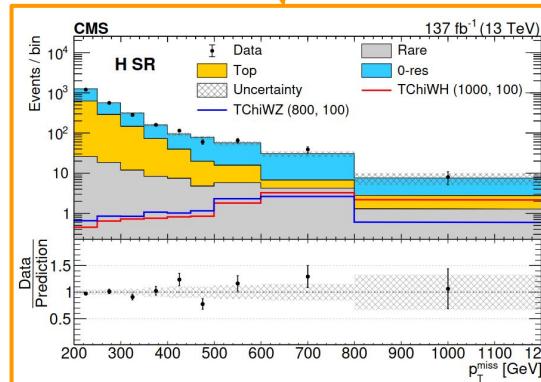
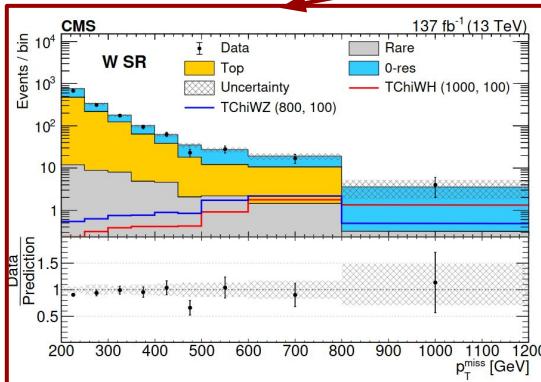
# Hadr WX search:

Signal strategy and observed/expected yields ([Phys.Lett.B 842 \(2023\) 137460](#))



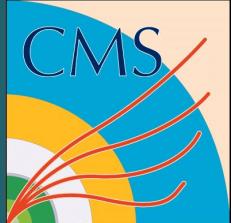
Hadr. WX: Fully hadronic final state

- ▶ At least 2 AK8 jets, compatible with W, Z and H bosons (Using machine learning algorithms).
- ▶ 2-6 AK4 jets
- ▶ Split in terms of b content:
  - **B-Veto SR**: AK8 jets with  $65 < m_j < 105$  GeV  
→  $\geq 1$  compatible with W and  $\geq 1$  with W/Z.
  - **B-Tag SR**: Subsplit in terms of the tagging  
→ AK8 jets compatible with **W,H** or **WH**, where  $H \rightarrow bb$ .



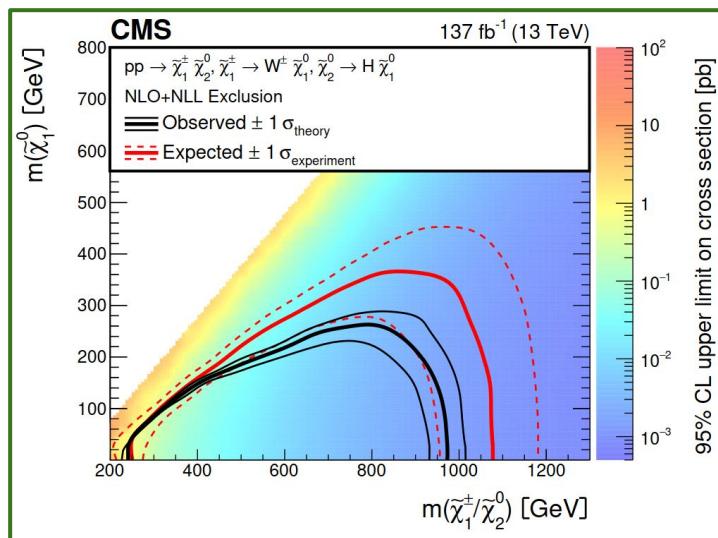
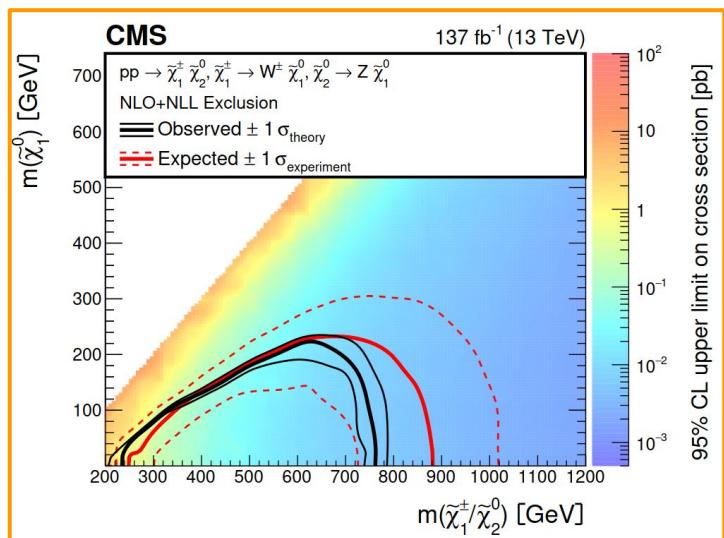
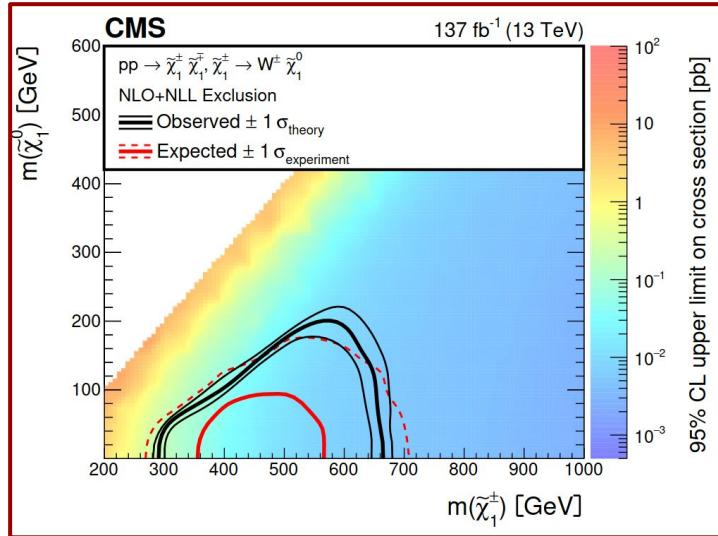
# Hadr WX search:

Observed/expected yields and limits (Phys.Lett.B 842 (2023) 137460)



Limits obtained for :

- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  decaying via **WW** bosons
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  decaying via **WZ** bosons
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  decaying via **WH** bosons

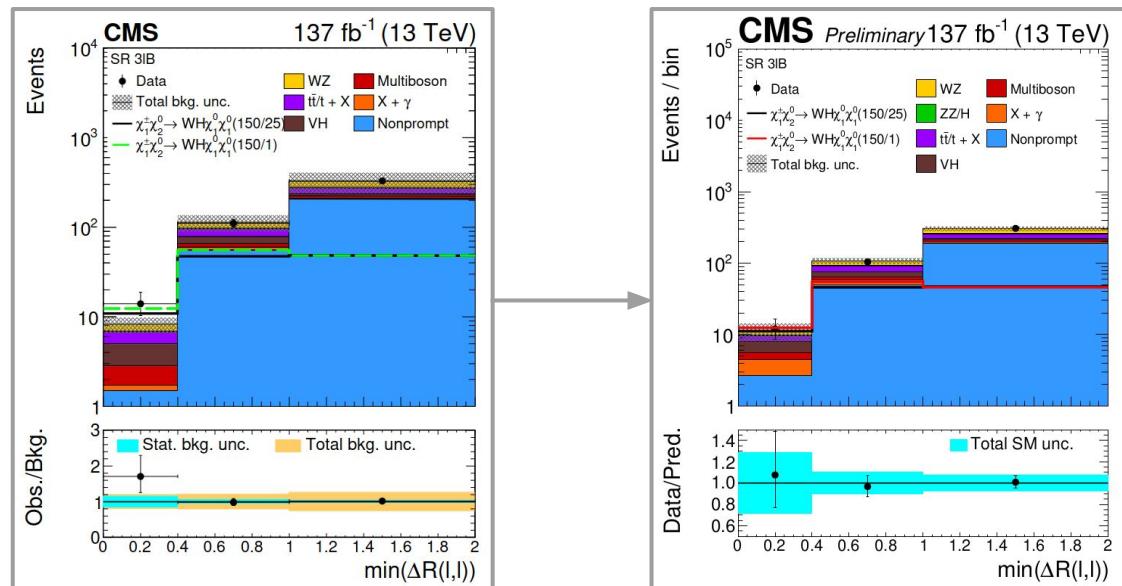
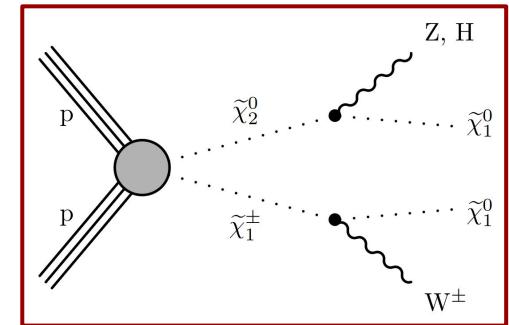


# Electroweakino Combination: overlaps

**CMS PAS SUS-21-008**

Two big overlaps existing between 3l regions of 2/3l soft analysis, and those in the 3l categories in the  $\geq 3l$  analysis:

- ▶ 3l WZ CR of 2/3l soft overlaps with the SR category of  $\geq 3l$ 
  - WZ CR removed from the fit, constrained through a nuisance parameter
- ▶ 3l soft SR ( $p_T^{ll} < 30$  GeV) with  $\geq 3l$  analysis ( $p_T^{ll} > 25$  GeV)
  - Updated the  $p_T^{ll}$  selection of  $\geq 3l$  analysis,
  - Only slight changes in the sensitivity (highest in the compressed WZ,  $\sim 1\text{-}10\%$  in  $20 < \Delta m < 70$  GeV)



# Combination strategy

## Leptonic analyses:

- 2/3l soft: [JHEP04\(2022\)091](#)
- 2l on-Z/non res: [JHEP04\(2021\)123](#)
- 3l: [JHEP04\(2022\)147](#)

## Hadronic/Semihadronic analyses:

- 1l 2b : [JHEP10\(2021\)045](#)
- 4b: [JHEP05\(2022\)014](#)
- Hadr. WX: [Phys.Lett.B 842 \(2023\) 137460](#)

Search	Gaugino		GMSB			Higgsino-bino			Sleptons
	WZ	WH	ZZ	ZH	HH	WW	HH	WH	$\ell^+\ell^-$
2/3 $\ell$ soft		all							2 $\ell$ soft
2 $\ell$ on-Z		EW		EW	EW				
2 $\ell$ non-res.									Slepton
$\geq 3\ell$	SS, A(NN)	SS, A-F	all	all	all				SS, A-F
1 $\ell$ 2b		all						all	
4b					all		3-b, 4-b, 2-bb		
Hadr. WX	all	b-tag				b-veto		b-tag	