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

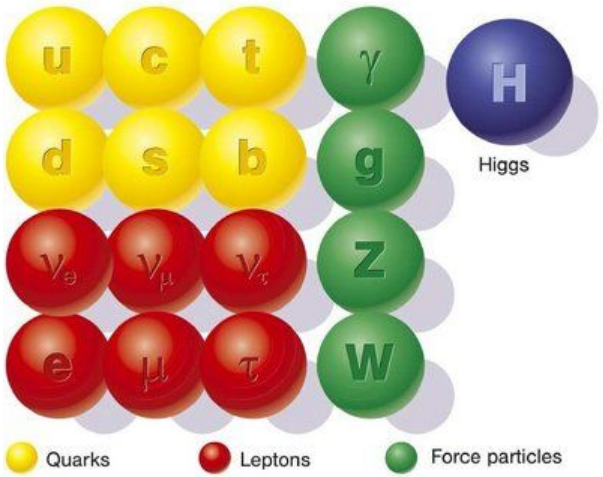
XV CPAN (Centro Nacional de Física de Partículas, Astropartículas y Nuclear) Days

Santander, Spain, 2nd October, 2023

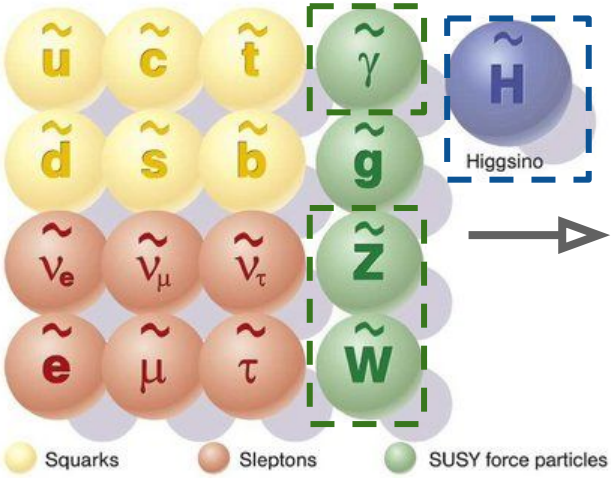
Electroweak SUSY in a nutshell

- 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 (~order of the TeV)

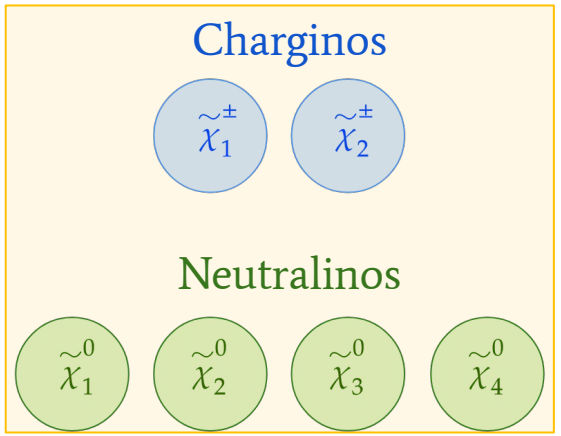
SM



MSSM



Electroweakinos



Electroweak SUSY: Challenges

Multiple SUSY models:

➞ Particles' masses unknown and large parameter space to cover

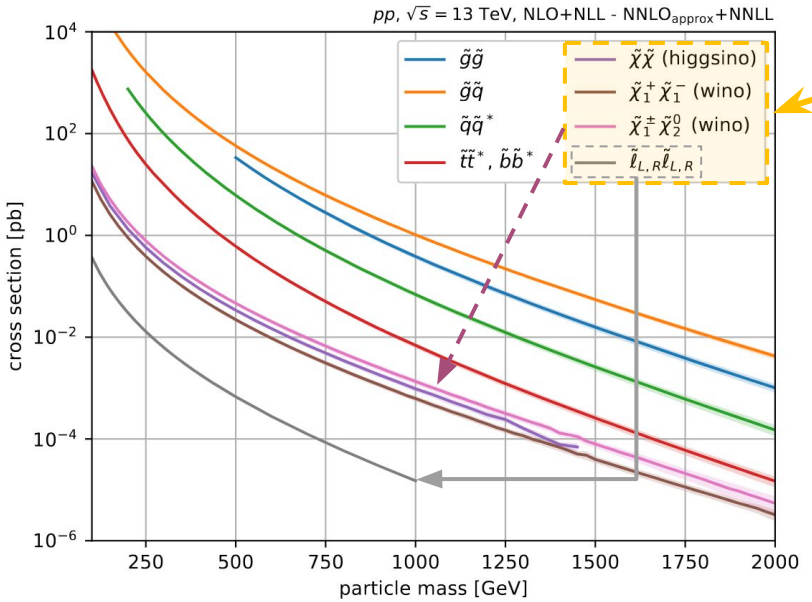
Challenges

- 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:

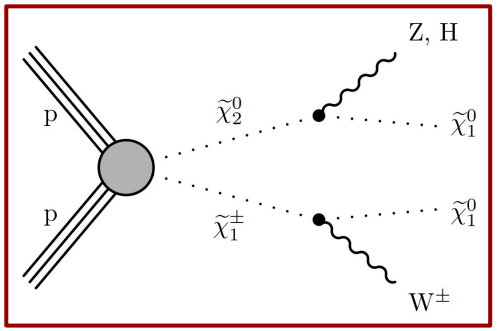
➞ **CMS PAS SUS-21-008**

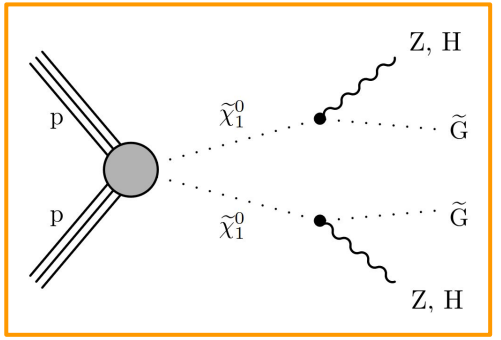


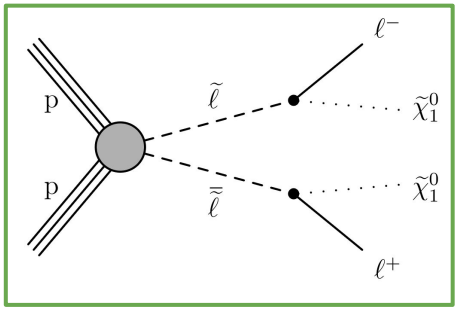
Electroweakino Combination: Considered Models

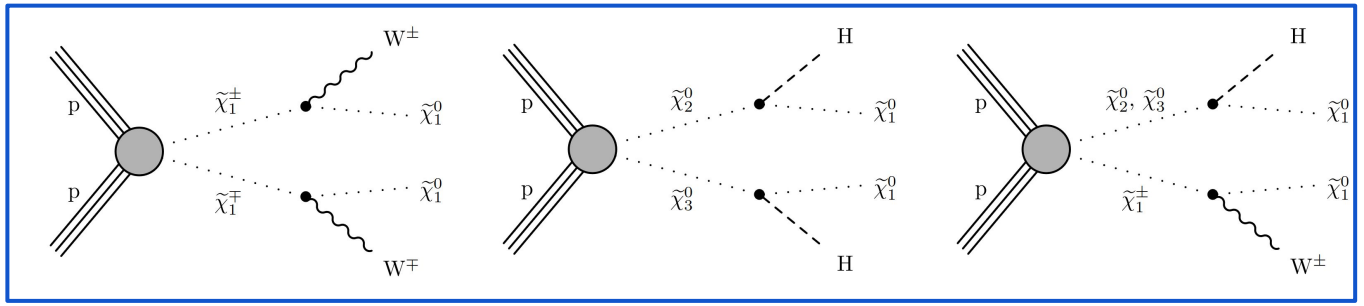
CMS PAS SUS-21-008

- An improvement respect the previous Eletroweakino 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









Combination strategy

Leptonic analyses:

- 2/3l soft: JHEP04(2022)091
- 2l on-Z/non res: JHEP04(2021)123
- ≥3l: JHEP04(2022)147

Hadronic/Semihardronic 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	✓								✓
2ℓ on-Z	✓		✓	✓					
2ℓ 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

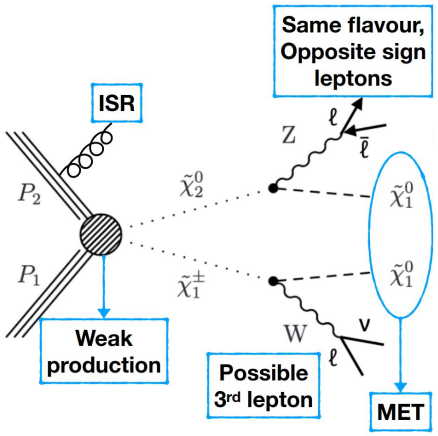
Leptonic analyses:

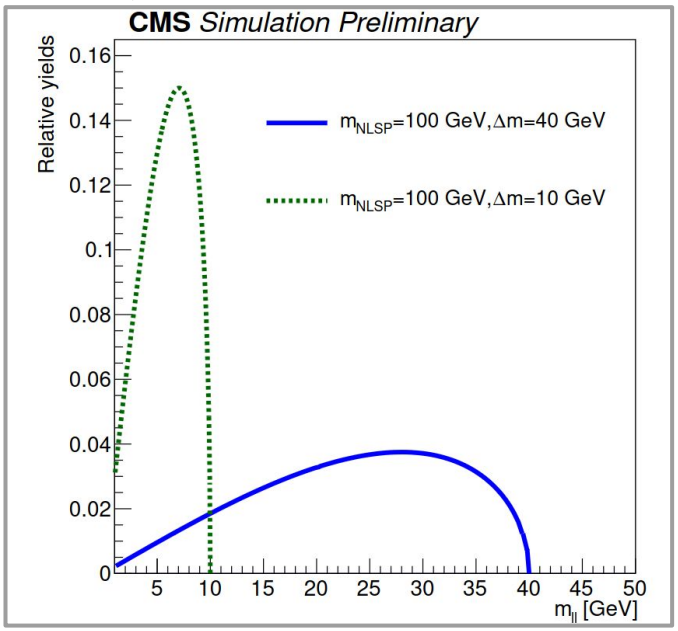
- **2/3l soft**: JHEP04(2022)09 (Compressed)
  - "2l bin": Two opposite sign (OS) same flavour (SF) lepton pair,
  - "3l bin": One additional SF lepton (e, μ)
  - 3.5 (5) < p_T(lep)<30 GeV for 2l (3l) bins and an ISR jet.
  - Further binned in terms of p_T^{miss} and m_{ll}
  - → New parametric signal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

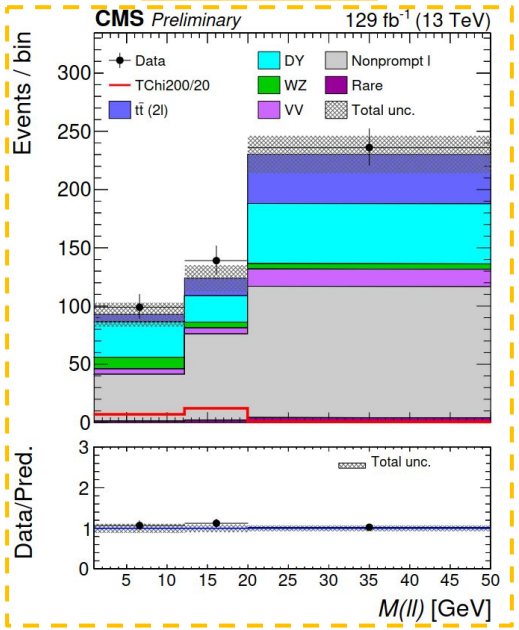
Optimisation of 2/3l soft analysis

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

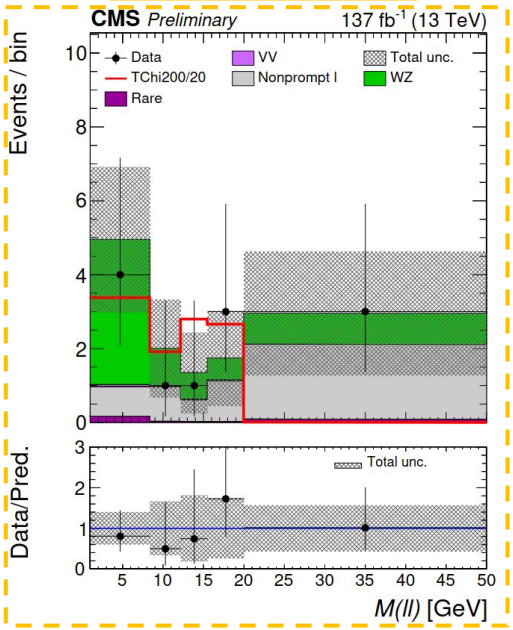




low p_T^{miss}, 2l



medium p_T^{miss}, 3l



Hadronic & semihadronic input analyses

Hadronic & Semihadronic analyses:

- **1l 2b**: JHEP10(2021)045
  - p_T^{l1}>30 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→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

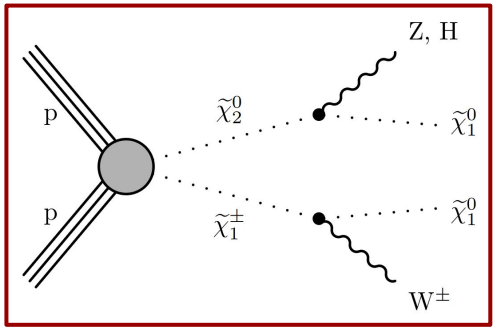
→ Additional sensitivity in the uncompressed spectra

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

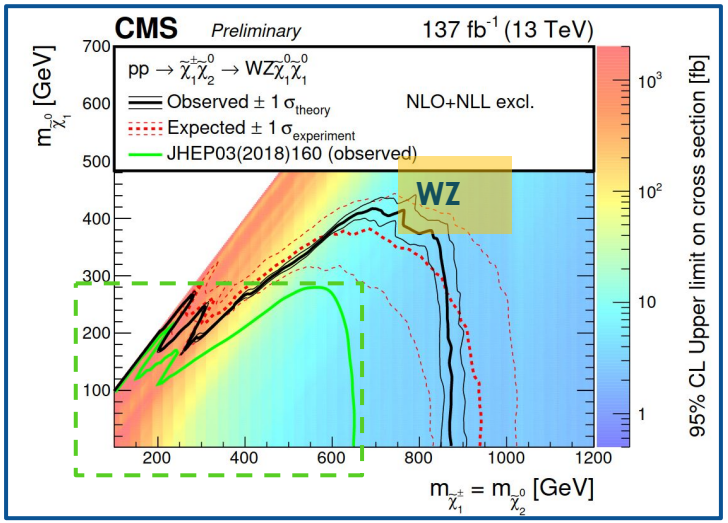
Chargino/neutralino production in WZ/WH final states

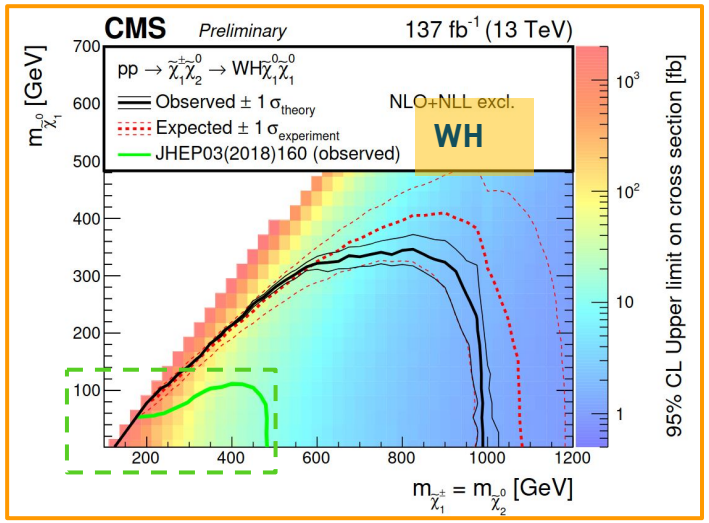
Several analyses contribute to the combined limit (more information in backup):

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



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

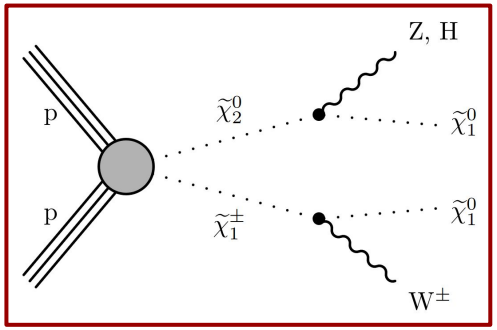


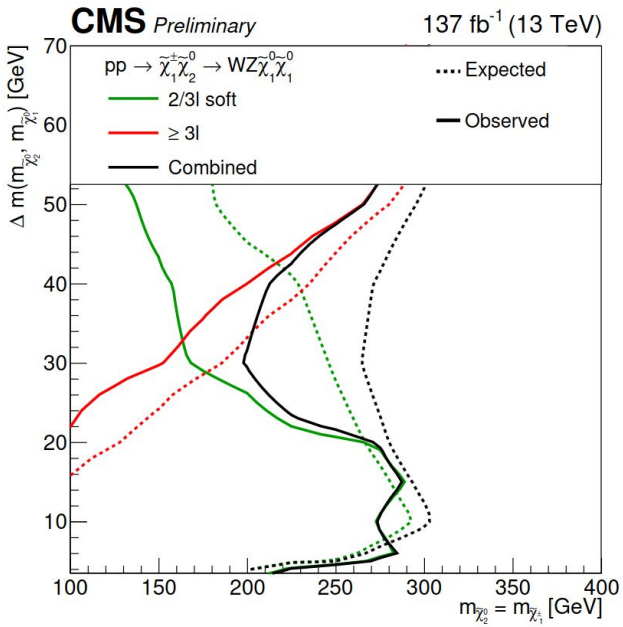


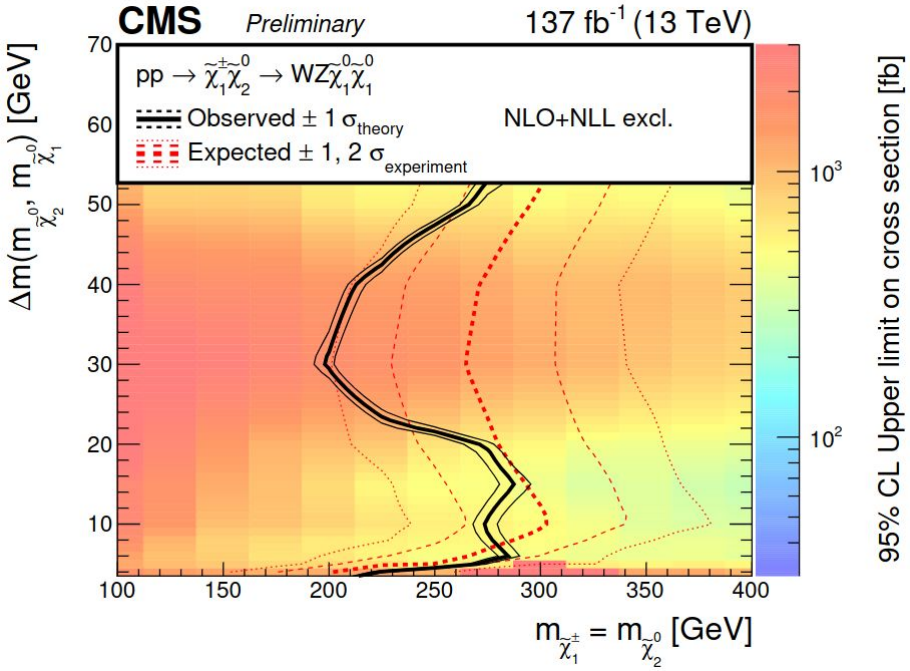
Chargino/neutralino production in WZ/WH final states
Compressed

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

- **2/3l soft** and **≥3l** analyses complement each other.
  - Orthogonal lepton p_T
  - Different discriminant variables
- Expected limits close gap at Δm~40 GeV, where a mild (2σ) excess is found



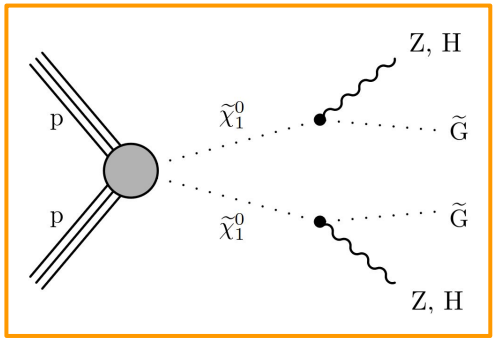




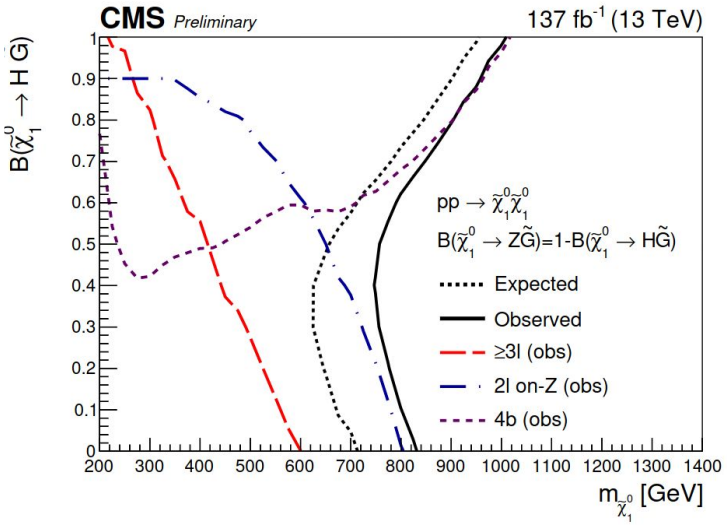
Chargino/neutralino production in GMSB models

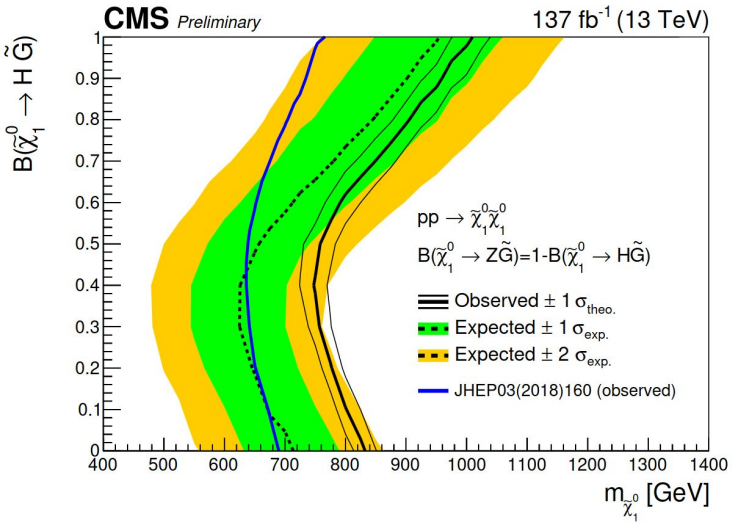
In GMSB models, $\chi_1^{\pm}$, χ_1^0 and χ_2^0 have minimal mass splitting:

- Models can be reduced to χ_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
$2/3\ell$ soft			
2ℓ on-Z	✓	✓	
2ℓ non-res.			
$\geq 3\ell$	✓	✓	✓
$1\ell 2b$			
4b			✓
Hadr. WX			

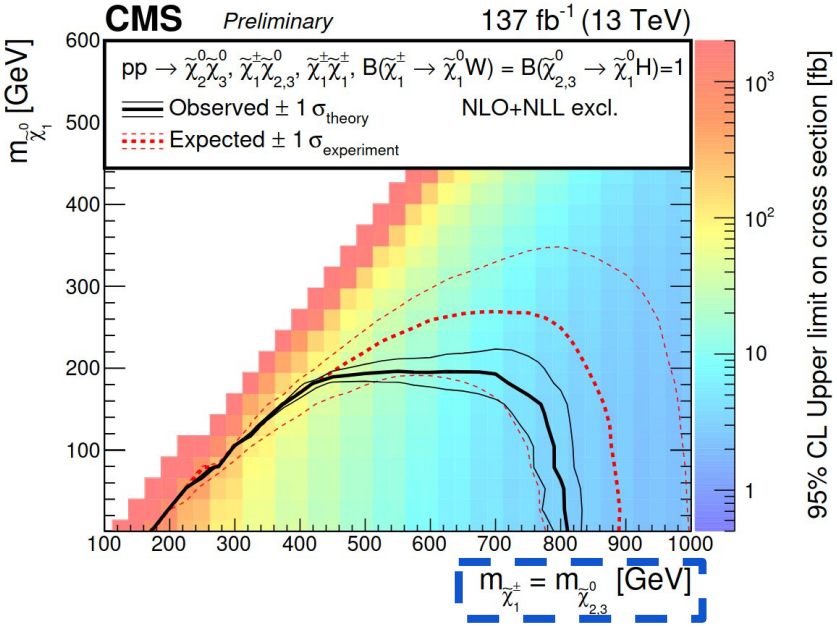


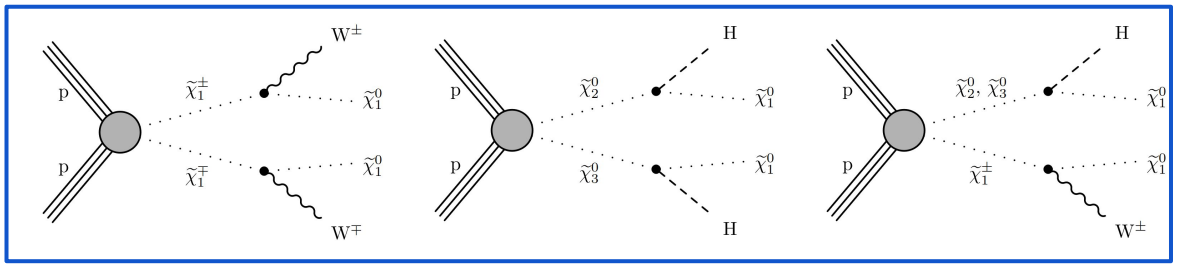


Chargino/neutralino production in Higgsino-bino models

New interpretation wrt JHEP04(2022)09

- χ_1^0 as LSP, and a **mass degenerate Higgsino triplet**:
- Target either WW, HH or WH final states with:
  - $B(\chi_1^{\pm} \rightarrow W\chi_1^0) = 100\%$
  - $B(\chi_{2,3}^0 \rightarrow H\chi_1^0) = 100\%$
- More sensitive to the uncompressed phase space



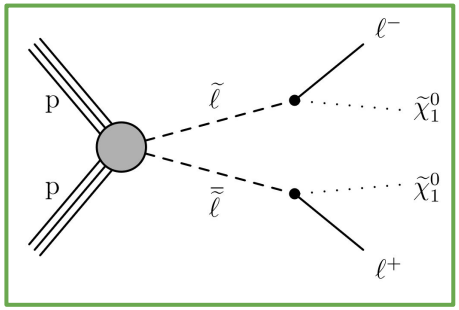


Search	Higgsino-bino		
	WW	HH	WH
2/3ℓ soft			
2ℓ on-Z			
2ℓ non-res.			
≥3ℓ			✓
1ℓ2b			✓
4b		✓	
Hadr. WX	✓		✓

Slepton production

Particularly difficult due to their small cross sections.

- Slepton as Next to LSP with lightest neutralino as LSP
- 1st & 2nd generation (3rd covered in CMS-PAS-SUS-21-001)



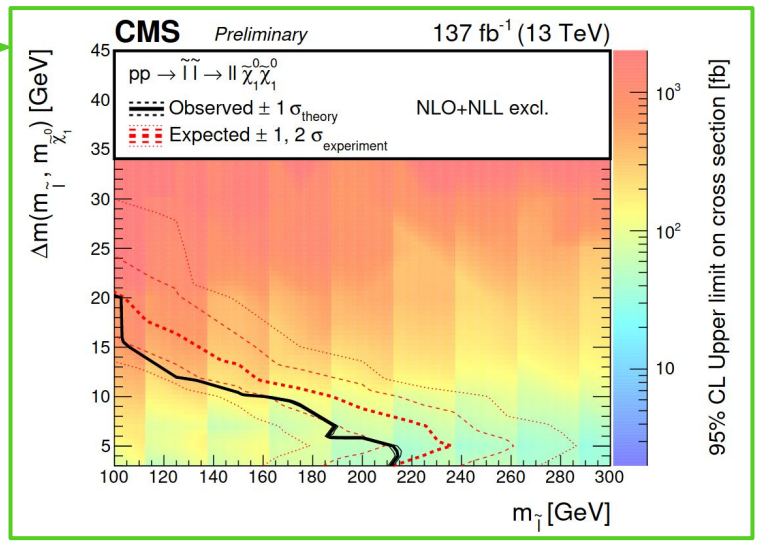
2/3l soft analysis targeting compressed signatures:

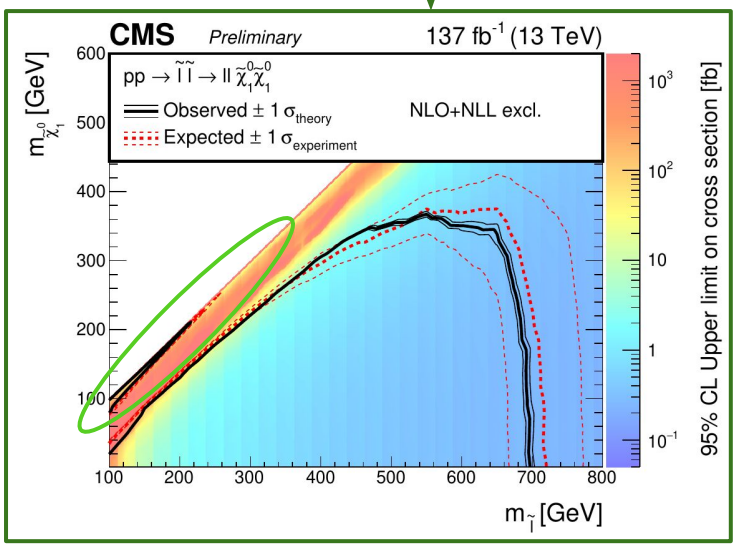
- Similar SR as for Wino-bino interpretation
- $m_{T2}(ll,\chi)$ as discriminant variable:

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

2l non resonant used for non compressed scenario:

- Equivalent SR as before

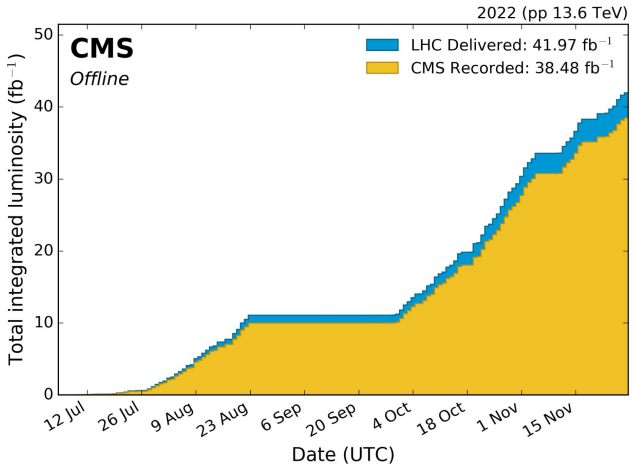




Summary and future prospects

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 **Δm=5 GeV** and **110-720 GeV** for **Δm=50 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

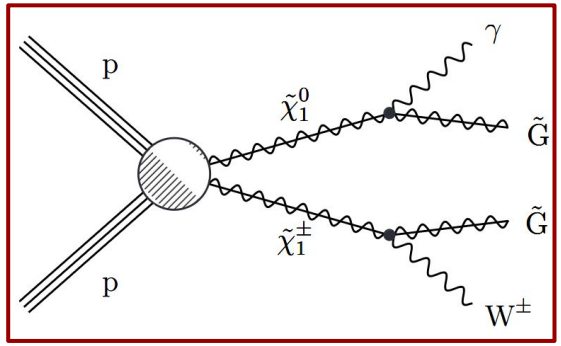
BACKUP

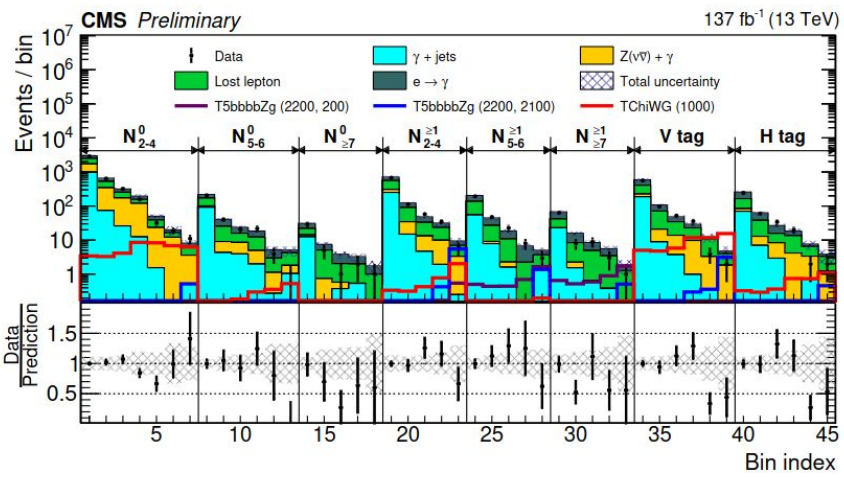
Search targeting final states with a photon, jets and large MET

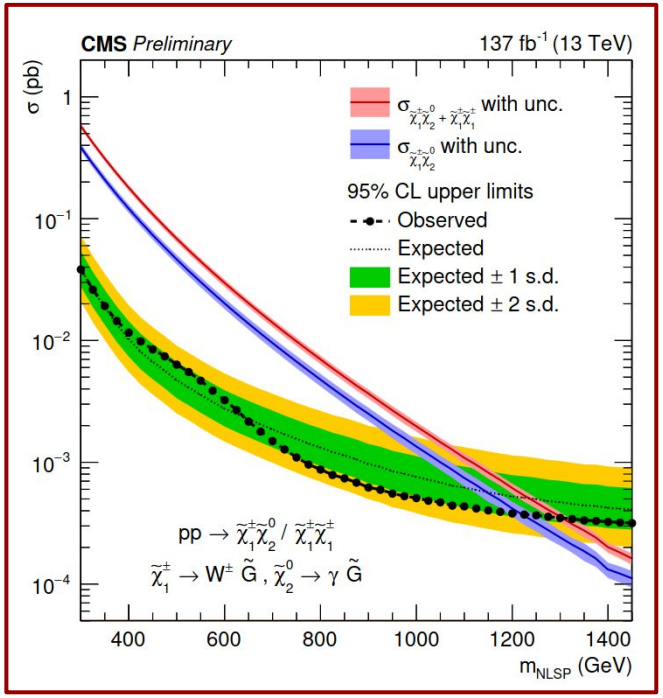
CMS-PAS-SUS-21-009

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

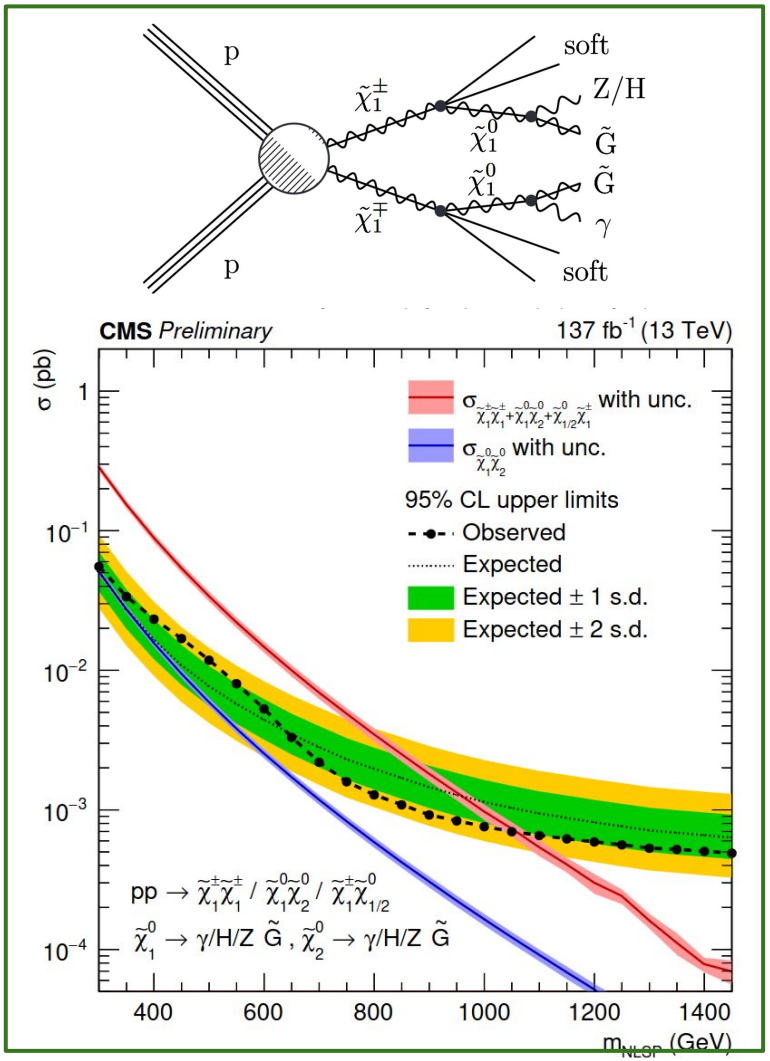




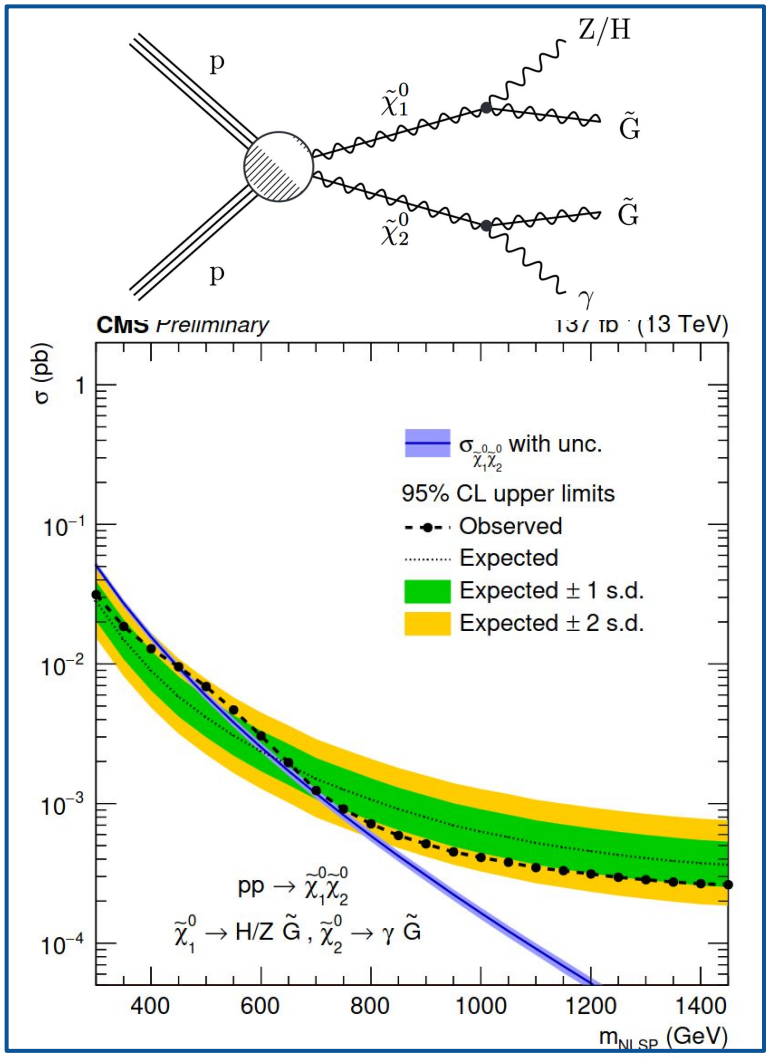


Search targeting final states with a photon, jets and large MET: Other models

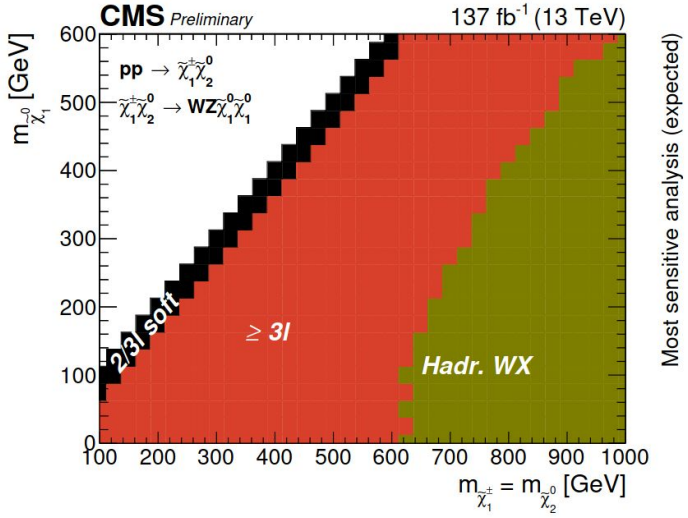
TChiNG model

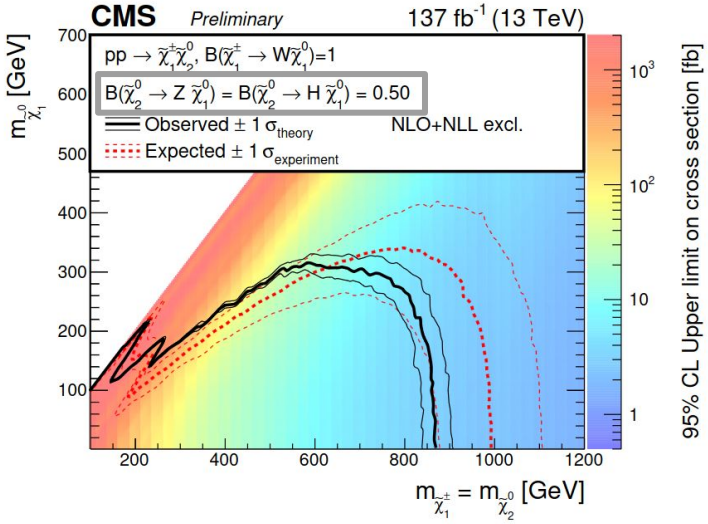


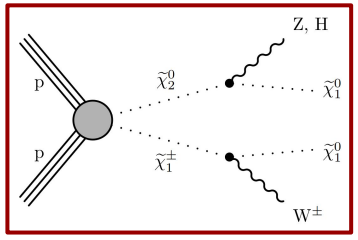
TChiNGnn model

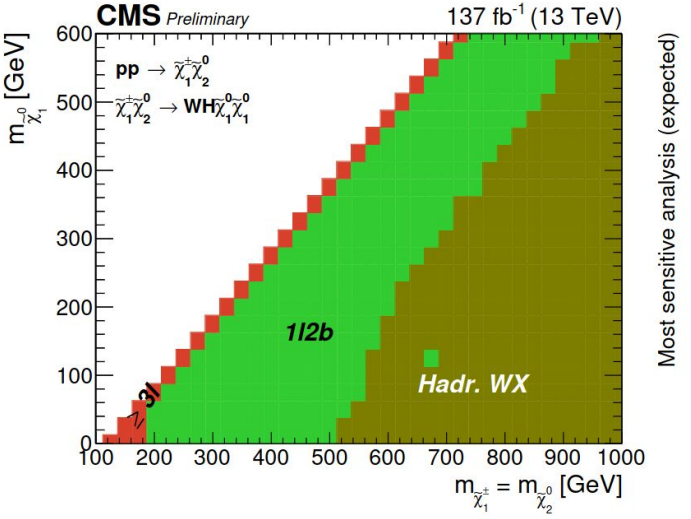


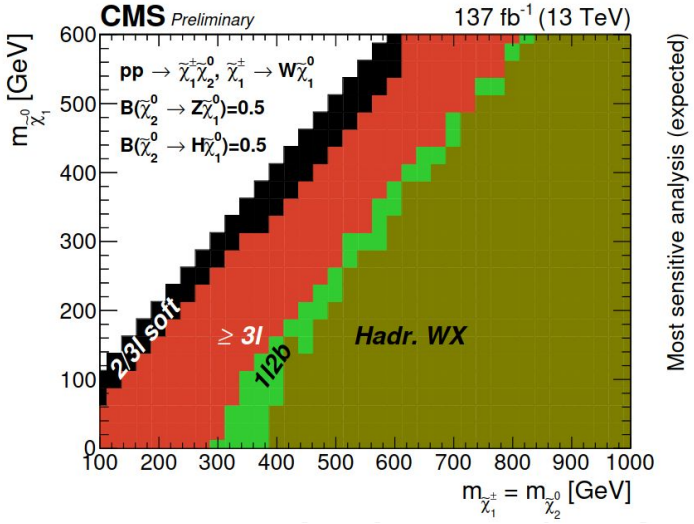
Chargino/neutralino production in WZ/WH final states:
Best exclusion limit per mass point + additional interpretations



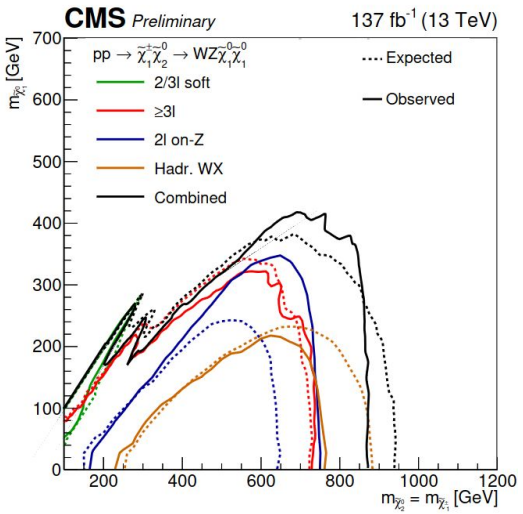


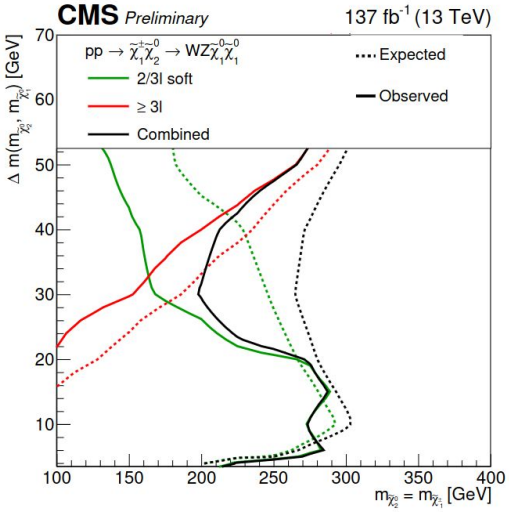


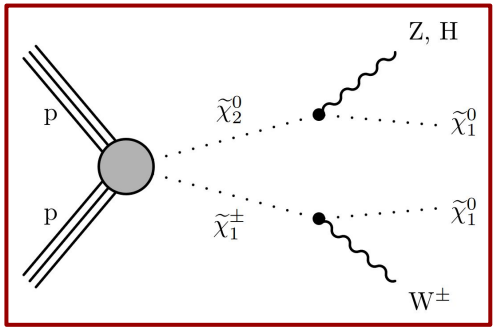


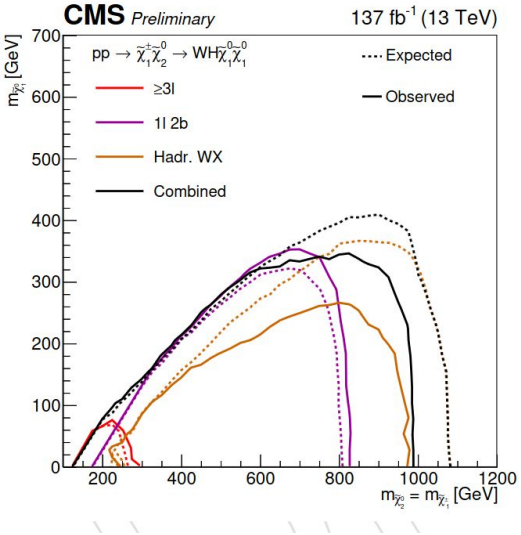


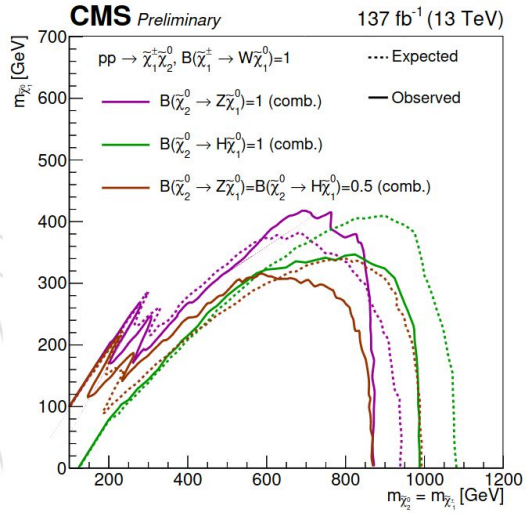
Chargino/neutralino production in WZ/WH final states:
Exclusion contours











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

Event variables' definition

- H_T: scalar p_T sum of all jets.
- Transverse mass:

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

- m_{T2}: Stransverse mass

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

- m_{T2}(ll,x) (slepton production in Z/SI soft lepton):

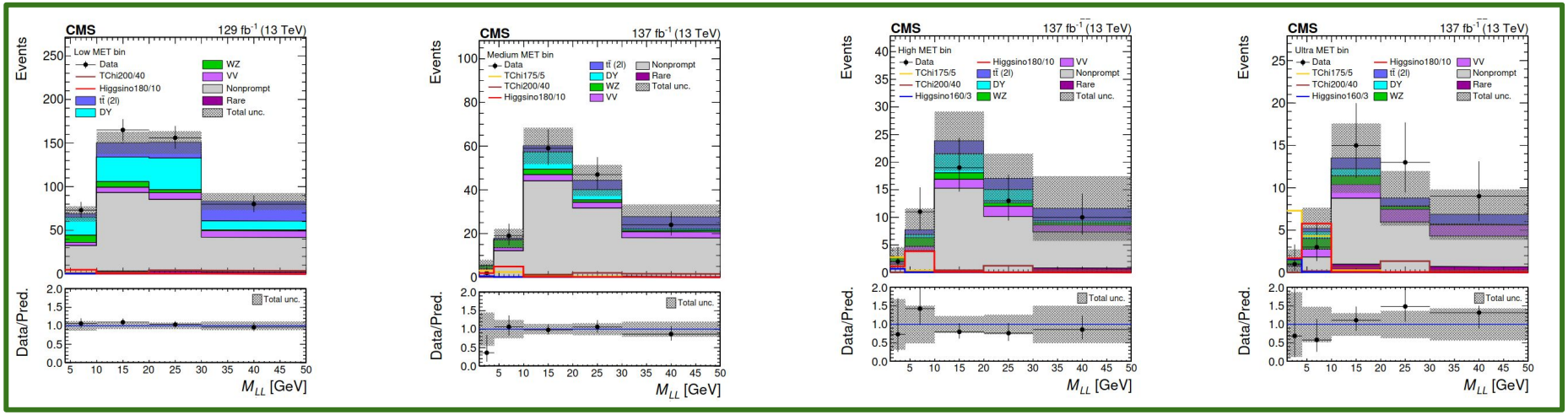
$$m_{\mathrm{T2}}(\ell\ell, \chi) = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(1)} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(2)} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max \left(\mathrm{M}_{\mathrm{T}}^{1}(m_\chi), \mathrm{M}_{\mathrm{T}}^{2}(m_\chi) \right) \right]$$

- d_0: the distance of the closest approach in the transverse plane of the helical trajectory of the track with respect to the beam axis. +info here

EWK SUSY Combination
Input analyses

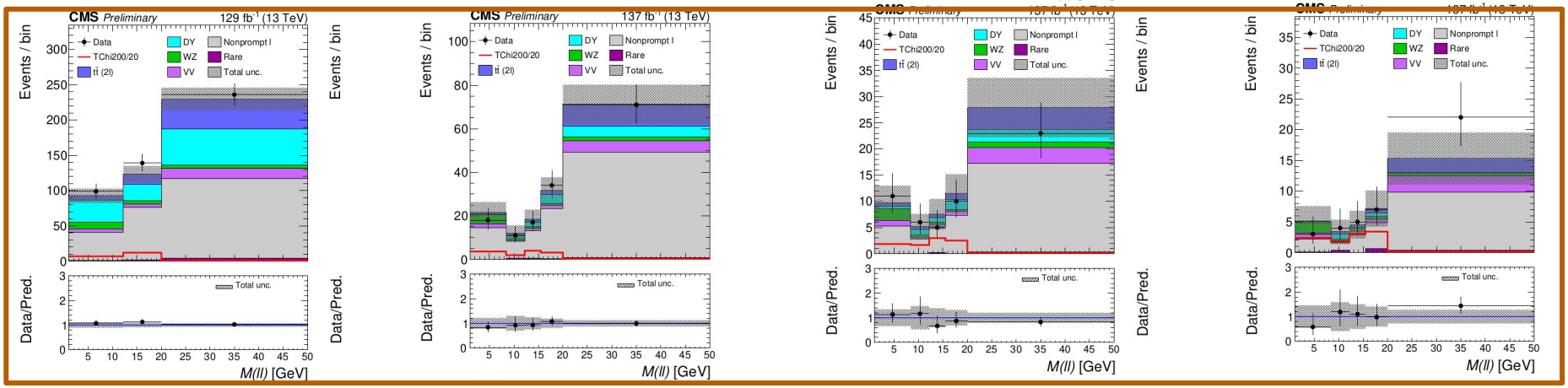
2/3l soft search:
Binning change in 2l soft SR

JHEP04(2022)091



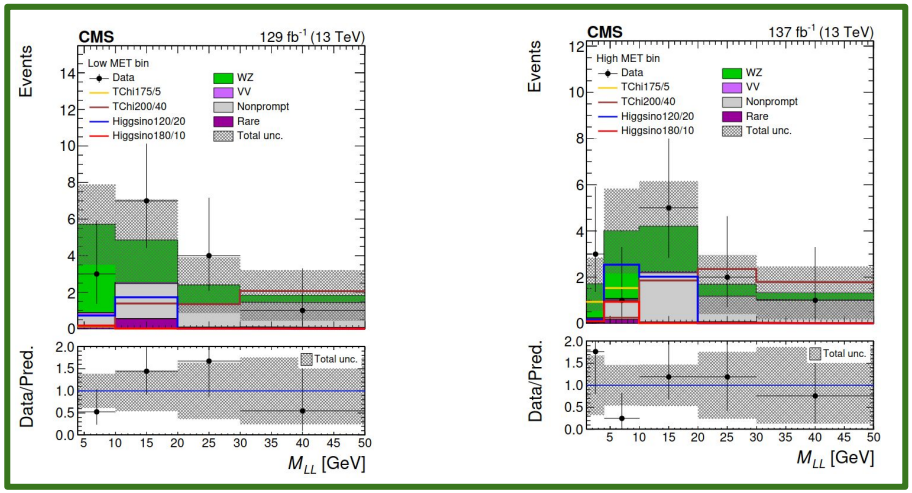
2l Low MET | 2l med MET | 2l high MET | 2l ultra MET

Updated binning



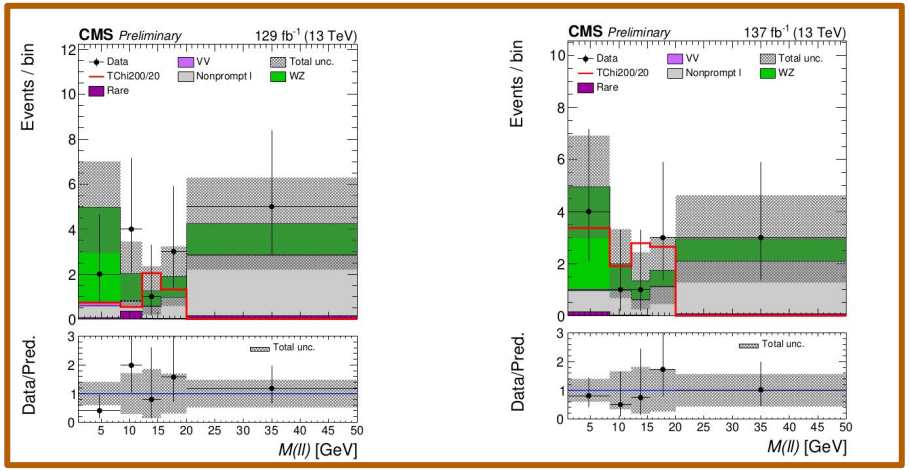
2/3l soft search:
Binning change in 3l soft SR and binning for slepton production

JHEP04(2022)091



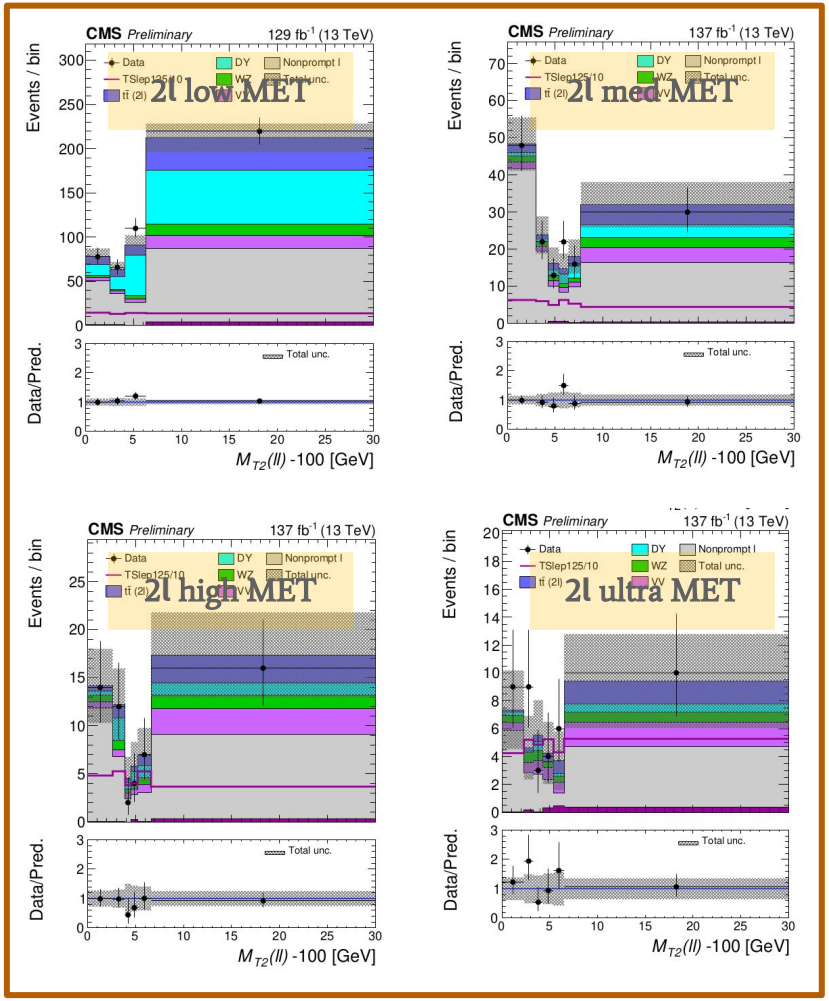
3l Low MET | 3l med MET

Updated binning

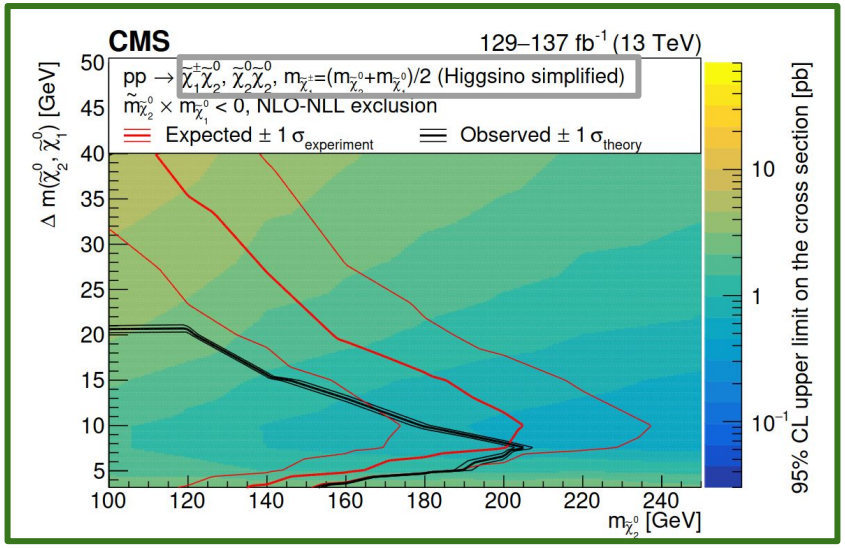


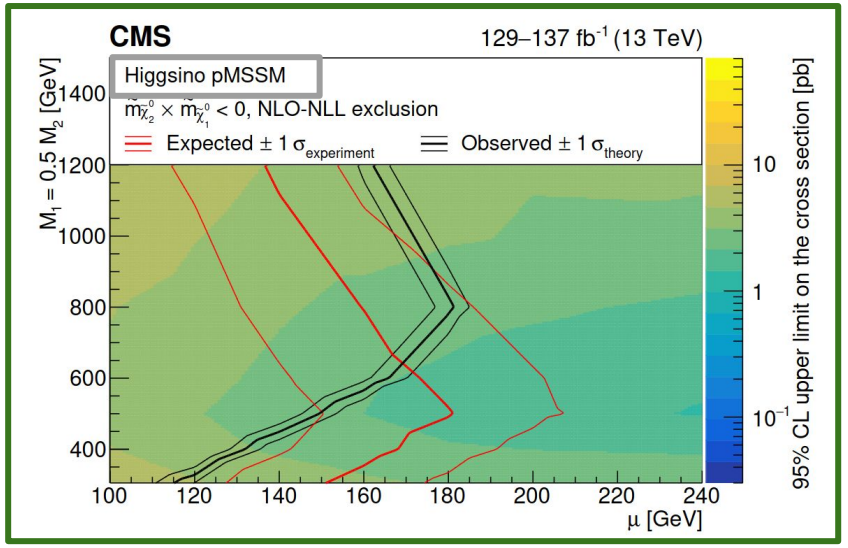
Binning for slepton production:

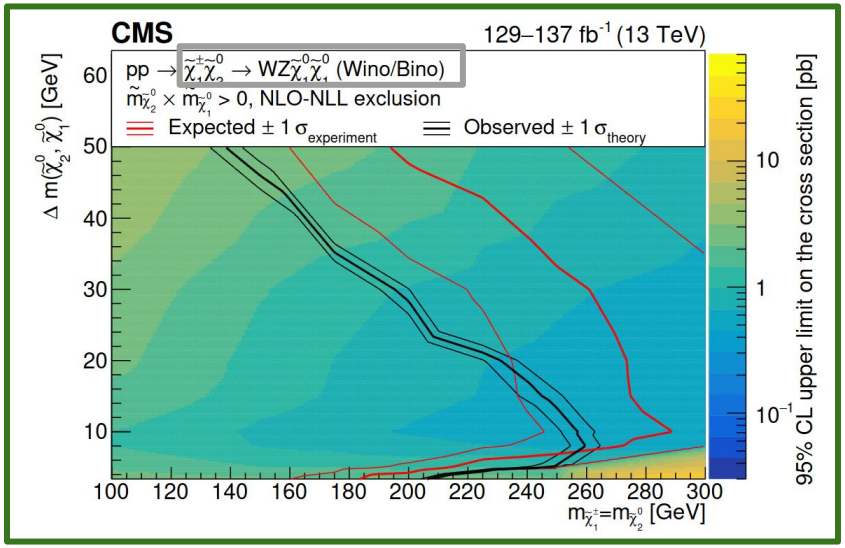
M_{ll} not meaningful: use M_{T2} with M_X=100 GeV

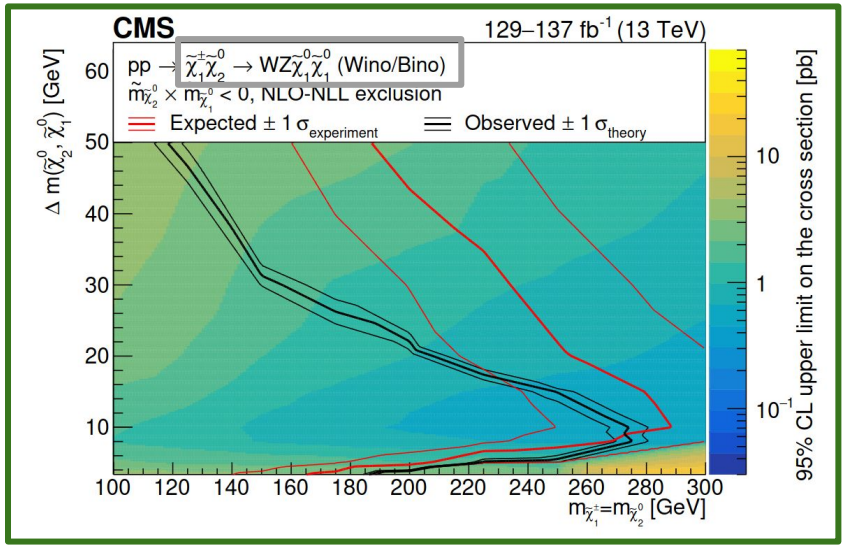


2/3l soft search:
Expected & Observed limits (JHEP04(2022)091)





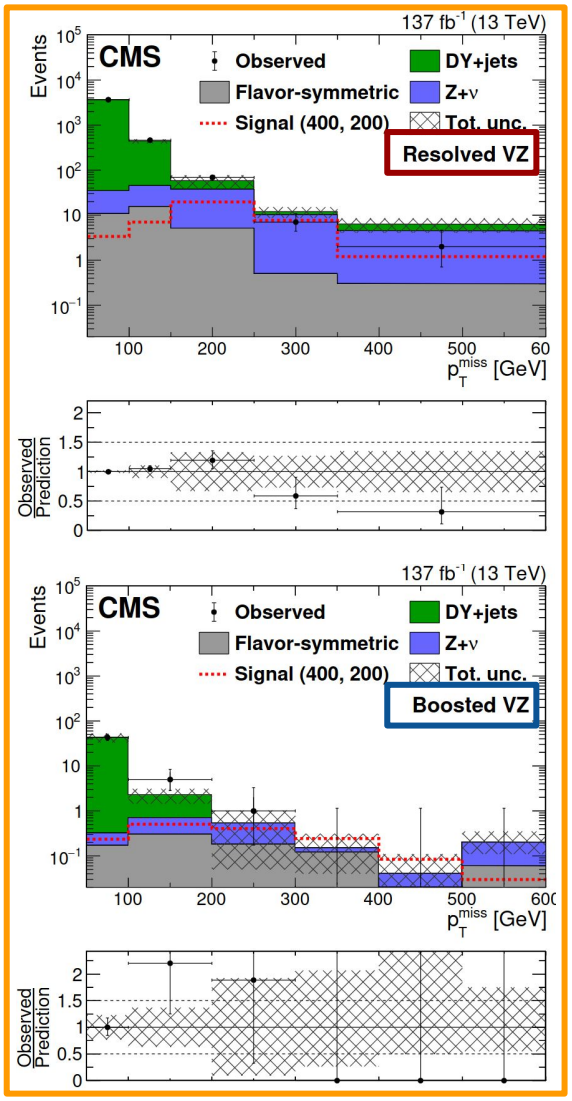


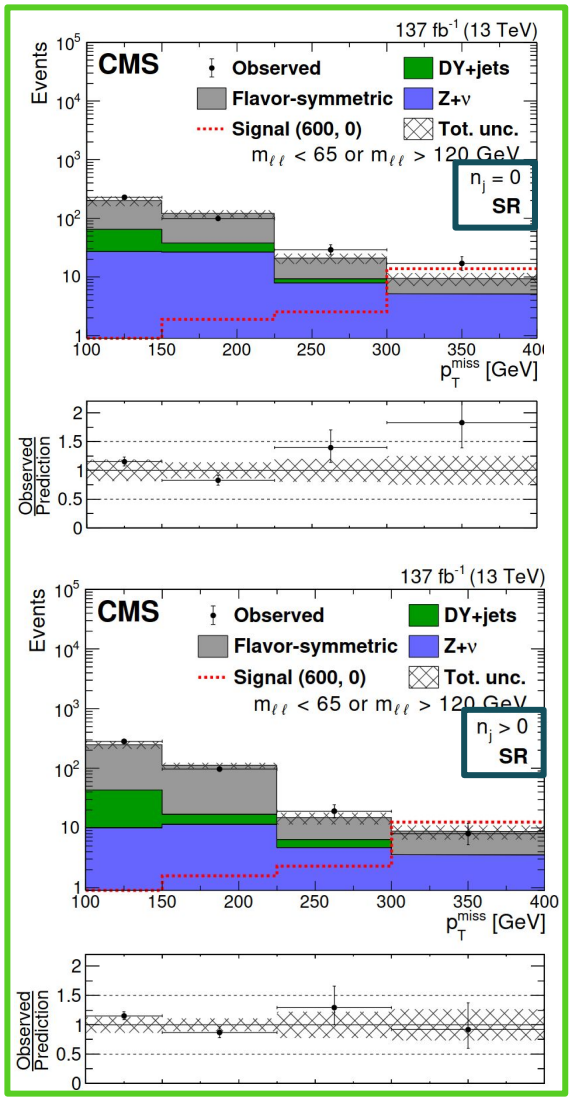


2l on Z/non resonant search:
Signal region strategy (JHEP04(2021)123)

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

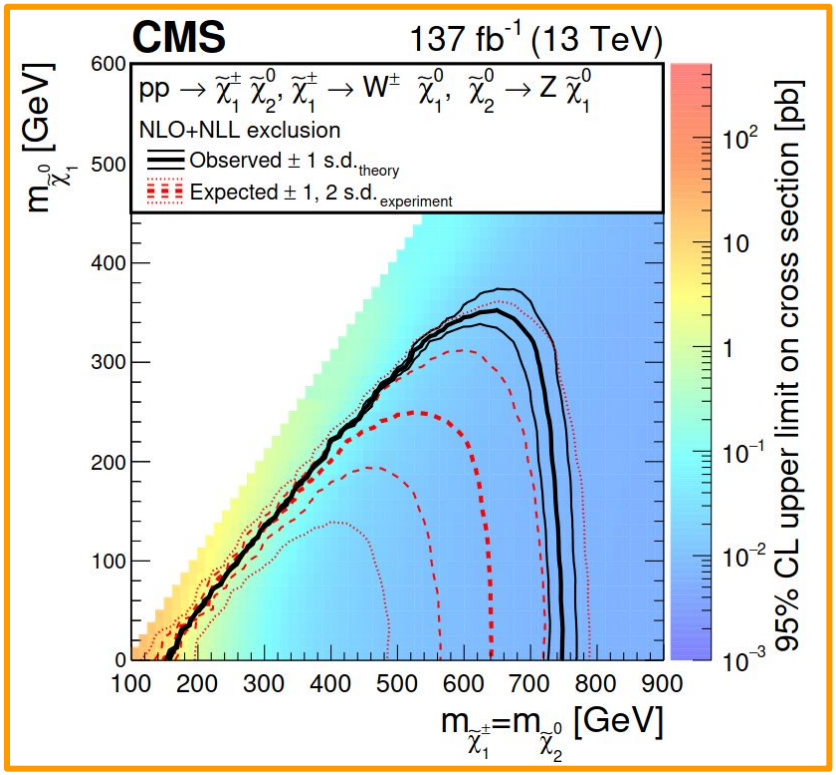
- Two OS SF leptons (ee/μμ), with SR split in terms of p_T^{miss}.
- on Z analysis (slepton production): $86<m_{ll}<96$ GeV, standard (AK4) & wider (AK8) jet reconstructions, further splitting in terms of **jet content.**
- off Z analysis (GMSB models): $20<m_{ll}<65$ GeV & $m_{ll}>120$ GeV. SR split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



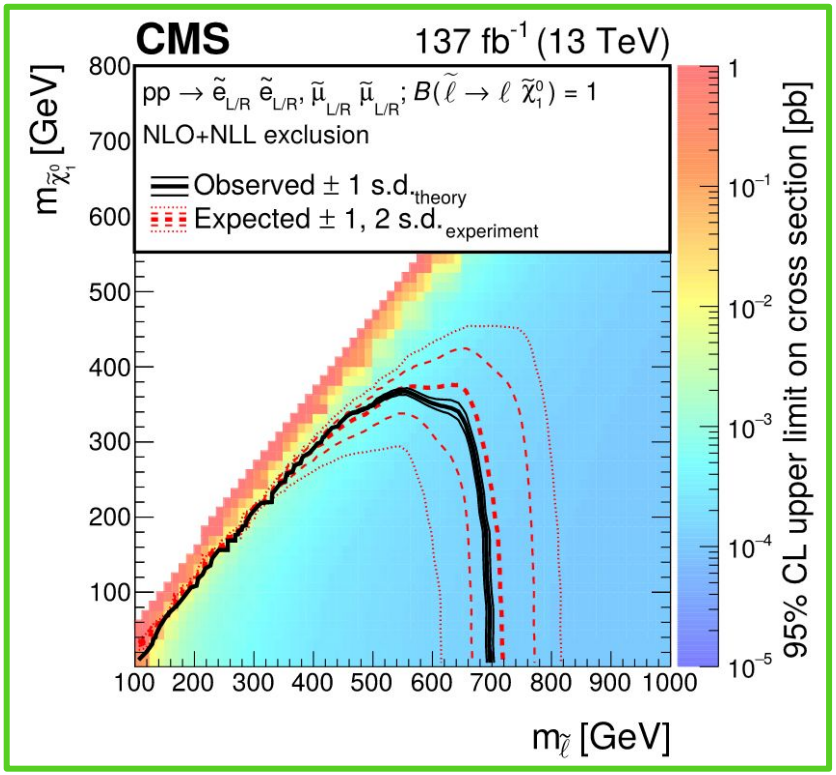


2l on Z/non resonant search:
Expected & Observed limits (JHEP04(2021)123)

GMSB models



Slepton production



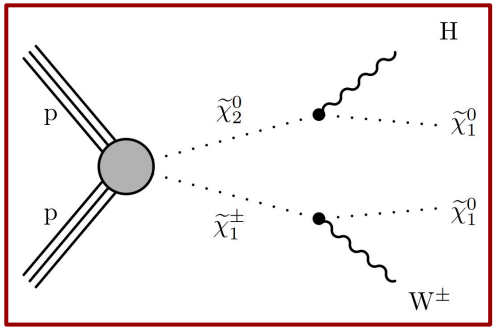
1ℓ 2b search:
Signal selection and observed/expected limits (JHEP10(2021)045)

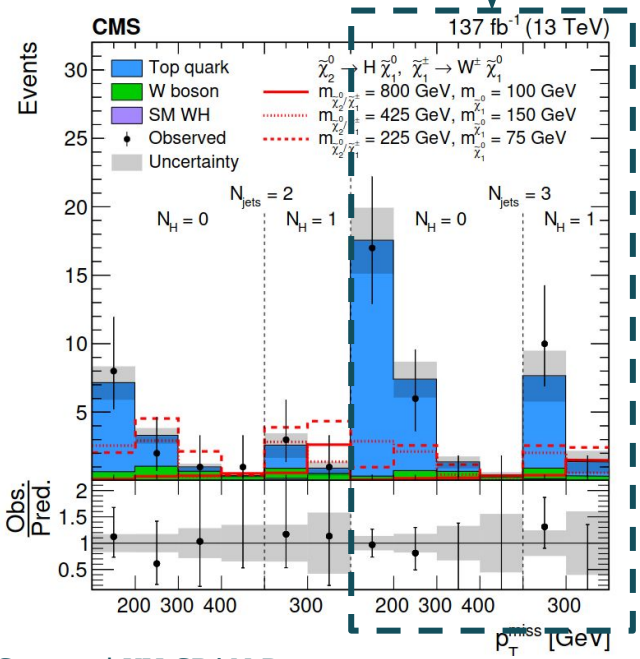
Targeting WH final states by selecting:

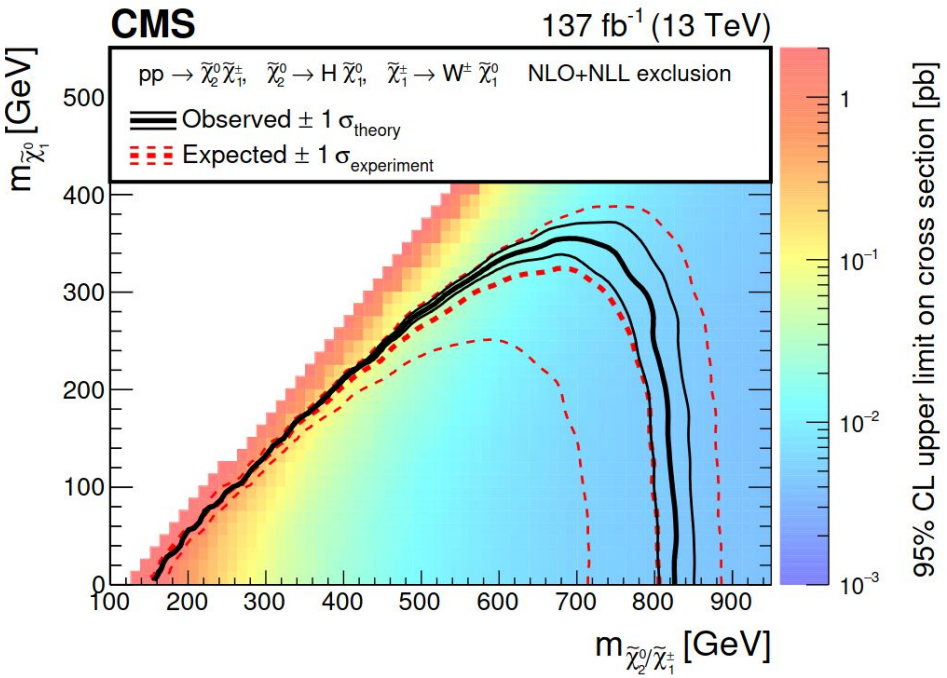
- $p_T^{\ell 1}$>30 GeV, 2 b-tagged jets consistent with the Higgs boson mass, and large p_T^{miss}.

Improvements wrt analysis using 2016 data (JHEP11(2017)029):

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



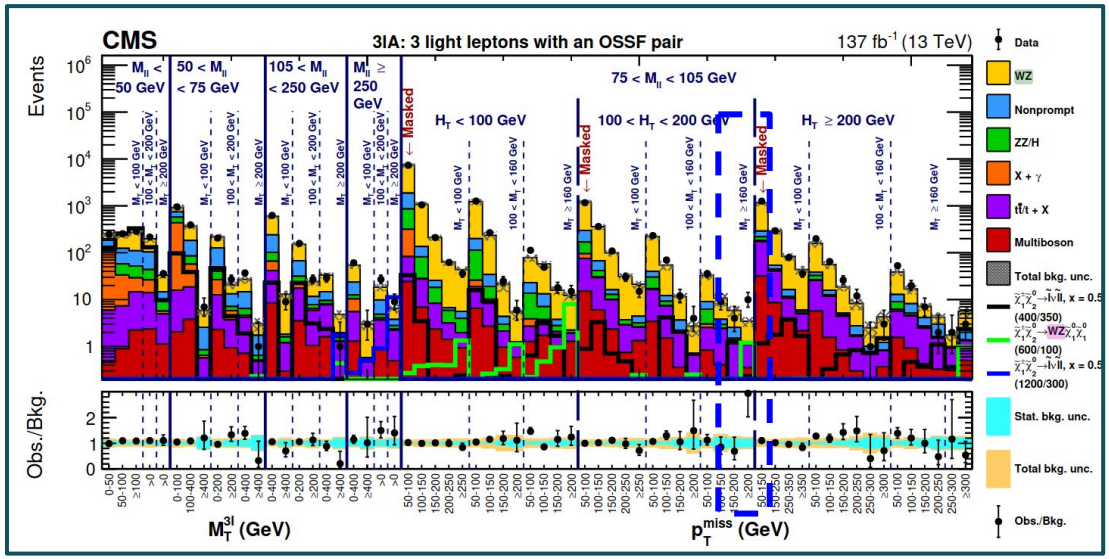


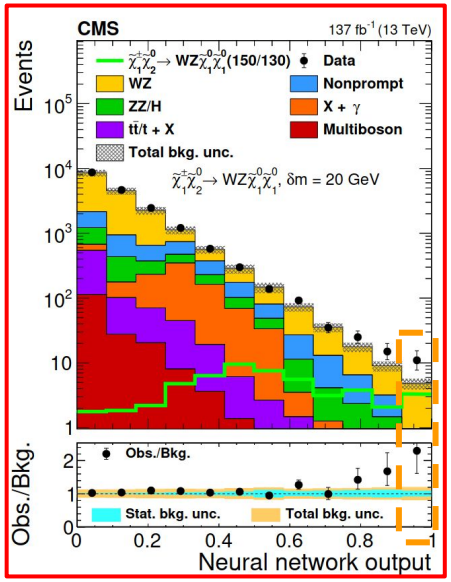


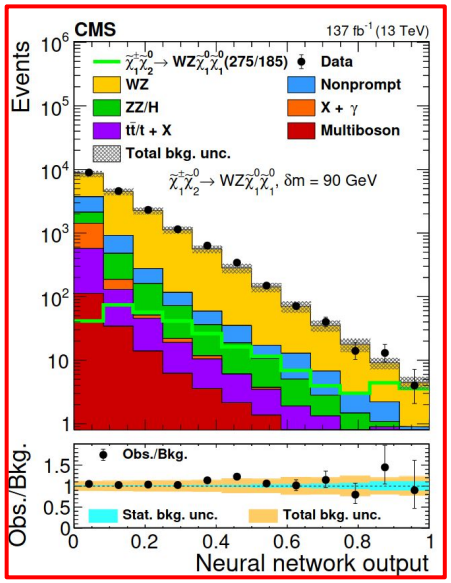
≥3l search:
Signal selection (JHEP04(2022)147)

A search that targets neutralino production in diboson final states:

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



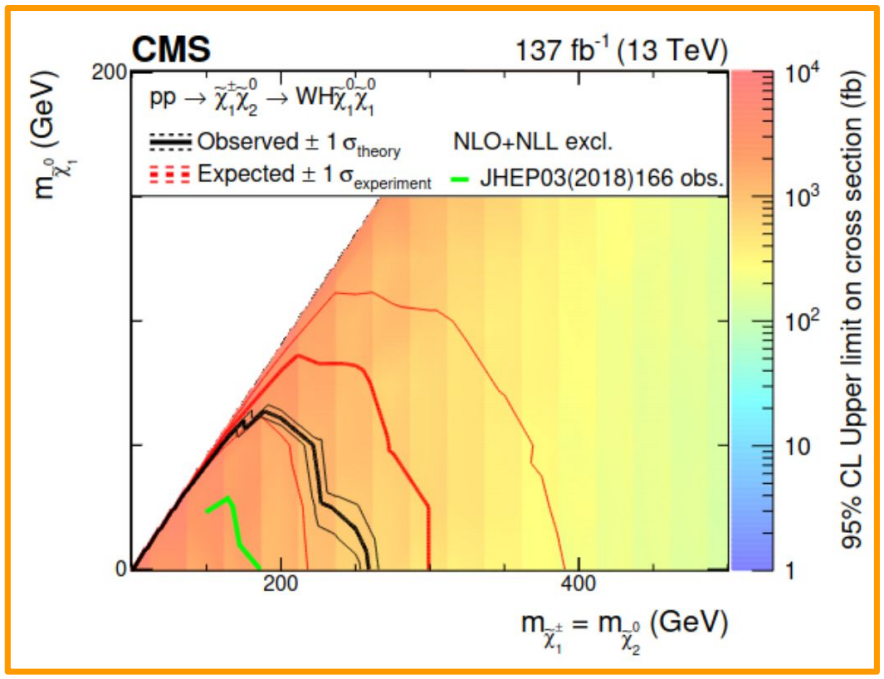




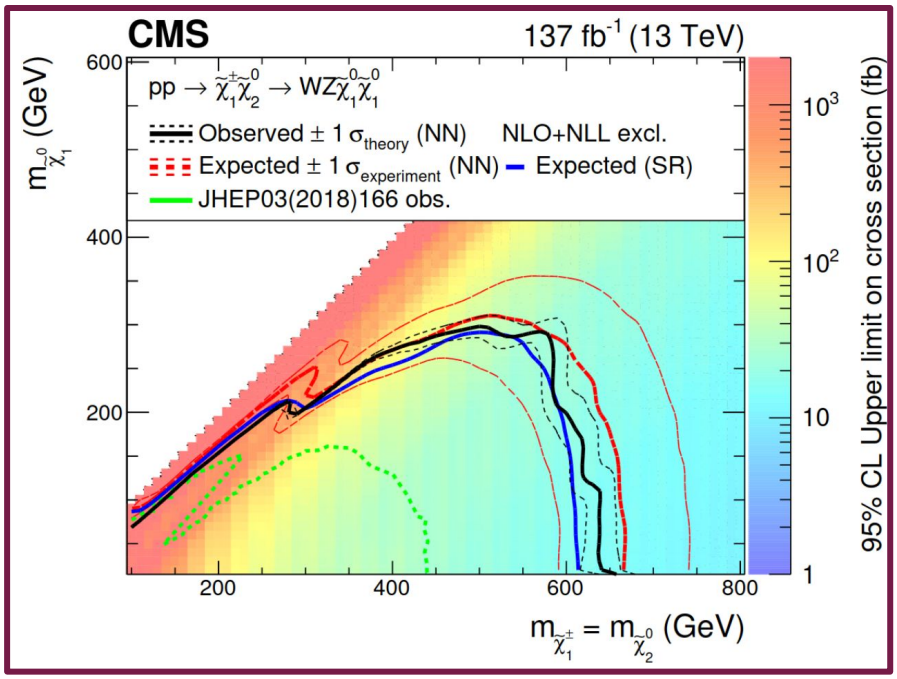
≥3l search:
Observed/expected limits (JHEP04(2022)147)

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

WH mediated decays



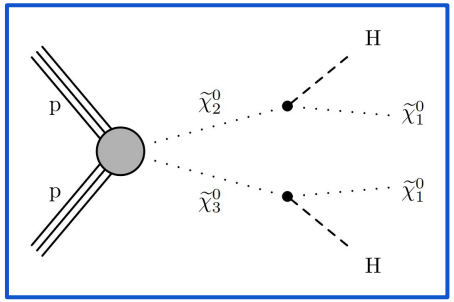
WZ mediated decays

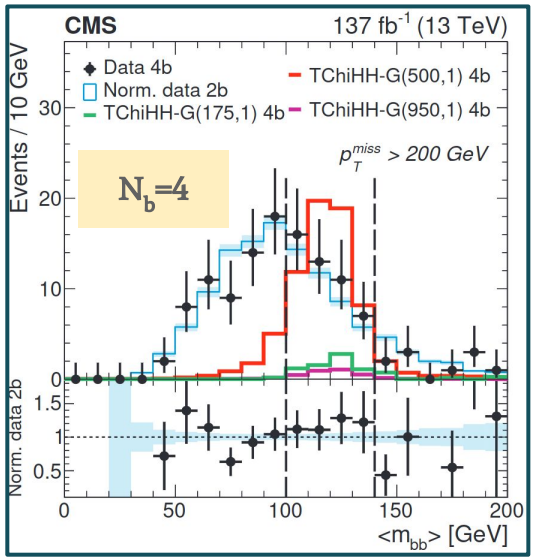


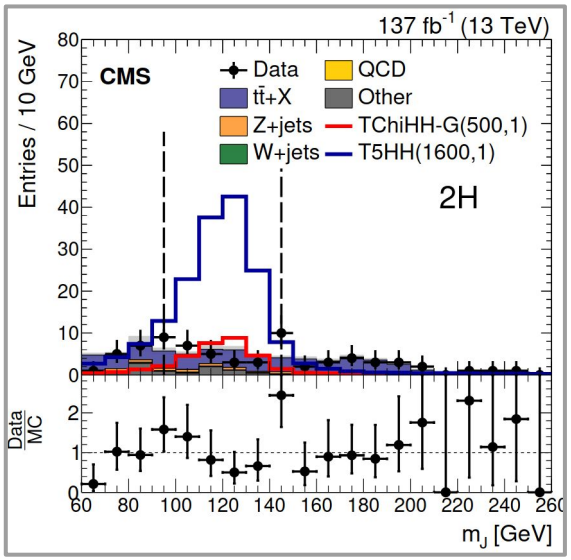
4b search:
Signal selection (JHEP05(2022)014)

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

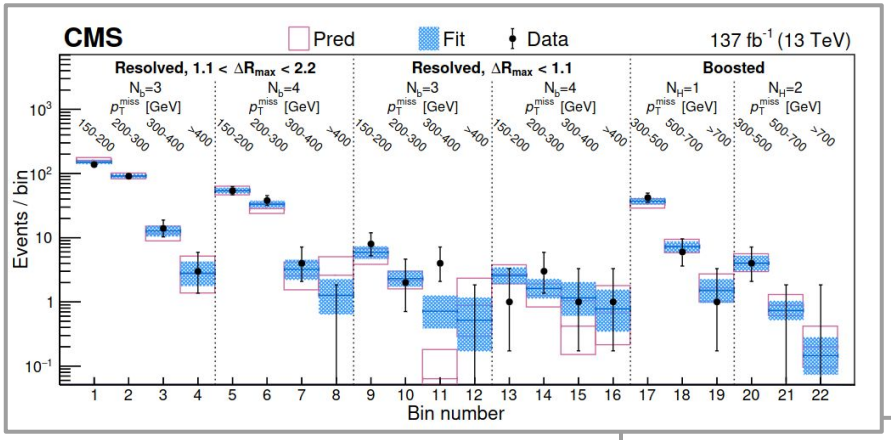
- **Resolved** scenario: 2 separate AK4 b-tagged jets.
  - Signal extracted in terms of the $\langle m_{bb} \rangle$ of the two b jets and $N_{b\text{-jets}}$
- **Boosted** scenario: 2b jets into an AK8 jet
  - Signal extracted in terms of the AK8 mass m_J and its n_H
- Main background, tt+X estimated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

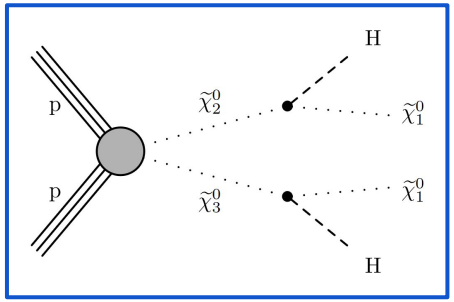


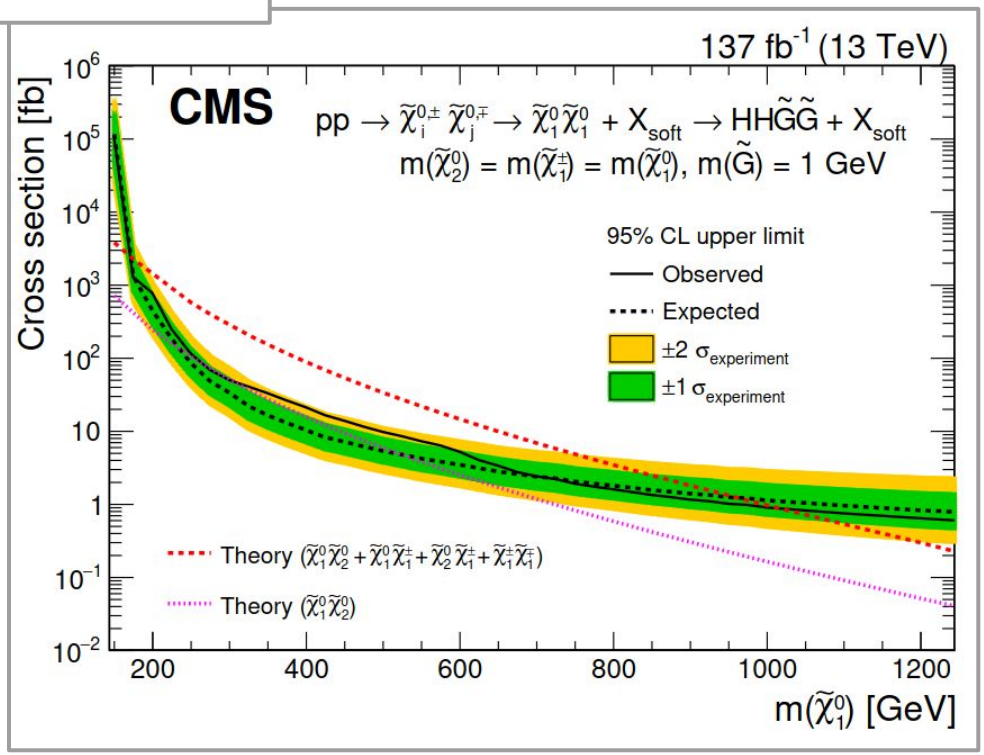




4b search:
Observed/expected yields and limits (JHEP05(2022)014)



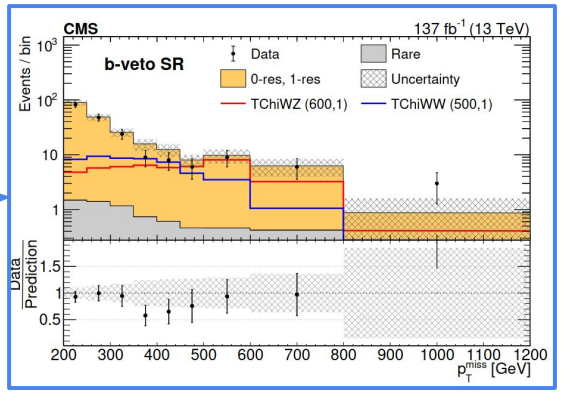


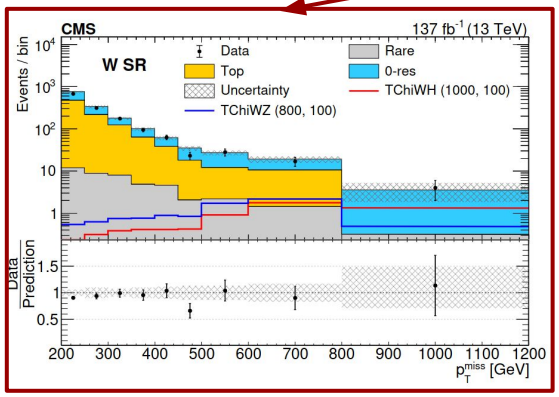


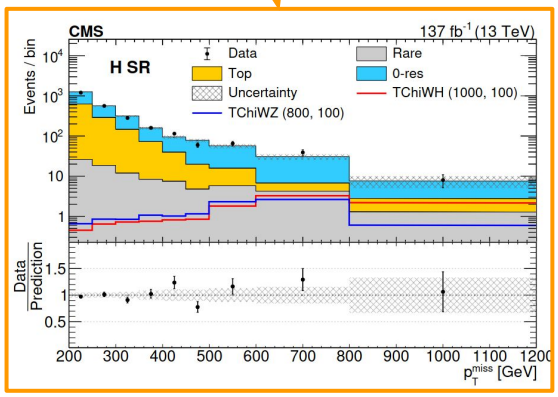
Hadr WX search:
Signal strategy and observed/expected yields (Phys.Lett.B 842 (2023) 137460)

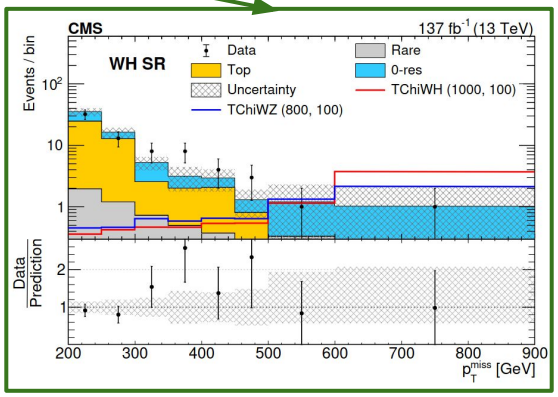
Hadr. WX: Fully hadronic final state

- 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
    - → ≥1 compatible with W and ≥1 with W/Z.
  - **B-Tag SR**: Subsplit in terms of the tagging
    - → AK8 jets compatible with **W**,**H** or **WH**, where H→bb.





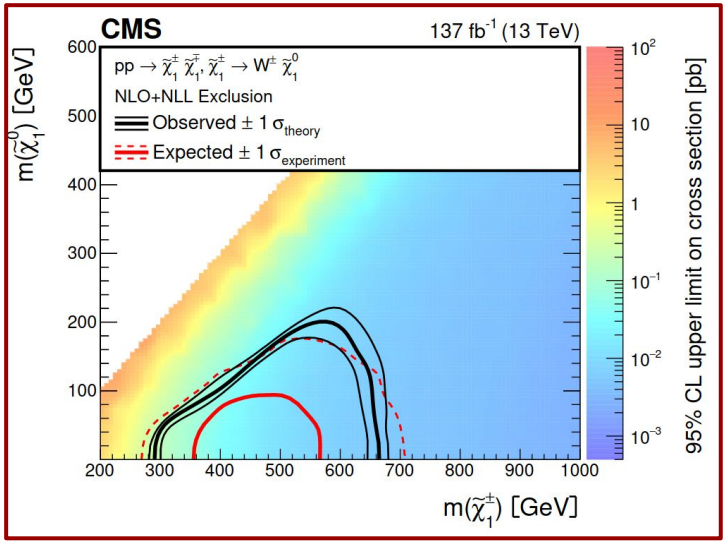


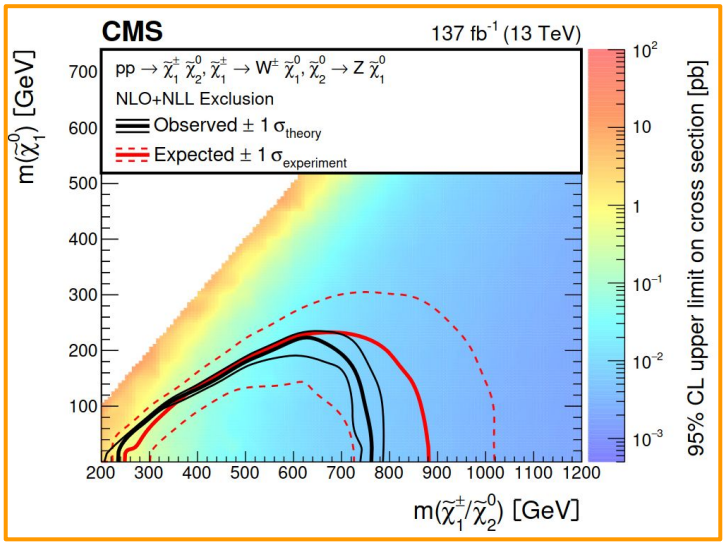


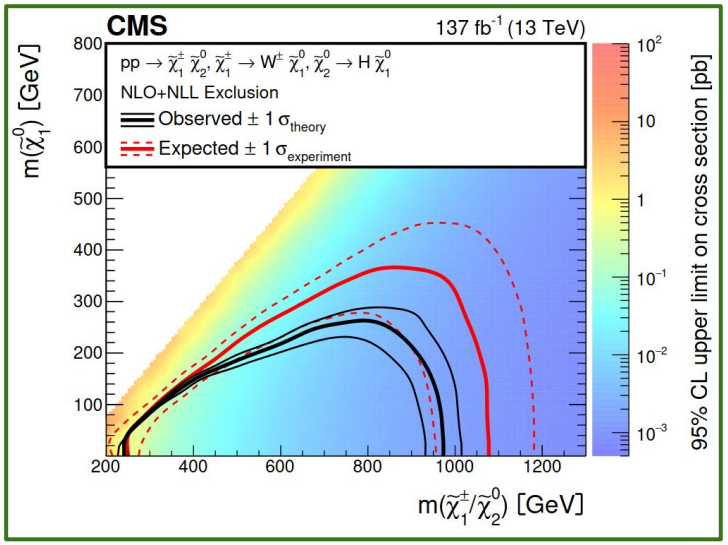
Hadr WX search:
Observed/expected yields and limits (Phys.Lett.B 842 (2023) 137460)

Limits obtained for :

- $\chi_1^{\pm}\chi_2^0$ decaying via **WW** bosons
- $\chi_1^{\pm}\chi_2^0$ decaying via **WZ** bosons
- $\chi_1^{\pm}\chi_2^0$ decaying via **WH** bosons





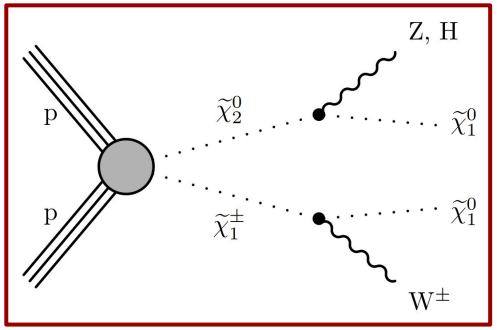


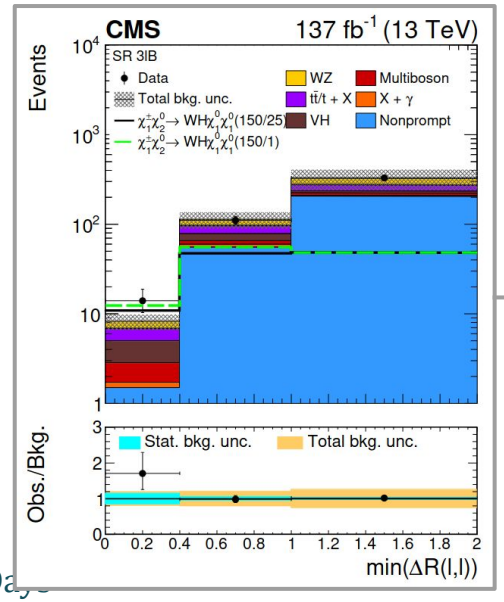
Electroweakino Combination: overlaps

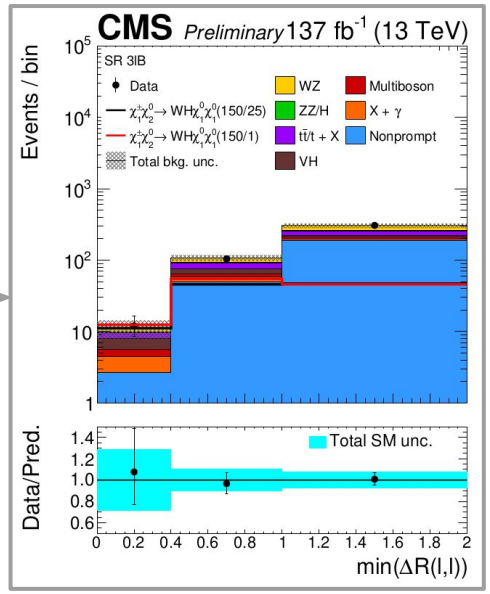
CMS PAS SUS-21-008

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

- 3l WZ CR of 2/3l soft overlaps with the SR category of ≥3 l
  - → WZ CR removed from the fit, constrained through a nuisance parameter
- 3l soft SR (p_T^{l1}<30 GeV) with ≥3l analysis (p_T^{l1}>25 GeV)
  - → Updated the p_T^{l1} selection of ≥3l analysis,
  - → Only slight changes in the sensitivity (highest in the compressed WZ, ~1-10% in 20<Δm<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/Semihardronic 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								2ℓ soft
2ℓ on-Z	EW		EW	EW					
2ℓ 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	