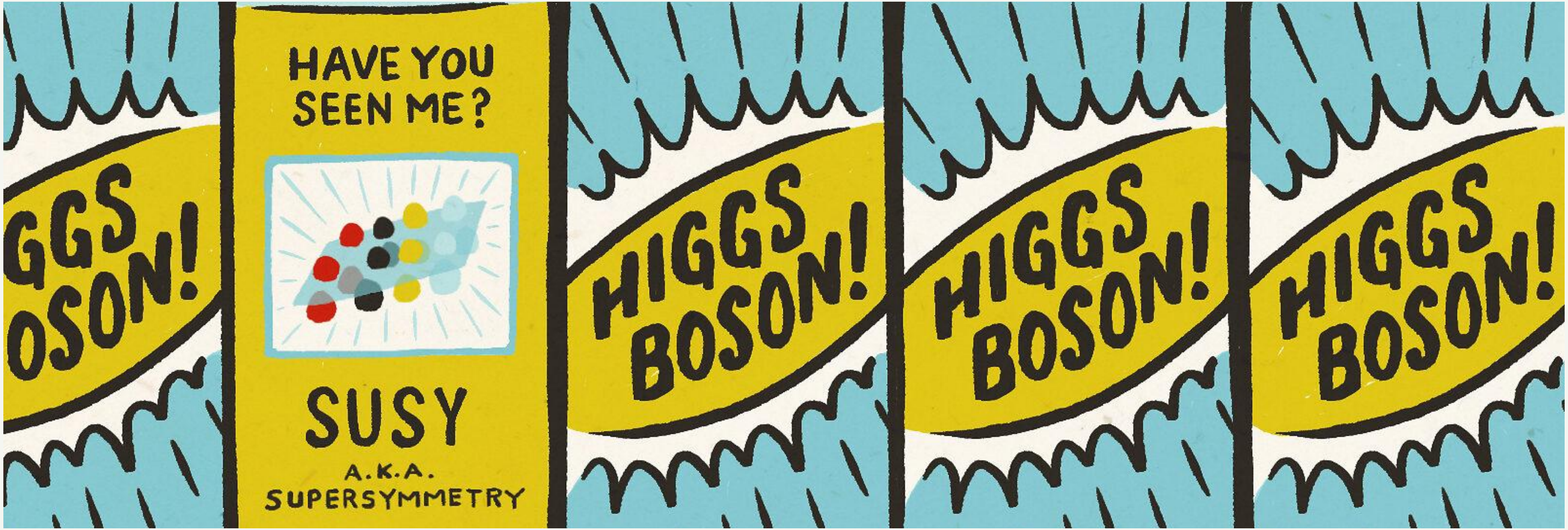


Illustration by Sandbox Studio, Chicago with Steve Shanabruch

Searching for SUSY at CMS: Latest results and electroweak SUSY combination

Jaana Heikkilä (University of Zürich) *on behalf of the CMS Collaboration*

Moriond Electroweak Interactions & Unified Theories (March 24 2023)

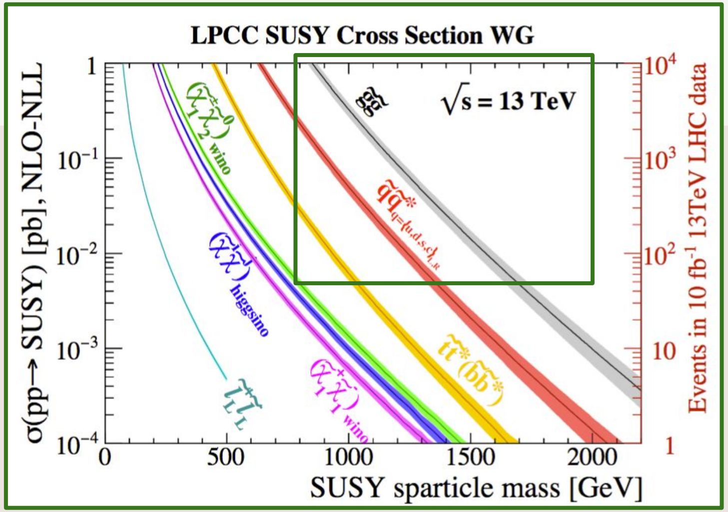
University of Zurich[UZH]

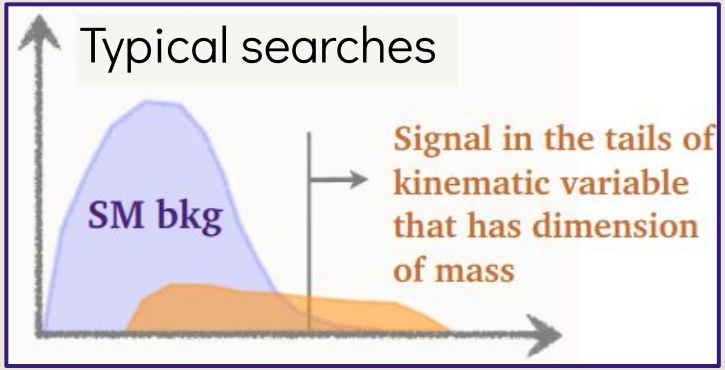
CMS

Expanding the SUSY search program

Targeting challenging and rare SUSY signatures

First statements on SUSY using full Run-2 data focused on the strong sector
→ Rely on **"typical" SUSY searches**: target final states with multiple SM objects, and **large missing energy from undetected SUSY states**





Expanding the SUSY search program

Targeting challenging and rare SUSY signatures

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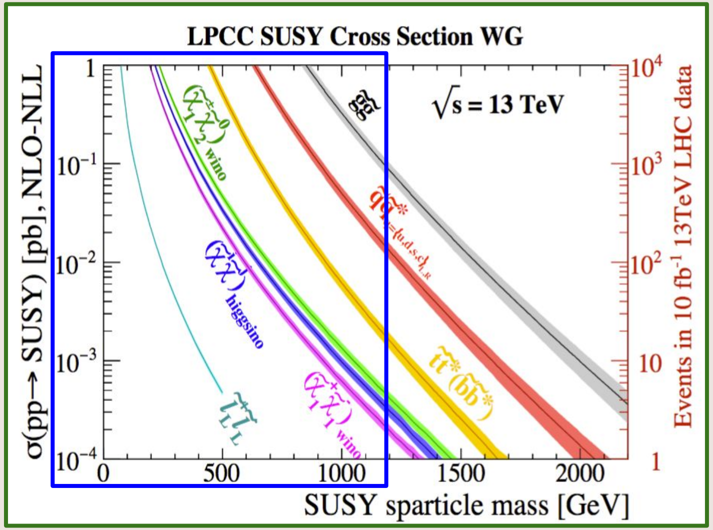


Full Run 2 data helps us to expand the SUSY search program further

- Target specific, challenging signatures (e.g. stealth SUSY sector)
- Exploit novel analysis techniques
- Explore previously uncovered corners
  - Compressed scenarios (small amount of visible energy)
  - Sleptons (extremely low cross sections)

Additionally: Combine SUSY searches to be more powerful together
→ Consider signal hypotheses that populate more than one final state, explored by multiple searches

Expanding the SUSY search program

Targeting challenging and rare SUSY signatures

First statem…
→ Rely on "…
objects, c…

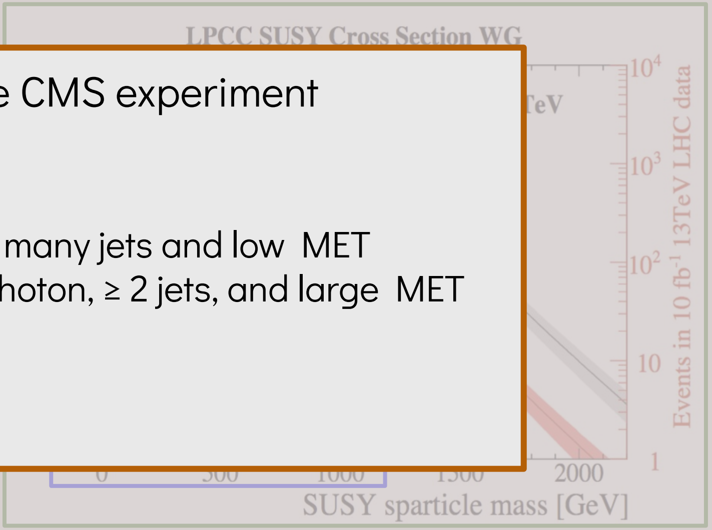
Today's topic: **three new Run 2 Legacy results** from the CMS experiment

Two recent searches using final states with photons

- Search for stealth SUSY in final states with two photons, many jets and low MET
- Search for strong and EWK SUSY in final states with a photon, ≥ 2 jets, and large MET

Combination of six electroweak SUSY searches

Full Run 2 d…
- Targe…
- Explo…
- Explo…



Additionally: Combine SUSY searches to be more powerful together
→ Consider signal hypotheses that populate more than one final state, explored by multiple searches

New SUSY searches in final states with photons

Search for stealth SUSY - final states with two photons, jets, and low MET

NEW

Neutralino $\tilde{\chi}_1^0$ (the lightest supersymmetric particle LSP of visible sector) decays into stealth* sector singlino $\tilde{S}$ and photon

→ Final state with a singlet S (decaying into gluons) and low-momentum gravitino $\tilde{G}$ (LSP of hidden sector)

CMS-PAS-SUS-19-001

Select 2 photons, ≥ 2 jets, and low MET

→ *S_T>1300 GeV*

(scalar p_T sum)

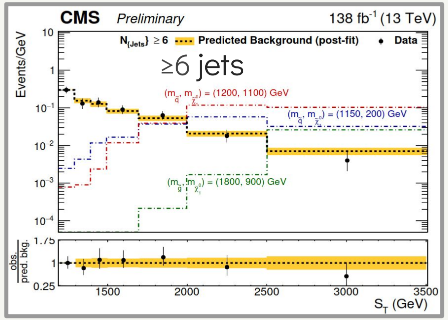
Signal extraction: S_T

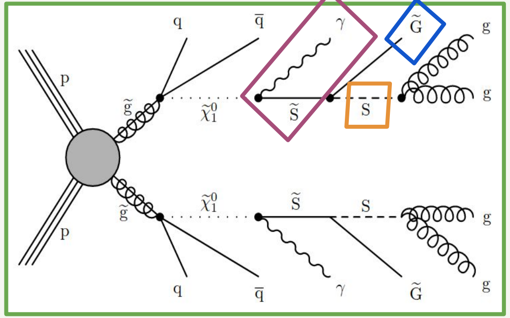
→ Bin in jet multiplicity (4, 5, or ≥6 jets)

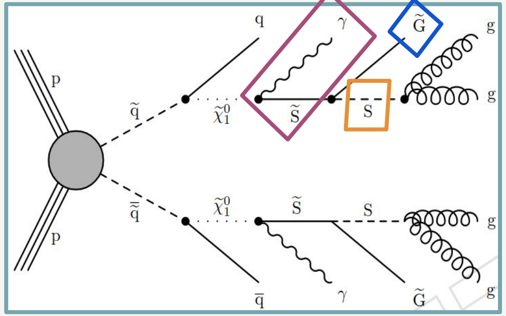
Main background: multijet events (two γs from the initial scattering)

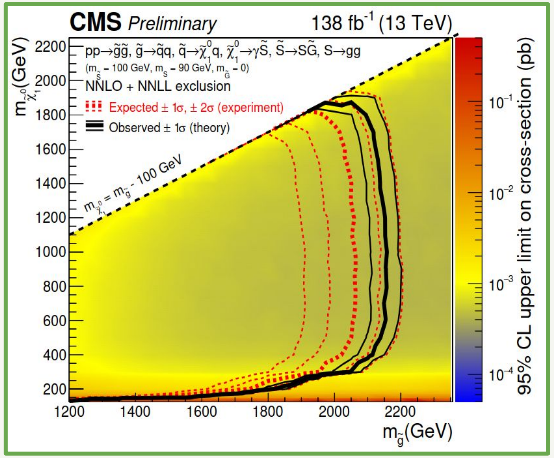
→ Data-driven estimation uses the S_T shape in events with low jet multiplicity

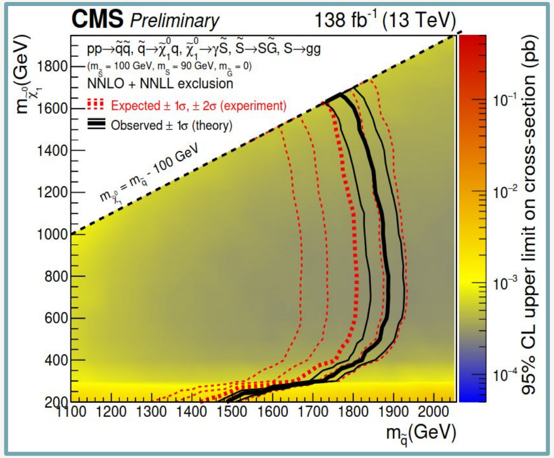
$$S_T \equiv \sum_{\text{photons}} |\vec{p_T}| + \sum_{\text{jets}} |\vec{p_T}| + |\vec{p_T}^{\text{miss}}|$$











Exclude gluinos (squarks) with masses up to 2.15 (1.85) TeV: most stringent limits on these models!

**Stealth SUSY: MSSM + a light hidden sector with novel particles near the weak scale (~mass degenerate)*

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

NEW

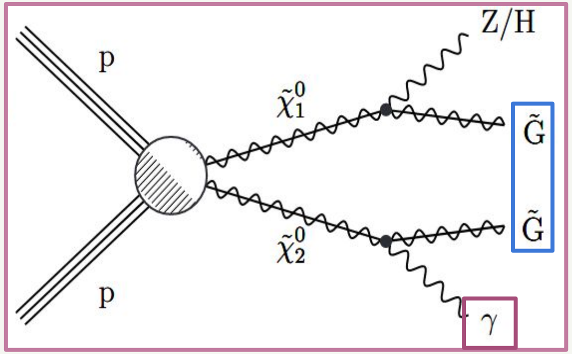
Explore GMSB (gauge-mediated SUSY breaking) scenarios, using both **EWK** and **strong** SUSY production models
→ Various possible models explored - full details in the backup!

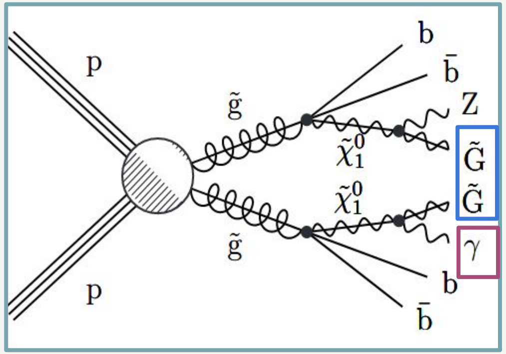
Select ≥ 1 photon, ≥ 2 jets, and large MET
→ Veto events with leptons
→ S_T>300 GeV (scalar p_T sum of γ + jets)

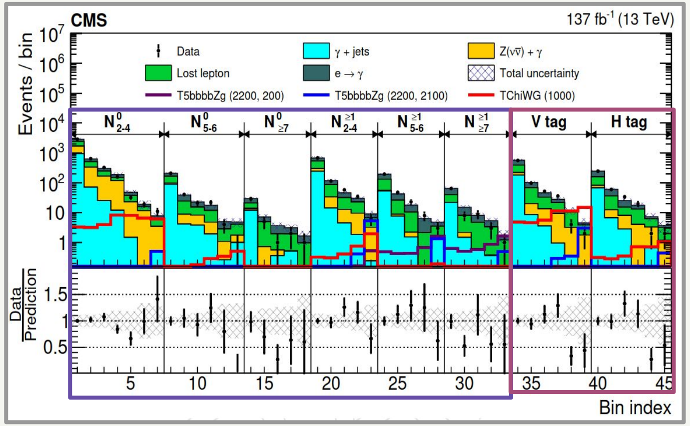
Two search categories:
with or **without** *a tagged W/Z/H boson*
→ Binned in MET and N_{jets}

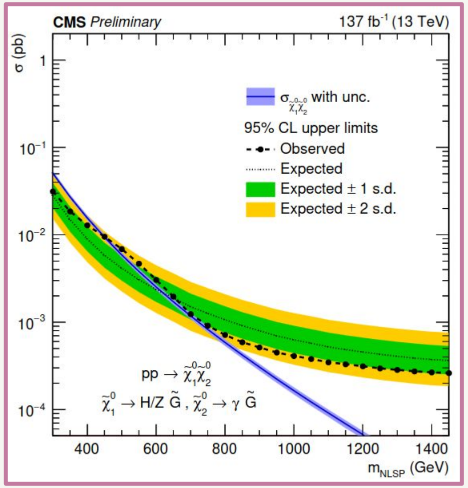
Main background:
"lost lepton" processes (Wγ +jets, ttγ+jets))
→ Data-driven estimations with transfer factors

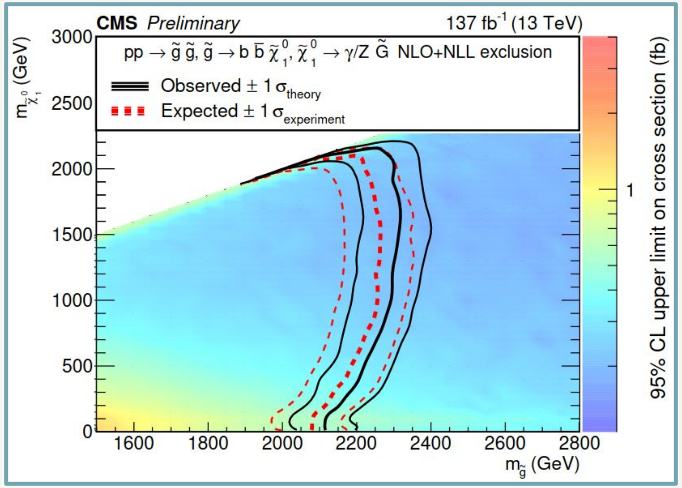
CMS-PAS-SUS-21-009









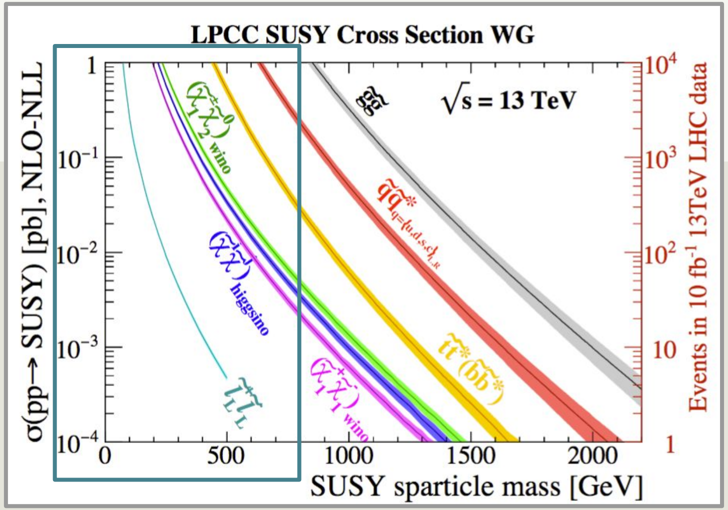


Exclude neutralinos (gluinos) with masses up to 0.5 (2.32) TeV!

NEW

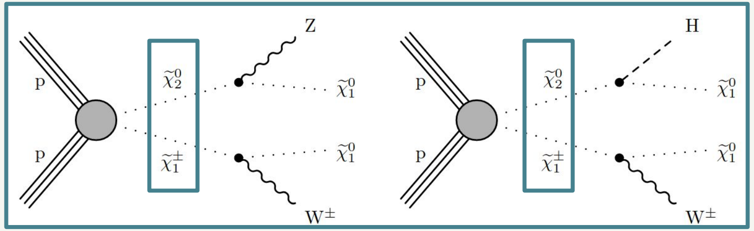
Combination of six EWK SUSY searches

CMS-PAS-SUS-21-008

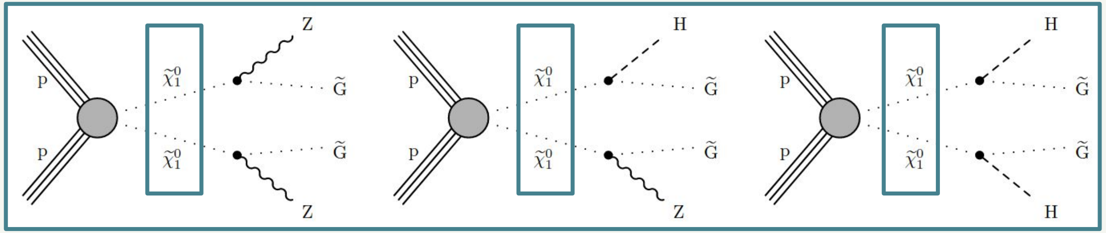


EWKino Combination: Legacy of Run 2

Previous EWK combination relied on 2016 data and targeted **the electroweak production of charginos, and neutralinos**



Wino-like chargino and neutralino (Bino-like LSP, $\tilde{\chi}_1^0$)



Gauge-mediated SUSY breaking (GMSB) model with quasi-degenerate Higgsinos

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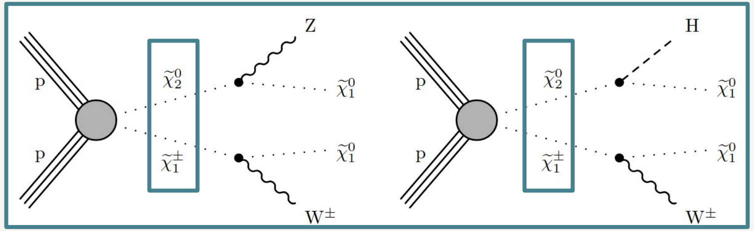

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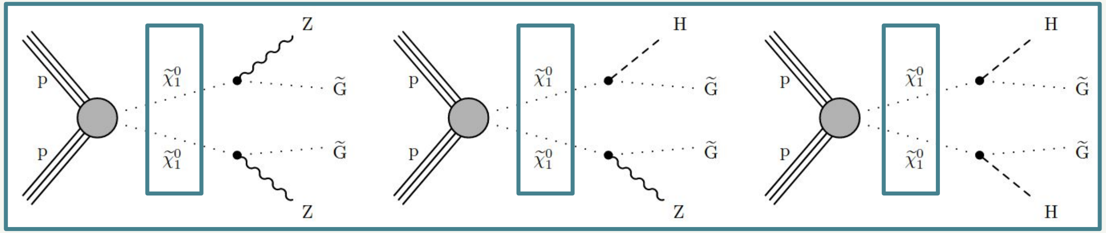
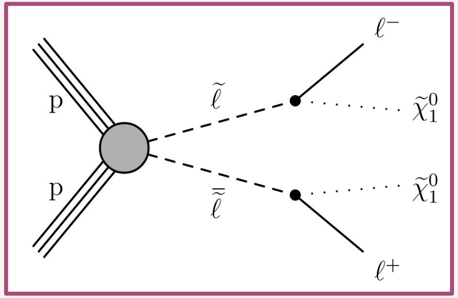


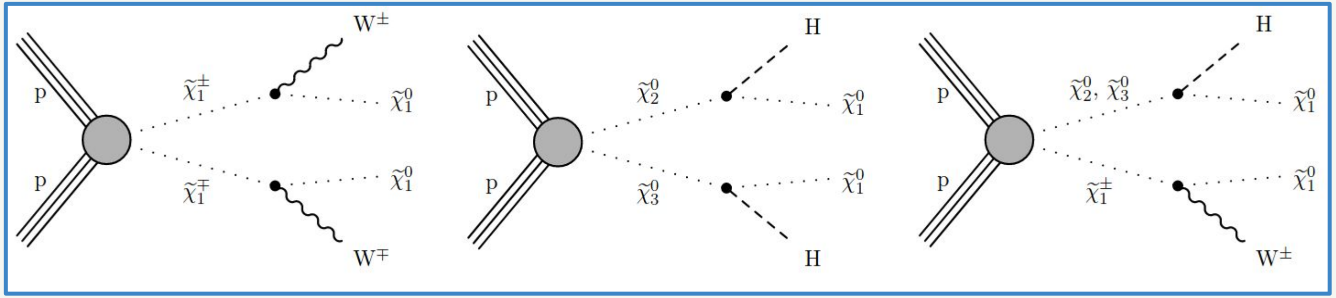
Gauge-mediated SUSY breaking (GMSB) model with quasi-degenerate Higgsinos

Legacy Run 2 combination: *cover the same interpretations, and* ***provide improvements as well as new interpretations***

→ Explore various parts of the parameter space: both compressed and uncompressed regions



Slepton pair production



Higgsino-bino model (chargino/neutralino)

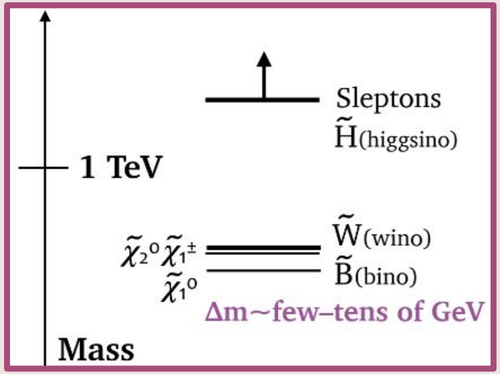
Compressed EWK sector

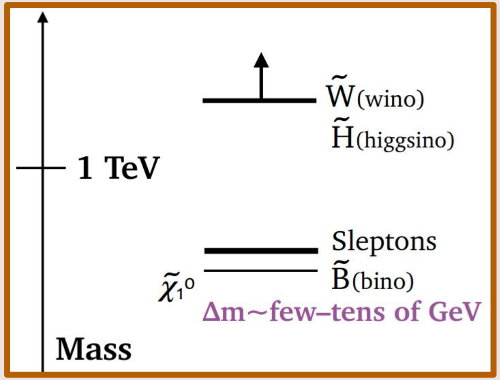
neutralinos: $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \tilde{\chi}_3^0 \tilde{\chi}_4^0$
charginos: $\tilde{\chi}_1^\pm \tilde{\chi}_2^\pm$

LSP: the lightest supersymmetric particle (*stable and neutral*)
EWKinos (neutralinos and charginos): mass eigenstates formed by the mixing of *Winos, Bino, and Higgsinos* (spartners of the SM EWK bosons)

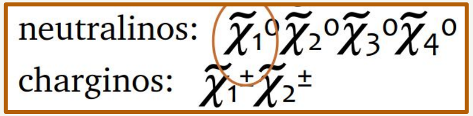
Compressed spectra: small mass splitting between the next-to-LSP and the LSP
→ Can be explored in many models, such as **with Bino LSP, and Wino NLSP or Slepton NLSP**

But…. such scenarios come with little visible energy
→ Require e.g. an ISR jet to access the compressed cases
→ Aim to retain as much as signal sensitivity as possible (low XS)
→ **Extremely challenging searches - benefit from combinations!**





Compressed EWK sector



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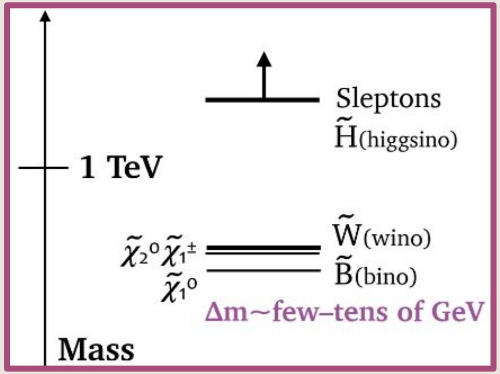
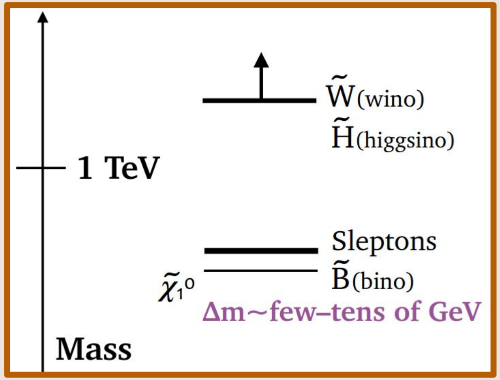
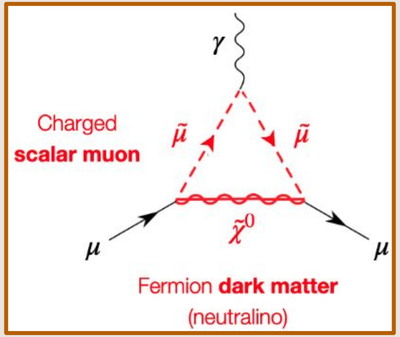
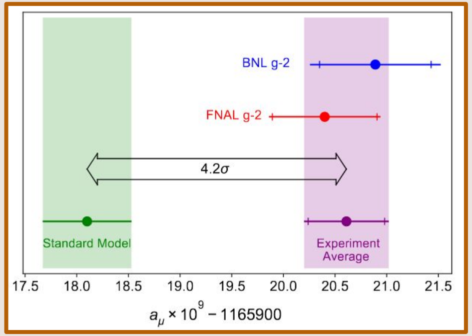
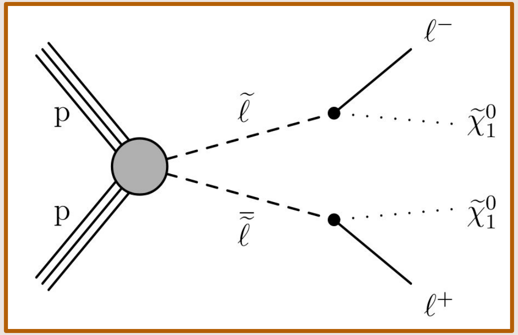
The sleptons could explain the results ***on the muon g-2 anomaly, measured by the Fermilab and BNL experiments***











Combination in a nutshell

Leptonic

compressed

"2/3l soft"
2111.06296
Two or three e (mu),
Opposite-sign, same-flavour pair
5(3.5) < lepton p_T < 30 GeV

Improved signal extraction
Extension to slepton pair production

(semi)compressed

"≥ 3l" (+2l SS)
2106.14246
Two same-sign (SS) light leptons, or
three/four leptons (up to 2 hadr. decaying taus)
Leading lepton p_T > 25 GeV (3l)*

"2l on-Z/non-resonant"
2012.08600
Two e(mu)
Opposite-sign, same-flavour pair
Either on-shell or off-shell Z

(semi)Hadronic

"1l 2b" (WH)
2107.12553
One e(mu), H→bb

"4b" (HH)
2201.04206
No leptons - two Higgs bosons (H→bb)

"Hadr. WX"
2205.09597
Fully hadronic final state;
at least 2 jets (AK8), and 2-6 jets (AK4)

New input analysis wrt previous combination

Two new interpretations!

Search	gaugino WZ	gaugino WH	GMSB ZZ	GMSB HZ	GMSB HH	higgsino-bino WW	higgsino-bino HH	higgsino-bino WH	sleptons $\ell^+\ell^-$
$2/3\ell$ soft	✓								✓
2ℓ on-Z	✓		✓	✓					
2ℓ non-resonant									✓
$\geq 3\ell$	✓	✓	✓	✓	✓			✓	
$1\ell 2$b		✓						✓	
4b					✓		✓		
Hadr. WX	✓	✓				✓		✓	

A more comprehensive coverage of the model parameter space than in the original individual searches!

Following slides display a snapshot of the results (full details in the back-up)

**A small update for the combination: Increase the p_T selection to 30 GeV for the leading lepton to avoid overlaps with the 2/3l soft analysis*

Leptonic input analyses

Leptonic

compressed

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Either on-shell or off-shell Z

Leptonic searches cover both (semi)compressed and uncompressed spectra
→ *New parametric signal extraction for 2/3l soft improves the sensitivity for the low Δm values!*

	gaugino		GMSB			higgsino-bino			sleptons
Search	WZ	WH	ZZ	HZ	HH	WW	HH	WH	$\ell^+\ell^-$
$2/3\ell$ soft	✓								✓
2ℓ on-Z	✓		✓	✓					
2ℓ non-resonant									✓
$\geq 3\ell$	✓	✓	✓	✓	✓			✓	
$1\ell 2$b		✓						✓	
4b					✓		✓		
Hadr. WX	✓	✓				✓		✓	

**A small update for the combination: Increase the p_T selection to 30 GeV for the leading lepton to avoid overlaps with the 2/3l soft analysis*

2/3l soft search

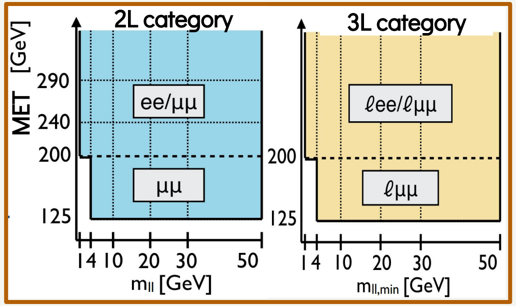
compressed

Leptonic

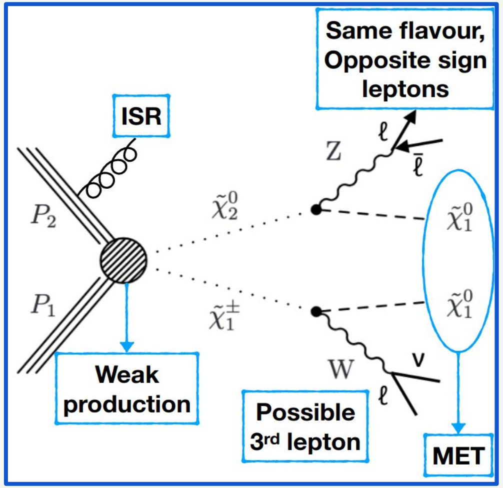
“2/3l soft”
2111.06296
Two or three e (mu), Opposite-sign, same-flavour pair
5(3.5) < lepton p_T < 30 GeV

Two categories; **2 or 3 low pT leptons**
- 3l category is new (wrt 2016)
- Require an ISR jet (enhance the MET from LSP)

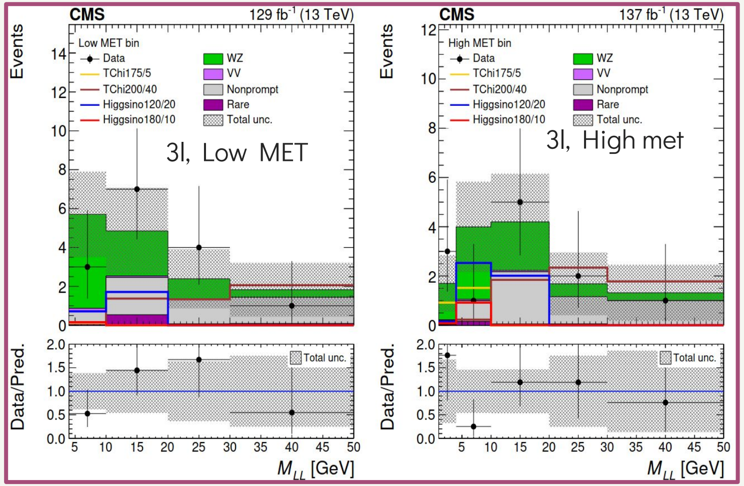
Aims to reconstruct mass of Z*:
mll serves as proxy for Δm(N2,N1)
→ Search regions binned in MET & mll



Targets mass-splittings as low as 5 GeV



Static binning



Updated signal extraction for the *EWKino combination:*
Provide a parametric binning for each $\Delta m(\chi_2^0,\chi_1^0)$ *scenario*

Parametric signal extraction for the 2/3l soft search

NEW

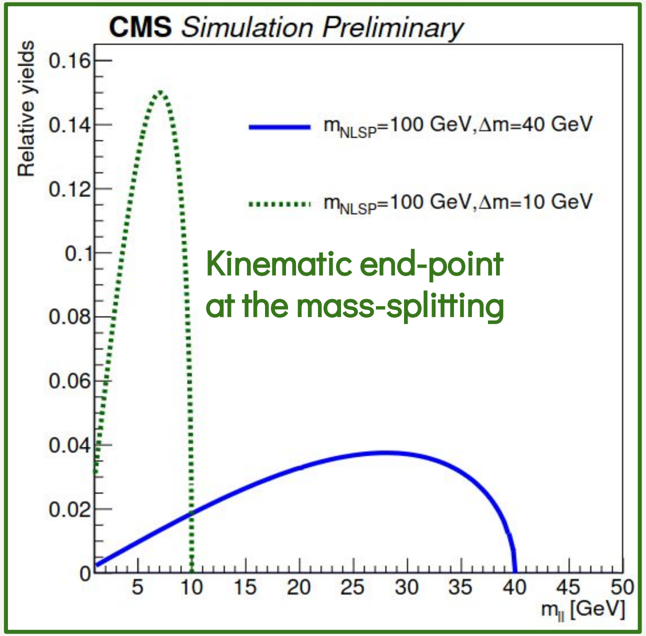
Goal: Target a wide parameter space of NLSP and LSP masses

The single mll binning utilised by the search is rarely optimal for all considered signal hypotheses

*Improve the sensitivity by using **a parametric binning for each $\Delta m(\chi_2^0,\chi_1^0)$ scenario** (similar to that of ≥3l analysis)*

→ Use m_{ll} as a discriminating variable (i.e. no multivariate discriminant)

Optimize m_{ll} binnings per mass-splitting using **theoretical signal shape**



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*Improve the sensitivity by using **a parametric binning for each $\Delta m(\chi_2^0,\chi_1^0)$ scenario** (similar to that of ≥3l analysis)*

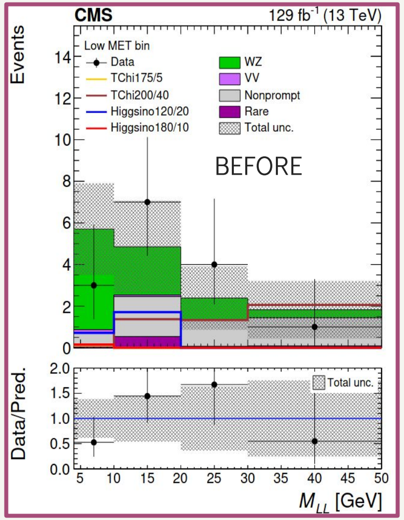
→ Use m_{ll} as a discriminating variable (i.e. no multivariate discriminant)

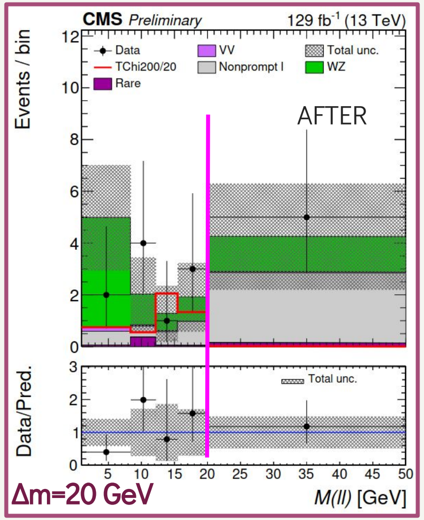
Optimize m_{ll} binnings per mass-splitting using theoretical signal shape

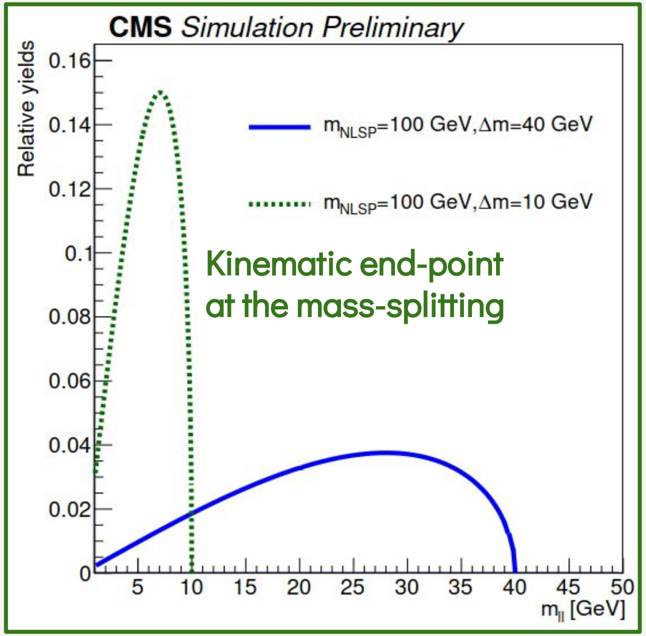
→ Provide an individual binning for each Δm and SR

Example:

3l signal region, low MET







The largest gains are obtained for mass splittings of Δm < 20 GeV:
Expected exclusion on NLSP mass increased by between 5 and 25 GeV depending on the targeted Δm!

(semi)Hadronic input analyses

Leptonic

compressed

"2/3l soft"
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Two or three e (mu), Opposite-sign, same-flavour pair 5(3.5) < lepton p_T < 30 GeV

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No leptons - two Higgs bosons (H→bb)

"Hadr. WX"
2205.09597
Fully hadronic final state;
at least 2 jets (AK8), and 2-6 jets (AK4)

New input analysis wrt previous combination

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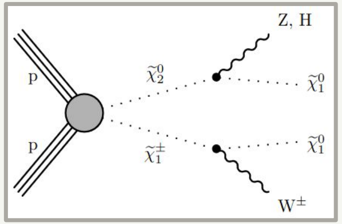
$2/3\ell$ soft	✓								✓
2ℓ on-Z	✓		✓	✓					
2ℓ non-resonant									✓
$\geq 3\ell$	✓	✓	✓	✓	✓			✓	
$1\ell 2b$		✓						✓	
4b					✓		✓		
Hadr. WX	✓	✓				✓		✓	

Add sensitivity towards the uncompressed spectra!

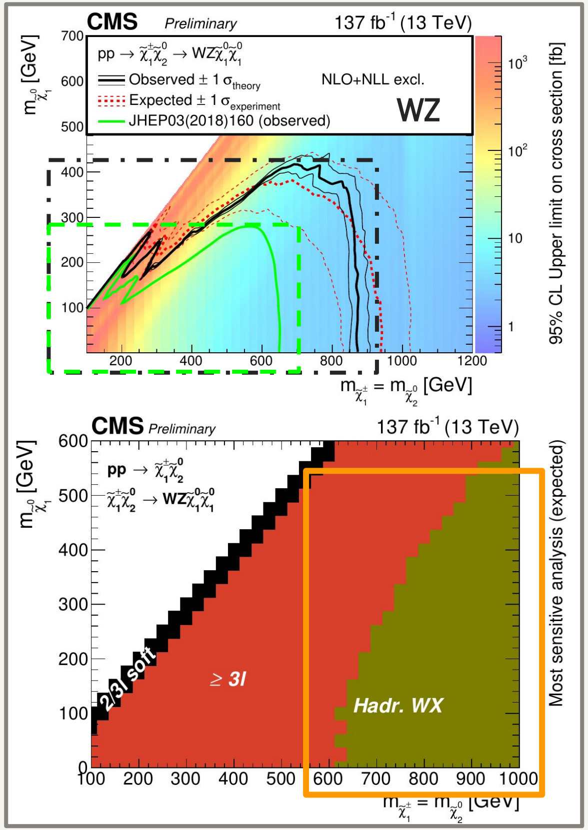
Production chargino and neutralinos (WZ/WH)

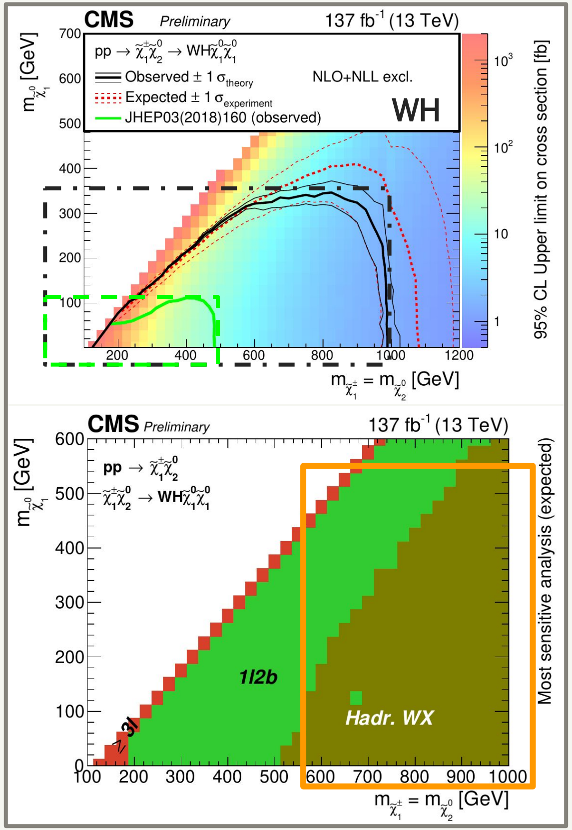
Wino-like chargino and neutralino (Bino-like LSP, $\tilde{\chi}_1^0$)



The limits are notably improved since
the 2016 EWKino Combination

The new, fully hadronic input analysis
Hadr. WX improves the sensitivity to higher NLSP masses and uncompressed region

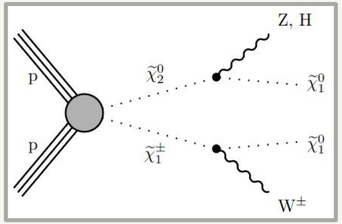




Search	gaugino WZ	gaugino WH
$2/3\ell$ soft	✓	
2ℓ on-Z	✓	
2ℓ non-resonant		
$\geq 3\ell$	✓	✓
$1\ell 2$b		✓
4b		
Hadr. WX	✓	✓

Production chargino and neutralinos (WZ/WH)

Wino-like chargino and neutralino (Bino-like LSP, $\tilde{\chi}_1^0$)

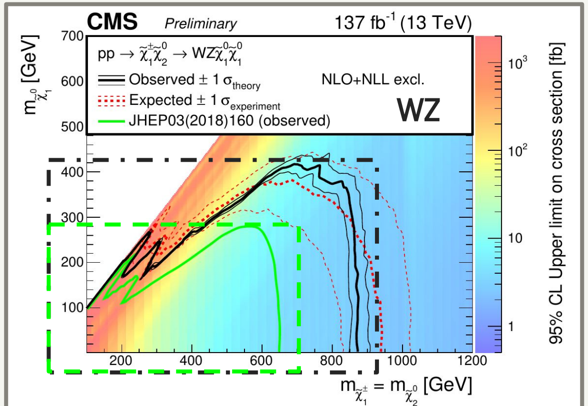


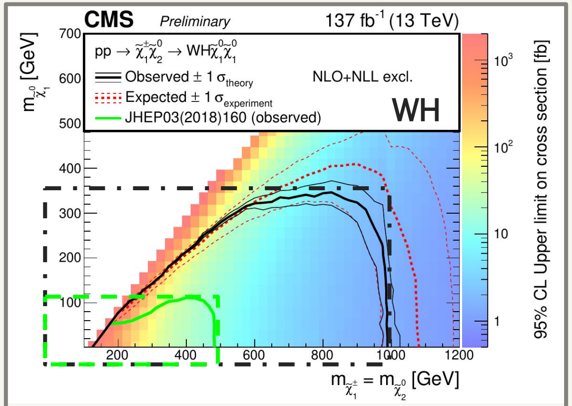
The limits are notably improved since
the 2016 EWKino Combination

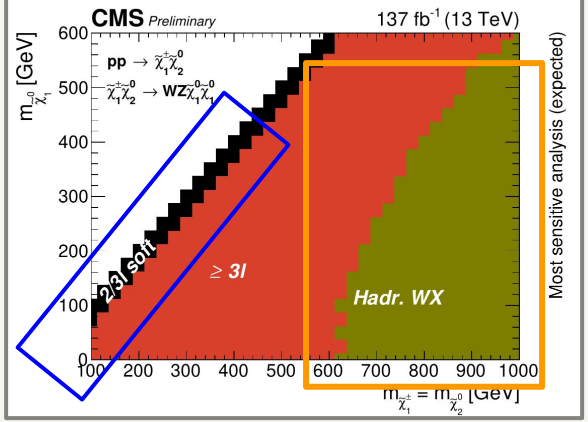
The new, fully hadronic input analysis
Hadr. WX improves the sensitivity to higher NLSP masses and uncompressed region

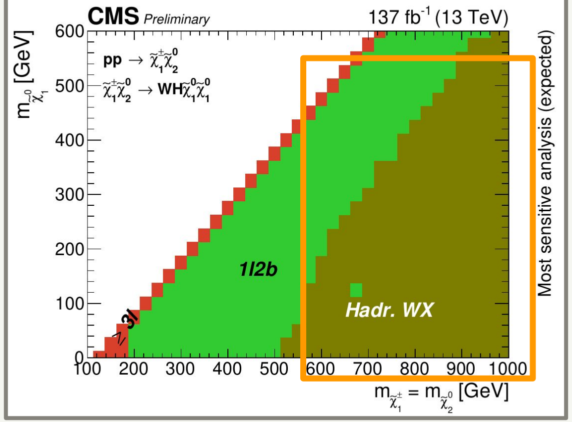
The exploration of the **compressed region** depends on the Full Run 2 data set as well as the novel techniques utilised by **the 2/3l soft and ≥ 3l analyses:**
What is the performance of the EWKino combination in the compressed region?

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

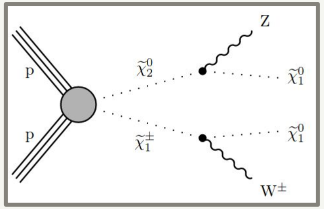








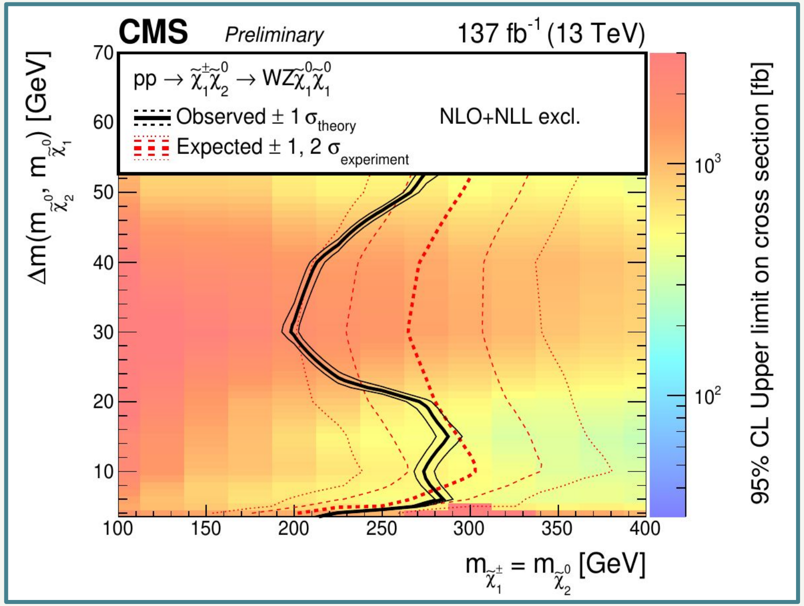
Production chargino and neutralinos: WZ compressed

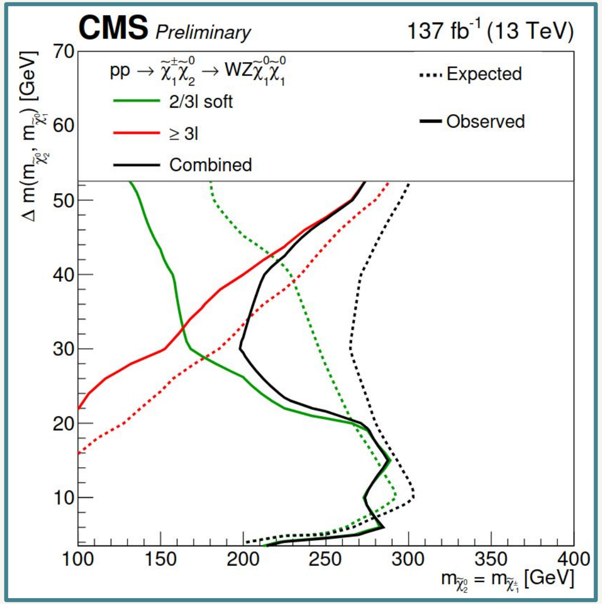


Wino-like chargino and neutralino (Bino-like LSP, $\tilde{\chi}_1^0$) with small mass-splittings

- The **2/3l soft** and **≥3l analyses** complement each other in the compressed region
  - Orthogonal lepton p_T ranges but different selections (e.g. MET for 2/3l soft)
    → Challenging to be fully optimal in the crossover regime

Search	gaugino WZ	WH
2/3ℓ soft	✓	
2ℓ on-Z	✓	
2ℓ non-resonant		
≥3ℓ	✓	✓
1ℓ2b		✓
4b		
Hadr. WX	✓	✓

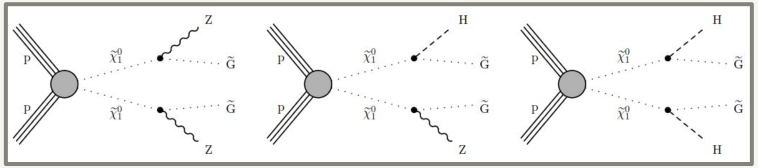




The combination closes the gap *between the analyses around Δm~40 GeV*

We observe a mild excess (~2σ) at Δm~30-40 GeV - due to both 2/3l soft and ≥3l analyses

Quasi-degenerate Higgsinos (GMSB)



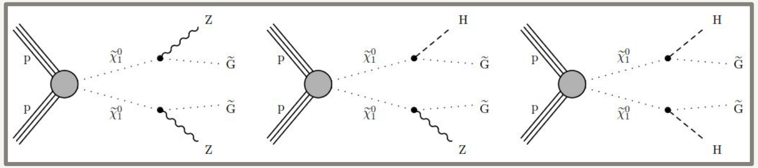
Gauge-mediated SUSY breaking (GMSB) model **with quasi-degenerate Higgsinos**

- Quasi-degenerate Higgsino triplet (χ_2^0, $\chi_1^\pm$, χ_1^0) with a minimal mass splitting
  → Effectively resulting in $\chi_1^0\chi_1^0$ pair production
  → Neutralinos decay to LSP Gravitino (m_G=1 GeV) and SM H/Z boson

	GMSB		
Search	ZZ	HZ	HH
2/3ℓ soft			
2ℓ on-Z	✓	✓	
2ℓ non-resonant			
≥3ℓ	✓	✓	✓
1ℓ2b			
4b			✓
Hadr. WX			

Quasi-degenerate Higgsinos (GMSB)

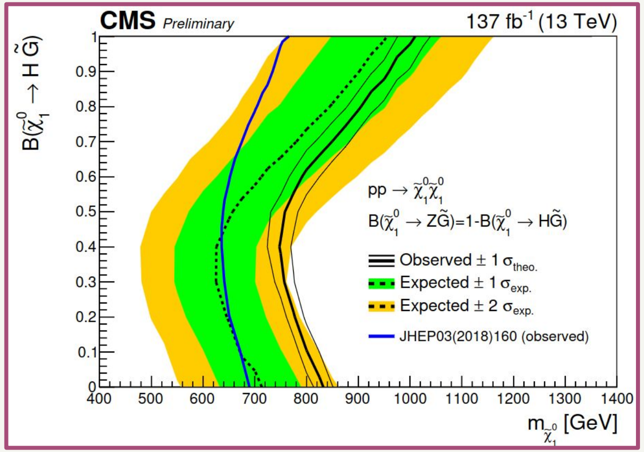
Gauge-mediated SUSY breaking (GMSB) model **with quasi-degenerate Higgsinos**

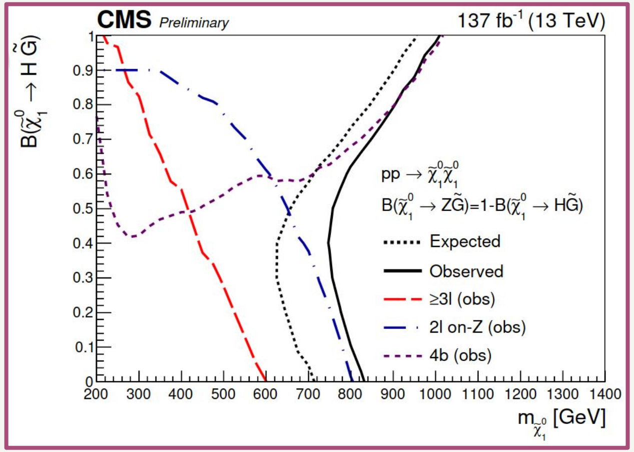


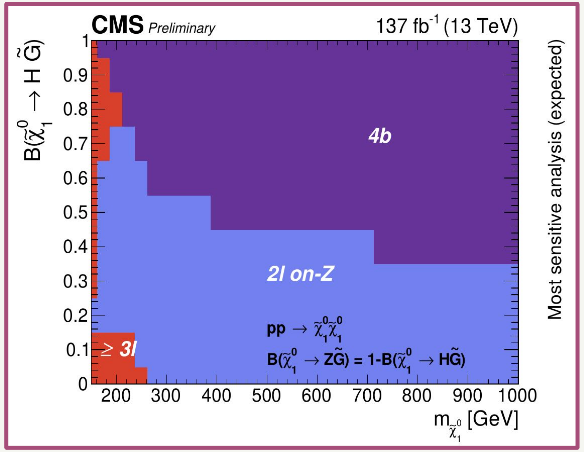
Search	GMSB ZZ	HZ	HH
$2/3\ell$ soft			
2ℓ on-Z	✓	✓	
2ℓ non-resonant			
$\geq 3\ell$	✓	✓	✓
$1\ell 2$b			
4b			✓
Hadr. WX			

- Quasi-degenerate Higgsino triplet (χ_2^0, $\chi_1^\pm$, χ_1^0) with a minimal mass splitting
  → Effectively resulting in $\chi_1^0\chi_1^0$ pair production
  → Neutralinos decay to LSP Gravitino (m_G=1 GeV) and SM H/Z boson

- Performed scan of exclusion limits as function of B($\chi_1^0 \rightarrow$ H$\tilde{G}$) (also for fixed BRs)
  - Overall ~200 GeV increased mass-exclusion w.r.t. the previous combination
  - The 4b (2l on-Z) analysis pushes sensitivity at large (small) B($\chi_1^0 \rightarrow$ H$\tilde{G}$)

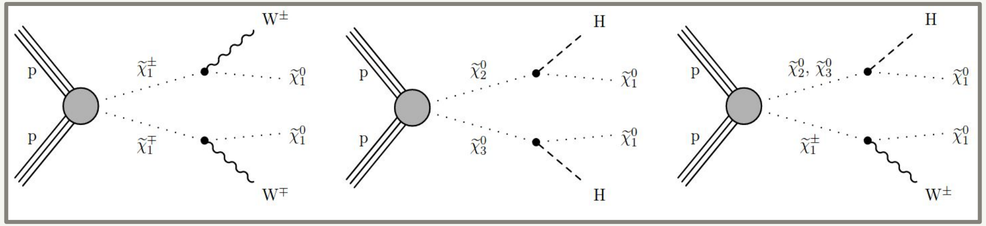






Higgsino-bino model

Bino-like LSP (neutralino $\tilde{\chi}_1^0$) and the existence of a mass-degenerate Higgsino triplet



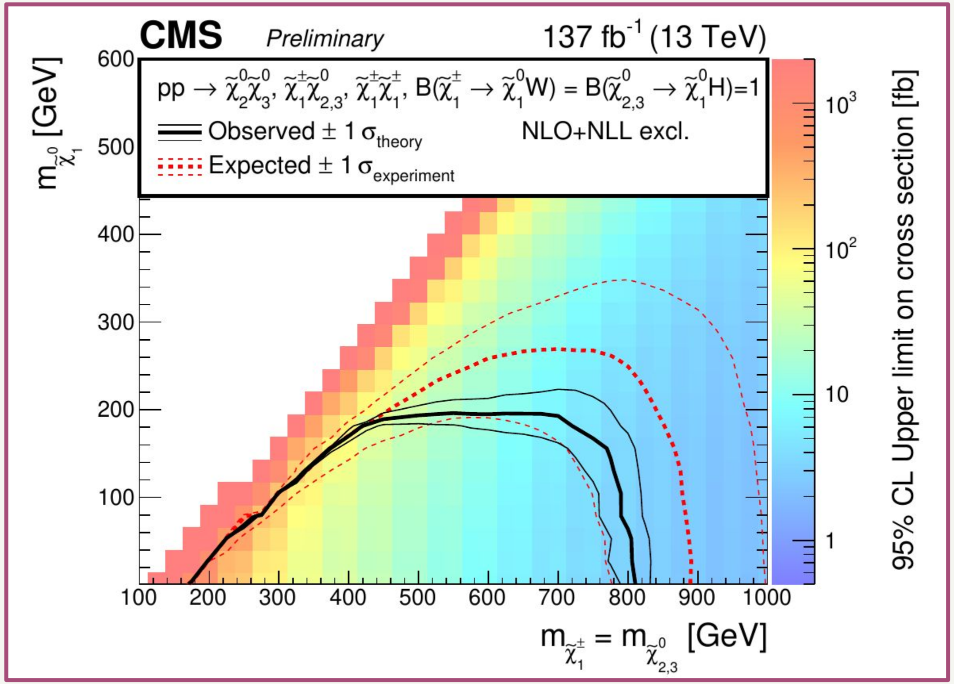
Completely new interpretation wrt the previous combination!

Target three final states; WW, HH, and WH, assuming

- $B(\tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0) = 100\%$,
- $B(\tilde{\chi}_{2,3}^0 \rightarrow H\tilde{\chi}_1^0) = 100\%$

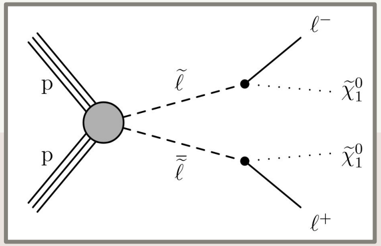
→ Cover the uncompressed phase-space, and large Higgsino masses

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



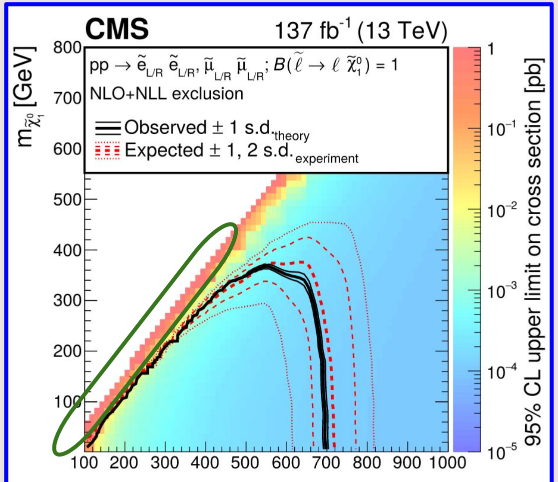
Mirror mirror on the wall - who is the rarest of them all?

Sleptons - the superpartners of SM leptons



Slepton models are hard to probe due to low production cross sections

Uncompressed phase space probed by the 2l non-resonant analysis,
we now extend our search to the compressed phase space with the 2/3l soft analysis!
→ A slepton is the NLSP, with the lightest neutralino $\tilde{\chi}_1^0$ as the LSP

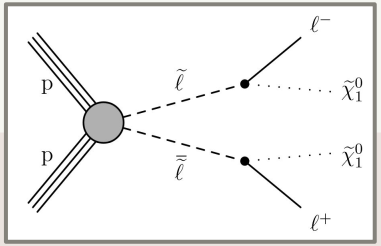


[2012.08600](2012.08600)

Search	sleptons $\ell^+\ell^-$
$2/3\ell$ soft	✓
2ℓ on-Z	
2ℓ non-resonant	✓
$\geq 3\ell$	
$1\ell 2b$	
4b	
Hadr. WX	

Mirror mirror on the wall - who is the rarest of them all?

Sleptons - the superpartners of SM leptons



Slepton models are hard to probe due to low production cross sections

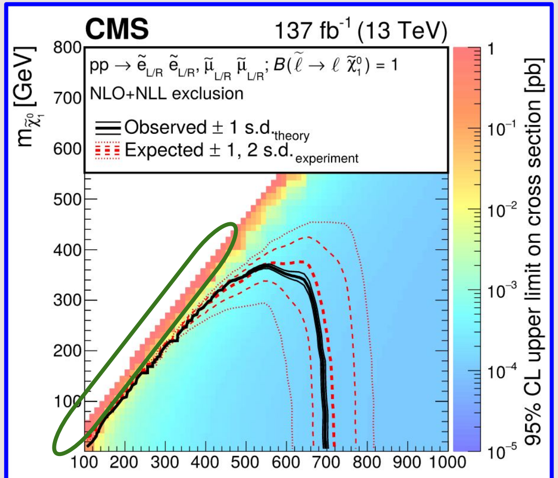
Uncompressed phase space probed by the 2l non-resonant analysis,
we now extend our search to the compressed phase space with the 2/3l soft analysis!
→ A slepton is the NLSP, with the lightest neutralino $\tilde{\chi}_1^0$ as the LSP

Strategy for the 2/3l soft search - largely unchanged

→ Same 2l SRs and background estimation methods as for the Wino-bino interpretation
→ **Update the search region fit-variable: a $M_{T,2}$ variable** (m$_{ll}$ not meaningful for this process)

Utilise parametric binning as done for the Wino-bino model

→ Binnings driven by shape of each signal hypothesis



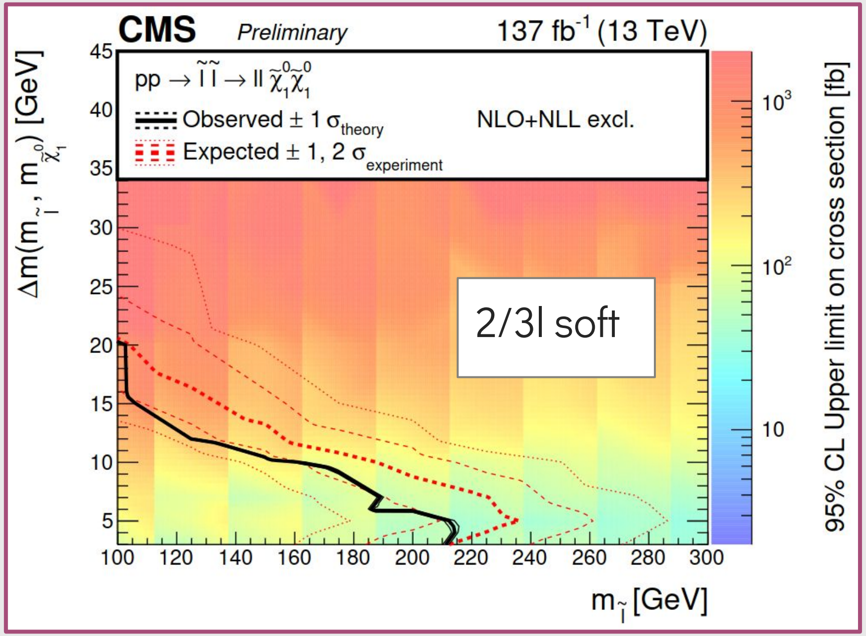
2012.08600

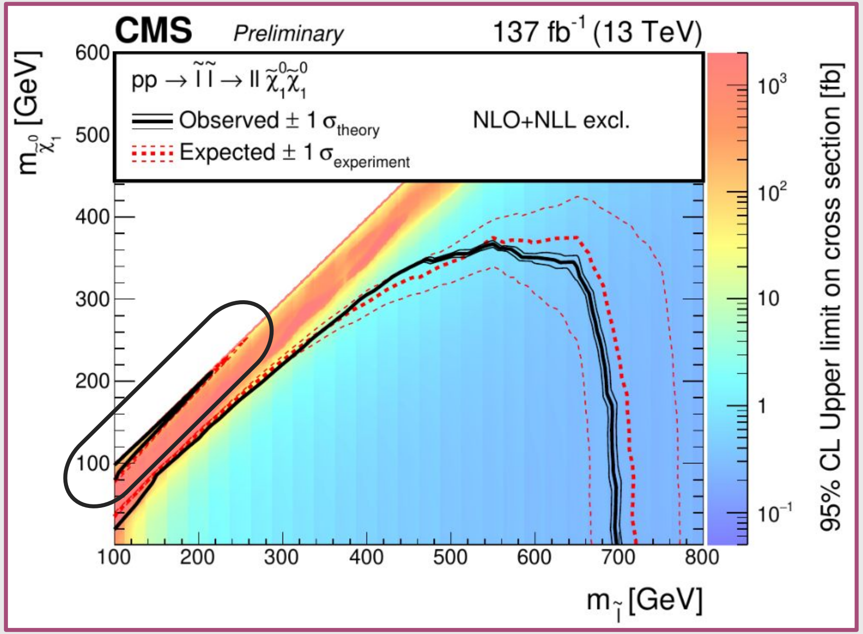
Search	sleptons $\ell^+\ell^-$
$2/3\ell$ soft	✓
2ℓ on-Z	
2ℓ non-resonant	✓
$\geq 3\ell$	
$1\ell 2$b	
4b	
Hadr. WX	

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

$$(M_T^{(i)})^2 = (m^{\text{vis}(i)})^2 + m_X^2 + 2\left(E_T^{\text{vis}(i)} E_T^{X(i)} - \vec{p}_T^{\text{vis}(i)} \cdot \vec{p}_T^{X(i)}\right)$$

Results: slepton pair production





Reach slepton masses of ~215 GeV at Δm=5 GeV

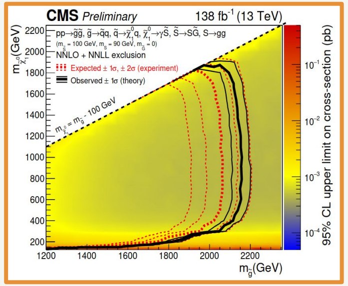
4b
Hadr. WX

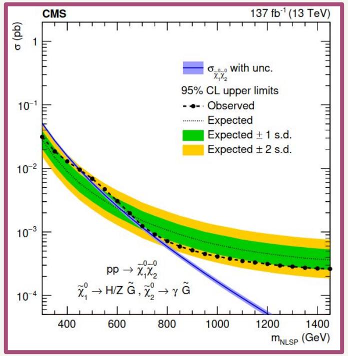
Summary

The full Run 2 data set allowed us to extend the SUSY search program beyond the typical searches

→ Recent searches target specific signatures, and exploit challenging final states (e.g. photons, low MET)

- **A search for Stealth SUSY sets most stringent limits on such models:**
  → *Exclude gluinos (squarks) with masses up to 2.15 (1.85) TeV*
- **Another search explores GMSB scenarios, using both EWK and strong SUSY production models:**
  →*Exclude neutralinos (gluinos) with masses up to 0.5 (2.32) TeV*





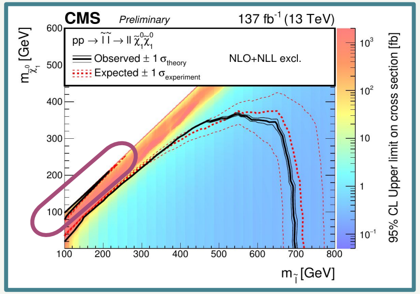
Combining multiple analyses provides an opportunity to increase our sensitivity towards SUSY

→ *Consider signals that populate more than one final state, and cover various sectors of the SUSY parameter space*

Legacy Run 2 combination utilises six searches targeting EWK SUSY processes

- *Account for numerous orthogonal final states (leptonic and hadronic)*
- *Provide novel parametric signal extractions in some input analyses*
- *Cover new interpretations: sleptons, Higgsino-bino model (chargino/neutralino)*

→ ***Set constraints among the most stringent to date on a range of models of EWK SUSY production,*** *and explore in particular* ***the compressed spectra further in the Wino-bino model and slepton pair production***



Thanks for your attention!

Back-up

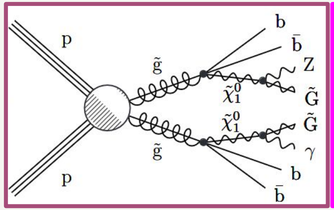
Back-up (part 1):
Results of the search targeting final states with a photon, jets, and large MET

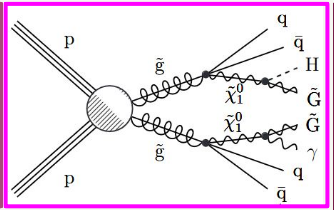
CMS-PAS-SUS-21-009

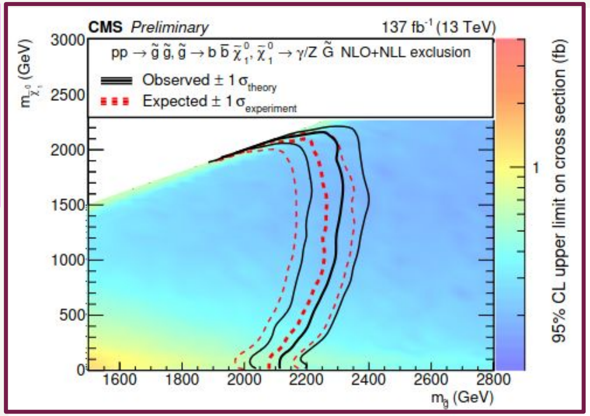
Search targeting final states with a photon, jets, and large MET

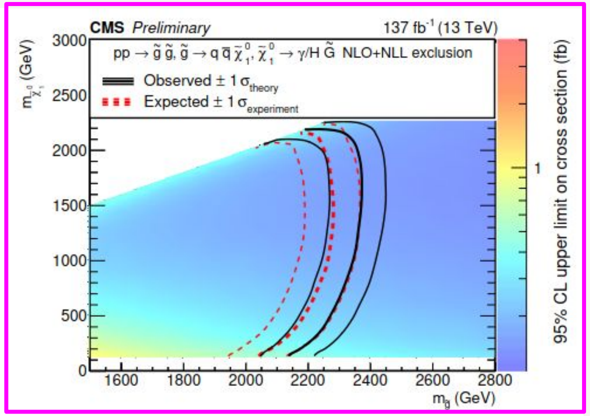
NEW

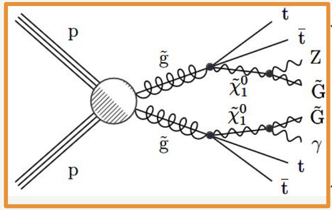
Explore GMSB (gauge-mediated SUSY breaking) scenarios: **strong** SUSY production models

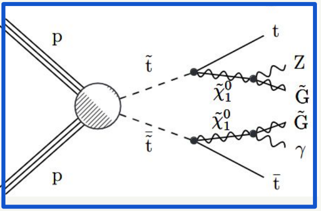


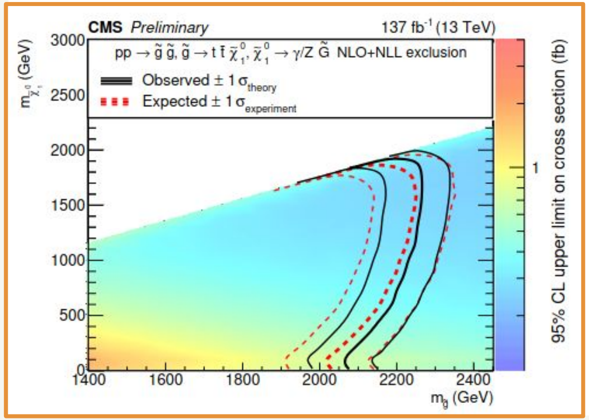


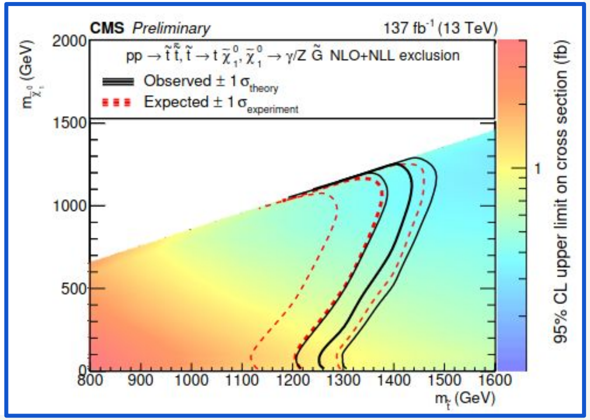












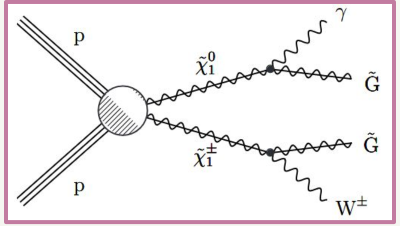
CMS-PAS-SUS-21-009

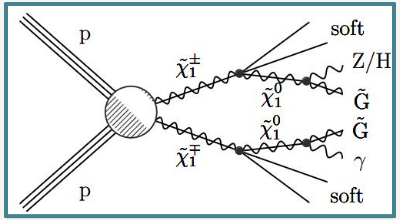
Search targeting final states with a photon, jets, and large MET

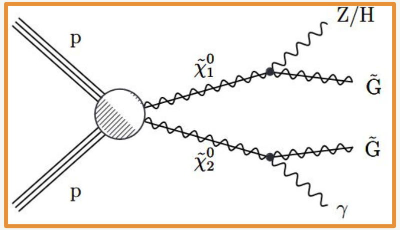
NEW

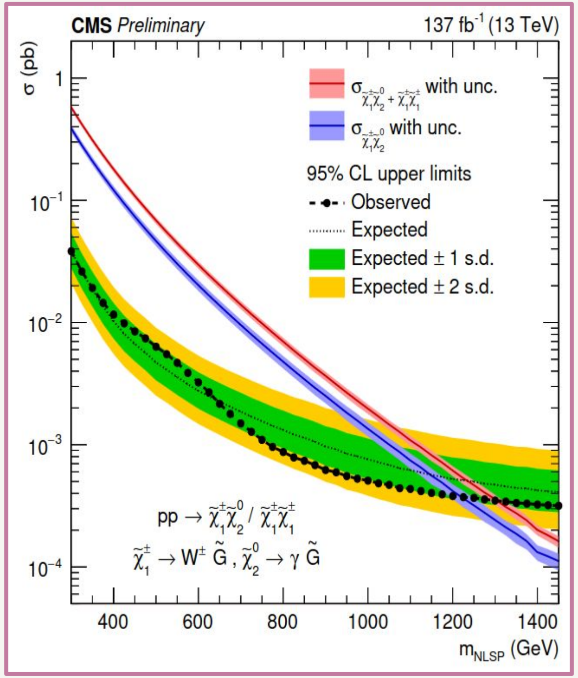
Explore GMSB (gauge-mediated SUSY breaking) scenarios: EWK SUSY production models

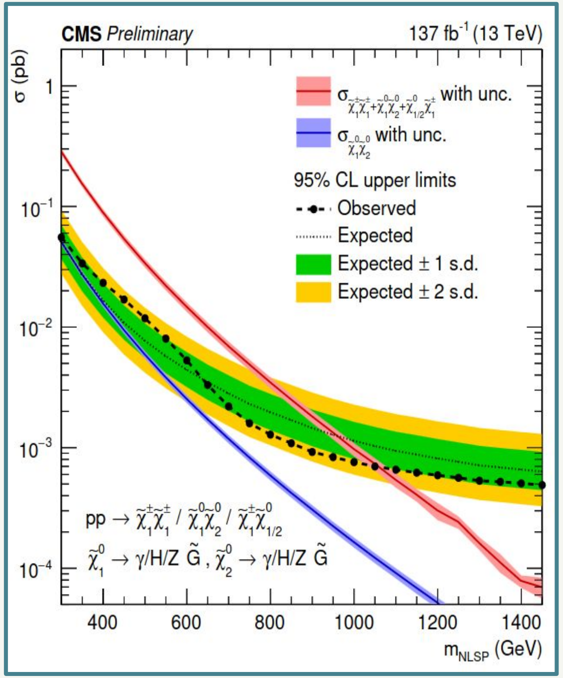
CMS-PAS-SUS-21-009

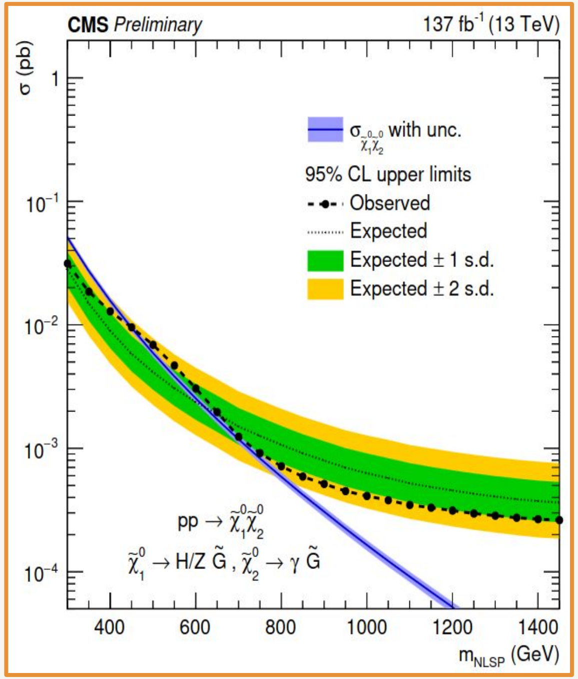








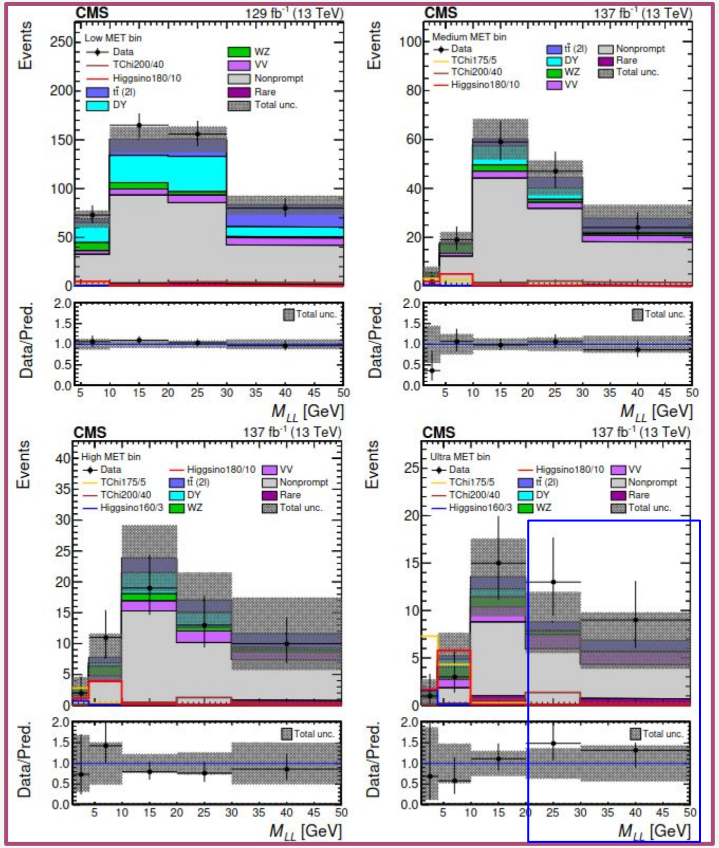


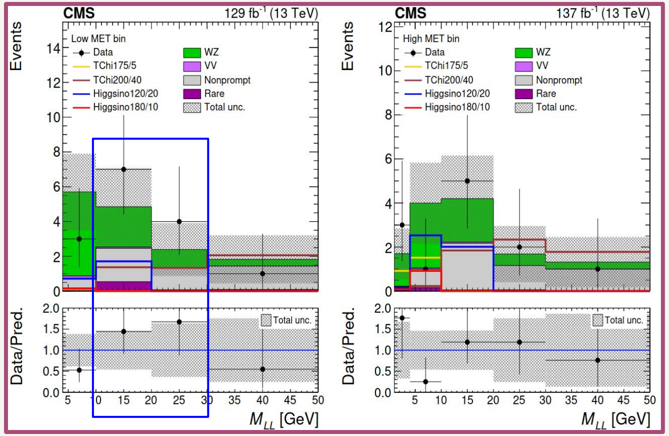


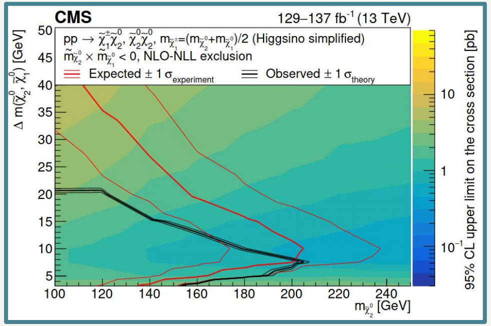
Back-up (part 2):
Combination of EWK SUSY searches

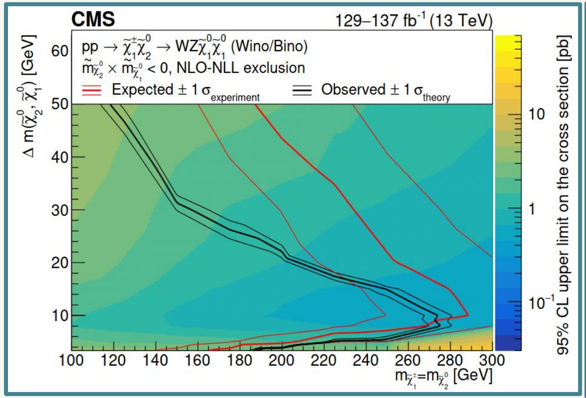
CMS-PAS-SUS-21-008

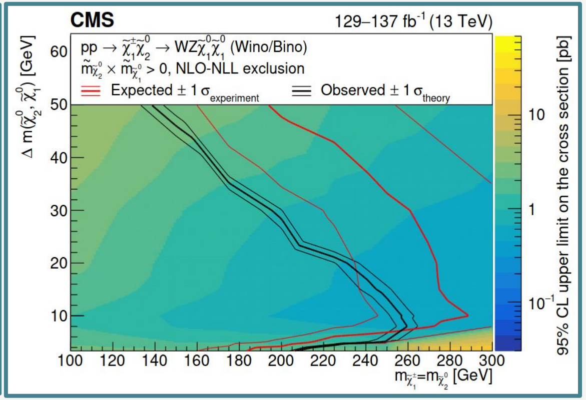
2/3l soft search - published results ([2111.06296])





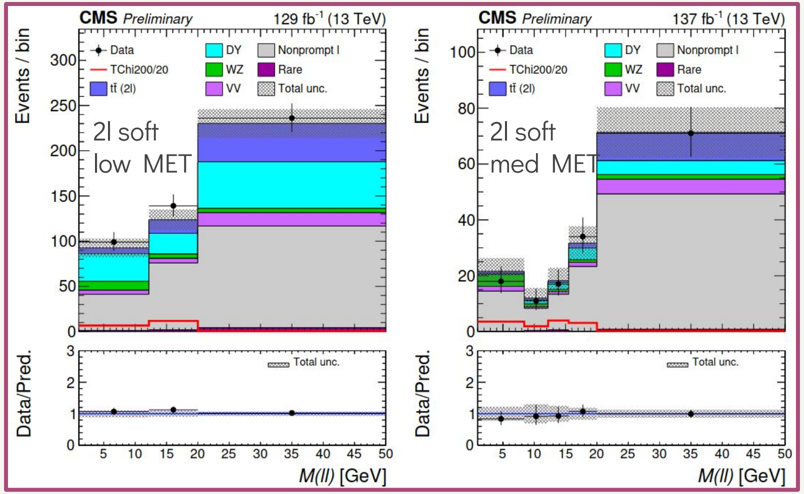






Signal region plots with the parametric approach

NEW



Individual m_{ll} binnings per signal region and MET bin;

reflecting theoretical signal shapes for the $\Delta m(\chi_2^0, \chi_1^0)$ signal hypothesis

→ *Finer bins in around peak, courser in tails;*

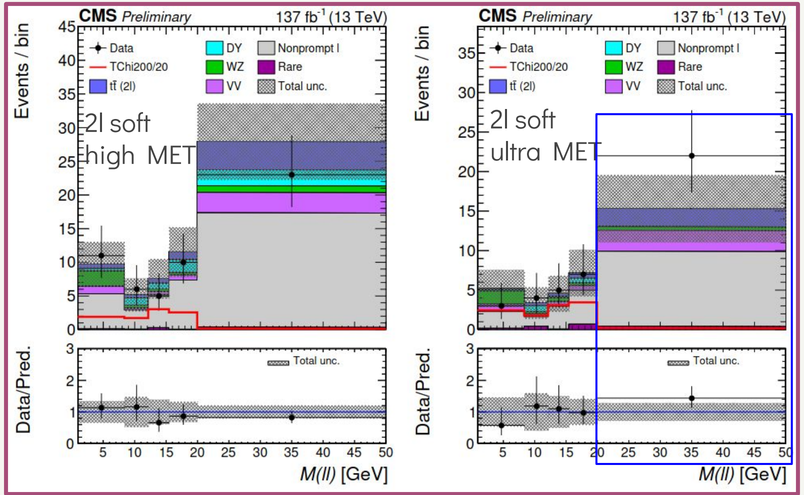
kinematic end-point at the mass-splitting

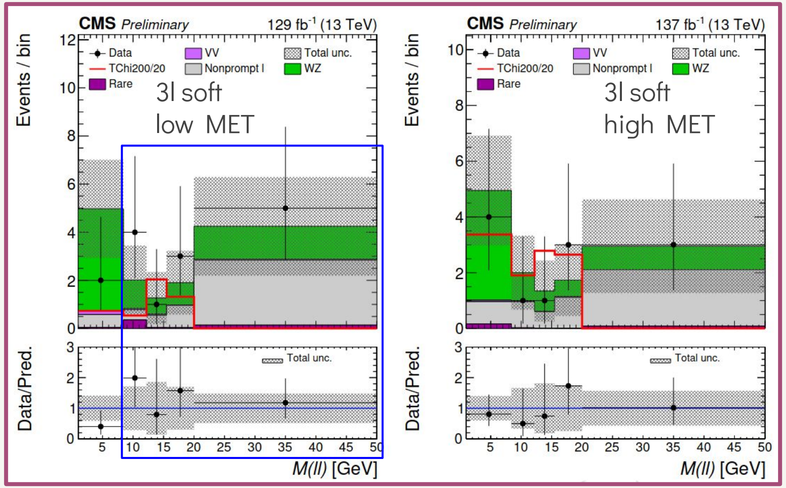
Signal region plots for Δm=20 GeV

NB: Published analysis already had an excess:

2l soft [*ultra MET, mll 20-30 GeV*] and 3l soft [*low MET, mll 10-30 GeV*]

[Additionally in WZ CTRL region incl. in the fit: mll 10-20 GeV, both MET bins]



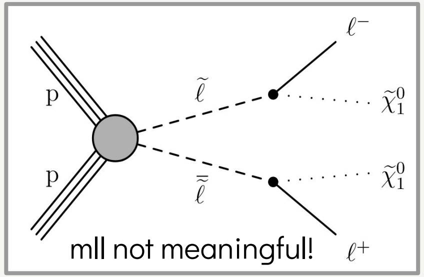


2/3l soft extension to slepton production

NEW

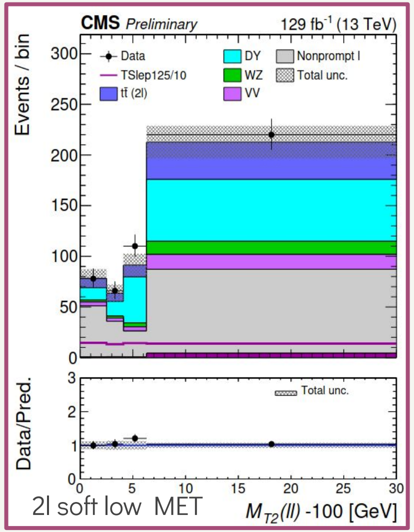
- **Analysis strategy largely unchanged: target two soft leptons + MET**
    - 3l soft SR ignored: negligible sensitivity (otherwise same SR + background estimation)
- SR fit variable: ***Stransverse mass M_{T2} with the test mass M_x = 100 GeV***
    - Well-established variable* but no analytical description for a given signal hypothesis

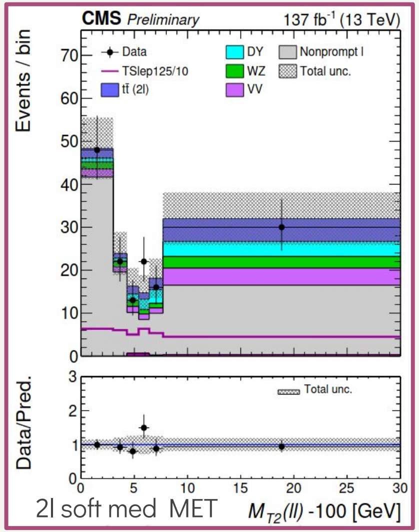
→ Use MC signal shape to provide individual binning for each signal mass-point and SR category

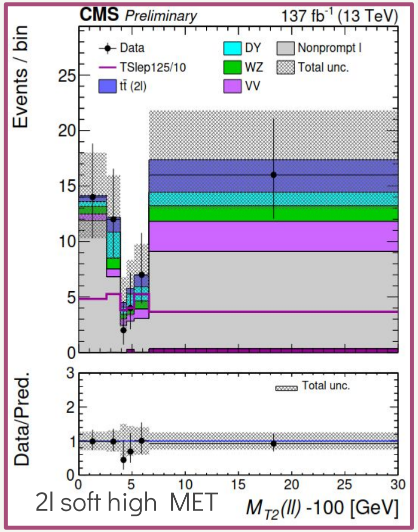


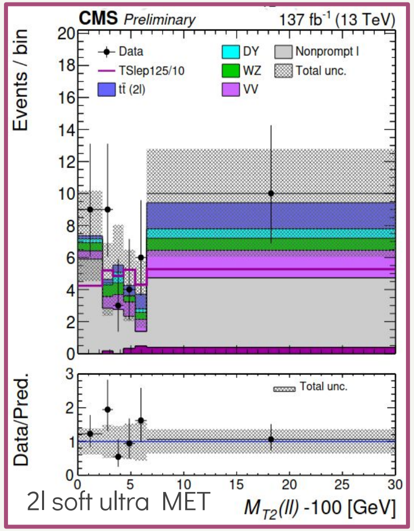
$$M_{T2}(m_X) = \min_{\vec{p}_T^{X(1)}+\vec{p}_T^{X(2)}=\vec{p}_T^{miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)}\right) \right]$$

$$(M_T^{(i)})^2 = (m^{vis(i)})^2 + m_X^2 + 2\left(E_T^{vis(i)} E_T^{X(i)} - \vec{p}_T^{\,vis(i)} \cdot \vec{p}_T^{\,X(i)}\right)$$









* *"-- measure the mass of pair-produced particles in situations where both particles decay to a final state containing an undetected particle X of mass mX"*

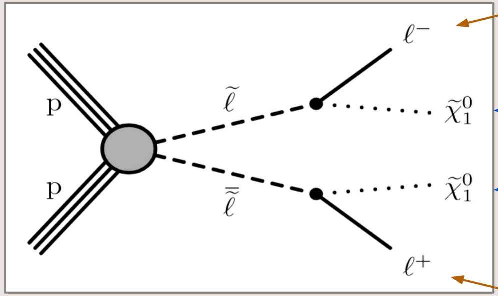
$M_{T,2}$ variable

- **$M_{T,2}$ variable** generalises M_T for symmetric event topologies where two identical particles each decay into a visible and invisible product (1502.04358)

$$(M_T^{(i)})^2 = (m^{\text{vis}(i)})^2 + m_X^2 + 2\left(E_T^{\text{vis}(i)} E_T^{X(i)} - \vec{p}_T^{\,\text{vis}(i)} \cdot \vec{p}_T^{\,X(i)}\right)$$

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

A minimization is performed over trial momenta of the undetected particles fulfilling the p_T^{miss} constraint. The unknown mass mx is a free parameter.



$m^{vis(1)}$, $E_T^{vis(1)}$, $\mathbf{p}_T^{vis(1)}$

m_X, $E_T^{X(1)}$, $\mathbf{p}_T^{X(1)}$

m_X, $E_T^{X(2)}$, $\mathbf{p}_T^{X(2)}$

$m^{vis(2)}$, $E_T^{vis(2)}$, $\mathbf{p}_T^{vis(2)}$

The **visible parts** of each decay chain (leptons) are reconstructed

The **invisible parts** are unknown! We only reconstruct the total missing transverse energy!

Input analyses for the CMS EWKino Combination

Leptonic

2106.14246

"≥ 3l" (2l SS)

Three or four leptons
(up to 2 hadronically decaying taus)
or two same-sign (SS) light leptons
Leading lepton pT > 25 GeV (3l)*

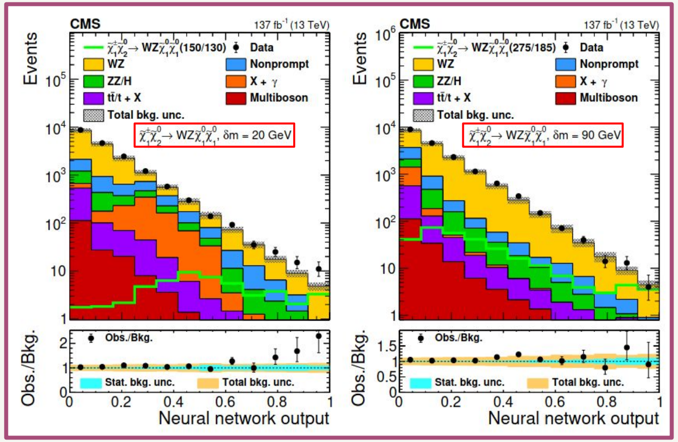
An exhaustive search that considers up to 13 different leptonic final states

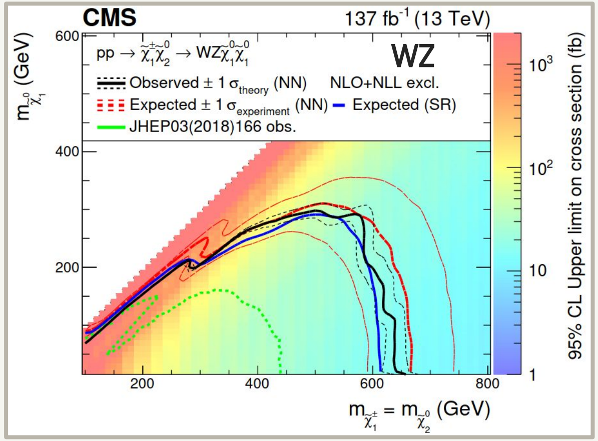
2l (SS): light leptons (compressed regions)

3l and 4l: up to 2 hadr. decaying taus in addition to light leptons

Update since 2016 for the 3l category: Parametric signal extraction to target different models with wildly varying kinematics

Parametric Neural Networks using mass-splitting (m_{NLSP}-m_{LSP}) as a variable
→ Target each signal model [for the wino-bino model with WZ final state]
→ Individual background (and signal) distribution for each dM





Around ~50 GeV in m_{NLSP} are gained with the use of the parametric neural network

- *Small excesses in the categories involving two leptons of the same sign*
  - Regions with low M_{T2} and high M_{T2} but low pT(ll)): generally populated by the low Δm signals

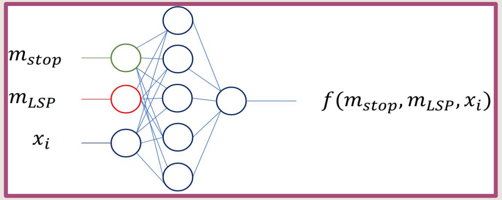
**Update for the combination: Increase the pT selection to 30 GeV for the leading lepton to avoid overlaps with the 2/3l soft analysis*

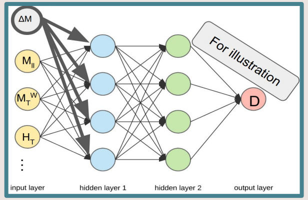
Machine Learning in CMS stop and multilepton searches

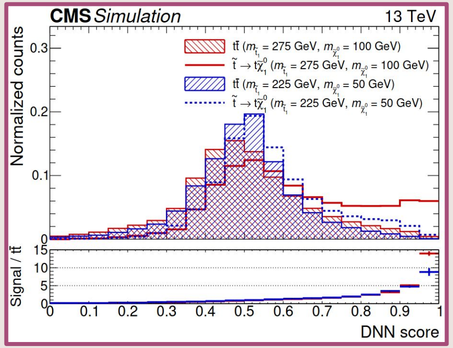
Parametric Neural Network (NN) is used to learn peculiarities of the signal kinematics depending on SUSY parameters and to provide an optimal performance at ~any signal point

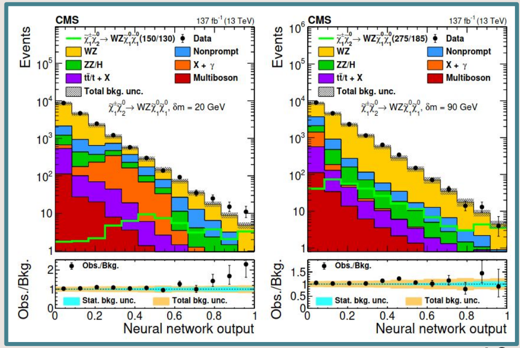
- **Parametric NN: introduce a generator-level training variable specific to the signal hypotheses**
  → Parameter in background is randomized to follow the training variable's signal distribution (no discrimination directly from parameter)
  → The NN learns the correlations of the parameter with other training variables, improving performance
- **The NN output is provided for each signal hypotheses (data and background is redistributed!)**
- Both **stop combination (2107.10892)** as well as the **multilepton search (2106.14246)** utilise parametric NN
  - Stop: target top corridor where mass splitting between the top squark and the lightest neutralino is close to top quark mass
  - Multilepton: Provide sensitivity even for interpolated mass-splitting values that were not used for training

Details	Stop combination (2107.10892)	Multilepton search (2106.14246)
Chosen variable?	Top squark and neutralino masses	Mass-splitting between NLSP and LSP
Other training variables	$p_T^{e\mu}$, $\Delta\phi$, $\Delta\eta$, $p_T(l_0)$, $\eta(l_0)$, $p_T(l_1)$, $\eta(l_1)$, p_T^{miss}, $m_{e\mu}$, $m_{T2}(e\mu)$, H_T	m_{ll}, m_T^W, m_T^{3l}, m_{3l}, H_T, p_T^{miss}, $L_T+p_T^{miss}$
Input to training?	Signal: top production, stop mass ranging 145–295 GeV and |dM-top mass| 0-30 GeV Background: simulated tt with eμ decays.	Corresponding signal per model (4 parametric NNs: TChiWZ, SlepSnu0p95, SlepSnu0p5, SlepSnu0p05) Background is all process in the SR weighted appropriately









Input analyses - 2l on-Z/non-resonant

Leptonic

[2012.08600](2012.08600)

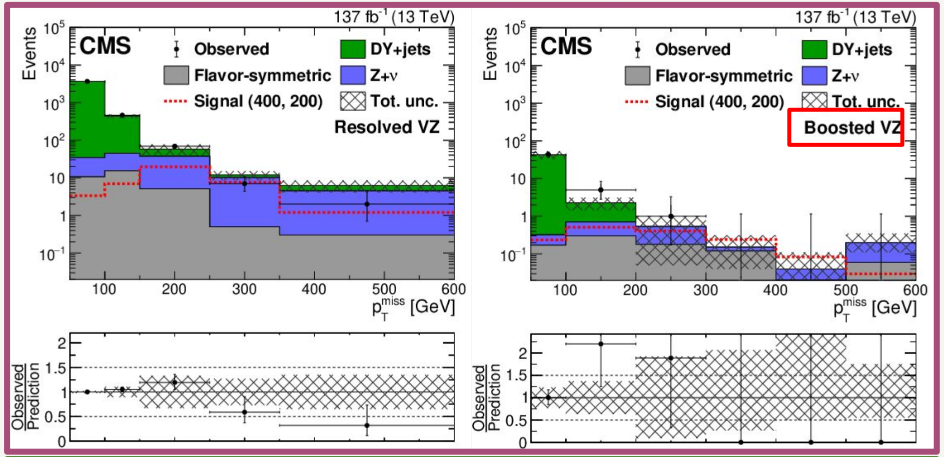
"2l on-Z/non-resonant"

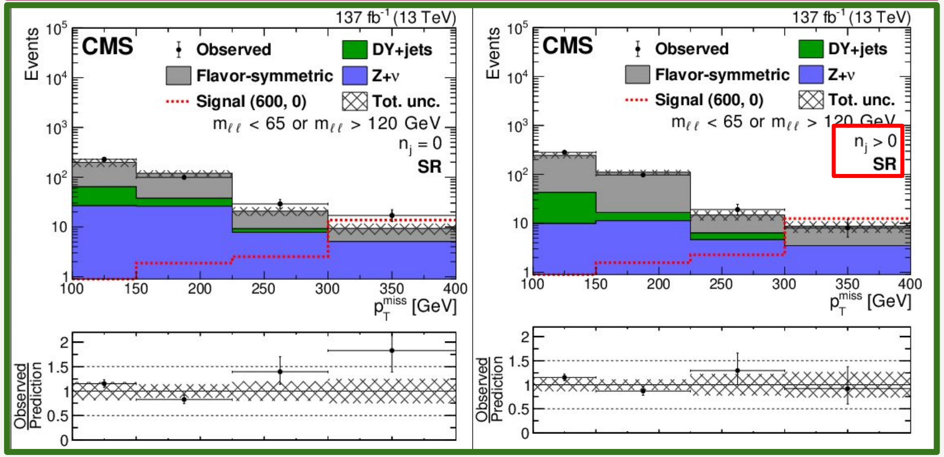
Two e(mu)
Opposite-sign, same-flavour pair
Either on-shell or off-shell Z

Two categories, targeting

1. On-Z events (neutralino/chargino):
A new region with boosted jets

2. Non-resonant (sleptons):
New ISR jet regions,
reoptimization of analysis selection





2l on-Z/non-resonant: results

Leptonic

2012.08600

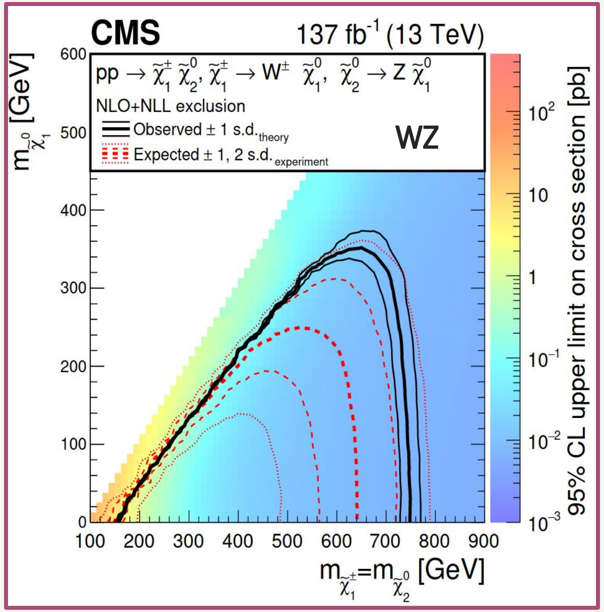
"2l on-Z/non-resonant"

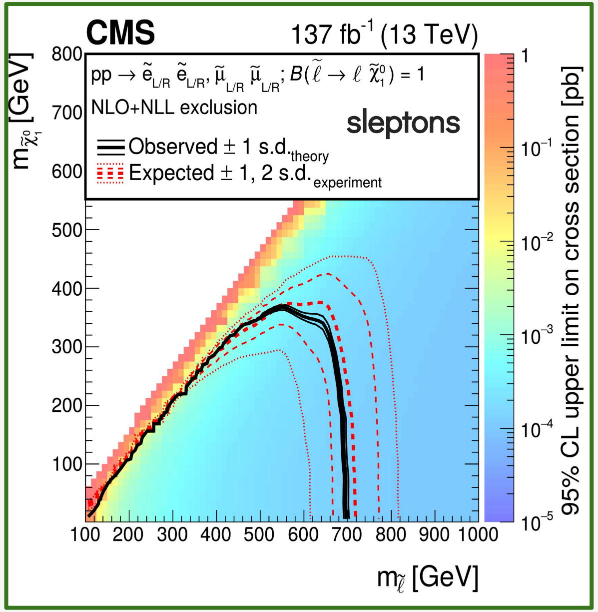
Two e(mu)
Opposite-sign, same-flavour pair
Either on-shell or off-shell Z

Two categories, targeting

1. On-Z events (neutralino/chargino):
A new region with boosted jets

2. Non-resonant (sleptons):
New ISR jet regions,
reoptimization of analysis selection





Input analyses - 1l *2b*

(semi)Hadronic

2107.12553
"1l *2b*" - WH

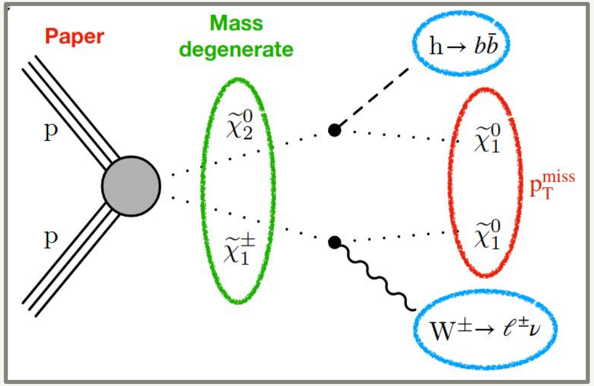
One e(mu), H→bb

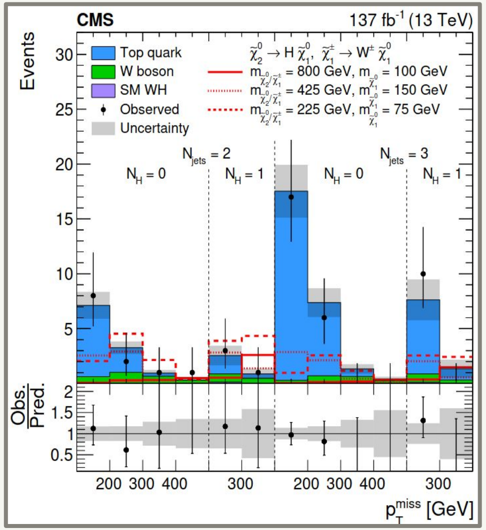
Improvements since 2016 include:

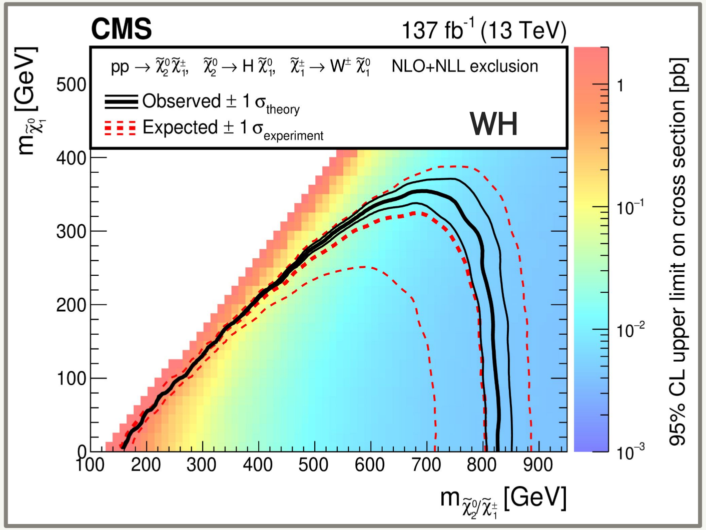
Utilization of boosted tagger (targets high mass-splitting models):
→ Identify Higgs boson decays collimated into large-radius jets

Inclusion of 3 jet SR:
allows for 1 additional jet from ISR

Expansion of pTmiss binning:
[125, 200+]→ [125, 200, 300, 400+] GeV







Input analyses - 4b

Hadronic

2201.04206

"4b" - HH

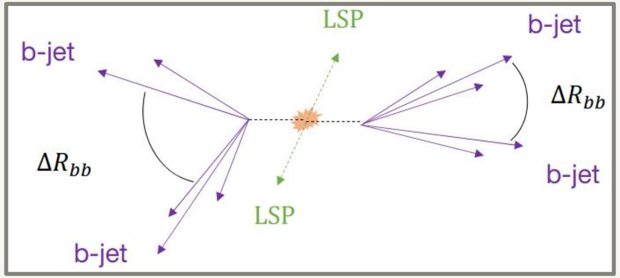
No leptons
Two Higgs bosons; H→bb

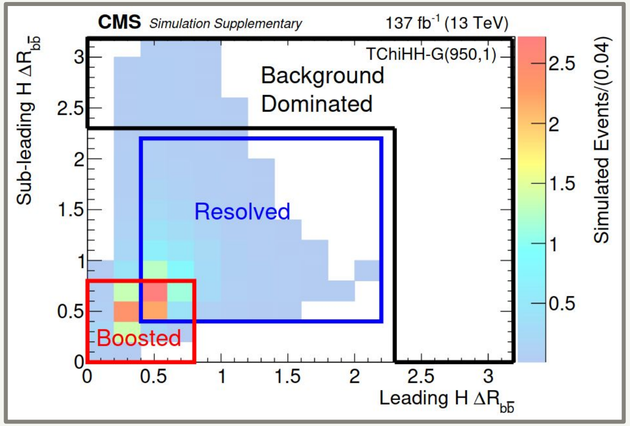
Two separate categories optimized for specific parts of the parameter space

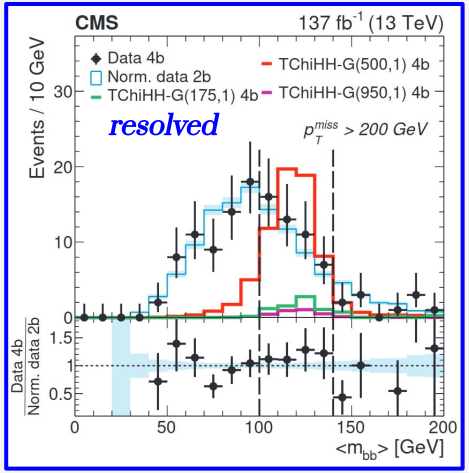
Resolved analysis (typically lower pTmiss):
the b jets are separate AK4 jets
→ Signal extraction: the average mass $\langle m_{bb} \rangle$ of the two Higgs boson candidates

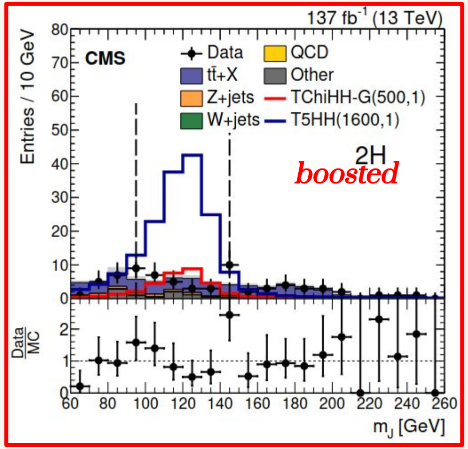
Boosted analysis (typically higher pTmiss):
2b merged into a large radius jet (AK8)
→ Relies on **a boosted tagger**
→ Signal extraction: m_J attributed to an AK8 jet
of the two Higgs boson candidates

Main background: ttbar
Measured with data-driven ABCD method with different variables ($\langle m_{bb} \rangle$, N_b) vs (m_J, N_H)
(*boosted: also pTmiss shape measurement*)









4b: results

Hadronic

2201.04206

“4b” - HH

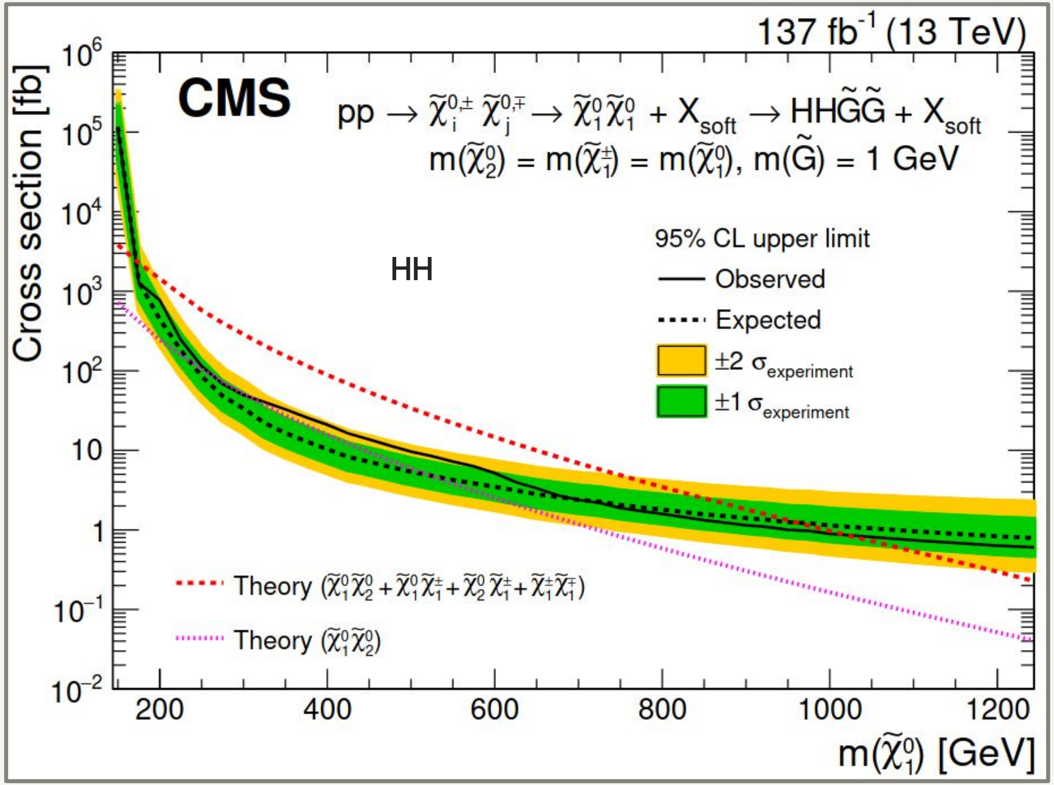
No leptons
Two Higgs bosons; H→bb

Two separate categories optimized for specific parts of the parameter space

Resolved analysis (typically lower pTmiss):
the b jets are separate AK4 jets
→ Signal extraction: the average mass $\langle m_{bb} \rangle$ of the two Higgs boson candidates

Boosted analysis (typically higher pTmiss):
2b merged into a large radius jet (AK8)
→ Relies on **a boosted tagger**
→ Signal extraction: m_J attributed to an AK8 jet
of the two Higgs boson candidates

Main background: ttbar
Measured with data-driven ABCD method with different variables (**$\langle m_{bb} \rangle$, N_b**) vs (**m_J, N_H**)
(*boosted: also pTmiss shape measurement*)



NEW

Input analyses - Hadr. WX

Hadronic

2205.09597
"Hadr. WX"

Fully hadronic final state;
at least 2 jets (AK8),
and 2-6 jets (AK4)

Perform H/Z/W-tagging with ML algorithms

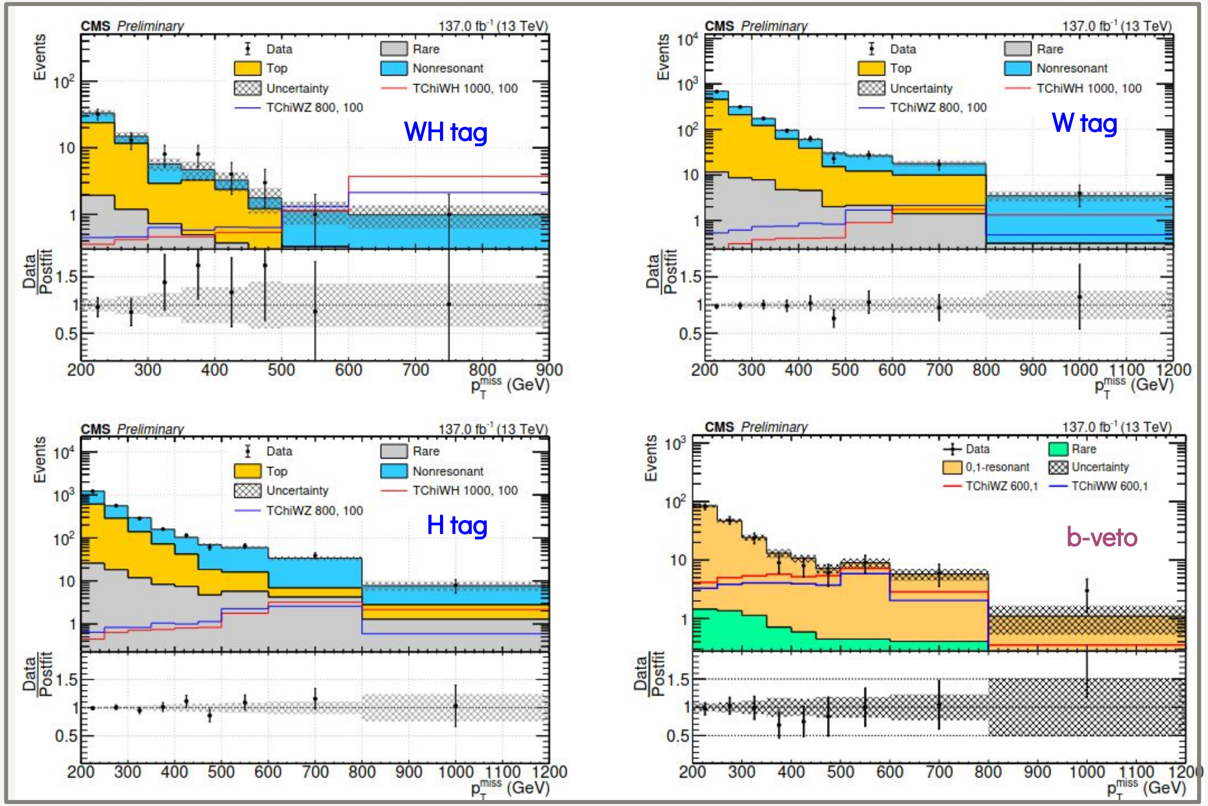
Four signal regions targeting models without and with b jets

B-veto signal region (WW, WZ) requires
≥ 2 AK8 jets with WZ-mass (65-105 GeV)
Tagging: DeepW & DeepW-MD

Regions with b jets (WH, WZ, or ZH)
WHTag: DeepW (W/Z candidate)
& Deepbb (Z/H candidate)

WTag: DeepW (W/Z candidate, not in WHTag)

HTag: Deepbb (Z/H, not in WHTag)



NEW

Hadr. WX: results

Hadronic

2205.09597
"Hadr. WX"

Fully hadronic final state;
at least 2 jets (AK8),
and 2-6 jets (AK4)

Perform H/Z/W-tagging with ML algorithms

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WHTag: DeepW (W/Z candidate)
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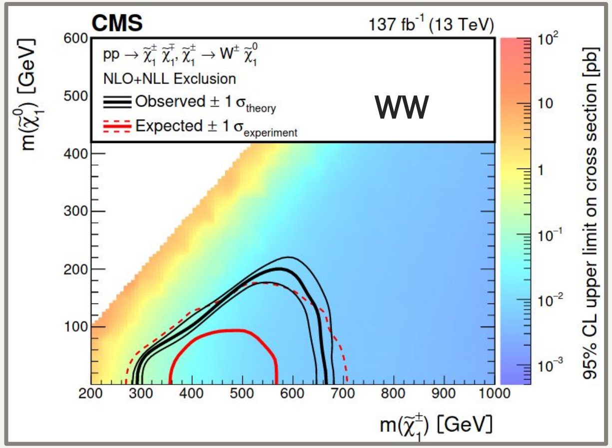
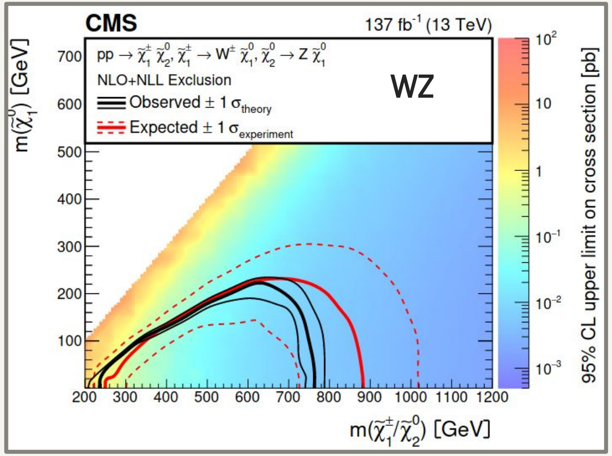
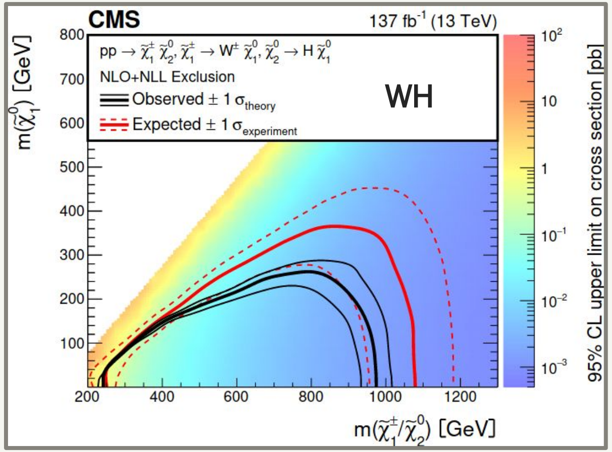
WTag: DeepW (W/Z candidate, not in WHTag)

HTag: Deepbb (Z/H, not in WHTag)







Correlation scheme

SM background normalization

Generally uncorrelated, except for WZ:
→ Constrain WZ normalization in the 2/3l soft analysis using the region of ≥3l analysis (WZ control region of 2/3l soft search removed in the fit due to overlaps)

Trigger efficiency

Large variety in HLT paths used in input analyses results in complicated trigger efficiency correlations
→ Correlate efficiencies of **MET triggers** and **lepton triggers** separately

Lepton efficiency

Multitude of lepton definitions (flavor/ID/selections) between analyses

Exception for slepton production:
Decorrelate as completed different phase spaces targeted!

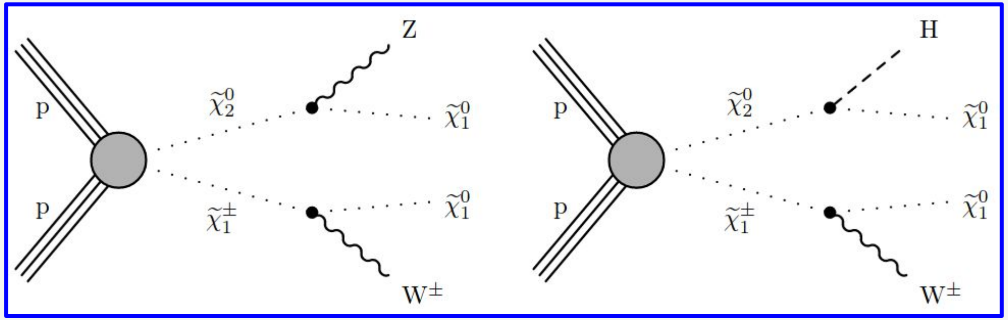
Table 5: Sources of systematic uncertainties and the level of correlation between analyses.

Notes:
1. The WZ background normalization is correlated between the "$\geq 3\ell$" [18] and the "$2/3\ell$ soft" [17] searches.
2. Except for slepton pair production, for which the two contributing searches, "$2/3\ell$ soft" [17] and "2ℓ non-resonant" [15], cover disjoint regions of the model parameter space.

Source	Correlated?
General	
MC sample size	No
SM background normalization	No[1]
Luminosity	Yes
Trigger efficiency	Partially
Pileup	Yes
Trigger timing	Yes
Objects and signal modeling	
Lepton efficiency	Yes[2]
Jet energy resolution	Yes
Jet energy scale	Yes
b (mis)tagging efficiency	Yes
AK8 bb tagging efficiency	Yes
AK8 jet mass resolution	Yes
ISR modeling	Yes
Scales μ_R and μ_F	Partially
Attributable to the CMS fast simulation	
p_T^{miss} modeling	Yes
b (mis)tagging	Yes
b mistagging	Yes
AK8 bb tagging	Yes
AK8 bb mass	Yes

Legacy of Run 2: EWKino Combination

1. *Production of Wino-like chargino and neutralino* (Bino-like LSP, $\tilde{\chi}_1^0$)



+ Mixed case: 50% BR to Z and H

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

Two important overlaps between **3l regions of 2/3l soft** and **those in the A and B (3l) categories of >3l analysis**

1. **3l WZ CR overlaps** almost fully with **the A category**
   → WZ CR removed from the combined fit; background constrained through a common nuisance parameter

2. **3l soft SR** and **A and B** categories: overlap due to the pT selection: <30 GeV vs >25 GeV
   → >3l analysis updated the leading lepton pT selection **in both categories (both enter the mixed topology!)**
   → Only slight changes in the sensitivity;
   Largest drops seen in compressed WZ where the loss ranges between 1 and 10 % (dM 70 to 20 GeV)

- Category A: three light leptons, including an OSSF lepton pair.
- Category B: three light leptons, with no OSSF lepton pairs.

Effect of the leading leg pT selection in >3l analysis: A and B category

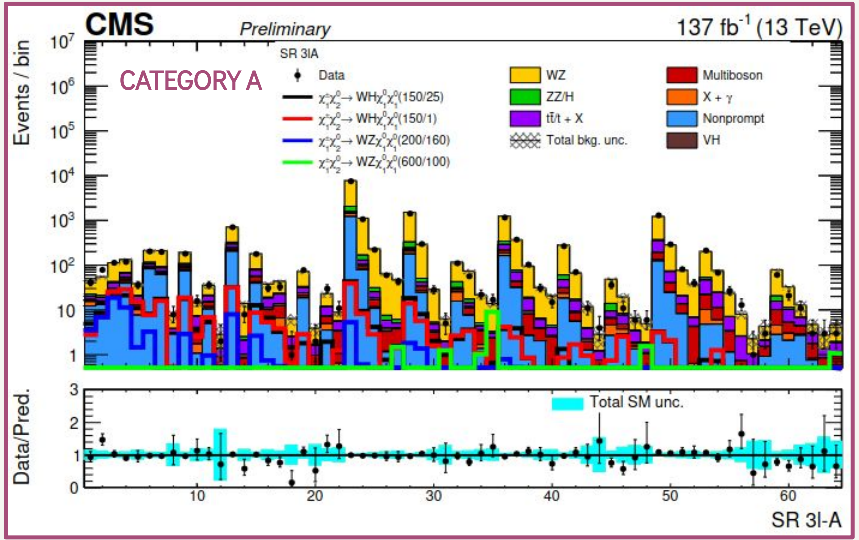
- Category A:
  - Backgrounds: Reduction in yields is less than 1%, except for regions with low invariant mass (mll < 75 GeV) where the decrease in the background yields can be up to 7%
  - Signal models that target uncompressed scenarios are largely unaffected, while those that include compressed spectra have a reduction in overall yields of 5-7%
- Category B:
  - Background contributions are reduced by roughly 5%, with the largest differences in the signal-depleted second and third bins. Signal efficiency is reduced by 1-2%.

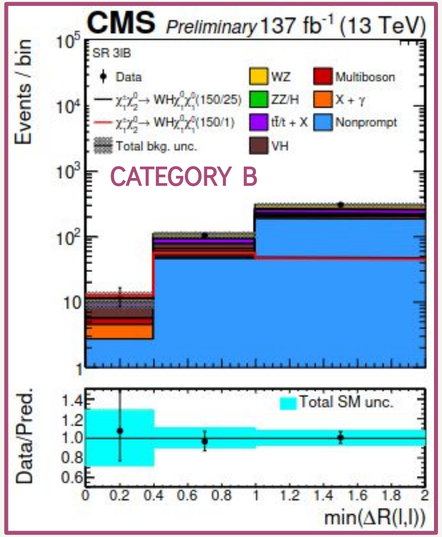
Table 3: Definitions of the SRs in category A, off-Z.

M_T (GeV)	$M_T^{3\ell}$ (GeV)	$m_{\ell\ell} < 50$ GeV	$50 \leq m_{\ell\ell} < 75$ GeV	$105 \leq m_{\ell\ell} < 250$ GeV	$m_{\ell\ell} \geq 250$ GeV
0–100	0–50	A01	A06	A13	A19
	50–100	A02			
	100–400	A03	A07		
	≥400		A08	A14	A20
100–200	0–200	A04	A09	A15	A21
	≥200		A10	A16	
≥200	0–400	A05	A11	A17	A22
	≥400		A12	A18	

Table 2: Definitions of the SRs in category A, on-Z.

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

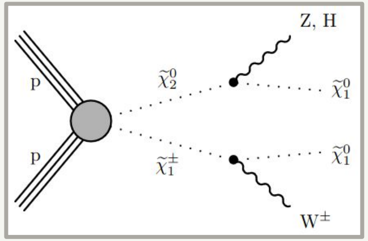




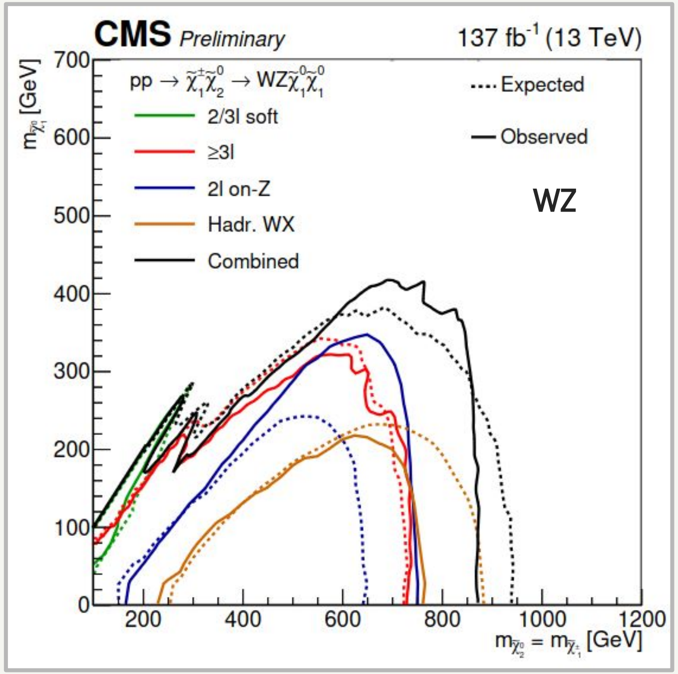
Production chargino and neutralinos (WZ/WH)

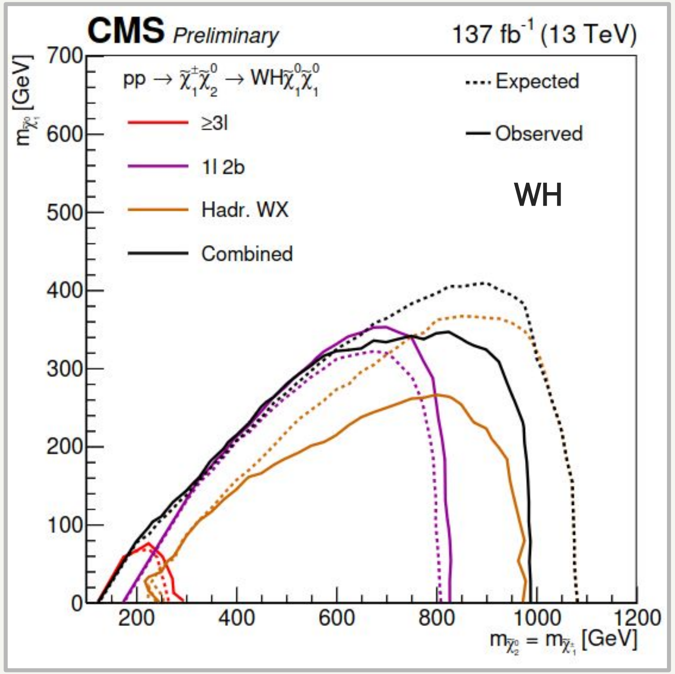
Wino-like chargino and neutralino (Bino-like LSP, $\tilde{\chi}_1^0$)

NEW



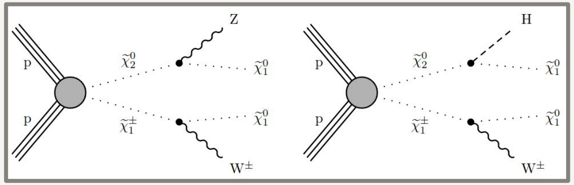
Search	gaugino WZ	gaugino WH
$2/3\ell$ soft	✓	
2ℓ on-Z	✓	
2ℓ non-resonant		
$\geq 3\ell$	✓	✓
$1\ell 2b$		✓
4b		
Hadr. WX	✓	✓





Wino-bino model: W(Z+H) -mixed

NEW

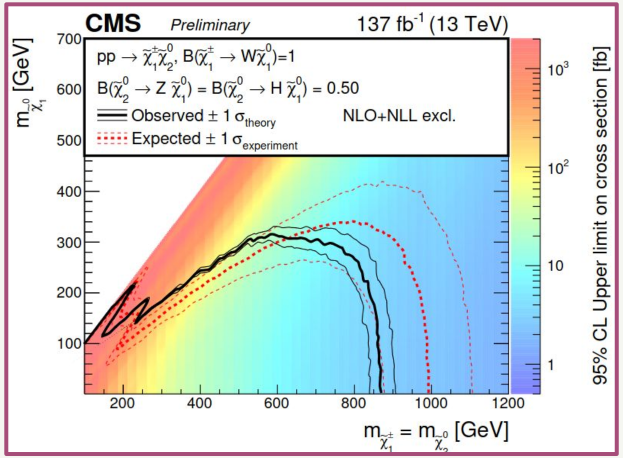


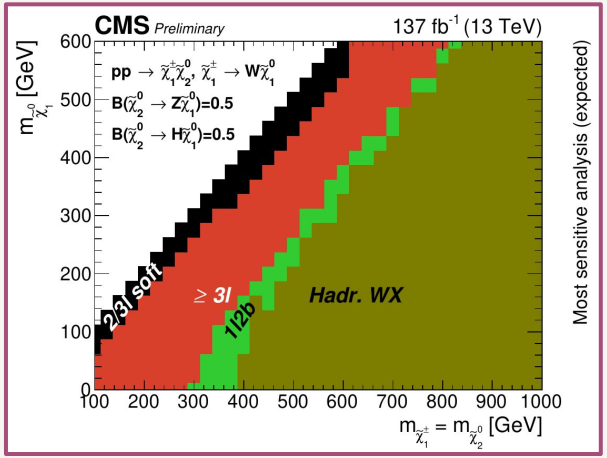
- Pair production of Wino-like $\chi_2^0\chi_1^\pm$, decaying to Bino-like χ_1^0 and SM boson
  - Assuming BR($\chi_1^\pm \rightarrow \chi_1^0$ W±) = 100%
  - Assuming **BR($\chi_2^0 \rightarrow \chi_1^0$ H) = BR($\chi_2^0 \rightarrow \chi_1^0$ Z) = 50%**

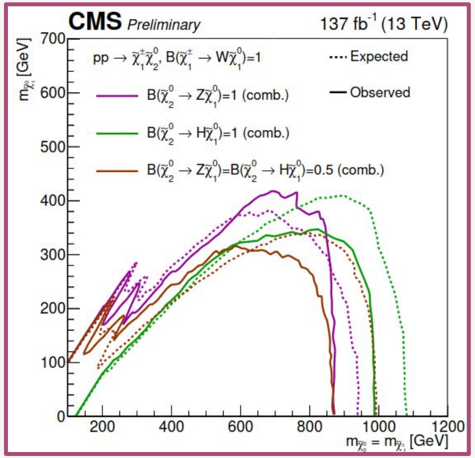
- Exclusion in <u>compressed</u> region up to mNLSP ~200 GeV

- Exclusion in <u>uncompressed</u> region mNLSP ~850 GeV

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





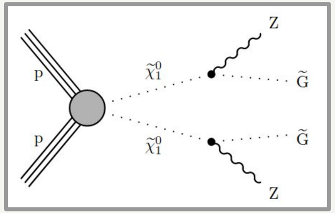


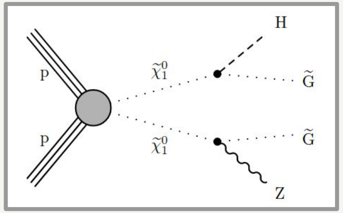
Quasi-degenerate Higgsinos (GMSB): Fixed BR

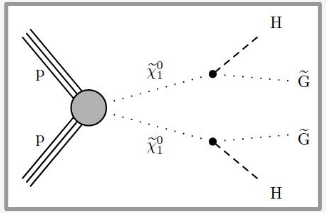
NEW

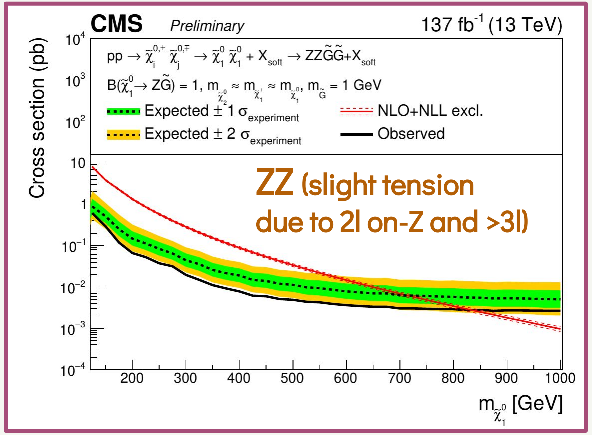
Search	GMSB ZZ	GMSB HZ	GMSB HH
$2/3\ell$ soft			
2ℓ on-Z	✓	✓	
2ℓ non-resonant			
$\geq 3\ell$	✓	✓	✓
$1\ell 2b$			
4b			✓
Hadr. WX			

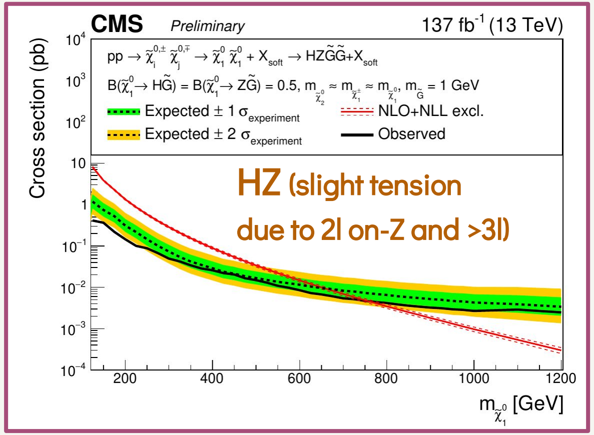
- Quasi-degenerate Higgsino triplet (χ_2^0, $\chi_1^\pm$, χ_1^0)
  → Effectively resulting in $\chi_1^0\chi_1^0$ pair production
- Neutralinos decay to LSP Gravitino (m_G=1 GeV) and SM Higgs- or Z-boson

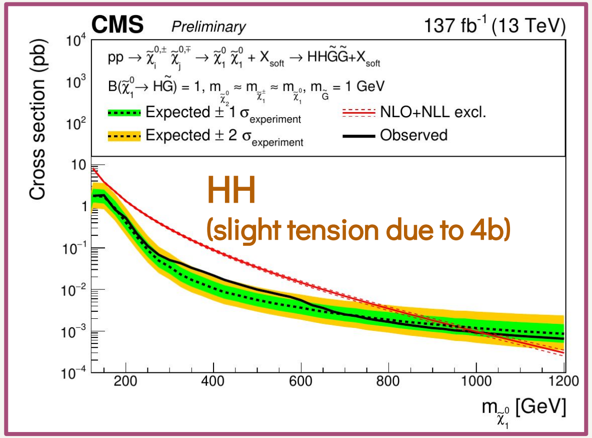








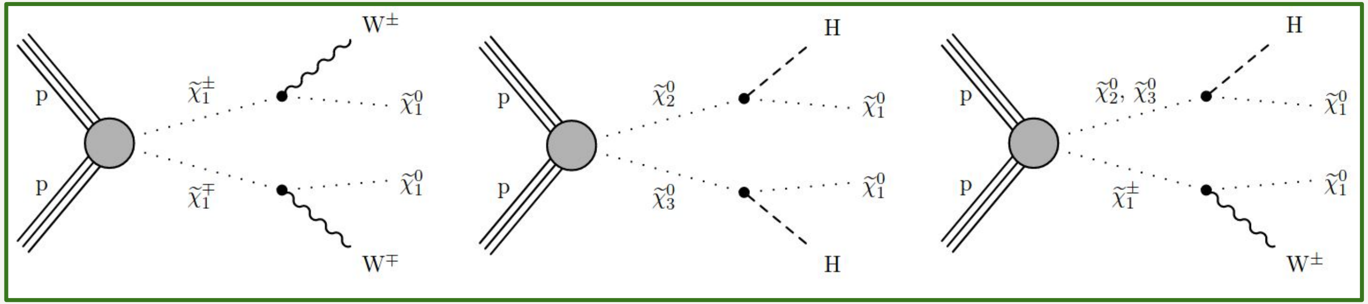




Legacy of Run 2: New interpretations

NEW

Higgsino-bino model: Bino-like LSP (neutralino $\tilde{\chi}_1^0$) and the existence of a mass-degenerate Higgsino triplet



	higgsino-bino		
Search	WW	HH	WH
$2/3\ell$ soft			
2ℓ on-Z			
2ℓ non-resonant			
$\geq 3\ell$			✓
$1\ell 2b$			✓
4b		✓	
Hadr. WX	✓		✓

Some overlap between **4B** and **hadr. WX**

→ Remove regions of least importance in both analysis:

1. **The single bb-tag region signal and control regions** of 4B
2. **The H-tag regions of hadr. WX**

→ Reduce sensitivity by few percent (in exclusion limits)