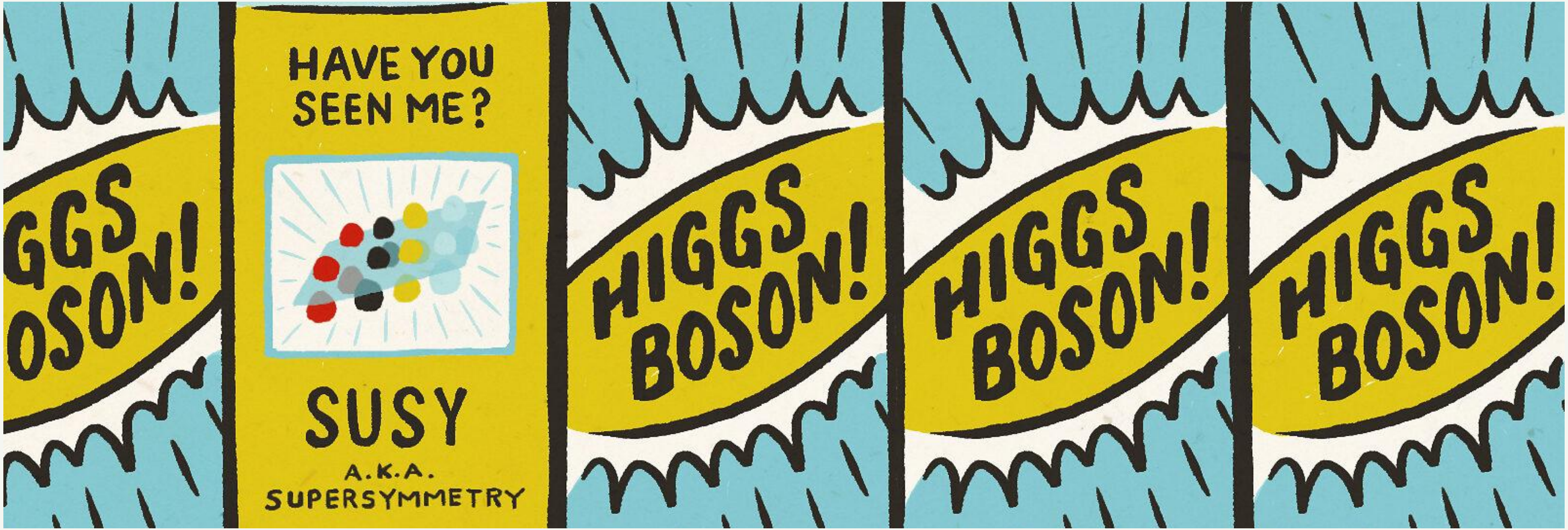


Illustration by Sandbox Studio, Chicago with Steve Shanabruch

Searching for SUSY at CMS: The latest Electroweak SUSY combination

Jaana Heikkilä (CERN) *on behalf of the CMS Collaboration*

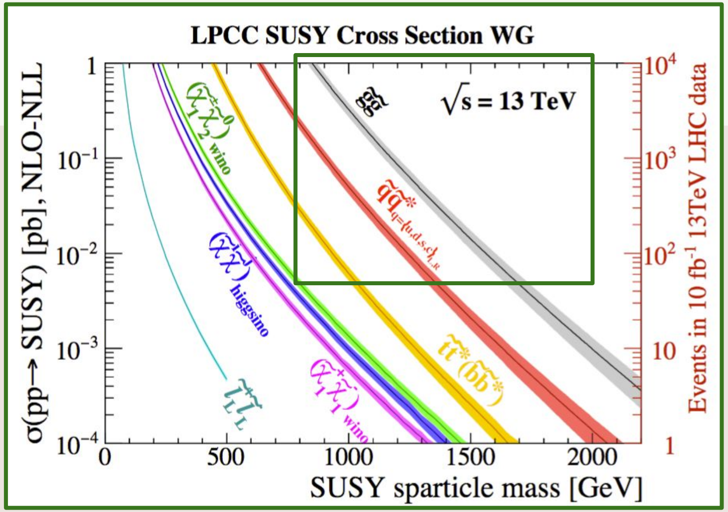
CATCH22+2 (May 4 2024)

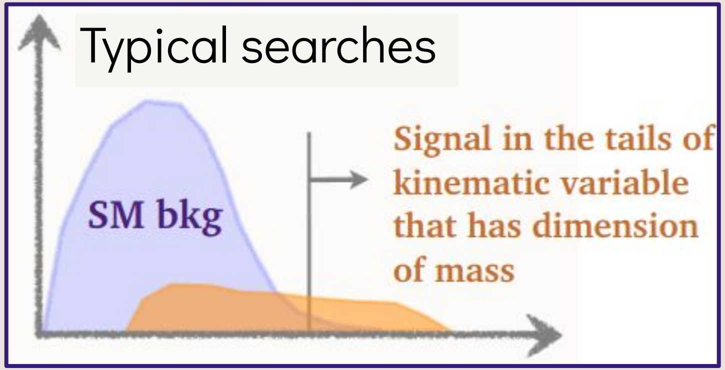
Dublin, Ireland

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





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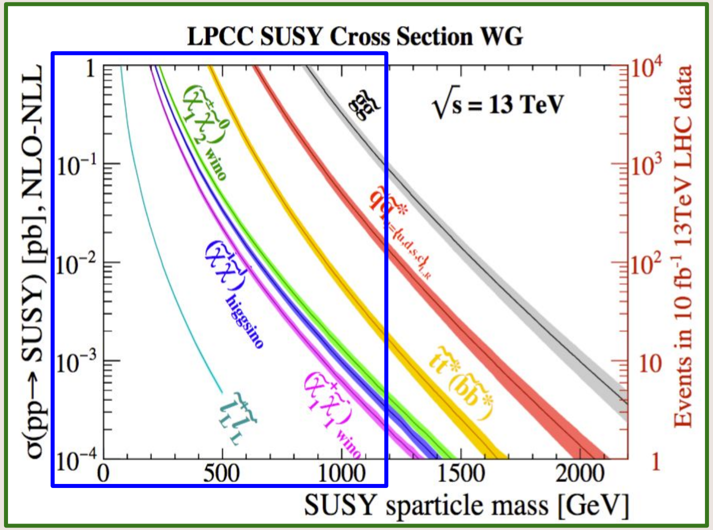

Full Run 2 data helps us to expand the SUSY search program further

- 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

As of today, there are no significant excesses - where do we go from here?

Expanding the SUSY search program

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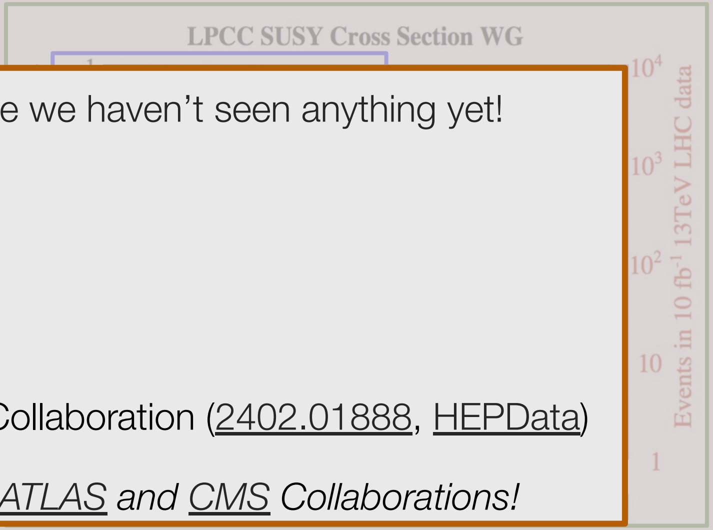

My personal opinion: no reason to discard SUSY simply because we haven't seen anything yet!

Today's topic: the (numerous) caveats of SUSY exclusion limits

- What are the underlying assumptions?
- How realistic is the model in the first place?
- What would be needed for a reinterpretation?

Case study: the latest EWK SUSY Combination from the CMS Collaboration (2402.01888, HEPData)

For a complete set of latest SUSY results, see webpages of ATLAS and CMS Collaborations!

Additionally: Combine SUSY searches to be more powerful together

→ Consider signal hypotheses that populate more than one final state, explored by multiple searches

As of today, there are no significant excesses - where do we go from here?

Cropping the EWK SUSY landscape to perform a search…

Supersymmetry: each boson (fermion) of the SM is accompanied by a fermionic (bosonic) superpartner [R-parity: $R=(-1)^{3(B-L)+2S}$]

Minimal Supersymmetric extension of the Standard Model (MSSM):

O(100) parameters after supersymmetry breaking

→ Phenomenology defined by the underlying (unknown) mechanism of SUSY breaking

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

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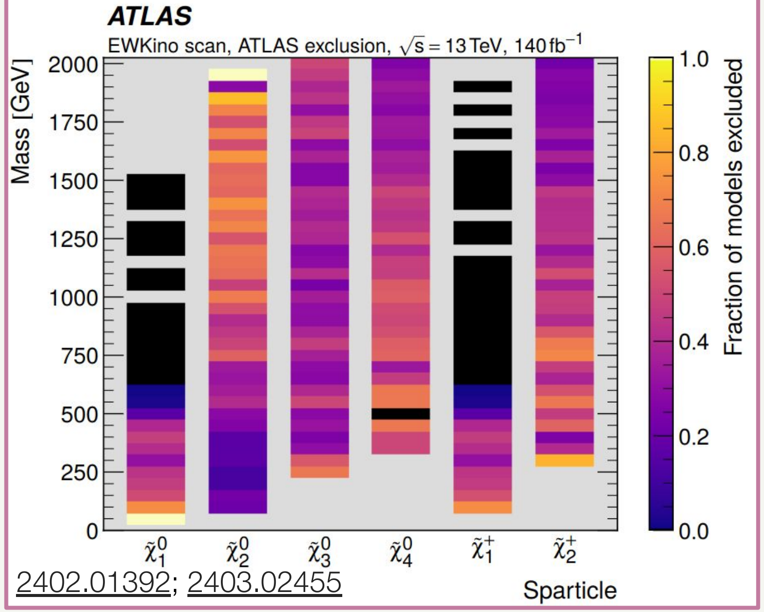
Absence of new sources of CP violation beyond that present in the CKM matrix
No flavour-changing neutral currents
First and second sfermion generation universality at low energy

Phenomenological MSSM (pMSSM): *O(20) free-parameters*
→ Tens of thousands of models - cannot be targeted by a usual search
→ Investigated in detail both by the ATLAS and CMS Collaborations



2402.01392; 2403.02455

$\tan\beta$: the ratio of the vevs of the two–Higgs doublet fields.
$m^2_{H_u}, m^2_{H_d}$: the Higgs mass parameters squared.
M_1, M_2, M_3: the bino, wino and gluino mass parameters.
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$: the first/second generation sfermion mass parameters.
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$: the third generation sfermion mass parameters.
A_u, A_d, A_e: the first/second generation trilinear couplings.
A_t, A_b, A_τ: the third generation trilinear couplings.

Very few models are excluded - a similar CMS analysis is in progress!

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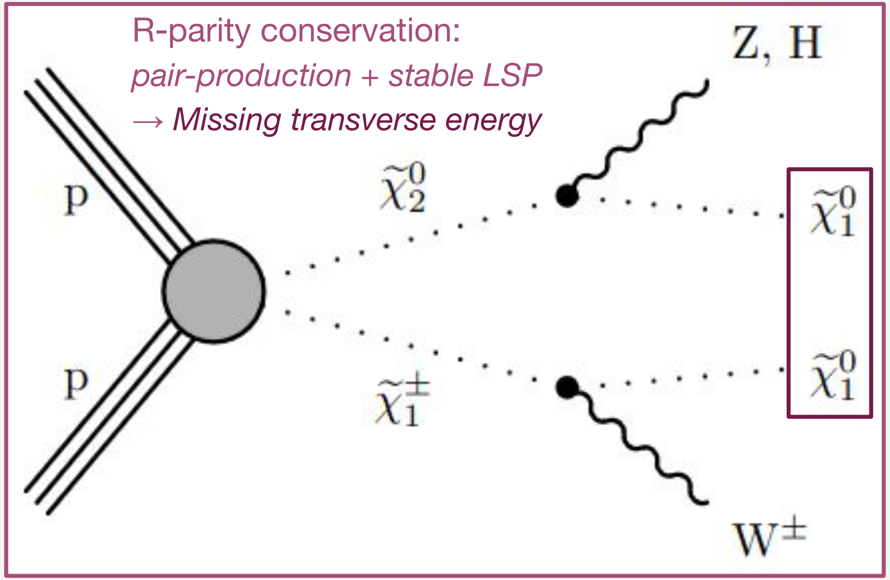
Target only the "relevant" particles; other sparticles decoupled
Pure-state sparticles (EWKinos with minimal mixing)
Given production mode and decay channel of a sparticle

Simplified model spectra (SMS): a handful of parameters
→ R-parity (non-)conservation drives the phenomenology
→ Lightest sparticle (LSP) potential dark matter candidate

→ *A suitable handle for searches at LHC that can be used as an input for pMSSM interpretations!*



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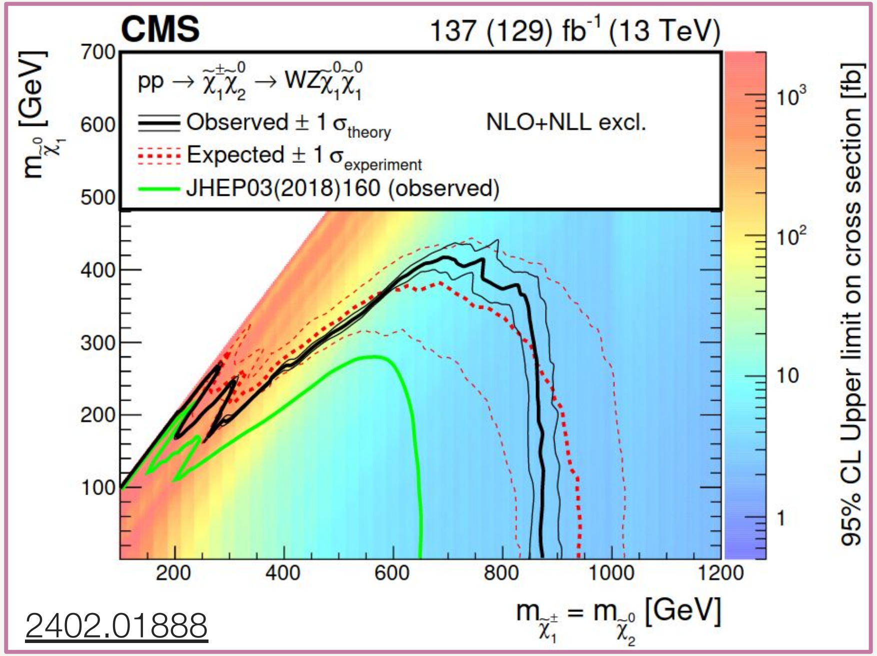
Proceed with caution: SMS often provides more strict exclusion limits than pMSSM…
[E.g. expected cross section depends on the assumed state of the EWKinos…]



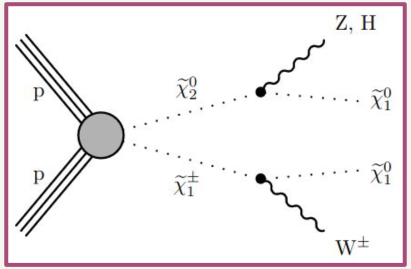
2402.01888

Targeting rare processes with EWKino Combination

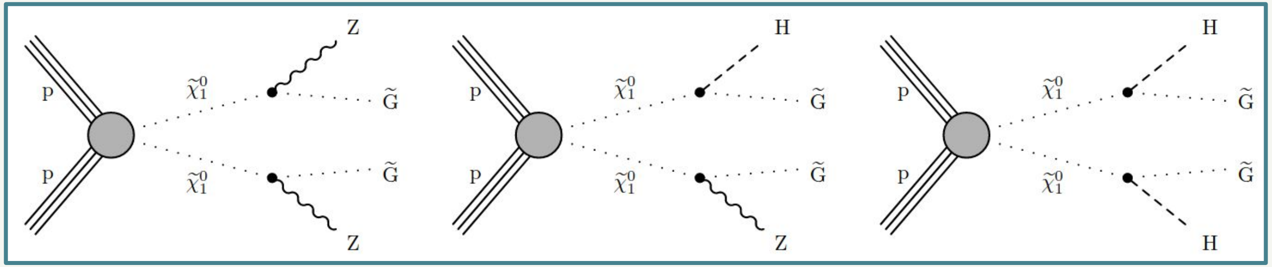
Various SMS models and final state topologies covered with 6 orthogonal input searches by the CMS Collaboration

→ *Emphasis on the rare and experimentally challenging processes: compressed scenarios and slepton pair production*

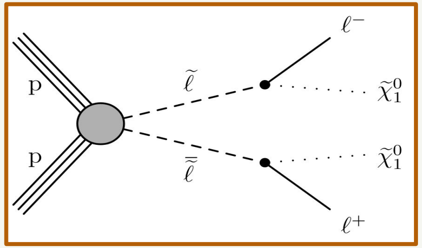
→ *Following slides display a snapshot of the results - more details in the back-up!*



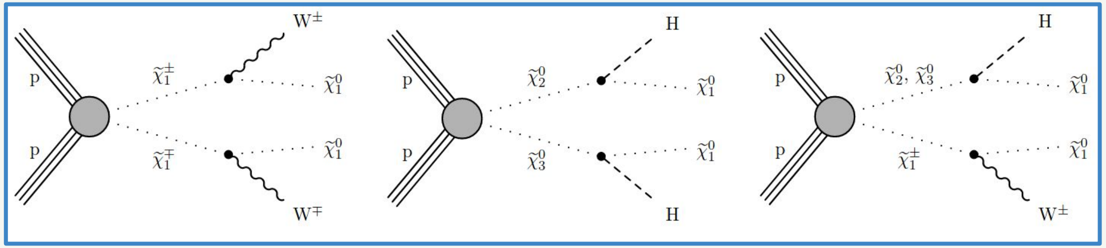
Wino-like chargino and neutralino



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



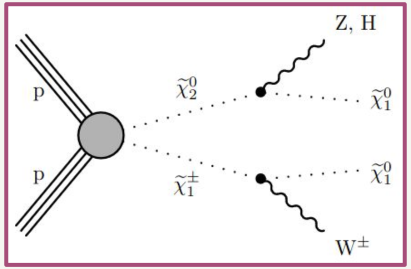
Slepton pair production



Higgsino-bino model (chargino/neutralino)

Compressed EWK sector

Compressed spectra: small mass splitting between the NLSP and the LSP
→ Can be explored in many models, such as Bino LSP and Wino/Slepton NLSP
→ *Little visible energy from the "soft" final state objects (low pT)*



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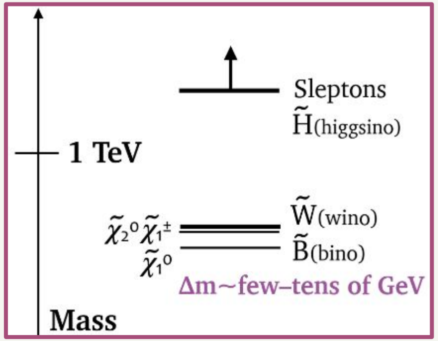

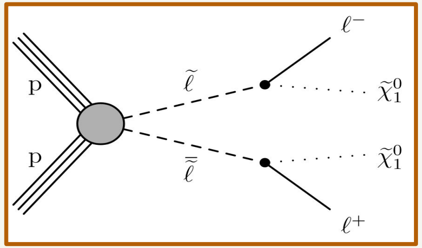

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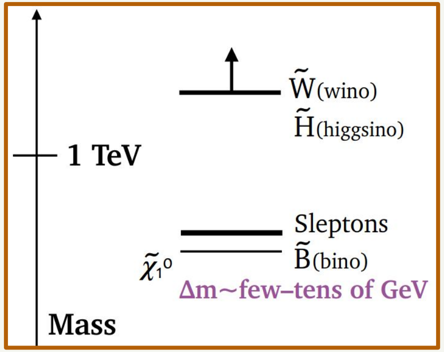

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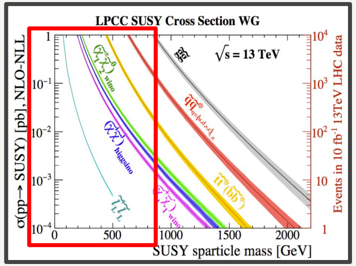

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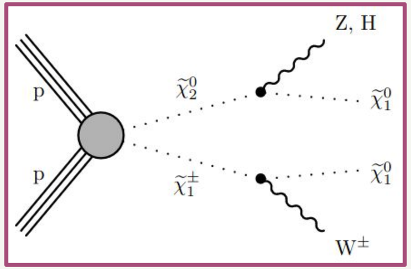

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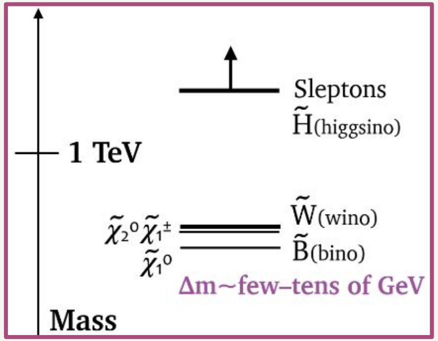

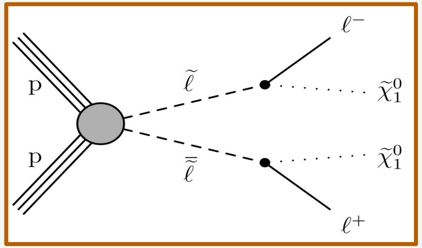

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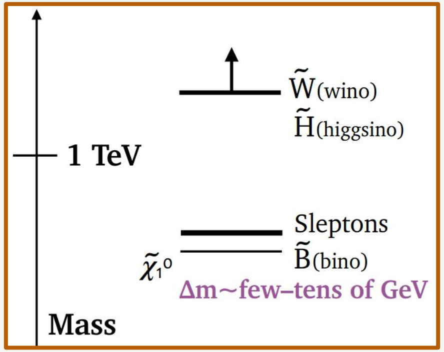
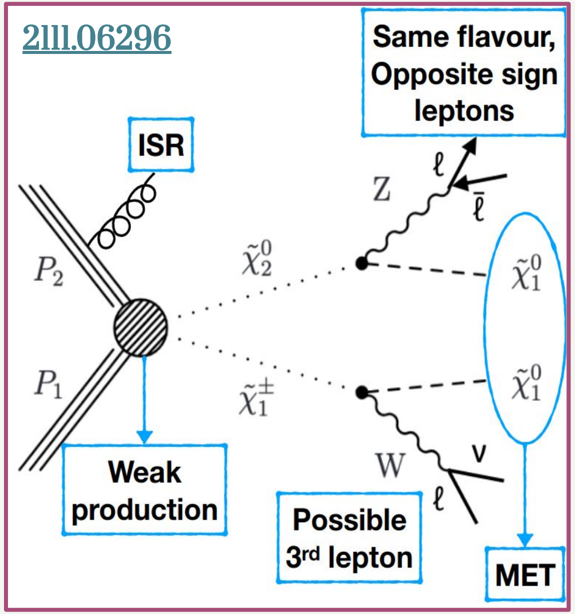




Low MET: require e.g. an ISR jet to access the scenarios

→ A true challenge to retain signal sensitivity (low XS)

→ Extremely difficult searches - benefit from combinations!

Chargino-neutralino production

Targeted by two complementary leptonic searches

Orthogonal lepton p_T ranges but different selections (MET)
→ Challenging to be fully optimal in the crossover regime!

compressed

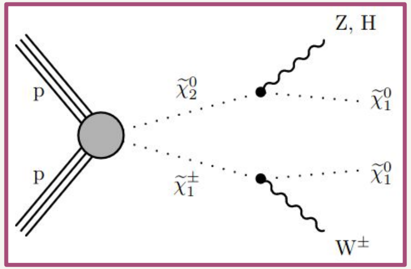
"2/3l soft"
2111.06296

Two or three e (mu),
Opposite-sign, same-flavour pair
5(3.5) < lepton p_T < 30 GeV

(semi)compressed

"2SSl/≥ 3l"
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*)



Wino-like chargino and neutralino

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

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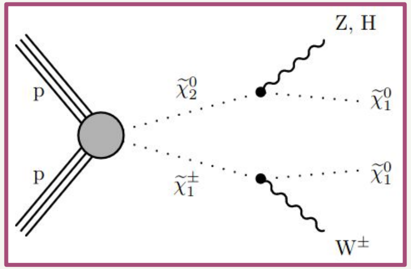
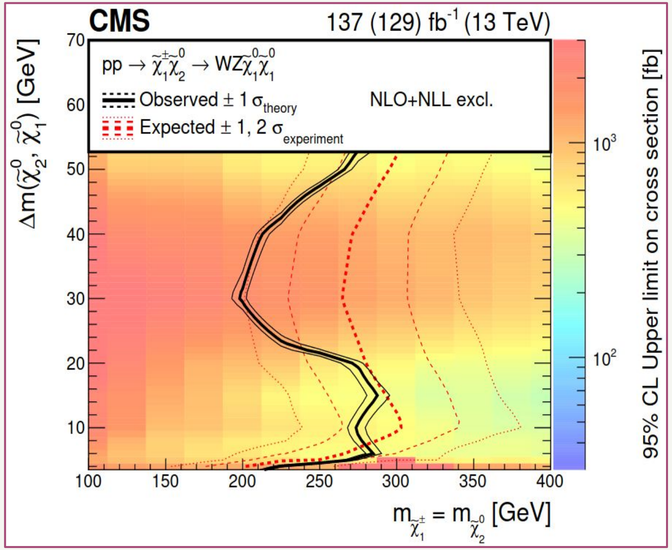
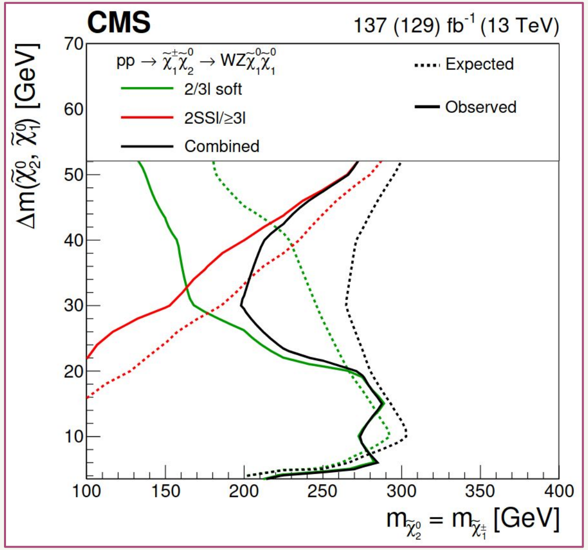


Wino-like chargino and neutralino

Exploring smaller mass-splittings ***under this specific process*** *requires e.g. lower lepton p_T, whereas targeting larger chargino masses is limited by the XS…*
→ A new CMS search is in progress!





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 searches!

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

Slepton pair production

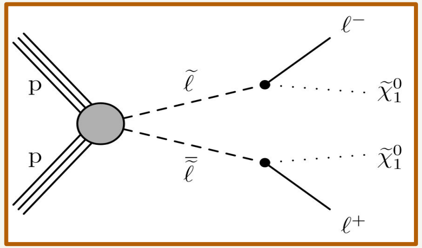
Uncompressed phase space probed by the 2l non-resonant analysis, we now extend our search to the compressed phase space with the 2/3l soft analysis!

compressed

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

uncompressed

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



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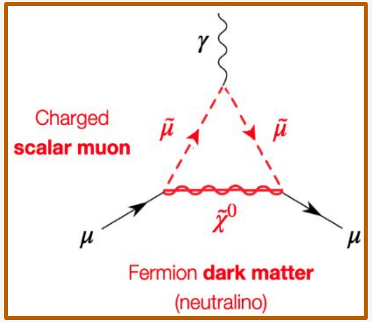

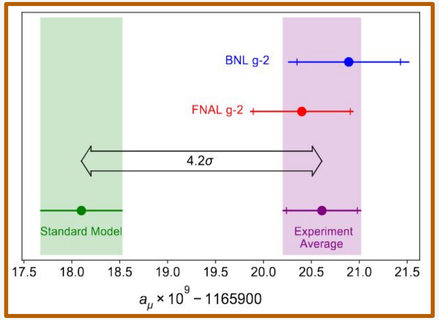

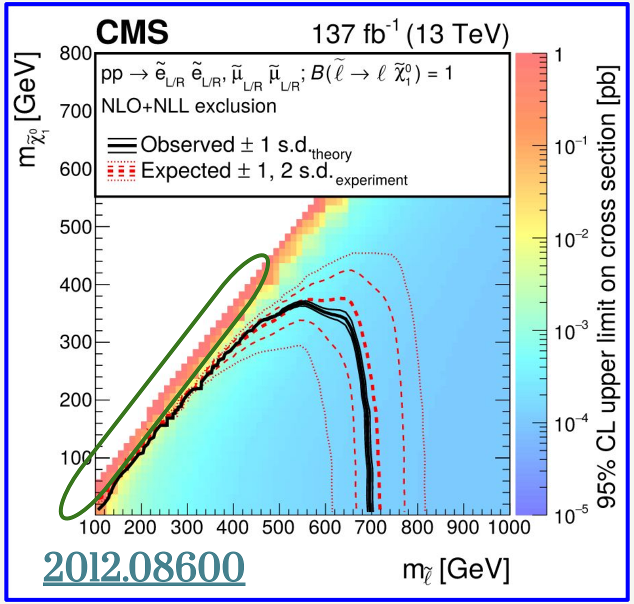

2012.08600

The sleptons could explain the results on the muon g-2 anomaly, measured by the Fermilab and BNL experiments (pending last word on the prediction from the theory community!)

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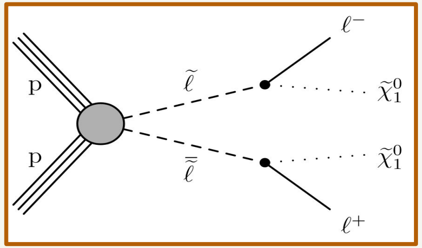
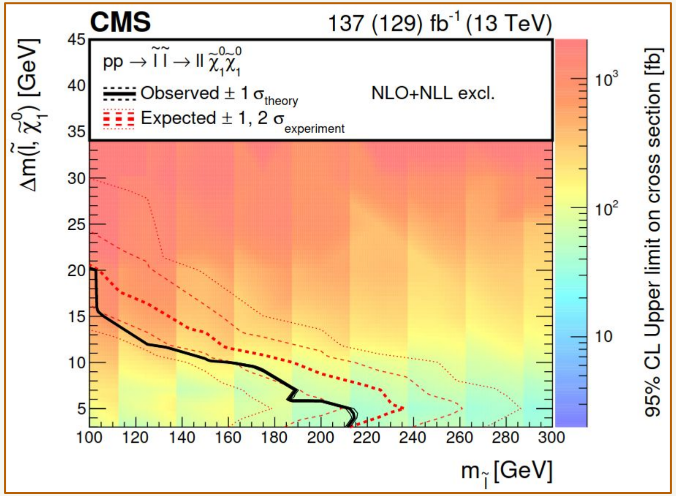
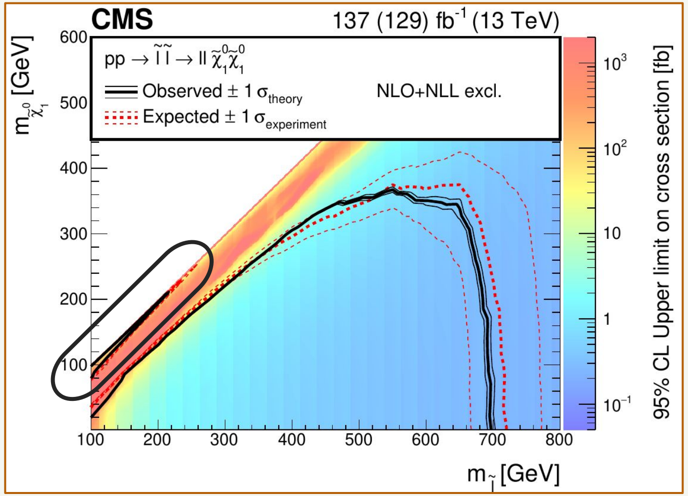


Slepton pair production

Low production cross sections hinder a more complete exploration of the parameter space… intermediate mass-splittings typically characterised by a large background contribution from the WW production!





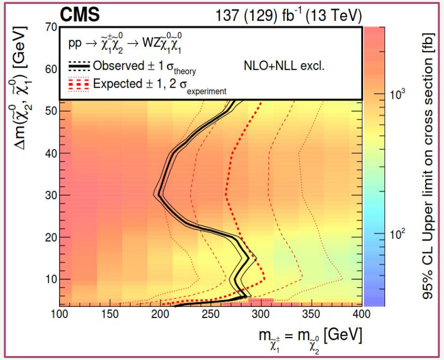
Reach slepton masses of ~215 GeV at Δm=5 GeV!

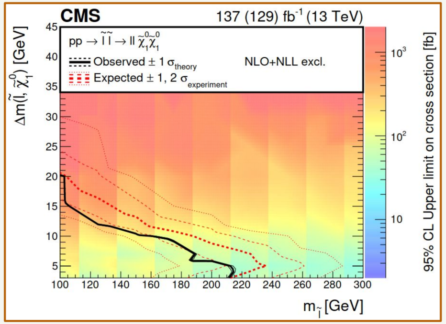
Summary

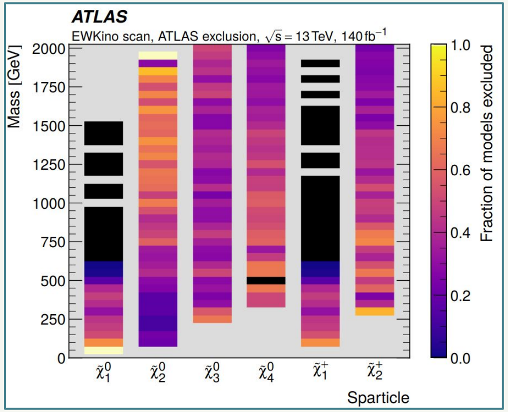
The full Run 2 data set allowed us to extend the SUSY search program beyond the typical searches
→ *Combining multiple analyses provides an opportunity to increase our sensitivity towards SUSY*

Legacy Run 2 combination utilises six searches targeting EWK SUSY processes
→ *Set constraints among the most stringent to date, exploring various simplified models*
→ *Increased sensitivity towards the compressed spectra in the Wino-bino model and slepton pair production*

Both ATLAS and CMS Collaboration have investigated the pMSSM parameter space
→ *The latest results from ATLAS indicate that very few models are excluded with the current results!*







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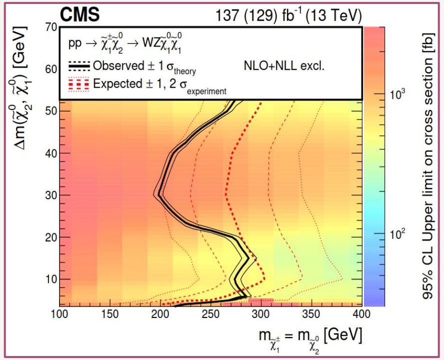
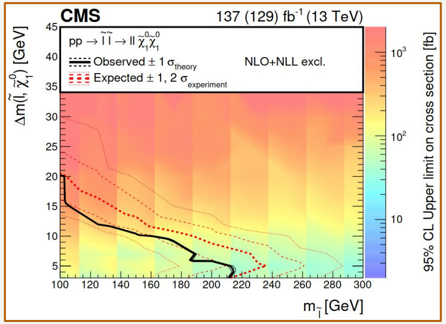
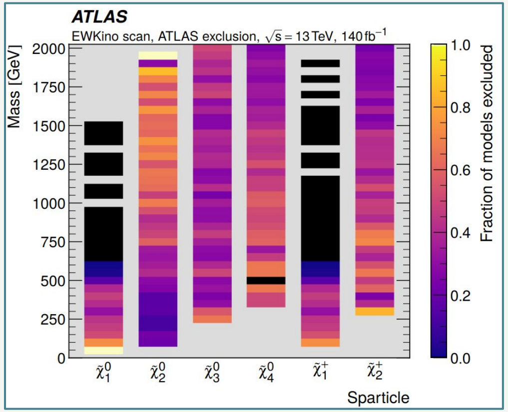
→ *The latest results from ATLAS indicate that very few models are excluded with the current results!*





"The reports of my death are greatly exaggerated."
- ~~Mark Twain~~ Supersymmetry



For the coffee break: Both collaborations work towards providing results in a format suitable for reproducibility. What would be needed for a reinterpretation of our results by the theory community?

Back-up

EWK 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

“2SSl/≥ 3l”
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	Wino-bino WZ	Wino-bino 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									✓
$2SS\ell/\geq 3\ell$	✓	✓	✓	✓	✓			✓	
$1\ell 2b$		✓						✓	
4b					✓		✓		
Hadr. WX	✓	✓				✓		✓	

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

Full details available at 2402.01888

*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

"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

"2SSl/≥ 3l"
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

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!

Search	Wino-bino WZ	Wino-bino 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									✓
$2SS\ell/>3\ell$	✓	✓	✓	✓	✓			✓	
$1\ell 2b$		✓						✓	
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

Input analyses - 2/3l soft search

compressed

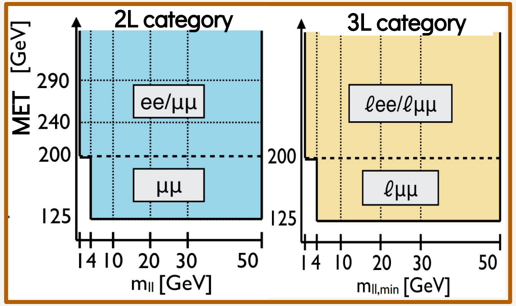
Leptonic

"2/3l soft"
2111.06296

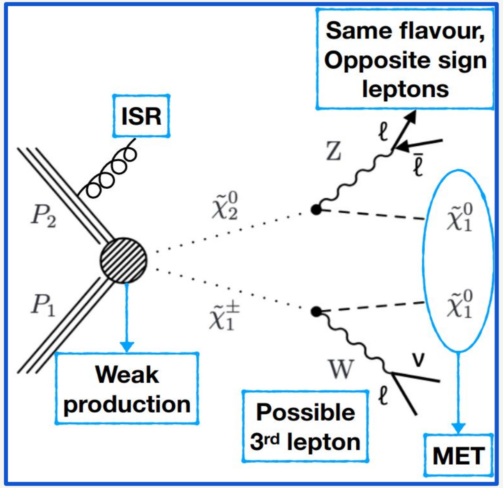
Two or three e (mu),
Opposite-sign, same-flavour pair
5(3.5) < lepton p_T < 30 GeV

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

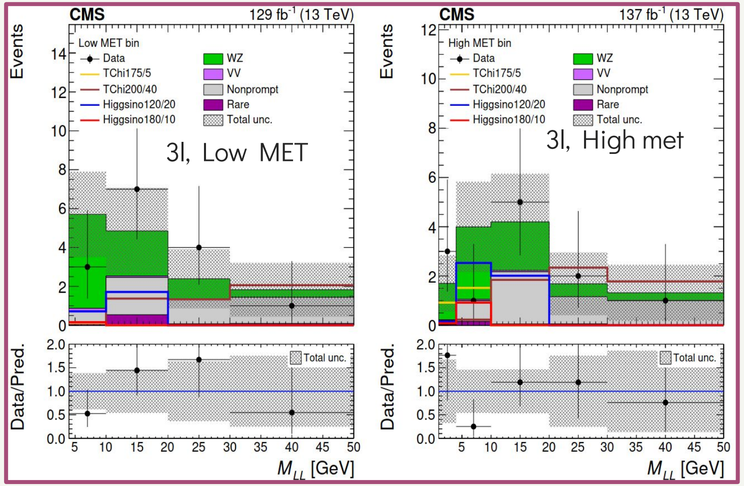
Aims to reconstruct mass of Z*:
mll serves as proxy for Δm(N2,N1)
→ Search regions binned in MET & mll



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

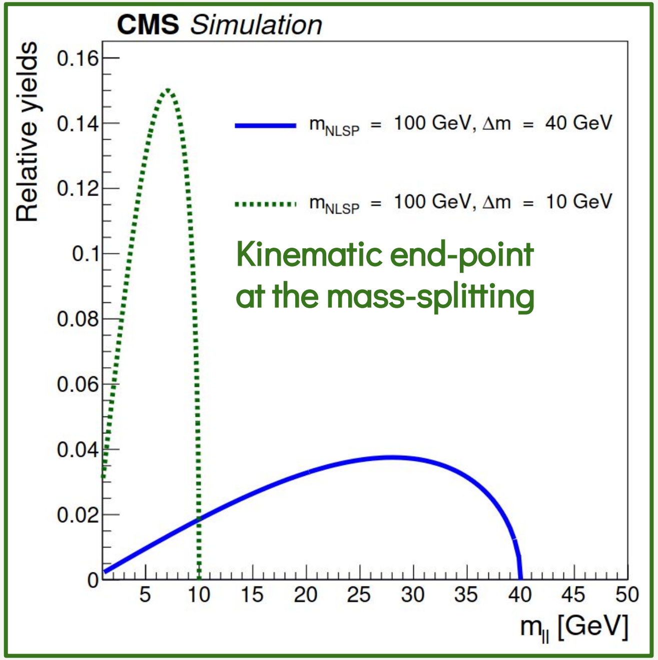
Goal: Target a wide parameter space of NLSP and LSP masses

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**



Parametric signal extraction for the 2/3l soft search

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)*

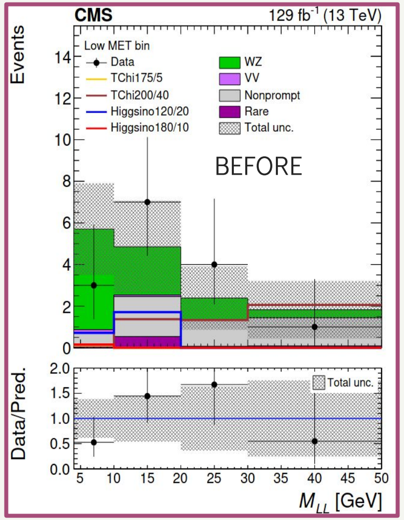
→ Use m_{ll} as a discriminating variable (i.e. no multivariate discriminant)

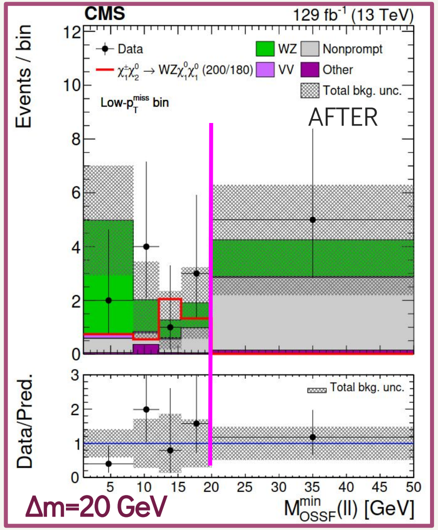
Optimize m_{ll} binnings per mass-splitting using theoretical signal shape

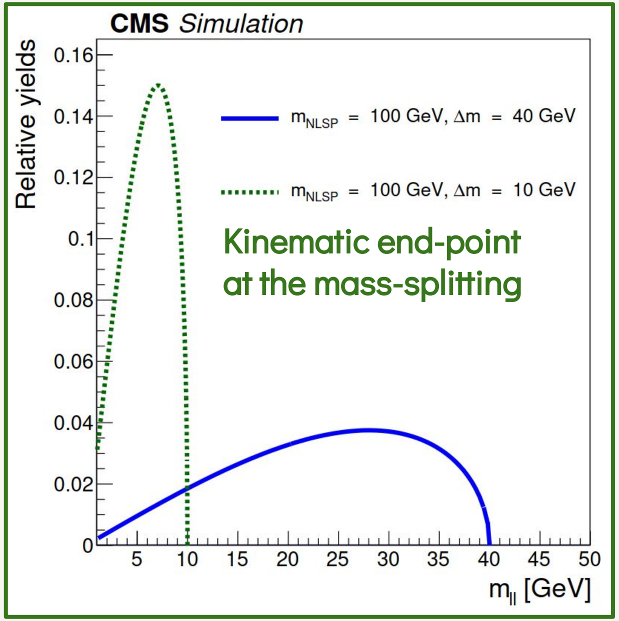
→ **Provide an individual binning for each Δm and SR**

Example:

3l signal region, low MET

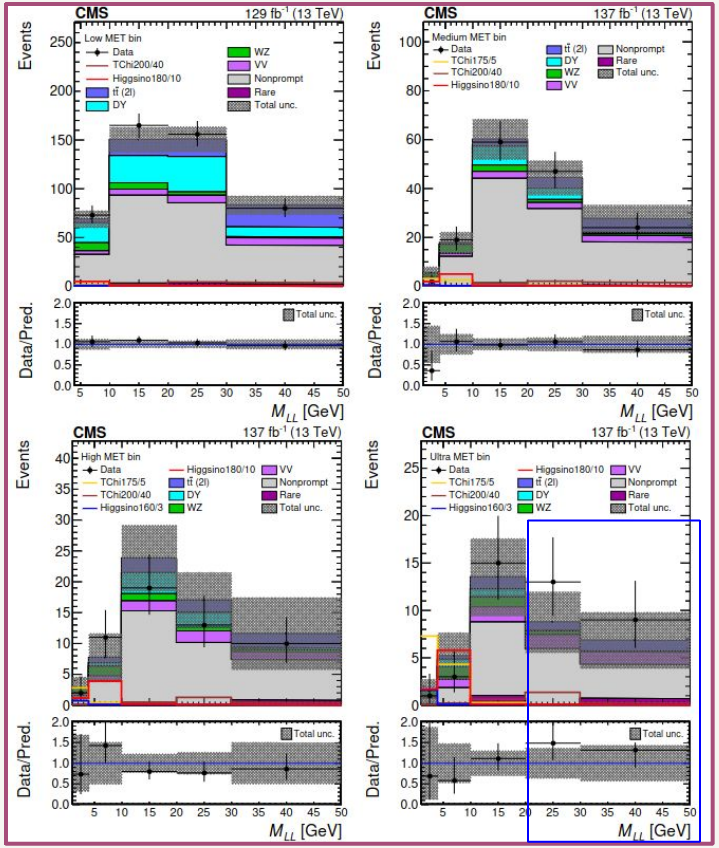


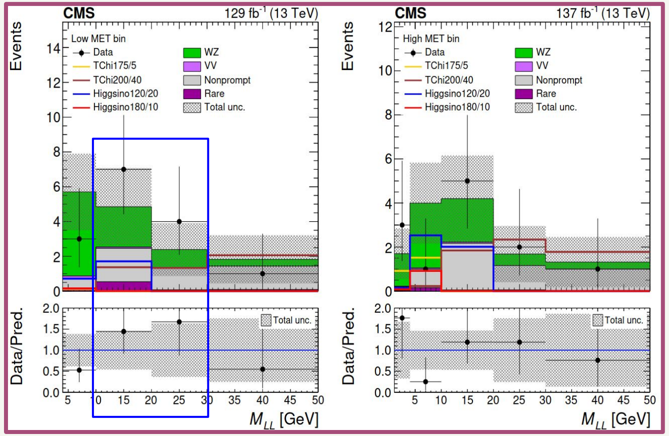


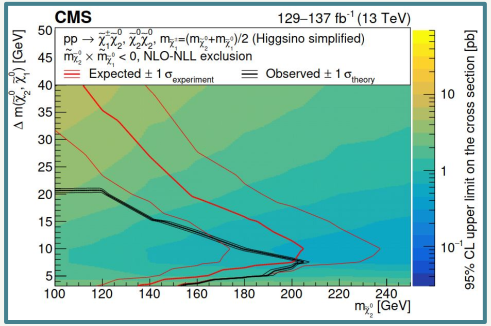


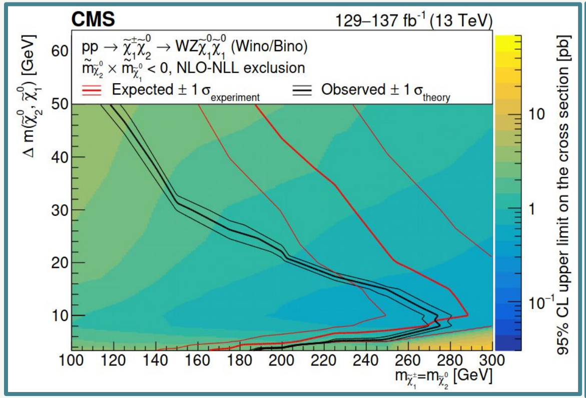
The largest gains are obtained for mass splittings of Δm < 20 GeV:
Expected exclusion on NLSP mass increased by between 5 and 25 GeV depending on the targeted Δm!

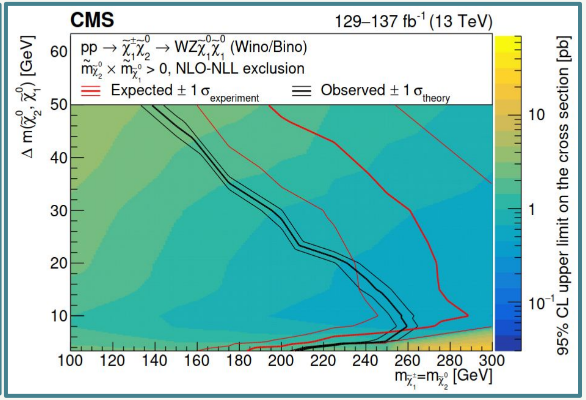
2/3l soft search - previously published results (2111.06296)



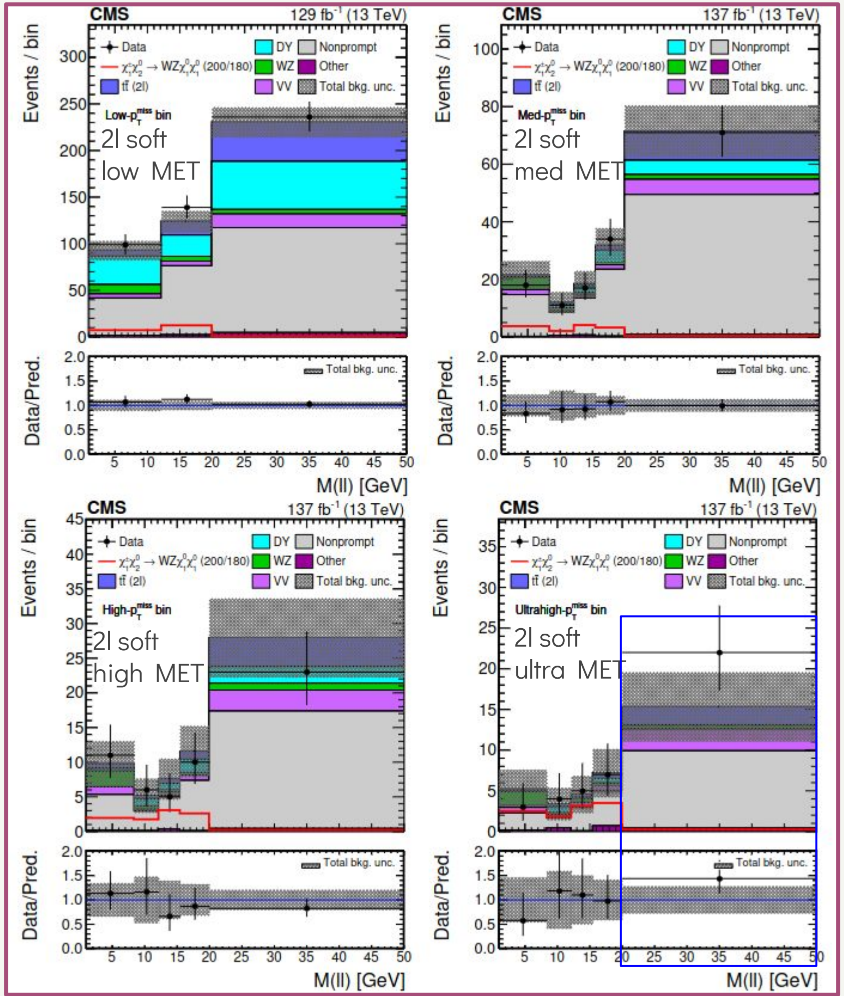








Signal region plots with the parametric approach



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

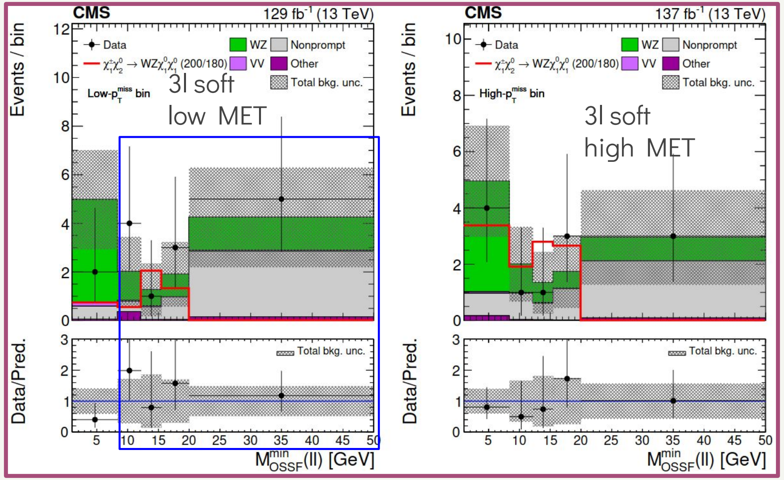
→ *Finer bins in around peak, courser in tails; kinematic end-point at the mass-splitting*

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]

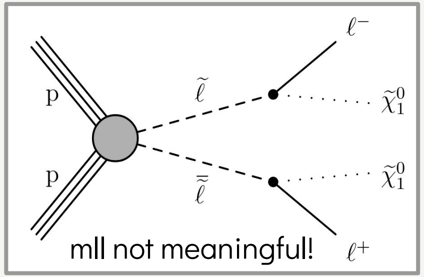


2/3l soft extension to slepton production

- **Analysis strategy largely unchanged: target two soft leptons + MET**
  - 3l soft SR ignored: negligible sensitivity (otherwise same SR + background estimation)

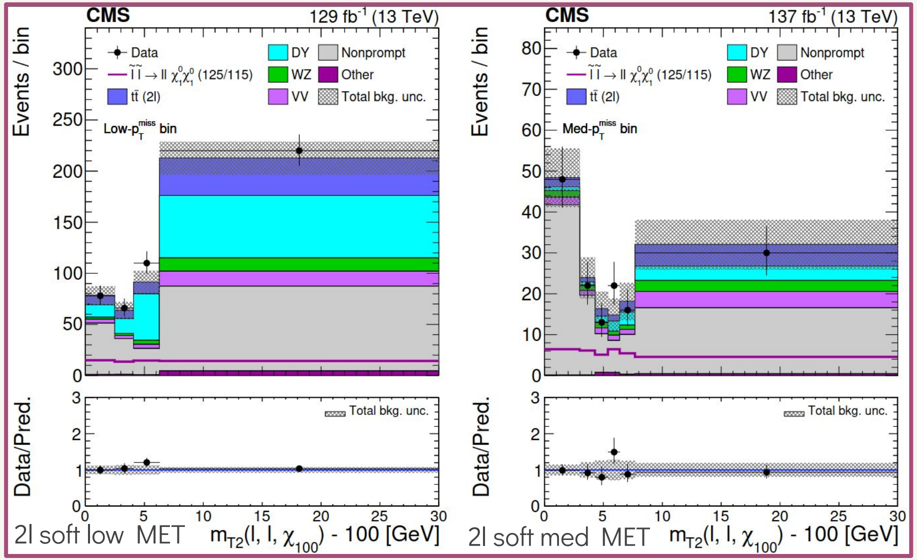
- SR fit variable: ***Stransverse mass*** M_{T2} ***with the test mass*** M_x ***= 100 GeV***
  - Well-established variable* but no analytical description for a given signal hypothesis

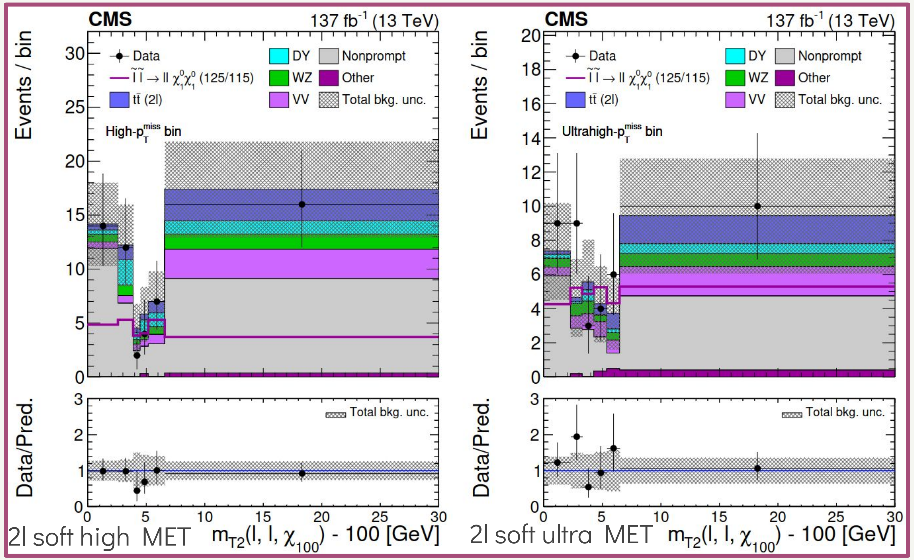
→ **Use MC signal shape to provide individual binning for each signal mass-point and SR category**



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

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





* *"-- 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"*

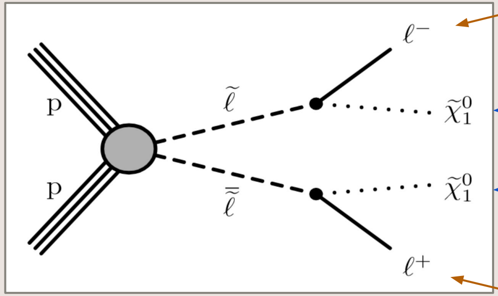
$M_{T,2}$ variable

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

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

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

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 - multilepton search

Leptonic

2106.14246

“2SSl/≥ 3l”

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)

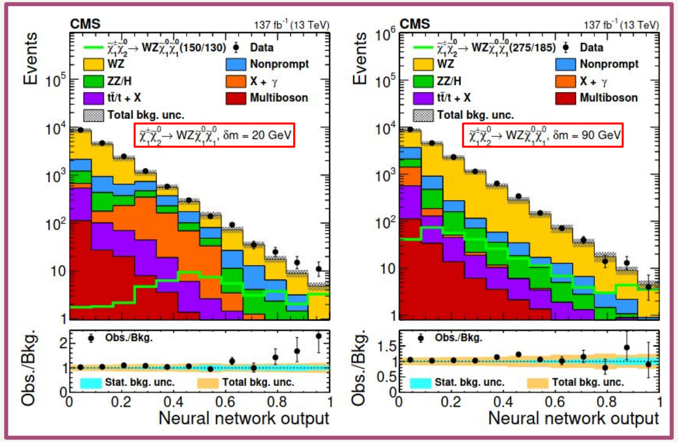
3l and 4l: up to 2 hadr. decaying taus in addition to light leptons

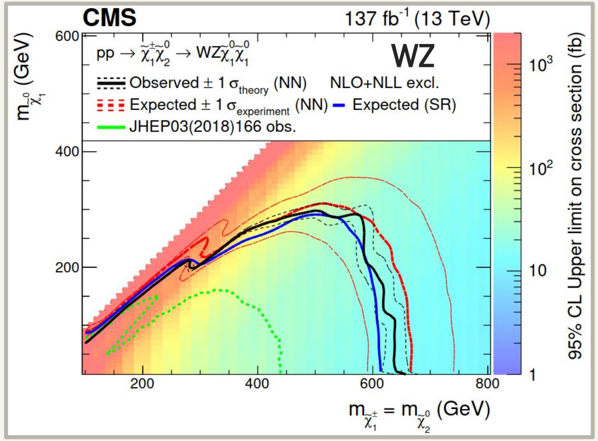
Update since 2016 for the 3l category: Parametric signal extraction to target different models with wildly varying kinematics

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

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

Leptonic

2012.08600

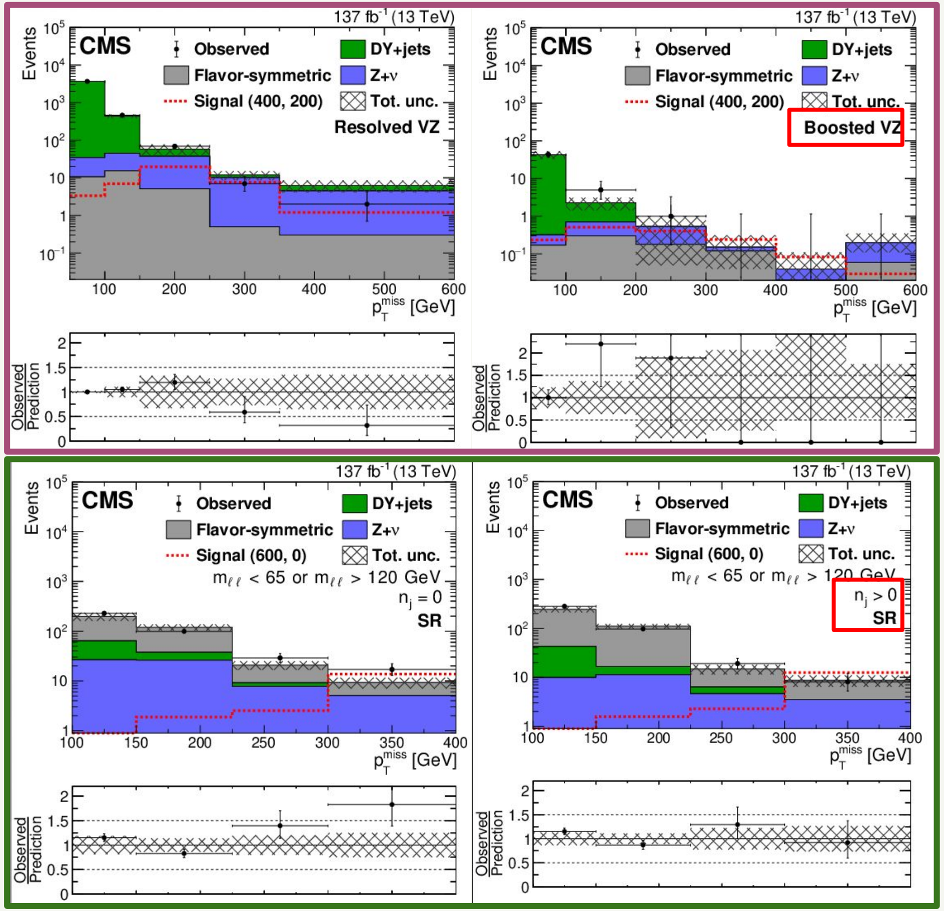
"2l on-Z/non-resonant"

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



2l on-Z/non-resonant: results

Leptonic

[2012.08600](2012.08600)

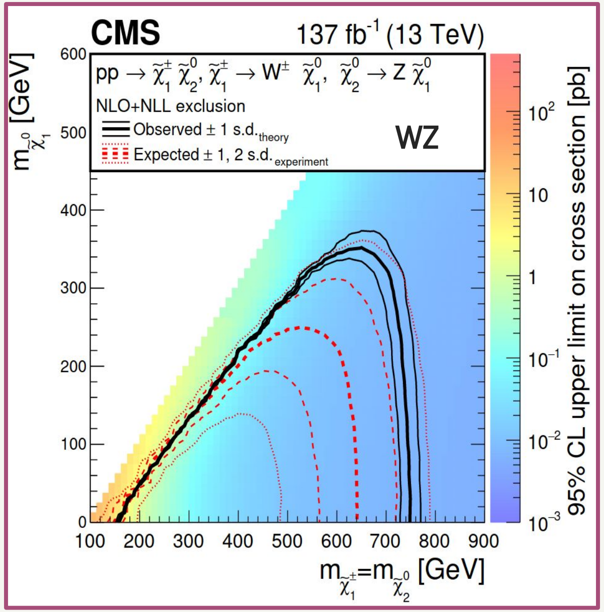
"2l on-Z/non-resonant"

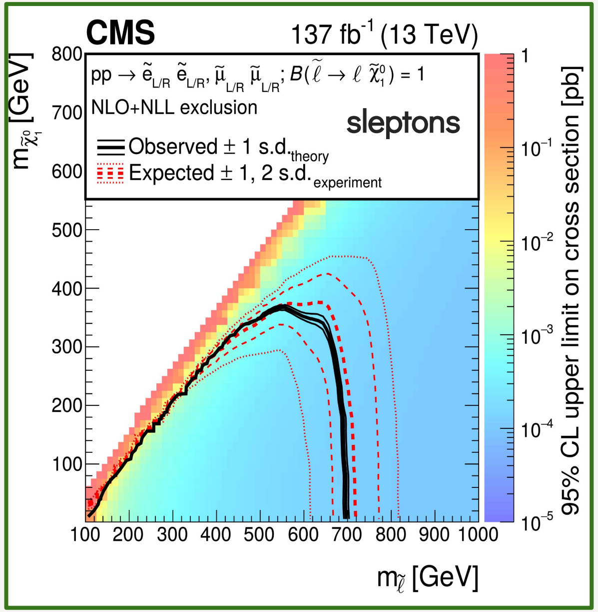
Two e(mu)
Opposite-sign, same-flavour pair
Either on-shell or off-shell Z

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





(semi)Hadronic input analyses

compressed | *(semi)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

"2SSl/≥ 3l"
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

Search	Wino-bino WZ	Wino-bino 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									✓
$2SS\ell/>3\ell$	✓	✓	✓	✓	✓			✓	
$1\ell2b$		✓						✓	
4b					✓		✓		
Hadr. WX	✓	✓				✓		✓	

Add sensitivity towards the uncompressed spectra!

Input analyses - 1l *2b*

(semi)Hadronic

2107.12553
"1l *2b*" - WH

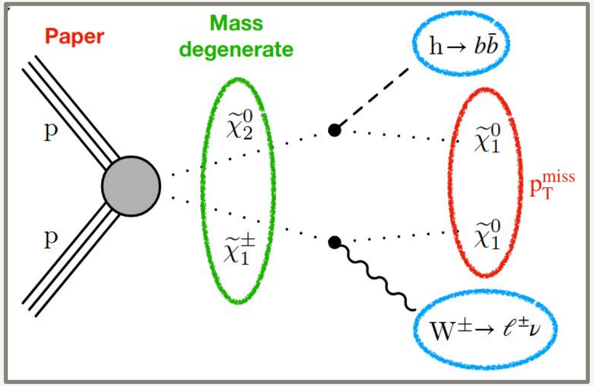
One e(mu), H→bb

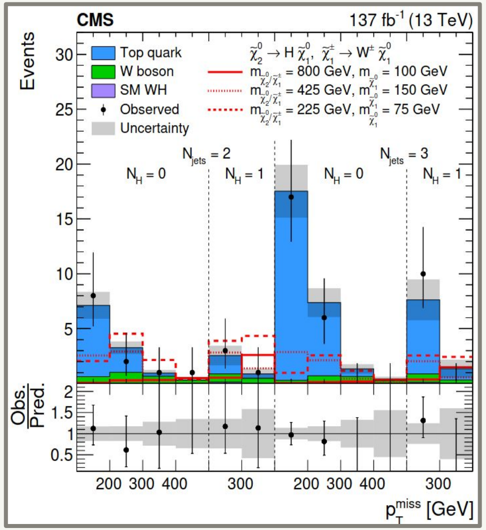
Improvements since 2016 include:

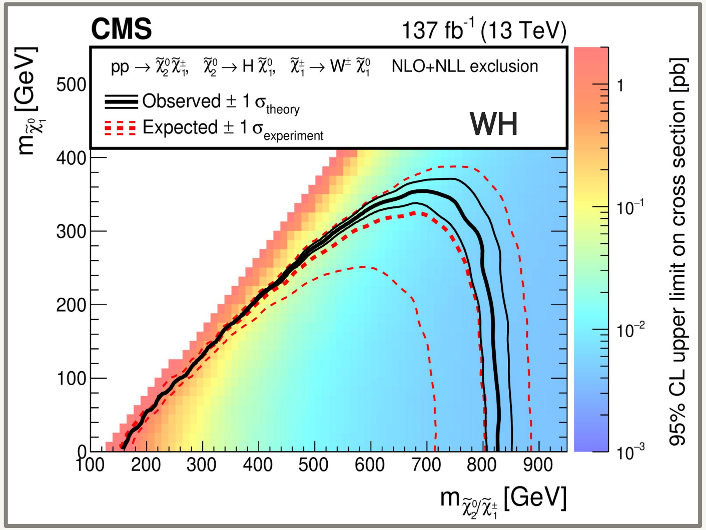
Utilization of boosted tagger (targets high mass-splitting models):
→ Identify Higgs boson decays collimated into large-radius jets

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

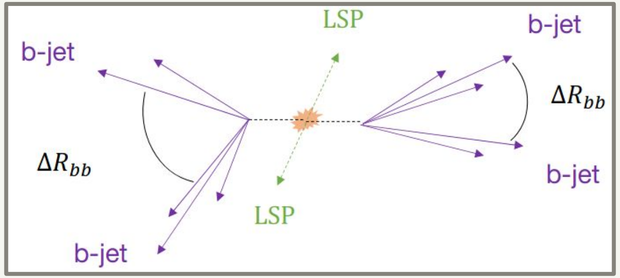
No leptons
Two Higgs bosons; H→bb

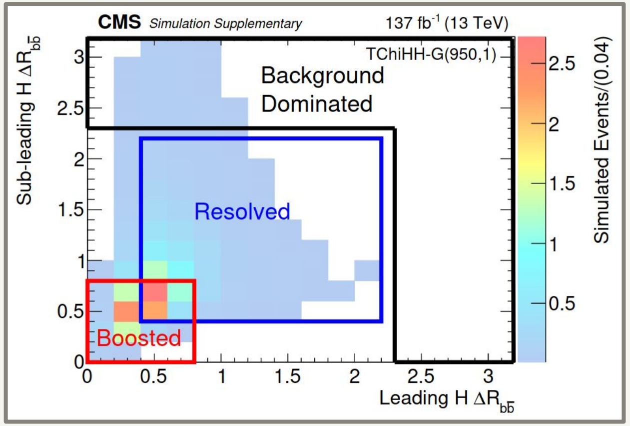
Two separate categories optimized for specific parts of the parameter space

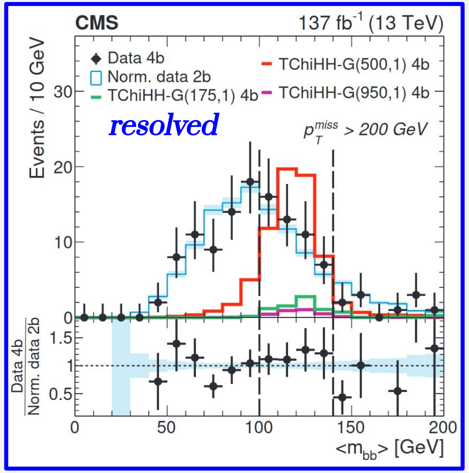
Resolved analysis (typically lower pTmiss):
the b jets are separate AK4 jets
→ Signal extraction: the average mass $\langle m_{bb} \rangle$ of the two Higgs boson candidates

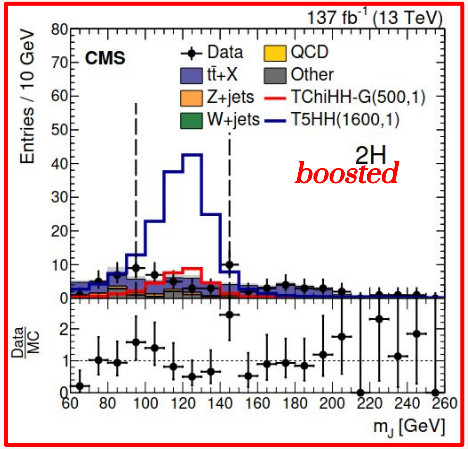
Boosted analysis (typically higher pTmiss):
2b merged into a large radius jet (AK8)
→ Relies on **a boosted tagger**
→ Signal extraction: m_J attributed to an AK8 jet of the two Higgs boson candidates

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

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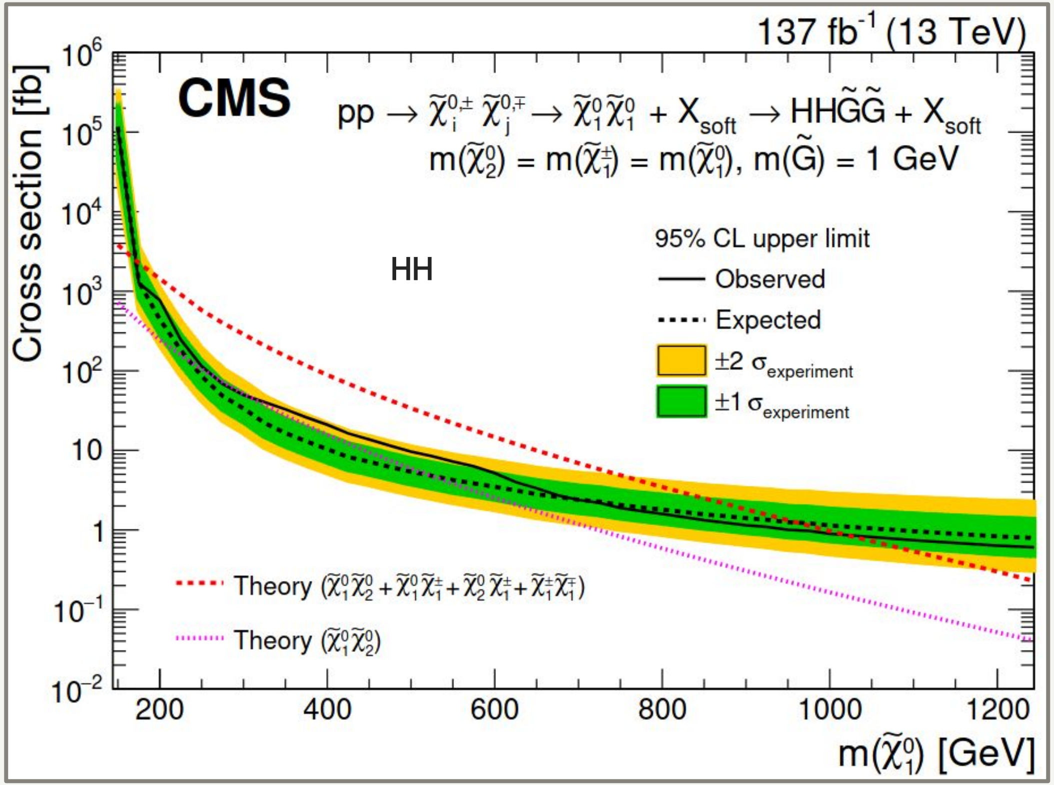
Measured with data-driven ABCD method with different variables ($\langle m_{bb} \rangle$, N_b) vs (m_J, N_H)
(*boosted: also pTmiss shape measurement*)



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

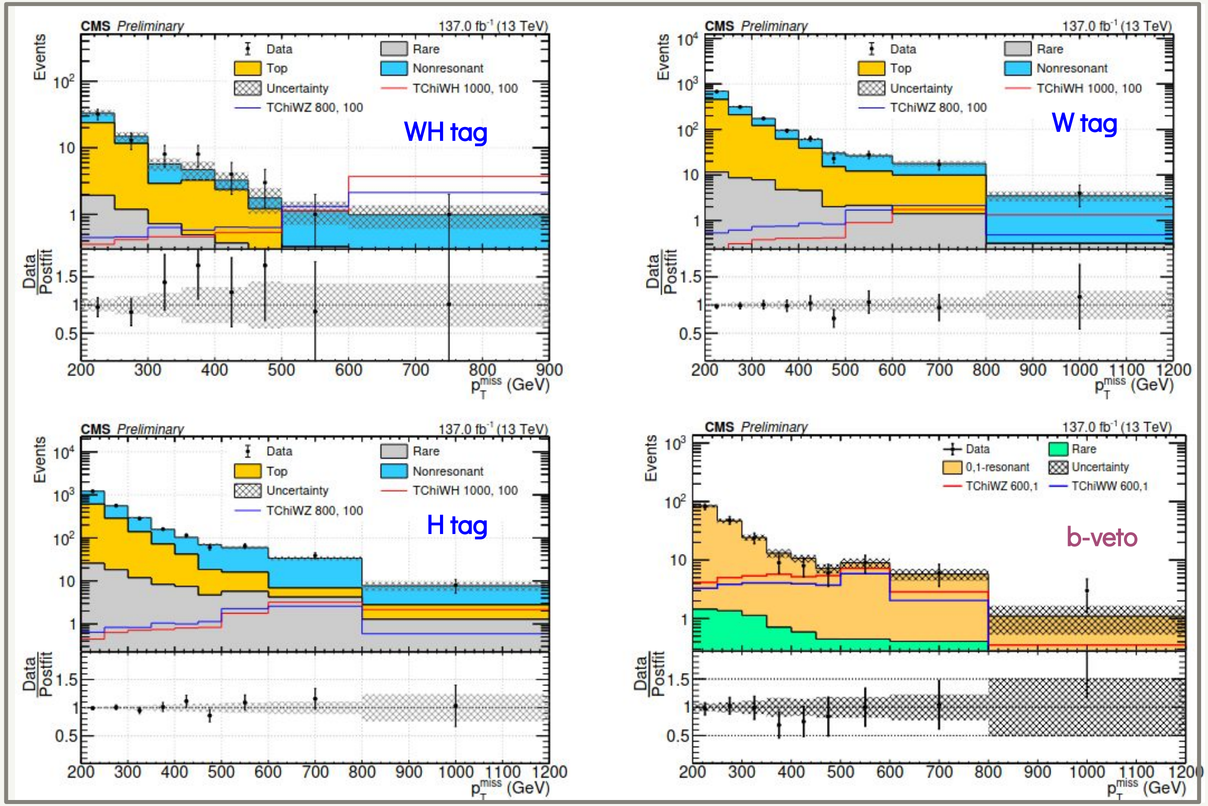
Four signal regions targeting models without and with b jets

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)



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

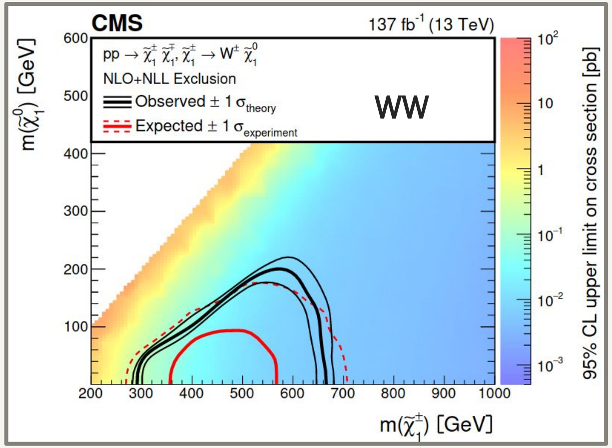
Four signal regions targeting models without and with b jets

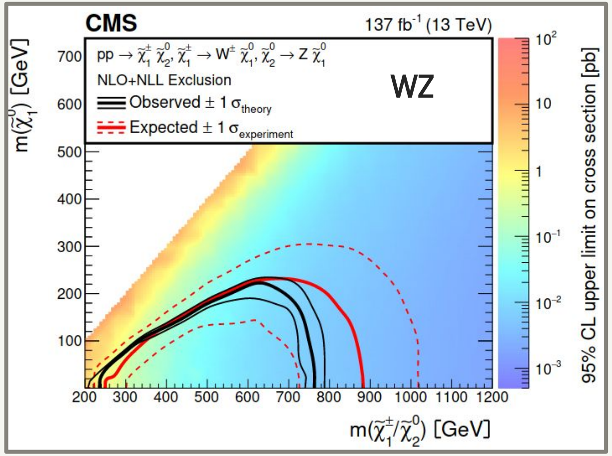
B-veto signal region (WW, WZ) requires
≥ 2 AK8 jets with WZ-mass (65-105 GeV)
Tagging: DeepW & DeepW-MD

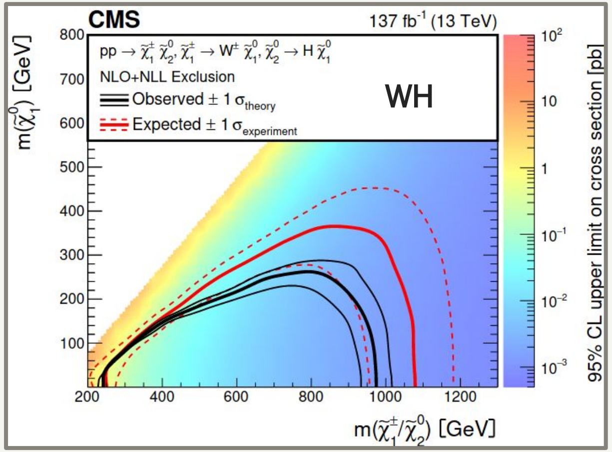
Regions with b jets (WH, WZ, or ZH)
WHTag: DeepW (W/Z candidate)
& Deepbb (Z/H candidate)

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

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

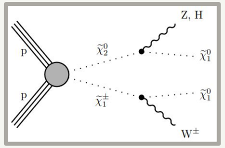






Production chargino and neutralinos (WZ/WH)

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

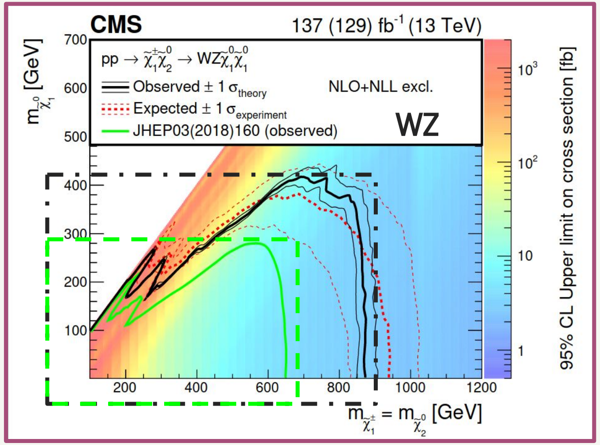


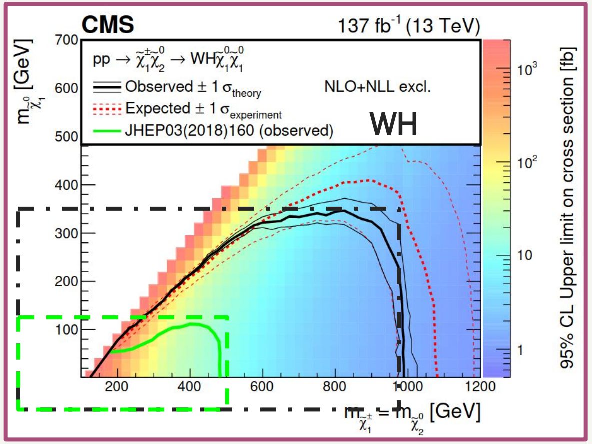
The limits are notably improved since
the 2016 EWKino Combination

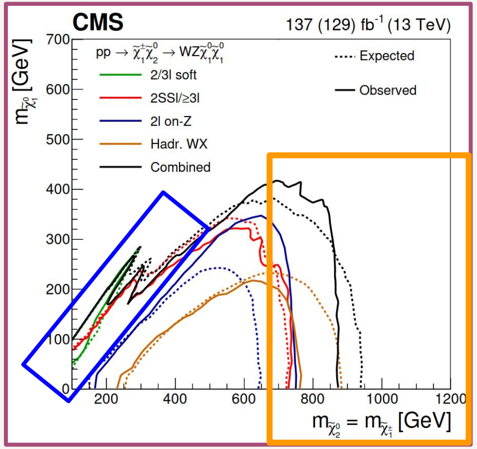
The new, fully hadronic input analysis
Hadr. WX improves the sensitivity to higher NLSP masses and uncompressed region

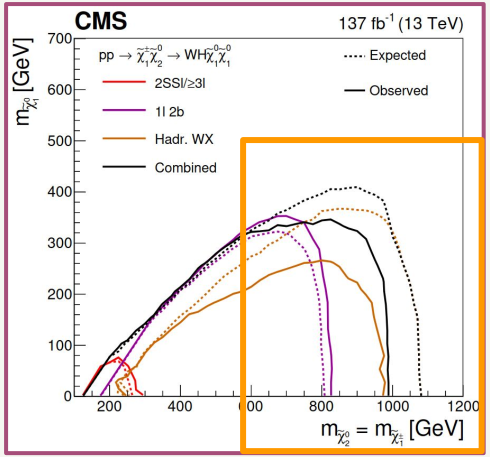
The exploration of the **compressed region** depends on the Full Run 2 data set as well as the novel techniques utilised by **the 2/3l soft and ≥ 3l analyses.**

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

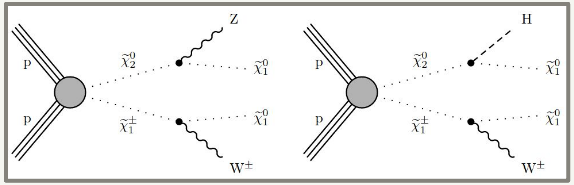








Wino-bino model: W(Z+H) -mixed

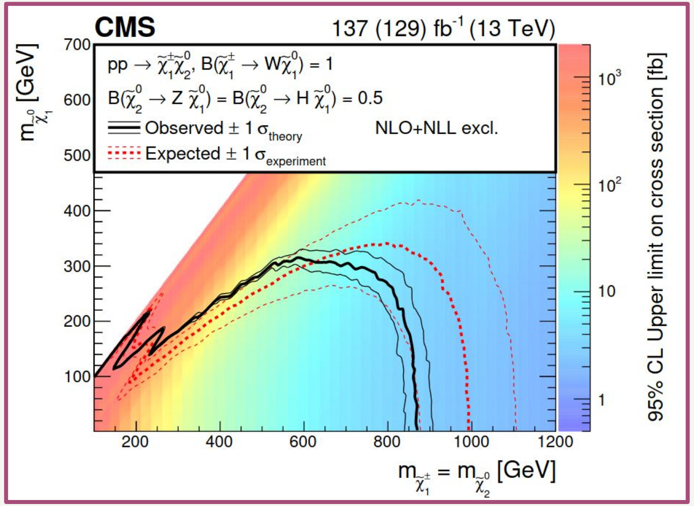


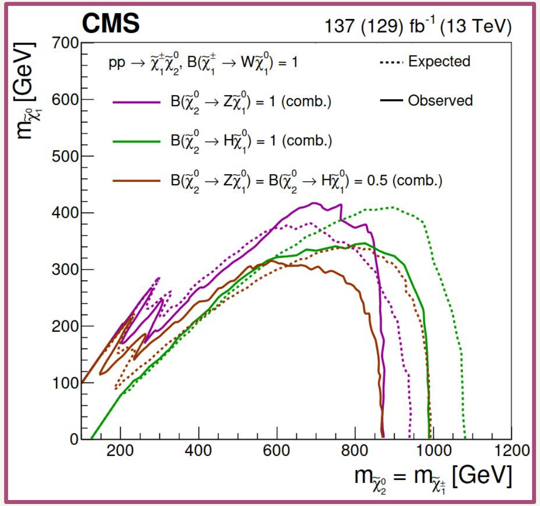
- Pair production of Wino-like $\chi_2^0\chi_1^\pm$, decaying to Bino-like χ_1^0 and SM boson
  - Assuming BR($\chi_1^\pm \rightarrow \chi_1^0$ W±) = 100%
  - Assuming **BR($\chi_2^0 \rightarrow \chi_1^0$ H) = BR($\chi_2^0 \rightarrow \chi_1^0$ Z) = 50%**

- Exclusion in compressed region up to mNLSP ~200 GeV

- Exclusion in uncompressed region mNLSP ~850 GeV

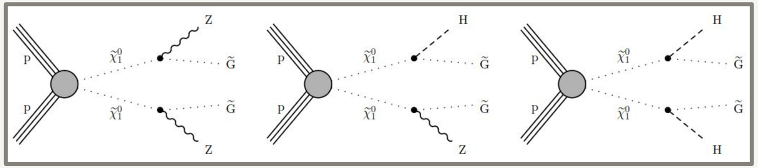
Search	Wino-bino WZ	Wino-bino WH
$2/3\ell$ soft	✓	
2ℓ on-Z	✓	
2ℓ non-resonant		
$2\mathrm{SS}\ell/\geq 3\ell$	✓	✓
$1\ell 2$b		✓
4b		
Hadr. WX	✓	✓





Quasi-degenerate Higgsinos (GMSB)

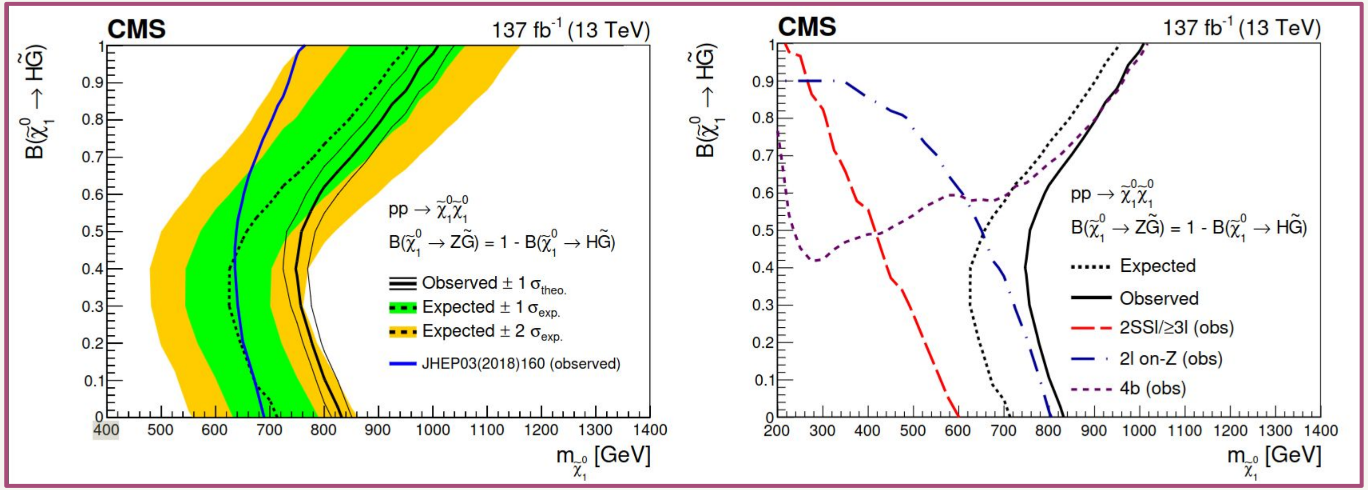
Gauge-mediated SUSY breaking (GMSB) model **with quasi-degenerate Higgsinos**



- 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

- Performed scan of exclusion limits as function of B(χ_1^0→ 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(χ_1^0→ H$\tilde{G}$)

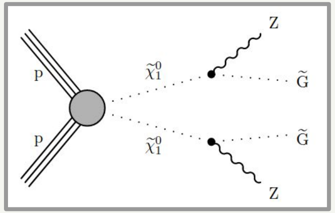
	GMSB		
Search	ZZ	HZ	HH
2/3ℓ soft			
2ℓ on-Z	✓	✓	
2ℓ non-resonant			
2SSℓ/≥ 3ℓ	✓	✓	✓
1ℓ2b			
4b			✓
Hadr. WX			

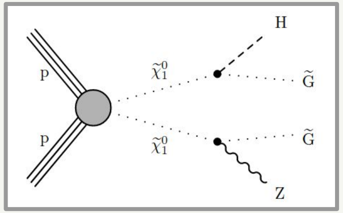


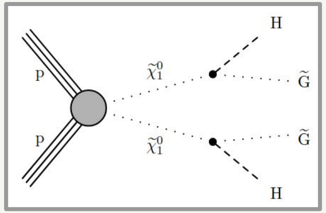
Quasi-degenerate Higgsinos (GMSB): Fixed BR

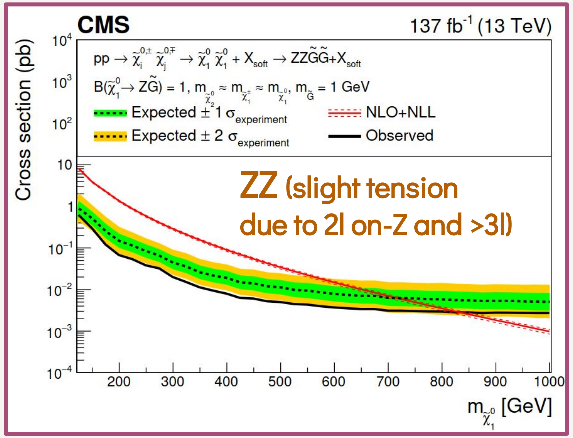
- Quasi-degenerate Higgsino triplet (χ_2^0, $\chi_1^\pm$, χ_1^0)
  → Effectively resulting in $\chi_1^0\chi_1^0$ pair production
- Neutralinos decay to LSP Gravitino (m_G=1 GeV) and SM Higgs- or Z-boson

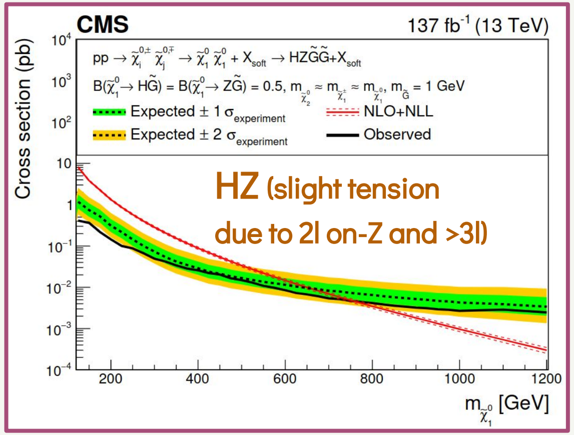
Search	GMSB ZZ	GMSB HZ	GMSB HH
$2/3\ell$ soft			
2ℓ on-Z	✓	✓	
2ℓ non-resonant			
$2SS\ell/\geq 3\ell$	✓	✓	✓
$1\ell 2b$			
4b			✓
Hadr. WX			

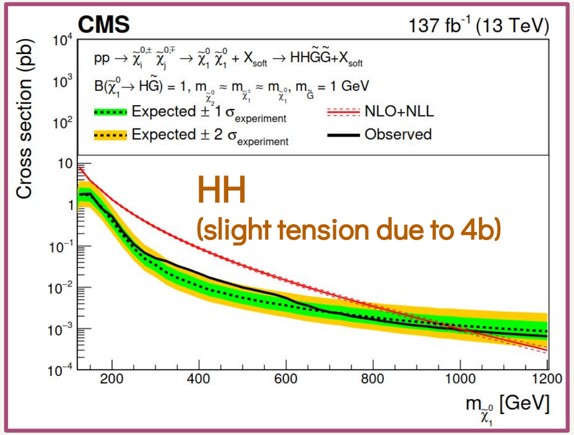






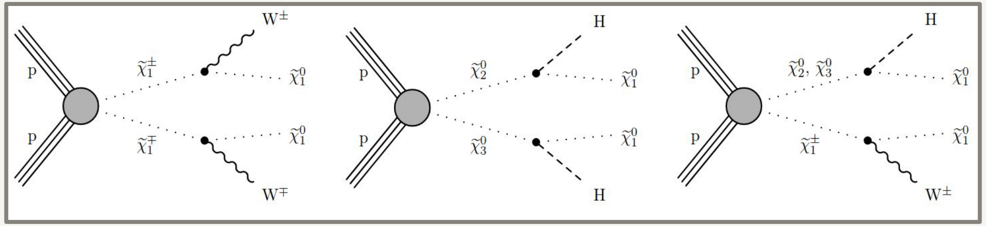






Higgsino-bino model

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

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

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

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