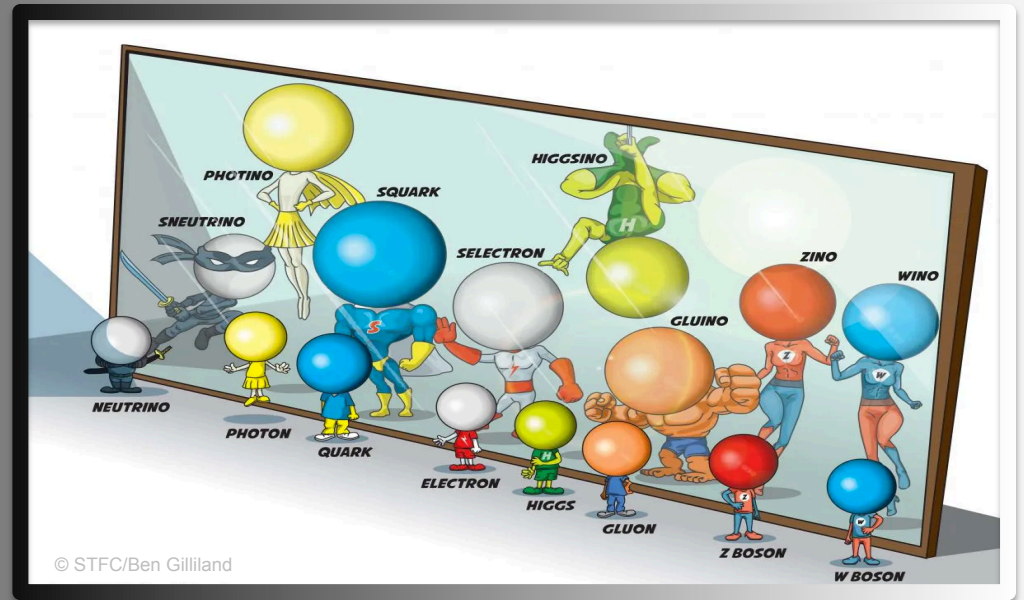


# SUSY searches with the CMS detector at the CERN LHC

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The 31<sup>st</sup> International Conference on Supersymmetry and Unification  
of Fundamental Interactions



# Introduction

- There is no evidence of **SuperSymmetry...**
  - although it is highly motivated and expected to solve Nature's mysteries
  - **It can not be ruled out**
- CMS conducts extensive searches for **New Physics** including **SUSY** with **BSM Higgs** and **Dark Matter**
- Many *supersymmetric possibilities* are under consideration:
  - *Natural SUSY*
  - Compressed mass spectra
  - Cascade decays
  - Light Higgsinos
  - Dark Matter
  - Stealth SUSY
  - R-parity Violating
  - And many more...
    - *Many exotic signatures (e.g. long-lived particles) taken by EXO searches*
- In this talk, the focus is on **results** lately released or published
  - from **full Run-2** (2016-2018) up to **140/fb @  $\sqrt{s} = 13$  TeV**



# Classical SUSY searches

## Natural SUSY:

### ■ TeV-scale sparticles

- **Strong** production favoured

**First full Run-2 searches focused on the strong/color sector!**

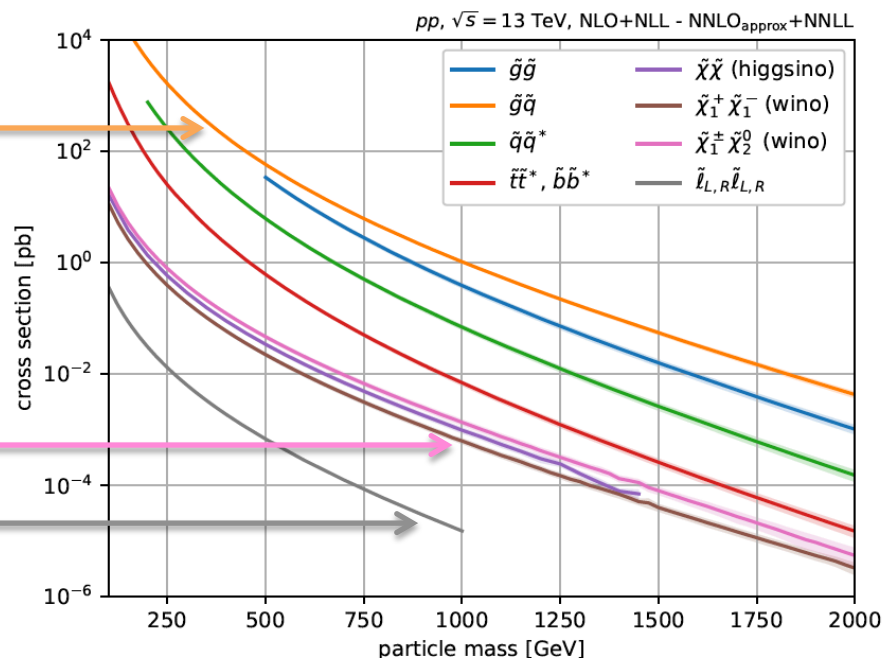
- **EWK** production
- **Sleptons**

### ■ R-parity conserved

- SUSY particles pair produced
- **Lightest SUSY particle (LSP)**
  - **Dark Matter** candidate

### ■ Simplified models:

- Simple production and decay channels with a few free parameters
- **BUT not realistic SUSY scenarios!**



## Use of:

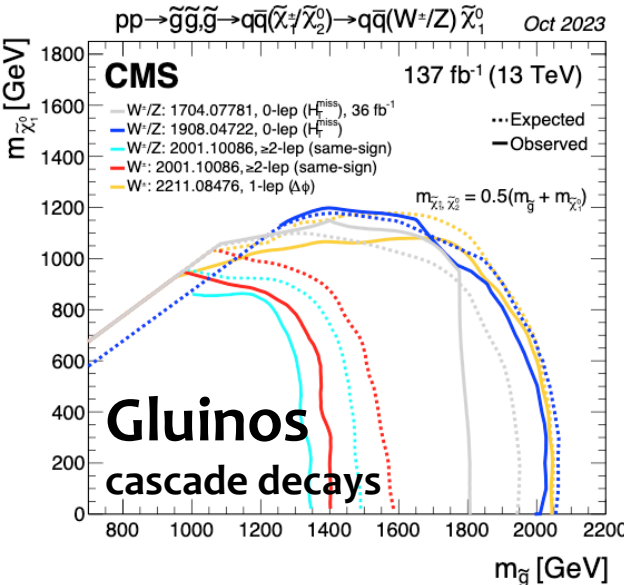
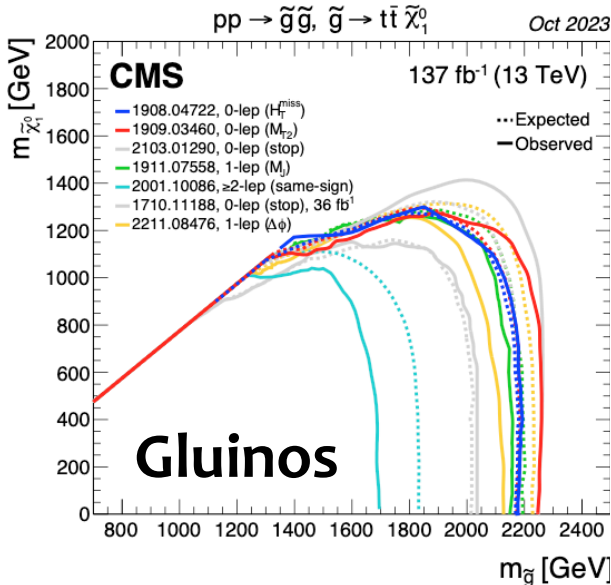
### ■ Standard (SM) objects

- Leptons, photons, jets

### ■ SUSY observables

- **Missing transverse energy ( $p_T^{\text{miss}}$ )**
- Transverse mass,  $M_T$ ,  $H_T$ ,  $M_{\ell\ell}$  and more...

# Present CMS Run-2 Limits on SUSY



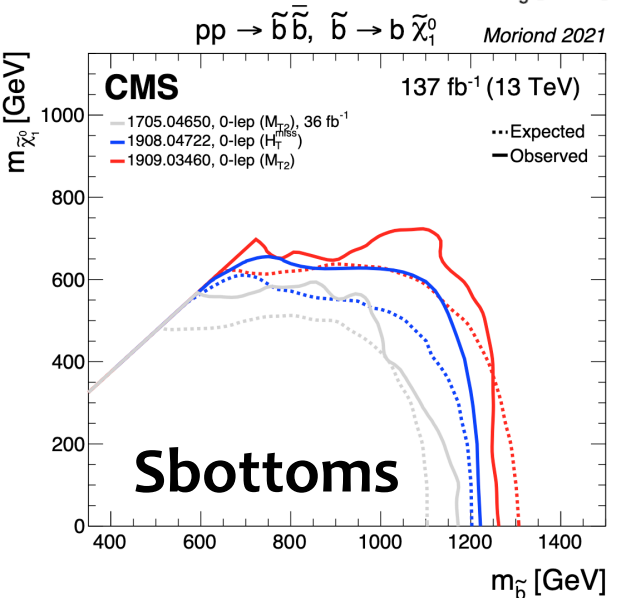
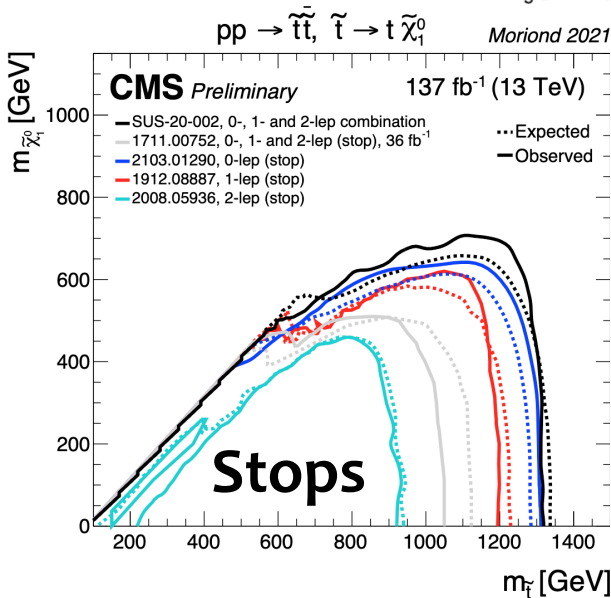
## CMS Sensitivity with Run-2 data @ 13 TeV

[Simplified models]

- ~ 2.2 TeV for gluinos
- ~ 2.0 TeV for gluinos cascade decays
- ~ 1.3 TeV for stops
- ~ 1.2 TeV for sbottoms

## SUSY strong/color production at LHC is limited by the quickly falling cross section

- Mass reach will increase slowly with more LHC data
- BUT more space for discoveries remains with EWK production





# Latest Electroweak SUSY combination

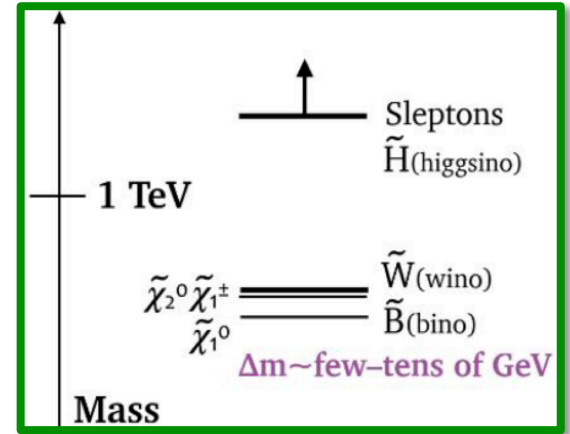
- **Goal:** improve CMS sensitivity to rare SUSY signatures, which are **experimentally extremely challenging**

- Special focus on **Compressed Mass** scenarios :  
 $m_{NLSP} - m_{LSP} = (\Delta m) \sim \text{small [few GeV]}$

- **SUSY with R-parity conserved**

- Direct pair-production NLSP + stable LSP ( $p_T^{\text{miss}}$ )

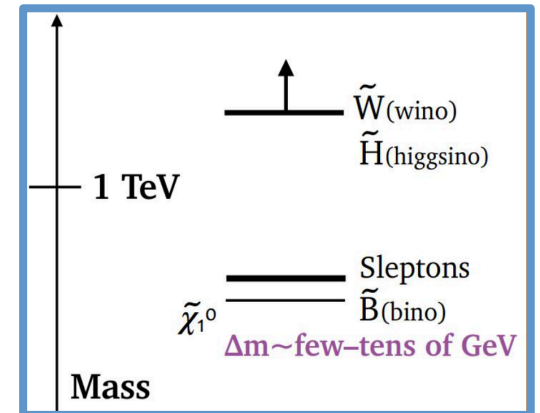
- ✓ **EWK-inos** (charginos and neutralinos), where NLSP  $\rightarrow$  LSP (lightest neutralino)  $\mathbf{X^{SM}}$  ( $\mathbf{X^{SM}} = \mathbf{W, Z, H}$ )



- ✓ **Sleptons pair production**, where  $\tilde{\ell} \rightarrow \ell \text{ LSP}$

- **4 EWK simplified models:**

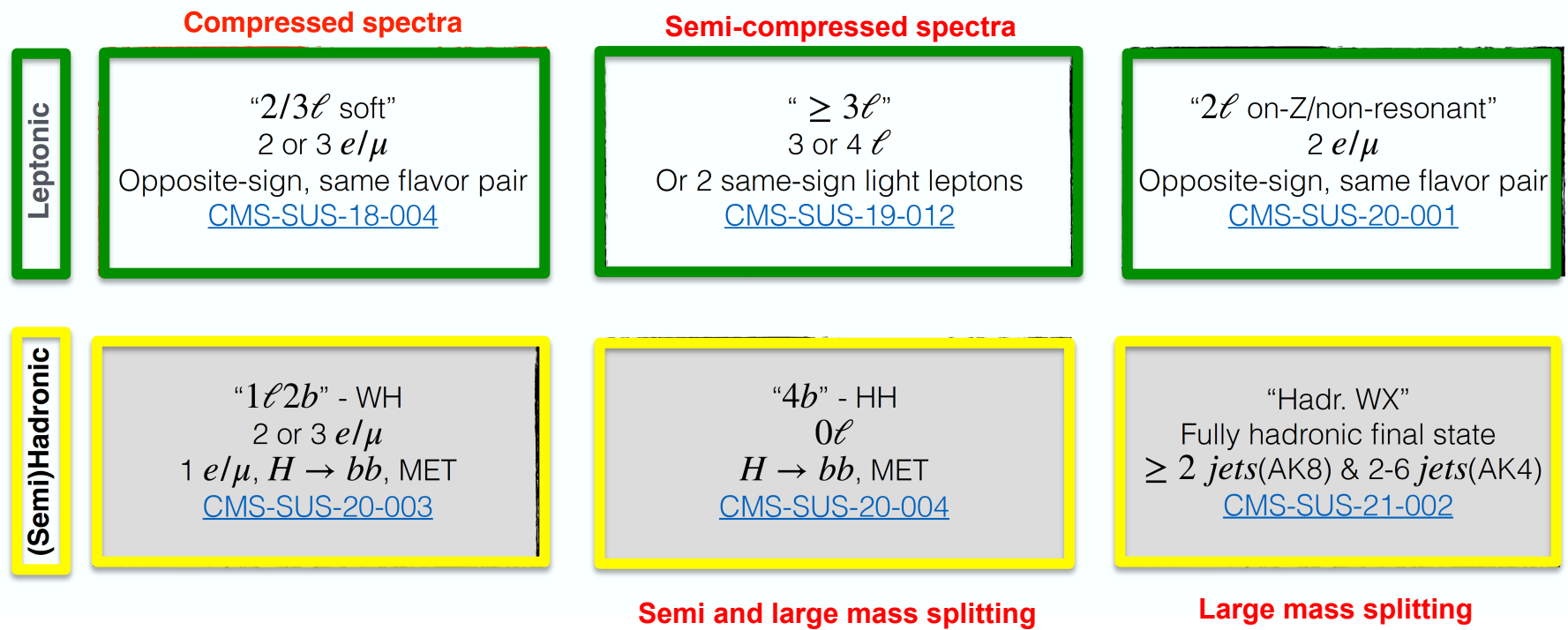
- ✓ **Wino-bino:** Wino-like chargino and Bino-like neutralino
- ✓ **Higgsino-bino** model (chargino/neutralino)
- ✓ **GMSB** Gauge-mediated SUSY breaking model with quasi-degenerate Higgsinos (results in backup)
- ✓ **Slepton-neutralino**, slepton pair production





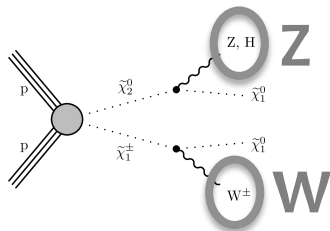
# Latest Electroweak SUSY combination

- Combination of 6 different SUSY searches with **leptonic** and **hadronic** decay topologies



→ **Benefit from combinations expected**

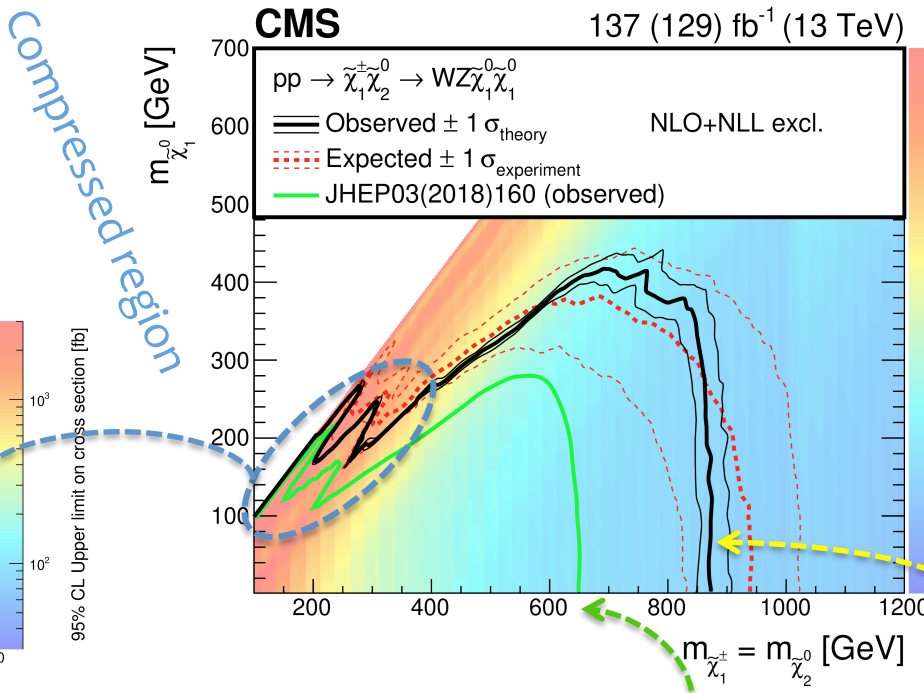
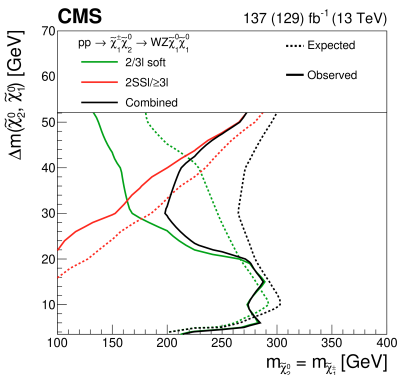
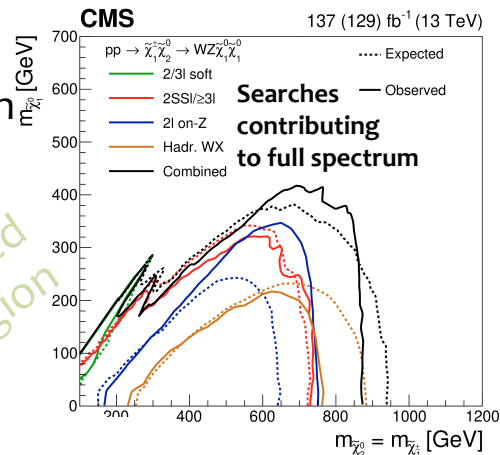
# EWK SUSY EWK-inos



■ **Wino-bino model for charginos  $\tilde{\chi}_1^\pm$  and neutralinos  $\tilde{\chi}_2^0$  production**

■ **Limits for decay topology: W Z**

- For compressed region, the lepton reconstruction method was improved
- For larger chargino masses, the search limited by the XS

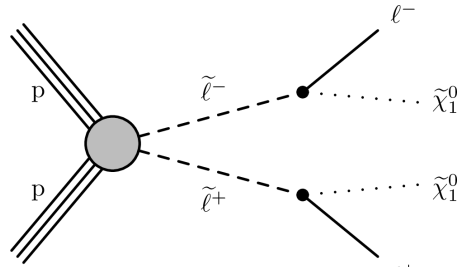


Small excess ( $\sim 1\sigma$ ) in **Hadr. WX** search slightly recusing sensitivity in combination

**CMS exclusion reach for  $\tilde{\chi}_1^\pm = \tilde{\chi}_2^0$  (WZ)  $\sim 875$  GeV**

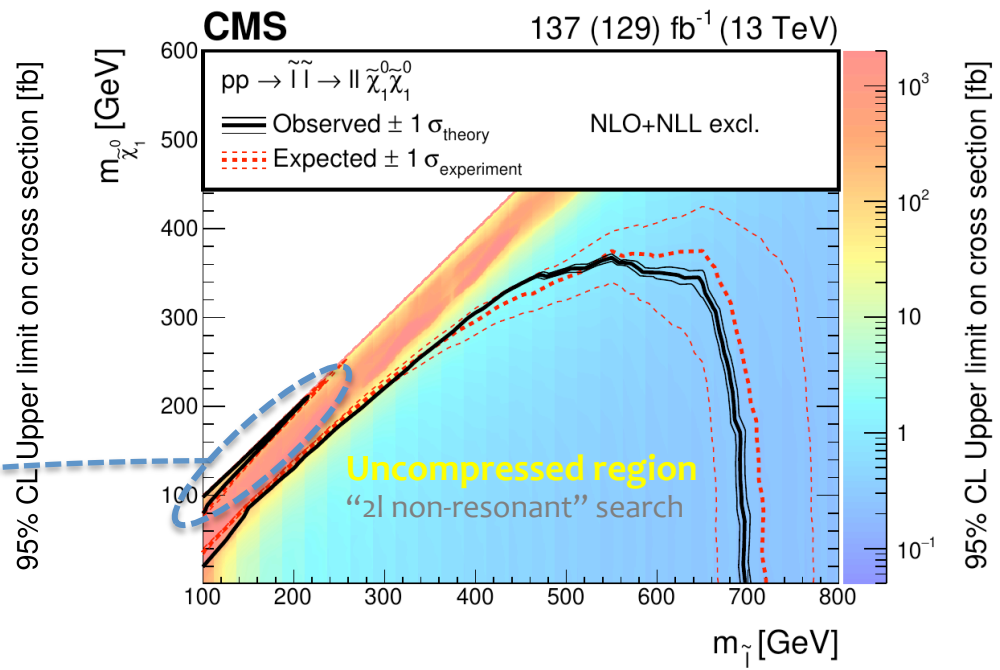
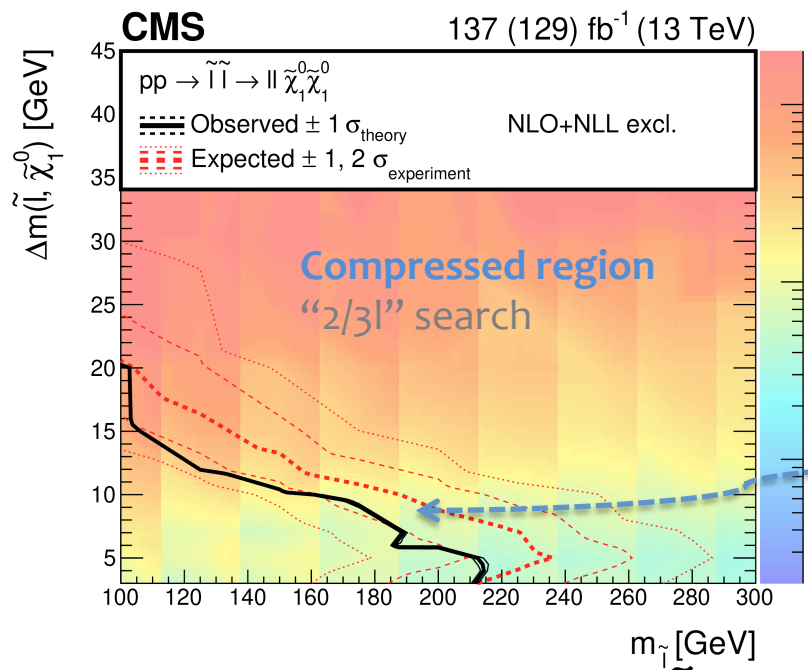
Small excess ( $\sim 2\sigma$ ) at  $\Delta m \sim 30-40$  GeV present in both searches  $\rightarrow$  **Weaker exclusion limits!**

Significant improvement wrt. **previous 2016** combination



# EWK SUSY sleptons

- **Slepton-neutralino model** for NLSP sleptons decaying to neutralino LSP
  - **Mass degenerate** 1st/2nd generation sleptons (left and right-handed)
  - Challenging due to **very small cross sections** (2 orders smaller than EWK-inos)



For a **5 GeV difference** between  $\tilde{\ell}$  and  $\tilde{\chi}_1^0$ , slepton masses up to **~ 215 GeV** excluded

Observed exclusion for  $m_{LSP} < 50$  GeV in the **slepton mass is ~ 130 – 700 GeV**

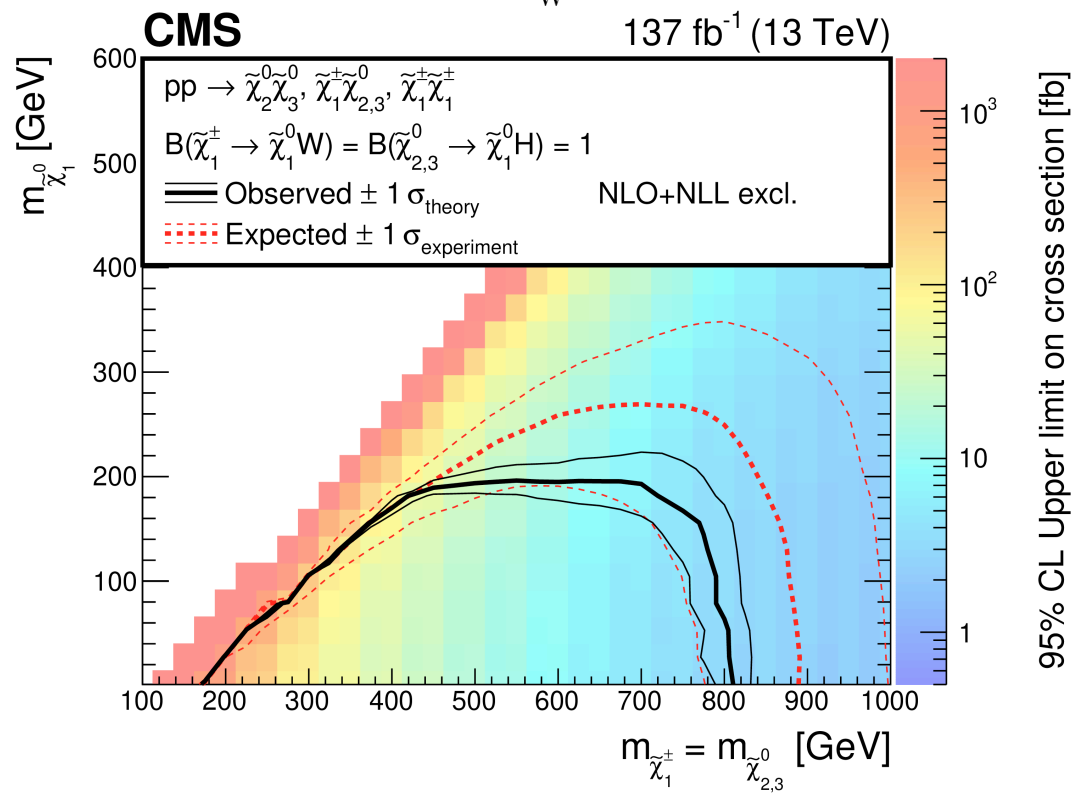
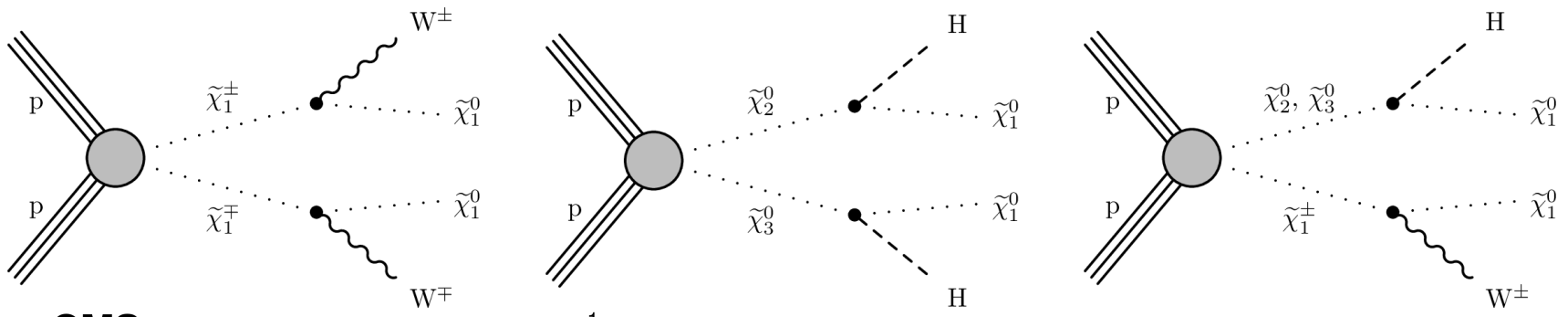
*First CMS limits for compressed slepton spectra!*





# EWK SUSY Higgsinos

## Higgsino-bino model for Higgsino-like NLSP decaying to Bino-like neutralino LSP and W H



Observed exclusion for  
 $m_{\text{LSP}} < 50 \text{ GeV}$   
 in the masses:  
**225 – 800 GeV**



# Novel SUSY searches

We do not know how **supersymmetric** is the **Nature** if at all:

- **R-parity** can be **violated\***
- SUSY can be **broken** in a specific way
- Can live in a **hidden sector\***

■ Therefore, CMS considers **different scenarios**:

- **Inclusive, multi-bin analyses\*** looking at multiple final states
- Dedicated searches for a **very specific final state\***

■ Especially interested in **more complicated signatures**:

- **Compressed spectra\***
- **Low cross sections\*** (e.g. for sleptons)
- **Long-lived particles** (widely studied as **Exotic signatures** by CMS EXO group)
- **Dark Matter\*** searches in SUSY
- Low  $p_T^{\text{miss}}$  (e.g. **RPV\***, **Stealth SUSY\***)
- Exotic **Higgs decays (2HDM)\***

■ **New search approaches**:

- New **reco algorithms** for **low energetic leptons, photons, jets\***
- New search tools with **machine learning ML techniques\***
- New **triggers**

■ **Precise predictions of the SM background** (importance of it)\*

## Exotic signatures:

- highly ionizing particles: dE/dx, delayed
- **disappearing tracks\***
- appearing tracks
- displaced vertices
- non-pointing photons, lep, jets
- kinks in tracks

\* in this talk

# New! RPV SUSY in trilepton + jets

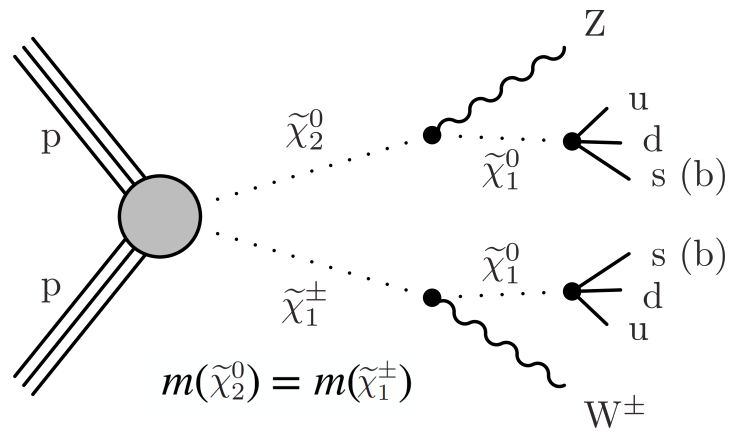


- Search for **weak production** and **strong decay** of wino/bino-like superpartners in **trilepton plus jets** final states

## SUSY Signal:

2 distinct models and signatures:

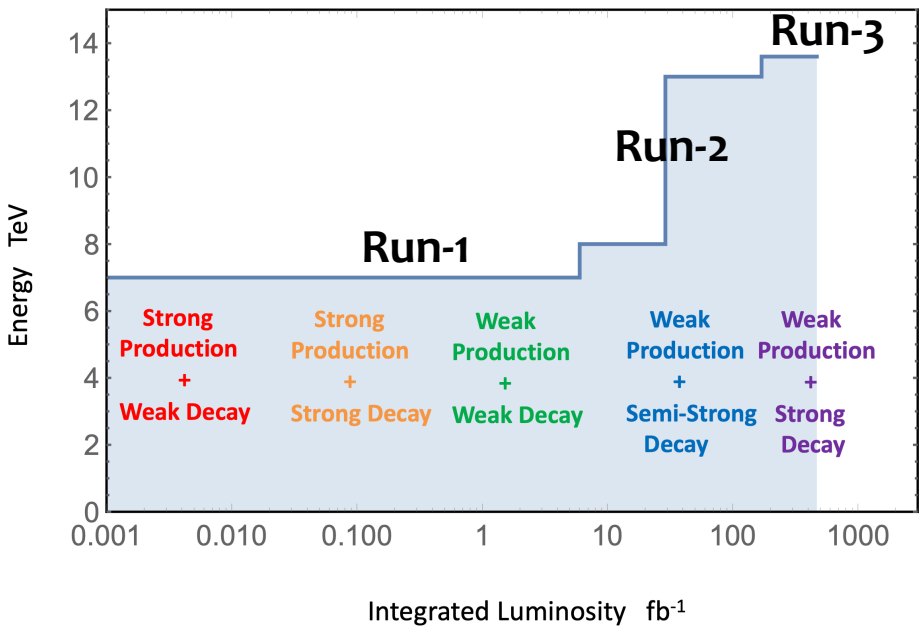
- RPVq**: LSP  $\rightarrow$  uds via  $\lambda''_{112}$   
W+Z + 6 light quark jets
- RPVb**: LSP  $\rightarrow$  udb via  $\lambda''_{113}$   
W+Z + 4 light, 2b quark jets



**First search** of this type at the LHC!

## A new frontier at LHC!

- Challenging signals requiring more than 100/fb to probe SUSY

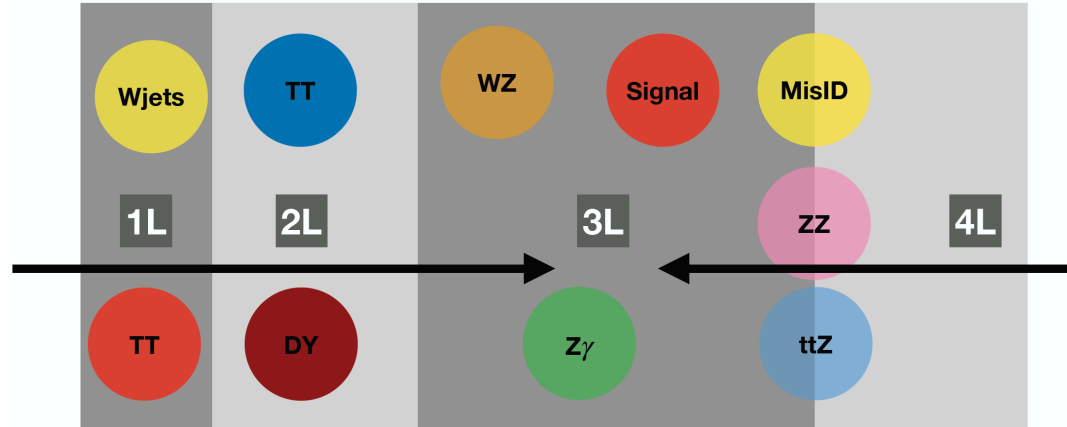


# RPV SUSY in trilepton + jets



## Analysis strategy:

- Search employs a **comparison of jet multiplicity distributions** in 1L, 2L, and 4L lepton events to **calibrate and probe background**



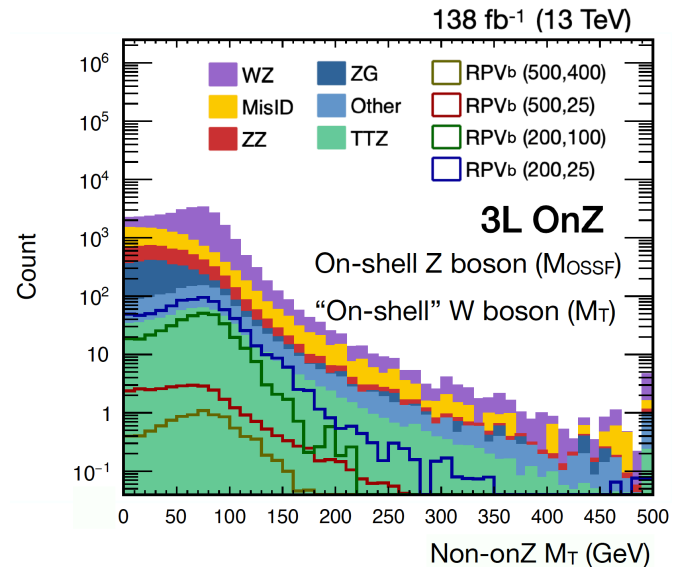
## Challenging phase space:

- Dominated by backgrounds signal sits in traditional CRs
- Traditional variables (MT) are insensitive
- Data-driven corrections from 1L/2L to irreducible backgrounds are used to capture missing higher order QCD effects

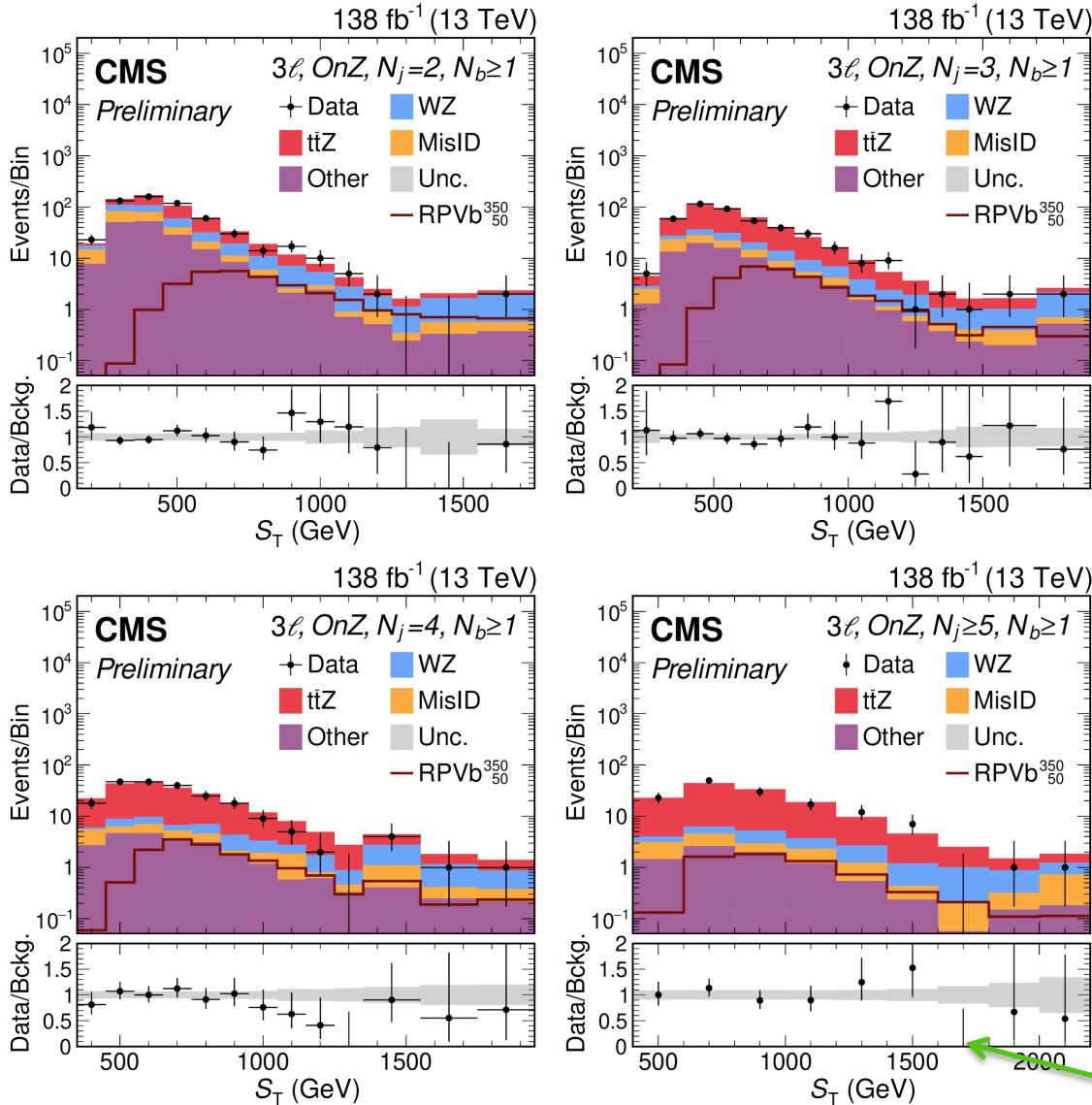
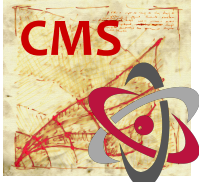
- Commissioning of MC
- Njet corrections
- Background normalizations
- Sanity checks
- Background normalizations
- Sanity checks
- Signal region
- Njet corrections

## Signal Region:

- events with **3 leptons** in association with **multiple jets**



# RPV SUSY in trilepton + jets



## Results:

- In bins of kinematical variable  $S_T$  for bins of  $N_{jet}=2,3,4, \geq 5$  if  $N_{b-jet} \geq 1$
- There is no significant disagreement between data and predictions

Largest deviation:  
 1.7 sigma deficit

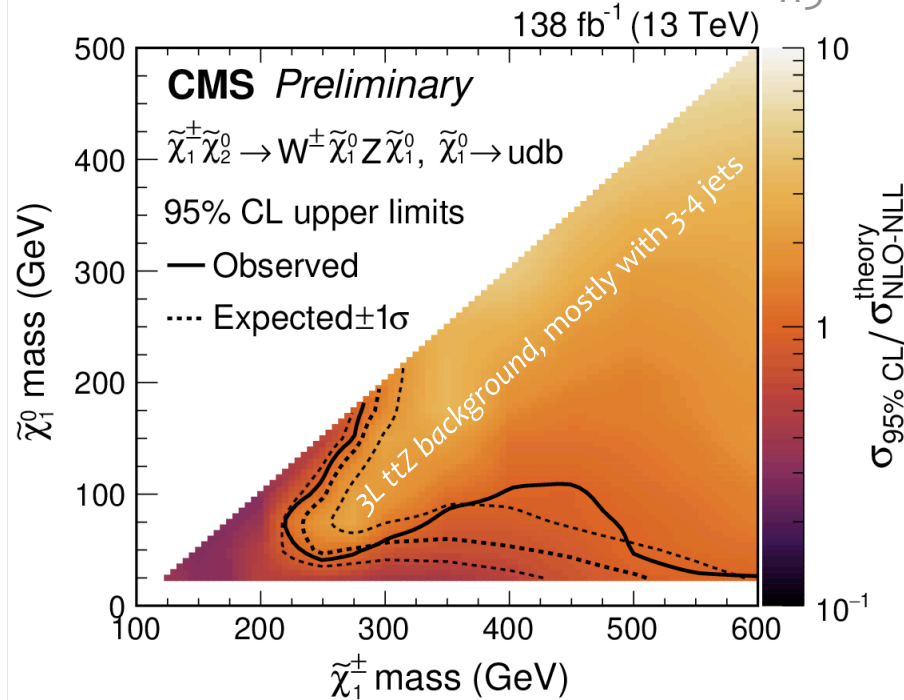
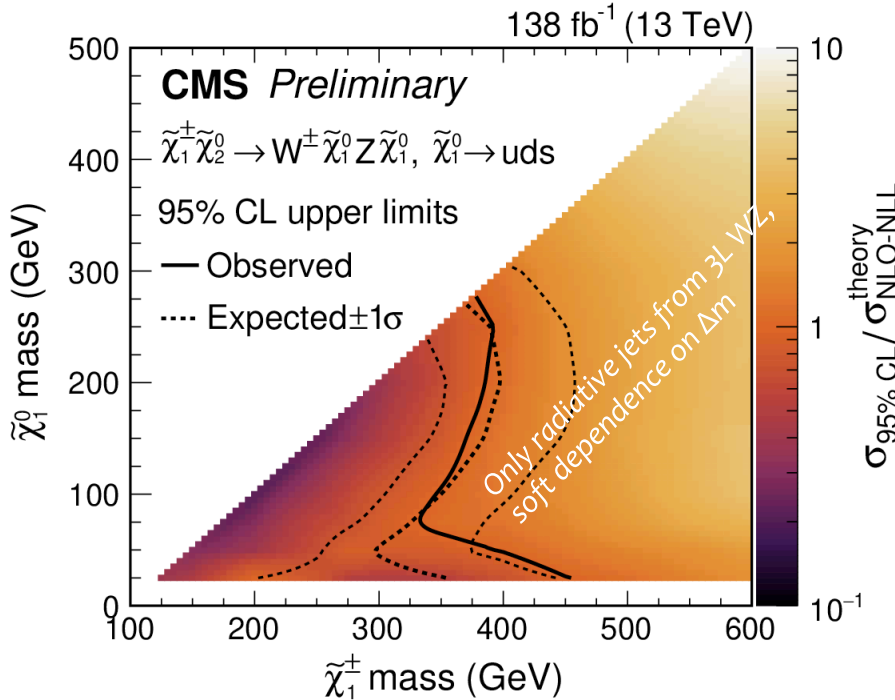


# RPV SUSY in trilepton + jets

## Results:

**RPVq:** LSP  $\rightarrow$  uds via  $\lambda''_{112}$

**RPVb:** LSP  $\rightarrow$  udb via  $\lambda''_{113}$



Constraints at 95% CL level on the **wino-like chargino-neutralino** with masses in the range:

**125-450 GeV**

**125-600 GeV**

Such scenarios are excluded for **bino-like LSP neutralino** masses up to:

**275 GeV**

**180 GeV**

→ Weak superpartners could still be hiding at the electroweak scale...

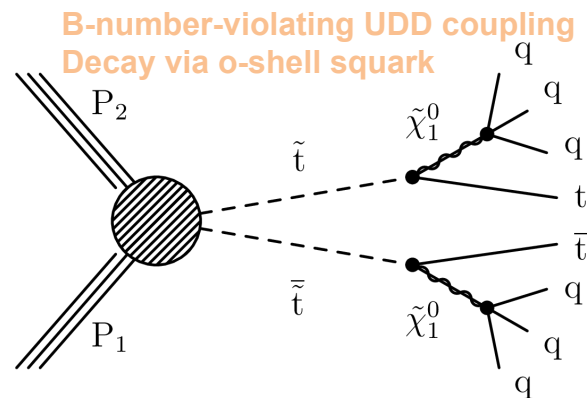


# RPV and Stealth SUSY

- Many new physics models, predict the production of events with **top quarks**, **low  $p_T^{\text{miss}}$**  (vs. large  $p_T^{\text{miss}}$ ) and **many additional quarks or gluons**

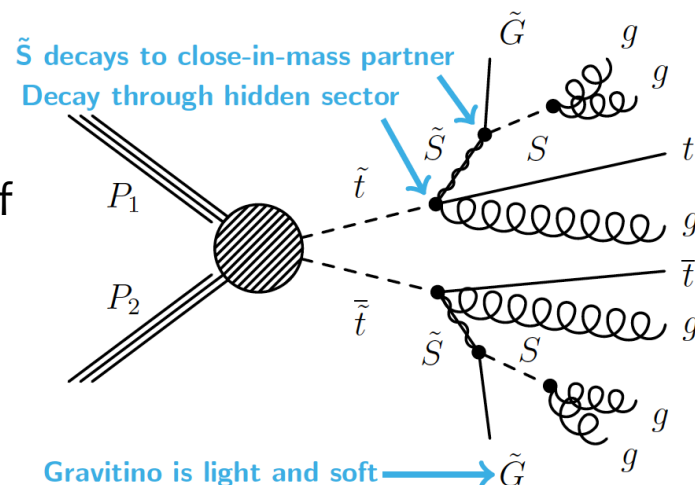
## RPV SUSY:

- R-parity is not conserved** allowing for an additional interaction via the UDD coupling
- LSP neutralino is no longer stable** and decays to SM products (no source of significant  $p_T^{\text{miss}}$ )
- Neutralino mass** is assumed to be **100 GeV** for this analysis



## Stealth SYY SUSY:

- Extension of MSSM with a hidden sector comprised of  **$\tilde{S}$  (singlino)** and  **$S$  (singlet)**
- Weakly coupled to SUSY-breaking sector ( $\approx$  SUSY)  
 $\Rightarrow$  Nearly degenerated (in this analysis):  **$M_{\tilde{S}} = 100 \text{ GeV}$** ,  **$M_S = 90 \text{ GeV}$**
- Gravitino is LSP** and it is produced via  **$\tilde{S} \rightarrow S \tilde{G}$**   
 $\Rightarrow$  low energy gravitino (1 GeV), too light to produce noticeable  $p_T^{\text{miss}}$





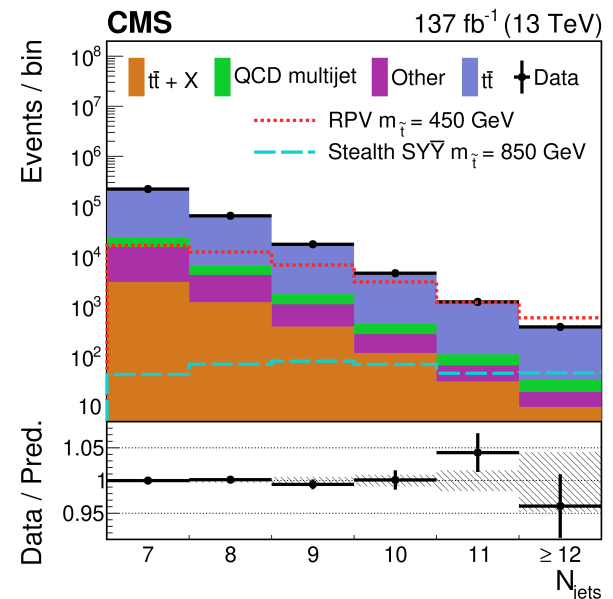
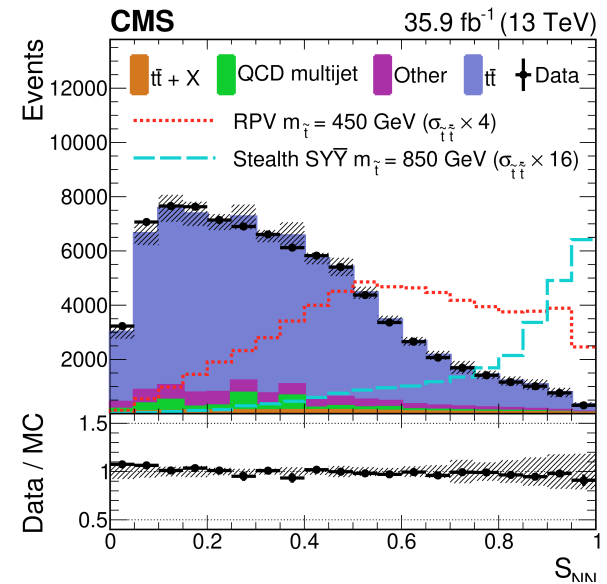
# RPV and Stealth SUSY

■ A first of its kind **CMS** search from **2021** for **SUSY** signal in final states with **tt + jets with no  $p_T^{\text{miss}}$**

- Signal topology feature: **high jet multiplicity**
- Low missing transverse energy, **no cut on  $p_T^{\text{miss}}$**
- **One lepton** helps reduce **QCD** background
- **Jet multiplicity is hard to model** at high multiplicity  
⇒ rely on data and **fit the  $N_{\text{jets}}$  distribution**

- **Main strategy:** train the **neural network (NN)** to discriminate signal from irreducible tt + jets, assuming NN variables are independent on  $N_{\text{jet}}$  shape
  - Then perform fit/ $N_{\text{jet}}$  shape procedure

- **Result:**  
In bkg prediction from the background-only fit wrt. data
- **Some excess** was observed



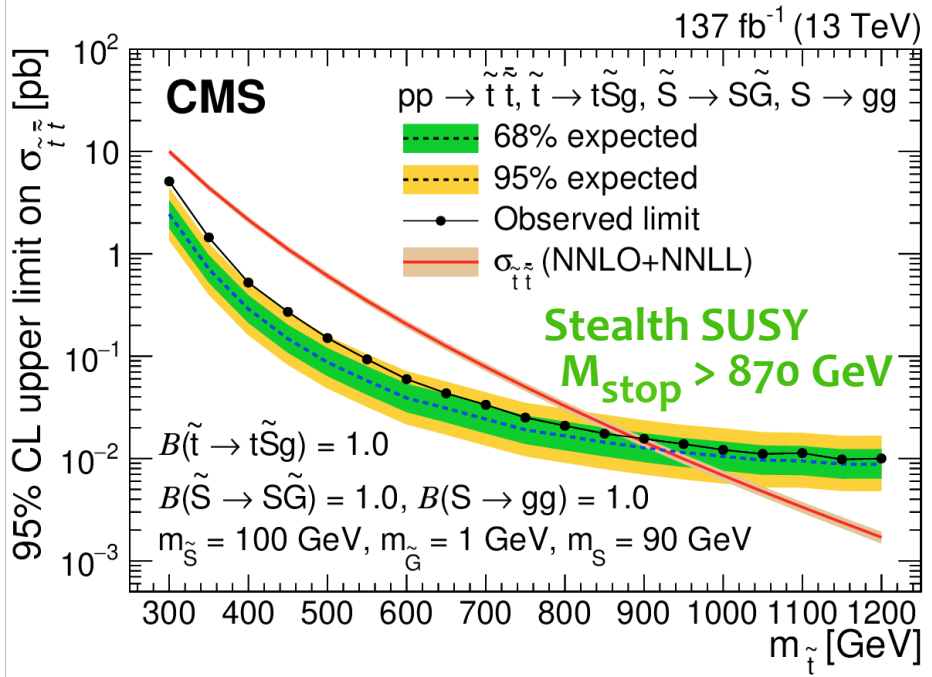
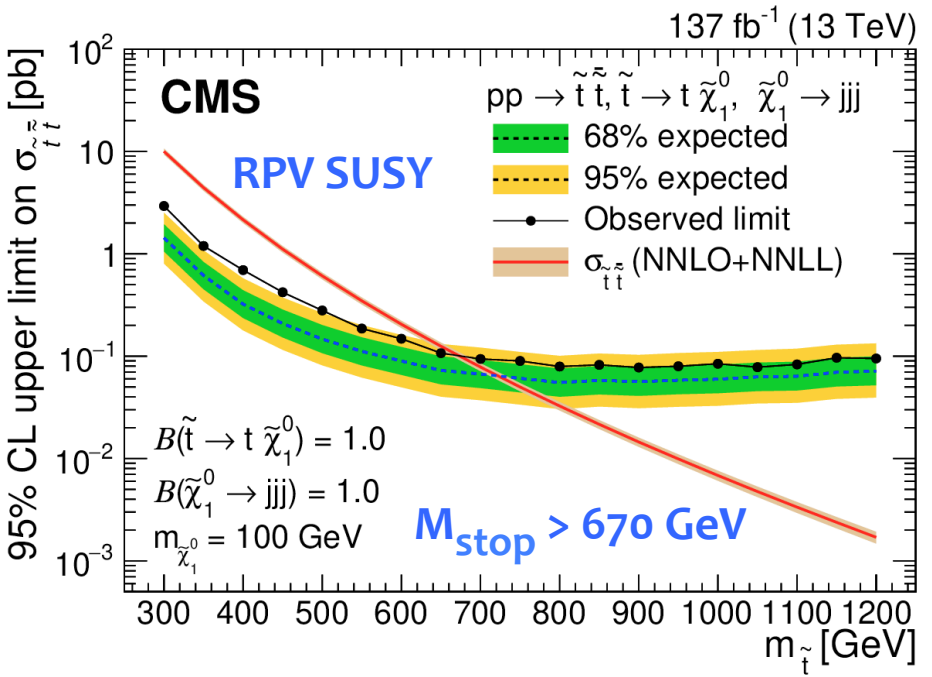
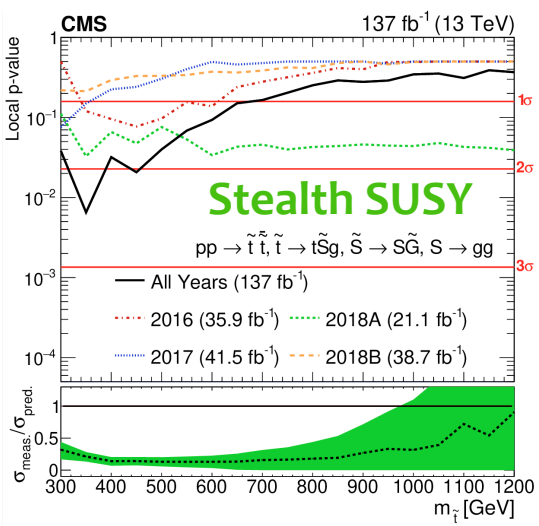
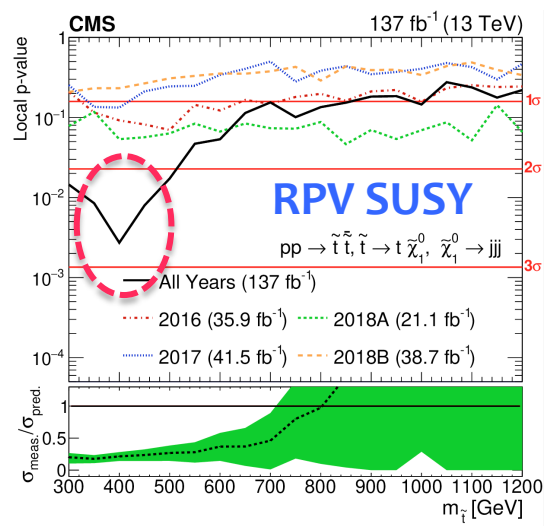




# RPV and Stealth SUSY

## RPV SUSY:

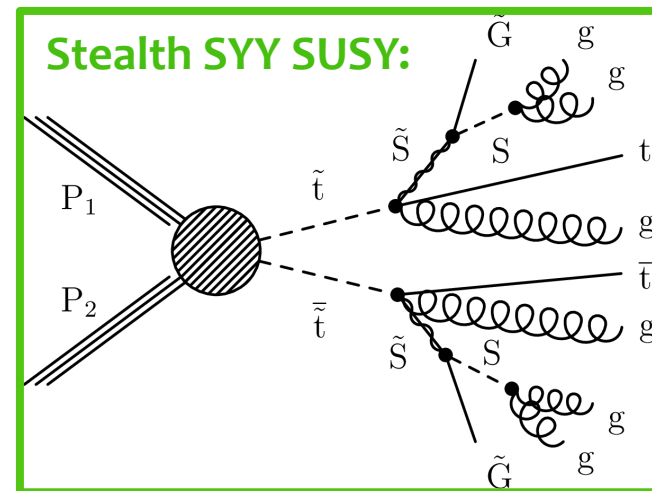
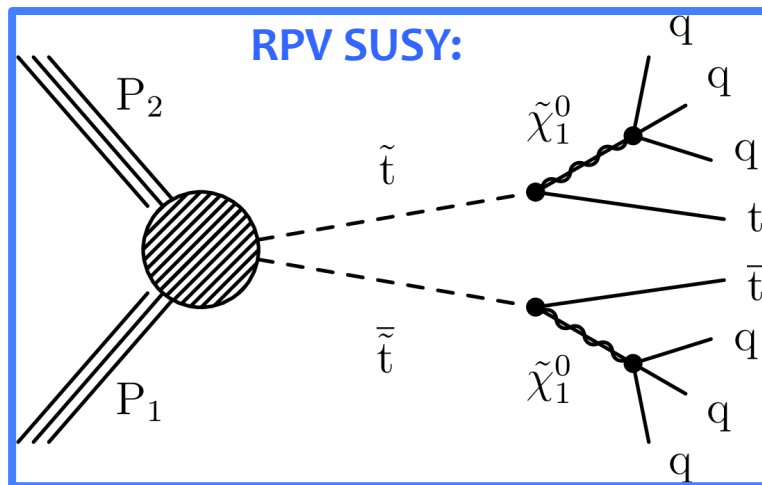
**2.8 $\sigma$**  local significance  
for  $m_{\text{stop}} = 400$  GeV mass point  
corresponding to  
a signal strength of  
 **$r = 0.21 \pm 0.07$**



# New! RPV and Stealth SUSY

Very new result!

- Search for **SUSY signal** in final states with **tt + jets with low -  $p_T^{\text{miss}}$** 
  - The **same signature** as in [SUS-19-004]
    - many additional quarks or gluons (at least 6 light jets)
    - low missing transverse energy (no cut on  $p_T^{\text{miss}}$ )
  - New: Add 0- and 2-lepton channels to the 1-lepton channel to allow for checking of compatibility with final states containing tt

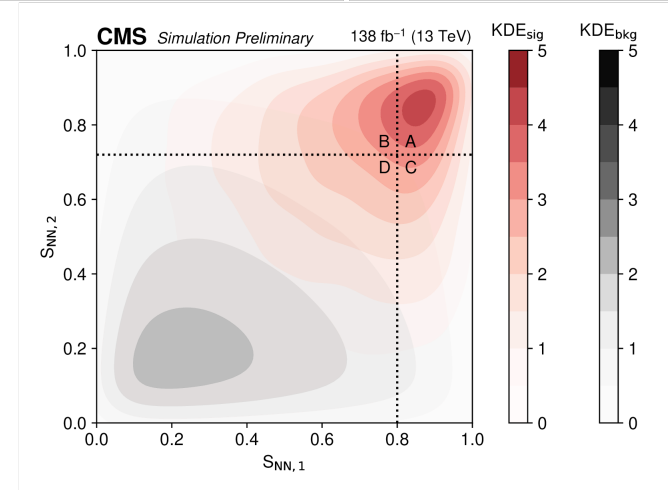
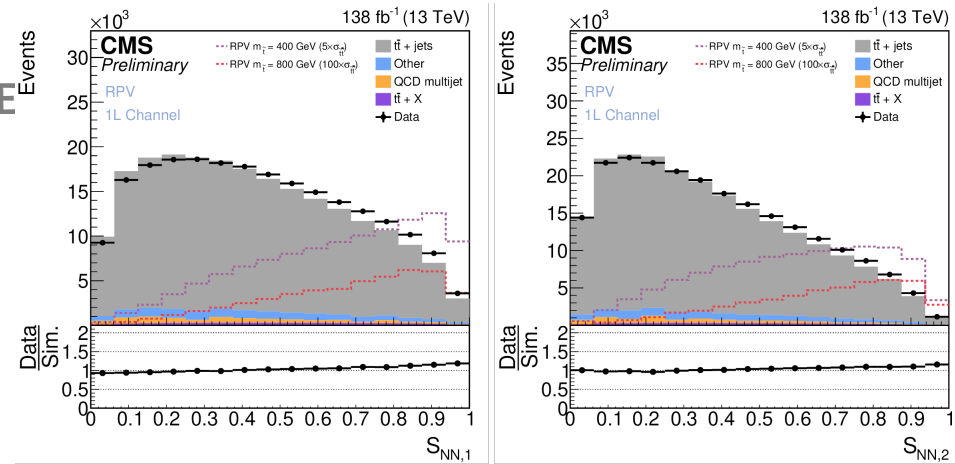




# RPV and Stealth SUSY

## Analysis strategy:

- Completely **new**  $t\bar{t}$  + jets **estimation method** to reduce impact of syst. unc. on  $N_{\text{jets}}$  shape in  $t\bar{t}$  + jets
- The new Neural Network ABCDisCoTE** to generate **two independent signal vs bkg. discriminants**  $S_{\text{NN},1}$  vs  $S_{\text{NN},2}$
- Signal** and  $t\bar{t}$  + jets **estimated separately** in  $N_{\text{jets}}$  bins with simultaneous fit to data in four ABCD bins of  $S_{\text{NN},1}$  vs  $S_{\text{NN},2}$  plane
- Extract the prediction for the **QCD multijet** background from a dedicated **control region**
- Three analysis channels with lepton:  $0\ell, 1\ell, 2\ell$**  combined in a simultaneous multi-bin fit separated by jet multiplicity





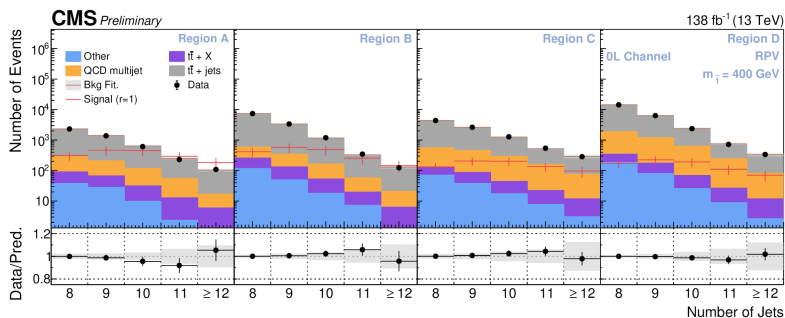
# RPV and Stealth SUSY

- Background-only post-fit plots per N jets for the three channels for **RPV  $M_{stop} = 400$  GeV**

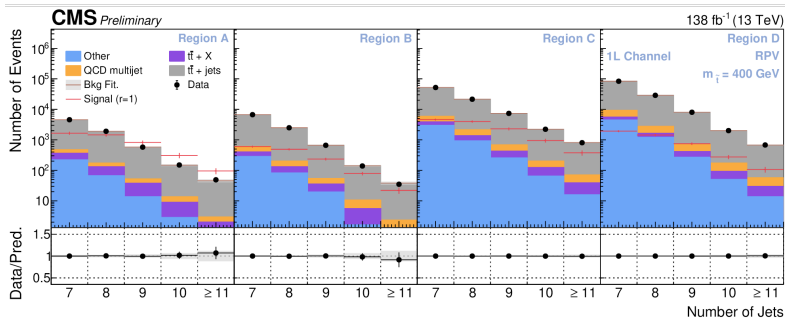
- Good agreement!** for all optimizations and signal models between background-only fits and data

- Combined limits for **all lepton channels improved!**

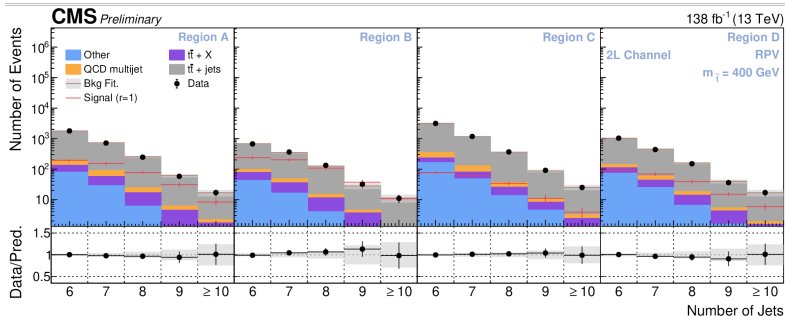
0l



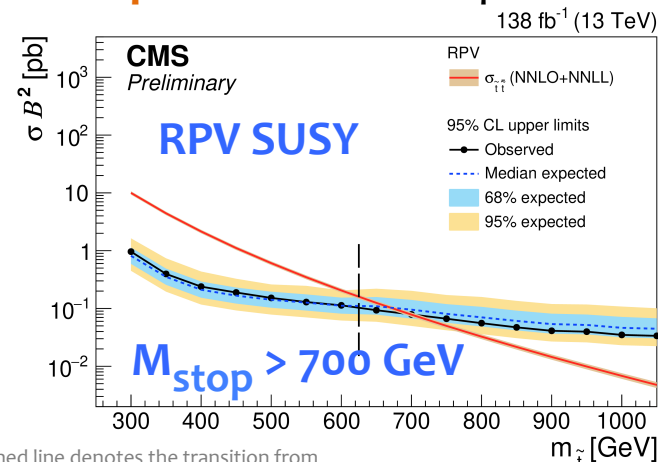
1l



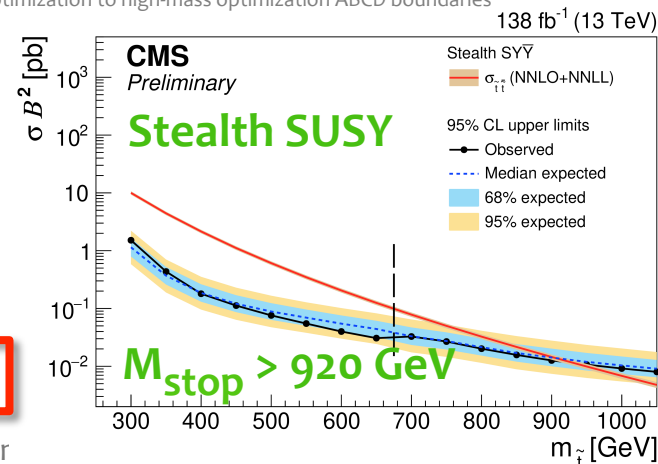
2l

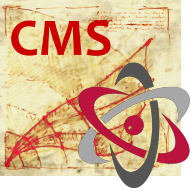


The deviation ( $2.8\sigma$ ) observed previously is not confirmed!



The vertical dashed line denotes the transition from the low-mass optimization to high-mass optimization ABCD boundaries

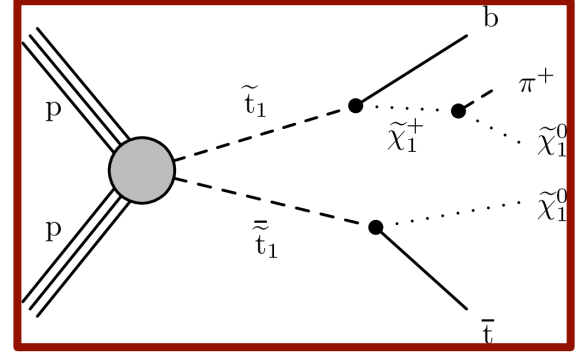




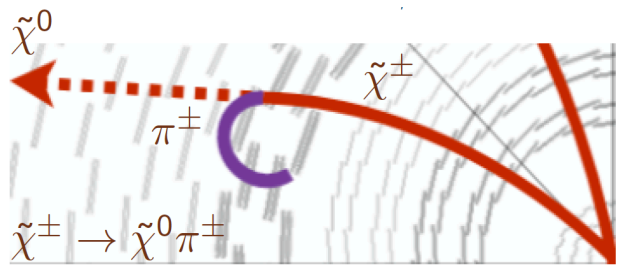
# SUSY with disappearing tracks

- **(Very) Compressed SUSY**

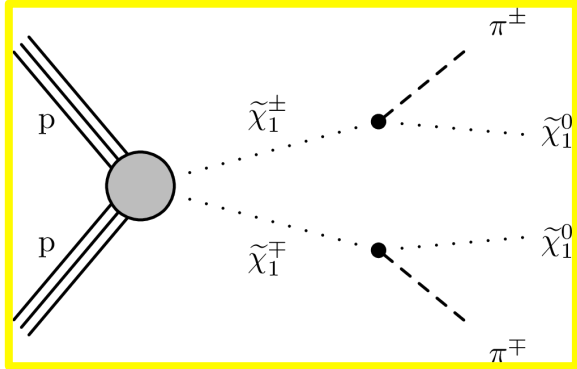
Small mass splitting: chargino NLSP with the LSP neutralino,  $\Delta m(\tilde{\chi}^{\pm 1}, \tilde{\chi}_1^0) \sim \mathcal{O}(100) \text{ MeV}$



- Chargino  $\tilde{\chi}^{\pm 1}$  is long-lived
- Decays inside tracker to a **soft undetectable  $\pi^\pm + \mathbf{p}_{\text{miss}}^T$**



**Short track (DT)**  
in the tracker

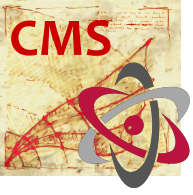


- **Analysis strategy:**

- Target long-lived  $\tilde{\chi}^{\pm 1}$  from **strong** or **EWK** production (6 models)
- $\geq 1$  disappearing track +  $\mathbf{p}_T^{\text{miss}}$  +  $\geq 1$  jet + 0/1 lepton

- **DTs selection:**

- Categorize into **short (pixel-only)** and **long (pixel+strip) DTk** selections to search for a **range of lifetimes**
- **Boosted decision tree** classifiers used to improve DTk purity



# SUSY with disappearing tracks

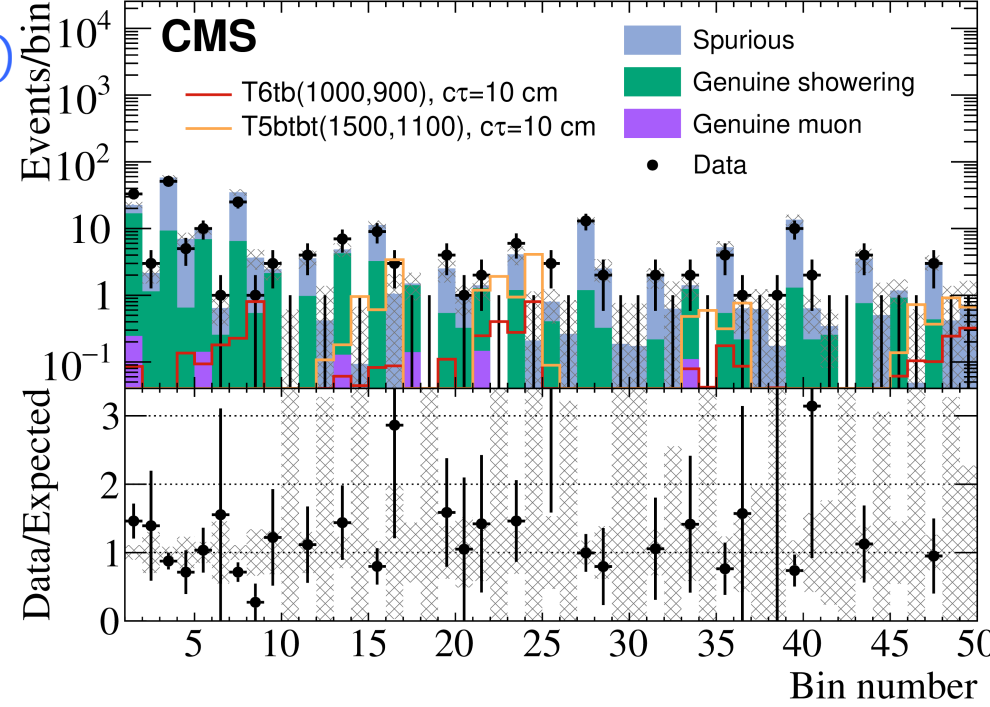
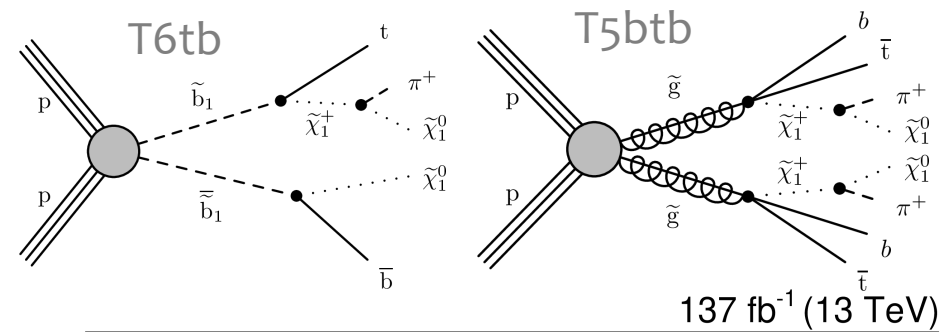
- **3 channels:**  
hadronic (0 lep)+DTk, e+DTk,  $\mu$ +DTk
- **49 search bins in**  
hard  $p_T^{\text{miss}}$ ,  $N_b$ -jets,  $N_{\text{jets}}$ ,  
 $N_{\text{short-tracks}}$ ,  $N_{\text{long-tracks}}$ ,  
**pixel  $dE/dx$  (for the first time used in DTs)**

### Backgrounds:

- Hadrons and leptons **poorly reconstructed** in tracker
- Tracks built **out of chance alignment** of hits from different particles

### Background estimation:

- **Data-driven:** calculate transfer factors in sideband regions and apply to DTk candidates in control regions

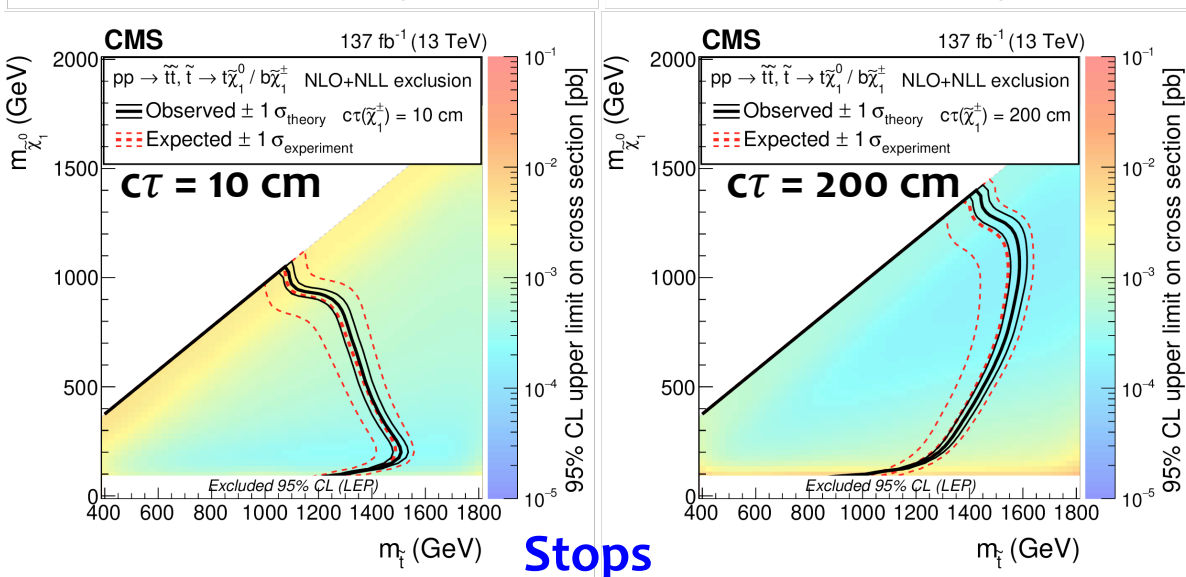
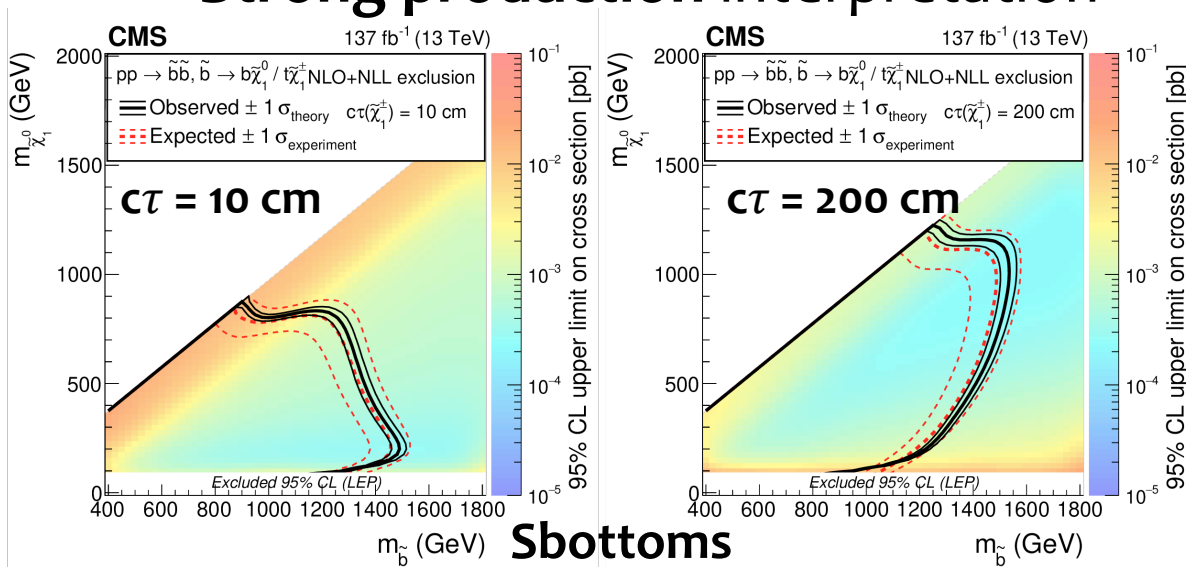


No statistically significant excess observed in any SR



# SUSY with disappearing tracks

## Strong production interpretation



Max mass reach  
of **neutralino  $\tilde{\chi}_1^0$**   
up to **0.9 TeV** for  $c\tau = 10 \text{ cm}$   
**1.3 TeV** for  $c\tau = 200 \text{ cm}$

Up to **~500 GeV** neutralino mass improvement in the compressed region wrt. prompt searches (esp. for long lifetimes)

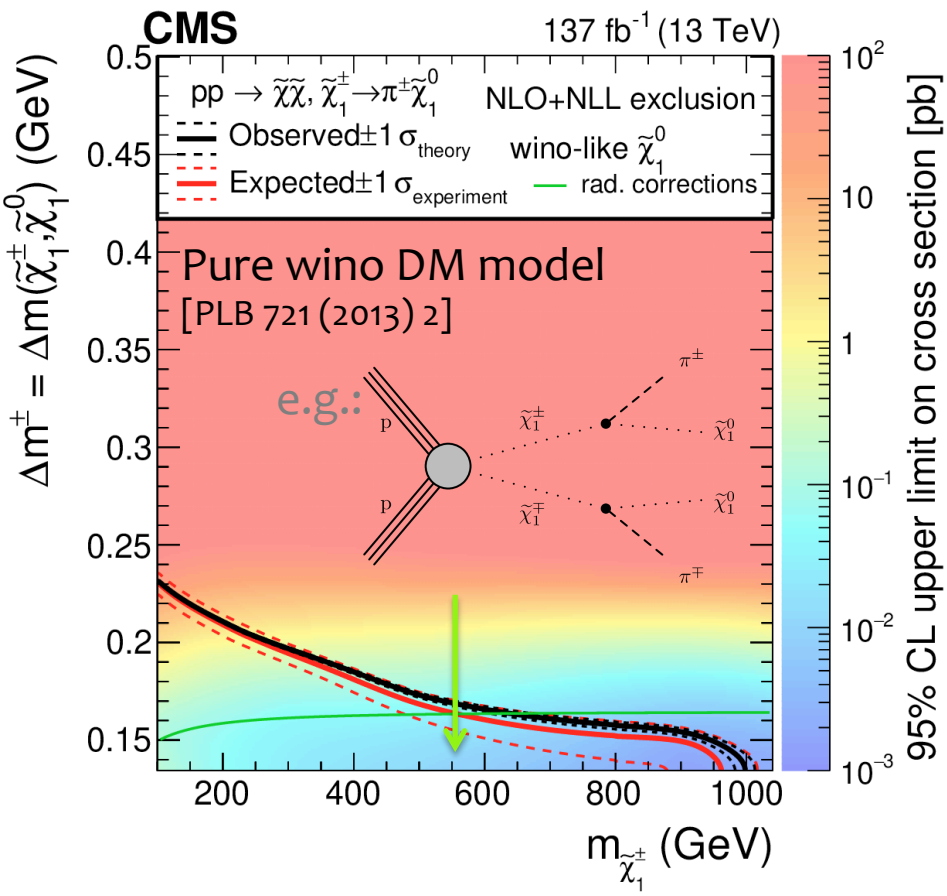
Max mass reach  
of **neutralino  $\tilde{\chi}_1^0$**   
up to **1.1 TeV** for  $c\tau = 10 \text{ cm}$   
**1.4 TeV** for  $c\tau = 200 \text{ cm}$

Up to **~200 GeV** neutralino mass improvement in the compressed region wrt. previous DTk search [SUS-19-005]

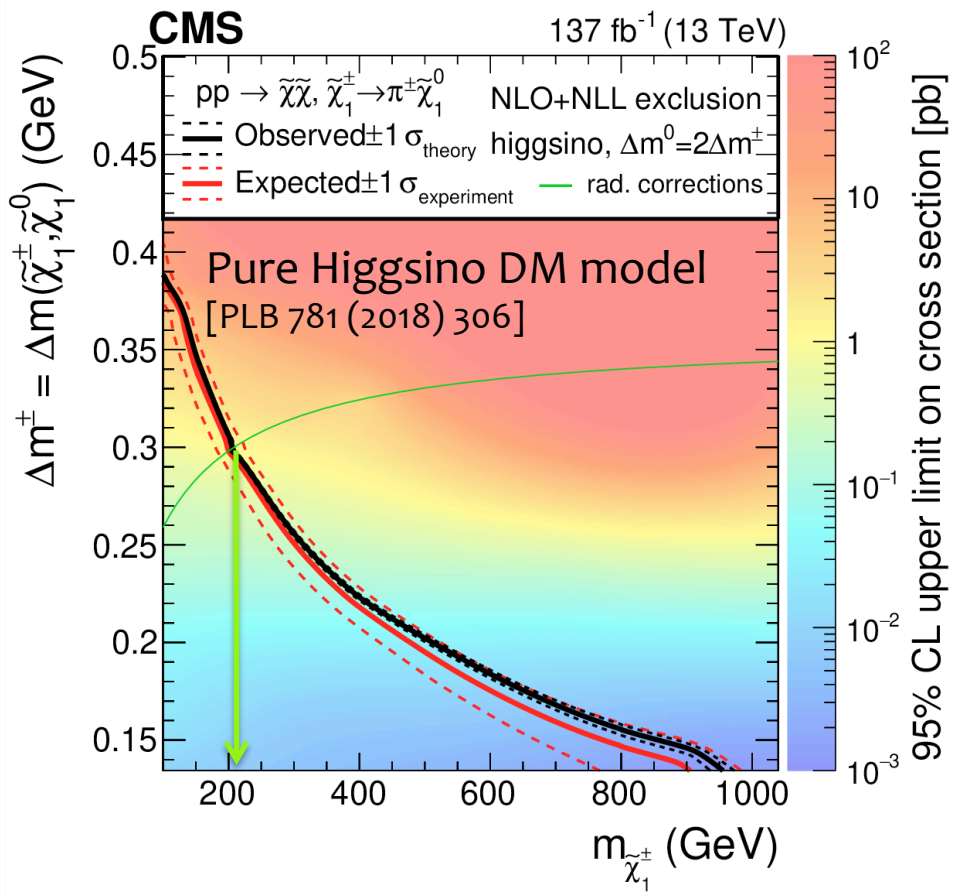
# SUSY with disappearing tracks

## Dark Matter interpretation

for models with only **radiative corrections** to  $\tilde{\chi}^{\pm 1}$  and  $\tilde{\chi}^0_1$  mass splitting (**green lines**)



Exclude Wino- $\tilde{\chi}^{\pm 1}$  mass up to  $\approx 550$  GeV

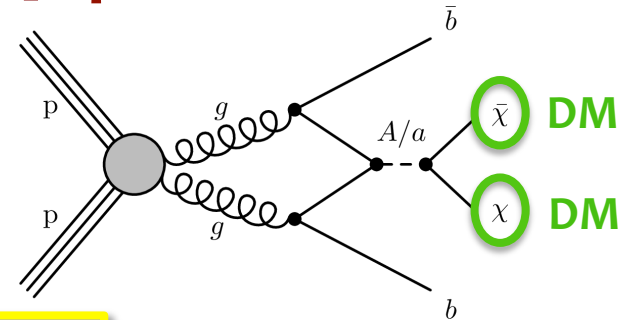


Exclude Higgsino- $\tilde{\chi}^{\pm 1}$  mass up to  $\approx 210$  GeV



# New! DM in $bb + p_T^{\text{miss}}$

- Search for **Dark Matter** in channel of non-resonant pair of bottom quarks,  $bb$  and **large** missing transverse energy,  $p_T^{\text{miss}}$



**First search** of DM in  $bb + p_T^{\text{miss}}$  channel at the LHC!

## DM Signal: 2HDM+a

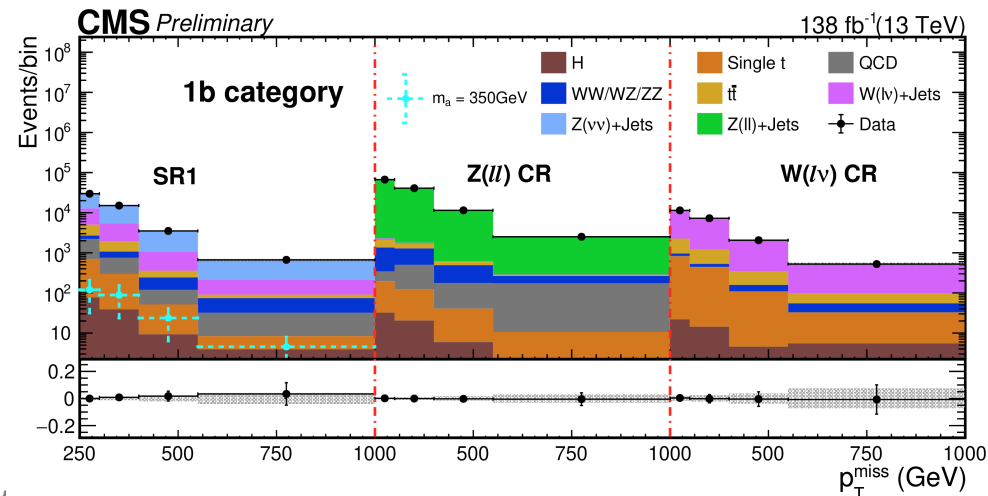
Type II two-Higgs doublet model with an additional pseudo-scalar

- 5 free parameters:  $m_A, m_a, m_\chi, \sin \theta, \tan \beta$  w/constraints:

$$\left\{ \begin{array}{l} \cos(\beta - \alpha) = 0, \tan \beta = (1, 50) \\ m_H = m_{H^\pm} = m_A > 580 \text{ GeV}, \\ m_a > 100 \text{ GeV}, \\ \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3 \end{array} \right.$$

## Analysis strategy:

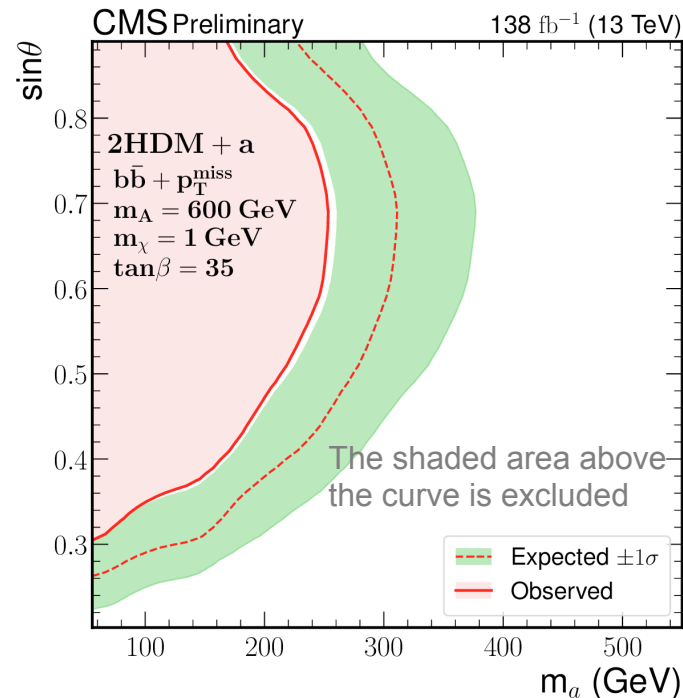
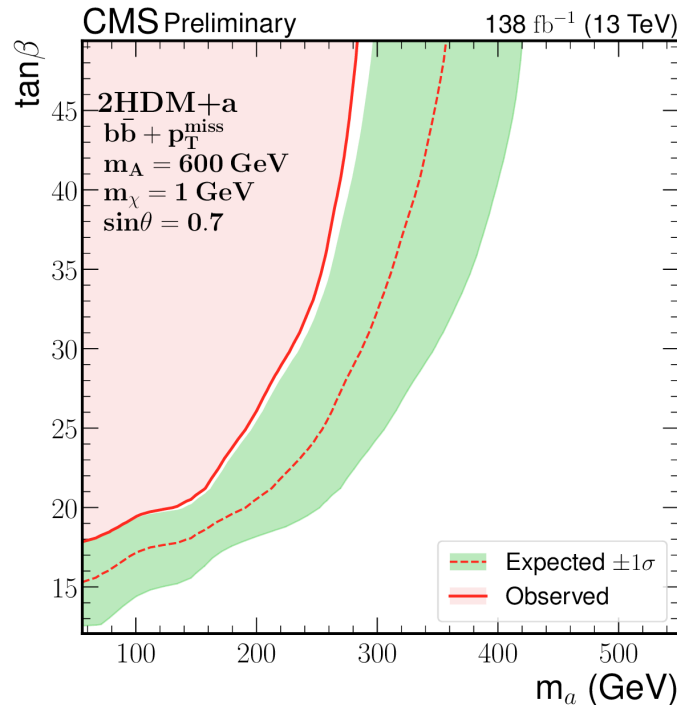
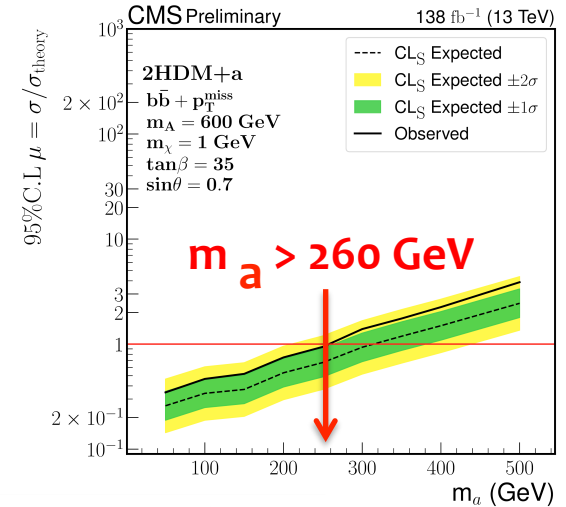
- Two independent categories with different multiplicities of **b jets** (one shown here)
- Veto on leptons ( $e/\mu$ )
- Data and bkg predictions agrees well





# DM in $b\bar{b} b\bar{b} + p_T^{\text{miss}}$

- Limits are set on the **DM production cross section** in the context of **2HDM+a** model
- Search is complementary to most mono-X DM searches

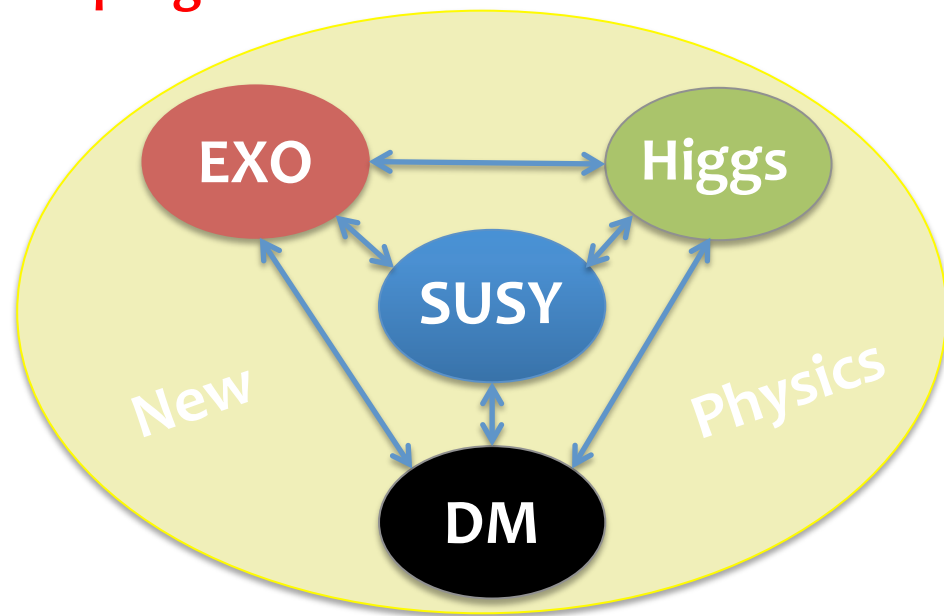




# SUSY searches with CMS – Summary

- CMS experiment builds up a rich program of **SUSY** searches:
  - First searches looked for the **strong/color** SUSY production
  - **With no discovery**, the **SUSY search program evolves** to:

- Large variety of **signatures**:
  - **EWK-inos** and **sleptons**
  - **Compressed spectra** models
  - **RPV** and **Stealth SUSY**
  - **Dark Sector** manifestation
  - **Heavy higgs** boson
  - **Long-lived** particles
  - and more ...



- **Precise predictions of the Standard Model background** underlines the searches
- Experimental techniques evolves to more **sensitive to low masses objects** and more **sophisticated approaches** using **ML tools**
- **More improvements** and analyses with **full Run-2 and Run-3 data** expected
- <https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS>



# Thank you!

## Details in other CMS talks at SUSY'2024

### SUSY:

- *General Searches for Compressed SUSY*, **Andres Abreu**
- *Stealth and RPV SUSY searches with CMS*, **Anton Stepennov**
- *Recent searches for electroweak production of SUSY particles and 3rd generation SUSY particles with CMS*, **Pablo Martinez Ruiz Del Arbol**

### EXO:

- *Exotics at CMS (Dark sectors, ALPs, LLPs, ...)* Speaker: *Eirini Tziaferi*
- *Searches in CMS for long-lived particles and other non-conventional signatures*, **Petar Maksimovic**

### DM:

- *Searches for dark matter with CMS*, **Antimo Cagnotta**

### Higgs:

- *Measurements on SM Higgs at ATLAS and CMS*, **Javier Cuevas**
- *Searches for non-SM Higgs at CMS*, **Alexis Kalogeropoulos**
- *Searches for rare decays of the Higgs boson into light pseudoscalars at CMS*, **Maria Cepeda**
- *Searches for Higgs boson pair production at CMS*, **Elvira Martin Viscasillas**

**Granted by the Polish Ministry of Science, 2022/WK/14**



# Backup slides



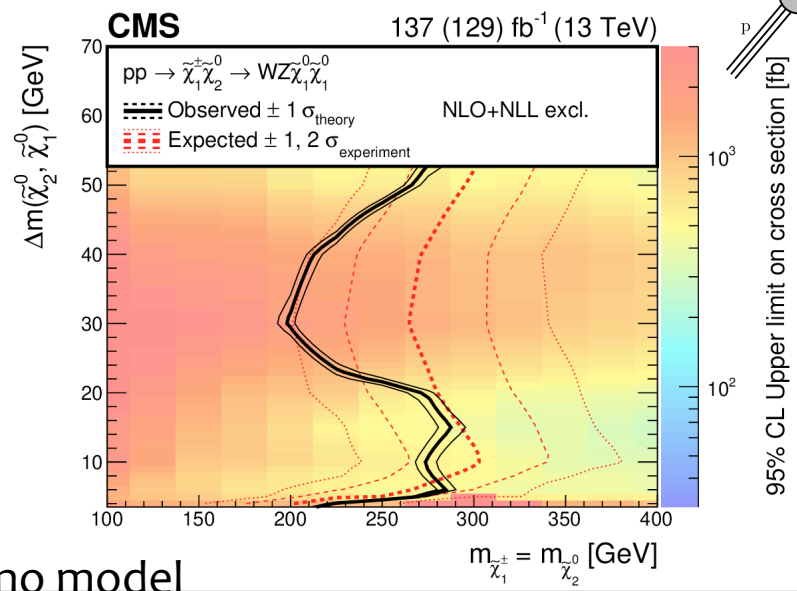
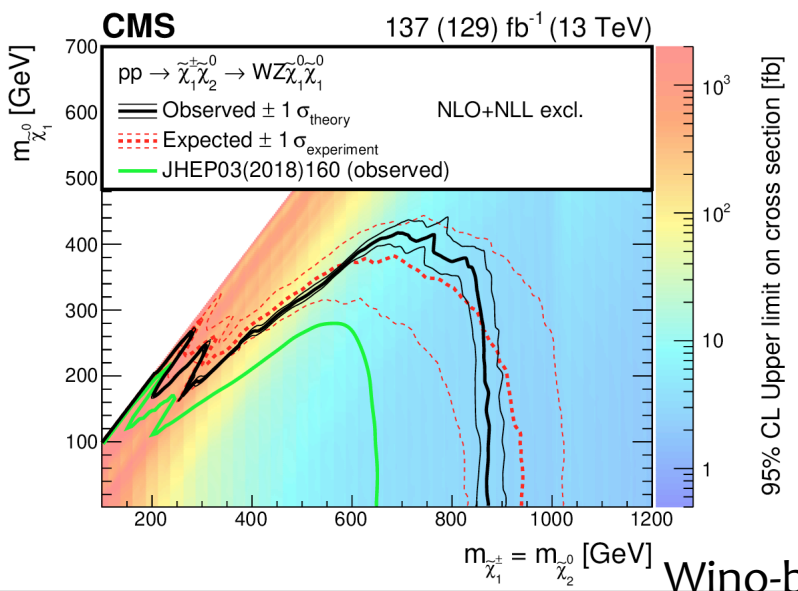
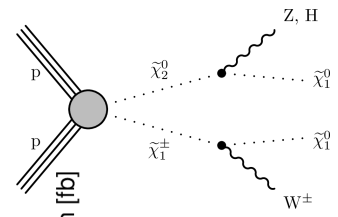
# Bibliography

## SUSY searches at CMS:

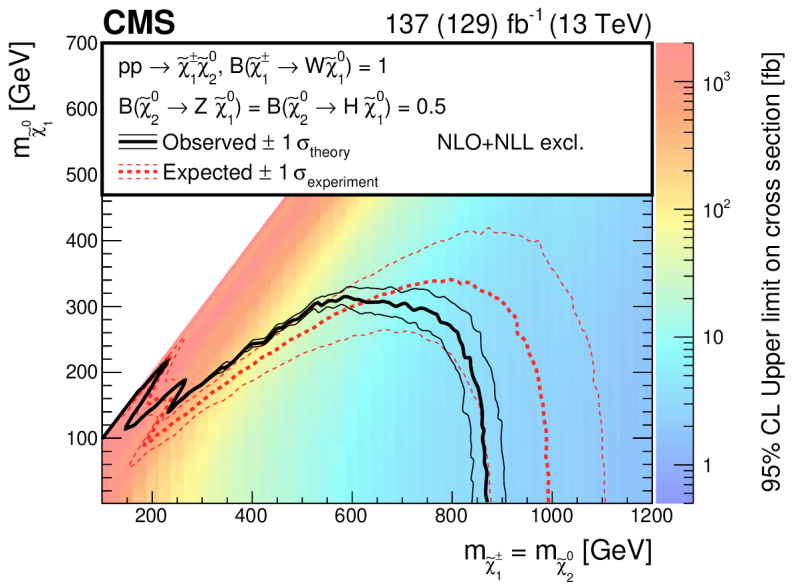
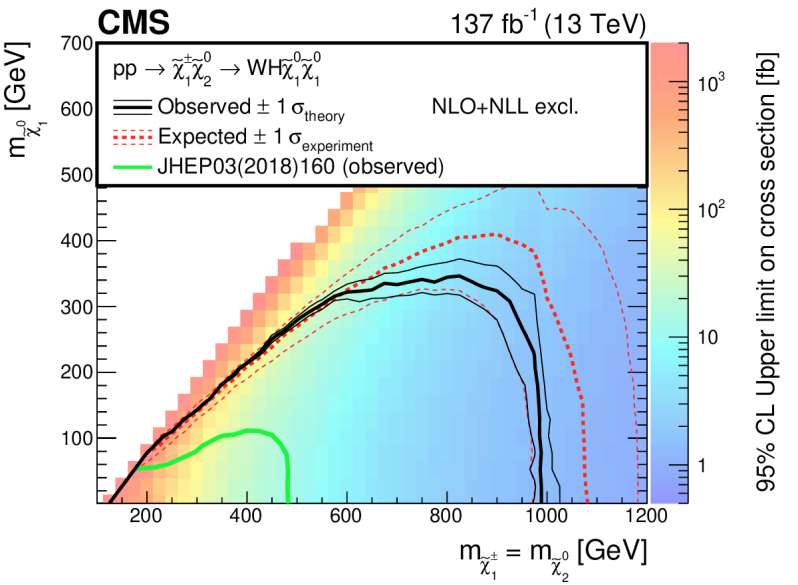
- [CMS-PAS-SUS-23-001](#) Search for top squarks in final states with many light flavor jets and 0, 1, or 2 leptons in proton-proton collisions at  $\sqrt{s}=13$  TeV; 6 June 2024 \*New release
- [CMS-PAS-SUS-23-008](#) Search for dark matter produced in association with a pair of bottom quarks in proton-proton collisions at  $\sqrt{s}=13$  TeV; 2 April 2024
- [CMS-PAS-SUS-23-015](#) Search for hadronic R-parity violating decays of electroweak superpartners using jet scaling patterns in multilepton events at  $\sqrt{s}=13$  TeV; 29 March 2024
- [CMS-PAS-SUS-21-006](#) Search for supersymmetry in final states with disappearing tracks in proton-proton collisions at 13 TeV; [PRD 109 \(2024\) 072007](#); 24 May 2023
- [CMS-PAS-SUS-21-008](#) Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at  $\sqrt{s}=13$  TeV; [Accepted by PRD](#)
- [CMS-SUS-19-004](#) Search for top squarks in final states with two top quarks and several light-flavor jets in proton-proton collisions at  $\sqrt{s}=13$  TeV [PRD 104 \(2021\) 032006](#)



# EWK SUSY EWK-inos

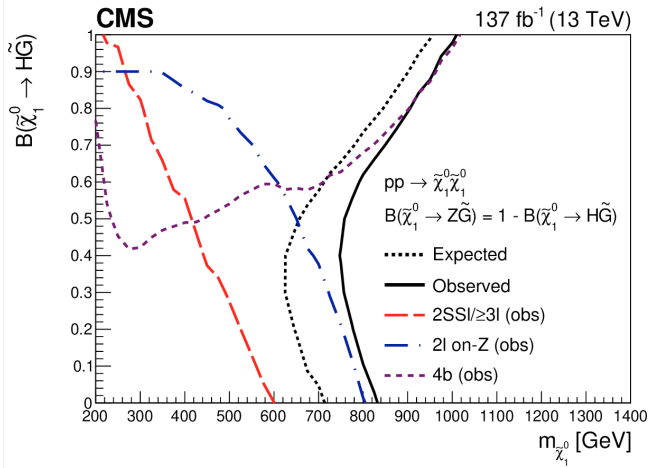
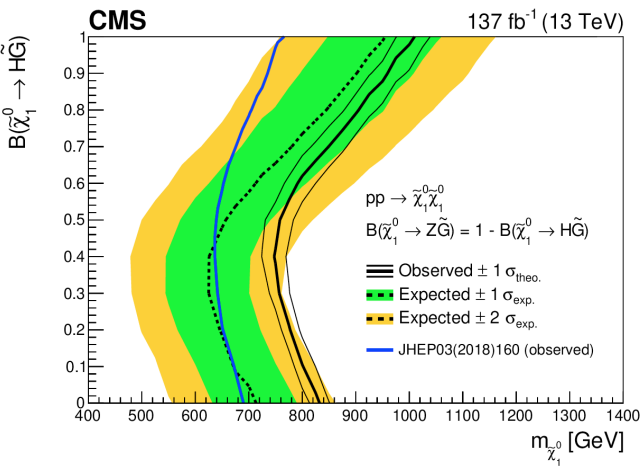
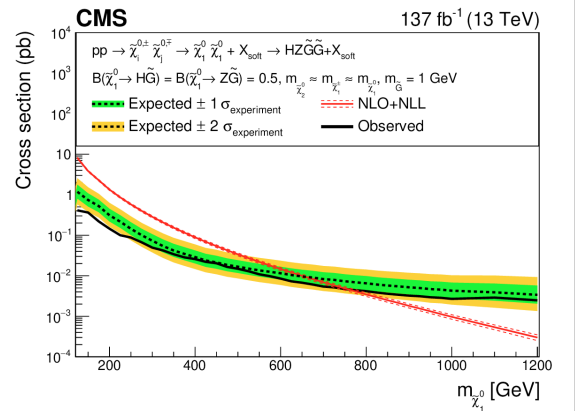
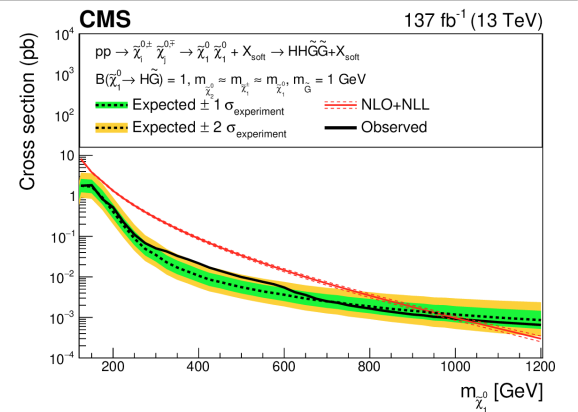
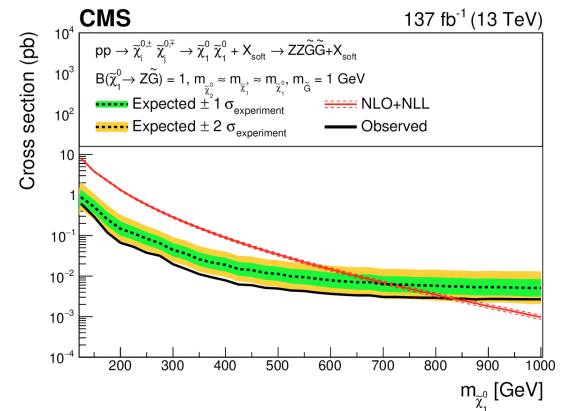
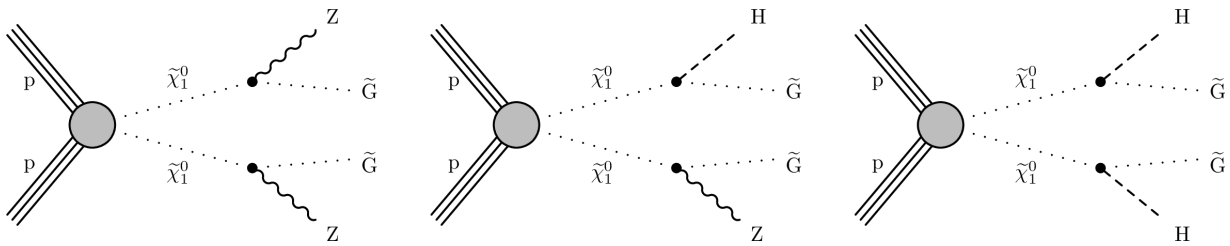


Wino-bino model





# EWK SUSY GMSB







# Solving $g-2$ puzzle with 4 taus

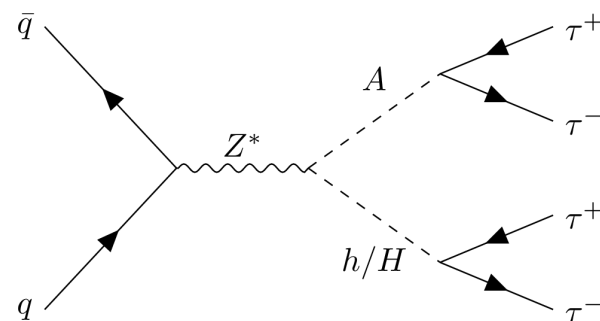
## Motivation:

- **2HDM Type X** ("lepton-specific") could explain the **tension** between the experimental and theoretical values of the **muon anomalous magnetic moment,  $g-2$**

Additional Higgs bosons have enhanced couplings to leptons and suppressed couplings to quarks. The enhanced couplings to muons allow for the additional Higgs bosons to contribute significantly to the muon's magnetic moment, explaining the observed deviation.

## Signature: $4\tau$ 's

- Production of two additional Higgs bosons from an **off-shell Z boson**, where both decay to  **$\tau$  lepton pairs**



## Analysis strategy:

- Very challenging reconstruction of 4 taus in the event:
- Tau main decays to:
  - **electron** + neutrinos (BR =  $\frac{1}{6}$ ), a **muon** + neutrinos (BR =  $\frac{1}{6}$ ), or a **hadronic** combination of charged hadrons, neutral hadrons, and a neutrino (the remaining fraction)
  - Final states with **2 hadronic taus make up ~87% of the decays**
  - **7 decay channels** in total

## Use of:

- Total transverse mass,  $m_T^{\text{tot}}$ , which is higher for signals than for SM Higgs bosons can not be may not be correctly reconstructed due to presence of neutrinos

Channel	e	$\mu$	$\tau_h$
$\tau_h\tau_h\tau_h\tau_h$	0	0	$\geq 4$
$\tau_h\tau_h\tau_h$	0	0	3
$\mu\tau_h\tau_h\tau_h$	0	1	$\geq 3$
$e\tau_h\tau_h\tau_h$	1	0	$\geq 3$
$e\mu\tau_h\tau_h$	1	1	$\geq 2$
$\mu\mu\tau_h\tau_h$	0	2	$\geq 2$
$ee\tau_h\tau_h$	2	0	$\geq 2$

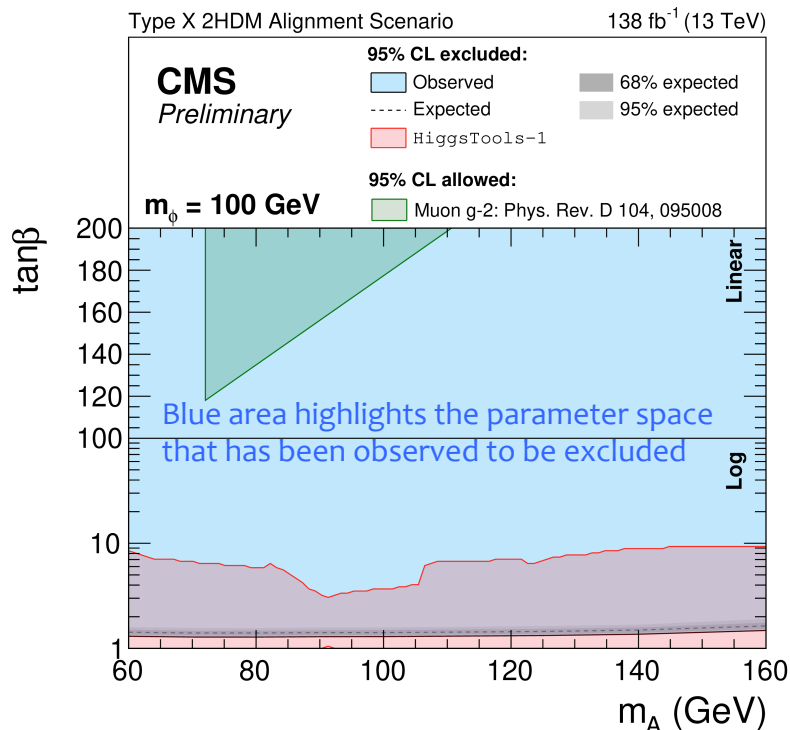
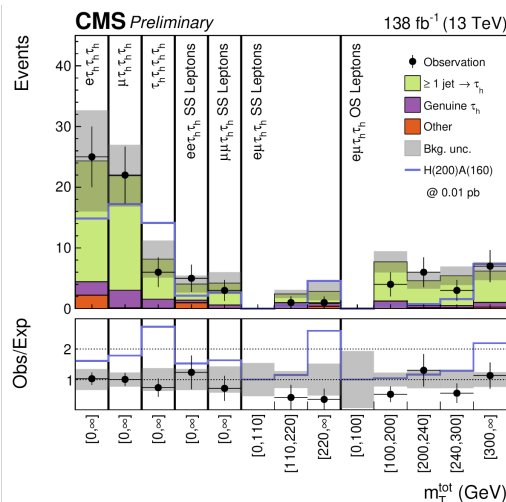
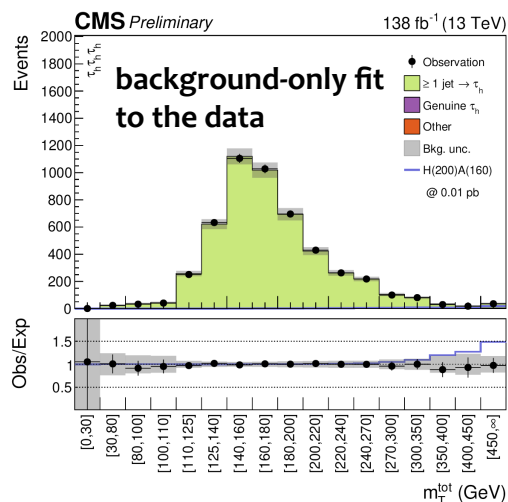


# Solving $g-2$ puzzle with 4 taus

## Background modelling:

- Events where 1 or more hadronic taus are faked by a jet
  - Modelled from data by an **advanced ML fake factor method**

## Results: good agreement of data and predictions



## Conclusions:

- There is no sign of events that could be a signature of the Type-X 2HDM
- Therefore, this **analysis excludes the Type-X 2HDM model** as a possible explanation for  $g-2$  puzzle