# Searches for Electroweak production of SUSY at CMS

EPS-HEP 2019, Ghent, 10-17 July

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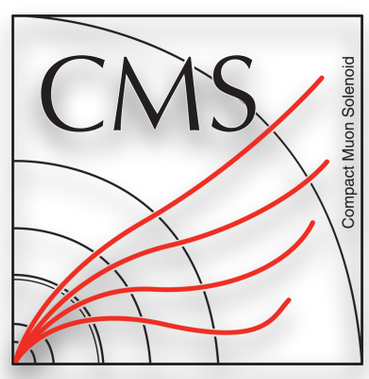
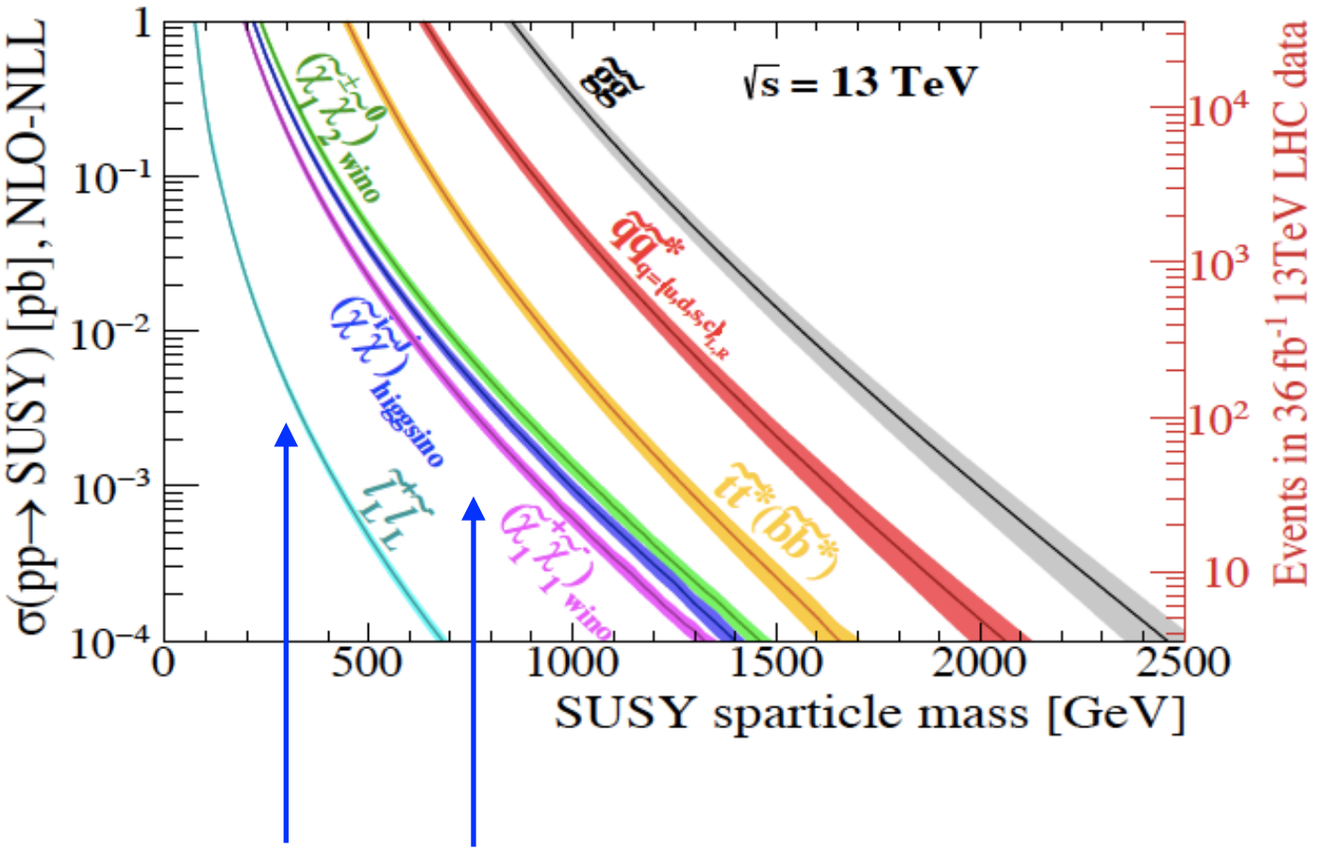
*on behalf of the CMS Collaboration*

# Motivation

Strong limits from LHC on strong SUSY production, electroweak production less constrained. ***If colored sparticles are at higher masses, electroweak sector could be key to finding SUSY at the LHC***

Higgsinos key to stabilizing Higgs mass, light Higgsinos important aspect of "natural" SUSY




Smaller cross sections, possible to significantly extend reach with Run-2 dataset

# Electroweak SUSY searches at CMS

## Covered in this talk

EWKino production, decays via SM bosons

Direct slepton pair production

Resonant slepton (RPV)

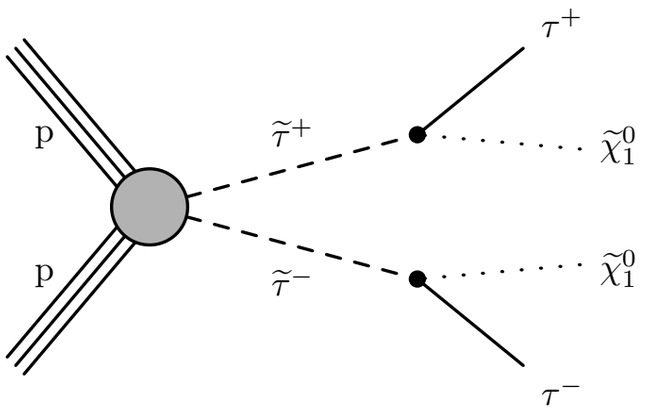
| Analysis | Final state | Models | Dataset | Analysis identifier |
|---|---|---|---|---|
| **Direct stau** | $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$ | Direct stau | 77fb$^{-1}$ | CMS-PAS-SUS-18-006 |
| **RPV smuon** | $\mu^{\pm}\mu^{\pm}$ | Resonant smuon | 36fb$^{-1}$ | CMS-SUS-17-008 |
| **Photon combination** | ■ $\gamma\gamma$<br>■ $\gamma$ + e/$\mu$<br>■ $\gamma$ + $S_T^{\gamma}$<br>■ $\gamma$ + $H_T^{\gamma}$ | Chargino-neutralino | 36fb$^{-1}$ | CMS-SUS-18-005 |
| **H→$\gamma\gamma$** | H($\gamma\gamma$) | Chargino-neutralino | 77fb$^{-1}$ | CMS-PAS-SUS-18-007 |

***Disclaimer**:* just a selection of recent results. Many searches currently being updated with full Run-2 dataset

Final states with leptons (e, μ, τ) or photons

# Direct stau pair production

## CMS-PAS-SUS-18-006 *CMS-PAS-SUS-18-006*



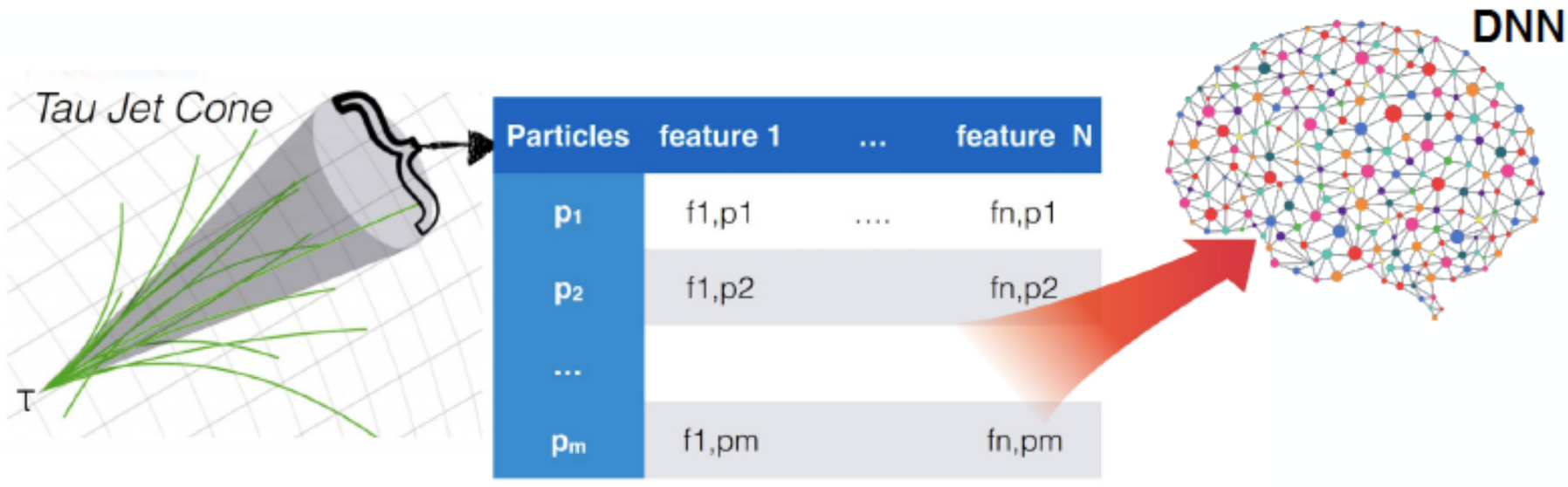

*Light stau coannihilation with bino LSP (small Δm) could account for observed DM relic density*

***Selection***: $\tau^+\tau^-$ ($\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$ final states)

***Search strategy***: $M_{T2}$, $\Sigma M_T$, N(jet) binning for $\tau_h\tau_h$, BDT shape analysis for $e\tau_h$, $\mu\tau_h$

**New DNN approach** for $\tau_h$ isolation used in $\tau_h\tau_h$ channel to reject fakes

- Convolutional neural network with features of particles in tau isolation cone as inputs
- Average CNN score with standard CMS isolation BDT score (high-level inputs)

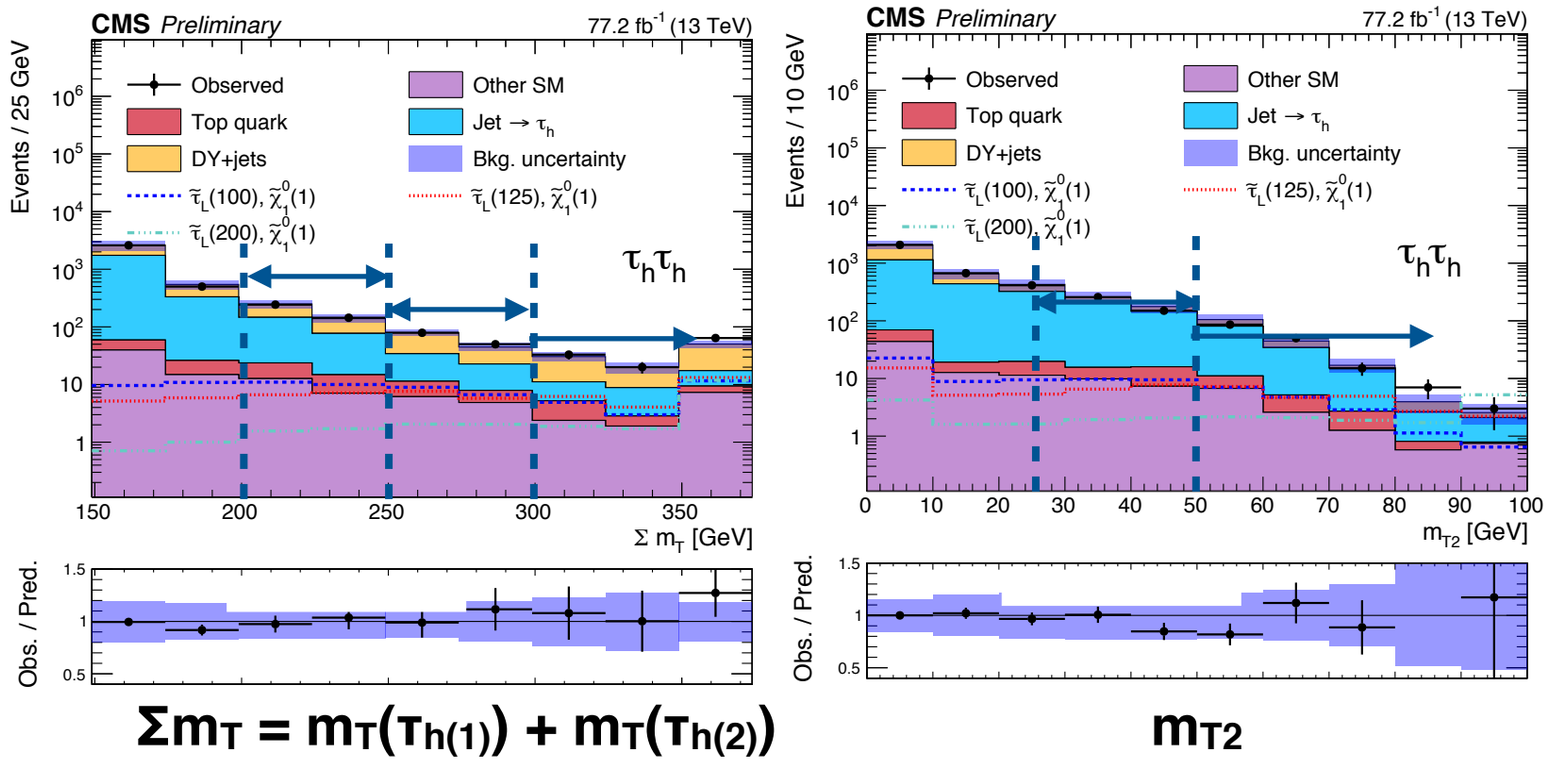



*~2x reduction in fake rate over BDT-based isolation for same efficiency*

# Direct stau pair production

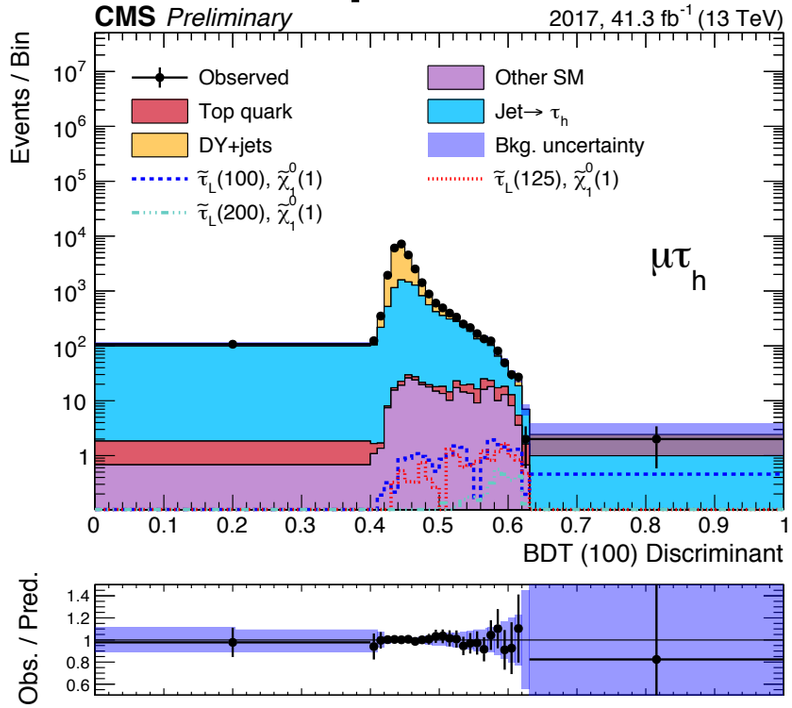
## CMS-PAS-SUS-18-006 *CMS-PAS-SUS-18-006*

**$\tau_h\tau_h$**




$\Sigma m_T = m_T(\tau_{h(1)}) + m_T(\tau_{h(2)})$ $m_{T2}$

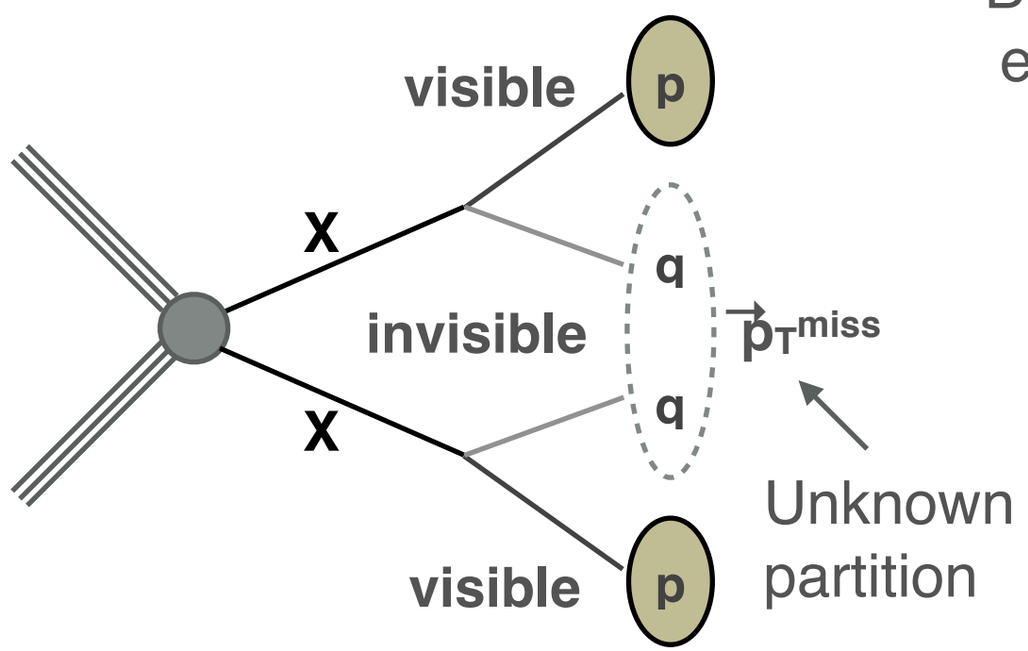
**$\mu\tau_h$**




BDT inputs for $e\tau_h/\mu\tau_h$ include e/μ, $\tau_h$ kinematics, $p_T^{miss}$, $m_{T2}$

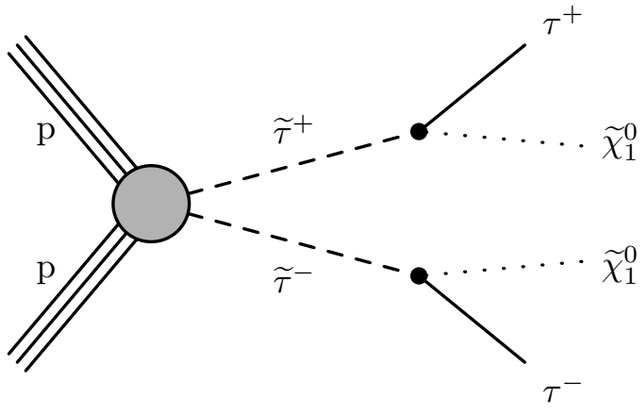
***Main backgrounds***: DY→ττ+jets, fakes from quark/gluon jets. Fake background contribution estimated by extrapolating from lower to higher isolation

**$m_{T2}$**: Kinematic endpoint given by m(X) (pair produced, visible (p) + invisible (q) decay products) → minimize $m_T$(p, q) solutions over possible $p_T^{miss}$ partitions.



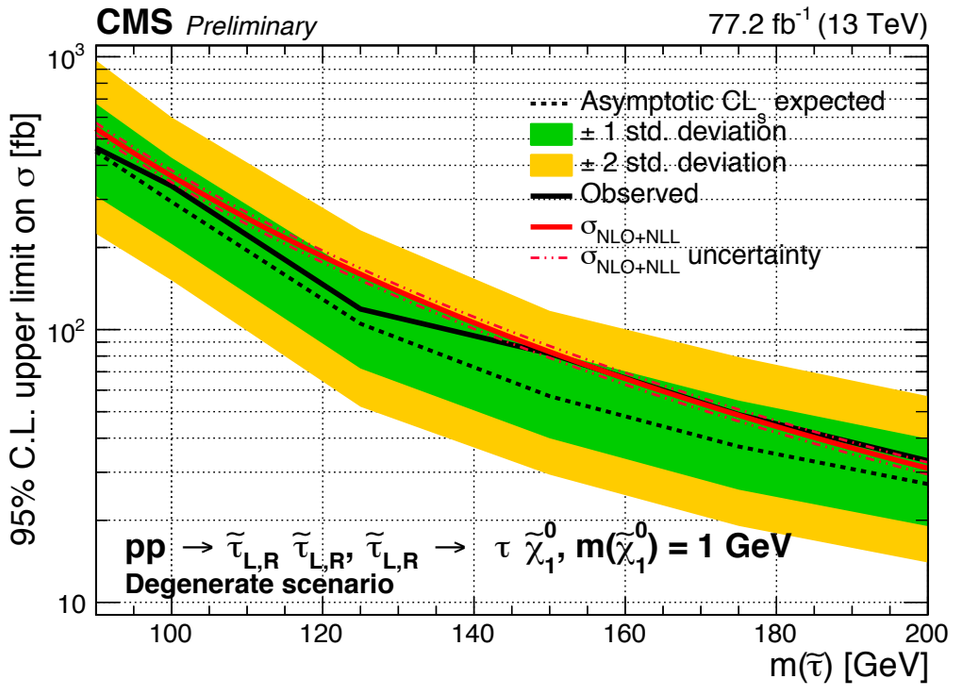
# Direct stau pair production

## CMS-PAS-SUS-18-006 *CMS-PAS-SUS-18-006*



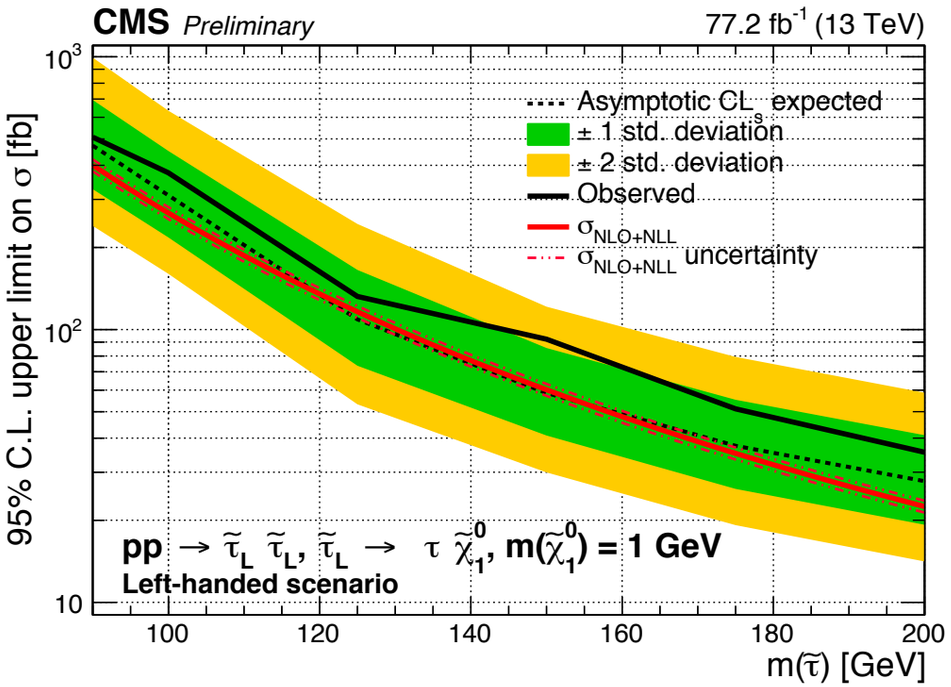

$\tilde{l}_L/\tilde{l}_R$: superpartners of left-/right-handed leptons. ~3x smaller cross section for $\tilde{l}_R\tilde{l}_R$ vs $\tilde{l}_L\tilde{l}_L$ of same mass

### $\tilde{\tau}_L\tilde{\tau}_L + \tilde{\tau}_R\tilde{\tau}_R$ production




Exclusion up to m($\tilde{\tau}$) = 150 GeV for ~massless $\tilde{\chi}_1^0$

### $\tilde{\tau}_L\tilde{\tau}_L$ production



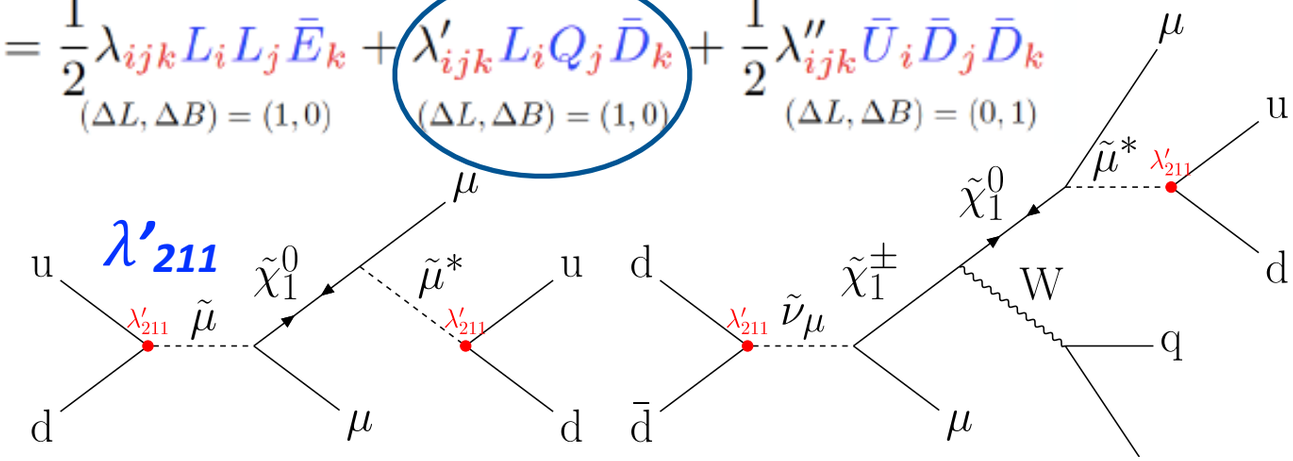

Strongest limit at m($\tilde{\tau}$) = 125 GeV for ~massless $\tilde{\chi}_1^0$

*Pushing past LEP stau limits for the first time at the LHC!*

# RPV smuon

## CMS-SUS-17-008 *Eur. Phys. J. C 79 (2019) 305*

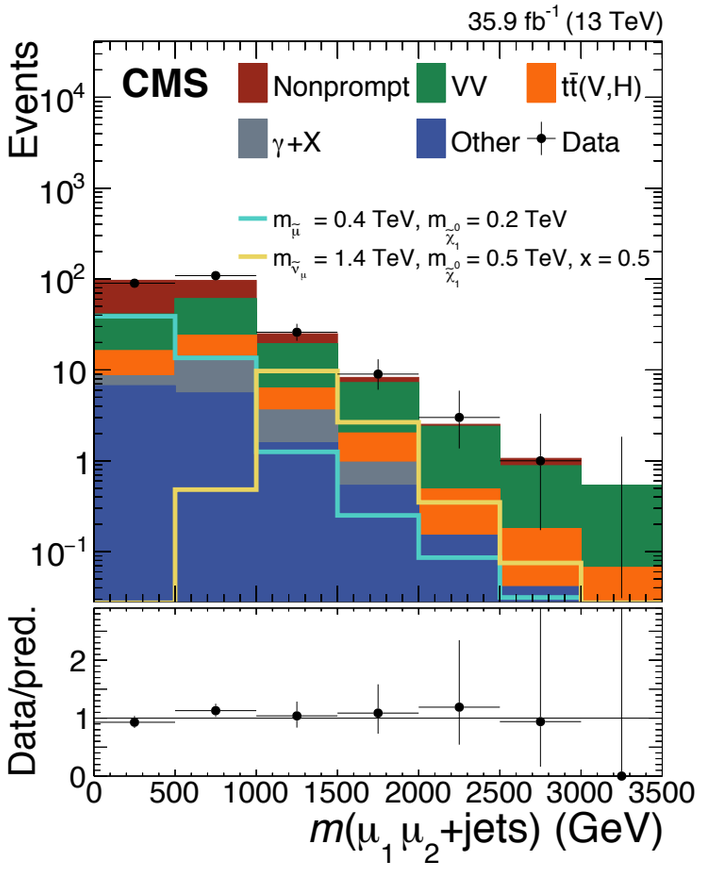
$$W_{\mathrm{RPV}} = \underbrace{\frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k}_{(\Delta L, \Delta B) = (1,0)} + \underbrace{\lambda'_{ijk} L_i Q_j \bar{D}_k}_{(\Delta L, \Delta B) = (1,0)} + \underbrace{\frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{(\Delta L, \Delta B) = (0,1)}$$



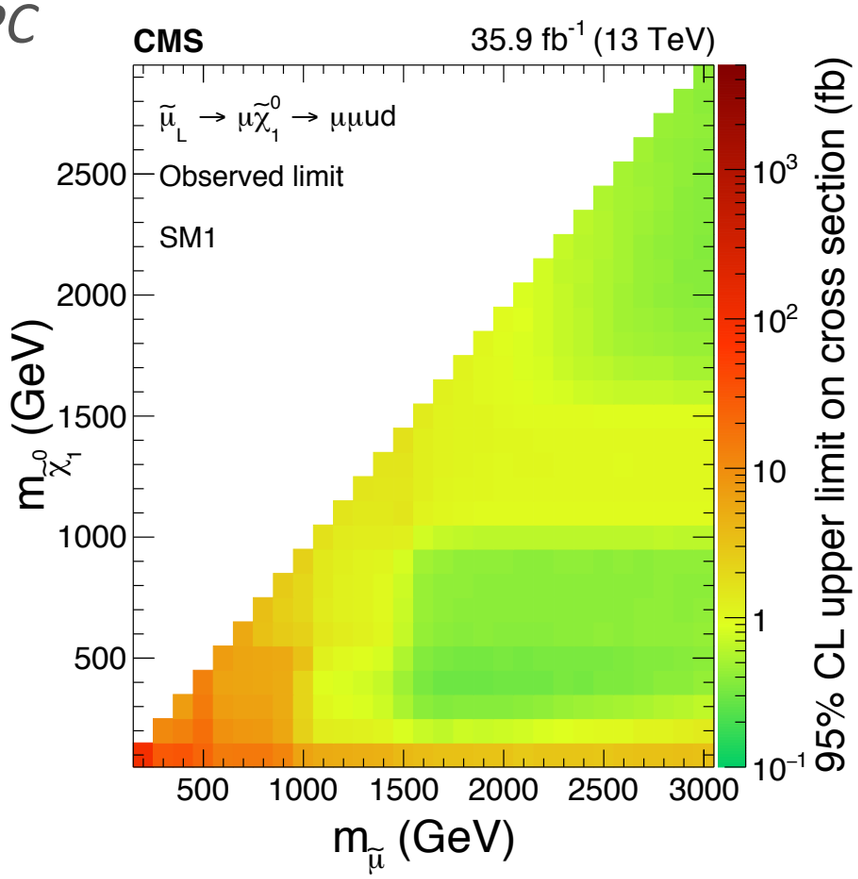

**Selection**: μ±μ± + ≥2 jets, 0b

**Search strategy**: $M_{slepton}$ [$M(\mu_1,\mu_2,jets)$], $M_\chi$ [$M(\mu_2,j_1,j_2)$] binning

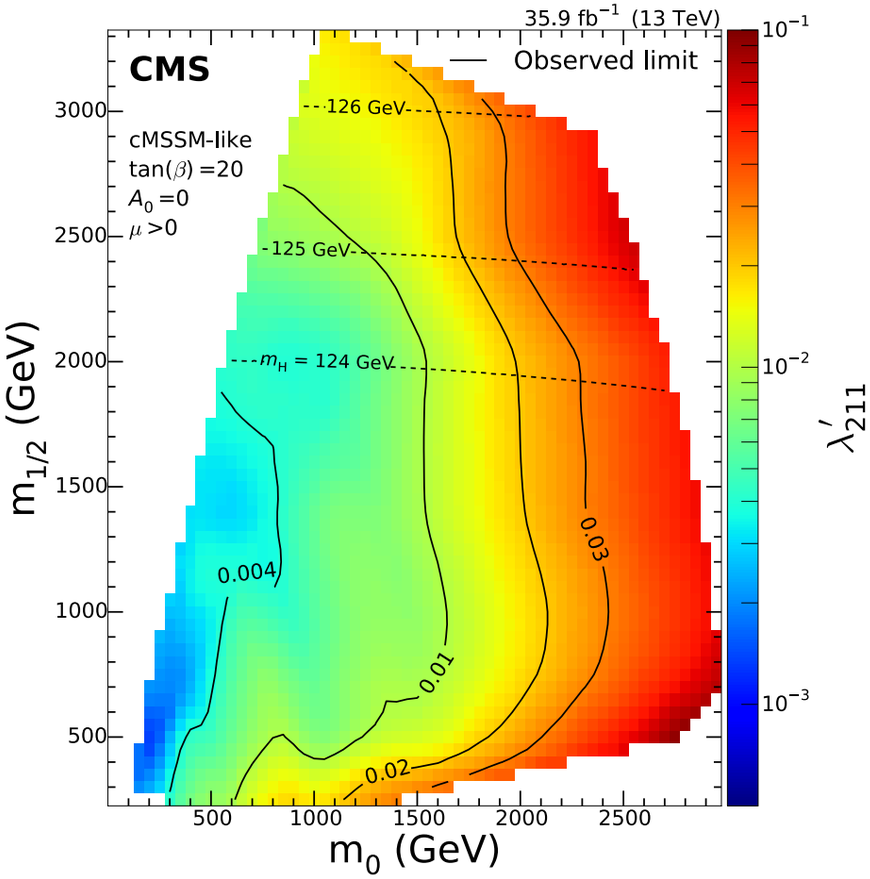
*RPV SUSY parameter space much less constrained than RPC*




**Resonant μ̃ simplified model**



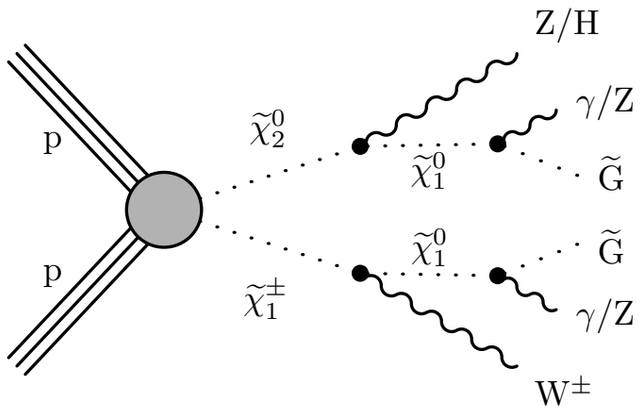

**Modified CMSSM**



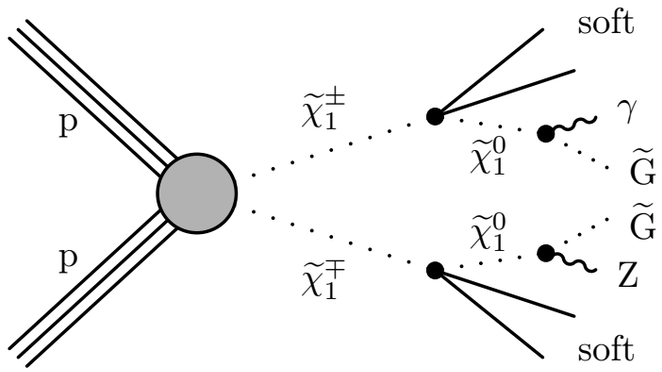

$\lambda'_{211}$ coupling limits

# SUSY with photons combination

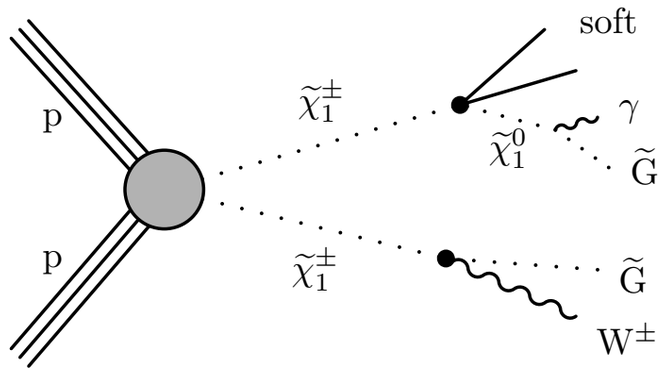
## CMS-SUS-18-005 *Submitted to Phys. Lett. B*




GGM scenario



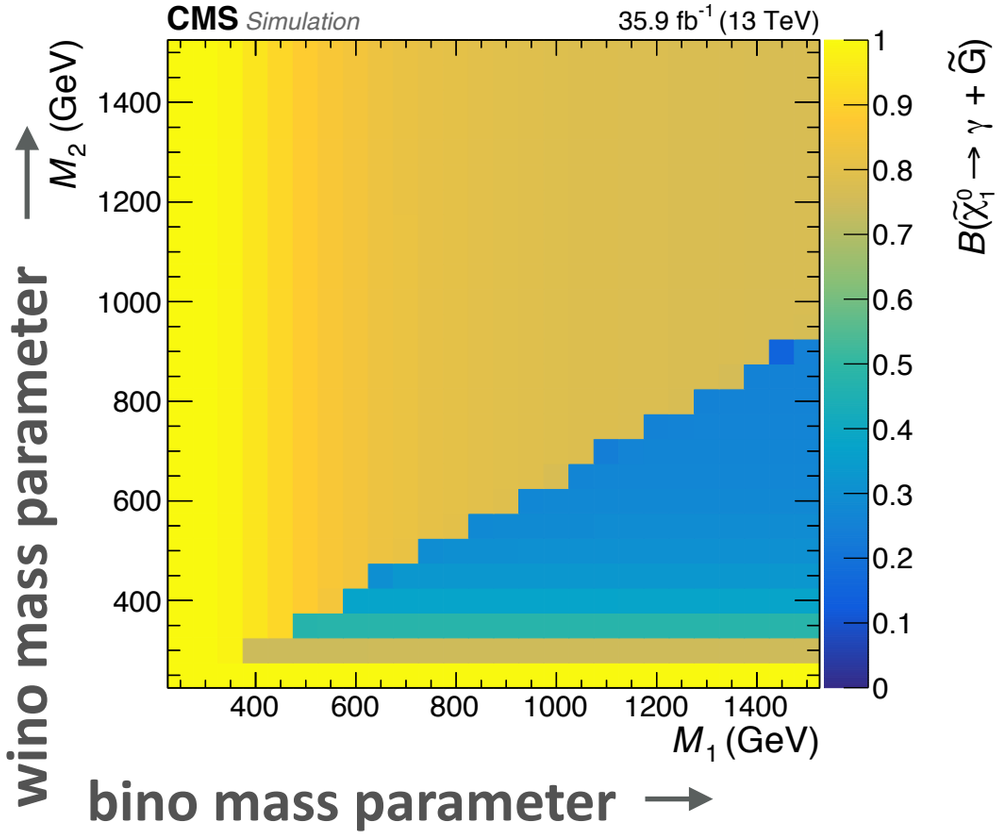

simplified models




Gravitino LSP, $\tilde{\chi}_1^0$ NLSP

**Combination of 4 analyses in final states with photons**, targeting general gauge-mediated (GGM) SUSY breaking scenarios

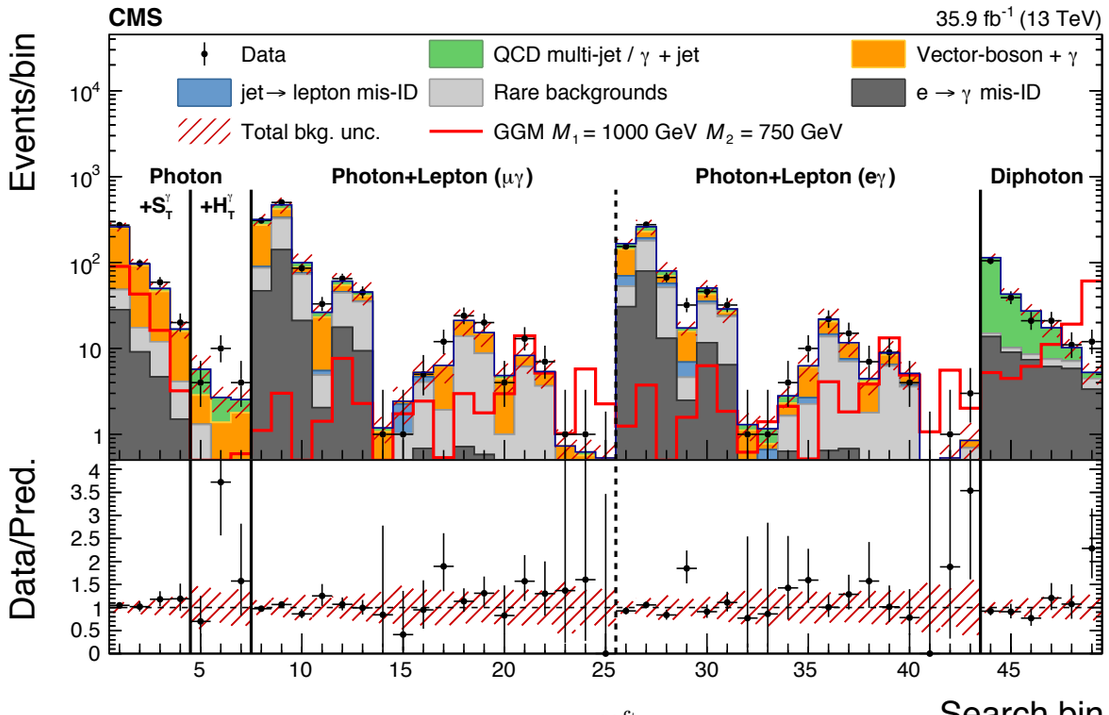
- Diphoton
- Photon + lepton (e/μ)
- Photon + $S_T^{\gamma}$ (scalar sum of $p_T^{miss}$ and photon $p_T$s)
- Photon + $H_T^{\gamma}$ (scalar sum of jet $p_T$s and leading photon $p_T$)

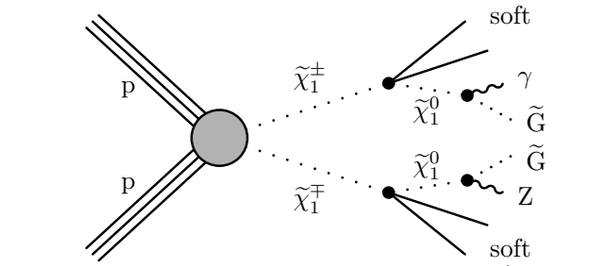


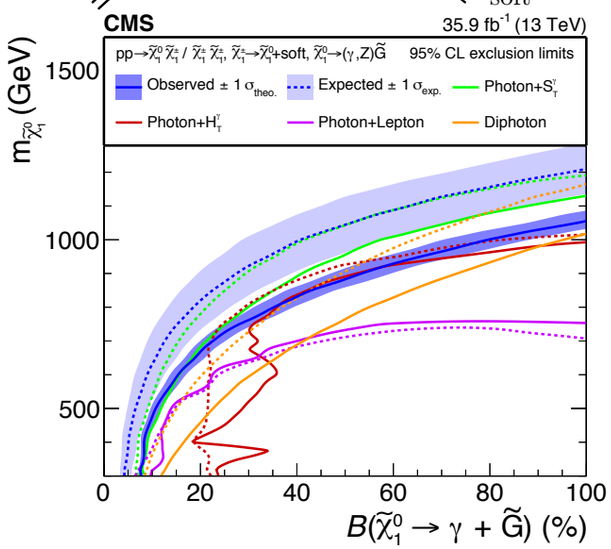

$B(\tilde{\chi}_1^0 \to \gamma\tilde{G})$ vs $B(\tilde{\chi}_1^0 \to Z\tilde{G})$ depends on bino/wino nature of $\tilde{\chi}_1^0$

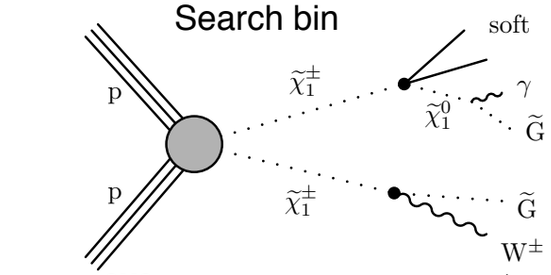
# SUSY with photons combination

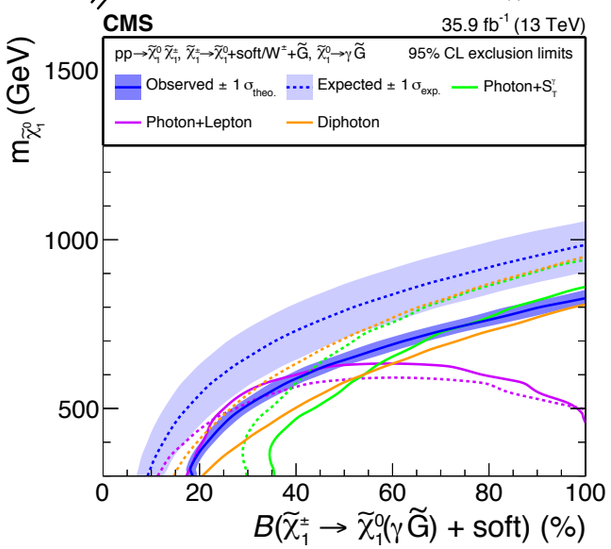
## CMS-SUS-18-005 *Submitted to Phys. Lett. B*



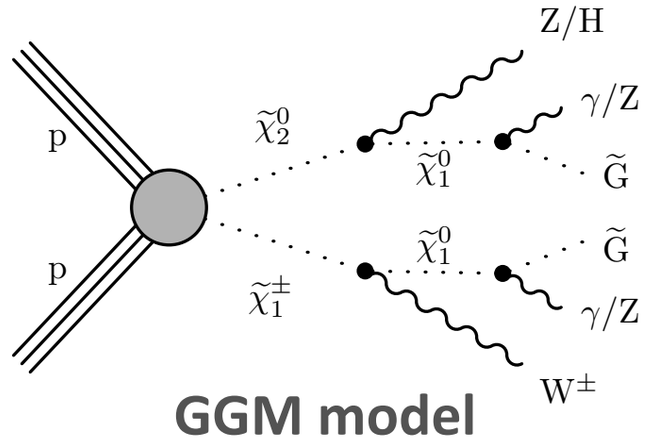



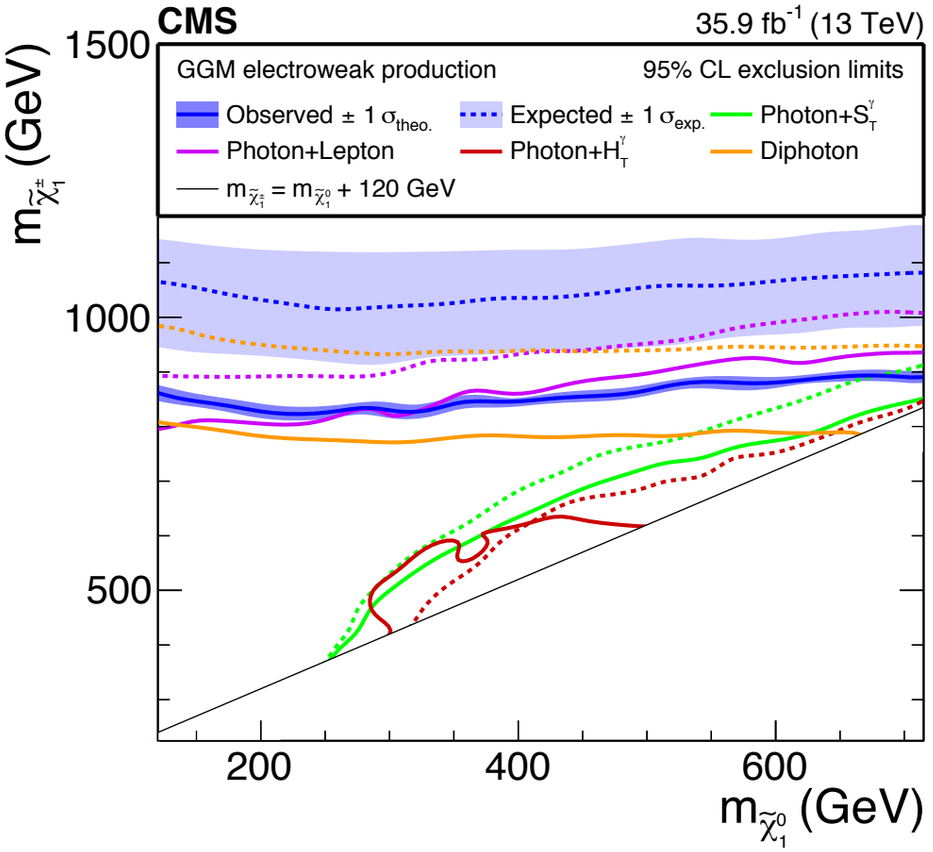




**Simplified models**




**GGM model**

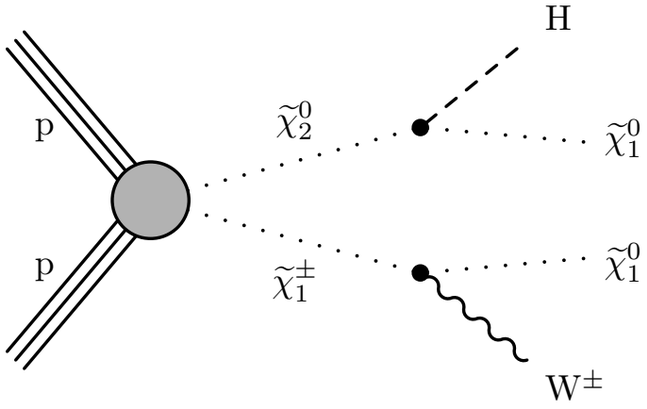


# Chargino/neutralino with H→γγ

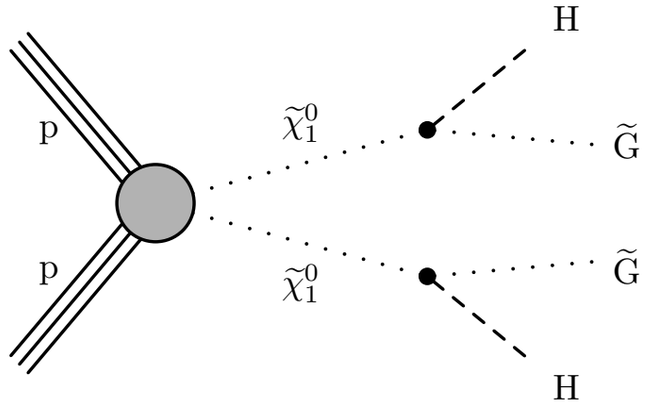
## CMS-PAS-SUS-18-007

*CMS-PAS-SUS-18-007*

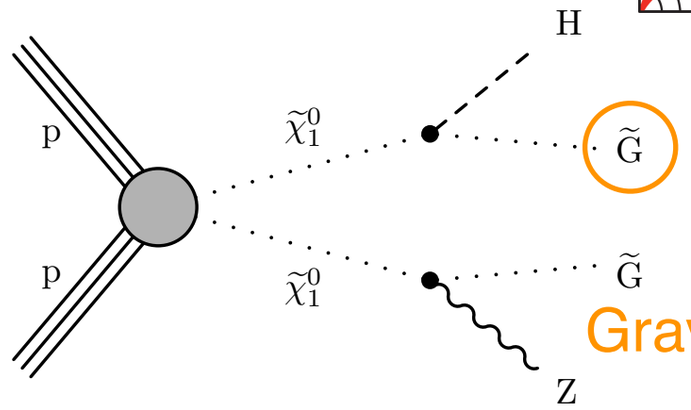
**GMSB models**




H→γγ, W→lν




H→γγ, H→bb

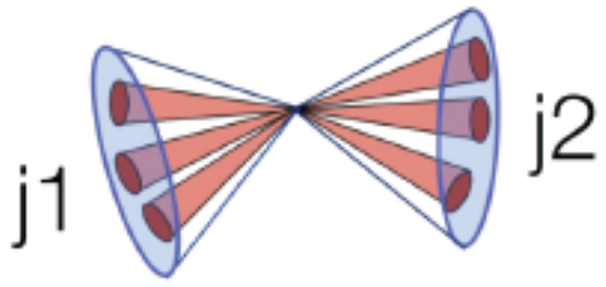



H→γγ, Z→bb/ll

Gravitino LSP

***Selection***: ≥2γ, H→γγ tag, 1 e/μ OR $e^+e^-/\mu^+\mu^-$ pair close to m(Z) OR ≥1 jet

***Search strategy***: Bins in "Razor" variables $M_R$/$R^2$, H→γγ $p_T$. 0-lepton category: H/Z→bb tag, events with no H/Z tag and low γγ $p_T$ categorized by γγ mass resolution




**Razor variables $M_R/R^2$**: Sensitive to pair production of massive particles decaying to weakly interacting stable particles. Cluster H→γγ candidate, leptons, jets into two "megajets" $j_1$, $j_2$

$$M_R = \sqrt{(|\vec{p}^{j1}| + |\vec{p}^{j2}|)^2 - (p_z^{j1} + p_z^{j2})}$$ ← *mass scale*

$$M_T^R = (1/\sqrt{2})\sqrt{p_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}$$

$$R^2 = \left(\frac{M_T^R}{M_R}\right)^2$$ ← *SUSY vs SM discrimination*

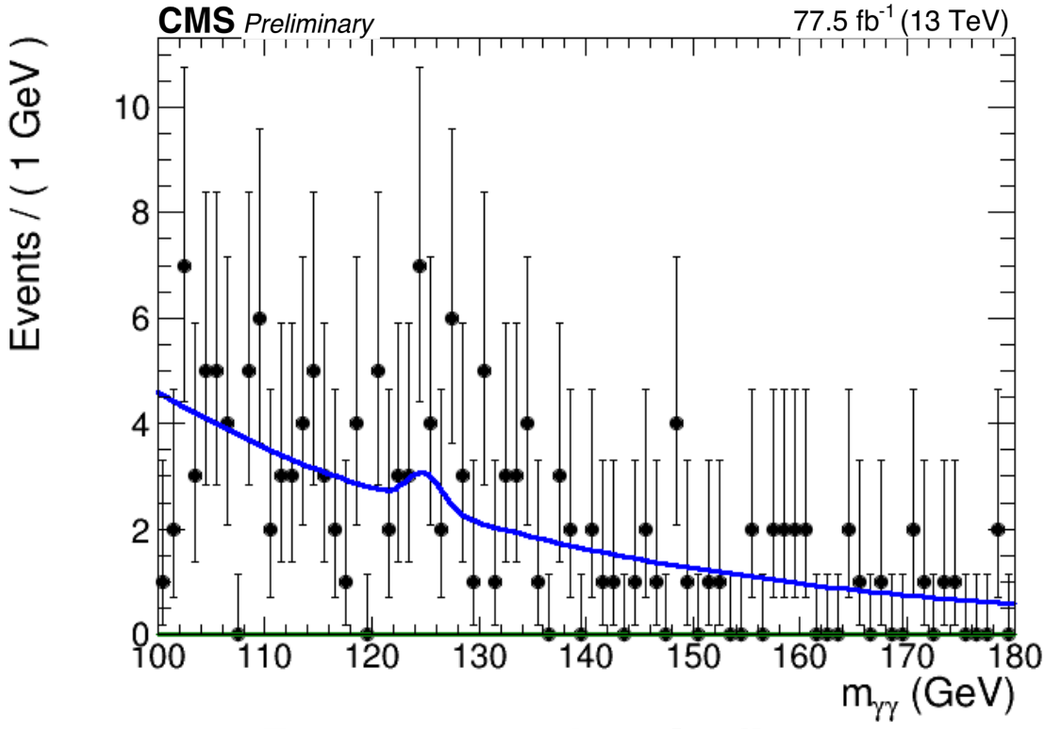
# Chargino/neutralino with H→γγ

## CMS-PAS-SUS-18-007 *CMS-PAS-SUS-18-007*

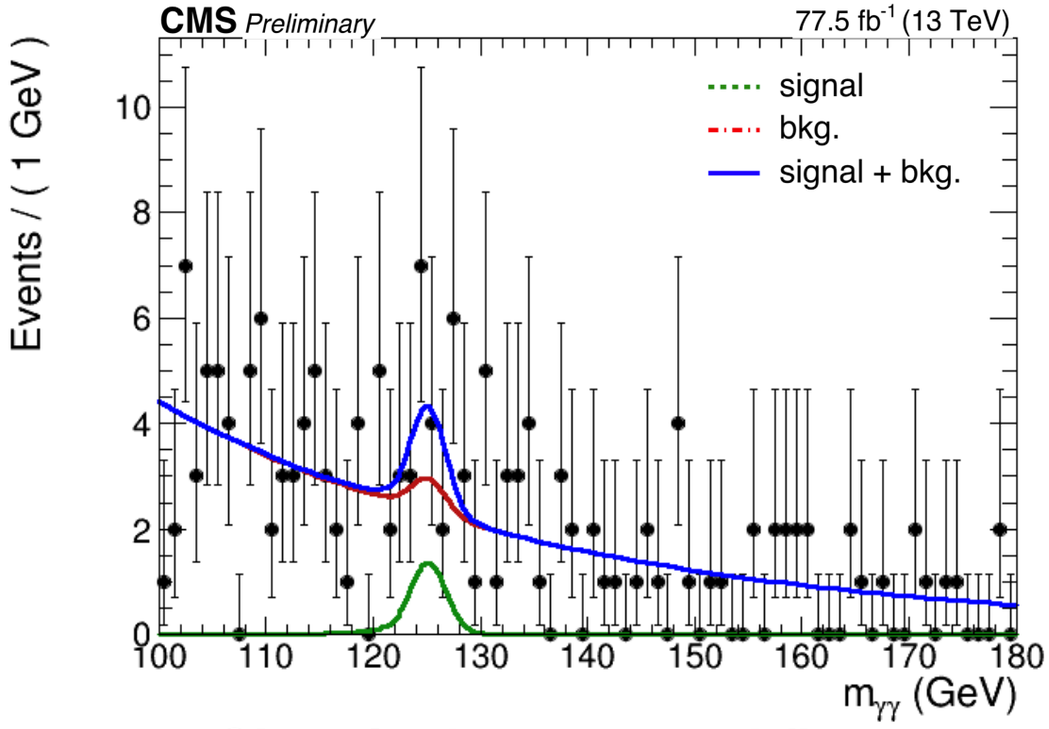
**Signal extraction by fitting m(γγ)** to data in each bin

***Backgrounds***: resonant (H→γγ) modeled with simulation, non-resonant (γγ/γ + jet) modeled with functional form, fit to data

**H→bb tag, high $M_R$, $R^2$**



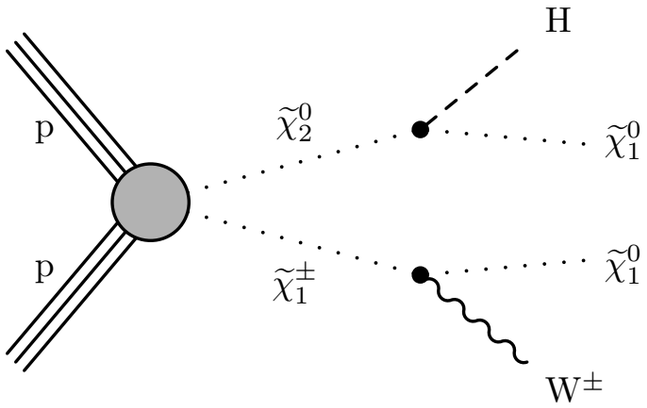

**Background-only fit**



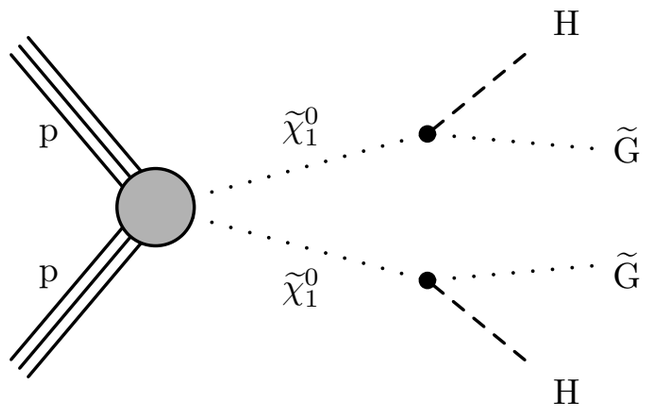

**Signal + background fit**

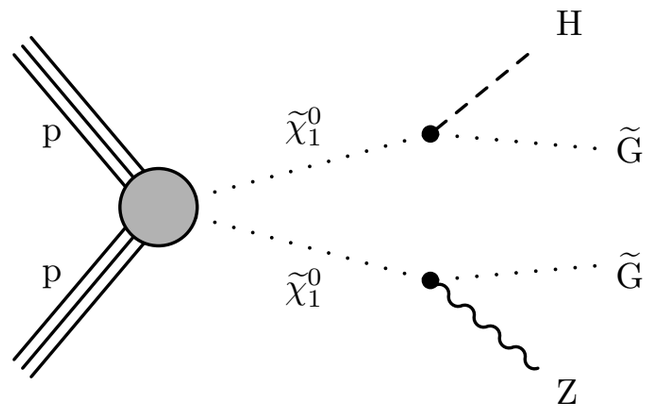
# Chargino/neutralino with H→γγ

## CMS-PAS-SUS-18-007 *CMS-PAS-SUS-18-007*

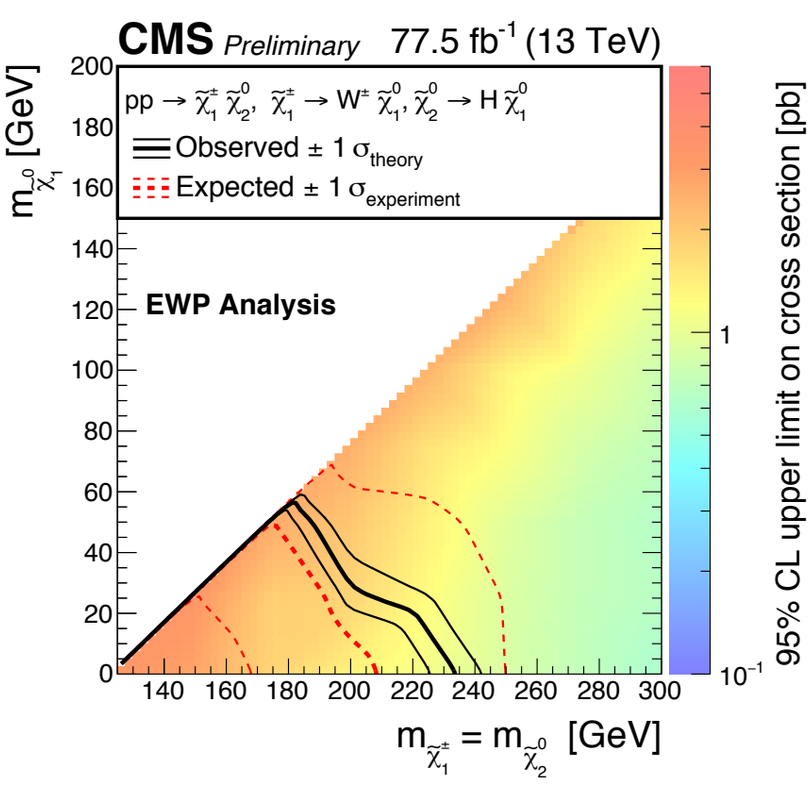


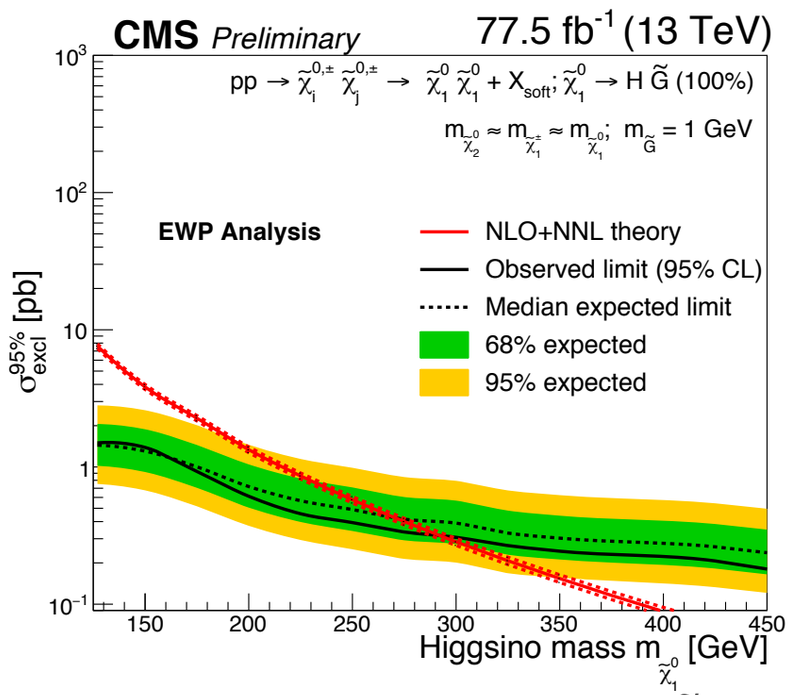

Wino-like



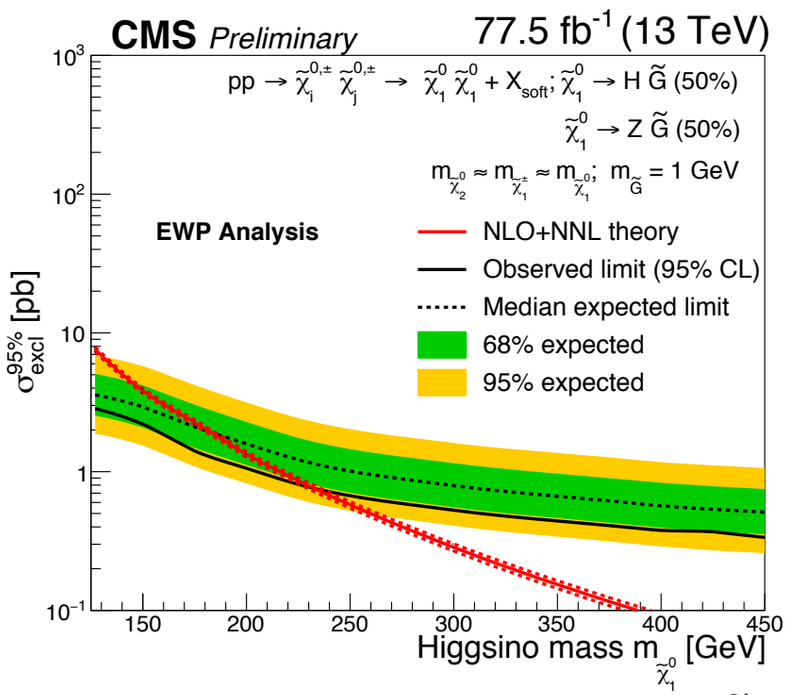




Higgsino-like




100% BR for $\tilde{\chi}_1^0 \to H\tilde{G}$
Exclusion up to $m(\tilde{\chi}_1^0)$=290 GeV for ~massless $\tilde{G}$




50/50% BR for $\tilde{\chi}_1^0 \to H/Z\tilde{G}$
Exclusion up to $m(\tilde{\chi}_1^0)$=230 GeV for ~massless $\tilde{G}$

# Summary

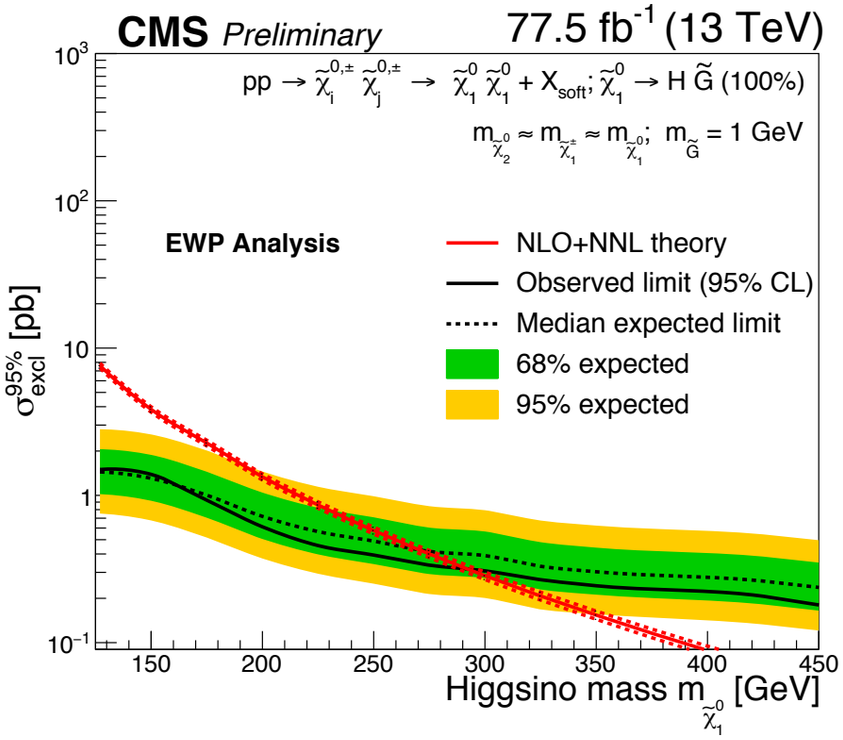
Rapidly improving electroweak SUSY sector reach with Run 2 data, up to 77 $fb^{-1}$ analyzed so far

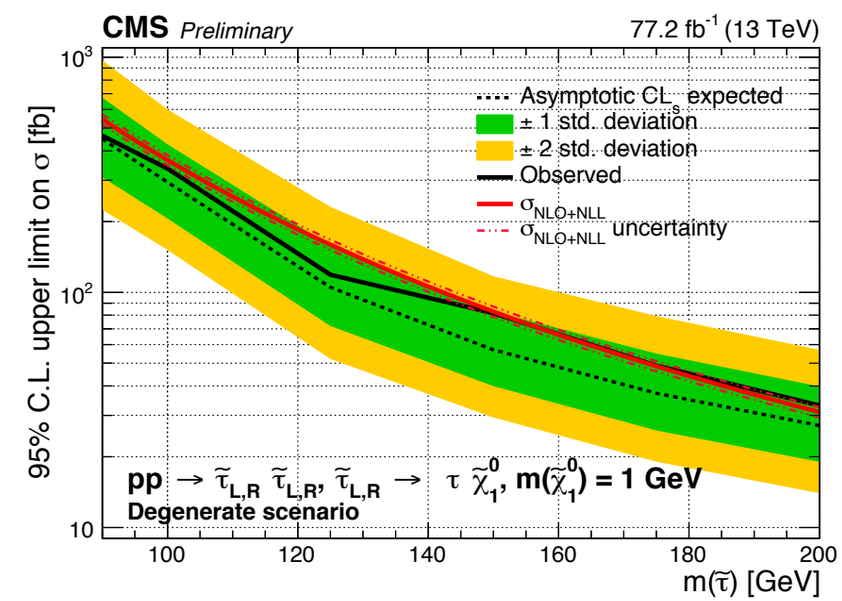
Broad program of searches in leptonic and photon final states covering many scenarios … just a snapshot shown here!

Strong sensitivity to electroweakinos in many scenarios (results in backup)

Pushing into new territory with stau searches, starting to probe challenging Higgsino-like scenarios

Full Run-2 dataset (137 $fb^{-1}$) being analyzed, many more interesting results expected in the next year!

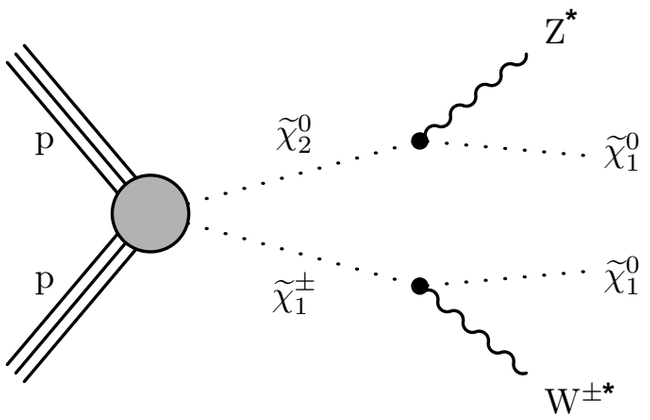


# Additional Material

# 2 soft leptons + ISR

## CMS-SUS-16-048 *Phys. Lett. B 782 (2018)*

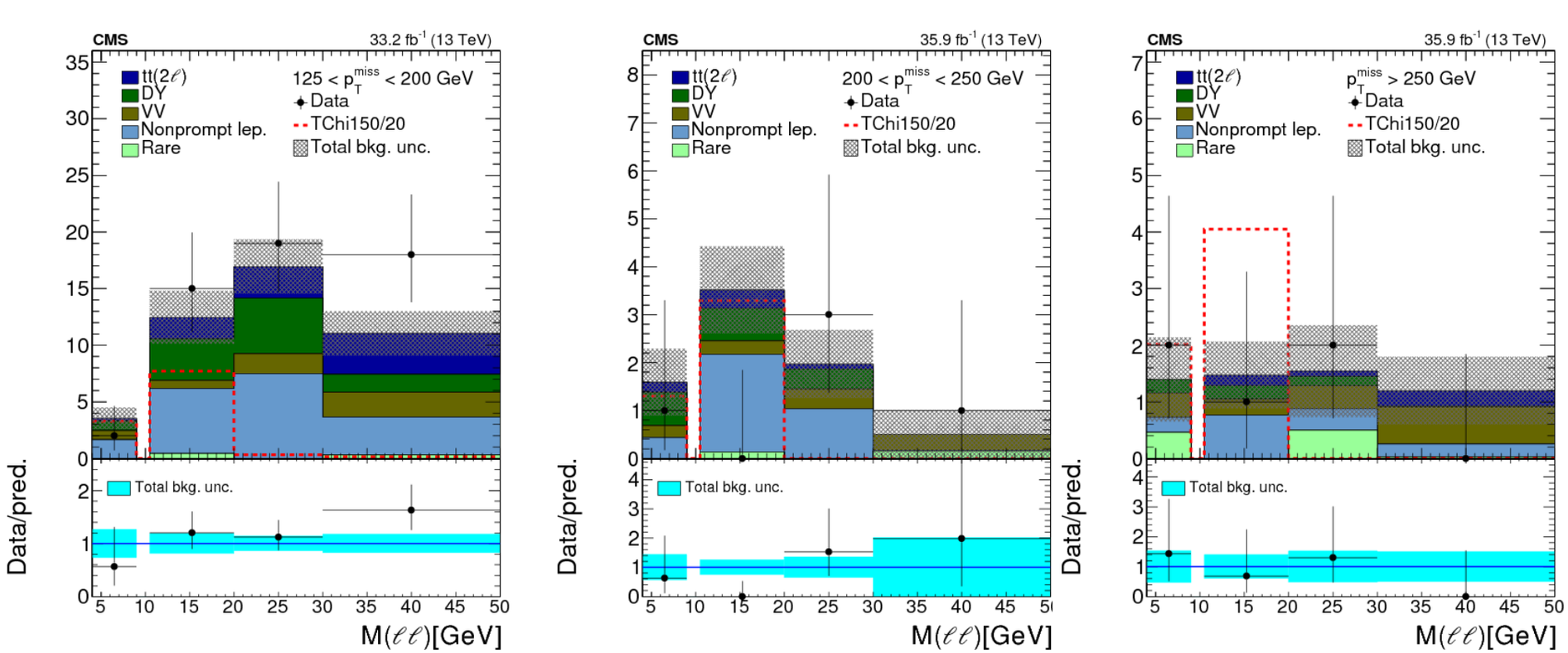



***Selection***: Low-momentum lepton (e/μ) pair + ISR jet, 0b

- *Dedicated low $p_T$ di-μ trigger gives access to lower $p_T^{miss}$ events*

***Search strategy***: Binning in M(ll), $p_T^{miss}$

Exploiting initial state radiation (ISR): important for many compressed SUSY searches; boosted system, improved signal vs background discrimination

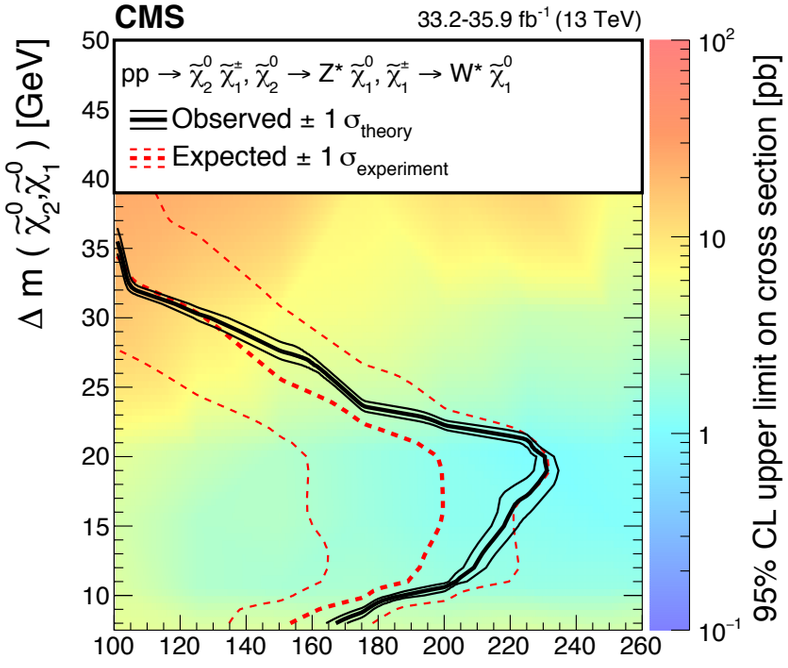


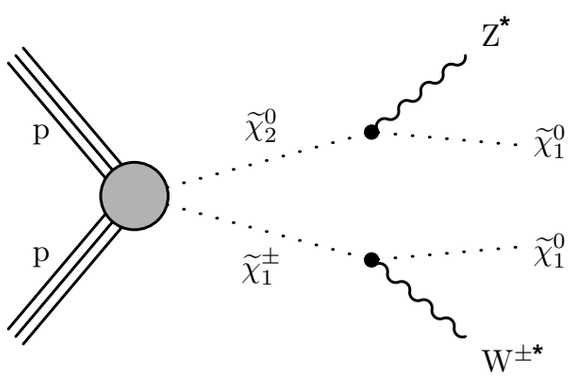
# 2 soft leptons + ISR

## CMS-SUS-16-048 *Phys. Lett. B 782 (2018)*

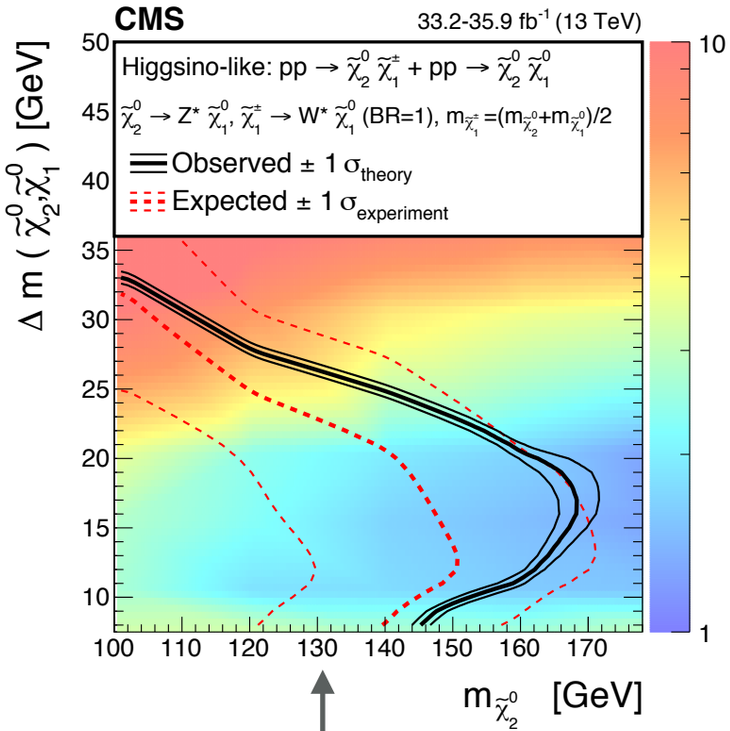
### Simplified model interpretations (chargino-neutralino production)

Wino, mass-degenerate $\chi_1^{\pm}$, $\chi_2^0$, bino $\chi_1^0$



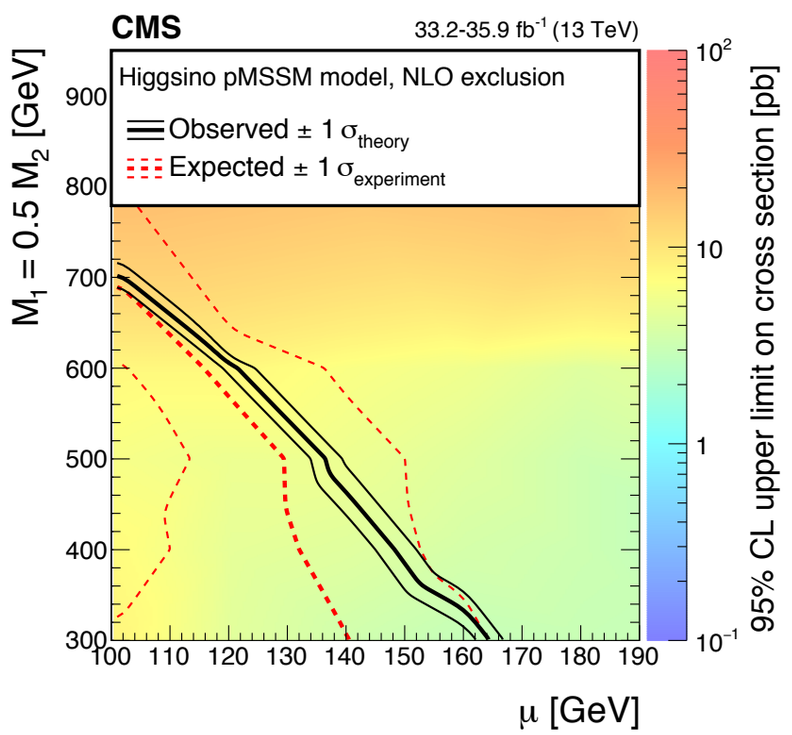

Higgsino-like, include $\chi_1^0\chi_2^0$ production




Assume m($\chi_1^{\pm}$) = 0.5[m( $\chi_1^0$) + m($\chi_2^0$)]

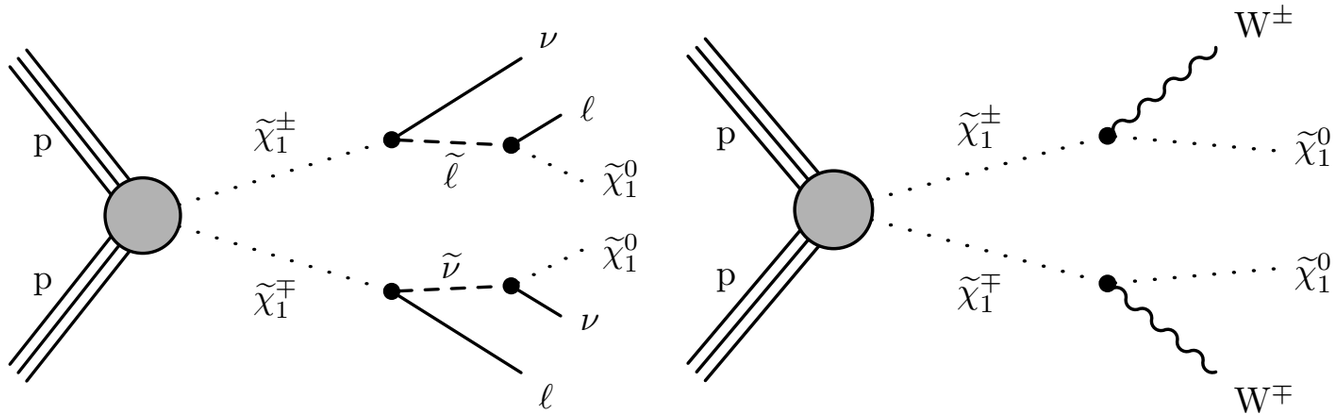
### Higgsino pMSSM model

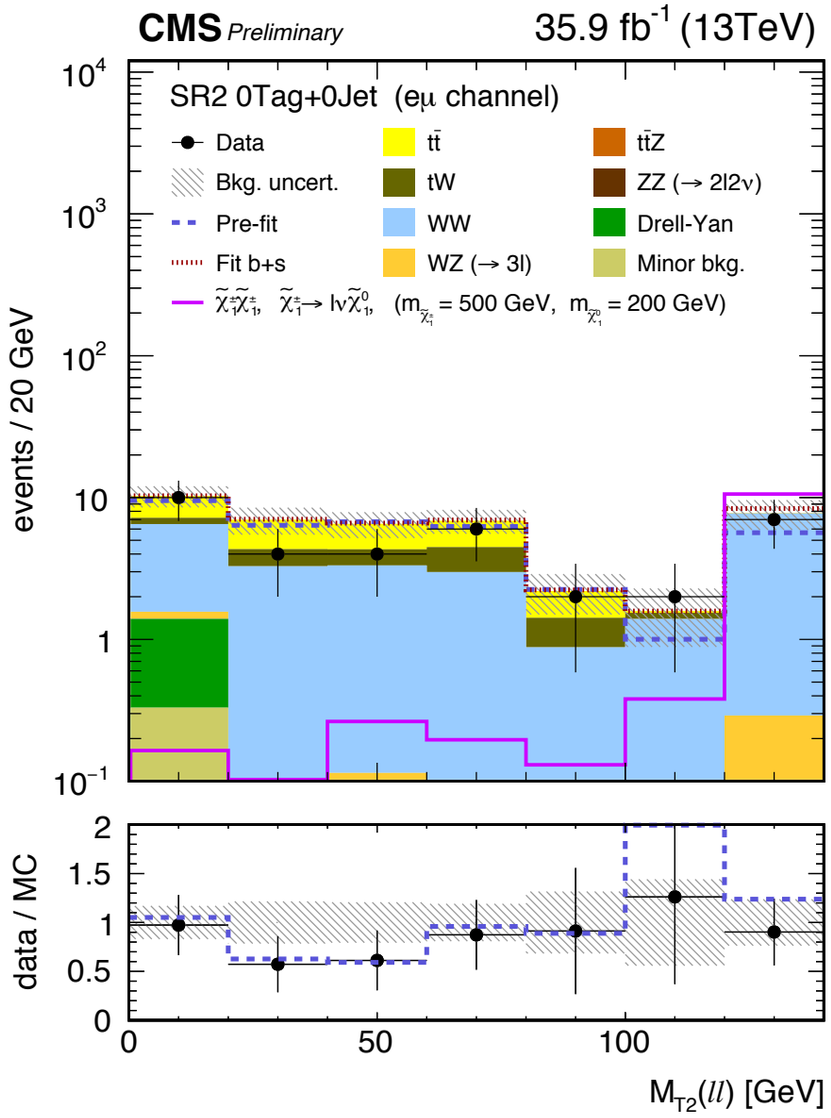
Scan Higgsino vs bino mass parameter, fixed ratio of wino to bino mass (2), tan β (10)



# 2 opposite charge leptons (off-Z)

## CMS-SUS-17-010 *JHEP 11 (2018) 079*




***Selection***: $e^+e^-/\mu^+\mu^-/e^{\pm}\mu^{\mp}$ + b-veto (reject top), M(ll) cuts (reject Z)

***Search strategy***: $p_T^{miss}$ + N(jet) categories, $M_{T2}$ shape for signal extraction

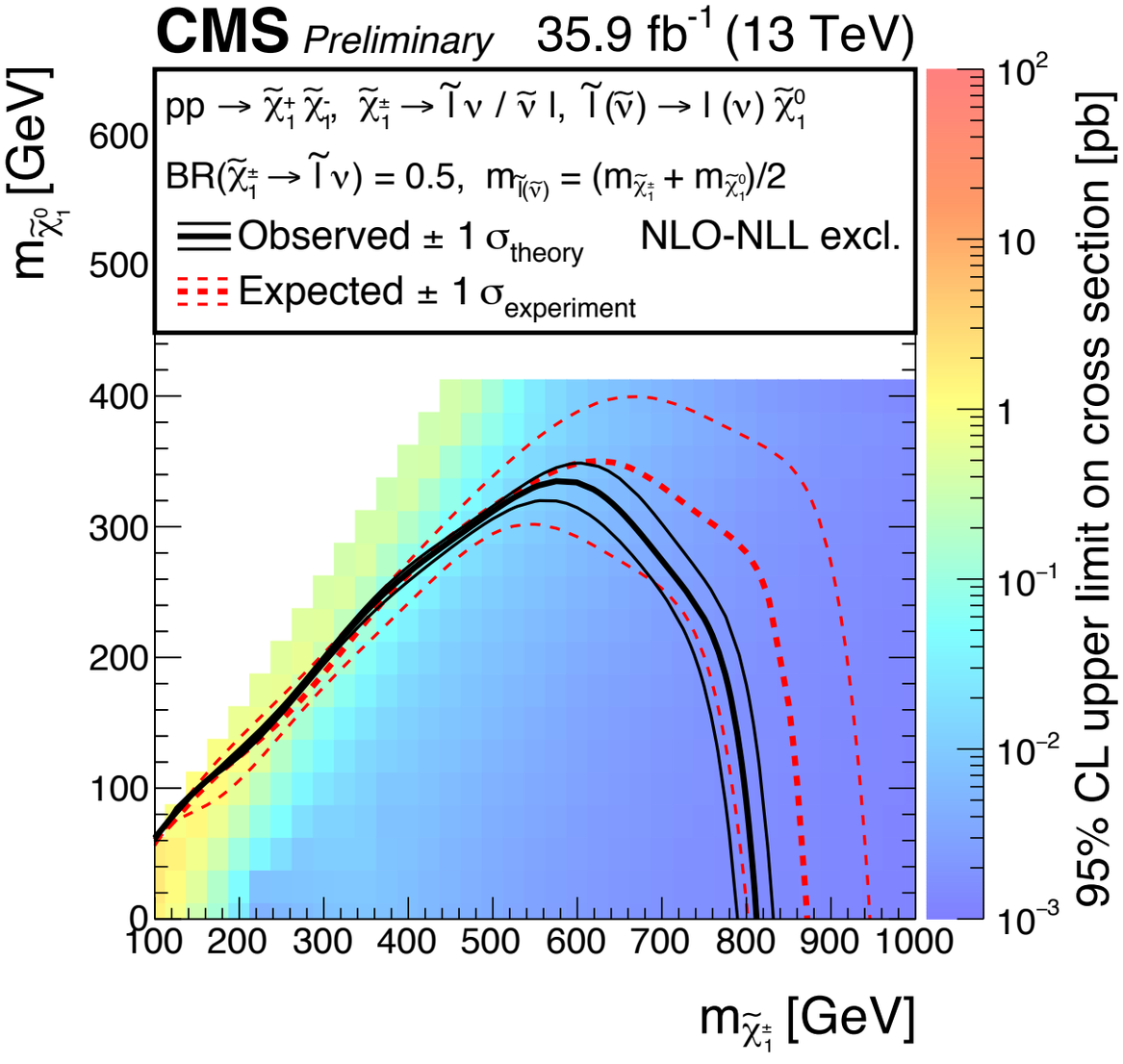
# 2 opposite charge leptons (off-Z)

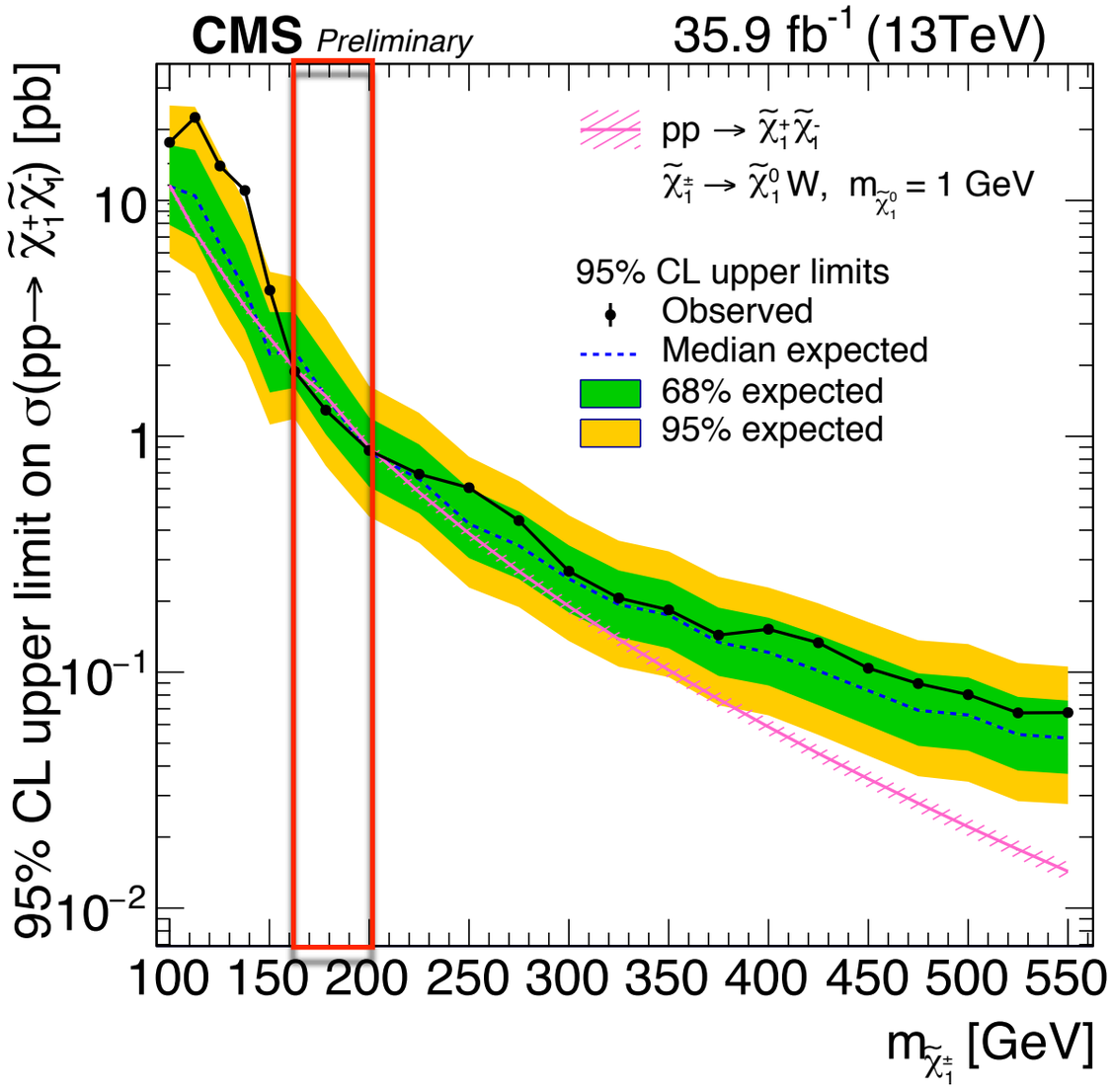
## CMS-SUS-17-010 *JHEP 11 (2018) 079*

### Chargino-pair production

Decays via $\tilde{l}/\tilde{\nu}$ (assume all 3 generations degenerate)

Decays to W: exclude m($\chi_1^{\pm}$) ~170-200 GeV for m($\chi_1^0$) = 1 GeV



# Electroweakino combination

## CMS-SUS-17-004 *JHEP 03 (2018) 160*

Statistical combination of analyses targeting chargino-neutralino / neutralino pair production with direct decays to SM W/Z/H bosons

| | Signal topology | | | | |
|---|---|---|---|---|---|
| Search | WZ | WH | ZZ | ZH | HH |
| $1\ell$ 2b | | ✓ | | | |
| 4b | | | | | ✓ |
| $2\ell$ on-Z | ✓ | | ✓ | ✓ | |
| $2\ell$ soft | ✓ | | | | |
| $\geq 3\ell$ | ✓ | ✓ | ✓ | ✓ | ✓ |
| H($\gamma\gamma$) | | ✓ | | ✓ | ✓ |

*JHEP 11 (2017) 029*

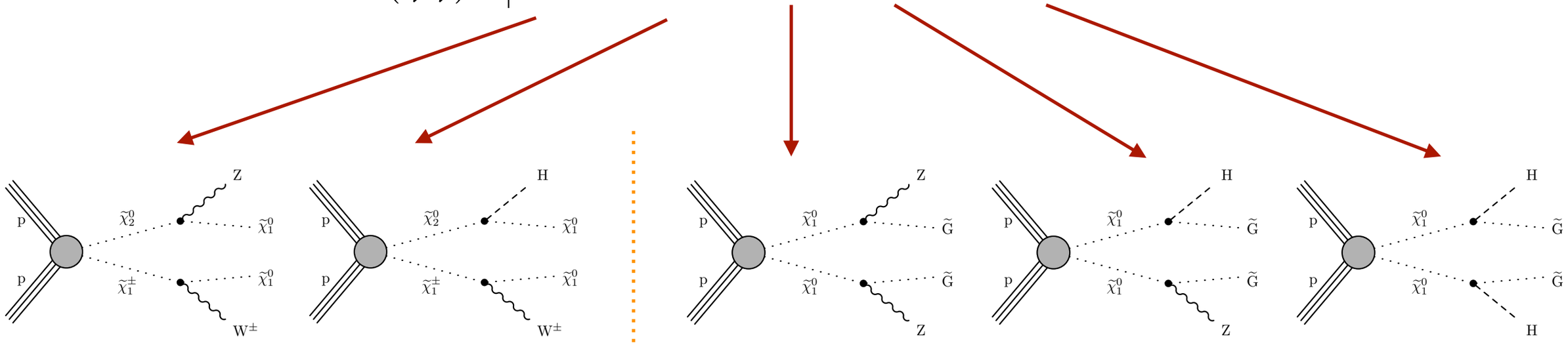
*JHEP 03 (2018) 076*

*JHEP 03 (2018) 166*

*Phys. Rev. D 97 (2018) 032007*

*Phys. Lett. B 782 (2018)*

*Phys. Lett. B 779 (2018) 166*




**GMSB models**

# Electroweakino combination

## CMS-SUS-17-004 *JHEP 03 (2018) 160*

Statistical combination of analyses targeting chargino-neutralino / neutralino pair production with direct decays to SM W/Z/H bosons

| Search | Signal topology: WZ | WH | ZZ | ZH | HH |
|---|---|---|---|---|---|
| $1\ell$ 2b | | ✓ | | | |
| 4b | | | | | ✓ |
| $2\ell$ on-Z | ✓ | | ✓ | ✓ | |
| $2\ell$ soft | ✓ | | | | |
| $\geq 3\ell$ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $H(\gamma\gamma)$ | | ✓ | | ✓ | ✓ |

1 e/μ, 2 b-jets consistent with m(H), large $p_T^{miss}$

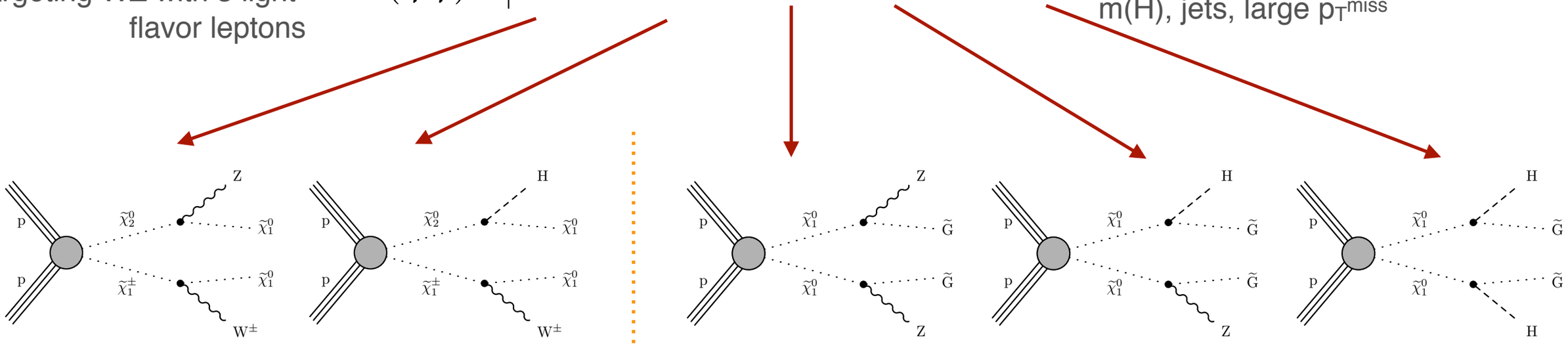
2 OC, SF e/μ consistent with m(Z), large $p_T^{miss}$

≥3 charged leptons (e, μ, up to two $\tau_h$) + category targeting WZ with 3 light-flavor leptons

4-5 jets, ≥2 b-jets, large $p_T^{miss}$, form 2 2-jet groupings, average mass consistent with m(H)

2 low $p_T$ OC, SF e/μ, jets, large $p_T^{miss}$

2 photons consistent with m(H), jets, large $p_T^{miss}$

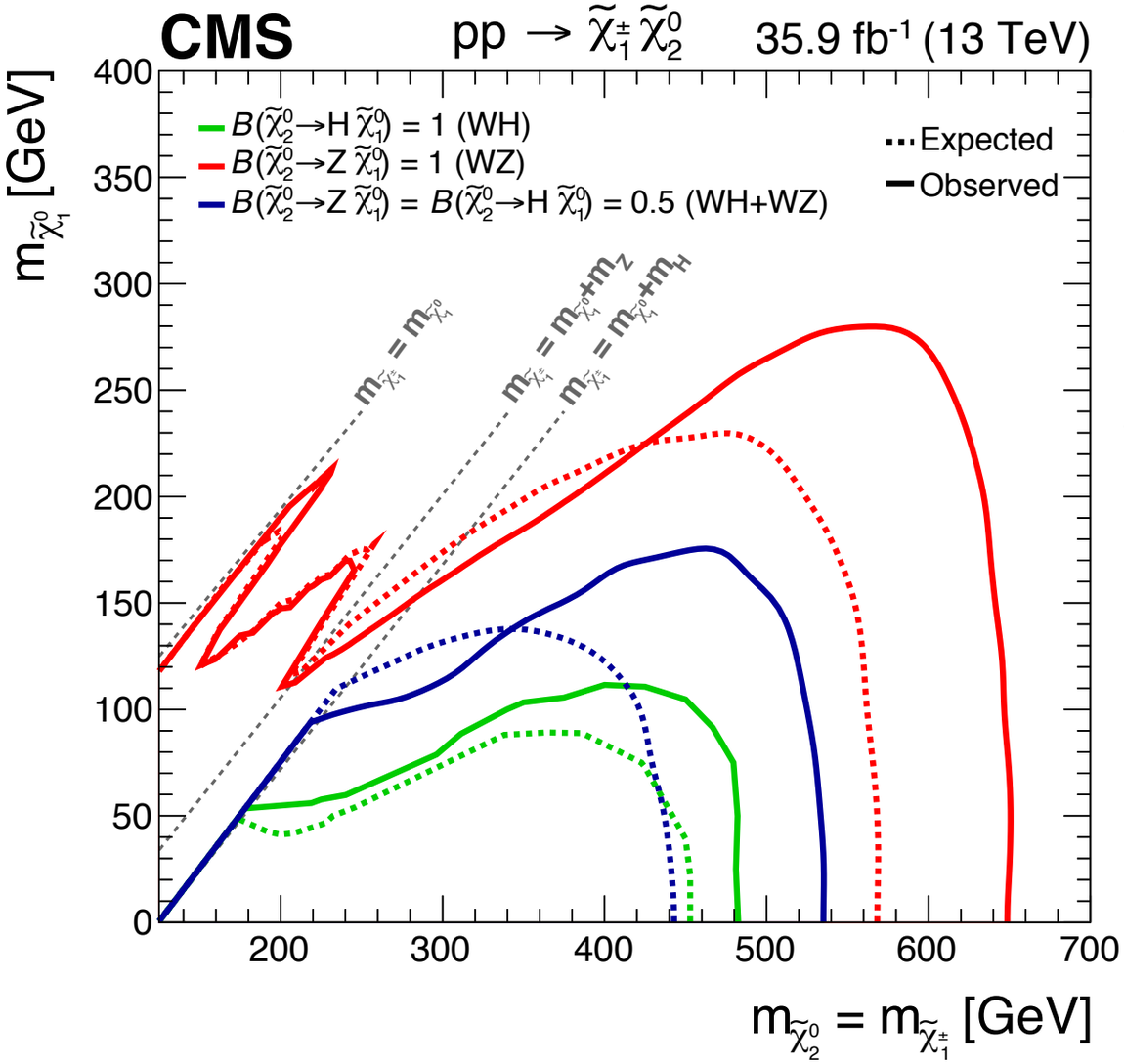


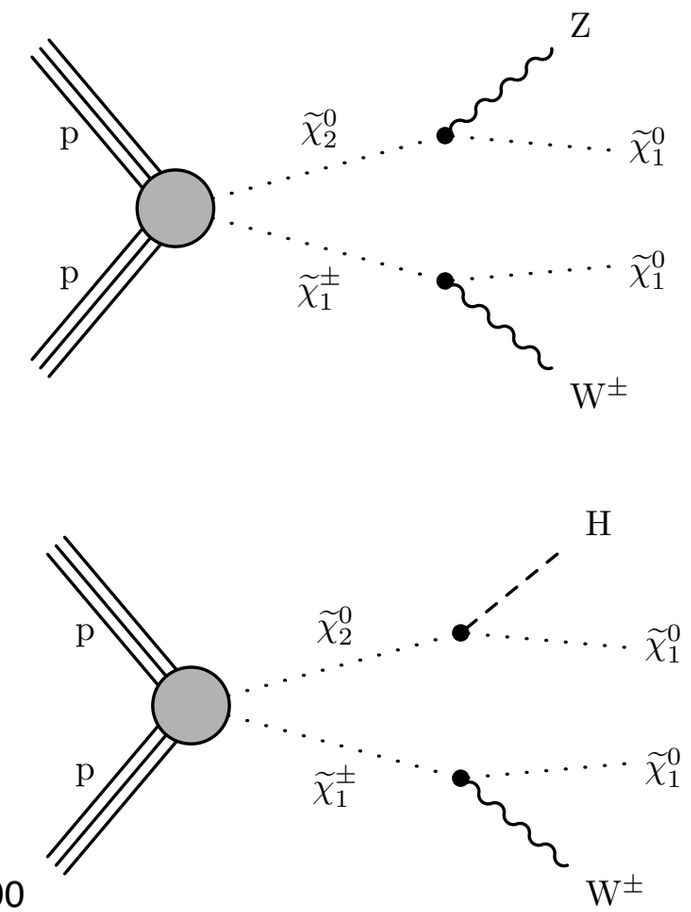

**GMSB models**

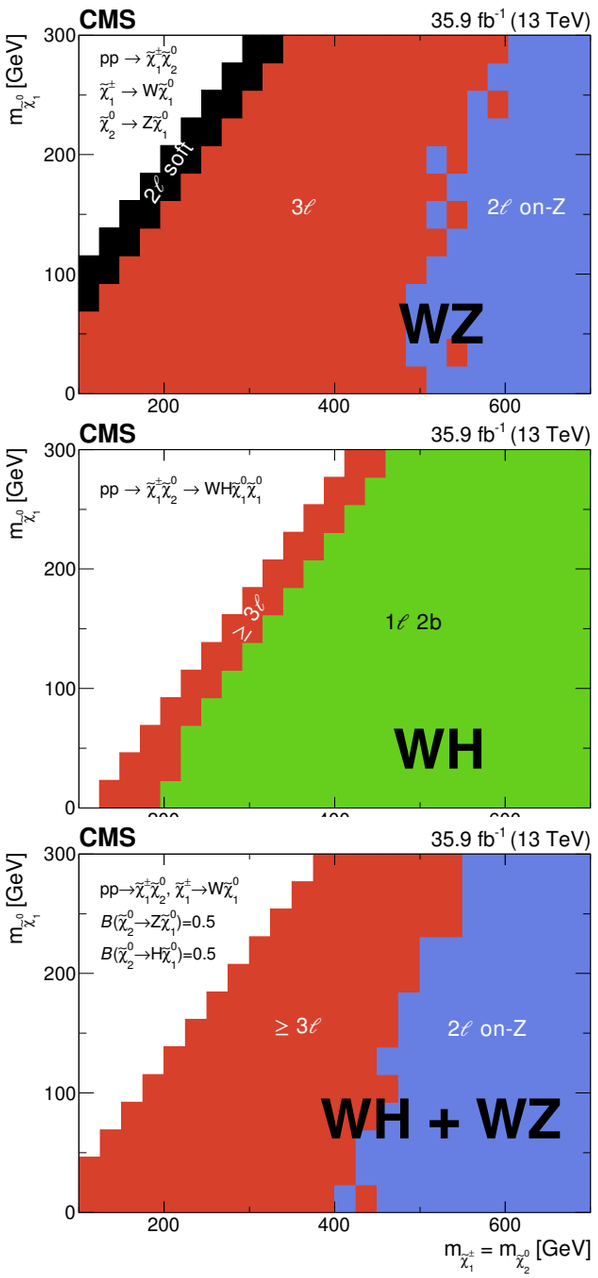
# Electroweakino combination

## CMS-SUS-17-004 *JHEP 03 (2018) 160*

### Chargino-neutralino production



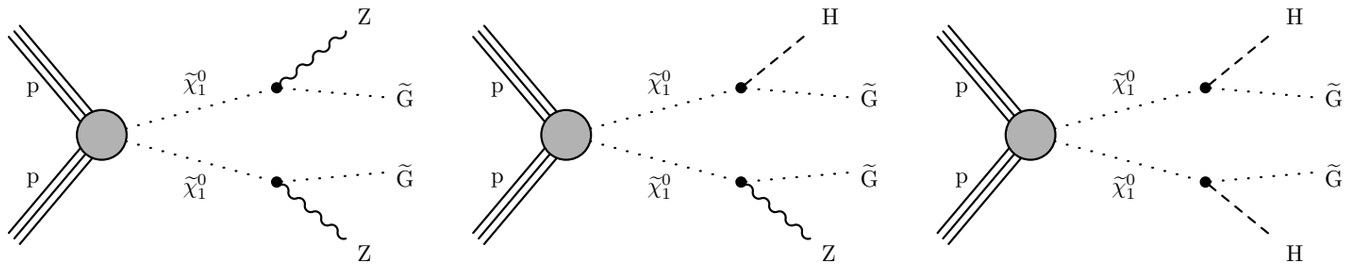

3 assumptions for B($\chi_2^0 \to$ Z/H $\chi_1^0$)

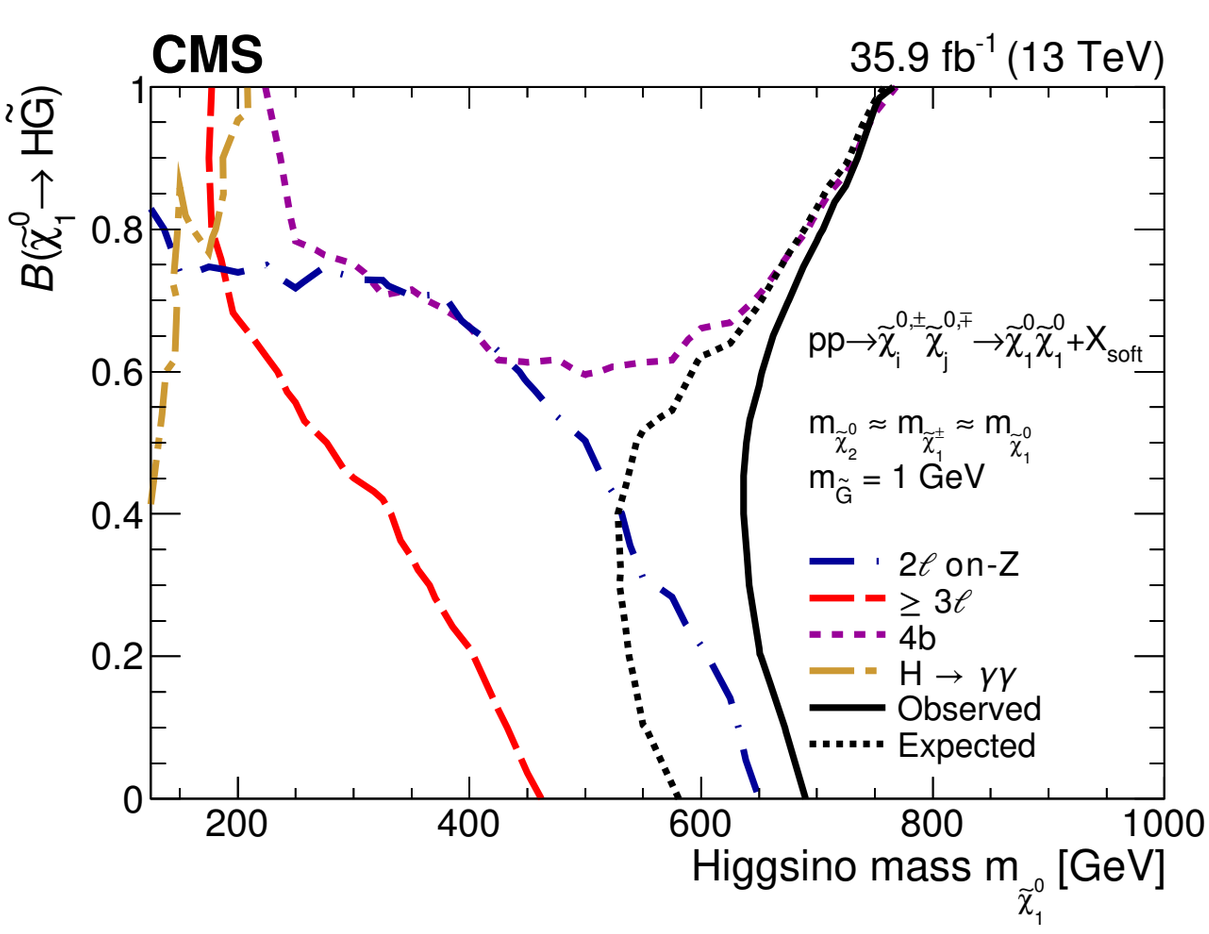
Complementarity of analyses

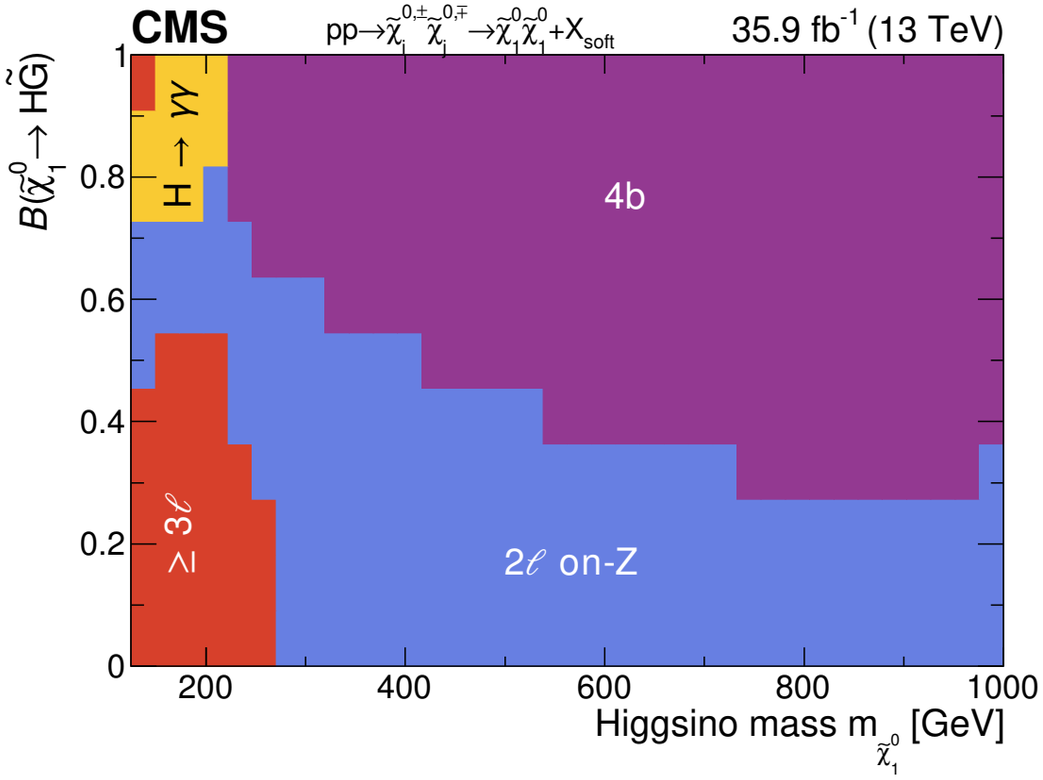
# Electroweakino combination

## CMS-SUS-17-004 *JHEP 03 (2018) 160*

**GMSB model with Higgsino NLSP, gravitino LSP**



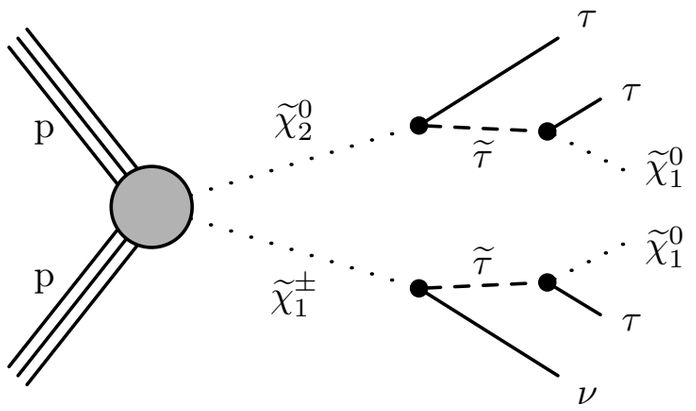




Complementarity of analyses

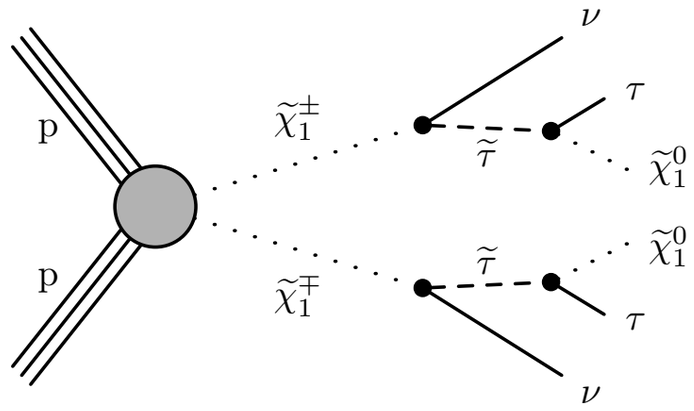
# Chargino/neutralino→stau

## CMS-SUS-17-003 *JHEP 11 (2018) 151*

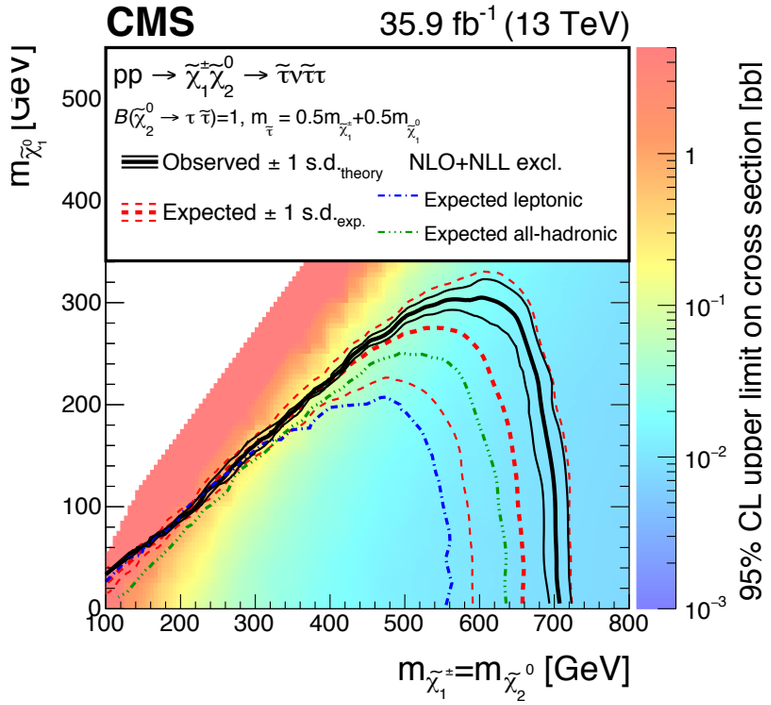
Decays via $\tilde{\tau}/\tilde{\nu}_\tau$

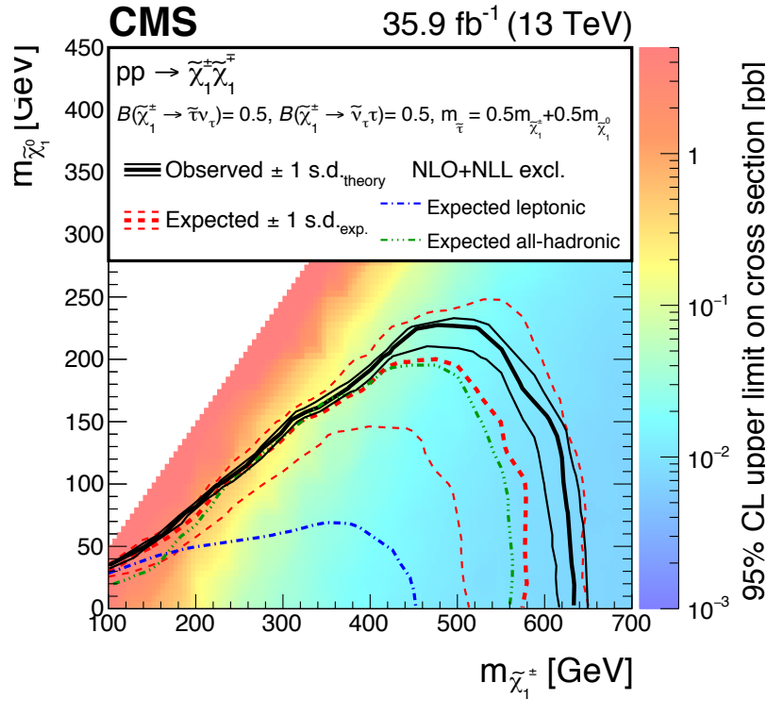



**Chargino-neutralino production**



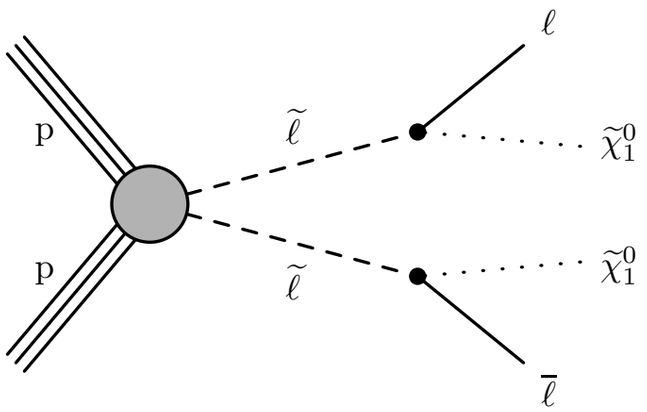

**Chargino-pair production**



# Selectrons and smuons

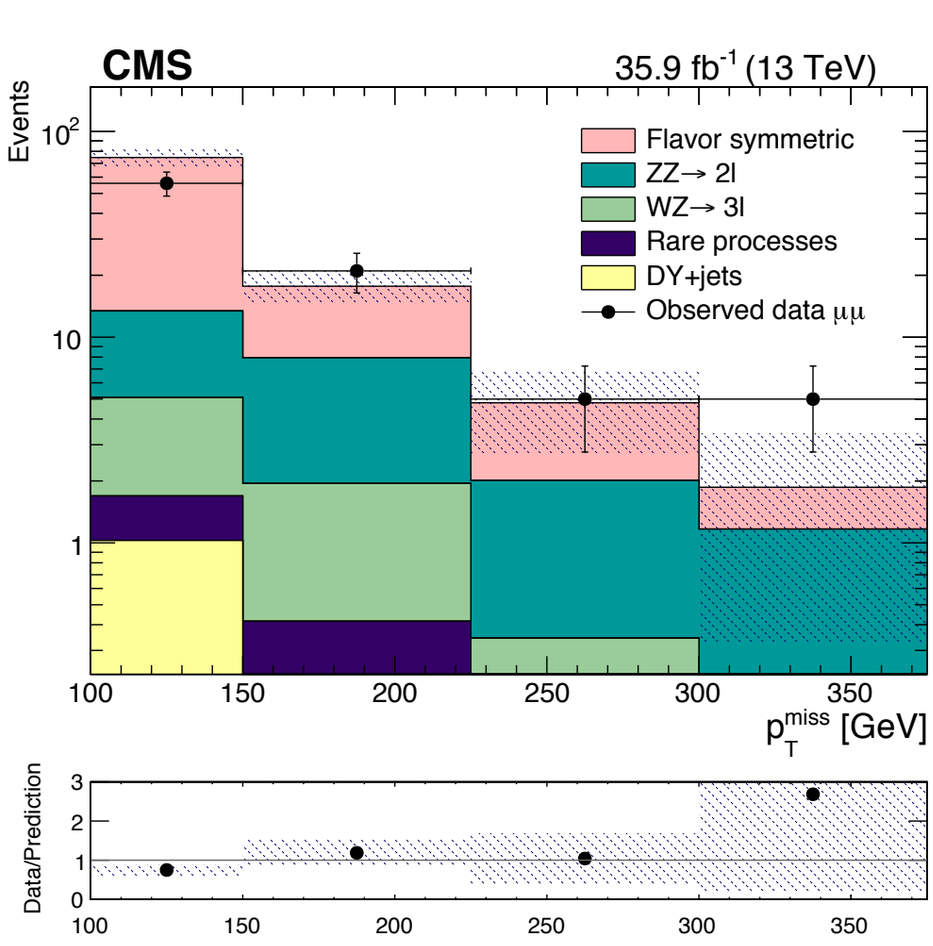
## CMS-SUS-17-009 *Phys. Lett. B 790 (2019) 005*

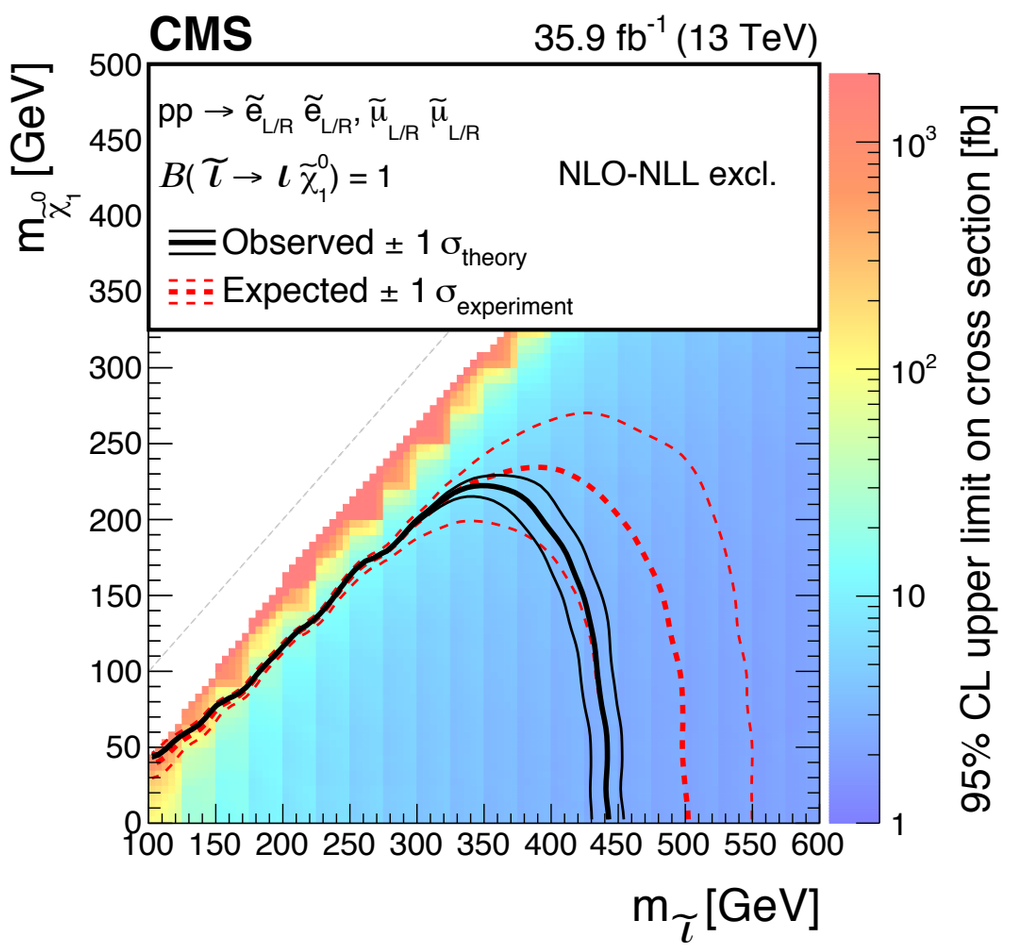



***Selection***: $e^+e^-/\mu^+\mu^-$ + jet veto, Z rejection through M(ll)

***Search strategy***: Large $M_{T2}$ + binning in $p_T^{miss}$

**Direct left- and right-handed ẽ/μ̃ pair production**

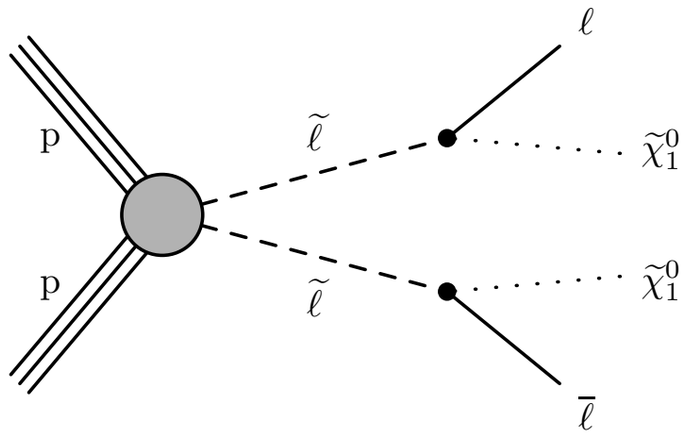



Assume mass-degenerate ẽ, μ̃

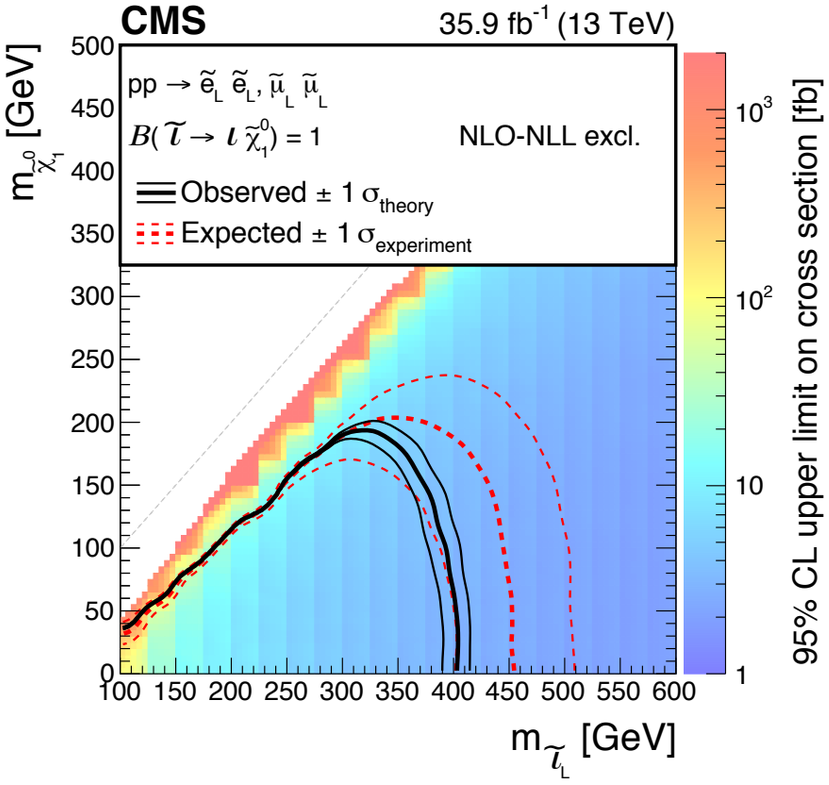
# Selectrons and smuons

## CMS-SUS-17-009 *Phys. Lett. B 790 (2019) 005*

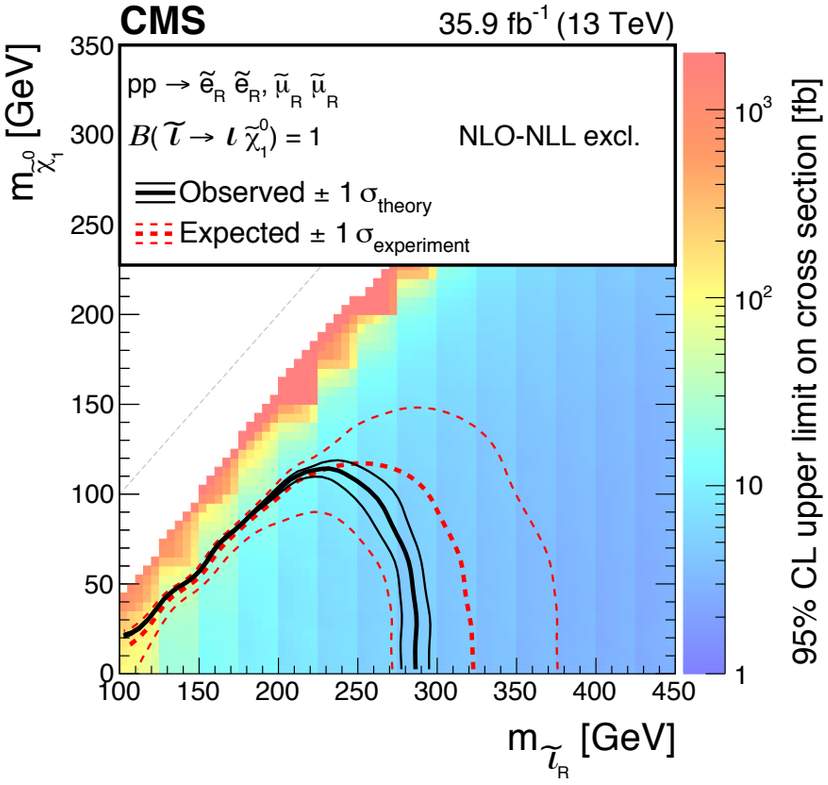



Assume mass-degenerate selectrons, smuons

**Direct left-handed selectron/ smuon pair production**




**Direct right-handed selectron/ smuon pair production**




**Direct left- and right-handed selectron/smuon pair production**