# Progress with electroweak-ino SUSY searches at LHC

*Moriond EWK, 20 March 2017*

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*On behalf of the ATLAS and CMS collaboration*

# *Introduction*

The SUper-SYmmetry (SUSY) is a powerful and favored extension of the Standard Model (SM) able to solve several unanswered questions left by the SM :

- dark matter candidate?
- naturalness problem ?

SUSY postulates the existence of new particles, partner of the SM particles

## In this talk

- Focus on the electroweak SUSY production searches performed by ATLAS and CMS @ 13 TeV

- Further SUSY results in Emma's, Andreas's and Lesya's talks

# *Focus : electroweak SUSY production searches*

0 | 1 | 2 | 3 | 4+ — Number of leptons

**CMS-SUS-16-044**
- 0 lepton
- 4b jets

**CMS-SUS-16-046**
- last minute result !
- 1 photon
- $\not{E}_T$

**CMS-SUS-16-026**
- 1 lepton + $\not{E}_T$ + 2b jets

**CMS-SUS-16-039**
- 2 same-sign leptons
- 3+ leptons

**ATLAS-CONF-2016-093**
- multi-hadronic taus (2+)

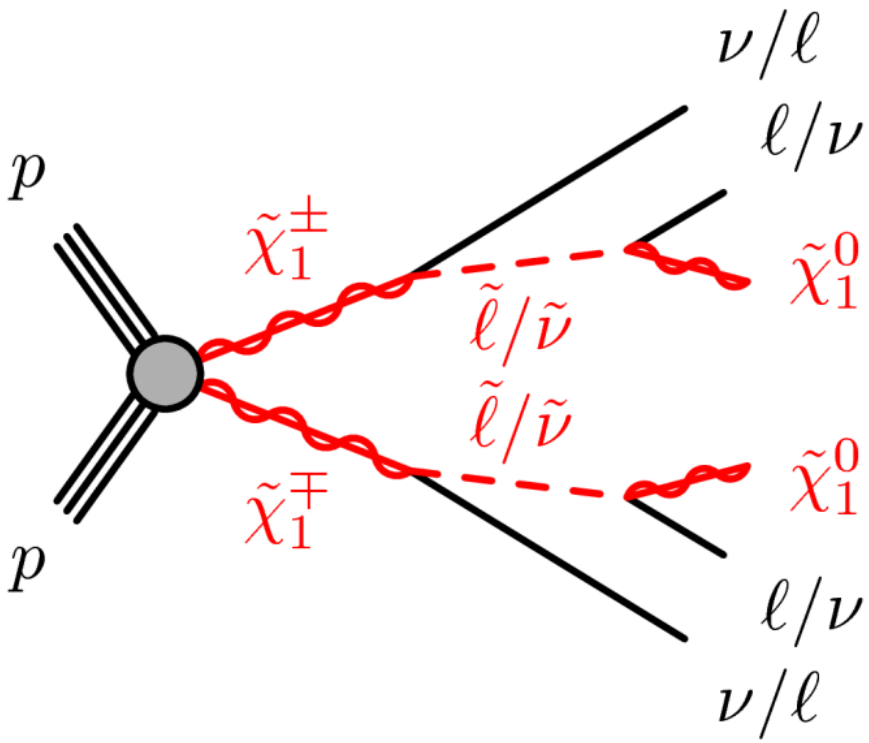
**ATLAS-CONF-2016-096**
- opposite-sign dileptons
- multileptons (3l)

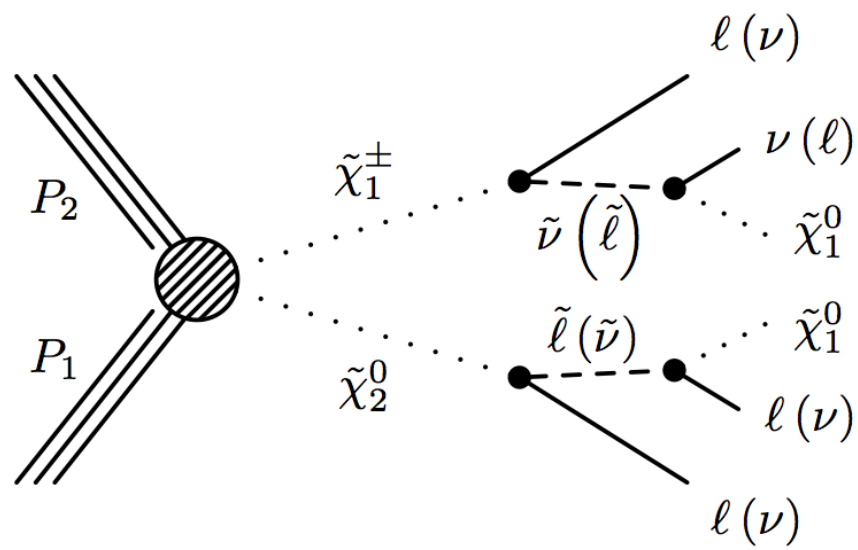
**ATLAS-CONF-2016-075**
- multileptons (4+)
- RPV search

: updated or new result

- interpretation usually performed with simplified SUSY models
- an analysis can probe several models
- results can be interpreted model-independently

# *Chargino-chargino/neutralino production with slepton mediated decays*




- CMS-SUS-16-039
- ATLAS-CONF-2016-093
- ATLAS-CONF-2016-096

# *Di-leptons and multileptons @ ATLAS*

Targets events with opposite-sign (OS) dilepton pair or 3 leptons (e/μ)

ATLAS-CONF-2016-096, 13 fb$^{-1}$

## Three signal regions

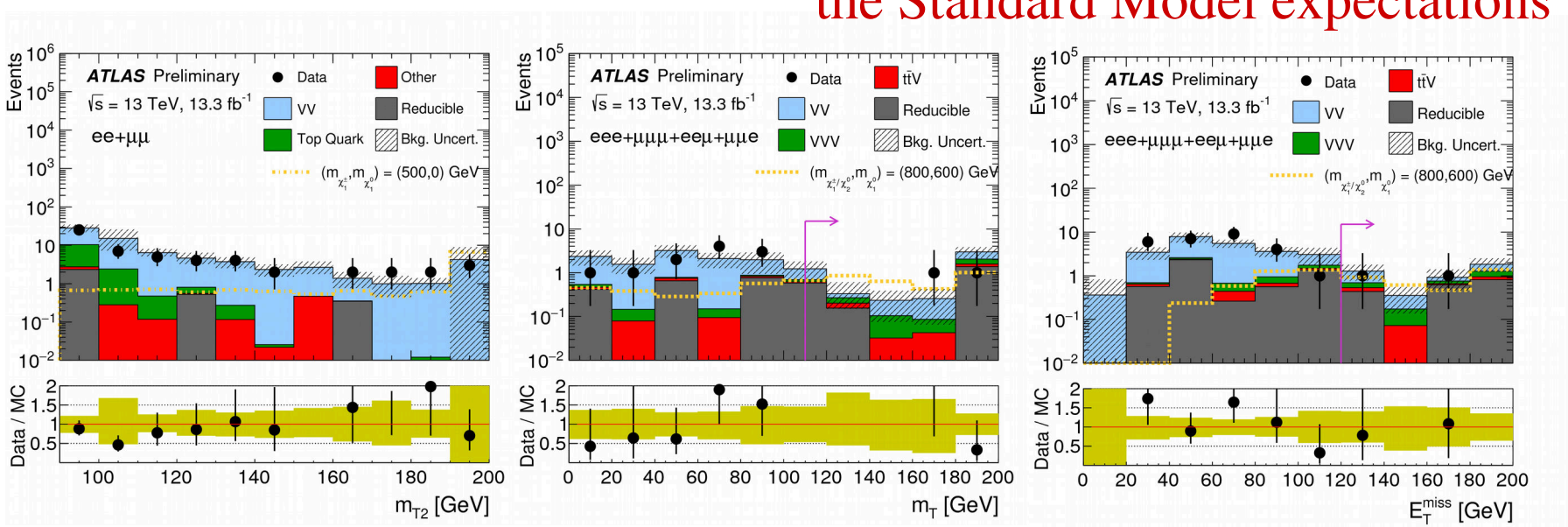
| | SR2ℓ | SR3ℓ-I | SR3ℓ-H |
|---|---|---|---|
| leptons | $\ell^+\ell^-$ | $\ell^+\ell^-\ell^\mp$ | |
| jet/b-jet veto | ×/× | –/× | |
| $m_T >$ | – | 110 GeV | |
| $m_{T2} >$ | 90, 120, 150 | – | |
| Z veto/$m_{\ell\ell}$ selection | × | × | > 101.2 GeV |
| $p_T(3^{rd}\ \ell)$ | – | 30 | 80 |
| $\not{E}_T >$ | – | 120 GeV | 60 GeV |

## Use of transverse and "s-tranverse" masses

$$m_T = \sqrt{2\, p_T(l)\, \not{E}_T \left(1 - \cos\Delta\phi(l, \not{E}_T)\right)}$$

$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{miss} - \mathbf{q}_T)\right)\right]$$

No evidence of an excess above the Standard Model expectations




OS dileptons | trileptons "intermediate mass" | trileptons "high mass"

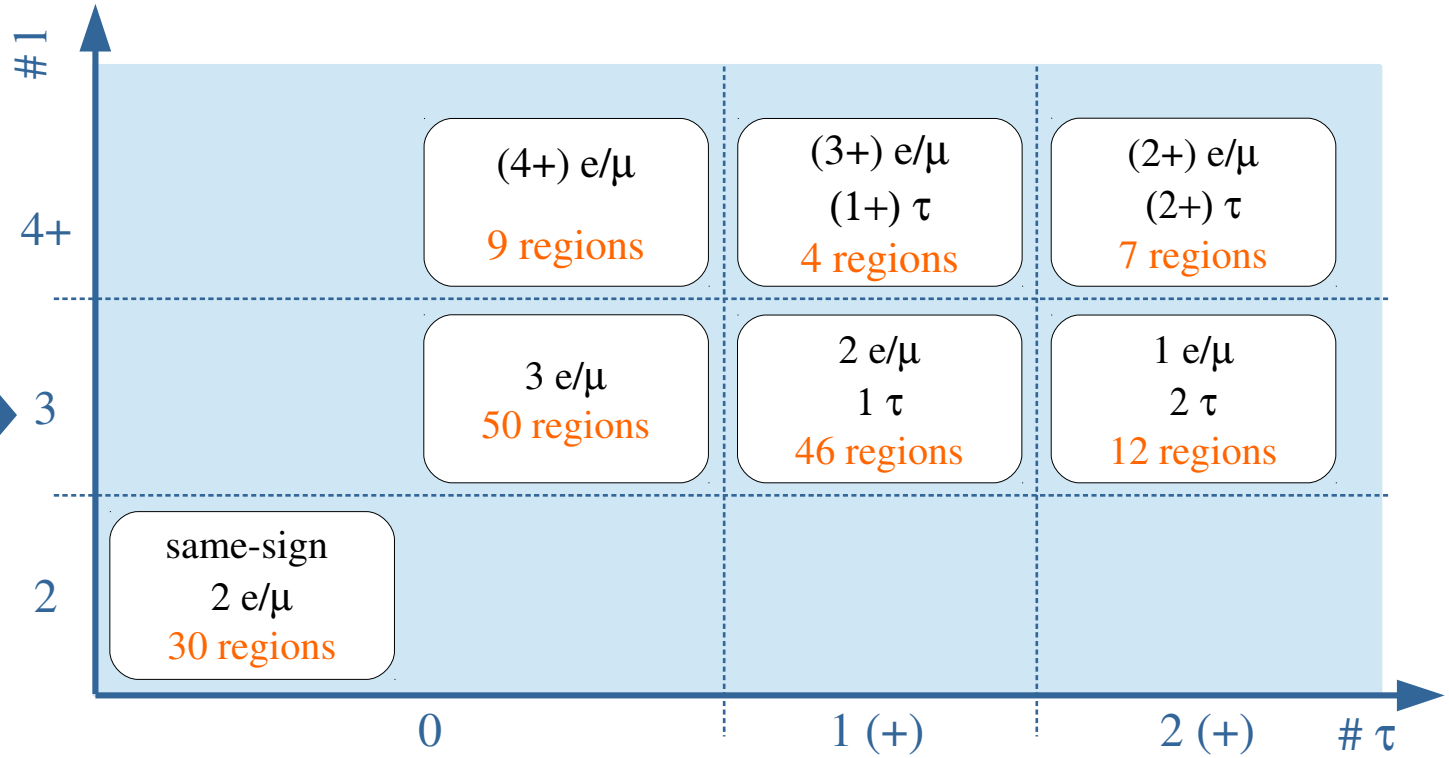
# *Di-leptons and multileptons @ CMS*

NEW

CMS-SUS-16-039
36 fb$^{-1}$

## Analysis strategy

- use of (many) leptonic final states
- region of interest built with discriminant variables :




| variables | major vetoes |
|---|---|
| common | |
| $m_{\ell\ell}$, $m_T$, $\not{E}_T$ | – |
| specific $2\ell$ | |
| $p_T(\ell\ell)$, charge$(\ell\ell)$, $N_{\text{jet}}$ | $N_{\text{jet}} \leq 1$, Z veto |
| specific $3\ell$ | |
| $m_{T2}$, $N_Z$ | $\lvert m_{\ell\ell\ell} - m_Z \rvert > 15$ GeV |

Total of 158 regions (!), allows :

- sensitivity to a broad variety of models
- sensitivity to a wide SUSY mass space

# *Di-leptons and multileptons @ CMS*

NEW

Dominant backgrounds controlled with data

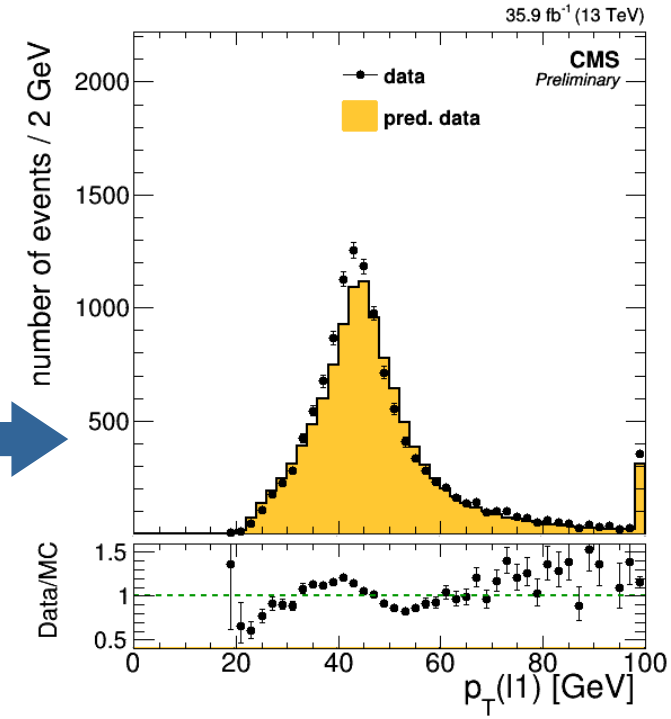
CMS-SUS-16-039, 36 fb$^{-1}$

## lepton / charge misidentification

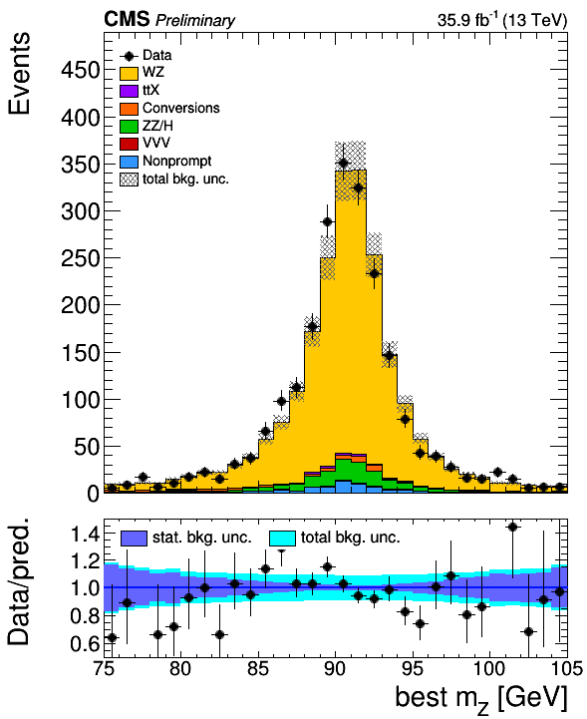
control region → ×*transfer factor* → signal region

control regions

- lepton misidentification : lepton identification/isolation relaxed
- charge misidentification : use of events with OS dilepton pair




Charge misidentification validation




## WZ process

- $m_T$ and $\not{E}_T$ shapes validated with W$\gamma$ sample
- normalization constraints from control sample

# *Di-leptons and multileptons @ CMS*

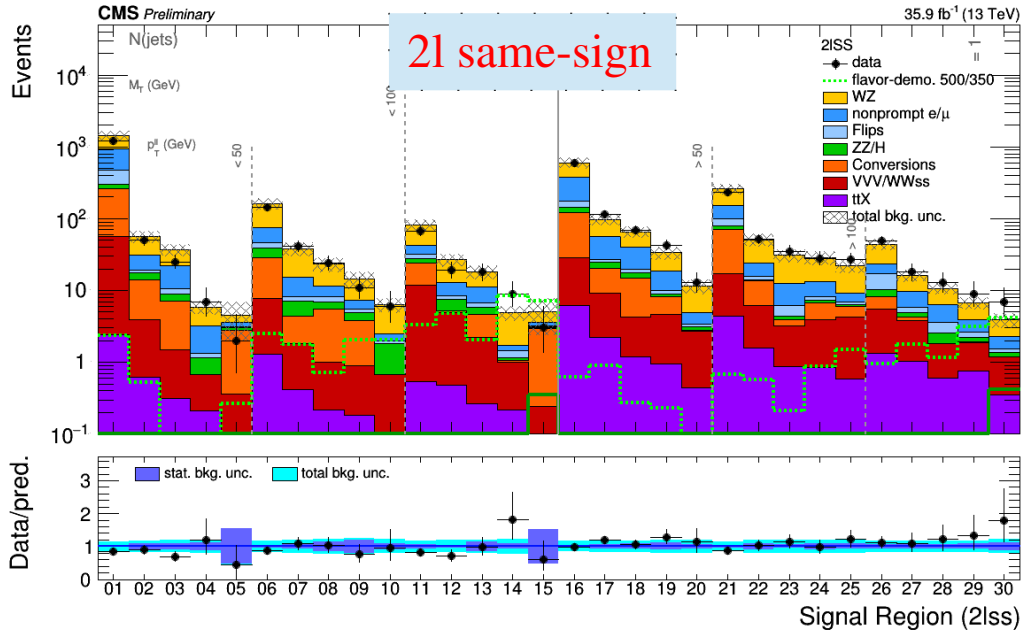
NEW

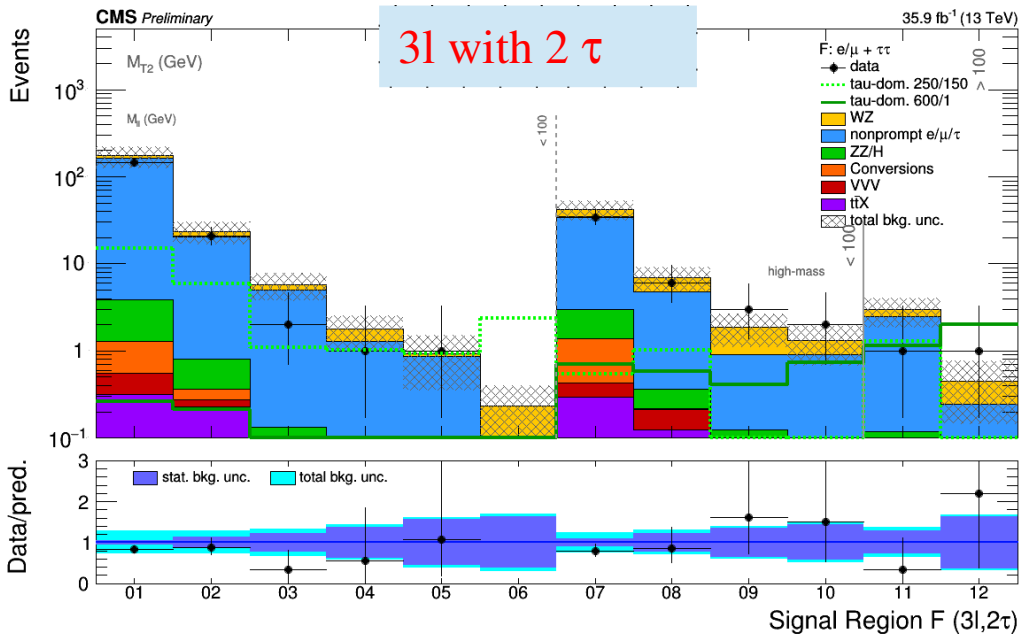
## CMS-SUS-16-039, 36 fb$^{-1}$

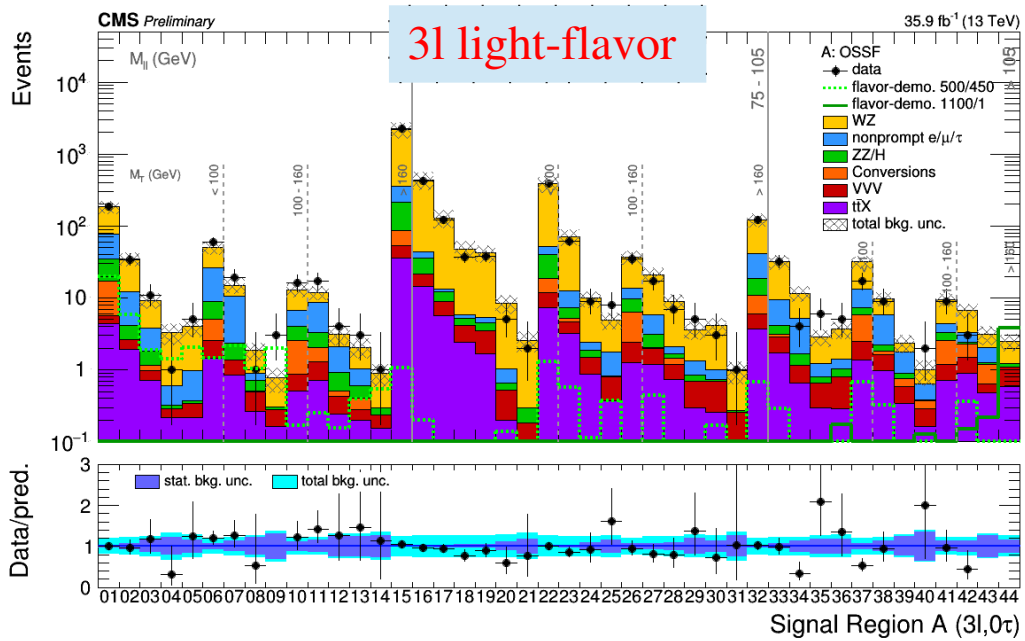
Only a subpart of the signal regions are shown here :

- same-sign dilepton
- tri-lepton (e/μ) w/ OS same flavor pair
- tri-lepton with 2 hadronic taus

Data are in good agreement with Standard Model expectations



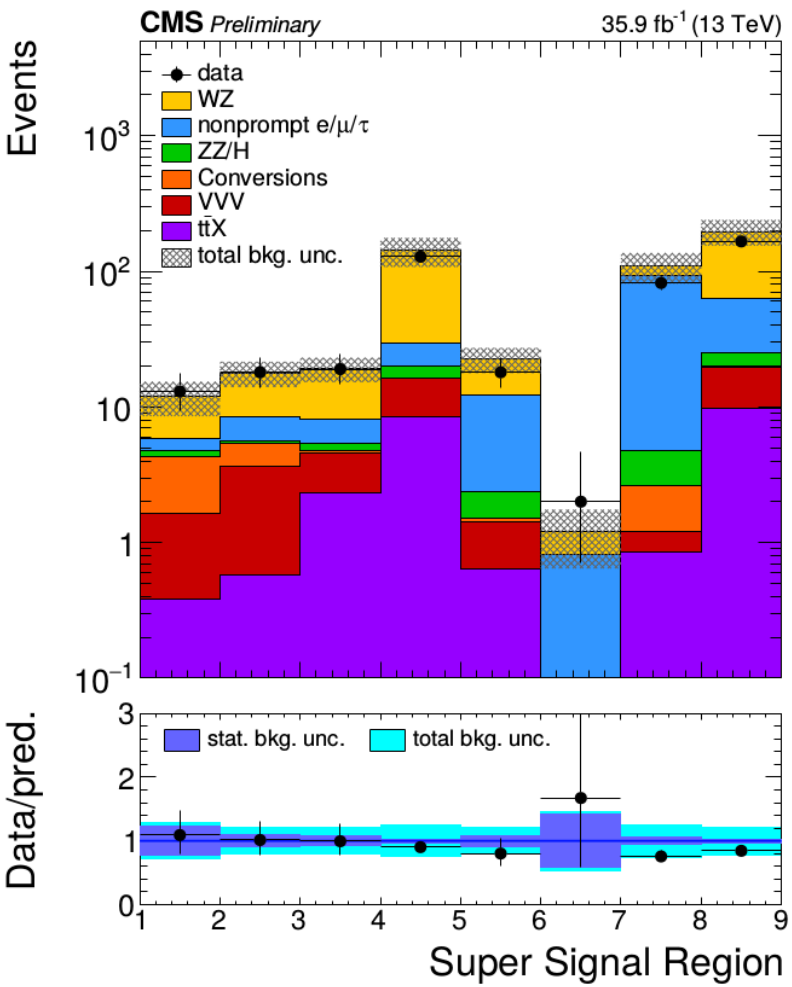



# *Di-leptons and multileptons @ CMS*

NEW

Theoretical interpretation with large number of regions can be complicated...

- Results in "aggregate" signal regions are also provided




| nb | final state | definition | event yield | |
|---|---|---|---|---|
| 1 | 2 same-sign leptons | 0 jets, $M_T > 100$ GeV and $E_T^{miss} > 140$ GeV | $12 \pm 3$ | 13 |
| 2 | 2 same-sign leptons | 1 jets, $M_T < 100$ GeV, $p_T^{\ell\ell} < 100$ GeV and $E_T^{miss} > 200$ GeV | $18 \pm 4$ | 18 |
| 3 | 3 light leptons | $M_T > 120$ GeV and $E_T^{miss} > 200$ GeV | $19 \pm 4$ | 19 |
| 4 | 3 light leptons | $E_T^{miss} > 250$ GeV | $142 \pm 34$ | 128 |
| 5 | 2 light leptons and 1 tau | $M_{T2}(\ell_1, \tau) > 50$ GeV and $E_T^{miss} > 200$ GeV | $22 \pm 5$ | 18 |
| 6 | 1 light lepton and 2 taus | $M_{T2}(\ell, \tau_1) > 50$ GeV and $E_T^{miss} > 200$ GeV | $1.2 \pm 0.6$ | 2 |
| 7 | 1 light lepton and 2 taus | $E_T^{miss} > 75$ GeV | $109 \pm 28$ | 82 |
| 8 | more than 3 leptons | $E_T^{miss} > 200$ GeV | $197 \pm 42$ | 166 |

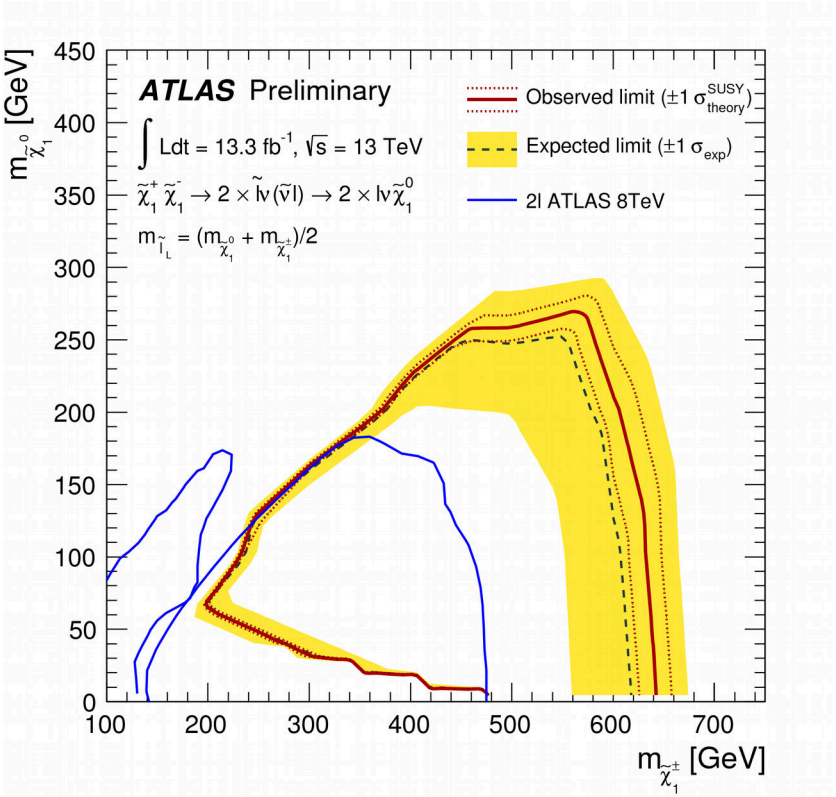
- ease the theoretical interpretation of the observations
- correlation matrix also provided to re-use results in the simplified likelihood approach (also described here)

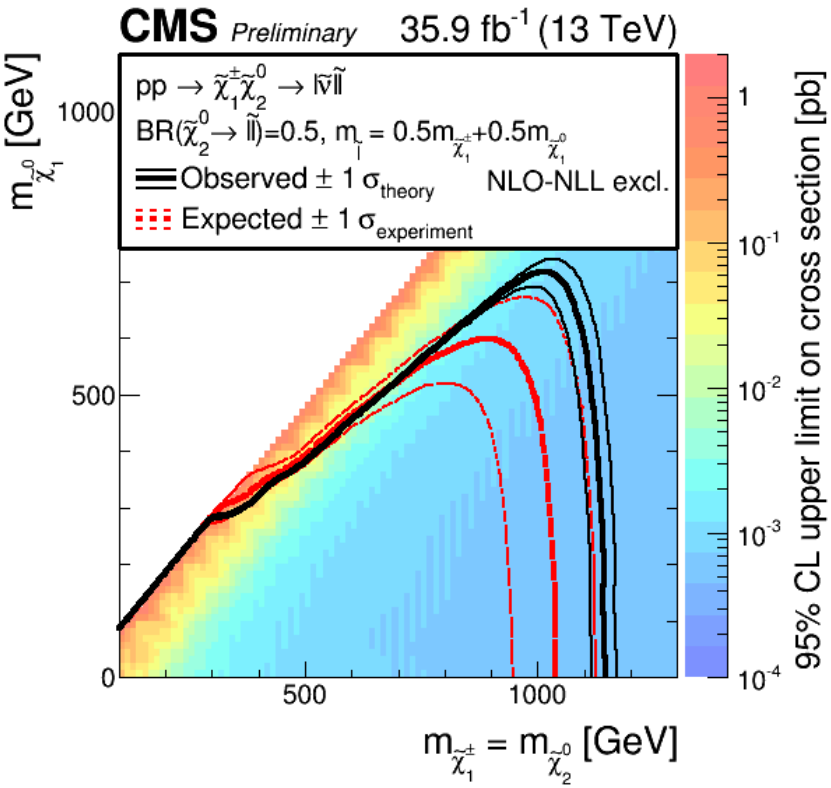
# General $\tilde{l}_L/\tilde{\nu}_l$ mediated decays

ATLAS multileptons (ATLAS-CONF-2016-096)

- separation of production modes

Most stringent constraints on $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production




CMS multileptons (CMS-SUS-16-039)

- only $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production mode studied
- several mass splitting models probed
- not all regions used for each interpretation

Most stringent limits on $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production

# *Probing $\tilde{\tau}/\tilde{\nu}_\tau$ mediated decays (I)*

ATLAS-CONF-2016-093, 15 fb$^{-1}$

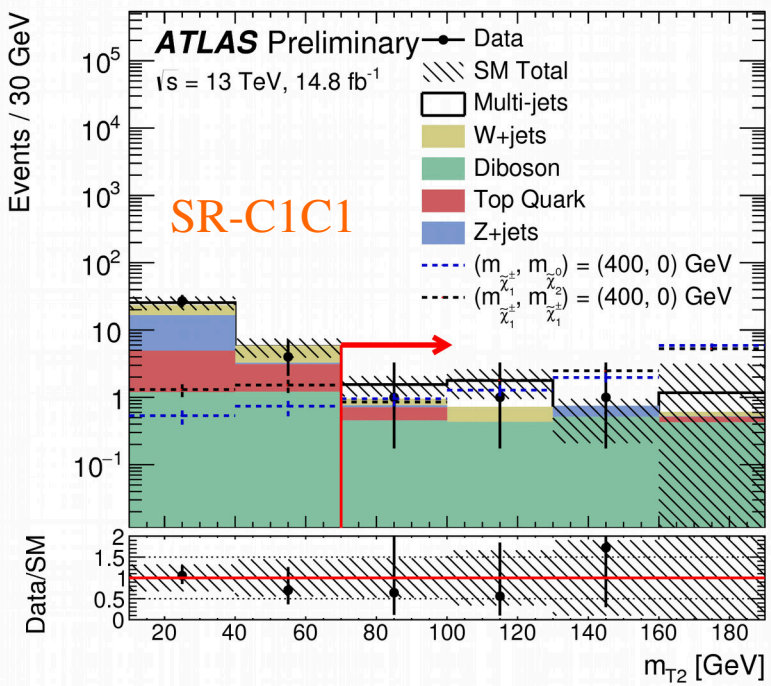
## Analysis in a nutshell :

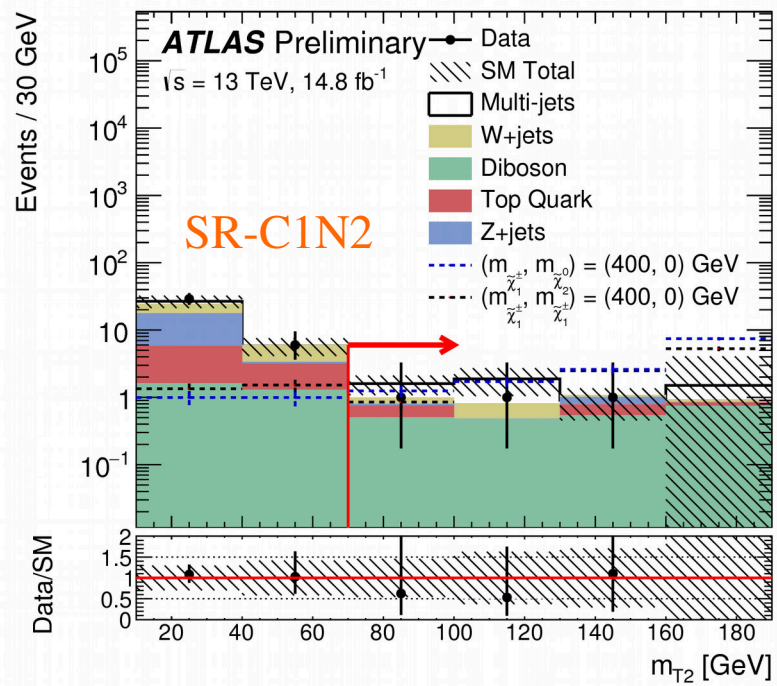
- two opposite sign hadronic taus
- veto $Z \rightarrow \tau\tau$ events
- two signal regions

| | SR-C1C1 | SR-C1N2 |
|---|---|---|
| production mode | $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ | $\tilde{\chi}_1^\pm \tilde{\chi}_0^2$ |
| light lepton veto | $\times$ | – |

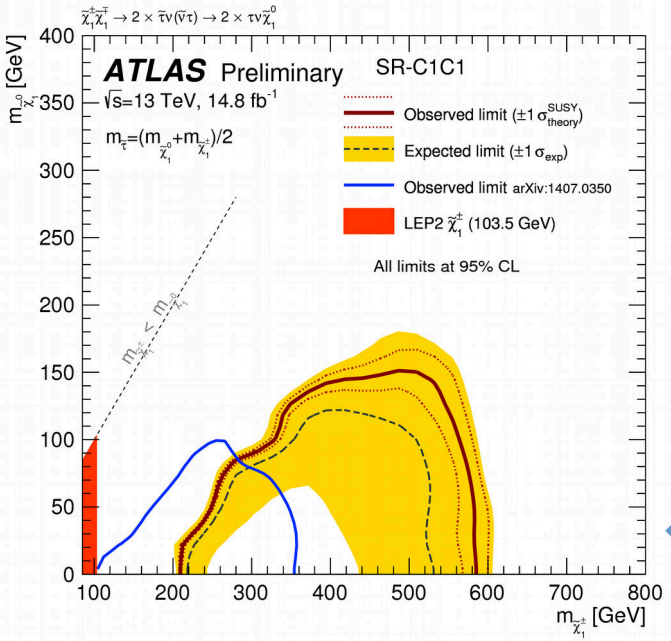
- look for excess at large $\not{E}_T$ / $m_{T2}$

Data in agreement with SM expectations



# *Probing $\tilde{\tau}/\tilde{\nu}_\tau$ mediated decays (II)*

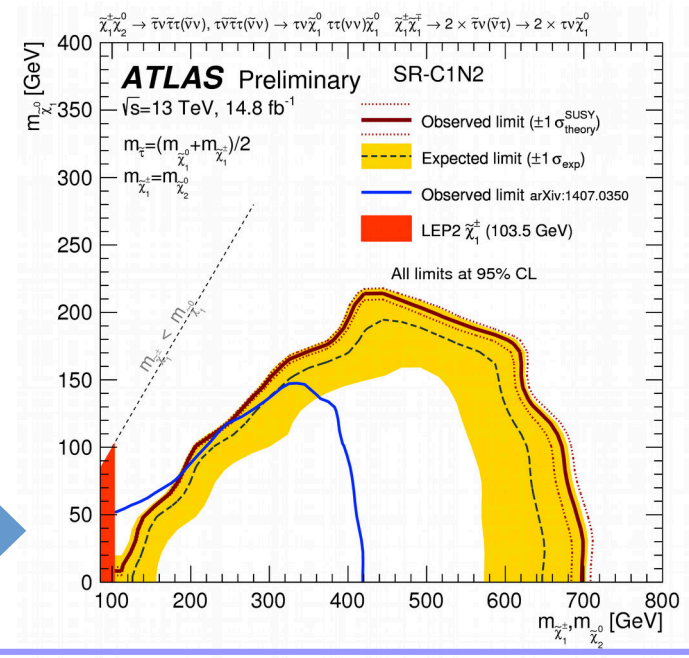



ATLAS multitaus (ATLAS-conf-2016-093)

better sensitivity at low $m_{\tilde{\chi}_1^0}$ values

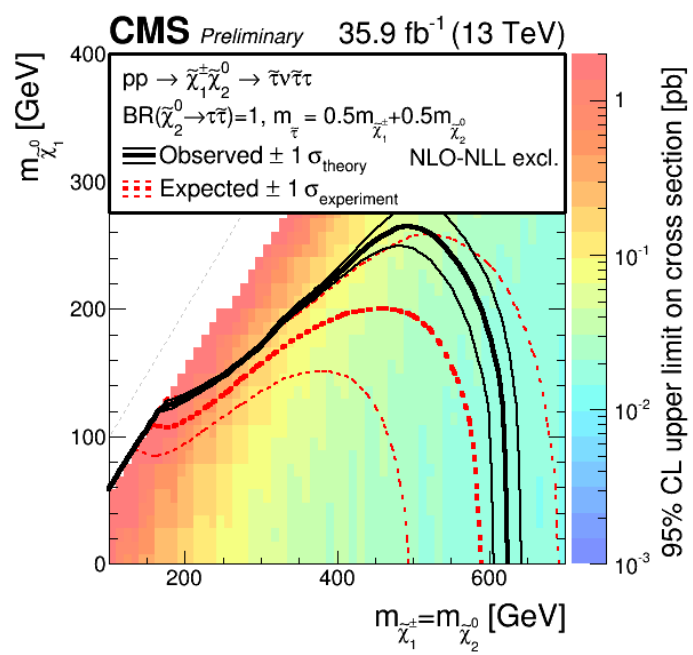
Limits set independently on both production modes

$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$

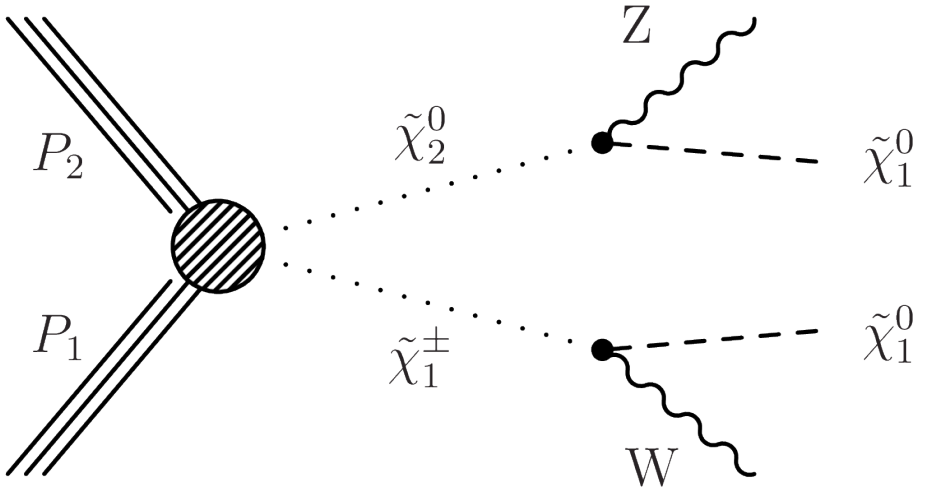


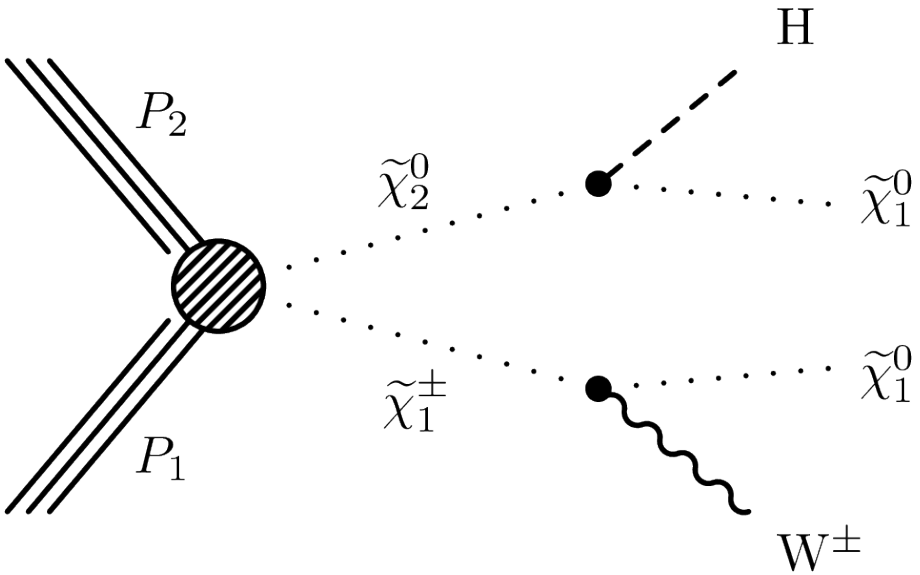

CMS multileptons (SUS-16-039)

constrains efficiently compressed part of the plane



# *Chargino-neutralino production with* $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0$ *and* $\tilde{\chi}_2^0 \rightarrow (Z/H)\tilde{\chi}_1^0$




- CMS-SUS-16-026
- CMS-SUS-16-039

# 1 lepton, 2b-jet and MET final states

Probing $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow (H\,\tilde{\chi}_1^0)(W\,\tilde{\chi}_1^0) \rightarrow (bb)(l\nu)\tilde{\chi}_1^0\tilde{\chi}_1^0$ final states

CMS-SUS-16-026, 13 fb$^{-1}$

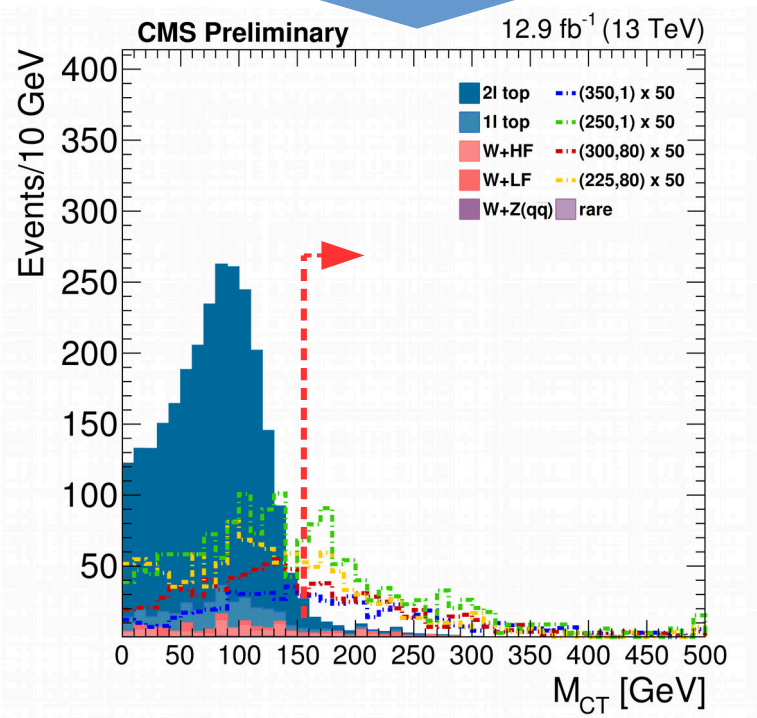
## Analysis specificities :

- use of reconstructed masses to discriminate background from potential signal :

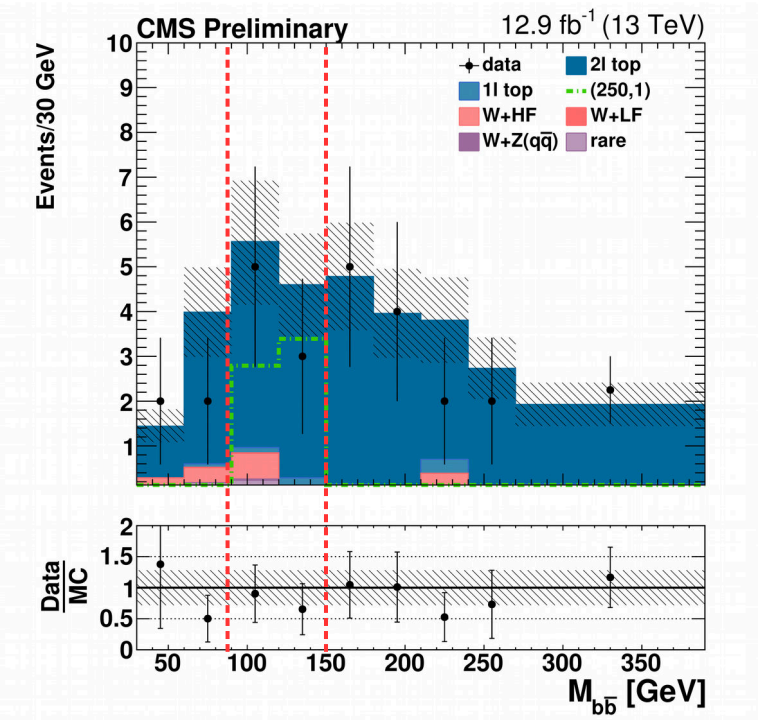
$$M_T = \sqrt{2\,p_T(l)\,\not{E}_T\,(1-\cos\Delta\phi(l,\not{E}_T))}$$

$$M_{CT} = \sqrt{2\,p_T^{b1}\,p_T^{b2}\,(1+\cos\Delta\phi_{bb})}$$

| Cut | Signal Region |
|---|---|
| N(leptons) | $=1$ |
| Isolated track veto | ✓ |
| Tau candidate veto | ✓ |
| N(b-tags) | $=2$ |
| $M_{b\bar{b}}$ | $\in$[90,150] GeV |
| $E_T^{miss}$ | $>100$ GeV |
| $M_T$ | $>150$ GeV |
| $M_{CT}$ | $>150$ GeV |




No evidence of excess above the SM expectations



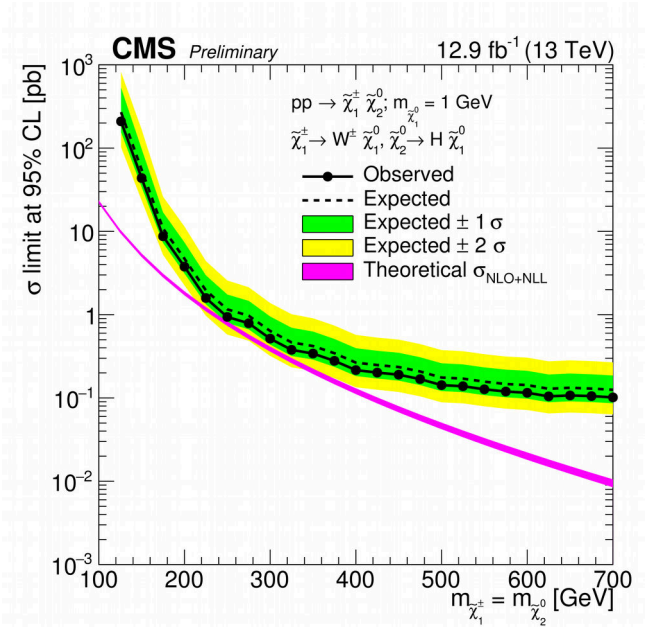
# *Probing EWK SUSY*

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W^{\pm} H \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W^{\pm} Z \tilde{\chi}_1^0 \tilde{\chi}_1^0$

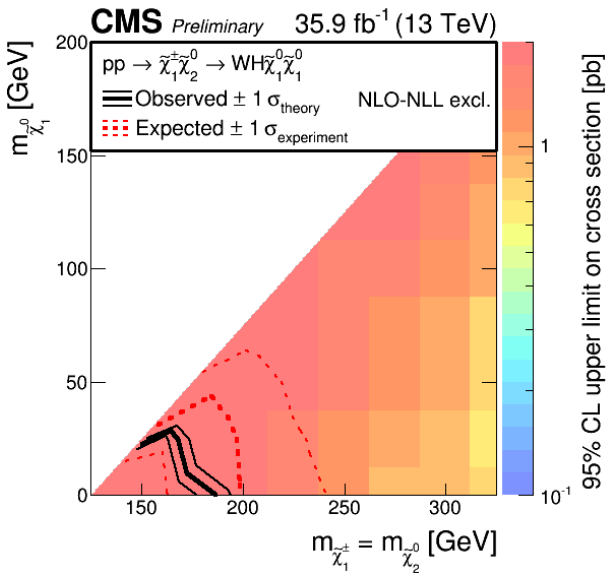
ll + 2b + MET (CMS-SUS-16-026)

Not sensitive enough with 13 fb$^{-1}$

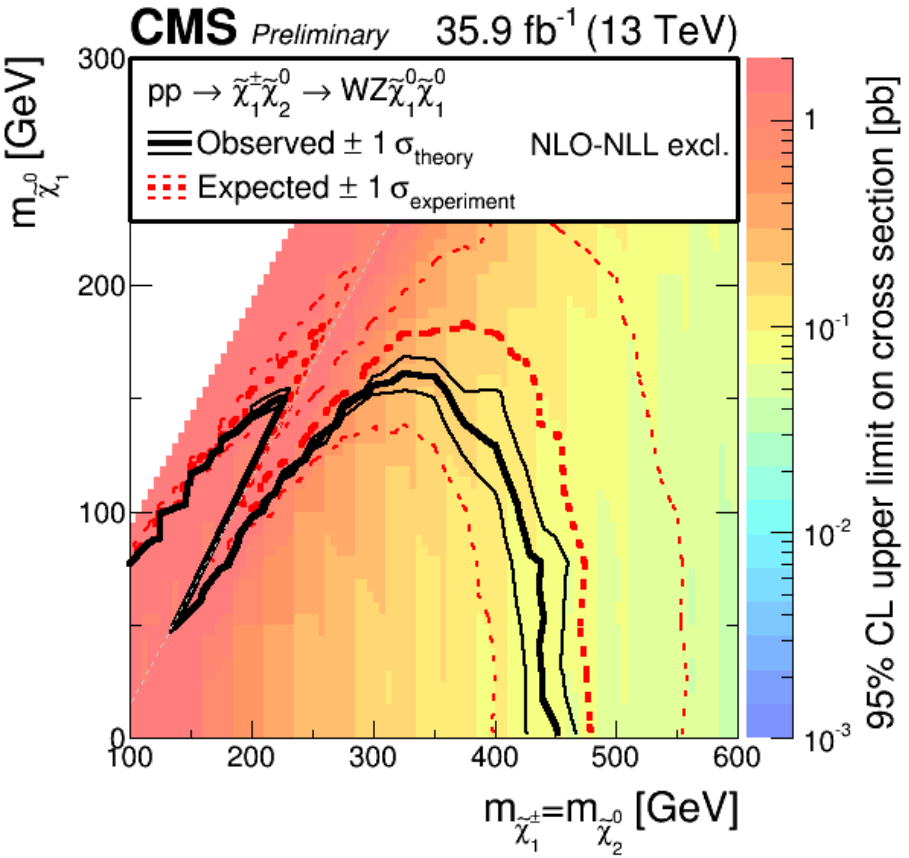



CMS multileptons (CMS-SUS-16-039)

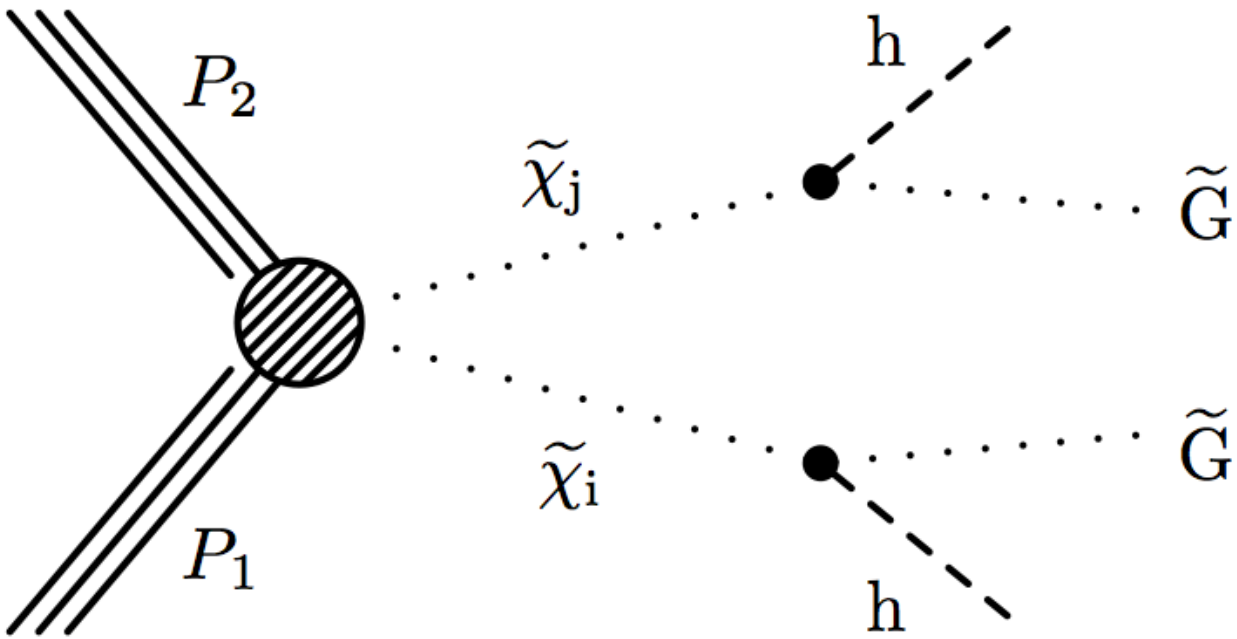
Sensitivity at low $m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^{\pm}}$




CMS multileptons (SUS-16-039)



# *Neutralino-neutralino production with* $\tilde{\chi}_i^0 \rightarrow (H)\tilde{G}$




Neutralino-neutralino production
Specific GMSB model :

- higgsino as next-to-LSP
- Goldstino as LSP

- CMS-SUS-16-044

# *HH production searches with $H \to b\bar{b}$*

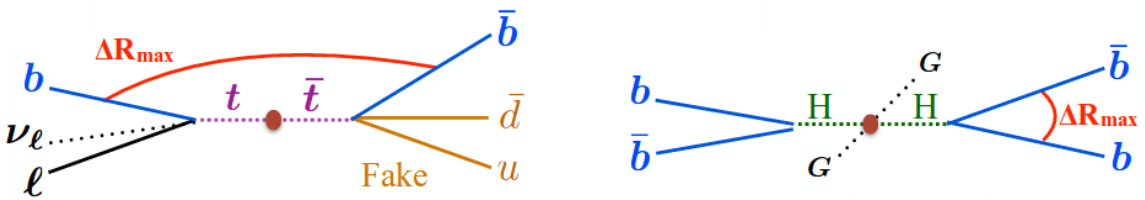
NEW

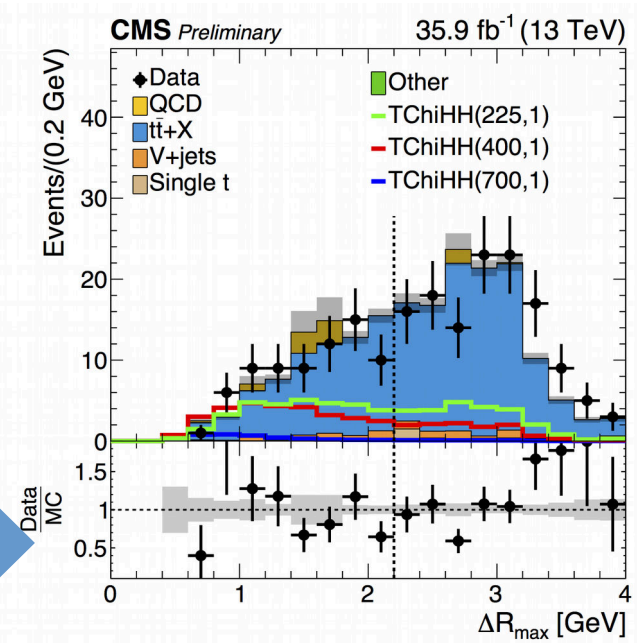
CMS-SUS-16-044 36 fb$^{-1}$

## Signature targeted

- large $\not{E}_T$ > 150 GeV, four bins
- 4 or 5 jets events ($p_T$>30 GeV, |η|<2.4)
- pick the 4 most b-like
  - → use of deep learning b-tagging!
- lepton veto

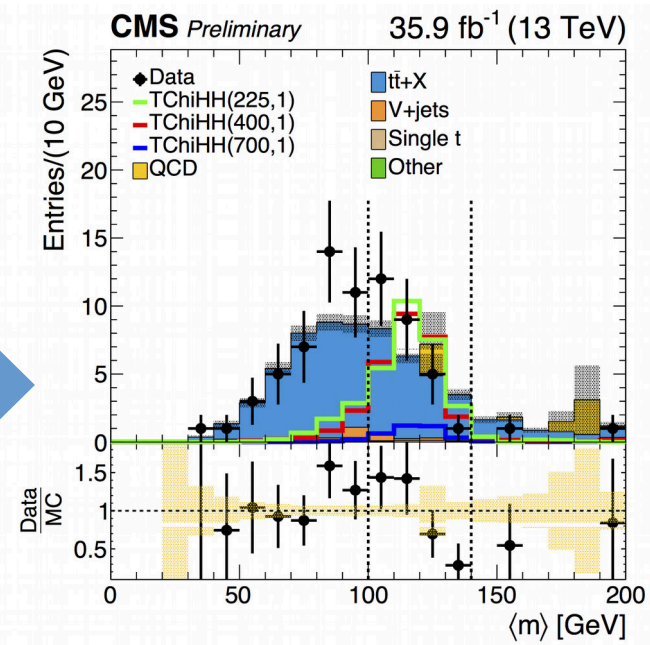
- use of advanced kinematic variables




- use of $m_H$ reconstruction

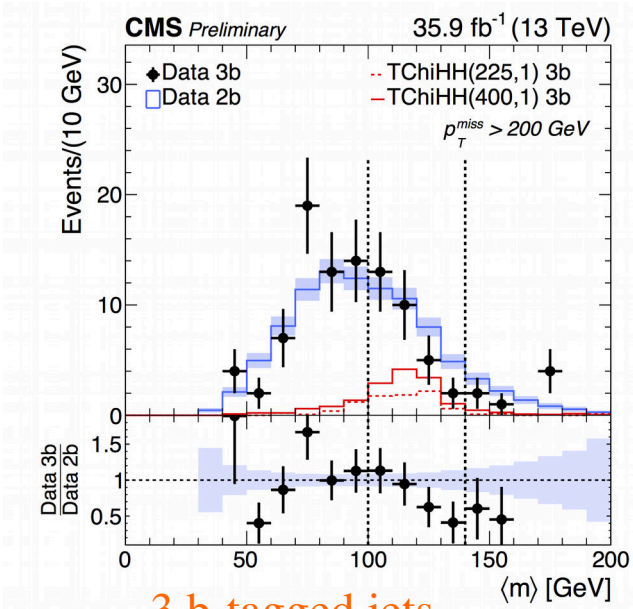
$$\begin{cases} \Delta m = \min_{i=1}^{3}(|m^i_{H_1} - m^i_{H_2}|) < 40\,\text{GeV} \\ 100\,\text{GeV} < \langle m \rangle = \dfrac{m_{H_1} + m_{H_2}}{2} \leq 140\,\text{GeV} \end{cases}$$



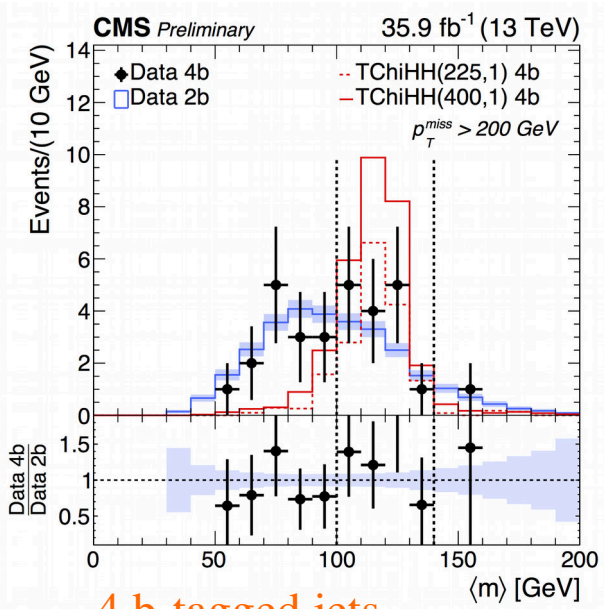
# $\tilde{\chi}_i^0 \tilde{\chi}_j^0$ production interpretation

NEW

HH → 4b (SUS-16-044)




3 b-tagged jets

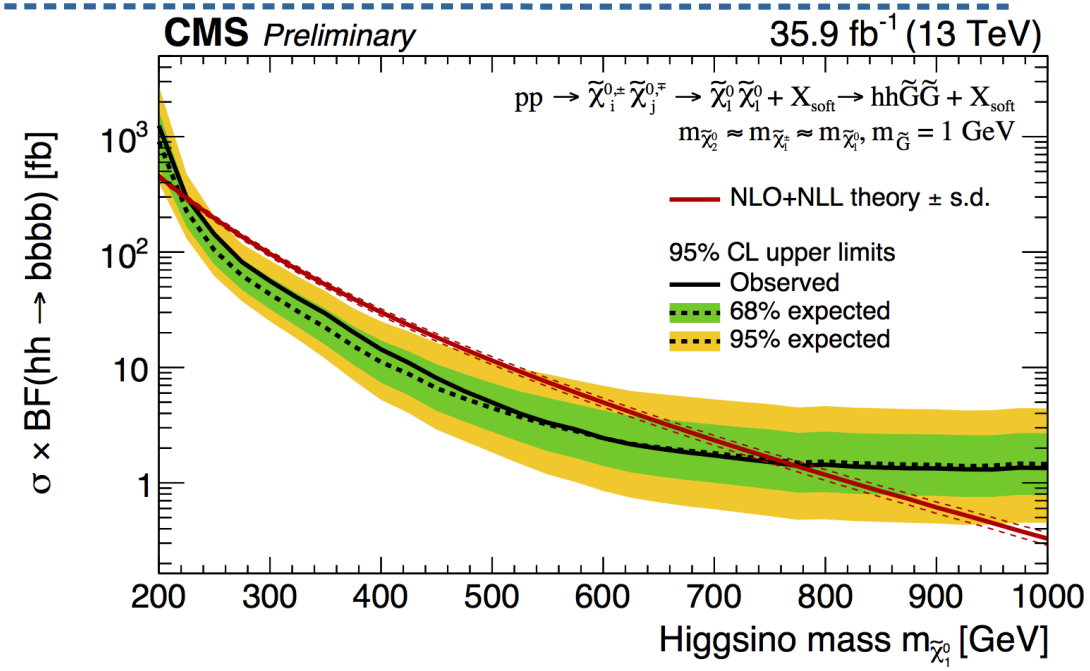



4 b-tagged jets

Observations consistent with SM expectations

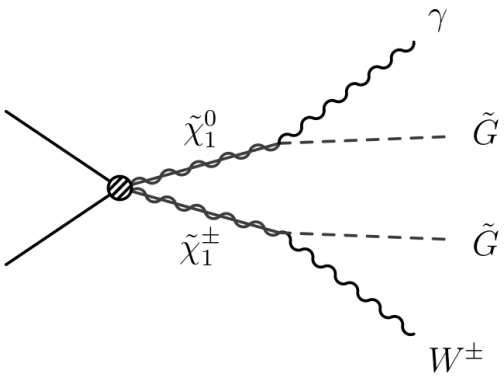
- Goldstino mass set to 1 GeV
- exclusion limit set on Higgsino mass

Higgsino masses excluded in [ 225, 770 ] GeV range



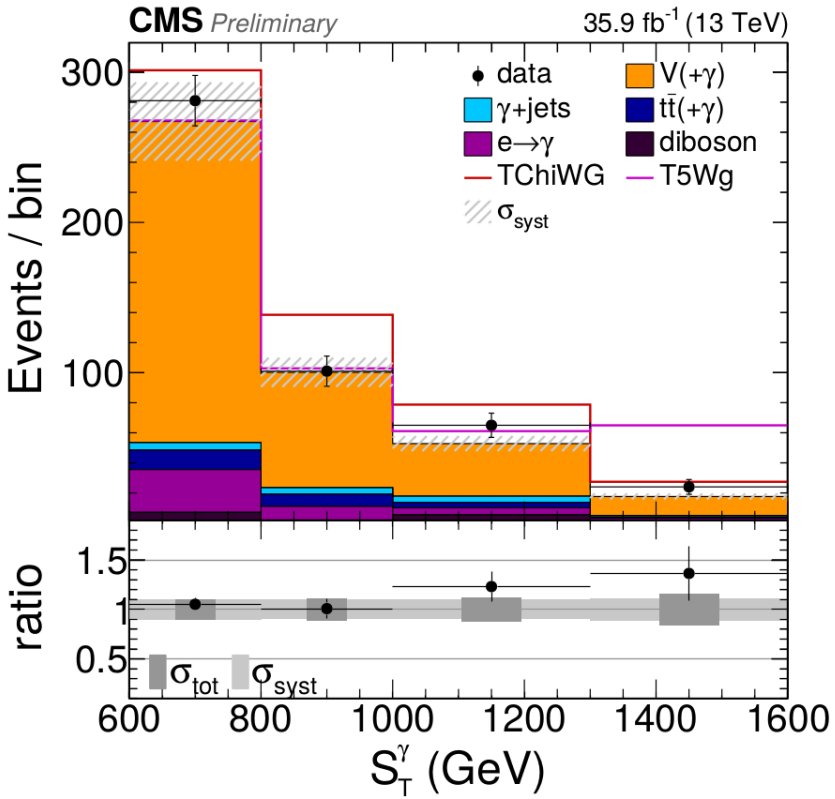
# *Last minute result : γ+MET search*

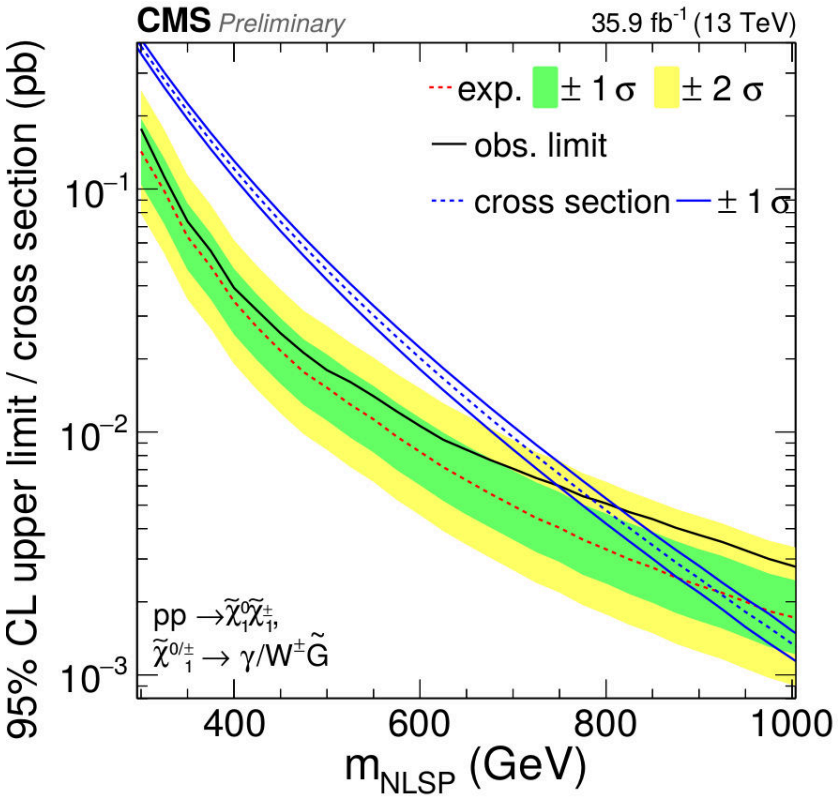
NEW




- 36 fb$^{-1}$
- one photon with pT > 180 GeV
- large $\not{E}_T$
- large $m_T$
- use of

$$S_T^\gamma = \not{E}_T + \sum_\gamma p_T$$



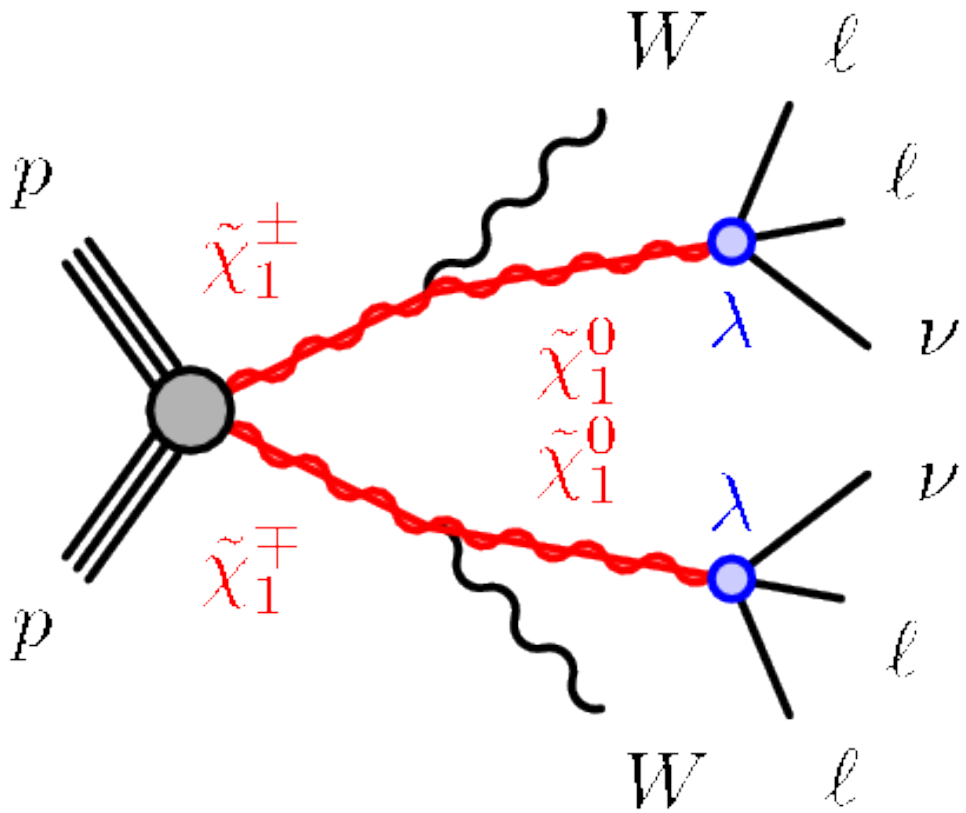




No evidence of an excess

NLSP masses excluded below 750 GeV

CMS-SUS-16-046

# *Chargino-chargino production with R parity-violating decays*




▶ ATLAS-CONF-2016-075

# *Looking for RPV decays with 4+ lepton signatures*

## ATLAS-CONF-2016-075, 13 fb$^{-1}$

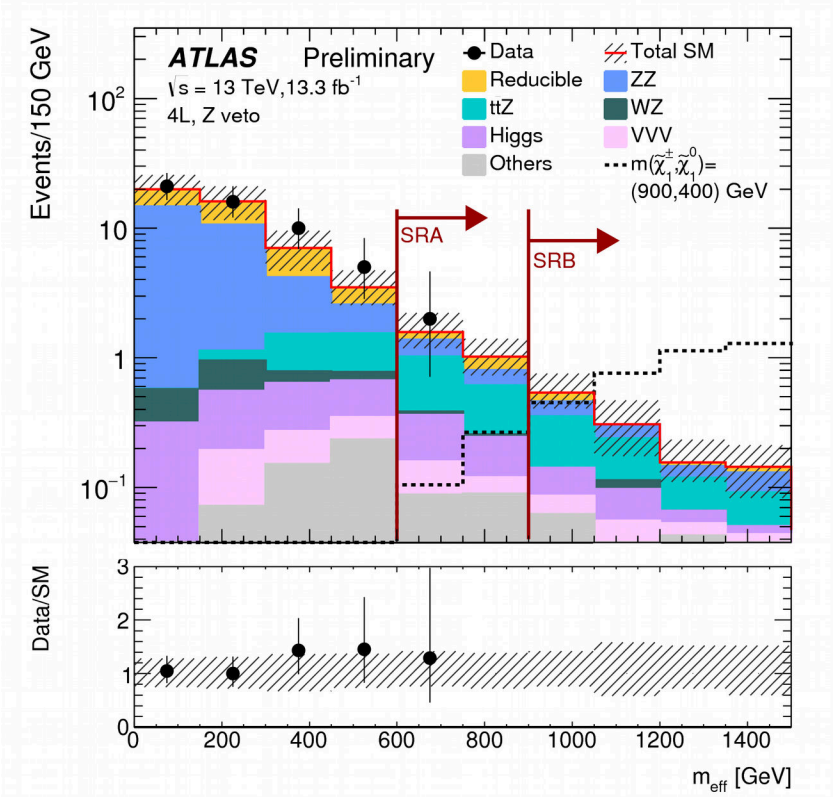
### Considers RPV decays

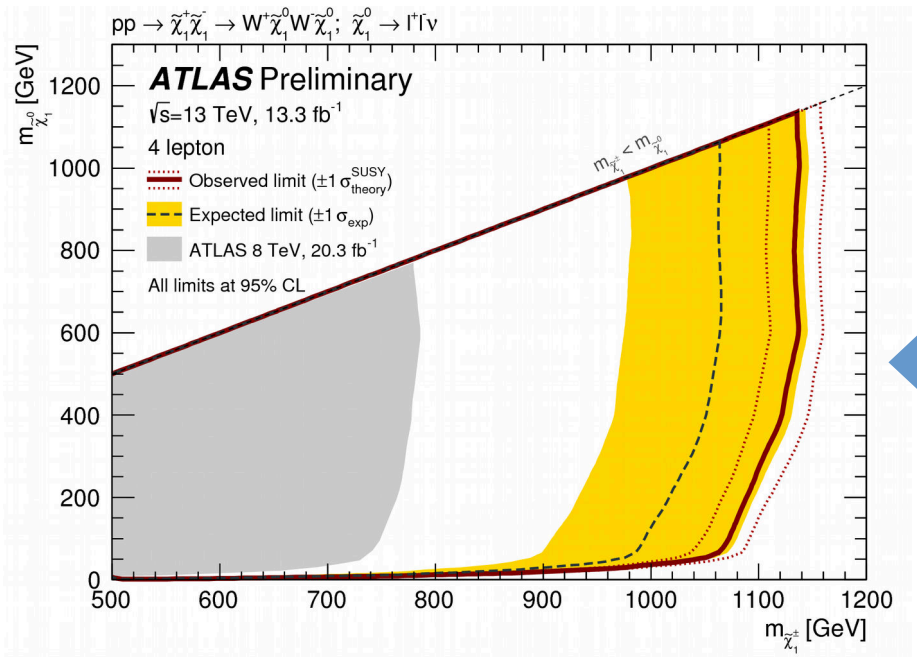
$$\tilde{\chi}_1^0 \rightarrow \ell_k^{\pm}\ell_{i/j}^{\mp}\nu_{j/i} \quad \text{with i,j,k} \in \text{e,}\mu$$

### Analysis specificities

- large number of leptons expected
- use of $m_{eff}$ as main discriminator

$$m_{eff} = \not{E}_T + \sum_{\text{leptons}} p_T + \sum_{\text{jets}(p_T>40\text{GeV})} p_T$$



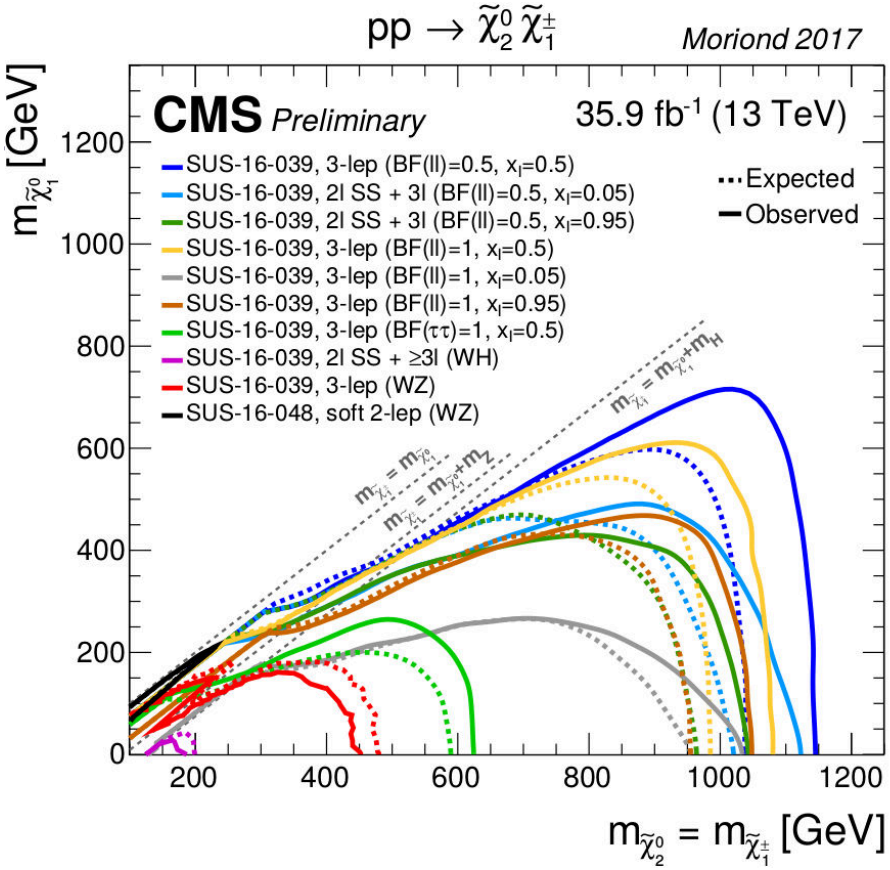

Good agreement with SM expectations

- Setting exclusion limits in $(\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0)$ plane

# *Summary*

Electroweak supersymmetric signatures have been probed in

- various production modes
- various mass ranges
- various final states




No significant excess indicating presence of physics beyond the Standard Model has been found in 13 TeV pp collision data

Few analyses have been already updated using 36 fb$^{-1}$ of 13 TeV datasets recorded by ATLAS or CMS : stay tuned for further results!

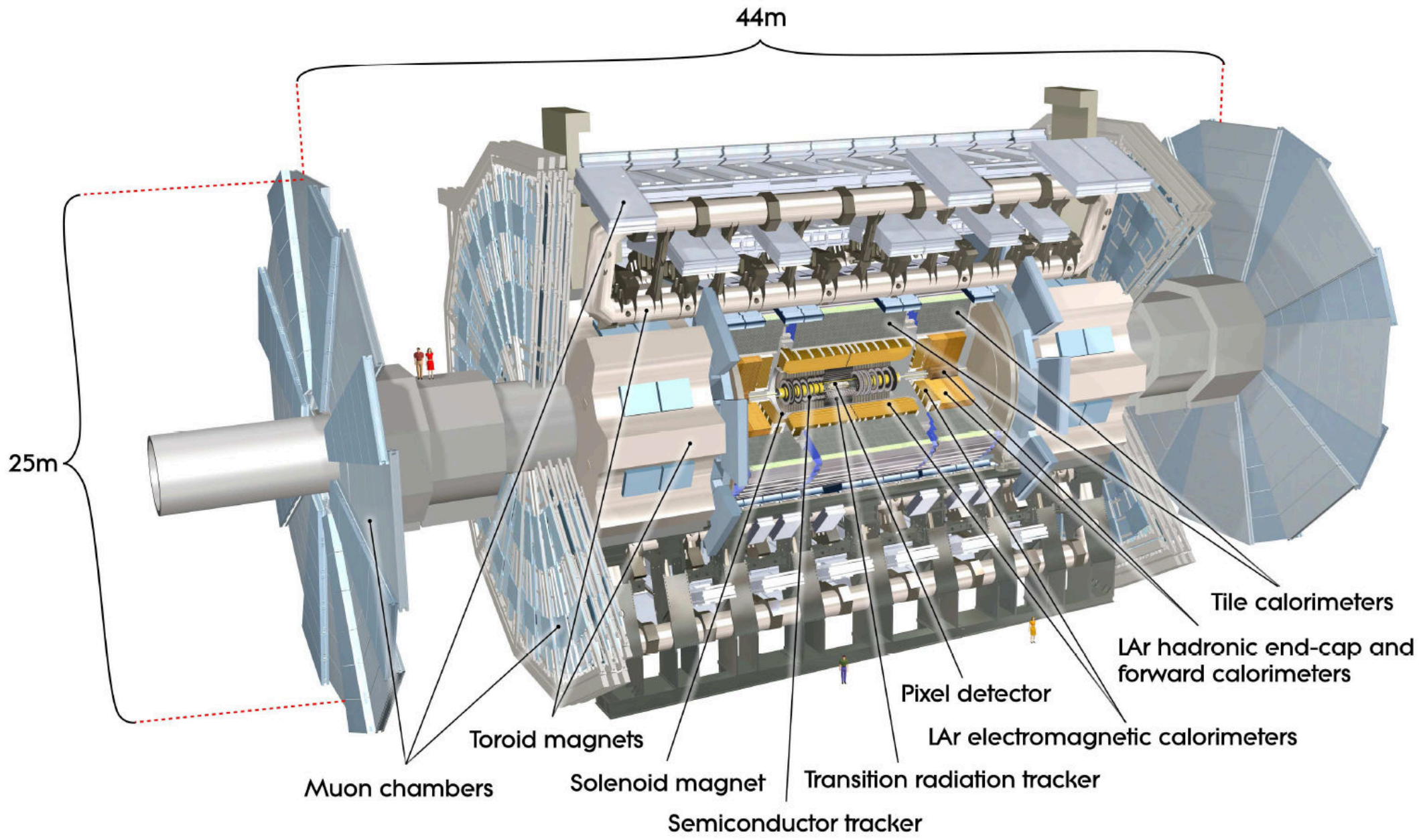
Thank you for your attention!

# *References*

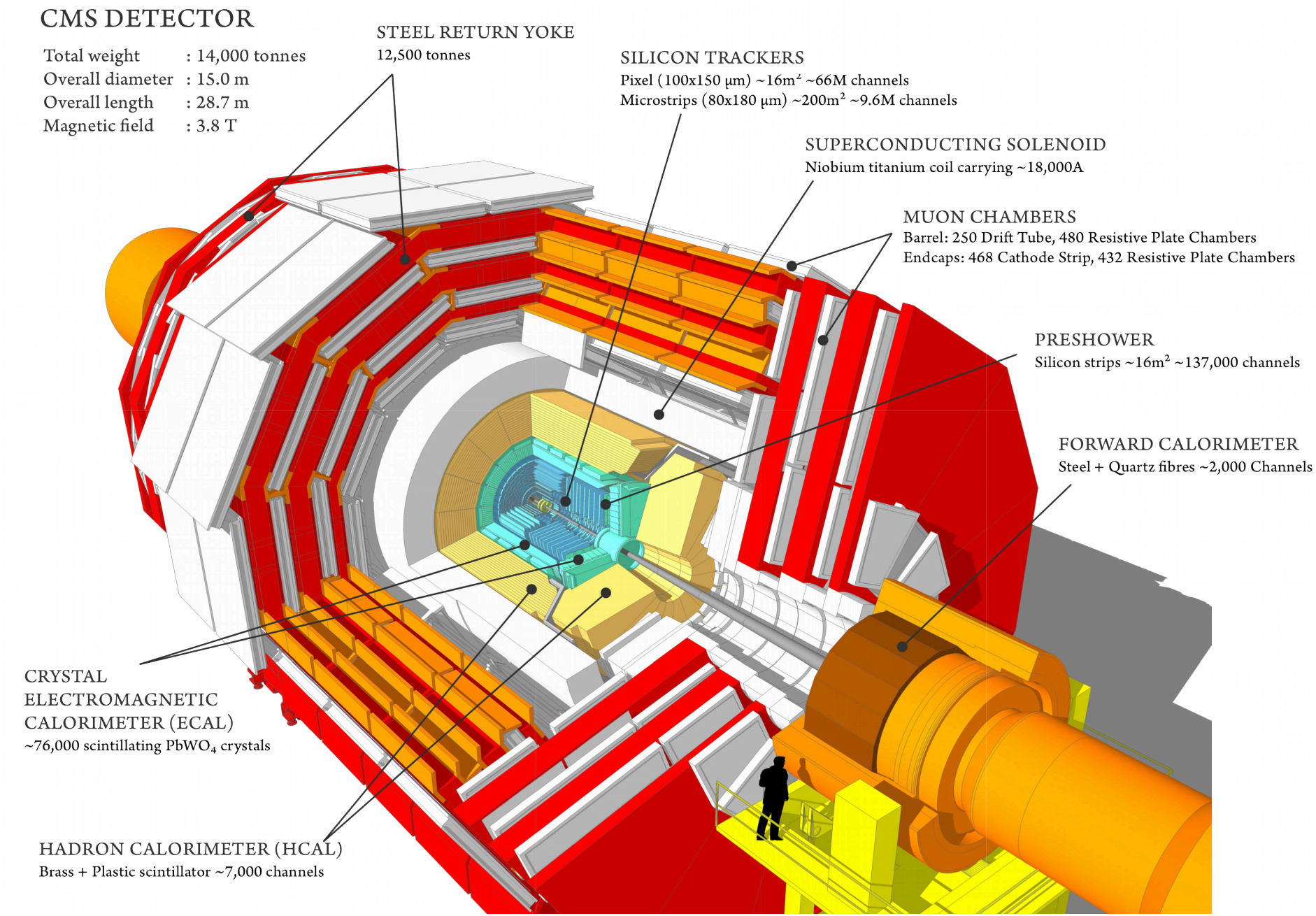
| | ATLAS | CMS |
|---|---|---|
| 0 leptons | – | CMS-SUS-16-044 |
| | | CMS-SUS-16-046 |
| 1 lepton | – | CMS-SUS-16-026 |
| 2+ leptons | ATLAS-CONF-2016-093 | CMS-SUS-16-021 |
| | ATLAS-CONF-2016-096 | CMS-SUS-16-039 |
| 4+ leptons (RPV) | ATLAS-CONF-2016-075 | – |

# *Additional material*

# *The ATLAS experiment*

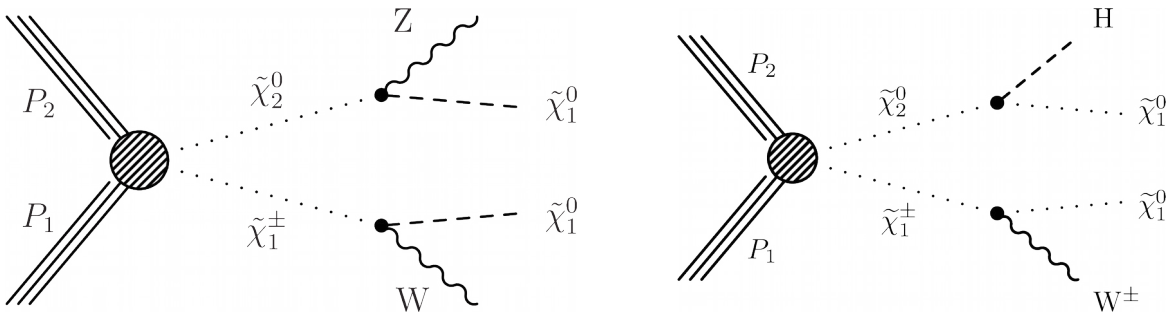


# *The CMS experiment*



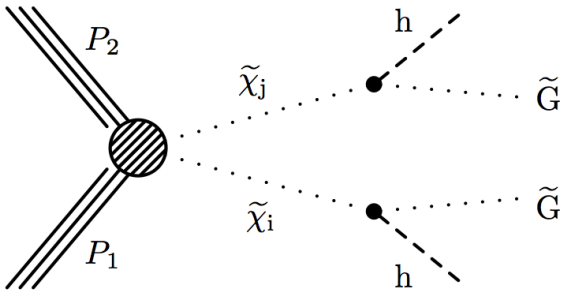
# *Which signal models are probed?*

Chargino-neutralino production
Direct electroweakino decay
into LSP + electroweak boson

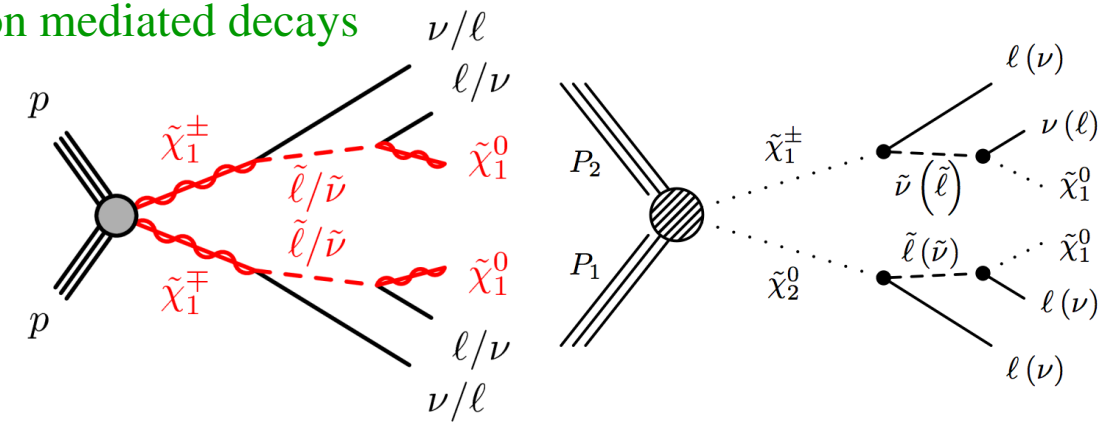



Neutralino-neutralino production
Specific GMSB model :

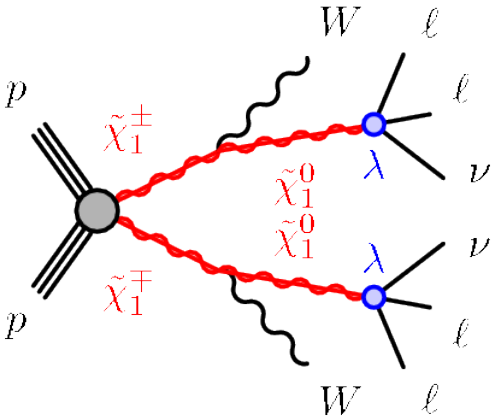
- higgsino as next-to-LSP
- Goldstino as LSP




Slepton mediated decays

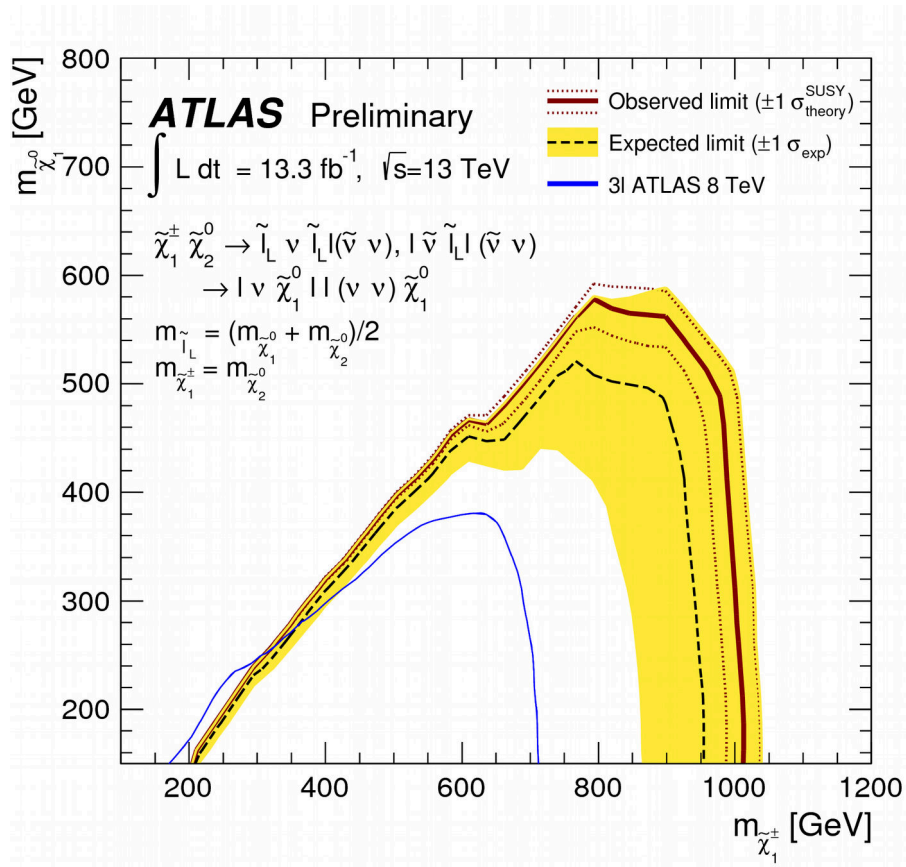



RPV decays related to operators $\lambda_{ijk} L_i L_j \overline{E}_k$



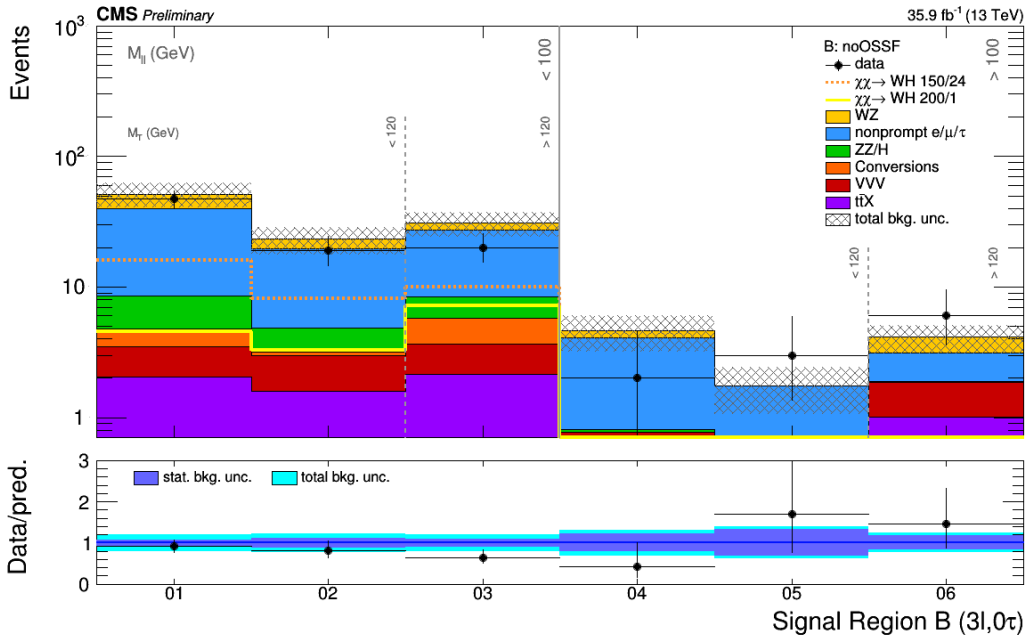
# *ATLAS-CONF-2016-096*

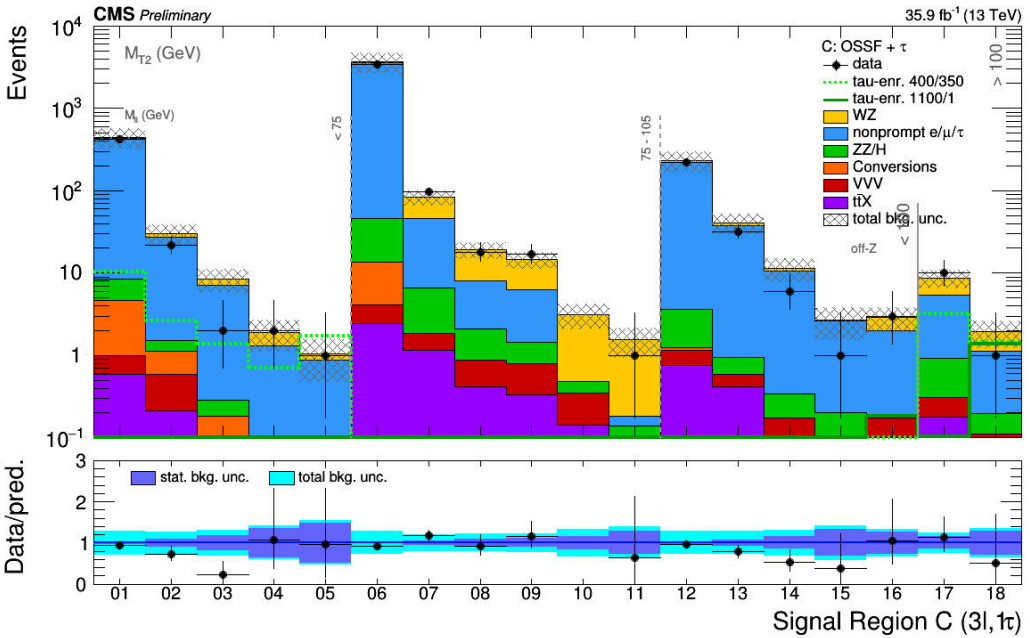
Chargino-neutralino production exclusion limits

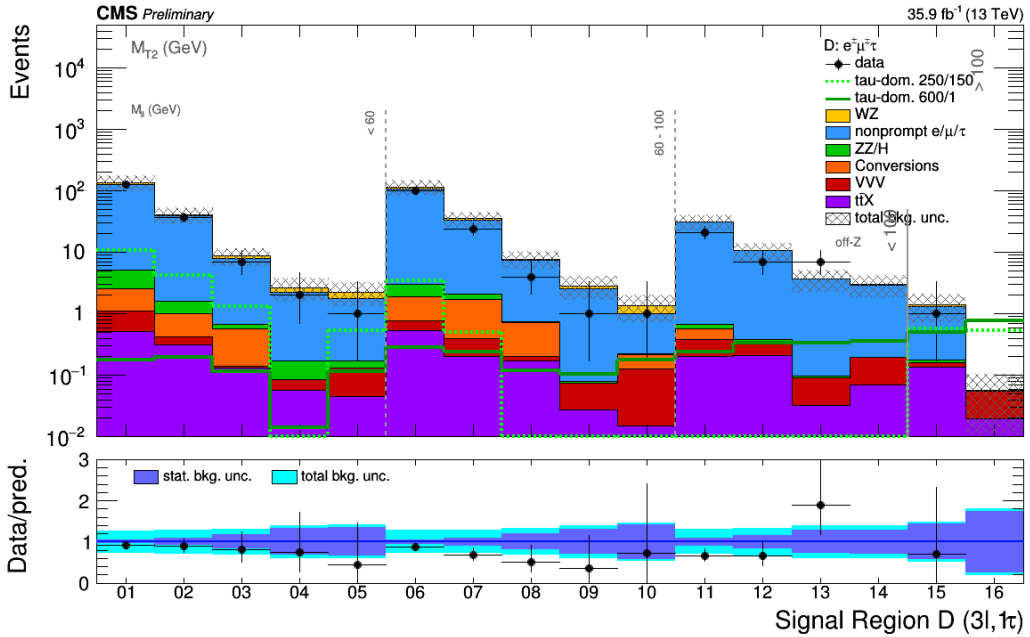


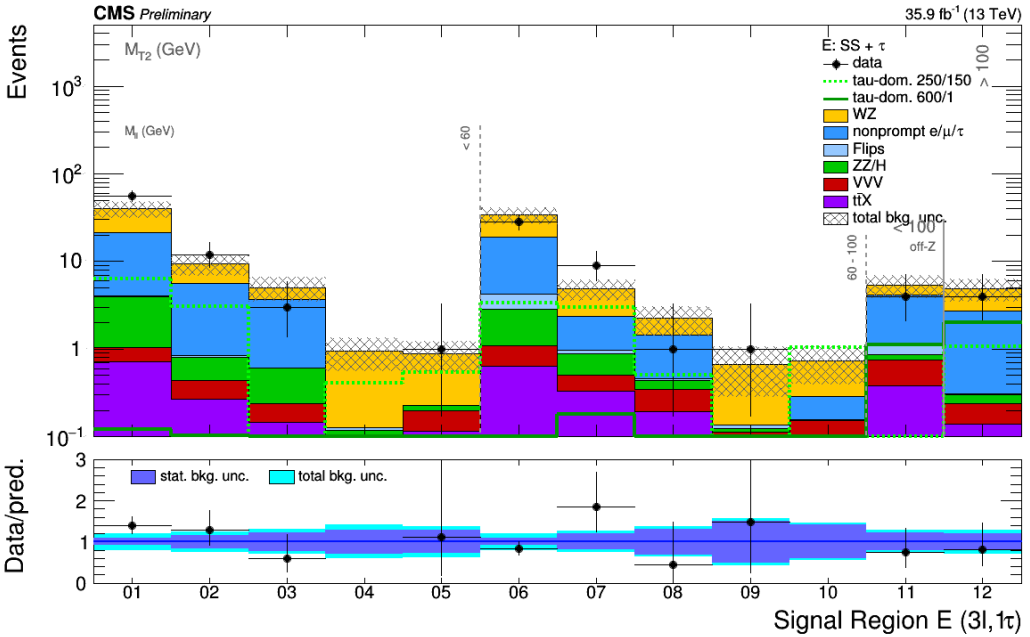

| Systematic | SR3ℓI | SR3ℓH |
|---|---|---|
| Statistical uncertainty | 18% | 20% |
| Jet Energy Scale/Resolution | 6% | 6% |
| Theory | 15% | 55% |
| Electron Energy Scale/Resolution | 2% | 6% |
| Reducible closure | 13% | −− |

# CMS-SUS-16-039 results

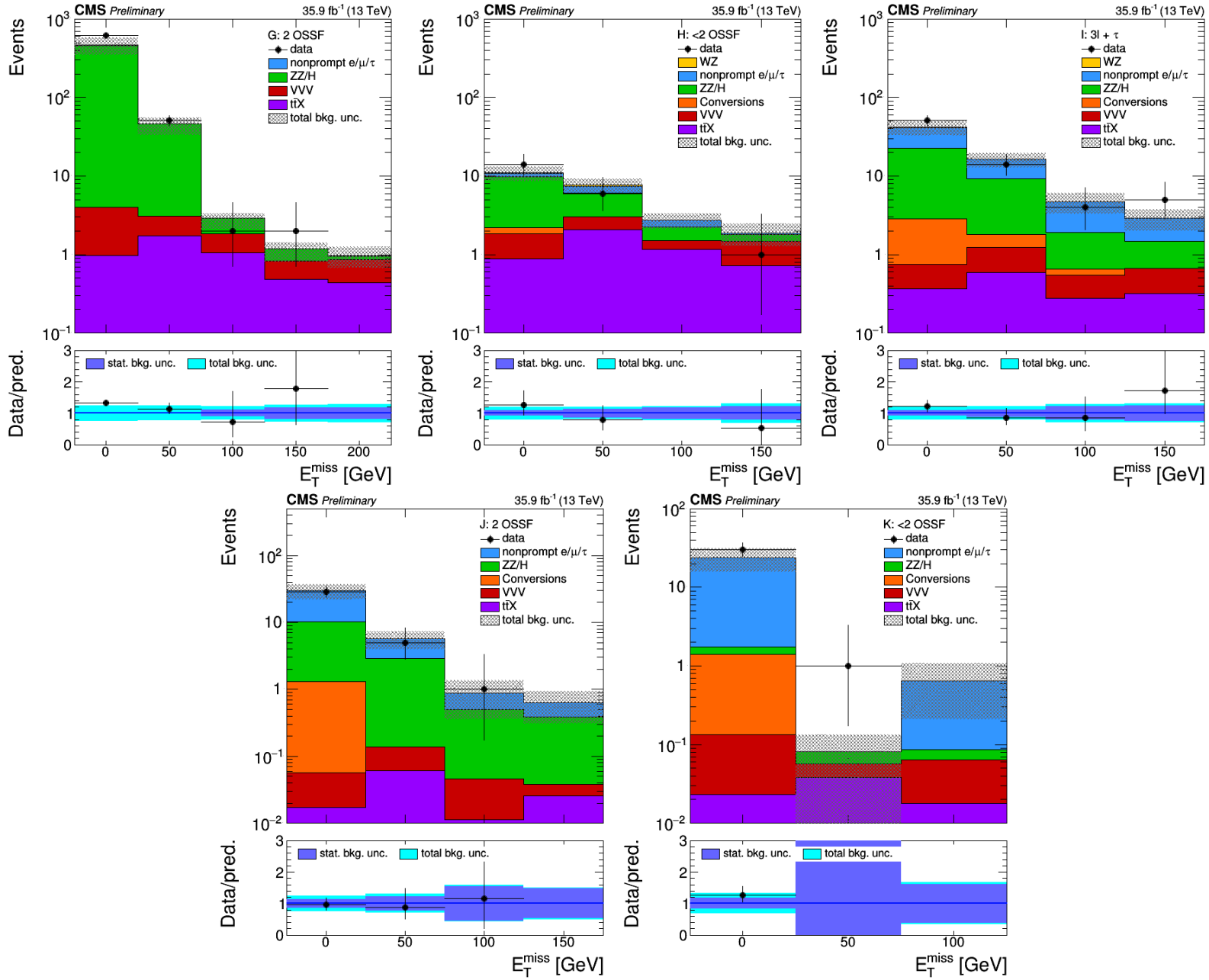


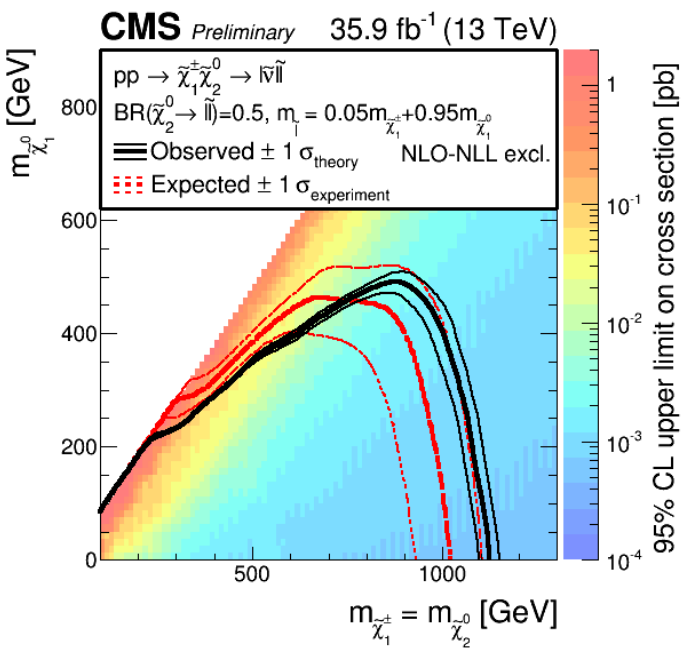



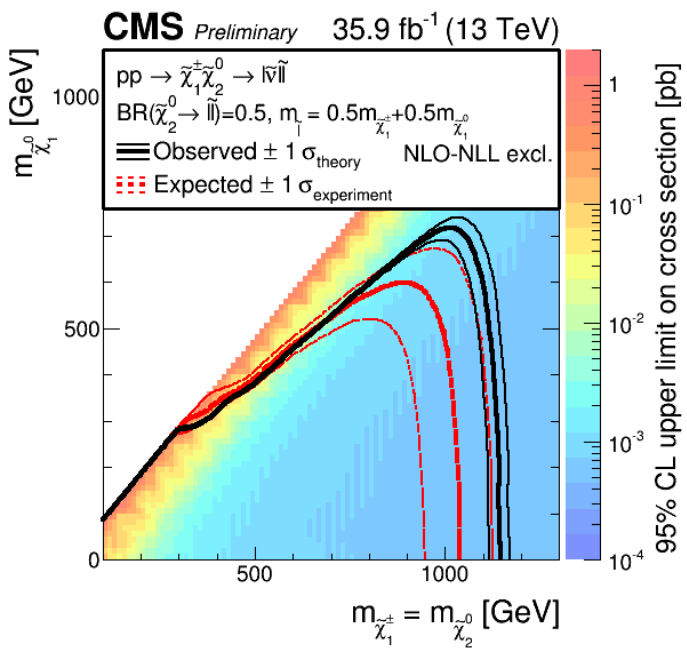
# *CMS-SUS-16-039 results*



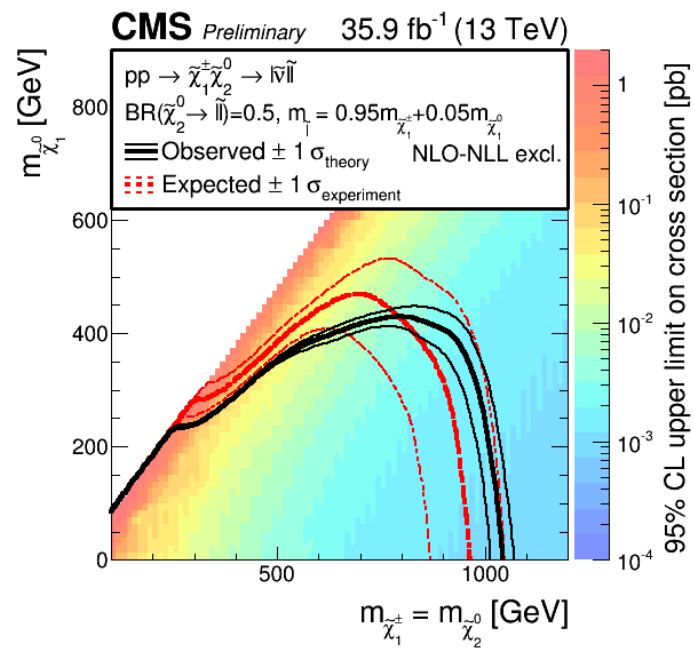
# *CMS-SUS-16-039 slepton interpretations*




Almost degenerated slepton-LSP masses

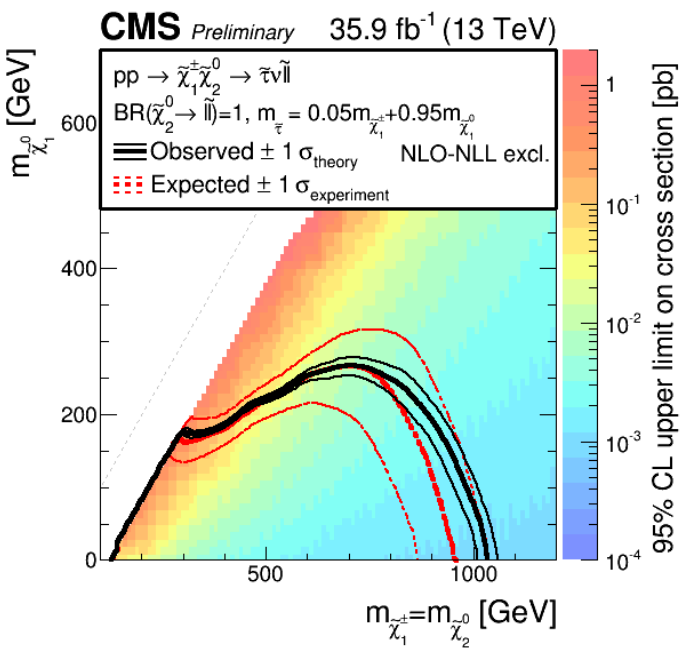



Median slepton mass

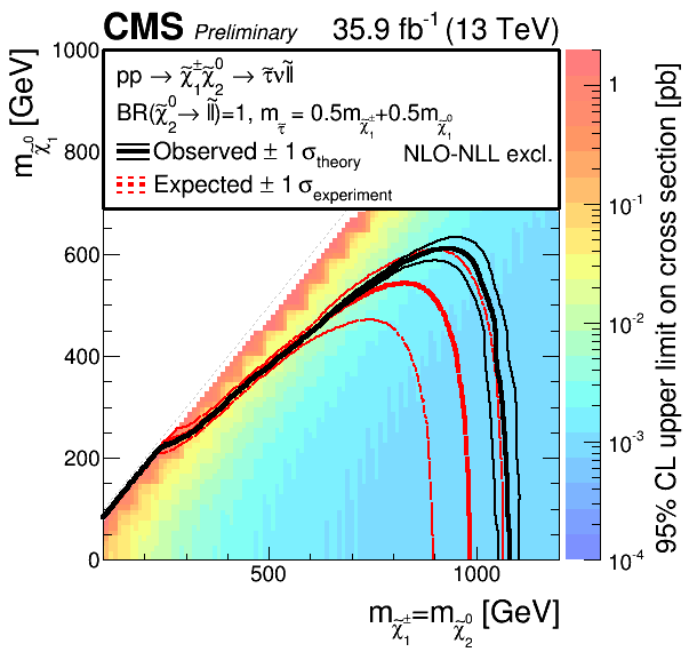



Almost degenerated slepton- $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses

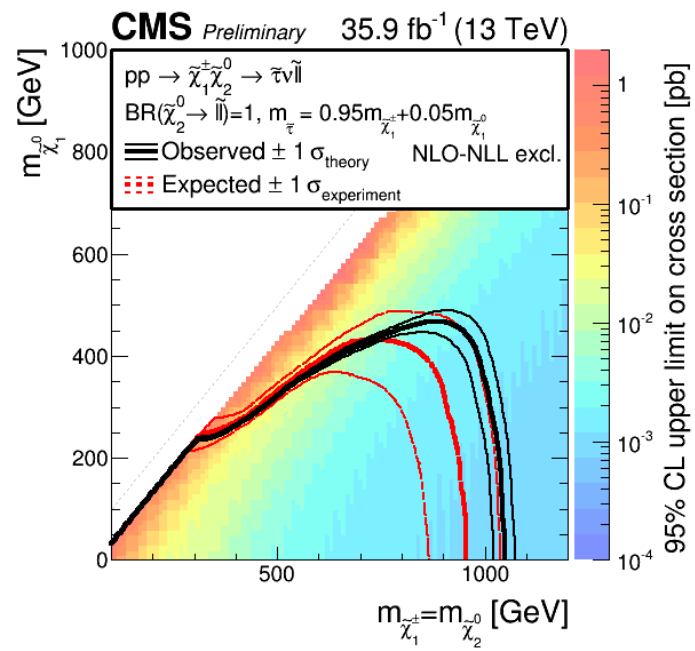
# *CMS-SUS-16-039 stau enriched interpretations*




Almost degenerated slepton-LSP masses




Median slepton mass



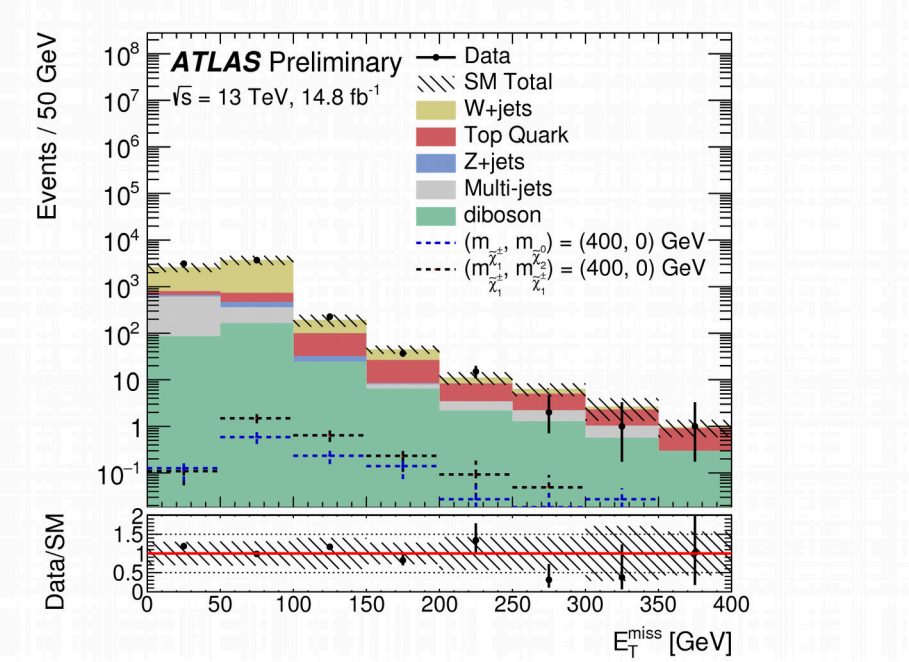

Almost degenerated slepton- $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses

# *CMS-SUS-16-039 uncertainties*

| Source | Estimated uncertainty (%) | Treatment |
|---|---|---|
| $e/\mu$ selection | 3 | flat |
| $\tau_h$ selection | 5 | flat |
| Trigger efficiency | 1–3 | flat |
| Jet energy scale | 2–10 | shape |
| b tag veto | 1-2 | shape |
| Pileup | 1–5 | shape |
| Integrated luminosity | 2.6 | flat |
| Scale variations and PDF ($t\bar{t}Z$ and $t\bar{t}W$) | 15 | flat |
| Theoretical (ZZ) | 25 | flat |
| Conversions | 15 | flat |
| Other backgrounds | 50 | flat |
| Monte Carlo statistical precision | 1–30 | flat |
| Nonprompt leptons (closure) | 30–36 | flat |
| Nonprompt leptons (ewk subtraction) | 5-20 | shape |
| Charge misidentification | 20 | flat |
| WZ normalization | 10 | flat |
| WZ shape | 5–50 | shape |
| ISR uncertainty | 1–5 | shape |
| Scale variations for signal processes | 1–2 | shape |
| Lepton efficiencies | 2 | flat |
| Signal acceptance ($E_T^{miss}$ modeling) | 1–5 | shape |

# *ATLAS-CONF-2016-093*

W+jet validation region



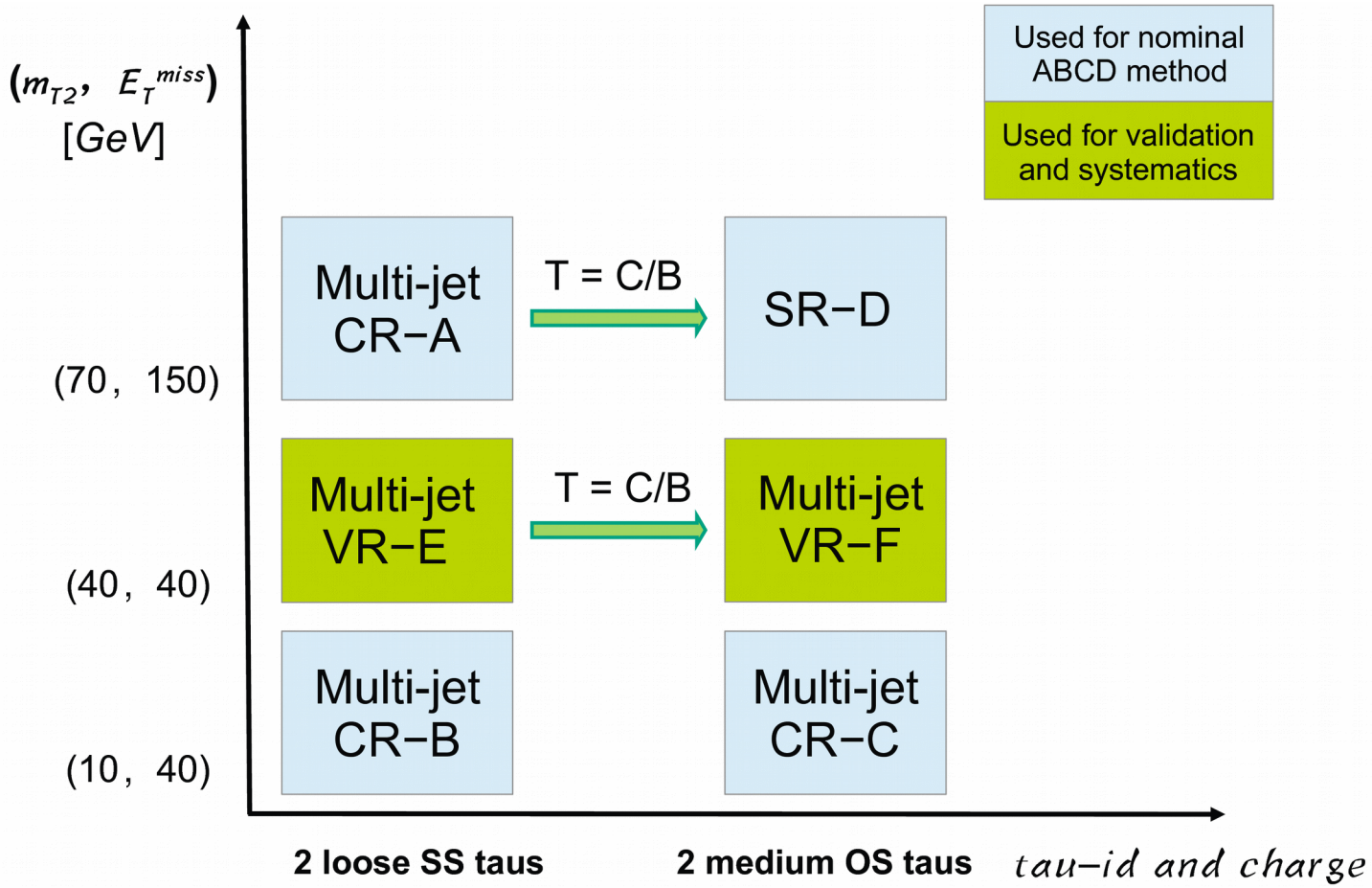

Important backgrounds controlled with collision data :

- multijet → ABCD method
- W+jet → normalized from data

| SM process | SR-C1C1 | SR-C1N2 |
|---|---|---|
| diboson | $1.8 \pm 0.7$ | $2.3 \pm 0.9$ |
| $W$+jets | $0.57 \pm 0.33$ | $0.67 \pm 0.34$ |
| top | $0.35^{+0.47}_{-0.35}$ | $0.6 \pm 0.5$ |
| $Z$+jets | $0.29 \pm 0.12$ | $0.28 \pm 0.12$ |
| multi-jet | $2.1 \pm 1.6$ | $2.1 \pm 1.6$ |
| SM total | $5.1 \pm 2.0$ | $5.9 \pm 2.1$ |
| Observed | 3 | 3 |
| Reference point 1 | $10.1 \pm 2.0$ | $13.0 \pm 2.6$ |
| Reference point 2 | $10.4 \pm 2.0$ | $10.4 \pm 2.0$ |
| Expected $\sigma^{95}_{\text{vis}}$ [fb] | $0.41^{+0.20}_{-0.12}$ | $0.43^{+0.21}_{-0.12}$ |
| Observed $\sigma^{95}_{\text{vis}}$ [fb] | 0.33 | 0.32 |
| $S^{95}_{\text{obs}}$ | 4.9 | 4.7 |
| $\text{CL}_b$ | 0.28 | 0.22 |

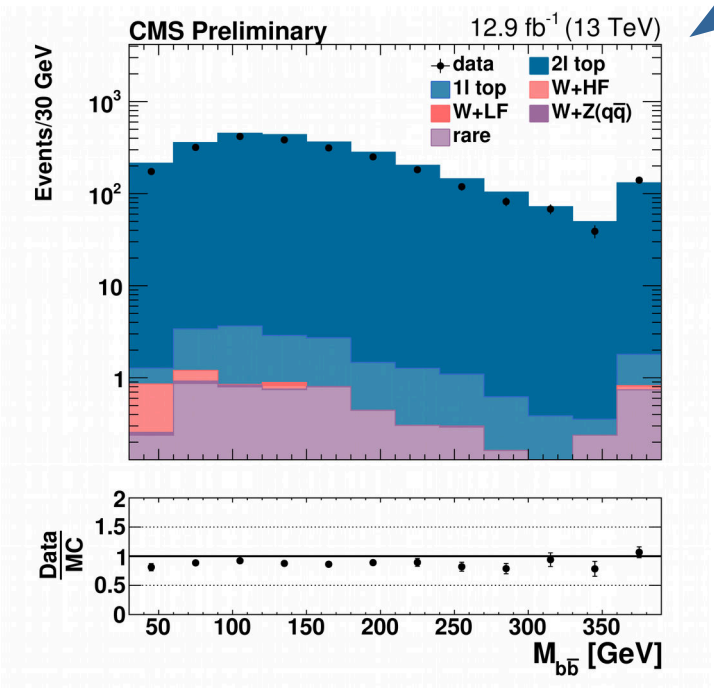
Results

# ATLAS-CONF-2016-093 : ABCD method



# *CMS-SUS-16-026*

| Cut | Signal Region | CR2$\ell$ | CR0b | CRMb$\bar{b}$ |
|---|---|---|---|---|
| N(leptons) | $= 1$ | $= 1$ or 2 | $= 1$ | $= 1$ |
| Isolated track veto | ✓ | inverted if 1$\ell$ | ✓ | ✓ |
| Tau candidate veto | ✓ | inverted if 1$\ell$ | ✓ | ✓ |
| N(b-tags) | $= 2$ | $= 2$ | $= 0$ | $= 2$ |
| $M_{b\bar{b}}$ | $\in$[90,150] GeV | - | $\in$[90,150] GeV | $\notin$[90,150] GeV |
| $E_T^{miss}$ | $> 100$ GeV | $> 100$ GeV | $> 100$ GeV | $> 100$ GeV |
| $M_T$ | $> 150$ GeV | $> 50$ GeV | $> 150$ GeV | $> 150$ GeV |
| $M_{CT}$ | $> 150$ GeV | - | $> 150$ GeV | $> 150$ GeV |




2 lepton control region

| Source | Typical Values |
|---|---|
| Integrated luminosity | 6.2% |
| MC statistics | 3–40% |
| Renormalization and factorization scales | 1–3% |
| B-tagging efficiency | 2–3% |
| Lepton efficiency | 2–5% |
| Trigger efficiency | 1–5% |
| Jet energy scale | 1–27% |
| Fastsim $E_T^{miss}$ resolution | 5–50% |

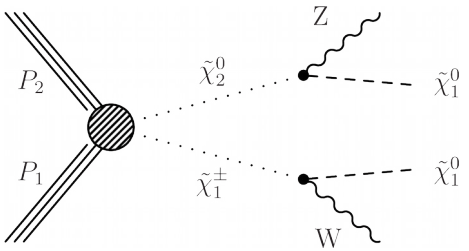
uncertainties

# *Search with opposite-sign dilepton signatures*

CMS-SUS-16-021, 13 $fb^{-1}$

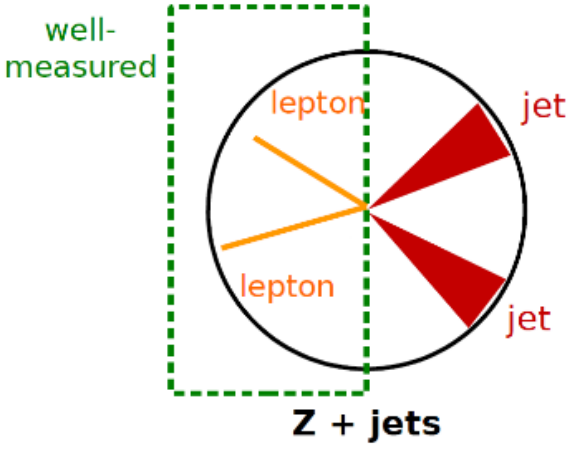
## Look for events with :

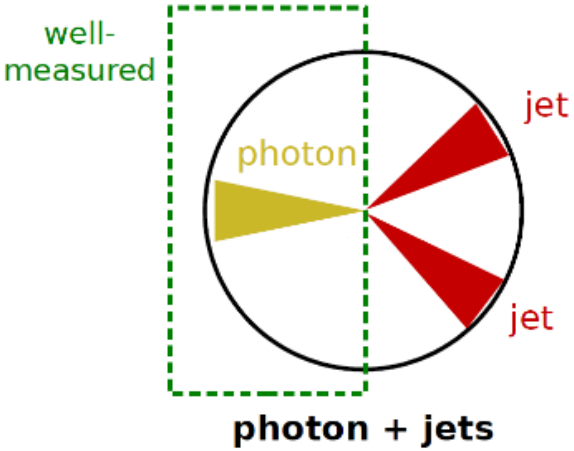
- same flavor dilepton pair ($p_T$> 25,20 GeV)
- 81 < $m_{ll}$ < 101 GeV
- $\not{E}_T$ > 150 GeV
- at least 2 jets with $p_T$ > 25 GeV
- $m_{T2}(ll)$ > 80 GeV
- additional $\not{E}_T$ cleaning selection ($\Delta\phi$, etc.)




## Dominant background : Drell-Yan process

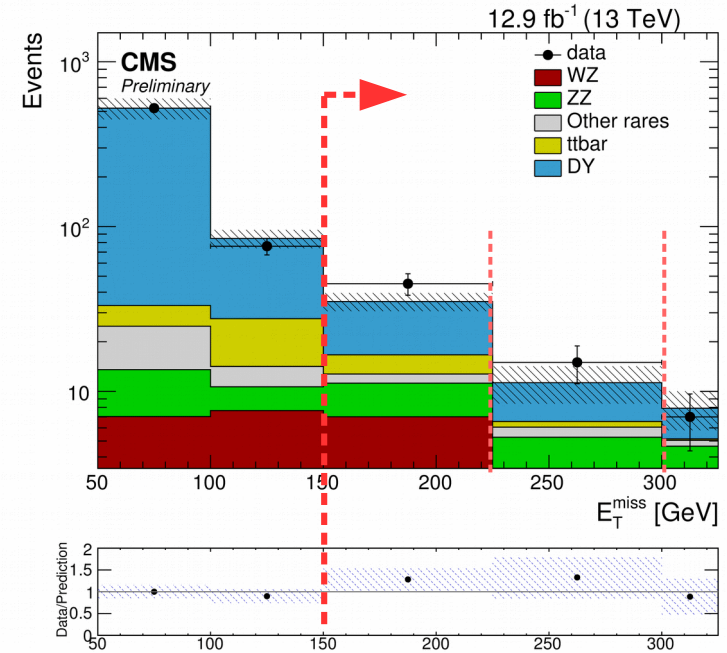
- measured using $\not{E}_T$ templates determined with $\gamma$+jets events




- includes artificial photon decay to compute $m_{T2}$ variables

Use of three large MET bins




No significant excess observed in data

# *CMS-SUS-16-021*

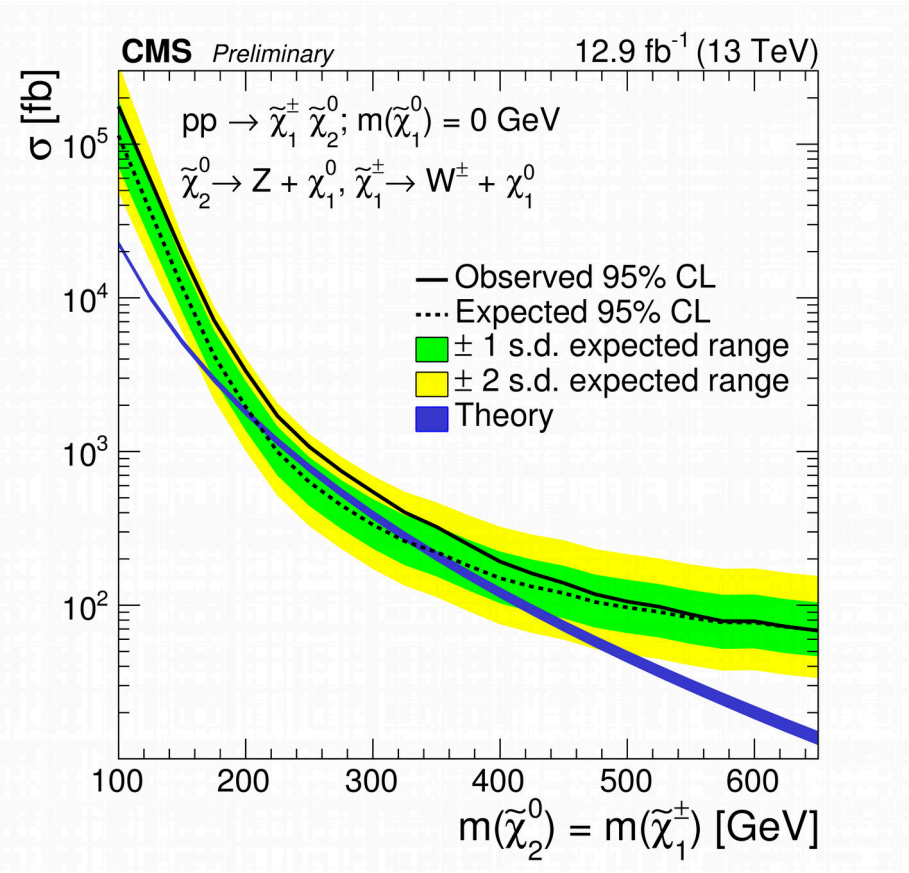
uncertainties

| Source | Typical Values |
|---|---|
| Integrated luminosity | 6.2% |
| MC statistics | 3–40% |
| Renormalization and factorization scales | 1–3% |
| B-tagging efficiency | 2–3% |
| Lepton efficiency | 2–5% |
| Trigger efficiency | 1–5% |
| Jet energy scale | 1–27% |
| Fastsim $E_T^{miss}$ resolution | 5–50% |

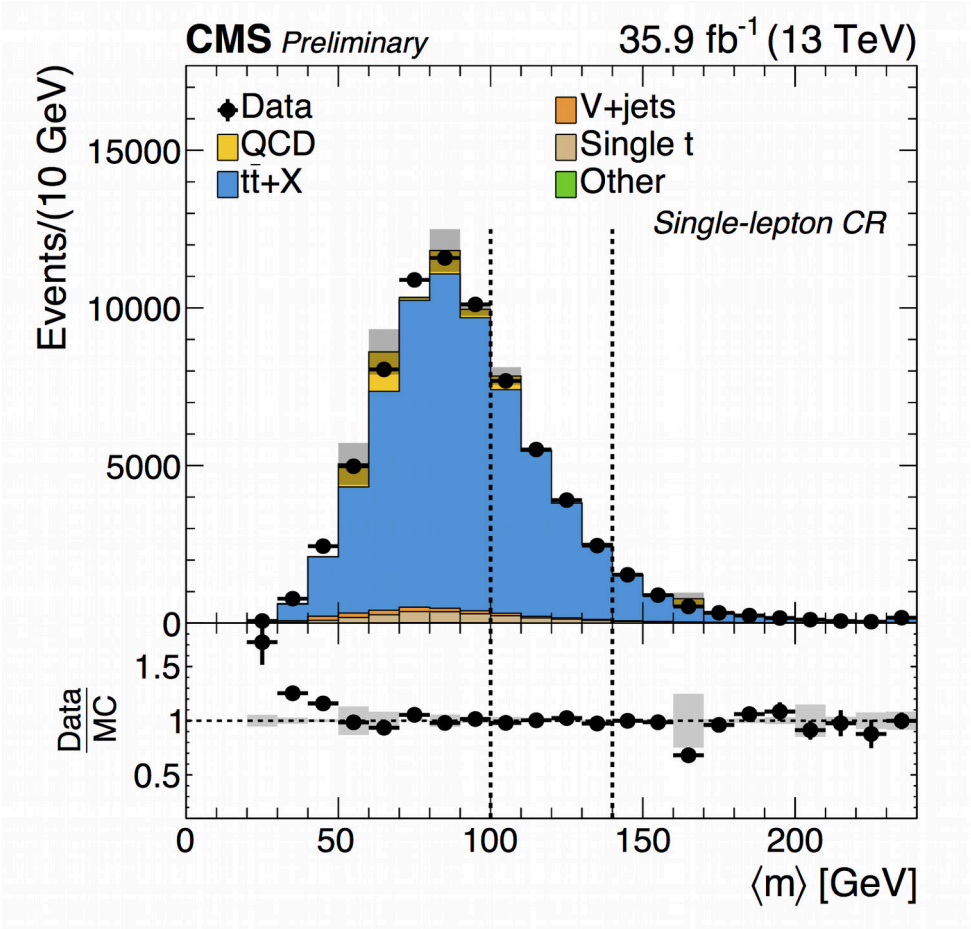
results

| MET region | 150 – 225 GeV | 225 – 300 GeV | $\geq$ 300 GeV |
|---|---|---|---|
| Other rare | $1.53 \pm 0.79$ | $0.80 \pm 0.45$ | $0.40 \pm 0.23$ |
| WZ | $7.01 \pm 2.16$ | $2.67 \pm 0.85$ | $2.61 \pm 0.84$ |
| ZZ | $4.20 \pm 1.98$ | $2.60 \pm 1.36$ | $2.03 \pm 1.08$ |
| DY prediction | $18.28 \pm 2.91$ | $4.69 \pm 2.32$ | $2.73 \pm 1.56$ |
| $t\bar{t}$ | $3.91 \pm 1.36$ | $0.50 \pm 0.27$ | $0.10 \pm 0.11$ |
| Total bkg | $34.9 \pm 4.4$ | $11.3 \pm 2.9$ | $7.9 \pm 2.1$ |
| Observed | 45 | 15 | 7 |

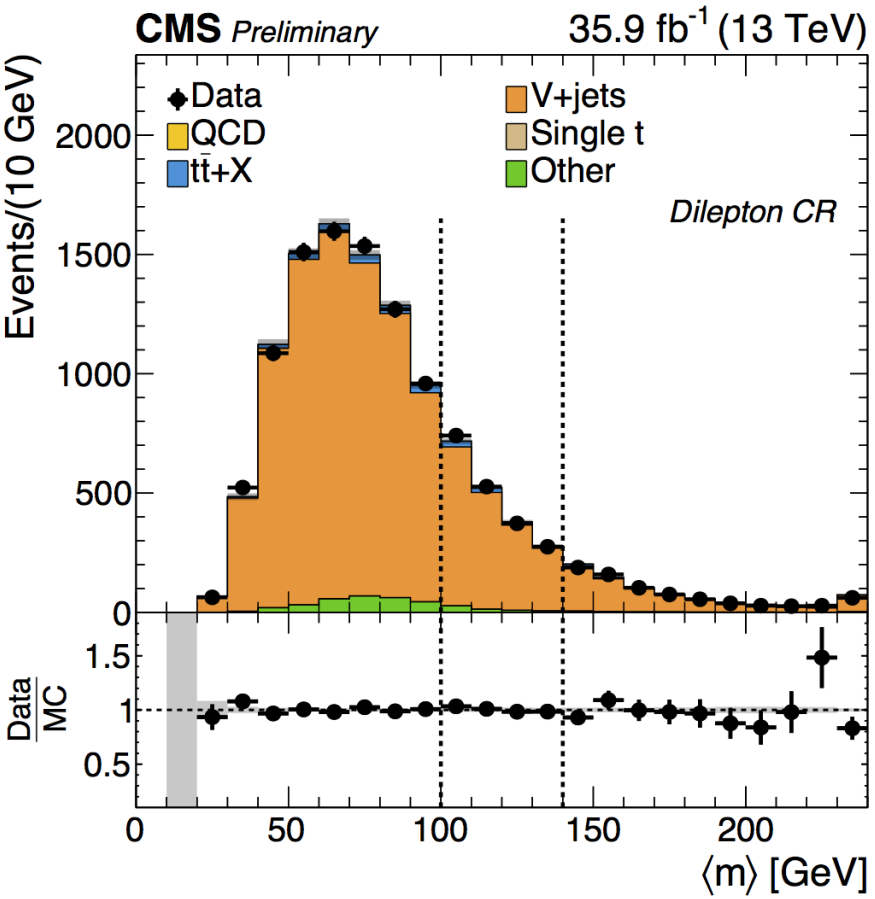
Limits on electroweakino masses (for low LSP masses)



# *CMS-SUS-16-044 : background control*

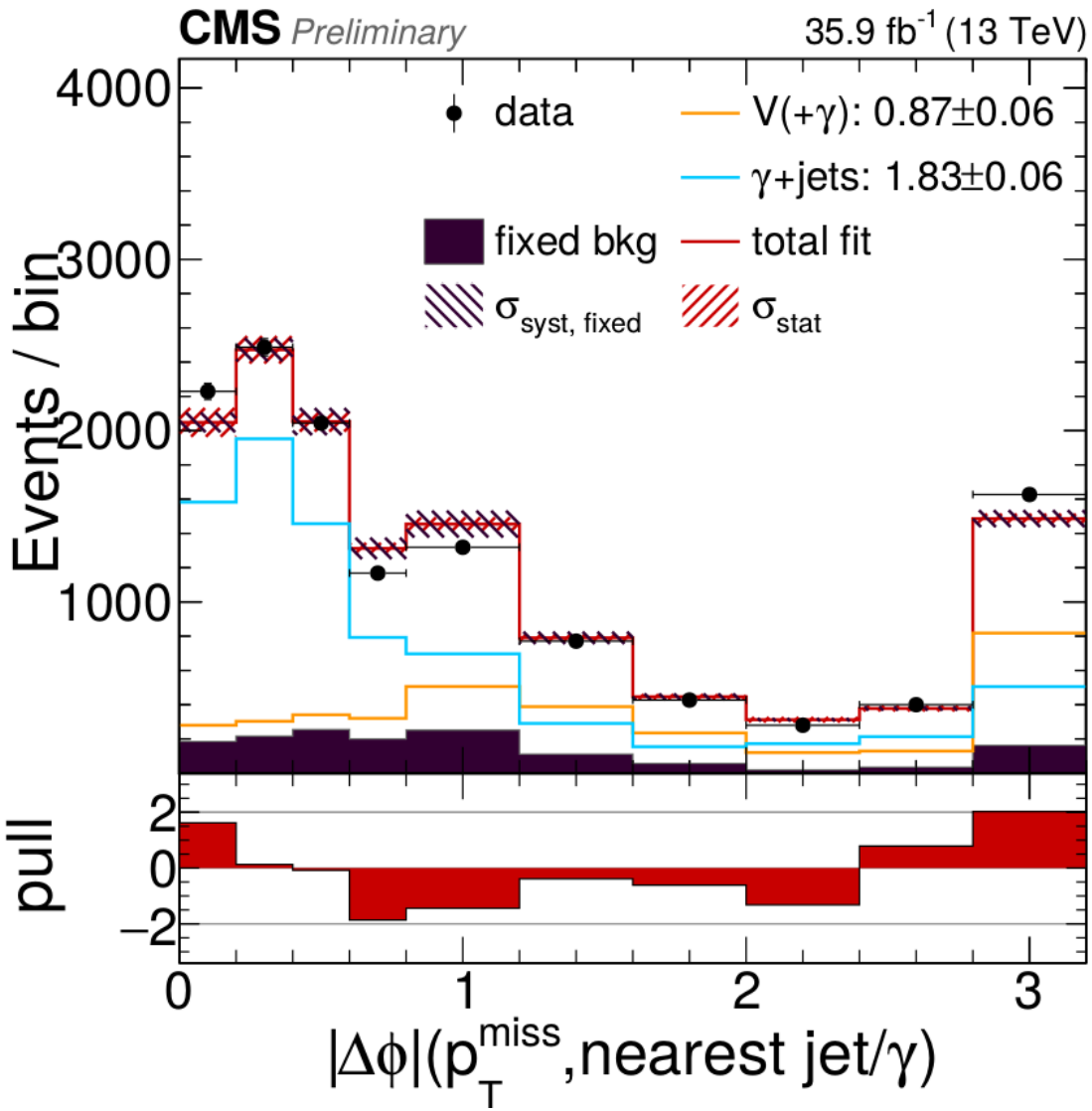



Top background control region




EWK background control region

# *CMS-SUS-16-046 : background estimation*




Templated fit

# *ATLAS-CONF-2016-075*

## control regions

| Sample | $N(e,\mu)$ signal | $N(e,\mu)$ loose | $Z$ boson | $m_{\text{eff}}$ [GeV] |
|---|---|---|---|---|
| SRA | >= 4 | >= 0 | veto | > 600 |
| CR-SRA | = 2 | >= 2 | veto | > 600 |
| SRB | >= 4 | >= 0 | veto | > 900 |
| CR-SRB | = 2 | >= 2 | veto | > 900 |
| VR | >= 4 | >= 0 | veto | < 600 |
| CR-VR | = 2 | >= 2 | veto | < 600 |

## uncertainties

| Experimental (% of total SM) | | Theoretical (% of each process) | |
|---|---|---|---|
| $e$ efficiency | 3.9% | $\sigma$: $t\bar{t}Z$ | 12% |
| $\mu$ efficiency | 1.9–2.8% | $\sigma$: $t\bar{t}W$ | 13% |
| Jet energy scale | 3.0–3.4% | $\sigma$: $ZZ$,$WZ$ | 6% |
| Luminosity | 2.9% | $\sigma$: $VVV$/t$WZ$ | 20% |
| MC statistics | 2.7–2.5% | $A\epsilon$: $ZZ$ | 56–80% |
| CR statistics | 4.5–6.4% | $A\epsilon$: $t\bar{t}Z$ | 9–12% |
| | | $\sigma A\epsilon$: $VH$/VBF $H$ | 20% |
| | | $\sigma A\epsilon$: $ggF$ $H$/ $t\bar{t}$H | 100% |