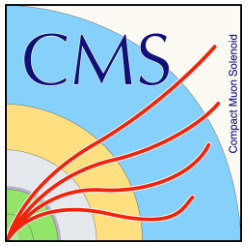







# SEARCHING FOR PAIR PRODUCTION OF TOP SQUARKS AT CMS EXPERIMENT

**Andrea Trapote**

**(On behalf of the CMS Collaboration)**

- Phenomenology 2020 Symposium -

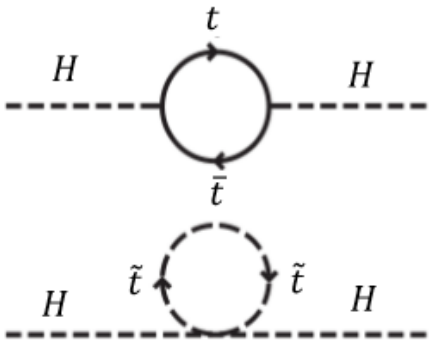
4-6 May 2020

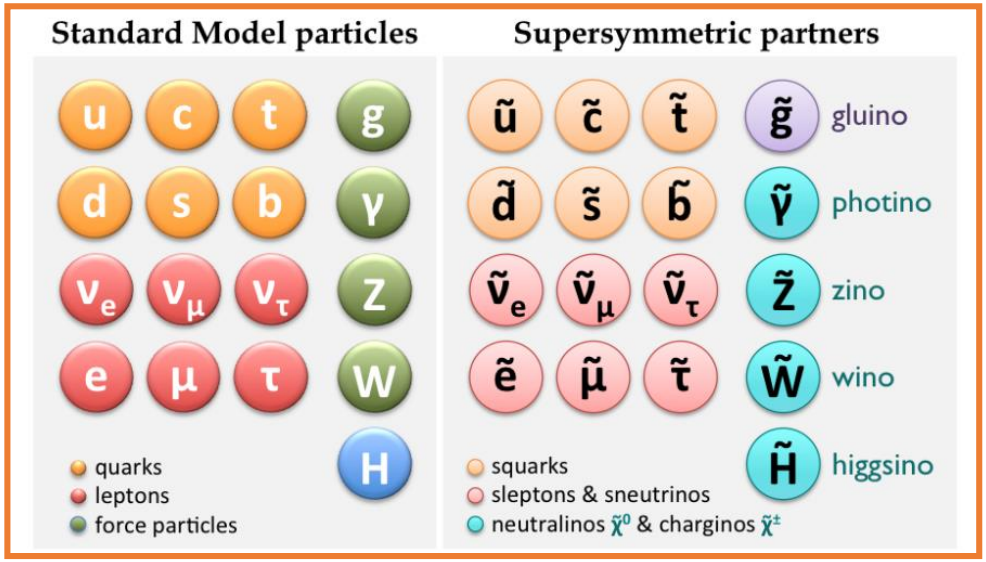
andrea.trapote.fernandez@cern.ch

# INTRODUCTION

- **Supersymmetry** is an extension of the SM that assigns a new particle (**supertpartner**) to every SM particle differing only in ½ of spin.

- This model can solve several shortcomings of the SM:
  - **Unification.**
  - If R-parity is conserved, the lightest supersymmetric particle (**LSP**) is stable and potentially massive, providing a good candidate for **Dark Matter**.
  - The **hierarchy problem** since the quantum loop corrections to the Higgs mass, due mainly to the top quark, can be compensated by the effect of the top quark supertpartner.



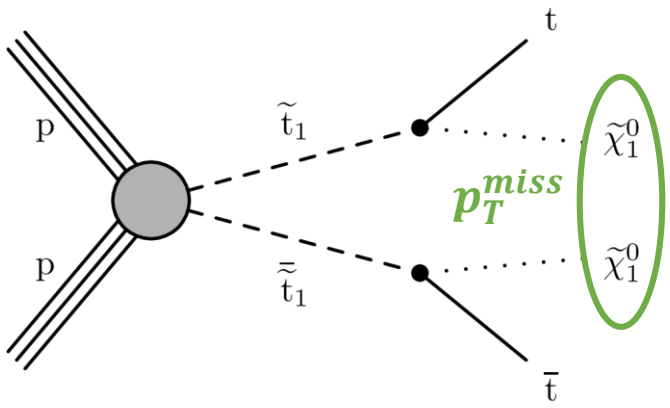



# TOP SQUARK PRODUCTION

- The top quark plays an essential role in understanding the structure of the SM and SUSY.

**Simplified Model Spectra "T2tt"**

100% branching ratio assumed for the stop to top + neutralino decay.



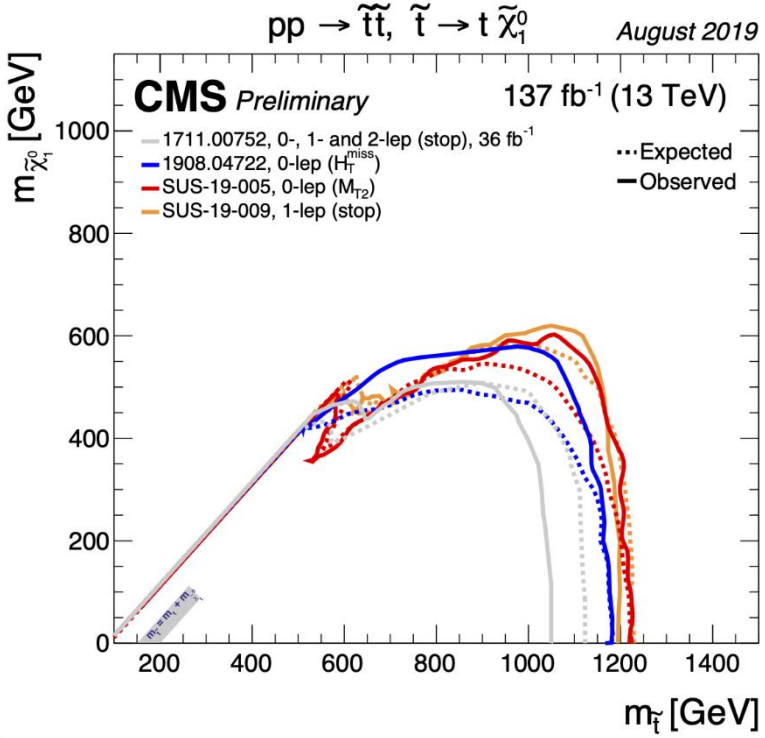

**Final states selected include 0, 1 and 2 leptons.** But there are more decay modes possible also being investigated.

- Several results with full **Run 2 dataset** have been published, and others are under way.

- **0 leptons**: SUS-19-005
- **1 lepton**: SUS-19-009
- **2 leptons** (eμ, "top corridor"): SUS-18-003*
- **2 leptons** (ττ): SUS-19-003 (2016+2017 datasets)

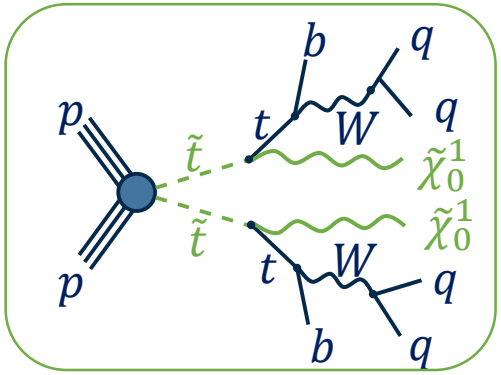
- There are many more searches with partial datasets.

*only 2016 dataset



# STOP 0 LEPTON SEARCH

*Eur. Phys. J. C 80 (2020) 3*



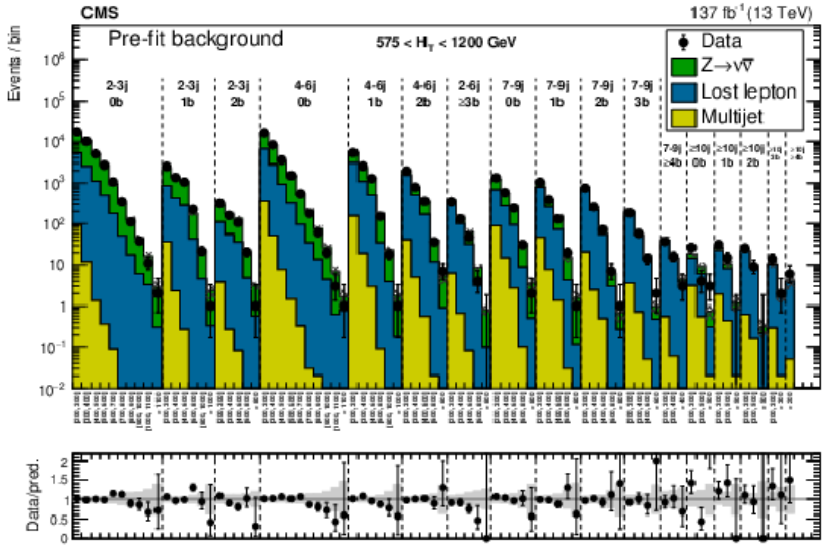

## ➢ Event selection and strategy

- **All-hadronic** search: veto on leptons and isolated tracks.
- Events classified by $H_T$, $N_j$, $N_b$ **and** $M_{T2}$.
- Monojet regions binned in $N_b$ and jet $p_T$.

## ➢ Backgrounds estimated from data control regions

- **Lost lepton**: genuine $p_T^{miss}$ from semi-leptonic W decay (W+jets, tt+jets).
- **Irreducible background**: Z+jets events where the Z boson decays to neutrinos.
- **QCD multijet**: fake $p_T^{miss}$ from mis-measured jets.

### $M_{T2}$ bins for medium $H_T$



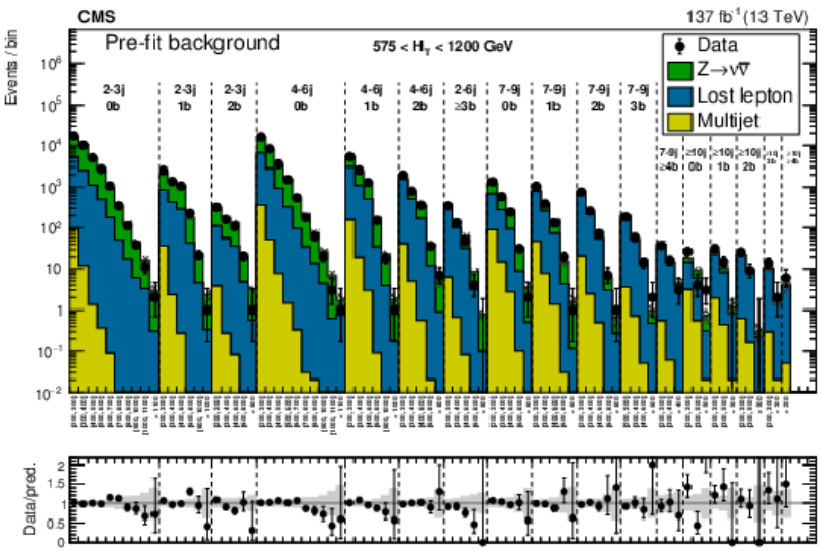

**This is an inclusive analysis that has sensitivity also to other models.**

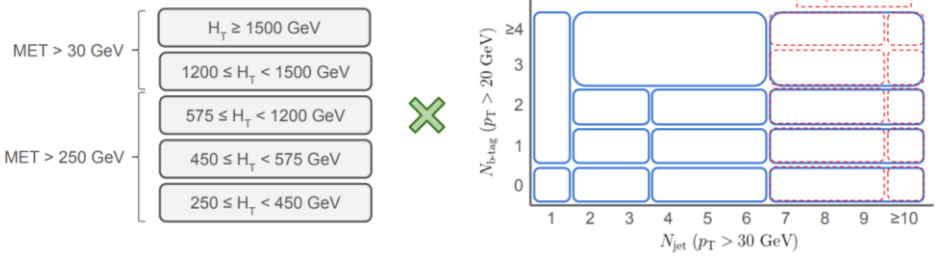
# STOP 0 LEPTON SEARCH

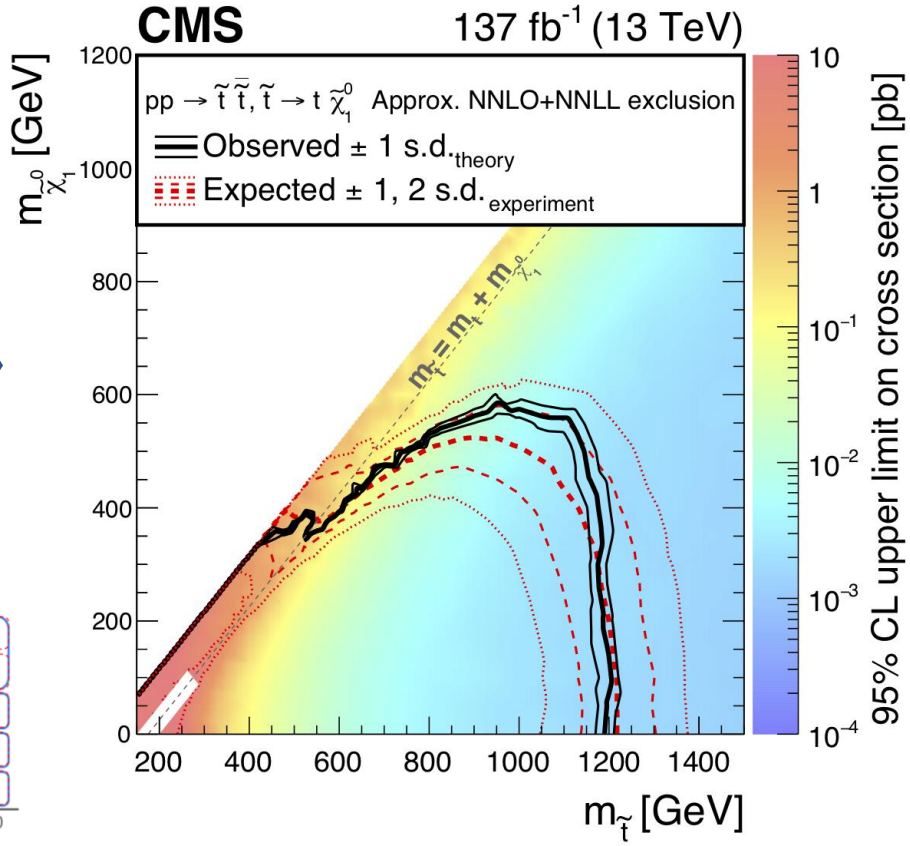
Eur. Phys. J. C 80 (2020) 3

- Interpret **results** in terms of **exclusion limits** on simplified models of SUSY.

**$M_{T2}$ bins for medium $H_T$**



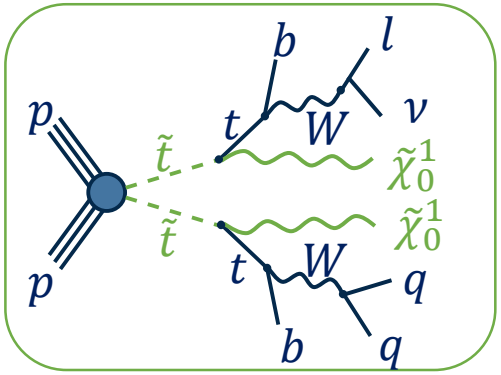




**Stop masses excluded up to 1.2 TeV**

# STOP 1 LEPTON SEARCH

Accepted by JHEP
arXiv:1912.08887

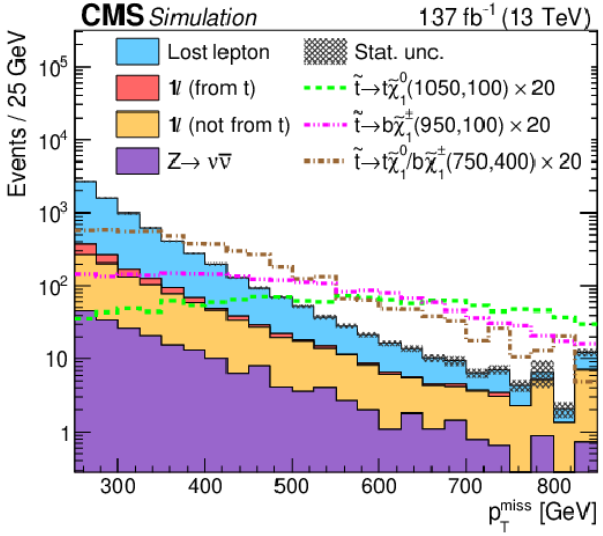


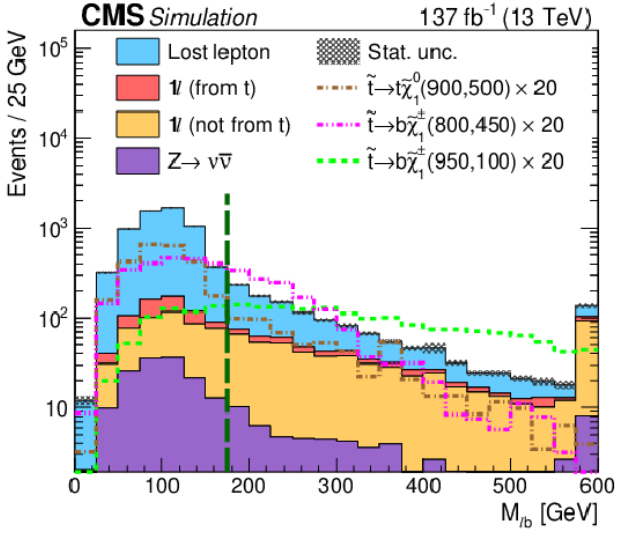

## ➢ Event selection and strategy

- Exactly **one** isolated **electron or muon**, $N_j \geq 2$, $N_b \geq 1$ and $p_T^{miss} > 250GeV$ .
- Events classified by $\boldsymbol{N_j}$ , $\boldsymbol{p_T^{miss}}$, $\boldsymbol{M_{lb}}$, $\boldsymbol{t_{mod}}$ and 3 top quark tagging categories (**untagged, merged and resolved**).
- **2 additional regions**: $\Delta m(\tilde{t}, \tilde{\chi}_0^1) \sim m_W$ and $\Delta m(\tilde{t}, \tilde{\chi}_0^1) \sim m_t$.

## ➢ Backgrounds estimated using control samples and simulation

- **Lost lepton**: one bad lepton from a W boson decaying leptonically ($t\bar{t}$, single top).
- **Z → νν** : events where the Z boson decays to neutrinos.
- **One lepton**: single W boson decaying leptonically without any additional genuine $p_T^{miss}$.

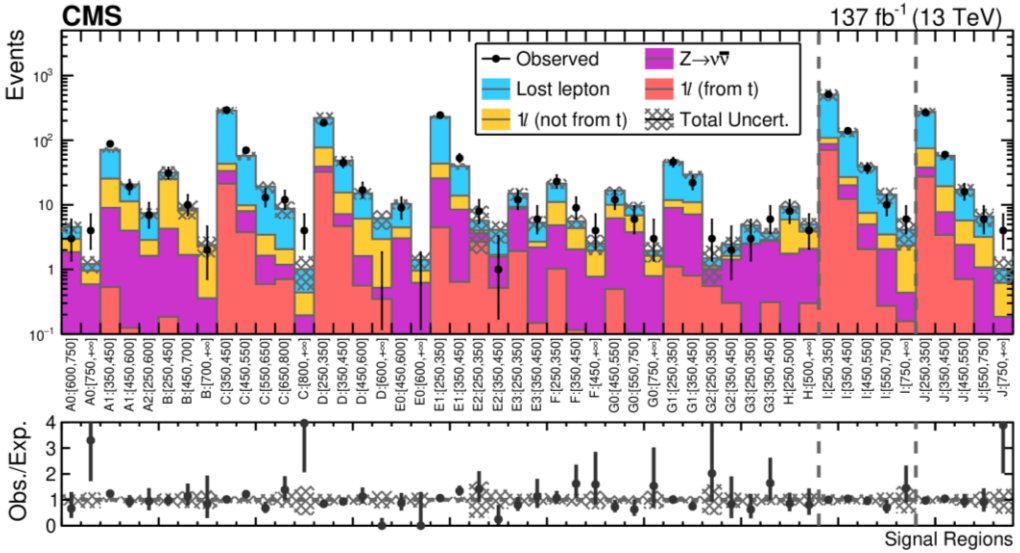


# STOP 1 LEPTON SEARCH

Accepted by JHEP
arXiv:1912.08887

- Interpret **results** in terms of **exclusion limits** on simplified models of SUSY.




**Stop masses excluded up to 1.2 TeV**

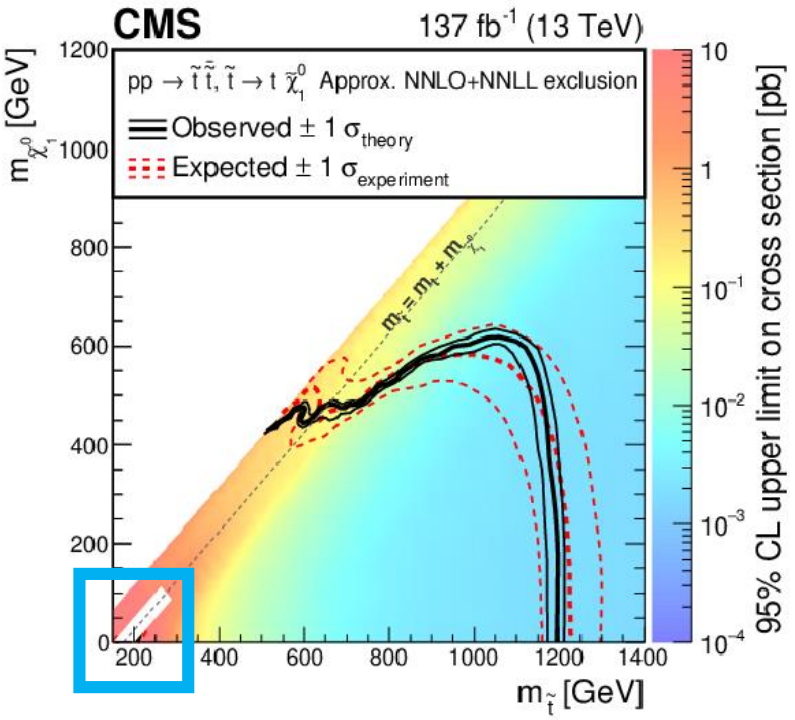
| | $N_J$ | $t_{mod}$ | $M_{lb}$ [GeV] |
|---|---|---|---|
| A | 2–3 | > 10 | ≤ 175 |
| B | 2–3 | > 10 | > 175 |
| C | ≥ 4 | ≤ 0 | ≤ 175 |
| D | ≥ 4 | ≤ 0 | > 175 |
| E | ≥ 4 | 0–10 | ≤ 175 |
| F | ≥ 4 | 0–10 | > 175 |
| G | ≥ 4 | > 10 | ≤ 175 |
| H | ≥ 4 | > 10 | > 175 |

X0: Inclusive
X1: Untagged
X2: Merged t quark tag
X3: Resolved t quark tag

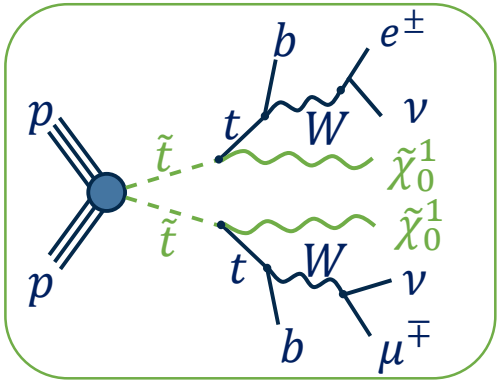
**Standard search**

I: $N_J \geq 5$, $N_{b,med} \geq 1$ → **Top corridor search**

J: $N_J \geq 3$, $N_{b,soft} \geq 1$ → **W corridor search**



# STOP 2 LEPTONS SEARCH: eμ CHANNEL IN TOP CORRIDOR [JHEP 03 (2019) 101]




## ➢ Event selection and strategy

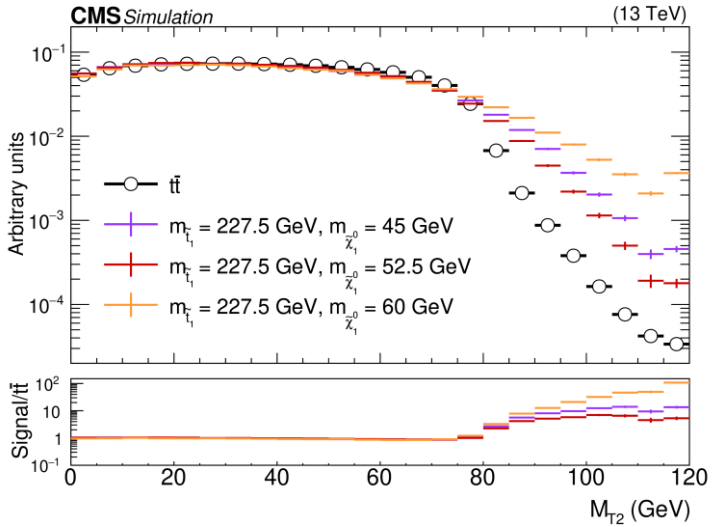
- Only **2016 dataset** used, 36 $fb^{-1}$.
- OS **eμ pair**, $N_j \geq 2$ and $N_b \geq 1$.
- Search for degenerate stop pair production in **3 diagonals**:

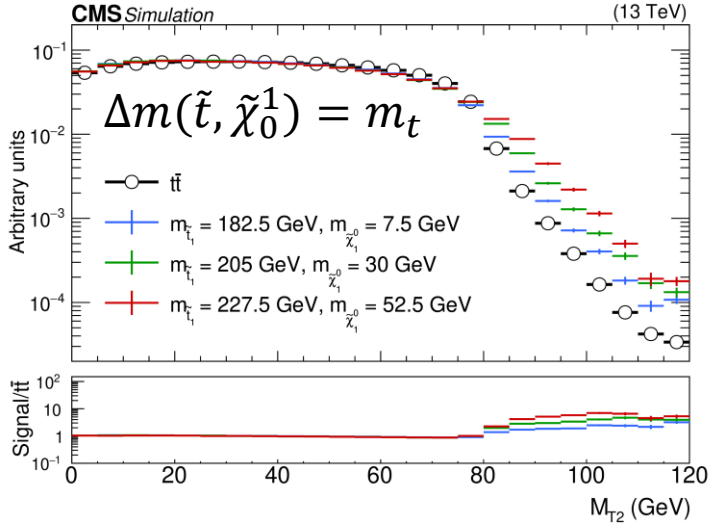
$$\Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t, m_t \pm 7.5\ GeV$$

- Main discriminating variable: $\boldsymbol{M_{T2}(e\mu)}$

## ➢ Backgrounds

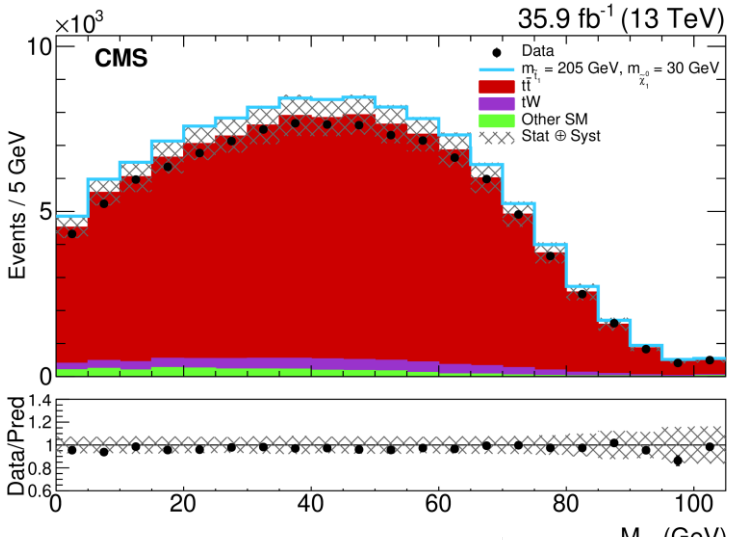
- The main background is $\boldsymbol{t\bar{t}}$ due to the similar kinematics with the signal process in this region. It is estimated from MC with an **accurate knowledge** coming from different comparisons of the MC with measured inclusive and differential cross-section.



# STOP 2 LEPTONS SEARCH: eμ CHANNEL IN TOP CORRIDOR [JHEP 03 (2019) 101]

- No excess observed, then interpret **results** in terms of **exclusion limits** on simplified models of SUSY.

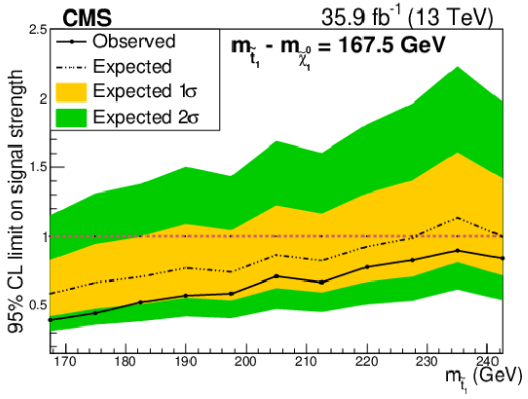


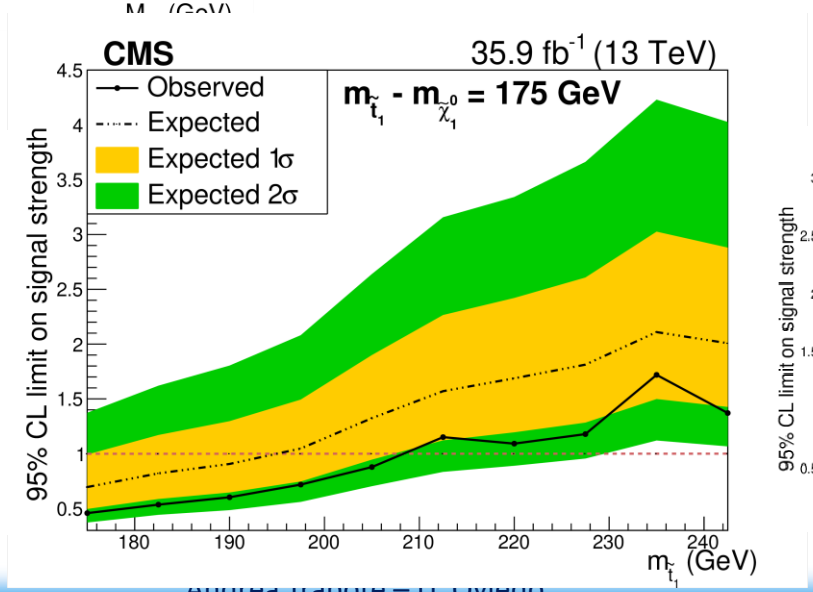

**Stop masses excluded up to:**

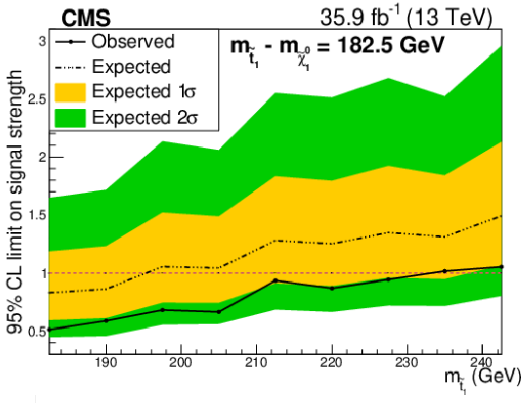
**208 GeV** in $\Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t$

**235 GeV** in $\Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t$-7.5 GeV

**242 GeV** in $\Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t$+7.5 GeV



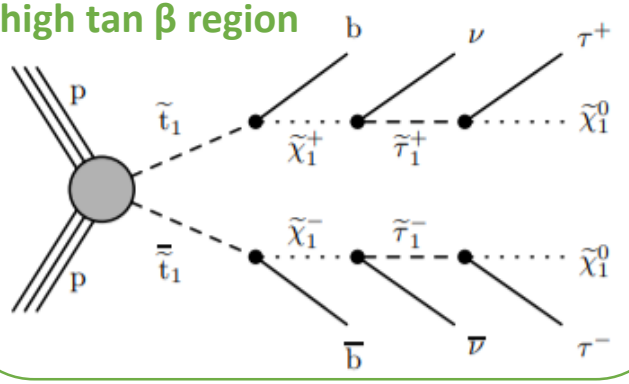
# STOP 2 LEPTONS SEARCH: ττ CHANNEL

*JHEP 02 (2020) 015*

## ➢ Event selection and strategy

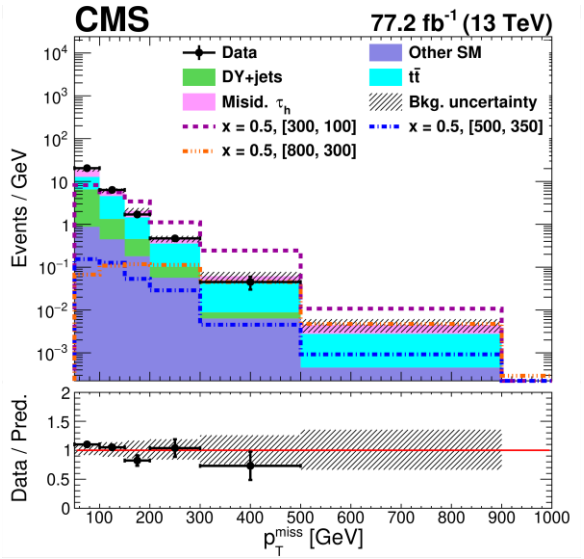
- Only **2016-2017 datasets** used, 77.2 $\text{fb}^{-1}$.
- OS hadronically decaying $\boldsymbol{\tau_h}$ **pair** $N_j \geq 2$, $N_b \geq 1$, $p_T^{miss} > 50GeV$ and $H_T > 100GeV$.
- Events classified by $\boldsymbol{p_T^{miss}}$, $\boldsymbol{M_{T2}}$ **and** $\boldsymbol{H_T}$.

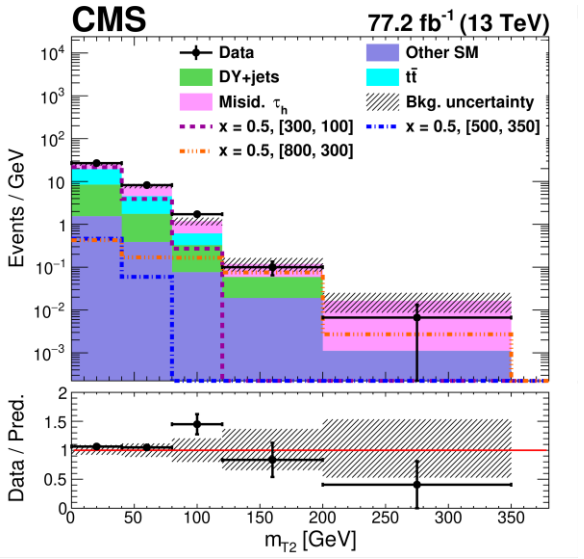
**Higgsino-like scenario and/or high tan β region**

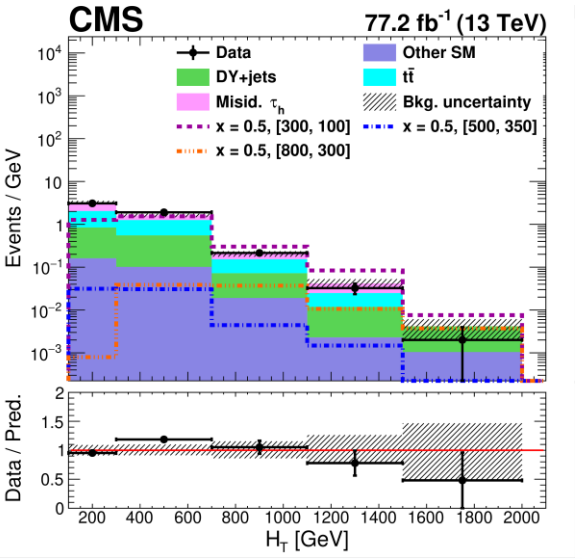



## ➢ Backgrounds, evaluated in control regions

- **Prompt $\boldsymbol{t\bar{t}}$**: $t\bar{t}$ events with two genuine $\tau_h$ decays.
- **Fake taus**: mostly from hadronic and semi-leptonic $t\bar{t}$ events with jets being misidentified as $\tau_h$ candidate.
- **DY + others SM:** minor backgrounds.



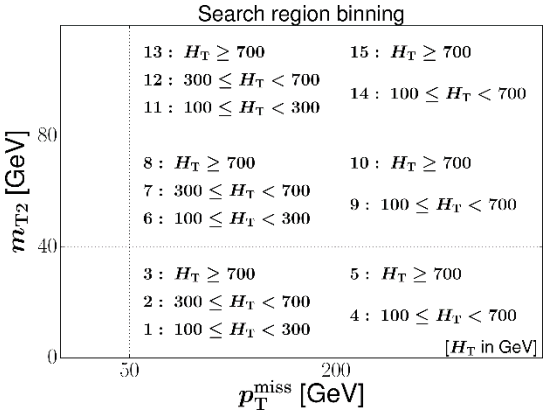



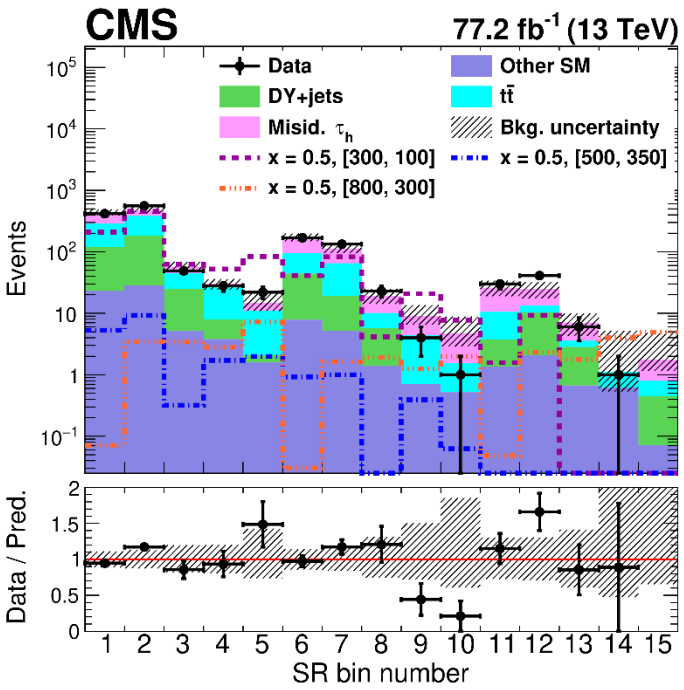



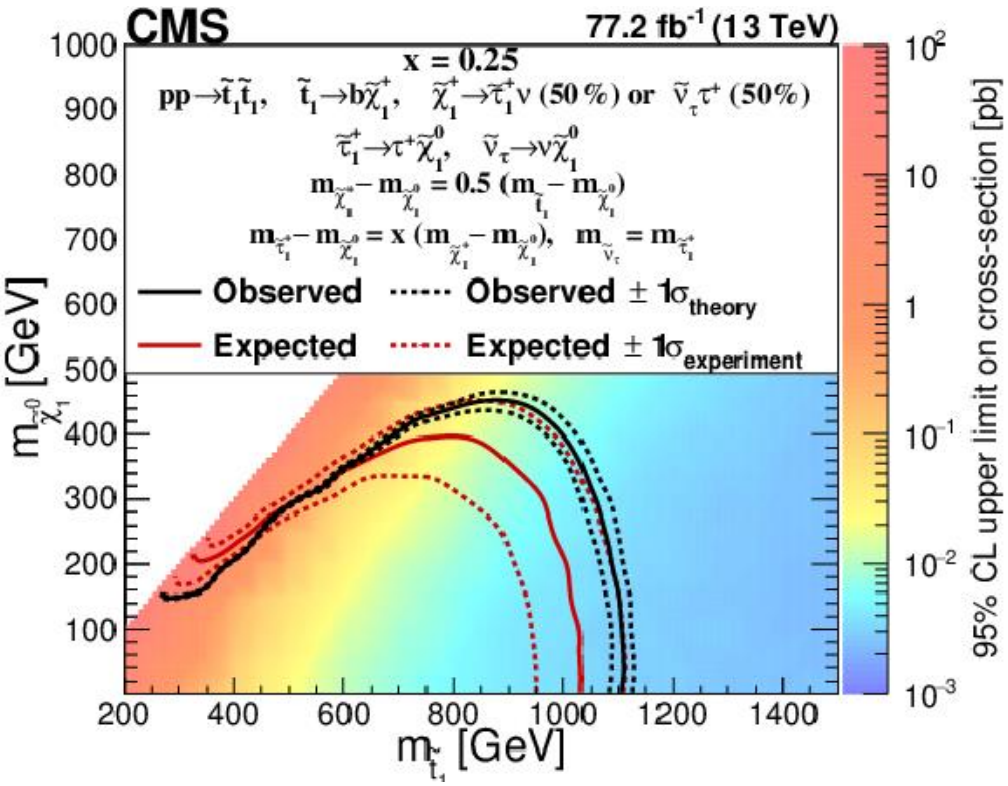
# STOP 2 LEPTONS SEARCH: ττ CHANNEL

*JHEP 02 (2020) 015*

- Interpret **results** in terms of **exclusion limits** on simplified models of SUSY.



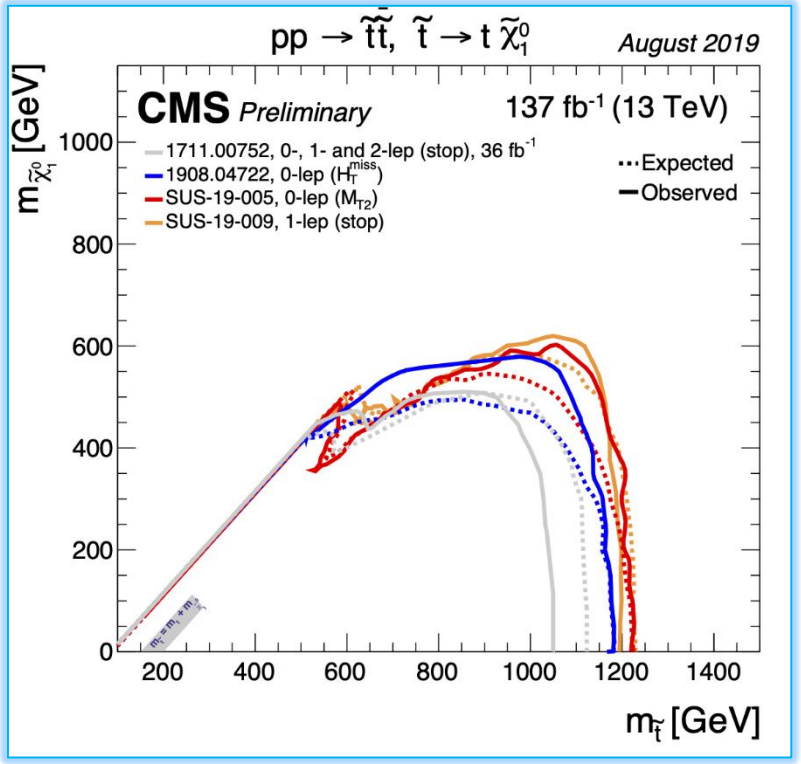




**Stop masses excluded up to 1.1 TeV**

# SUMMARY

- First analyses with **full Run 2 in CMS** achieve excellent exclusion limits, excluding stop quarks with masses up to **1.2 TeV.**
- **Several channels** have been explored with partial luminosity and are being studied with the full Run 2.
- **There are many more results on the way!**
- **Stay tuned!**




CMS Public SUSY Results:
http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/STOP.html

# BACK UP

# $M_{T2}$ variable

- Stop 0 leptons:

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

$\vec{p}_T^{\,missX(i)}$ $(i = 1, 2)$ are trial vectors obtained by decomposing $\vec{p}_T^{\,miss}$, and $M_T^{(i)}$ are the transverse masses obtained by pairing either of the trial vectors with one of the two pseudojets.

- Stop 2 leptons:

$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T},1}^{\,\mathrm{miss}} + \vec{p}_{\mathrm{T},2}^{\,\mathrm{miss}} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left( \max \left[ m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,\ell 1}, \vec{p}_{\mathrm{T},1}^{\,\mathrm{miss}}), m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,\ell 2}, \vec{p}_{\mathrm{T},2}^{\,\mathrm{miss}}) \right] \right)$$

# STOP 2 LEPTONS SEARCH: ττ CHANNEL

- The Minimal Supersymmetric Standard Model (MSSM) is one of the most promising BSM candidates currently.
- MSSM : SM + SM̃ + 2 Higgs doublets. **MSSM has five Higgs bosons:** $h, H, A, H^{\pm}$.
- The tree level CP-even $h$ receives substantial correction involving top squark loops:

$$m_h = m_Z|\cos 2\beta| + \frac{3m_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{m_s^2}{m_t^2} + \frac{X_t^2}{2m_s^2}\left(1 - \frac{X_t^2}{6m_s^2}\right)\right]$$

$$X_t = A_t - \mu\cot\beta$$

$$m_s = \sqrt{m_{t_1} m_{t_2}}$$

- **$h$ is the SM-like Higgs** with $m_h = 125$ GeV.

**For more information go to the approval talk of the analysis.**

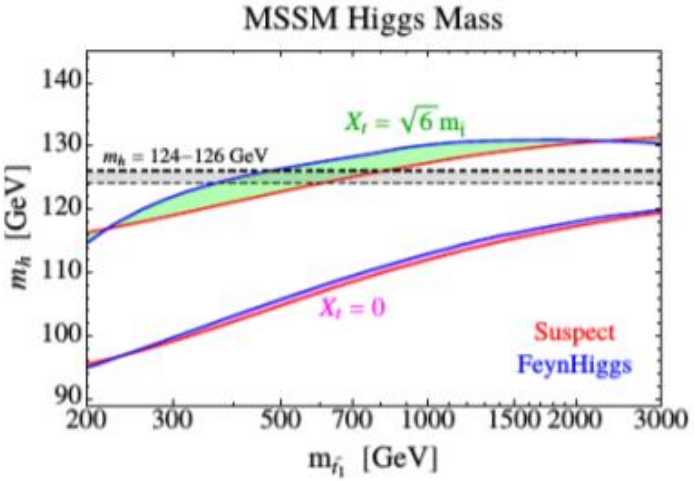



Figure: Ref: A. Djouadi et al. 1112.3028

- No mixing scenario ($X_t = 0$): stop mass needs to very high ($\sim$ 3 TeV) to get a 125 GeV Higgs.
- Maximal mixing scenario: Can get a lighter stop ($\sim$ 500 GeV) – **interesting in the LHC scenario.**
- This motivates us to look for top squarks at the LHC to establish Supersymmetry.

# STOP 2 LEPTONS SEARCH: ττ CHANNEL

- The chargino/neutralino has a gaugino and higgsino-like component:

$$\tilde{\chi}_i^{\pm} = C_{1i}\tilde{W}^{\pm} + C_{2i}\tilde{H}^{\pm}$$
$$\tilde{\chi}_i^0 = N_{1i}\tilde{\gamma} + N_{2i}\tilde{Z} + N_{3i}\tilde{H}_1^0 + N_{4i}\tilde{H}_2^0$$

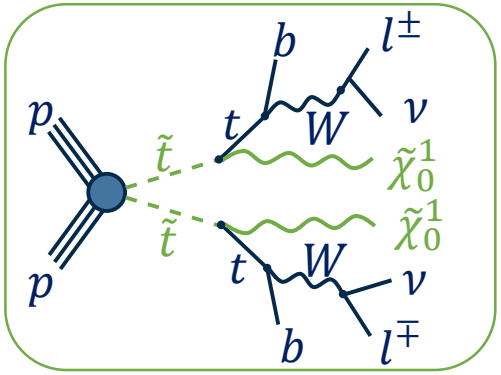
- The chargino/neutralino couples to sleptons as $\sim m_l/\cos\beta$ with the higgsino component.
- A higgsino like scenario implies:
  $|C_{2i}|^2 >> |C_{1i}|^2$ and $|N_{3i}|^2 + |N_{4i}|^2 >> |N_{1i}|^2 + |N_{2i}|^2$.
- $\tan\beta >> 1$ implies $1/\cos\beta >> 1$.
- Hence in a **higgsino-like scenario and/or high $\tan\beta$ region**, chargino/neutralino will preferably decay to a $\tau$ final state because $m_\tau >> m_e, m_\mu$:

$$\tilde{\chi}_1^{\pm} \to \tilde{\tau}_1\ \nu_\tau + \tilde{\nu}_\tau\ \tau \to \tau\ \nu_\tau\ \chi_1^0$$
$$\tilde{\chi}_2^0 \to \tilde{\tau}_1\ \tau \to \tau\ \tau\ \tilde{\chi}_1^0$$

- **Such SUSY cascade decays lead to final states with lots of taus.**
- The existing exclusions (hadronic/leptonic) are not applicable for a **higgsino-like and/or high $\tan\beta$ scenario** where the **chargino/neutralino will preferably decay to a $\tau$ final state**, and hence the need to search for tau lepton final states.

# STOP 2 LEPTONS SEARCH

Phys. Rev. D 97, 032009 (2018)

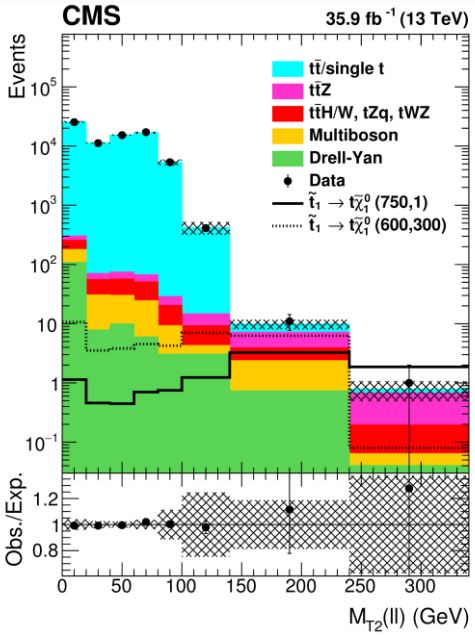


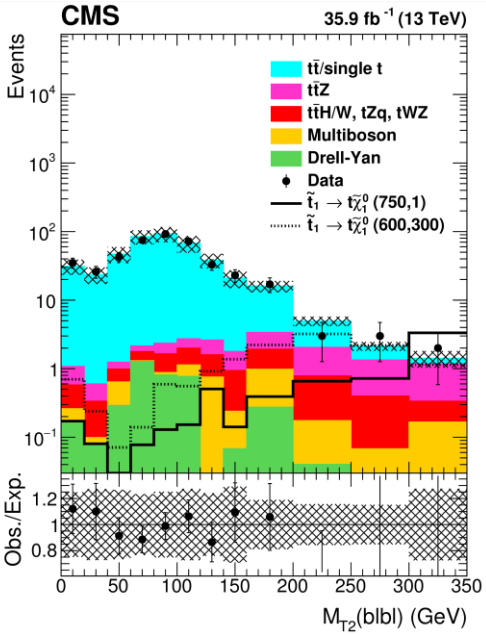

## ➢ Event selection and strategy

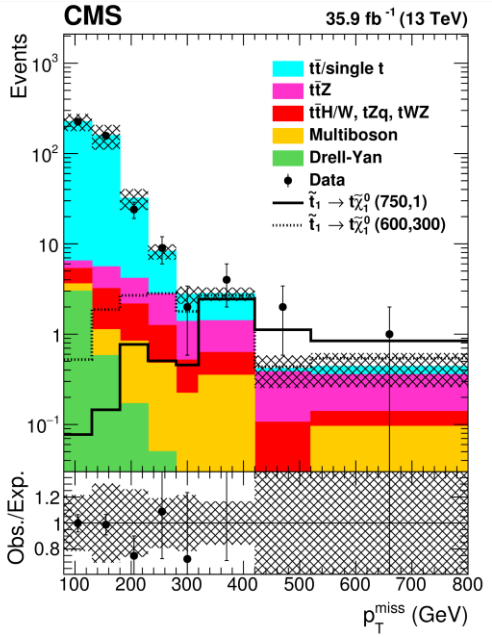
- Only **2016 dataset** used, 36 $fb^{-1}$.
- Two OS **electron or muon**, $N_j \geq 2$, $N_b \geq 1$, $p_T^{miss} > 80GeV$ and $M_{T2}(ll) > 100GeV$.
- Main discriminating variable: $\boldsymbol{M_{T2}(ll)}$.
- Events classified by $\boldsymbol{p_T^{miss}}$, $\boldsymbol{M_{T2}(ll)}$ **and** $\boldsymbol{M_{T2}(blbl)}$.

## ➢ Backgrounds, validated in several control regions

- Main backgrounds are $\boldsymbol{t\bar{t}}$ and **single top** quark events with either severely mismeasured $p_T^{miss}$ or misidentified leptons.



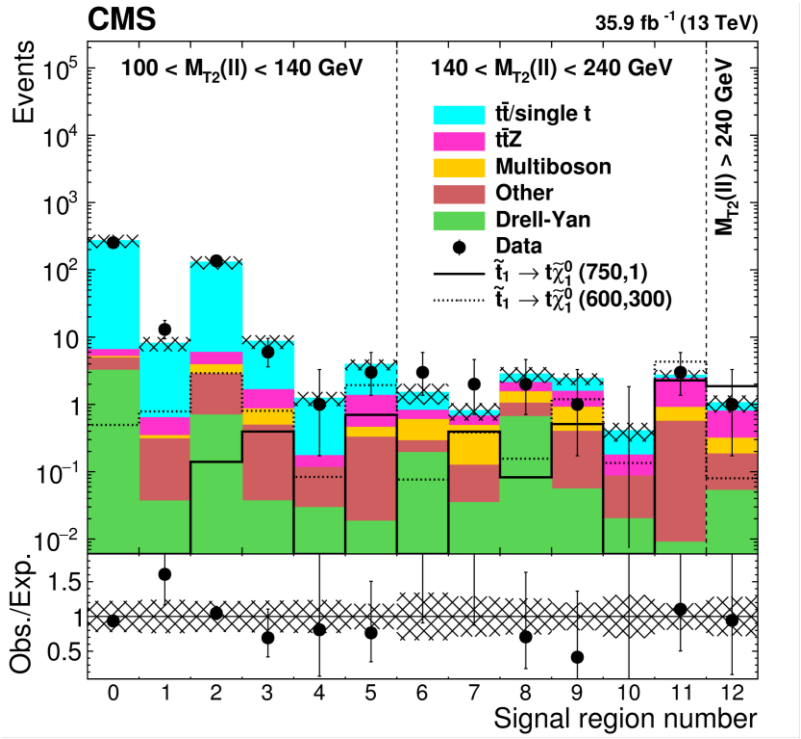



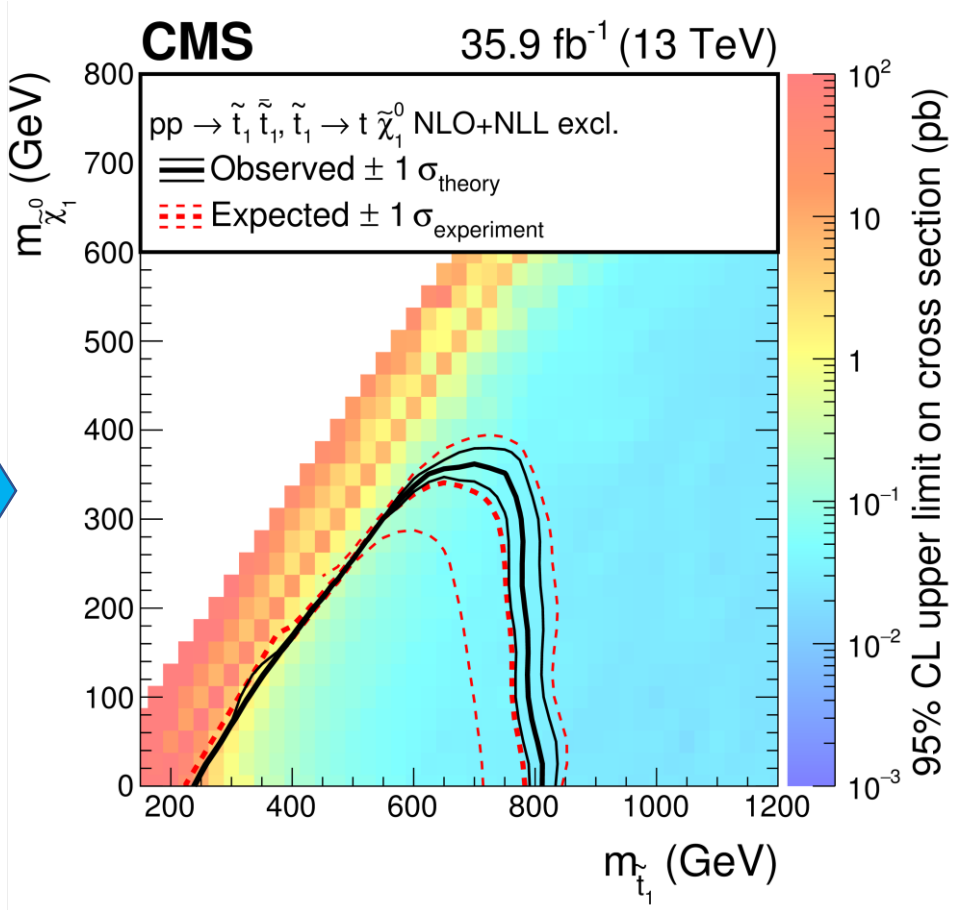
# STOP 2 LEPTONS SEARCH

[Phys. Rev. D 97, 032009 (2018)]

- Interpret **results** in terms of **exclusion limits** on simplified models of SUSY.

| $M_{T2}(b\ell b\ell)$ (GeV) | $p_T^{miss}$ (GeV) | $100 < M_{T2}(\ell\ell) < 140$ GeV | $140 < M_{T2}(\ell\ell) < 240$ GeV | $M_{T2}(\ell\ell) > 240$ GeV |
|---|---|---|---|---|
| 0–100 | 80–200 | SR0 | SR6 | SR12 |
| | >200 | SR1 | SR7 | |
| 100–200 | 80–200 | SR2 | SR8 | |
| | >200 | SR3 | SR9 | |
| >200 | 80–200 | SR4 | SR10 | |
| | >200 | SR5 | SR11 | |

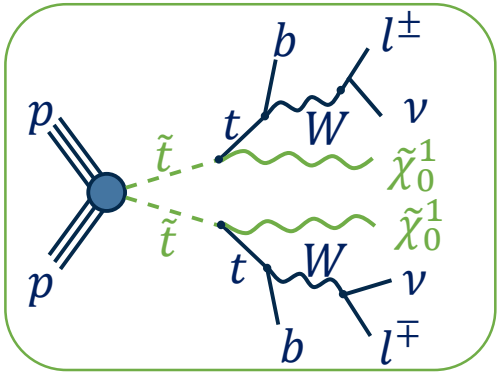



**Stop masses excluded up to 800 GeV**

# STOP 2 LEPTONS SEARCH: compressed stop

JHEP 11 (2018) 079

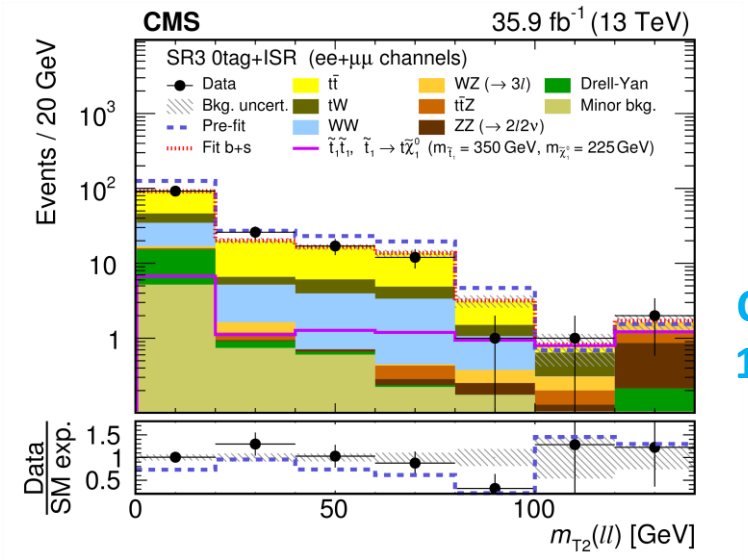



## ➢ Event selection and strategy

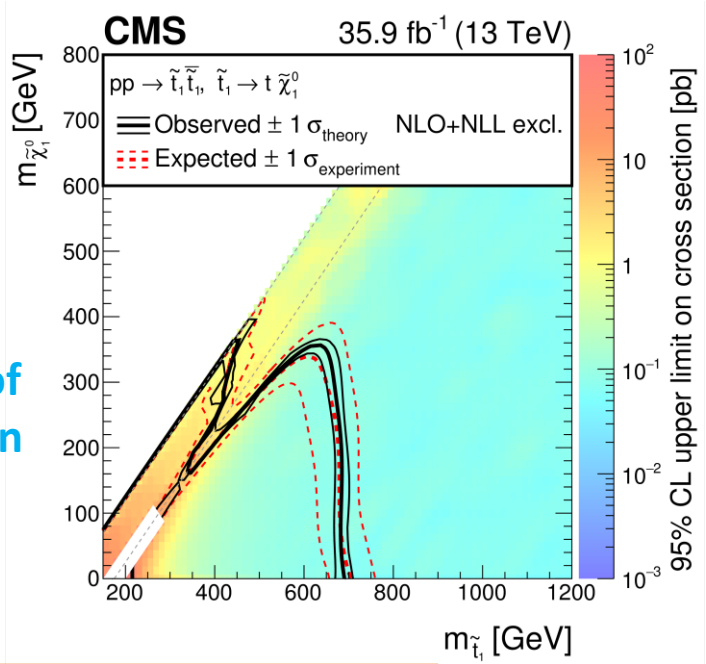
- Only **2016 dataset** used, 36 $fb^{-1}$.
- OS **electron or muon** pair and $p_T^{miss} > 140GeV$.
- Search for compressed stop: $\boldsymbol{m_W \leq \Delta m(\tilde{t}, \tilde{\chi}_0^1) \leq m_t}$
- Main discriminating variable: $\boldsymbol{M_{T2}(ll)}$.
- Events classified by $\boldsymbol{N_j, N_b, ISR_{jets}}$, **channels and** $\boldsymbol{M_{T2}(ll)}$.

## ➢ Backgrounds

- Main backgrounds: $\boldsymbol{t\bar{t}}$, $\boldsymbol{tW}$ and $\boldsymbol{WW}$.




**Combination of 12 signal region distributions**




**Stop masses excluded up to 420GeV**