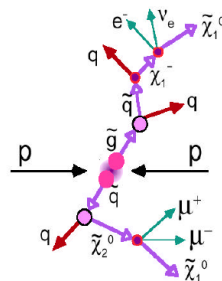
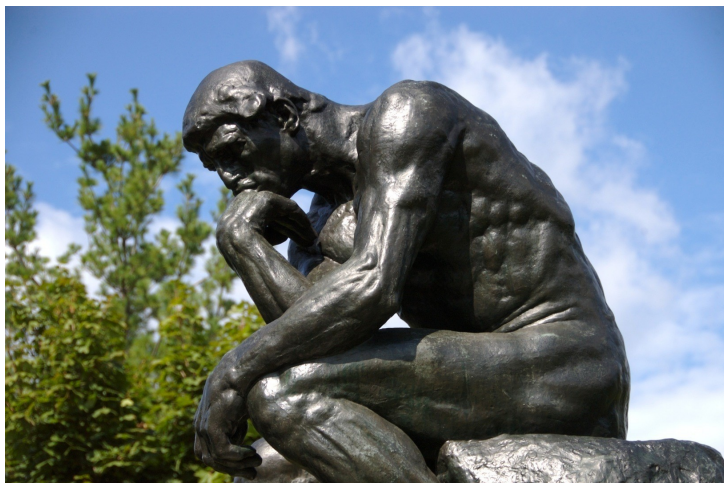


# Lepton Photon 2019



## Searches for supersymmetry at the LHC

Filip Moortgat (CERN)



# Introduction

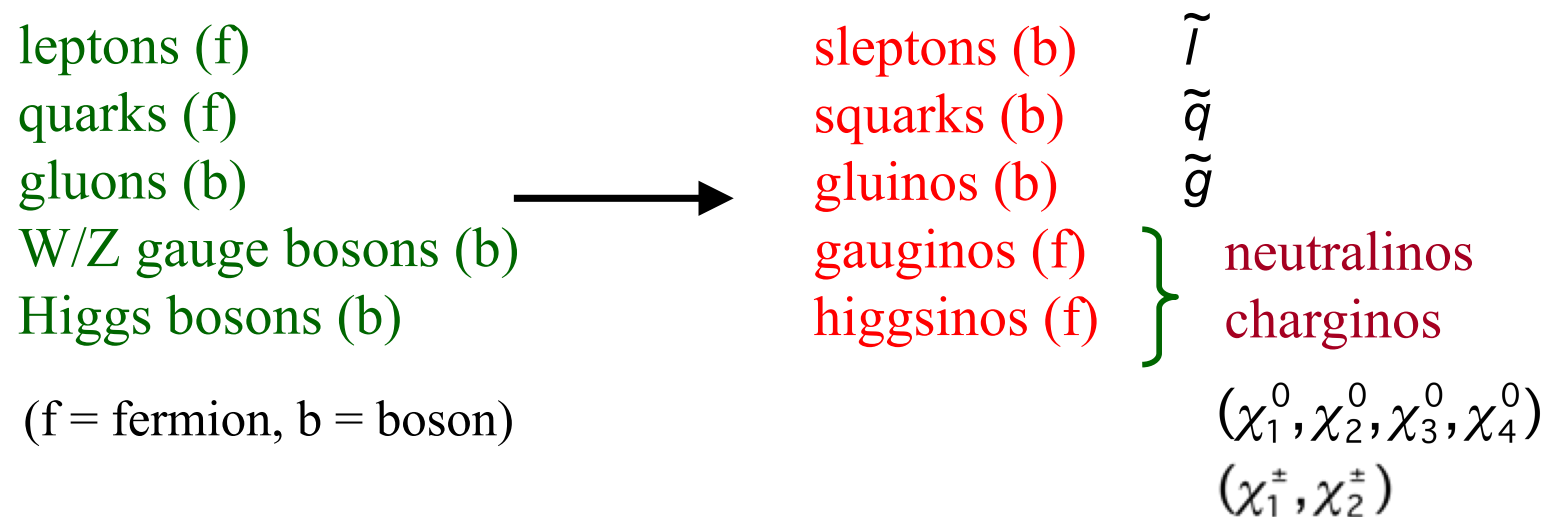


Why is there a dedicated talk (and working group) for SUSY searches at the LHC?  
(compared to other BSM searches)

# Introduction



Supersymmetry is a **spacetime symmetry** that adds a fermionic partner to each SM boson (“-ino”) and a bosonic partner to each SM fermion (“s-”)



SUSY is broken (breaking mechanism determines phenomenology)

Add a discrete symmetry **R-parity** to avoid rapid proton decay

→ SUSY particles produced in **pairs**

→ Lightest SUSY particle (LSP) is **stable** (and excellent DM candidate)

# Introduction (2)



- So, why is there a dedicated effort for SUSY searches at the LHC? (compared to other BSM searches)
  - **SUSY is unique** among all BSM theories for solving many shortcomings of the SM in one go:
    - Hierarchy problem
    - Gauge unification
    - Dark Matter
    - Radiative EWSB
    - ...
  - But searches are of course relevant to all other BSM theories that lead to similar topologies (Universal Extra Dimensions, Little Higgs with T-parity, ...)
    - SUSY is used as a **generic benchmark**

# Hierarchy problem



$$\mu^2 = \mu_{\text{bare}}^2 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$



pinch of salt

=



9.999999... billion tons of salt

-

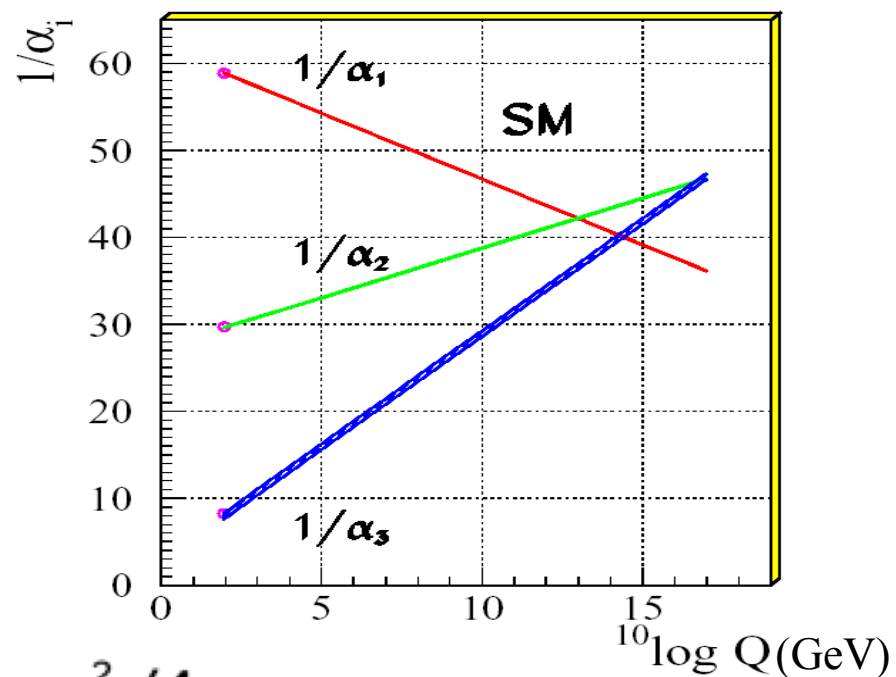


10 billion tons of salt

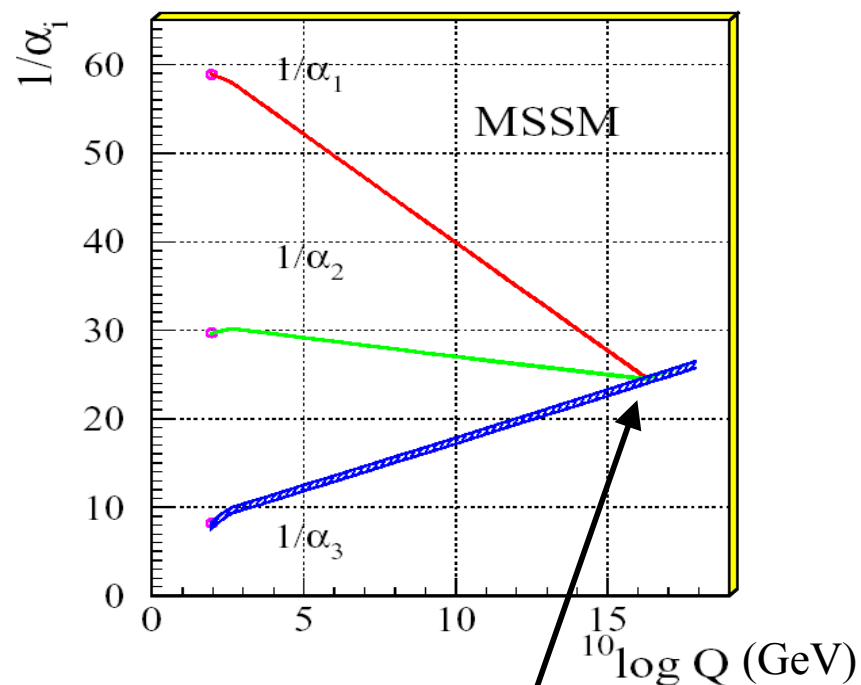
# Gauge Unification



SM



MSSM



$$\alpha_i = g_i^2 / 4\pi$$

(1 = electromagnetic, 2 = weak, 3 = strong)

- meet in 1 point
- energy scale ok with proton decay

# Inclusive versus targeted



Broadly speaking, there are two types of SUSY searches:

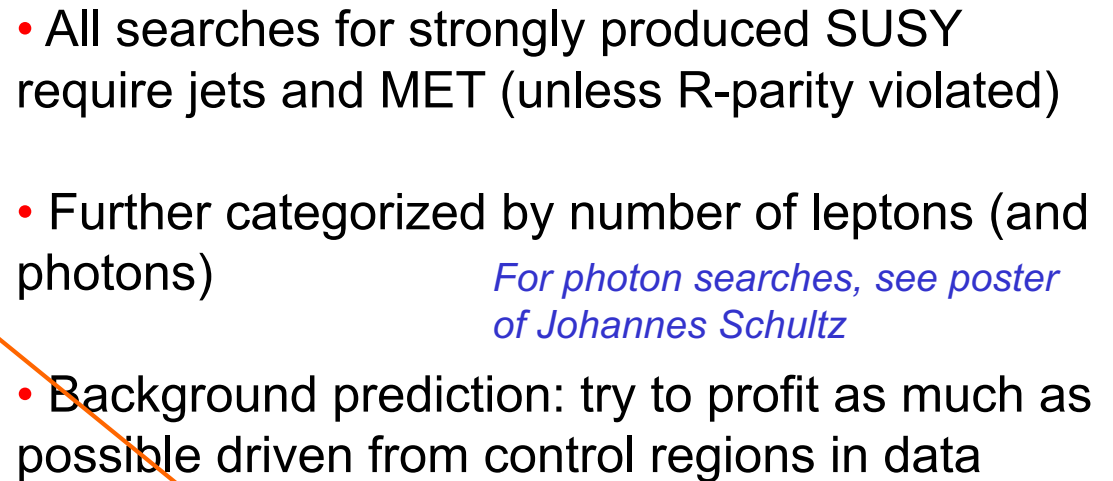
- 1) **Inclusive** analyses, which are based on **topologies** (jets,  $P_T^{\text{miss}}$ , leptons, ...) which are sensitive to broad classes of SUSY (and SUSY-like) signals.

Gluinos, squarks, ...

- 2) Analyses that are specifically **targeted** to delicate SUSY signals which merit dedicated analysis efforts

Stop/sbottom

Electroweak produced sparticles

8

# Simplified models

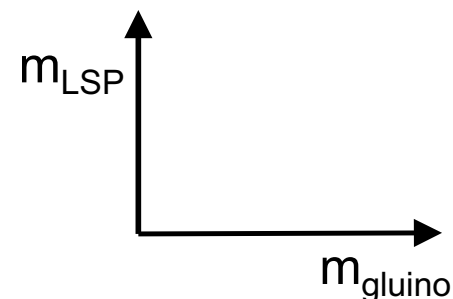
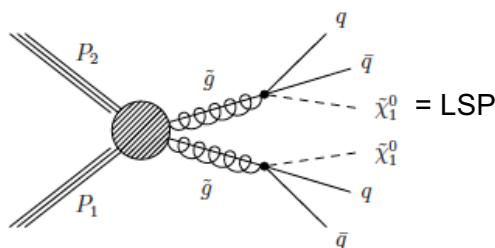


Many SUSY particles and many **cascade decays** possible

How to **simplify**?

- add additional theory assumptions (e.g. mSUGRA/CMSSM)
- only consider “simple” decay chains

E.g.



Paper is 2-dimensional → often only 2 parameters varied

**Warning:** branching ratios often assumed to be 100% and mass limits often quoted for “best case exclusion” for low mass LSP

# Squarks and gluinos: CMS



## Classic Jets & MET search

### Signal selection:

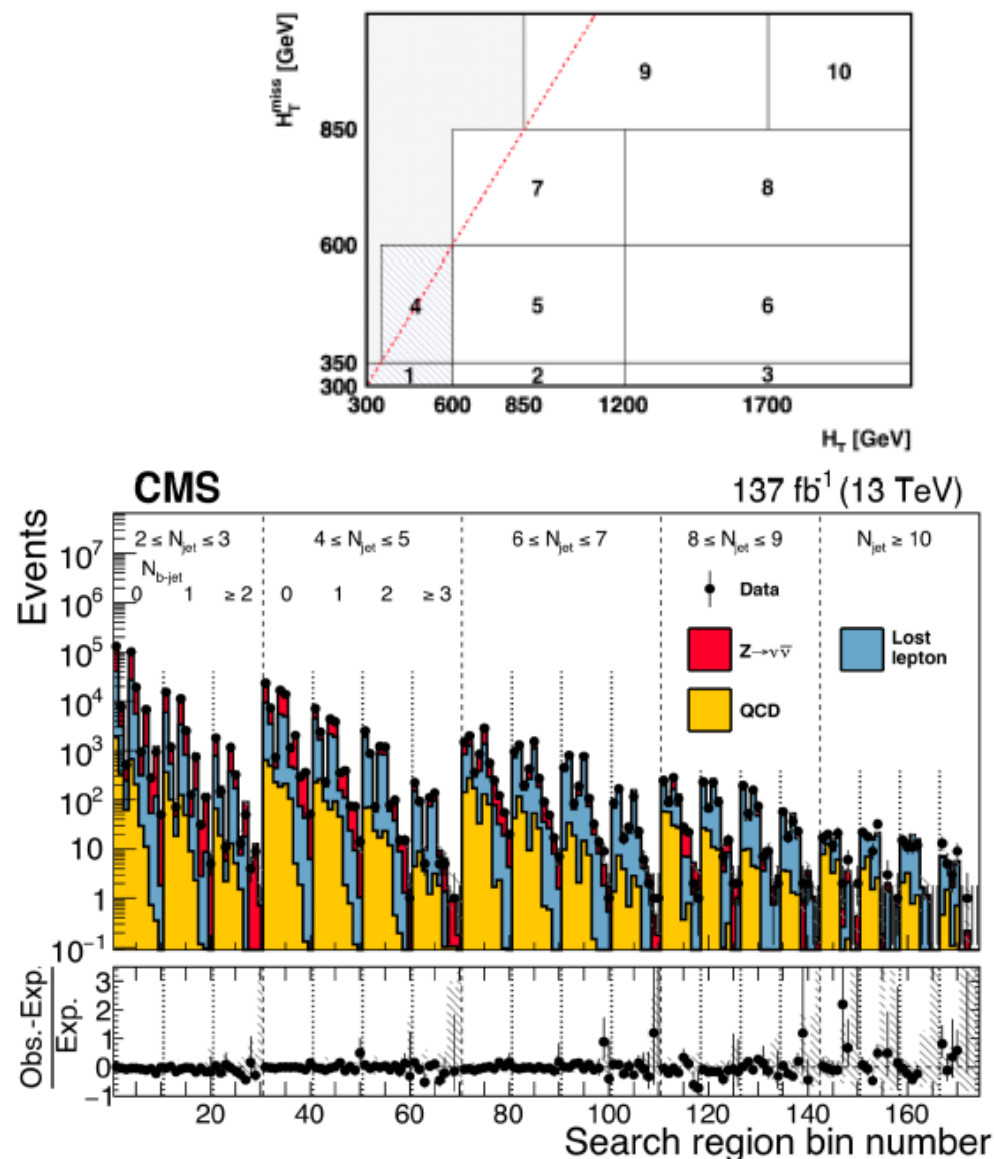
Binning in  $H_T$ ,  $H_T^{\text{miss}}$ ,  $\# \text{jets}$ ,  $\# \text{b-jets}$

### Main backgrounds:

- $t\bar{t}$  and  $W$  + jets where a lepton was lost  $\rightarrow$  predict from single lepton control region in data
- $Z \rightarrow \text{invisible}$  (genuine MET)  $\rightarrow$  predict from gamma + jet and  $Z \rightarrow \ell\ell$  control region in data
- QCD multijets (mismeasured jets leading to fake MET)  $\rightarrow$  predict from smeared events in data

CMS-SUS-19-006

Also: CMS-SUS-19-005



# Squarks and gluinos: ATLAS



NEW

## Classic Jets & $M_{\text{eff}}$ search

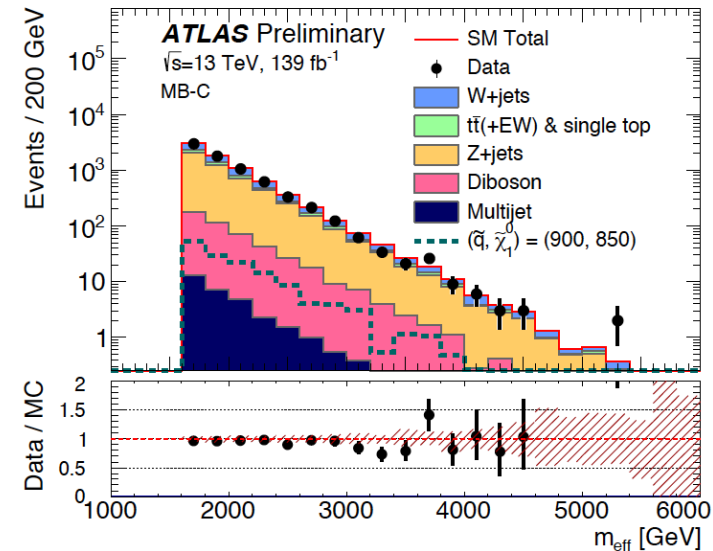
Signal selection:

Multibin search

Binning in  $m_{\text{eff}}$ , #jets,  $P_{\text{t}}^{\text{miss}}$  significance

Lepton veto	No baseline electron (muon) with $p_{\text{T}} > 7$ (6) GeV
$E_{\text{T}}^{\text{miss}}$ [GeV]	$> 300$
$p_{\text{T}}(j_1)$ [GeV]	$> 200$
$p_{\text{T}}(j_2)$ [GeV]	$> 50$
$\Delta\phi(j_{1,2(3)}, p_{\text{T}}^{\text{miss}})_{\text{min}}$ [rad.]	$> 0.4$
$m_{\text{eff}}$ [GeV]	$> 800$

	MB-SSd	MB-GGd	MB-C
$N_{\text{j}}$	$\geq 2$	$\geq 4$	$\geq 2$
$p_{\text{T}}(j_1)$ [GeV]	$> 200$	$> 200$	$> 600$
$p_{\text{T}}(j_{i=2, \dots, N_{\text{jmin}}})$ [GeV]	$> 100$	$> 100$	$> 50$
$ \eta(j_{i=1, \dots, N_{\text{jmin}}}) $	$< 2.0$	$< 2.0$	$< 2.8$
$\Delta\phi(j_{1,2(3)}, p_{\text{T}}^{\text{miss}})_{\text{min}}$	$> 0.8$	$> 0.4$	$> 0.4$
$\Delta\phi(j_{i>3}, p_{\text{T}}^{\text{miss}})_{\text{min}}$	$> 0.4$	$> 0.2$	$> 0.2$
Aplanarity	-	$> 0.04$	-
$E_{\text{T}}^{\text{miss}} / \sqrt{H_{\text{T}}} [\text{GeV}^{1/2}]$	$> 10$	$> 10$	$> 10$
$m_{\text{eff}}$ [GeV]	$> 1000$	$> 1000$	$> 1600$



$m_{\text{eff}}$  = sum of  $p_{\text{T}}$  of jets ( $> 50$  GeV) +  $P_{\text{T}}^{\text{miss}}$

Also: BDT search and single bin results

Main backgrounds: estimated from Control Regions which are used to normalize and modify the background MC simulation

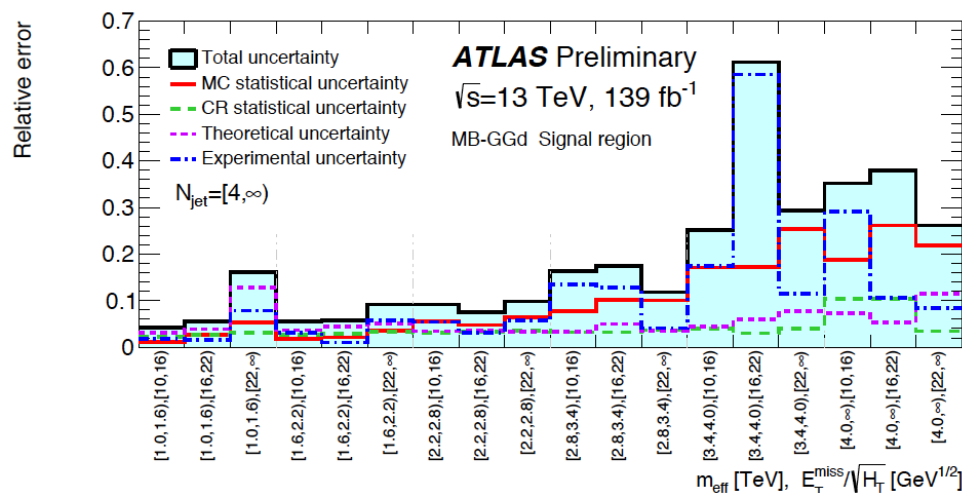
# Systematic uncertainties



To give some feeling for the systematic uncertainties ...



Overall total uncertainty in multibin regions:



Dominant experimental uncertainty often JES/JER

ATLAS-CONF-2019-040

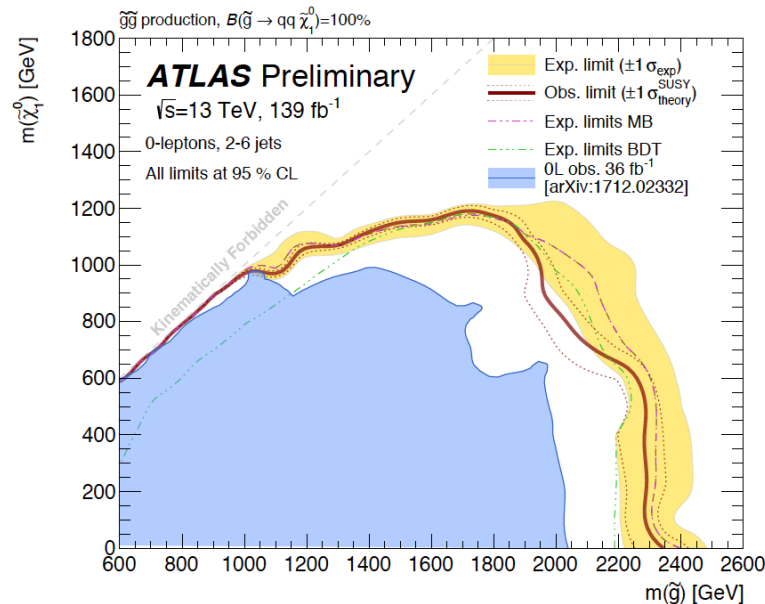
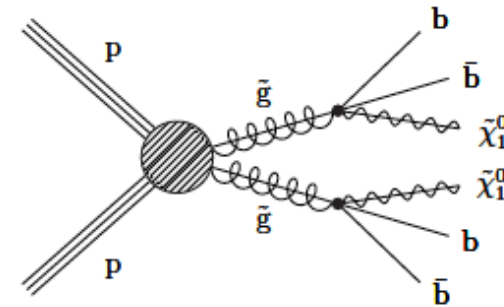
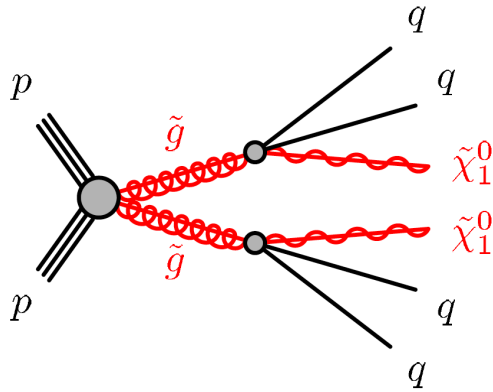
Signal systematics:

Item	Relative uncertainty (%)
Trigger efficiency (statistical)	0.2–2.6
Trigger efficiency (systematic)	2.0
Jet quality requirements	1.0
Initial-state radiation	0.0–14
Renormalization and factorization scales $\mu_R$ & $\mu_F$	0.0–5.7
Jet energy scale	0.0–14
Jet energy resolution	0.0–10
Statistical uncertainty of simulated samples	1.2–31
$H_T$ and $H_T^{\text{miss}}$ modeling	0.0–11
Pileup modeling	0.0–2.4
Isolated-lepton & isolated-track vetoes (T1tttt, T5qqqqVV, and T2tt models)	2.0
Integrated luminosity	2.3–2.5
Total	4.0–33

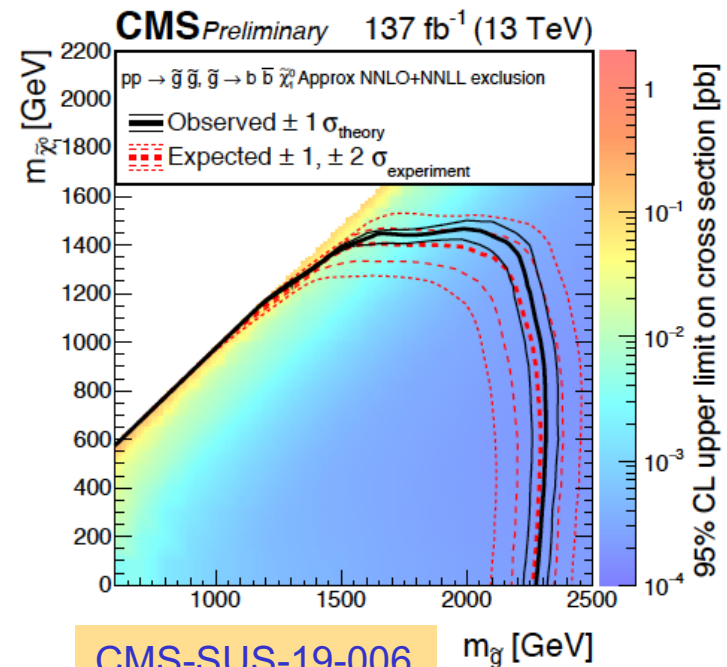
CMS-SUS-19-006

Both ATLAS and CMS: MC statistical uncertainty often important

# Gluino limits



ATLAS-CONF-2019-040

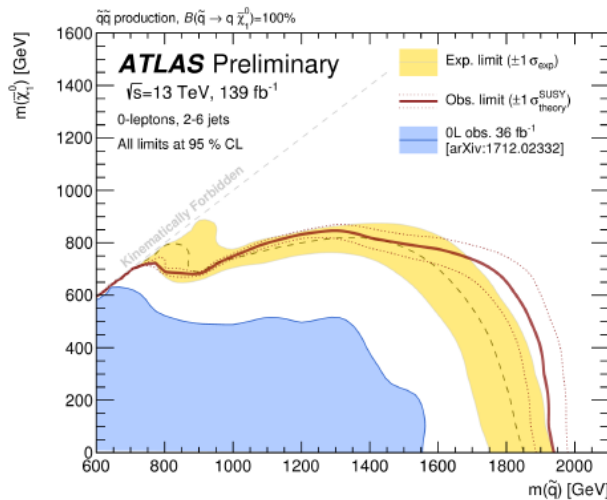
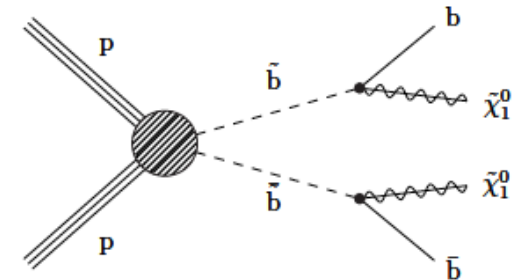
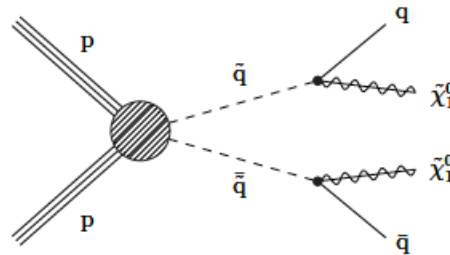
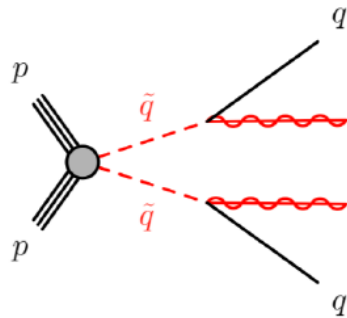


CMS-SUS-19-006  $m_{\tilde{g}}$  [GeV]

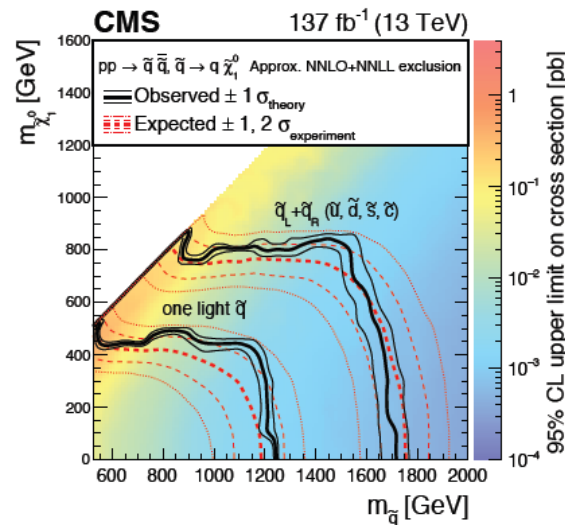
Mass limits have reached  $\sim 2.3$  TeV for low LSP masses

Lepton Photon, Toronto, August 2019

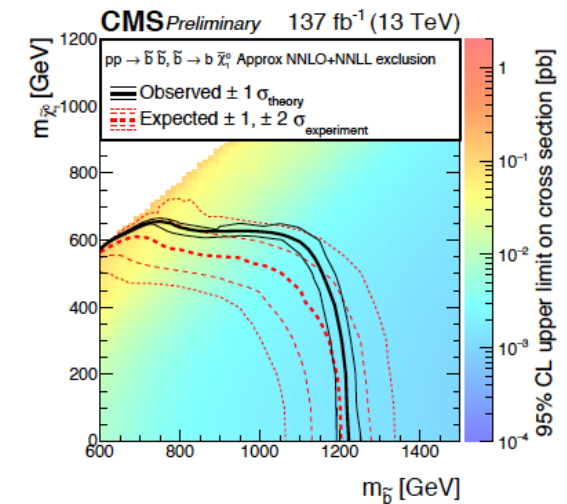
# Squark limits



ATLAS-CONF-2019-040



CMS-SUS-19-005



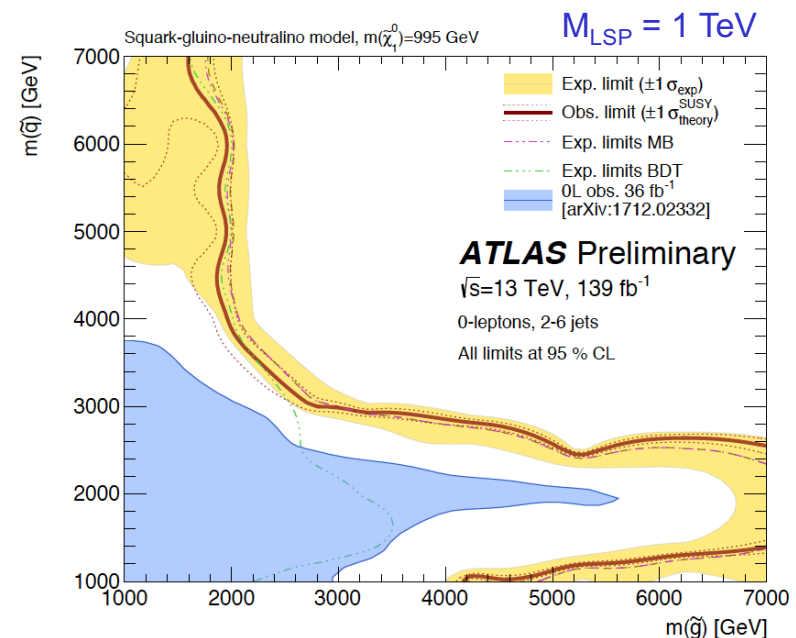
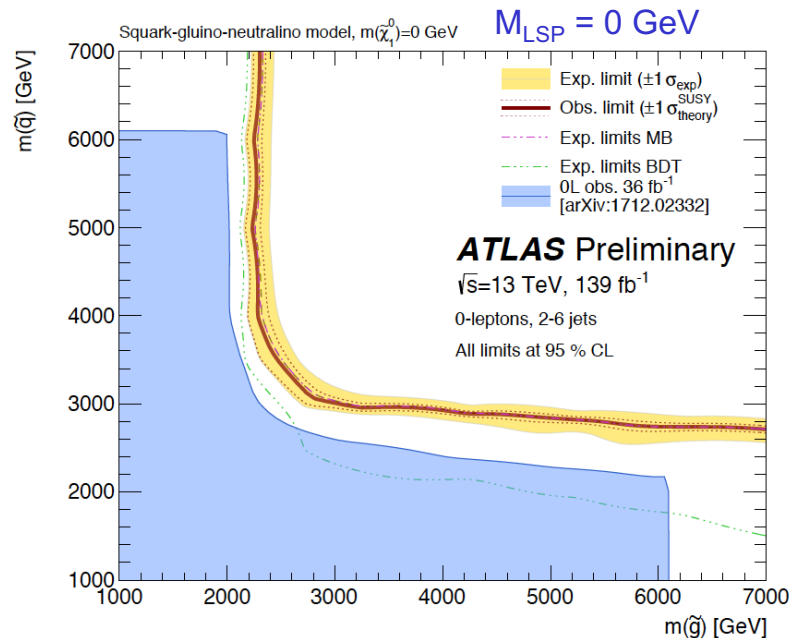
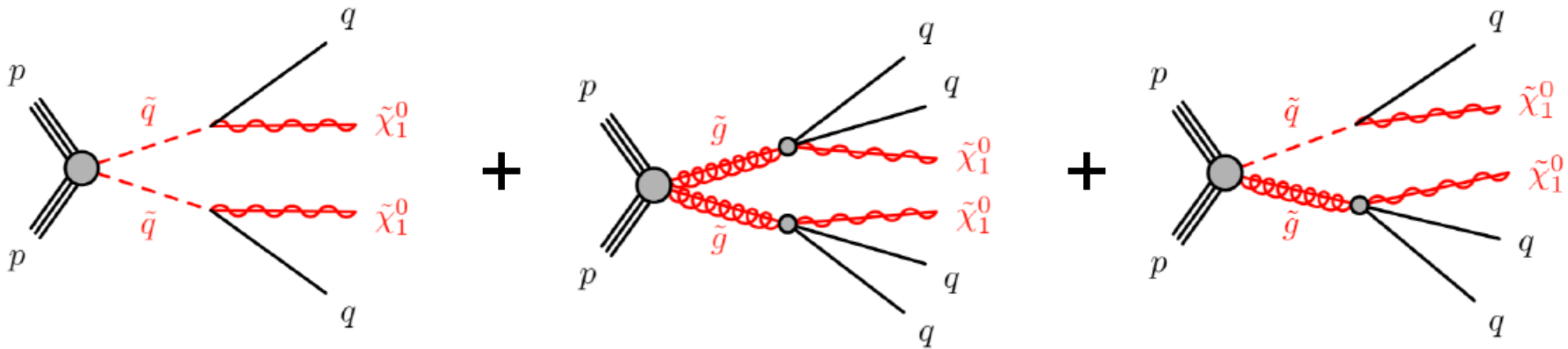
CMS-SUS-19-006

Mass limits have reached  $\sim 1.2$  TeV on individual squarks for low LSP masses and  $\sim 1.9$  TeV for 8-fold degenerate squarks

# Squark+gluino limits



Limits on squark-squark + gluino-gluino + squark-gluino production:



# Single lepton search



NEW

Single lepton search using sum of large-R jet masses ( $M_J$ )

$$M_J = \sum_{J_i = \text{large-R jets}} m(J_i).$$

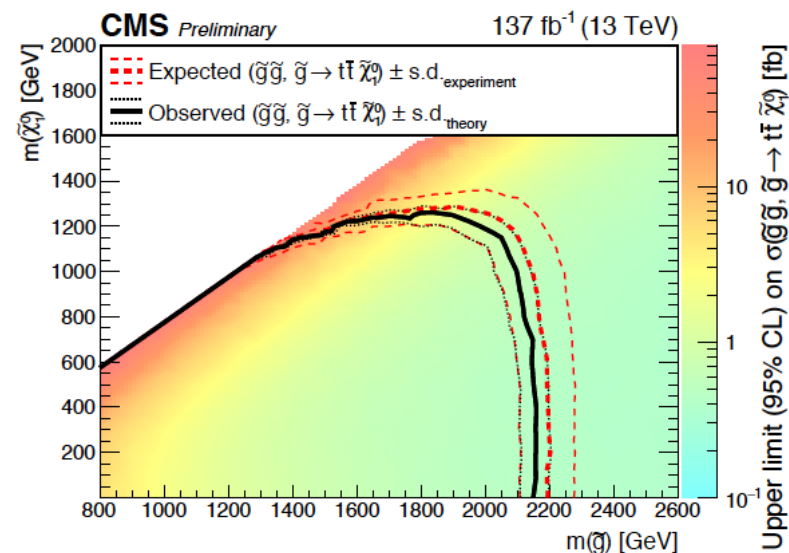
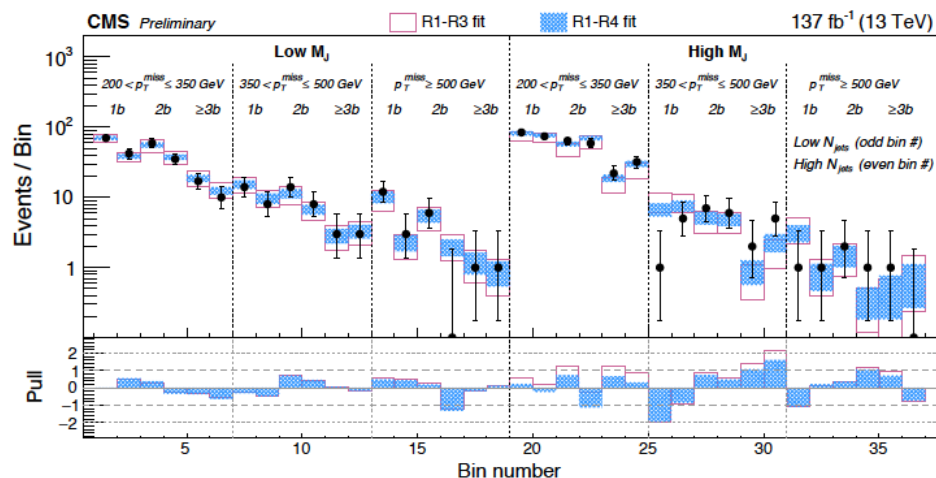
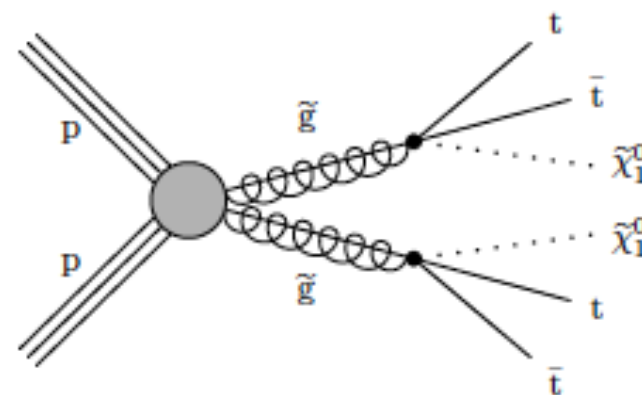
( $R=1.4$ )

Signal selection:

Single lepton +  $P_T^{\text{miss}}$ ,  $S_T$ , #jets, #b-jets,  $M_J$

Main backgrounds:

1l and 2l ttbar from control regions in  $M_J$  and  $M_T$



CMS-SUS-19-007

See talk by Ana Ovcharova for details

# Same-sign dileptons & more

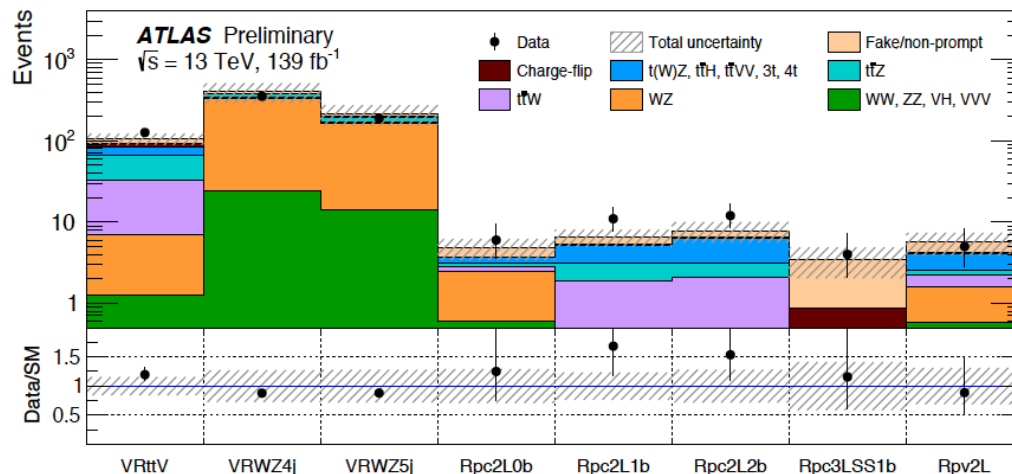


ATLAS-CONF-2019-015

## Same-sign 2l & > 3l search

### Signal selection:

SR	$n_\ell$	$n_b$	$n_j$	$E_T^{\text{miss}}$ [GeV]	$m_{\text{eff}}$ [GeV]	$E_T^{\text{miss}}/m_{\text{eff}}$
Rpv2L	$\geq 2 (\ell^\pm \ell^\pm)$	$\geq 0$	$\geq 6 (p_T > 40 \text{ GeV})$	—	$> 2600$	—
Rpc2L0b	$\geq 2 (\ell^\pm \ell^\pm)$	$= 0$	$\geq 6 (p_T > 40 \text{ GeV})$	$> 200$	$> 1000$	$> 0.2$
Rpc2L1b	$\geq 2 (\ell^\pm \ell^\pm)$	$\geq 1$	$\geq 6 (p_T > 40 \text{ GeV})$	—	—	$> 0.25$
Rpc2L2b	$\geq 2 (\ell^\pm \ell^\pm)$	$\geq 2$	$\geq 6 (p_T > 25 \text{ GeV})$	$> 300$	$> 1400$	$> 0.14$
Rpc3LSS1b	$\geq 3 (\ell^\pm \ell^\pm \ell^\pm)$	$\geq 1$	no cut but veto $81 \text{ GeV} < m_{\ell^+ \ell^-} < 101 \text{ GeV}$		$> 0.14$	



CMS-SUS-19-008

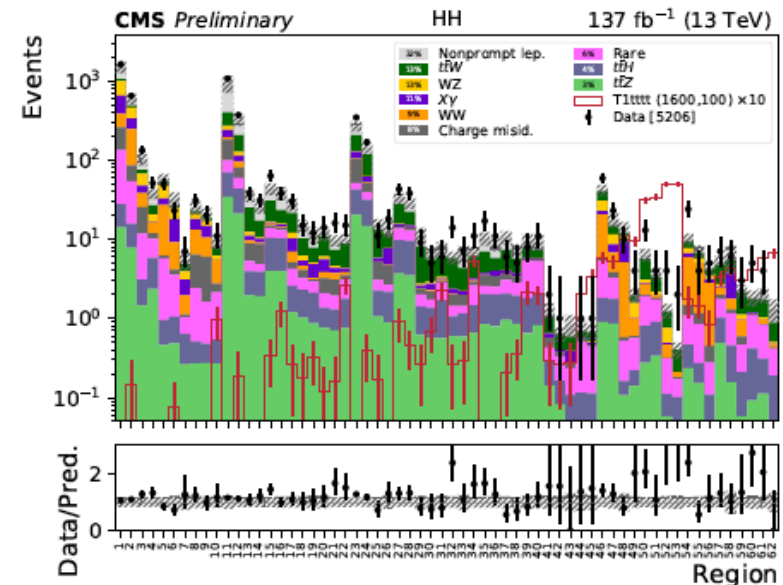
## Same-sign 2l & multilepton search

### Signal selection:

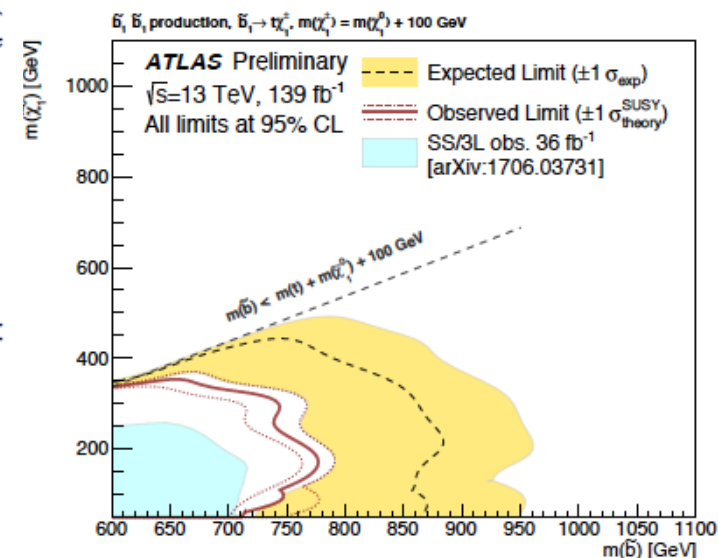
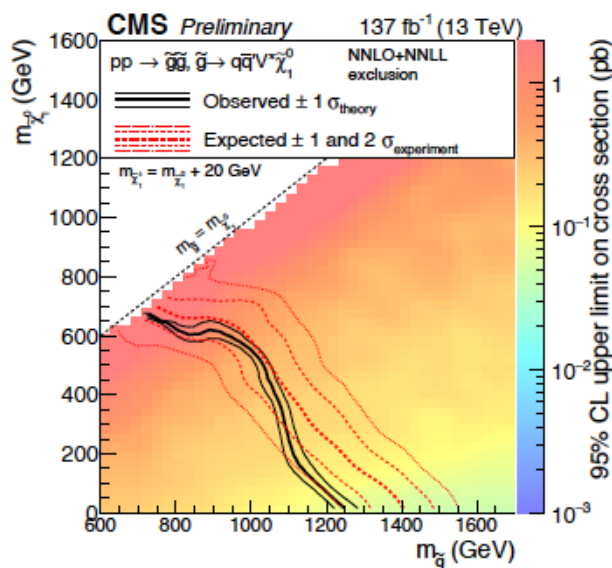
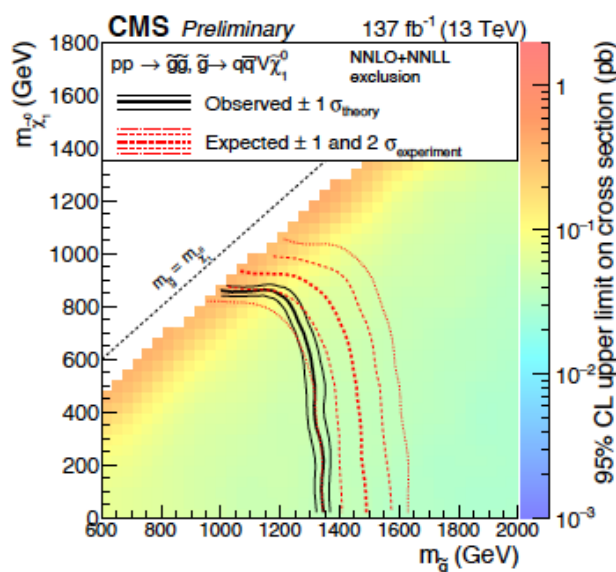
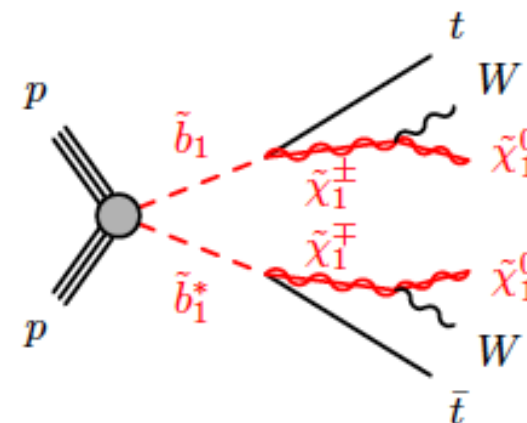
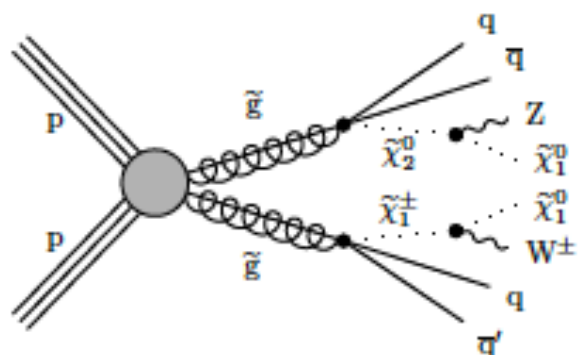
Binning in  $H_T$ ,  $p_T^{\text{miss}}$ ,  $m_T^{\text{min}}$ , #jets, #b-jets

### Main backgrounds:

- rare SM backgrounds ( $ttV$ ,  $W^\pm W^\pm$ ,  $WZ$ )
- background with non-prompt leptons ( $W$ +jets, QCD)



# Interpretations



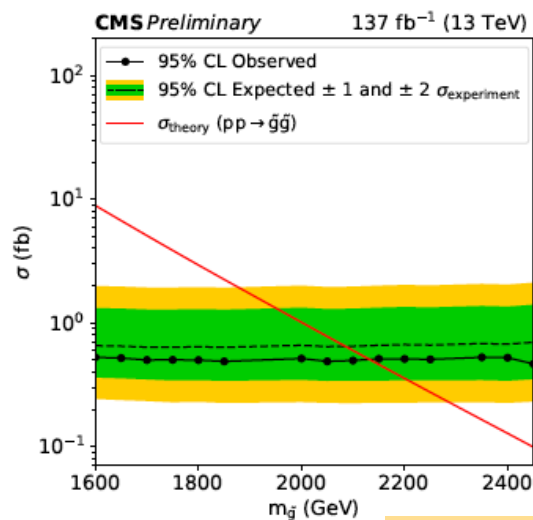
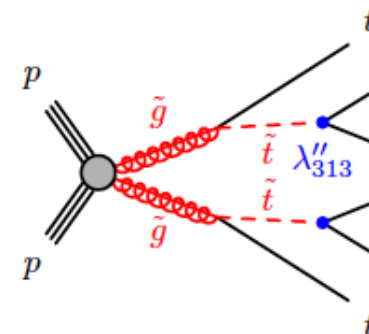
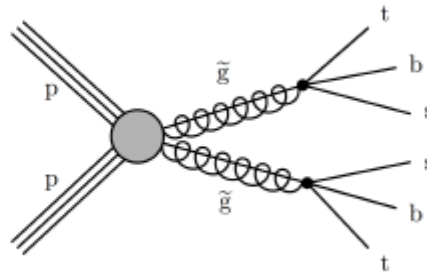
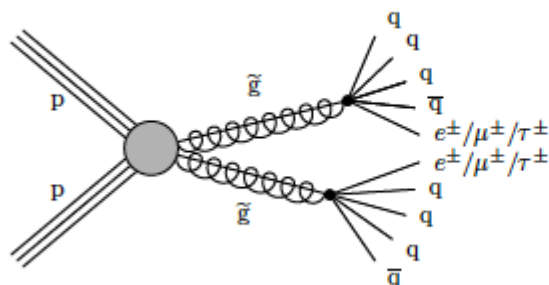
$$m_{\tilde{\chi}_1^\pm} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$$

$$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 20 \text{ GeV}$$

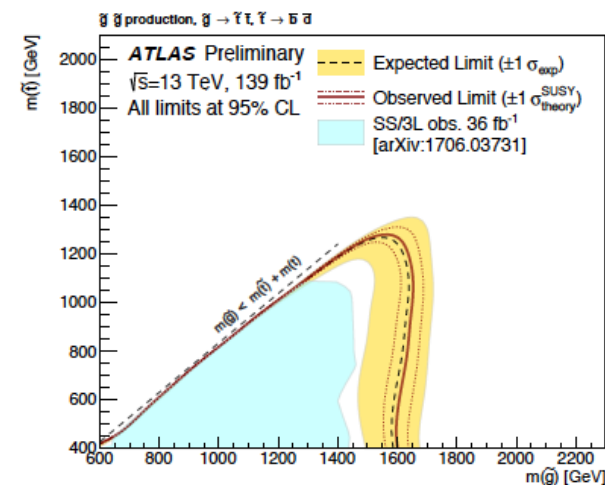
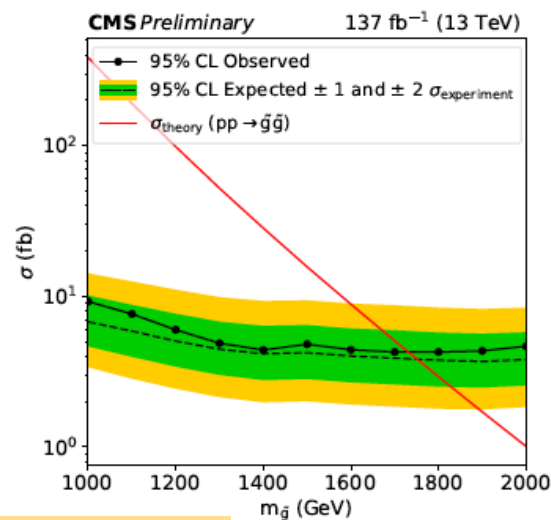
ATLAS-CONF-2019-015

CMS-SUS-19-008

# Also RPV SUSY limits



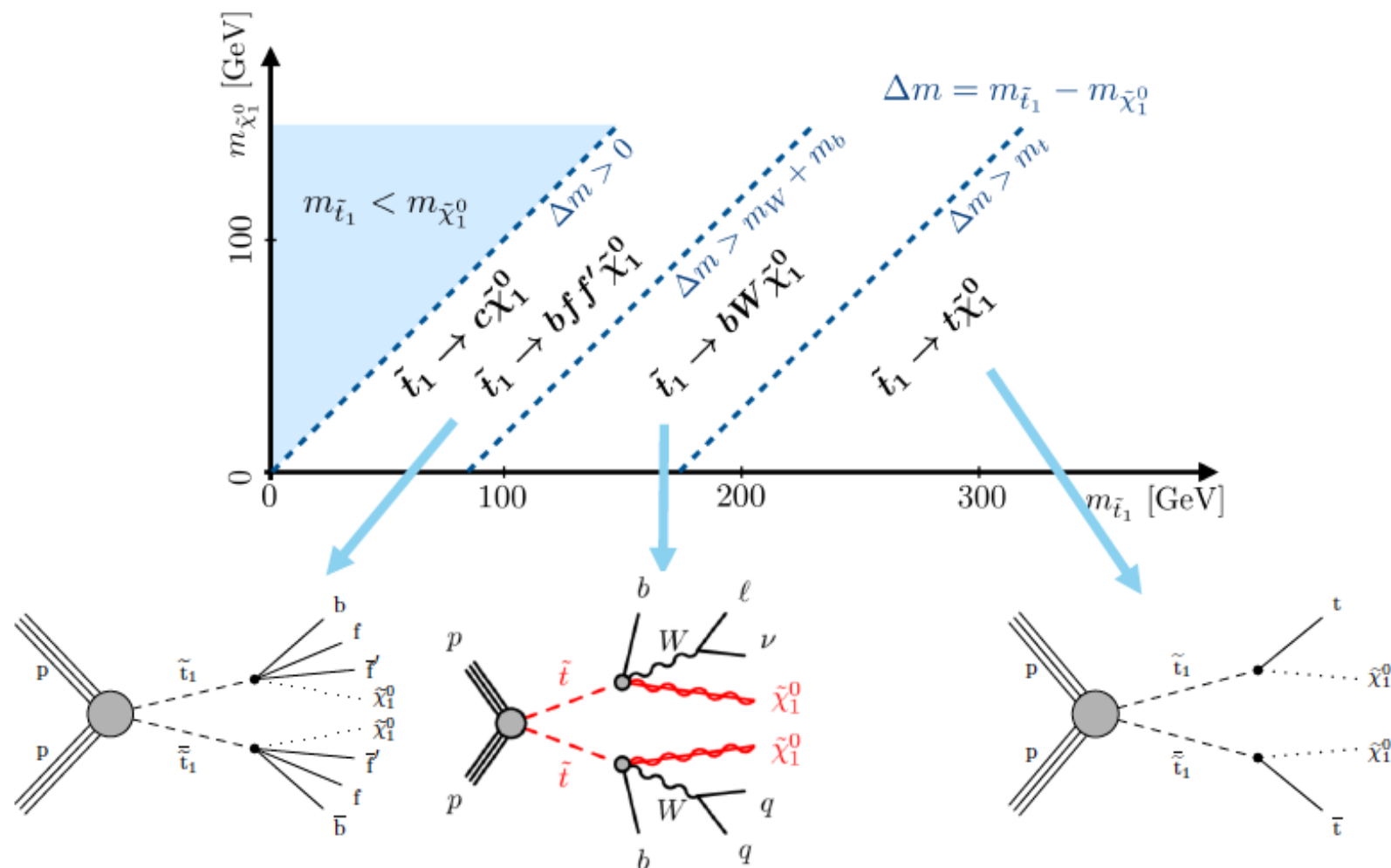
CMS-SUS-19-008



ATLAS-CONF-2019-015

Sensitivity up to gluino masses of 1.6 - 2.1 TeV

# Dedicated stop searches



# Stop single lepton



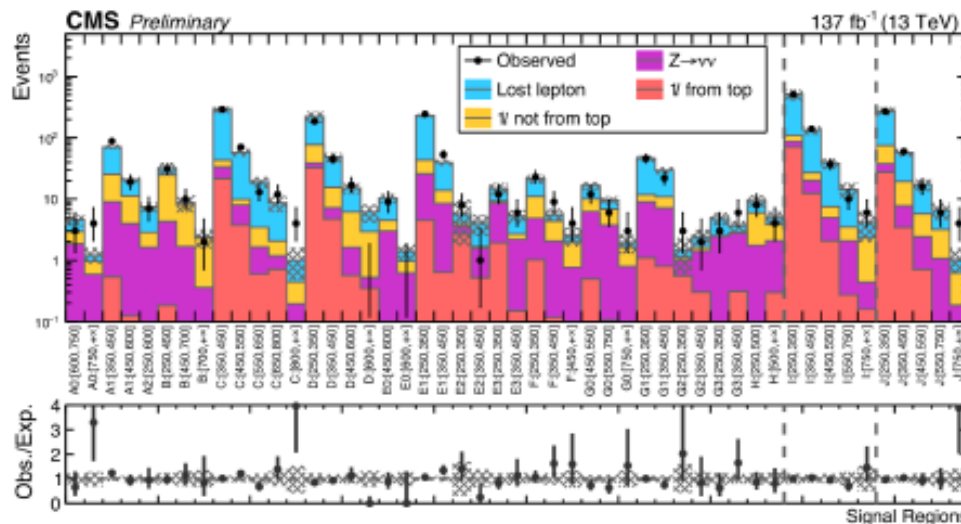
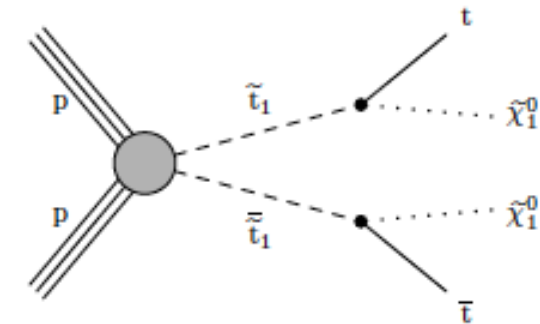
## Classic single lepton stop search

### Signal selection:

Binning in  $H_T$ ,  $H_T^{\text{miss}}$ , #jets, #b-jets  
+ resolved and boosted top-tagging

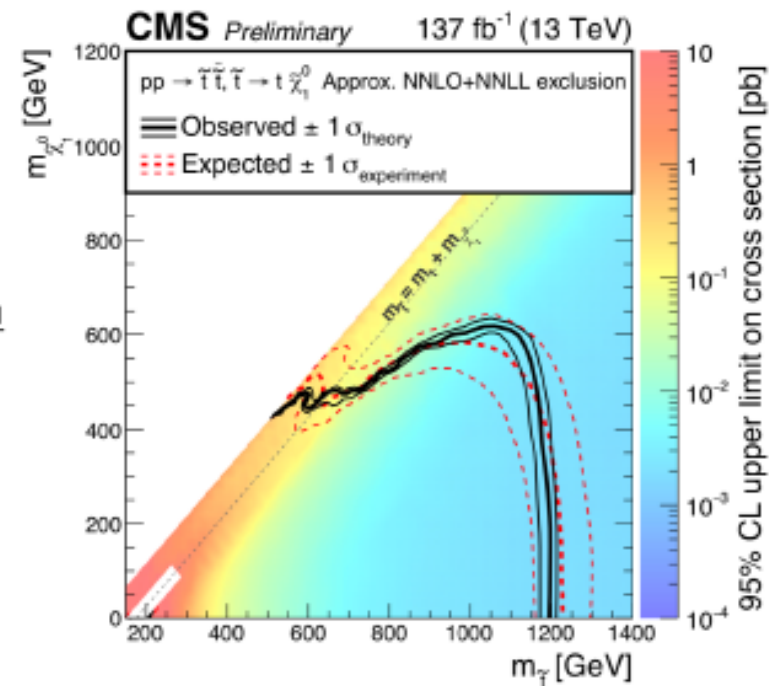
### Main backgrounds:

- $t\bar{t}$  and single top with 1 lost lepton  $\rightarrow$  predicted from dilepton control region in data
- $W$ +jets  $\rightarrow$  taken from 0b control region in data



	$N_j$	$t_{\text{mod}}$	$M_b$ [GeV]
A	2-3	$> 10$	$\leq 175$
B	2-3	$> 10$	$> 175$
C	$\geq 4$	$\leq 0$	$\leq 175$
D	$\geq 4$	$\leq 0$	$> 175$
E	$\geq 4$	0-10	$\leq 175$
F	$\geq 4$	0-10	$> 175$
G	$\geq 4$	$> 10$	$\leq 175$
H	$\geq 4$	$> 10$	$> 175$

X0: Inclusive  
X1: Untagged  
X2: Boosted top  
X3: Resolved top  
I:  $N_j \geq 5$ ,  $N_{b,\text{med}} \geq 1$   
J:  $N_j \geq 3$ ,  $N_{b,\text{soft}} \geq 1$

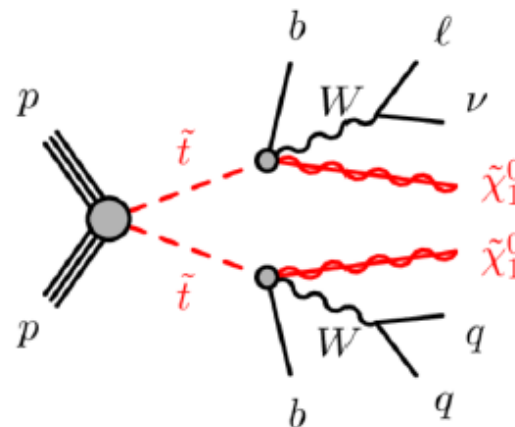
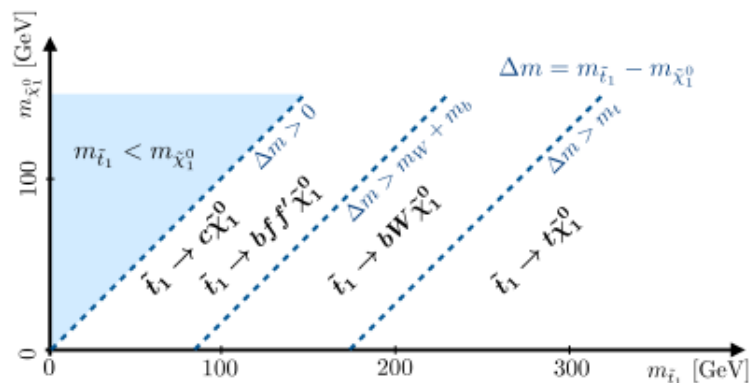


Limits up to 1.2 TeV  
for low LSP mass

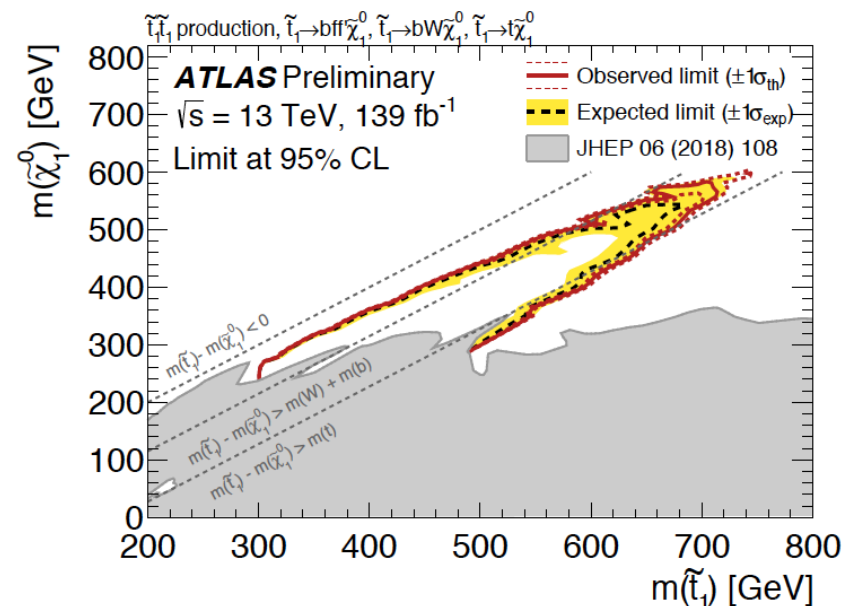
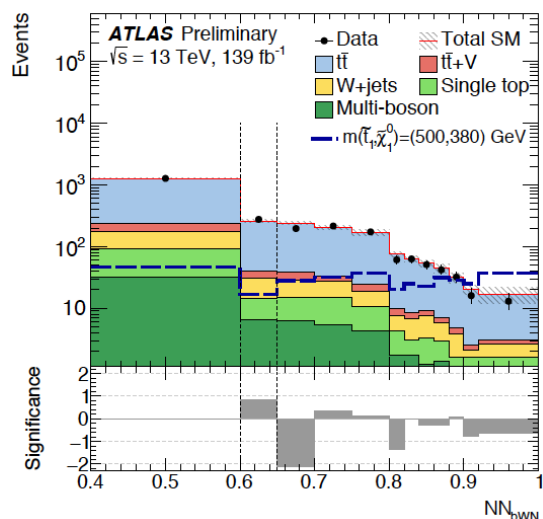
# Difficult regions



## Single lepton stop search targeting 3-body decays



## Dedicated recurrent neural network:



# Stop to taus



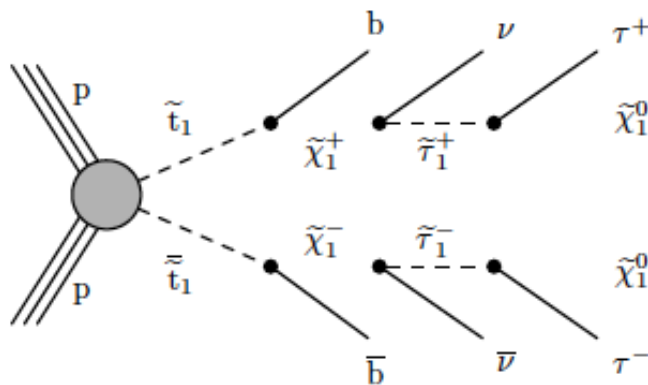
## Stop search in decays to tau leptons

### Signal selection:

Binning in  $H_T$ ,  $P_T^{\text{miss}}$ ,  $M_{T2}$

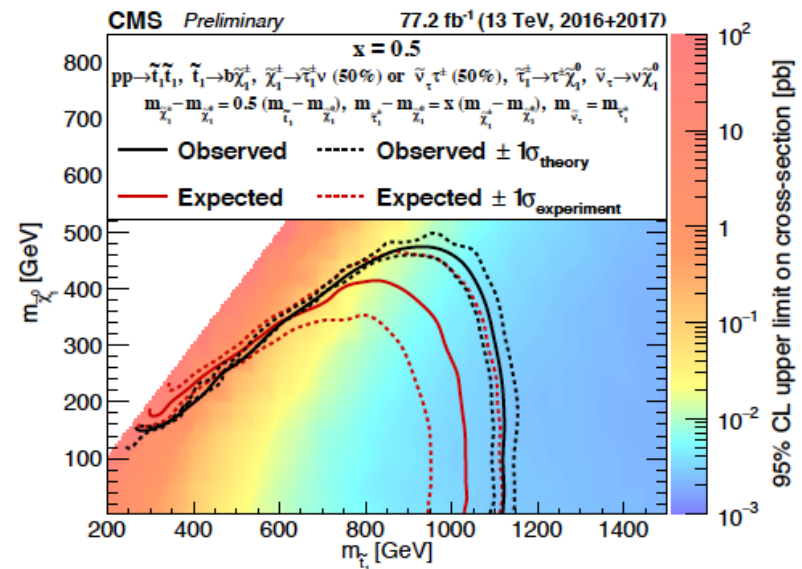
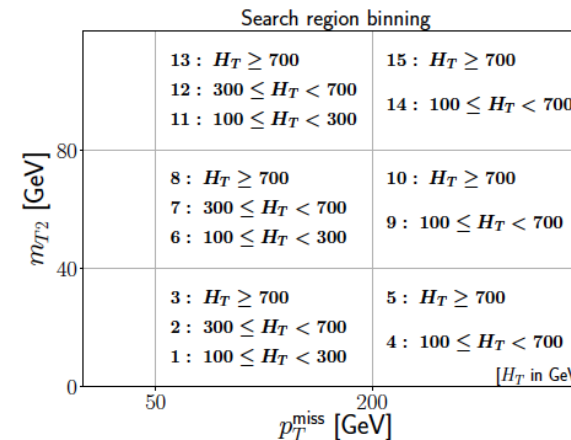
### Main backgrounds:

- $t\bar{t}$  with two genuine taus
- mis-identified taus



$$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 0.5 (m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0})$$

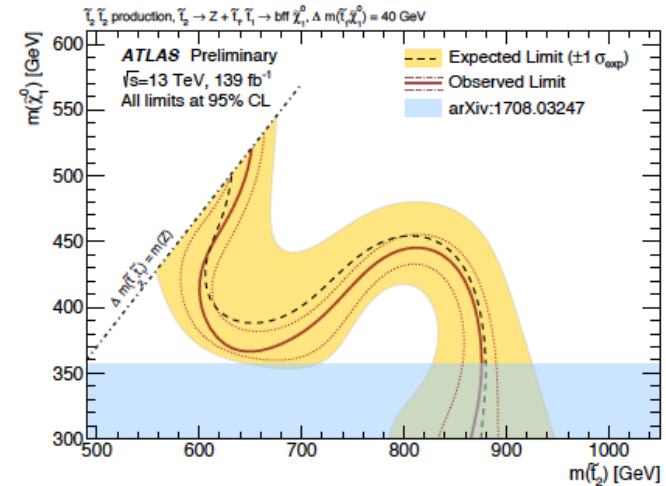
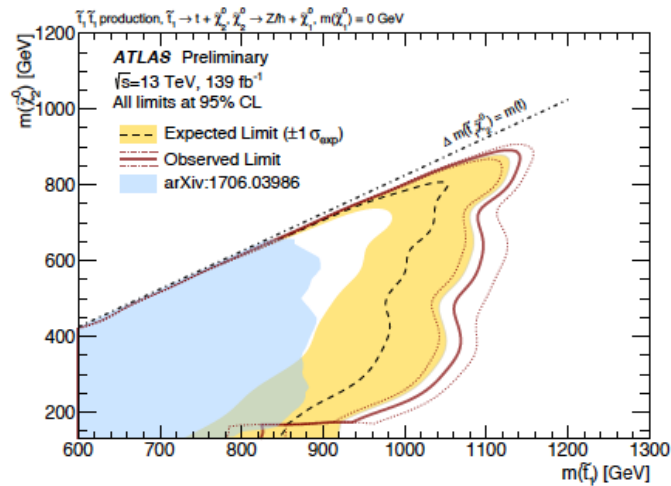
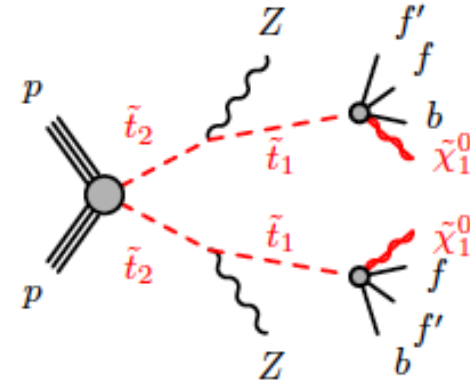
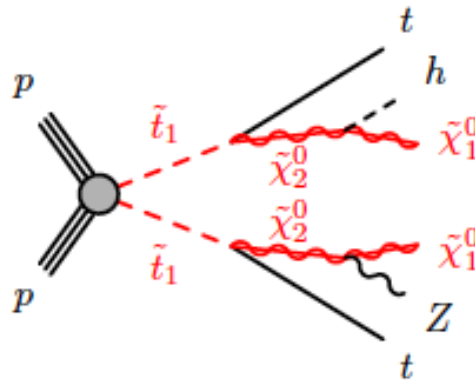
$$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 0.5 (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})$$



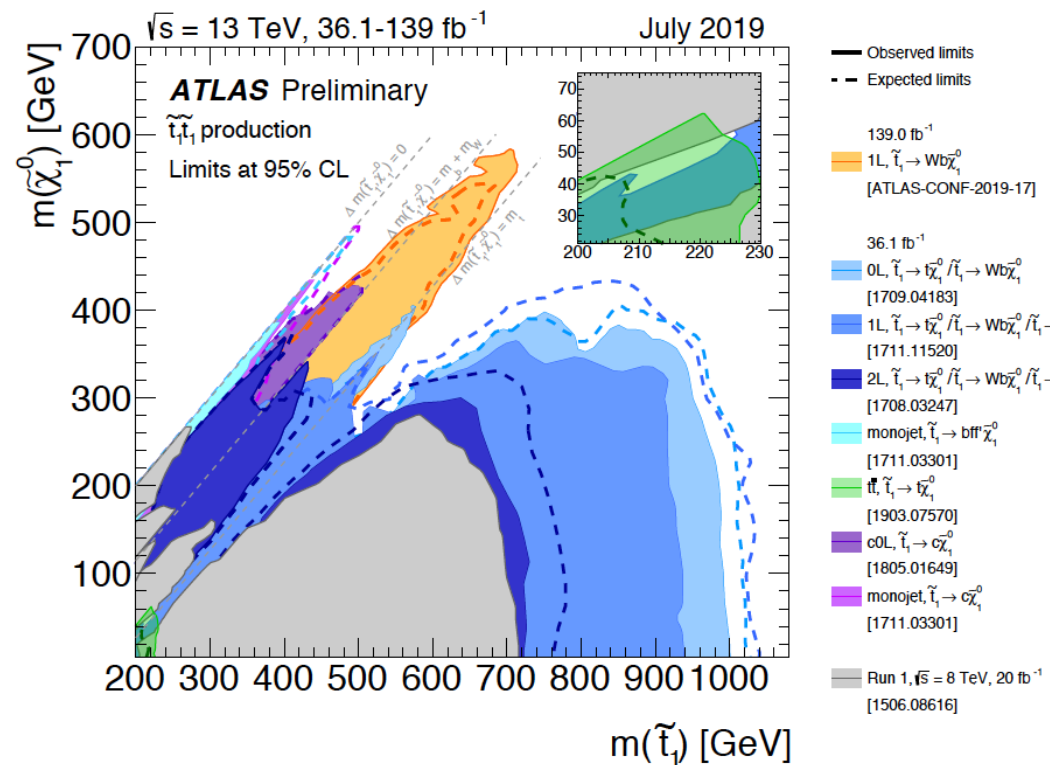
# Stop to Z



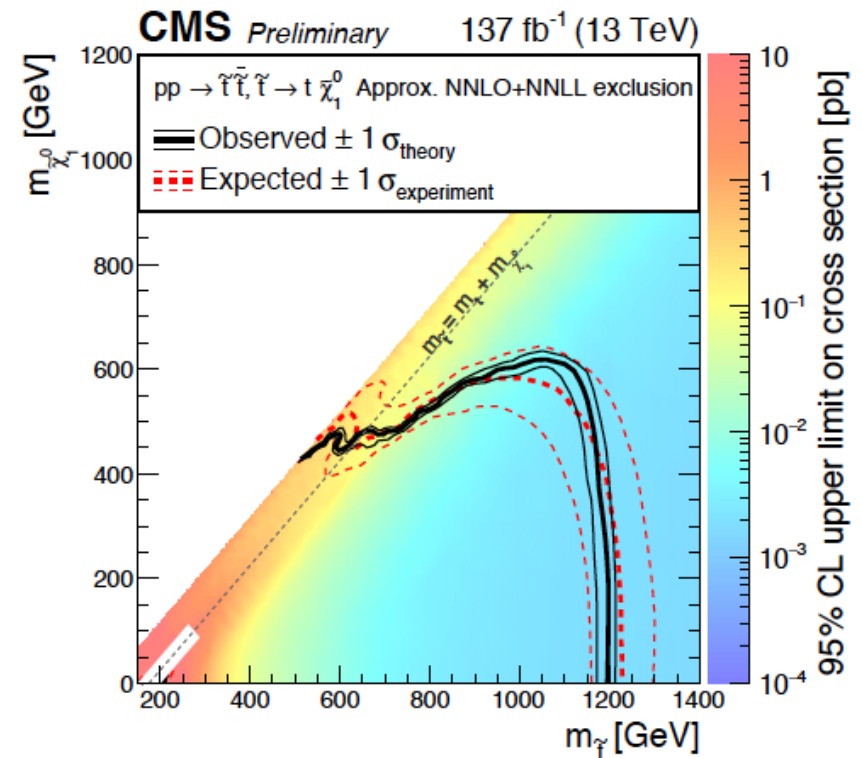
Search for stop decaying to Z-boson (decaying to a lepton pair)



# Summary: stop search



Several analyses targeting the difficult compressed regions



High mass: limits up to 1200 GeV

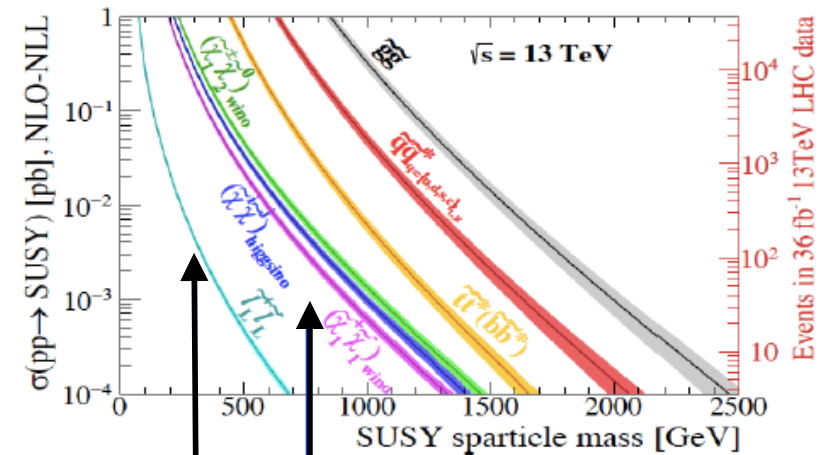
# Electroweak SUSY: intro



Direct electroweak production of charginos, neutralinos and sleptons is challenging due to the **low cross sections**

E.g.  $\sigma(500 \text{ GeV slepton}) = 0.5 \text{ fb}$

Decays of charginos and next-to-lightest neutralinos can be complex



Chargino/neutralino pair production depends on the bino/wino/higgsino composition

Direct slepton pair-production has the lowest cross section

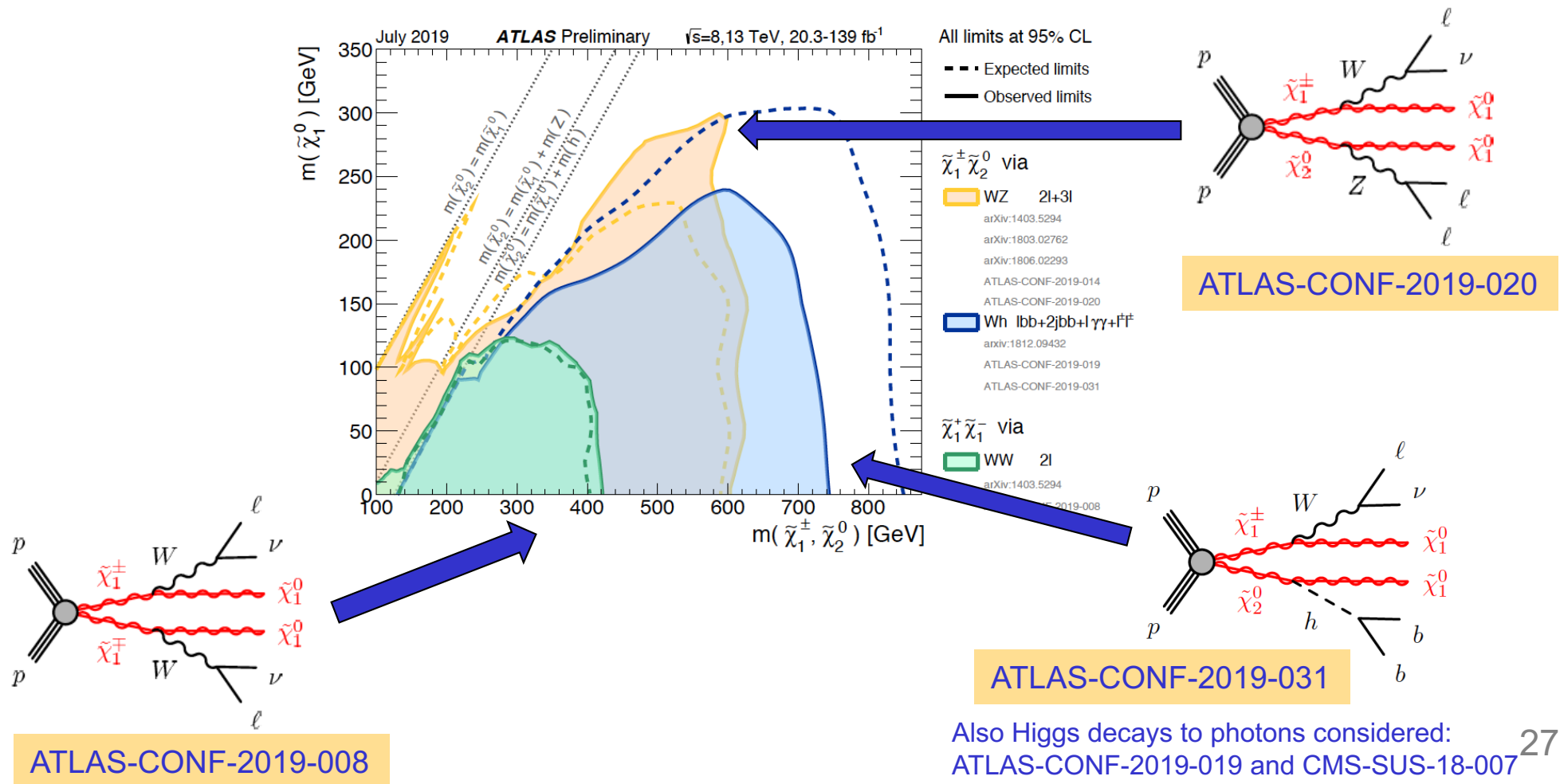
Bino		Wino		Higgsino	
$\tilde{q}_{L,R}$	—	$\tilde{q}_{L,R}$	—	$\tilde{q}_{L,R}$	—
$\tilde{H}_{u,d}$	— $\tilde{\chi}_{3,4}^0/\tilde{\chi}_2^\pm$	$\tilde{H}_{u,d}$	— $\tilde{\chi}_{3,4}^0/\tilde{\chi}_2^\pm$	$\tilde{W}$	— $\tilde{\chi}_4^0/\tilde{\chi}_2^\pm$
$\tilde{W}$	— $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$	$\tilde{B}$	— $\tilde{\chi}_2^0$	$\tilde{B}$	— $\tilde{\chi}_3^0$
$\tilde{B}$	— $\tilde{\chi}_1^0$	$\tilde{W}$	— $\tilde{\chi}_1^0/\tilde{\chi}_1^\pm$	$\tilde{H}_{u,d}$	— $\tilde{\chi}_{1,2}^0/\tilde{\chi}_1^\pm$

From 1902.11267

# Chargino/neutralino



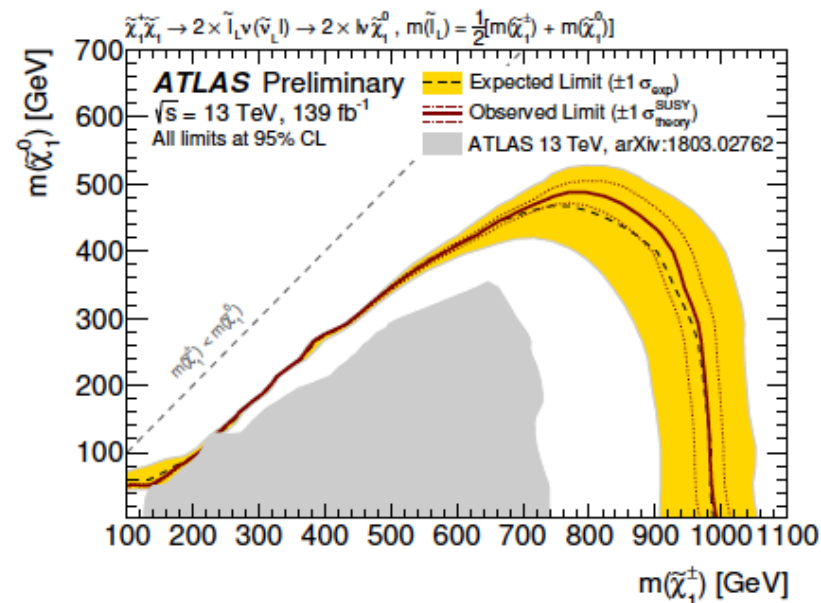
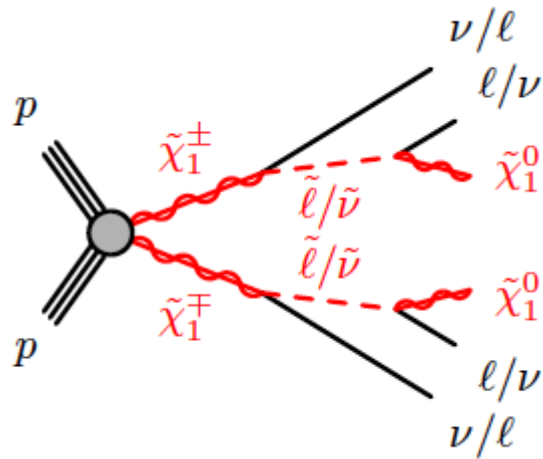
Chargino/chargino or chargino/neutralino pair production assuming decays to W/Z/h bosons



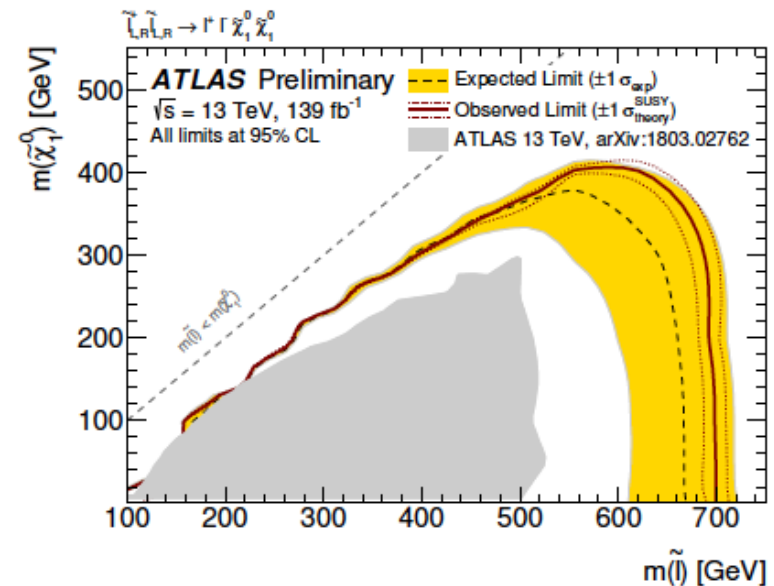
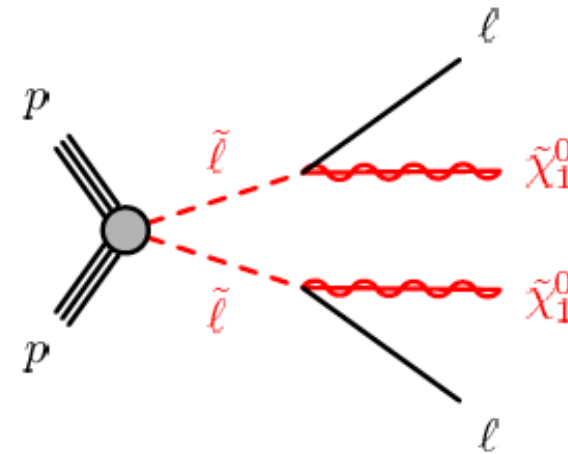
# Also



## Chargino decays through light sleptons



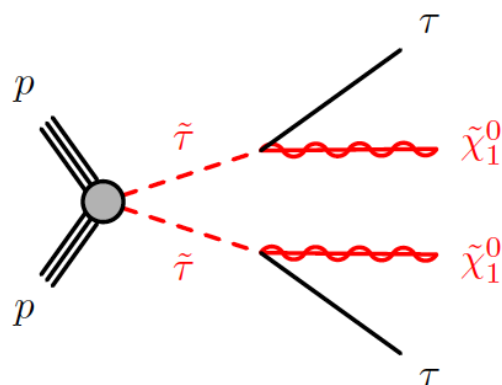
## Direct slepton pair production



# Staus

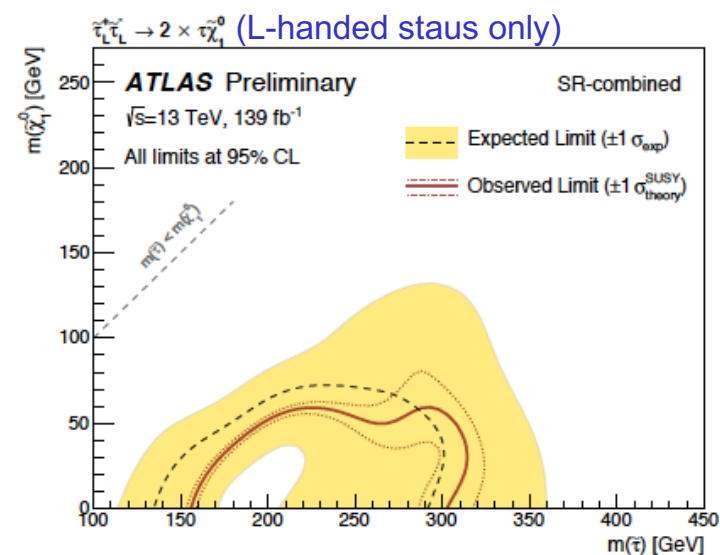
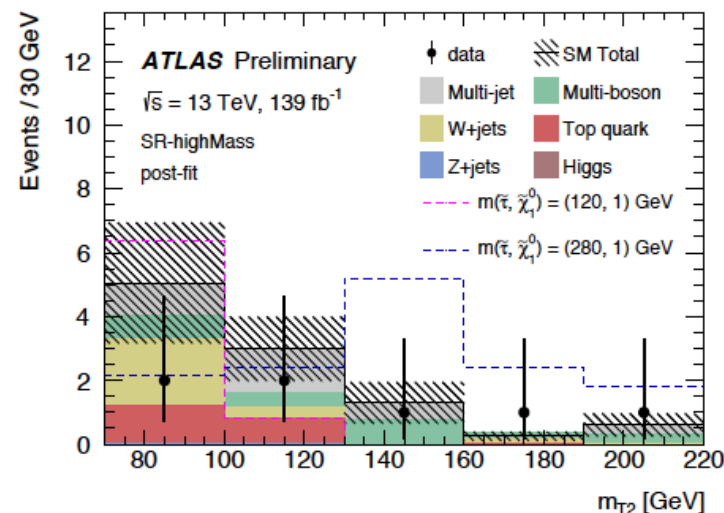


## Stau pair production



## Signal selection:

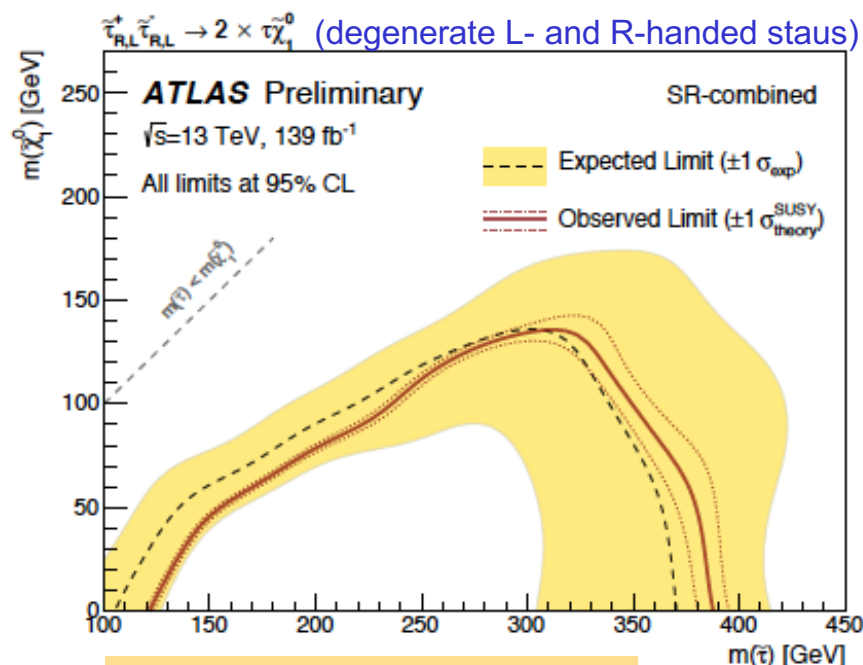
SR-lowMass	SR-highMass
2 tight $\tau$ s (OS)	2 medium $\tau$ s (OS), $\geq 1$ tight $\tau$
asymmetric di-tau trigger	di-tau+ $E_T^{\text{miss}}$ trigger
$75 < E_T^{\text{miss}} < 150$ GeV	$E_T^{\text{miss}} > 150$ GeV
tau $p_T$ and $E_T^{\text{miss}}$ cuts described in Section 5	
light lepton veto and 3rd medium $\tau$ veto	
$b$ -jet veto	
$Z/H$ veto ( $m(\tau_1, \tau_2) > 120$ GeV)	
$\Delta R(\tau_1, \tau_2) < 3.2$	
$ \Delta\phi(\tau_1, \tau_2)  > 0.8$	
$m_{T2} > 70$ GeV	



# Staus

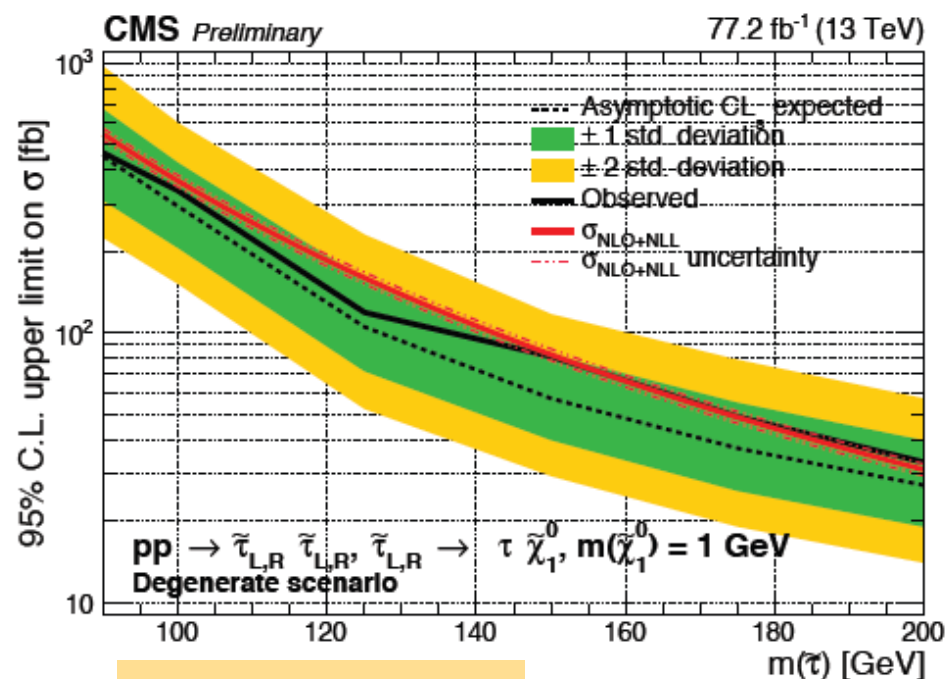


**ATLAS analysis:**  
Hadronic tau decays only  
Full Run 2 dataset



ATLAS-CONF-2019-018

**CMS analysis:**  
Including also semileptonic taus  
Partial Run 2 dataset



CMS-SUS-18-006

LEP excludes tau sleptons with masses up to 90 GeV (for  $\Delta M > 15$  GeV).

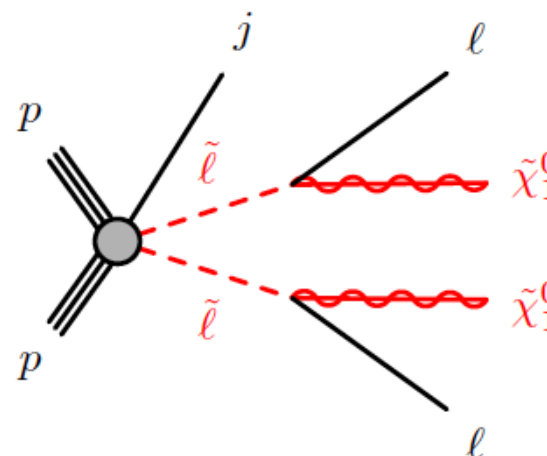
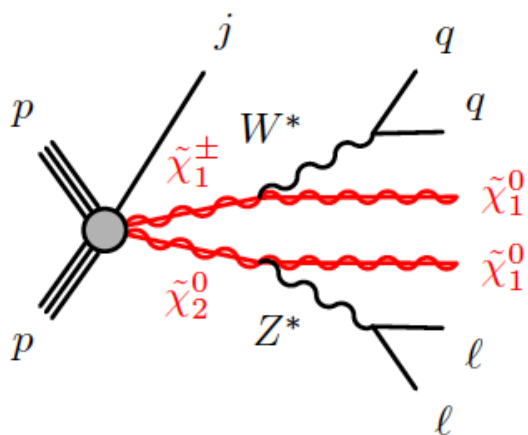
ATLAS excludes masses between 120 and 390 GeV.

CMS closes the gap between 90 and 120 GeV. Valid for low LSP masses.

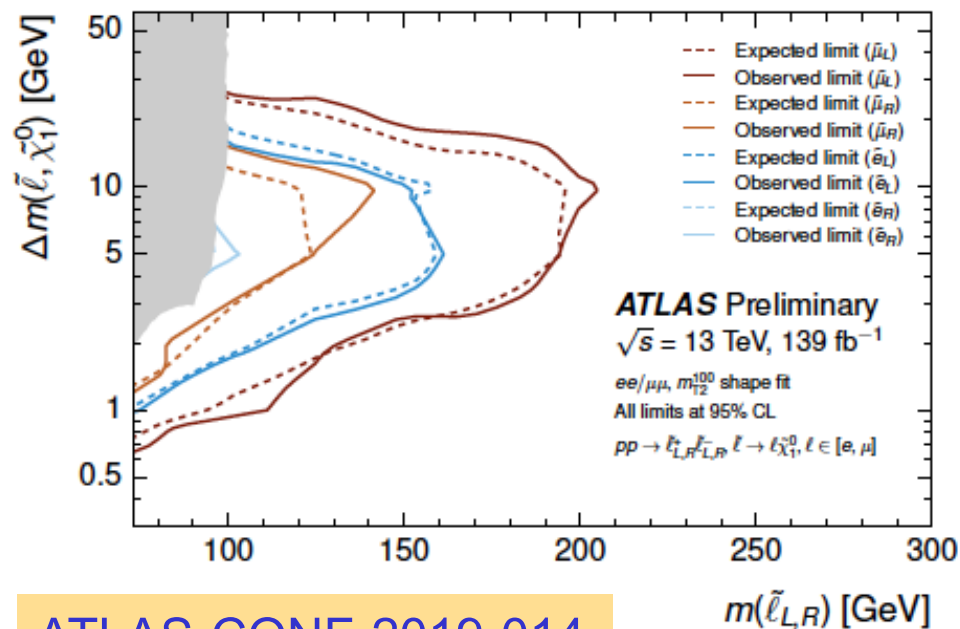
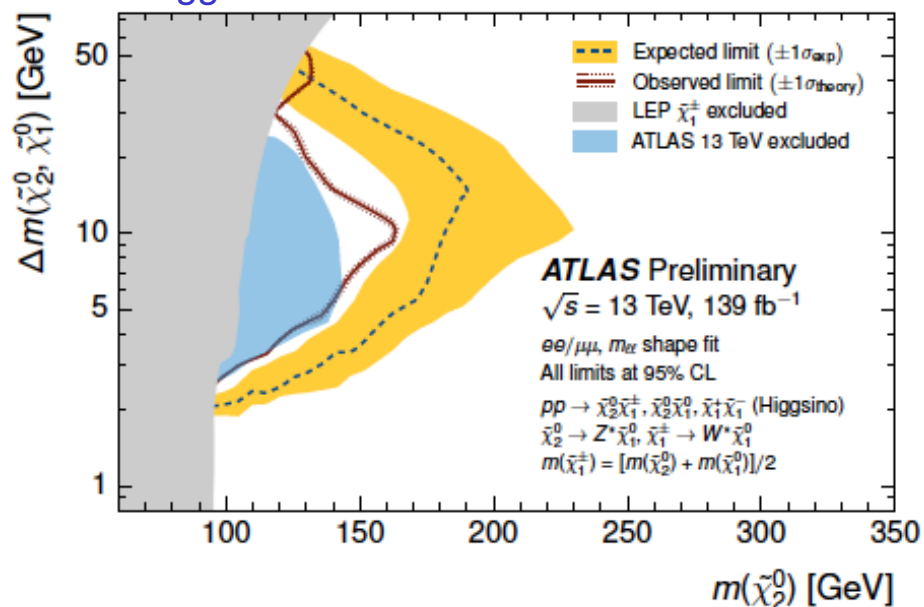
# Compressed ewkinos



Soft opposite sign dileptons, with ISR boost



Higgsino scenario



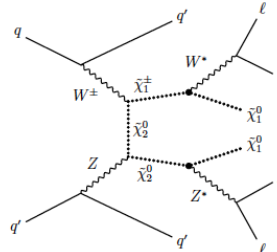
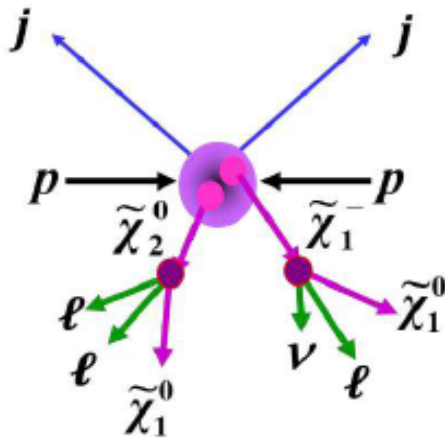
ATLAS-CONF-2019-014

$m(\tilde{\chi}_{L,R}^0)$  [GeV] 31

# VBF SUSY



## Chargino-neutralino production via Vector Boson Fusion (VBF)



### Signal selection:

0 or 1 soft lepton +  $P_T^{\text{miss}}$

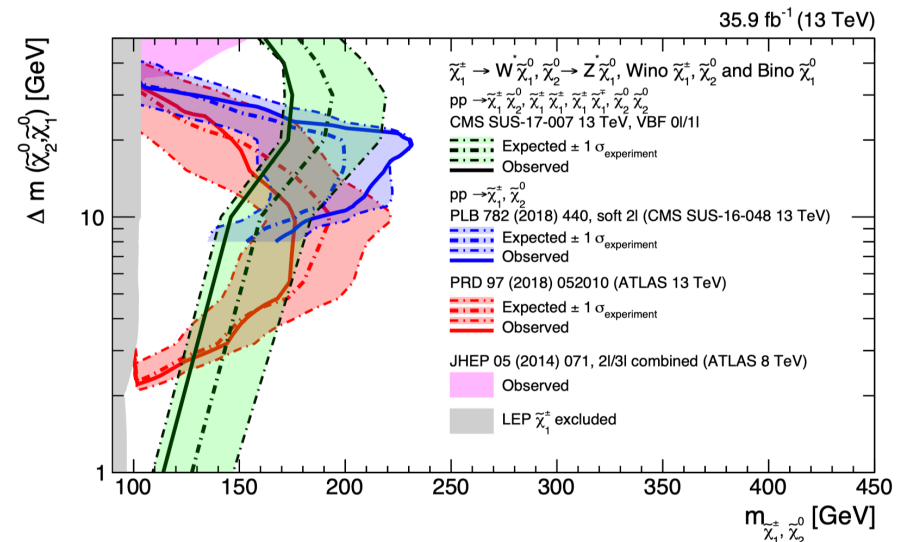
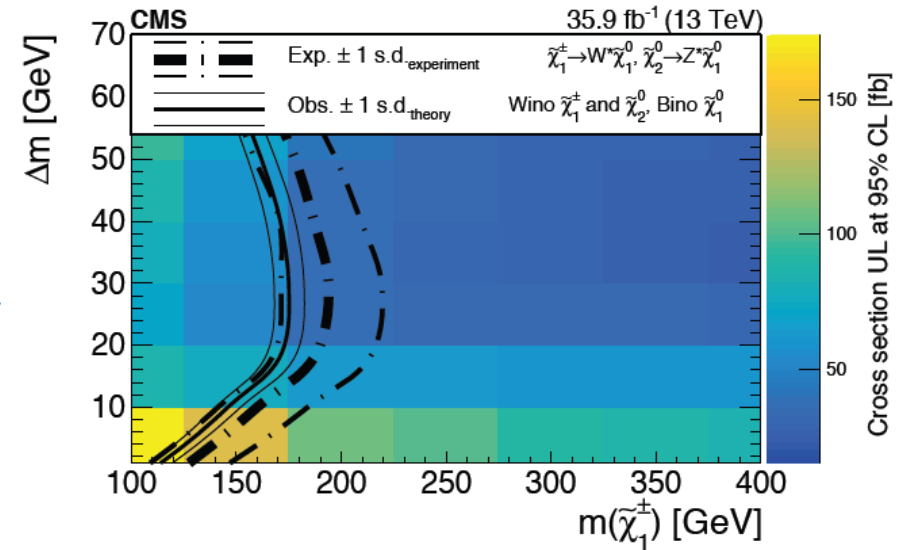
VBF selection:

Pairs of jets ( $p_T > 60$  GeV) with

$\Delta\eta > 3.6$  and  $\eta_1 \eta_2 < 0$

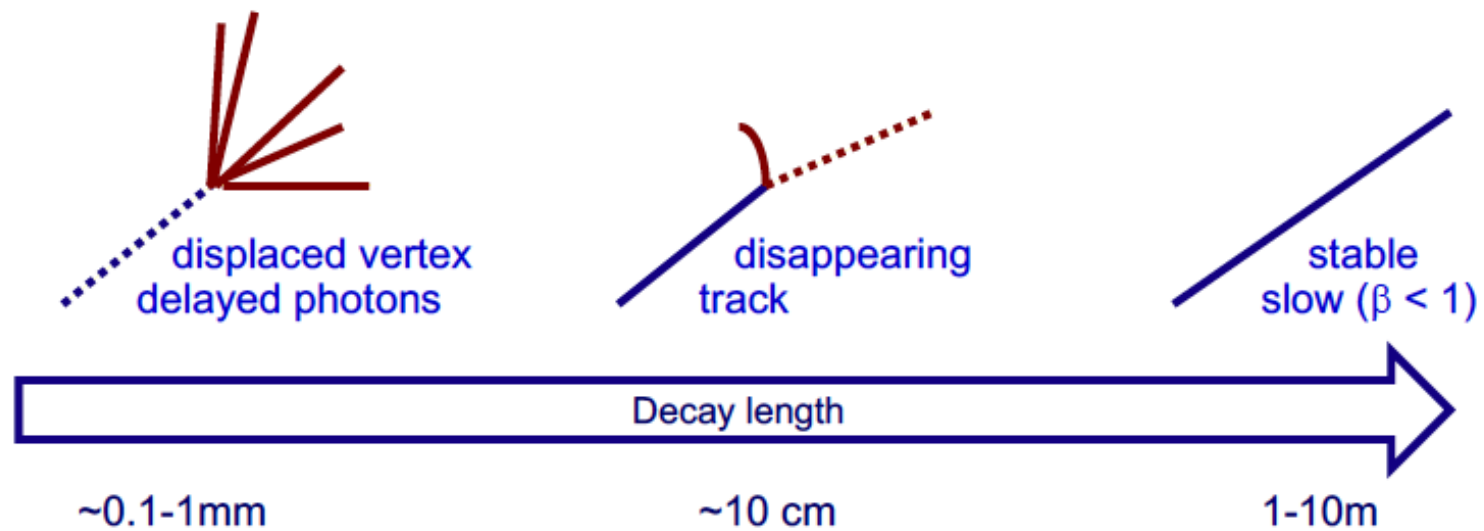
$m_{jj} > 1$  TeV

CMS-SUS-17-007



Lepton Photon, Toronto, August 2019

# Long-lived SUSY



# Long-lived

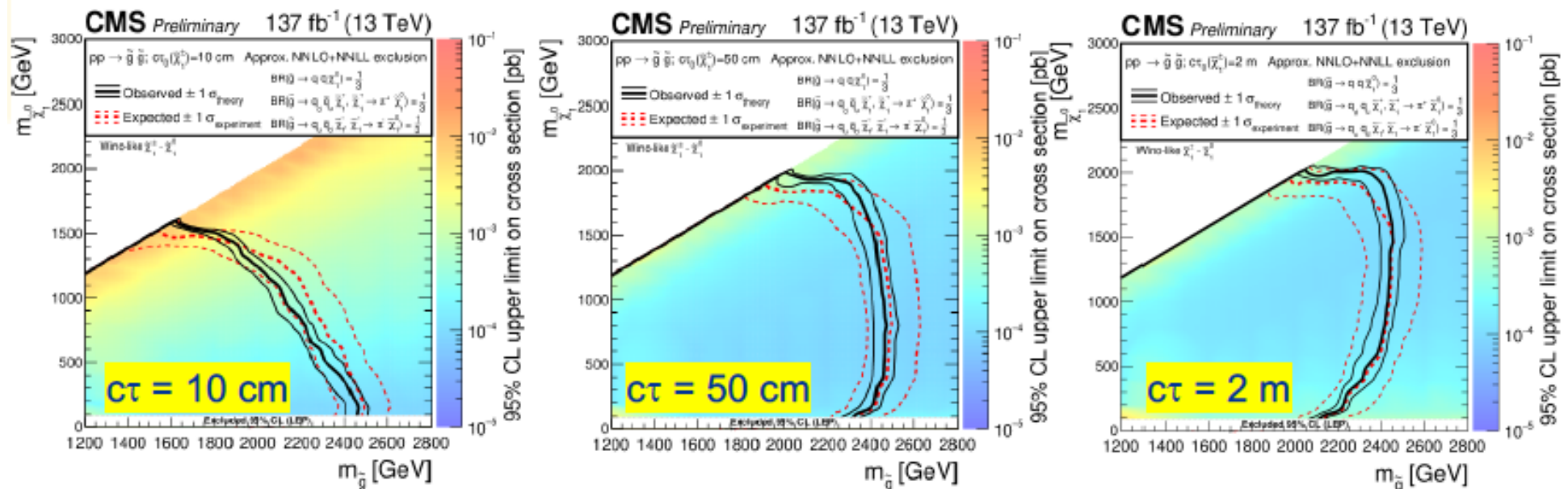
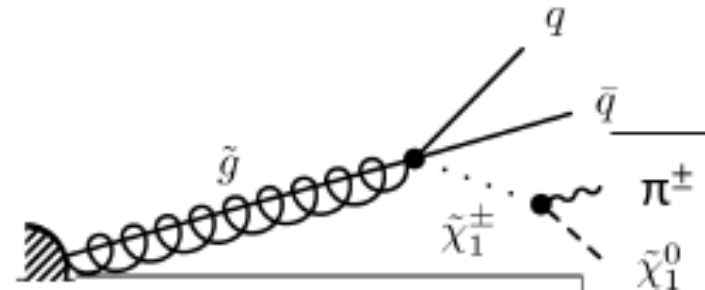


## Extension of “classic” hadronic MT2 search

### Signal selection:

Binning in  $H_T$ ,  $M_{T2}$ , #jets, #b-jets

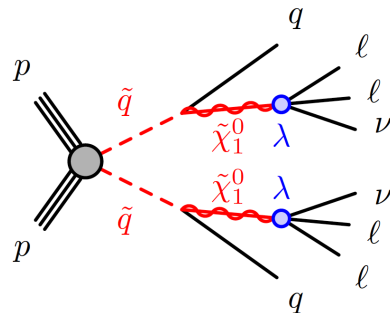
Extra categorization in short (pixel-only),  
medium (< 7 hits) and long (> 7 hits) tracks



# Displaced dilepton vertices



Search for opposite-charge lepton pairs (e-e, mu-mu, e-mu)

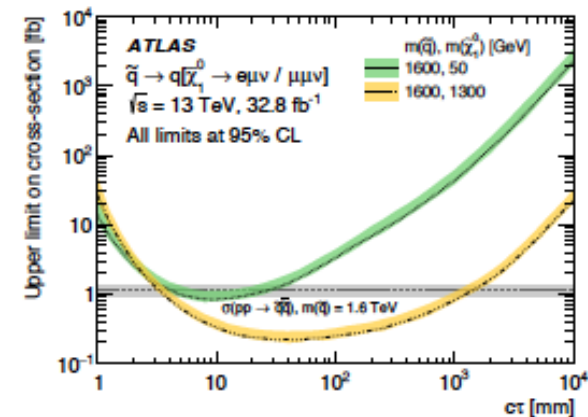
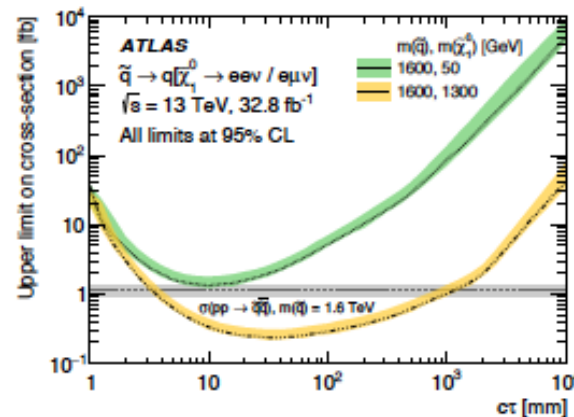
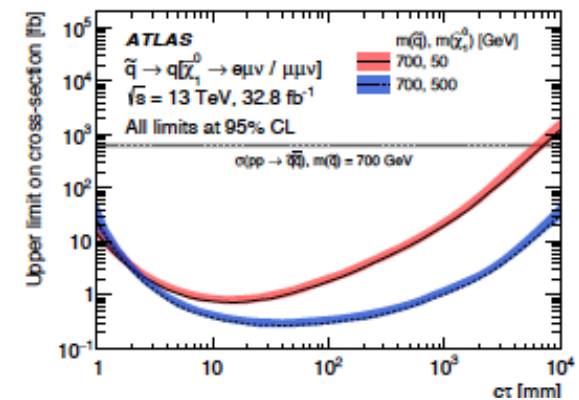
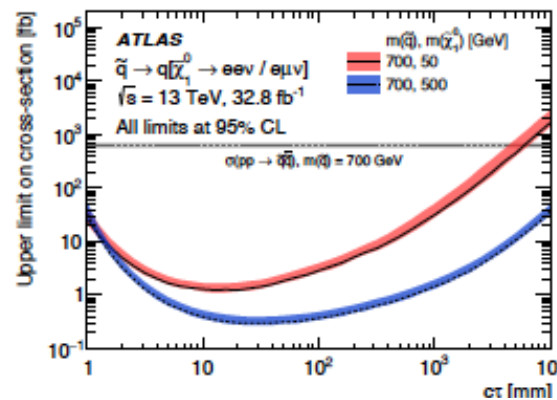


700 GeV squarks

1600 GeV squarks

$$\lambda_{121} \neq 0$$

$$\lambda_{122} \neq 0$$



# Outlook



Search results **with full Run 2 statistics** are starting to appear.  
Many more to come.

CERN is now preparing for Run 3 and the HL-LHC.

**Factor 20 in luminosity** still to come

(+ energy upgrade to **14 TeV**, which means a factor of 2 gain in cross-section for 2.3 TeV gluinos)

We are **slightly above half-way** (~60%) in the mass reach of the LHC (e.g. stop limit now at 1200 GeV, ultimate reach 2000 GeV)

Note that, while naturalness (i.e. low fine-tuning) prefers light stops ( $< 700$  GeV), a 1.5-2 TeV stop mass is more suitable for producing a 125 GeV Higgs boson through radiative corrections

# Extra

# ISR+tau



## ISR + tau + MET

