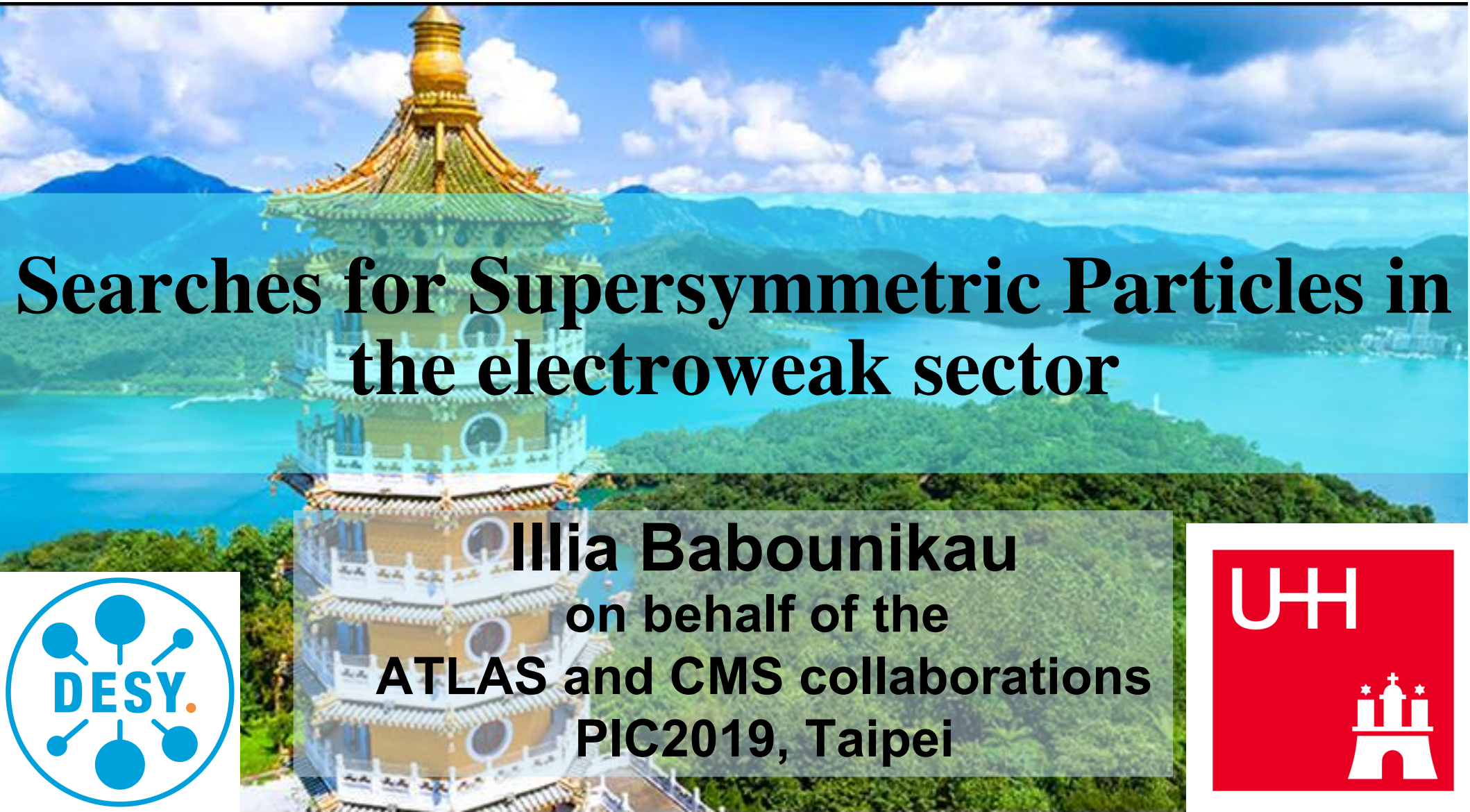


Searches for Supersymmetric Particles in the electroweak sector

Illia Babounikau

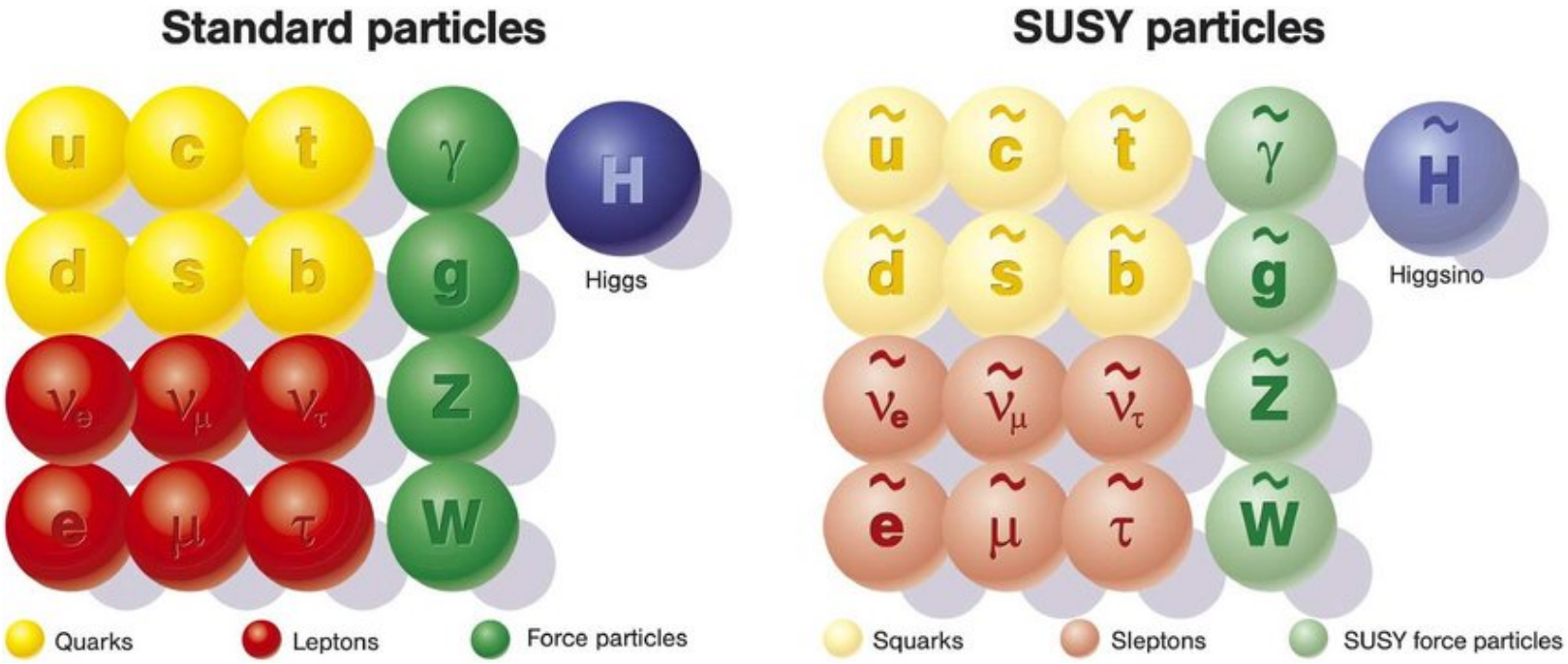
on behalf of the

ATLAS and CMS collaborations

PIC2019, Taipei

Supersymmetry and MSSM

Supersymmetry (SUSY) relates two classes of particles, bosons (integer spin) and fermions (half-integer spin)



Minimal Supersymmetric Standard Model (MSSM) is supersymmetric SM extension with the minimal number of new particle states and new interactions

General motivation

- Hierarchy problem

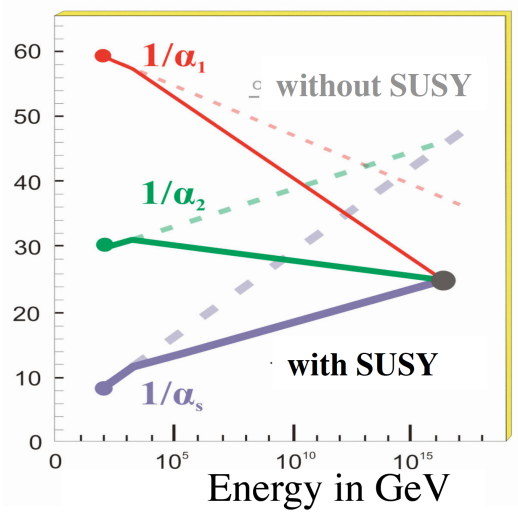
$$m_{phys}^2 \approx m_h^2 - \lambda'^2\left(\frac{1}{8\pi^2}\Lambda_{cut}^2 - m_f^2 ln\frac{\Lambda_{cut}^2}{m_f^2}\right)$$

- Dark matter candidate: Stable Lightest Supersymmetric Particle (LSP)

R-parity conservation

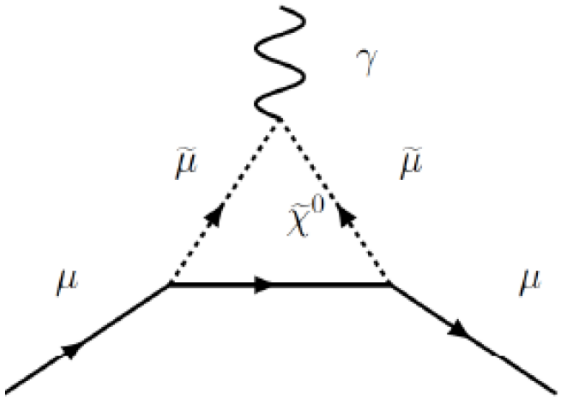
$$P_R = (-1)^{2S+3(B-L)}$$

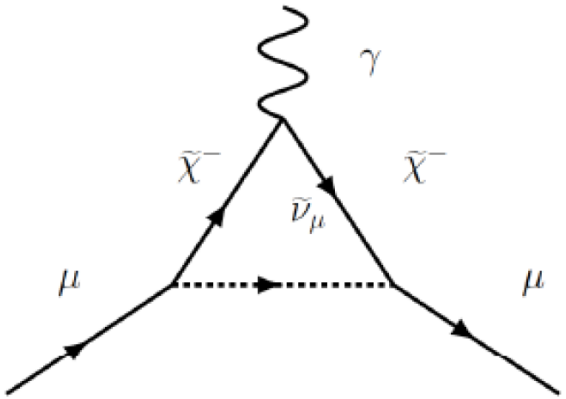
- Unification of the forces at about 10^{16} GeV



SUSY electroweak sector

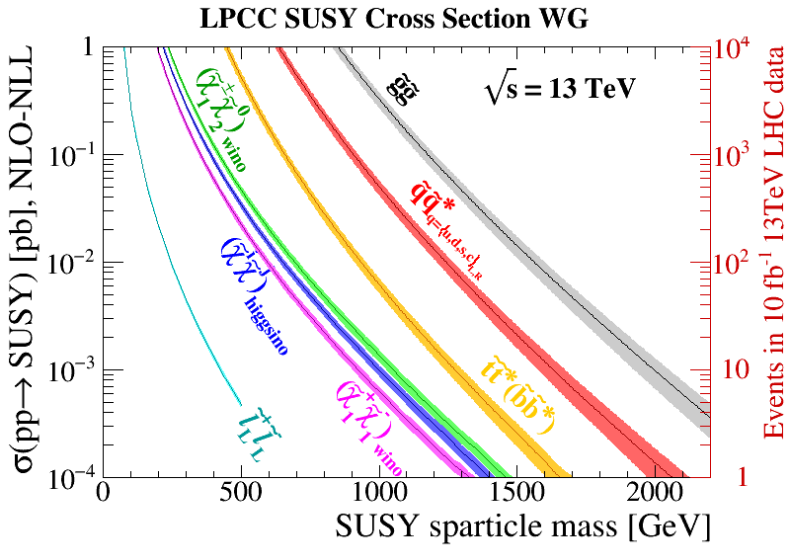
- SUSY can solve some of the SM problems and it is sufficient part of many new physics models.
  - SUSY must be broken → sparticles mass scale is undetermined
- Some hints why electroweak SUSY particles can be light:
  - Low fine-tuning → higgsinos mass is close to the weak sector
  - LSP co-annihilation with NLSP could explain the observed dark matter density → NLSP should have mass close to that of LSP
  - SUSY can explain ~3σ deviation of muon g – 2 from SM prediction → light smuon and chargino

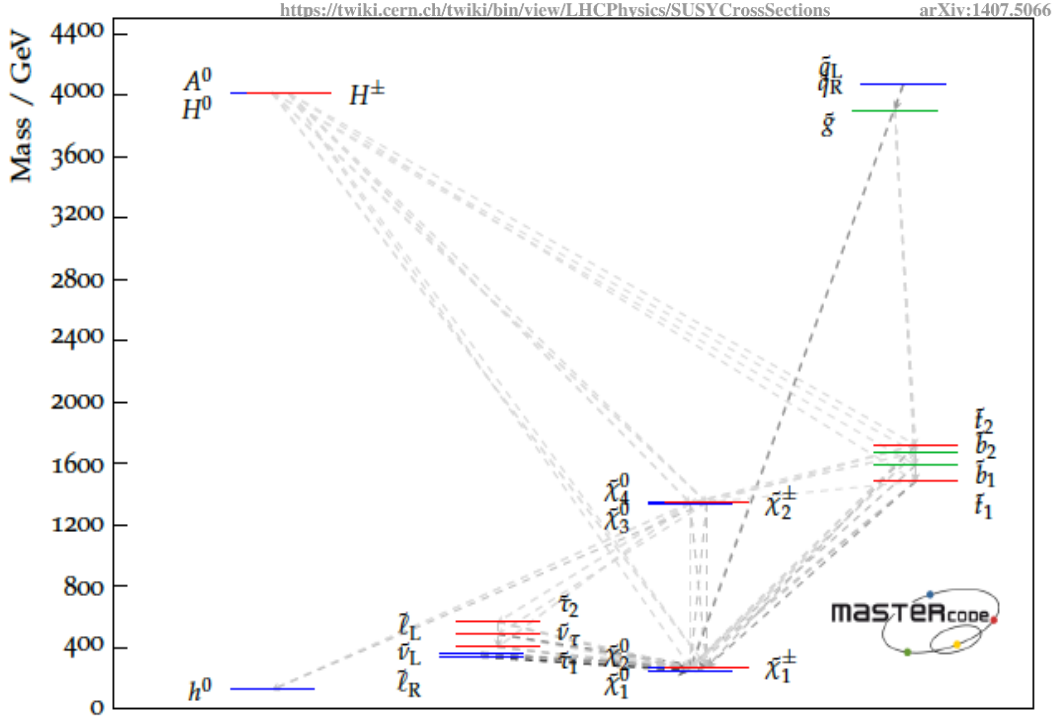




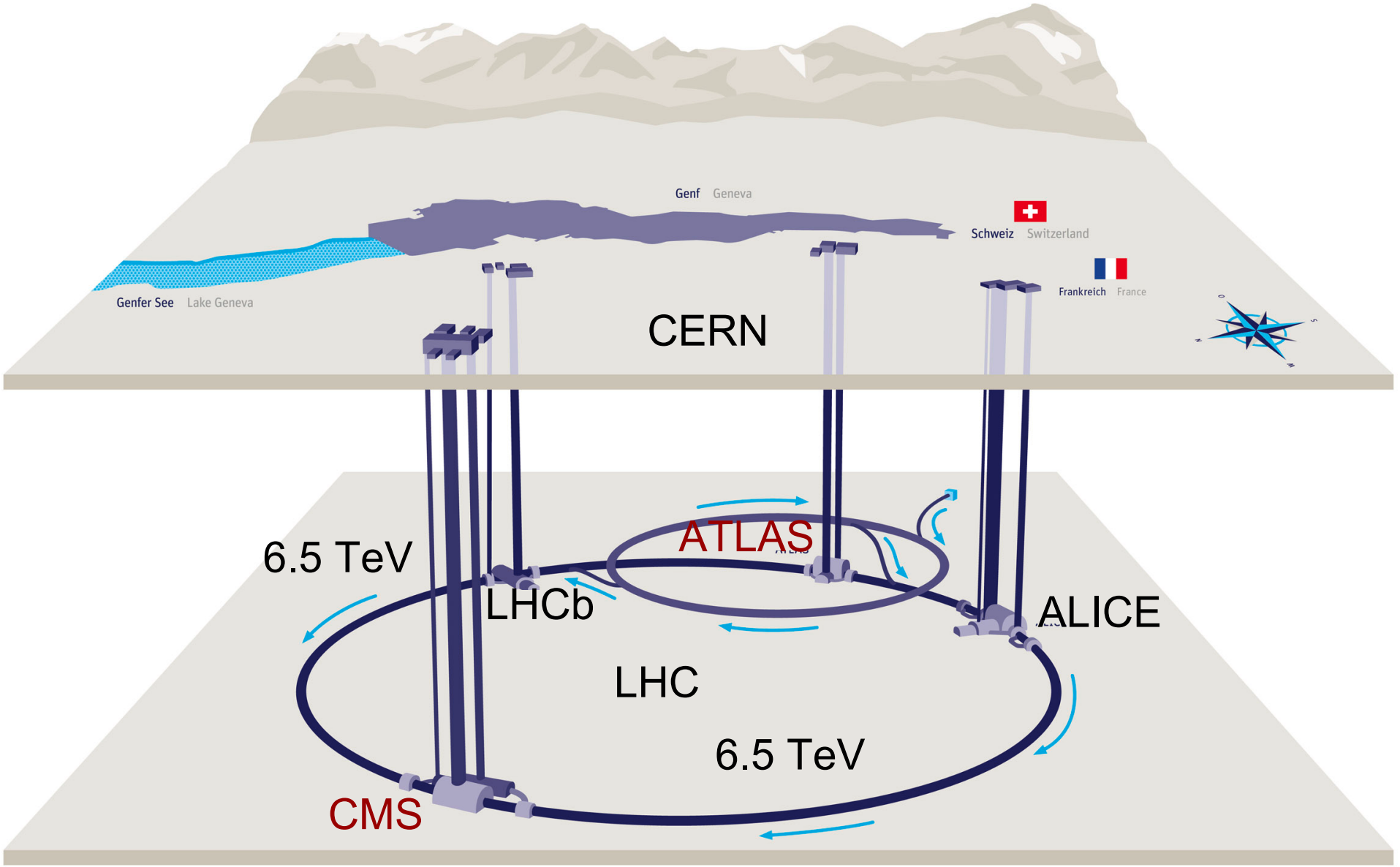
More motivation

- Limits from CMS and ATLAS on strong SUSY production are already pretty high → electroweak could be important to discover SUSY at the LHC
- Likelihood analysis of experimental constraints predicts light charginos, neutralinos and sleptons (arXiv:1710.11091v2)

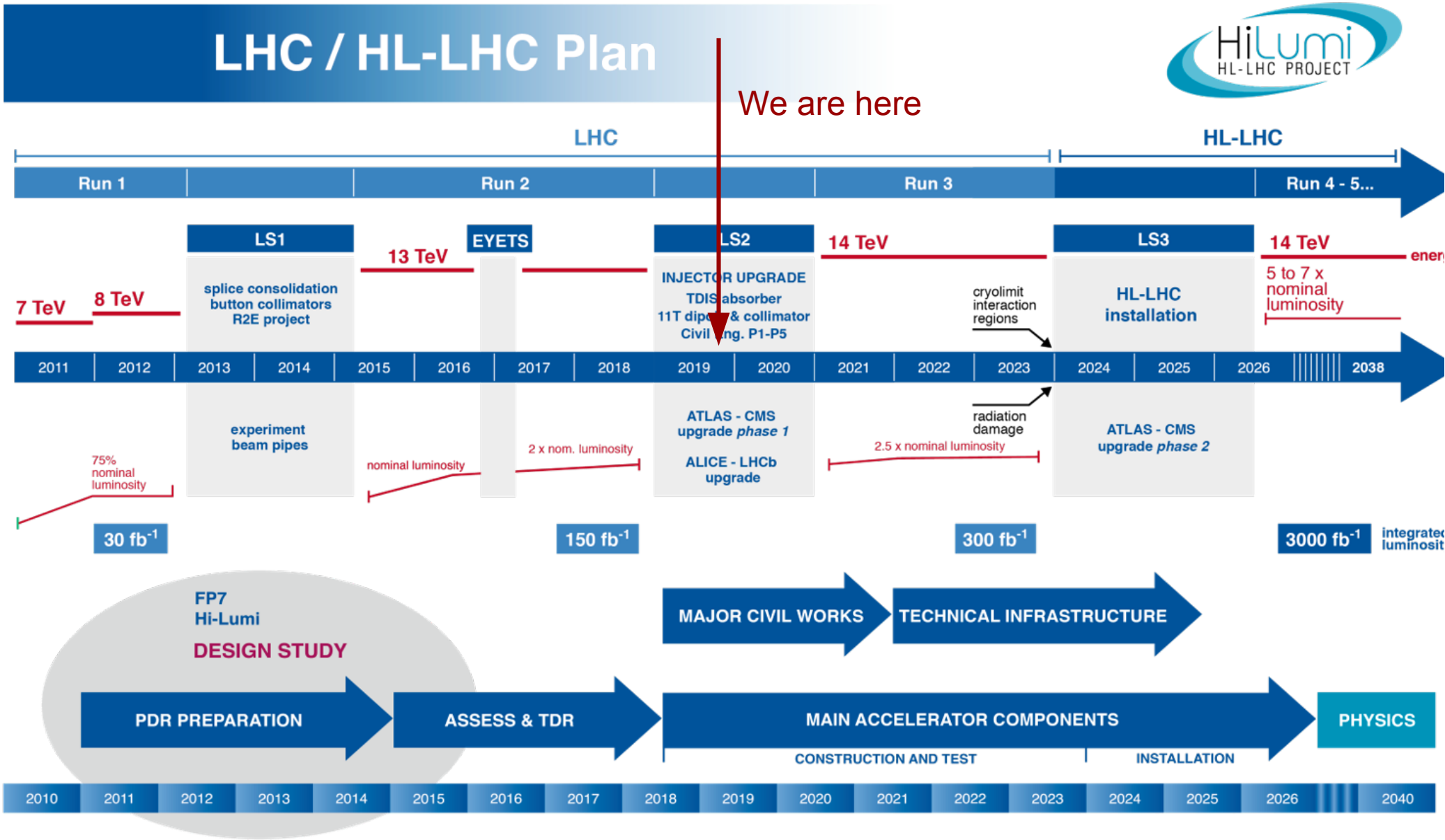




LHC


Genf Geneva
Schweiz Switzerland
Frankreich France
Genfer See Lake Geneva
CERN
ATLAS
6.5 TeV
LHCb
ALICE
LHC
6.5 TeV
CMS

LHC


LHC / HL-LHC Plan
HiLumi HL-LHC PROJECT
We are here
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
splice consolidation
button collimators
R2E project
INJECTOR UPGRADE
TDIS absorber
11T dipo & collimator
Civil eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2038
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
upgrade phase 2
75%
nominal
luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity
FP7
Hi-Lumi
DESIGN STUDY
MAJOR CIVIL WORKS
TECHNICAL INFRASTRUCTURE
PDR PREPARATION
ASSESS & TDR
MAIN ACCELERATOR COMPONENTS
PHYSICS
CONSTRUCTION AND TEST
INSTALLATION
2010
2011
2012
2013
2014
2015
2016
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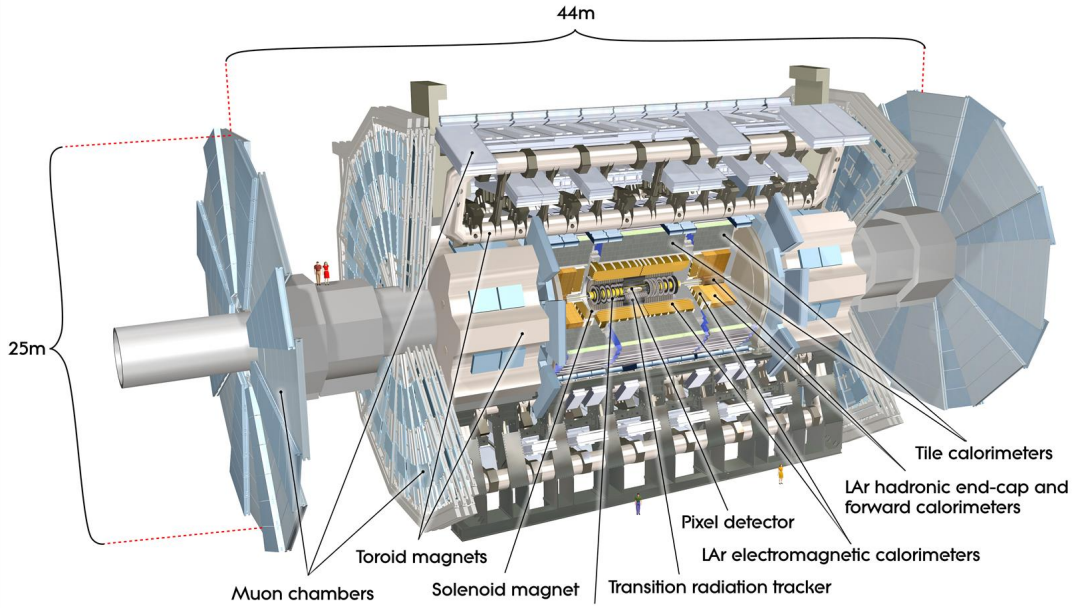
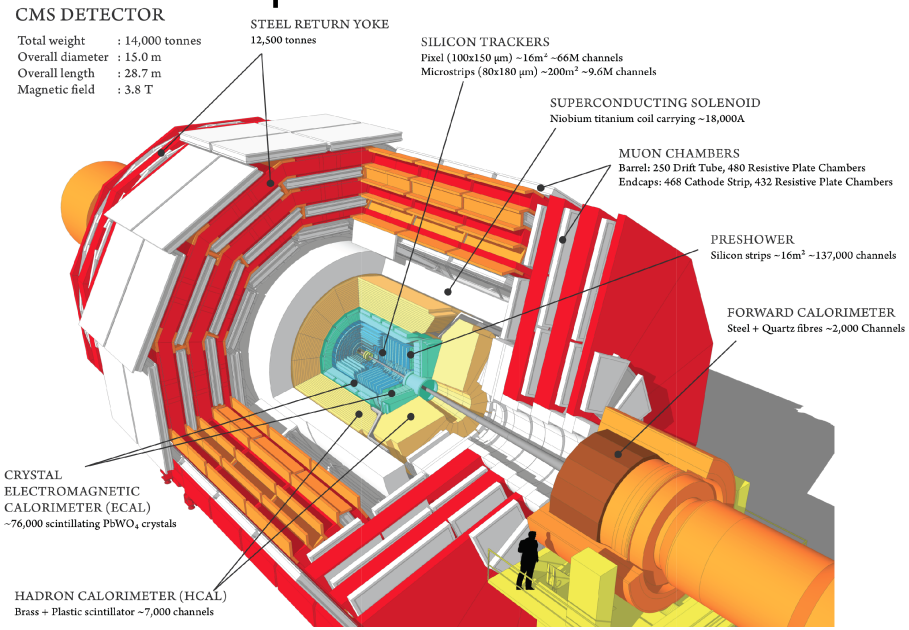
2040

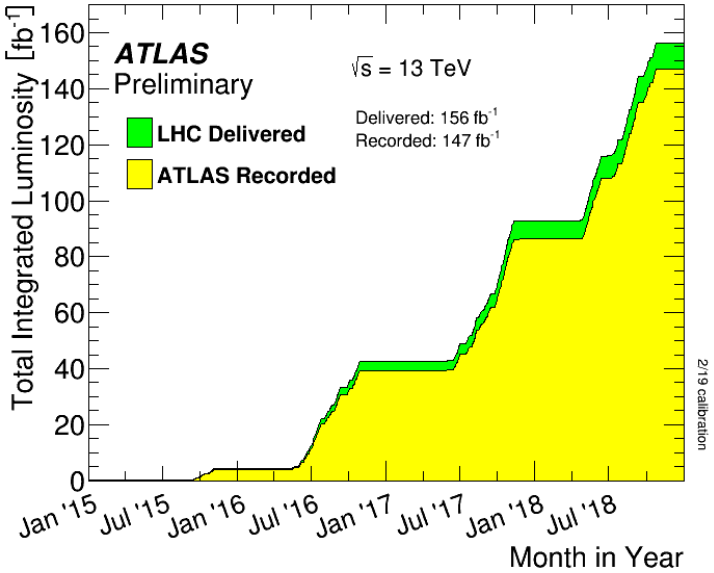
CMS and ATLAS

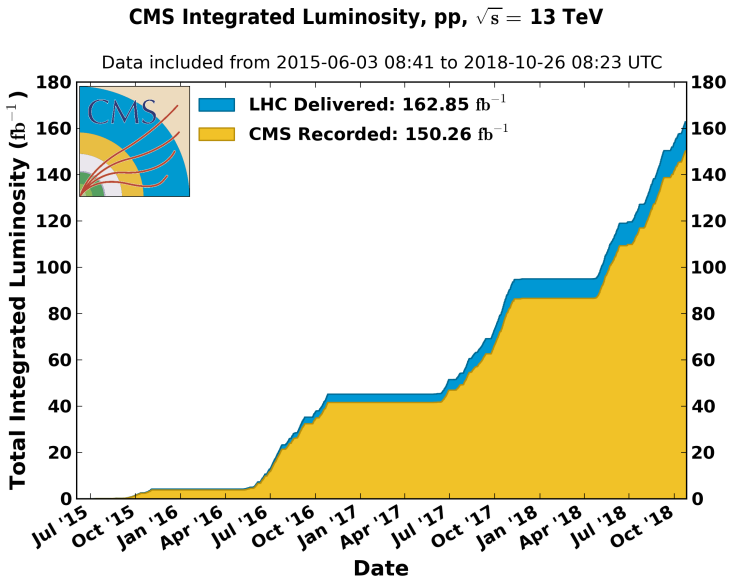
A Toroidal LHC ApparatuS



Compact Muon Solenoid

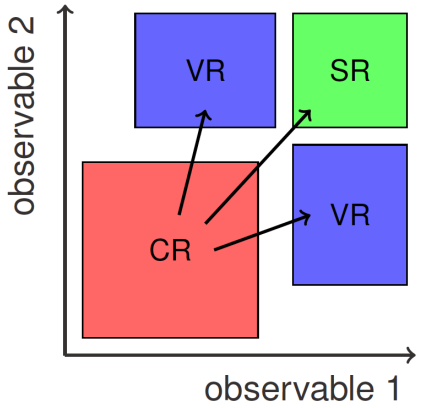




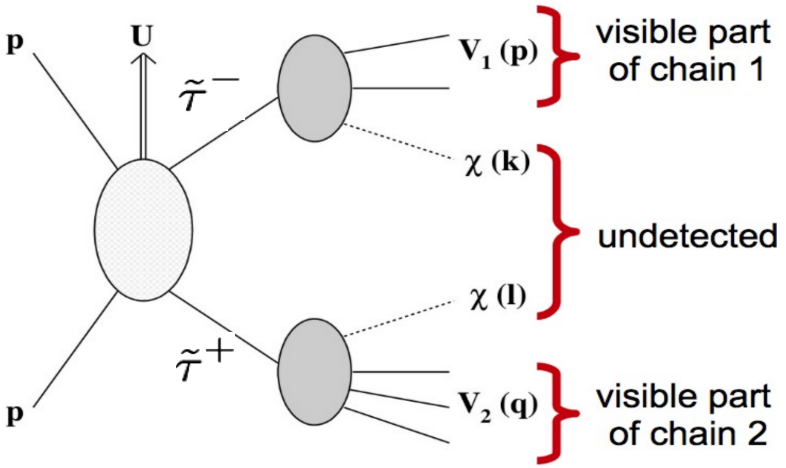


Analysis strategies

- Standard search
  - R-parity conservation → sparticles are produced in pairs and LSP is stable
  - Signature: energetic final SM particles + missing transverse momentum
  - Two major background approaches:
    - Data-driven techniques
    - MC corrected and normalized in dedicated control regions
  - Signal regions in bins of kinematic variables or MVA output
    - M_{T2} – “stransverse” mass

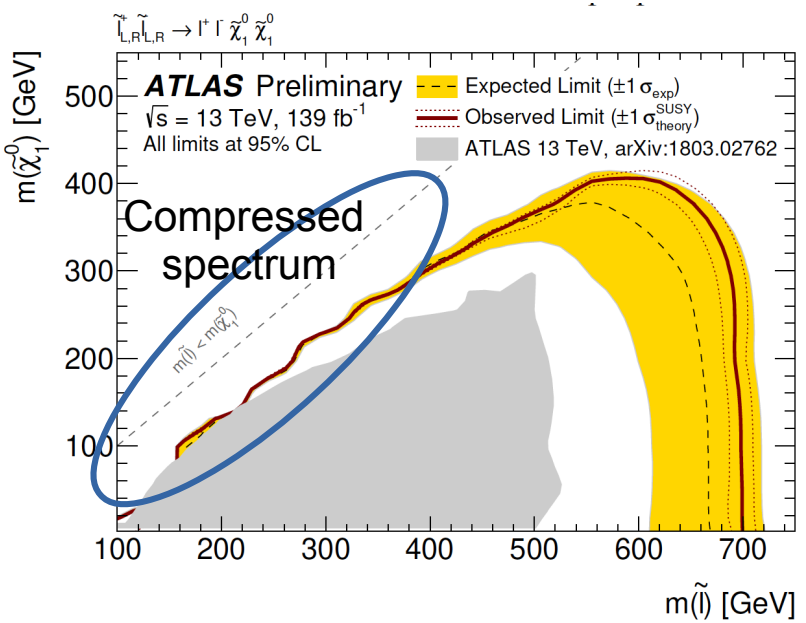


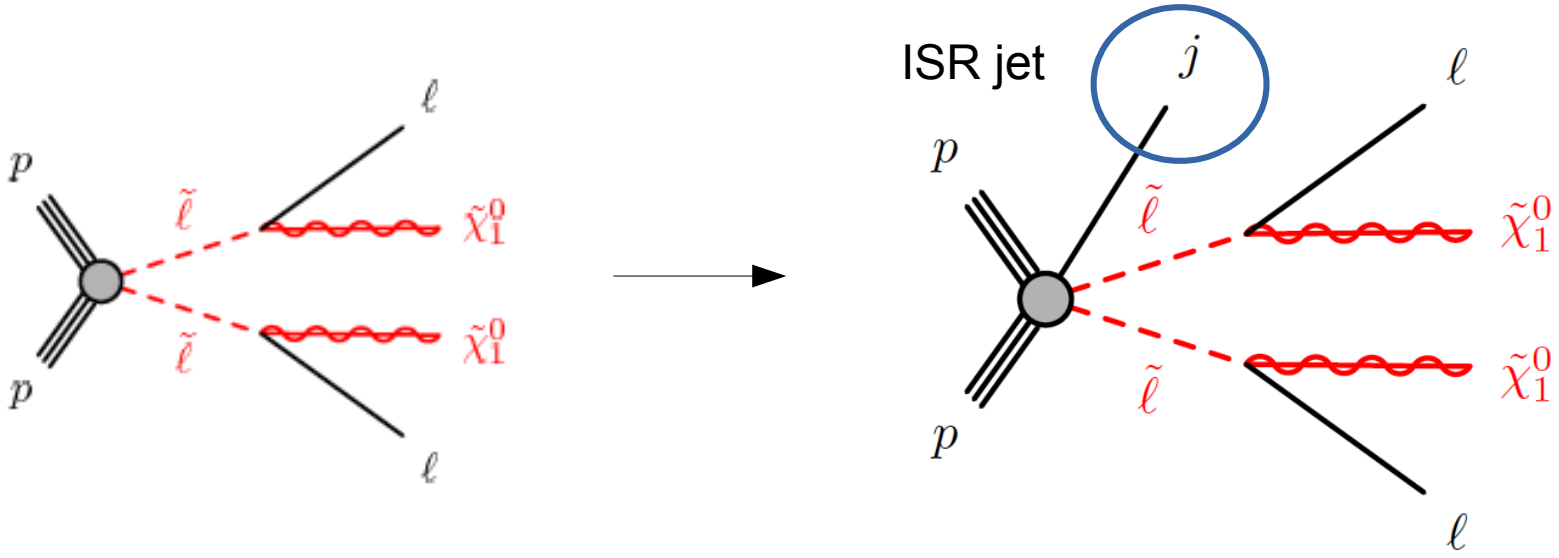
$$M_{T2}^2 = \min_{\vec{k}_T+\vec{l}_T=\text{tot miss } \vec{p}_T} \left\{ \max\left[M_T^2(\text{chain 1}), M_T^2(\text{chain 2}) \right] \right\} \leq m^2_{\tilde{\tau}}$$



Analysis strategies

- Compressed mass spectra
  - Highly motivated by LSP co-annihilation mechanism
  - Δm between LSP and NLSP is small → soft SM particles
  - The topology is boosted (for example by ISR jet)





Electroweak SUSY searches

Covered in this talk

Analysis	Final state	Model	Luminosity	Analysis identifier
Stau search	$\tau_h\tau_h$, $\tau_h\mu$, $\tau_h e$	Direct stau	77 fb-1 (CMS) 139 fb-1 (ATLAS)	arXiv:1907.13179 ATLAS-CONF-2019-018
Chargino-Neutralino production	$l\, j_b\, j_b$	Chargino-Neutralino	139 fb-1 (ATLAS)	ATLAS-CONF-2019-031
Chargino and slepton search	$l^{\pm}l^{\mp}$	Charginos and sleptons	139 fb-1 (ATLAS)	arXiv:1908.08215
Gauge-mediated supersymmetry	$\gamma\gamma$, γl, γ+pTmiss	Chargino-Neutralino (Gravitino as LSP)	35.9 fb-1 (CMS)	arXiv:1907.00857
Electroweak production in compressed mass spectra	$l^{\pm}l^{\mp}$ + ISR jet	Chargino-Neutralino and sleptons	139 fb-1 (ATLAS)	ATLAS-CONF-2019-014
The vector boson fusion topology	j j + 0 or 1 l/τ_h	Chargino-Neutralino	35.9 fb-1 (CMS)	arXiv:1905.13059v1
Indirect stau	τ_h + ISR jet	Chargino-Neutralino	77 fb-1 (CMS)	CMS PAS SUS-19-002

Compressed

Chargino and slepton search

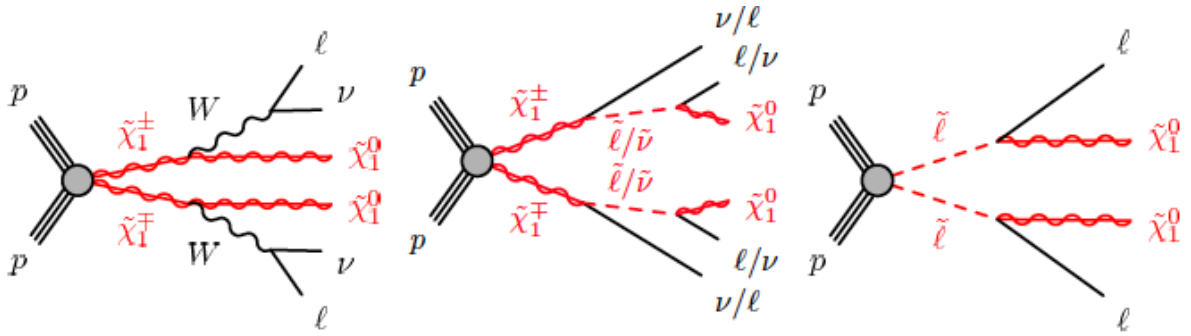
arXiv:1908.08215

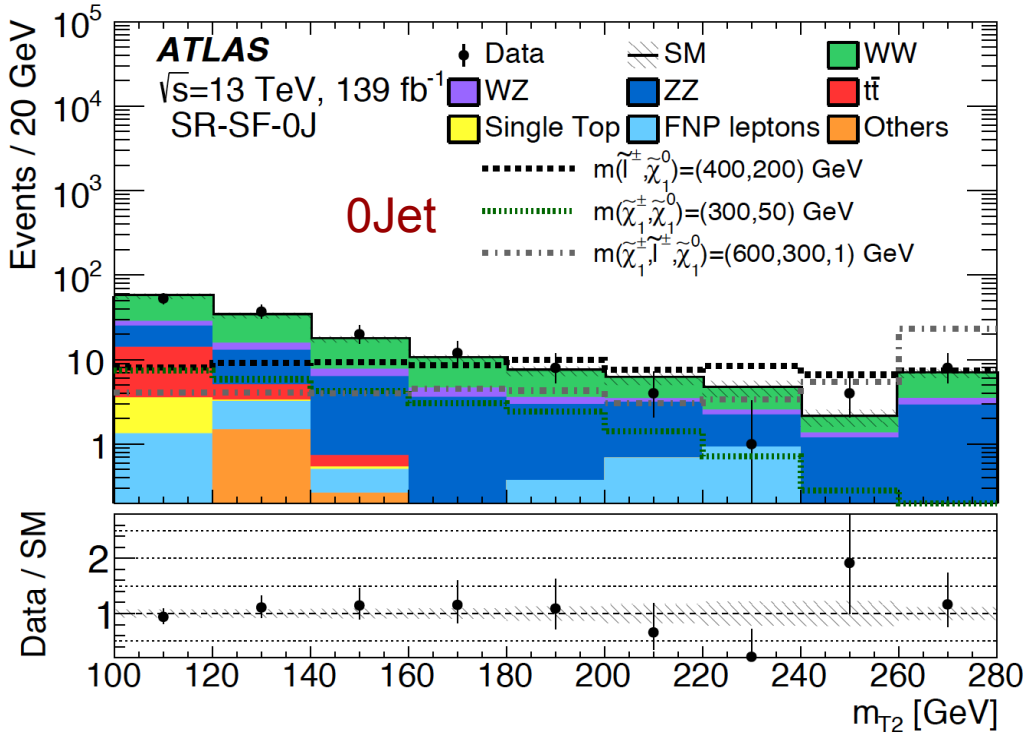
Signature

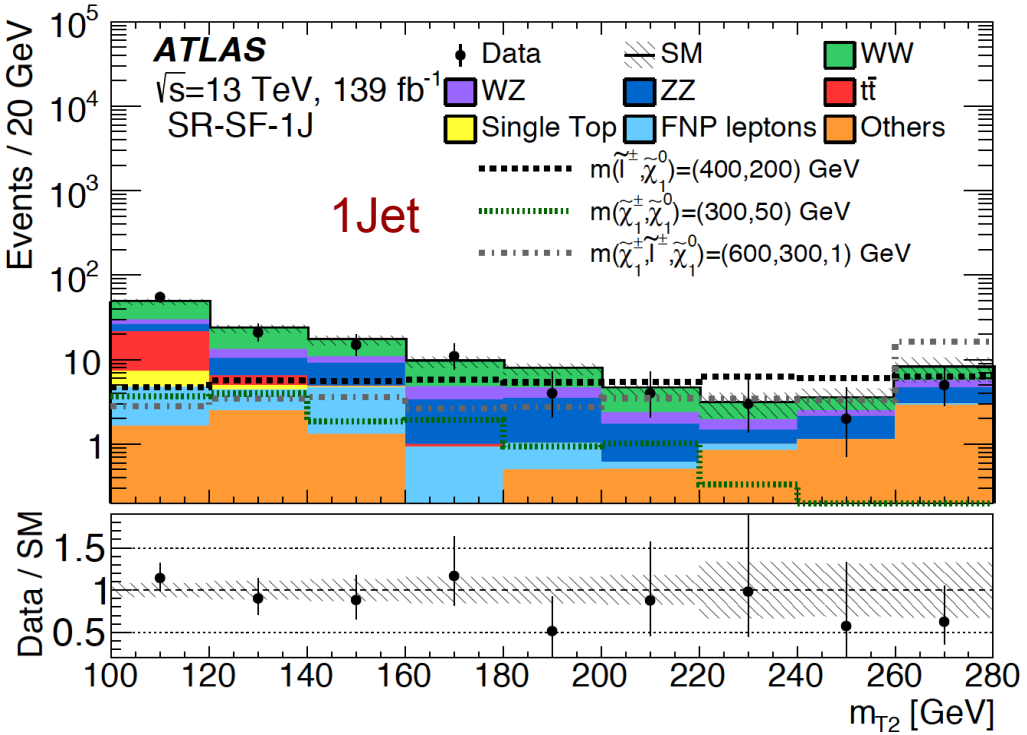
- Two opposite-charge leptons (electrons or muons) + significant missing transverse momentum (139 fb^{-1})

Main backgrounds

- Irreducible: SM diboson (WW, WZ, ZZ) and top-quark
- Reducible: fake leptons

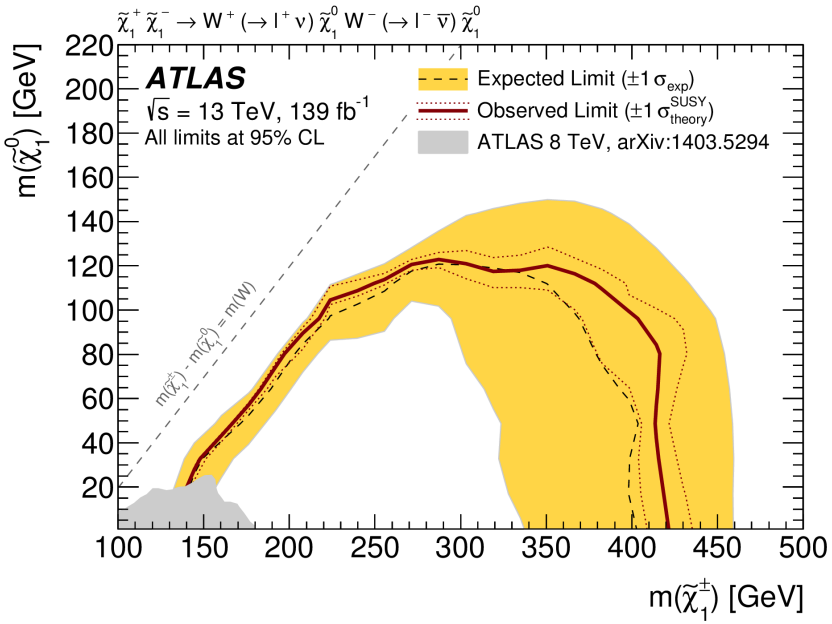


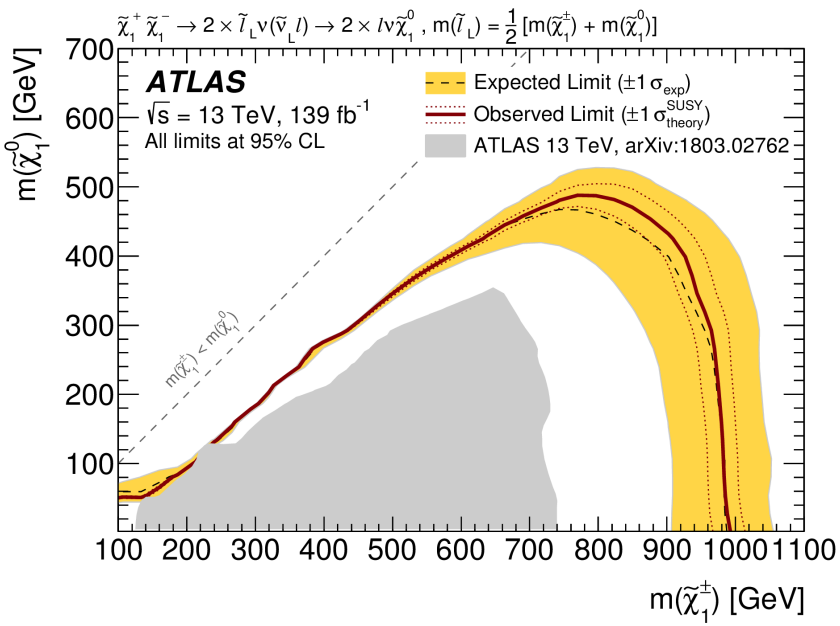


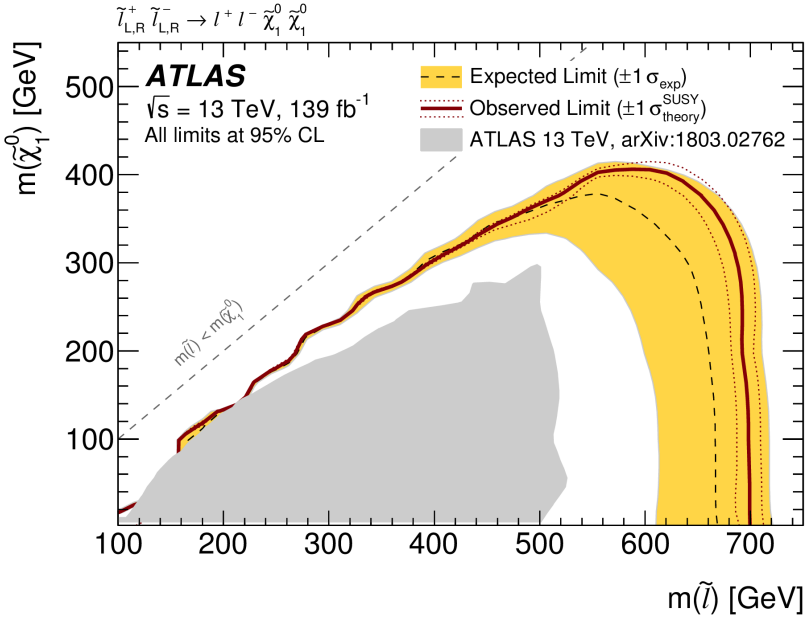


Chargino and slepton search

arXiv:1908.08215







For small $\tilde{\chi}^0_1$ masses:

Exclude $\tilde{\chi}^{\pm}_1$ up to 420 GeV

Exclude $\tilde{\chi}^{\pm}_1$ decaying through sleptons up to 1 TeV

Exclude light-flavour sleptons below 700 GeV

Gauge-mediated supersymmetry

arXiv:1907.00857

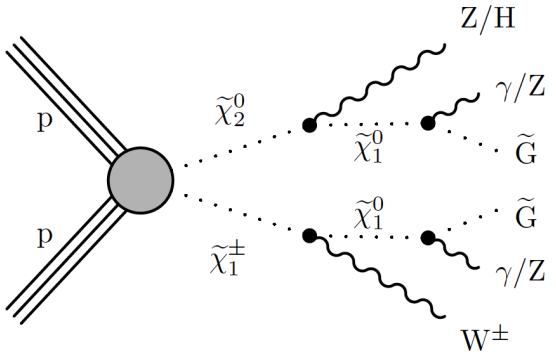
Signature (35.9 fb^{-1})

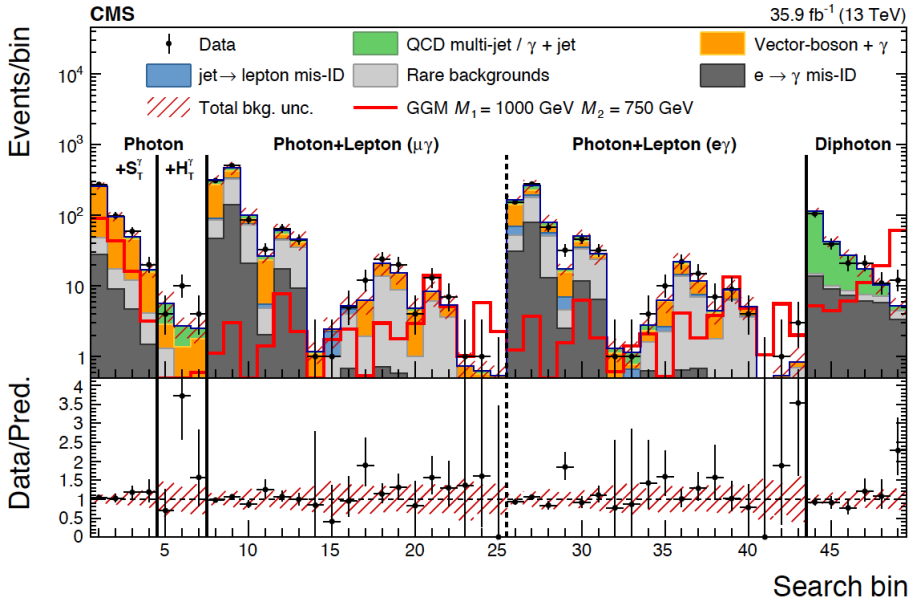
- two isolated photons
- Or one isolated photon as well as one isolated charged lepton
- Or one isolated photon and significant missing transverse momentum
- Or one isolated photon and significant hadronic activity

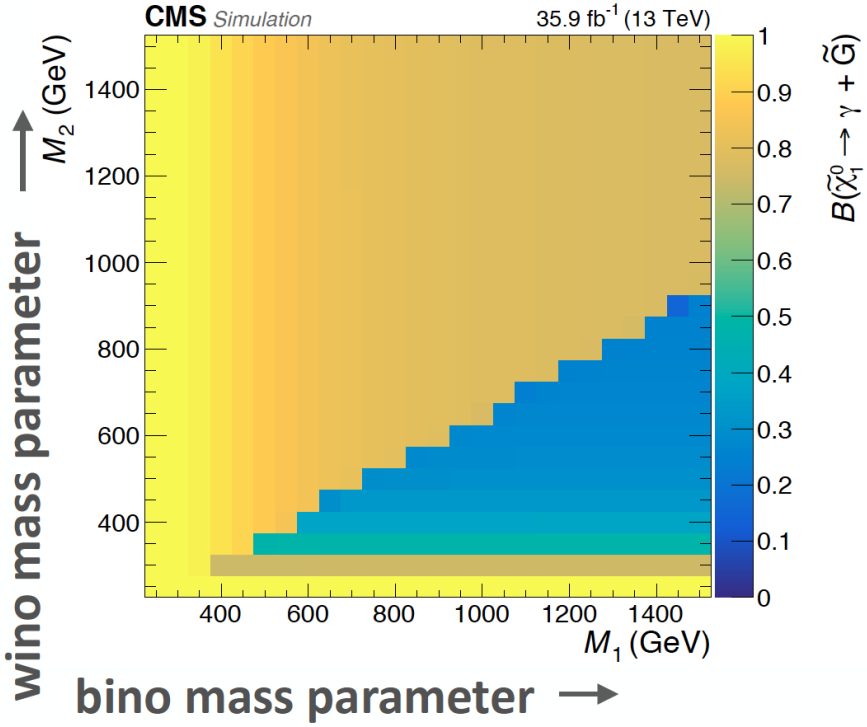
Main backgrounds

- Vector boson+γ, quantum chromodynamics (QCD) multijet processes and γ+jets

$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0}$, and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$

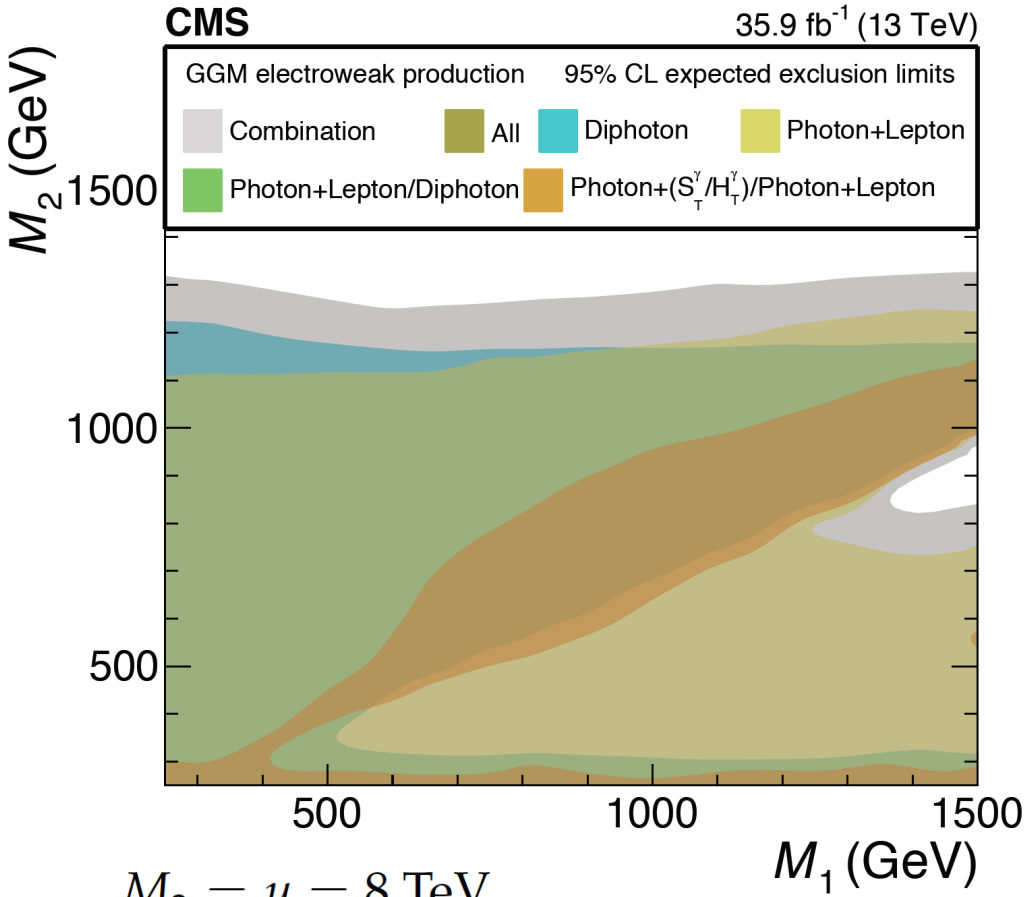


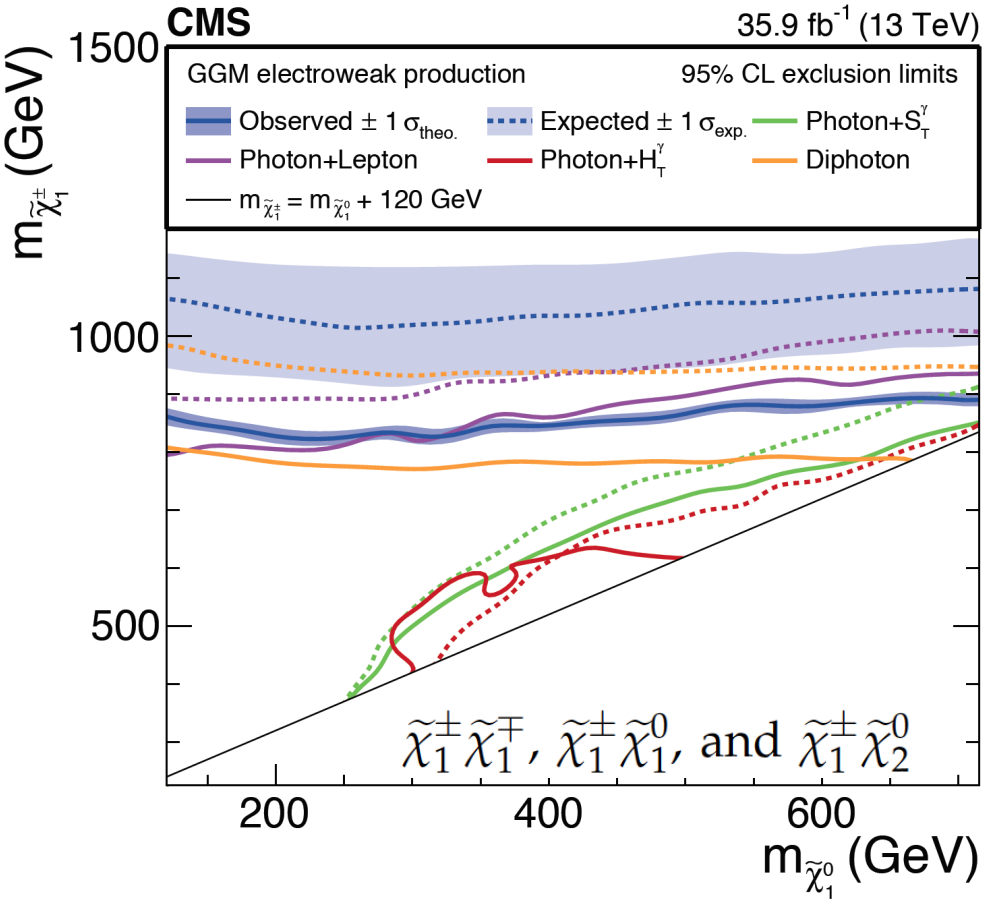




Gauge-mediated supersymmetry

arXiv:1907.00857





$M_3 = \mu = 8$ TeV

$m_Q = m_U = 10$ TeV

$m_D = 8$ TeV

$M_{mess} = 10^{15}$ GeV

Gravitino mass = 10 eV

General Gauge Mediation

Exclude M_2 up to 1100 GeV

Exclude $\tilde{\chi}^{\pm}_1$ up to 890 GeV

Chargino-Neutralino search

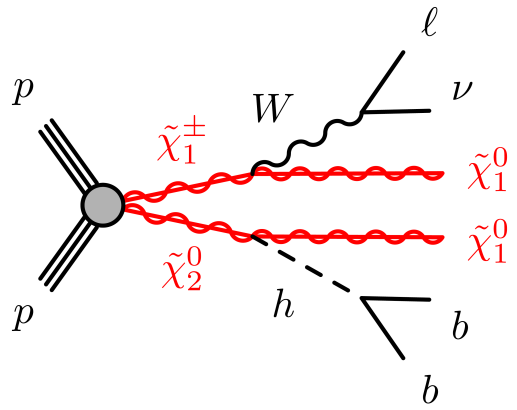
ATLAS-CONF-2019-031 New

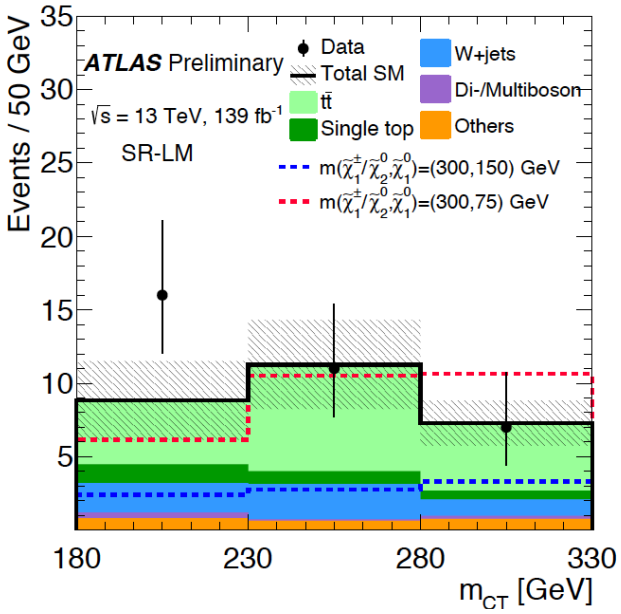
Signature

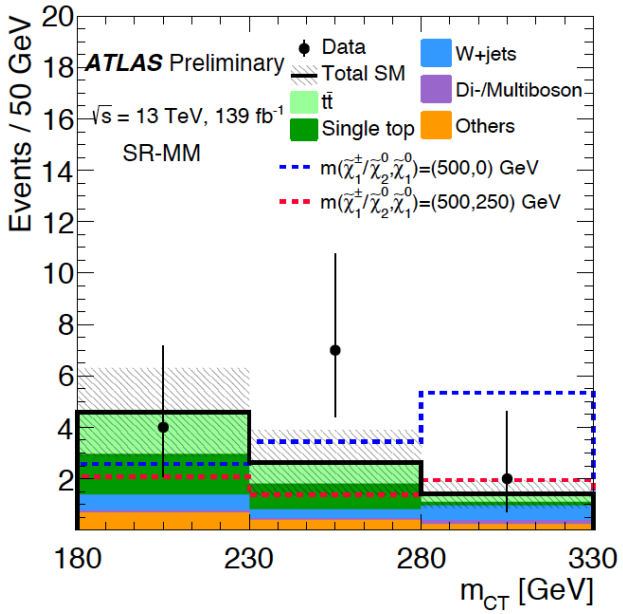
- Lepton (electron or muon) + two jets originating from the fragmentation of b-quarks (139 fb^{-1})

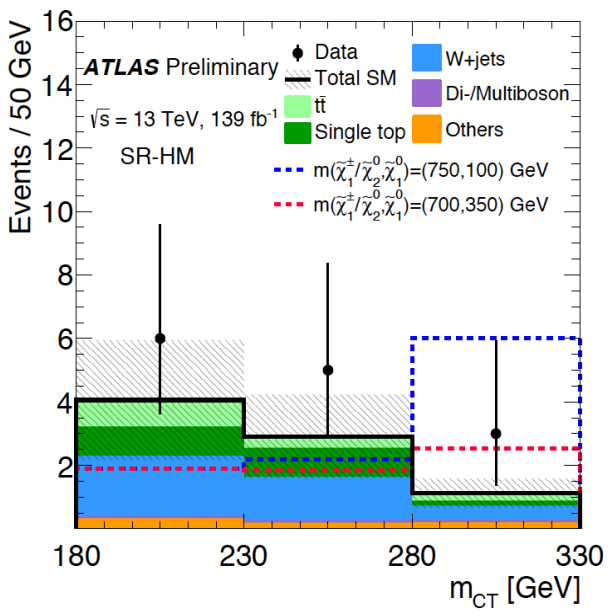
Main backgrounds

- t $\bar{t}$, single top (dominated by Wt in all considered regions) and W+jets processes





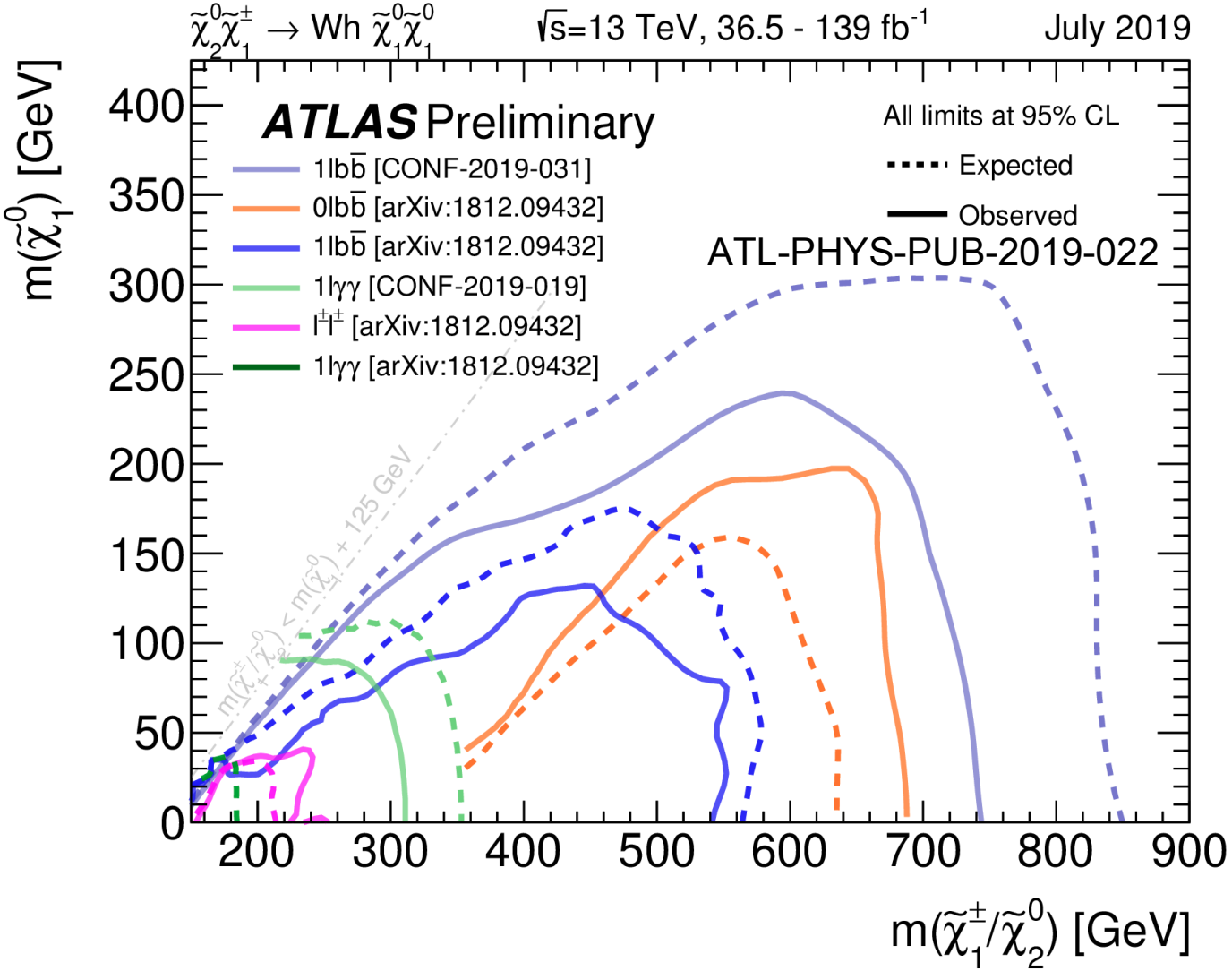




contransverse mass $m_{CT} = \sqrt{2p_T^{b_1} p_T^{b_2} (1 + \cos\Delta\phi_{bb})}$, For t $\bar{t}$ endpoint at $(m^2(t) - m^2(W))/m(t)$

Chargino-Neutralino search

ATLAS-CONF-2019-031 New



For small $\tilde{\chi}^0_1$ masses exclude $\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1$ with mass below 750 GeV → the most sensitive analysis for this model in the high mass region

Stau search

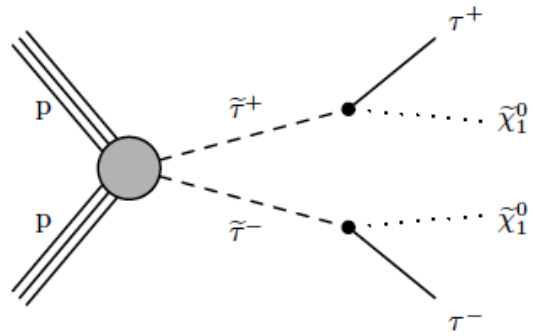
arXiv:1907.13179 ATLAS-CONF-2019-018

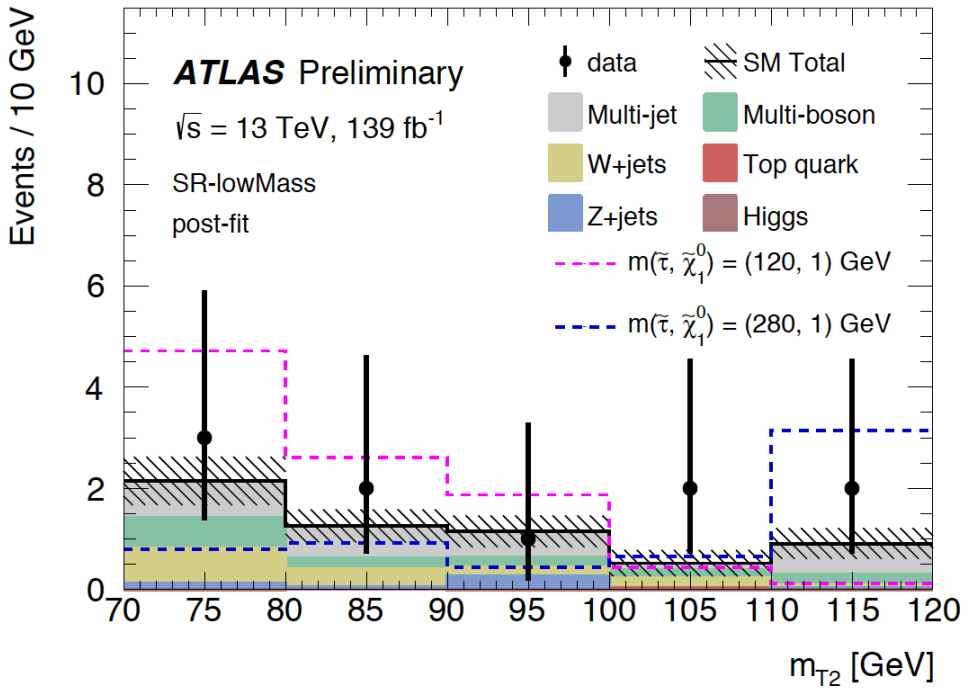
Signature

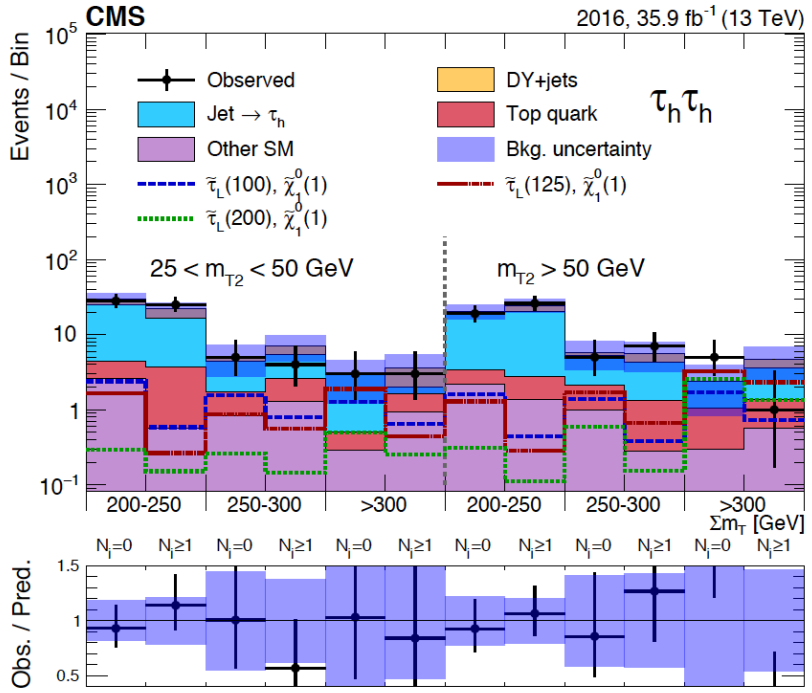
- ATLAS: two oppositely charged hadronically decaying tau + missing transverse momentum (139 fb^{-1})
- CMS: combination of full-hadronic and semileptonic channels (77.2 fb^{-1})

Main backgrounds

- Jets faking hadronic taus
- Geniune tau from Z or W decay



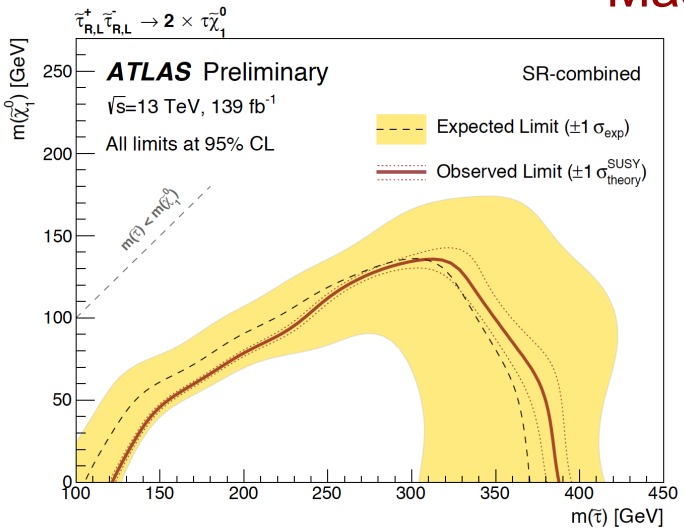


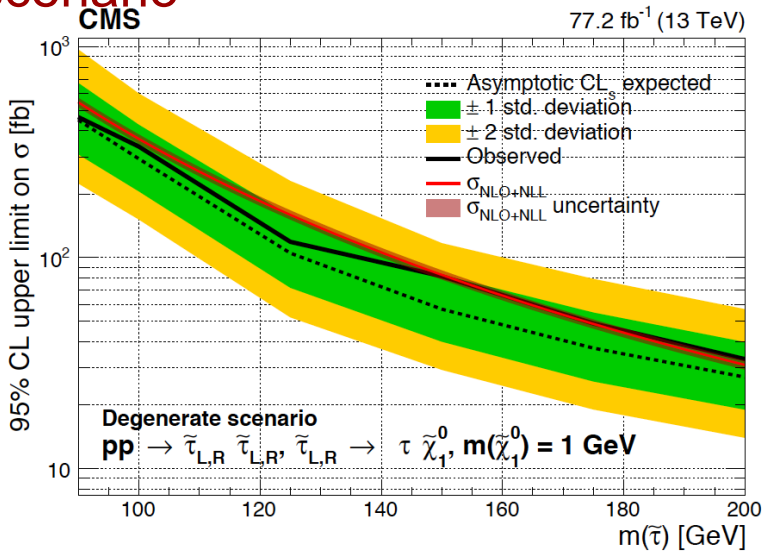


Stau search

arXiv:1907.13179 ATLAS-CONF-2019-018

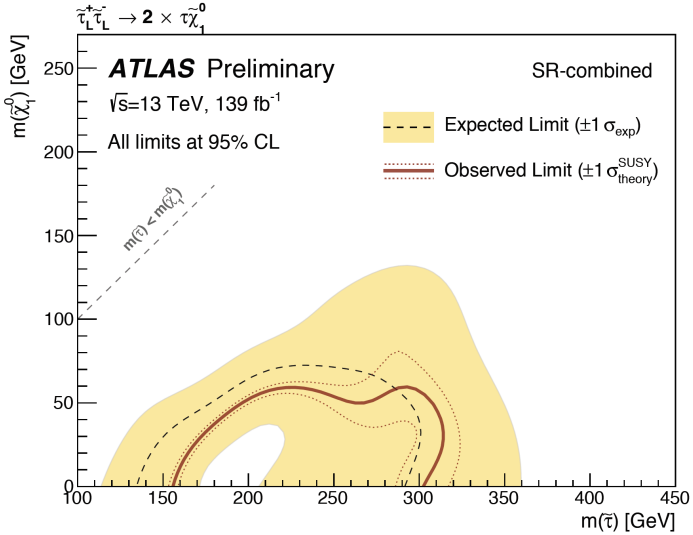
Mass degenerate scenario





ATLAS: excludes of tau sleptons with masses between 120 and 390 GeV,
CMS: closes the hole between 90 and 120 GeV for small $\tilde{\chi}^0_1$ masses

Left-handed scenario



ATLAS: excludes for the first time tau sleptons in the left-handed scenario with masses between 150 and 300 GeV for small $\tilde{\chi}^0_1$ masses

Compressed mass spectra

Electroweak production in compressed mass spectra

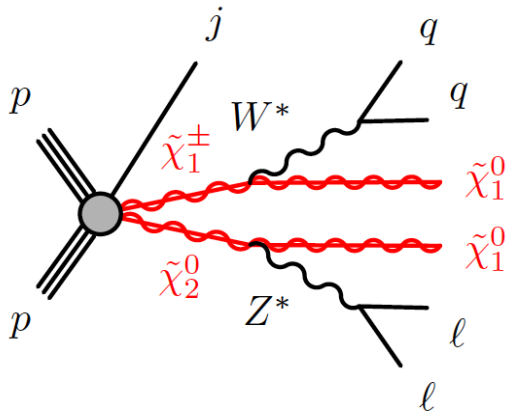
ATLAS-CONF-2019-014

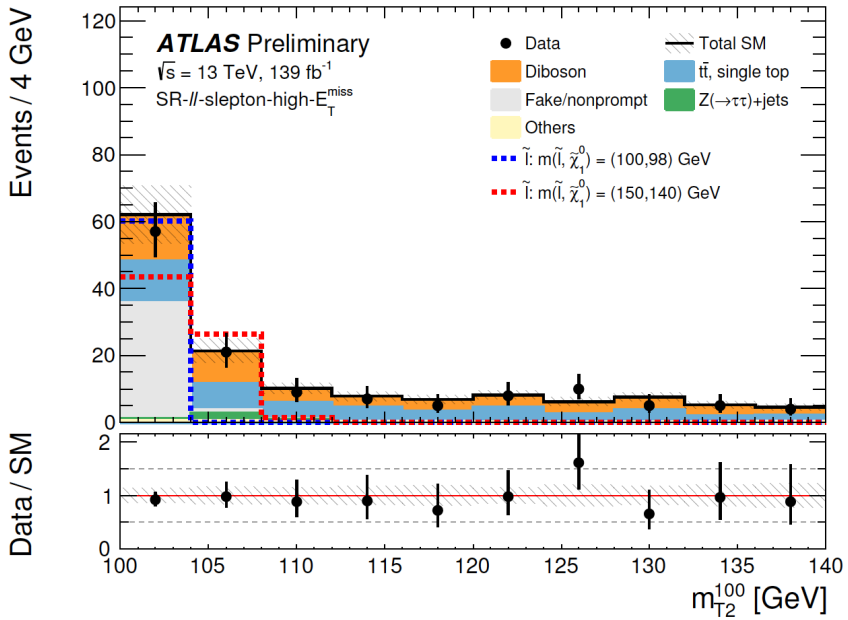
Signature

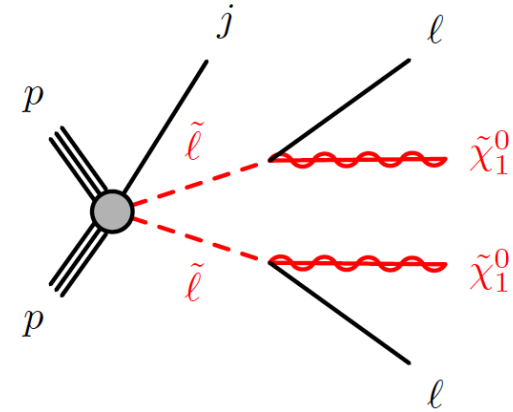
- Two soft same-flavour opposite-charge leptons (electrons or muons) or one soft lepton and one track
- Significant missing transverse momentum + ISR jet (139 fb^{-1})

Main backgrounds

- irreducible backgrounds (both leptons are genuine): $t\bar{t}$/tW, WW/WZ, and Z($\rightarrow\tau\tau$)+jets.
- Reducible backgrounds (one lepton is non genuine): jets misidentified as leptons, photon conversions, or semileptonic decays of heavy-flavour hadrons

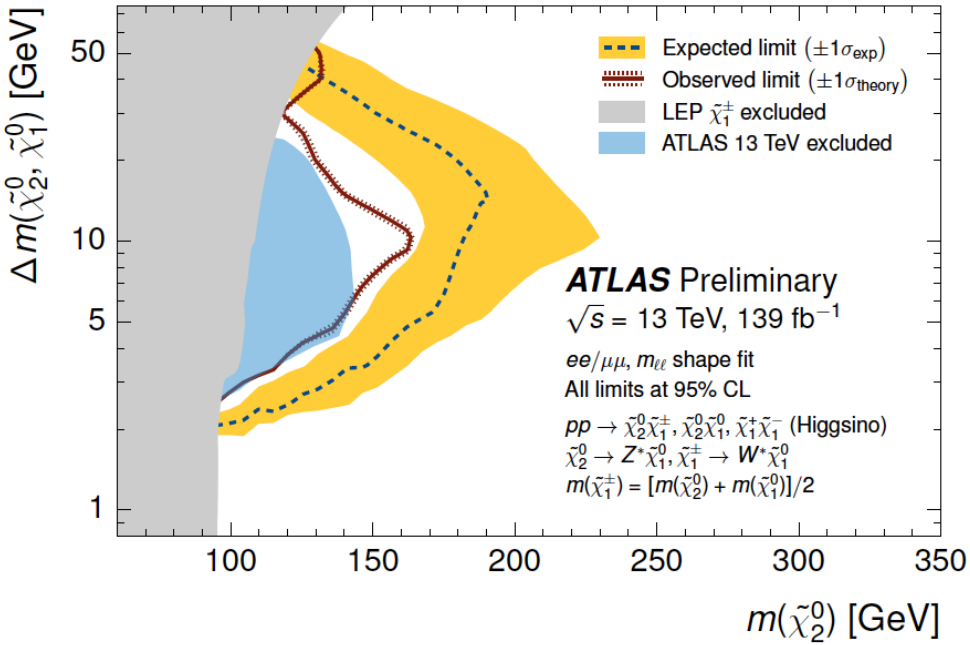


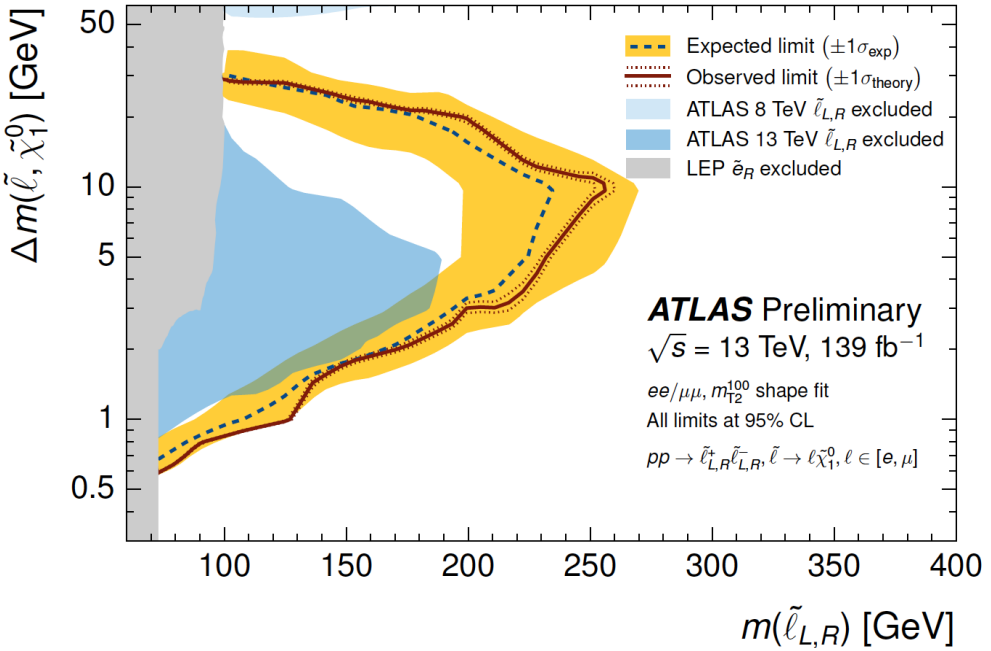




Electroweak production in compressed mass spectra

ATLAS-CONF-2019-014





Exclude $\tilde{\chi}^0_2$,$\tilde{\chi}^{\pm}_1$ (higgsino) up to 162 GeV mass for a mass splitting of 10 GeV

Exclude light-flavour sleptons below 256 GeV mass for a mass splitting of 10 GeV

The vector boson fusion topology

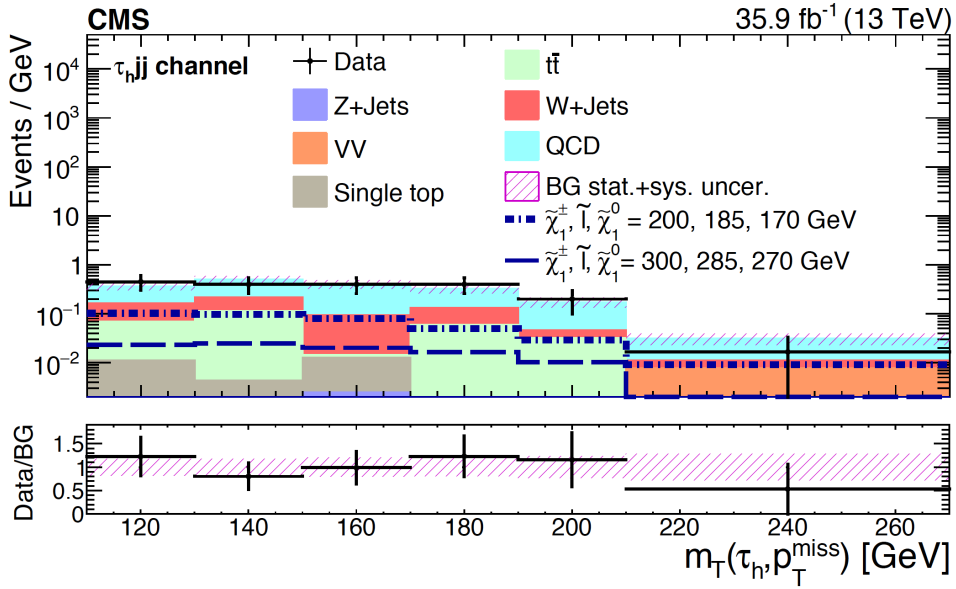
arXiv:1905.13059v1

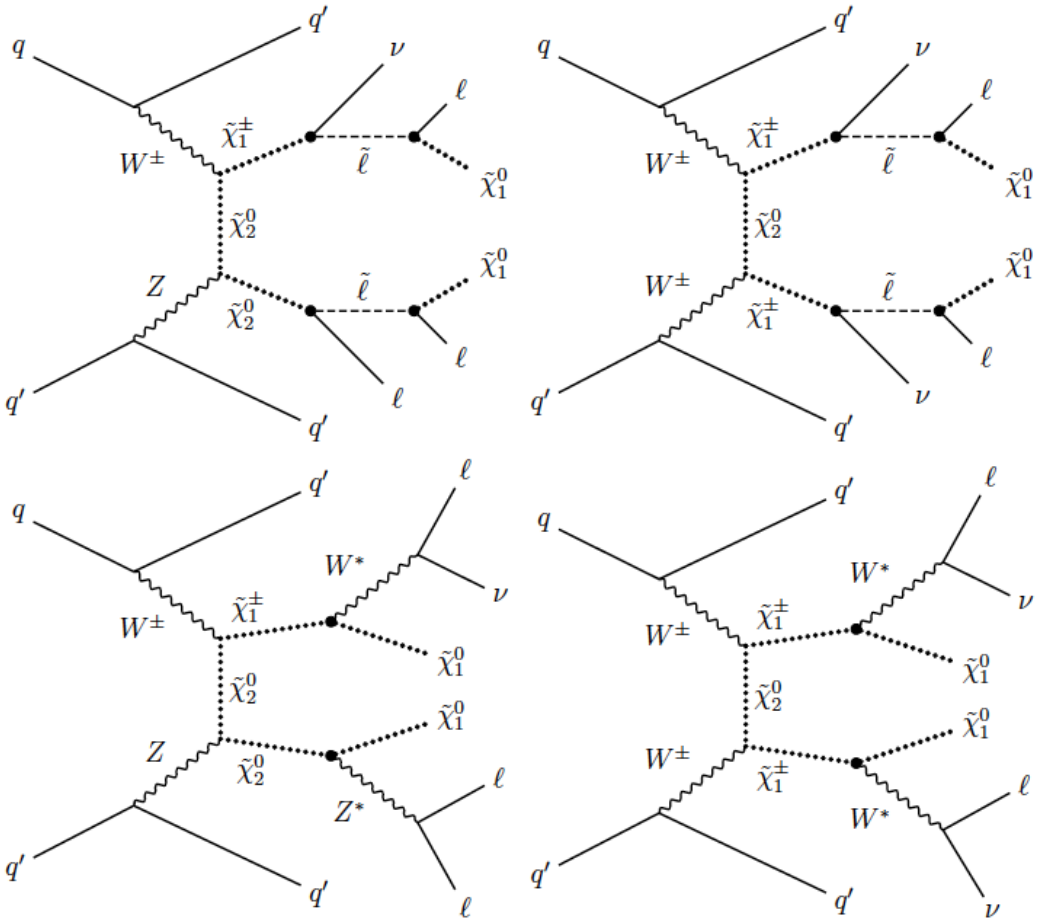
Signature

- two oppositely directed forward jets (define VBF topology) + significant missing transverse momentum + 0 or 1 soft lepton (35.9 fb^{-1})

Main backgrounds

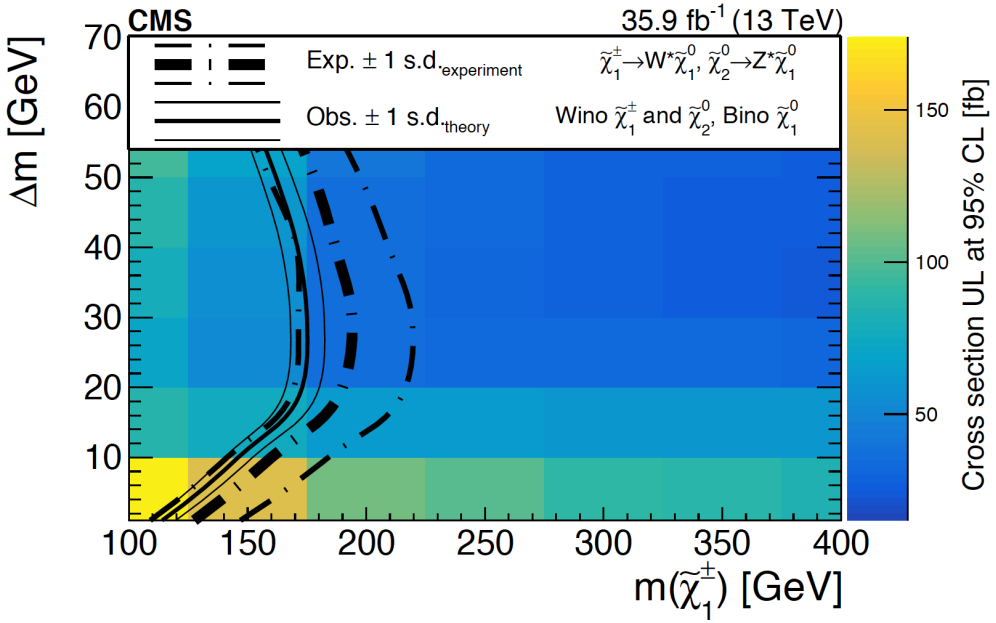
- t $\bar{t}$, W+jets, Z+jets, and Z($\rightarrow\nu\nu$)+jets
- QCD

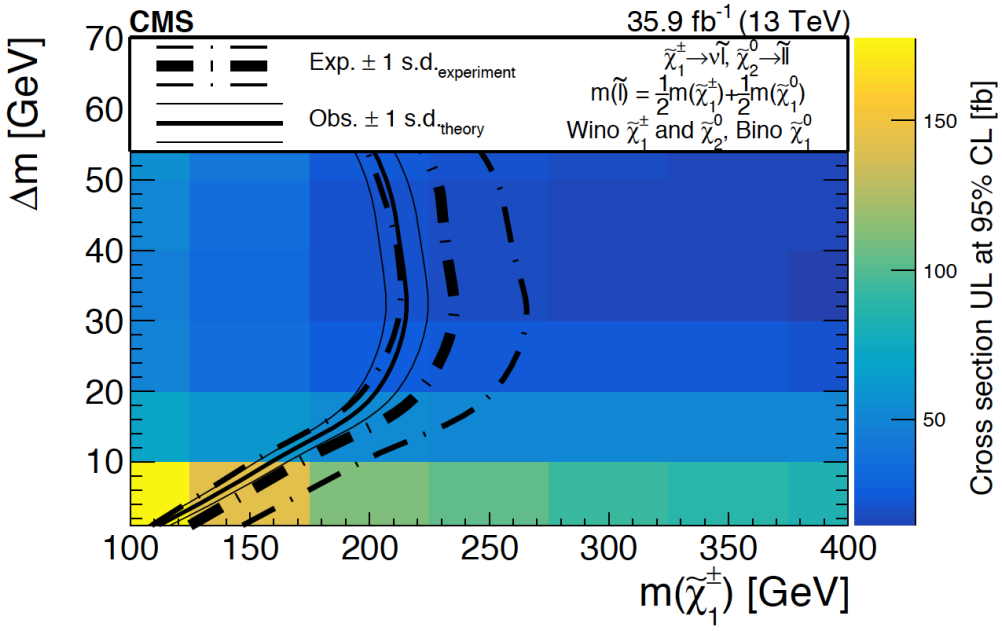




The vector boson fusion topology

arXiv:1905.13059v1





For a mass splitting of 1 (30) GeV:

Exclude $\tilde{\chi}^0_2, \tilde{\chi}^\pm_1$ (decay through sleptons) up to 112 (215) GeV mass

Exclude $\tilde{\chi}^0_2, \tilde{\chi}^\pm_1$ (decay through gauge bosons) up to 112 (175) GeV mass

Indirect stau

New

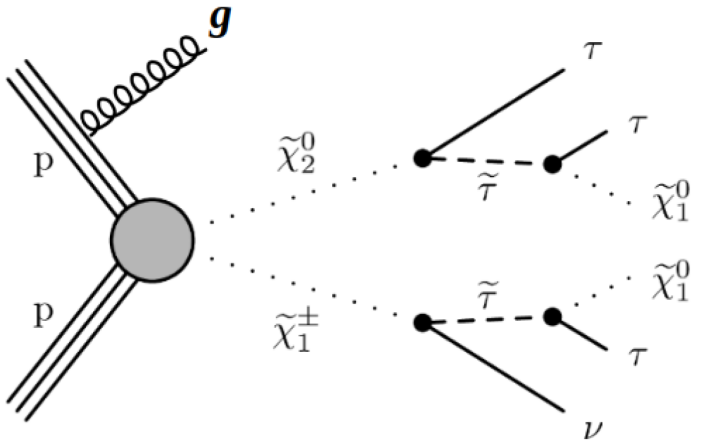
CMS PAS SUS-19-002

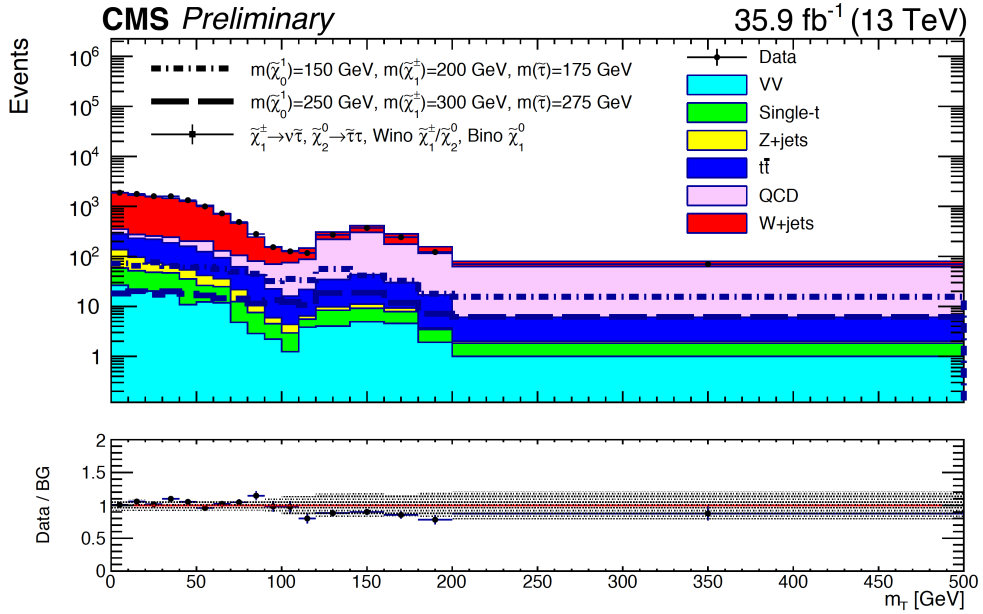
Signature

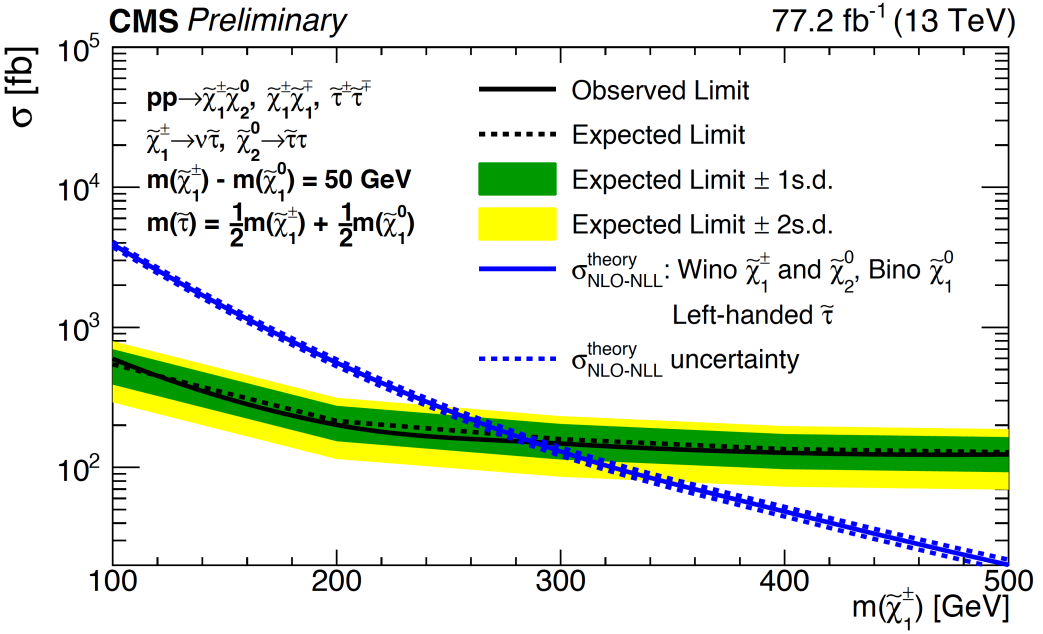
- Soft τ_h candidate recoiling against high p_T ISR jet (77.2 fb^{-1})

Main backgrounds

- t $\bar{t}$, W+jets, quantum chromodynamics (QCD) multijet processes, and Z($\rightarrow\tau\tau$)



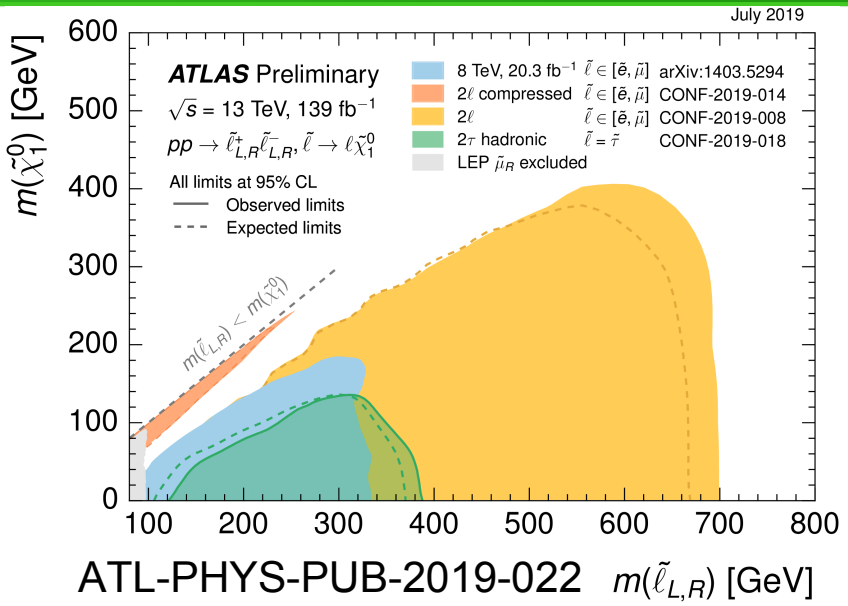




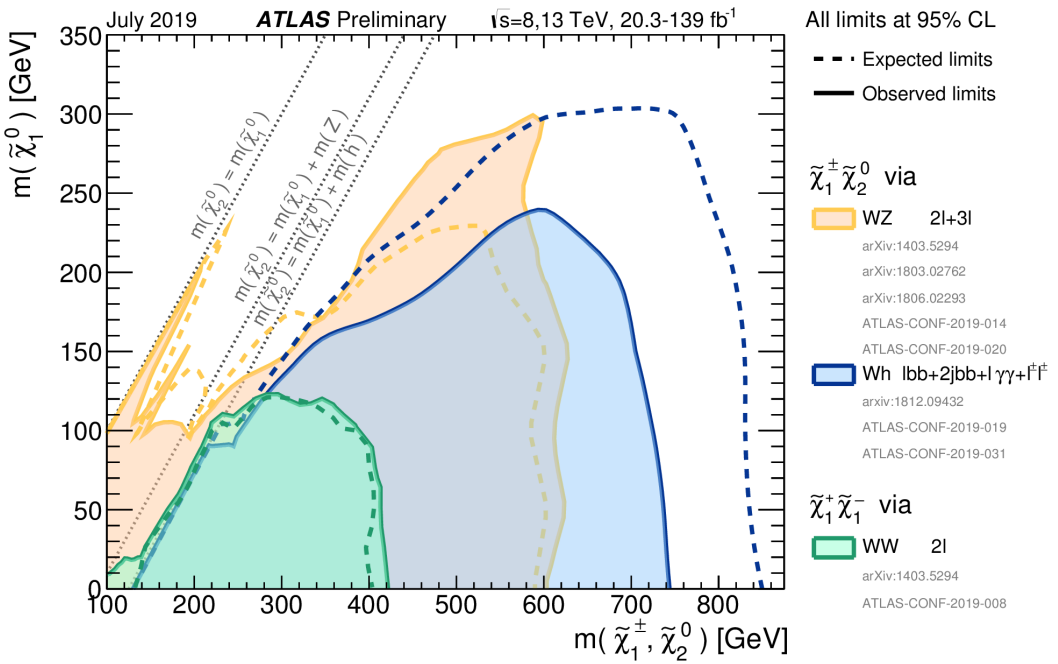
Exclude $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$ (decay through stau) up to 290 GeV mass for a mass splitting of 50 GeV

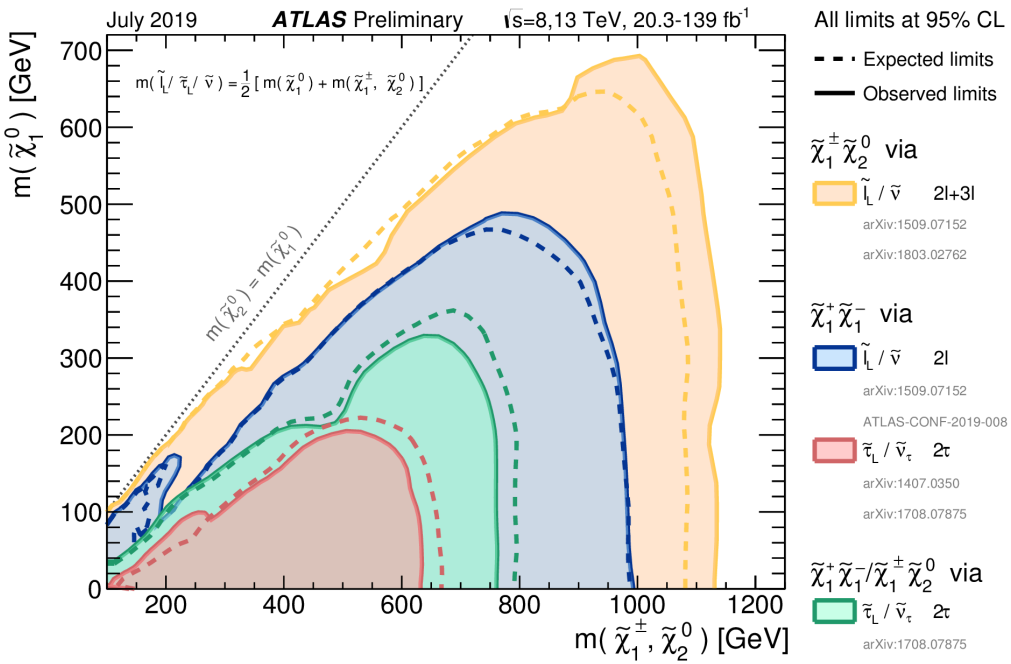
Summary

- More and more analysis are updated with full Run 2 luminosity
- Many new physically motivated specific simplified models
- More attention at the compressed spectrum
- More analyses will come soon!



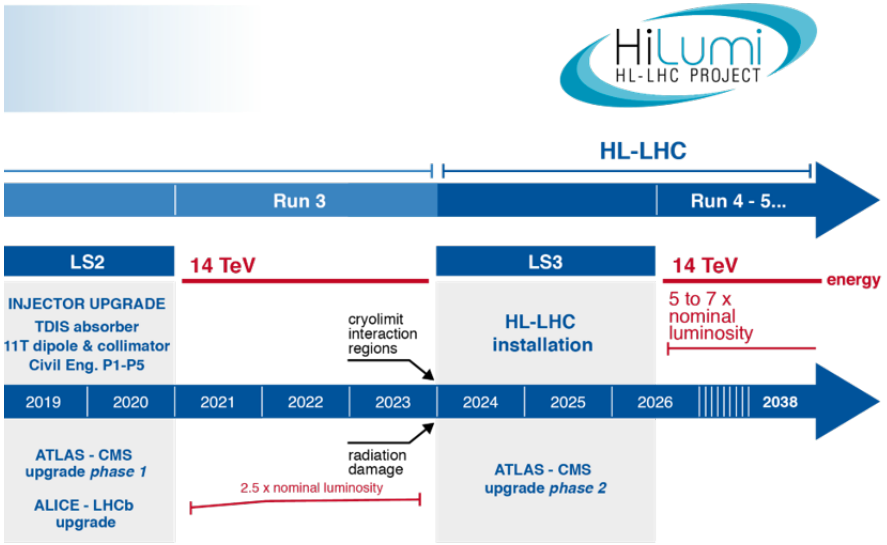
ATL-PHYS-PUB-2019-022



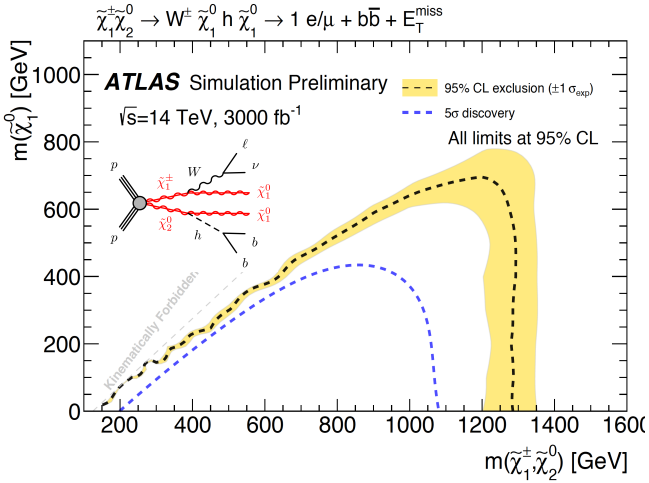


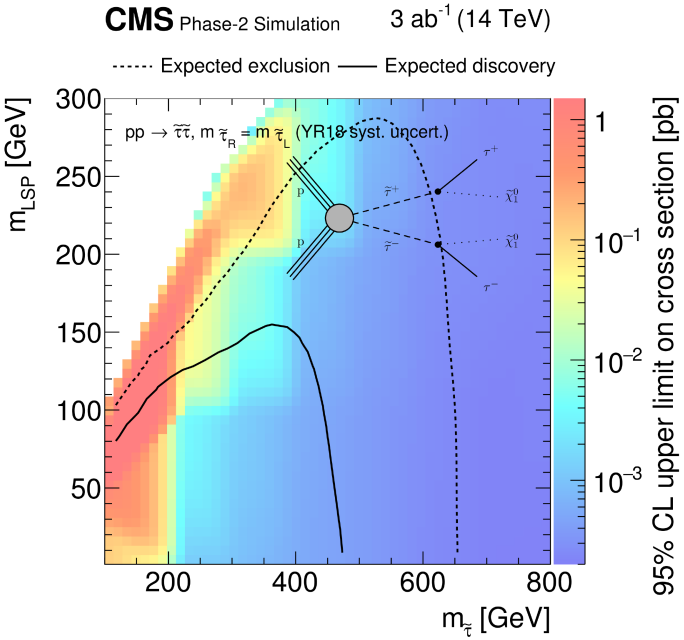
outlook

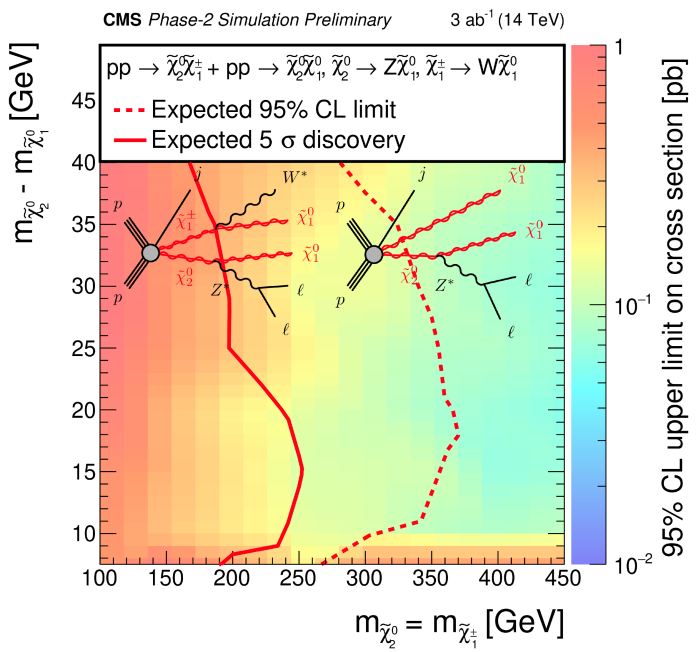
- Run 3 is coming → more luminosity
- Even more luminosity with HL-LHC → significantly boost of sensitivity
- Stay tuned!



arXiv:1812.07831







backup

Chargino and neutralino decay through Higgs boson

CMS PAS SUS-18-007

ATLAS-CONF-2019-019

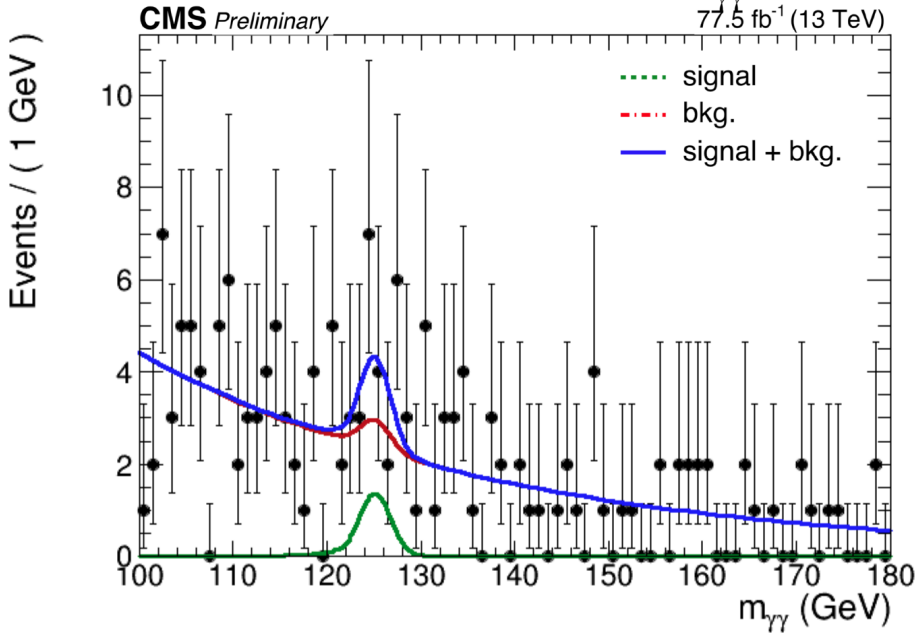
Signature (77.5 fb^{-1} CMS, 139 fb^{-1} ATLAS)

- two isolated photons (H→γγ tag)
- one isolated light lepton or two soft same-flavour opposite-charge leptons (electrons or muons) with invariant mass close to m_Z (CMS only)

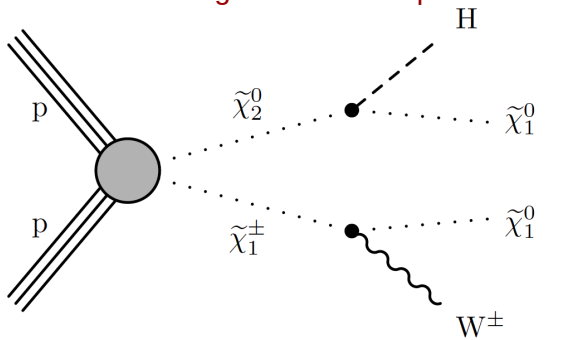
Main backgrounds

- Non-resonant: diphotons or a photon and a jet via QCD processes
- Resonant: SM Higgs boson production

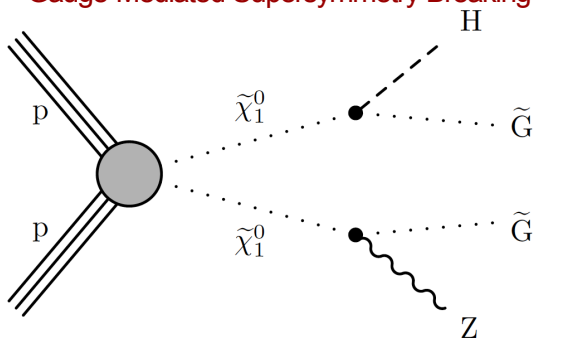
Background and signal ← fit in $m_{\gamma\gamma}$ in different regions

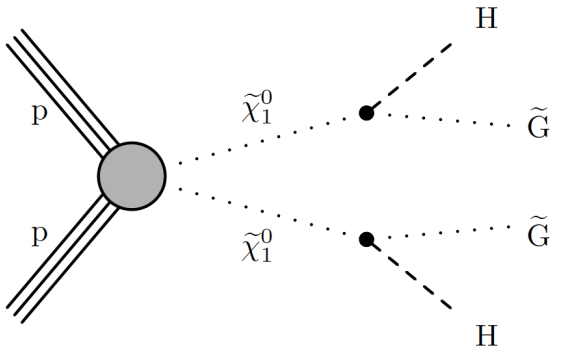


wino-like chargino-neutralino production



higgsino-like chargino-neutralino production
Gauge-Mediated Supersymmetry Breaking

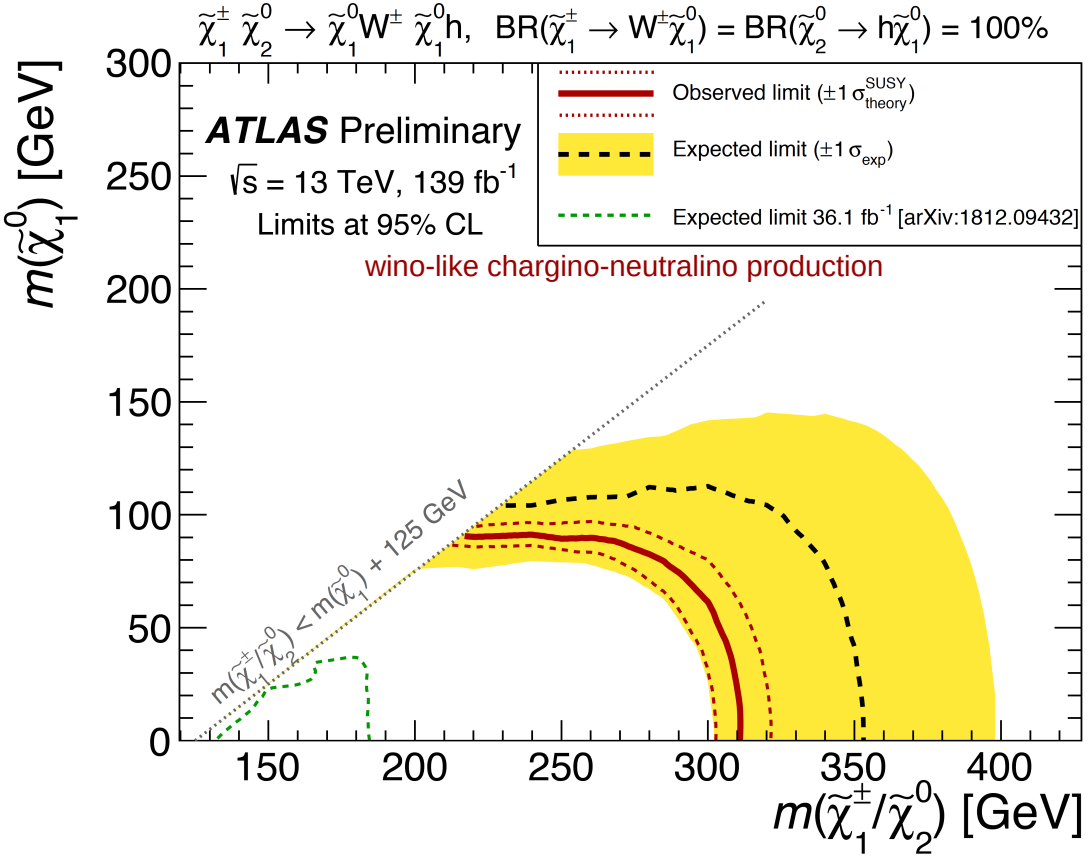




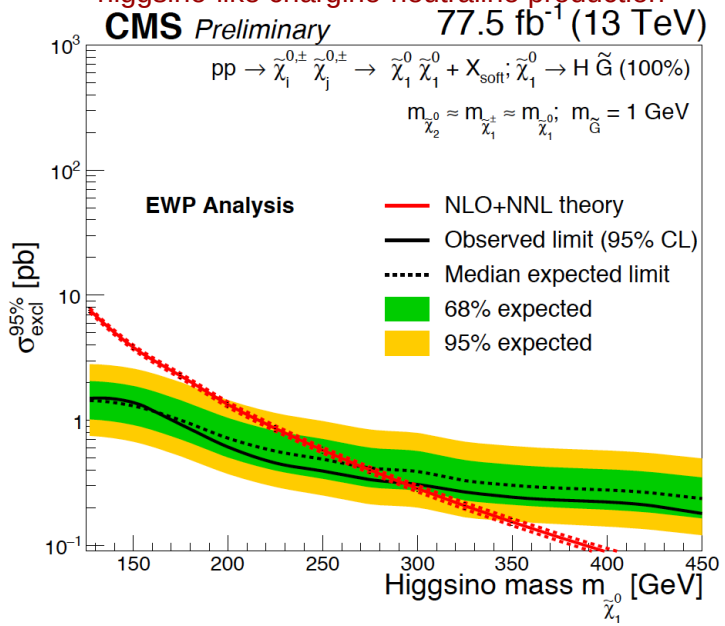
Chargino and neutralino decay through Higgs boson

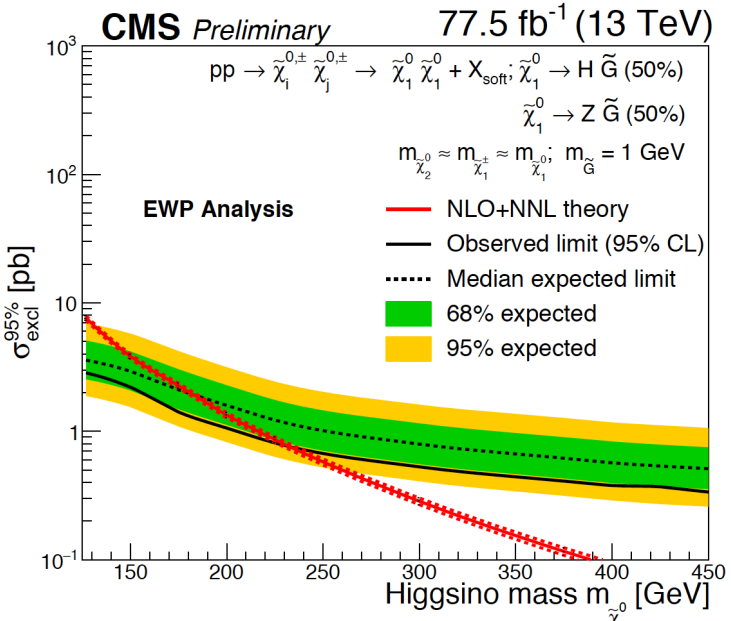
CMS PAS SUS-18-007

ATLAS-CONF-2019-019



higgsino-like chargino-neutralino production





For small $\tilde{\chi}^0_1$ masse in wino-like chargino-neutralino scenario exclude $\tilde{\chi}^0_2\tilde{\chi}^{\pm}_1$ masses up to 315 GeV

For higgsino-like chargino neutralino production exclude $\tilde{\chi}^0_1\tilde{\chi}^{\pm}_1$ masses up to 290 (230) GeV depending on the decay

Chargino and neutralino decay through Higgs boson

CMS PAS SUS-18-007

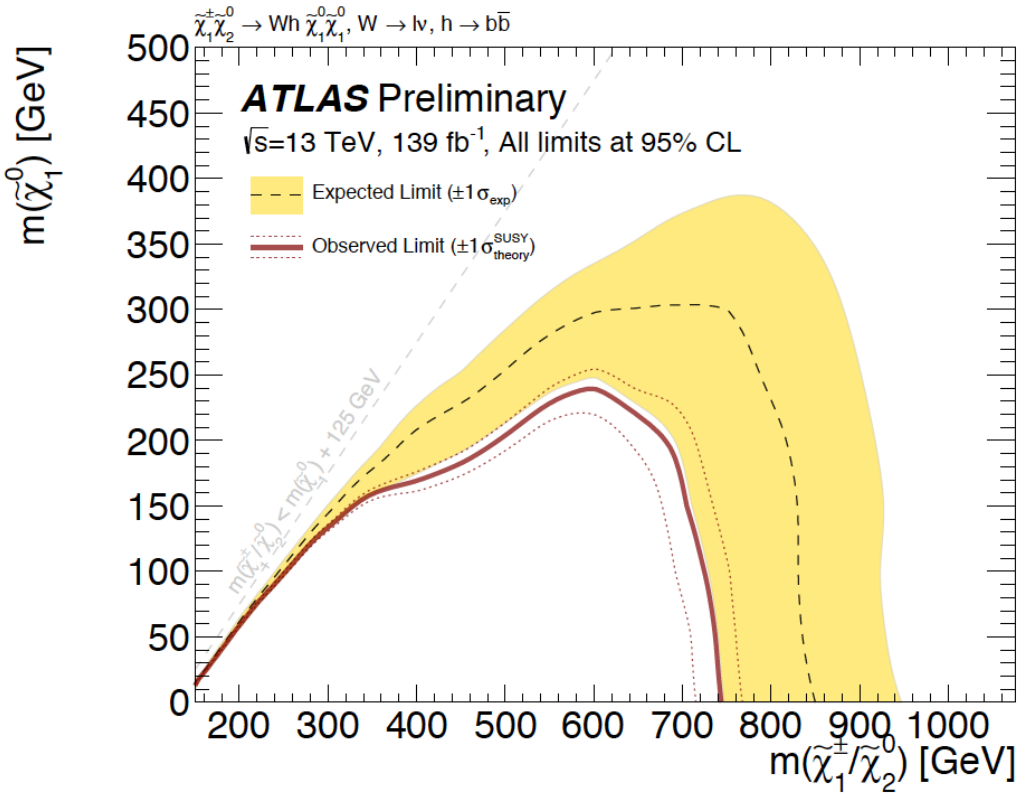
ATLAS-CONF-2019-019

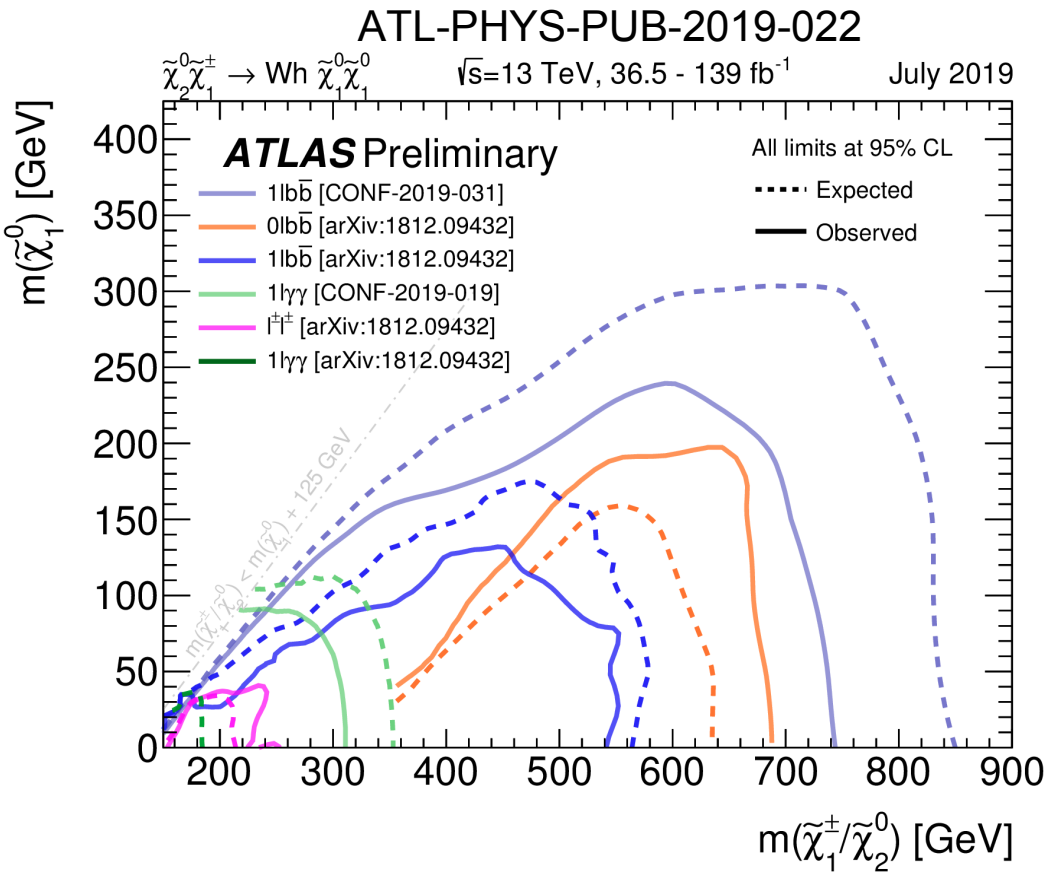
Table 1: Criteria used in the categorization.

Channels	Names	Selection
Leptonic	Category 1	$0 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 2, N_\ell \geq 1$
	Category 2	$2 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 4, N_\ell \geq 1$
	Category 3	$4 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 6, N_\ell \geq 1$
	Category 4	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 6, N_\ell \geq 1$
Hadronic	Category 5	$5 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 6, N_\ell = 0, N_j \geq 2, M_{jj} \in [40, 120]$ GeV
	Category 6	$6 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 7, N_\ell = 0, N_j \geq 2, M_{jj} \in [40, 120]$ GeV
	Category 7	$7 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 8, N_\ell = 0, N_j \geq 2, M_{jj} \in [40, 120]$ GeV
	Category 8	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 8, N_\ell = 0, N_j \geq 2, M_{jj} \in [40, 120]$ GeV
Rest	Category 9	$6 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 7, N_\ell = 0, N_j < 2$ or ($N_j \geq 2, M_{jj} \notin [40, 120]$ GeV)
	Category 10	$7 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 8, N_\ell = 0, N_j < 2$ or ($N_j \geq 2, M_{jj} \notin [40, 120]$ GeV)
	Category 11	$8 < S_{E_{\mathrm{T}}^{\mathrm{miss}}} \leq 9, N_\ell = 0, N_j < 2$ or ($N_j \geq 2, M_{jj} \notin [40, 120]$ GeV)
	Category 12	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 9, N_\ell = 0, N_j < 2$ or ($N_j \geq 2, M_{jj} \notin [40, 120]$ GeV)

Summary plots

ATLAS-CONF-2019-031 New





For small $\tilde{\chi}^0_1$ masses exclude $\tilde{\chi}^0_1$,$\tilde{\chi}^{\pm}_1$ with mass below 750 GeV → the most sensitive analysis for this model

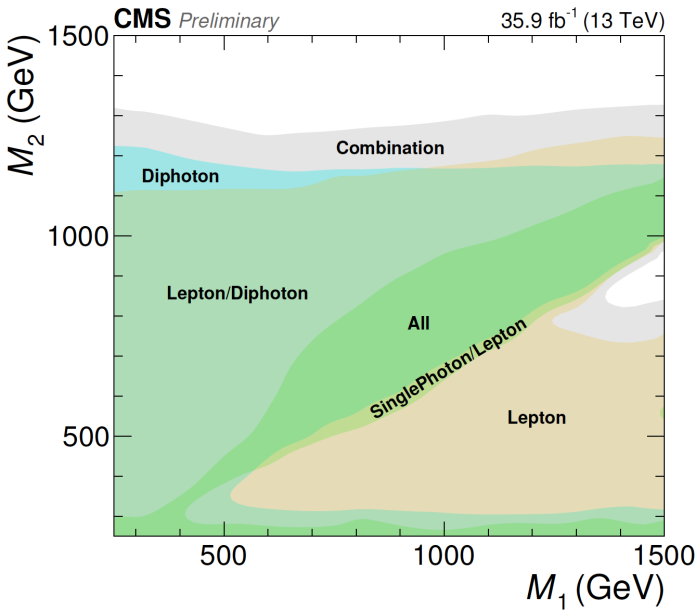
Electroweak production in compressed mass spectra

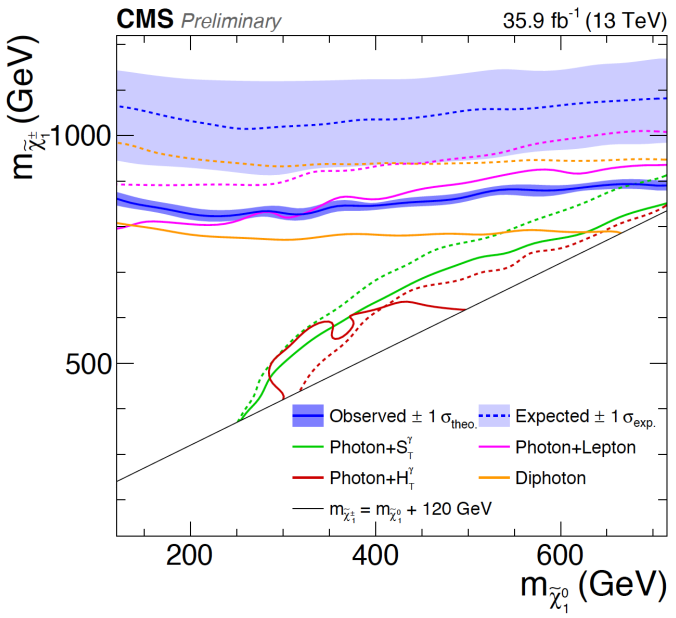
ATLAS-CONF-2019-014

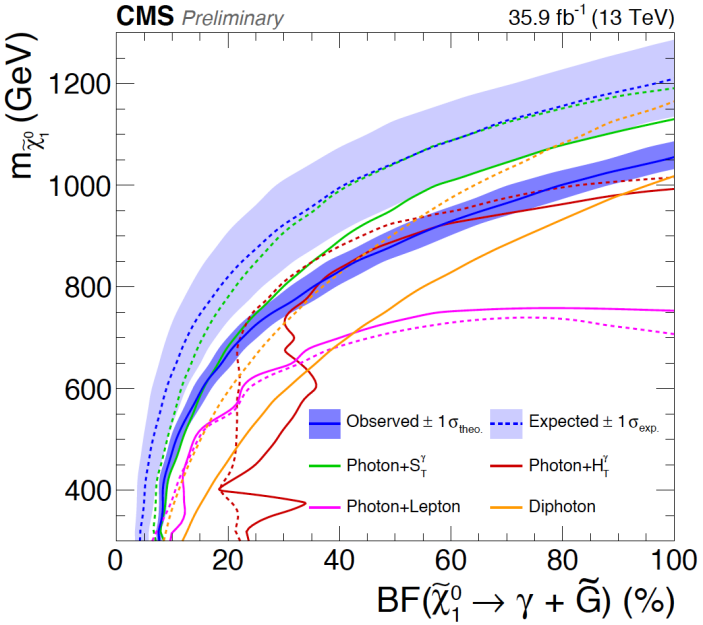
Variable	Electroweakino SR Requirements			
	Low-$E_{\mathrm{T}}^{\mathrm{miss}}$, low-$\Delta m$	Low-$E_{\mathrm{T}}^{\mathrm{miss}}$, high-$\Delta m$	High-$E_{\mathrm{T}}^{\mathrm{miss}}$	$1\ell 1T$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	[120, 200]	[120, 200]	> 200	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	> 10	< 10	–	> 30
$\Delta\phi(\mathrm{lep}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	–	–	–	< 1.0
Lepton or track p_{T} [GeV]	–	$p_{\mathrm{T}}^{\ell_2} > 5 + m_{\ell\ell}/4$	$p_{\mathrm{T}}^{\ell_2} > \min(10, 2 + m_{\ell\ell}/3)$	$p_{\mathrm{T}}^{\mathrm{track}} < 5$
$M_{\mathrm{T}}^{\mathrm{S}}$ [GeV]	< 50	–	–	–
$m_{\mathrm{T}}^{\ell_1}$ [GeV]	–	[10, 60]	< 60	–
R_{ISR}	–	[0.8, 1.0]	$[\max(0.85, 0.98 - 0.02 \times m_{\ell\ell}),\ 1.0]$	–

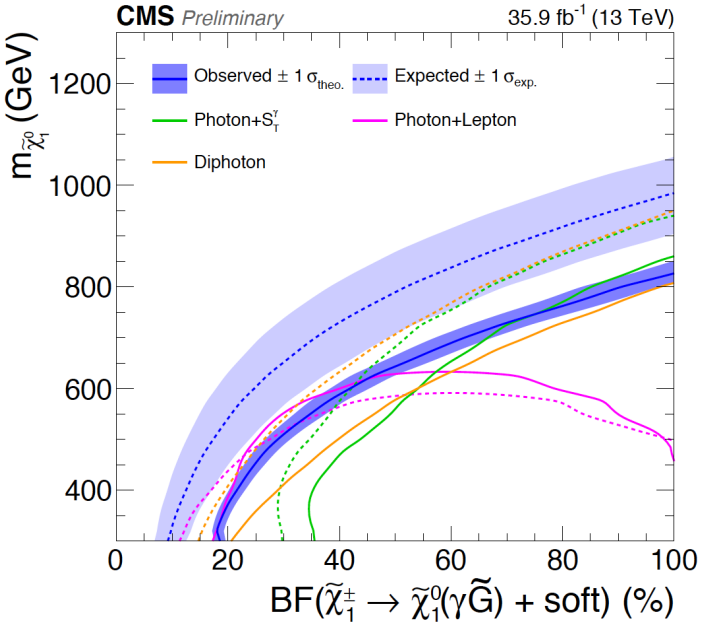
Gauge-mediated supersymmetry

arXiv:1907.00857









$$M_3 = \mu = 8\ \text{TeV}$$
$$m_Q = m_U = 10\ \text{TeV}$$
$$m_D = 8\ \text{TeV}$$
$$M_{mess} = 10^{15}\ \text{GeV}$$

Gravitino mass = 10 eV

General Gauge Mediation

Exclude M_2 up to 1100 GeV

Exclude $\widetilde{\chi}^{\pm}_1$ up to 890 GeV

Gauge-mediated supersymmetry

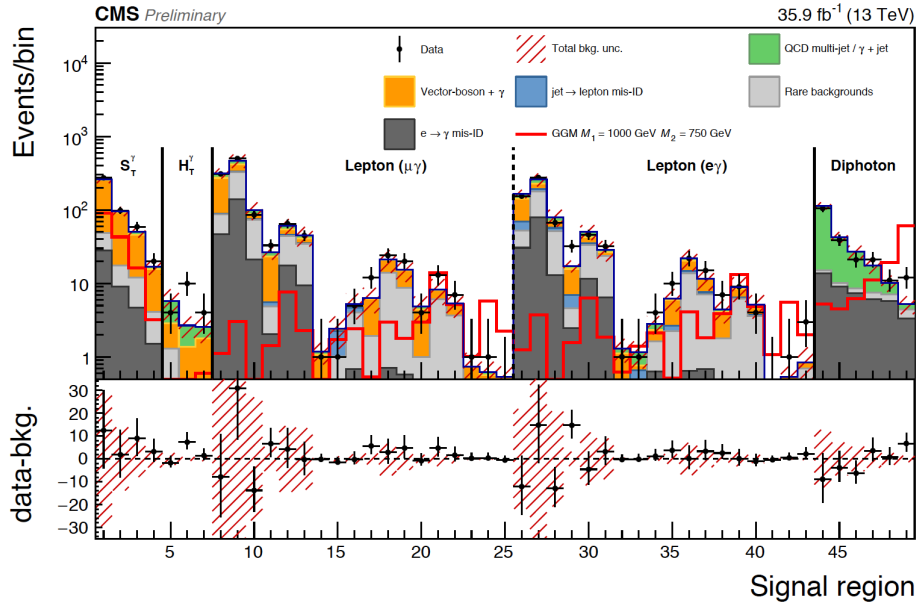
arXiv:1907.00857

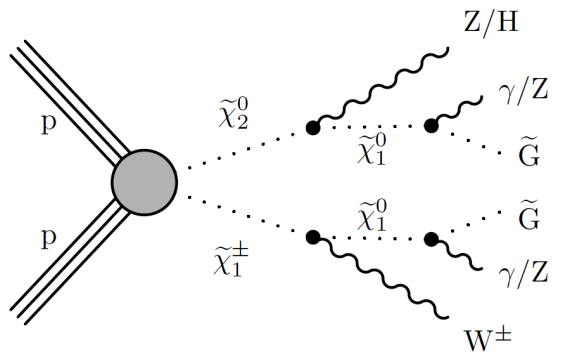
Signature (35.9 fb^{-1})

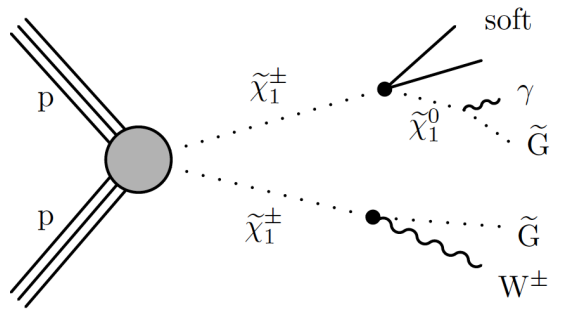
- two isolated photons
- Or one isolated photon as well as one isolated charged lepton
- Or one isolated photon and significant missing transverse momentum
- Or one isolated photon and significant hadronic activity

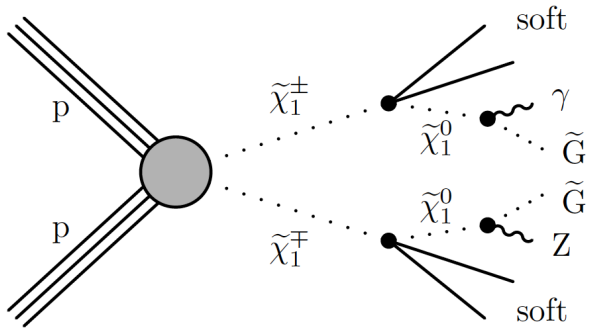
Main backgrounds

- Vector boson+γ, quantum chromodynamics (QCD) multijet processes and γ+jets









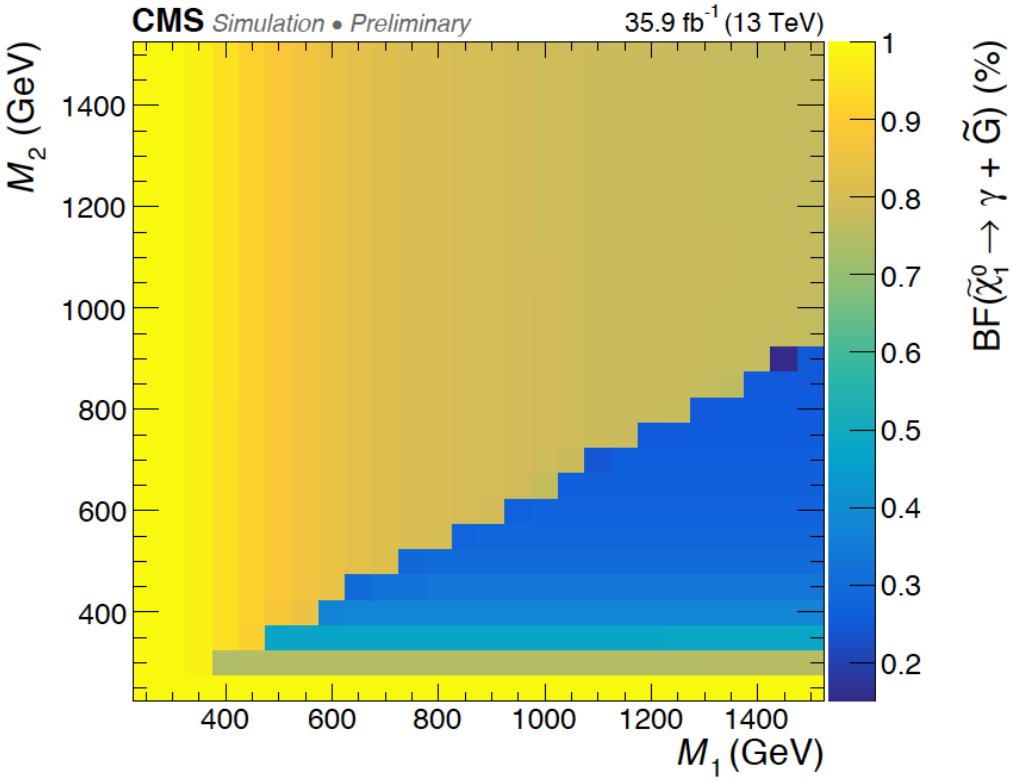
Summary plots

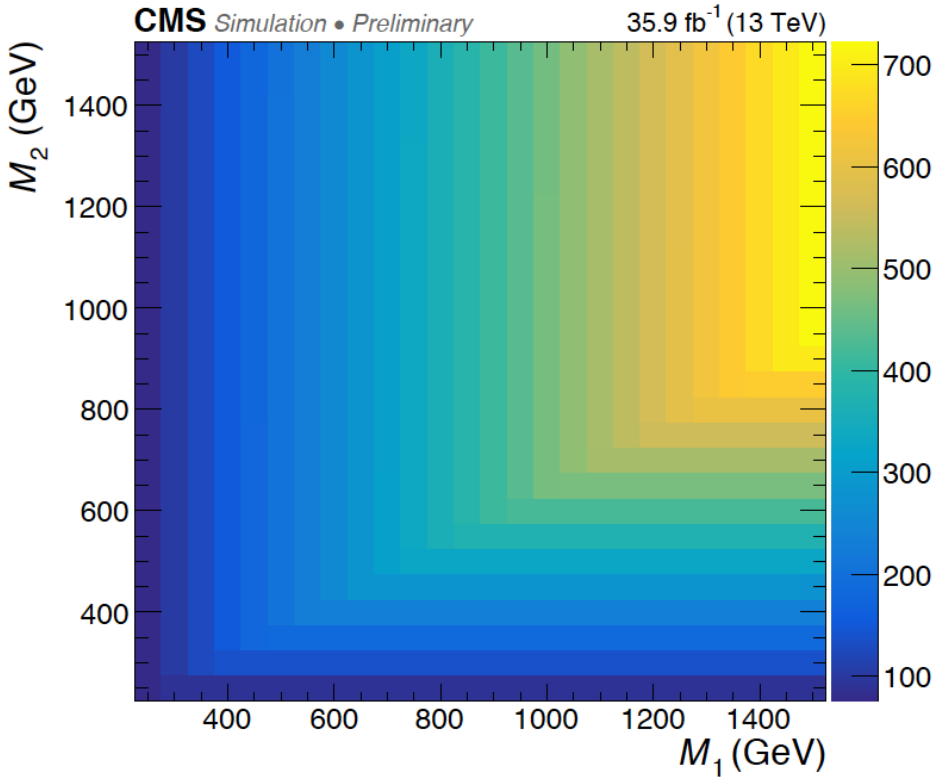
ATLAS-CONF-2019-031 New

	SR-LM	SR-MM	SR-HM
N_{lepton}	$= 1$		
p_{T}^{ℓ} [GeV]	$> 7(6)$ for $e(\mu)$		
N_{jet}	$= 2$ or 3		
$N_{b-\text{jet}}$	$= 2$		
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 240		
$m_{b\bar{b}}$ [GeV]	$\in [100, 140]$		
$m(\ell, b_1)$ [GeV]	–	–	> 120
m_{T} [GeV](excl.)	$\in [100, 160]$	$\in [160, 240]$	> 240
m_{CT} [GeV](excl.)	$\{\in [180, 230], \in [230, 280], > 280\}$		
m_{T} [GeV](disc.)	> 100	> 160	> 240
m_{CT} [GeV](disc.)	> 180		

Gauge-mediated supersymmetry

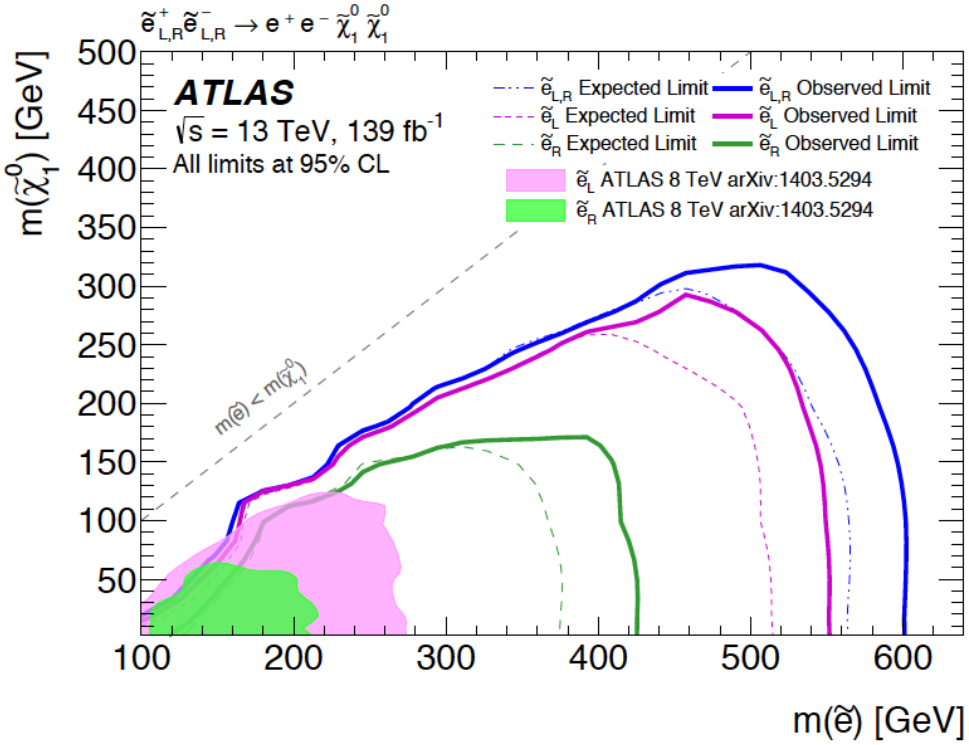
CMS PAS SUS-18-005



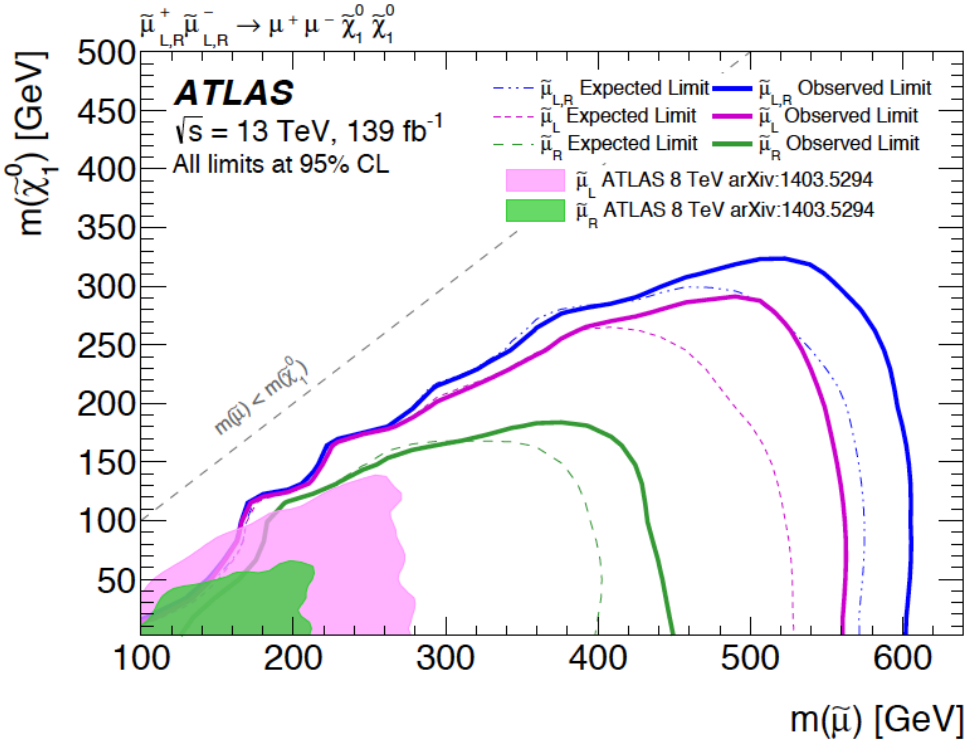


Chargino and slepton search

arXiv:1908.08215



(a) $\tilde{e}\tilde{e}$ production



(b) $\tilde{\mu}\tilde{\mu}$

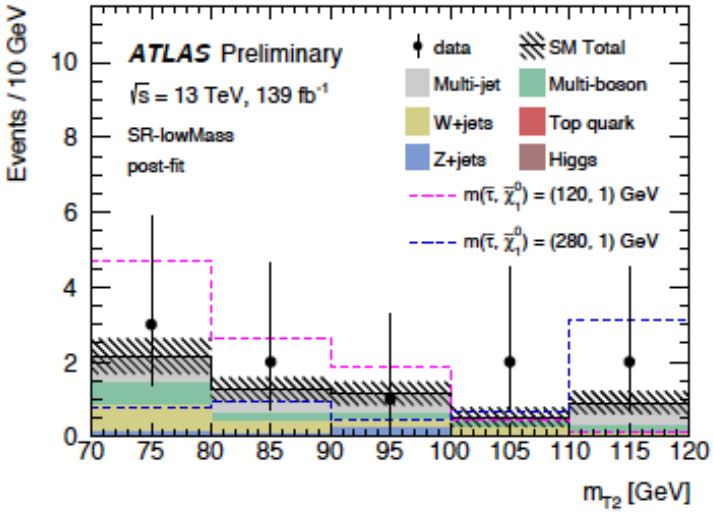
Stau search

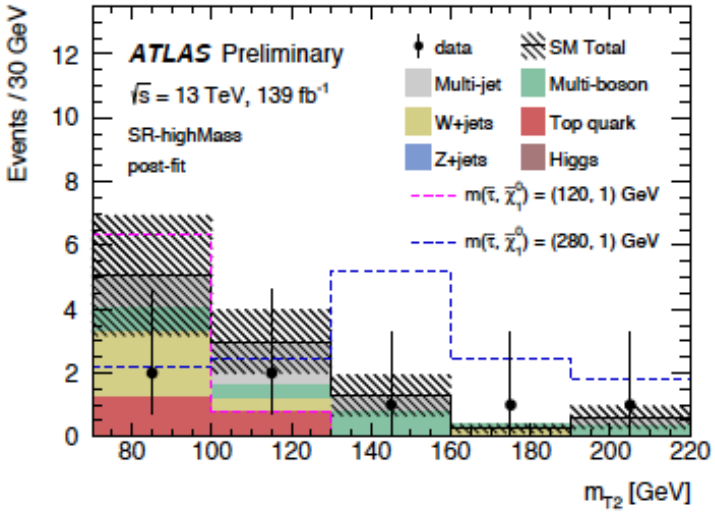
Table 1: Summary of selection requirements for the signal regions.

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

Table 1: Ranges in m_{T2}, Σm_{T}, and N_{j} used to define the SRs used in the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ analysis.

m_{T2} [GeV]	25–50						>50					
Σm_{T} [GeV]	200–250		250–300		>300		200–250		250–300		>300	
N_{j}	0	$\geq$1	0	$\geq$1	0	$\geq$1	0	$\geq$1	0	$\geq$1	0	$\geq$1





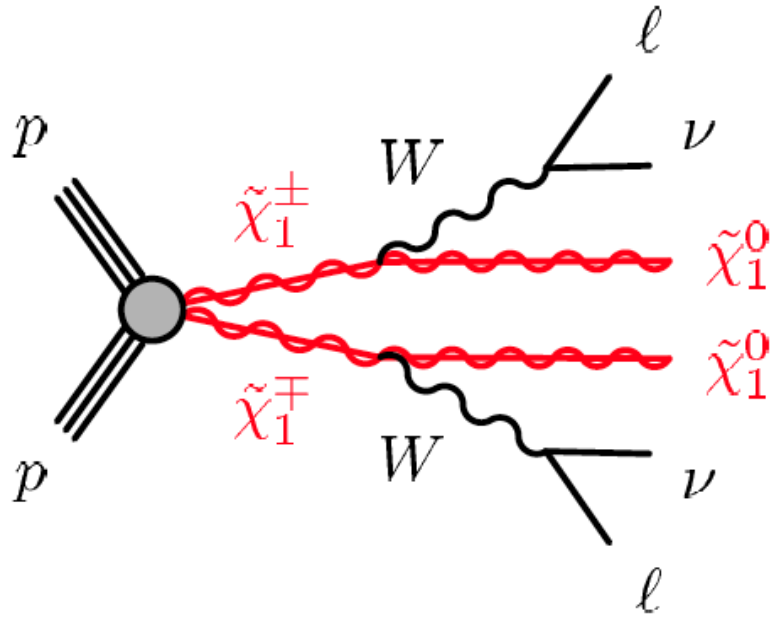
Search for direct chargino pair production with W-boson mediated decays in events with two leptons and missing transverse momentum

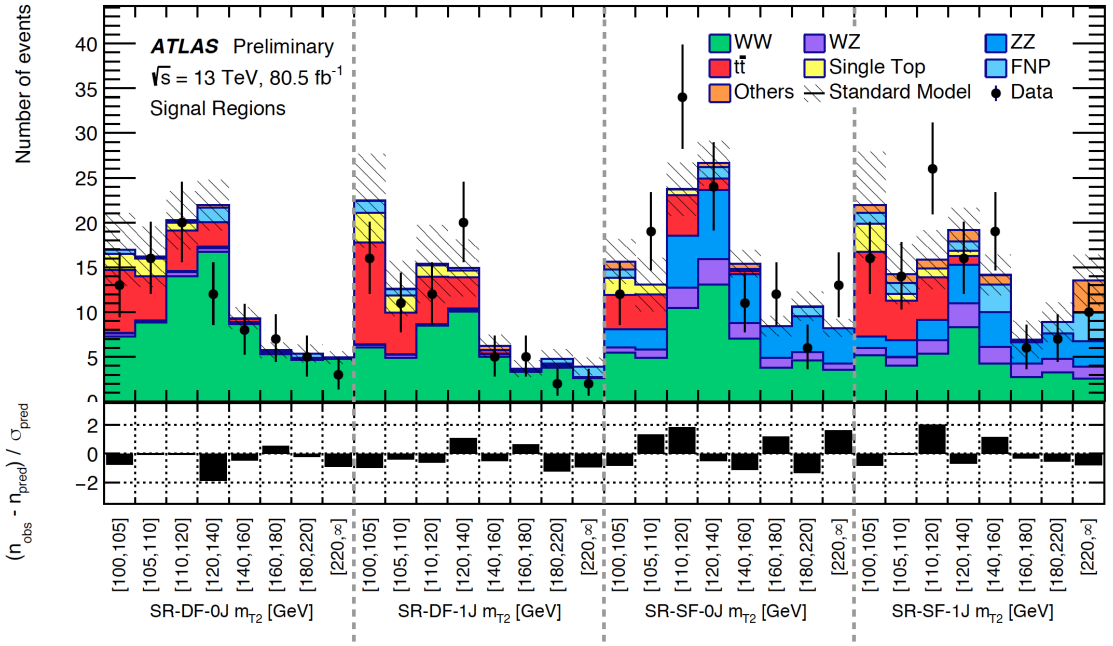
ATLAS-CONF-2018-042

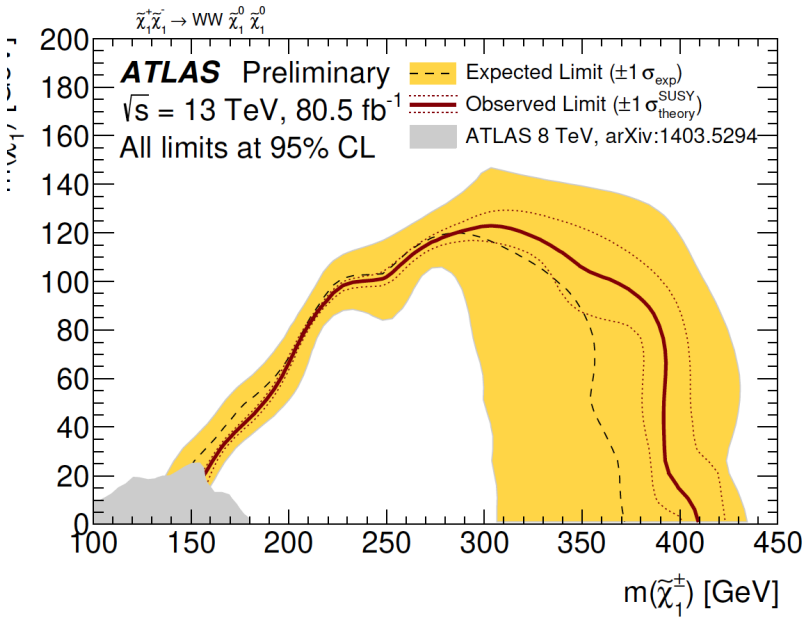
- **Signature**

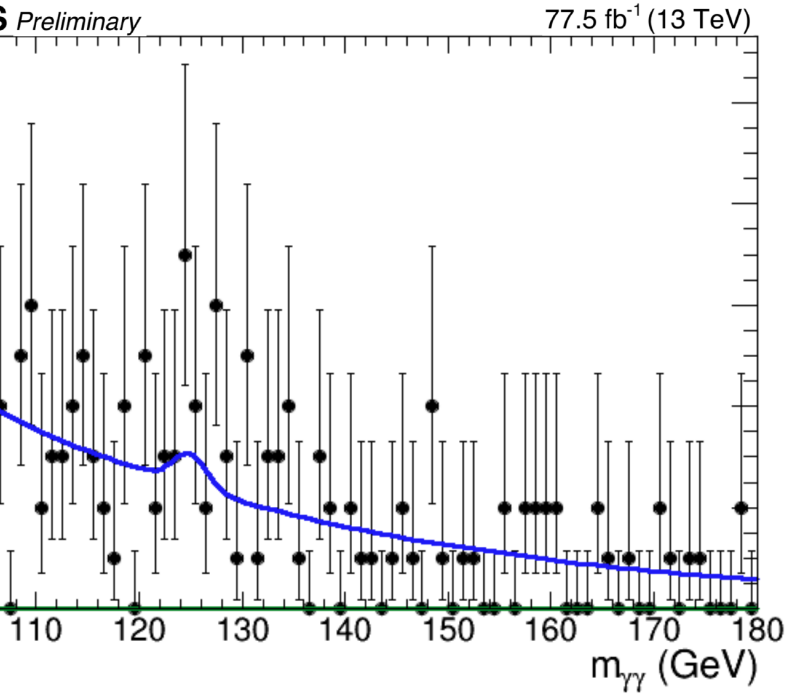
with two isolated leptons (electron or muon), missing transverse momentum and at most one light jet in the final state

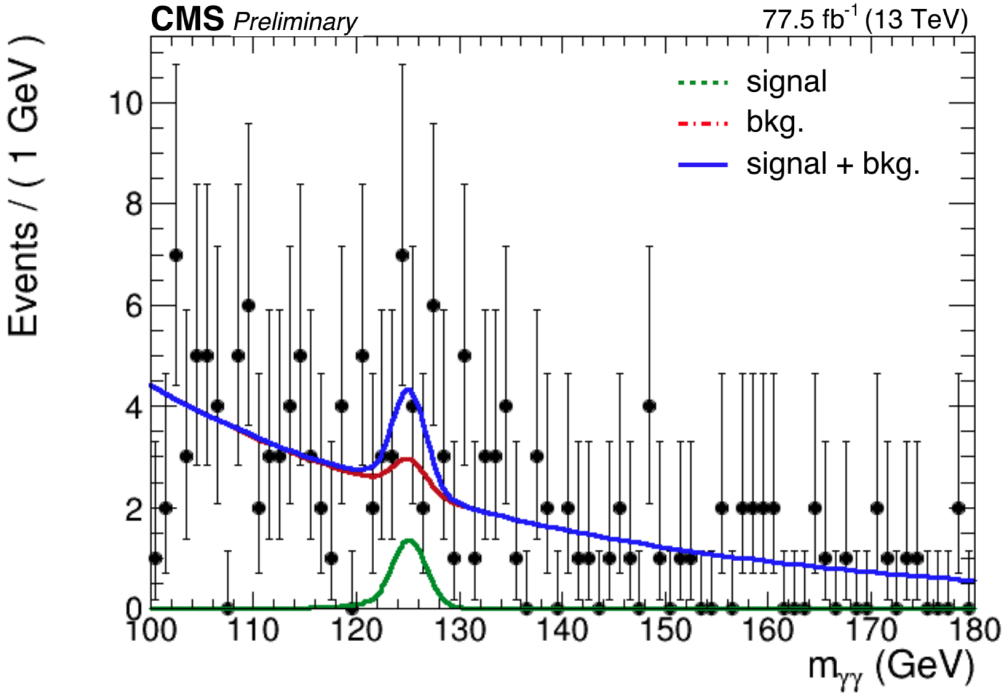
Main backgrounds





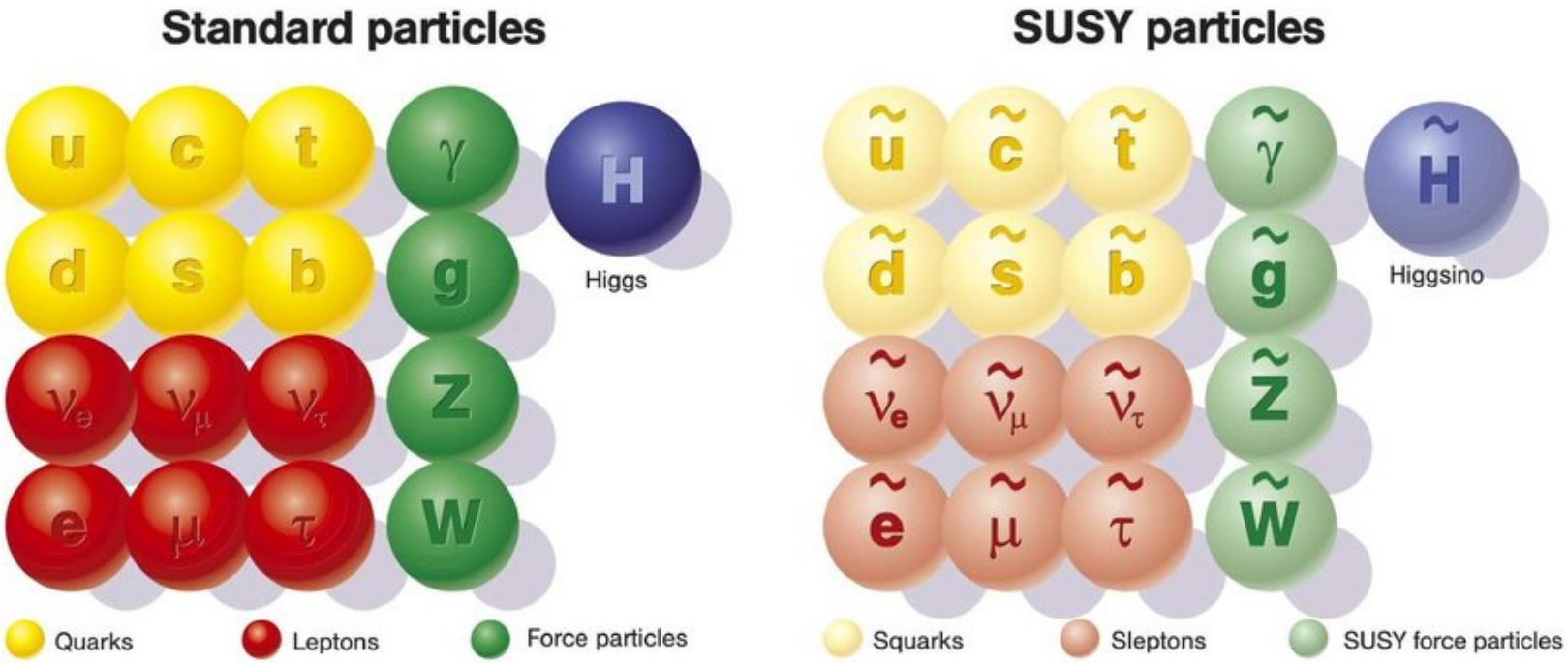



S Preliminary
77.5 fb-1 (13 TeV)
110
120
130
140
150
160
170
180
mγγ (GeV)


CMS Preliminary
77.5 fb-1 (13 TeV)
Events / (1 GeV)
signal
bkg.
signal + bkg.
0
2
4
6
8
10
100
110
120
130
140
150
160
170
180
mγγ (GeV)

Supersymmetry and MSSM

Supersymmetry (SUSY) relates two classes of particles, bosons (integer spin) and fermions (half-integer spin)



Minimal Supersymmetric Standard Model (MSSM) is supersymmetric SM extension with the minimal number of new particle states and new interactions