SEARCHES FOR SUSY WITH ATLAS AND CMS EXPERIMENTS

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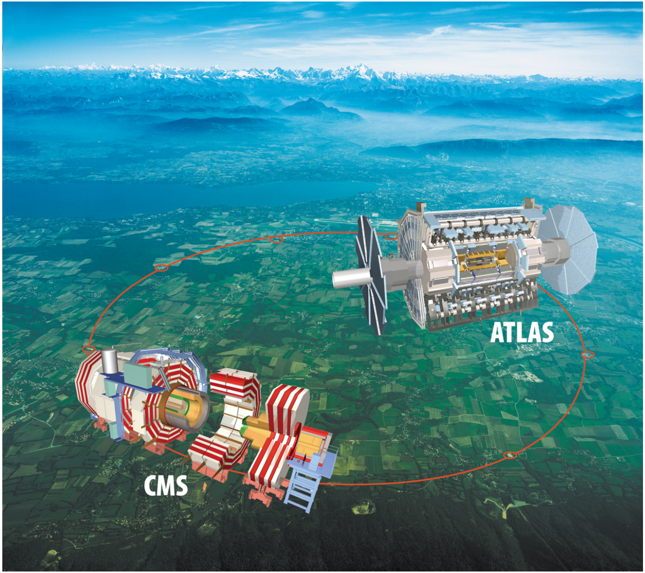
LHC: ATLAS AND CMS EXPERIMENTS



Today, showing some of the results obtained with Run-2 ATLAS (link) and CMS (link) data

SUPERSYMMETRY

Supersymmetry (SUSY) can solve most of the SM problems:

- A fundamental theory which unifies fermions (matter) and bosons (forces)

→ SM boson ↔ new fermion; SM fermion ↔ new scalar

		Proper states in		Spartners	Proper states in	
		interaction term	mass term		interaction term	mass term
$\begin{pmatrix}\nu\\ L\end{pmatrix}, l$	Leptons $S=1/2$	$\begin{pmatrix}\nu_e\\ e_L\end{pmatrix}, e_R$		Sleptons $S=0$	$\begin{pmatrix}\widetilde{\nu}_e\\ \widetilde{e}_L\end{pmatrix}, \widetilde{e}_R$	
		$\begin{pmatrix}\nu_\mu\\ \mu_L\end{pmatrix}, \mu_R$			$\begin{pmatrix}\widetilde{\nu}_\mu\\ \widetilde{\mu}_L\end{pmatrix}, \widetilde{\mu}_R$	
		$\begin{pmatrix}\nu_\tau\\ \tau_L\end{pmatrix}, \tau_R$			$\begin{pmatrix}\widetilde{\nu}_\tau\\ \widetilde{\tau}_L\end{pmatrix}, \widetilde{\tau}_R$	$\widetilde{\tau}_1, \widetilde{\tau}_2, \widetilde{\nu}_\tau$
$\begin{pmatrix}U\\ D\end{pmatrix}, u, d$	Quarks $S=1/2$	$\begin{pmatrix}u_L\\ d_L\end{pmatrix}, u_R, d_R$		Squarks $S=0$	$\begin{pmatrix}\widetilde{u}_L\\ \widetilde{d}_L\end{pmatrix}, \widetilde{u}_R, \widetilde{d}_R$	
		$\begin{pmatrix}c_L\\ s_L\end{pmatrix}, c_R, s_R$			$\begin{pmatrix}\widetilde{c}_L\\ \widetilde{s}_L\end{pmatrix}, \widetilde{c}_R, \widetilde{s}_R$	
		$\begin{pmatrix}t_L\\ b_L\end{pmatrix}, t_R, b_R$			$\begin{pmatrix}\widetilde{t}_L\\ \widetilde{b}_L\end{pmatrix}, \widetilde{t}_R, \widetilde{b}_R$	$\widetilde{t}_1, \widetilde{t}_2, \widetilde{b}_1, \widetilde{b}_2$
	Gauge Bosons $S=1$	$W^\pm, W^0, B, g$	$W^\pm, Z^0, \gamma, g$	Gauginos $S=1/2$	$\widetilde{W}^\pm, \widetilde{W}^0, \widetilde{B}, \widetilde{g}$	Gluino $\widetilde{g}$ Neutralinos $\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0$ Charginos $\widetilde{\chi}_1^\pm, \widetilde{\chi}_2^\pm$
H_u, H_d	Higgs Boson $S=0$	$\begin{pmatrix}H_u^+\\ H_u^0\end{pmatrix}, \begin{pmatrix}H_d^0\\ H_d^-\end{pmatrix}$	$h^0, H^0, A^0, H^\pm$	Higgsinos $S=1/2$	$\begin{pmatrix}\widetilde{H}_u^+\\ \widetilde{H}_u^0\end{pmatrix}, \begin{pmatrix}\widetilde{H}_d^0\\ \widetilde{H}_d^-\end{pmatrix}$	
G	Graviton $S=2$	G		Gravitino $S=\frac{3}{2}$	$\tilde{G}$	

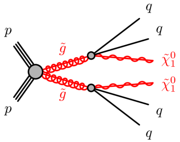
SUPERSYMMETRY AND R-PARITY

- Introduces R-parity, $(-1)^{3(B-L)+2S}$: *protects* baryon and lepton numbers conservation
  - → In SM R=+1, in SUSY R=–1

1) R-parity conserved (RPC): sparticles produced/annihilated in pairs

→ Lightest SUSY particle (LSP) can be stable and weakly interacting

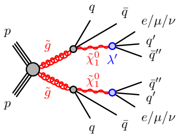
→ Final states with large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)



2) R-parity violated (RPV): allows the possibility of some RPV couplings to be non-zero

→ LSP unstable and decays in SM particles

→ $E_{\mathrm{T}}^{\mathrm{miss}}$ only generated through SM particles (neutrinos)

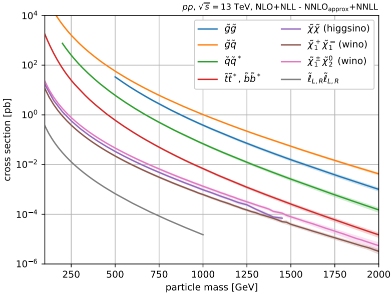


SUSY particles can be:

- **Short lived**: values of the coupling are large enough to ensure prompt decays of the LSP
- **Long lived** (LL): e.g in RPV SUSY, if small RPV couplings and/or large sfermion masses the LSP can become long-lived
  - → The LSP lifetime depends on the RPV coupling strength & masses of the sfermions involved in the decay

STRATEGY TO LOOK FOR SUSY (1)

To cover the entire SUSY phase space and ensure a good sensitivity, several channels are defined:



1) Strong-production: inclusive searches for gluinos and squarks, copiously produced at the LHC

→ final states with many light and/or *b*-tagged jets, zero or multiple leptons and (plenty of) missing transverse energy

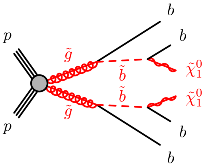
2) Third generation squarks (stop, sbottom): lighter than 1st and 2nd squarks

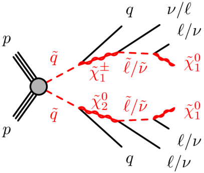
→ in the context of $\mathcal{N}$atural SUSY, with masses below/around the TeV scale

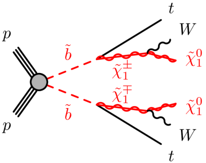
3) Ewkinos and sleptons pair production

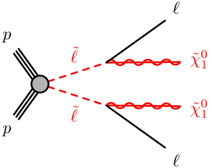
→ coloured spartners too heavy

→ direct gaugino/higgsino/slepton prod





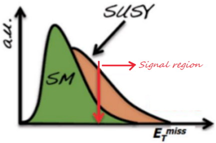




STRATEGY TO LOOK FOR SUSY (2)

All searches for SUSY (or other new physics) have some common points:

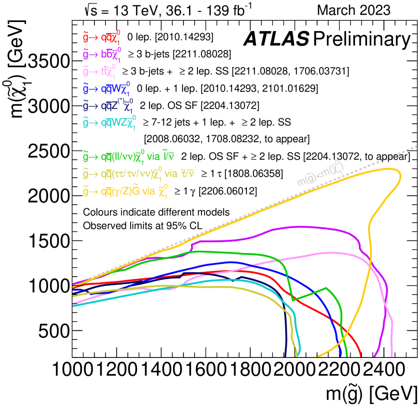
- Signal regions (SRs): regions targeting specific SUSY signal models
  - → Defined to have the best discovery potential in the selected models
  - → For one model, several SRs can be defined, to cover each region of the phase-space (low, intermediate and high mass difference between the sparticles)
  - → In Run-2: exploiting more new variables and using machine learning techniques

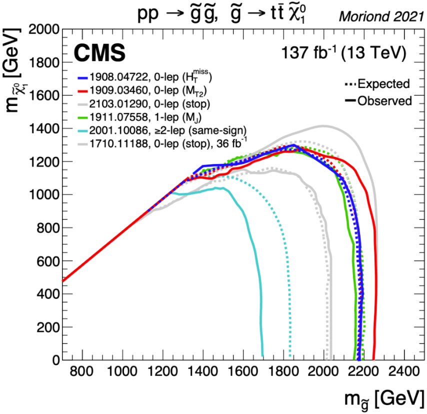


- Background (bkg): identify → understand → estimate as precise as possible → validate
  - → Standard Model (SM) bkg, or Detector bkg
  - → Estimated from Monte Carlo (MC) simulations, or using data control regions (CRs), or with data-based techniques, as appropriate
  - → In Run-2: an increased use of data-based bkg estimates to avoid dependence on MC
- Statistical interpretation: test the compatibility between data and bkg estimation in SRs
- In case of no excess:
  - → Set model dependent / independent exclusion limits

    The results are interpreted using SUSY simplified models, where particles not involved in production or decays are decoupled, i.e too heavy to be produced or affect the decays of the particles of interest

EXCLUSION LIMITS: GLUINOS





- Left: ATLAS; Right: CMS (only $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ shown here)

→ Analyses covering each corner of the phase space, targeting a wide range for the gluino decay mode, with the LSP being $\tilde{\chi}_1^0$ or $\tilde{G}$

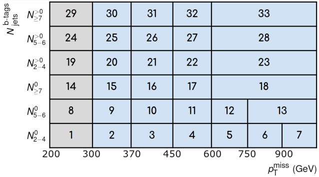
- When $\tilde{\chi}_1^0$ LSP, in the very compressed region with $\tilde{\chi}_1^0$ and $\tilde{g}$ masses very close, weaker limits

→ Work ongoing to improve this with more advanced SRs definitions (e.g using ML techniques with/without much softer objects)

CMS, GLUINO SEARCH WITH PHOTONS & JETS (1)

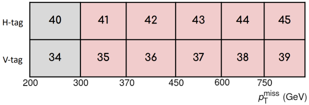
- Event selection with at least one photon with $p_T > 100$ GeV, 0-leptons, high $E_{\mathrm{T}}^{\mathrm{miss}}$ (> 300 GeV), and at least 2 jets

→ Using W/Z (V) and Higgs (H) taggers, to ensure maximum signal sensitivity, as well as multiple $E_{\mathrm{T}}^{\mathrm{miss}}$ - N jets/$b-$jets bins



$N_{\mathrm{jets}}^{\mathrm{b\text{-}tags}}$	200–300	300–370	370–450	450–600	600–750	750–900	900–
$N^{\geq 0}_{\geq 7}$	29	30	31	32	33		
$N^{\geq 0}_{5-6}$	24	25	26	27	28		
$N^{\geq 0}_{2-4}$	19	20	21	22	23		
$N^{0}_{\geq 7}$	14	15	16	17	18		
N^{0}_{5-6}	8	9	10	11	12	13	
N^{0}_{2-4}	1	2	3	4	5	6	7

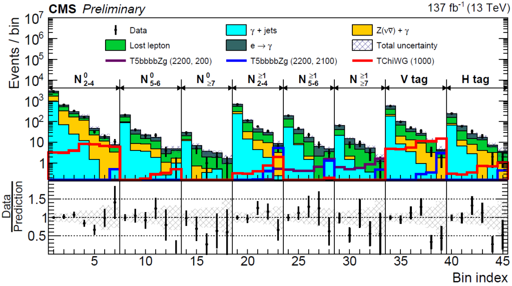
$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)

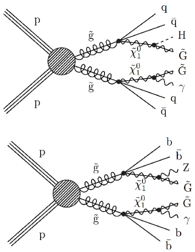


	200–300	300–370	370–450	450–600	600–750	750–
H-tag	40	41	42	43	44	45
V-tag	34	35	36	37	38	39

$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)

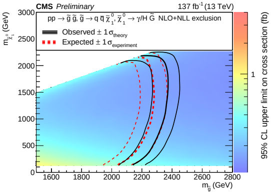
- **Dominant backgrounds:** $V\gamma$**+jets,** $t\bar{t}\gamma$**+jets,** γ**+jets,** W**+jets,** $t\bar{t}$**+jets, QCD**

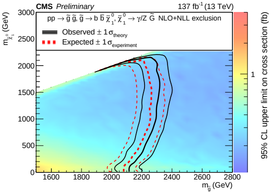


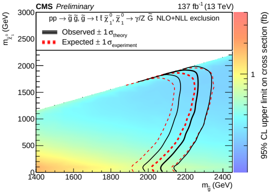


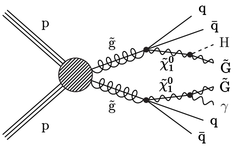
CMS, GLUINO SEARCH WITH PHOTONS & JETS (2)

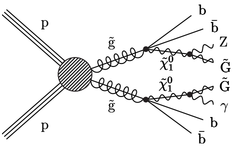
- As no excess in any of the defined signal regions:
  - → Upper limits on the production cross sections
  - → Exclusion limits on the gluino mass, given a selected LSP ($\tilde{\chi}_1^0$) mass

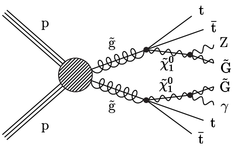










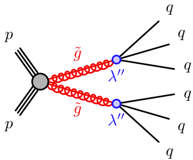


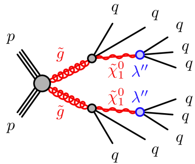
ATLAS, GLUINO SEARCH WITH MULTIPLE JETS

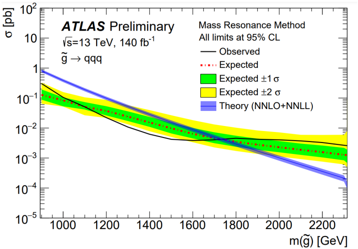
- An RPV ATLAS search, looking for gluinos with signatures that have:

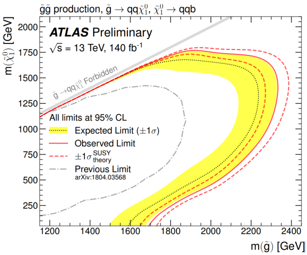
→ Direct decays for 3 jets, or cascade decays to 5 jets

- Jets that originate from either light quarks (UDS) or can contain a heavy flavour (UDB)



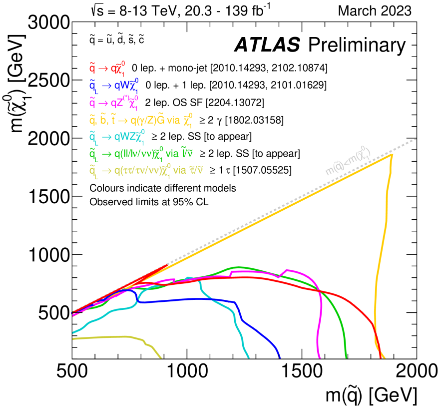


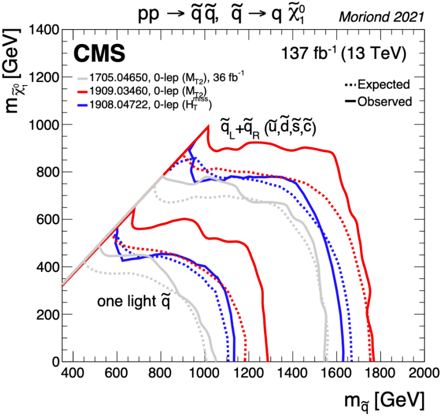




- Generally weaker limits when RPV (when comparing to RPC) due to challenging final states with very small E_T^{miss}
- Main analysis difficulty: QCD background estimation

EXCLUSION LIMITS: 1ST AND 2ND GEN SQUARKS





- Left: ATLAS; Right: CMS (only $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ shown)

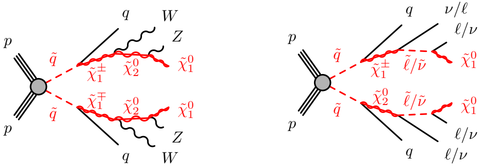
→ Again stronger limits when $\tilde{G}$ is the LSP (because of the extra handle from the decay products of neutralinos)

- When $\tilde{\chi}_1^0$ LSP, in the every compressed region much weaker limits

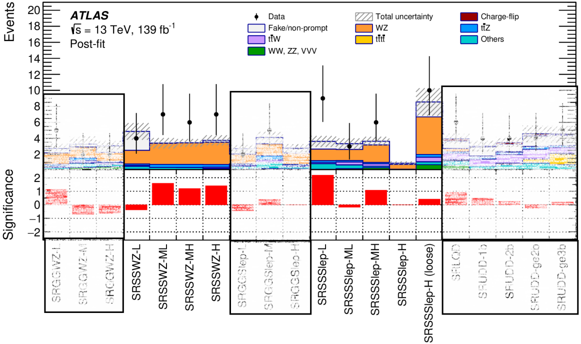
→ Decay products much softer, and/or E_T^{miss} much lower thus signal events more challenging to discriminate from the background, etc.

ATLAS, SQUARKS SEARCH WITH LEPTONS (1)

- Main characteristic: three leptons, 0 b-tagged jets, several jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ final states
- SRs with 'simple' variables like rational functions of objects p_T, that are closely tailored to target scenarios



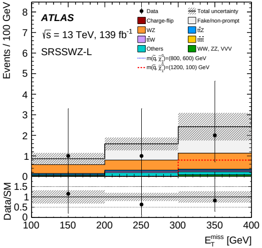
- **Main bkgs (data-driven): WZ+jets processes and the fake/non-prompt leptons**

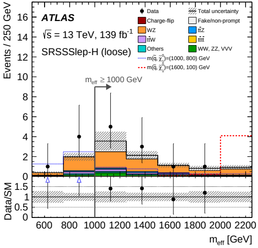


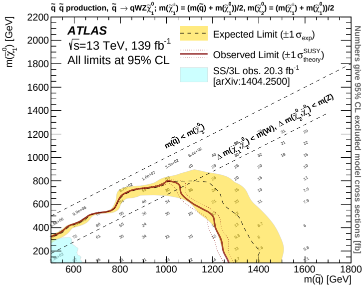
ATLAS, SQUARKS SEARCH WITH LEPTONS (2)

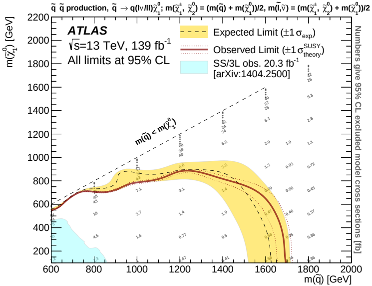
- To place exclusion mass limits, the SR with best expected sensitivity is chosen in each point

→ To ensure the best exclusion, the SRs are binned in $E_{\mathrm{T}}^{\mathrm{miss}}$ or m_{eff}







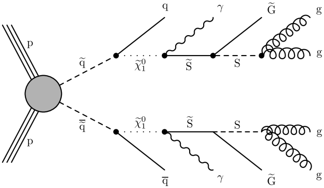


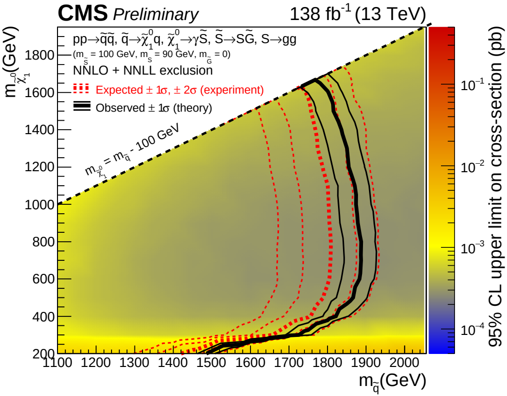
CMS, SQUARKS SEARCH WITH PHOTONS

- Using a stealth SUSY benchmark model with $\tilde{G}$ LSP produced through a decay of the stealth sector singlino: $\tilde{S} \rightarrow \tilde{G}\ S$ (the singlet, a scalar boson, with a mass of 90 GeV)

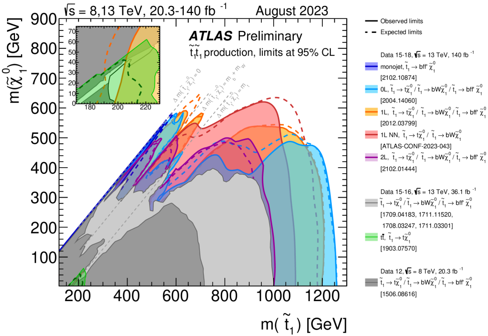
→ Very small $\tilde{S} - S$ mass difference (10 GeV): $\tilde{G}$ carries very small momentum

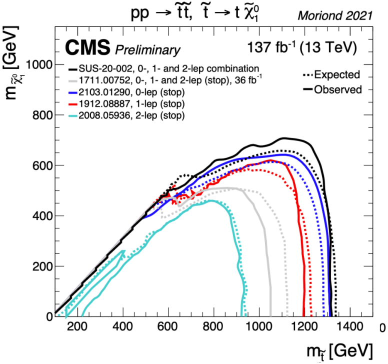
- **Event selection using two photons, many jets and low $E_{\mathrm{T}}^{\mathrm{miss}}$**





EXCLUSION LIMITS: STOP





- Left: ATLAS; Right: CMS (only $\tilde{t} \to t\tilde{\chi}_1^0$ shown)

→ Slightly better results in CMS

- Most challenging: improve the sensitivity in the compressed region

ATLAS: STOP SEARCHES STRATEGY

monojet [2102.10874]

fit binned E_T^{miss} distribution
a high-p_T recoiling ISR jet

0ℓ, 1ℓ [2004.14060, 2012.03799]

low-p_T objects:
- track-jet b-tag → 5 GeV
- muon → 4 GeV
- electron → 4.5 GeV
- soft b-tag (sec. vertex)

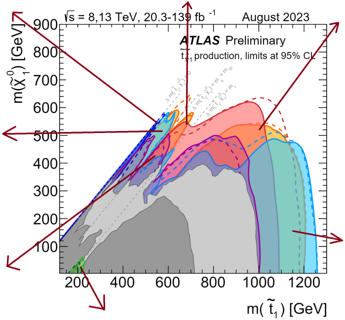
ISR event topology

2ℓ [2102.01444]

super-razor [1310.4827] vars.
E_T^{miss} significance

1ℓ [2012.03799, ATLAS-CONF-2023-043]

NN using lepton 4-mom. +
object multiplicities +
m_{XY} and $\Delta R(X, Y)$ +
RNN with jets 4-mom.



[1903.07570]

$t\bar{t}$ spin correlations

1ℓ [2012.03799, ATLAS-CONF-2023-043]

NN, but also
reconstruction of tops:
- mass of reclustered jets
- topness [1212.4495]
- $E_T^{\mathrm{miss}} \perp t\bar{t}$ system

m_{T2}^{τ} [1407.0583]

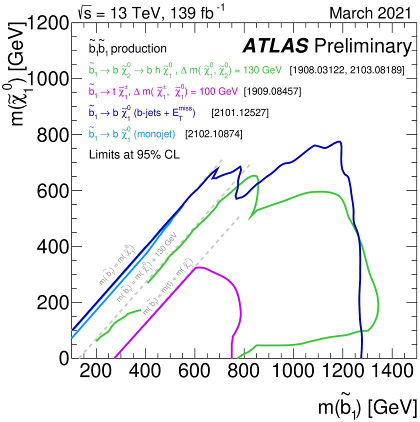
0ℓ [2004.14060]

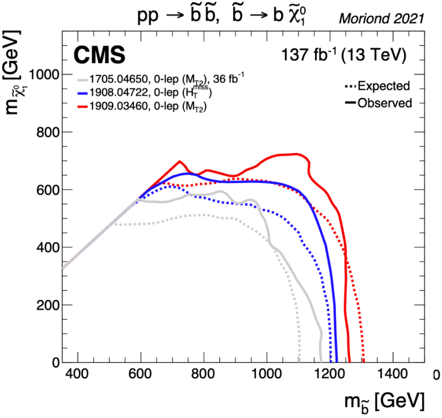
reclustered jet mass
E_T^{miss} significance
m_{T2} [hep-ph/9906349]
ΔR_{bb}
$m_T^{b,\mathrm{min}}$

+ always sophisticated lepton / jet / E_T^{miss} / reconstruction!

source

EXCLUSION LIMITS: SBOTTOM





- Left: ATLAS; Right: CMS (only $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ shown)

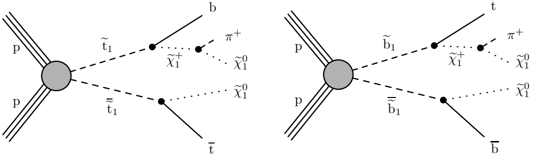
→ Very similar sensitivity at both ATLAS and CMS

- Various $\tilde{b}$ decay modes considered, via $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$, with $\tilde{\chi}_1^0$ as LSP

CMS, STOP AND SBOTTOM LL SEARCH (1)

- A search for stops and sbottoms considering final states with disappearing tracks

→ Considering a nearly pure wino-like or higgsino-like LSP that are consistent with the observed dark matter (DM) relic density



- The LSP and the $\tilde{\chi}_1^{\pm}$ nearly mass degenerate, with a mass difference of a few hundred MeV
- $\tilde{\chi}_1^{\pm}$ is LL, with a macroscopic lifetime (ns, @LHC decay length of several cm or more)

- **Unique experimental signature**: in $\tilde{\chi}^{\pm} \to \tilde{\chi}_1^0 \pi^{\pm}$ decays, $\pi^{\pm}$ has a momentum of only a few hundred MeV, generally too low to reconstruct
- $\tilde{\chi}^{\pm}$ is reconstructed as a track with hits up to its point of decay, with no hits recorded after

→ This leads to the *disappearing track* signature: a reconstructed track ends abruptly within the sensitive tracking volume, with a continuation that has "disappeared"

CMS, STOP AND SBOTTOM LL SEARCH (2)

- Search performed with a machine learning-based track classification method to improve the disappearing track selection efficiency and background rejection
- An additional increase in sensitivity at high LSP mass achieved by employing a measure of the dE/dx ionization energy loss of candidate tracks

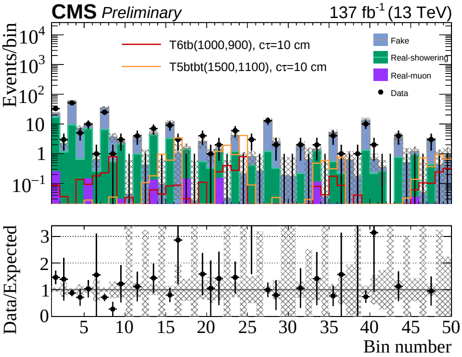
- Different search channels defined (a total of 49 bins/SRs):

→ Hadronic channel, with 0 leptons, 1 disappearing track

→ Muon channel, with ≥1 muon and 0 electrons, 1 disappearing track

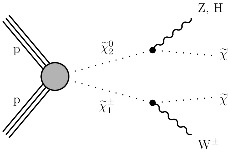
→ Electron channel, with ≥1 electrons, 1 disappearing track

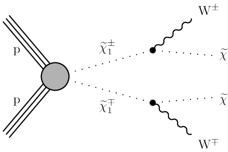
→ ≥2 disappearing tracks

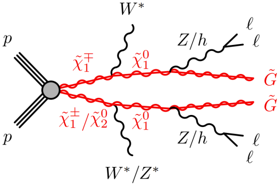


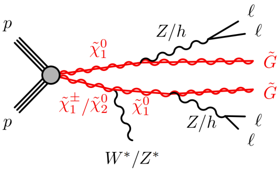
SEARCHES FOR EWKINOS

- Both ATLAS and CMS released the combined search for RPV electroweak direct production of winos, binos, higgsinos, and sleptons
  - ATLAS-CONF-2023-046 and CMS-PAS-SUS-21-008, CMS public plots
- **The combined analyses are statistically independent**
  - Intermediate states with W, Z or h bosons, and final states with 0→4 leptons





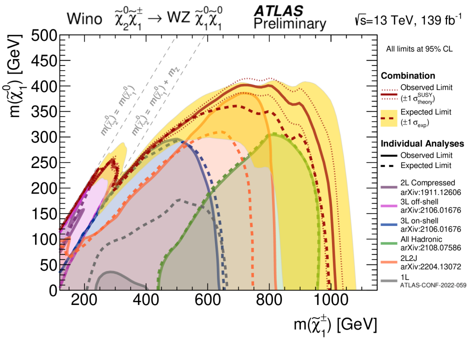


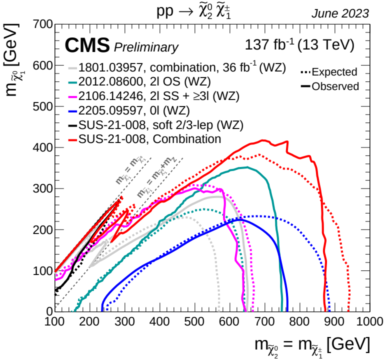


W OR Z BOSONS IN THE DECAY CHAIN

- Limits obtained using a combined profile likelihood fit of the observed data yields, the background yields, and the expected SUSY yields in the control and signal regions

- Model: pure-wino, mass-degenerate $\tilde{\chi}_1^{\pm}$-$\tilde{\chi}_2^0$ pair production, via W or Z bosons



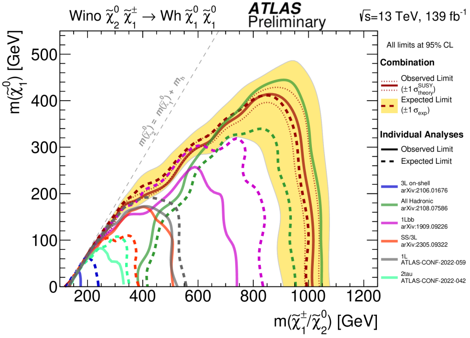


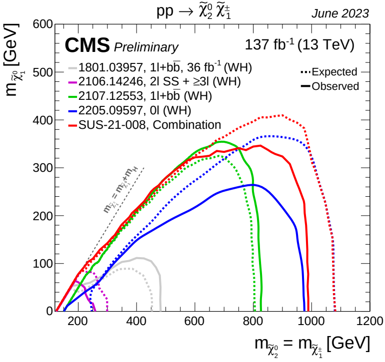
- Slightly better sensitivity for ATLAS in the $\tilde{\chi}_1^{\pm}$-$\tilde{\chi}_1^0$ mass plane

→ $\tilde{\chi}_1^{\pm}$ being excluded up to 1 TeV for low mass LSPs

W OR *h* BOSONS IN THE DECAY CHAIN

- Model: pure-wino, mass-degenerate $\tilde{\chi}_1^\pm$-$\tilde{\chi}_2^0$ pair production decaying to W or h, and $\tilde{\chi}_1^0$





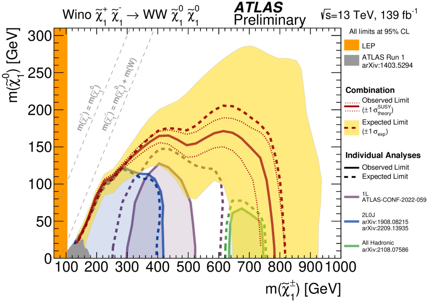
- Slightly better sensitivity for CMS in the $\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ mass plane

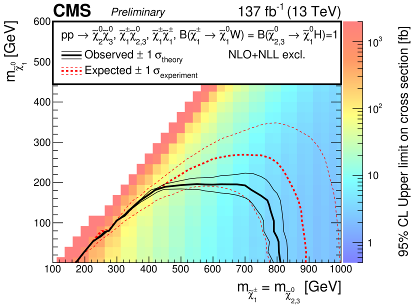
→ $\tilde{\chi}_1^\pm$ excluded up to approx. 1 TeV for low mass LSPs

W BOSONS IN THE DECAY CHAIN

- ATLAS model: pure-wino $\tilde{\chi}_1^\pm$ pair production decaying to W and $\tilde{\chi}_1^0$ (100% BR)
- CMS model: a higgsino-bino model, with bino LSP, and mass-degenerate light higgsinos

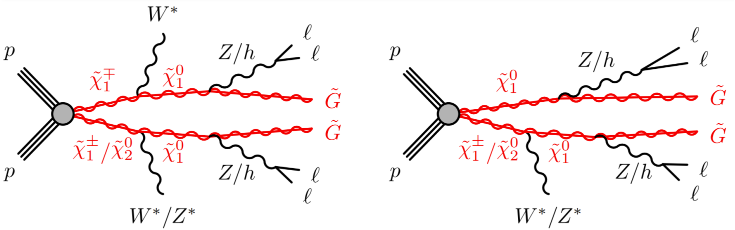
→ Several production modes considered: $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_3^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ and $\tilde{\chi}_3^0\tilde{\chi}_2^0$





→ $\tilde{\chi}_1^\pm$ excluded up to 800 GeV for LSP masses below 50 GeV in ATLAS, and up to 1 TeV in CMS

A GMSB MODEL (1)

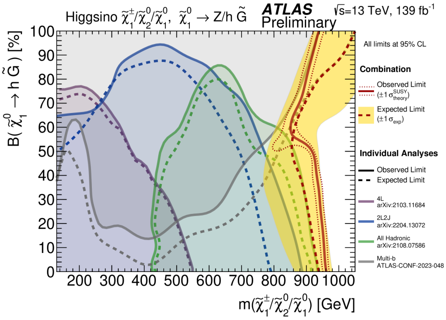


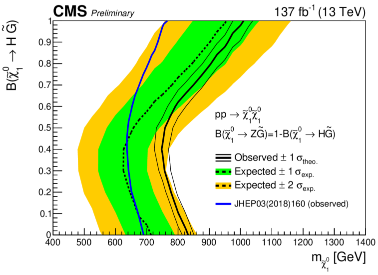
- As the direct pair production of neutralinos is expected to be vanishingly small, only the mass-degenerate higgsino like $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ case considered
- In this model the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay to $\tilde{\chi}_1^0$ via soft particles that escape the detector

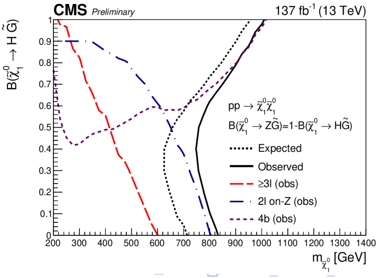
→ Resulting in effective $\tilde{\chi}_0^1$ pair production

- Signal regions defined using machine learning techniques, recursive-jigsaw reconstruction techniques, or the traditional cuts on key variables

A GMSB MODEL (2)







DISCUSSION

ATLAS SUSY public results and CMS SUSY public results

- Comprehensive set of results with the Run-2 dataset
- Unfortunately, no significant excess observed...

- While LHC Run-3 data is being recorded and understood, reanalysis of the Run-2 data:
  - Using more sophisticated techniques → more and more the ML is being used
  - Additional / new benchmark models are being included
  - Etc.

- **More results to come!**

BACKUP

LONG-LIVED PARTICLES (1)

Simplest definition for the long-lived particles (LLP):

→ Neutral particles decaying a macroscopic distance from the interaction point (IP)

→ Charged particles that decay as above or are quasistable on the detector scale

LLP can be (only few examples!):

- Supersymmetric (SUSY) models

→ Long-lived gluinos ($\tilde{g}$) due to very heavy squarks, or $\tilde{g}$-Bino co-annihilation

→ Long-lived charginos ($\tilde{\chi}$): Wino/Higgsino Lightest Stable Particle (LSP)

→ Long-lived neutralino/LSP ($\tilde{\chi}^0$): Gravitino LSP, R-parity violation, Wino-Bino co-annihilation

- Hidden/dark sector scenario

→ Long-lived dark photon: Higgs portal model

→ Long-lived neutral scalar: Heavy neutral boson portal model

- Others

→ Long-lived right-handed neutrino: Left-right symmetry extension of SM

→ Long-lived multi-charged particle: Monopole, Q-ball

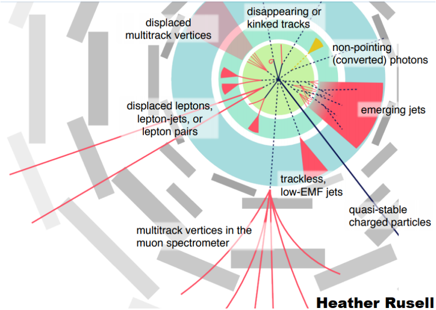
LONG-LIVED PARTICLES (2)

- LL particles can be light or heavy
- Experimental signature: LLP itself if it's stable, otherwise its decay products (jets, ℓ, etc)
- Can have an unique signature (lifetimes in the pico to nanoseconds range), for example:

→ Meta-stable LL charged particles: travel all the detector components, like muons but with a very different signature (interactions with the detector material)

→ Non-stable charged LLP: Disappearing or kinked tracks → presence of secondary (kinked) track dependent on the phase space of the decay vertex

→ LLP can decay to leptons: can look for displaced leptons or for displaced di-lepton vertices (with no track pointing back to the IP)



Heather Rusell

- Usually lower Standard Model (SM) background than in the traditional BSM searches
  - Cannot relay on MC simulations, and most of the time a fully data-driven background estimation is used
- Requires a deep understanding of the detector!