Supersymmetry searches at the LHC

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on behalf of the ATLAS and CMS Collaborations

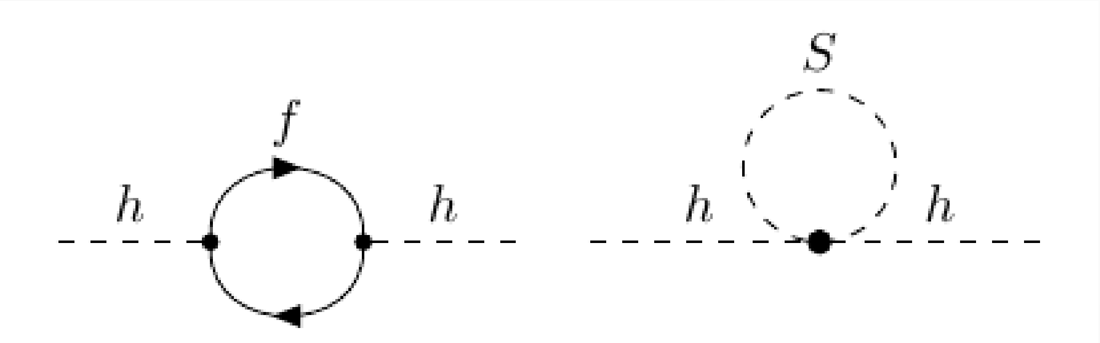
QUARK - LEPTON
AACHEN, GERMANY, 2020 SEP 21-24
Physics in Collision
40th International Symposium on Physics in Collision
RWTH Aachen University, Aachen, Germany | September 14-17, 2021

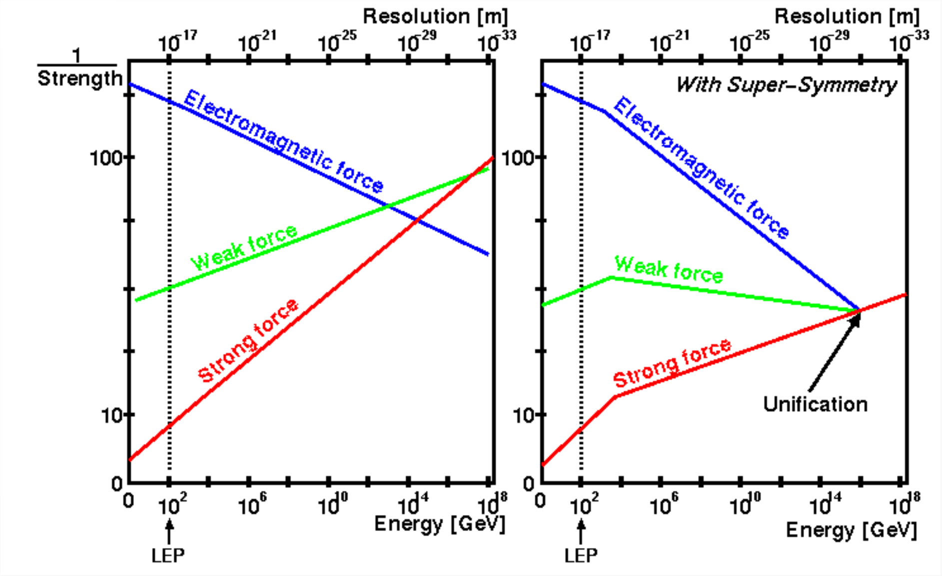
ATLAS EXPERIMENT

CMS
Compact Muon Solenoid

Supersymmetry (SUSY)

- Supersymmetry (SUSY) is still a promising Beyond Standard Model theories (hypotheses) till date.
- Holds many promises (pick your favourite):
  - Cancels out the large corrections to the Higgs mass, and stabilizes the EW scale.
  - Provides a Dark Matter candidate (for R-parity conserving scenarios).
  - Can unify gauge couplings at the GUT scale (running of the gauge couplings due to new particles).
  - Can incorporate gravity.
- Predicts a fermionic superpartner for each SM boson, and vice versa.
- However, no SUSY particles (sparticles) found at their SM counterpart masses.
- SUSY must be broken to move the sparticles to higher masses.



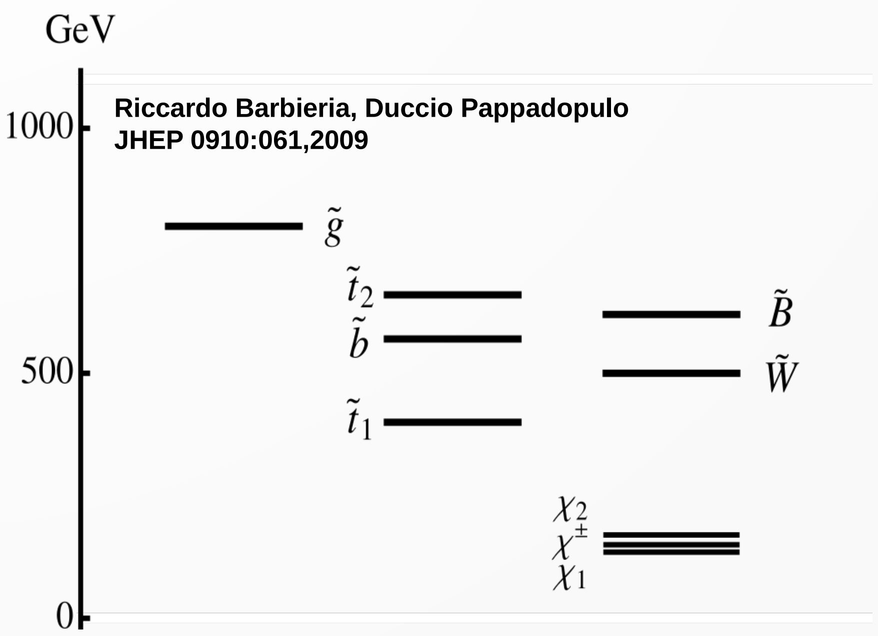


SUSY at the LHC

- Most searches are motivated by "naturalness".
- i.e. the corrections to the Higgs mass are comparable, and their sum is at the EW scale (vev ~246 GeV).
- Particles that contribute strongly to the Higgs mass correction, should not be too heavy.
  - Higgsinos: ~few 100 GeV
  - Top and bottom squarks, staus (1 loop corrections): ~few 100 GeV to ~TeV
  - Gluinos (2 loop corrections): < few TeV.
- Rest of the spectrum is decoupled (very heavy) – **decoupled spectrum**.
- **The "natural" SUSY spectrum brings the masses of a few SUSY particles within the LHC reach.**

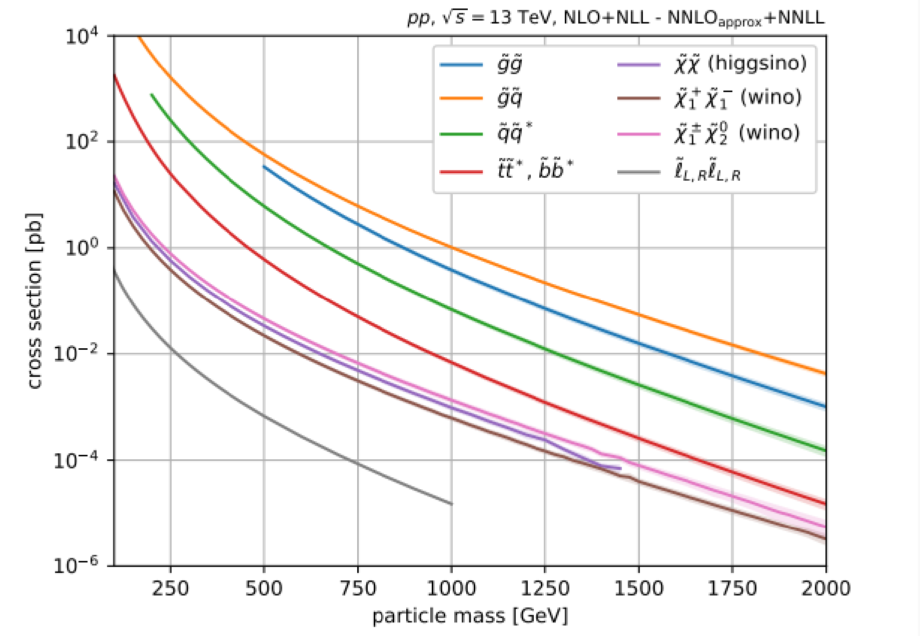
$$\frac{1}{2}M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$

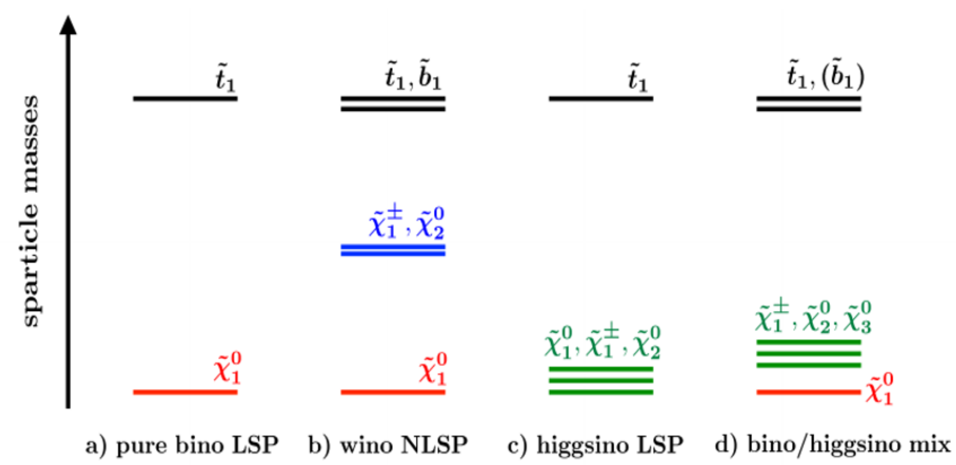
Baer et. al. JHEP05(2012)109



SUSY at the LHC: Simplified models

- Full SUSY models contain **O(100) free parameters**.
- Typical SUSY searches at the LHC are **presented in a Simplified Mass Spectrum (SMS) framework**.
  - Consider only those particle masses and parameters that are relevant to the decay chain being searched for.
  - Set the relevant parameter values (like branching ratios (BR), chirality, lifetime, etc.) by hand.
  - Rest of the sparticles too heavy (**decoupled spectrum**).
- For a given SMS mass point, calculate its experimental acceptance (acceptance * efficiency).
- Use the SM prediction (null hypothesis) and the observed data to calculate upper limits (at 95% conf. level) on x-sec*BR, for a given mass point.
- Can be reinterpreted in terms of realistic models using HEP-data.





SUSY at the LHC: Some typical search variables

Missing transverse energy: $E_T^{miss} = \left| - \sum_i^{n\,visible} \vec{p}_T^{\,visible} \right|$

Missing hadronic transverse momentum: $\not{H}_T = H_T^{miss} = - \sum_i^{n\,jets} \vec{p}_T^{\,jet_i}$

for neutral LSP: neutralinos, gravitinos...

Hadronic transverse energy $H_T = \sum_i^{n\,jet} p_T^{jet}$

Effective mass: $m_{\text{eff}} = E_T^{\text{miss}} + H_T$

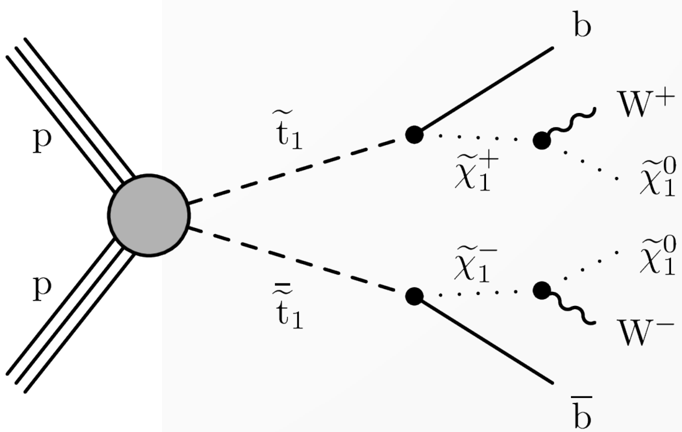
Stransverse mass: For $\tilde{q} \to X \tilde{\chi}_1^0$

$$m_{T2}(m_{\tilde{\chi}}) = \min_{\vec{p}_T^{\tilde{\chi}1} + \vec{p}_T^{\tilde{\chi}2} = \vec{p}_T^{miss}} \left[\max\left(m_T(\vec{p}_T^{j1}, \vec{p}_T^{\tilde{\chi}1}), m_T(\vec{p}_T^{j2}, \vec{p}_T^{\tilde{\chi}2}) \right) \right] \leq m_{\tilde{q}}^2$$

where the transverse mass is:

$$m_{T,W}^2 = m_\ell^2 + m_\nu^2 + 2(p_T^\ell p_T^\nu - \vec{p}_T^{\,\ell} \vec{p}_T^{\,\nu})$$
$$(m_\ell, m_\nu \sim 0 \to) \simeq 2 p_T^\ell p_T^\nu (1 - \cos\Delta\phi(\ell,\nu))$$

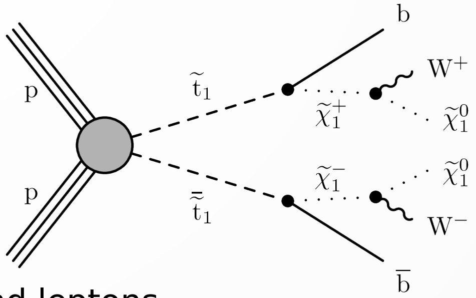
for high transverse activity

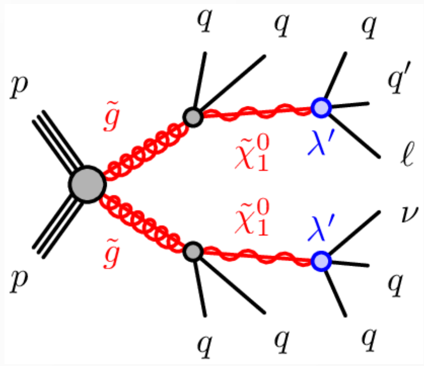


[From S. Sekmen's PIC 2017 slides]

SUSY at the LHC: General search strategy

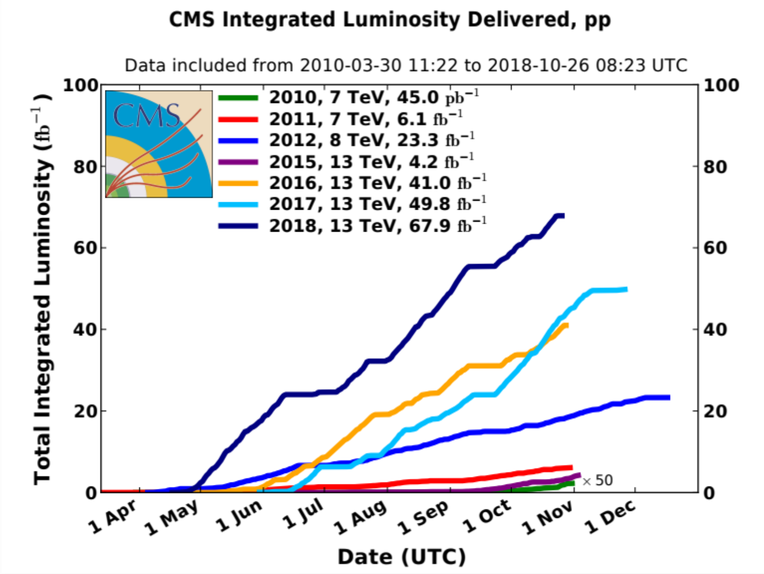
- Choose your favourite model to search for.
- Identify the characteristic final state objects (electrons, muons, jets, etc.) based on the model.
- Select appropriate trigger(s) based on the above.
- **Search strategy highly dependent on the model:**
  - R-parity conserving: large missing energy due to neutralino or gravitino.
  - R-parity violating: low to moderate missing energy along with lots of jets and leptons. Construct resonances.
  - Heavy objects in the final state (W/Z/top): use special tagging techniques if they're boosted.
  - Soft objects in the final state (e.g. compressed regions): use dedicated soft object (like soft leptons and soft b jets) reconstruction techniques.
  - Identify sensitive variables (like H_T, m_T, m_{T2}, missing energy, angular variables,…) based on the model topology.
  - **The latest searches often use Neural Network (NN) based techniques.**
- Select the search region based on the sensitive variables, that **maximizes the search sensitivity** (say $S/\sqrt{(S+B)}$).
- Estimate the irreducible (similar topology) backgrounds using data control regions, functional fits, etc.
- Estimate the systematic uncertainties (theoretical and experimental).
- **Compare the bkg. prediction with observation and interpret the result.**

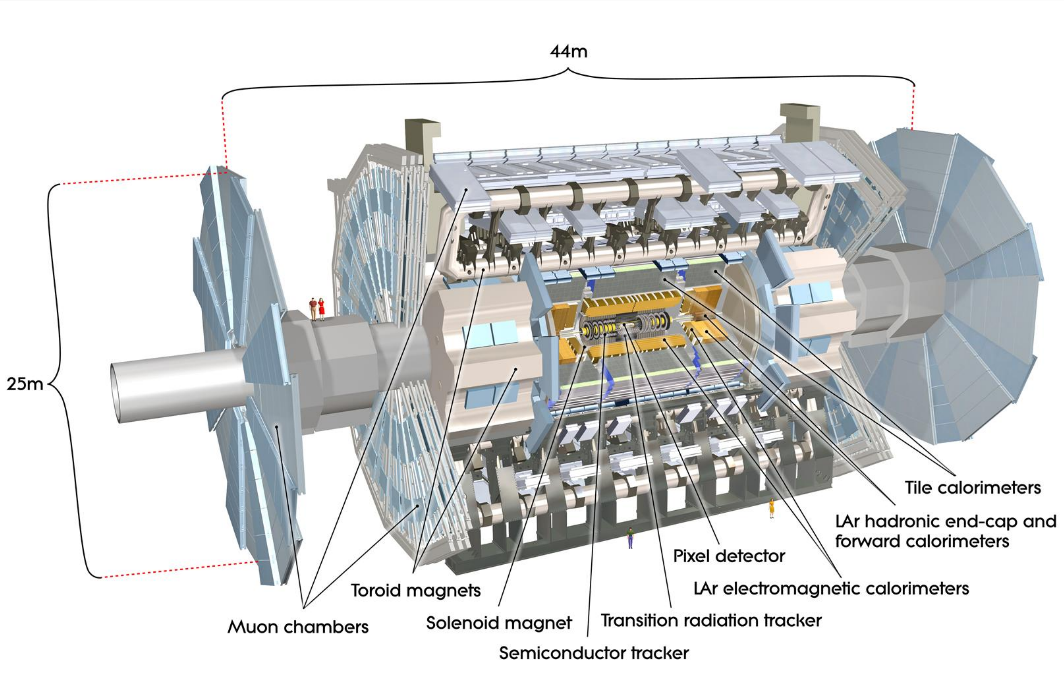


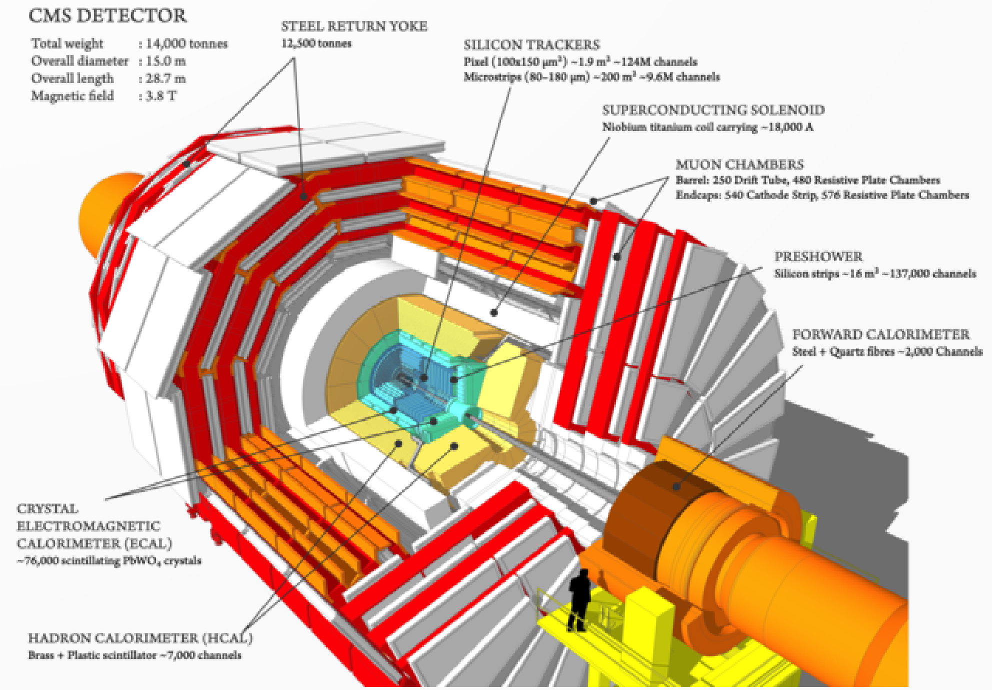


SUSY at the LHC: The ATLAS and CMS detectors

- **General purpose detectors with a very wide physics program.**
- Collected ~139 fb-1 of excellent quality proton-proton collision data during its Run-2 operation.
- ATLAS SUSY public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- CMS SUSY public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS



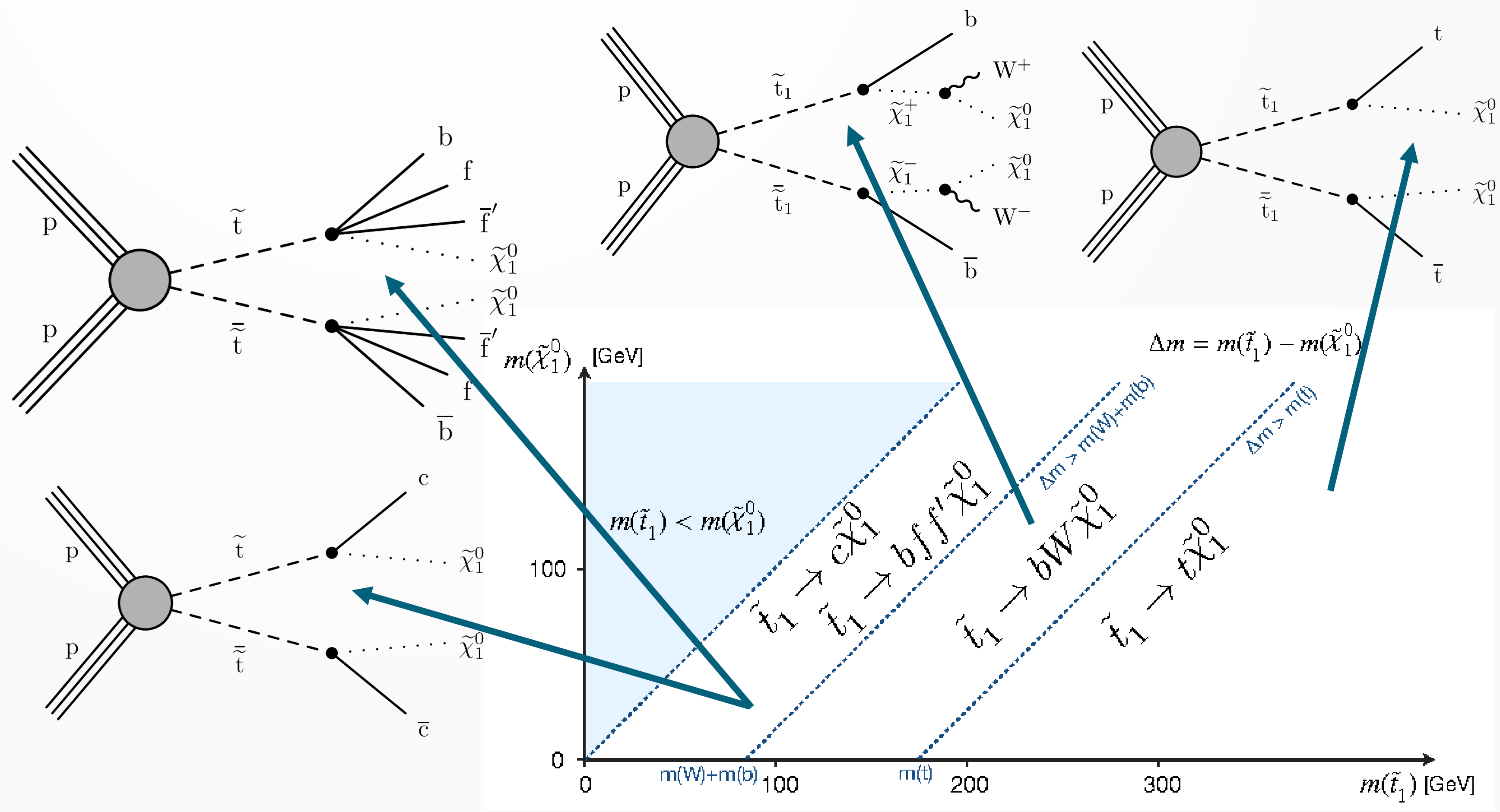




Searches for squarks and gluinos

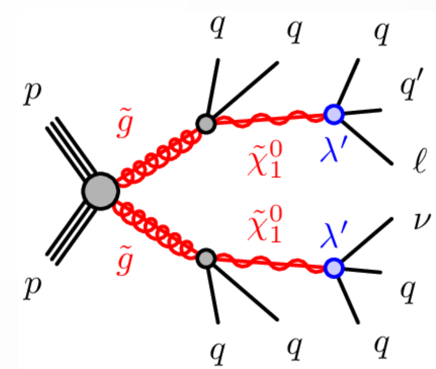
Searches for squarks and gluinos

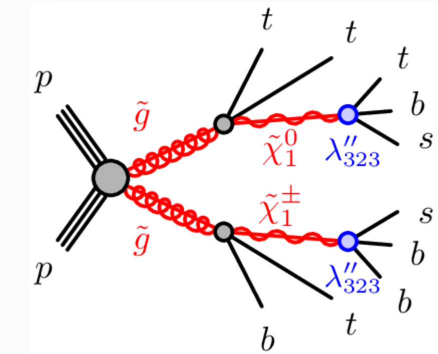
- Different region of the top squark-LSP mass plane is sensitive to different decays.
- Requires dedicated strategies to handle the widely different kinematics.

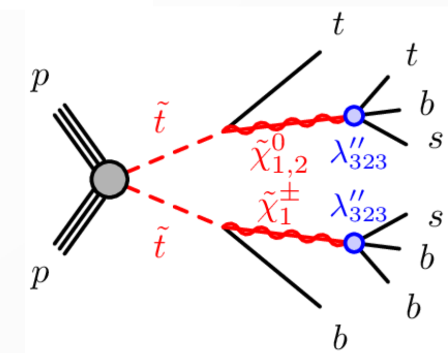


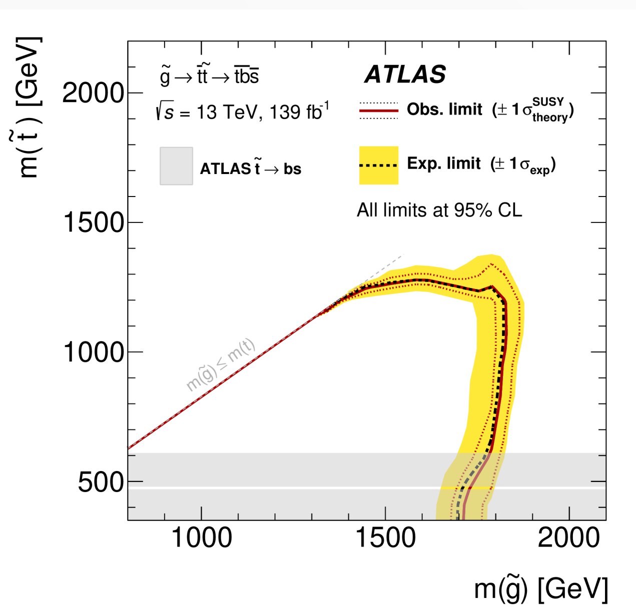
Searches for squarks and gluinos: recent results from ATLAS

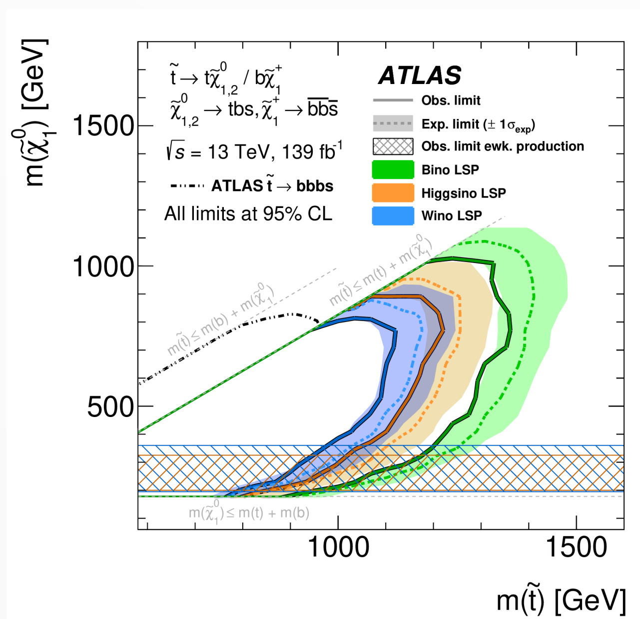
- **ATLAS-SUSY-2019-04: [arXiv 2106.09609]()**
- RPV motivated models.
- Final state includes 1 or 2 leptons, and a large number of jets.
- Data-driven approach to predict the bkg. in each jet multiplicity slice.
- A neural network (NN) is used to increase the sensitivity of the regions with at least 1 b-jet, where top-pair bkg. is dominant.









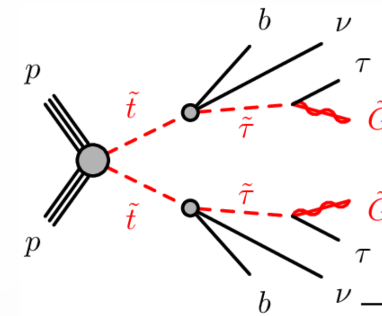


Lepton category	Jet multiplicity	Analysis regions
1ℓ category	$4\ldots7$ jets	$0b\ \ell^-$, $0b\ \ell^+$, $0b\ m_{\ell\ell}$, $1b$, $2b$, $3b$, $\geq 4b$
	$8\ldots\geq N^{1\ell}_{\text{last}}$ jets	$0b$, $1b$, $2b$, $3b$, $\geq 4b$
$2\ell^{sc}$ category	$4\ldots\geq N^{2\ell^{sc}}_{\text{last}}$ jets	$0b\ 3\ell$, $0b$, $1b$, $2b$, $3b$, $\geq 4b$

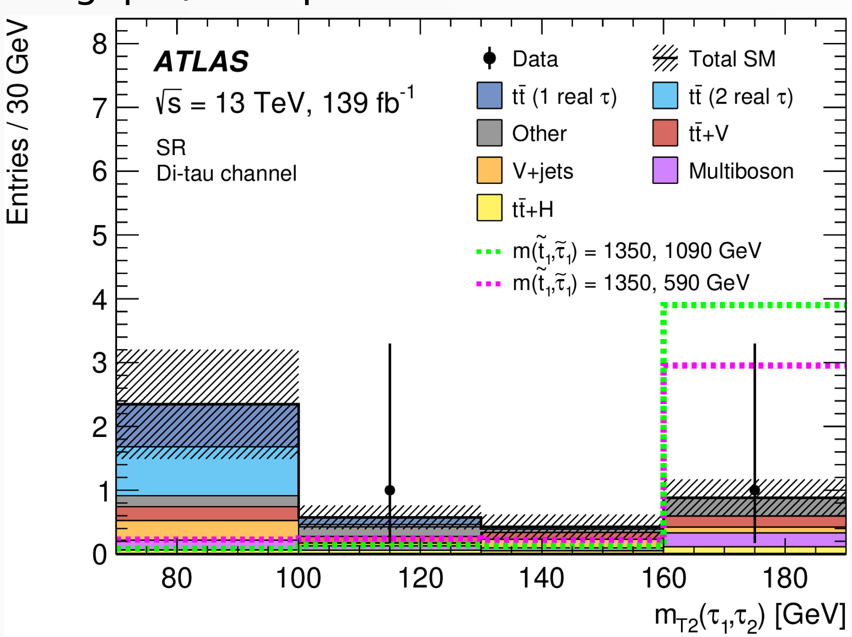
LSP type	Branching ratios: stop		Branching ratios: gluino			Cross-section [fb] for direct production		
	$t\tilde{\chi}^0_{1,2}$	$b\tilde{\chi}^\pm_1$	$tt\tilde{\chi}^0_{1,2}$	$bb\tilde{\chi}^0_{1,2}$	$tb\tilde{\chi}^\pm_1$	$\tilde{\chi}^\pm_1\tilde{\chi}^0_1$	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$	$\tilde{\chi}^0_2\tilde{\chi}^0_1$
Bino	100%	0%	100%	0%	0%	0	0	0
Wino	33%	67%	17%	17%	66%	387	0	0
Higgsino	50%	50%	50%	0%	50%	91	91	52

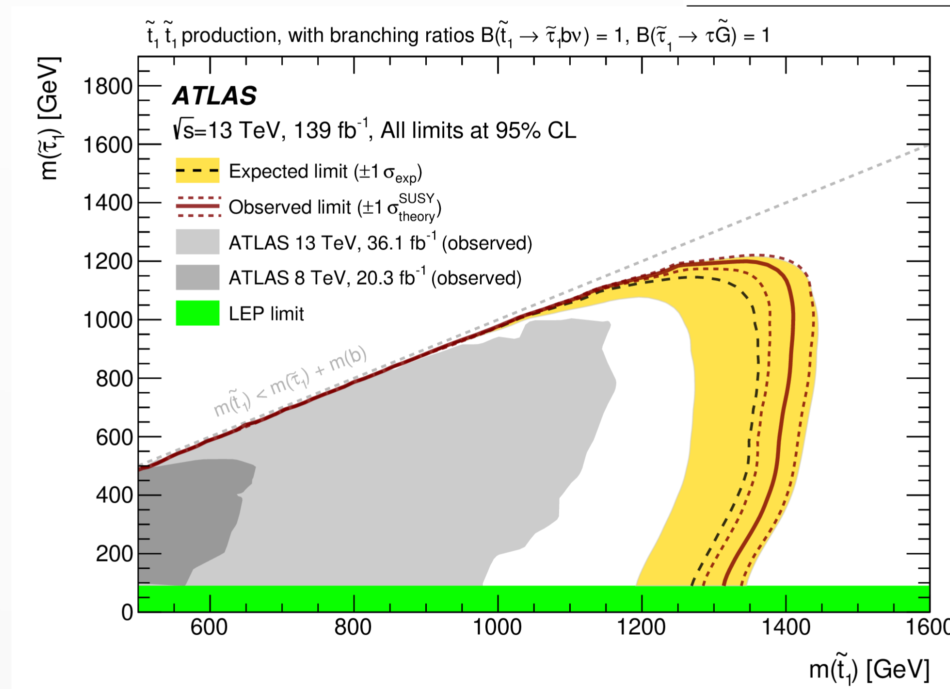
Searches for squarks and gluinos: recent results from ATLAS

- **ATLAS-SUSY-2019-18: arXiv 2108.07665**
- 3 body decay of the top squark to a tau slepton, via off-shell chargino.
- GMSB motivated model with a nearly massless Gravitino in the final state.
- Search region with 2 hadronically decaying tau (τ_h) targets low to moderate mass gaps b/w stop and stau.
- Search region with 1 τ_h targets mass points with a large mass gap b/w stop and stau.



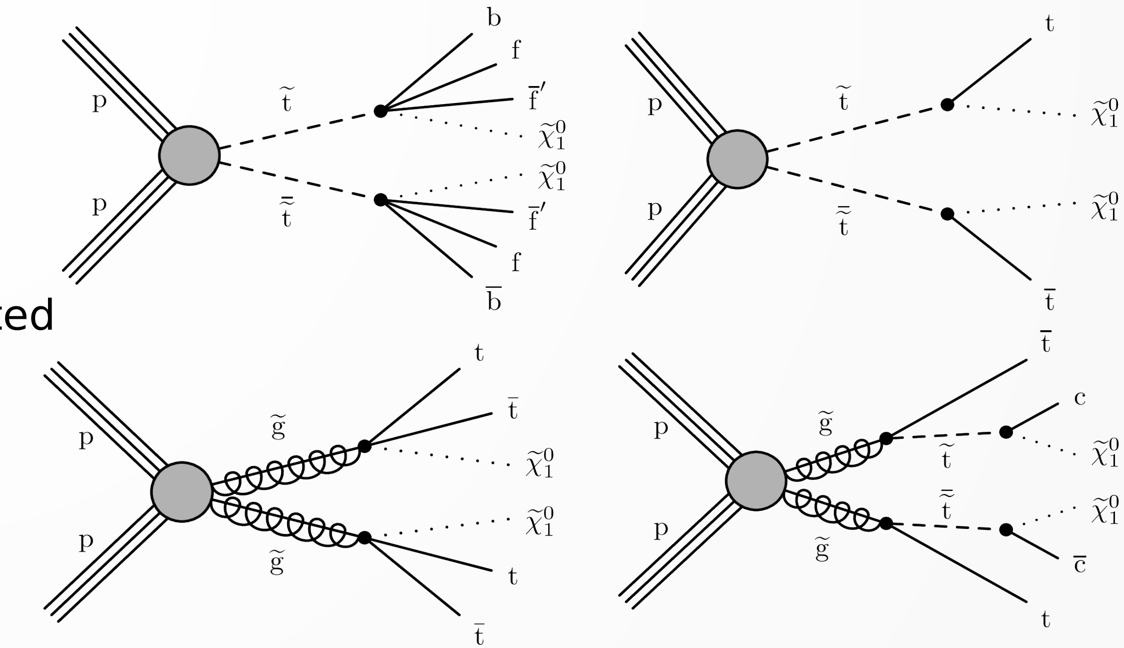
Di-tau preselection	Single-tau preselection
E_T^{miss}-trigger fired and $E_T^{miss} > 250$ GeV	
No light leptons (e/μ)	
At least two jets	
At least one b-tagged jet	
At least two hadronic tau leptons	Exactly one hadronic tau lepton
	At least two b-tagged jets

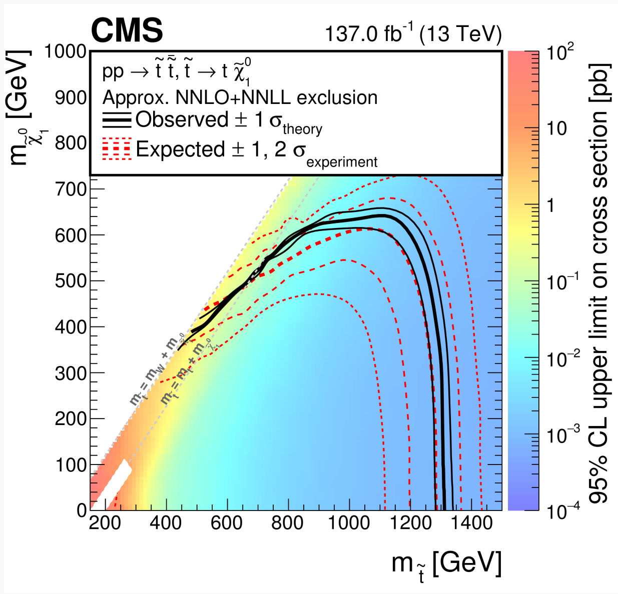


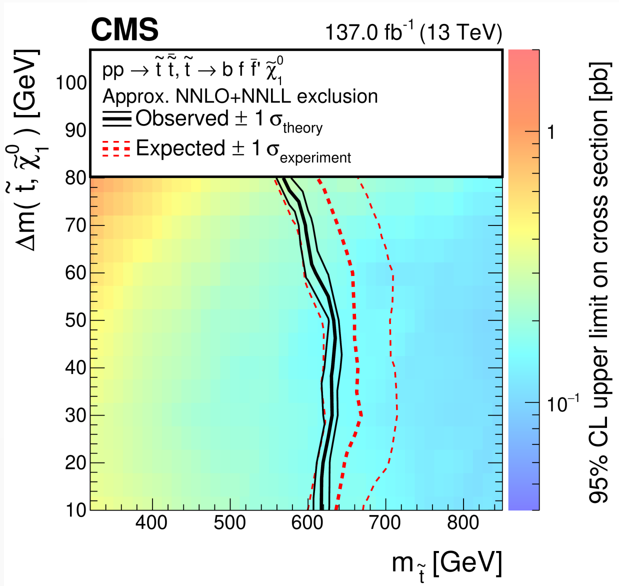


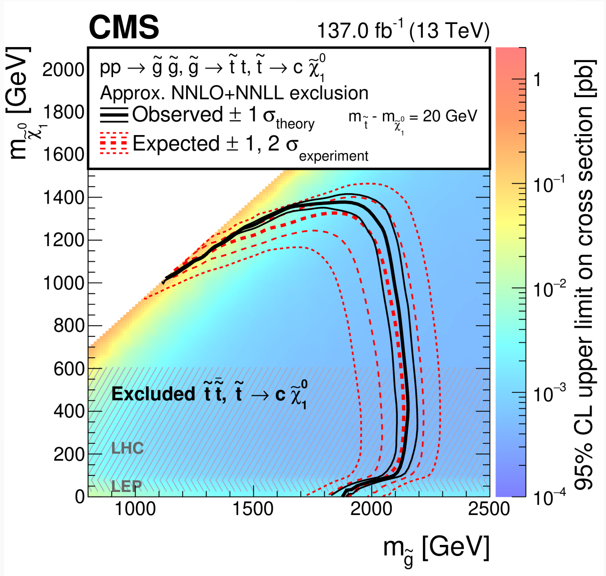
Searches for squarks and gluinos: recent results from CMS

- **CMS-SUS-19-010: arXiv 2103.01290.**
- Hadronic decay modes.
- Targets both large and small ΔM (compressed).
- Uses the deep NN based "DeepAK8" algorithm to tag boosted top quark and W bosons.
- Uses the deep NN based "DeepResolved" algorithm for the resolved top quarks.
- Requires ISR jet for increasing the sensitivity of the low ΔM region.



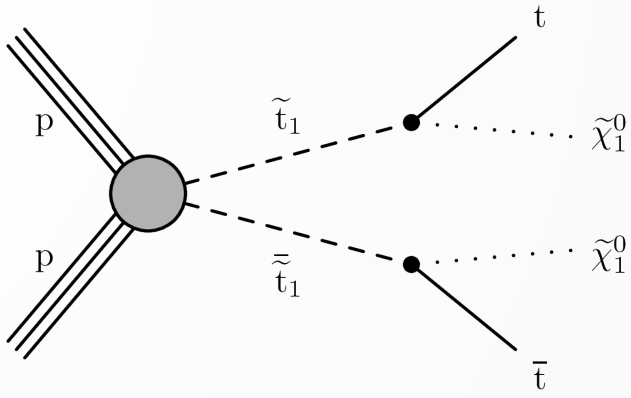


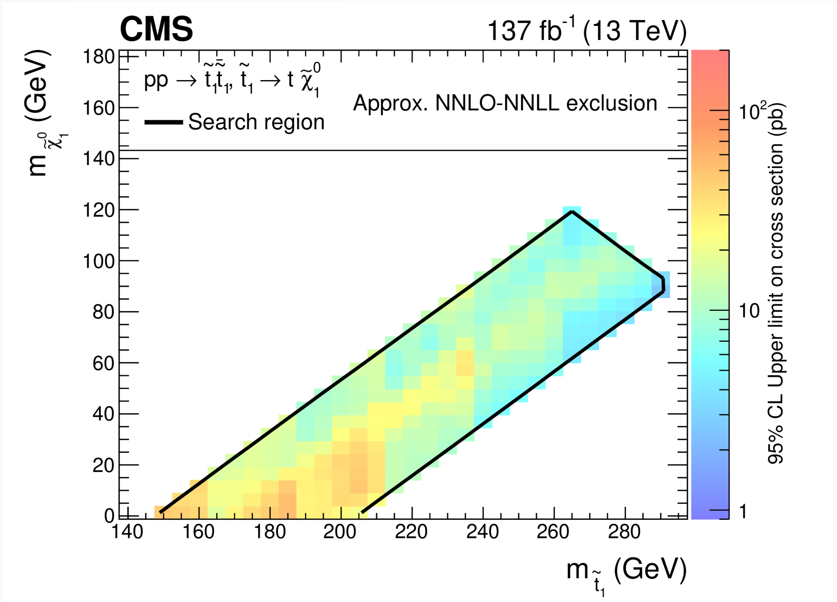




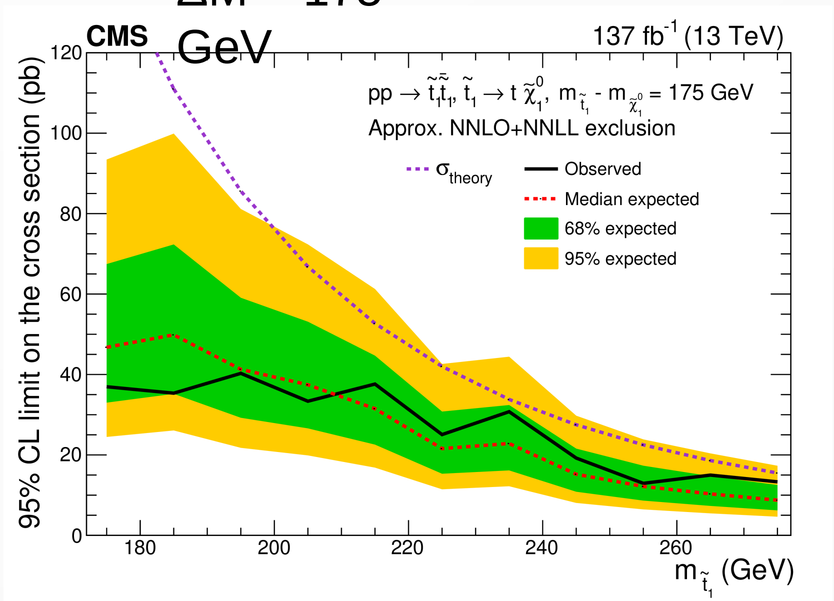
Searches for squarks and gluinos: recent results from CMS

- **CMS-SUS-20-002: arXiv 2107.10892**
- Dedicated search in the top corridor in an opposite sign dilepton final state.
- Uses a DNN to suppress the SM top background.
- Dilepton p_T, angle b/w the leptons, missing energy, H_T, etc. among the important variables).

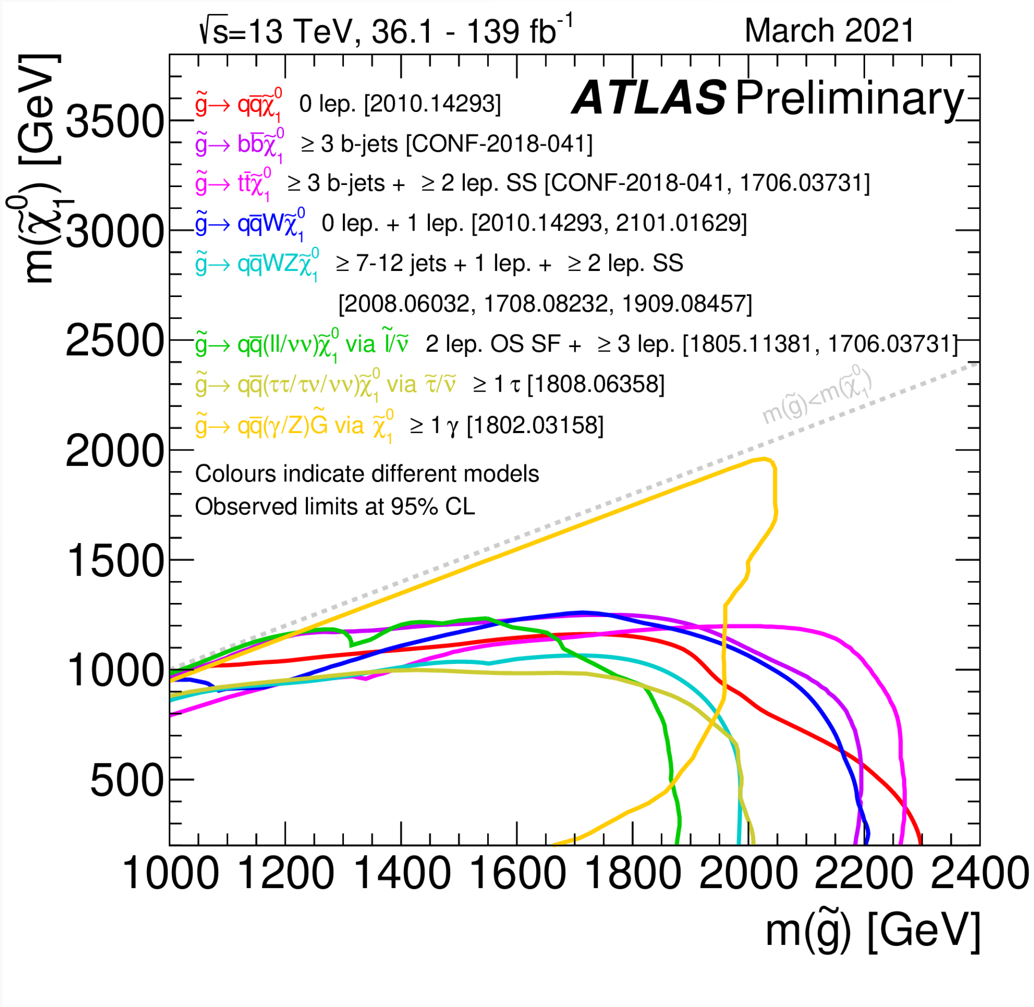




ΔM = 175 GeV

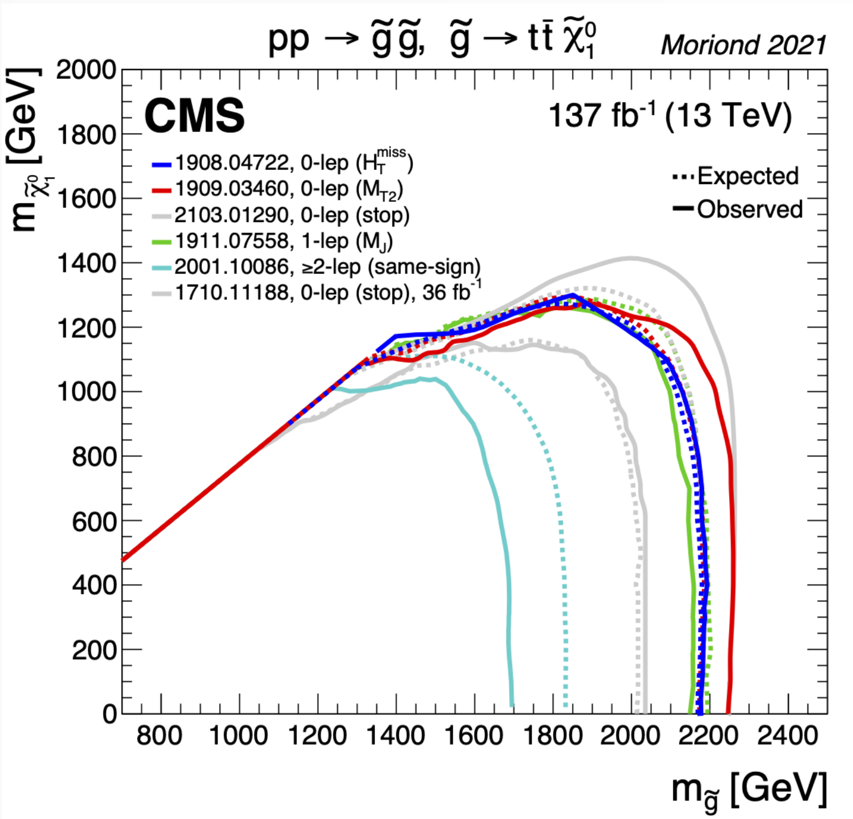


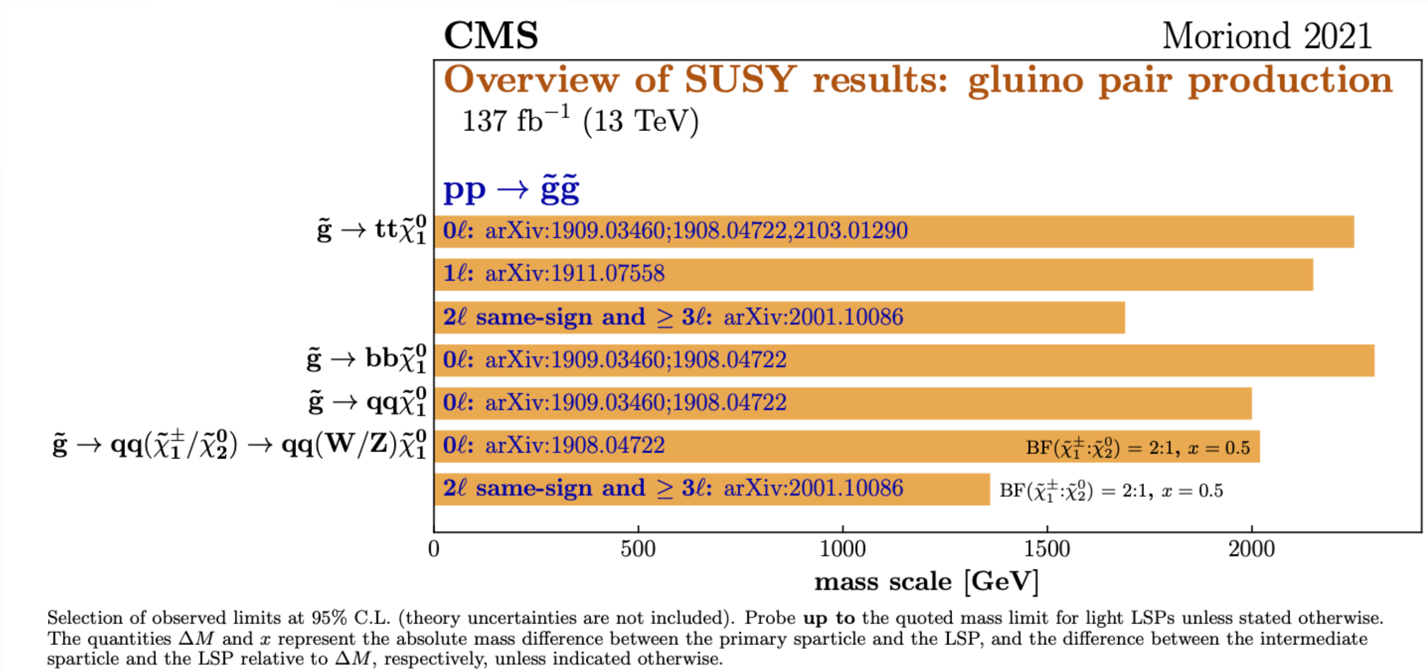
Searches for squarks and gluinos: ATLAS gluino summary



- Gluino masses excluded up to ~2.3 TeV using the Full Run 2 data

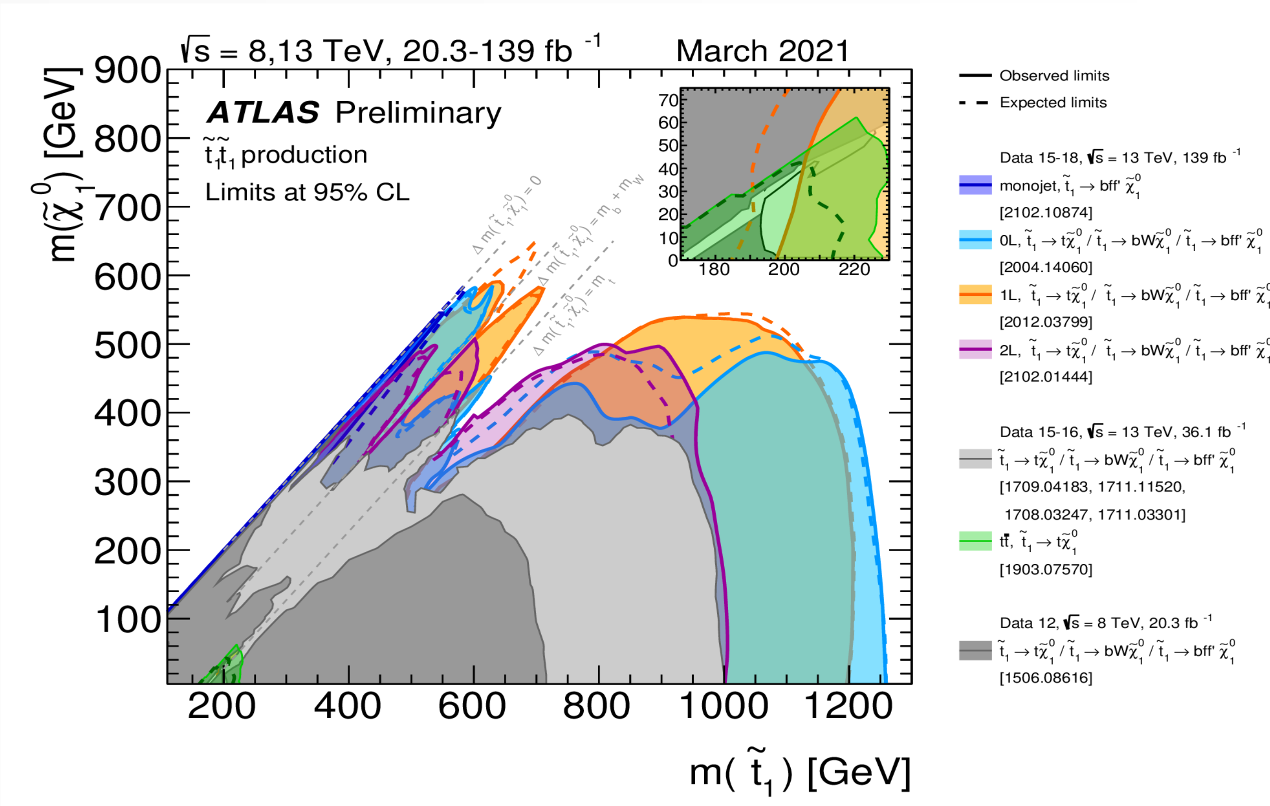
Searches for squarks and gluinos: CMS gluino summary

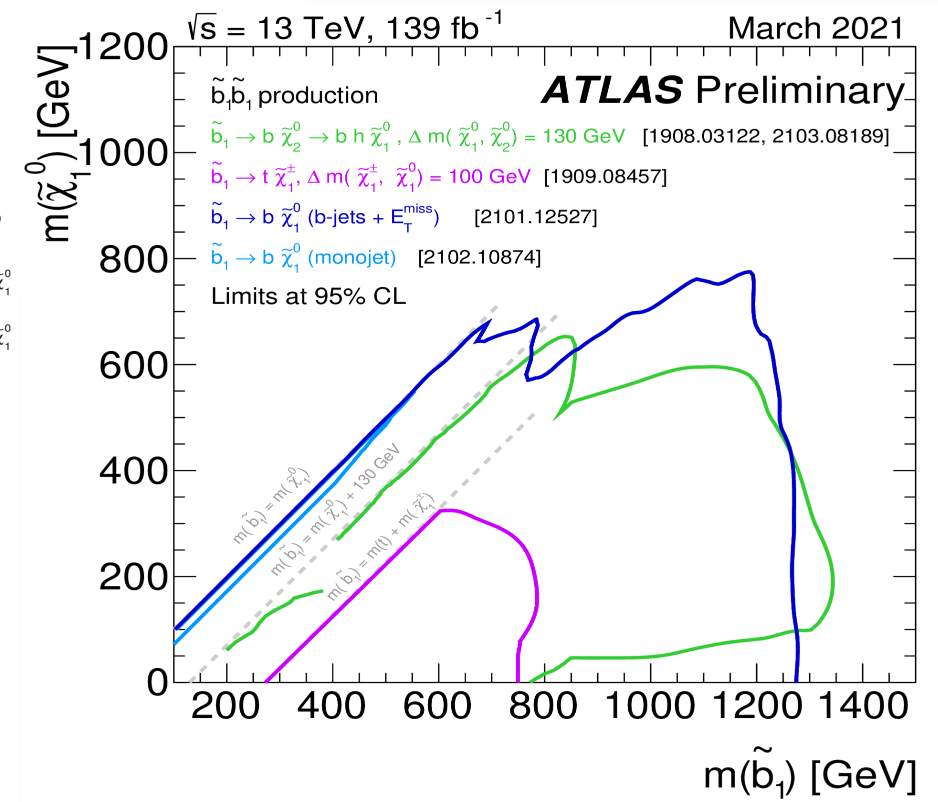




- Gluino masses excluded up to ~2.2 TeV.
- Strongest limits are from the hadronic channels.

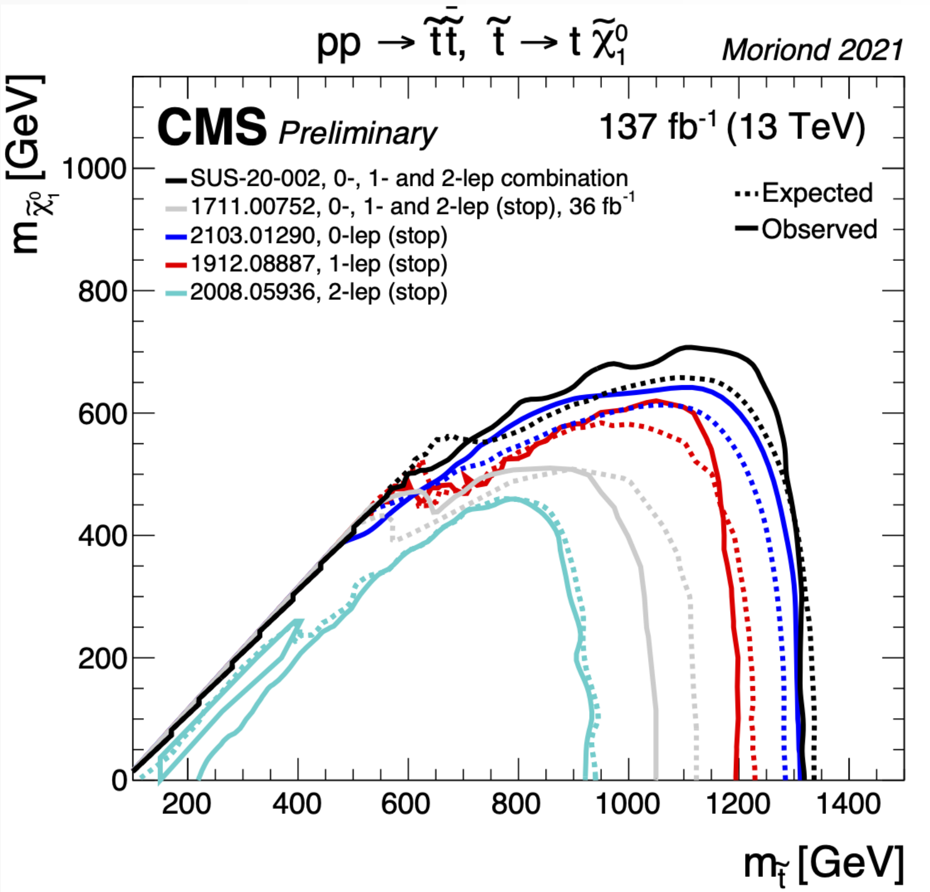
Searches for squarks and gluinos: ATLAS stop and sbottom summary

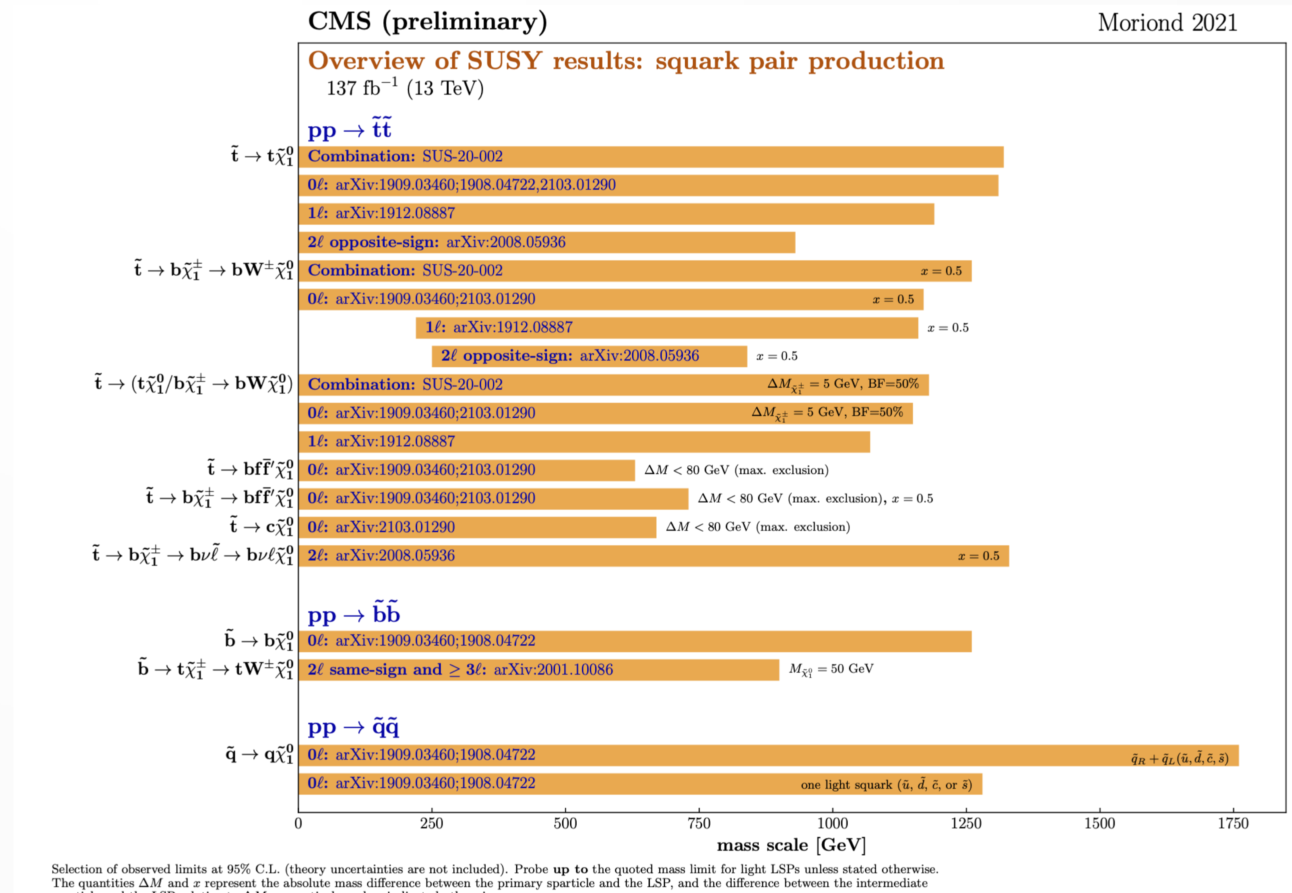




- Top squark limits reach ~1.2 TeV.
- Sbottom limits reach ~1.3 TeV.
- Dedicated searches for the compressed regions, top corridor, etc.

Searches for squarks and gluinos: CMS stop and sbottom summary



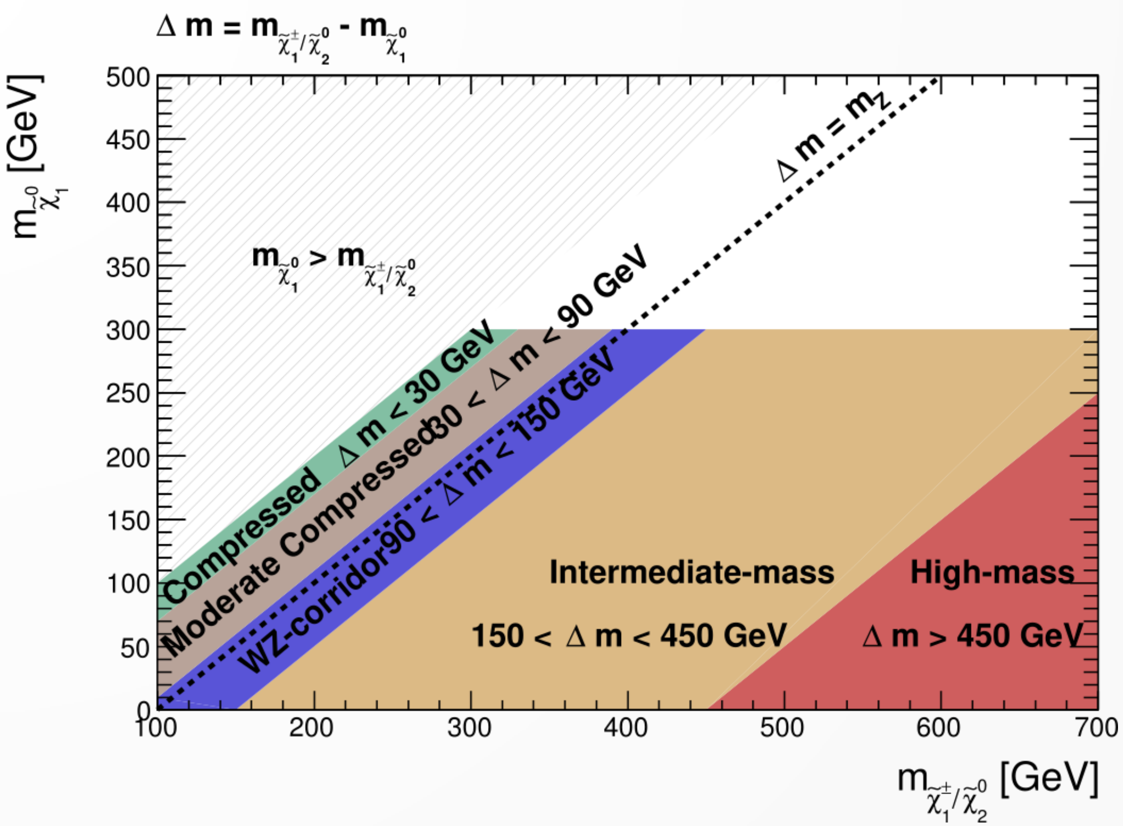


- Top squark limits reach ~1.3 TeV.
- Sbottom limits reach ~1.25 TeV.
- Specialized searches to probe different regions of the mass plane, and different decay channels.

Searches for electroweak SUSY

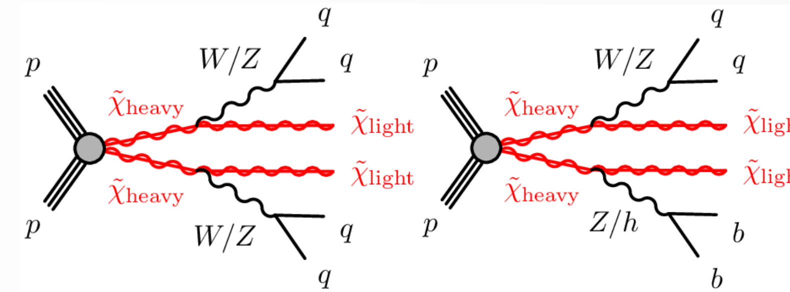
Searches for electroweak SUSY

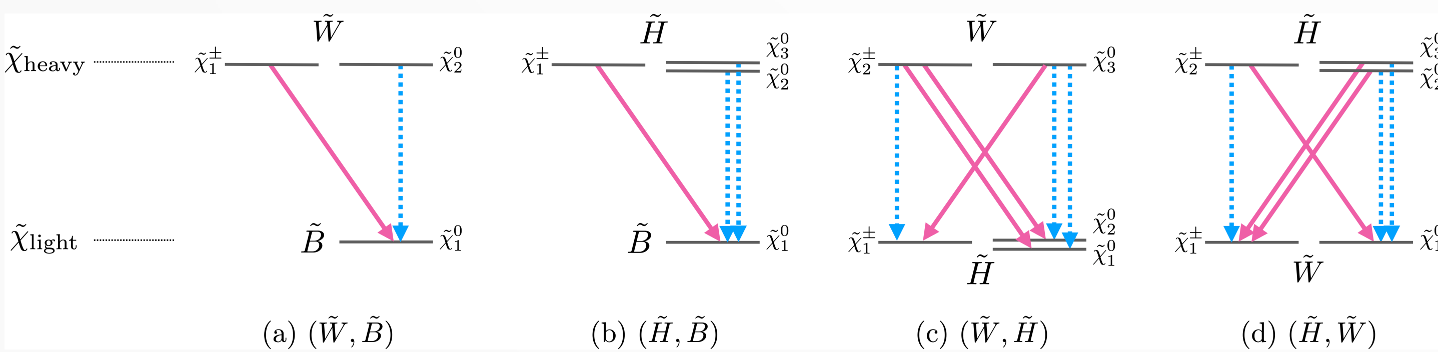
- Direct production of electroweak SUSY particles like charginos, neutralinos, sleptons.
- Different challenges compared to the strong sector.
- Significantly lower cross sections.
- Different strategies to probe different regions of the phase space.

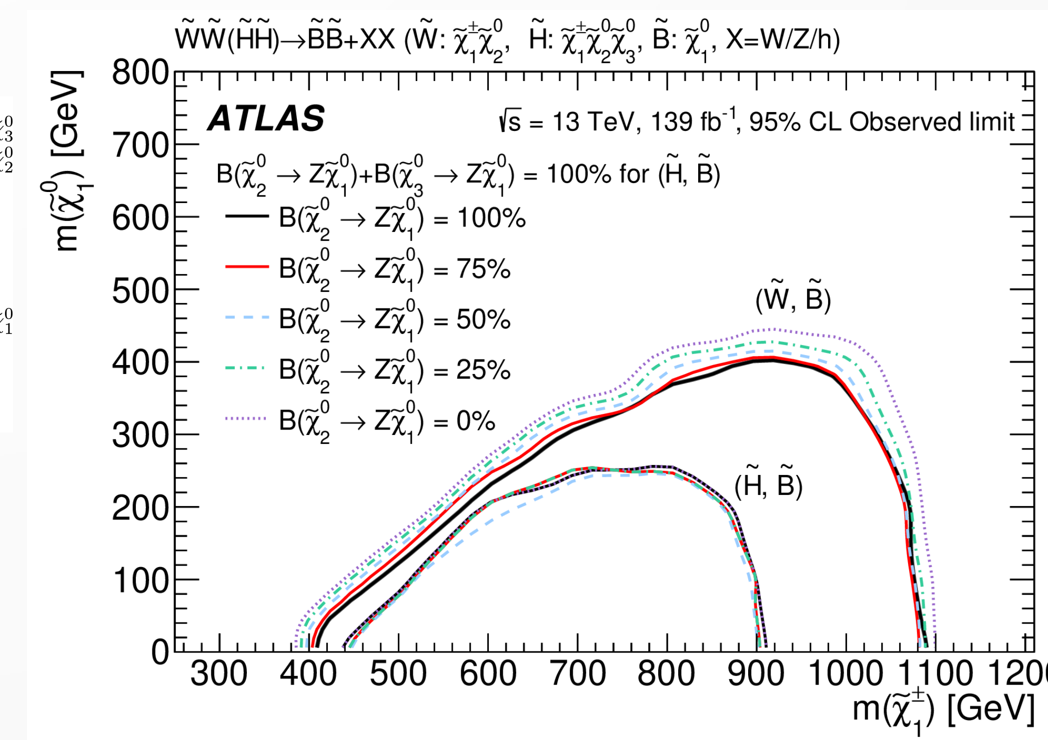


Searches for electroweak SUSY: chargino/neutralino in W/Z/H final states

- **ATLAS-SUSY-2018-41: arXiv 2108.07586**
- RPC models with a multijet final state.
- Several mass spectra explored.
- Final state must contain at least 2 large R (1.0) jets. Boosted boson tagging (non-ML based) performed on the large R jets.
- No. of b-tagged and non b-tagged jets define the search categories.

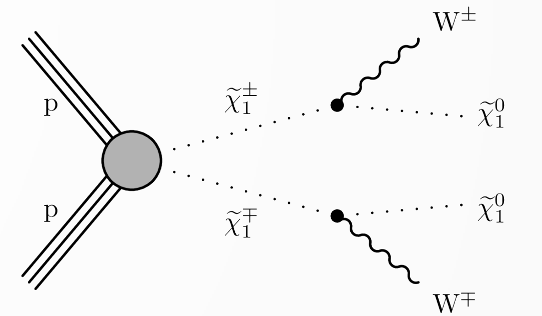


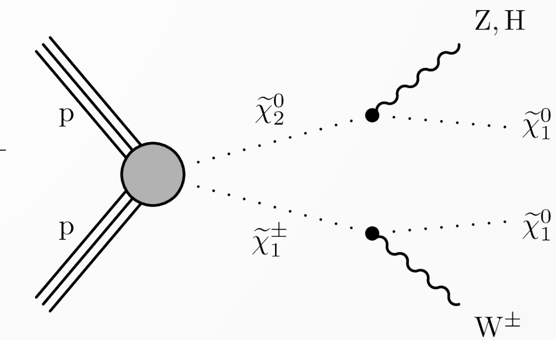




Searches for electroweak SUSY: chargino/neutralino in W/Z/H final states

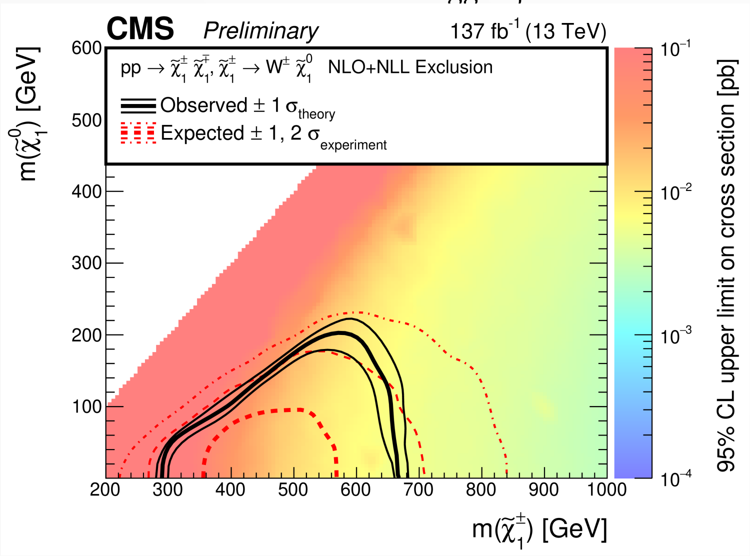
- **CMS-SUS-21-002**
- 3 scenarios:
  - chargino pair production
  - mass degenerate wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair with light bino like χ_1^0
  - mass degenerate higgsino like $\tilde{\chi}_1^{\pm}\tilde{\chi}_{2/3}^0$ pair with light bino like χ_1^0
- Anti-k_T jets with R=0.8 (AK8) jets are categorized using 3 taggers: W tagger, V tagger, $b\bar{b}$ tagger.
- Define search regions based on the number of b-tagged jets and H and W boson candidates.

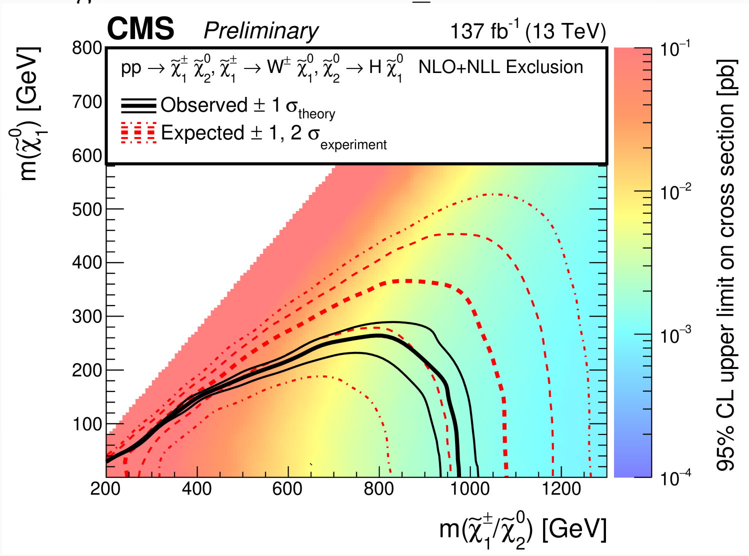


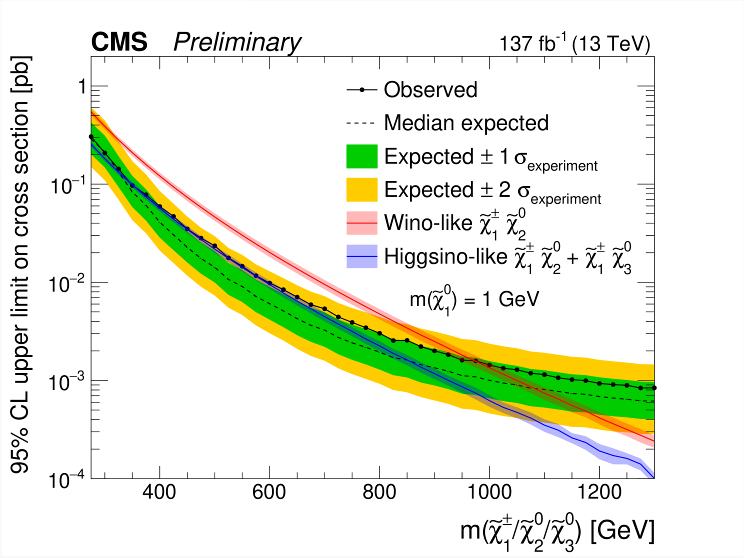


Region	Requirements
b-veto SR	≥1 V-tagged jet ≥1 W-tagged jet ≥2 V- or W-tagged jets
b-veto zero-tag CR	0 V-tagged jets 0 W-tagged jets
b-veto one-tag CR	1 V-tagged jet 0 other W-tagged jets

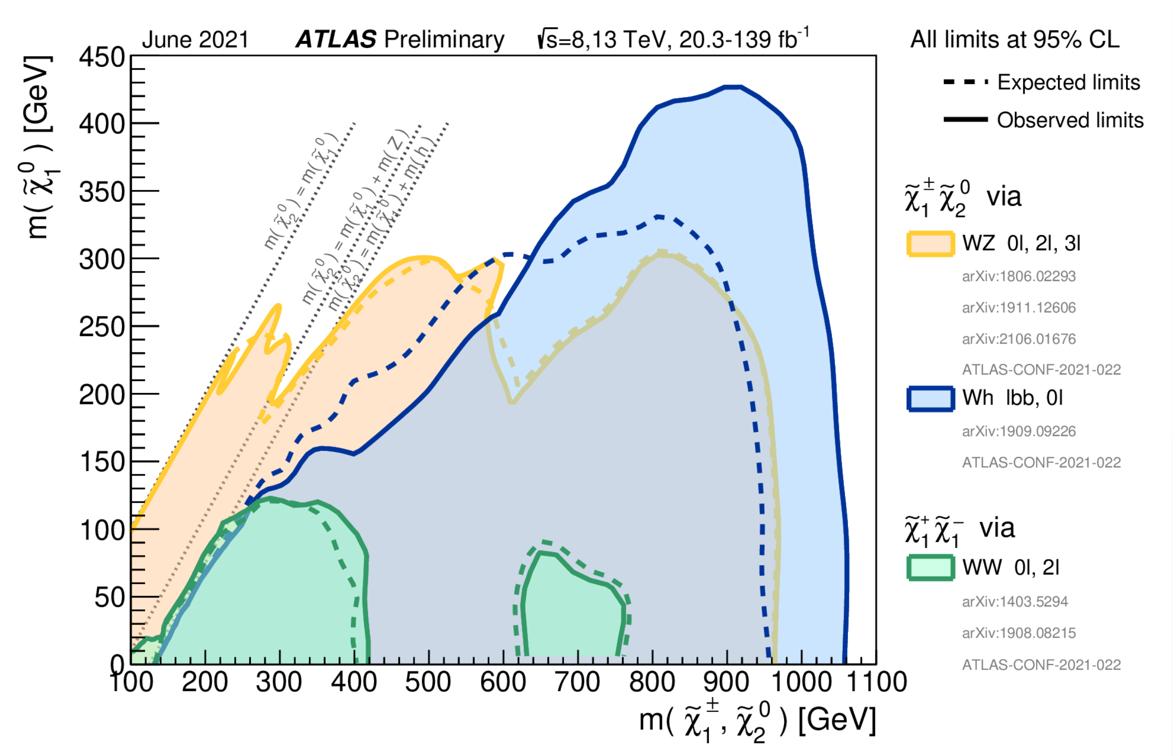
	Higgs boson candidate		Wboson candidate	
	$b\bar{b}$ tagged	not $b\bar{b}$ tagged	Wtagged	not Wtagged
WH SR	≥1	—	≥1	—
WSR	0	—	≥1	—
H SR	≥1	—	0	—
WH antitag CR	0	≥1	0	≥1
Wantitag CR	0	0	0	≥1
H antitag CR	0	≥1	0	0



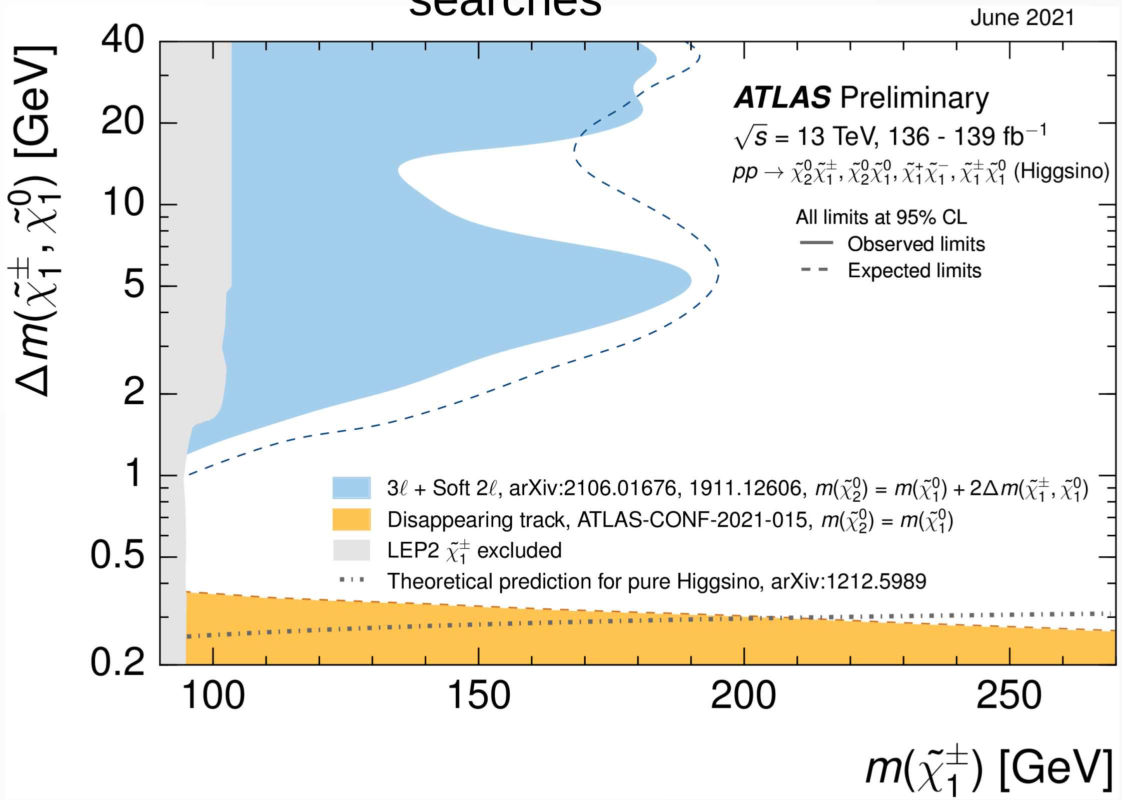




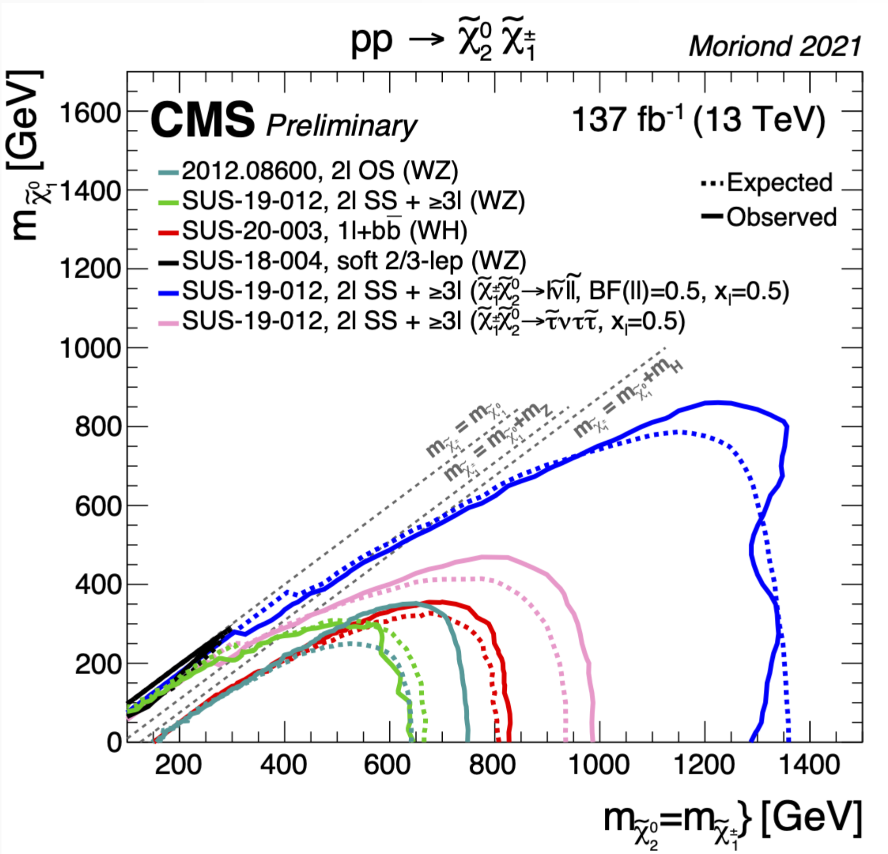
Searches for electroweak SUSY: ATLAS summary

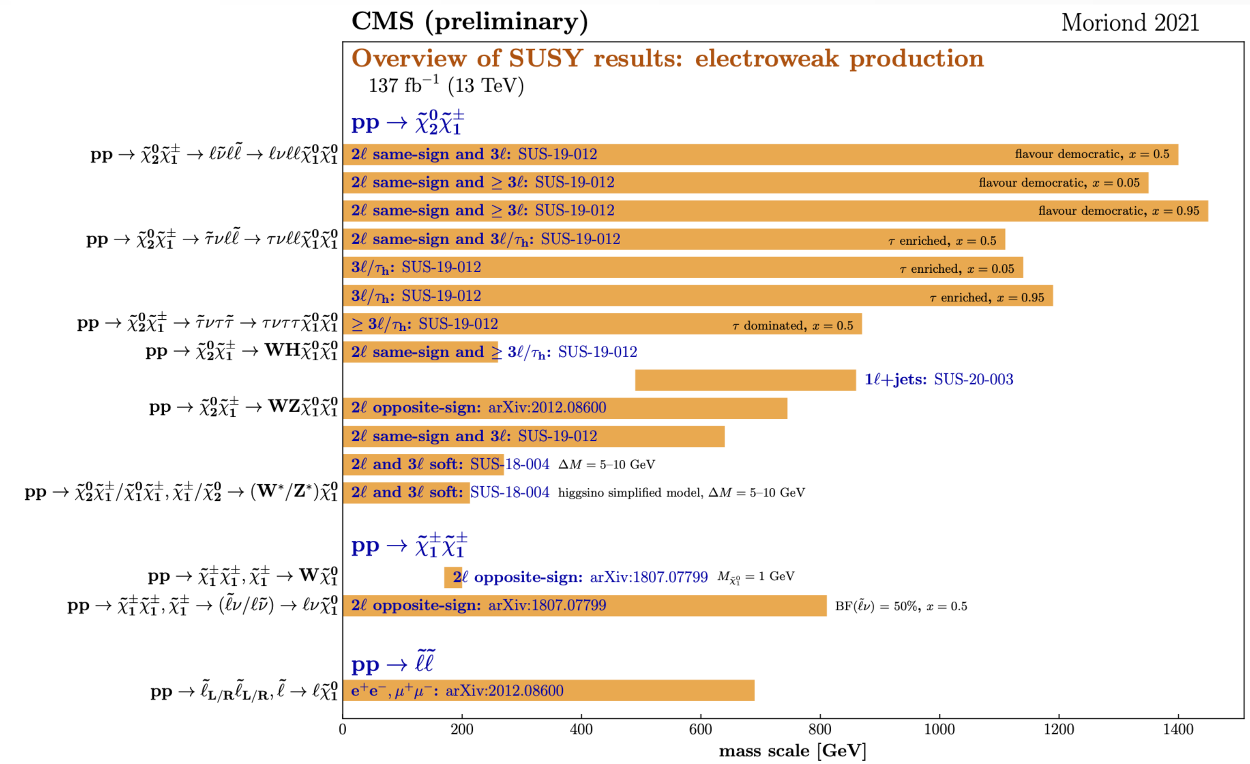


Higgsino searches



Searches for electroweak SUSY: CMS summary

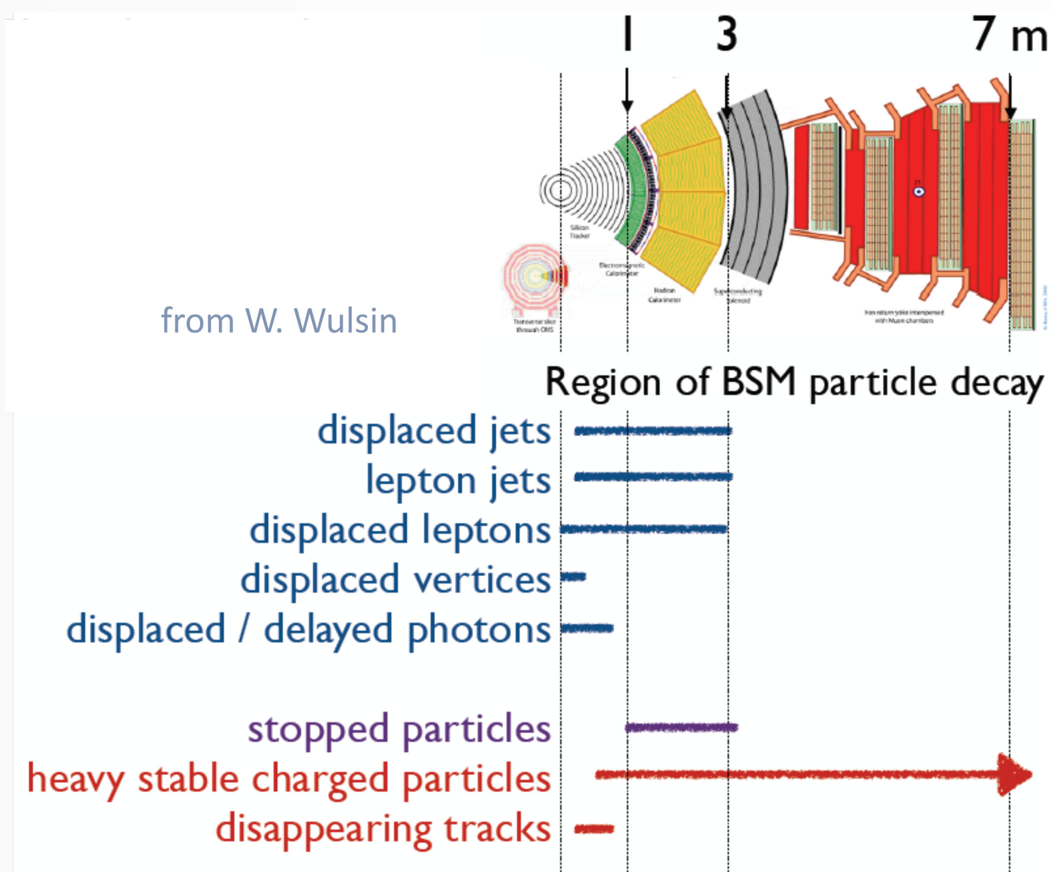




Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Long lived particle searches

- Unconventional signatures compared to the standard searches.
- Complementary to the prompt searches.
- Challenging triggers
- Not much SM background outside the beamspot.
- Instead one needs careful modeling of the detector noise, beam background, cosmic rays, reconstruction failure, etc.

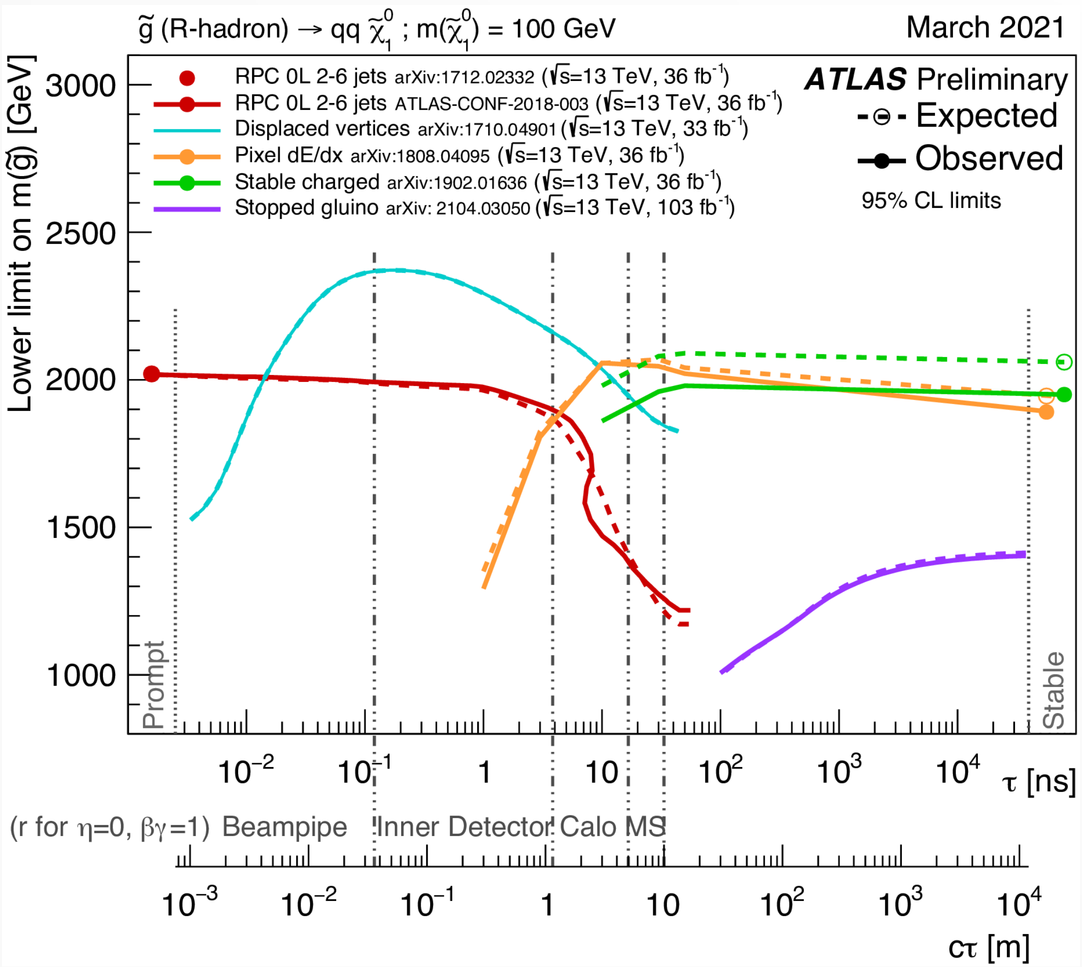


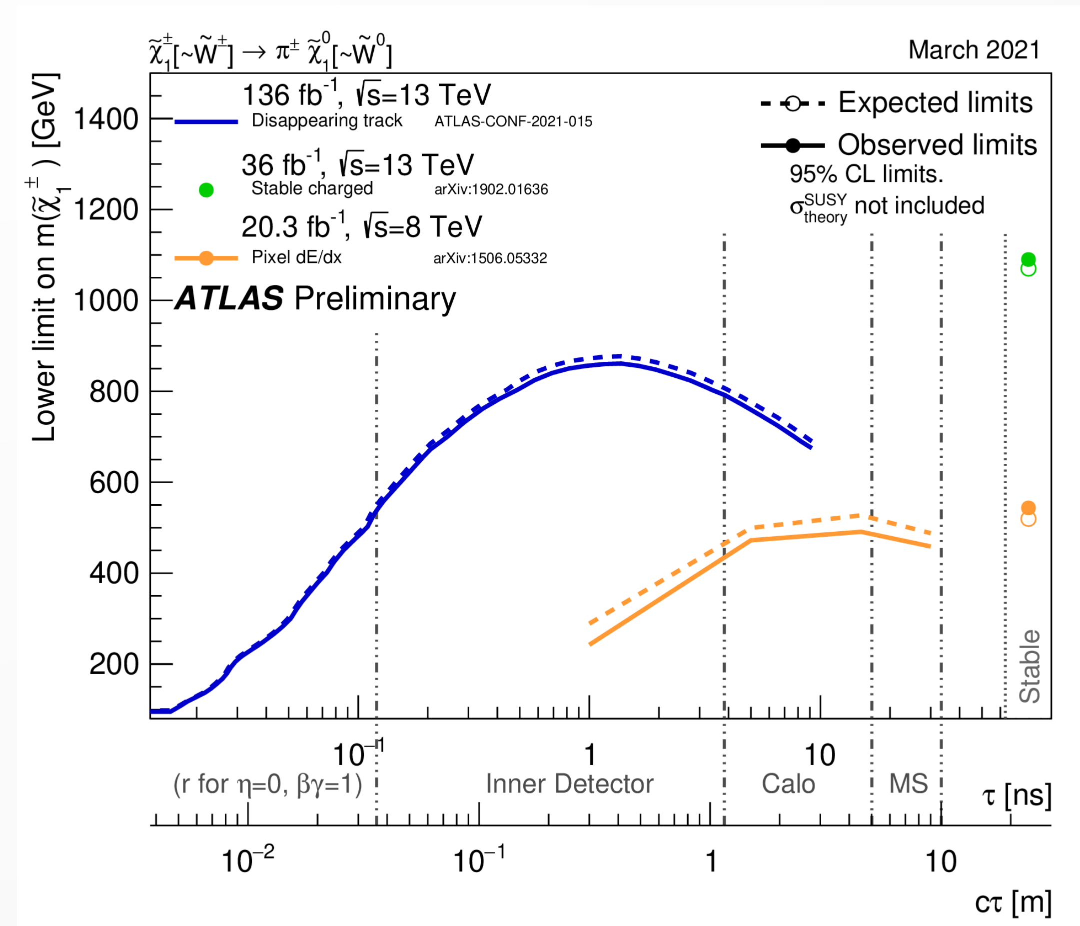
→ Hidden valley, RPV SUSY, stealth SUSY
→ dark photons
→ Hidden valley, RPV SUSY, displaced SUSY
→ Split SUSY, RPV, GMSB
→ GMSB

→ split SUSY gluino, stop, …
→ gluino, stop, GMSB slepton, chargino …
→ degenerate chargino

Long lived particle searches: ATLAS summary

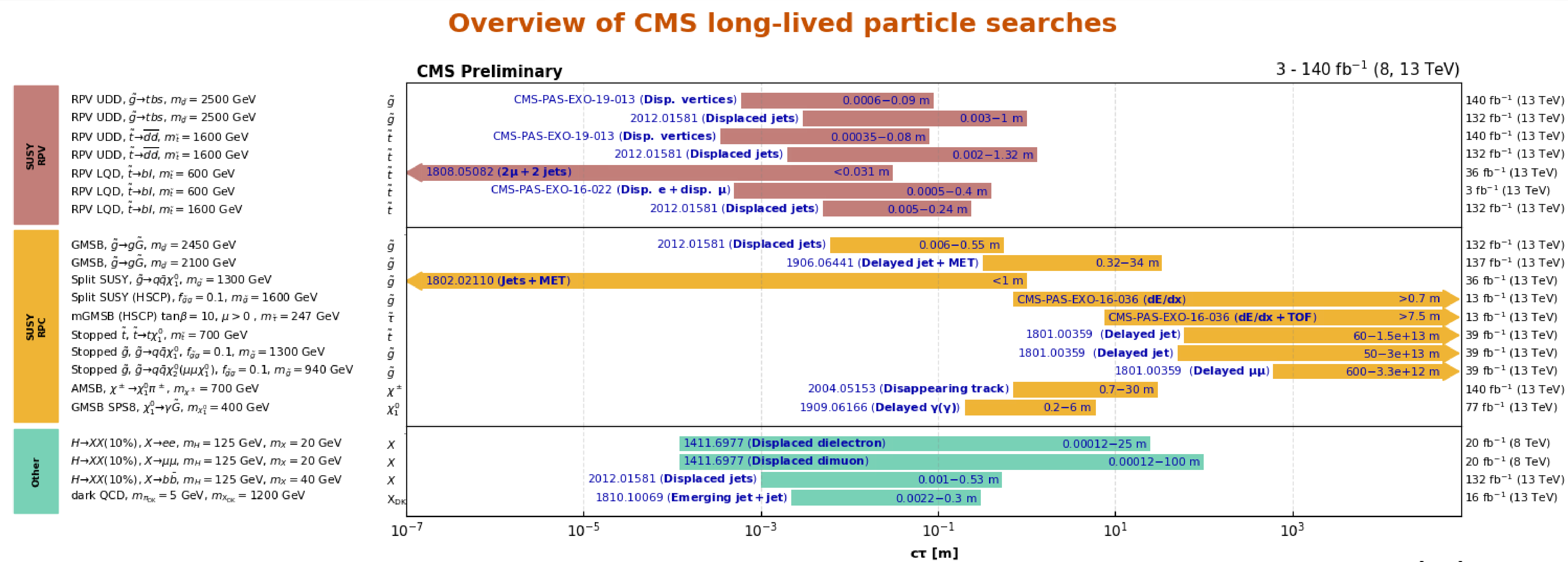
- Searches using pixel ionization loss dE/dx improves the sensitivity for higher lifetimes.
- Displaced vertex searches sensitive to low and intermediate lifetimes.
- Dedicated stopped gluino (R-hadron) searches for higher lifetimes.
- Specialized search for long lived charginos using disappearing track signatures, provides sensitivity for low and intermediate lifetimes.





Long lived particle searches: CMS summary

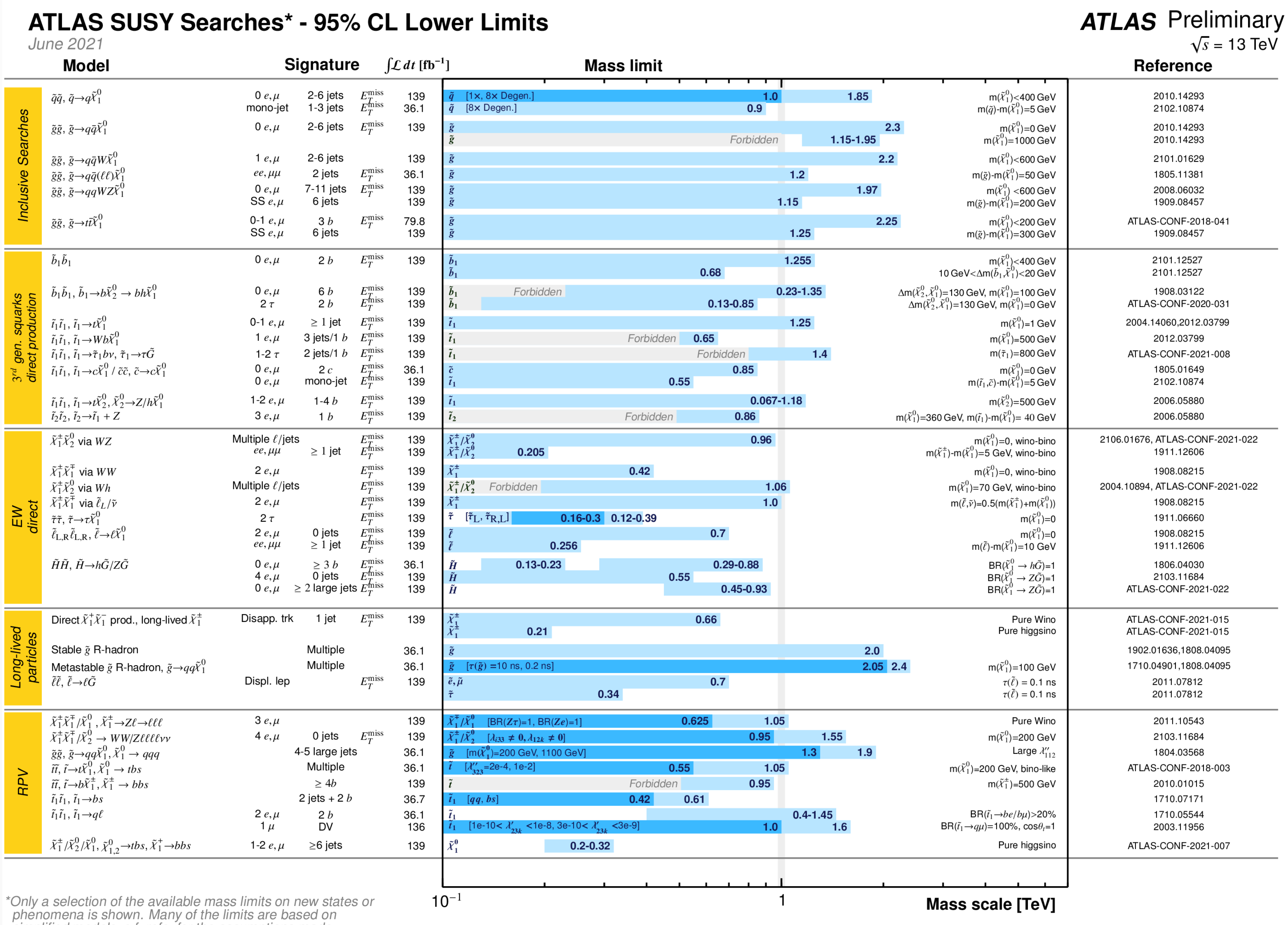
- Searches using ionization loss dE/dx and delayed objects provide sensitivity for higher lifetimes.
- Displaced object searches are sensitive to intermediate lifetimes.
- Enhanced sensitivities using dedicated displaced and delayed object triggers.



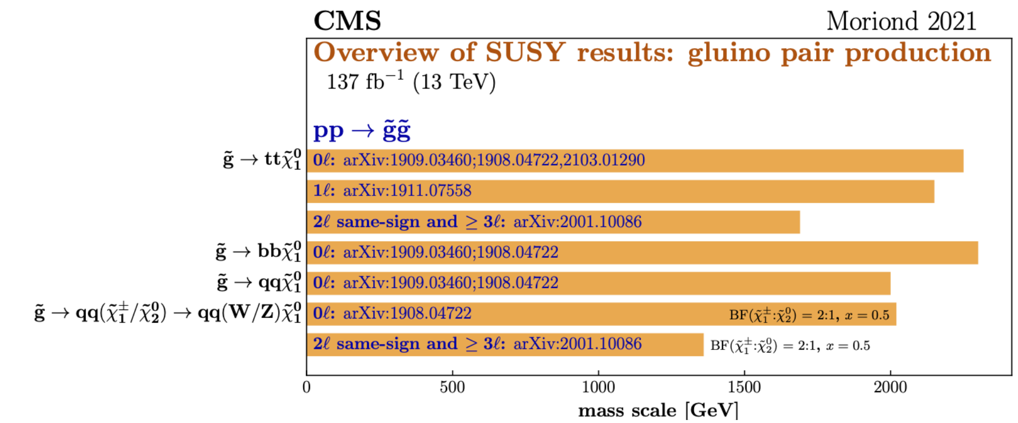
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

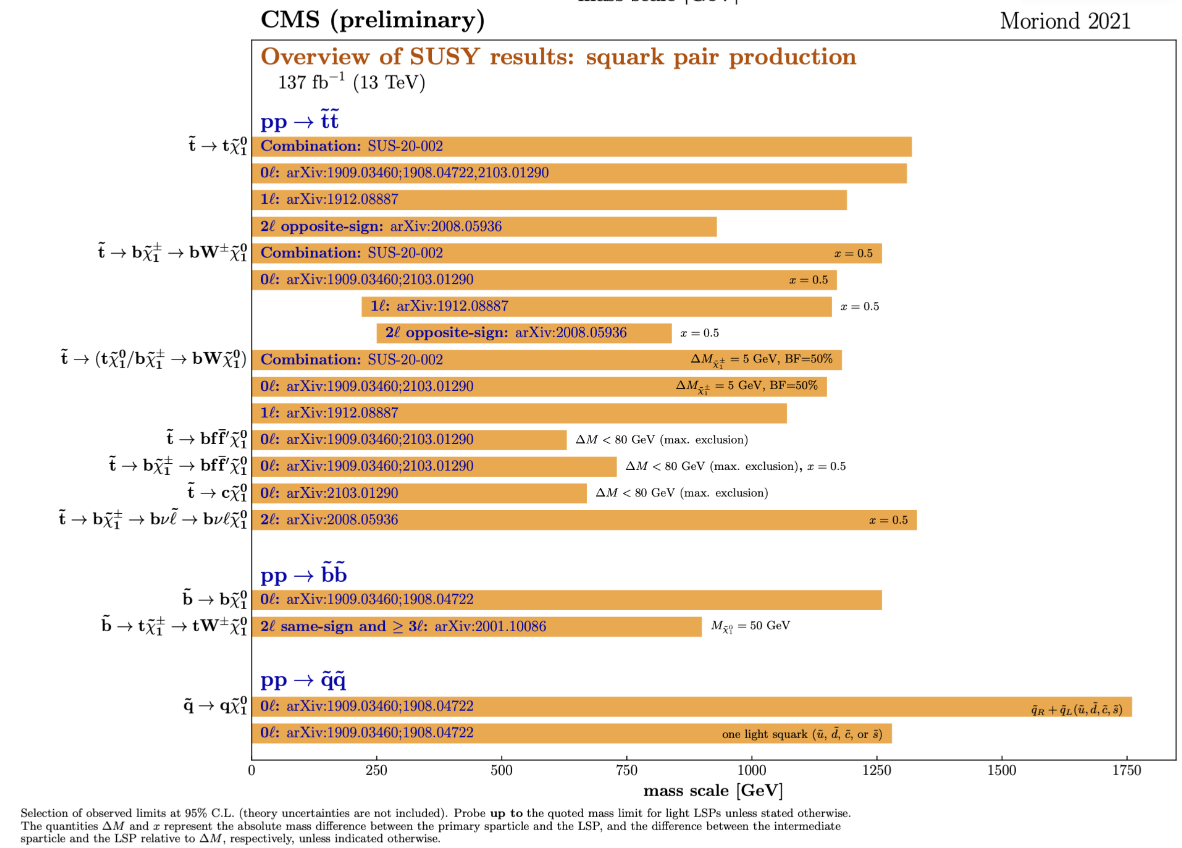
Summary

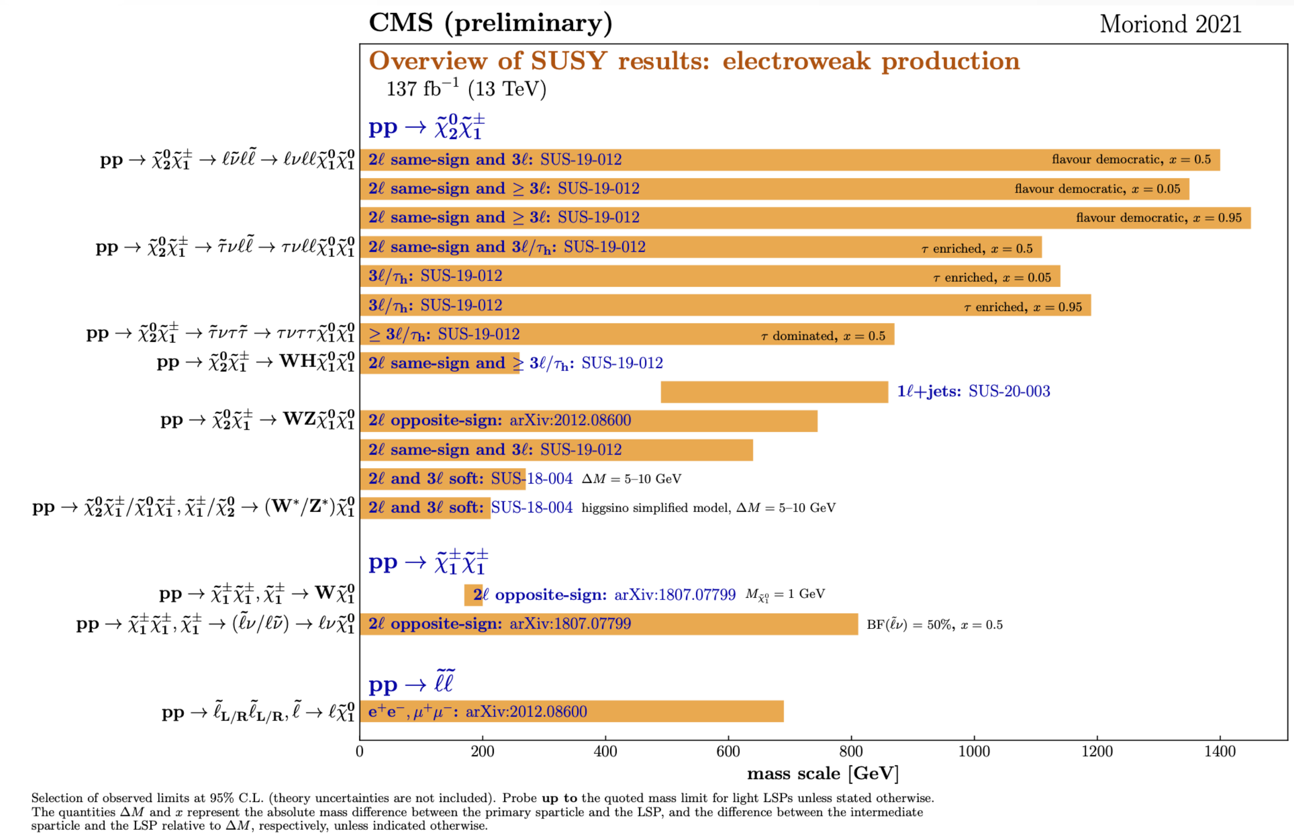
ATLAS SUSY summary



CMS SUSY summary







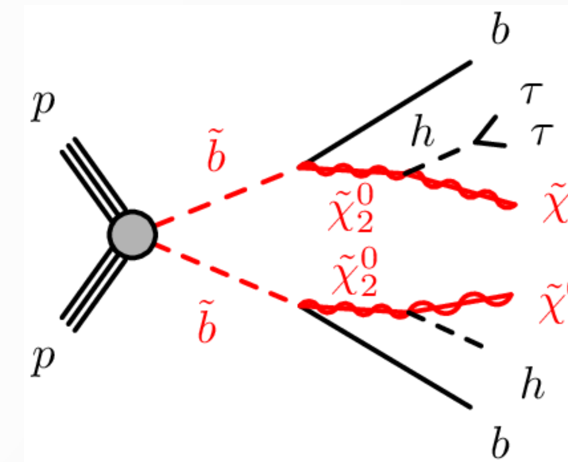
SUSY searches at the LHC: Summary

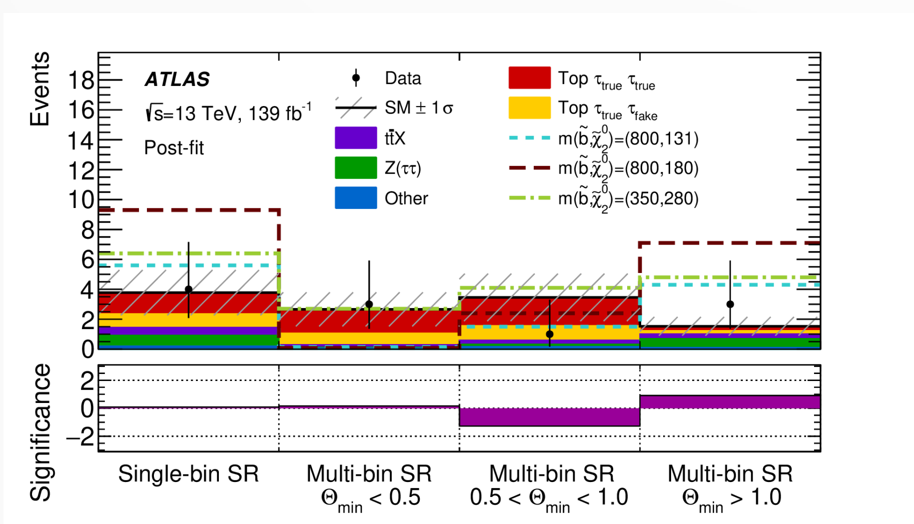
- **A huge variety of Supersymmetry searches have been carried out at both ATLAS and CMS.**
- The searches explore different models and final states – from conventional SUSY cascade decays to long-lived particles.
- Cannot do justice to all results – only highlighted a few recent ones. **In backup:**
  - ATLAS-SUSY-2018-40: ATLAS sbottom production.
  - ATLAS-SUSY-2018-02: ATLAS chargino/neutralino production (RPV, gauge mediated; multilepton final state).
  - CMS-SUS-21-001: CMS stau production (long lived).
  - CMS-SUS-19-012: CMS chargino neutralino production (W/Z mediated, gauge mediated; multilepton final state).
  - Full list here:
    https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
    https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
- Unfortunately, no sign of SUSY yet.
- **Constant effort ongoing to improve our searches:**
  - Heavy focus towards novel Machine Learning techniques.
  - Improve object reconstruction and identification.
  - Better signal vs. background event classification.
- Run-3 right around the corner.
- **More exciting results soon!**

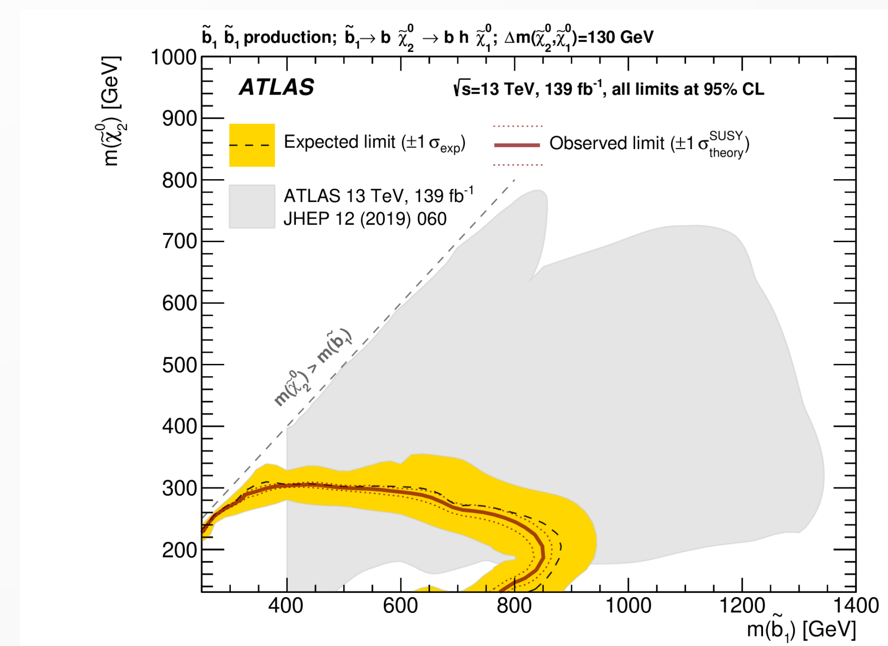
Backup

Searches for squarks and gluinos: direct sbottom production

- **ATLAS-SUSY-2018-40: arXiv 2103.08189**
- Sensitive to models where χ_1^0 is bino like and χ_2^0 is a wino-higssino mixture.
- χ_2^0 decays to an on-shell Higgs.
- Missing E_T+b jet triggers.
- Sensitive search variables:
  - The "stransverse mass" m_{T2}.
  - Θ_{min}: smallest 3D angle of the combinations b/w either of the 2 leading tau leptons and either of the 2 leading b jets.

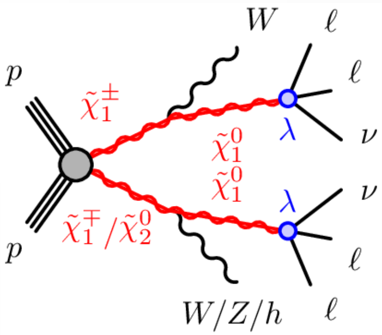


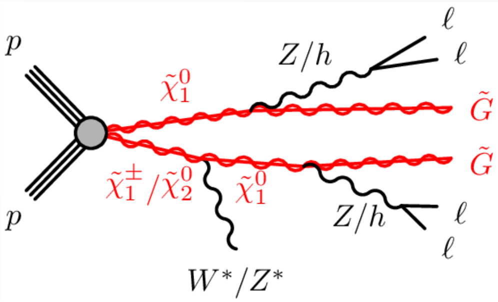


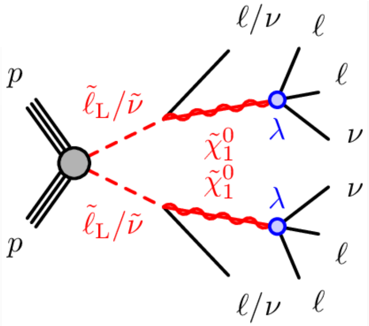


Searches for electroweak SUSY: chargino/neutralino in W/Z/H final states

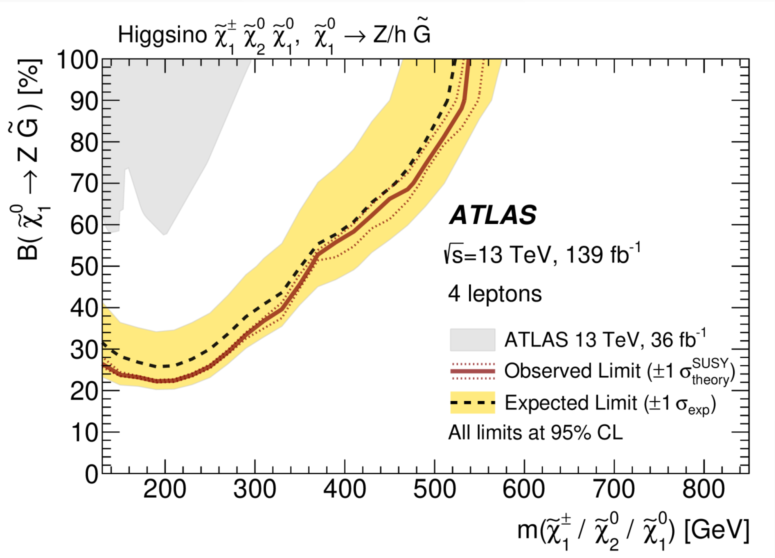
- **ATLAS-SUSY-2018-02: arXiv 2103.11684**
- General gauge mediated SUSY models with nearly massless gravitinos
- RPV SUSY models with leptons in the final state.
- Bin the phase space in terms of the number of leptons, τ_h (hadronically decaying tau leptons), b-tagged jets



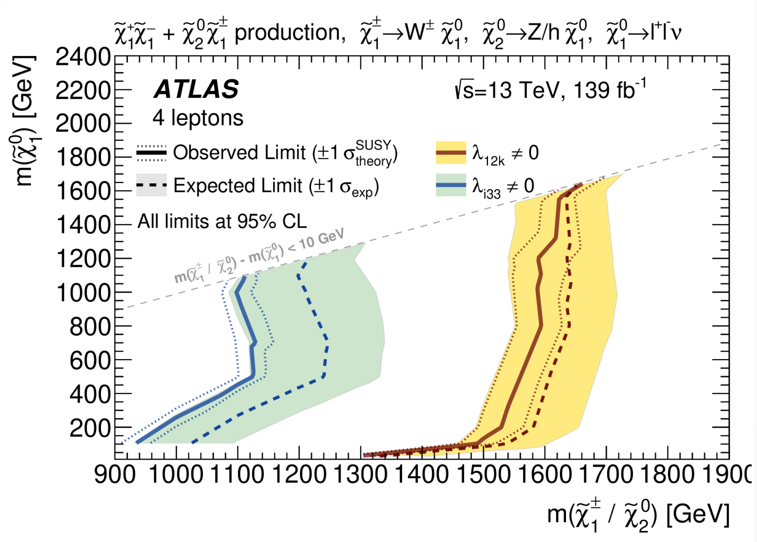




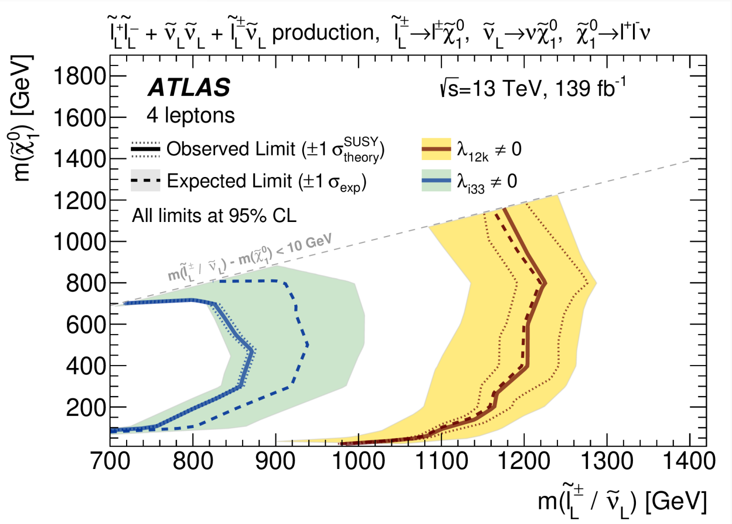
Higgsino GGM



RPV wino NLSP

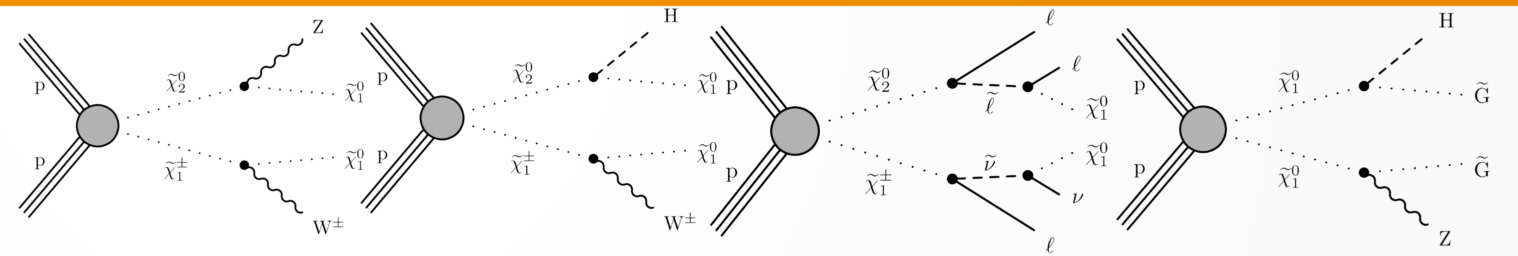


RPV slepton NLSP



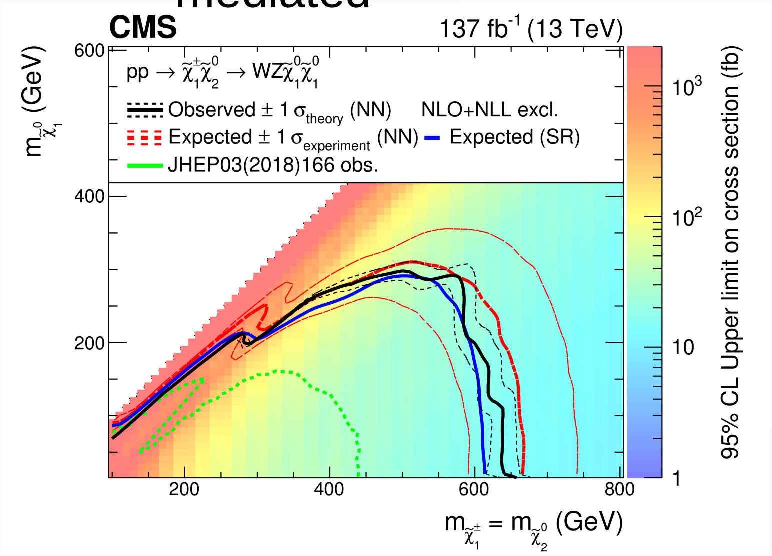
Searches for electroweak SUSY: chargino/neutralino in W/Z/H final states

- **CMS-SUS-19-012: arXiv 2106.14246**
- Direct chargino/neutralino production.
- Models with sleptons in the cascade decay.
  - flavor democratic and tau dominated scenarios
- Gauge mediated SUSY breaking (GMSMB) models with a nearly massless Gravitino in the final state.
- Search regions categorized in terms of the number, sign and flavor of the leptons.
- Bin search regions in terms of m_{T2}, di-lepton p_T, and missing energy.

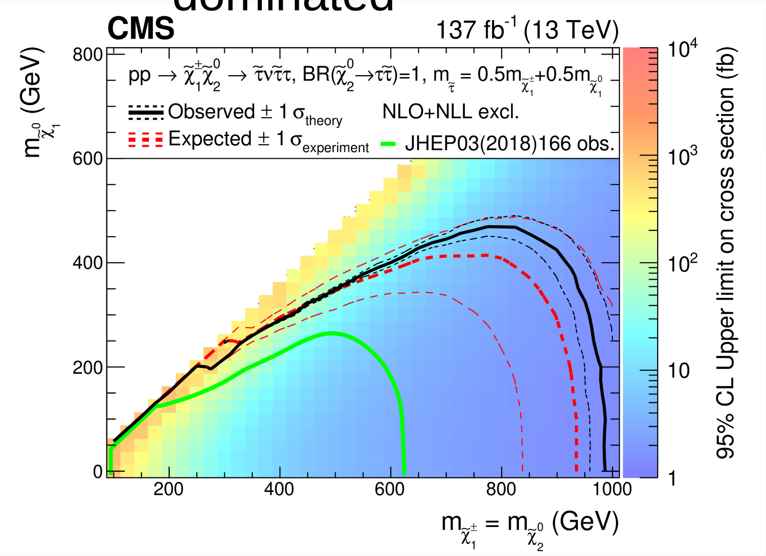


Category	Requirements
2ℓSS	Two light leptons with the same sign
3ℓA	Three light leptons including one or more OSSF pairs
3ℓB	Three light leptons including no OSSF pairs
3ℓC	A pair of light leptons forming an OSSF pair and a τ_h candidate
3ℓD	A pair of light leptons of different flavor and opposite sign and a τ_h candidate
3ℓE	A pair of light leptons of same sign and a τ_h candidate
3ℓF	A light lepton and two τ_h candidates
4ℓG	Four light leptons including two independent OSSF pairs
4ℓH	Four light leptons including one or less OSSF pairs
4ℓI	Three light leptons and a τ_h candidate
4ℓJ	Two light leptons and two τ_h candidates, including two OSSF pairs
4ℓK	Two light leptons and two τ_h candidates, including one or no OSSF pair

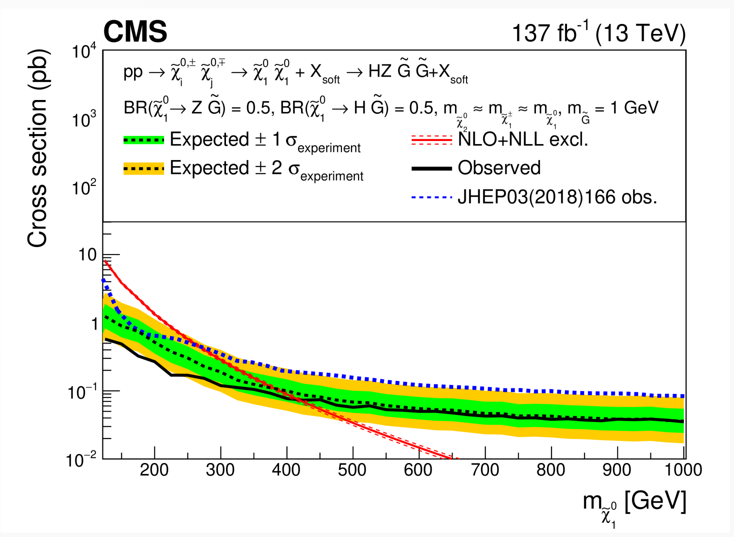
W/Z mediated



Tau dominated

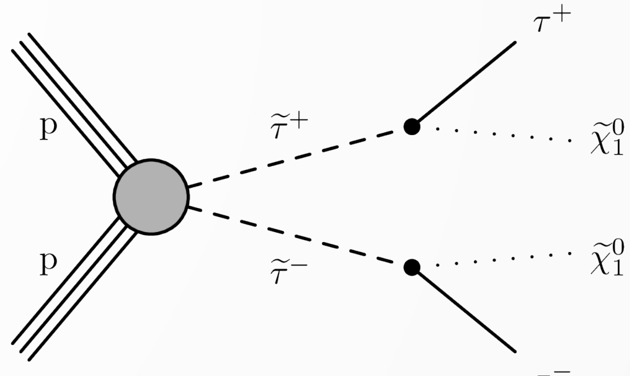


GMSMB

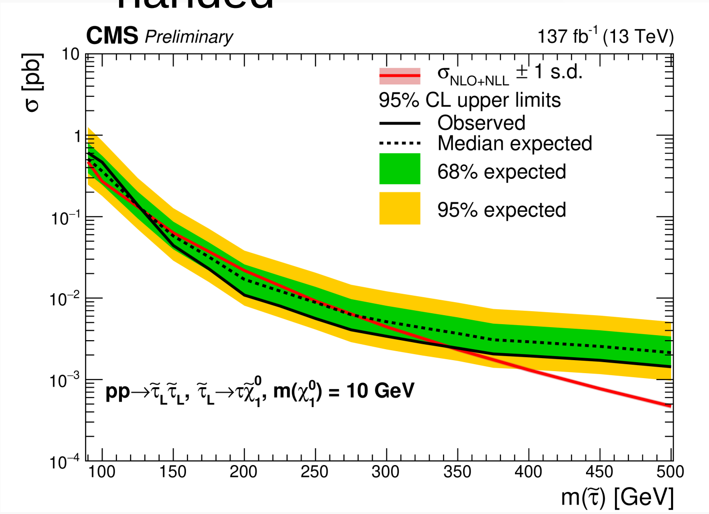


Searches for electroweak SUSY: direct tau slepton production

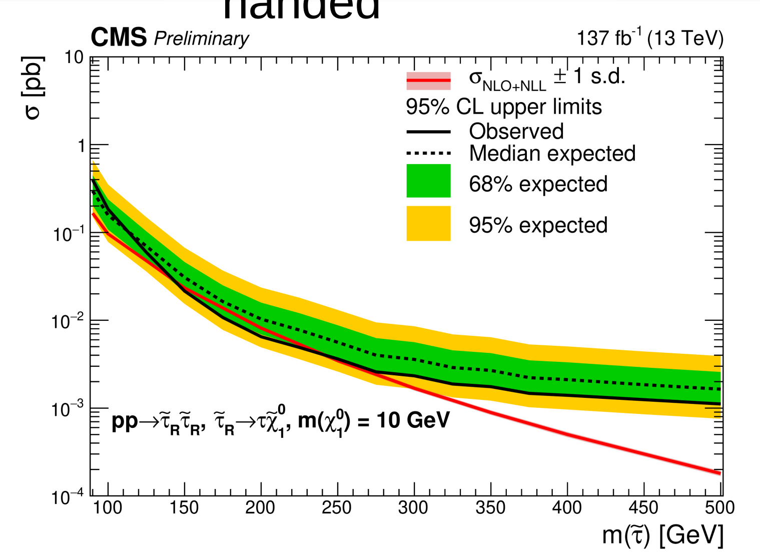
- **CMS-SUS-21-001**
- Direct stau production.
- Light NLSP stau:
  - Early universe stau-neutralino coannihilation models
  - Long lived NLSP staus – GMSB models
- Considers different mixtures of left and right handed staus
- Long lived: mean proper decay lengths $c\tau_0$ up to 2.5mm.
- Uses the deep NN based "DeepTau" algorithm to tag hadronically decaying taus.
- Uses transverse mass m_T and stransverse mass m_{T2} to bin the phase space.
- Challenging to measure the mis-id. Tau bkg – data driven.



Fully left handed



Fully right handed



Maximal mixing, $c\tau_0$=0.1mm