Searches for SUSY in hadronic final states at CMS

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on behalf of CMS collaboration

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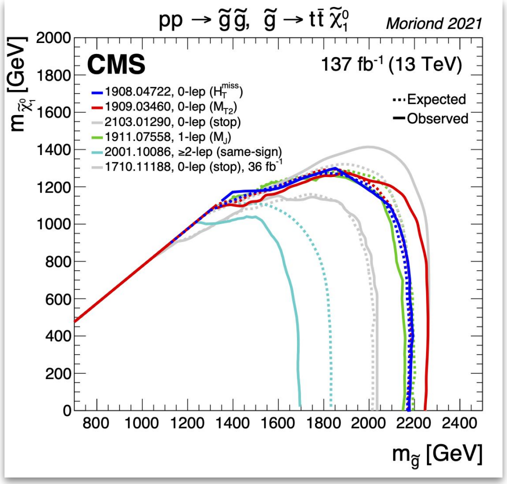
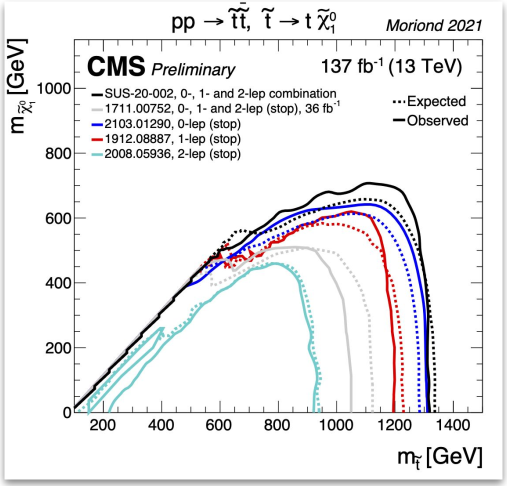
Introduction

- Several searches for strongly produced SUSY have been performed by CMS.
- Some of the most stringent limits on gluino/squark production have been placed by hadronic searches.

- Hadronic searches:
    - Benefit from larger branching fractions in the decay of W/Z/H/τ to hadrons.
    - Suffer from higher SM backgrounds compared to the leptonic searches.
    - More common in recent times due to large LHC dataset and new analysis techniques.





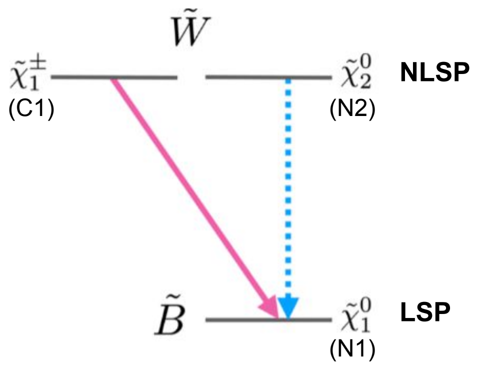
Searches covered today….

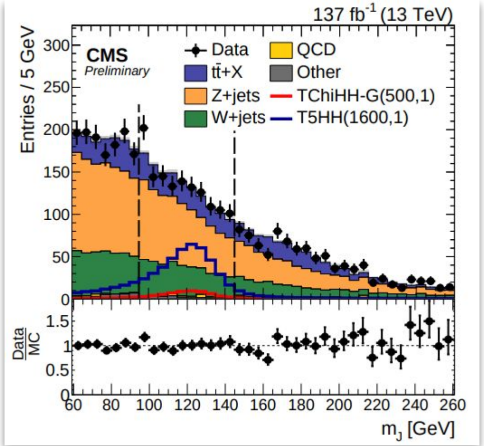
- Most recent searches with hadronic final state are covered.
- WX + p_T^{miss} (SUS-21-002) } **Electroweakino searches**
- HH + p_T^{miss} (SUS-20-004) }
- Stau lepton search (SUS-21-001)
- Electroweak searches are important:
  - Stringent constraints on strong production of SUSY.
  - Naturalness condition → light charginos and neutralinos.
  - Stau-neutralino coannihilation models → stau is NLSP.

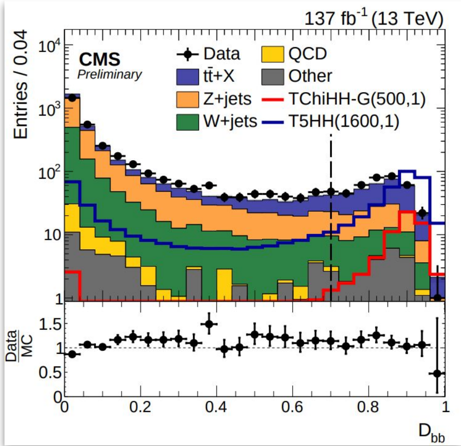
All other SUSY searches at CMS can be found here.

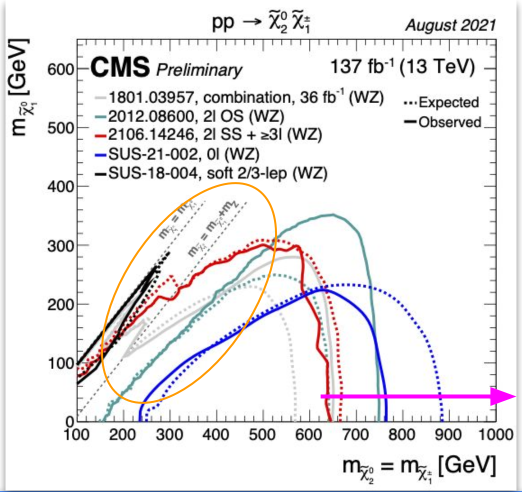
EWKino searches - Mass spectra and analysis techniques

- In the wino NLSP ($\chi^{\pm}_1$ / χ^0_2) scenario, if the mass difference between LSP (χ^0_1) and NLSP is small & m_{NLSP} is low
  - Good sensitivity from leptonic searches.
- For large mass difference and high m_{NLSP},
  - High momentum LSP → high p_T^{miss}.
  - High p_T bosons → collimated decay products.
  - Large radius jet with mass near the boson mass and DNNs using jet properties.

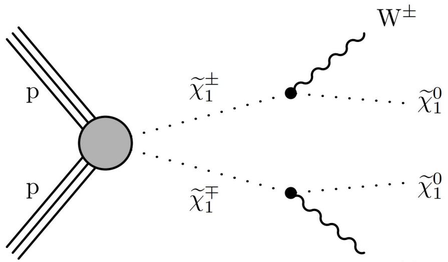




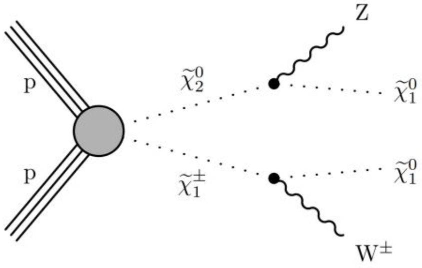




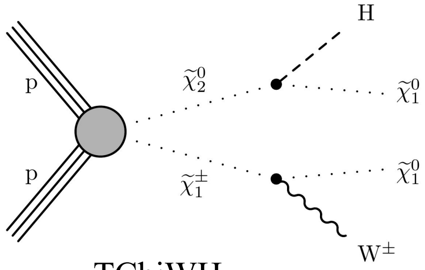
WX + p_T^{miss} final state search



TChiWW



TChiWZ



TChiWH

- 2 bosons decay hadronically, giving 2 AK8 jets.
- Search regions are designed based on the number of b-jet tags.

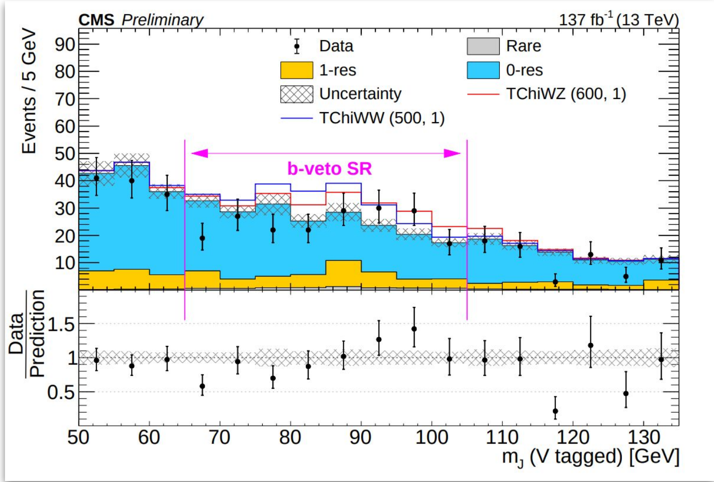
- **0 b**-tags

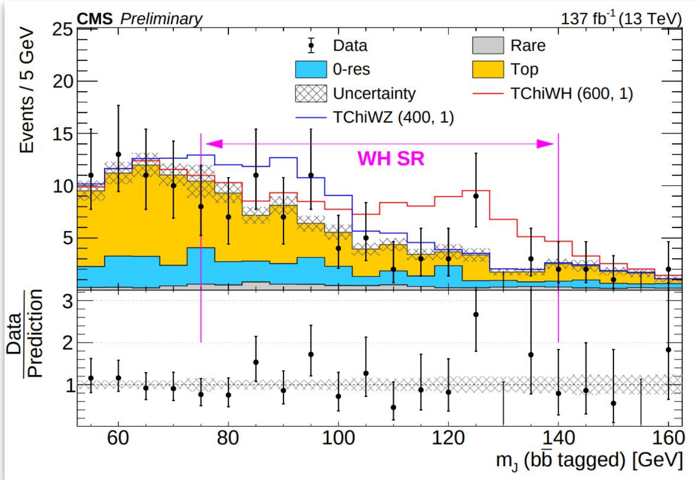
- **0 b-tags** when Z → qq
- **≥1 b-tags** when Z→ bb

- **≥1 b-tags** from H→ bb

Backgrounds and results

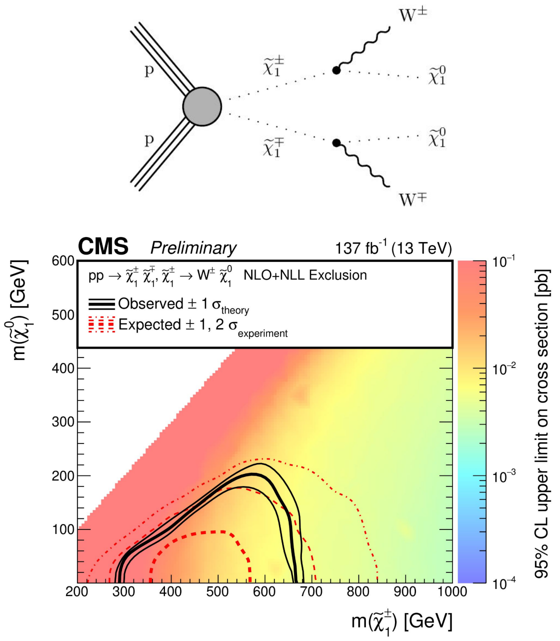
- Deep neural networks to discriminate QCD jets vs W/Z/H to qq decays.
- Z(*νν*), W(*lν*) and tt are the dominant SM backgrounds - estimation from leptonic regions and inverting the DNN discriminator.
- No significant deviations from SM predictions.



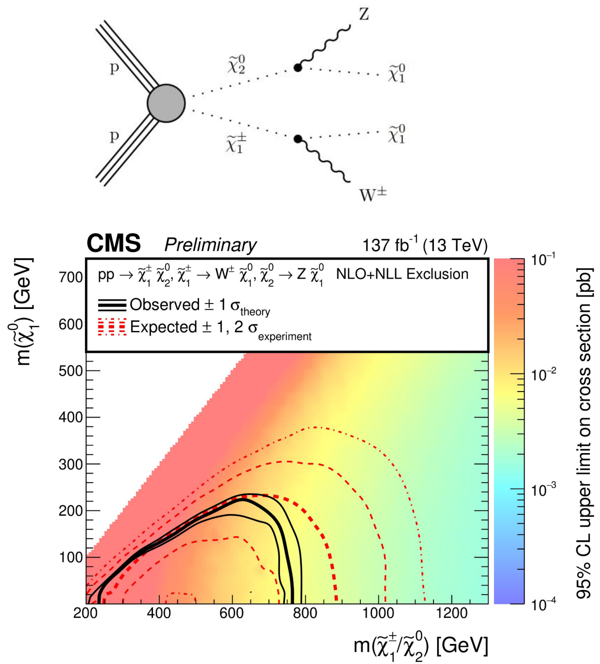


Simplified model interpretations

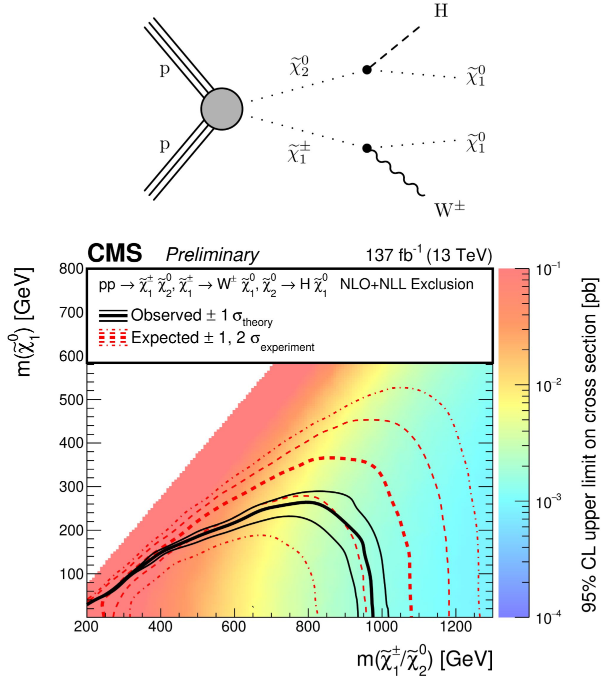
- For wino cross section scenarios with m_{LSP} ~ 0, the search places some of the most stringent limits.



Mass exclusion: 290 - 670 GeV



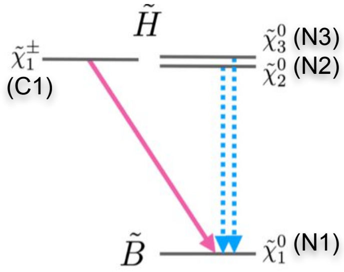
230 - 760 GeV

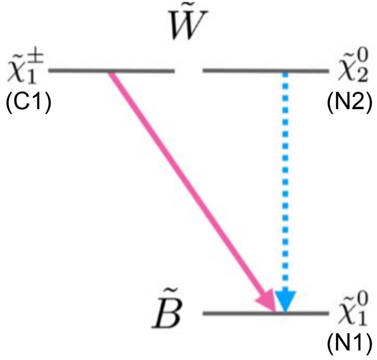


200 - 970 GeV

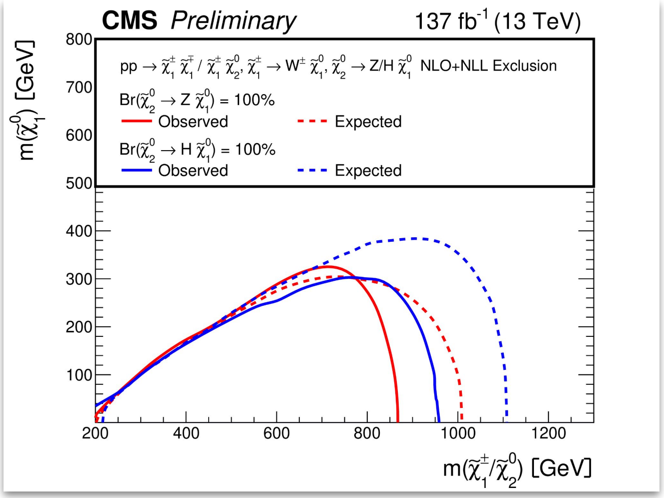
Interpretations - beyond simplified models

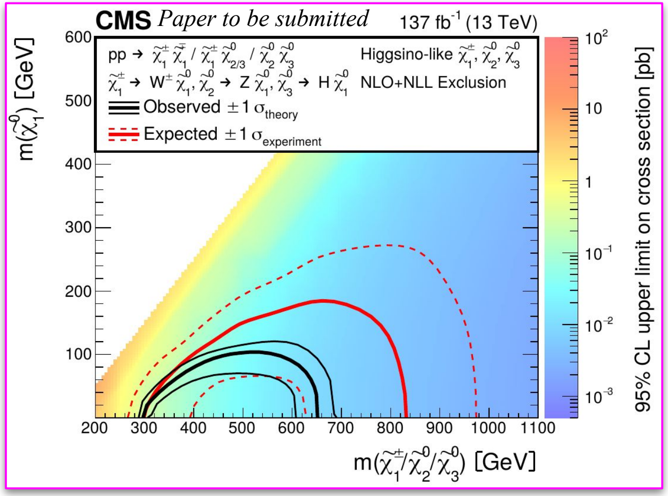
- Realistic wino scenarios involve $\chi^{\pm}_1\chi^{\pm}_1$ and $\chi^{\pm}_1\chi^0_2$ production. Two cases $\chi^0_2 \rightarrow Z + \chi^0_1$ with 100% BR or $\chi^0_2 \rightarrow H + \chi^0_1$ with 100% BR are considered.
- Search is also sensitive to higgsino models with $\chi^0_2 \rightarrow \chi^0_1 + Z$, $\chi^0_3 \rightarrow \chi^0_1 + H$.





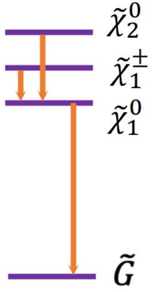
Wino scenario



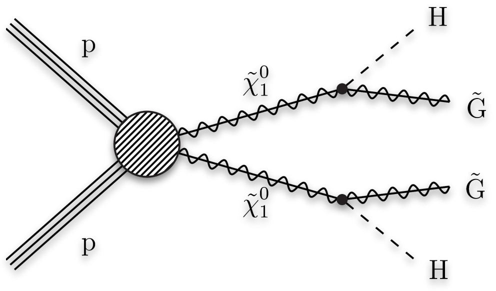


$HH+p_T^{miss}$ search - models targeted

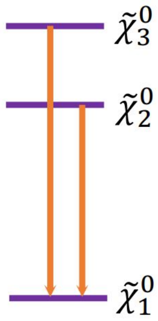
- Search for pair produced neutralinos with $H(bb)H(bb)$ and p_T^{miss} final state.
- GMSB scenario:
  - Higher $\chi^0_1\chi^0_1$ production since $\chi^\pm_1$, χ^0_1 and χ^0_2 are mass degenerate with $\chi^\pm_1/\chi^0_2 \rightarrow \chi^0_1$ + soft particles.
  - χ^0_1 is NLSP and goldstino, G~ is LSP.
- N2N3 scenario:
  - Only $\chi^0_2\chi^0_3$ production, $\chi^\pm_1$ is not accessible; χ^0_2 & χ^0_3 are mass degenerate.
  - χ^0_2 / χ^0_3 are co-NLSP and χ^0_1 is LSP.
- 100% BR for NLSP → H + LSP.



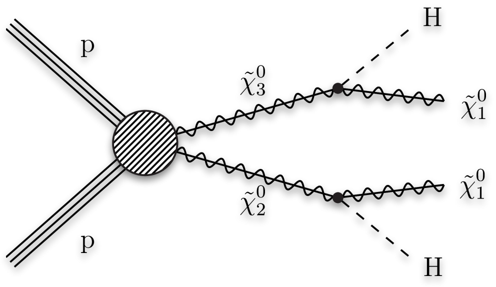
GMSB



TChiHH-G



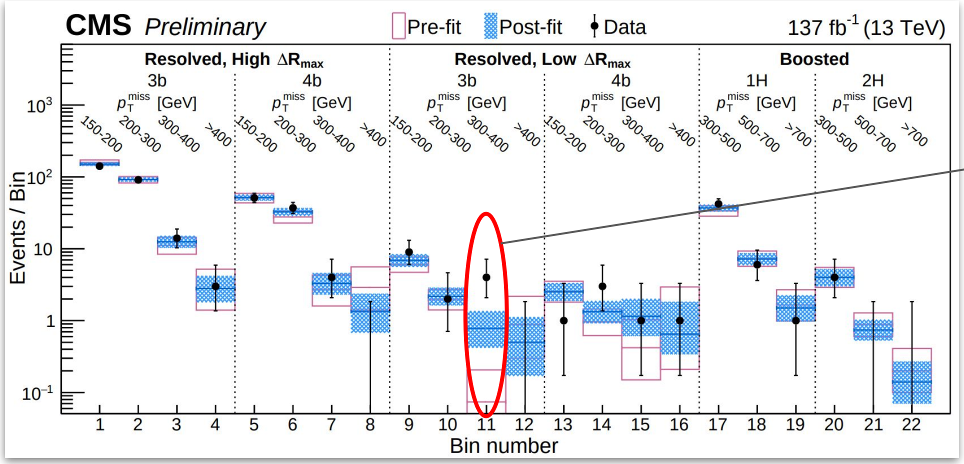
N2N3



TChiHH

Analysis strategy and results

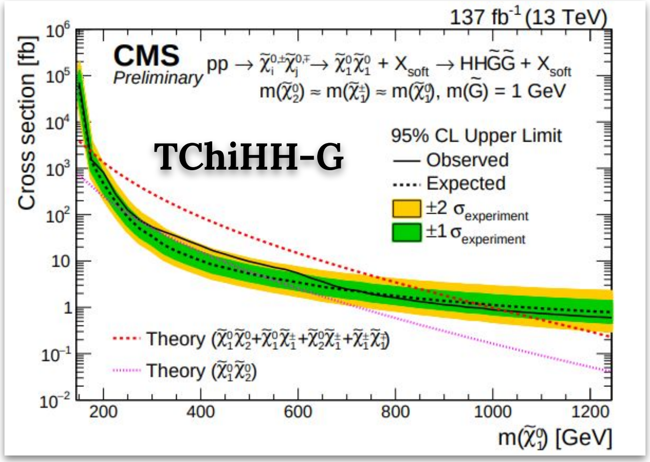
- Two types of search regions:
  - Resolved: targets low p_T Higgs boson scenarios.
  - Boosted: targets high p_T Higgs boson scenarios with AK8 jet mass and a DNN based bb tagger.
- tt and Z($\nu\nu$) are the dominant backgrounds.

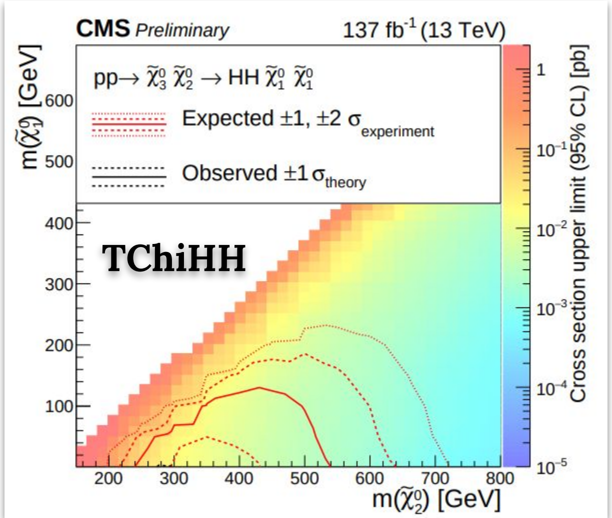


- ~3.2 σ local significance in one resolved category bin.
- A typical SUSY signal would populate several search bins - very unlikely to be a signal.

Interpretations

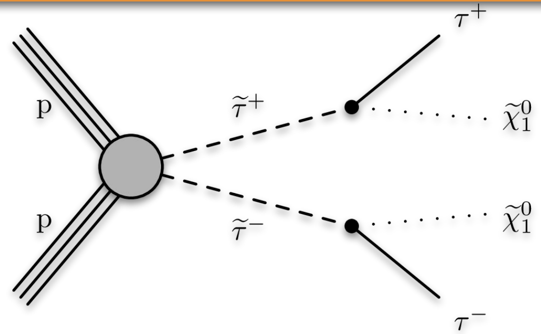
- GMSB scenario, TChiHH-G: mass exclusion 175 - 1025 GeV.
- N2N3 scenario, TChiHH: Starting to be sensitive to a large region of higgsino masses, even if there is no observed exclusion.



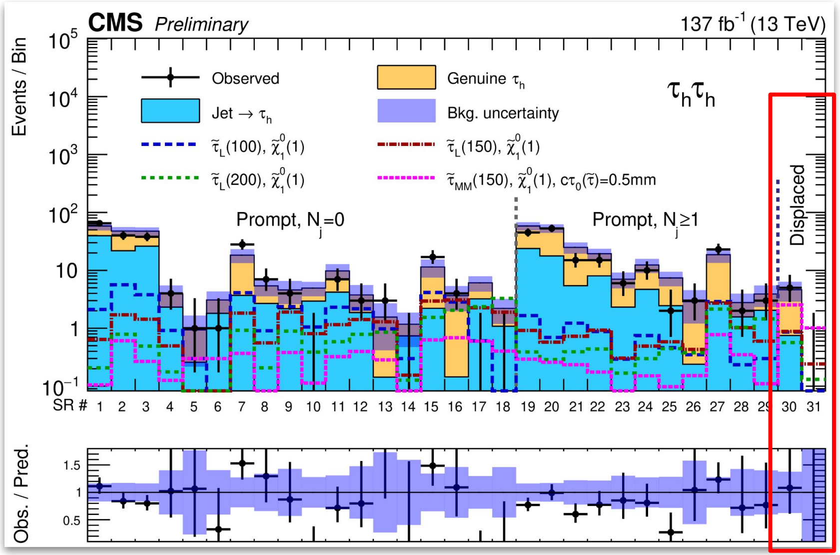


Stau pair search

- Direct pair production of staus (NSLP) with hadronic ditau final state.
- Promptly decaying stau and GMSB motivated long lived stau scenarios are considered.

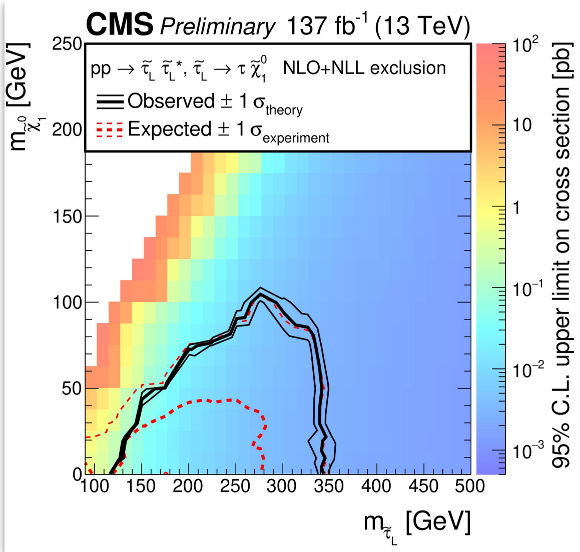


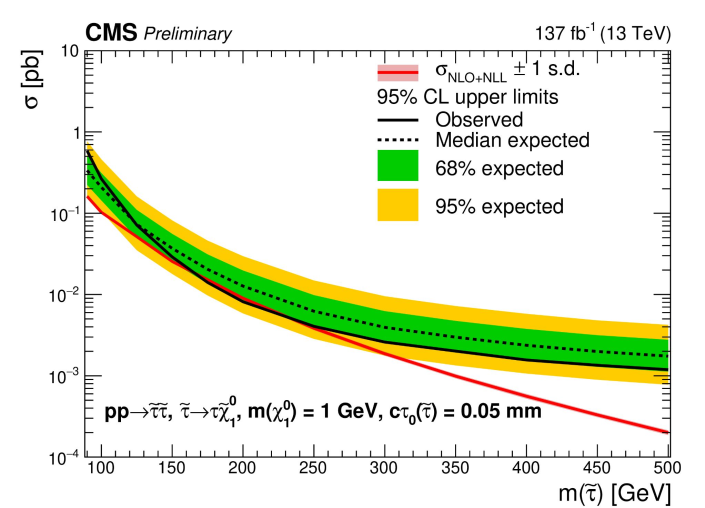
- m_T and m_{T2} are used to define search regions.
- Main background processes: DY→ $\tau\tau$, W($l\nu$), tt & QCD. DeepTau tagger is used to enhance signal to background discrimination.
- Observations are consistent with predictions from SM.



Interpretations

- Results are interpreted using left handed stau and degenerate stau scenarios.
  - Improvement from barely excluded stau-left results (using 77 fb^{-1}) to exclusion up to 350 GeV.
- Starting to exclude long lived stau scenarios as well.



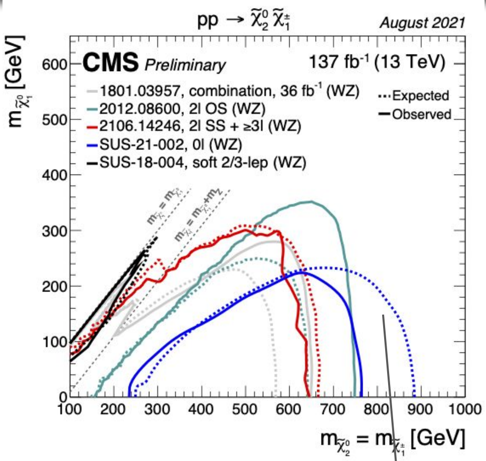


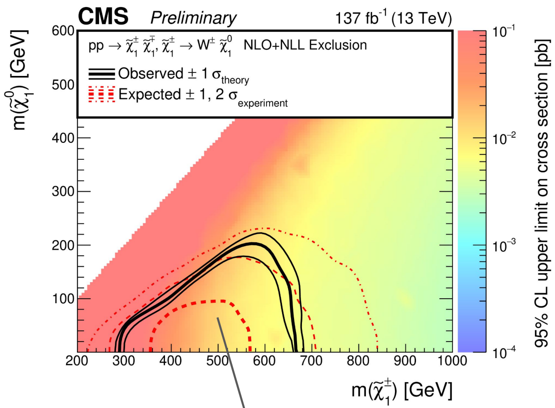
Summary & outlook

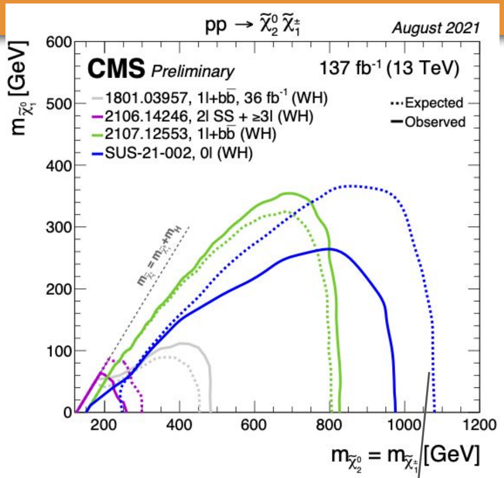
- With the help of new analysis techniques and large LHC dataset, CMS is expanding its hadronic final state searches.
- Expected chargino-neutralino limits for low m_{LSP} are
  - 880 GeV for WZ scenario (> 200 GeV better than leptonic searches).
  - 1100 GeV for WH scenario (~300 GeV better than leptonic searches).
- Significant improvements in sensitivity to higgsino scenarios and stau searches in the latest searches based on the full Run 2 dataset.
- Several new techniques have been developed in Run 2 and we'll improve them and *hope we discover* SUSY *in Run* 3!

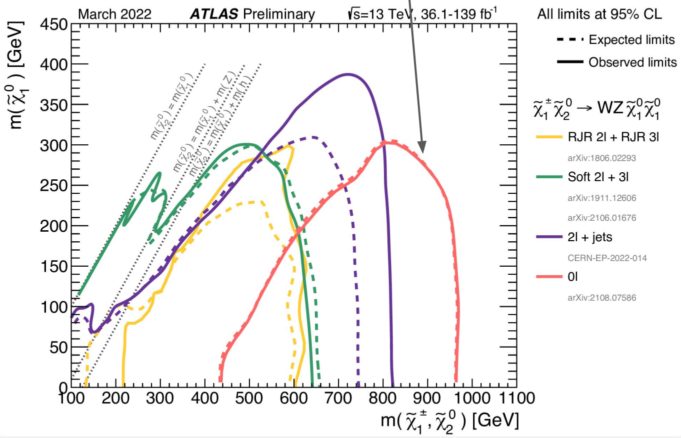
Additional information

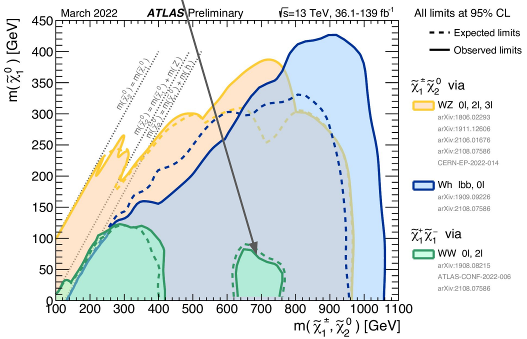
CMS vs ATLAS results - EW SUSY limits

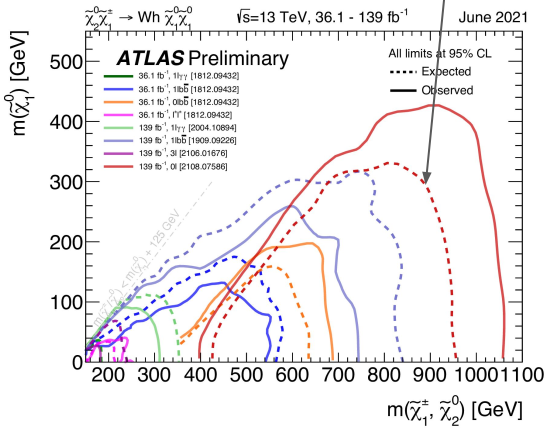




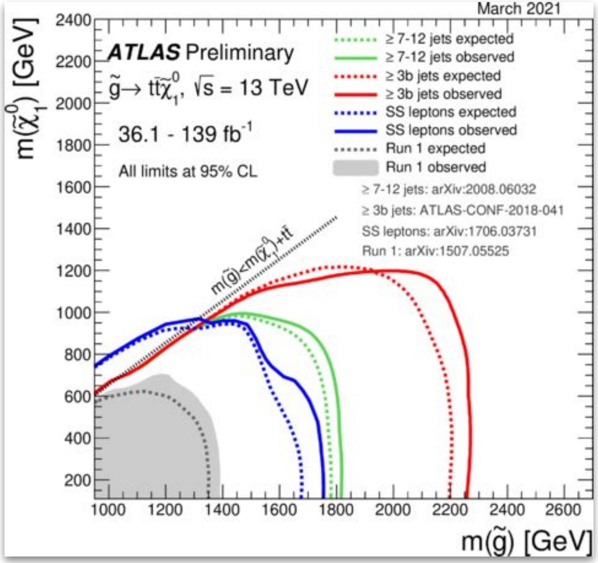


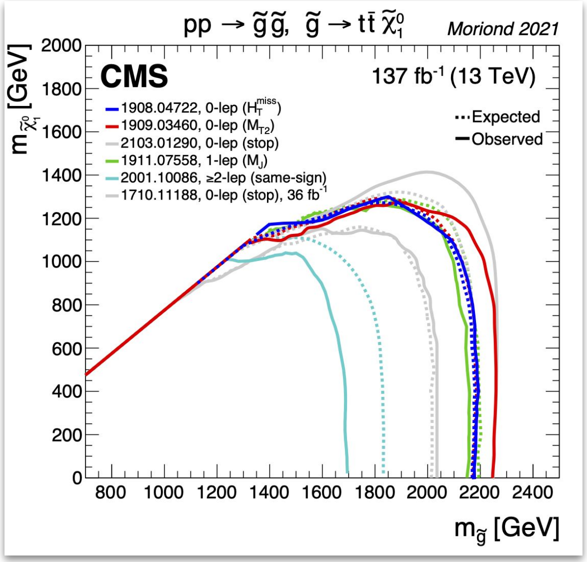






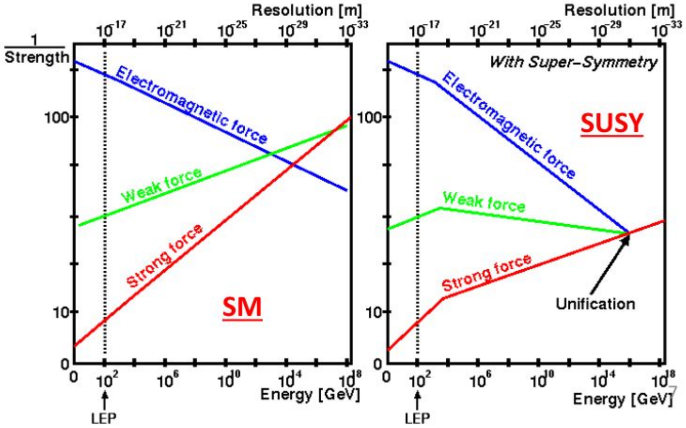
CMS vs ATLAS - Strong SUSY limits

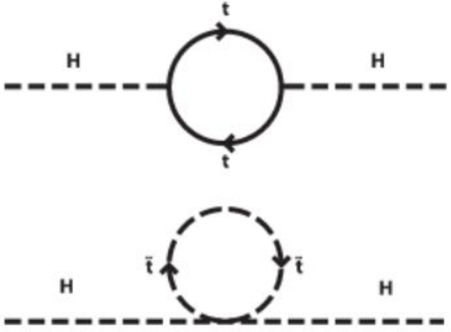




SUSY

- R-parity, $P_R = (-1)^{3(B-L)+2S}$, where B = baryon no., L = lepton no., S = spin. It is a multiplicative quantum number. SM particles have P_R = +1, SUSY particles have P_R = -1.
- RPC consequences = SUSY particles are pair produced and their decay must result in SUSY particles and SUSY particles cannot decay to SM particles only. Lightest SUSY particles (LSP) is stable.



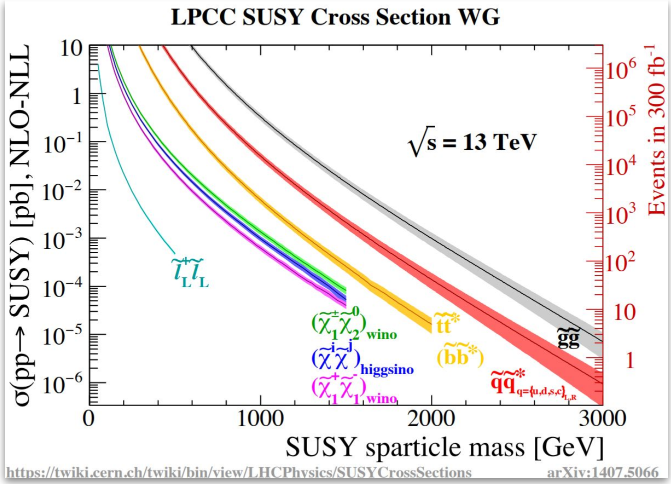


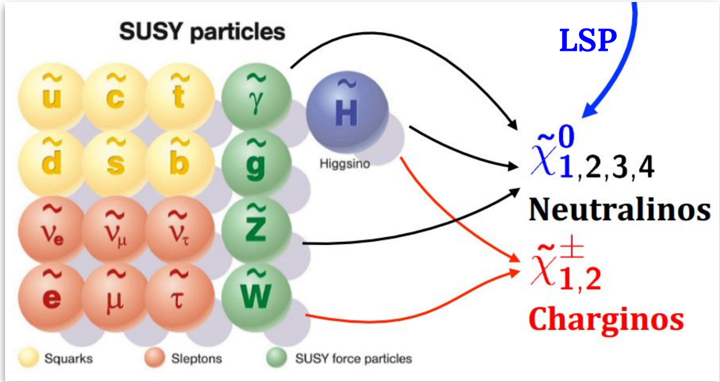
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\rm UV}^2 + ...].$$

$$\Delta m_H^2 = 2 \times \frac{\lambda_S}{16\pi^2}[\Lambda_{\rm UV}^2 + ...].$$

Exploring EW searches

- Strong SUSY production
  - Explored extensively since the start of LHC.
  - No hints for SUSY so far and limits are quite *strong*.
- Search for electroweak production is challenging since the cross sections are low.
- Naturalness → higgsinos mass near the EW scale.
- Probing small cross section EWKino:
  - leptonic signatures
  - advanced analysis techniques
  - large LHC dataset





SUSY - mass splitting

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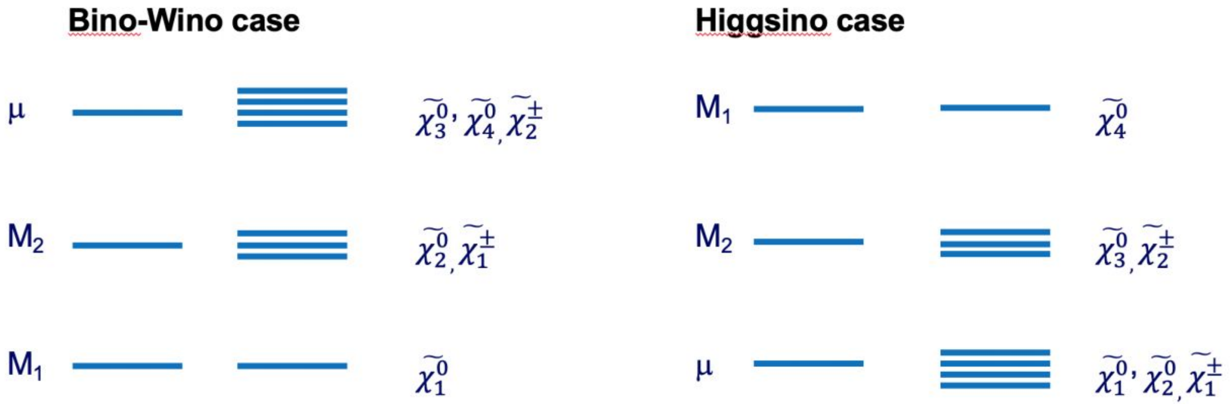
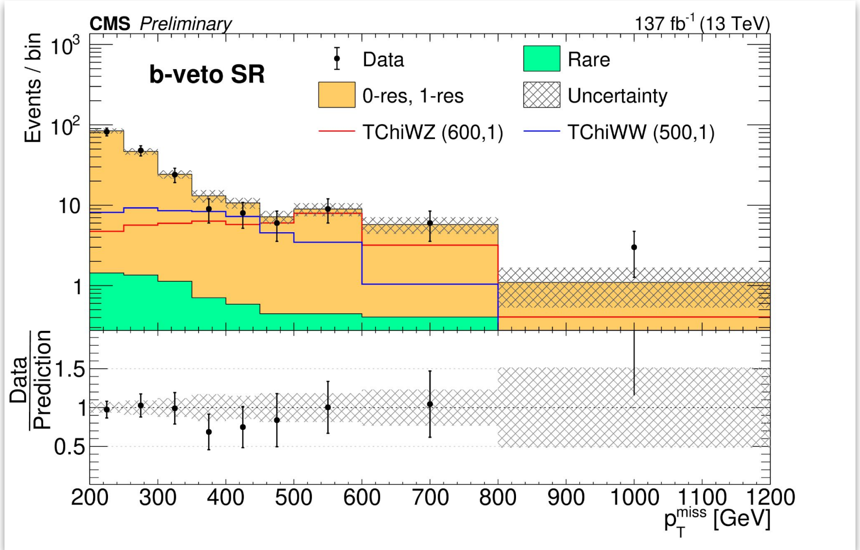
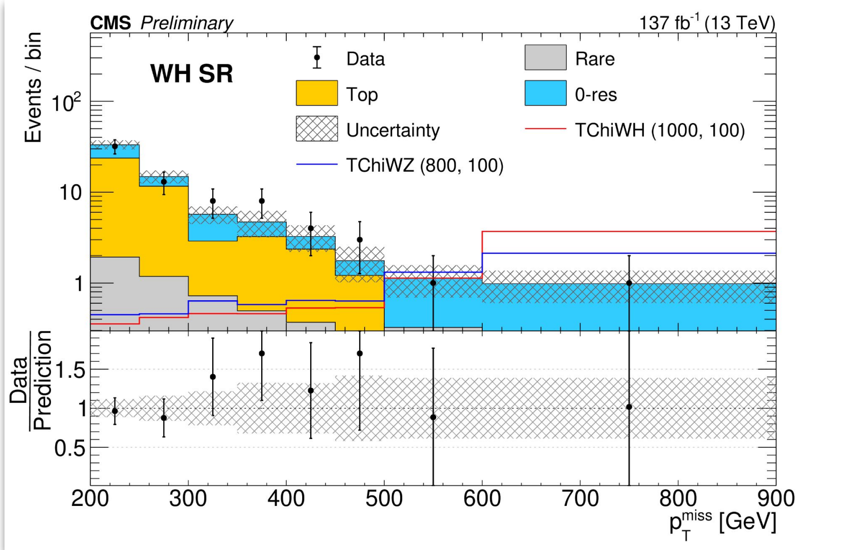


Background estimation and results

- Z(νν), W(lν) and tt are the dominant SM backgrounds.
- Background estimation uses control regions defined by inverting the deepAK8 discriminator cuts and single & dilepton regions.
- No significant deviations from SM predictions.





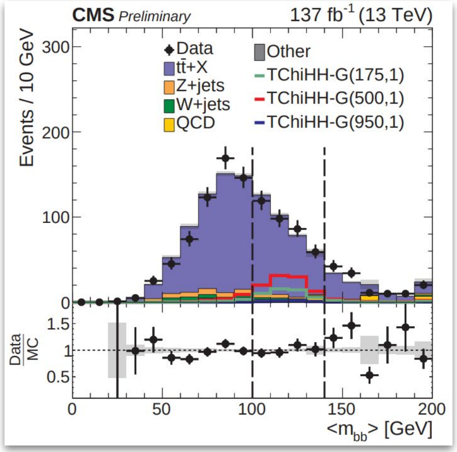
Analysis strategy

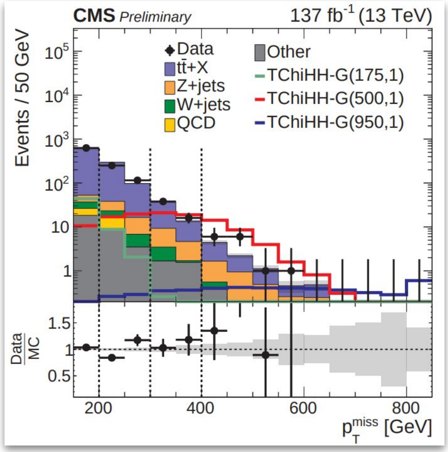
Resolved category

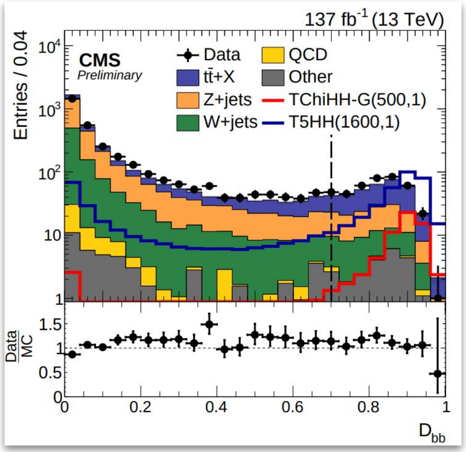
- Expect 4 AK4 jets from 2 low p_T H decays.
- Sensitive to low p_T^{miss} and $m_{NLSP} \sim m_{LSP}$ cases.
- Uses pairs of b-tagged jets to identify H candidates.

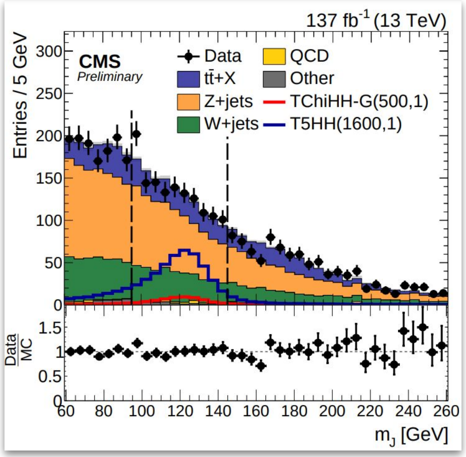
Boosted category

- Expect 2 AK8 jets from boosted H decays.
- Sensitive to high p_T^{miss}, high m_{NLSP} and $m_{NLSP} >> m_{LSP}$ cases.
- DeepAK8 bb-tagger to discriminate H candidates from background.



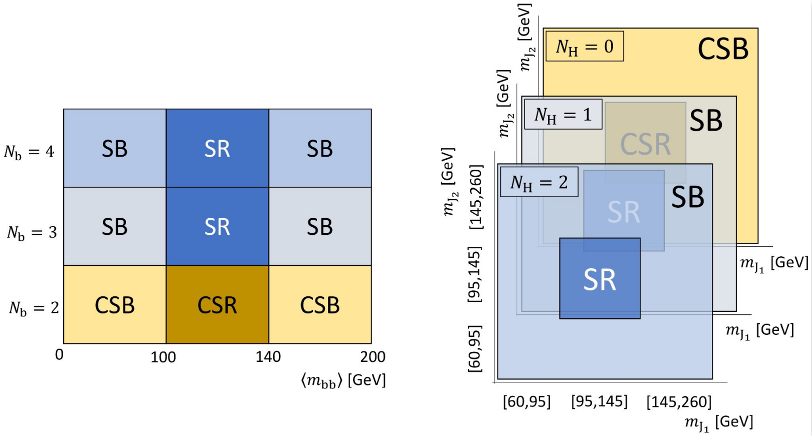


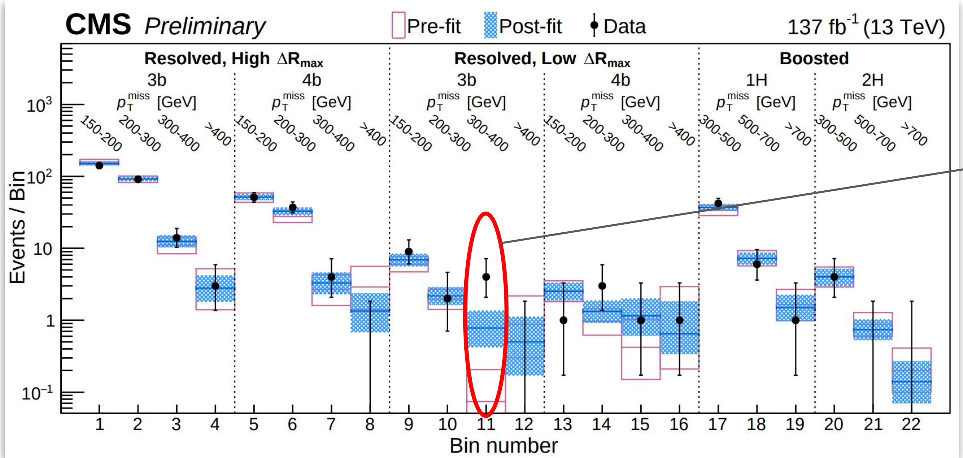




Background estimation and results

- tt and Z($\nu\nu$) are the dominant backgrounds.
- Background estimation uses *ABCD* method using mass sidebands and tagging.



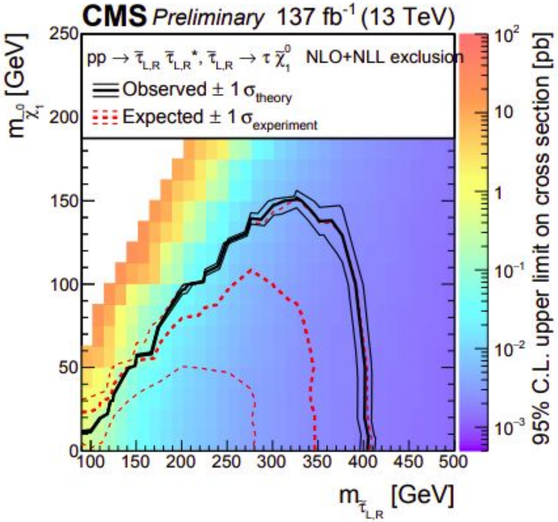


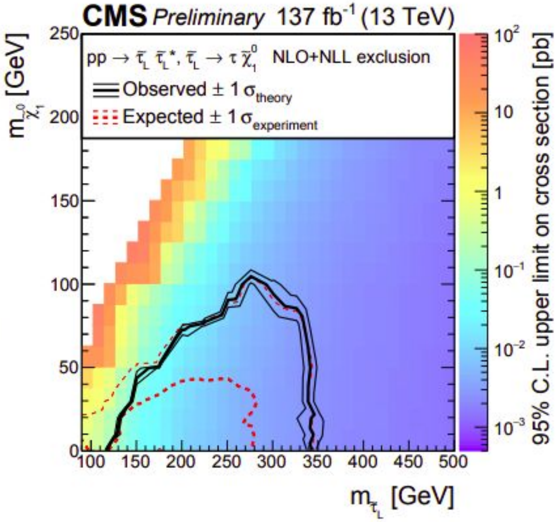
- ~3.2 σ local significance in one resolved category bin.
- A typical SUSY signal would populate several search bins - very unlikely to be a signal.

Stau search

$$\Sigma m_{\mathrm{T}} = m_{\mathrm{T}}(\tau_{\mathrm{h}}^{(1)}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}(\tau_{\mathrm{h}}^{(2)}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}),$$

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





Prompt SRs			
SR bin	Σm_T [GeV]	m_{T2} [GeV]	$p_T^{\tau_h 1}$ [GeV]
	$N_j = 0$		
1	200 – 250	25 – 50	< 90
2	200 – 250	25 – 50	> 90
3	200 – 250	50 – 75	< 90
4	200 – 250	50 – 75	> 90
5	200 – 250	> 75	—
6	250 – 300	25 – 50	< 90
7	250 – 300	25 – 50	> 90
8	250 – 300	50 – 75	< 90
9	250 – 300	50 – 75	> 90
10	250 – 300	> 75	—
11	300 – 350	25 – 50	—
12	300 – 350	50 – 75	—
13	300 – 350	75 – 100	—
14	300 – 350	> 100	—
15	> 350	25 – 50	—
16	> 350	50 – 75	—
17	> 350	75 – 100	—
18	> 350	> 100	—
	$N_j \geq 1$		
19	200 – 250	25 – 50	—
20	200 – 250	> 50	—
21	250 – 300	25 – 50	—
22	250 – 300	50 – 75	—
23	250 – 300	> 75	—
24	300 – 350	25 – 50	—
25	300 – 350	50 – 75	—
26	300 – 350	> 75	—
27	> 350	25 – 75	—
28	> 350	75 – 100	—
29	> 350	> 100	—
Displaced SRs			
SR bin		$p_T^{\tau_h 2}$ [GeV]	
30		< 110	
31		> 110	

What can we expect from HL-LHC?

- Run 2 → DeepAK8 taggers which clearly an improvement over previous tagging techniques. Run 3→ ParticleNet algorithms (something else?) have shown improvements over DeepAK8.
- ParticleNet regression techniques → improvement over soft-drop mass.
- As usual, we are going to have more data and better techniques! 😊