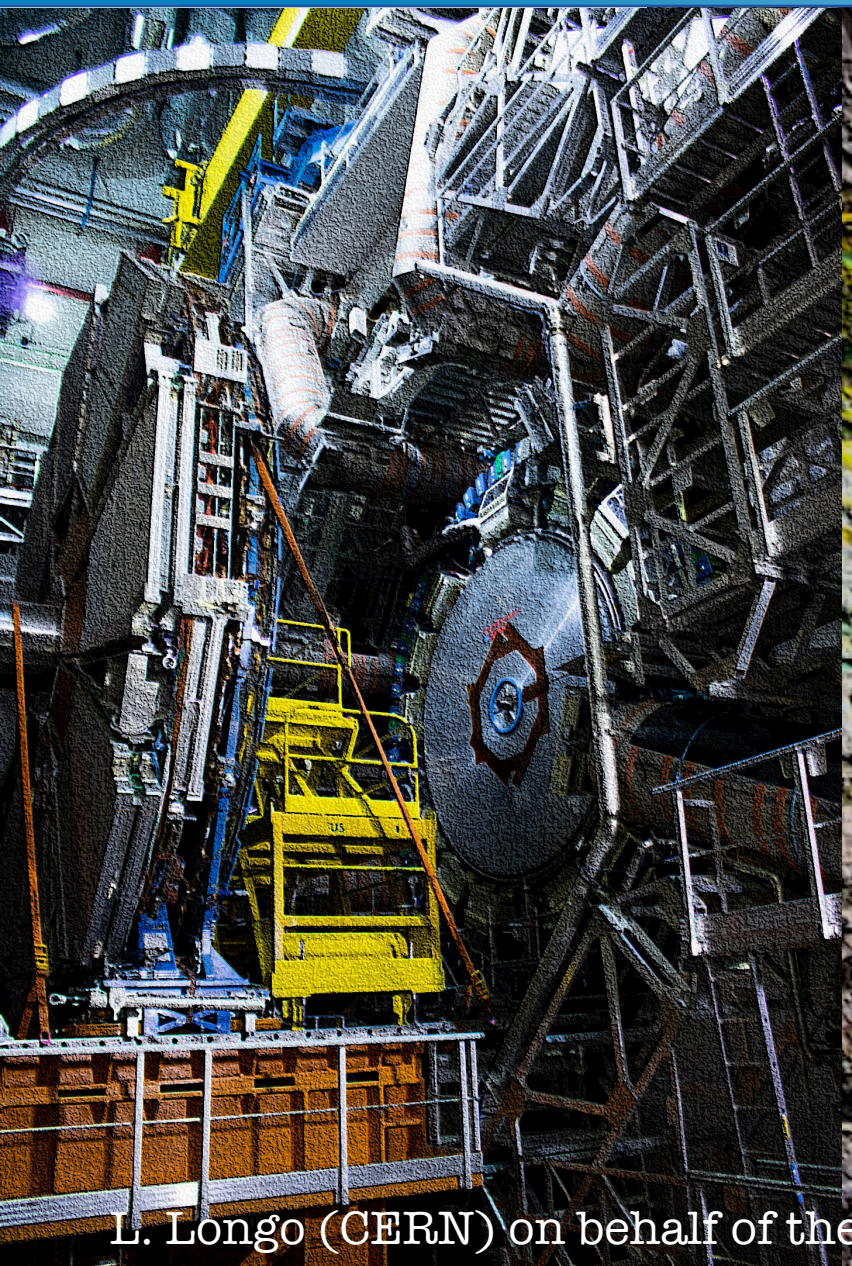
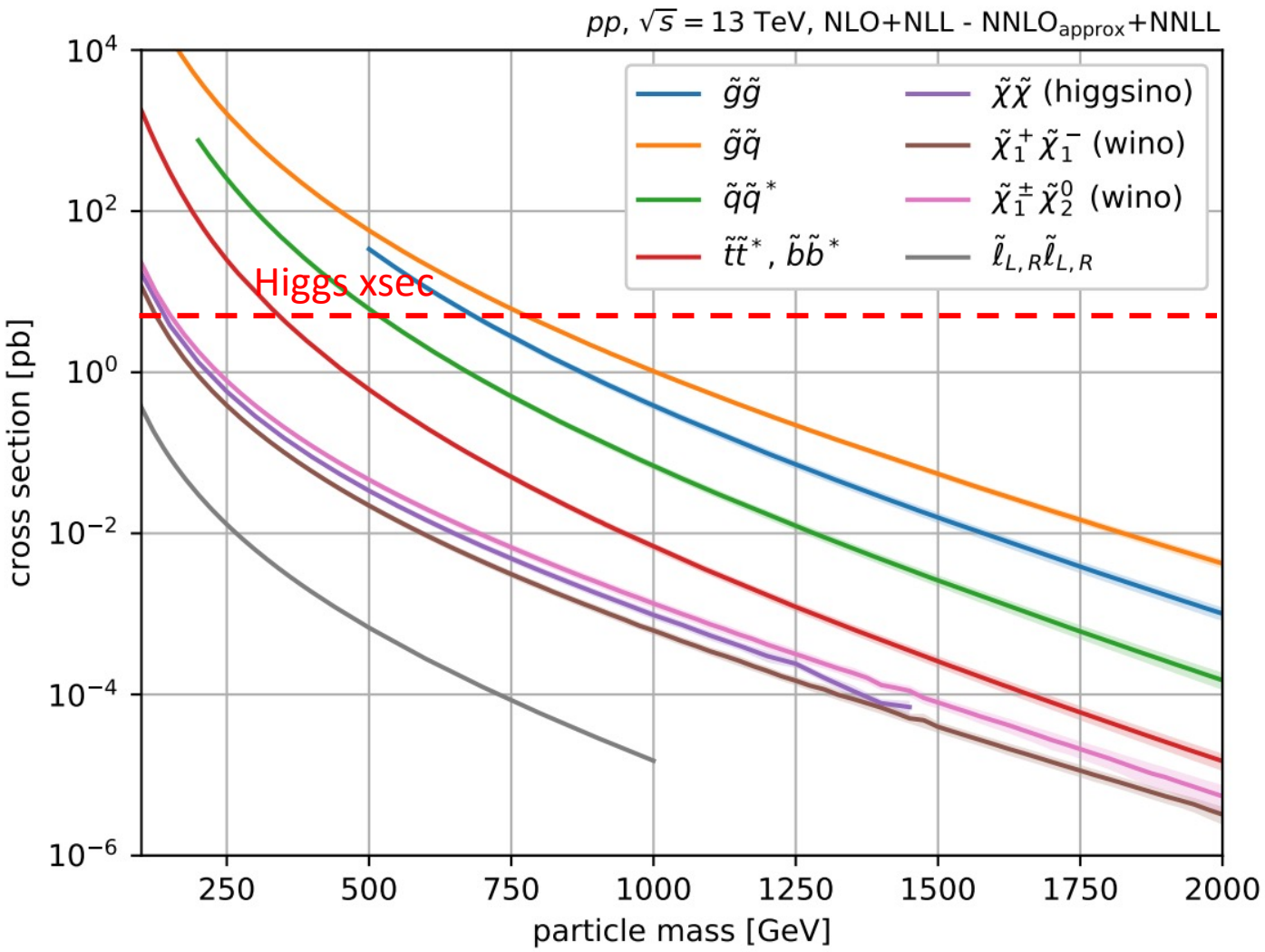


squark/gluino searches at ATLAS and CMS

SUSY2021

L. Longo (CERN) on behalf of the ATLAS and CMS Collaborations

Introduction



- Squarks/gluino largely investigated because of larger cross section
- Simplified models assumed as benchmarks for the analyses
- R-parity conserving models
- Depending on the signal model, squark and gluino masses have been excluded up to the TeV regime

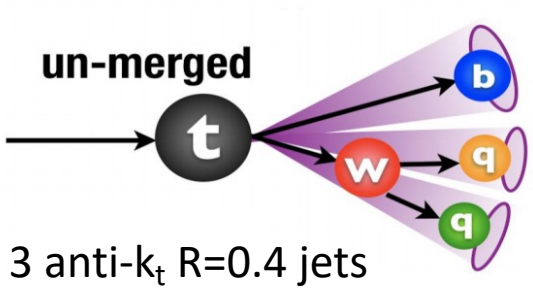
Introduction

To increase the sensitivity at higher masses and to close the gaps, different approaches/techniques have been followed/used:

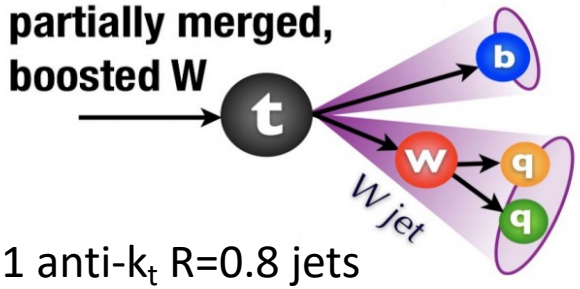
- top/W tagging
- Soft b-tagging
- Transverse missing energy (P_t^{miss}) significance
- machine learning
- new final state

$$h \to b\bar{b} \leftrightarrow h \to \tau\bar{\tau}$$

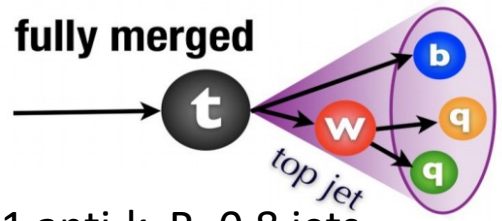
- combination



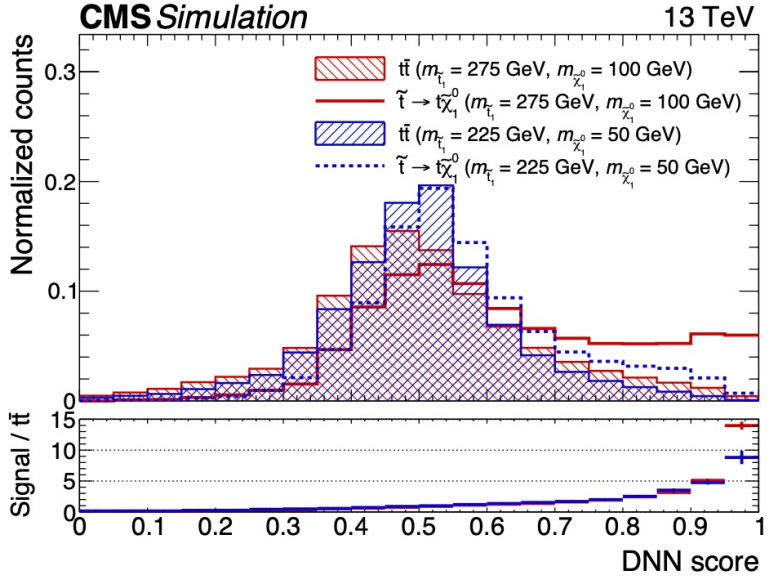
3 anti-k_t R=0.4 jets

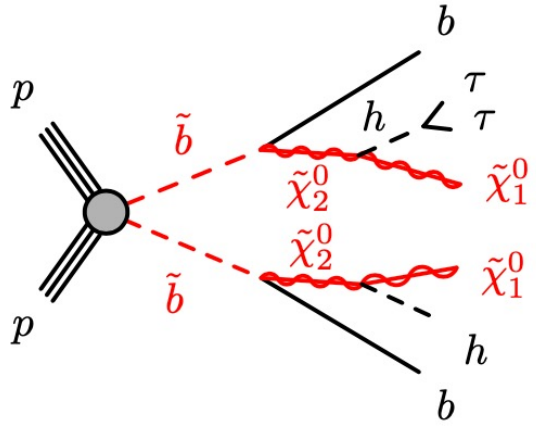


1 anti-k_t R=0.8 jets



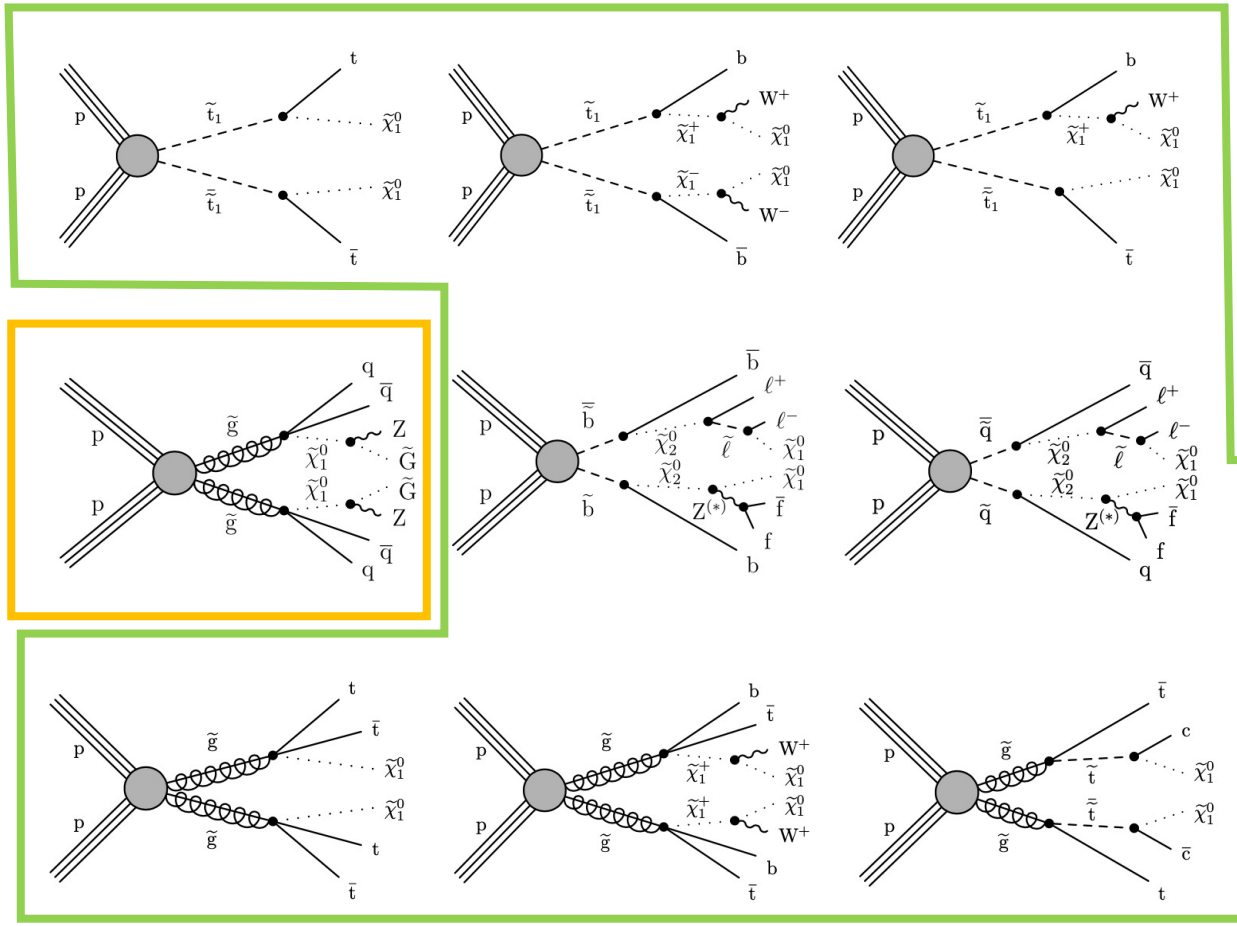
1 anti-k_t R=0.8 jets

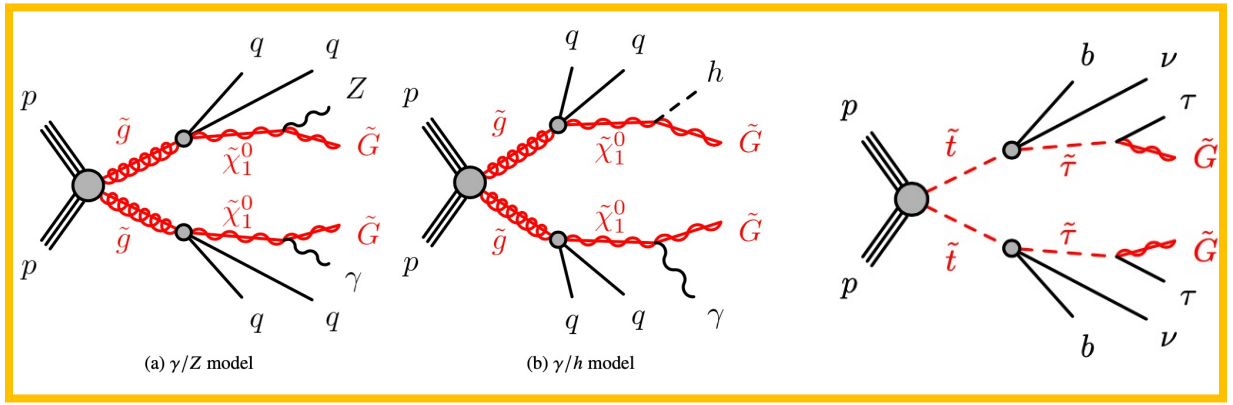


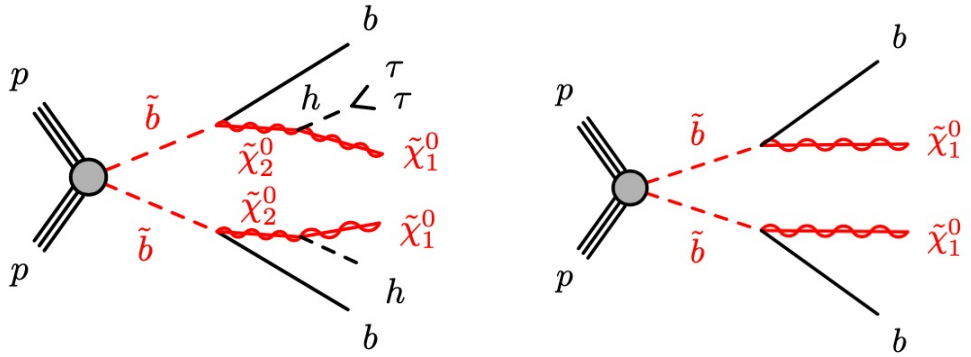


Introduction

Considered models assume the lightest neutralino or the gravitino as LSP







Analysis strategy optimize for similar final states

Introduction

CMS:

- Stop/gluino search in a fully hadronic final state - **arXiv:2103.01290**
- Stop search in a 2 leptons final state - **Eur. Phys. J. C 81 (2021) 3** & **arXiv:2107.10892**
- Combined results of the stop searches (0L, 1L, 2l) - **arXiv:2107.10892**
- Gluino/squark, sbottom search in a final state with 2 opposite sign same flavour leptons - **JHEP 04 (2021) 123**

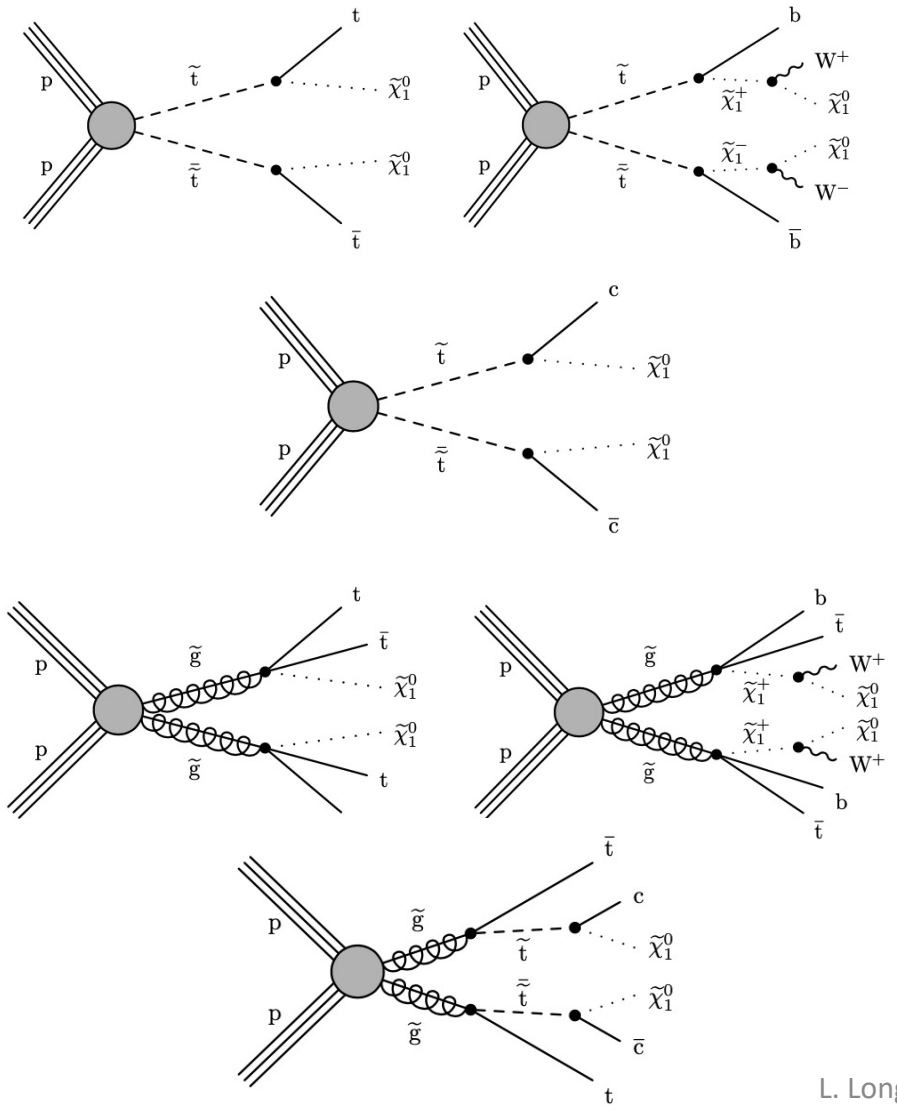
ATLAS:

- Gluino search with a photon and high jet multiplicity in the final state - **ATLAS-CONF-2021-028**
- Stop to stau search - **ATLAS-CONF-2021-008**
- Sbottom search with taus and b-quark in the final state - **arXiv:2103.08189**
- Sbottom search with only b-quark in the final state - **JHEP05 (2021) 093**

Stop/gluino - fully hadronic CMS

arXiv: 2103.01290

Several signal models considered in a fully hadronic final state:



Stop production

- $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(W)$
  - $\tilde{t}_1 \to t^* \tilde{\chi}_1^0$ with off-shell top and W
  - $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ with $\tilde{\chi}_1^\pm \to W^{+*} + \tilde{\chi}_1^0$, $m(\tilde{\chi}_1^\pm) = 0.5[m(\tilde{t}_1) + m(\tilde{\chi}_1^0)]$ with off-shell W
  - $\tilde{t}_1 \to c\tilde{\chi}_1^0$
  - ISR jet foreseen in the final state
- $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \geq m(W)$
  - the above decays $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ through on-shell W (and t if $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m(t)$)
  - a mixed decay mode of $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ (50%:50%) but with $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5$ GeV

Gluino production

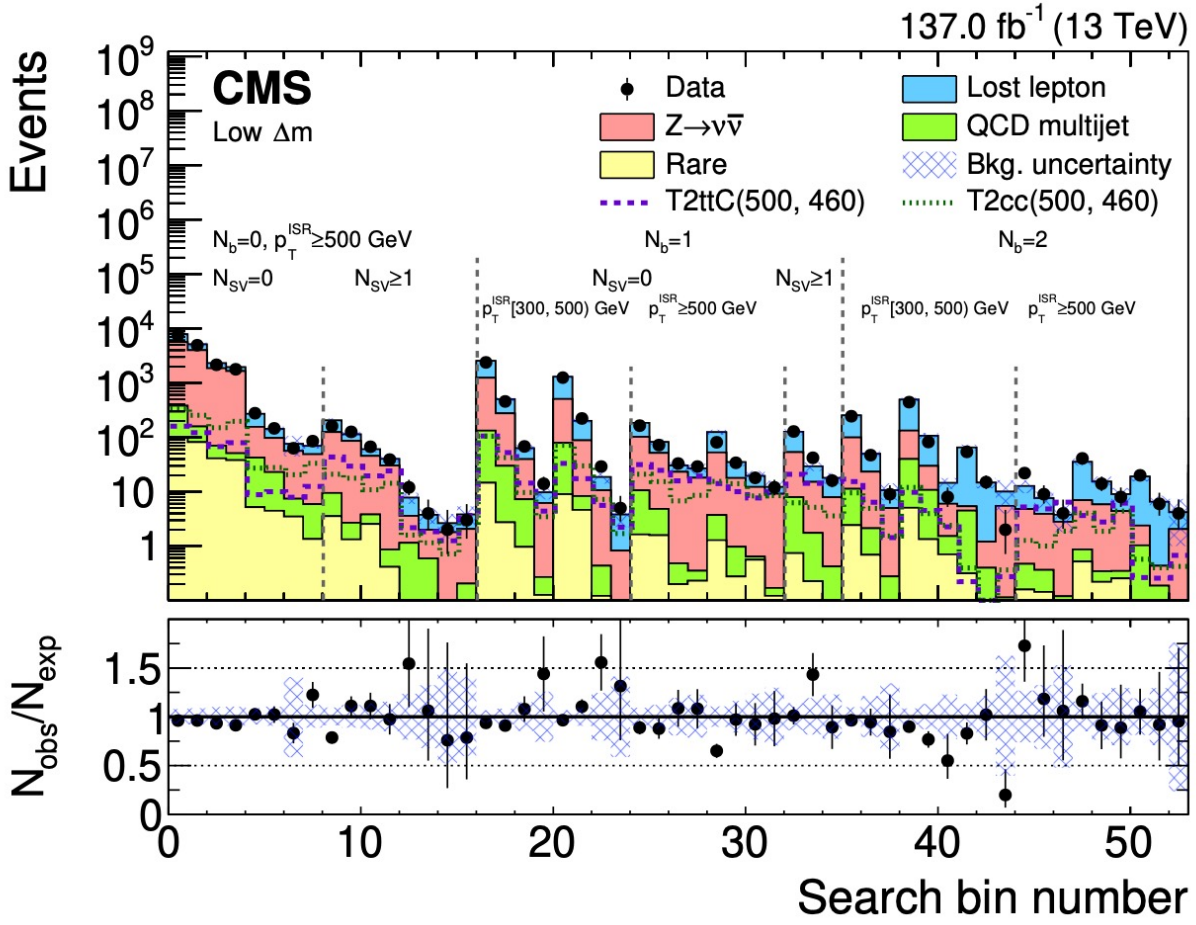
- $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ through an off-shell $\tilde{t}_1$
- a mixed decay mode with $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0(25\%), \tilde{g} \to \bar{t}b\tilde{\chi}_1^+(50\%), \tilde{g} \to t\bar{b}\tilde{\chi}_1^0(25\%)$ and $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5$ GeV
- $\tilde{g} \to \bar{t}\tilde{t}_1$ with $\tilde{t}_1 \to c\tilde{\chi}_1^0$, $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 20$ GeV $\to$ it can cover higher stop masses than $\tilde{t}_1 \to c\tilde{\chi}_1^0$

Stop/gluino - fully hadronic CMS

arXiv: 2103.01290

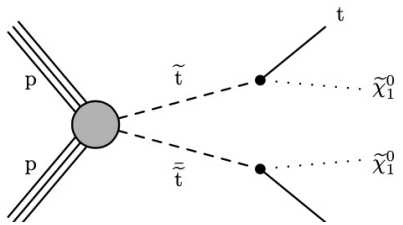
Low Δm analysis strategy:

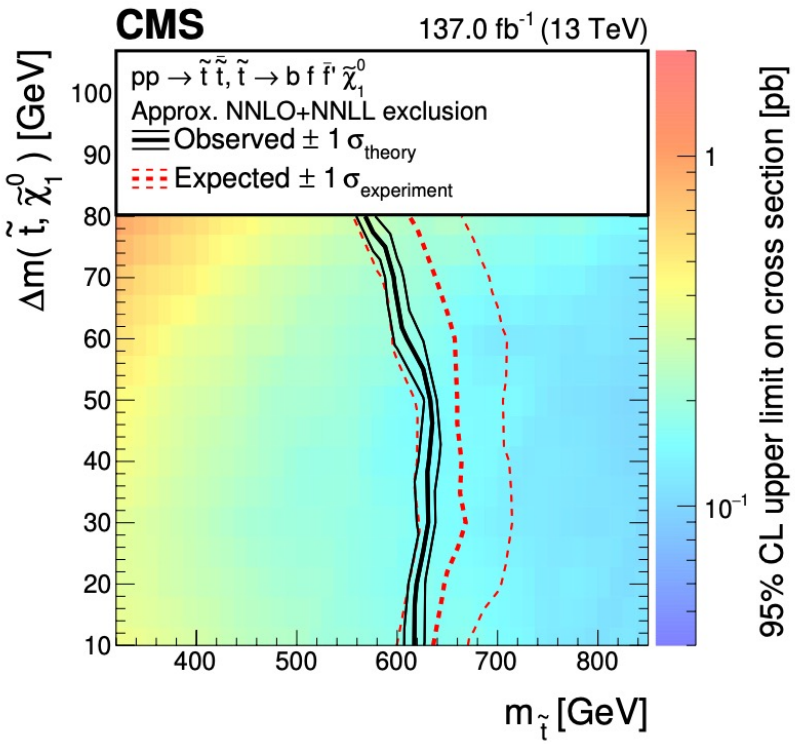
- ISR jet
- Categories based on:
  - secondary vertex (soft *b*-quark), N_{SV}
  - *b*-tagged jets
- Looking at different slices of
  - P_t of the ISR jet
  - P_t of the *b*-tagged jets
  - Transverse missing energy (P_t^{miss})

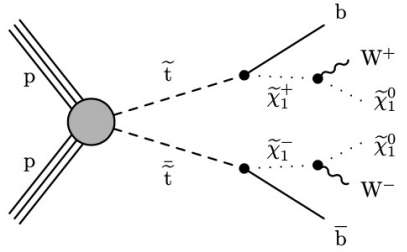


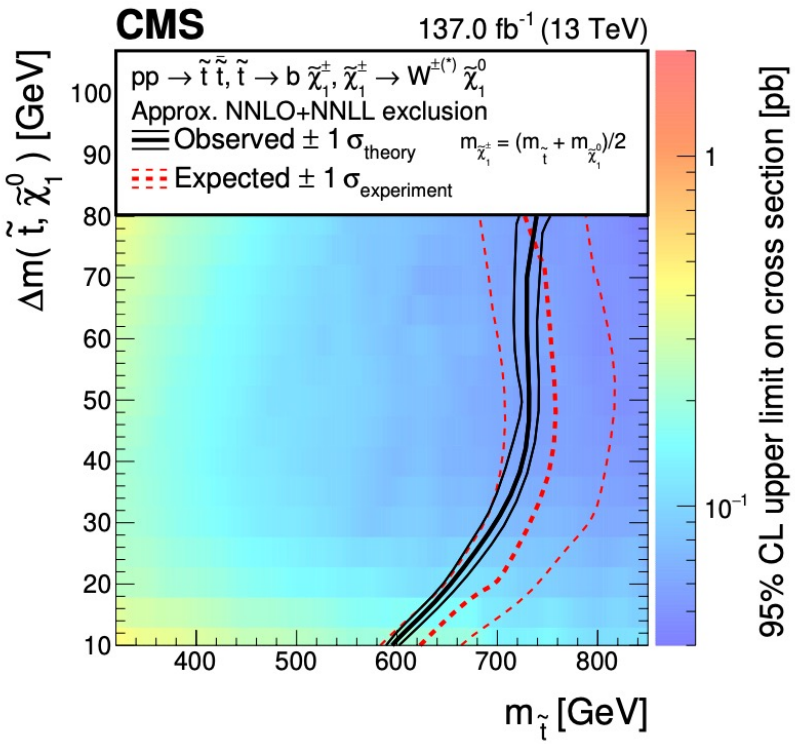
Stop/gluino - fully hadronic CMS

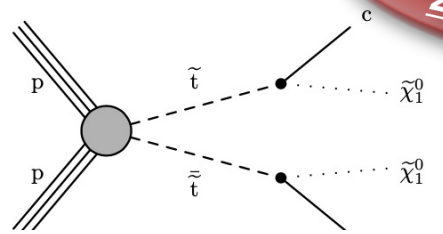
arXiv: 2103.01290

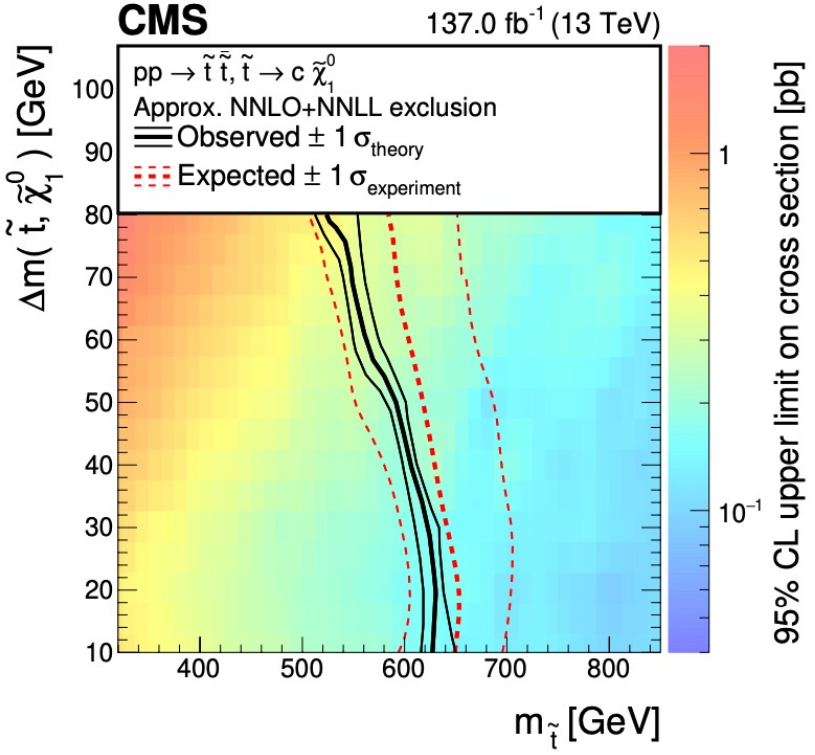








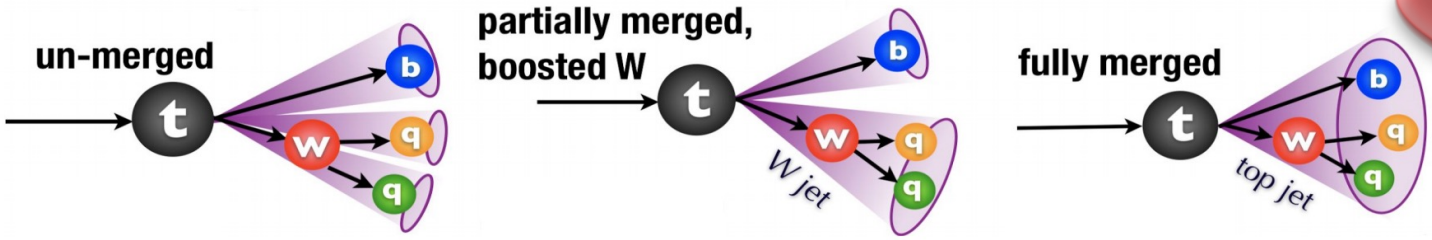




Stop/gluino - fully hadronic CMS

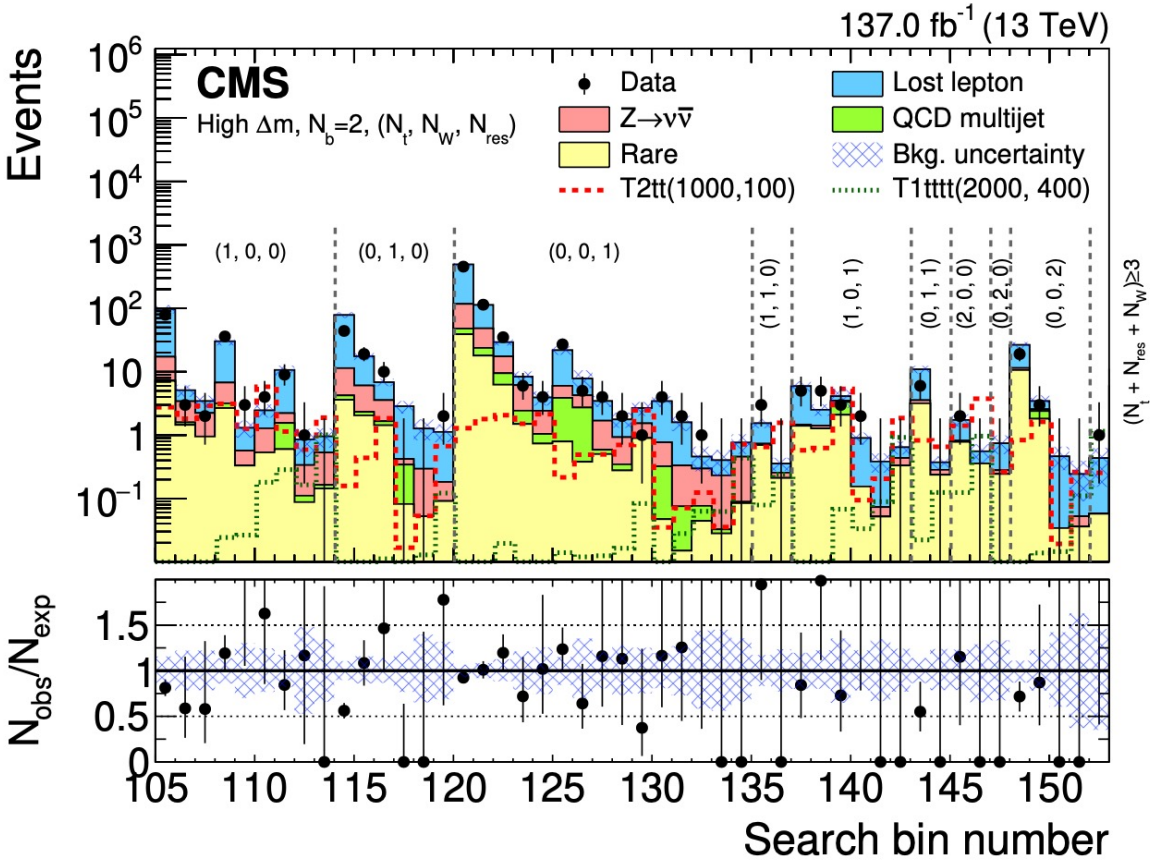
arXiv: 2103.01290

High Δm analysis strategy:



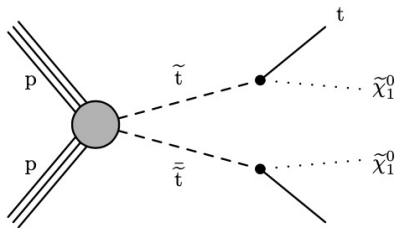
- Categories based on:
  - *b*-tagged jets
  - top-tagged jets
  - W-tagged jets
  - Number of residual tri-jets (not flagged as top, W candidate)

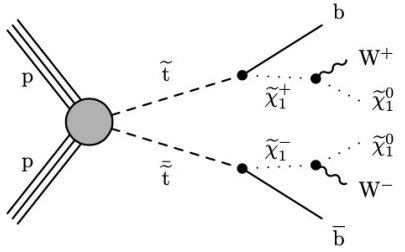
- Looking at different slices of
  - the scalar sum of the jets P_t (H_T)
  - P_t of the *b*-tagged jets
  - Transverse missing energy (P_t^{miss})

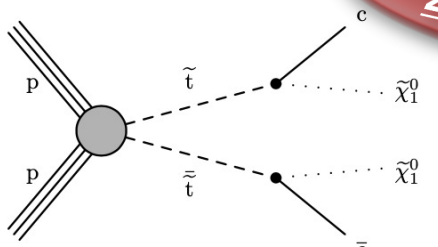


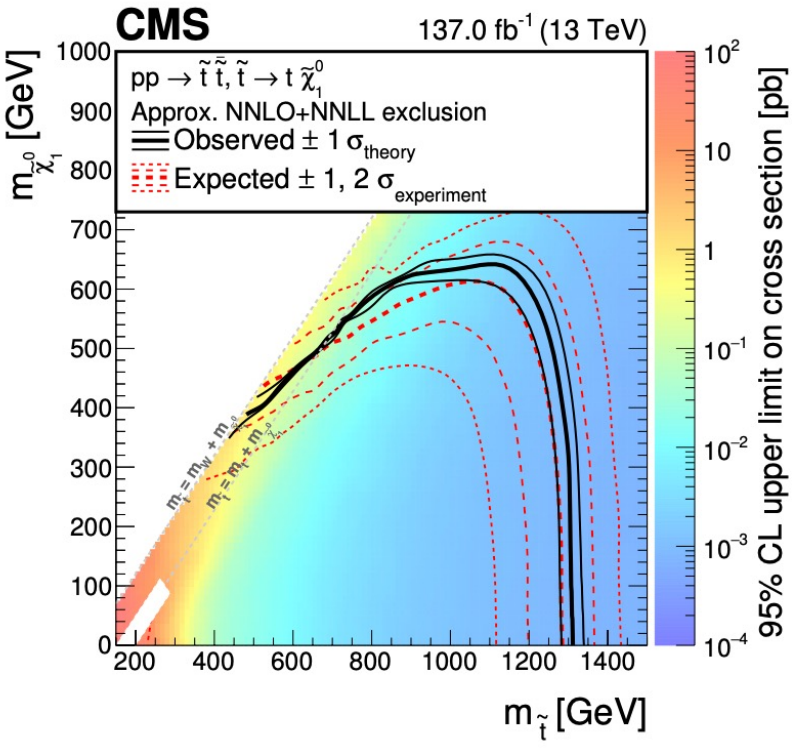
Stop/gluino - fully hadronic CMS

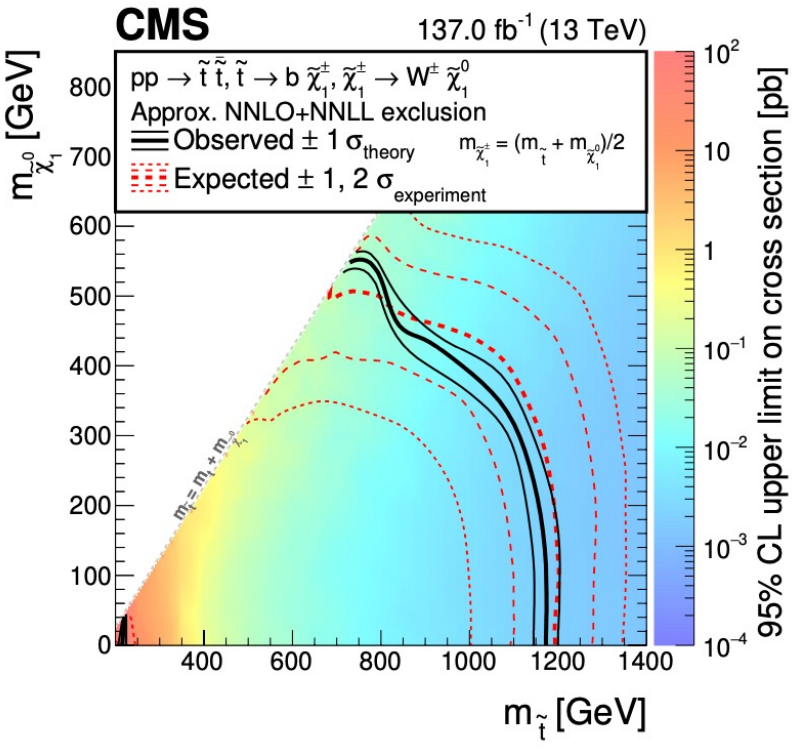
arXiv: 2103.01290

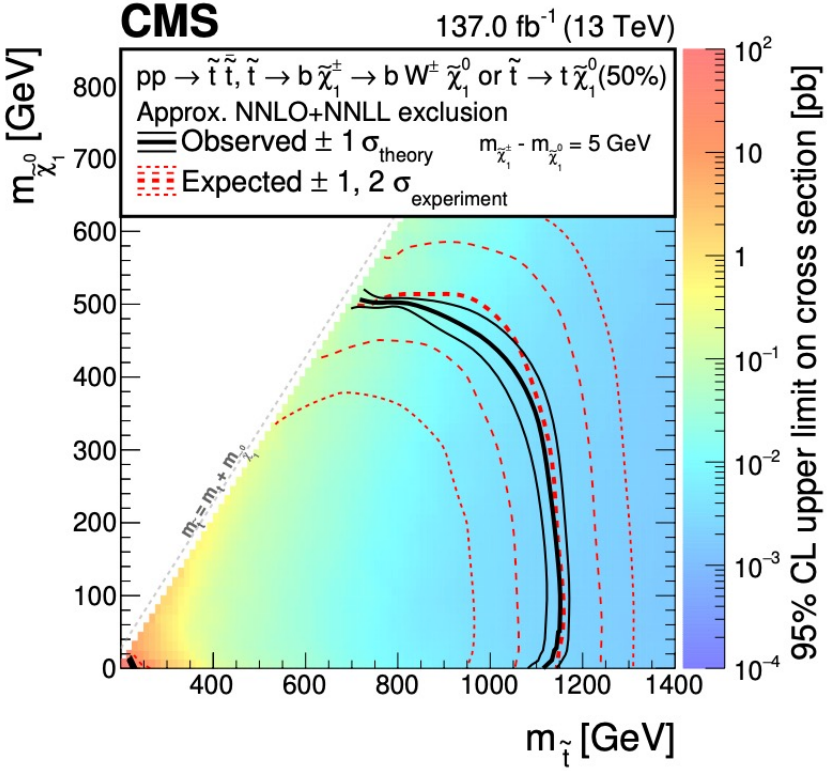






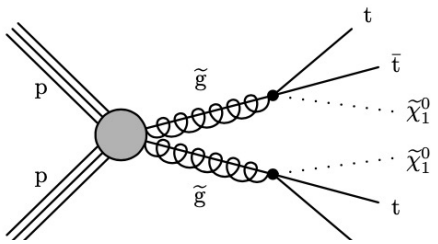


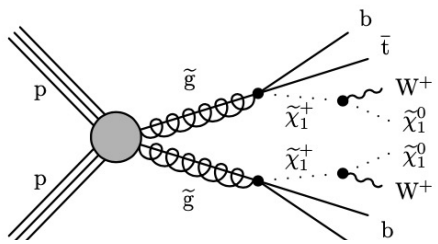


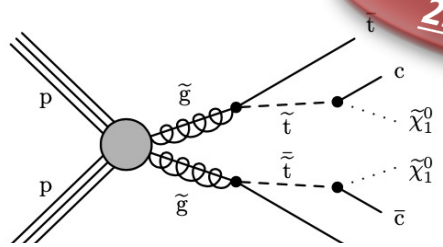


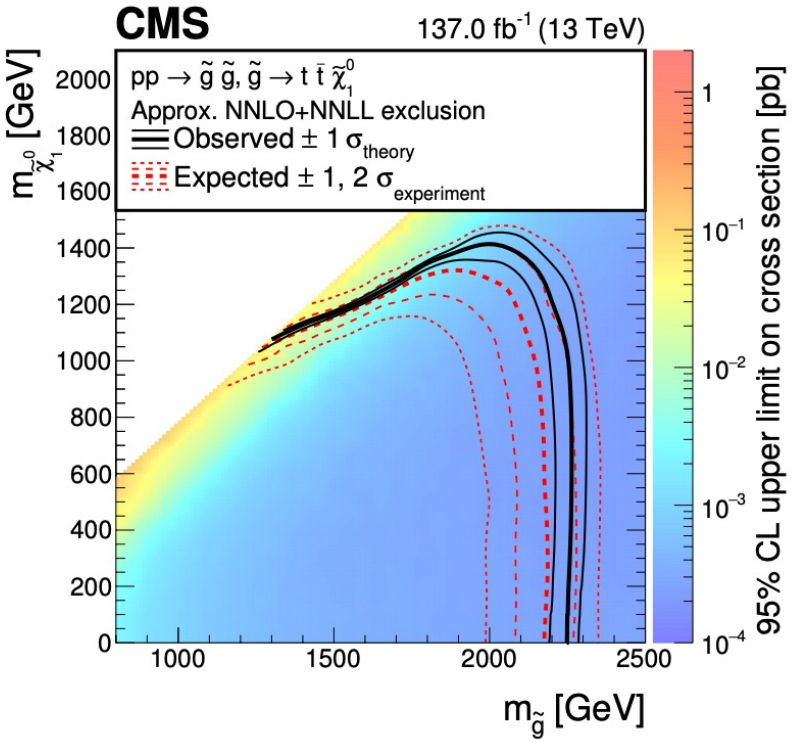
Stop/gluino - fully hadronic CMS

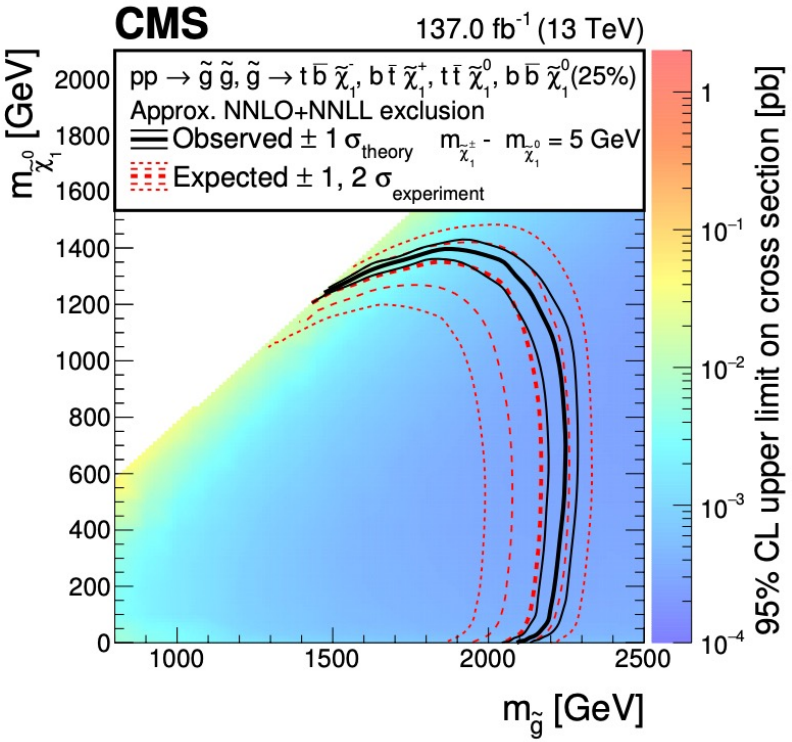
arXiv: 2103.01290

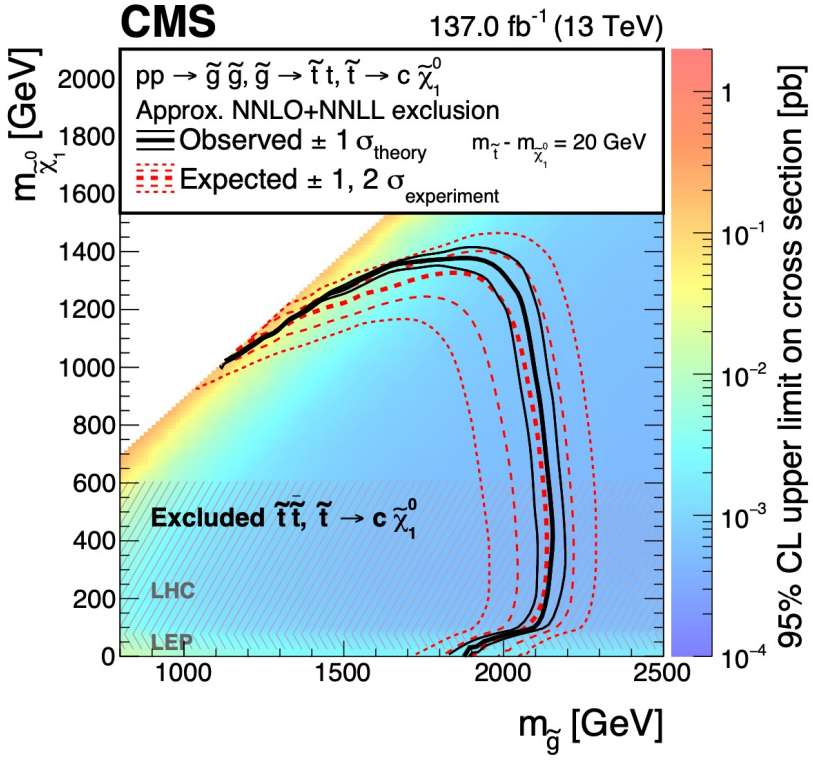








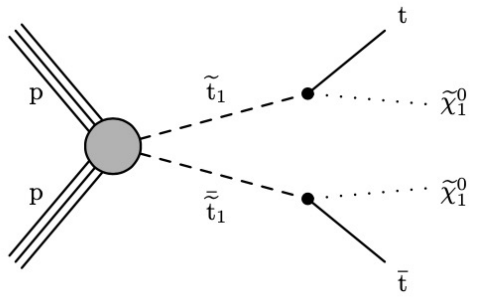


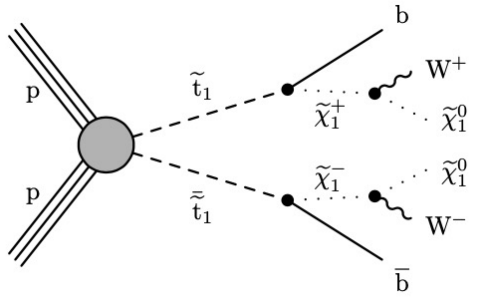


Stop – 2 leptons CMS

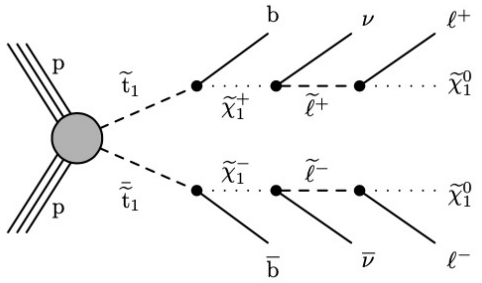
Eur. Phys. J. C 81 (2021) 3

Signal models:





$m(\tilde{\chi}_1^{\pm}) = 0.5[m(\tilde{t}_1) + m(\tilde{\chi}_1^0)]$



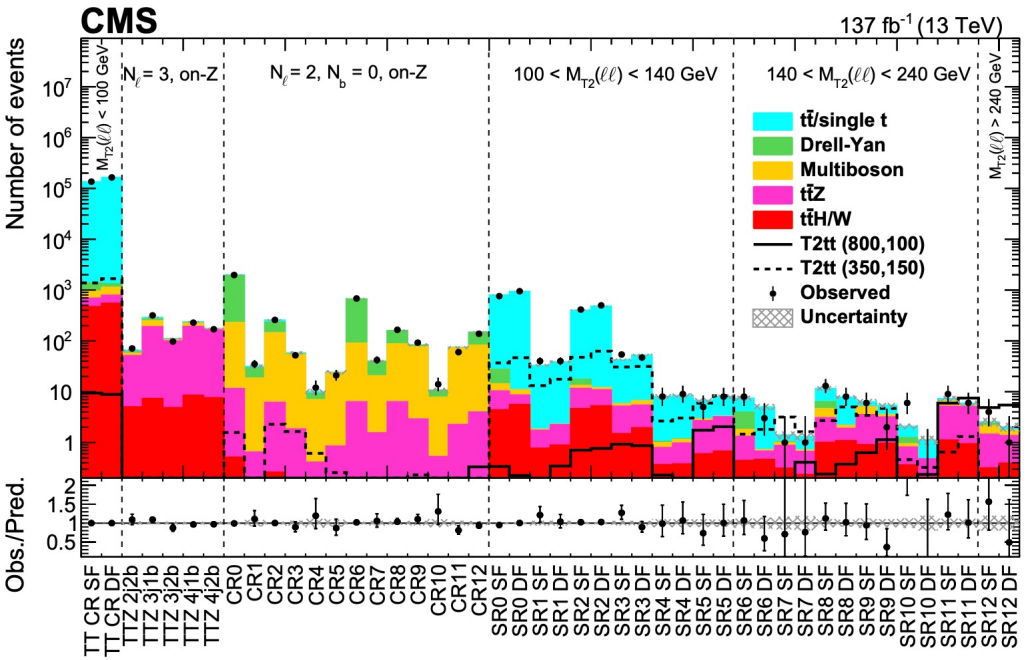
$m(\tilde{\chi}_1^{\pm}) = 0.5[m(\tilde{t}_1) + m(\tilde{\chi}_1^0)]$

$m(\tilde{l}) = x\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) + m(\tilde{\chi}_1^0)$ with x=(0.95, 0.50, 0.05)

Analysis strategy:

- Request of a genuine P_t^{miss} significance
- Categorization in terms of $M_{T2}(ll)$, $M_{T2}(blbl)$, P_t^{miss} significance

$$M_{T2}(\ell\ell) = \min_{\vec{p}_T^{miss1} + \vec{p}_T^{miss2} = \vec{p}_T^{miss}} \left(\max \left[M_T(\vec{p}_T^{vis1}, \vec{p}_T^{miss1}), M_T(\vec{p}_T^{vis2}, \vec{p}_T^{miss2}) \right] \right)$$



Stop – 2 leptons CMS

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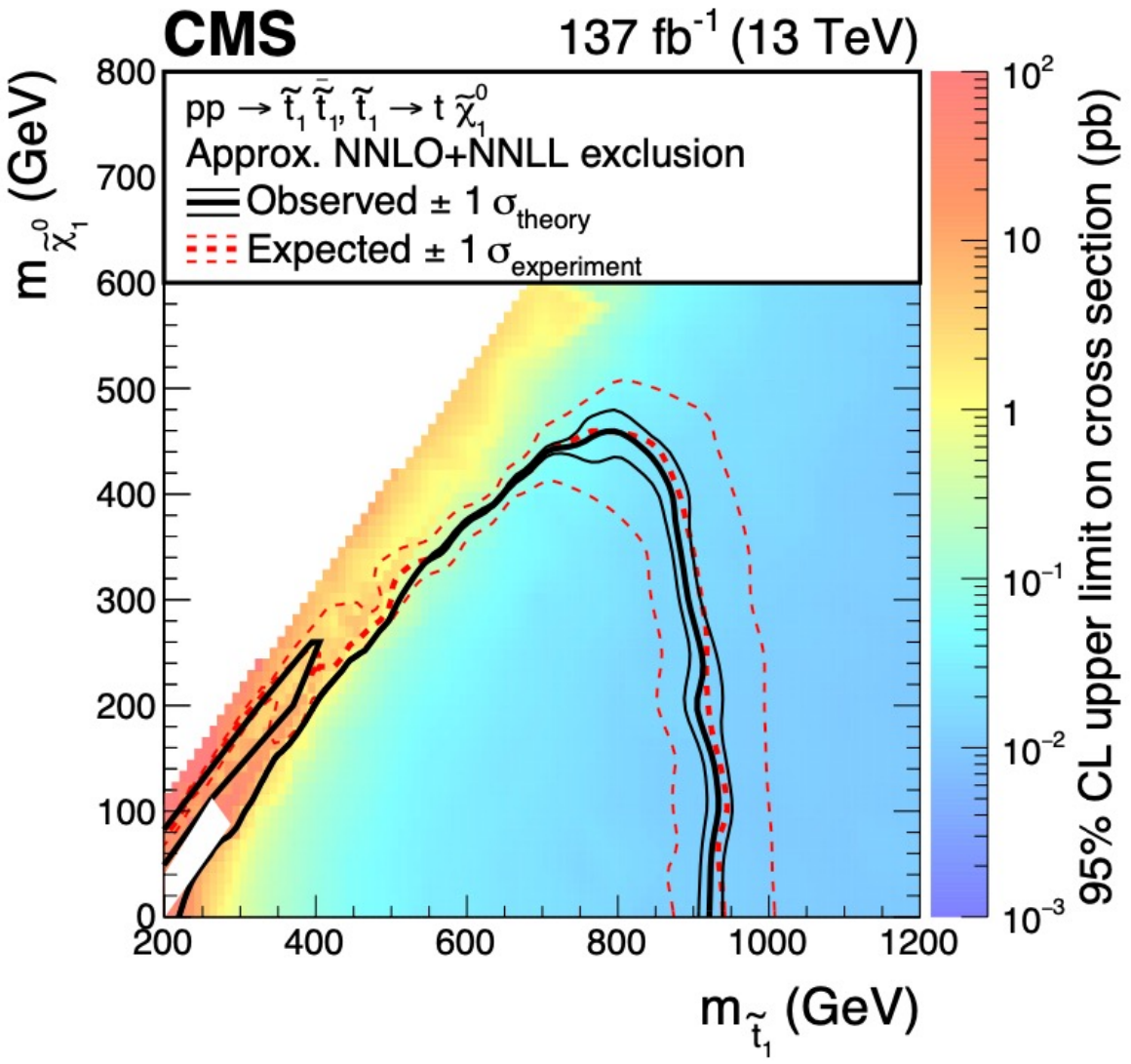
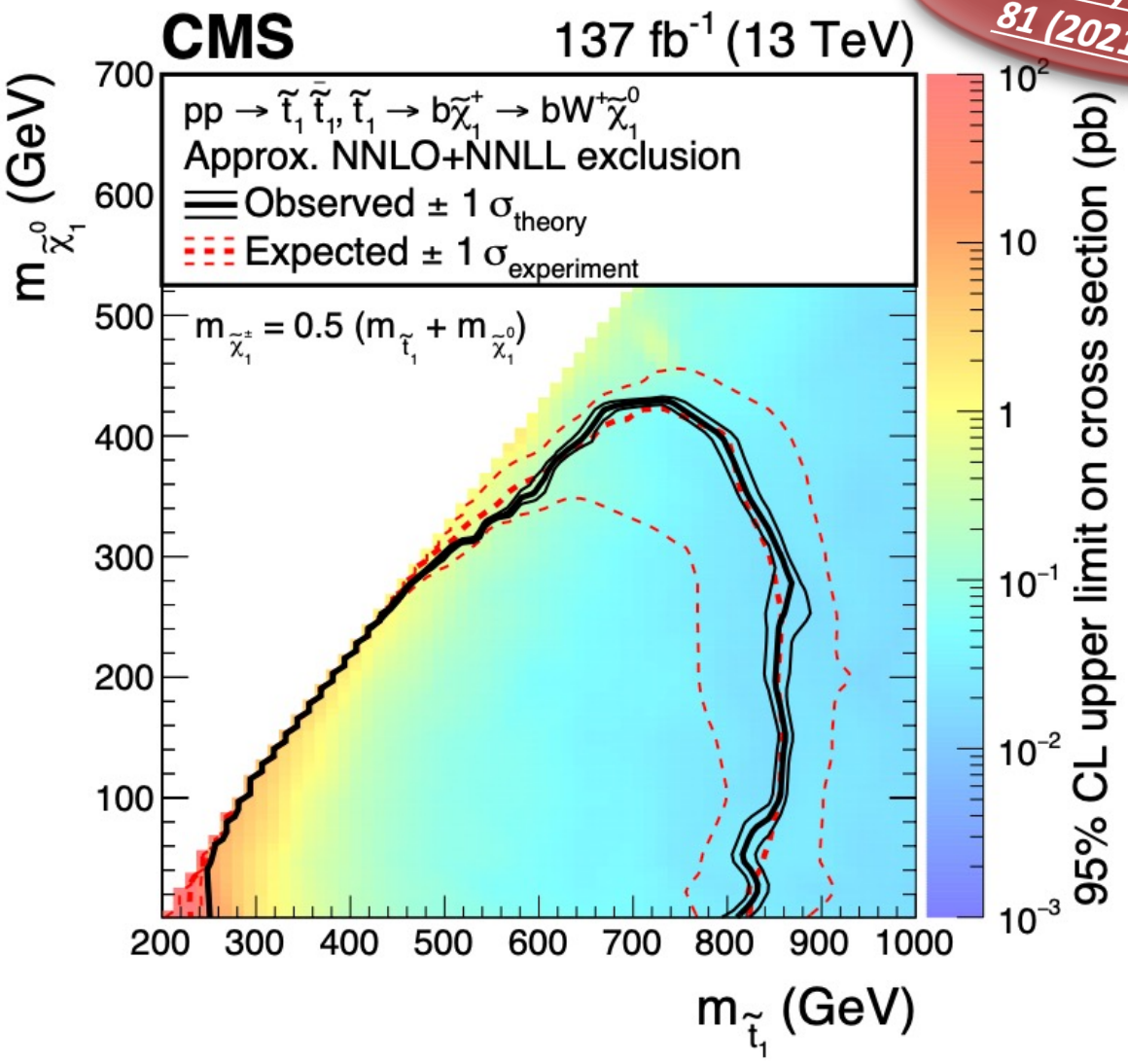
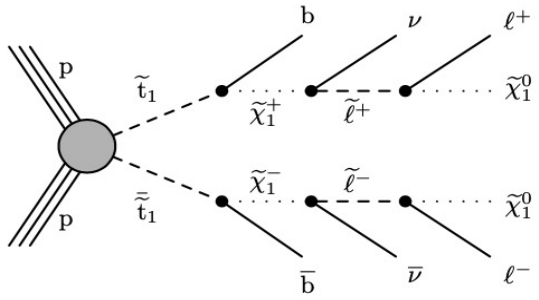
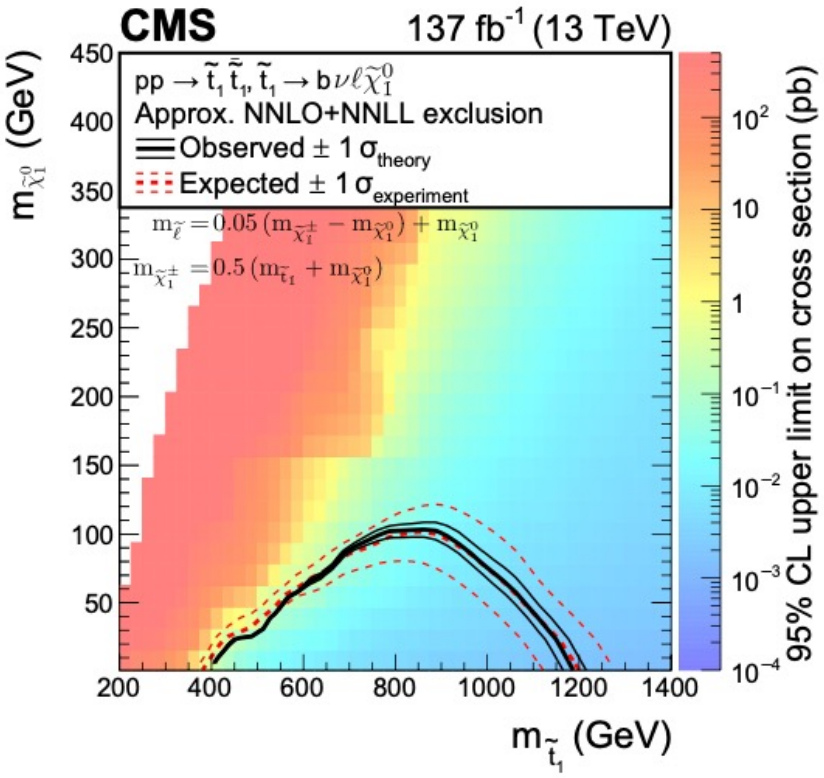


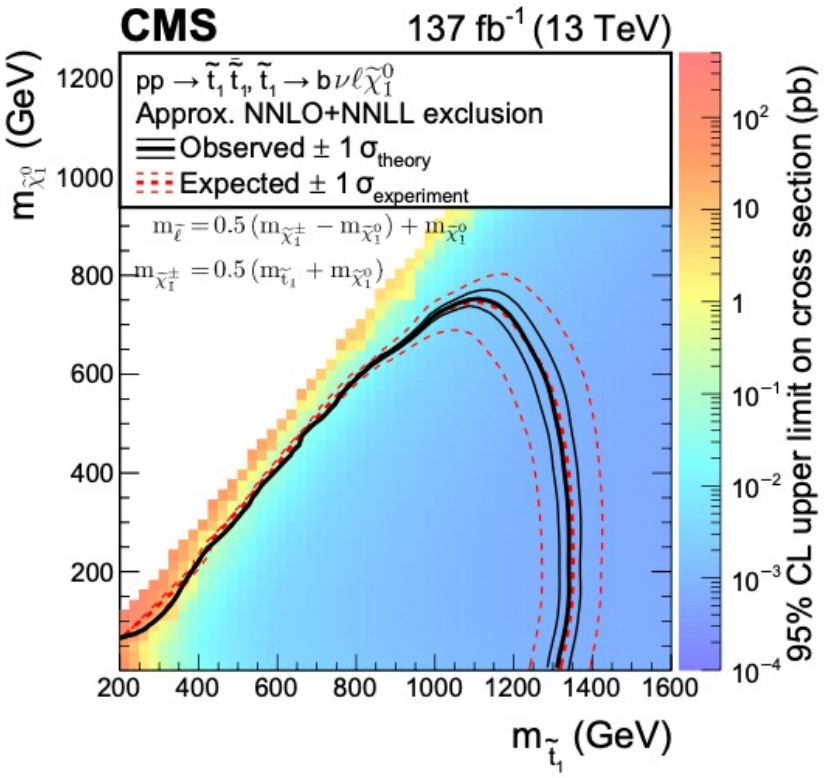


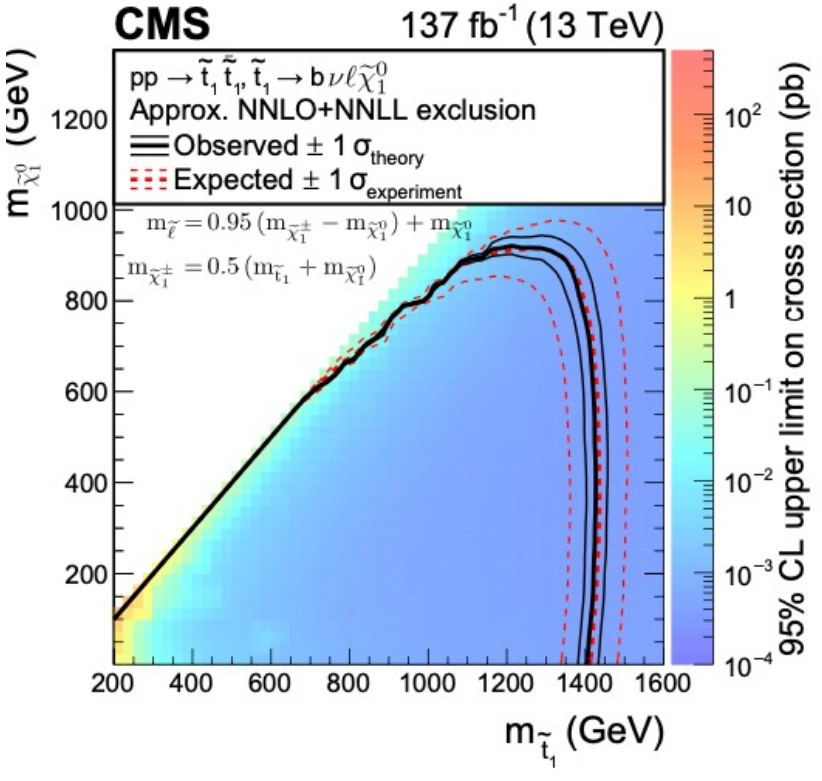
Stop – 2 leptons CMS

Eur. Phys. J. C 81 (2021) 3







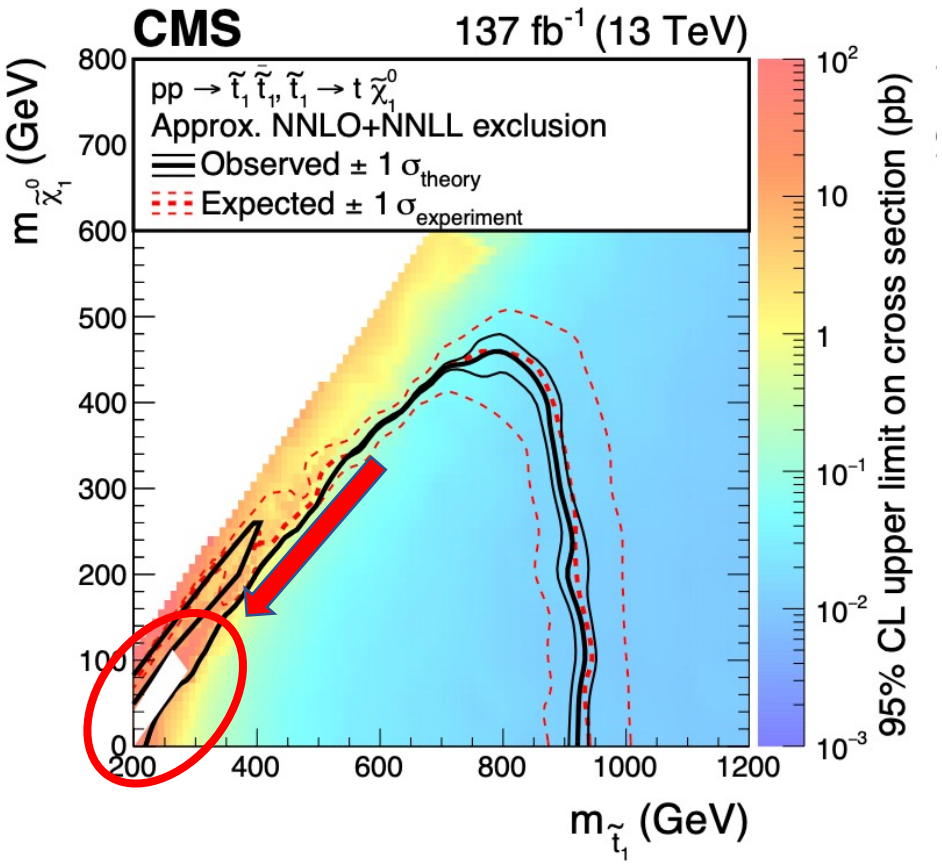


Stop – corridor CMS

arXiv: 2107.10892

Signal models:

$$|\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) - 175 \text{ GeV}| \leq 30 \text{ GeV with } m(\tilde{t}_1) < 275 \text{ GeV}$$



Analysis strategy:

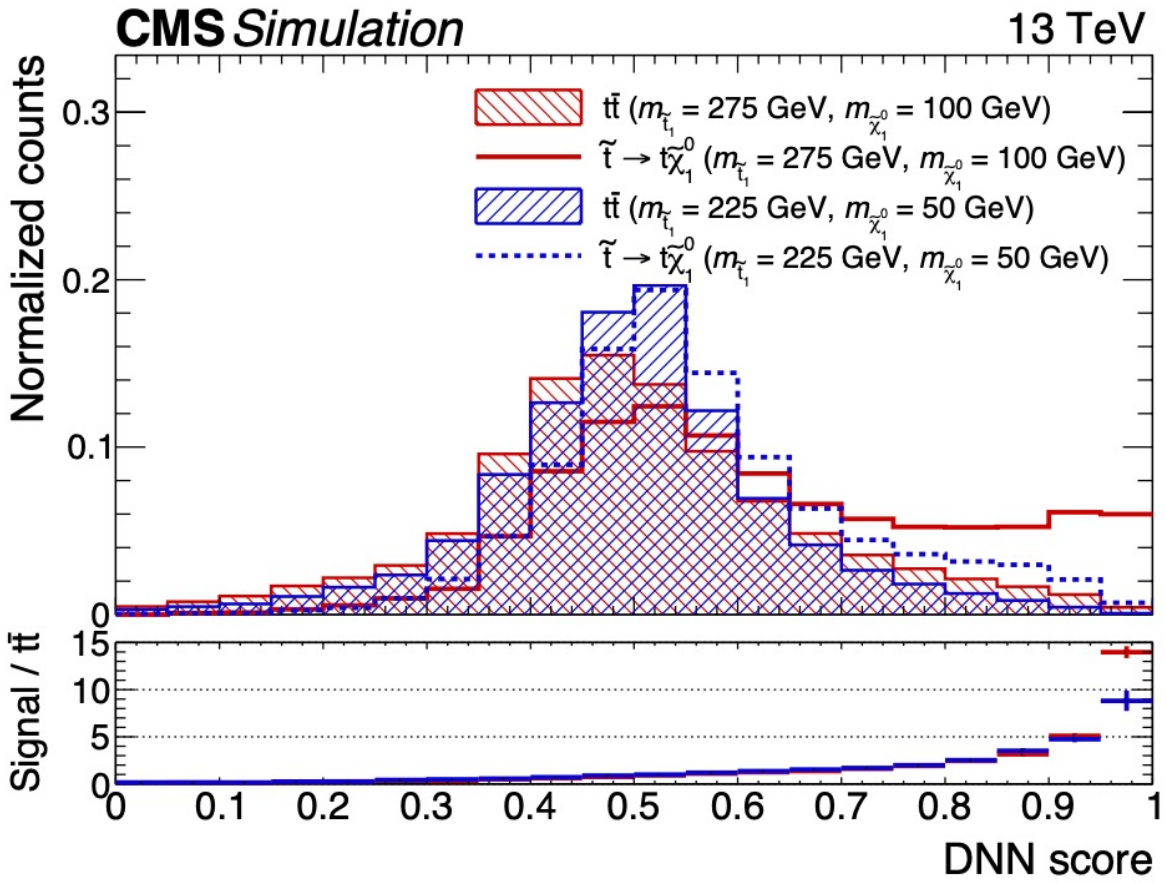
- 2 leptons in the final state
- 2 jets (whose 1 b-tagged)
- A low threshold for P_t^{miss} and $M_{T2}(ll)$, greater than 50 and 80 GeV respectively

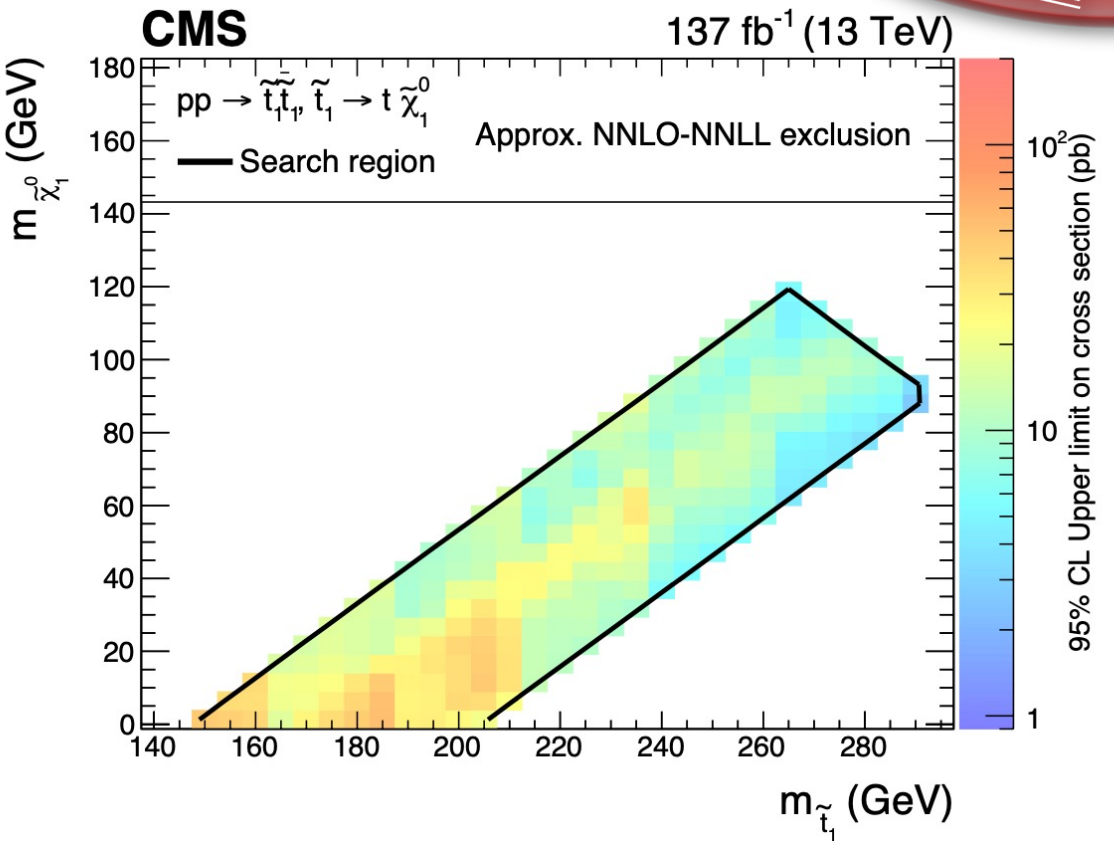
- DNN:
  - Training performed on tt and different signal models selecting eμ events

  - Momenta of the leptons, their angular variables, $M_{T2}(ll)$, H_T, M_{ll}, P_t^{miss} cosidered for the training together with stop and neutralino masses (for the bkg, random masses)

Stop – corridor CMS

arXiv: 2107.10892



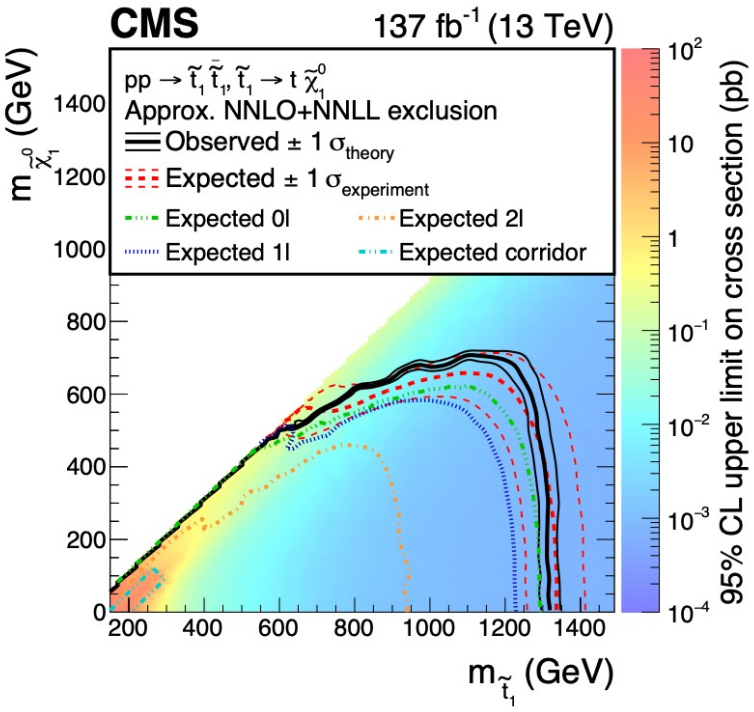


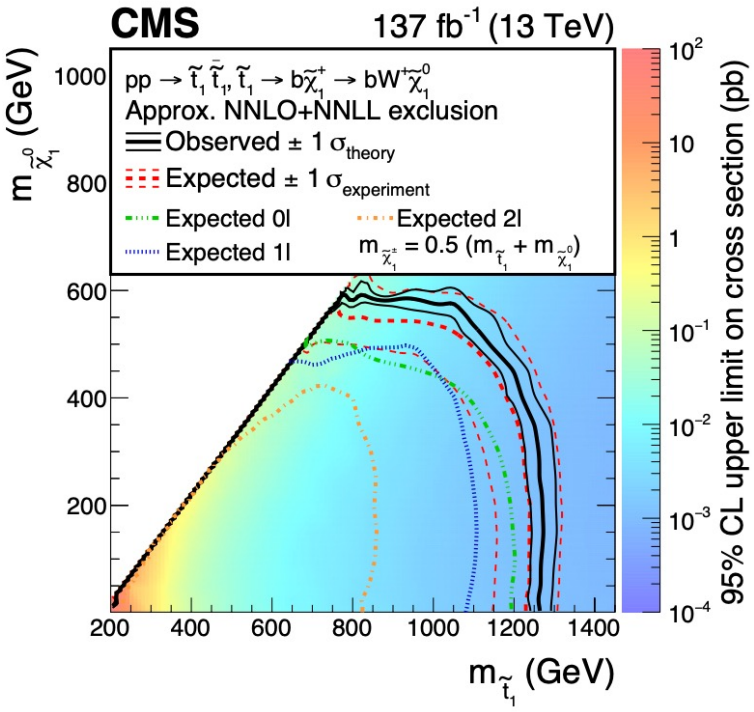
Combination of 9 channels: 3 data-taking period X 3 leptons flavours; binned DNN

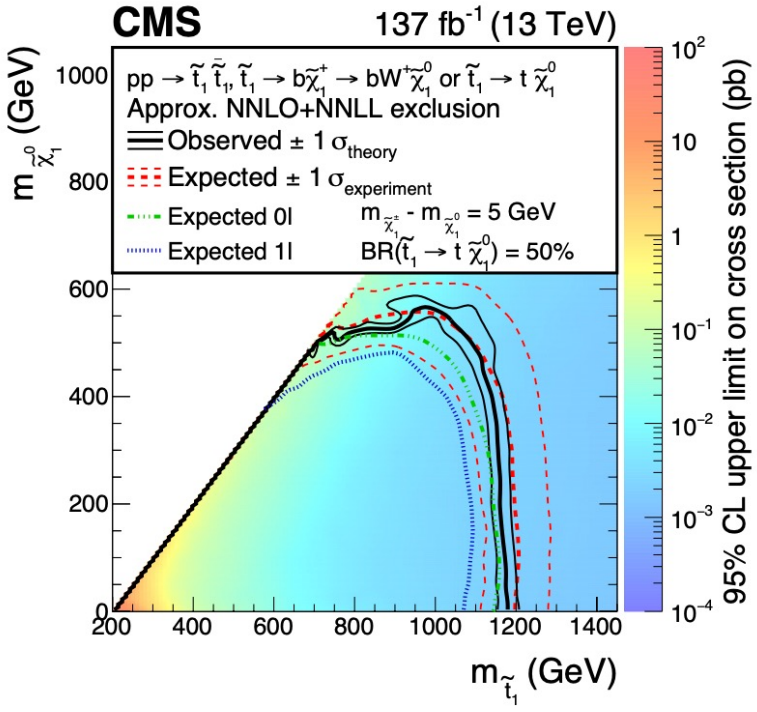
Stop – Combination CMS

Combination of 0, 1 and 2 leptons searches to ehnance the sensitivity

arXiv: 2107.10892

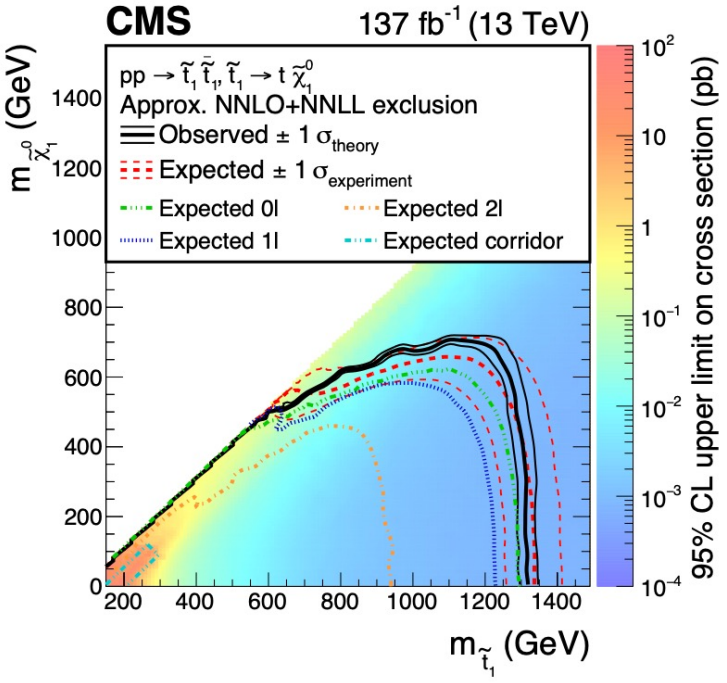


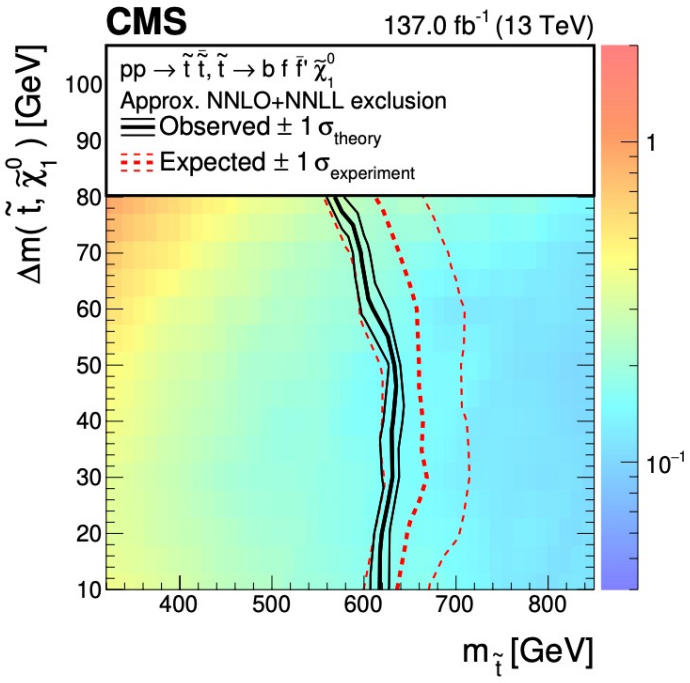


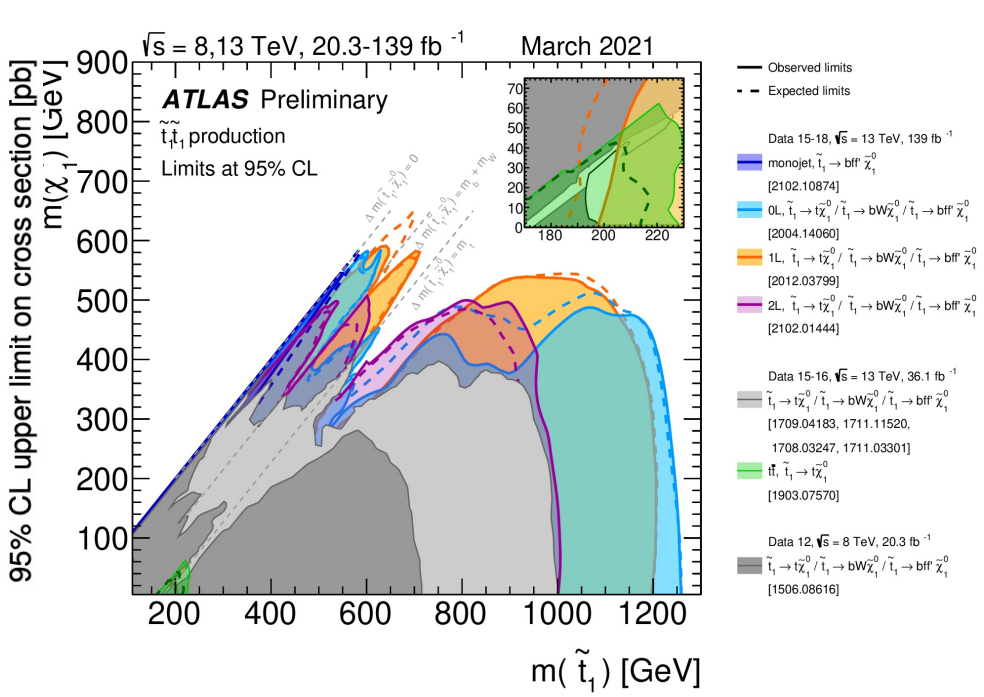


- 0 lepton search shows the largest sensitivity
- 0, 1 lepton searches compatitive when the difference in mass between stop and neutralino is small

Stop searches – ATLAS & CMS







- CMS performs slightly better than ATLAS for large mass difference (profiting of the many categories and the combination)
- Close to the top diagonal and for high values of stop mass, the ATLAS ttMET2L search performs better than CMS, thanks to the *super-razor* variables
- In the corridor ATLAS and CMS have 2 completely different approaches: DNN techniques for CMS, measurement of differential cross-sections for ATLAS
- In the 3-body regions ATLAS shows higher sensitivity thanks to the RNN analysis strategy of the 1L search
- In the 4-body regions both ATLAS (0,1 lepton) and CMS (0 lepton) show similar sensitivity; in both cases soft b-tagging technique has been applied (not the case for the ATLAS 2L search)

2 OS SF leptons + P_t^{miss} CMS

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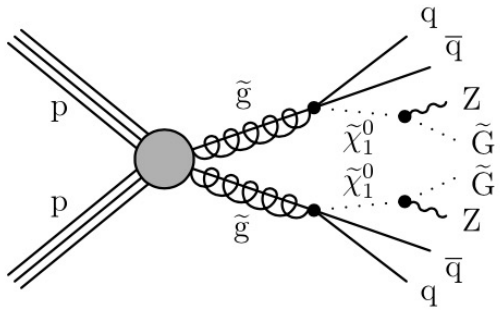
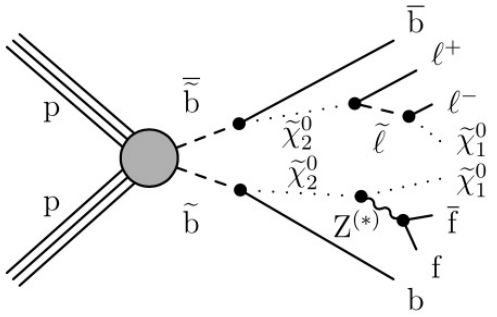
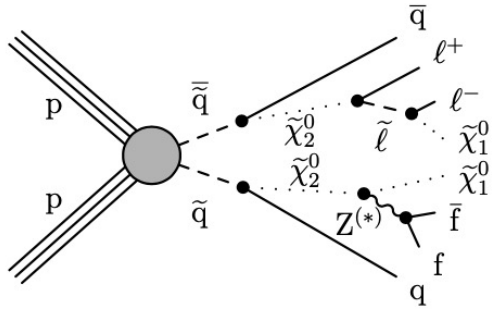
Signal models:



$m(\tilde{G}) = 1$ GeV

On-shell Z





$m(\tilde{\chi}_1^0) = 100$ GeV, $m(\tilde{l}) = 0.5[m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)]$

Off-shell Z

Analysis strategy:

- 2 Opposite-sign (OS) same flavour (SF) leptons in the final state & P_t^{miss}
- Minimum requests on H_T and $M_{T2}(ll)$
- Gluino search strategy:
  - leptons pair with an invariant mass close to the Z mass
  - Categorization in terms of jet/b-tagged multiplicity and binned in P_T^{miss}
- Sbottom/squark search strategy:
  - leptons pair with an invariant mass outside the Z window mass
  - Categorization in terms of b-veto/b-tag and tt-like events (based on likelihood discriminant built with $P_{\mathrm{T}}^{\mathrm{miss}}, P_{\mathrm{T}}^{\mathrm{ll}}, \Delta\phi(l_1, l_2), \sum_{i=1,2} m_{l_i,b_i}$)
  - Binned in Mll

2 OS SF lepton + P_t^{miss} CMS

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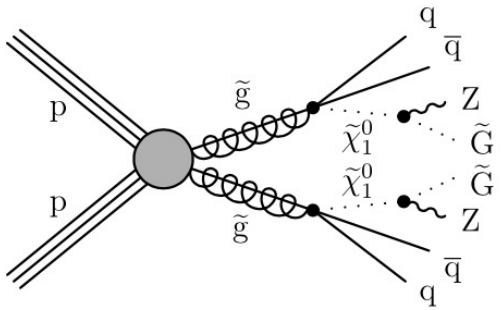

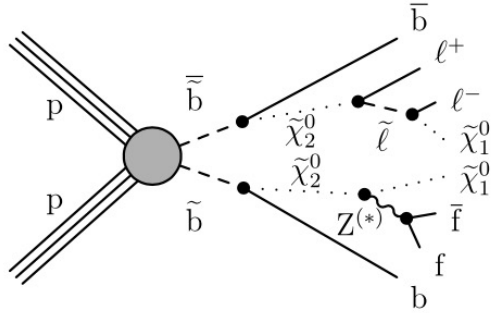

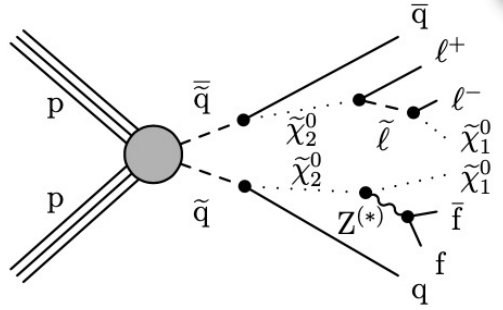

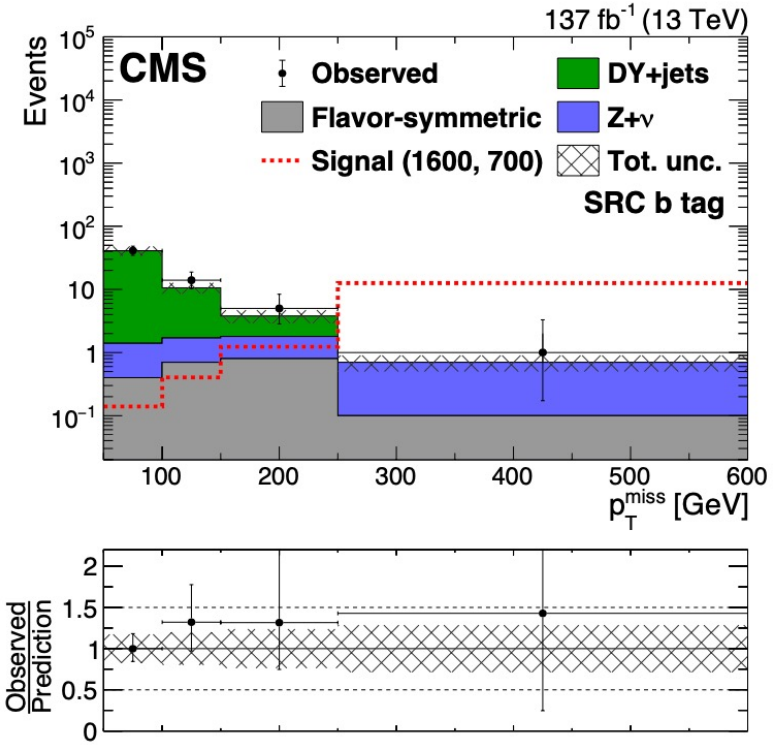

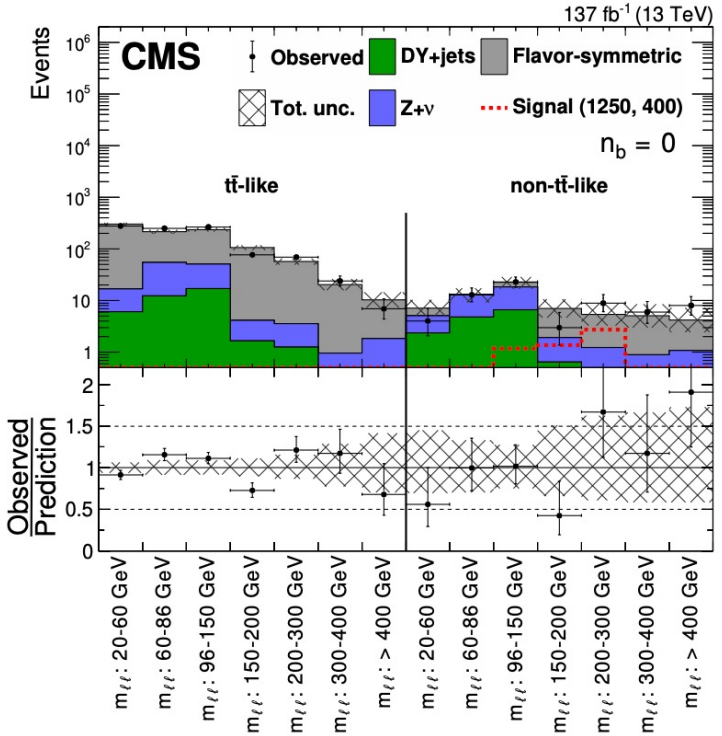

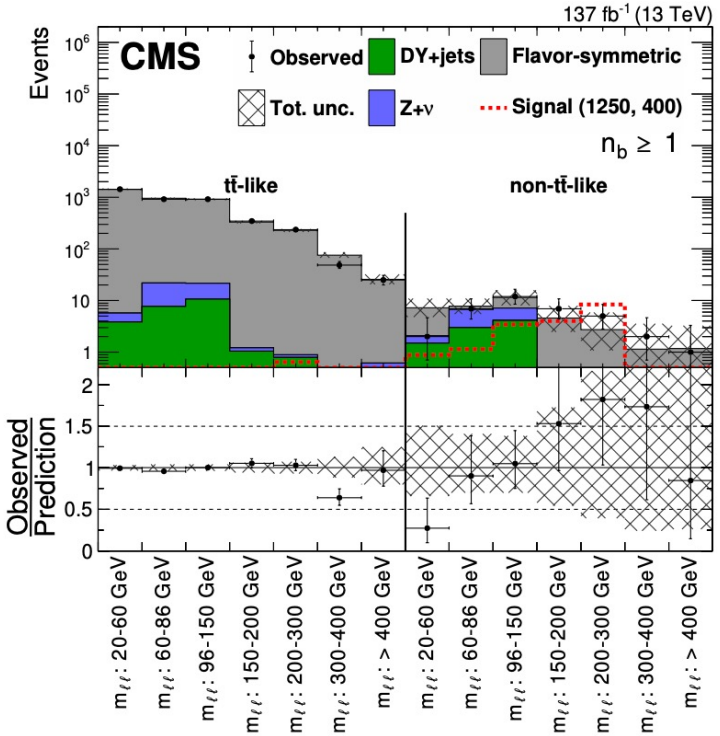

2 OS SF lepton + P_t^{miss} CMS

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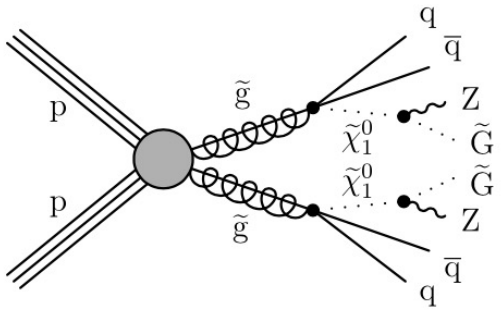
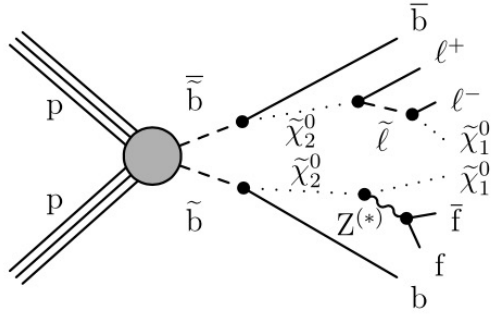
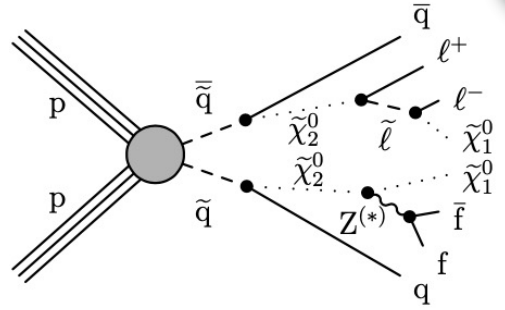
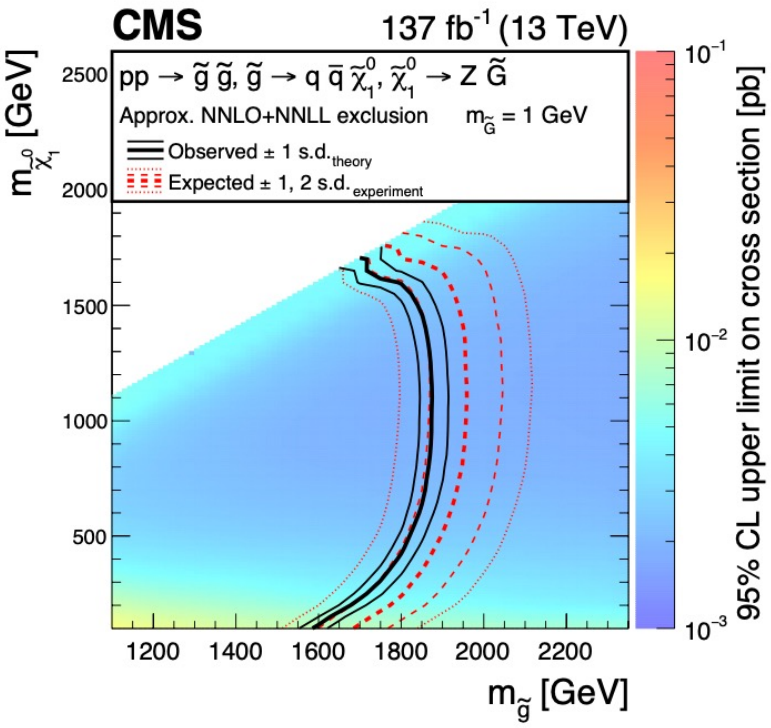
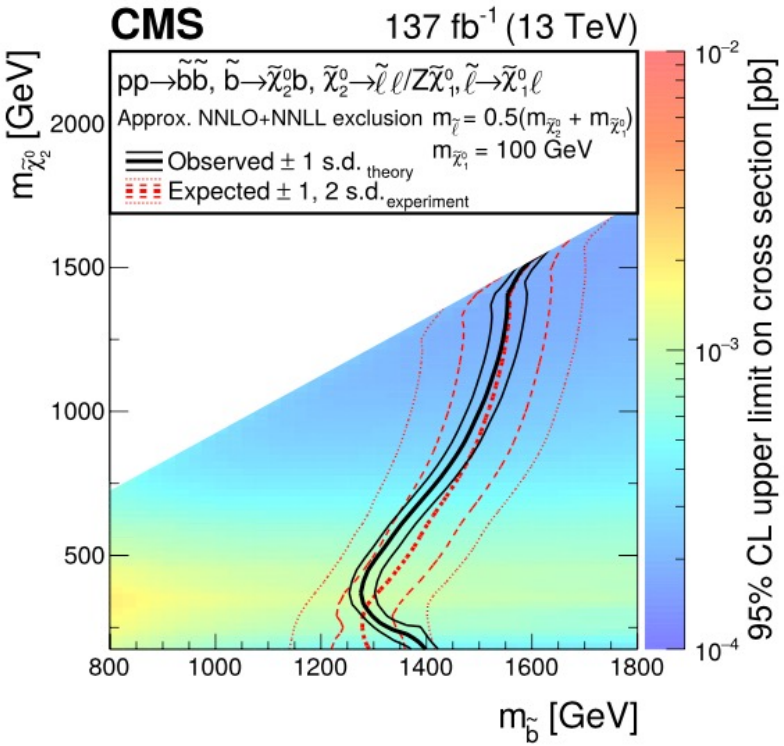
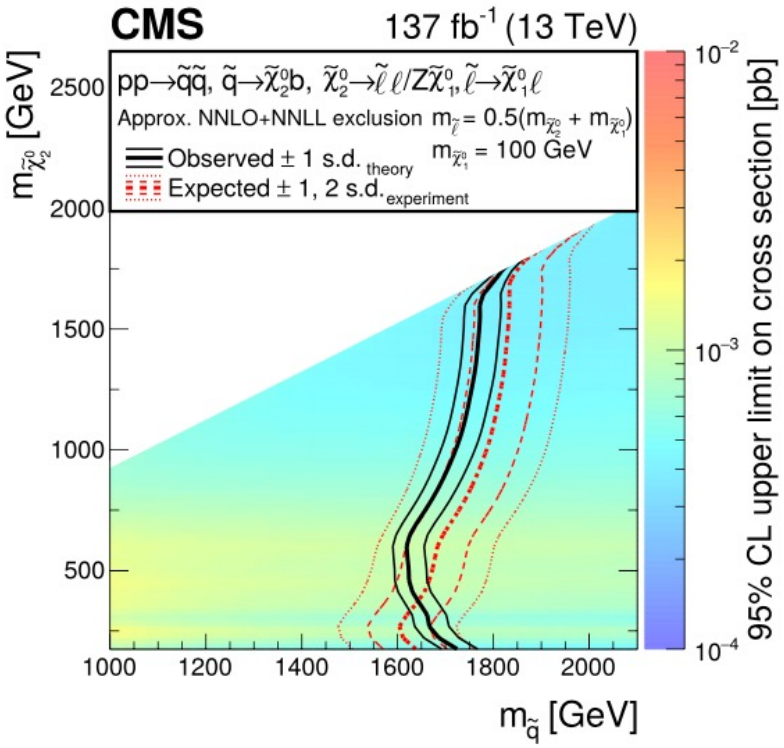








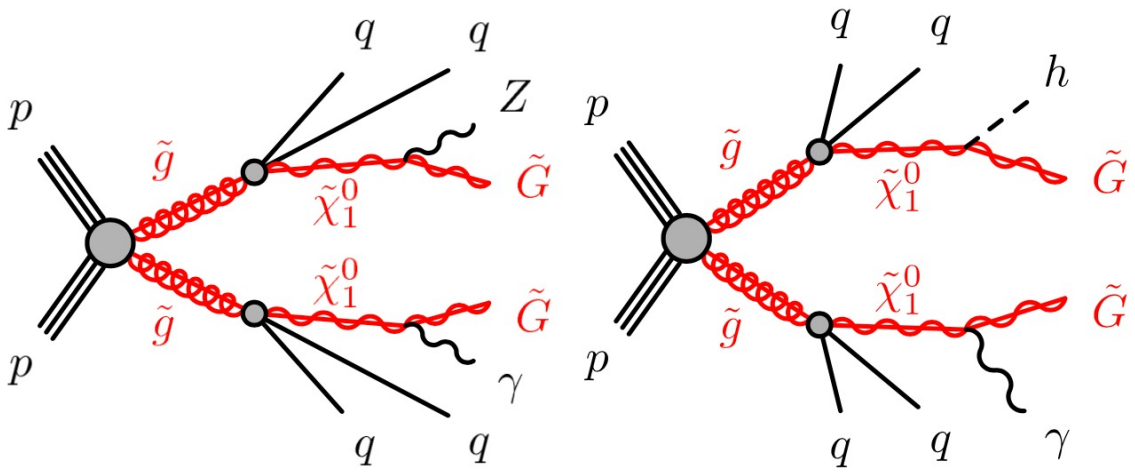




Jet+P_t^{miss}+Gamma ATLAS

ATLAS-CONF-2021-028

Signal models:



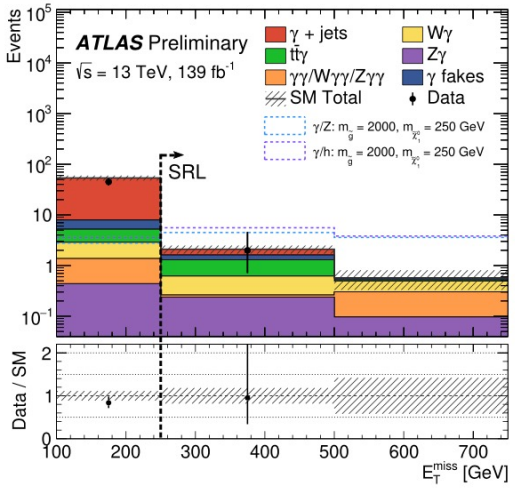
- Gravitino mass is sufficient light to ensure a prompt decay of the NLSP
- BR ∽ 50% for $\tilde{\chi}_1^0 \to h/\gamma/Z + \tilde{G}$

Analysis strategy:

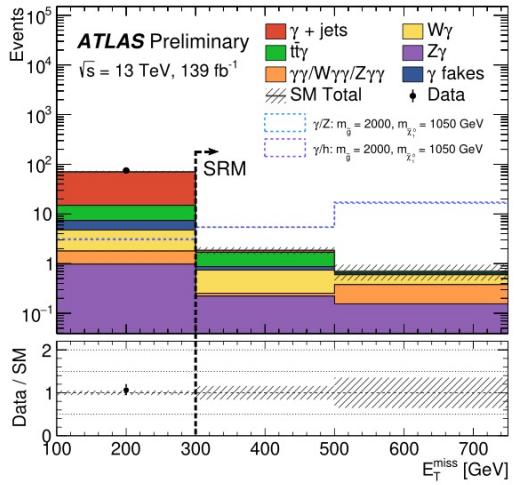
- High jets multiplicity, P_t^{miss} and a photon in the final state
- 3 different strategies to target signal models with *large*, *intermediate* and *small* difference in mass between gluino and neutralino:
  - increasing request on the P_t of the photon
  - Increasing request on P_t^{miss} and H_T
- Best expected sensitivity considered

Jet+P_t^{miss}+Gamma ATLAS

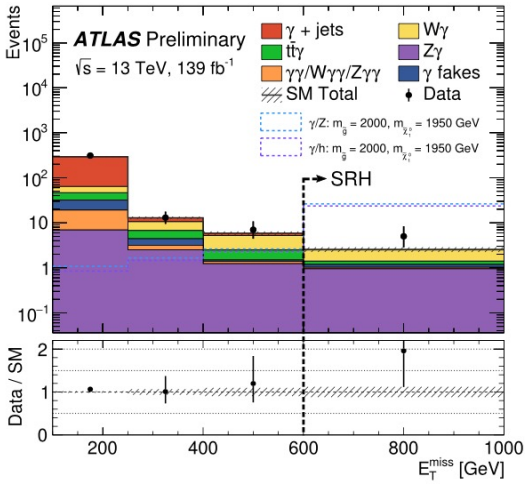
ATLAS-CONF-2021-028



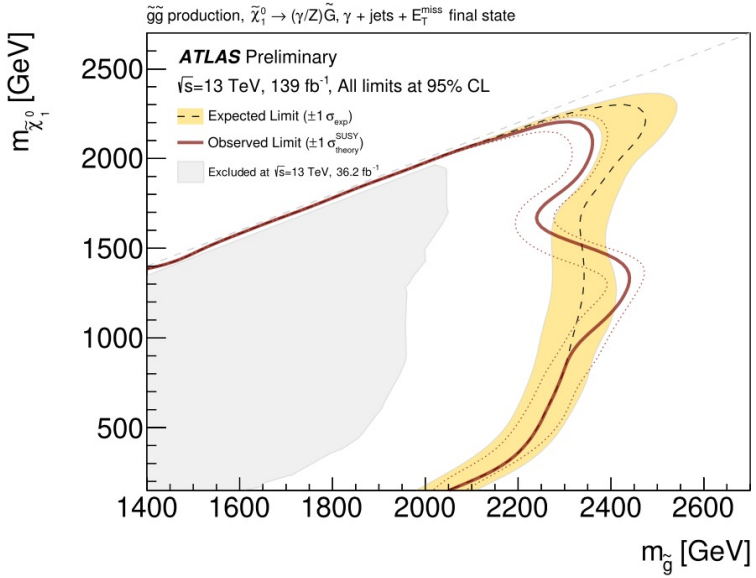
(a) SRL



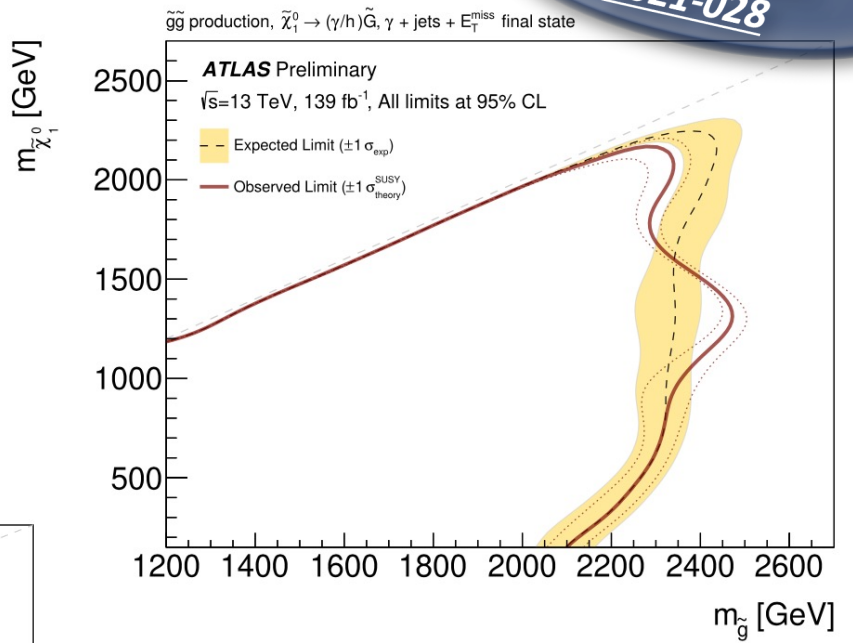
(b) SRM



(c) SRH



(a) γ/Z model

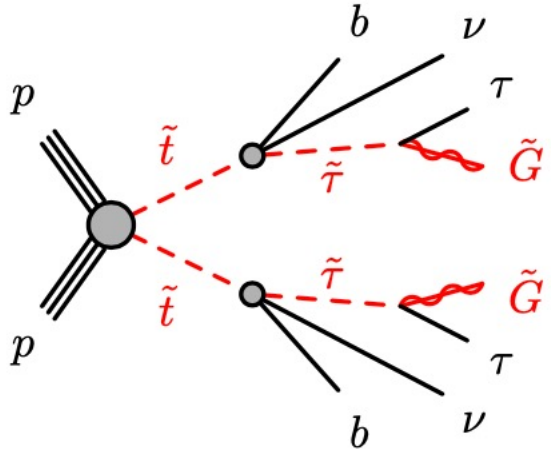


(b) γ/h model

Stop to Stau ATLAS

ATLAS-CONF-2021-008

Signal models:

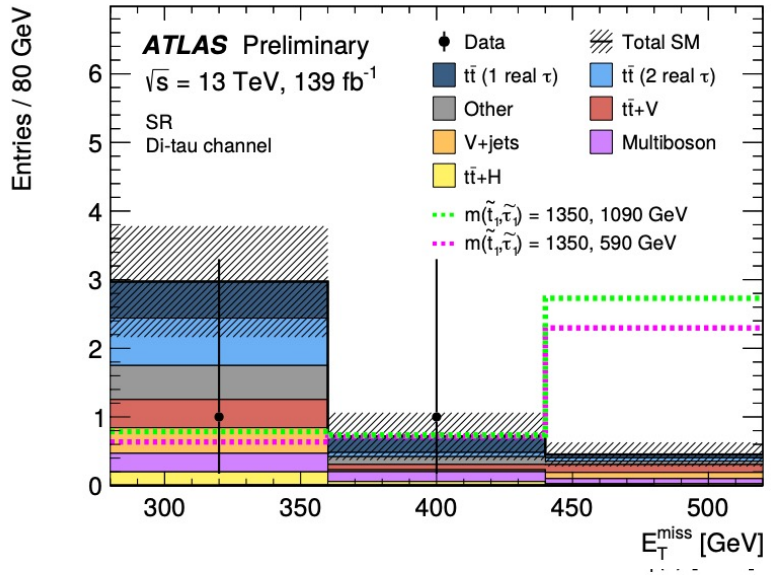


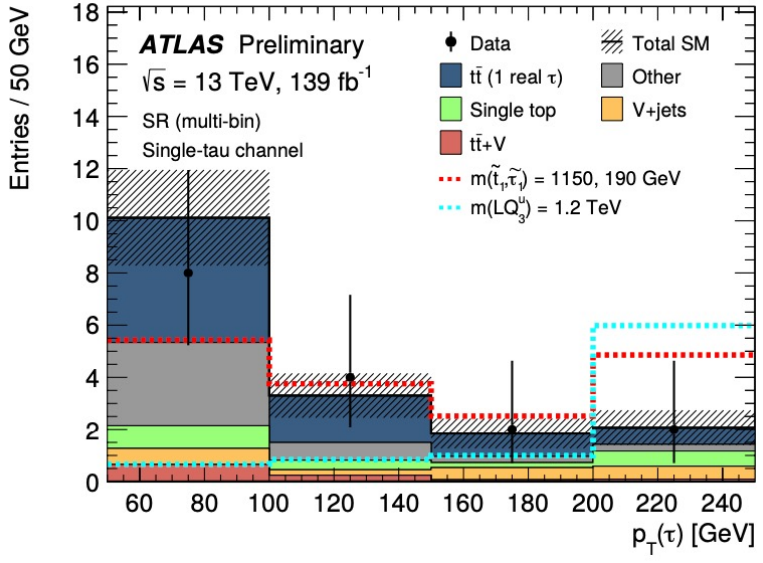
- Gravitino mass is sufficient light to ensure a prompt decay of the NLSP

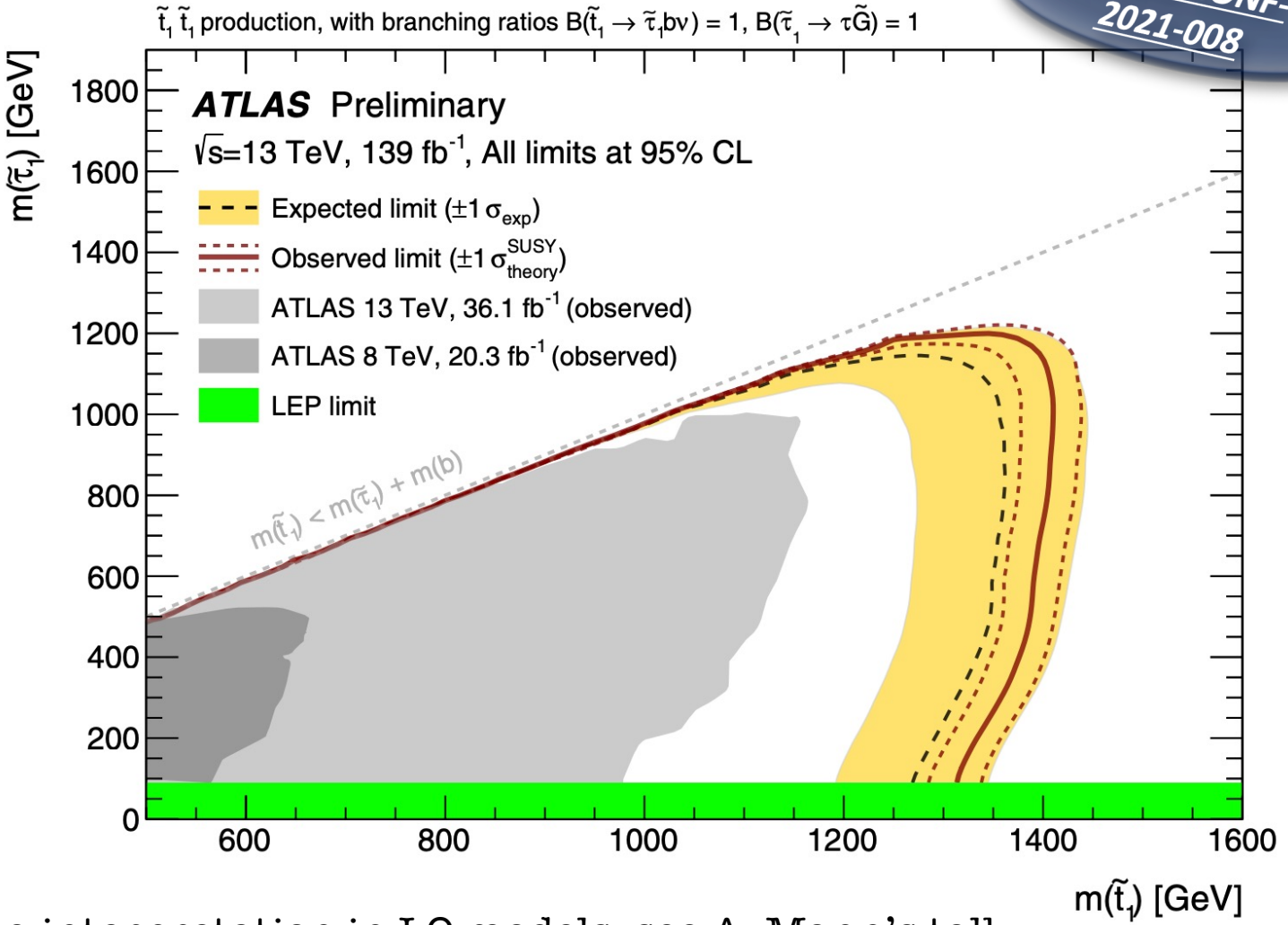
Analysis strategy:

- Final state carachterized by at least 2 jets, at least 1 b-tagged jets, tau and P_t^{miss}
- 2 different signal regions based on the number of taus:
  - Di-tau channel:
    - 2 OS taus, SR based on M_{T2}
  - Single-tau channel:
    - At least 2 b-tagged jets
    - SR based on the scalar sum of the transverse momenta of tau and 2 leading jet, tau transverse mass
    - Binned in tau P_t

Stop to Stau ATLAS







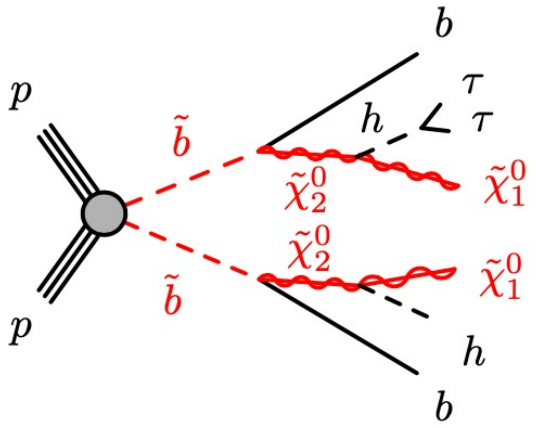
ATLAS-CONF-2021-008

Re-interpretation in LQ models; see A, Mann's talk

Sbottom to tau, P_t^{miss}, b ATLAS

arXiv: 2103.08189

Signal models:



$$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}$$

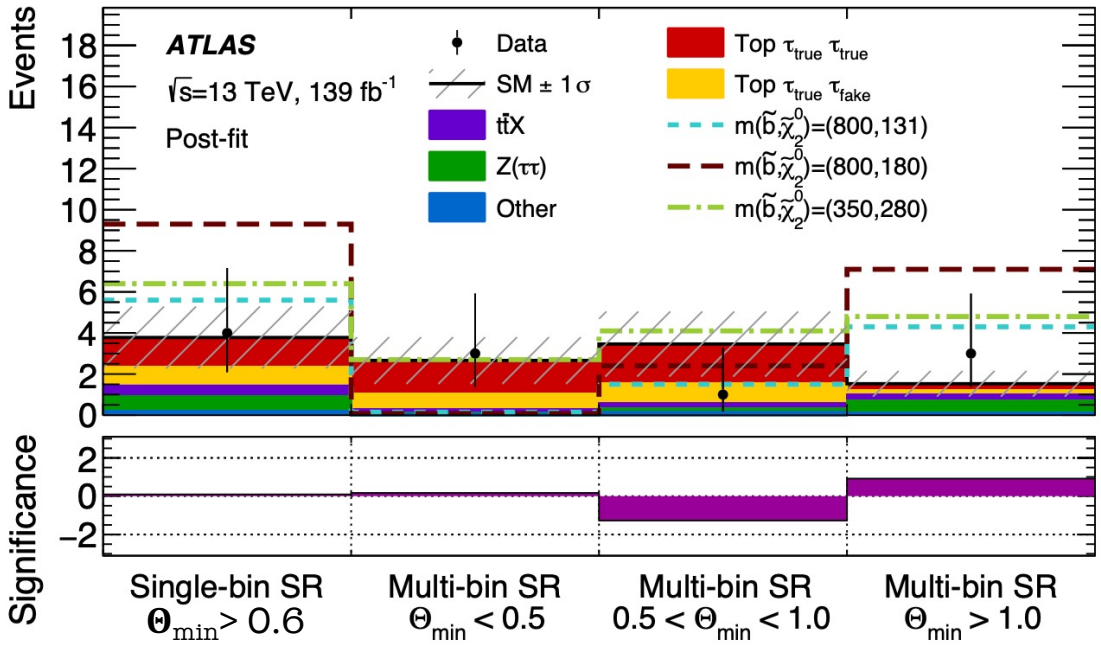
h is the SM Higgs boson

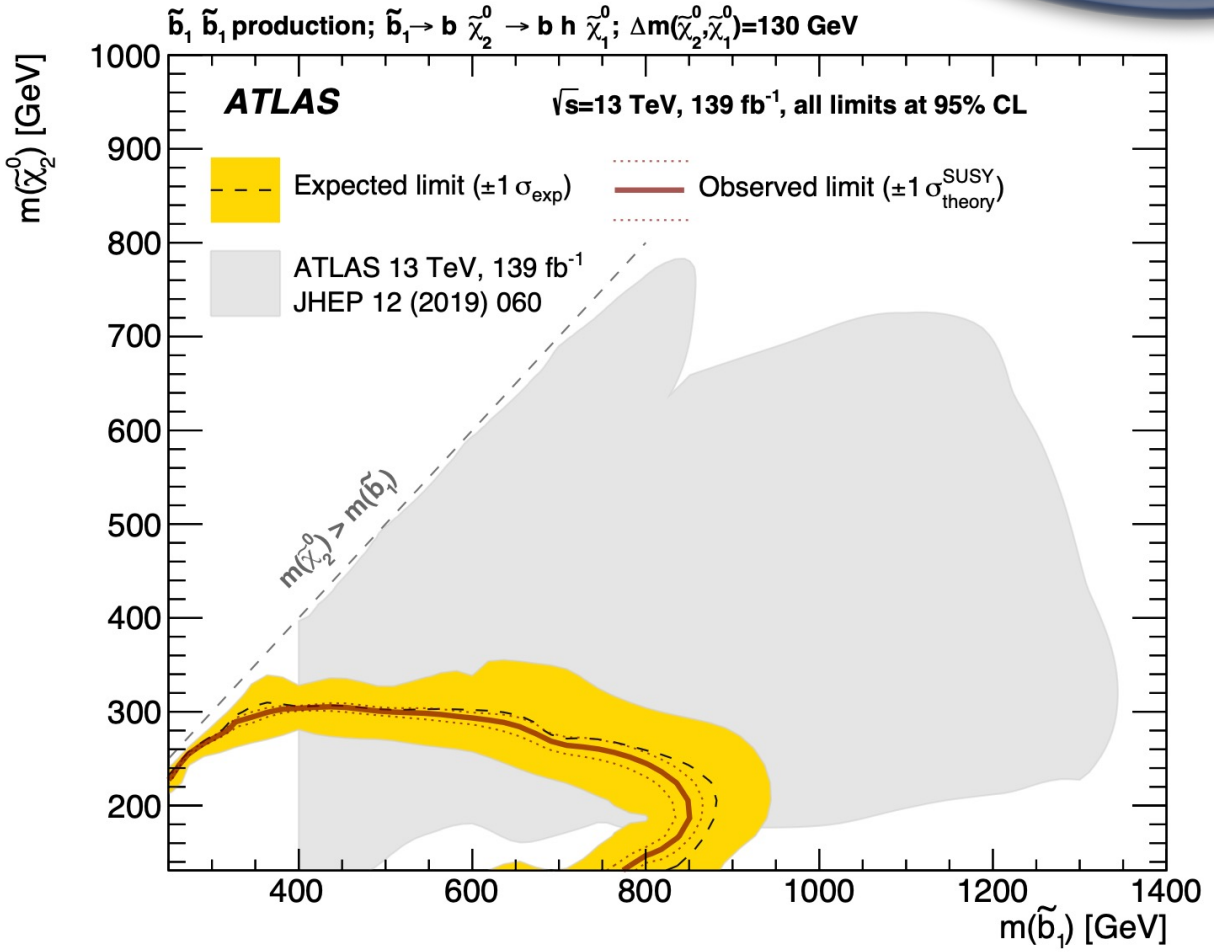
Analysis strategy:

- Final state carachterized by 2 OS taus whose invariant mass is between 55 and 120 GeV, at least 2 b-tagged jets
- Large values of M_{T2} (assumed an invisible mass of 120 GeV) and the scalar sum of the momenta of jets and taus
- Signal regions definition based on the minimum solid angle of the 4 combinations of the 2 leading taus and the 2 b-tagged jets (Θ_{min}):
  - Small angle when tau and b come from a top quark
  - For the signal, Θ_{min} increases with the sbottom mass

Sbottom to tau, P_t^{miss}, b ATLAS

arXiv: 2103.08189





Improvement in the sensitivity thanks to the different final state

Looked at $h \rightarrow$ tautau instead of $h \rightarrow bb$

Sbottom to b, P_t^{miss} ATLAS

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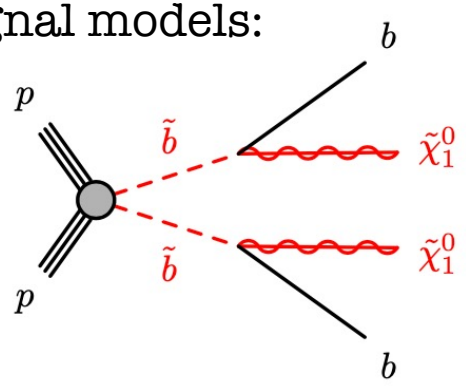
Signal models:



Three different analysis strategy defined for targeting different signal models:

- SRA for large values of $\Delta m(\tilde{b}, \tilde{\chi}_1^0)$
- SRB for intermediate values of $\Delta m(\tilde{b}, \tilde{\chi}_1^0)$ ([50,200] Gev)
- SRC for small values of $\Delta m(\tilde{b}, \tilde{\chi}_1^0)$ (less than 50 GeV)

SRA:

- Definition based on M_{CT} variable (transverse mass of the 2 visible particles)

$$M_{CT} = \frac{m_I^2 - m_X^2}{m_I}$$

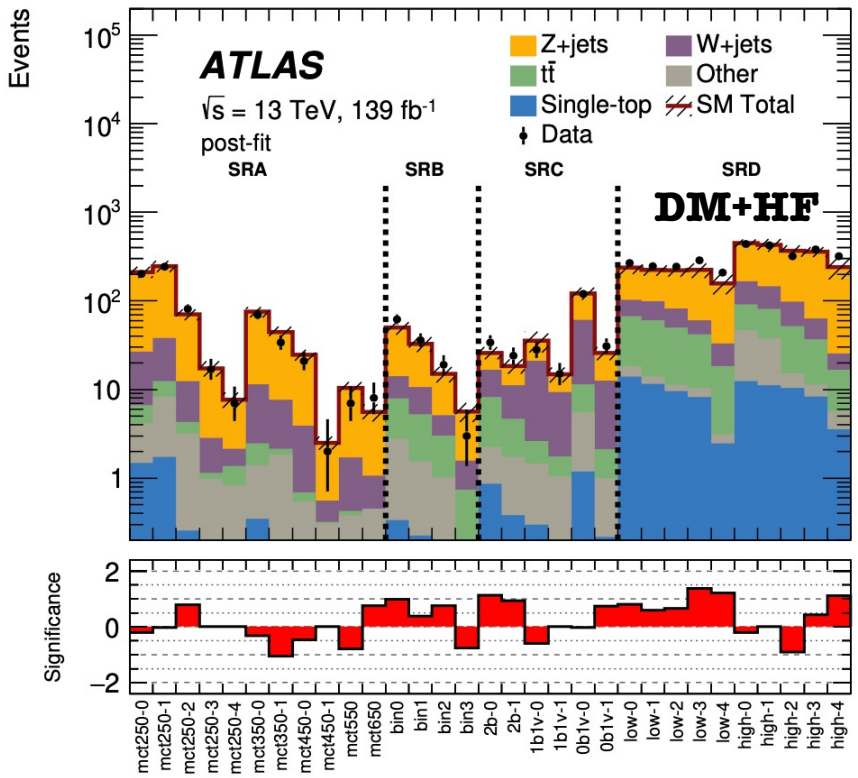
SRB:

- Orthogonal to SRA thanks to an upper cut on M_{CT}
- BDT is implemented with a multi-classification procedure $(Sig, t\bar{t}, Z + \text{jets}, W + \text{jets})$
- Inputs: jets momenta, *b*-tagging info, M_{CT}, scalar sum of P_t^{miss} and jets P_t, P_t^{miss} significance, $m_T^{min}(j_{1-4}, \mathbf{P}_t^{miss})$, $\Delta R(b_1, b_2)$
- Binned in BDT score

SRC:

- ISR jet
- 3 mutually exclusive SRs:
  - 2 *b*-tagged jets
  - 1 *b*-tagged jet and at least 1 secondary vertex (soft *b*-jet)
  - No *b*-tagged jet and at least 1 secondary vertex
- For exclusion additional binning in P_t^{miss}

Sbottom to b, P_t^{miss} ATLAS



SRA and SRB combined together
Best expected between SRA&B and SRC

Improvement thanks to BDT and soft *b*-tagging

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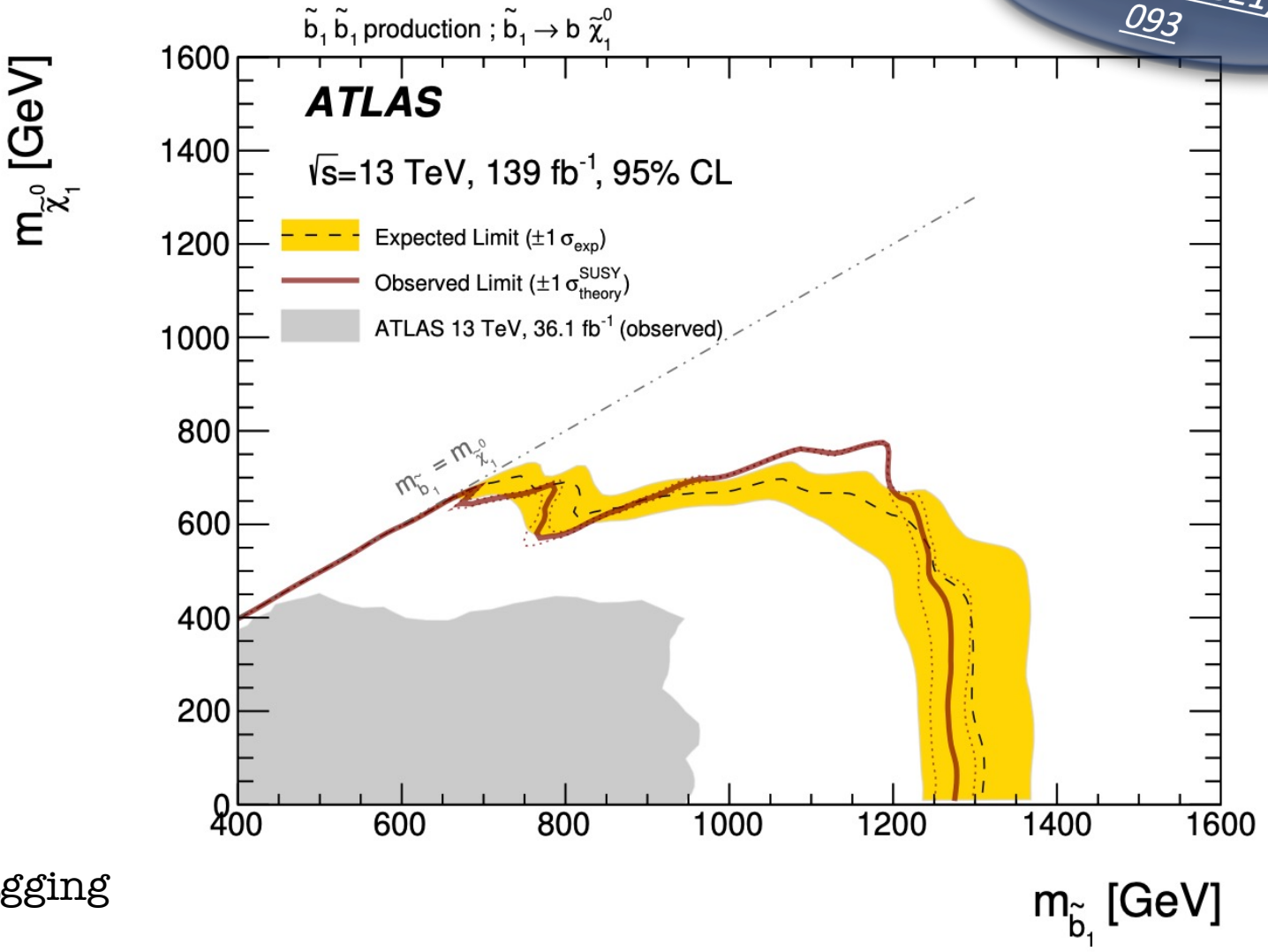
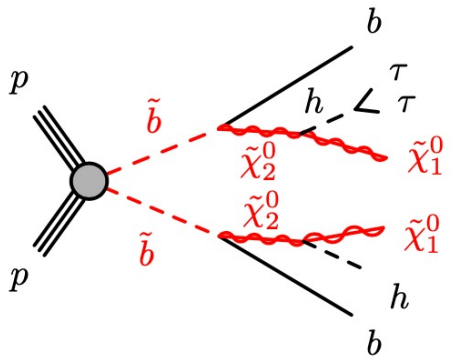
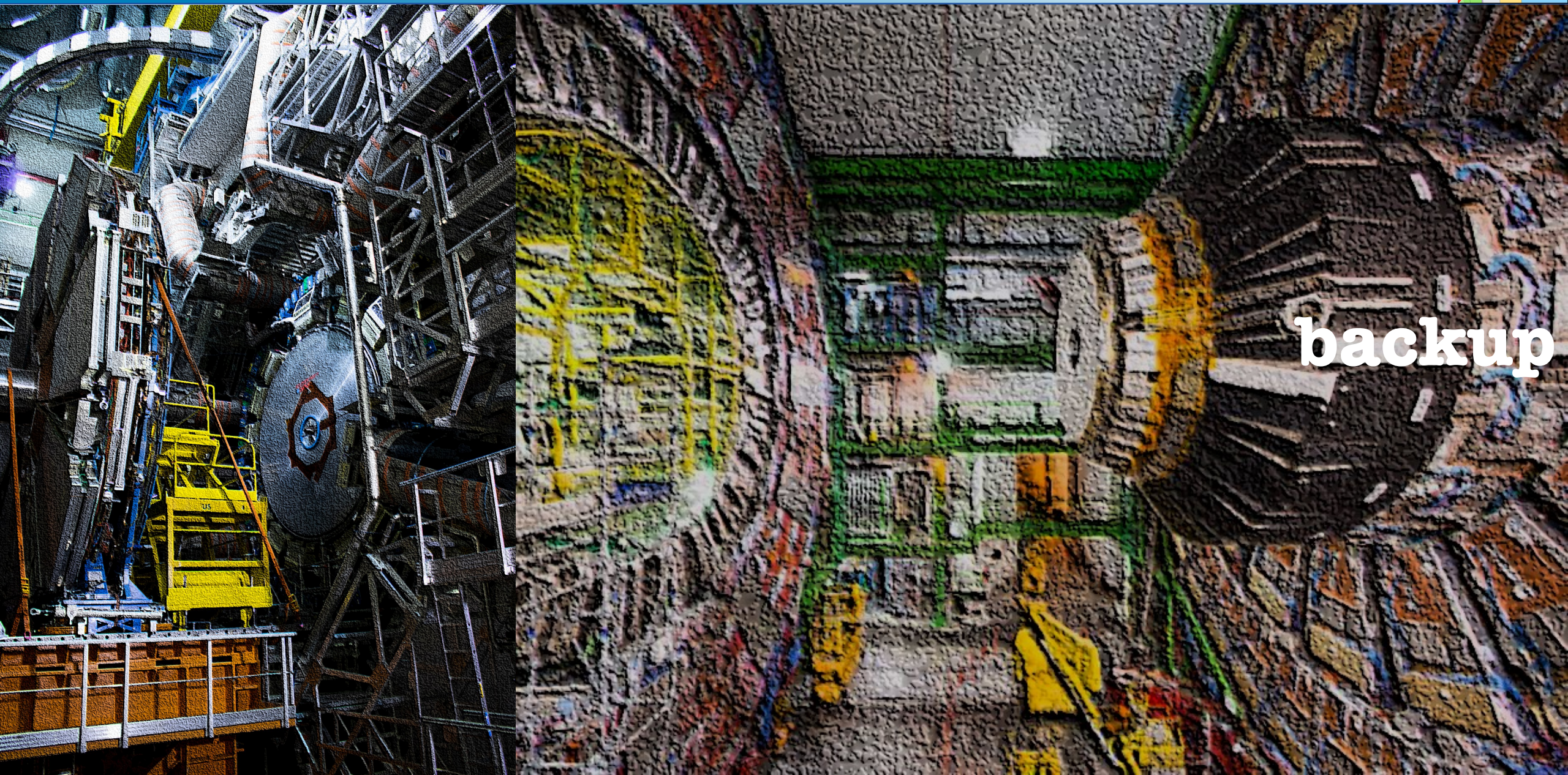


Conclusion

- Only the recent results have been shown; both experiments have a broad and solid program.
- Both ATLAS and CMS have increased their sensitivity thanks to:
  - new reconstruction techniques (top/W-tagging, soft b-tagging)
  - machine learning techniques (DNN, BDT)
  - new variables: P_t^{miss} significance, ttbar-likelihood discriminant
  - Combination of different analyses
  - new signatures

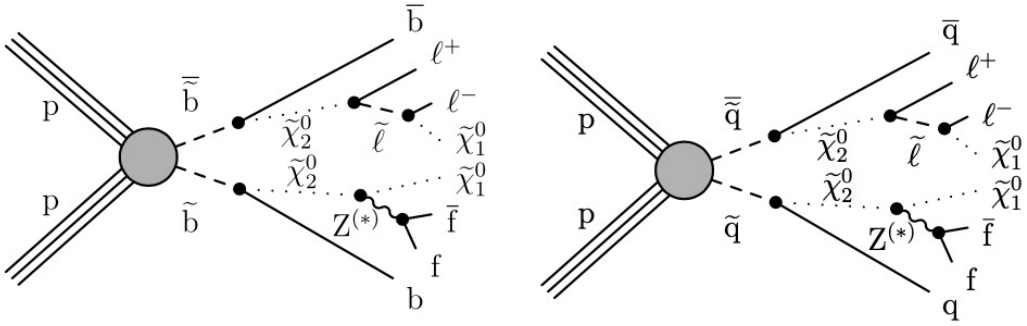


Like we are looking at a needle in a haystack


backup

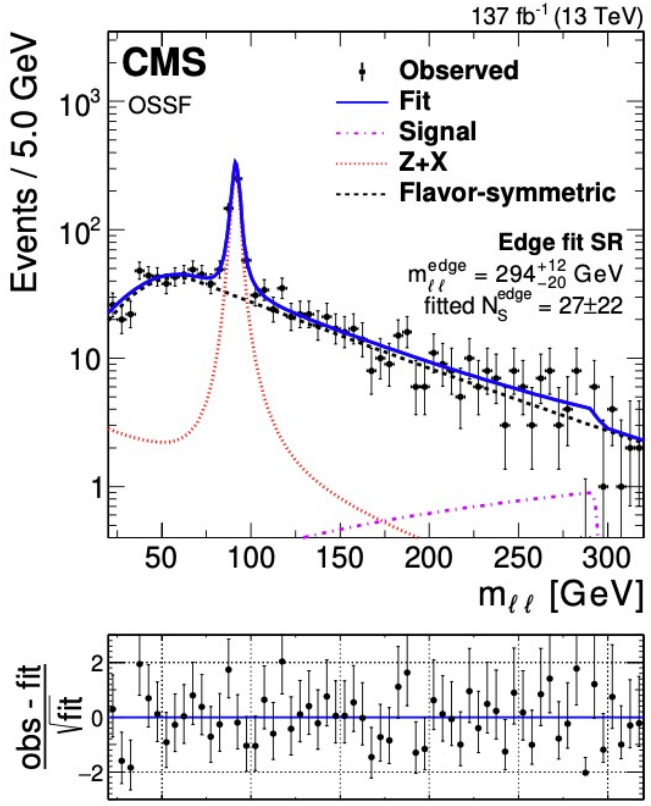
2 OS SF lepton + P_T^{miss}

CMS-SUS-20-01



Edge search sample ($20 < m_{\ell\ell} < 86$ or $m_{\ell\ell} > 96$ GeV)

Region	n_j	n_b	$M_{T2}(\ell\ell)$ [GeV]	p_T^{miss} [GeV]	$m_{\ell\ell}$ bins [GeV]
Edge fit	> 1	—	>80	>200	>20
b veto	> 1	=0	>80	>150	[20, 60, 86]+[96, 150, 200, 300, 400, ∞)
b tag	> 1	>0	>80	>150	[20, 60, 86]+[96, 150, 200, 300, 400, ∞)



Z/γ^*+X yield	447 ± 28
FS yield	1019 ± 29
$R_{SF/DF}$	1.02 ± 0.04
Signal events	27 ± 22
$m_{\ell\ell}^{edge}$	294^{+12}_{-20} GeV
Local significance	1.3 s.d.
Global significance	0.7 s.d.