Searching for pair production of SUSY particles in leptonic final states at the CMS experiment

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On behalf of the CMS Collaboration

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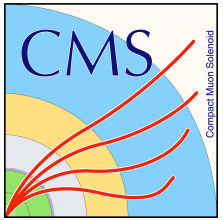
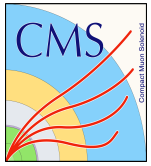
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

RWTH AACHEN UNIVERSITY



Simplified SUSY models with leptonic final states



This talk will focus on two SUSY searches with two or more leptons in the final state:

- *CMS analysis SUS-20-001*: Search for SUSY pair production in final states with two opposite-charge, same-flavor leptons.
- *CMS analysis SUS-19-008*: Search for SUSY pair production in final states with two same-sign or at least three charged leptons.

Both analyses are treated in the context of simplified models:

- With/without R-parity conservation
- Covering a wide range of final state particles: light jets (zero, few, many), b-jets, p_T^{miss}, and 2+ leptons
- Covering EWK, strong, or sleptons production mechanisms
- With/without on-shell Z lepton pairs
- Setting limits on masses for neutralino, charginos, sleptons, squarks, and sbottom quarks

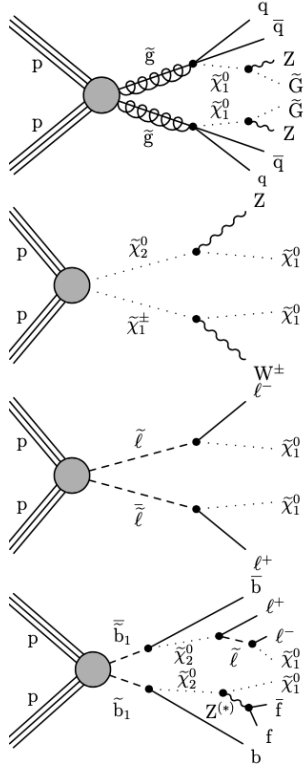
CMS analysis SUS-20-001

Search for physics beyond the standard model in final states with two opposite-charge, same-flavor leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$

Introduction

Signal models, baseline selections

- All the models are considered with R-parity conservation and SUSY pair production
  - Strong production: $pp \rightarrow \tilde{g}\tilde{g}$ (on-shell Z)
  - Electroweak production: $pp \rightarrow \tilde{\chi}_i^{\,0}\tilde{\chi}_i^{\,0}$ || $\tilde{\chi}_i^{\,0}\tilde{\chi}_i^{\,\pm}$ (on-shell Z)
  - Direct s-lepton production: $pp \rightarrow \tilde{l}\tilde{l}$ (off-shell Z)
  - Strong production (edge): $\tilde{b}\bar{\tilde{b}}$ || $\tilde{q}\bar{\tilde{q}}$ (off-shell Z)
- The signature is OSSF lepton pair associated with jets, p_T^{miss}
- Covering a wide range of final states and production mechanisms; baseline selection:
  - Exactly 2 OSSF leptons with $p_T \geq 25$ GeV for SRs
  - At least 2 OSDF leptons with $p_T \geq 25$ GeV for CRs
  - The two leading leptons are contributing to the calculations of m_{ll}
  - $p_T(ll) > 55$ GeV and $\Delta R(ll) > 0.1$
  - $\Delta\phi\left(\vec{p}_T(j_{1,2}), \vec{p}_T^{miss}\right) \geq 0.4$ (suppress background with instrumental p_T^{miss})



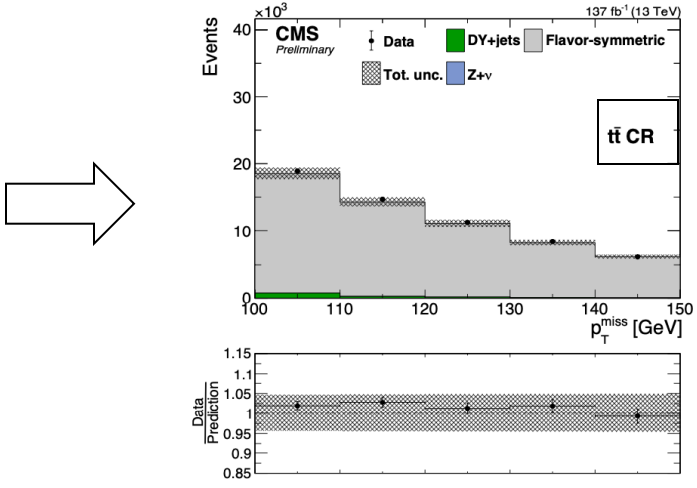
Opposite **S**ign **S**ame **F**lavour (OSSF)

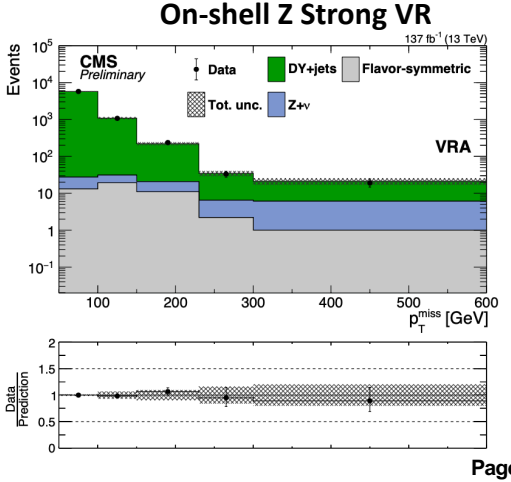
Opposite **S**ign **D**ifferent **F**lavour (OSDF)

SM backgrounds

Main backgrounds and estimation methods

- **Flavor-symmetric (FS) backgrounds ($t\bar{t}, WW$ etc.):**
  - Estimated from data using a DF sideband
  - Ratio between DF and SF yields deviates from 1 due to differences in lepton reconstruction and trigger efficiency
  - This deviation is corrected for by two correction factors
- **$Z + \nu$ (WZ, ZZ, $t\bar{t}$ Z) backgrounds:**
  - Estimated from simulation and normalized in 3(4)-lepton control regions and validated in CRs for each SR
- **DY+jets background:**
  - The p_T^{miss} here is purely instrumental (jet mismeasurement)
  - Estimated using γ+jets data as proxy reweighted to match the kinematics of Z+jets for each signal region
  - Normalize templates in 50-100 GeV p_T^{miss} region





Different **F**lavor (DF)

Same **F**lavor (SF)

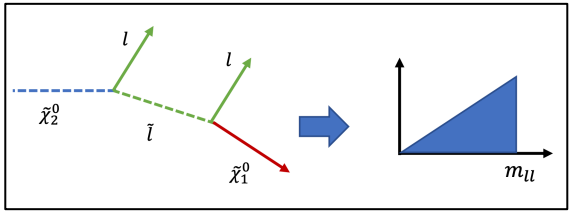
Edge signal

2 OSSF leptons, many/few jets, and no on-shell Z candidate

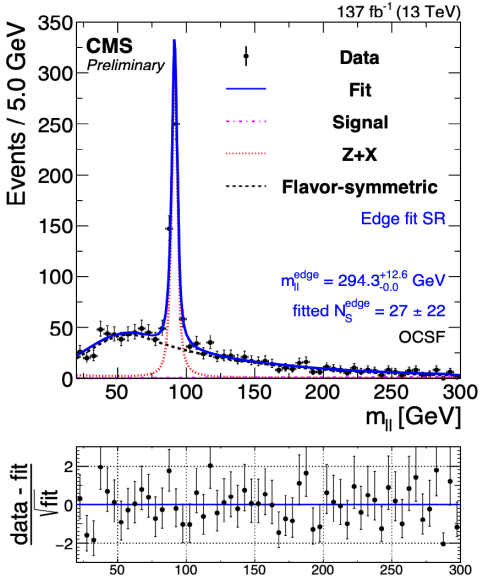
- Background is mainly $t\bar{t}$
- Naive Bayes discriminator to classify the backgrounds:
  - $t\bar{t}$-like and non-$t\bar{t}$-like.
- **Cut and count signal regions binning based on:**
  - M_{ll}, n_{bjets}, $t\bar{t}$ discriminator
- **M_{ll} kinematic fit signal region**
  - Require p_T^{miss} > 200 GeV

Z + X yield	447 ± 28
FS yield	1019 ± 29
$R_{SF/DF}$	1.02 ± 0.04
Signal events	27 ± 22
$m_{\ell\ell}^{edge}$	$293.4^{+12.6}_{-0.0}$ GeV
Local significance	1.3 s.d.
Global significance	0.7 s.d.

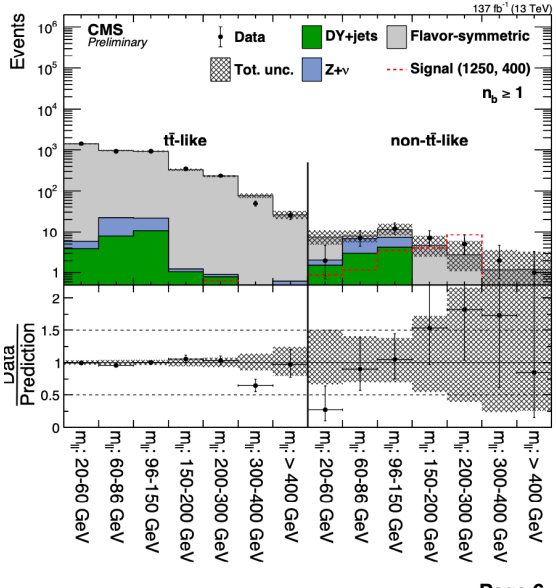
Edge



M_{ll} Kinematic fit



Cut and count

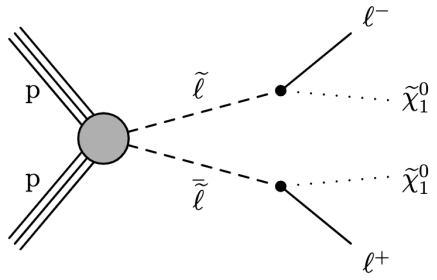


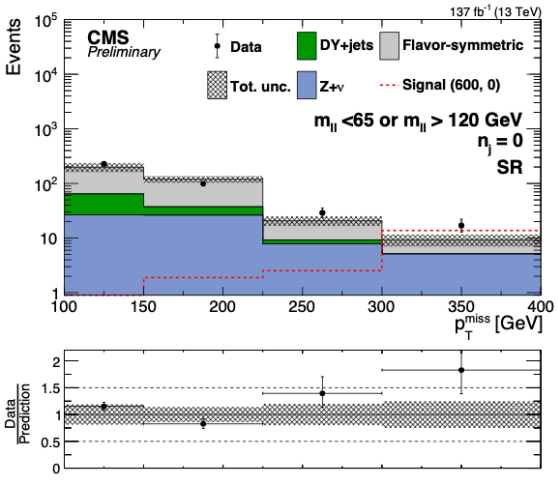
Interpretations: slepton direct production

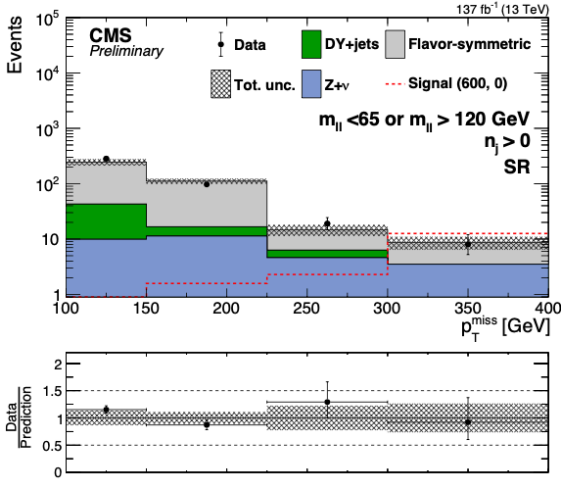
2 OSSF leptons, no jets, and no on-shell Z candidate

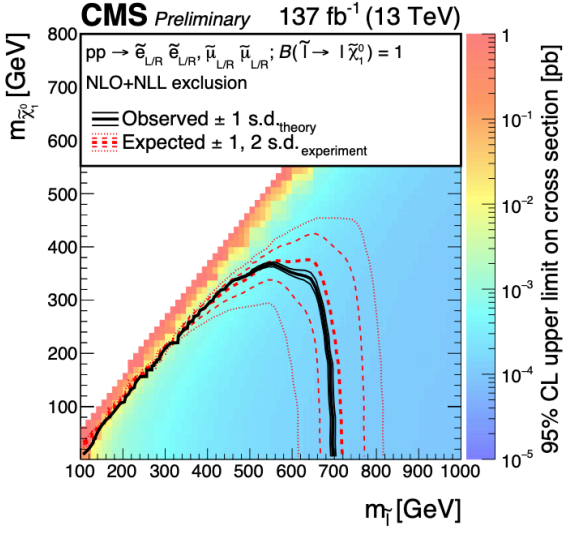
Consider slepton pair production mode:

- Sensitivity is driven by combining ~10 search bins based on n_{jets}, n_{bjets}, M_{T2} and p_T^{miss}
- Both on-Z and off-Z regions are included
- Events with no jets or few (ISR jets) are considered in the SRs
- Exclude slepton masses up to 650 GeV





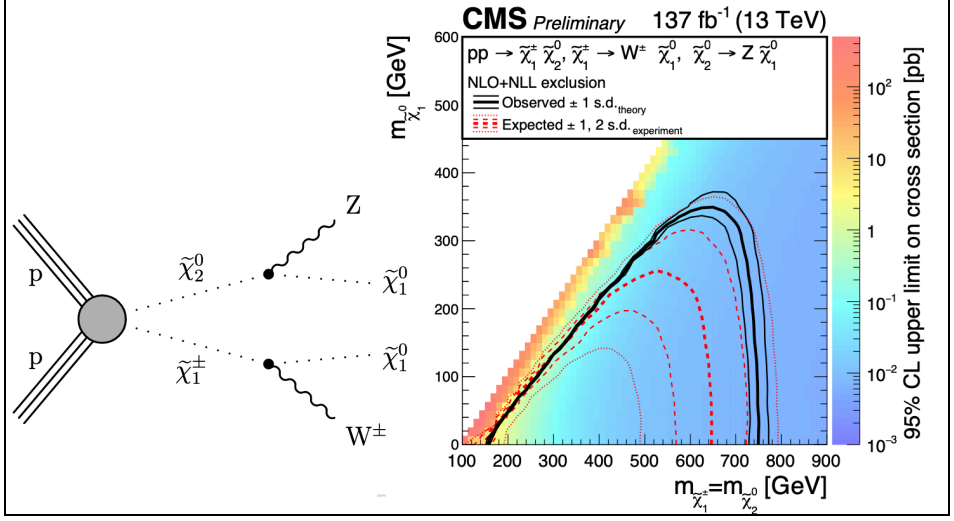




Interpretations: electroweak and strong productions

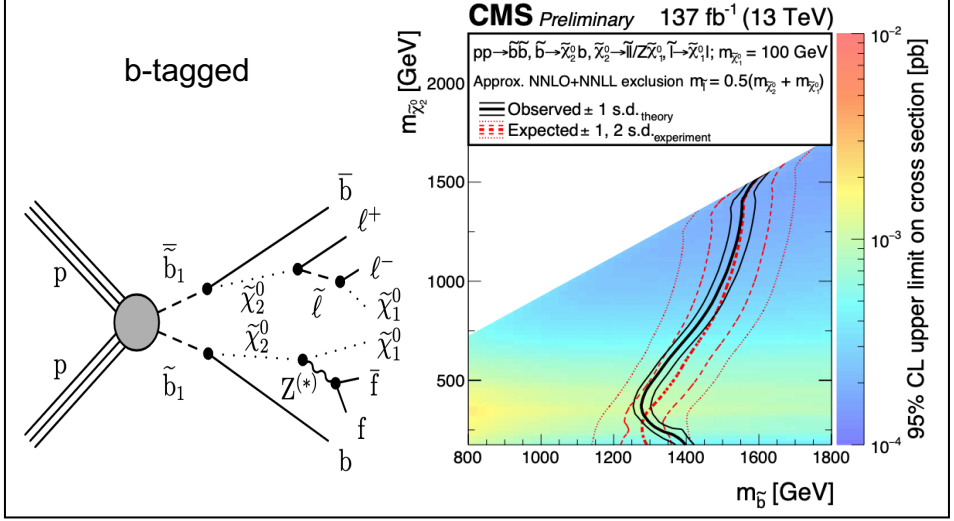
Electroweak production

- 2 OSSF leptons, few jets, and one on-shell Z candidate
- Model with Wino-like signal contributions
- More than 15 search bins based on n_{jets}, $n_{W/Z}^{boosted}$, n_{bjets}, di-jet mass, M_{T2} and p_T^{miss}
- WZ final states : Exclude $\tilde{\chi}_2^0$ mass up to 750 GeV



Strong production (edge)

- 2 OSSF leptons, jets, and no on-shell Z candidate
- M_{ll} with edge shape
- Model with strong productions:
- Cut and count and M_{ll} kinematic fit SRs are used
- Exclude $m_{\tilde{b}}$ mass up to 1400 GeV



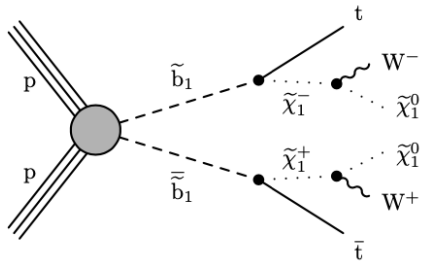
CMS analysis SUS-19-008

Search for physics beyond the standard model in events with jets and two same-sign or at least three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

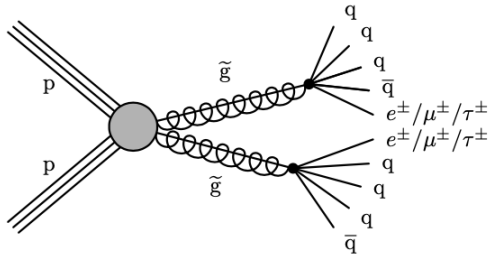
Introduction

2 or more SS leptons

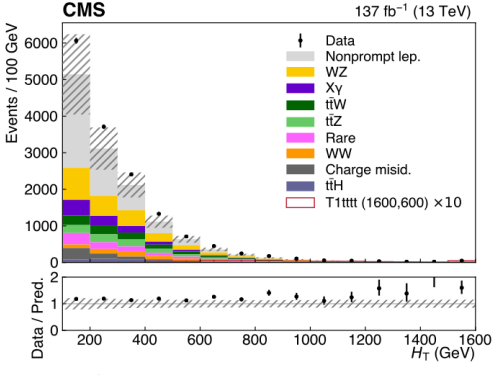
- **Final states with at least 2-jets one of the following:**
  - 2 same-sign leptons
  - 3 or more leptons
- These final states are rarely produced by SM backgrounds
- Target the strongly produced SUSY models considering both R-parity conserving and violating scenarios
- **Search regions consist of ~ 160 orthogonal SRs bins based on kinematical variables:**
  - Lepton p_T, charge and multiplicity
  - n_{jets}, n_{bjets}, and H_T
  - p_T^{miss}, M_T^{min}
  - Number of on-shell Z candidates

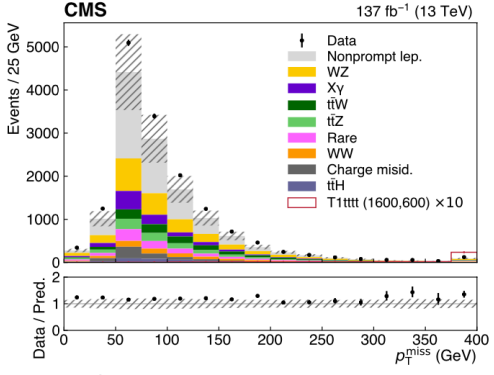


RPC



RPV



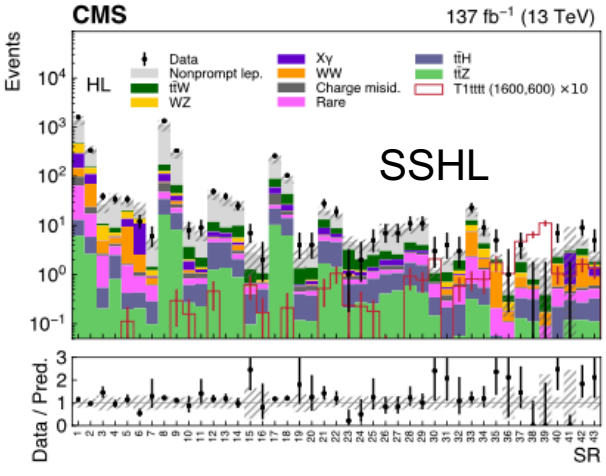


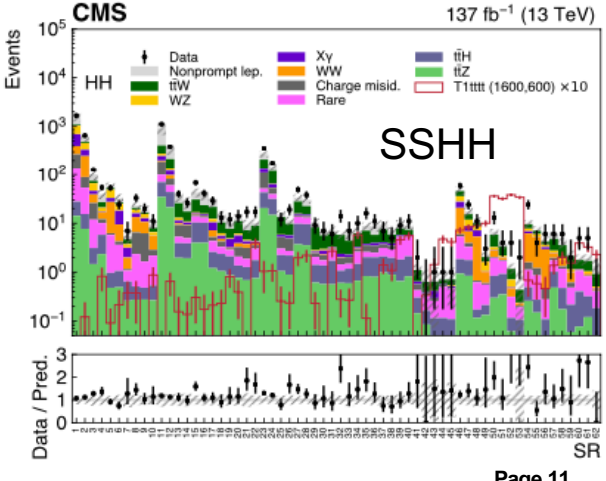
Search strategy and background modeling

Event categorization

- 6 signal categories based on the leptons p_T and multiplicities
- Further splitting according to n_{jets}, n_{bjets}, H_T, p_T^{miss}, M_T and the charge sum of the lepton pair
- **The background modeling is done as following:**
  - Fake/non-prompt leptons from $t\bar{t}, W + jets$ (data-driven)
  - Rare processes: $WZ, t\bar{t}V, X + \gamma$, .. (taken from simulation)
  - Charge flip (data-driven)

nLep	Category	Definition
Dilep.	SSHH	= 2l both with p_T > 25 GeV, p_T^{miss} > 50 GeV.
	SSHL	=2l one with p_T >25 GeV,one with pT < 25GeV, p_T^{miss} > 50 GeV
	SSLL	=2l both with p_T < 25 GeV, p_T^{miss} > 50 GeV.
	SSLowMET	=2l both with p_T > 25 GeV, no Z candidate and p_T^{miss} < 50 GeV.
Multi-lep	On-shell Z	≥3l, ≥ 1 Z candidate, p_T^{miss} > 50GeV.
	Off-shell Z	≥ 3 l, no Z candidate, p_T^{miss} > 50 GeV.

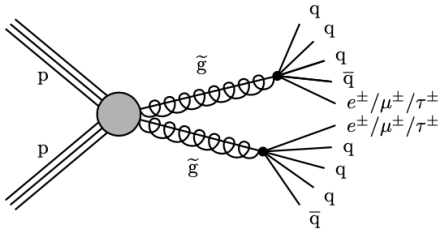


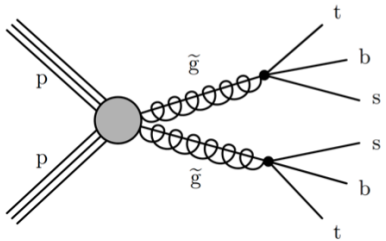


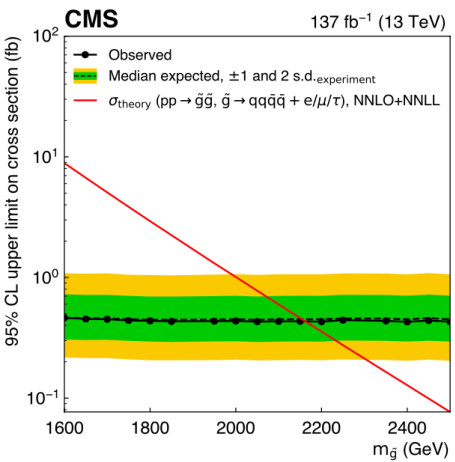
Interpretations

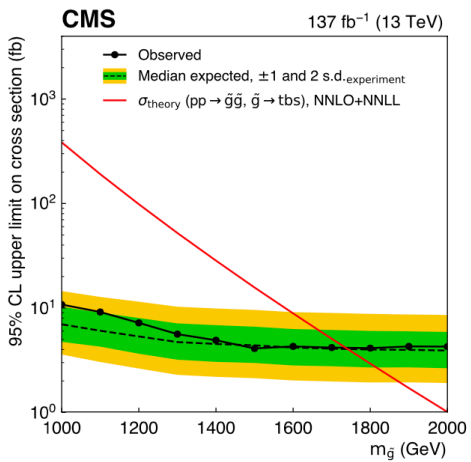
RPV and RPC

RPV gluino pair production:
Exclude gluino masses up to 2.1 TeV for 5-body decay (left) and 1.7 TeV for 3-body decay (right).



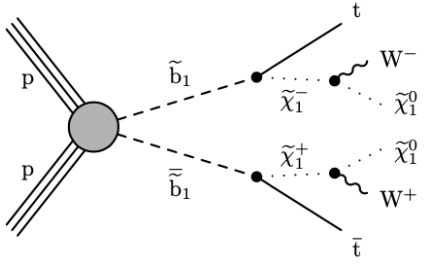


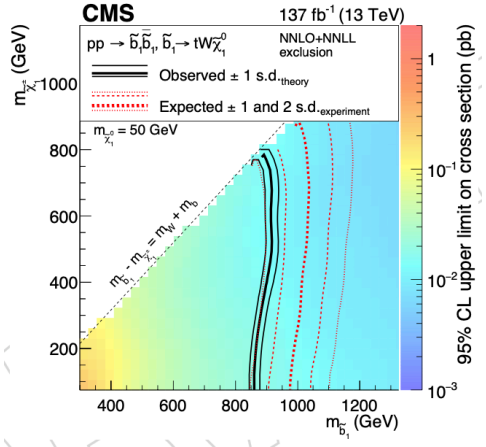




RPC sbottom quark pair production:
$m_{\tilde{b}_1}$ up to 900-1000 GeV is excluded

$m_{\tilde{\chi}_1^0} = 50\ GeV$





More results will be shown in Soham's talk later and in the backup

Summary

- Searches for supersymmetry in events containing an OSSF/SS dilepton or multileptons with jets and p_T^{miss} signatures are concluded with:
  - No significant excess is found in the search regions
  - Limits on SUSY particle masses are set in the context of relevant SUSY models
- Results are interpreted with several SUSY models, both R-parity conserving and R-parity violating
- Full Run 2 (2016-18) dataset has been used in these searches that enable exploiting many SUSY models with a wide range of final/initial states
- Sophisticated analysis methods are mandatory to gain more sensitivity especially in the high mass regime and there are more yet to come:
  - Soft object tagging
  - Heavy object tagging
  - New analysis methods such as Deep Neural Network (DNN)

Thank you

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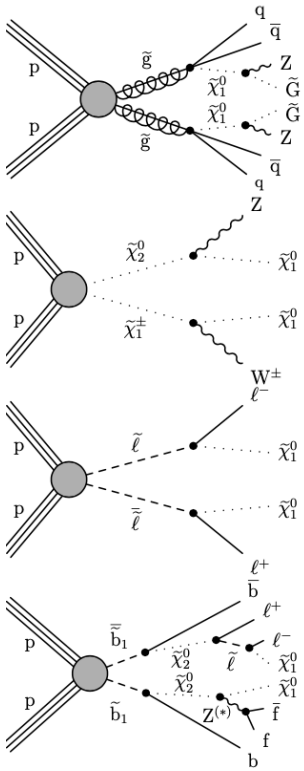
Search strategies



Strong on-Z search sample ($86 < m_{\ell\ell} < 96$ GeV)

Region	n_j	n_b	H_T [GeV]	$M_{T2}(\ell\ell)$ [GeV]	p_T^{miss} bins [GeV]
SRA b veto	2–3	$= 0$	> 500	> 80	[100,150,230,300,∞)
SRB b veto	4–5	$= 0$	> 500	> 80	[100,150,230,300,∞)
SRC b veto	≥ 6	$= 0$	—	> 80	[100,150,250,∞)
SRA b tag	2–3	≥ 1	> 200	> 100	[100,150,230,300,∞)
SRB b tag	4–5	≥ 1	> 200	> 100	[100,150,230,300,∞)
SRC b tag	≥ 6	≥ 1	—	> 100	[100,150,250,∞)

Update

EW on-Z search sample ($86 < m_{\ell\ell} < 96$ GeV)

Region	n_j ($n_{W^\pm/Z}^{boosted}$)	n_b	Dijet mass [GeV]	M_{T2} [GeV]	p_T^{miss} bins [GeV]
Boosted VZ	< 2 (≥ 1)	$= 0$	—	—	[100,200,300,400,500,∞)
Resolved VZ	≥ 2	$= 0$	$m_{jj} < 110$	$M_{T2}(\ell\ell) > 80$	[100,150,250,350,∞)
HZ	≥ 2	$= 2$	$m_{bb} < 150$	$M_{T2}(\ell b \ell b) > 200$	[100,150,250,∞)

Slepton search sample ($m_{\ell\ell} < 65$ or $m_{\ell\ell} > 120$ GeV)

Region	n_j	n_b	$p_T^{\ell_2}/p_T^{j_1}$	M_{T2} [GeV]	p_T^{miss} bins [GeV]
Slepton jet-less	$= 0$	$= 0$	—	$M_{T2}(\ell\ell) > 100$	[100,150,225,300,∞)
Slepton with jets	> 0	$= 0$	> 1.2	$M_{T2}(\ell\ell) > 100$	[100,150,225,300,∞)

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

Region	n_j	n_b	$M_{T2}(\ell\ell)$ [GeV]	p_T^{miss} [GeV]	$t\bar{t}$ likelihood	$m_{\ell\ell}$ bins [GeV]
Edge fit	≥ 2	—	> 80	> 200	—	> 20
$t\bar{t}$-like b veto	≥ 2	$= 0$	> 80	> 150	< 24	[20,60,86]+[96,150,200,300,400,∞)
non-$t\bar{t}$-like b veto	≥ 2	$= 0$	> 80	> 150	> 24	[20,60,86]+[96,150,200,300,400,∞)
$t\bar{t}$-like b tag	≥ 2	≥ 1	> 80	> 150	< 24	[20,60,86]+[96,150,200,300,400,∞)
non-$t\bar{t}$-like b tag	≥ 2	≥ 1	> 80	> 150	> 24	[20,60,86]+[96,150,200,300,400,∞)

SM backgrounds

Main backgrounds and estimation methods

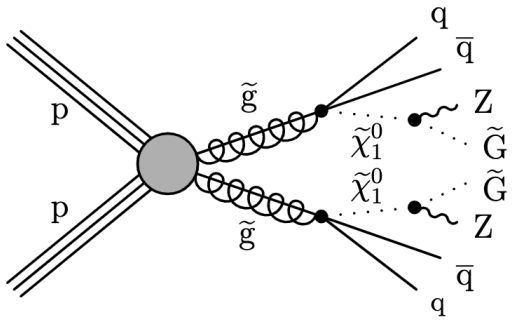
- DY+jets backgrounds:
  - The p_T^{miss} in this backgrounds are due to the mismeasurement of hadronic recoil (instrumental)
  - Estimated using γ+ Jets data as proxy by reweighting it to match the kinematics of the Z+jets
  - The reweighting is done by:
    - Create control regions containing DY and γ+Jets MC samples for each signal region, having the same selections
    - Obtain weights for each p_T bin by dividing the DY MC p_T
    - distribution by the γ+Jets MC p_T distribution (after normalizing for area)
    - Use these p_T dependent weights on the Photon CR data to get the DY estimate

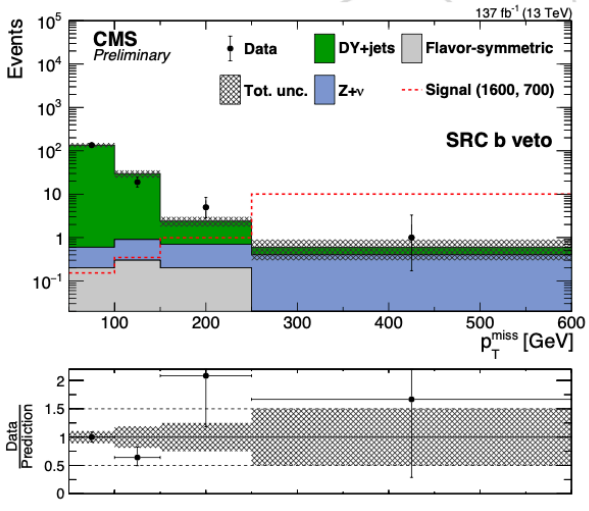
Interpretations: strong production

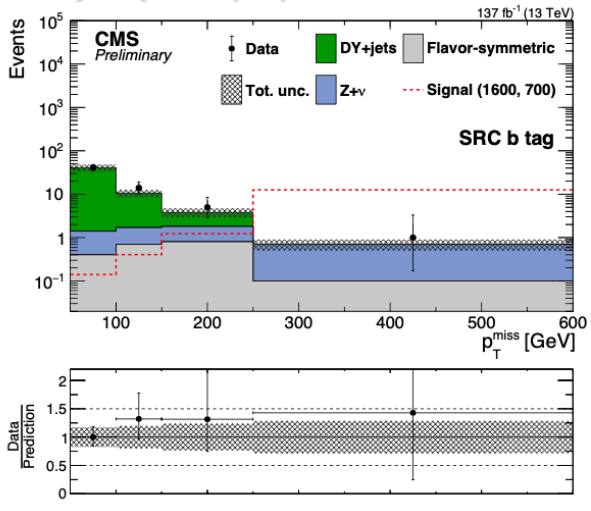
2 OSSF leptons, many jets, and one on-shell Z candidate

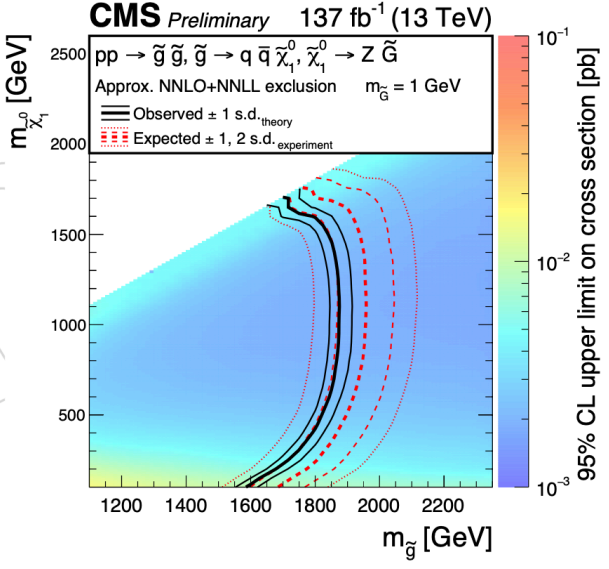
Models of gluino-like contributions

- Sensitivity is driven by combining ~ 28 search bins based on n_{jets}, n_{bjets}, H_T, M_{T2} and p_T^{miss}
- Gluino masses up to 1850 GeV are excluded



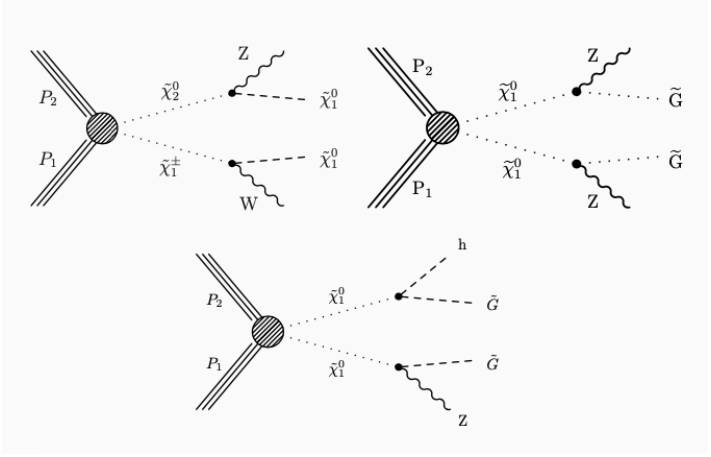


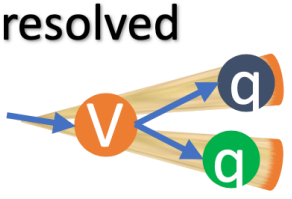


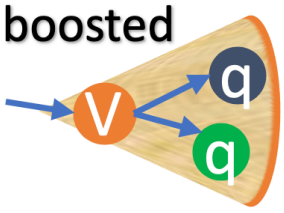


On Z Electroweak signal regions

- 86 GeV < M_{ll} < 96 GeV
- p_T^{miss} > 50 GeV
- AK8 jet (fatjet) selections case of 0 b-tag in final states
- M_{T2}* cut is required to reduce the $t\bar{t}$ background
- In case of non-boosted W/Z decaying to $q\bar{q}$:
  - Jets are expected to be resolved
  - Require n-jets (AK4) ≥ 2 and 0 b-tag
- In case of boosted W/Z decaying to $q\bar{q}$:
  - Jets are expected to be collimated forming an AK8 jets
  - Require n-jets (AK8) ≥ 1 and 0 b-tag
- In case of b-tag pair in the final state:
  - Require n-btag = 2 and $m_{bb} < 150$ GeV



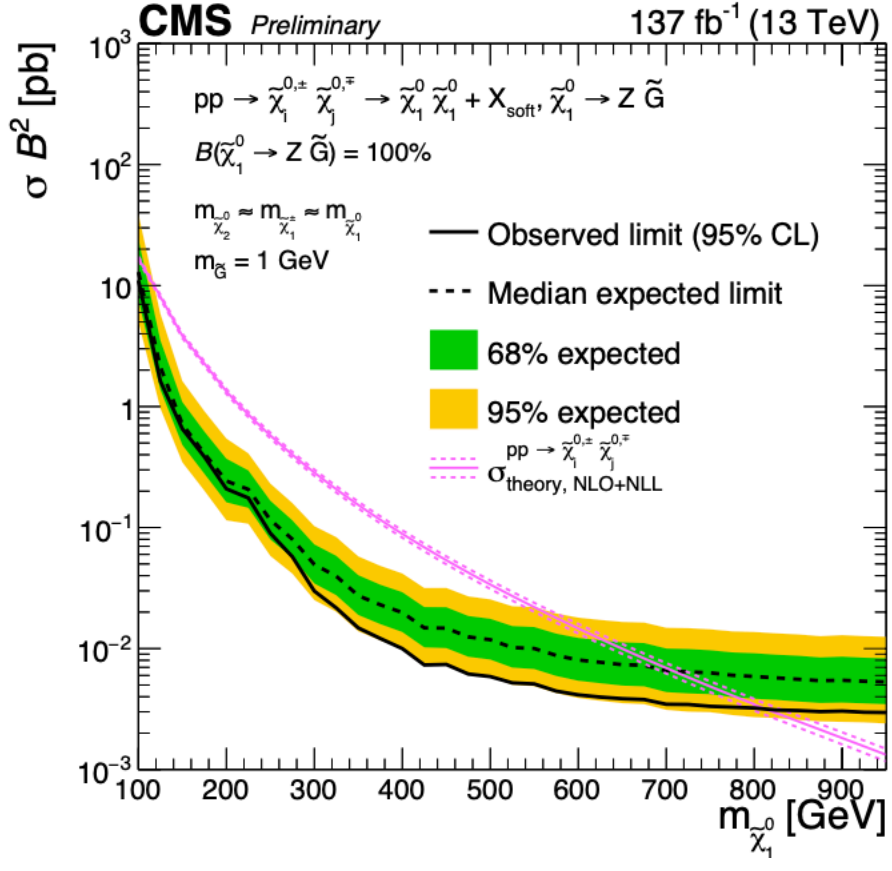


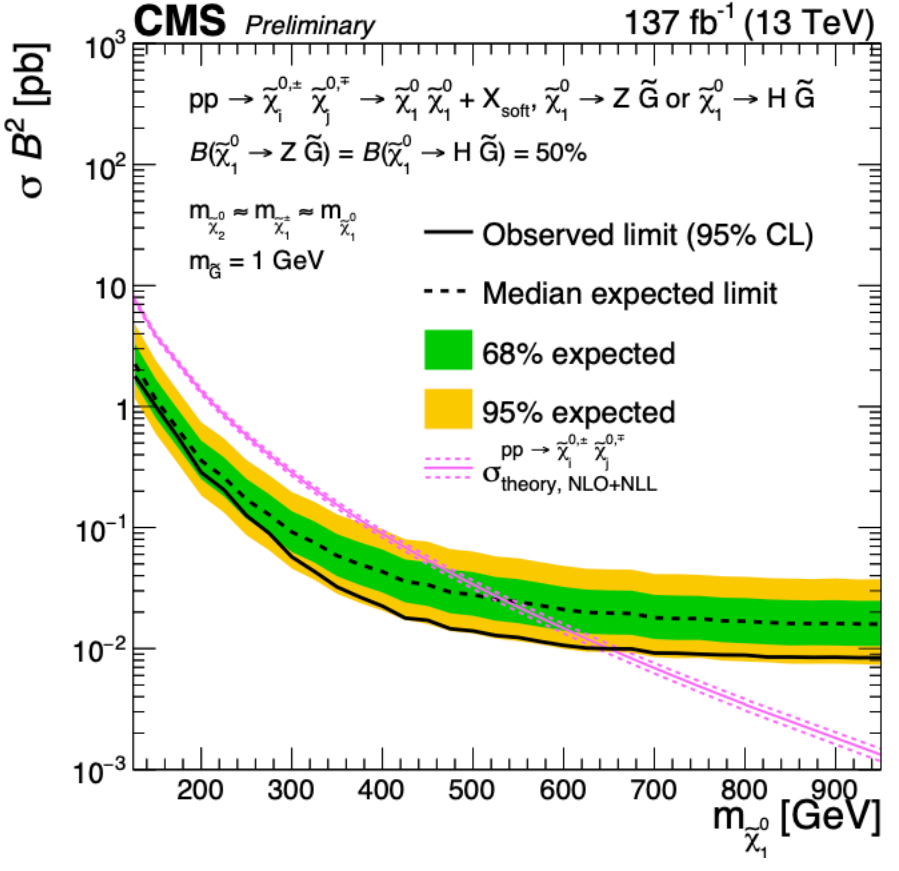


Region	n_j ($n_{W/Z}^{boosted}$)	n_b	Dijet mass [GeV]	M_{T2} [GeV]	p_T^{miss} binning [GeV]
Boosted VZ	<2 (≥1)	=0	—	—	[100,200,300,400,500,>500]
Resolved VZ	≥2	=0	$m_{jj} < 110$	$M_{T2}(ll) > 80$	[100,150,250,350,>350]
HZ	≥2	=2	$m_{bb} < 150$	$M_{T2}(lblb) > 200$	[100,150,250, >250]

* $M_{T2} = \min_{\vec{p}_T^{miss(1)} + \vec{p}_T^{miss(2)} = \vec{p}_T^{miss}} \left[\max \left(M_T^{(1)}, M_T^{(2)} \right) \right]$

On Z Electroweak interpretation higgssino

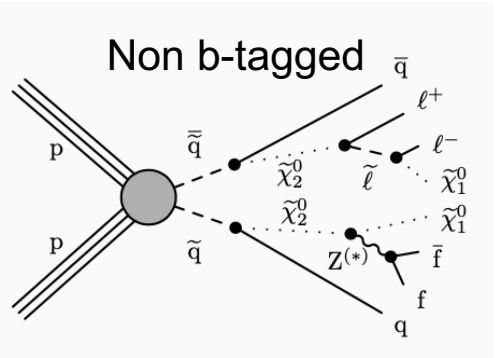


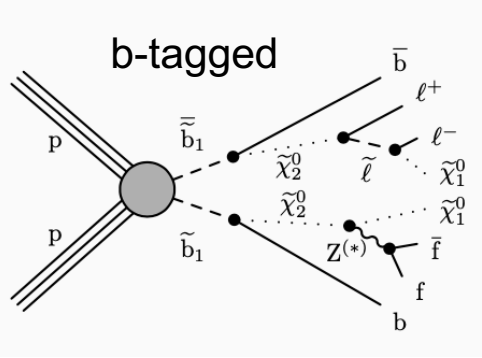


Off Z Edge signal models - T6qq(bb)llslepton

Two slepton edge models are considered with two different nb-tag final states

- The $\tilde{\chi}_1^0$ mass is fixed to be 100 GeV → edge mass end = $(m_{\tilde{\chi}_2^0} - 100)$
- 100% Br of $\tilde{l} \rightarrow l\tilde{\chi}_1^0$
- Both right and left-handed sleptons are considered in this model
- Slectrons and smuons are degenerated in mass
- DY is suppressed by requiring off-shell Z and the main background is $t\bar{t}$
- To maximize the sensitivity for all the phase space, two complementary search methods are considered
- Cut and count signal regions :
  - M_{ll} binning (GeV) : 20-60, 60-86, 96-150, 150-200, 200-300, 300-400, >400
  - b jet multiplicity binning : =0, ≥ 1
  - Negative Log Likelihood binning ($t\bar{t}$ and non- $t\bar{t}$)
- M_{ll} kinematic fit signal region
  - Require p_T^{miss} > 200 GeV





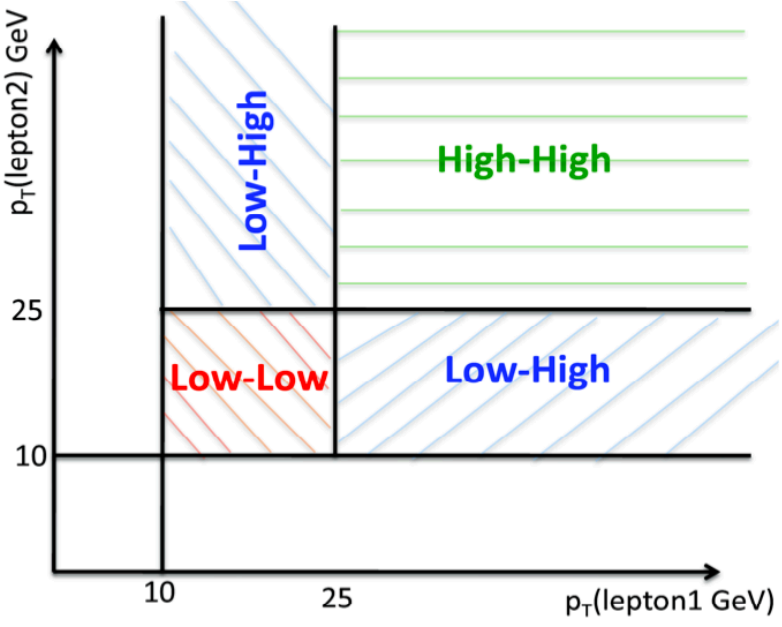
Edge signal interpretations

2 OCSF leptons, many/few jets and no resonance in the Z peak

- Require p_T^{miss} > 200 GeV
- Simultaneous fit to ee, $\mu\mu$, and $e\mu$ M_{ll} shapes in data in fit signal region
- Background are $Z \rightarrow ll$ and flavor-symmetric
- Signal shape is a triangle with gaussian smearing
- Free parameters are edge position and number of events

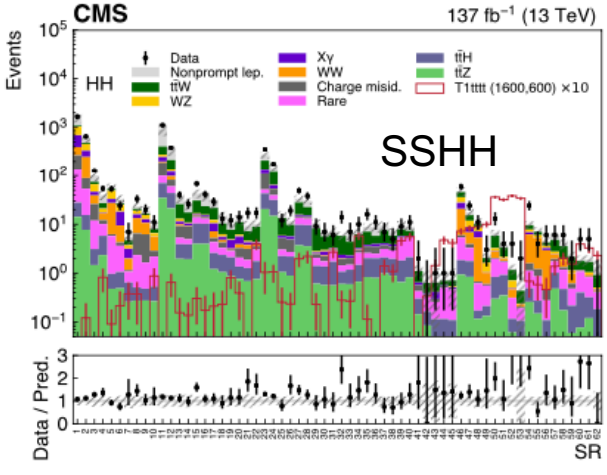
Same-sign dilepton Interpretations

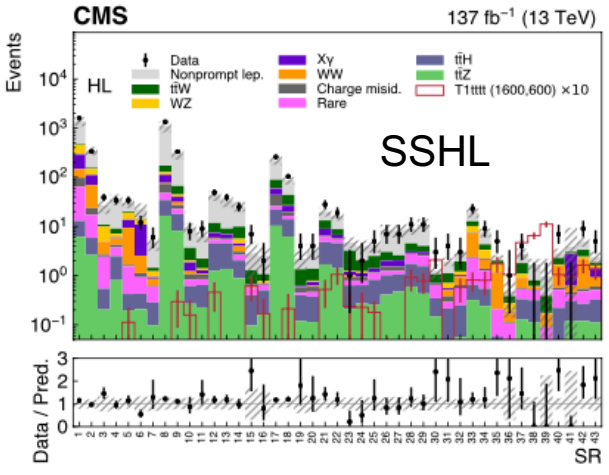
Event categorization

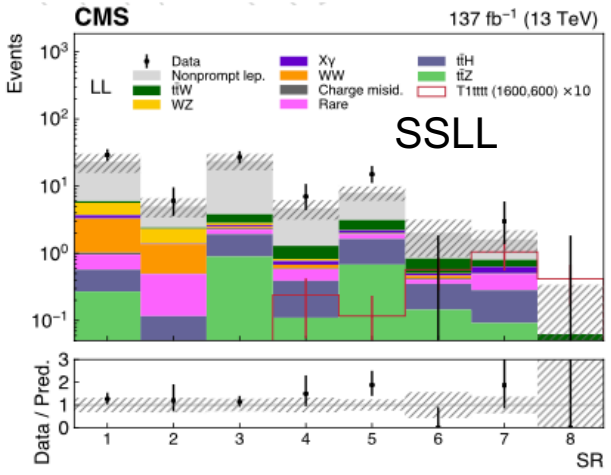


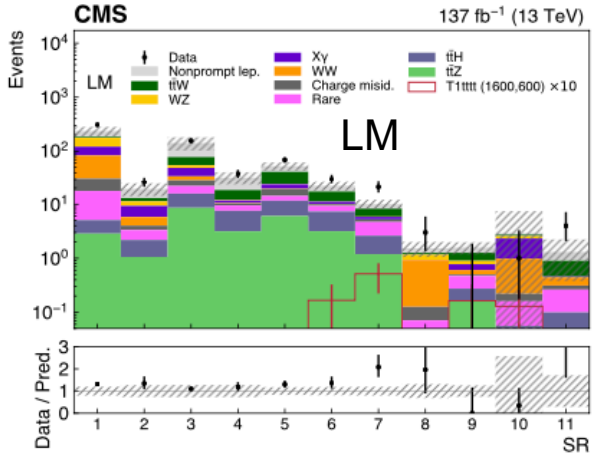
Same-sign dilepton Interpretations

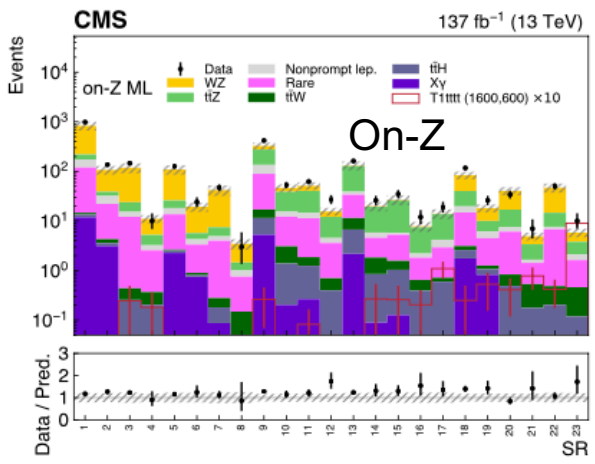
Event categorization

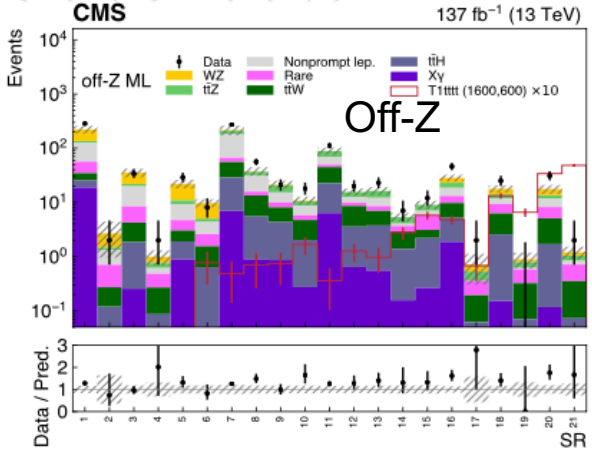










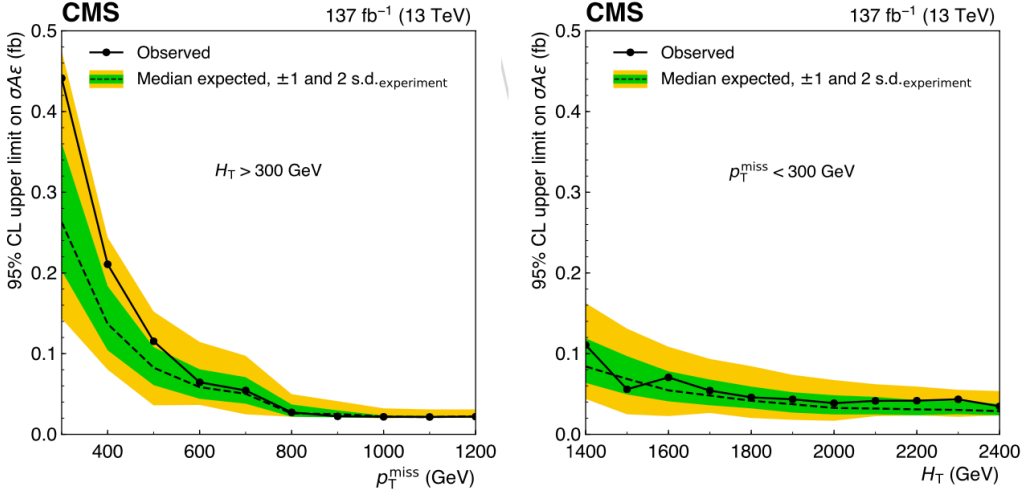


RPV and model independent results

Model independent limits

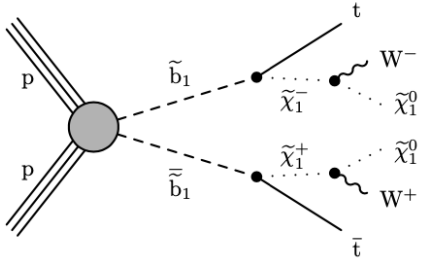
$\sigma A\varepsilon$, to produce an SS lepton pair with at least two jets, as a function of the:

- **Minimum p_T^{miss} threshold, when H_T > 300 GeV (left),**
- **Minimum H_T threshold, when p_T^{miss} < 300 GeV (right)**

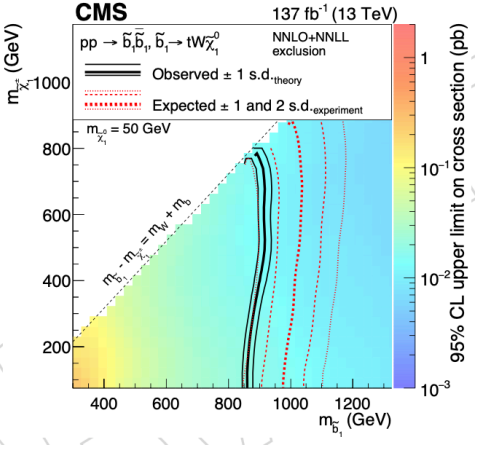


RPC models interpretations

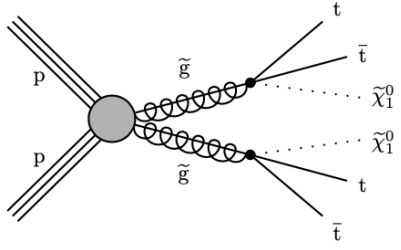
3rd generation squarks, top squark and bottom squark

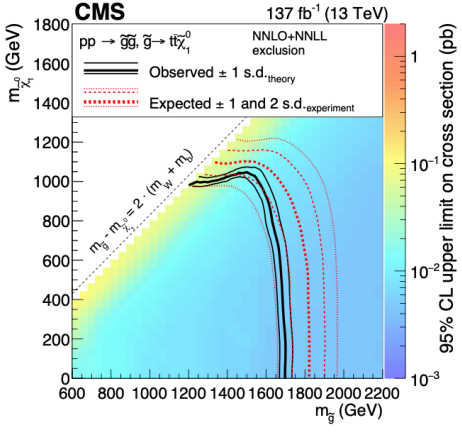


$m_{\tilde{\chi}_1^0} = 50\ GeV$

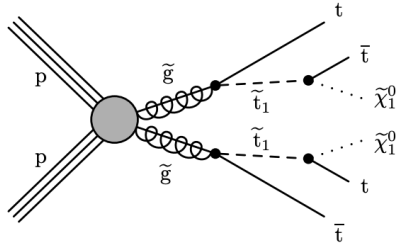


off-shell 3rd gen. squarks





on-shell 3rd gen. squarks



$m_{\tilde{t}} = m_{\tilde{\chi}_1^0} + m_t$