Searches for supersymmetry in hadronic final states with the CMS experiment

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SUSY has many variations and final states
- Low mass stop, charginos, or neutralinos well motivated
- Decay cascades often have top, $W$, $Z$, $H$
- Large branching ratios to jets
- Hadronic final states have good statistics
  - Backgrounds challenging, but surmountable
- Complementary to lepton final states, small backgrounds but small rates
- Focus today on Run 2 searches in hadronic final states for:
  - Stop squarks
  - Charginos or neutralinos
  - Higgsinos
Many models of stop production

With R-parity conserved, LSP is stable, stop decays to LSP + SM particles

LSP invisible in CMS—missing $p_T$

Final state determined by $\Delta m$ (mass difference between stop and LSP)

For the model shown on the left:

- Top + LSP when $\Delta m > m(t)$
- $Wb + LSP$ when $\Delta m > m(W) + m(b)$
- Compressed region when $\Delta m < m(W) + m(b)$—many final states
- Top corridor at $\Delta m \sim m(\text{top})$: signal very similar to SM

Generally missing $p_T$, lots of jets

- How much missing $p_T$ depends on $\Delta m$
Search for $R$-parity conserving stops in missing $p_T +$ jets

Many improvements over previous searches

Require zero charged leptons, many jets, large missing $p_T$

Cover all $\Delta m$ except top corridor

Many final states have multiple tops, $W$ bosons, $b$ jets

Deep NN top, $W$ taggers give sensitivity to different models
  
  Resolved+merged top taggers cover wide range of top $p_T$

Also use combination of low-$p_T$ and high-$p_T$ $b$ taggers
Major backgrounds, data-driven methods:

- “Lost lepton”: SM backgrounds like $t\bar{t}$, $W + \text{jets}$ that produce a lepton but it is not reconstructed
- $Z + \text{jets}$ with $Z \rightarrow \nu\bar{\nu}$
- QCD multijet

For each major background, define a control region enriched in that background, depleted of signal

Use Monte Carlo to extrapolate control region data to search region

Many search bins, based on number of tagged objects ($b$, $t$, $W$), number of jets, $H_T$, missing $p_T$, and others

Some search bins more sensitive to low $\Delta m$ models (upper plot), others to high $\Delta m$ (lower plot)

Only about half the 183 search bins shown here

No excess of data above the SM prediction
Set limits on signal cross sections as function of sparticle masses
- Top corridor not considered
- Only one model shown here, for high $\Delta m$
- Exclude parameter space where experimental cross section limit smaller than theoretical cross section
- Stop masses up to 1310 GeV excluded, depending on LSP mass
- Improvement over previous analyses ($\sim 200$ GeV extension of excluded region) comes from
  - Additional data
  - Use of top and $W$ taggers
  - Re-optimized search bins

![Graph showing CMS exclusion limits on stop mass and chargino mass](image)
Electroweakino searches

▶ Even if squarks too massive, still expect charginos/neutralinos at $\sim 1$ TeV
▶ Search for chargino-neutralino or chargino pair
▶ Assume:
  ▶ $R$-parity conserved
  ▶ LSP is lightest neutralino, bino-like
  ▶ Lightest chargino is NLSP and is wino-like
  ▶ In chargino-neutralino production, second lightest neutralino is mass-degenerate with lightest chargino and is wino-like
▶ Decay to $WW$, $WZ$, or $WH$ plus two LSPs
▶ Hadronic decay of $W$, $Z$, $H$
▶ Lots of jets and missing $p_T$
▶ Try to identify boson decays using NNs
Electroweakino searches

**WW, WZ, WH: CMS-PAS-SUS-21-002**

- Select events with missing $p_T$, at least two large-radius jets ("AK8"), and 2–6 normal-radius jets ("AK4")
- Intend to capture decay products of bosons in one AK8 jet each
- Employ three taggers for AK8 jets:
  - $W$ tagger targets $W$ decays
  - $V$ tagger (upper figure) targets $Z$ or $W$ decays
  - $b\bar{b}$ tagger (lower figure) targets $H$ or $Z \rightarrow b\bar{b}$
- Also use AK4 jet $b$ tagger
- Many possible combinations of taggers
- Some used as search regions, others as control or validation regions
- Highest-level division based on AK4 $b$ tagger
- *b* veto region requires zero AK4 *b* tags
- Sensitive to $WW$ and $WZ$, but not $WH$
- Use $W$ tagger and $V$ tagger to define search region
- Backgrounds are events with zero or only one boson, called “0-res” and “1-res”, plus rare events (e.g. triboson)
- 0-res and 1-res background estimates derived from control regions
- Control regions defined by vetoing $W$ and $V$ tags in various combinations
- Search region binned in missing $p_T$
- No excess in data above expected backgrounds
- $b$ tag search region requires at least one AK4 $b$ tag
- Sensitive to $WH$ and to $WZ$
- Use $W$ tagger and $b\bar{b}$ tagger to define search regions
- Background from top production becomes important here
- Use tagger veto to define control regions, and also use events with one charged lepton for more control regions
- Lepton control regions constrain top backgrounds, tag-veto control regions constrain 0-res backgrounds
No excess observed above expected SM backgrounds

Establish 95% CL limits on all considered models as functions of LSP and NLSP masses

Showing limits combining chargino pair and chargino-neutralino production, assuming NLSP neutralino decays to $Z$ or to $H$

For very light LSP, NLSP masses up to 870 (960) GeV are excluded for the $Z$ ($H$) case
Search for higgsino pair production

Two Higgs bosons decaying to $b\bar{b}$, plus missing $p_T$

Divide search according to $H$ boson $p_T$
  - low $p_T$: resolved $b$ jets (AK4 $b$ jets)
  - high $p_T$: merged $b\bar{b}$ AK8 jet

$H$ boson $p_T$ determined by mass splitting between higgsino and daughter sparticle (Goldstino or lightest neutralino)

Select events with missing $p_T$, zero charged leptons and jets:
  - low $p_T$: 4 or 5 AK4 jets
  - high $p_T$: 2 AK8 jets

Apply $b$-tagging algorithms to AK4 and AK8 jets

Attempt to reconstruct two $H$ boson candidates
Split events according to $H$ boson $p_T$, missing $p_T$, number of reconstructed candidates, and (for low $p_T$ case) largest dijet separation

- Estimate backgrounds using control regions and simulation
- Low $p_T$ backgrounds dominated by top pair production
- High $p_T$ backgrounds dominated by QCD and top
- No more than modest excess in one or two bins
- Set 95% CL limits
- For electroweak production (left), no exclusion possible
- For gauge-mediated model (upper right), higgsino masses between 175 and 1025 GeV excluded
- For strong production of gluino pairs (lower right), exclude higgsino masses below 2330 GeV
- Strongest constraints on higgsino production from CMS to date
Hadronic stop search extends stop exclusion by $\sim 200 \text{ GeV}$

Chargino/neutralino search most sensitive to date for boosted phase space, uses deep NN taggers

Higgsino pair search combines resolved and boosted phase spaces, obtains strong constraints on gauge-mediated models and gluino production models

Hadronic final states are a critical part of the hunt for SUSY
- stop mass vs LSP mass figure taken from arXiv:1407.0583
- All-hadronic stop search: PRD 104 052001 (2021)
- WW, WZ, WH: CMS-PAS-SUS-21-002
- Di-Higgs plus MET: CMS-PAS-SUS-20-004
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Approx. NNLO+NNLL exclusion

95% CL upper limit on cross section [pb]
Approx. NNLO+NNLL exclusion

- Observed ± 1 \( \sigma_{\text{theory}} \)
- Expected ± 1, 2 \( \sigma_{\text{experiment}} \)

 CMS hadronic SUSY

\( m_{\tilde{g}} \) [GeV] vs. \( m_{\tilde{\chi}_1^0} \) [GeV]

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CMS

137.0 fb\(^{-1}\) (13 TeV)

pp → \tilde{g} \tilde{g}, \tilde{g} → \tilde{t} \tilde{t}, \tilde{t} → c \tilde{\chi}_1^0

Approx. NNLO+NNLL exclusion

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- Expected ± 1, 2 \sigma_{\text{experiment}}

95% CL upper limit on cross section [pb]