Searches for strong production of SUSY particles in CMS

- Introduction
- Limits from 13 TeV
- Some recent analyses:
  - All hadronic inclusive $\alpha_T$ analysis
  - All hadronic with top tagger
  - Stops in 1$\ell$ final state with $\Delta\phi(\ell,W)$
  - Gluinos with $H\rightarrow b\bar{b}$
- Conclusions
Higgs at $m_H = 125$ GeV leads to large stop mass or large mixing in MSSM

Naturalness favors light stops and higgsinos

Currently sensitive to $\sigma(\text{SUSY}) \sim 10^{-3}$ pb

Highest cross section for squarks, gluinos $\rightarrow$ strong production

This talk will only cover strong production, conserved R-parity and large mass splits

Use Simplified Mass Spectra

Order $\geq 4$ sparticles, $\sim 2$ masses are free
- Assume all others are heavy & decoupled

Compute the acceptance $\times$ efficiency

Determine 95% CL upper limit on $\sigma \times \text{BR}^2$
Strong production limits in Run2

- Gluinos > 1.9 TeV
- Squarks > 1.5 TeV
- Stops > 1.1 TeV
- Sbottoms > 1.2 TeV

- MSSM and natural spectra heavily disfavored (not yet completely excluded)

- Complementarity of analyses
  - Many bins in several observables to obtain good sensitivity
  - Stay open to scenarios beyond benchmark models
  - Results in "aggregate" regions to facilitate interpretation

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Background determination

Take all hadronic stop search as an example

- Control regions kinematically similar to signal region, but not overlapping
  - Use transfer factors to estimate SR yield from CR
- $t\bar{t}$ and $W+$jets (lost lepton) background:
  - $\mu+$jets sample: invert $\ell$ veto, $N_b$ bins
  - Correct TF for $\ell$ eff. and different background composition
- $Z\rightarrow\nu\nu$ background:
  - From $Z\rightarrow\ell\ell$ and $\gamma+$jets, enriched samples
  - Main unc. from b-tag, $\varepsilon_\gamma$, stats in CR
- QCD multijet background:
  - Enhance multijet by requiring MET and jets to overlap
  - TF determined on low-MET region and extrapolated using MC
- Check prediction in validation samples, or performing closure tests

\[
N_{LL}^{\text{pred}} = \frac{N_{MC}^{0\ell}}{N_{MC}^{1\ell}} \times N_{\text{data}}^{1\ell}
\]

\[
N_{Z\rightarrow\nu\nu}^{\text{pred}} = \frac{N_{Z\rightarrow\ell\ell}^{\text{MC}}}{N_{Z\rightarrow\ell\ell}^{\text{data}}} \times \frac{N_{MC}^{\gamma+jets}}{N_{\text{data}}^{\gamma+jets}}\left(E_T^{\gamma}\right)
\]

\[
N_{QCD}^{\Delta\phi} = \left(N_{\text{data}}^{\Delta\phi} - N_{\text{otherbkg.}}^{\Delta\phi}\right) \times \frac{N_{MC}^{\Delta\phi}}{N_{MC}^{\Delta\phi}}
\]
Inclusive hadronic search with $\alpha_T$

- 35.9 fb$^{-1}$ search binned in $N_j$, $N_b$, $H_T$, and MHT
- All jets defined by $p_T > 40$ GeV and $|\eta| < 2.4$
- MHT/MET < 1.25, $H_T > 200$ GeV, MHT > 200 GeV
- Misreco'd jets rejection: $\alpha_T \gtrsim 0.55$, $\Delta \phi_{\text{min}}^* > 0.5$
  - $\Delta \phi_{\text{min}}^*$ = minimum angle between jet and MHT vector without that jet
  - A factor $10^5$ reduction in QCD background

$$\alpha_T = \frac{E_{T,j}^2}{M_T} = m \to 0 \sqrt{\frac{E_{T,2}}{2E_{T,1}(1 - \cos \phi)}} \to \frac{H_T - \Delta H_T}{2\sqrt{H_T^2 - \Delta H_T^2}}$$

$\Delta H_T = 0$
$H_T = 0$
$\alpha_T = 0.5$

$\Delta H_T > 0$
$H_T > 0$
$\alpha_T < 0.5$

$H_T = 0$
$\alpha_T > 0.5$

$\Delta \phi_{\text{min}}^* = \sum_{i \in \text{jet}} |\vec{p}_{T,i}^j|$
Backgrounds in $\alpha_T$ search (1)

- Two control regions:
  - Single muon data $\rightarrow \bar{t}t$ and W+jets
  - $\mu\mu$+jets data $\rightarrow Z(\nu\nu)$+jets
- Use transfer factors to predict backgrounds
- Check with fit in control regions only: constrain non-multijet backgrounds

![Histogram diagram showing $N_{\text{jet}}$, $N_b$, $H_T$, and $H_{miss}$ for various bins.](image)

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Backgrounds in $\alpha_T$ search (2)

- Two control regions:
  - Single muon data $\rightarrow t\bar{t}$ and W+jets
  - $\mu\mu$+jets data $\rightarrow Z(\nu\bar{\nu})$+jets

- Use transfer factors to predict backgrounds

- Final results from a simultaneous fit between the signal and control regions

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**CMS Supplementary**

**Post-fit (CR + SR)**

- Data
- SM pred.
- $Z\rightarrow\nu\bar{\nu}$
- $W$, $t\bar{t}$, residual SM
- Multijet

Events per $H_T^{\text{miss}}$ bin

- $N_{\text{jet}}$
- $N_b$
- $H_T$
- $H_T^{\text{miss}}$ [GeV]

35.9 fb$^{-1}$ (13 TeV)

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**α_T search results**

- **Gluinos > 1.9 TeV → Neutralino > 1.2 TeV**
- **Squarks > 1.3 TeV → Neutralino > 575 GeV**
- **Complementary analysis to other more targeted searches**
- **Similar sensitivity to M_{T2} search**
- **Additional interpretation in split SUSY models with long-lived gluinos**

SUS-16-038; JHEP 05 (2018) 025

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SUSY strong production
All hadronic with identified top quarks

- 35.9 fb\(^{-1}\) Three categories:
  - Unmerged: Three anti-\(k_T\) 0.4 (AK4) jets
  - Partially merged: AK8 is boosted W, combined with AK4 jet
  - Fully merged: AK8 is boosted top
    - Different \(p_T\), softdrop mass, and N-subjetiness cuts

- Top tagger provides high \(\varepsilon\) over large \(p_T\) range
- Baseline: MET\(>250\) GeV; \(H_T\)\(>300\) GeV; 1 btag (\(\varepsilon_b\sim65\%\))
- Estimate \(t\bar{t}\) bkgd from data with translation factors
- 84 bins in \(N_b\), \(N_{top}\), \(M_{T2}(H_T)\), MET

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All hadronic with identified top quarks

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SUSY strong production
Stops and charginos in $1\ell$ with $\Delta\phi$

- 35.9 fb$^{-1}$
  - $L_T = \text{MET} + p_T(\ell) > 250$ GeV, 5+ jets, $H_T > 500$ GeV
  - Discriminant variable: $\Delta\phi(\ell, W)$
  - Main backgrounds $W$+jets and $t\bar{t}$: small $\Delta\phi$

- Background prediction $N_{MB}^{SR} = \kappa \frac{N_{SB}^{SR}}{N_{CR}^{QCD, SB}} N_{MB}^{CR}$
  - $\kappa$: MC corr. for differences in (b-) jet multiplicity between side band (SB) and main band (MB)
  - Search performed in $b$-tagged ($t\bar{t}$ dominated) and $b$-veto ($W$+jets and $t\bar{t}$) regions
  - QCD estimated from tight-to-loose ratio

- MB: $n_{jet} \geq 5,6$
- SB: $n_{jet} \in [3,4],[4,5]$
Single lepton search with $\Delta\phi$

**b-tagged**

SUS-16-042
PLB 780 (2018) 384

**b-veto**

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Gluinos+hadronic Higgs

- Signature: two Higgs bosons with two AK8 jets
  - Large gluino m: H is boosted; H→bb has 58% BR
  - $H_T > 600 \text{ GeV, MET} > 300 \text{ GeV}$
  - 2 AK8 jets with $p_T > 300 \text{ GeV, } 50 < m_j < 250 \text{ GeV}$
  - H-tag: MVA algorithm resolves decays of two b-hadrons inside AK8 jet; require $85 < m_j < 135 \text{ GeV}$
  - Jet pruning to improve mass resolution

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Gluinos+hadronic Higgs

- Estimate the background as an ensemble using “ABCD” method
- Sideband regions (B,D) are used to make background prediction in the signal region (A,C)
- Scaling ratios are not the same for all samples
  - Composition changes with MET
- A combination of data and MC is used to correct for the non-closure
- High-mass gluino points rely on sensitivity from high MET bins
- Low-mass gluinos have a large $\sigma$ and all bins contribute to the sensitivity
- Gluino mass > 2 TeV in HH model
- Gluino mass > 1.8 TeV in ZH model

SUS-17-006 (PRL) arXiv:1712.08501

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Conclusions

- SUSY strong production involves the dominant production modes
  - Both inclusive and dedicated searches → complementary analyses
    - Covering specific signatures with dedicated tools, top taggers, angular variables...
    - Fine binning targeting limits and more generic “aggregate” search bins
- No evidence yet for SUSY → stringent constraints
- “Natural” SUSY could still be hidden
  - Focus on compressed scenarios, RPV, split SUSY, EW production, VBF…
  - Work on isolation, soft leptons, boosted objects, high pileup
  - Expand interpretations
- Analyses with full Run2 dataset will come in 2019 (>100 fb⁻¹)

Typical limits from 13 TeV data:

- \( m_{\text{gluino}} > 2 \) TeV
- \( m_{\text{squarks}} > 1.5 \) TeV
- \( m_{\text{stop}} > 1.1 \) TeV
- \( m_{\text{sbottom}} > 1.4 \) TeV

Latest results in this link
Extras