Search for supersymmetry using boosted Higgs bosons and missing transverse momentum in proton-proton collisions at 13 TeV

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The existence of an additional type of matter which does not directly couple to photons is suggested by observations of galactic rotation curves & gravitational lensing, for example.

There is a need for delicate fine-tuning in the quantum corrections of the Higgs mass calculation to achieve the measured value of 125 GeV.

Supersymmetry helps the convergence of the gauge coupling constants.

Super Symmetry (SUSY) is an extension to the Standard Model which is able to address these issues.
Search topologies

- Searches for SUSY have yet to discover new physics.
  - Searches are pushing potentially new particles to larger and larger masses.
- Need to explore all regions of SUSY parameter space.
- We have devised a search strategy to look for new physics with high $p_T$ Higgs bosons and missing energy (MET) in the final state.

**example model:**

**Boosted Higgs bosons decaying to $bb$ (57% branching fraction)**

**Supersymmetric particles escape detection creating missing energy**
Higgs kinematics

- Decay products of high $p_T$ objects are emitted at small angles.

\[ \Delta R \approx 2m/p_T \]

- Underlying jet structure can be used for particle identification...

- Higgs bosons generally have $p_T > 300$ GeV in our models of interest.

- $b$-quark daughters are typically contained in a cone of $\Delta R < 0.8$

\[ \Delta R^2 = \Delta \phi^2 + \Delta \eta^2 \]
Higgs tagging (jet selection)

- Reconstruct jets with characteristic size of 0.8 using anti-$k_T$ algorithm (AK8 jets).

- $p_T$ of leading AK8 jet in event: cut at $p_T > 300$ GeV keeps most signal

- Mass of leading AK8 jet in event: cut at $50 < M < 250$ GeV to include Higgs region

- Dedicated MVA used to find compatibility of jet coming from the decay of two B-hadrons.
**Backgrounds**

**true MET**

\[ Z \rightarrow \nu_e \nu_e \]

**unidentified leptons + true MET**

\[ W^\pm \rightarrow e \nu_e \]

**fake MET**

mis-measured jets

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**Baseline Selection**

- HT > 600 GeV (AK4 jets)
- MET > 300 GeV
- 2 or more AK8 jets
  - \( p_T > 300 \text{ GeV}, 50 < \text{mass} < 250 \text{ GeV} \)
- All hadronic search
  - veto electrons, muons & isolated tracks
- Suppress QCD: \( \Delta \phi_{1,2,3,4} > 0.5, 0.5, 0.3, 0.3 \) (AK4 jets)

**MET**

\[ \text{MET} = \left\| \sum_{\text{candidates}} p_T^\gamma \right\| \]

**HT**

\[ \text{HT} = \sum_{\text{AK4 jets}} \left\| p_T^\gamma \right\| \]
Background estimation

- Estimate the background as an ensemble

- Data are binned in signal & sideband regions

\[
\frac{A}{B} = \frac{C}{D} \quad \rightarrow \quad A = B \frac{C}{D}
\]

Agreement of $\kappa$ with unity indicates consistency of the method. Corrections could be applied for large deviations.

MC validation of the background estimation procedure

**single Higgs tag**
- Both jets pass mass requirements
- One and only one pass b-tagging

**double Higgs tag**
- Both jets pass mass and b-tagging requirements

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Data validation regions

- **Validation regions** allow us to test the background estimation procedure on real data before looking in the search regions.
- The low $\Delta\phi$ validation region is obtained by inverting any of the $\Delta\phi$ cuts - it is a QCD enriched sample.
- The single-lepton validation region requires a single lepton in the event - sample enriched in W and top events.
- We also make use of a single-photon validation region with similar kinematics to Z boson events.
- The background prediction method is observed to work well in the validation regions.
**MET distributions**

- Yields for the statistical treatment are placed in a 3-bin MET histogram in both a single and double-Higgs tagged region.

**Baseline selection**

**Single Higgs tag**

**Double Higgs tag**

**Very low backgrounds!**
Expected limits

\[ m_{\tilde{g}} - m_{\tilde{\chi}_2^0} = 50 \text{ GeV} \]
\[ m_{\tilde{\chi}_1^0} = 1 \text{ GeV} \]

The signal region is still blind
Summary

• Presented a search for supersymmetry in events with boosted Higgs bosons and missing transverse energy
  • fully hadronic final states with Higgs decays to b-quarks

• Very low expected background, especially in high MET bins.

• Sensitivity to gluinos with masses up to 2100 or 1900 GeV for the Higgs-Higgs or Higgs-Z final states, respectively.

• Expect to unblind the signal region for the 2016 dataset soon!
Some current limits...

![Graphs showing cross sections and limits for SUS-12-024 and SUS-16-033, with unboosted events highlighted.](image)

\[ m(\chi_2^0) = m(\chi_1^\pm) = m(\chi_1^0) + 200 \text{ GeV} \]

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\[ m_{\tilde{\chi}_2^0} = 0.5(m_{\tilde{\chi}_1^0} + m_\tilde{g}) \]
Higgs Tagging (sub-leading jet selection)

Events vs subleading bb-tag

Events vs subleading $m_J$ [GeV]

Events vs subleading $p_{T_J}$ [GeV]
single $\mu$ validation region - data / MC comparison leading jet

![Graphs showing data/MC comparisons for $m_J$ and bb-disc distributions.](image-url)
low $\Delta\phi$ validation region - data / MC comparison subleading jet

**Figure 1:**
- **Top Left:** Distribution of bb-tag in the low $\Delta\phi$ region.
- **Bottom Left:** Ratio of Data/MC in the low $\Delta\phi$ region.

**Figure 2:**
- **Top Right:** Distribution of $m_J$ in the low $\Delta\phi$ region.
- **Bottom Right:** Ratio of Data/MC in the low $\Delta\phi$ region.
Compact Muon Solenoid - CMS

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with muon chambers

- Muon
- Electron
- Charged hadron (e.g. pion)
- Neutral hadron (e.g. neutron)
- Photon