Searches for SUSY via strong production in fully hadronic final states at CMS

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Why fully hadronic?

Largest cross section for strong production, gluinos & squarks, of SUSY

Largest branching ratio to jets

Fully hadronic searches of strongly produced SUSY

→ discovery channel at energy frontier
Four fully hadronic searches at CMS

<table>
<thead>
<tr>
<th>$H_T^{\text{miss}}$</th>
<th>SUS-16-033 arxiv1704.07781</th>
<th>35.9 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{T_2}$</td>
<td>SUS-16-036 arxiv1705.04650</td>
<td>35.9 fb$^{-1}$</td>
</tr>
</tbody>
</table>

Focus on these latest results in this talk

Razor

| SUS-16-016 | 12.9 fb$^{-1}$ |

$\alpha_T$

| SUS-15-004 | 2.3 fb$^{-1}$ |

Plus many other SUSY searches at CMS that will be presented:

- 1+ lepton (C. Schomakers)
- 3rd gen. squark production (I. Suarez)
- EW produced SUSY (M. Liu)
- Compressed and cascades with Higgs (C. Heidegger)
- Final states with photons (M. Weinberg)
Strategy for fully hadronic inclusive searches

- Lepton veto
- Large $\mathcal{M}_T$ from neutralinos
- Many jets
- A lot of hadronic activity

- Sensitivity to very different signals through binning in jet & b-jet multiplicity
- Binning in $H_T$ for energy scale sensitivity
- Discovery variables $H_T^{\text{miss}}$ & $M_{T2}$

\[
H_T = \sum_{jets} |p_T^-| \\
H_T^{\text{miss}} = \left| - \sum_{jets} p_T^- \right|
\]

\[
M_{T2}(m_c) = \min_{{\vec{p}_T^c(1), \vec{p}_T^c(2)} = \vec{p}_T^{\text{miss}}} \left[ \max(M_T^{(1)}, M_T^{(2)}) \right]
\]
Main backgrounds

- **QCD multi-jet:**
  - Mis-measurement of a jet leads to imbalanced event → **instrumental** $\mathcal{M}_T$
- **W-jets & $t\bar{t}$ (Lost lepton):**
  - $\mathcal{M}_T$ from **neutrino** from leptonic W decay
  - Charged lepton not caught by lepton veto because of acceptance, reconstruction or isolation
- **$Z_{\nu\nu}$+jets:**
  - $\mathcal{M}_T$ from the two neutrinos
QCD multi-jet events have no intrinsic $\text{ME}_T$, only **instrumental** $\text{ME}_T$ due to detector response that depends on $\eta$ & $p_T$ of jets

Good agreement with out of the box simulation.
Lost Lepton estimate

- Charged lepton not seen because of:
  - Acceptance of detector
  - Reconstruction/ID
  - Non-isolation

- Suppress with efficient lepton veto

Single lepton (e/μ) control region

0 lepton signal region

Probability from MC to lose it

e/μ control region
Special estimate of hadronic Tau decays for $H_T^{\text{miss}}$ analysis

- Single $\mu$ control region in data
- Smear $\mu$ $p_T$ with $\tau_h$ response function
- Recompute event kinematics

![Graph 1](image1)

![Graph 2](image2)
**Z → νν Estimate**

- **γ+jets**
  - High stats control region
  - Large systematic uncertainties due to fragmentation photons & theoretical uncertainty on Z/γ ratio

- **Z → ll**
  - Lower stats, now possible with 40 fb⁻¹
  - Lower uncertainties (same process)
  - Account for purity due to Top from eμ data control region

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Selected results

**$H_{T}^{\text{miss}}$**

CMS

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

Good agreement with the standard model

**$M_{T2}$**

Highest $H_T$ region

$H_T > 1500$ GeV

Post-fit background

Entries in bins of $M_{T2}$

$N_{b,jet} (p_T > 30$ GeV)
Aggregate signal regions & covariance matrix for easier reinterpretation

Also available as root files

$M_{T2}$

$H_T^{\text{miss}}$

Full analysis give significantly better limits than the best aggregate region

<table>
<thead>
<tr>
<th>Signal</th>
<th>Expected limit [fb] (full analysis)</th>
<th>Expected limit [fb] (best aggregated region)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to gg, g \to b\bar{b}X^0$ ($m_g = 1700$ GeV, $m_{X^0} = 0$ GeV)</td>
<td>1.80</td>
<td>3.84</td>
</tr>
<tr>
<td>$pp \to gg, g \to b\bar{b}X^0$ ($m_g = 1000$ GeV, $m_{X^0} = 950$ GeV)</td>
<td>234</td>
<td>498</td>
</tr>
</tbody>
</table>
Similar reach for both analyses

Hadronic analyses have similar reach as leptonic channels

Extended reach up to about 2 TeV along gluino mass
Exclusion Limits – Direct squark production

- Similar reach for both analyses
- Have similar reach as leptonic channels for stop production
- Extended reach by to about 1TeV along squark mass
Conclusions

- Showed results of 2 fully hadronic inclusive searches for SUSY with 35.9 fb$^{-1}$ collected by the CMS detector

- Probed the direct squark and gluino production at the energy frontier

- No significant excess over background predictions:
  → Exclude masses of up to about 2 TeV for gluinos and 1 TeV for squarks with two independent approaches
BACK UP
The CMS detector

Very-forward Calorimeter

Superconducting Solenoid

Silicon Tracker

Pixel Detector

Preshower

Hadronic Calorimeter

Electromagnetic Calorimeter

Muon Detectors

Compact Muon Solenoid
The $M_{T2}$ Variable

- $M_{T2}$ is a generalized $M_{E_T}$ like variable for decays with 2 unobserved particles

\[
M_{T2}(m_c) = \min_{\vec{p}_T^{c(1)} + \vec{p}_T^{c(2)} = \vec{p}_T^{miss}} [\max(M_T^{(1)}, M_T^{(2)})]
\]

- Split visible part of event into 2 hemispheres (pseudojets) for calculation of $M_{T2}$

Approximative formula:
\[
(M_{T2})^2 \sim p_T(J1) \cdot p_T(J2) \cdot (1 + \cos \phi_{12})
\]

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**QCD background estimate via delta Phi**

- Invert $\Delta \phi(M_{E_T}, \text{jets})$ cut
  
  $$r_\phi = \frac{N(\Delta \phi_{\text{min}}(\text{jets}, E_{T}^{\text{miss}}) > 0.3)}{N(\Delta \phi_{\text{min}}(\text{jets}, E_{T}^{\text{miss}}) < 0.3)}$$

- Fit $r_\phi$ at low $M_{T2}$ & extrapolate to signal region inclusively in each $H_T$ region
  
  → Then split among $N_j/N_b$ with data based transfer factors

- $N_{CR}$ coming from signal triggers

\[
N_{QCD}^{SR} = N_{CR}^{CR}(H_T, M_{T2}) \cdot r_\phi(M_{T2}) \cdot f_j(H_T) \cdot r_b(N_j)
\]

In each $H_T$ region: