Search for Supersymmetry in Hadronic Final States with the CMS Detector at the LHC

Anwar A Bhatti
The Rockefeller University
CMS Collaboration
2nd International Conference on Particle Physics
Istanbul, Turkey
June 23, 2011
Supersymmetry (SUSY)

- SUSY is a fundamental global symmetry between fermions and bosons.
  - Each fermion has a boson super partner, and vice versa
  - Higgs mass stabilizes against loop correction (fine tuning problem)
  - Modifies running of SM gauge couplings just enough to give “Grand Unification” at single scale
  - SUSY is broken (sparticles have not been seen)

- MSSM: Simple SUSY model consistent w/ SM
  - R-parity conservation
    - $R= (-1)^{2S+3B+L}$
    - Sparticles produced in pairs, decay to an odd number of Lightest Supersymmetry Particle (LSP)
    - LSP is a dark matter candidate
  - SUSY breaking
    - mSUGRA, GMSB, …
Experimental Signature

- Signature: MultiJets + MET

- Squarks & Gluinos cascade decays: produce a number of quarks and gluons, leptons and possibly weakly interacting stable neutral particles (WIMP).

In the detector, WIMPs / Lightest SUSY particles appears as the momentum imbalance in the transverse plane (Missing ET!)
SUSY Searches at CMS using 2010 Data

- Fully hadronic searches
  - SUS-10-005: Inclusive search in jets + MET (>=3 jets)
  - arXiv:1101.1628: Search in jets+MET with $\alpha_T$
  - SUS-10-009: Inclusive search with ``Razor variables’’
  - SUS-10-011: Search in b-tagged jets + MET with $\alpha_T$

- Searches with leptons
  - SUS-10-006: Search with single lepton + jets + MET
  - arXiv1104.3168: SUS-10-004: Search with same sign dileptons + jets + MET
  - arXiv1103:1348, SUS-10-007: Search with opposite sign dileptons
  - SUS-10-008: Search with multileptons

- Searches with photons
  - arXiv:1103.0953, SUS-10-002: Search in Jets+MET+diphotons
  - SUS-11-002: Search with lepton + photon + MET

Analysis written in blue are highlighted. Full results are available on: 
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
Hadronic Search in Jets + MET

Event Selection:
- \( \geq 3 \) jets
  - \( |\eta|<2.5, P_T>50 \text{ GeV} \)
- Veto isolated e/mu
  - Suppress W, Z & Top BGs
- \( \Delta\phi(MHT,j1,2,3) > 0.5,0.5,0.3 \) (rad)
  - Suppress QCD background
- Baseline:
  - HT>300 GeV, MHT>150 GeV
- Search Selection:
  - HT>300 GeV, MHT>250 GeV
  - HT>500 GeV, MHT>150 GeV

Main Backgrounds:
- QCD
- Top & W+jets
- Z(\(\rightarrow\)vv)+jets
Determined by data-driven techniques

LM1*: \( m_0=60 \text{ GeV}, m_{1/2}=250 \text{ GeV}, A_0=0, \tan\beta=10, \text{sign}(\mu)>0 \)
\( m_{\text{gluino}}=611, m_{\text{squark}}=599, m_{\text{LPS}}=96 \text{ GeV} \)
Data vs Standard Model MCs

An out-of-box comparison of Data vs MC for search variables HT and MHT

Baseline selection w/o MHT cut

High MHT

Baseline selection

High HT
Invisible Z background

- $Z(\rightarrow \nu\nu) + \text{multijets}$: Irreducible background in this search
- Three different methods using boson+jets were employed to obtain the data-driven estimates of this background (substitute boson with MHT)

Cross check of different channels is important as they have different sensitivities to potential new physics signal

- Lower statistics than $\gamma$ and $W$
  - Suffer from $\text{Br}(Z\rightarrow\mu\mu)/\text{Br}(Z\rightarrow\nu\nu)=1/6$
- Similar event topology
- Higher stat than $Z\rightarrow\nu\nu$
  - (W+jets rate is about $\times 2.5$ of $Z$+jets)
- Similar to $Z$+jets at large Pt (MHT)
  - High stat (no branching ratio)
Z Invisible From Photons

<table>
<thead>
<tr>
<th>Selection</th>
<th># events in $\gamma$+jets data sample</th>
<th># $Z \rightarrow \nu\bar{\nu}$ events predicted</th>
<th># $Z \rightarrow \nu\bar{\nu}$ events from simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline selection</td>
<td>72</td>
<td>$26.3 \pm 3.2$ (stat.) $\pm 3.6$ (syst.)</td>
<td>$21.2 \pm 1.4$</td>
</tr>
<tr>
<td>High-$H_T$ selection</td>
<td>16</td>
<td>$7.1 \pm 1.8$ (stat.) $\pm 1.3$ (syst.)</td>
<td>$6.3 \pm 0.8$</td>
</tr>
<tr>
<td>High-$H_T$ selection</td>
<td>22</td>
<td>$8.4 \pm 1.8$ (stat.) $\pm 1.4$ (syst.)</td>
<td>$5.8 \pm 0.7$</td>
</tr>
</tbody>
</table>
Veto leptons (e, \( \mu \)) to suppress BGs, still occasionally fail to find and veto leptons. Hadronically-decaying taus also constitute BG.
W/Top + (Lost Leptons) + \nu + Jets

- Leptons failing the lepton veto contribute to background
- There can be 3 reasons to lose leptons
  - the lepton is not reconstructed
  - not isolated
  - out of acceptance
- Start with a control sample of events with exactly one muon
- Measure the identification and isolation (in)efficiencies from data
- Scale the control sample according to the measured (in)efficiencies from data

<table>
<thead>
<tr>
<th>Method</th>
<th>Baseline selection (stat.) / (syst.)</th>
<th>High-(H_T) selection</th>
<th>High-(H_T) selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate from data</td>
<td>33.0 ±5.5 / +6.0 / -5.7</td>
<td>4.8 ±1.8 / +0.8 / -0.6</td>
<td>10.9 ±3.0 / +1.7 / -1.7</td>
</tr>
<tr>
<td>Estimate (PYTHIA)</td>
<td>22.9 ±1.3 / -2.6</td>
<td>3.2 ±0.4 / +0.5 / -0.5</td>
<td>7.2 ±0.7 / +1.1 / -1.1</td>
</tr>
<tr>
<td>MC Truth (PYTHIA)</td>
<td>23.6 ±1.0</td>
<td>3.6 ±0.3</td>
<td>7.8 ±0.5</td>
</tr>
<tr>
<td>Estimate (MADGRAPH)</td>
<td>20.4 ±1.5 / +2.6</td>
<td>2.4 ±0.3 / +0.3 / -0.3</td>
<td>4.8 ±0.4 / +0.6 / -0.5</td>
</tr>
<tr>
<td>MC Truth (MADGRAPH)</td>
<td>21.4 ±0.7</td>
<td>3.0 ±0.3</td>
<td>5.9 ±0.4</td>
</tr>
</tbody>
</table>

April 6, 2011
Top / $W +$ hadronic tau + $\nu +$ Jets

- Start with a muon+jets sample
- Replace the muon by tau response template derived from MC
- Recalculate HT and MHT including this expected energy from Tau
- Correct for
  - muon acceptance
  - Trigger efficiency, Reco efficiency
  - $\text{BR}(W \rightarrow \text{Tau})/\text{BR}(W \rightarrow \text{mu}) \times \text{BR}($ Tau$\rightarrow$ Hadrons$)$

<table>
<thead>
<tr>
<th>Selection</th>
<th>Predicted $W/t\bar{t} \rightarrow \tau_{\text{hadr}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline selection</td>
<td>$22.3 \pm 4.0 \text{ (stat.)} \pm 2.2 \text{ (syst.)}$</td>
</tr>
<tr>
<td>High-$H_T$ selection</td>
<td>$6.7 \pm 2.1 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$</td>
</tr>
<tr>
<td>High-$H_T$ selection</td>
<td>$8.5 \pm 2.5 \text{ (stat.)} \pm 0.7 \text{ (syst.)}$</td>
</tr>
</tbody>
</table>
Jet Response functions can be used to smear a sample of perfectly balanced events and get back the QCD sample as measured in Data.

- **Requirement**: Full jet response (including tails) measured from data to rebalance and resmear the multijet events.
- **Resolution** is measured using Gamma+Jets events (low pT) and DiJet events (high pT)
QCD: Rebalance + Smear

- Step 1: **Rebalance** the data events (jets with Pt>10 GeV) using jet Pt resolutions by maximizing likelihood, \( L_{\text{Jets}} \) subject to constraint MHT=0
  \[ L_{\text{jets}}(p_{T,1}^{\text{true}}, \ldots, p_{T,n}^{\text{true}}) = \prod_{i=1}^{n} r(p_{T,i}^{\text{reco}} | p_{T,i}^{\text{true}}) \]
  
- Step 2: **Smear** rebalanced jets with Pt>10 GeV with resolution functions

  R+S predicts full event kinematics (jet Pt and angular distributions)

- Contamination by SM & Signal processes with real MHT is negligible as such events are made “QCD like” by rebalancing

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### Results

No excess of data events over expected Standard Model prediction observed 😞 Setting limits.

<table>
<thead>
<tr>
<th>Method</th>
<th>Baseline selection</th>
<th>High-$H_T$ selection</th>
<th>High-$H_T$ selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu\bar{\nu}$ from $\gamma + \text{jets}$</td>
<td>26.3 ±4.8</td>
<td>7.1 ±2.2</td>
<td>8.4 ±2.3</td>
</tr>
<tr>
<td>$t\bar{t}/W \rightarrow e, \mu + X$ lost-lepton method</td>
<td>33.0 ±8.1</td>
<td>4.8 ±1.9</td>
<td>10.9 ±3.4</td>
</tr>
<tr>
<td>$t\bar{t}/W \rightarrow \tau_{\text{had}} + X$ method</td>
<td>22.3 ±4.6</td>
<td>6.7 ±2.1</td>
<td>8.5 ±2.5</td>
</tr>
<tr>
<td>QCD Rebalance+Smear method</td>
<td>29.7 ±15.2</td>
<td>0.16 ±0.10</td>
<td>16.0 ±7.9</td>
</tr>
<tr>
<td>QCD factorization method</td>
<td>25.2 ±13.4</td>
<td>0.4 ±0.3</td>
<td>17.3 ±9.4</td>
</tr>
<tr>
<td>Total data-driven background</td>
<td>111.3 ±18.5</td>
<td>18.8 ±3.5</td>
<td>43.8 ±9.2</td>
</tr>
<tr>
<td>Observed in 36 pb$^{-1}$ of data</td>
<td>111</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>95% C.L. limit on signal events</td>
<td>40.4</td>
<td>9.6</td>
<td>19.6</td>
</tr>
</tbody>
</table>

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### Results expressed in terms of 95% CL in CMSSM

- Extend limit from Tevatron searches
SUSY search using kinematic variable $\alpha_T$

$\alpha$ (Randal-Tucker-Smith)  

$$\alpha = \frac{E_T^{j2}}{M_{\text{inv}}^{j1,j2}}$$  

$$\alpha = \frac{E_T^{j2}}{\sqrt{2E_T^{j1}E_T^{j2}(1 - \cos \Theta)}}$$

Transverse $\alpha_T$  

$$\alpha_T = \frac{E_T^{j2}}{M_{\text{inv}}^{j1,j2}}$$  

$$\alpha_T = \frac{E_T^{j2}}{\sqrt{2E_T^{j1}E_T^{j2}(1 - \cos \Delta\phi)}}$$

QCD: back to back jets i.e. $\cos\Delta\phi < 1 \Rightarrow \alpha(\alpha_T) \leq 0.5.$

SUSY: $\alpha (\alpha_T)$ can be $> 0.5.$

Generalized to multijet events by reconstructing pseudo jets J1 and J2 from primary jets from clustering algorithm

**N-Jet system:**  

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{M_T}, \quad \Delta H_T = E_T(PJ_1) - E_T(PJ_2)$$

**arXiv:0806.1049**
• Event Selection:
  • At least two AK5 calorimeter jets $p_T > 50 \text{ GeV}$ and $|\eta| < 3.0$
  • Two leading jets with $p_T > 100 \text{ GeV}$, leading jet $|\eta| < 2.5$
  • Veto on isolated leptons and photons
  • $H_T > 350 \text{ GeV}$  13 events
Data-driven Background Estimate

**Inclusive background estimate**

\[ R_{\alpha_T} = \frac{N(\alpha_T > \theta)}{N(\alpha_T < \theta)} \]

- \( \theta = 0.51 \) QCD dominated, ratio falls with HT
- \( \theta = 0.55 \) EW dominated, ratio flat with HT

\[ \Rightarrow \alpha_T > 0.55 \text{ almost free of QCD} \]

Assume

\[ R_R = \frac{R_{\alpha_T}(H_T > 350)}{R_{\alpha_T}(H_T > 300)} = \frac{R_{\alpha_T}(H_T > 300)}{R_{\alpha_T}(H_T > 250)} \]

\[ N(H_T350) = 9.4^{+4.8}_{-4.0} \text{ (stat) } \pm 1.0 \text{ (syst)} \]

**Impendent EWK background estimations**

\[ N(W + \text{jets, } t\bar{t}) = 6.1^{+2.8}_{-1.9} \text{ (stat) } \pm 1.8 \text{ (syst)} \text{ from } W(\mu\nu) + \text{jets} \]

\[ N(Z(\nu\nu) + \text{jets}) = 4.4^{+2.3}_{-1.6} \text{ (stat)} \pm 1.8 \text{ (syst)} \text{ from } \gamma + \text{jets} \text{ (see later)} \]

**Total:** \( 10.5^{+3.6}_{-2.5} \) in agreement with inclusive prediction \( 9.4^{+4.8}_{-4.0} \text{ (stat) } \pm 1.0 \text{ (syst)} \)

Further x-checks: \( W(\mu\nu) \) from \( \gamma \) and \( Z(\nu\nu) \) from \( W(\mu\nu) \) all within agreement
RAZOR

- Assume heavy particle pair produce and decay in LSP+X
- Define two variables related to the mass scale
  \[ M_\Delta = \frac{M_q^2 - M_{\tilde{\chi}}^2}{M_q} \]

  \[ M_R \] is estimator of \( M_\Delta \), peaks at mass scale.

- \( M^R_T \) transverse mass with endpoint at \( M_\Delta \)
- Use dimensionless ratio \[ R = \frac{M_L}{M_\Delta} \]
- Reduce event into two mega jets by clustering the visible decay products
- In terms of mega jets, event resembles \[ pp \rightarrow \tilde{q}\tilde{q} \rightarrow j_1 j_2 \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
R and $M_R$ distributions for different events

Figure 1: The razor plane: $M_R$ versus $R$ yields for 10 pb$^{-1}$ Monte Carlo simulated samples: QCD multijets (top left), $W$+jets (top right), $t$+X (bottom left) and a CMS SUSY benchmark model (LM1 [8]) with $M_A = 597$ GeV.
Hadronic RAZOR Search

Basic Selection:
- At least two jets $\text{PtJet}>30$ GeV, $|\eta|<3.0$
- Classify events as hadron, muon and electron boxes.
- Decompose event in two hemispheres.
- Cluster particles in each hemisphere into a mega-jet
- Require $\Delta\phi$ (mega-jets) $< 2.8$

Background:
- Shapes from lepton boxes
- QCD shape from low threshold dijet data
- $Z(\nu\nu)$ Shapes from 2\textsuperscript{nd} component of W
- $Z(ll)$ Efficiencies from data
- Fit in $80 < M_R < 400$ GeV region
- Normalization from lepton boxes
- Extrapolate to high $M_R$ region

<table>
<thead>
<tr>
<th>$M_R$ cut</th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_R &gt; 500$ GeV</td>
<td>$5.5 \pm 1.4$</td>
<td>7</td>
</tr>
</tbody>
</table>
α_T and RAZOR results

- Kinematic variable α_T
  - Optimized for fast discovery
  \[ \alpha_T = \frac{E_{T,12}}{M_{T,12}} = \frac{\sqrt{E_{T,12}/E_{T,1}}} \sqrt{2(1-\cos \Delta \phi)} \]

- "Razor" variables: M_R & R
  - Designed to characterize pair-production of heavy particles
  - Combine all particles into two hemispheres, boost back to rest frame

These kinematics-based searches are complementary in approach to the jets + MHT search which is based on understanding the detector in detail.

arXiv:1101.1628, CMS-PAS-SUS-10-003 & 11-001

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CMS-PAS-SUS-10-009
Comparison of different techniques

CMS preliminary \( L_{int} = 36 \text{ pb}^{-1}, \sqrt{s} = 7 \text{ TeV} \)

- CDF \( \tilde{g}, \tilde{q}, \tan\beta=5, \mu<0 \)
- D0 \( \tilde{g}, \tilde{q}, \tan\beta=3, \mu<0 \)
- LEP2 \( \tilde{\chi}_1^0 \)
- LEP2 \( \tilde{\tau}^\pm \)
- \( \tan\beta = 10, A_0 = 0, \mu > 0 \)

- Razor
- Jets+MHT
- Lepton+MET
- OS Dilepton
- SS Dilepton
- \( \alpha_s + b\)-tag
- \( \alpha_T \)
- \( q(650) \text{ GeV} \)
- \( q(800) \text{ GeV} \)
- \( q(500) \text{ GeV} \)
Summary

- CMS has performed hadronic SUSY search using three different methods using 2010 data.
- SM backgrounds are directly measured from the data using minimal information from the Monte Carlo event generators.
- No excess of events over the SM expectation is observed.
- These data are used to further constraint the susy parameter space.
- Ready and looking forward to discovering new physics in 2011.
An interesting event

- $\text{MHT} = 693 \text{ GeV}$
- $\text{HT} = 1132 \text{ GeV}$
- $M_{\text{eff}} = \text{MHT}+\text{HT} = 1.83 \text{ TeV}$
- No b-tagged jet
- No isolated lepton
- Incompatible with W or top mass
- Invisible Z???
Particle Flow (PF) Algorithm

- In this search, all physics objects (jets, leptons, HT, MHT etc) are reconstructed with the particle flow algorithm
- Basic idea:
  - Reconstruct and identify all different types of particles
  - Apply corresponding calibrations
  - The list of “particles” is given to the jet clustering and missing ET (MET) reconstruction algorithm
Simplified Model

- Focus on topology instead of underlying physics model
- Any model with same topology (parent particle mass, decay chain, daughters mass) can be “easily” compared with experimental results.

Combined results for:
- $\alpha_T$
- jets + MHT
- Razor
Relation of $\alpha_T$ to $E_{Tj2}/E_{Tj1}$ and $\Delta \varphi$

- $\alpha_T > 0.6$
- $\alpha_T > 0.55$
- $\alpha_T > 0.5$

QCD

LM1

Z$\rightarrow$\nu\nu

tt,W,Z+jets
**Data-Driven Background Estimates**

**Invisible Z (→ ν ν) + Jets**
- Remove the identified boson (photon/W/Z) to mimic neutrino
- Photon+Jets : high event yield (use photon/Z correction from theory)
- Z → l l + Jets (straightforward prediction but limited by statistics)

**Top / W + Jets**
- Top/W (→ lost lepton + ν ) + Jets :
  - Lepton is not identified or is outside detector acceptance. Estimated from W→μν sample.
- Top/W (→ hadronic τ + ν )+ Jets :
  - Estimated by replacing μ in W→μν events with τ using a τ response template

**QCD MultiJets (jet mis-measurements resulting in imbalance)**
- R+S : rebalance event and smear ‘rebalanced’ sample with jet resolutions
- Factorization : extrapolate two-variable correlation to signal region