Searches with Missing $E_T$ at the LHC

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Acknowledgements, and References

- Work presented here is derived/taken from
  - ATLAS, CMS TDRs, analysis & conference notes and presentations
  - Thanks!

- ATLAS Physics TDR: CERN/LHCC 1999-14/15

- CMS PTDR II CERN/LHCC 2006-021
- Data driven estimation of invisible Z background in the SUSY MET plus jets search CMS PAS SUS-08-002
- SUSY searches with di-jet events CMS PAS SUS-08-005
- CMS search plans and sensitivity to new physics using dijets CMS PAS SBM-07-001

Models with Missing Energy Signatures

Many New Physics Models provide signatures with Missing Energy in the final state

- R-parity conserving Supersymmetry
  - minimal super gravity mSugra (neutralino)
  - Gauge mediated SUSY (gravitino)
- Universal Extra Dimensions
- Warped Extra Dimensions
- Little Higgs Models
- Technicolor Models
- plus more…. (and probably more can be made available…)

Production of WIMP’s in cascade decays of heavy new particles

- WIMP’s escape the detector and remain undetected
- Leads to a missing energy signature
Sources

- $E_{T\text{miss}}$ from neutrinos: from the direct decay of new heavy particles to neutrinos, or decays of new heavy particles to top, $W$'s, $Z$'s, or $\gamma$'s.
  - look for anomalies in the energetic tails of data sets with reconstructed top, $W$'s or $Z$'s.
- $E_{T\text{miss}}$ originates from a single weakly interacting exotic particle in the final state.
  - graviton production in models with large extra dimensions leading to monojets+large $E_{\text{miss}}$ in case of strong production.
- $E_{T\text{miss}}$ originates from many weakly interacting exotic particles in the final state.
  - Hidden valley models (light pions of the hidden sector)
Missing ET signatures:
An Example from SUSY

- $E_{T\text{miss}}$ originates from two weakly interacting exotic particles in the final state
  - SUSY with R-parity conserved
  - e.g. gluino pair-production
- lots of missing energy, many jets, and possibly leptons in the final state

**Missing Energy:**
- from LSP

**Multi-Jet:**
- from cascade decay (gaugino)

**Multi-Leptons:**
- from decay of charginos and neutralinos
Missing $E_T$ signatures:  
...in more general scenario

- pair production of new heavy particles

**Missing Energy:**
- Nwimp - end of the cascade

**Multi-Jet:**
- from decay of the Ns (possibly via heavy SM particles like top, W/Z)

**Multi-Leptons:**
- from decay of the N’s

Model examples are Extra dimensions, Little Higgs, Technicolour, etc
Searches using Missing Energy

- Most of the signatures which have missing energy in the final state have been studied in the context of SUSY searches.
- However, the procedures for determination of SM backgrounds for these searches are applicable to other similar searches as well.

- Before claiming SUSY/other discovery need to understand SM at LHC with high precision
- If excess beyond SM is observed, then still much work needed to determine underlying model (SUSY or others)

- Typical analysis based on final state lepton and jet multiplicity
  - More leptons $\rightarrow$ less signal but better S/B
Signatures:

- Analyses designed by number of leptons and or jets in the final state. In the table ✓ means covered by CMS/ATLAS

<table>
<thead>
<tr>
<th></th>
<th>1 jet</th>
<th>2 jet</th>
<th>3 jets</th>
<th>4 jets</th>
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<td><strong>0 lepton</strong></td>
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</tr>
<tr>
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<tr>
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<tr>
<td><strong>taus</strong></td>
<td></td>
<td>✓</td>
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<td>✓</td>
</tr>
<tr>
<td><strong>b’s</strong></td>
<td>✓</td>
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<td>✓</td>
</tr>
</tbody>
</table>

- Dominant backgrounds are
  - W+jets, top pair production, Z → νν+jets, Z→ll+jets, QCD multijet
Definition of some Observables

- **ATLAS:**

\[ M_{\text{eff}} = \sum_{i=1}^{N} p_{Tj}^{\text{jet},i} + \sum_{i=1}^{N} p_{Tl}^{\text{lep},i} + \cancel{E_T} \]

4 highest \( p_T \) jets in \(|\eta| < 2.5\)

\[ S_T = \frac{2\lambda_2}{(\lambda_1 + \lambda_2)} \text{ with } \lambda_1, \lambda_2 \text{ eigenvalues of } S_{ij} = \sum_k p_{ki} p^{kj} \]

all jets with \( p_T > 20 \text{ GeV} \) and leptons in \(|\eta| < 2.5\)

\[ m_{T2}^2 \equiv \min_{q_T^{(1)}, q_T^{(2)} = \cancel{E_T}} \left[ \max \left\{ m_T^2(p_T^{\alpha}, q_T^{(1)}; m_{\alpha}, m_{\chi}), m_T^2(p_T^{\beta}, q_T^{(2)}; m_{\beta}, m_{\chi}) \right\} \right] \]


- **CMS:**

\[ H_T \equiv E_{T(2)} + E_{T(3)} + E_{T(4)} + E_T^{\text{miss}} \]

Where 2, 3, 4 index selected jets sorted by \( p_T \)
One Lepton + jets + Missing Energy
One lepton mode SUSY:

SUSY event selection:

1. jet $p_T > 100 \text{ GeV}$
2. $4$ jets $p_T > 50 \text{ GeV}$
3. lepton $p_T > 20 \text{ GeV}$
4. 2nd lepton veto
5. $E_T > 100 \text{ GeV}$

Dominant backgrounds:

<table>
<thead>
<tr>
<th>sample</th>
<th>$x$-sec (pb)</th>
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<tbody>
<tr>
<td>top pair</td>
<td>833</td>
</tr>
<tr>
<td>W+jets</td>
<td>10 -10000</td>
</tr>
<tr>
<td>QCD</td>
<td>10000 -100000000</td>
</tr>
<tr>
<td>Z+jets</td>
<td>10 -1000</td>
</tr>
<tr>
<td>SUSY</td>
<td>5 -300</td>
</tr>
</tbody>
</table>
Background Estimation

- **Problem:**
  - no clean SM measurement possible if SUSY exists
  - SM shape at high missing ET unknown & MC possibly unreliable

- data-driven estimation

- **Control region:**
  - dominated by SM + small contamination SUSY

- **Signal region:**
  - dominated by SUSY + small SM background
Background Estimation

**Problem:**
- no clean SM measurement possible if SUSY exists
- SM shape at high missing ET unknown & MC possibly unreliable

*data-driven estimation*

**Observables helpful in removing Wjets, ttbar background**
- $M_T =$ transverse mass mass missing $E_T +$ lepton
  - (needed to distinguish $W$+jets background)
- $M_{top} =$ invariant mass of 3 jet system with highest sum $p_T$
  - (needed to distinguish ttbar background)
Method 1: W+jets, ttbar backgrounds

- Analyse data in an L-shaped region at both:
  - low missing $E_T$ in full MT-range
  - low $M_T$ in full missing ET-range
  - (both regions practically SUSY-free from kinematic considerations)

- Perform a 2D extrapolation into the SUSY signal region (high missing $E_T$, $M_T$)
- Explicitly account for SUSY contamination in control region
Method 1: W+jets, ttbar backgrounds

- Combined fit method:
  - Construct a 3D model for each background
  - Build combined model by simple addition
  - Separate three distinct components of background by fitting combined model to data

- Empirical models taking physics features into account:
  - 1) Top mass peak
  - 2) Jacobian W-peak in $M_T$
  - 3) Dileptonic ttbar different from semileptonic
Method 1: accounting for SUSY in bkg

- Different SUSY models look surprisingly similar in control region
- SUSY contamination in control region determined by adding a generic Ansatz shape to the combined fit

\[
\begin{align*}
N_{tt1l} &= -1.1 \pm 3.9, \\
N_{tt2l} &= 4.7 \pm 7.9, \\
N_{wjets} &= -1.2 \pm 2.7, \\
N_{su3} &= 95.6 \pm 4.0.
\end{align*}
\]

Almost no dependence on simulation as shape parameters are floated as well as yields of backgrounds
**Method 2: HT2 method**

- Use HT2 (leading jet excluded) and missing ET significance as nearly independent variables

\[
E_{\text{miss}}^{\text{significance}} = \frac{E_{\text{miss}}}{\sqrt{\sum E_T}}
\]

\[
\text{HT2} = \sum_{i=2}^{4} p_T^{\text{jet}i} + p_T^{\text{lepton}}
\]

- Define signal region as HT2 > 300 GeV (control region HT2 < 300 GeV)
- Shape of missing ET significance is taken from control region
- This distribution is normalized to the number of events in signal region
- Subtract background estimation from measured distribution of missing ET significance
Removing Dileptonic top background

- With an additional cut on $M_T > 100$ GeV dileptonic $t\bar{t}$bar left as the main background component

- How dileptonic $t\bar{t}$bar passes veto on 2\textsuperscript{nd} lepton:
  - 1 lepton is tau (51%)
  - 1 lepton misidentified (20%)
  - 1 lepton inside a jet (17%)
  - 1 lepton out of acceptance (9%)
  - both leptons are tau (3%)
Dileptonic top background: Kinematic reconstruction method

- Define dileptonic top control sample:
  - 2 opposite charge leptons
  - N jets ≥ 3 (p_T > 50 GeV)

- Solve system of equations for every combination of jets:
  - If system has a real solution the jet-pair is considered a b-jet pair
  - Selecting N b-jetpair ≥ 1 enhances dileptonic ttbar in background

- Take background events and resimulate:
  - resimulate decay of one lepton as a tau
  - replace 1 lepton by jet (misidentified lepton)
  - estimate background from resimulated events
Jets + Missing Energy
(no lepton)
Four Jets + Missing Energy

SUSY event selection:
1. jet $p_T > 100$ GeV
4. jet $p_T > 50$ GeV
   $\not{E}_T > 100$ GeV
   lepton veto
   $\Delta\phi(\not{E}_T - jet_i) > 0.2$ (i = 1,2,3)
Z+jets background using replace method

- $Z \rightarrow \nu \nu$ and associated jets is one of the main backgrounds
- Use $Z \rightarrow ll+\text{jets}$ as control sample with standard selection and:
  - replace missing $E_T$ by $p_T(\ell \ell)$
  - $81 < M(\ell \ell) < 101$ GeV
  - missing $E_T < 30$ GeV

- Corrections:
  - Kinematic: additional cuts used
  - Fiducial: good lepton detection only for $|\eta| < 2.5$
  - Lepton identification efficiency using tag-and-probe method
Three jets + Missing Energy

- Potentially high QCD backgrounds
- L1: $E_{T}^{\text{miss}, L1} > 46 \text{ GeV}$, $E_{T} > 88 \text{ GeV}$, HLT: $E_{T}^{\text{miss}} > 200 \text{ GeV}$
- Cuts:
  - 3 jets:
    - $E_{T,j(1)} > 180 \text{ GeV}$, $|\eta_j^{1j}| < 1.7$
    - $E_{T,j(2)} > 110 \text{ GeV}$, $|\eta_j| < 3$
    - $E_{T} > 30 \text{ GeV}$, $|\eta| < 3$
    - $E_{T}^{\text{miss}} > 200 \text{ GeV}$
    - $\delta \phi_{\text{min}} (E_{T}^{\text{miss}} - \text{jet}) \geq 0.3 \text{ rad}$
    - $\delta \phi (E_{T}^{\text{miss}} - j(2)) > 20^\circ$
  - No isol. tracks with $p_T > 15 \text{ GeV}$
  - $f_{\text{em}}(j(1)), f_{\text{em}}(j(2)) < 0.9$
  - $H_{T} > 500 \text{ GeV}$

Implicit lepton veto against $tt$, $V+j$
Background Estimation

- Use the dataset \(Z(\rightarrow \mu\mu) + 2 \text{ jets}\) for normalisation:
  - Estimate the \(Z(\rightarrow \nu\bar{\nu}) + \geq 3 \text{ jets}\) contribution from data:
  - Normalize using:
    \[
    R = \frac{dN_{\text{events}}}{dN_{\text{jets}}} = \frac{\mathcal{L}d\sigma}{dN_{\text{jets}}}
    \]
    - Ratio of \(Z(\rightarrow \mu\mu)\) to \(Z(\rightarrow \nu\bar{\nu})\)
    - Require \(Z\) boson \(P_T > 200\text{ GeV}\) in all samples

- Similarly, estimate \(W(\rightarrow \tau\nu) + \geq 2 \text{ jets}\) :

  - Use:
    \[
    \rho \equiv \frac{\sigma(pp\rightarrow W(\rightarrow \mu\nu)+\text{jets})}{\sigma(pp\rightarrow Z(\rightarrow \mu^+\mu^-)+\text{jets})}
    \]

  - Needed data sample:
    - \(\sim 1.5\text{ fb}^{-1}\)

- Estimate systematics due to raw \(E_T^{\text{miss}}\) from data
di-jets + Missing Energy (M_{T2} method)

- Using variable m_{T2} (large \( p_T \), \( \not{E}_T \) and \( \delta \phi \)):

\[
m_{T2}^2 \equiv \min_{\Delta \phi^{(1)} + \Delta \phi^{(2)} = \not{E}_T} \left[ \max \left\{ m_T(p_T, \phi^{(1)}_T; m_\alpha, m_\chi), m_T(p_T, \phi^{(2)}_T; m_\beta, m_\chi) \right\} \right]
\]

- Trigger: \( E_T^{\text{jet}} > 70 \text{ GeV} \) and \( \not{E}_T > 70 \text{ GeV} \)

- Cuts:
  2 jets in \( |\eta| < 2.5 \):
  - \( j_1: P_T^{\text{jet1}} > 150 \text{ GeV} \)
  - \( j_2: P_T^{\text{jet2}} > 100 \text{ GeV} \)
  - \( \not{E}_T > 100 \text{ GeV} \)
  - \( m_{T2} > 400 \text{ GeV} \)
  - No isolated leptons
di-jets + Missing Energy (α method)

- **CMS study: PAS-SUS-08/005**

- **Idea:**
  - Squarks pair produced and directly decaying to quarks and neutralinos

- **Event topology**
  - Only two jets + missing energy

- **Background:**
  - QCD dijet events
    - No real missing momentum
  - \(Z \rightarrow \nu\nu\) events
    - Irreducible background due to real missing ET
  - \(W \rightarrow l\nu\)
    - Leads to missing Et when lepton not reconstructed or out of acceptance

- **Diagram:**
  - Signal topology (SQUARK pair plus LSP)
  - Background topology (QCD dijet)
  - Transverse momentum conservation
  - Jets back-to-back in phi
  - \(E_T\) of jets equal in magnitude
Discriminating Variables

- **Exploit kinematics of the event**
  - Define variable $\alpha$ (Randall – Tucker-Smith):
    \[
    \alpha = \frac{E_{T,j_2}}{M_{j_1j_2}} = \frac{E_{T,j_2}}{\sqrt{2E_1E_2(1 - \cos \theta)}}
    \]
    - Can be at most 0.5 for QCD, $\alpha < 0.5$
    - $\alpha > 0.5$ implies missing momentum
  - And transverse $\alpha_T$:
    \[
    \alpha_T = \frac{E_{T,j_2}}{M_{T,j_1j_2}} = \frac{\sqrt{E_{T,j_2}/E_{T,j_1}}}{\sqrt{2(1 - \cos \Delta \varphi)}}
    \]
    - Exploits that for QCD jets need to be back-to-back and of equal magnitude
    - For QCD dijets $\alpha = 0.5$

Analysis does not rely on calorimetric MET, MHT inferred from 2 jets

$\Rightarrow$ well suited for early data
Event Selection

- **Main variables of interest**
  - $\Delta \varphi$ between the jets
  - $\alpha [\alpha_T]$ from 2 leading jets
  - Scalar sum of Jet $p_T$'s:
    - $HT = p_{T_{\text{Jet1}}} + p_{T_{\text{Jet2}}}$
  - Jet based missing $E_T$:
    - $MHT = -(p_{T_{\text{Jet1}}} + p_{T_{\text{Jet2}}})$
  - but also $p_T$ of a possible 3rd jet

- **Trigger**
  - di-jet trigger
    - two jets with $p_T > 150$ GeV

- **Preselection:**
  - Jet Selection
    - 2 jets with $p_T > 50$ GeV, $F_{\text{em}} < 0.9$
    - 3rd jet veto: $p_T < 50$ GeV
    - $\Delta \varphi(MHT,\text{jet1,2,3}) > 0.3$ rad
    - $|\eta_{\text{j1}}| < 2.5$
  - Lepton veto's:
    - no $e, \mu$ with $p_T > 10$ GeV

- **Full Selection**
  - $HT > 500$ GeV
  - $\alpha (\alpha_T) > 0.55$
  - $(\Delta \varphi < 2\pi/3)$
Discriminating Variables

- Cuts applied: Preselection & HT > 500 GeV
- $\alpha (\alpha_\tau) > 0.5$

1 fb$^{-1}$

Sharp drop of QCD background for $\alpha (\alpha_\tau) > 0.5$

QCD peaking at $\Delta \phi = \pi$

- $Z\rightarrow\nu\nu$ is main background
- $W$ and other $Z$ decays small
Background Estimation

An illustrative example: $Z \rightarrow \nu\nu + \text{jets}$

Irreducible background for Jets+$E_t^{\text{mis}}$ search

Data driven strategy:
- define control samples and understand their strength and weaknesses:

$Z \rightarrow \mu\mu + \text{jets}$

**Strength:**
- very clean, easy to select

**Weakness:**
- low statistic: factor 6 suppressed wrt. to $Z \rightarrow \nu\nu$

$W \rightarrow \ell\nu + \text{jets}$

**Strength:**
- larger statistic

**Weakness:**
- not so clean, SM and signal contamination

$\gamma + \text{jets}$

**Strength:**
- large stat, clean for high $E_\gamma$

**Weakness:**
- not clean for $E_\gamma < 100$ GeV,
- possible theo. issues for normalization (u. investigation)
**γ+jets: Estimate Z to invisible**

**γ+jets selection & properties:**
- $E_\gamma > 150$ GeV
  - clean sample: $S/B > 20$
  - ratio $\sigma(Z+jet)/\sigma(\gamma+jet)$ constant

**γ+jets: Strategy:**
- remove $\gamma$ from the event:
  - $\gamma$ becomes $E_T^{\text{mis}}$
- take $\sigma(Z+jet)/\sigma(\gamma+jet)$ for $E_\gamma > 200$ GeV from MC or measure in data
Conclusions

- Discussed some examples of analyses for events with Missing $E_T$.

- Data-driven backgrounds determinations have been developed
  - Exploit uncorrelated observables to predict backgrounds in signal region from control samples (HT2, Missing Energy Significance, $M_T$)
  - Subtraction of all backgrounds using matrix method
  - Modeling of $Z\rightarrow\nu\nu$ from $Z\rightarrow ll$ and from $\gamma +$ jets

- Di-jet analysis exploiting particular event topology
  - Shown results do not rely on calorimetric MET
    - Useful for early running.

- Extension to a calorimetric MET independent multi-jet analyses under study

- Eagerly awaiting first collisions and discoveries in fall of this year.