SUSY searches in CMS

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1 June 2011
Early SUSY signatures

- The theoretical framework of supersymmetry allows for a large amount of diverse phenomenological features:
  - various mass spectra with distinct decay channels
  - different cross sections and branching ratios

- For early SUSY searches at CMS the focus lies on signatures that have **two features in common**:
  - high-$p_T$ jets
    - due to strong production of SUSY particles
    - strong production has high cross sections, hence suitable for small luminosities
  - a **large excess of missing energy**
    - decay chains contain (or even end with) massive weakly-interacting sparticles (e.g. LSP in mSUGRA)
    - natural dark matter candidate
CMS strategy for SUSY searches

- Search for inclusive signatures of the kind MET + jets + X
  - overlaps of signatures as small as possible

- So far, results using the data recorded in 2010 ($L_{\text{int}} \sim 36 \text{ pb}^{-1}$), have been made public for these signatures:
  - MET + jets
  - MET + jets + b-tag
  - MET + jets + multi-leptons
  - MET + jets + same-sign di-leptons
  - MET + jets + opposite-sign di-leptons
  - MET + jets + single lepton
  - MET + jets + single lepton + photon
  - MET + jets + di-photons
  - MET + jets + Z

- Recent efforts to interpret results in a generalized, less model-dependent manner by means of phenomenologically simplified models
Backgrounds for SUSY searches at the LHC

• SUSY cross sections are expected to be orders of magnitude smaller than typical QCD cross sections:
  – backgrounds from QCD processes have to be understood and controlled

• Modeling and controlling the high-energy tails of QCD processes is very difficult:
  – QCD cross sections are not predicted with high enough precision
  – key topological and kinematic distributions such as the number of jets and their $p_T$ spectra are difficult to predict

• Determination of backgrounds using data-driven methods:
  – use dedicated control samples
  – use multiple methods for cross-checks whenever possible
SUSY searches in CMS

Hadronic signatures

• Highest potential for early discoveries due to large cross-sections for strong processes at the LHC

• Search signature
  – events with high-\(p_T\) jets
  – large missing transverse energy
  – veto on isolated, high-\(p_T\) leptons

• Three complementary approaches:
  – \(\alpha_T\) method (with & without b-tagging):
    • reduces QCD background drastically by exploiting kinematical constraints
  – razor method:
    • tests kinematic consistency of events against the hypothesis of heavy particle pair-production
  – inclusive method:
    • estimates all backgrounds with high precision without applying kinematical constraints
The razor method

- Divide events in hemispheres and combine all jets in each hemisphere into a “mega-jet”
  - hemisphere algorithm selects jet combinations minimizing the invariant masses
  - resulting kinematics correspond to pair production of two heavy squarks (with $\tilde{q} \rightarrow \text{jet} + \tilde{\chi}_0$)

- Characterize resulting system kinematically:
  - transverse variable $M_T^R$ (similar to $m_T$):
    \[
    M_T^R = \sqrt{\frac{E_T^{\text{miss}} \left( p_T^{j1} + p_T^{j2} \right) - \vec{E}_T^{\text{miss}} \cdot \left( \vec{p}_T^{j1} + \vec{p}_T^{j2} \right)}{2}}
    \]
  - event-by-event estimator $M_R$:
    \[
    M_R = 2 \sqrt{\frac{\left( E^{j1} p_z^{j2} - E^{j2} p_z^{j1} \right)^2}{\left( p_z^{j1} - p_z^{j2} \right)^2 - \left( E^{j1} - E^{j2} \right)^2}}
    \]
  - background suppressing razor variable $R = \frac{M_T^R}{M_R}$
The razor method

- SUSY decay-chains arise from pair production of heavy sparticles and end with an LSP:
  - $M_R$ peaks around $M_\Delta \equiv (M_{q\sim}^2 - M_{\chi\sim}^2)^2/M_{q\sim}$
  - signal region: $M_R \geq 500$ GeV and $R \geq 0.5$

- QCD background estimation:
  - only relevant scale for backgrounds is $\sqrt{s}$
    - distribution of $M_R$ is falling exponentially
  - slopes of background distribution shapes can be parameterized as a function of $R^2$

- W/Z+jets and t+X background estimation:
  - similar to QCD estimate, but use control samples including leptons into the hemisphere algorithm
  - relative and absolute normalizations of background distributions shapes
    - cross-section measurements
    - data-driven corrections from simulation
Results for hadronic signatures

- Results show great improvement with respect to previous studies
- Results from all hadronic analyses give a coherent picture
- Example:
  - mSUGRA exclusions with $\tan\beta = 3$, $\mu > 0$, $A_0 = 0$
Leptonic signatures

- Isolated high-p\(_T\) lepton:
  - in conjunction with large amounts of missing transverse energy an indication of a weak decay of a heavy object
  - reduced QCD background
- Search signature:
  - events with high-p\(_T\) jets
  - large missing transverse energy
  - well isolated, high-p\(_T\) leptons
- Four complementary approaches:
  - multi-lepton analysis
  - opposite-sign di-lepton analysis
  - same-sign di-lepton analysis
  - single lepton analysis
- Small topological overlap between leptonic searches allows for clear phenomenological interpretations
SUSY searches in CMS

The single lepton analysis

- Search for excesses in region with $H_T > 500$ GeV and $E_T > 250$ GeV
- Background estimation:
  - **lepton-spectrum method:**
    - $p_T$ distributions of lepton and neutrinos from W-two body decays are closely related
    - determine spectrum of $E_T$ from lepton $p_T$ spectrum from $t\bar{t}$- and W-backgrounds
    - robust against signal contamination from typical SUSY topologies
  - cross-checked with **ABCD-method** (matrix method):
    - uses (almost) uncorrelated observables $H_T$ and $y \equiv E_T/\sqrt{H_T}$

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**CMS simulation** $\sqrt{s} = 7$ TeV

**Background**

**SUSY LM1**

**CMS preliminary** 36 pb$^{-1}$, $\sqrt{s} = 7$ TeV

1 $\mu$, $\geq$ 4 jets

- Observed
- Background prediction
Results for leptonic signatures

- Results show improvements with respect to previous studies
  - even though much smaller cross-section than for fully hadronic processes
- Consistent with hadronic analyses
- Example:
  - mSUGRA exclusions with $\tan\beta = 3$, $\mu > 0$ and $A_0 = 0$
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**Simplified models**

- Simplified models allow for more generalized interpretations
  - reduced SUSY-like particle content
  - masses are generic, not model dependant
  - assume constant cross sections, branching ratios are described by phase space
  - broadens reach of kinematically accessible regions of parameter space
  - describe features of data in a way that is useful for further model-building

- Results can be used by theorists outside of the LHC collaborations
  - good interface between experimentalists and theorists

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**95% C.L. limit on**

- $m_{\text{gluino}}$ (GeV) vs $m_{\text{LSP}}$ (GeV)
- $m_{\text{squark}}$ (GeV) vs $m_{\text{LSP}}$ (GeV)

CMS Preliminary $L_{\text{int}} = 35 \text{ pb}^{-1}$ $\sqrt{s} = 7 \text{ TeV}$

$\prod_{\text{Prod}} = \frac{1}{3} \prod_{\text{NLO-QCD}}$

(Hadronic Searches)

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Simplified models

- Extended interpretation of all hadronic analysis
  - two simplified models based on proposals from the LHC New Physics Working Group
    - group of theorists addressing questions regarding characterization of BSM at the LHC
    - initiated by a workshop at a joint CMS, ATLAS and theory meeting in June 2010
  - Considered signatures:
    - pair-produced gluinos, gluinos decay to 2 light quarks and an LSP
    - pair-produced squarks, squark decay to 1 jet and an LSP
  - Generated with Pythia and CMS fast simulation
Conclusions and outlook

• The CMS effort to discover supersymmetry covers a broad range of signatures

• All analyses have pushed the previously known exclusion limits further using the LHC data recorded in 2010

• Characterization of new results through simplified models allows for generalized, model-independent BSM searches inspired by SUSY

• The CMS analysis effort is not focused on optimized exclusions, but rather on identifying possible new signals

• With the excellent performance of the LHC in mind, we hope for new physics to be just around the corner …
- “The CMS Experiment at the CERN LHC”, JINST 3, S08004
- “Search for Supersymmetry in pp Collisions at $\sqrt{s} = 7$ TeV in Events with Two Photons and Missing Transverse Energy”, CMS Physics Analysis Summary: SUS-10-002
- “Search for Supersymmetry in pp Collisions at 7 TeV in Events with Jets and Missing Transverse Energy”, CMS Physics Analysis Summary: SUS-10-003
- “Search for new physics with same-sign isolated dilepton events with jets and missing transverse energy at the LHC”, CMS Physics Analysis Summary: SUS-10-004
- “Search for new physics at CMS with jets and missing momentum”, CMS Physics Analysis Summary: SUS-10-005
- “Search for Physics Beyond the Standard Model in Opposite-sign Dilepton Events in pp Collisions at $\sqrt{s} = 7$ TeV”, CMS Physics Analysis Summary: SUS-10-007
- “Inclusive search for squarks and gluinos at $\sqrt{s} = 7$ TeV”, CMS Physics Analysis Summary: SUS-10-009
- “Search for Supersymmetry in Final States with b Jets and Missing Energy at the LHC”, CMS Physics Analysis Summary: SUS-10-011
- “Further interpretation of the search for supersymmetry based on $\alpha_T$”, CMS Physics Analysis Summary: SUS-11-001
Backup Slides
Low mass benchmark scenarios

- All **benchmark points** are mSUGRA scenarios
- Parameterized by only five different parameters ($m_{1/2}$, $m_0$, tan $\beta$, $A_0$, sign $\mu$)
- **Pros:**
  - beyond the exclusion reaches of SPS, LEP, Tevatron, etc.
  - cover a large variety of distinct signatures
  - very well understood
- **Cons:**
  - restrictive ($m_{\text{gluino}} \sim 6 m_{\text{LSP}}$)
The $\alpha_T$ method

- Using the kinematic variables $H_T$ and $\alpha_T$ to suppress SM backgrounds:
  - characterize the overall $p_T$-balance of the event
    
    $$
    H_T = \sum_{\text{jets } j} p_{T,j} \quad \Delta H_T = \min_{\text{jets}} (p_{T,\text{pseudojet}_1} - p_{T,\text{pseudojet}_2})
    $$
    
    $$
    MHT = \sum_{\text{jets } j} -\tilde{p}_{T,j} \quad \alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - (MHT)^2}}
    $$
  
  - motivated by di-jet analyses, generalized for multi-jet events

- Properties extensively validated on data:
  - SM backgrounds mostly confined to $\alpha_T < 0.55$
  - suppression improves with increasing $H_T$
  - ratio of background events failing an $\alpha_T$-cut decreases exponentially
  - allows for background estimates in higher $H_T$-bins
Validating $\alpha_T$ on data

- Jet-triggered QCD events (blue) decrease exponentially with increasing $H_T$
  - behavior can be used to calculate a limit for higher $H_T$-bins

- Artificially degraded data shows a consistent exponential trend
  - emulation of jet-loss with a 5-10 times increased removal probability (red)
  - photon-triggered events, dominated by misidentified jets (green)
  - the momentum of 10% of all jets is smeared using a one-sided Gaussian with $\sigma=0.5\cdot p_T$ (violet)
Validating $\alpha_T$ on data

- Distribution of leading jets w.r.t. $\eta$ is uniform for QCD events failing $\alpha_T < 0.55$
  - robustness: even when introducing artificial MET by randomly removing jets the uniformity remains

- SUSY events are produced more centrally
  - aim: use $\eta$-sidebands of leading jets to estimate background
The inclusive method

- search for deviations from expected SM distributions in $H_T$ and $H^\prime_T$
- event selection aims to be as inclusive as possible
  - avoid topological restrictions due to kinematical constraints
- all sources of backgrounds are measured from data, including the complete QCD background
  - invisible $Z \rightarrow \nu\bar{\nu}$:
    - directly from $Z \rightarrow l^+l^-$ (small sample)
    - via $Z/\gamma$-correspondence at large $p_T$ from $\gamma$+jets
  - $W$ and top:
    - estimate events with lost leptons from $\mu$+jets data sample using efficiency information from tag&probe
    - mimic effect from hadronic $\tau$’s using by replacing $\mu$’s with $\tau$-jet templates in $\mu$+jets data samples
The inclusive method

- QCD background estimation:
  - “Rebalance and Smear” method
    - predicts full kinematics in multi-jet events
    - unaffected by events with true missing momentum
    - produce so-called seed events in “Rebalance” step:
      - adjust jet momenta such that $H_T \approx 0$
    - use seed events in “Smear” step:
      - scale jets with values drawn from jet resolution distribution
      - apply search cut to the resulting events to predict complete jet kinematics and correlations
    - cross-check using factorization method
      - uses relation between $H_T$ and $\Delta \phi_{\text{min}}$ (minimum azimuthal angle between $H_T$ and three leading jets)
      - $H_T$ and $\Delta \phi_{\text{min}}$ are not uncorrelated: functional form of the correlation is estimated at low $H_T$
      - use relation to estimate background in signal region (high $H_T$, low $\Delta \phi_{\text{min}}$) from sideband (high $H_T$, low $\Delta \phi_{\text{min}}$)
The opposite-sign di-lepton analysis

- Search for signals in region with:
  - high hadronic activity: \( H_T > 300 \text{ GeV} \)
  - significant amount of missing transverse energy: \( y \equiv E_T/\sqrt{H_T} > 8.5 \text{ GeV}^{1/2} \)

- Require isolated opposite-sign lepton pairs
  - Drell-Yan suppression via invariant mass exclusion interval: \( M_{ll} < 76 \text{ GeV} \) and \( M_{ll} > 106 \text{ GeV} \)

- Background estimation:
  - apply ABCD method
    - \( H_T \) and \( y \) are (almost) uncorrelated
    - estimate \( N_D = N_A \times N_C/N_b \)
  - cross-check using \( p_T(II)\)-method
    - \( p_T \) distributions of lepton and neutrinos from \( W \)-two body decays are closely related
    - correct lepton spectrum for differences in pre-selection efficiency and \( W \) polarization
The same-sign di-lepton analysis

- Search for excesses in regions with $H_T > 200$ GeV and $E_T > 80$ GeV
- Same-sign isolated lepton pairs from hadron collisions are very rare
- Analysis includes **hadronically decayed $\tau$’s**
  - use neural network, trained to identify the hadronic $\tau$-decay modes using the kinematics of the reconstructed charged and neutral pions
- Background estimation with **tight-loose method**:
  - determine probability $\varepsilon_{TL}$ for leptons passing a loose isolation selection to also pass the tight analysis selection
  - measure in a QCD multi-jet sample
  - applying $\varepsilon_{TL}$ to a sample of di-lepton events, where one of the leptons fails the tight selection but passes the loose one
The di-photon channel

- **Aims for general gauge-mediation scenarios:**
  - decay chains include one or several quarks/gluons plus a neutralino, which in turn decays to a photon and a *gravitino*
  - the gravitino escapes detection, leading to a significant amount of **missing transverse energy**

- **Search signature:**
  - two or more isolated high-\(p_T\) photons (\(p_T \geq 30\) GeV)
  - at least one high-\(p_T\) jet (\(p_T \geq 30\) GeV)
  - large missing transverse energy (\(E_T \geq 30\) GeV)

- **QCD Background:**
  - direct photons
  - quarks/gluons hadronizing predominantly to \(\pi^0\)s decaying into photons
  - estimated from two control samples:
    - events containing two fake photons
    - events containing 2 electrons with invariant mass 70 - 110 GeV (mostly \(Z \rightarrow ee\))
The di-photon channel

- Electroweak background:
  - events with a genuine or fake photon and a W that decays into a neutrino and an electron, with the latter mis-identified as a photon
  - estimated from events containing 1 electron plus 1 photon