Searches for New Physics at CMS

Henning Flaecher

on behalf of the CMS Collaboration

XXV Rencontres de Physique de La Vallee d'Aoste
Search for New Physics (in all shapes and sizes)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

La Thuile 2011
Henning Flaecher
March 4th, 2011
Overview

- CMS is looking for signs of New Physics in all possible directions
- All results based on full 2010 dataset: ~35 pb⁻¹

In this talk:
- “Exotica”
  - W’ and Z’ searches
  - Leptoquarks
  - Extra Dimensions
    - Microscopic Black Holes
- SUSY missing energy searches
  - Jets + missing energy
  - Jets + missing energy + 2 OS leptons
  - Jets + missing energy + 2 photons
- Higgs
  - WW production & H→W⁺W⁻
The CMS detector

Works beautifully!
(talks by G. Tonelli & M. de Gruttola)
Exotica Searches: Overview

- **Excited Vector Bosons**
  - $W'$ – search for enhancement/peak in transverse mass spectrum
  - $Z'$ – search for resonance in dilepton invariant mass spectrum

- **Leptoquarks**
  - 1$^{st}$ and 2$^{nd}$ generation searches via pair-production from gluon fusion
  - decay to quark and lepton

- **Extra Dimensions**
  - Microscopic Black Hole search
    - Decay via Hawking radiation with equal probability to all SM particles
  - (additionally, searches for large ED in dimuon events and Randall-Sundrum gravitons in diphoton channel)
W’ searches

- W’ a heavy analogue of SM W with same couplings
- Identify high $p_T$ lepton (e or $\mu$), $p_T > 30$ GeV
- Search for peak/enhancement in transverse mass spectrum ($e/\mu$ + missing transverse energy)

$$M_T = \sqrt{2 \cdot p_T \cdot E_T^{miss} \cdot (1 - \cos \Delta \phi_{,\nu})}$$

- Data agree with SM expectation
  - from $W' \rightarrow e \nu$ channel exclude W’ masses below 1.36 TeV
  - from $W' \rightarrow \mu \nu$ channel exclude W’ masses below 1.40 TeV

- Combination of $e$ and $\mu$ channel results in 95% CL exclusion of W’ masses below 1.58 TeV

more stringent limit compared
D0 & CDF
(1.1 TeV)

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Z’ searches

- Search for resonance in di-lepton mass distribution

- Identify 2 muons with \( p_T > 20 \) GeV or 2 electrons with \( p_T > 25 \) GeV

- Dilepton invariant mass spectra consistent with SM expectations

- No sign of new resonance

- \( Z'_\text{SSM} \) with Standard-Model-like couplings can be excluded below 1140 GeV

- Superstring-inspired \( Z' \) excluded below 887 GeV

- RS Kaluza-Klein gravitons below 855–1079 GeV for couplings of 0.05–0.1

(all at 95% C.L.)

EXO-10-013
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EXO-10-013
Leptoquarks

- Pair production of leptoquarks
  - search for events with two leptons (e and $\mu$) and two jets
  - lepton $p_T > 30$ GeV and $|\eta| < 2.5$ (2.4 for $\mu$ ‘s)
  - jets with $p_T > 30$ GeV and $|\eta| < 3.0$

- Discriminating variables:
  - dilepton invariant mass
    - require large mass to reject Z’s
    - $M_{ee}$ ($M_{\mu\mu}$) $> 125$ (115) GeV
  - scalar sum of transverse energies of leading and subleading leptons and jets
    - $S_T = E_T(l_1) + E_T(l_2) + E_T(j_1) + E_T(j_2)$
    - mass dependent $S_T$ cut (>250 GeV)

- Main backgrounds from Drell-Yann + jets and top pair production
  - Normalise DY background in Z control region

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arXiv:1012.4031

1st Generation: LQ$\rightarrow$qe

Discriminating variables:
- dilepton invariant mass
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Main backgrounds from Drell-Yann + jets and top pair production
- Normalise DY background in Z control region

similar for 2nd generation: LQ$\rightarrow$q$\mu$

arXiv:1012.4033
Leptoquarks

- Set limit on BF * Cross section in absence of excess
  - $\beta$ is BF for LQ $\rightarrow$ qe
  - $(1-V \beta)$ is BF for LQ $\rightarrow$ q $\nu_e$
- $M_{LQ} > 384$ GeV for $\beta = 1$ (1st gen)
- $M_{LQ} > 394$ GeV for $\beta = 1$ (2nd gen)

arXiv:1012.4031

Exceed Tevatron limits

arXiv:1012.4033
Extra Dimensions: Black Holes

- Creation of microscopic Black Holes possible when the two partons from colliding beams pass each other at a distance smaller than the Schwarzschild radius corresponding to their invariant mass:
  
  \[ r_S = \frac{1}{\sqrt{\pi M_D}} \left[ \frac{M_{BH}}{M_D} \frac{8 \Gamma \left( \frac{n+3}{2} \right)}{n+2} \right]^{1/(n+1)} \]

  \[ M_{Pl}^2 = 8\pi M_D^{n+2} r^n \]

- Black holes instantaneously decay via Hawking evaporation with an emission of large number of energetic objects:
  - dominated (75%) by quark and gluons, with the rest going into leptons, photons, W/Z, h, etc.

- Discriminating variable:
  - \( S_T = \sum E_T \), where the sum is over all the objects with \( E_T > 50 \text{ GeV} \), including ME\( T \)

- Completely data-driven QCD background determination using a novel technique:
  - \( S_T \)-invariance of the final state multiplicity

\[ \text{arXiv:1012.3375} \]
Extra Dimensions: Black Holes

- In absence of an excess, set limits on the minimum BH mass
- 3.5-4.5 TeV in semi-classical approximation
- 10 jet candidate event with $S_T = 1.3$ TeV

arXiv:1012.3375
Supersymmetry an excellent candidate for Dark Matter

R-parity conserving SUSY gives rise to stable lightest SUSY particle (LSP)
- missing energy signature

CMS follows a topology driven approach:

Search for heavy pair-produced particles that decay to SM particles and LSP
- direct decay of squarks or gluinos to quarks (jets) + LSP
- cascade decays via charginos resulting in leptons

In case of GGM, neutralino decay to photon + gravitino (LSP)
- diphoton + jets + missing energy signature
SUSY searches: jets + missing energy

- Pair production of heavy particles whose decay results in high $p_T$ jets
- Main problem: huge QCD multijet background!
- Basic idea: deploy a simple and robust analysis based on kinematics – appropriate for early data
  - Simplicity: use of kinematic information ($\alpha_T$ variable)
  - Robustness: protection against mis-measurements of jets in QCD events; signal region is practically QCD free
- Result: remaining backgrounds dominated by processes with real MET [i.e. EWK+top]

Define:
- $H_T = \Sigma p_T(j_i)$
- $MH_T = |\Sigma p_T(j_i)|$
- $\Delta H_T = E_T(pj_1) - E_T(pj_2)$

### $\alpha_T$ for dijets:

$$\alpha_T = \frac{E_T(j_2)}{M_{T_{j1j2}}} = \frac{\sqrt{E_T(j_2)/E_T(j_1)}}{\sqrt{2(1 - \cos \Delta \varphi)}} \leq 0.5$$

Expectation for QCD: $\alpha_T = 0.5$
Jet mis-measurements: $\alpha_T < 0.5$

### $\alpha_T$ for $n$ jets:

(form form two pseudo-jets – defined by balance in “pseudo-jet” $H_T = \Sigma E_T$)

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{M_T}$$

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SUSY searches: 
jets + missing energy

- Event selection:
  - Require $\geq 2$ jets with $p_T > 50$ GeV
  - leading 2 jets with $p_T > 100$ GeV
  - Scalar sum of jet $p_T$, $H_T > 350$ GeV
  - Explicit veto on
    - isolated $e$/$\mu$ with $p_T > 10$ GeV
    - photons with $p_T > 25$ GeV
  - $\alpha_T > 0.55$
  - QCD multijet events eliminated

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>SM</th>
<th>QCD multijet</th>
<th>$Z \rightarrow \nu\bar{\nu}$</th>
<th>$W +$ jets</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_T &gt; 250$ GeV</td>
<td>4.68M</td>
<td>5.81M</td>
<td>5.81M</td>
<td>290</td>
<td>2.0k</td>
<td>2.5k</td>
</tr>
<tr>
<td>$E_T^{jet} &gt; 100$ GeV</td>
<td>2.89M</td>
<td>3.40M</td>
<td>3.40M</td>
<td>160</td>
<td>610</td>
<td>830</td>
</tr>
<tr>
<td>$H_T &gt; 350$ GeV</td>
<td>908k</td>
<td>1.11M</td>
<td>1.11M</td>
<td>80</td>
<td>280</td>
<td>650</td>
</tr>
<tr>
<td>$\alpha_T &gt; 0.55$</td>
<td>37</td>
<td>30.5±4.7</td>
<td>19.5±4.6</td>
<td>4.2±0.6</td>
<td>3.9±0.7</td>
<td>2.8±0.1</td>
</tr>
<tr>
<td>$\Delta R_{\text{cal}} &gt; 0.3 \lor \Delta \phi &gt; 0.5$</td>
<td>32</td>
<td>24.5±4.2</td>
<td>14.3±4.1</td>
<td>4.2±0.6</td>
<td>3.6±0.6</td>
<td>2.4±0.1</td>
</tr>
<tr>
<td>$R_{\text{miss}} &lt; 1.25$</td>
<td>13</td>
<td>9.3±0.9</td>
<td>0.03±0.02</td>
<td>4.1±0.6</td>
<td>3.3±0.6</td>
<td>1.8±0.1</td>
</tr>
</tbody>
</table>

\[ \int L \, dt = 35 \, \text{pb}^{-1}, \sqrt{s} = 7 \, \text{TeV} \]

2 jets also works for $\geq 3$ jets!
SUSY searches: jets + missing energy

SM backgrounds predicted with 3 data-driven methods

- Total background (QCD, W/tt, Z→vv) extrapolating $\alpha_T$ ratio $\langle R_{\alpha_T} \rangle$ from low $H_T$ to high $H_T$ region
  - Two methods based on data only:
    1) exponential $H_T$ dependence: $9.4^{+4.8}_{-4.0 \text{ stat}} \pm 1.0_{\text{syst}}$
    2) No $H_T$ dependence (const. $R_{\alpha_T}$) $12.5 \pm 1.9_{\text{stat}} \pm 0.7_{\text{syst}}$

- W/tt background from muon control sample
  - invert muon veto
  - $6.1^{+2.8}_{-1.9 \text{stat}} \pm 1.8_{\text{syst}}$

- Z→vv background from photon control sample
  - invert photon veto
  - $4.4^{+2.3}_{-1.6 \text{stat}} \pm 1.8_{\text{syst}}$

- 13 events in data after full selection
- kinematic properties compatible with SM expectation
- $M_{\text{eff}} = H_T + M_{H_T}$

La Thuile 2011  arXiv:1101.1628  Henning

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Exclusion in the CMSSM

- CMSSM: 4 parameter model assuming common gaugino and scalar masses at GUT scale ($m_{1/2}$, $m_0$)
- In absence of signal, calculate 95% CL exclusion limit using Feldman-Cousins
- $\tan\beta$ independent exclusion
- Exclude squark and gluino masses of ~550-650 GeV in CMSSM

Selection efficiency approximately production-process independent

12% uncertainty on signal efficiency, dominated by 11% luminosity uncertainty

arXiv:1101.1628
**SUSY Searches: jets+ME_T+2leptons (OS)**

- **Selection:**
  - 2 isolated leptons (e or \(\mu\)) with \(p_T > 10\) GeV
  - opposite charge
  - Presence of leptons strongly reduce QCD background
  - \(\geq 2\) jets with \(p_T > 30\) GeV and \(|\eta| < 2.5\)

- require \(H_T > 300\) GeV and \(y = ME_T/\sqrt{H_T} > 8.5\) \(\sqrt{\text{GeV}}\) to suppress top background
  - define signal and control regions in both variables (uncorrelated)
  - Relate SM BG in signal region as \(N_D = N_A N_C / N_B\)

- Additionally use similarity of lepton and neutrino spectra to model missing energy distribution
- Cross check same flavour tt background with opposite flavour events

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SUSY Searches: jets+ME_T+leptons

- Set limit in absence of signal
- 95% CL upper limit on BSM contribution is 4.7 events
- limit $\tan \beta$ dependent and most sensitive for low $\tan \beta$ values
- extended reach over Tevatron tri-lepton analysis
- Equivalent search in same sign dilepton channel: SUS-10-004

<table>
<thead>
<tr>
<th>Data</th>
<th>BG Prediction</th>
<th>SM MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4 ± 0.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

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SUS-10-007

CMS preliminary

$L_{\text{int}} = 34 \text{ pb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

$\tan \beta = 3, A_0 = 0, \mu > 0$

$\tilde{\tau} = \text{LSP}$

$\tilde{q}(650)_{\text{GeV}}$

$\tilde{q}(800)_{\text{GeV}}$

$\tilde{g}(650)_{\text{GeV}}$

$\tilde{g}(500)_{\text{GeV}}$

$\tilde{g}(800)_{\text{GeV}}$
SUSY Searches: 
jets+ME_{T}+diphotons

- Search for General Gauge Mediated SUSY Breaking
  - LSP is the gravitino
  - Neutralino is NLSP
    - decaying to photon and gravitino
- Event selection
  - photon candidates with \( p_T > 30 \text{ GeV} \) and \(| \eta | < 1.4 \) (barrel)
  - \( \geq 1 \) jet with \( p_T > 30 \text{ GeV} \) and \(| \eta | < 2.6 \)
- Main Backgrounds:
  - QCD processes with diphoton or photon + jet production
  - \( W \rightarrow \nu e + \) jets with electron misidentified as photon
  - estimated from \( Z \rightarrow \text{ee} \) data control sample

No excess of diphotons events observed
Upper limits on production cross-section in squark-gluino mass plane ranging from 0.3 – 1.1 pb for gluino and squark masses between 500 – 2000 GeV

assumes Neutralino mass of 150 GeV

95% CL limit excluded squark and gluino masses

SUS-10-002
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WW production and consequences for Higgs search

- Diboson production main background to $H \rightarrow W^+W^-$ channel
  - select two high-$p_T$, oppositely charged isolated leptons
    - $p_T > 20$ GeV
  - Missing $E_T > 20$ GeV and projected $ME_T > 35$ GeV
  - $Z$ veto: $M_{ll} > M_Z + 15$ GeV
  - top veto:
    - jet veto ($p_T > 25$ GeV), soft muon & b-tag veto
- To gain sensitivity to Higgs$\rightarrow W^+W^-$ consider opening angle of leptons $\Delta \Phi_{ll}$ and $M_{ll}$

$W^+W^-$ cross section:
- 13 events in data with estimated BG of $3.3\pm 0.5_{\text{stat}} \pm 1.1_{\text{syst}}$
- $\sigma_{W^+W^-} = 41.1 \pm 15.3_{\text{stat}} \pm 5.8_{\text{syst}} \pm 4.5_{\text{lumi}}$ pb
- SM: $\sigma_{W^+W^-} = 43.0 \pm 2.0$ pb @ NLO
- SM $H \rightarrow W^+W^-$ cross section limits:
  - 3 times SM @ $M_H = 160$ GeV @ 95%CL
- Sequential fourth family of fermions with very high masses and Higgs with SM couplings
  - $144 < M_H < 207$ GeV excluded @ 95% CL

arXiv:1102.5429

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Conclusions & Outlook

- New Physics searches well underway
  - with focus on data driven background estimation methods
- Investigating a wide variety of New Physics scenarios:
  - Excited V-Bosons
  - Leptoquarks
  - Extra-Dimensions
  - Supersymmetry
  - Higgs
  - and many more I didn’t have time to cover
- see [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults)
- Unfortunately no smoking gun seen so far, but
- CMS (and ATLAS) have entered new territory, superseeding Tevatron searches in many areas
- Many more exciting results can be expected for Summer