Recent results of searches for new physics with the CMS detector

Filip Moortgat (ETH Zurich)

Seminar @ EPFL, April 18, 2011
Outline

• Introduction
  • Reminder of design features of CMS
  • LHC/CMS performance in 2010

• Searches for supersymmetry
  • Hadronic final states
  • Leptonic final states
  • SUSY Higgs

• Searches for other new physics (if time allows)
  • Z’, W’, KK gravitons, black holes …
CMS Detector

SILICON TRACKER
- Pixels: (100 x 150 μm²)
- ~1m² ~66M channels
- Microstrips: (80-180μm)
- ~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76k scintillating PbWO₄ crystals

PRESHOWER
- Silicon strips
- ~16m² ~137k channels

STEEL RETURN YOKE
- ~13000 tonnes

SUPERCONDUCTING SOLENOID
- Niobium-titanium coil
- carrying ~18000 A

HADRON CALORIMETER (HCAL)
- Brass + plastic scintillator
- ~7k channels

FORWARD CALORIMETER
- Steel + quartz fibres
- ~2k channels

MUON CHAMBERS
- Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
- Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

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Transverse view of CMS

- 3.8T Superconducting Solenoid
- Lead tungstate E/M Calorimeter (ECAL)
- Hermetic ($|\eta|<5.2$) Hadron Calorimeter (HCAL) [scintillators & brass]
- All Silicon Tracker (Pixels and Microstrips)
- Redundant Muon System (RPCs, Drift Tubes, Cathode Strip Chambers)
• LHC delivered 47 pb\(^{-1}\) in 2010
• CMS recorded 43 pb\(^{-1}\) (92%)
• 5 orders of magnitude in instantaneous luminosity

• average fraction of functional detector channels > 99%
• lowest still > 98%
• results below based on ~ 35 pb\(^{-1}\)
Leptons @ CMS

Electrons

Muons

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Another example of CMS muon performance:
For jets and MET: use Particle Flow to improve resolution
Default jet algorithm: anti-kT with R=0.5
Noise cleaning important!  Particle Flow improves resolution with factor ~2
Supersymmetry

A possible extension of the SM:

a symmetry between fermions and bosons
= supersymmetry

Solves several problems at once:

• hierarchy problem
• opening towards a theory of gravity
• unification of gauge couplings (in MSSM, not in SM)
• dark matter candidate (= lightest supersymmetric particle)
• allows to explain why the Higgs mechanism works
SUSY introduces new particles (but no new couplings!): 

- leptons (f)
- quarks (f)
- gauge bosons (b)
- Higgs bosons (b)

- sleptons (b) \( (\tilde{l}, \tilde{q}) \)
- squarks (b)
- gauginos (f)
- higgsinos (f)

\( (\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0) \)
\( (\chi_1^\pm, \chi_2^\pm) \)

(f = fermion, b = boson)
Generic SUSY signatures

General characteristics of R-parity conserving SUSY:

• sparticles pair produced and LSP stable
  \[ \rightarrow \] large amount of missing transverse energy

• coloured sparticles are copiously produced and cascade down to the LSP with emission of many hard jets and sometimes leptons

\[ \text{Generic SUSY signatures are } E_T^{\text{miss}} + \text{multi-jets (and multi-leptons)} \]

Same signature: UED, Little Higgs with T-parity, …
• All searches require jets and MET
• Further categorized by number of leptons (and photons)
• All counting experiments at this point

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Hadronic searches for SUSY

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- Most sensitive to SUSY since only relies on strong production
- But most challenging due to large background
- Different analyses in CMS based on different kinematical variables:
  \[ \alpha_T, \text{MHT}, R \text{ and } M_R , \ldots \]
- In the future, extending to b, \( \tau \), and top-tagged final states
First CMS analysis based on
- $H_T = \text{scalar sum of jets (scale)}$
- $\alpha_T (\text{shape})$:

$$
\alpha_T \equiv \frac{E_T^{j_2}}{M_T(j_1j_2)} = \frac{\sqrt{E_T^{j_2}} / E_T^{j_1}}{\sqrt{2(1 - \cos \Delta \varphi)}}
$$

Variable stable against QCD mis-measurements
- In the case of more than 2 jets: make 2 “pseudo-jets” (see next slide)
Group jets in the event into 2 hemispheres

- For SUSY cascade decays: group decay products from 2 initial sparticles together
- For QCD: bring multi-jets back to a (pseudo) di-jet configuration (back-to-back)

(Slightly) different ways of associating jets to the 2 groups:
- Minimal mass squared of both hemispheres (Razor)
- HT balance (RA1)

F. M., Luc Pape,
CMS PTDR2, Ch. 13.2
Event selection:

• at least 2 jets with $E_T > 100$, 50 GeV and $|\eta| < 3$ (anti-kT 0.5)
• veto events with isolated leptons
• event cleaning cuts
• $H_T > 350$ GeV and $\alpha_T > 0.55$

Type of backgrounds:
1. QCD mis-measurements
2. $W+\text{jets, ttbar}$
3. $Z\rightarrow\nu\nu + \text{jets}$ (irreducible)

Inclusive background estimate

$$R_{\alpha_T} = \frac{N(\alpha_T>x)}{N(\alpha_T<x)}$$
Interpretation:

- Done in CMSSW for easy comparison
- Also in the framework of simplified models
- Significant extension of excluded region with respect to LEP and Tevatron
Jet+MET search for SUSY

• THE classic SUSY search  
(MHT=vector sum of jets)

• Requires detailed understanding of 
the detector

• Baseline selection:
  - At least 3 jets with $E_T>50$ GeV & $|\eta|<2.5$ anti-kT (0.5)
  - $H_T>300$ GeV and MHT > 150 GeV
  - Veto isolated electrons and muons

• Backgrounds:
  - Multi-jet QCD, $Z \rightarrow vv$, $W+jets$, $t\bar{t}bar$
  - All determined from data-driven techniques
Main method: “rebalance and smear”

- Idea: derive a smearing function per jet from data and apply this to a seed sample to predict the high MET tail in data
- Derive smearing function from photon + jet (core) and di-jet (non-Gaussian tails) data →
- Obtain a well-balanced seed sample by rebalancing multi-jet events
- Apply smearing to each jet to get a background prediction
$Z \rightarrow \nu \nu$ is an irreducible background

- use replacement techniques:

$Z \rightarrow ll + jets$
Strength: very clean
Weakness: low statistics

$W \rightarrow l\nu + jets$
Strength: larger statistics
Weakness: background from SM and SUSY

$\gamma + jets$
Strength: large statistics and clean at high $E_T$
Weakness: background at low $E_T$, theoretical errors

$W$+jet and top background:
- estimate lost leptons using lepton efficiencies from tag/probe
- for taus: replace $\mu$ by simulated $\tau$ had.
Result

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHT &gt; 250 GeV</td>
<td>18.8 ± 3.5</td>
<td>15</td>
</tr>
<tr>
<td>H_T &gt; 500 GeV</td>
<td>43.9 ± 8.8</td>
<td>40</td>
</tr>
</tbody>
</table>

Interpretation in the CMSSW

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In CM frame, final state objects have momentum equal to

\[ M_\Delta = \frac{m_{q}^2 - m_{\tilde{\chi}_1^0}^2}{2m_q} \]

R-frame: “rough approximation” to CM frame:
- equalize magnitude of 2 hemispheres
- R-frame = CM frame if 1) ISR neglected and
  2) squarks produced at threshold

**Scale:**
\[
M_R = 2\sqrt{\frac{(|p|q_x - |q|p_x)^2}{(p_x - q_x)^2 - (|p| - |q|)^2}}
\]
\[
M_T^R = \sqrt{\frac{|\vec{M}|(|\vec{p} + \vec{q}) - \vec{M} \cdot (\vec{p} + \vec{q})}{2}}
\]

**Peaks at**
\[
M_\Delta = \frac{m_{q}^2 - m_{\tilde{\chi}_1^0}^2}{2m_q}
\]

**Edge at**
\[
M_\Delta = \frac{m_{q}^2 - m_{\tilde{\chi}_1^0}^2}{2m_q}
\]

**Example:** \( \tilde{q}\tilde{q} \rightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0) \)

**Angle:**
\[
R = \frac{M_T^R}{M_R}
\]

arxiv:1006:2727  
SUS-10-009
Exponential scaling property in $M_R$ used for background estimation

- Use electron, muon, and low $M_R$ hadronic control samples to predict background in hadronic signal region.
- Only low $M_R$ regions used to determine backgrounds. Higher $M_R$ regions in e/μ control boxes are also searches.
- Similar limits to jets+MHT analysis
- Complementary use of kinematics instead of detailed detector understanding
Model-independent interpretation

- Also give results in “Simplified Models”
  - Models proposed at: http://www.lhcnewphysics.org
  - Agreed on reference topologies for early searches
  - Cover what one might see in the first ~50 pb⁻¹
  - All initiated by strong production

- Squark anti-squark pair production with decay squark → q + χ
- Gluino pair production with decay gluino → qqbar + χ
- Direct case $m_{gluino}(m_{squark})$ vs $m_{LSP}$ 2D plot
Model-independent interpretation (2)

- Limits are the best of the three hadronic searches
- Black lines represent QCD-like cross sections
Single lepton search

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- Lepton requirement reduces backgrounds considerably
- Mainly W+jets and top backgrounds left
- Again, data-driven background prediction methods used
Single lepton selection

- **Baseline selection:**
  - Isolated lepton:
    - $p_T > 20$ GeV
  - 4 jets:
    - $p_T > 30$ GeV, $|\eta|<2.4$

- **Final selection:**
  - MET > 250 GeV
  - HT > 500 GeV

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\ell = \mu$</th>
<th>$\ell = \epsilon$</th>
</tr>
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<tr>
<td>Predicted SM 1 $\ell$</td>
<td>$1.7 \pm 1.4$</td>
<td>$1.2 \pm 1.0$</td>
</tr>
<tr>
<td>Predicted SM dilepton</td>
<td>$0.0^{+0.8}_{-0.0}$</td>
<td>$0.0^{+0.6}_{-0.0}$</td>
</tr>
<tr>
<td>Predicted single $\tau$</td>
<td>$0.29 \pm 0.22$</td>
<td>$0.32^{+0.38}_{-0.32}$</td>
</tr>
<tr>
<td>Predicted QCD background</td>
<td>$0.09 \pm 0.09$</td>
<td>$0.0^{+0.16}_{-0.0}$</td>
</tr>
<tr>
<td>Total predicted SM</td>
<td>$2.1 \pm 1.5$</td>
<td>$1.5 \pm 1.2$</td>
</tr>
<tr>
<td>Observed signal region</td>
<td>2</td>
<td>0</td>
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Background determination

Exploit the fact that for W decays the charged lepton and neutrino $p_T$ spectra are on average approximately the same.

Use lepton $p_T$ spectra to predict MET.

- Take muon $p_T$ spectrum (cleaner than electron).
- Correct for acceptance, efficiency and polarisation effects.
- MET resolution worse than for $e/\mu \rightarrow$ measure in data and smear.
- Powerful technique based on fundamental physics.
- Other techniques for smaller backgrounds (ttbar to dileptons, QCD etc.)
- All backgrounds also determined using ABCD/matrix method (described later).
### Opposite-sign di-lepton

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- Second lepton requirement reduces QCD and W background further
- Two separate analysis: inside and outside of the Z peak
- Top is the main background: several prediction techniques, including opposite-sign opposite flavour subtraction
- Channel very suitable for sparticle mass reconstruction from endpoint measurements
Top background determination

- Exploit the observation that $H_T$ and $y = \text{MET}/\sqrt{H_T}$ are almost uncorrelated.

- Define signal region:
  - $H_T > 300 \text{ GeV}$
  - $y > 8.5 \sqrt{\text{GeV}}$

- Use ABCD/matrix method to determine background.

- Also use lepton $p_T$ spectrum method described earlier.
• Limit in CMSSM beyond previous Tevatron searches
• Also result from opposite-sign opposite-flavour subtraction
  □ Observed in data: ee:0 μμ:0  Predicted background: ee: 0.1$^{+1.2}_{-0.4}$ μμ: 0.5$^{+1.2}_{-0.4}$
## Same-sign di-leptons

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- Almost SM background free
- In SUSY, expect significant production through charginos in gluino cascades
Same-sign dileptons

Signal:

\[ pp \rightarrow \tilde{g}\tilde{u}_L + X \]

\[ \tilde{t} \rightarrow \tilde{\chi}_1^0 \nu_\mu \]

\[ \tilde{\chi}_1^0 \nu_\mu \rightarrow \tilde{\chi}_1^0 \nu_\mu \]

\[ \tilde{\chi}_1^0 \nu_\mu \rightarrow \tilde{\chi}_1^0 \nu_\mu \]

\[ \rightarrow \text{require well-isolated leptons} \]

Background:

\[ pp \rightarrow \tilde{t}\tilde{t} + X \]

\[ W^+b \rightarrow \mu^+ + Y \]

\[ \mu^+ + Y \]

\[ \rightarrow \text{require well-isolated leptons} \]
Same-sign selection

- Search in all three lepton species and four search regions

  - **High-\(p_T\) leptons**
  - **Low-\(p_T\) leptons**
  - **Final states with \(\tau\)'s**

- **Dominant backgrounds**
  - \(t\bar{t}\)bar: one isolated lepton from \(W\), one from semi-lep \(b/c\) decay in jet
  - QCD: larger for hadronic \(\tau\) final states

  \(\rightarrow\) use fake ratio method:
  - Tight to Loose lepton ID probability from multi-jet sample
  - Apply measured probability to side-band sample with loose lepton ID to predict background with tight lepton ID
Fake ratio method

\( f \) = 'fake ratio' tight-to-loose from a background-dominated sample, e.g. Jet events
\( p \) = 'prompt ratio' ratio tight-to-loose from a signal-dominated sample, e.g. from a Z boson decays → need to correct for real muon contamination.

Use the definitions of \( f \) and \( p \) to write down a system of equations:

\[
\begin{align*}
    N_I &= N_{pp} + N_{fp} + N_{ff} = N_{t2} + N_{t1} + N_{t0} \\
    N_{t0} &= (1 - p)^2 N_{pp} + (1 - p)(1 - f) N_{fp} + (1 - f)^2 N_{ff} \\
    N_{t1} &= 2p(1 - p)N_{pp} + [f(1 - p) + p(1 - f)] N_{fp} + 2f(1 - f) N_{ff} \\
    N_{t2} &= p^2 N_{pp} + pf N_{fp} + f^2 N_{ff}
\end{align*}
\]

\( N_I \) = total \#events with at least two 'loose' muons
\( N_{t0}, N_{t1}, N_{t2} \) = \#events with 0,1,2 muons passing 'tight' selection cuts (but not signal cuts)
\( N_{pp}, N_{fp}, N_{ff} \) = \#events with prompt-prompt, fake-prompt, fake-fake muons (unknown)
Same-sign results

- Include hadronic $\tau$ channels $e-\tau$, $\mu-\tau$, and $\tau-\tau$
  - Increased background from QCD jets faking hadronic $\tau$
  - Use similar tight to loose probability

- Final background estimates:
  - No sign of new physics $\Rightarrow$
  - Set limits....
Limit in CMSSM
- Also provide information on efficiencies for model builders
- Test this ourselves and reproduce our limit well (dashed line)
### Multi-leptons

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- Very clean signature with very low Standard Model background
- Include all three generations of leptons and all combinations
Multi-lepton search

- Search in events with at least three isolated leptons
  - Backgrounds suppressed drastically
  - More inclusive search $\rightarrow$ wide phase space

- Baseline
  - At least three leptons ($e, \mu, \tau$) with $p_T$ thresholds from 8 GeV
  - Require one non-$\tau$ lepton (trigger)

- Two final selections
  - $\text{MET} > 50$ GeV
  - $H_T > 200$ GeV

MET and $H_T$ both suppress background effectively, but probe complementary SUSY phase space
Backgrounds

- **Backgrounds:**
  - Irreducible: WZ+Jets, ZZ+Jets - estimated from simulation
  - ttbar - simulation
  - Z+Jets, WW+Jets, W+Jets, QCD - data-driven using fake rate

- **Analysis based on combination 55 exclusive channels**
  - Opposite-sign/same-sign/Z peak/off peak/MET/$H_T$....
  - Channels combined statistically to give final result
  - No excess observed (but some beautifully events)
- Set limits in CMSSM for comparison with previous expts.
- Also consider more phenomenological interpretation in GGM model
- Multi-lepton signatures also arise naturally in co-NLSP model with mass degenerate sleptons decaying to leptons and Gravitino
Comparison exclusion limits in CMSSM plane

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

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

\(\tan \beta = 10, A_0 = 0, \mu > 0\)
Still a long way to go

Where we need to go:

LHC, 14 TeV

mSUGRA reach in various final states for 100 fb⁻¹
Interesting event displays
MSSM contains 2 Higgs doublets, therefore 5 physical Higgs states: $h^0$, $H^0$, $A^0$, $H^\pm$

- Masses & couplings depend at tree level only on 2 parameters, say $m_A$ & $\tan\beta$:

\[ m_{H^\pm}^2 = m_{A^0}^2 + m_W^2 \]
\[ m_{h^0,H^0}^2 = \frac{1}{2} \left( m_{A^0}^2 + m_{Z^0}^2 + \sqrt{(m_{A^0}^2 + m_{Z^0}^2)^2 - 4m_{Z^0}^2m_{A^0}^2\cos^2 2\beta} \right) \]

- Radiative corrections can be important (e.g. for $h^0$!!)

\[ \sim \text{degenerate in mass for high } m_A \]

- Looks like $H_{SM}$ (but $m_h < 130$ GeV)

$\phantom{.}$
Promising channel:

\[ h/A/H \rightarrow \tau\tau \]

where the taus can decay leptonically or hadronically:

1. lepton + lepton
2. lepton + hadron : \( M_A < 350 \text{ GeV} \)
3. hadron + hadron : \( M_A > 350 \text{ GeV} \)
Backgrounds

- **Main background from Standard Model Z → ττ**
  - Taken from simulation and normalised to Z → μμ data

- **Backgrounds from QCD multi-jets determined in two ways**
  - From ratio of SS to OS dilepton events
  - From tau fake rate studies in QCD multi-jet sample

<table>
<thead>
<tr>
<th>Process</th>
<th>μττ</th>
<th>eττ</th>
<th>eμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z → ττ</td>
<td>329±77</td>
<td>190±44</td>
<td>88±5</td>
</tr>
<tr>
<td>tt</td>
<td>6±3</td>
<td>2.5±1.3</td>
<td>7.1±1.3</td>
</tr>
<tr>
<td>Z → ℓℓ, jet → ττ</td>
<td>6.4±2.4</td>
<td>15±6.2</td>
<td></td>
</tr>
<tr>
<td>Z → ℓℓ, ℓ → ττ</td>
<td>13.3±3.6</td>
<td>119±28</td>
<td></td>
</tr>
<tr>
<td>W → ℓν</td>
<td>54.9±4.8</td>
<td>30.6±3.1</td>
<td>3.9±1.2</td>
</tr>
<tr>
<td>W → τν</td>
<td>14.7±1.3</td>
<td>7.0±0.7</td>
<td>3.9±1.2</td>
</tr>
<tr>
<td>QCD</td>
<td>132±14</td>
<td>181±23</td>
<td></td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
<td>1.6±0.8</td>
<td>0.8±0.4</td>
<td>3.0±0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>558±79</td>
<td>546±57</td>
<td>102±5</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>540</td>
<td>517</td>
<td>101</td>
</tr>
</tbody>
</table>

**Signal Efficiency (m_A=120 GeV/c^2)**

|                | 0.0253 | 0.0156 | 0.00561 |

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Tau pair mass reconstruction

- Likelihood fit to $\tau$ momenta
- Use all available kinematic information and probability density for $\tau p_T$ spectra
- Improvement in resolution compared to visible mass
Limit on $\sigma \times \text{BR}$ for $\tan \beta = 30$

Excluded region in MSSM $m_h^{\text{max}}$ scenario

Significantly extends previous limits
20 searches are detailed in:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
Di-Lepton Resonances

Bump hunt in $M(\ell\ell)$ spectrum
- No significant deviation from SM, set limits

CMS limits (35 – 40 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mu\mu$</th>
<th>$ee$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{SSM}$</td>
<td>1027 GeV</td>
<td>958 GeV</td>
<td>1140 GeV</td>
</tr>
<tr>
<td>$Z_{\psi}$</td>
<td>792 GeV</td>
<td>731 GeV</td>
<td>887 GeV</td>
</tr>
<tr>
<td>$G_{KK}$, $k/M_{Pl} = 0.05$</td>
<td>778 GeV</td>
<td>729 GeV</td>
<td>855 GeV</td>
</tr>
<tr>
<td>$G_{KK}$, $k/M_{Pl} = 0.10$</td>
<td>987 GeV</td>
<td>931 GeV</td>
<td>1079 GeV</td>
</tr>
</tbody>
</table>

$G_{KK} \rightarrow \gamma\gamma$ channel
$M_{GKK} > 945$ GeV
$k/M_{Pl} = 0.1$
EXO-10-019

Published CDF/D0 limits
**D0, ee, $\gamma\gamma$ 5.4 fb$^{-1}$:**
$M(Z'_{SSM}) > 1023$ GeV
$M(G_{KK}, k/M_{Pl} = 0.1) > 1050$ GeV

**CDF, $\mu\mu$, 2.3 fb$^{-1}$:**
$M(Z'_{SSM}) > 1030$ GeV
$M(G_{KK}, k/M_{Pl} = 0.1) > 921$ GeV

**CDF, ee, 2.5 fb$^{-1}$:**
$M(Z'_{SSM}) > 963$ GeV
$M(G_{KK}, k/M_{Pl} = 0.1) > 848$ GeV

arXiv:1103.0981, Submitted to JHEP
Bump hunt in $M_T(l\nu)$ spectrum

$$M_T = \sqrt{2E_T^\ell E_T^{miss}[1 - \cos \Delta \phi(\ell, E_T^{miss})]}$$

- No significant deviation from SM, set limits

$e\nu \rightarrow \text{arXiv:1012.5945, Accepted by PLB}$
$\mu\nu \rightarrow \text{arXiv:1103.0030, Submitted to PLB}$

**CMS limits (36 pb$^{-1}$)**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\nu$</td>
<td>1.36</td>
</tr>
<tr>
<td>$\mu\nu$</td>
<td>1.4</td>
</tr>
<tr>
<td>$e\nu + \mu\nu$</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Published CDF/D0 limits

CDF, $e\nu$, 5.3 fb$^{-1}$:
$M(W') > 1.12 \text{ TeV}$

D0, $e\nu$, 1 fb$^{-1}$:
$M(W') > 1 \text{ TeV}$
Large Extra Dimensions  
(γγ and µµ)

Look for excess at high mass in γγ or µµ spectrum

- No event observed with $M_{γγ} (M_{µµ}) > 500 \text{ (600)}$ GeV
- Set lower limits on $M_S \text{ (TeV)}$ vs $n$

<table>
<thead>
<tr>
<th></th>
<th>GRW</th>
<th>Hewett Pos.</th>
<th>Hewett Neg.</th>
<th>HLLZ $n_{ED} = 2$</th>
<th>HLLZ $n_{ED} = 3$</th>
<th>HLLZ $n_{ED} = 4$</th>
<th>HLLZ $n_{ED} = 5$</th>
<th>HLLZ $n_{ED} = 6$</th>
<th>HLLZ $n_{ED} = 7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>γγ</td>
<td>Full</td>
<td>1.94</td>
<td>1.74</td>
<td>1.71</td>
<td>1.89</td>
<td>2.31</td>
<td>1.94</td>
<td>1.76</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>Trunc.</td>
<td>1.84</td>
<td>1.60</td>
<td>1.50</td>
<td>1.80</td>
<td>2.23</td>
<td>1.84</td>
<td>1.63</td>
<td>1.46</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$Λ_T \text{ [TeV]} \text{ (GRW)}$</th>
<th>$M_S \text{ [TeV/c²]} \text{ (HLLZ)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>µµ</td>
<td>Full</td>
<td>$n = 2$</td>
</tr>
<tr>
<td></td>
<td>1.80</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>Truncated</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Extend Tevatron limits in all but the $n_{ED} = 2$ case
Large Extra Dimensions

**(mono-jet + MET)**

- One high $p_T$ jet + large MET + no leptons
  - Suppress cosmic/beam halo/instrumental backgrounds
  - Data-driven estimate for $Z\to\text{inv} + \text{jets}$ background
  - Data consistent with SM, set limits on $M_D$ vs $\delta$

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{DATA}}$</td>
<td>275</td>
</tr>
<tr>
<td>$N_{\text{BKG}}$ (data-driven)</td>
<td>$297 \pm 45$</td>
</tr>
<tr>
<td>$N_{\text{SIGNAL}}(M_D=2,\delta=2)$</td>
<td>115.2</td>
</tr>
</tbody>
</table>

$M_D$ = “True” Planck scale
$\delta =$ number of extra dimensions

**CMS limits on $M_D$ (36 pb$^{-1}$)**

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>With K-Factor$^\star\star$</th>
<th>No K-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.37 TeV</td>
<td>2.16 TeV</td>
</tr>
<tr>
<td>3</td>
<td>1.98 TeV</td>
<td>1.83 TeV</td>
</tr>
<tr>
<td>4</td>
<td>1.77 TeV</td>
<td>1.67 TeV</td>
</tr>
</tbody>
</table>

$^\star\star = 1.5 (1.4)$ for $\delta=2,3 (4)$

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>CDF</th>
<th>LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.4 TeV</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>3</td>
<td>1.15 TeV</td>
<td>1.2 TeV</td>
</tr>
<tr>
<td>4</td>
<td>1.04 TeV</td>
<td>0.94 TeV</td>
</tr>
</tbody>
</table>
Searches for Black Holes

- **Smoking gun signature of TeV scale gravity**
- **Democratic BH decay via Hawking radiation to all SM degrees of freedom (mostly quarks and gluons)**
- **Search for deviation in $S_T$ distribution in bins of “object multiplicity” (N)**
  
  \[ S_T = \sum_N E_T \quad \text{for jets, } e, \gamma, \mu \text{ with } E_T > 50 \text{ GeV} \]
  
  + MET

- **Use $S_T$ spectrum from N=2 to predict N=3,4,5, where signal would be present**
- **No excess observed, set limits (semi-classical approximation)**
LHC and CMS performed beautifully in 2010

- ~35 pb\(^{-1}\) of integrated luminosity at 7 TeV collected
- Many searches for new physics have been performed
  - No evidence for new physics found so far
  - Exclusion limits have been set – they often extend significantly beyond the Tevatron & LEP limits

- More than 250 pb\(^{-1}\) of integrated luminosity already collected in 2011
  - Expect 500-1000 pb\(^{-1}\) by Summer
  - And few fb\(^{-1}\) by end of the year

- So stay tuned for 2011 results!
Since graviton can propagate in the bulk, energy and momentum are not conserved in the $G_{KK}$ emission from the point of view of our 3+1 space-time.

Depending on whether the $G_{KK}$ leaves our world or remains virtual, the collider signatures include single photons/Z/jets with missing $E_T$ or fermion/vector boson pair production.

Graviton emission: direct sensitivity to the fundamental Planck scale $M_D$.

Virtual effects: sensitive to the ultraviolet cutoff $M_S$, expected to be $\sim M_D$ (and likely $< M_D$).

The two processes are complementary.
Large extra dimensions

ADD

- Model with n “large” extra dimensions
  - $M_{\text{PL}}$ is an effective scale, restricted to 4 dimensions. The real Planck mass in n+4 dimensions is $M_D = M_{\text{PL}}[n+4]$ related to $M_{\text{PL}}$ by
    \[
    G_N \frac{m_1 m_2}{r^2} = G' \frac{m_1 m_2}{r^2 (2\pi r)^n}, \quad \text{for} \quad r = R \quad \Rightarrow \quad G' = G_N (2\pi R)^n
    \]
  
  - Compactification radius $R < 0.2$ mm (from gravity experiment)
  - Only the gravitons propagate in the extra dimensions
    
    Appearance of Kaluza–Klein excitations for the graviton
      - Mass: $M_n^2 = M_0^2 + n^2/R^2$
      - Coupling to the SM particles: $L = 1/M_{\text{PL}} \ G^{(n)}_{\mu\nu} T^{\mu\nu}$
      - The large number of states (degenerated in mass) compensate the weak coupling $(1/M_{\text{PL}}): \sigma \sim (\sqrt{s}/M_D^2)^n$
ADD(1): virtual $G(kk)$ exchange

- **Cuts:** 2 isolated $l$ or $\gamma$ in $|\eta| < 2.5$ and $P_t > 50$ GeV, $M_{ll/\gamma\gamma} > 0.8$ TeV
- **No resonance anymore, but a continuum of $G^{(KK)}$ states.** Excess in di-leptons mass distribution (same for di-photons), event distribution of $\gamma\gamma$ (s-channel) more central than in SM ($t$ and $u$ channels). FB asymmetry can be measured

- **Significance:** $S/\sqrt{S+B}$
- **Fast simulation**
- **Sensitivity for $\int L = 100$ fb$^{-1}$:** $M_S \sim 5-6$ TeV
LHC results so far: dimuons

CMS preliminary  \( \sqrt{s} = 7 \text{ TeV} \int L \, dt = 40 \text{ pb}^{-1} \)

<table>
<thead>
<tr>
<th>( \Lambda_T [\text{TeV}] ) (GRW)</th>
<th>( M_s [\text{TeV}/c^2] ) (HLZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>Truncated</td>
</tr>
<tr>
<td>1.80</td>
<td>1.68</td>
</tr>
<tr>
<td>1.75 ( n=2 )</td>
<td>1.67 ( n=2 )</td>
</tr>
<tr>
<td>2.15 ( n=3 )</td>
<td>2.09 ( n=3 )</td>
</tr>
<tr>
<td>1.80 ( n=4 )</td>
<td>1.68 ( n=4 )</td>
</tr>
<tr>
<td>1.63 ( n=5 )</td>
<td>1.49 ( n=5 )</td>
</tr>
<tr>
<td>1.52 ( n=6 )</td>
<td>1.34 ( n=6 )</td>
</tr>
<tr>
<td>1.43 ( n=7 )</td>
<td>1.24 ( n=7 )</td>
</tr>
</tbody>
</table>

ADD k-factor: 1.3
LHC results so far: diphotons

---

**CMS**

36 pb\(^{-1}\) at 7 TeV

---

**Table**

<table>
<thead>
<tr>
<th></th>
<th>GRW</th>
<th>Hewett</th>
<th>(n_{\text{ED}}) = 2</th>
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Beyond the Standard Model

SS 2011  ETH Zurich
Scalar Leptoquarks (1)

- LQs decay to lepton and quark
  - $\beta =$ BR$(\text{LQ} \rightarrow lq)$
  - $1-\beta =$ BR$(\text{LQ} \rightarrow \nu q)$
- Search for 1st ($e$) and 2nd ($\mu$) generation LQs
- No excess at high $S_T$

$S_T = p_T^{l1} + p_T^{l2} + p_T^{j1} + p_T^{j2}$

$S_T = p_T^{l1} + \text{MET} + p_T^{j1} + p_T^{j2}$

**lljj channel**

**lvjj channel**

**eejj channel**

**evjj channel**
Scalar Leptoquark (2)

$M_{LQ} > 340, 384$ GeV for $\beta = 0.5, 1$

Exceed Tevatron limits for almost the entire $\beta$ range
**b’ → tW and ttbar Resonances**

- Pair produced b’ → tW → WWb
- Like-sign dilepton and trilepton (e, μ) decays + jets (BR=7.3%)
- $N_{\text{background}} = 0.3 \pm 0.2$ events (tt+jets)
- 0 events observed

$arXiv:1102.4746$, Submitted to PLB

---

- Bump hunt in M(ttbar) spectrum
- Lepton+jets channels (e and μ)
- No bump seen in data
- Set limits, competitive with Tevatron

---

Similar to a new CDF limit of 372 GeV, $arXiv:1101.5728$ (4.8 fb$^{-1}$)
1) Di-jet mass spectrum (→ narrow resonances)

2) Di-jet angular distributions (→ contact interactions)

\[ \chi = e^{2\gamma^*} = \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|} \]

PRL 105:262001, 2010

\[ R_\eta \equiv \frac{N_{2j}(|\eta| < 0.7)}{N_{2j}(0.7 < |\eta| < 1.3)} \]

\[ M_{\text{String}} > 2.5 \text{ TeV} \quad M_{q^*} > 1.58 \text{ TeV} \]

\[ \Lambda > 4 \text{ TeV} \quad \Lambda > 5.6 \text{ TeV} \]

(.expected \( \Lambda > 2.9 \text{ TeV} \))

(.expected \( \Lambda > 5 \text{ TeV} \))
Quark Compositeness ($q^* \rightarrow qZ$)

- Complementary to $q^* \rightarrow jj$ decay channel
- **Search for bump/deviations in $Z p_T$ spectrum**
- No deviation from SM prediction, set limits

**Gauge Interactions**

\[ M_{q^*} = \Lambda, \quad f = f' = f_S = 1 \quad M_{q^*} > 0.91 \text{ TeV} \]

**Contact Interactions**

\[ M_{q^*} = \Lambda, \quad f = f' = 1, f_S = 0 \quad M_{q^*} > 1.17 \text{ TeV} \]

(H1 limit, 475 pb$^{-1}$, gauge int., $f_S=0$, $M_{q^*}>252$ GeV)
Lepton compositeness

Production via new contact interaction → Decay

- Search for excess in data at high \( M(e\gamma) \) or \( M(\mu\gamma) \)
- Reducible backgrounds from data
  - Fake \( \gamma \): Z+jets (l+l- + fake \( \gamma \))
  - Fake l: W\(\gamma\)+jets (l + fake l + \(\gamma\))
- 0 events observed at high \( M(l\gamma) \)
- Set limits, exceed Tevatron

\[ \mathcal{L}_{CI} = \frac{g^2}{2\Lambda^2} j^\mu j^\mu \]
Lepton jets (Hidden Valley)

- Hidden sector contains a new low mass particle ($m_1 \sim$ few GeV)
- It decays into SM pairs (i.e. $\mu\mu$)
- **Collimated groups of di-muons [$\mu\mu$]**
  - opposite charge, $m_{\mu\mu} < 9$ GeV, consistent vertex
- Search for new $\mu\mu$ resonances in various event topologies: [$\mu\mu$], [$\mu\mu$] [$\mu\mu$], etc.

- These are the backgrounds
- $M(\mu\mu)$ background shape from control sample of data at low $P_T$
- Then look at high $P_T$ ...
Lepton jets (Hidden Valley)

- No new $\mu\mu$ resonance seen
- Set model independent upper limits on $\sigma \times \text{BR} \times \alpha$ ($\sim 0.1\text{–}0.5\text{ pb}$)
- Verified sensitivity in various benchmark models (ex. NMSSM Higgs, MSSM + $\gamma_{\text{DARK}}$)

EXO-11-013
Massive Long-lived Particles (1)

- Benchmark model: “split SUSY”
- Gluinos hadronize forming R-Hadrons
  - bound state of SUSY particle + quarks/gluons

Since massive they have **low velocity**

$$\beta Y = \frac{p}{m}$$

1) Massive charged particles with large dE/dX in silicon tracker

2) Stopped particles stopped in the detector due to energy loss, decaying out-of-time w.r.t. to collisions
Massive Long-lived Particles (2)

- Benchmark model: “split SUSY”
- Gluinos hadronize forming R-Hadrons
  - bound state of SUSY particle + quarks/gluons

Since massive they have low velocity

\[ \beta \gamma = \frac{p}{m} \]

1) Massive charged particles with large dE/dX in silicon tracker

2) Stopped particles stopped in the detector due to energy loss, decaying out-of-time w.r.t. to collisions

M_{\text{gluino}} > 311-398 GeV

Ref: PRL 106, 011801 (2011)

arXiv:1101.1645, submitted to JHEP
Di-photon resonance

- RS-1 model
- Branching fraction \(\sim 4\%\) (vs. 2\% for \(ee\) or \(\mu\mu\))
- A CMS calorimetry design goal \((H\to\gamma\gamma)\)
  \(\to\) photons are strong experimental handles

L = 36.1 pb\(^{-1}\)

\(m_{\gamma\gamma} [\text{GeV}]\)

\(\sqrt{s}=7\text{ TeV}\)

L = 36.1 pb\(^{-1}\)

Graviton Mass (GeV/c\(^2\))

Electroweak Limits

95\% CL Limit

excluded

unmotivated

excluded
• ADD model

• Translated into limits on:
  • strength of ED effects ($\eta_G$)
  • in the $n_{ED} = 2$ case on the UV cutoff ($M_s$)

---

**ADD in di-photon**

- **Signal region**
  - CMS Preliminary
  - 33.8 pb$^{-1}$ at $\sqrt{s} = 7$ TeV
  - 95% CL cross section limit

- **Control region**
  - CMS Preliminary
  - 33.8 pb$^{-1}$ at $\sqrt{s} = 7$ TeV
  - 95% CL limit: 0.081 TeV$^2$
ADD in di-muon

- ADD model
- Translated into limits on:
  - phenomenological parameter $\Lambda_T$ (GRW convention)

An example of signal

No signal with $M_{\mu\mu}$

Signal region

Events/(20 GeV/c²)

$M_{\mu\mu}$ [GeV/c²]
Jet + invisible search

- ADD model
- MET & central-jet final state
  - vetoes on leptons, dijets, cosmic ray events, beam halo events, etc.

An example of signal from $W \rightarrow \mu \nu$ and $Z \rightarrow \mu \mu$ control data

Summary plot

$\int L \, dt = 36.1 \, \text{pb}^{-1}$ at $\sqrt{s} = 7 \, \text{TeV}$

Signal region

<table>
<thead>
<tr>
<th>Events / 25 [GeV/c]</th>
<th>$M_D$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^1</td>
<td>2.5</td>
</tr>
<tr>
<td>10^2</td>
<td>3.0</td>
</tr>
<tr>
<td>10^3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

CMS Preliminary

- CMS monojet, 36 pb^{-1}
- CMS di-\gamma, 36 pb^{-1}
- CMS di-\mu, 36 pb^{-1}
- CDF combin., 2.0 fb^{-1}
W’ search

Reference model

- W’ has W-like fermionic couplings
- W’ does not couple to other gauge bosons
- Tevatron limits: $m_{W'} > 1.1\text{TeV}$

$\int L \, dt = 36.1 \text{pb}^{-1}$
$\sqrt{s} = 7 \text{TeV}$

$\rightarrow M_{W'} > 1.56 \text{TeV}$
Pair production of heavy, 4th generation $b'$. Each $b' \rightarrow tW \rightarrow bWW$

Distinctive events.
Selected based on leptons, $N_{\text{jets}}$, and

Similar to new Tevatron limit: $m_{b'} > 385 \text{GeV}$
Excited lepton search

Experimental signature
• Two isolated electrons/muons of opposite charge
• Isolated photon ($\Delta R(\gamma, l) > 0.5$)

No events observed in signal regions

From data, procedures checked with simulation

Drell-Yan + ISR/FSR: MC w. NLO x-section
High $p_T$ Z boson production

Reference model:
weakly decaying excited quark
- $q^* \rightarrow qZ \rightarrow q\mu^+\mu^-$
- $\Lambda = m_{q^*}$ and $f = f' = 1$

Decay may be rare, but clean
- $< 5\%$ background (top pairs & di-bosons)

Gauge interaction
$$\mathcal{L}_{\text{trans}} = \frac{1}{2\Lambda} f_R^* \sigma^{\mu\nu} \left( g_s f_s \frac{\lambda^a}{2} G^{a\mu\nu} + g f \frac{\tau}{2} W^{\mu\nu} + g' f' \frac{Y}{2} B^{\mu\nu} \right) f_L + h.c.$$  

Contact interaction
$$\mathcal{L}_{\text{contact}} = \frac{g_s^2}{\Lambda^2} \frac{1}{2} j^\mu j_\mu$$

>1.17 TeV for $f_S = 0$
Exceed HERA limit >252 GeV