Searches for Extra Dimensions, Leptoquarks, and Technicolor at the LHC

Rencontres de Moriond

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on behalf of the ATLAS and CMS collaborations
**A Breakthrough in Physics**

ATLAS and CMS jointly announce discovery of Higgs-like particle

**Within the Standard Model:**
Comparison between the direct measurements of $M_W$ and $m_t$ (green) and their indirect determination from a global fit to electroweak precision measurements including the “Higgs” (blue).

Fit p-value = 0.08

Single channel measurements and EW global fit consistent with SM. But convincing?
Open Questions

- Is it the SM Higgs and source of EWSB dynamics?
  - Detailed measurement of properties needed

- Still room for other, Higgs-less, theories that break EW symmetry?
  - Technicolor, composite Higgs, extra-dimensional EWSB

- Other unsolved problems in SM
  - Hierarchy problem: $m_{EW}/M_{Pl} \sim 10^{-16}$
  - Dark matter/energy
  - Matter-antimatter asymmetry
  - Origin of generations …

→ Physics beyond the Standard Model (BSM) well motivated

- Searches for (non-SUSY) physics BSM scenarios in different signatures

  - CMS and ATLAS with ~65 publications each on exotics searches
BSM @ LHC – Extra Dimensional Models

Address hierarchy problem, effective Planck scale lowered to $O(\text{TeV})$

Large ED model (ADD)

- $n$ extra dimensions of size $R$. For gravity only $\to$ weakens gravitational coupling to SM

Reduced Planck scale in $4+n$ dimensions assumed at $O(\text{TeV})$:

$$M_D \sim \sqrt{\frac{R^{-n}}{M_{Pl}^2}}$$

Signatures:

- Direct KK graviton emission plus $g/\gamma$
  $\to$ missing energy and single jet or photon
- Virtual KK graviton exchange, continuous spectrum
  $\to$ Dilepton, diphoton final states, broad excess over SM

Randall-Sundrum (RS1, RS2)

- One extra warped dimension
  RS1: for gravity, RS2 for all SM particles

Scale on weakbrane

$$\Lambda_\pi \sim M_{Pl} e^{-kR\pi}$$

- $k$ – curvature
- $R$ – size of ED

Signatures:

- Virtual KK graviton exchange, narrow separated states
  $\to$ resonant excess over SM prediction
Technicolor (TC)

- Effective theories with a new strong force dynamics to provide mechanism for EWSB
  - No Higgs (composite Higgs state for EWSB), no hierarchy problem
- Bound states: technimesons $\pi_T$, $\rho_T$, $\omega_T$, $a_T$
- Explorable at LHC: Low scale TC (LSTC) and Minimal Walking Technicolor (MWT)
- Search for narrow resonances e.g. in dilepton or diboson final states

Leptoquarks (LQ)

- Color-triplet bosons, couple to leptons and baryons of the same generation
- Masses at GUT scale, some TC models predict LQ at TeV scale
- At LHC: produced in pairs or with associated lepton
  
  ![Diagram of LQ production]

- LQ signature: high $p_T$ leptons, $E_T$ jets, missing $E_T$
Resonant Di-Boson Production

- Many SM extensions predict the existence of heavy resonances decaying to pairs of electroweak gauge bosons
  - $W'$ in the Extended Gauge Model (EGM)
  - Technimesons (LSTC)
  - RS graviton

Charged ($WZ/\gamma$)
- $W'$ (spin 1)
  - Triple gauge coupling $W'WZ$
  - Fermionic coupling like $W$

- $\rho_T$ (spin 1), $a_T$ (spin 0)

Neutral ($WWZZ/\gamma\gamma$)
- RS graviton (spin 2)
Search for resonant ZZ production in $Z \rightarrow llqq \ (l=e/\mu)$

**Signal selection**

**Leptons:**
- Above 25 GeV (20 GeV for subleading)
- Fiducial constrains, Lepton ID, isolated from hadronic activity, origin PV
- Invariant mass near $M_Z$

**Jets:**
- anti-kt algorithm ($R = 0.4$)
- $p_T > 30$GeV, contained in tracking volume

**Two signal regions to treat jet-jet overlap**
- *Resolved:* $p_T(ll) > 50$GeV
  - Two leading jets: $\Delta \phi_{jj} < 1.6$, $65 < m_{jj} < 115$ GeV
- *Merged:* $p_T(ll) > 200$GeV
  - Leading jet: $p_T(j) > 200$GeV, $m_j > 40$ GeV

Only the green jet is considered $m_{\mu\mu} = 2.9$ TeV, the red is outside the tracking volume
Search for resonant ZZ production

- **Backgrounds**
  - Z+jets
  - Irreducible non-resonant WW/WZ/ZZ
  - ttbar (real leptons, different kinematics)

- Cross check: data compared with MC simulation, after resolved (merged) signal selection is applied

- Parameterized background estimate

\[
f(m; p_{0,1,2,3}) = p_0 \frac{(1 - x)^{p_1}}{x^{p_2 + p_3 \ln(x)}}
\]

- Use of BumpHunter algorithm (arxiv: 1101.0390) to test for the presence of a resonant signal and fit with the smooth background hypothesis
Search for resonant ZZ production – Bulk G* limits

No signal feature observed

Combination uses resolved (merged) selection below (above) 1 TeV, as the expected limits are better in the respective regions.

Limits on bulk RS G* with $\kappa/m_{Pl} = 1.0$

Upper limit on $\sigma(pp\rightarrow G^*) \times \text{BR}(G^* \rightarrow ZZ)$

Lower limit $m_{G^*}$: 850 GeV @ 95% C.L.
Search for resonant WZ production

WZ→ lνll signal selection (l=e,m)

- **Z:**
  - 2 leptons \( p_T > 25 \text{ GeV} \)
    - Fiducial, isolation, PV, lepton ID
  - \( |m_{ll} - m_Z| < 20 \text{ GeV} \)

- **W:**
  - Lepton with \( p_T > 25 \text{ GeV} \)
  - \( E_T^{\text{miss}} > 25 \text{ GeV} \)
  - \( m_T^W = \sqrt{2p_T^{\ell} E_T^{\text{miss}}(1 - \cos \Delta \phi)} < 100 \text{ GeV} \)
    (suppresses events with poor \( E_T^{\text{miss}} \))

- **Non-resonant WZ background suppression**
  - \( \Delta y(W,Z) < 1.8 \) and \( \Delta \phi(W,Z) > 2.6 \)

- **Understanding pileup is crucial**
  - Track based pileup suppression
  - Pileup overlay in MC

**Average pileup per bunch for 7/8 TeV**

Understanding pileup is crucial for missing ET.

**ETmiss resolution vs Number Primary Vtx**

Pileup suppression based on tracks from vertex. Minimum bias events are added to MC.
Search for resonant WZ production - Backgrounds

- Diboson background ($ZZ$, $WZ$, $Z\gamma$, $W\gamma$) estimated from MC
  - Corrected with lepton data/MC scale factors, normalized to luminosity

- Fake leptons from $ll+jets$ processes ($Z+jets$, $ttbar$, $Wt$) estimated from data
  - Di-jet enriched sample to measure lepton-fake factor $f$
    - $f =$ ratio between bad (loose) and good (tight) quality leptons
    - $f$ is applied to samples with two good and one bad quality lepton

- Two control regions with modified signal selection
  - $WZ$ control region: $\Delta y(W,Z) > 1.8$ and $\Delta\phi(W,Z) < 2.6$
  - $Z+jet$ control region: $E_T^{miss} < 25$ GeV, $m_T^W < 25$ GeV

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**Diboson background validation**

**Fake lepton background validation**
Search for resonant WZ production – Result

~ no significant excess observed

\[ p_T^Z \text{ spectrum: MC-data comparison after signal selection} \]

\[ M_{WZ} \text{ spectrum: MC-data comparison after signal selection} \]

- Predicted W' and $\rho_T$ sample signals for illustration

3/10/13  J.Stelzer - Exotics Searches
Search for resonant WZ production – W’ and \( \rho_T \) Limits

- **Upper limits on \( \sigma \times \text{BR} \)**

- **W’ in EGM**
  
  \( pp \rightarrow W' \rightarrow WZ \)

  Lower EGM W’ mass limit
  
<table>
<thead>
<tr>
<th>Expected</th>
<th>1300 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>1180 GeV</td>
</tr>
</tbody>
</table>

- **Low scale TC**

  \( pp \rightarrow \rho_T \rightarrow WZ \) (assuming W’-like kinematics)

  Lower \( \rho_T \) mass limit
  
  \[
  m_{aT} = 1.1 m_{\rho_T} \quad 920 \text{ GeV} \\
  m_{aT} \gg m_{\rho_T} \quad 920 \text{ GeV}
  \]

  Benchmark parameterization:
  
  \[ m_{\rho_T} = m_{\pi_T} + m_W, \sin \chi = 1/3 \]
Non-resonant dilepton searches – ADD Theory

- Broad enhancement at large $M_{ll}$ over the SM prediction

- Dilepton event selection and background estimate follows $Z'$ analysis
  - See talk of Sam Harper this morning
  - Good MC-data agreement in control regions $M_{ll} < 1.8$ TeV

- Signal LO cross-section
  - UV cut off imposed at $\Lambda$ to avoid divergences when summing over KK modes
  - Two possible parameterizations:
    - GRW: single parameter $\Lambda_T$
    - HLZ: $n$ and $M_s(\Lambda)=M_{Pl}(4+n)$

- ADD signal modeled using templates $\Lambda_T \in [1.6, 5.2]$ TeV
  - Integrate over signal region $M_{ll} \in [1.8, 8]$ TeV

CMS-PAS-EXO-12-027
CMS-PAS-EXO-12-031
Non-resonant dilepton searches – Limits on $\sigma \times \text{BR}$ and $\Lambda_T$

- **GRW parameterization**
  
- **HLZ parameterization**
  - Assume different ranges of validity, no signal contribution beyond $M_{\text{max}}$

### Upper limits on $\sigma \times \text{BR}$ ($pp \rightarrow G_{KK} \rightarrow \mu\mu$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>n=2</th>
<th>n=3</th>
<th>n=4</th>
<th>n=5</th>
<th>n=6</th>
<th>n=7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$</td>
<td>0.25 fb</td>
<td>0.19 fb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ee</td>
<td>0.25 fb</td>
<td>0.19 fb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>combined</td>
<td>0.25 fb</td>
<td>0.19 fb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Lower limits on $M_S$ vs UV cutoff

<table>
<thead>
<tr>
<th>Channel</th>
<th>M_S [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$</td>
<td>3.69 4.49 3.77 3.41 3.17 3.00</td>
</tr>
<tr>
<td>ee</td>
<td>3.99 4.77 4.01 3.63 3.37 3.19</td>
</tr>
<tr>
<td>combined</td>
<td>4.35 4.94 4.15 3.75 3.49 3.30</td>
</tr>
</tbody>
</table>
Evolution of $M_S$ limits

- CMS combination of $e\bar{e}$ and $\mu\bar{\mu}$ channel compared to previous results

Comparison of current CMS limits with previous results

- CMS Preliminary

Limit on $M_S$ [TeV]

$M_S$ limits for different channels and experiments, including CMS, Atlas, and DØ.
Reconstruction, signal selection (ATLAS)
- High momentum central jet
- Missing $E_T$ (separated from any second jet)
- Lepton veto to suppress EW and top background
- Four signal regions SR1, …, SR4:
  $M_{ET}$ and jet $p_T > (120, 220, 350, 500)$ GeV

Data driven background estimation
- $Z/W+$jets, ttbar, diboson
  - Simulated distributions bin-by-bin corrected using data-derived control regions ($Z+$jets, $W+$jets)
- QCD multi-jet estimated from jets-enriched data control samples
Comparison of data to the SM backgrounds predictions.

ADD signal illustrated

\[ p_T \text{ spectrum for Signal Region 3} \]

\[ \text{Comparison of data to the SM backgrounds predictions.} \]

\[ \text{ADD signal illustrated} \]

\[ \sim \text{ no significant excess observed} \]
### ATLAS

Upper limits on $\sigma \times A \times \epsilon$ (pp → jet+$G_{KK}$)

### CMS

<table>
<thead>
<tr>
<th>n extra dim.</th>
<th>LO 95% CL observed limit on $M_D$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5.10</td>
</tr>
<tr>
<td>3</td>
<td>3.94</td>
</tr>
<tr>
<td>4</td>
<td>3.44</td>
</tr>
<tr>
<td>5</td>
<td>3.10</td>
</tr>
<tr>
<td>6</td>
<td>2.94</td>
</tr>
</tbody>
</table>

Evolution of lower limits on $M_D$
High-Mass Resonances – RS G* Limits

- Dilepton resonance search at ATLAS (Sam Harper’s talk)
- Dijet resonance search at CMS (John Paul Chou’s talk)

\[ \sim \text{no significant excess observed} \]

CMS G* → gg/qq: \( m_{G^*} > 1.58 \text{ TeV} \) (\( k/M_{Pl} = 0.1 \))

ATLAS G* → ll: \( m_{G^*} > 2.47 \text{ TeV} \) (\( k/M_{Pl} = 0.1 \))

<table>
<thead>
<tr>
<th>Event Channel</th>
<th>Observed mass limit [TeV]</th>
<th>Expected mass limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G^* \rightarrow e^+e^- )</td>
<td>2.40</td>
<td>2.39</td>
</tr>
<tr>
<td>( G^* \rightarrow \mu^+\mu^- )</td>
<td>2.08</td>
<td>2.14</td>
</tr>
<tr>
<td>( G^* \rightarrow \ell^+\ell^- )</td>
<td>2.47</td>
<td>2.47</td>
</tr>
</tbody>
</table>

[Image of CMS Preliminary and RS Graviton graphs]

[Image of ATLAS plot for G* → ll]
New results on 7 TeV data

- LSTC Limits from $W \gamma$ and $Z \gamma$ from ATLAS with 4.6 fb$^{-1}$ at $\sqrt{s} = 7$ TeV
  - $m_{\omega_T} > 494$ GeV @ 95% C.L.
  - $m_{a_T} > 703$ GeV @ 95% C.L.

- 3rd Generation Scalar Leptoquarks from ATLAS with 4.7 fb$^{-1}$ at $\sqrt{s} = 7$ TeV
  - $M_{LQ} > 534$ GeV @ 95% C.L.
ATLAS and CMS study many signatures to look for physics beyond the SM

- Presented searches for signatures ADD and RS ED models, LSTC model, and LQ
- No significant excess above SM prediction observed
- Set stronger limits on $\sigma \times BR$ and on the masses of new particles

First analyses using full 8 TeV data are becoming public

- Stay tuned for updates on the large number of searches
BACKUP
Diphoton searches

- Looking for KK gravitons in $pp \rightarrow G^* \rightarrow \gamma\gamma$

4.9 fb$^{-1}$
$\sqrt{s} = 7$ TeV
ATLAS
RS G* exclusion limits with ll and gg combined

- Combination of dilepton channel result with γγ channel for RS G* search.
- Diphoton channel has twice higher BR