Searches for Beyond the Standard Model Physics at ATLAS

Carlo Dallapiccola
University of Massachusetts
Exotic Searches for Beyond the Standard Model Physics at ATLAS

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Motivation for expectation of physics Beyond the Standard Model (BSM) rather familiar
Introduction: Theoretical Motivation

Motivation for expectation of physics Beyond the Standard Model (BSM) rather familiar

No striking, unambiguous evidence for BSM physics
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Compelling reasons, however, for expecting it to be within reach....
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**Compelling reasons, however, for expecting it to be within reach....**
Motivation for expectation of physics Beyond the Standard Model (BSM) rather familiar

No striking, unambiguous evidence for BSM physics

Compelling reasons, however, for expecting it to be within reach....

- Stability of the electroweak scale (hierarchy)
- Dark matter
- Neutrino masses
- Flavor puzzle
Supersymmetry

- Hierarchy problem
- Dark matter
- Unify couplings

- Heavy superpartners
- Light neutral Higgs

- 126 more parameters
Supersymmetry

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Extra Dimensions

- Hierarchy problem
- Dark matter
- Unify couplings

- TeV-scale gravity
- KK graviton decays
- Black holes, string balls

- Few parameters
Supersymmetry

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- Few parameters

Strong Dynamics

- Hierarchy problem
- Dark matter
- New heavy gauge bosons (W', Z')
- Composite Higgs
- 4th generation quarks
- Few parameters
Solutions: New BSM Physics

**Supersymmetry**
- Hierarchy problem
- Dark matter
- Unify couplings
- Heavy superpartners
- Light neutral Higgs
- 126 more parameters

**Extra Dimensions**
- Hierarchy problem
- Dark matter
- Unify couplings
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- Few parameters

**Strong Dynamics**
- Hierarchy problem
- Dark matter
- New heavy gauge bosons (W', Z')
- Composite Higgs
- 4th. generation quarks
- Few parameters

**Hidden Valley**
- Framework for various models
- Heavy messenger (Z', H)
- Displaced vertices

C. Dallapiccola
JETP Seminar, FNAL, 11 May 2012
Univ. of Massachusetts
Experimental Tools: the LHC
### Experimental Tools: the LHC

<table>
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<tr>
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Results using 1-5 fb$^{-1}$ integrated luminosity
Searches Covered Here

Lots of ground to cover

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: March 2012)

*Only a selection of the available mass limits on new states or phenomena shown
Searches Covered Here

Lots of ground to cover

- Searches bit off beaten path (not always covered)
- Analyses close to things my group works on
- Analyses that emphasize strong points of ATLAS
- Benchmark analyses

**Signature based searches**

Model-indep. fiducial cross section limits + limits on model params

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Extra Spatial Dimensions

Varieties
- Universal extra dim (UED)
- Single large warped dim (RS)
- Compact large dim (ADD)

Phenomena
- KK towers of SM particles
- KK gravitons
- Quantum gravity (string ball)
- Classical mini black holes

Signatures
- Monojet (ADD graviton)
- Dijet (QBH)
- Multijet (ADD BH)
- Multijet+lepton (ADD BH)
- Diphoton (ADD/RS graviton, UED)
- Dimuon (ADD BH)
- Dilepton (RS graviton)
- Ditop (RS KK gluon)
- Diboson (RS graviton)
Extra Dimensions (ED) II: TeV-Scale Gravity

Gravity $\Rightarrow$ Higher Dimensional (4+n) Bulk

SM Fields $\Rightarrow$ 4-d Brane
ADD: Extra dim. \((n = 2-6)\) periodic

- Massive KK gravitons \(\rightarrow\) small \(\Delta m\), \(~\text{continuum of states}\)
- Production: \(jet + G^*\) (missing \(E_T\))
- Decay: \(G^* \rightarrow qq'/\gamma\gamma/\ell^+\ell^-\)
- Black Holes for \(\sqrt{s} \geq M_D\)

Phenomenology characterized by \(n\) and \(M_D\)
Extra Dimensions (ED) II: TeV-Scale Gravity

Gravity $\Rightarrow$ Higher Dimensional (4+n) Bulk

SM Fields $\Rightarrow$ 4-d Brane

**ADD:** Extra dim. ($n = 2-6$) periodic

- Massive KK gravitons $\rightarrow$ small $\Delta m$, $\sim$continuum of states
- Production: jet + $G^*$ (missing $E_T$)
- Decay: $G^* \rightarrow qq'/\gamma/\ell^+\ell^-$
- Black Holes for $\sqrt{s} \gtrsim M_D$
  - Phenomenology characterized by $n$ and $M_D$

$$\mathcal{M}^2_{Pl} = M_D^{n+2} R^n$$

$\sim 10^{16}$ TeV

**RS:** Extra warped dim. ($n = 1$) bound by SM/Planck branes

- Massive KK gravitons $\rightarrow$ large $\Delta m$, $\sim$narrow resonances
- Decay: $G^* \rightarrow \gamma/\ell^+\ell^-$
- Characterized by $k/M_{Pl}$ ($k \approx 0.1 * M_{Pl}$ is “warp factor”) and $M_G$
Graviton Searches
Trigger: $E_T^{miss} > 60 \text{ GeV}$

Selection:
- Reject events with e or $\mu$
- Leading jet $p_T > 250 \text{ GeV}$
- No other jet with $p_T > 60 \text{ GeV}$
- $E_T^{miss} > 220 \text{ GeV}$

Backgrounds:
- $Z (\rightarrow \nu\bar{\nu}) + \text{jets}$
- $W (\rightarrow \ell\bar{\nu}) + \text{jets}$
Extra Dimensions: Monojets (1 fb⁻¹)

**Trigger:** \(E_T^{miss} > 60\) GeV

**Selection:**
- Reject events with \(e\) or \(\mu\)
- Leading jet \(p_T > 250\) GeV
- No other jet with \(p_T > 60\) GeV
- \(E_T^{miss} > 220\) GeV

**Backgrounds:**
- \(Z (\rightarrow \nu\bar{\nu}) + \) jets
- \(W (\rightarrow \ell\nu) + \) jets

<table>
<thead>
<tr>
<th>Number ADD ED ((n))</th>
<th>(M_D) Lower Limit 95% CL ((\text{TeV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td>3</td>
<td>2.6</td>
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<tr>
<td>4</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>2.1</td>
</tr>
<tr>
<td>6</td>
<td>2.0</td>
</tr>
</tbody>
</table>
**Trigger:** \( \geq 2e, E_T > 20 \text{ GeV} \)
\( \geq 1\mu , p_T > 22 \text{ GeV} \)

**Selection:**
- Oppositely charged, isolated \( e/\mu \)
- \( E_T(p_T) > 25 \ (25) \text{ GeV} \)
- \( E_T(p_T) \) res. \( 1-2\% \ (10-25\%) \) at 1 TeV
- Signal efficiency 72\% (47\%)

**Background:**
- Drell-Yan dileptons

\[ \sigma \times \text{BF} \text{ v/s Mass} \]

\[ \sigma \times \text{BF} \text{ v/s Mass} \]
**Trigger:** ≥ 2e, \( E_T > 20 \text{ GeV} \)  
≥ 1μ, \( p_T > 22 \text{ GeV} \)

**Selection:**
- Oppositely charged, isolated e/μ  
- \( E_T (p_T) > 25 (25) \text{ GeV} \)
- \( E_T (p_T) \) res. 1-2% (10-25%) at 1 TeV  
- Signal efficiency 72% (47%)

**Background:**
- Drell-Yan dileptons

\[ \begin{array}{|c|c|} 
\hline
k/M_{Pl} & M_G > (\text{TeV}) 95\% \text{ CL} \\
\hline
0.01 & 0.9 \\
0.03 & 1.4 \\
0.05 & 1.7 \\
0.1 & 2.2 \\
\hline
\end{array} \]
Extra Dimensions: Diphotons (2.1 fb⁻¹)

Trigger: ≥ 2 photons  
\( E_T > 20 \text{ GeV} \)

Selection:
- At least two isolated photons
- Two leading photons taken: \( E_T > 25 \text{ GeV} \)

Background:
- SM diphoton, photon-jet
Extra Dimensions: Diphotons (2.1 fb⁻¹)

Trigger: ≥2 photons  
\( E_T > 20 \text{ GeV} \)

Selection:
• At least two isolated photons
• Two leading photons taken:  
  \( E_T > 25 \text{ GeV} \)

Background:
• SM diphoton, photon-jet

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<tr>
<th>No. ED (n)</th>
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<tr>
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</tr>
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<td>2.4</td>
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\( M_S = \text{Ultraviolet cutoff (} \sim M_D \text{) } \)

\[ k/M_{Pl} \text{ v/s } M_G \]

\[ \sigma \times \text{BF v/s Mass} \]
Extra Dimensions: Diphotons (2.1 fb\(^{-1}\))

**Trigger:** \(\geq 2\) photons 
\(E_T > 20\) GeV

**Selection:**
- At least two *isolated* photons
- Two leading photons taken: 
\(E_T > 25\) GeV

**Background:**
- SM diphoton, photon-jet

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\(M_S =\) Ultraviolet cutoff (~\(M_D\))

\(k/M_{Pl}\) v/s \(M_G\)

\(\sigma\) BF v/s Mass

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<tr>
<th>(k/M_{Pl})</th>
<th>(M_G &gt; (\text{TeV})) 95% CL</th>
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<tr>
<td>0.01</td>
<td>0.8</td>
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<tr>
<td>0.03</td>
<td>1.4</td>
</tr>
<tr>
<td>0.05</td>
<td>1.6</td>
</tr>
<tr>
<td>0.1</td>
<td>2.0</td>
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</table>

Results combined with dileptons (~1 fb\(^{-1}\))
**Extra Dimensions: Ditop (2 fb⁻¹)**

**Trigger:** \( \geq 1 \text{e}, E_T > 22 \text{ GeV} \)
\( \geq 1 \mu, p_T > 18 \text{ GeV} \)

**Selection:**
- Only one isolated e/\(\mu\), \(\geq 1\) b-jet
- Lepton \(E_T(p_T) > 25\) (25) GeV
- At least 3 jets (\(p_T > 25\) GeV)
- Jet \(p_T(\text{lead}) > 60\) GeV
- \(E_T\text{miss} > 35\) (20) GeV

**Backgrounds:**
- SM \(tt\bar{t}\)
- \(W+\text{jets}\)

---

**Graphs and Plots:**
- ATLAS Preliminary: Event distributions for different masses.
- ATLAS Preliminary: Mass distribution for different \(m_{\text{jj}\ell}\) values.
- ATLAS Preliminary: Observation of 95% CL upper limit on \(\sigma \times \text{BR}(g_{KK} \rightarrow t\bar{t})\) for different \(g_{KK}\) masses.

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**Trigger:** $\geq 1e, E_T > 22\,\text{GeV}$
$\geq 1\mu, p_T > 18\,\text{GeV}$

**Selection:**
- Only one isolated $e/\mu, \geq 1\text{b-jet}$
- Lepton $E_T (p_T) > 25\,(25)\,\text{GeV}$
- At least 3 jets ($p_T > 25\,\text{GeV}$)
- Jet $p_T(\text{lead}) > 60\,\text{GeV}$
- $E_T^{\text{miss}} > 35\,(20)\,\text{GeV}$

**Backgrounds:**
- SM $ttbar$
- $W+$jets

Exclude RS KK gluons (95% CL):
$500 < M(g_{KK}) < 1025\,\text{GeV}$
Black Hole Search
parton-parton collisions at TeV scale $\Rightarrow$ strong gravity at TeV scale $\Rightarrow$ black hole?

Two scales: $M_D$ (Planck) < $M_{th}$ (threshold for classical BH production)

- Excited string state (“string ball”) $\rightarrow$ thermal
- “Quantum black hole” $\rightarrow$ few emissions

- Classical black hole $\rightarrow$ thermal
- Hawking radiation $\rightarrow$ many emissions
- High $p_T$ for each emission
- Gravity couples democratically
- Leptons in relatively large fraction ($\approx 20\%$)

High multiplicity

High energy particles

Jet $p_T$

Lepton $p_T$
**Trigger:** single **electron** \((E_T > 20 \text{ GeV})\) or single **muon** \((p_T > 18 \text{ GeV})\)

**Preselection:** \(\geq 1\) isolated lepton \((p_T > 40 \text{ GeV})\) and \(\geq 2\) additional obj. (lepton or jet) \((p_T > 40 \text{ GeV})\)

\[\sum p_T > 300 \text{ GeV} \]  (sum over objects w/ \(p_T > 40 \text{ GeV}\))

\[\int L \, dt = 1.04 \text{ fb}^{-1}\]

**e channel**

**μ channel**
Black Hole Search: (Control and Signal Regions)

**Signal:** High $p_T$ leptons and jets (> 100 GeV)  High $\sum p_T$ (> 700 GeV)

**Backgrounds:** $W(\rightarrow \ell \nu)$+jets  top  QCD multijet (e)  $Z(\rightarrow \ell \ell)$+jets

**Control regions (CR)**
- No overlap with signal (SR)
- Kinematically similar to SR
- Sufficiently large statistics
- Enhance individual bkgd.
- Compare data to MC in CR

$$\sum p_T < 700 \text{ GeV}$$
$$\text{Object } p_T < 40 \text{ GeV}$$
$$\sum p_T > 300 \text{ GeV}$$

**single/dilepton (W/Z)**

Scale Factor (electron) : $0.93 \pm 0.02 \pm 0.13$
Scale Factor (muon) : $1.05 \pm 0.02 \pm 0.13$

Scale Factor (electron) : $0.93 \pm 0.03 \pm 0.08$
Scale Factor (muon) : $0.85 \pm 0.04 \pm 0.14$
Reference Signal Models:

**Black Hole**
- $M_D = 0.8 \text{ TeV}$
- $M_{TH} = 4 \text{ TeV}$
- $n = 6$

**String Ball**
- $M_S = 1 \text{ TeV}$
- $M_D = 1.26 \text{ TeV}$
- $M_{TH} = 3 \text{ TeV}$
- $n = 6$

**Signal Regions:**

- $\sum p_T > 700 \text{ GeV}$
  - > 800
  - > 900
  - > 1000
  - > 1200
  - > 1500
Black Hole Search: Results (1 fb⁻¹)

Electron Channel

<table>
<thead>
<tr>
<th>$\sum p_T$ (GeV)</th>
<th>QCD</th>
<th>$W+\text{jets}/tt$</th>
<th>$Z+\text{jets}$</th>
<th>Total SM</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 700</td>
<td>137 ± 10 ± 45</td>
<td>371 ± 10 ± 77</td>
<td>119 ± 4 ± 22</td>
<td>627 ± 15 ± 92</td>
<td>586</td>
</tr>
<tr>
<td>&gt; 800</td>
<td>75 ± 7 ± 25</td>
<td>210 ± 6 ± 42</td>
<td>74 ± 4 ± 13</td>
<td>358 ± 10 ± 51</td>
<td>348</td>
</tr>
<tr>
<td>&gt; 900</td>
<td>42 ± 5 ± 14</td>
<td>122 ± 5 ± 28</td>
<td>46.9 ± 2.8 ± 8.6</td>
<td>210 ± 8 ± 33</td>
<td>196</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>24.6 ± 4.2 ± 8.0</td>
<td>73 ± 3 ± 17</td>
<td>22.2 ± 1.8 ± 4.5</td>
<td>119 ± 5 ± 20</td>
<td>113</td>
</tr>
<tr>
<td>&gt; 1200</td>
<td>8.1 ± 2.5 ± 2.7</td>
<td>28.5 ± 1.8 ± 7.6</td>
<td>9.1 ± 1.0 ± 1.9</td>
<td>45.7 ± 3.2 ± 8.3</td>
<td>41</td>
</tr>
<tr>
<td>&gt; 1500</td>
<td>1.3 ± 1.1 ± 0.4</td>
<td>6.3 ± 0.8 ± 2.5</td>
<td>2.6 ± 0.5 ± 0.5</td>
<td>10.2 ± 1.4 ± 2.6</td>
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Muon Channel

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<th>$\sum p_T$ (GeV)</th>
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<tr>
<td>&gt; 700</td>
<td>236 ± 7 ± 43</td>
<td>49 ± 3 ± 11</td>
<td>285 ± 8 ± 44</td>
<td>241</td>
</tr>
<tr>
<td>&gt; 800</td>
<td>129 ± 4 ± 25</td>
<td>32.0 ± 2.4 ± 7.5</td>
<td>161 ± 5 ± 26</td>
<td>145</td>
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<tr>
<td>&gt; 900</td>
<td>71 ± 3 ± 16</td>
<td>19.5 ± 1.7 ± 5.0</td>
<td>91 ± 3 ± 16</td>
<td>78</td>
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<tr>
<td>&gt; 1000</td>
<td>38.9 ± 2.3 ± 8.3</td>
<td>13.1 ± 1.3 ± 3.1</td>
<td>52.0 ± 2.6 ± 8.9</td>
<td>46</td>
</tr>
<tr>
<td>&gt; 1200</td>
<td>9.9 ± 1.2 ± 3.6</td>
<td>4.0 ± 0.6 ± 1.2</td>
<td>14.0 ± 1.3 ± 3.8</td>
<td>15</td>
</tr>
<tr>
<td>&gt; 1500</td>
<td>2.2 ± 0.5 ± 1.1</td>
<td>0.6 ± 0.2 ± 0.4</td>
<td>2.8 ± 0.5 ± 1.1</td>
<td>2</td>
</tr>
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Largest systematics (top/$W+\text{jets}$): Generator, PDF choice, jet energy scale → associated with extrapolation from CR to SR
95% CL upper limit (model independent) cross section * acceptance

\[ \text{Exclude } \sigma > 16.7 \text{ fb} \text{ (for } \sum p_T > 1.5 \text{ TeV)} \]

\[ n = 6 \]
Quantum Black Holes: Dijets (4.8 fb$^{-1}$)

**Trigger:** $\geq 1$ high $p_T$ jet (some prescaled)

**Selection:**
- At least two jets
- No jets with $p_T > 0.3^* p_T_{(subleading)}$
- Jet rapidities in regions of uniform acceptance

**Background:**
- QCD multijets
Quantum Black Holes: Dijets (4.8 fb$^{-1}$)

**Trigger:** $\geq 1$ high $p_T$ jet (some prescaled)

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</tr>
<tr>
<td>7</td>
<td>4.2</td>
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Hidden Valley
Large class of theories have a **hidden sector** (no SM charges) at **low mass scale** → “hidden valley” (HV)

Very weak coupling between HV and SM (not copious)
- Mediator → new gauge symmetry ($Z'$)
  → Higgs
- Large mediator mass (>100 GeV) → SM-HV interactions weak at low energies, but within LHC reach

Content of HV? Example: Strongly-interacting HV quarks
- HV quarks hadronize
- HV hadrons → cascade decay to lightest HV hadron
- Lightest HV hadrons ($\pi_v$) → decay to SM particles

**Experimental Signature**
- **Very displaced vertices** (long-lived $\pi_v$)
- High multiplicity of soft particles in the resulting jet
Searching for high-multiplicity vertices within the muon spectrometer

Standalone tracking with 3 layers of muon stations in toroidal magnetic field
Search for $h \rightarrow \pi_{\nu} \pi_{\nu}$ with both $\pi_{\nu}$ decaying within the muon spectrometer ($4 < R < 7m$)

Model Parameters

- $M(h) = 120, 140$ GeV
- $M(\pi_{\nu}) = 20, 40$ GeV
- Lifetime $\pi_{\nu} = 1-20$ m

Production/Decay Characteristics

- Cross section $\sim 12-17$ pb
- $\sim 10$ low $p_T$ charged hadrons, $\sim 5 \pi^0$
- Two vertices back-to-back

Acceptance v/s decay length

Expected events for 1.94 fb$^{-1}$
Muon RoI Cluster Trig

- > 2 RoI in cone $\Delta R<0.4$
- Isolated wrt leptons and ID tracks
- Barrel only: $|\eta| < 1$

$\pi_\nu$ decay just outside HCAL (MC)
**Muon RoI Cluster Trig**

- > 2 RoI in cone $\Delta R < 0.4$
- Isolated wrt leptons and ID tracks
- Barrel only: $|\eta| < 1$

### Vtx. Eff. v/s $r$

### $r_{\text{true}} = r_{\text{reco}}$
**Background:** Calculate directly from data, from measurement of probability random event will have an MS vertex (~10^{-8} from zero bias data) and probability to reconstruct event, given there was an RoI trigger (~10^{-2}).

Predicted background: \( N_{\text{fake}} = 0.03 \pm 0.02 \)

Observed events in data (1.94 fb^{-1}) : 0

Set limits on production cross section, as fraction of SM Higgs production cross section, as function of proper lifetime of the \( \pi_v \)

<table>
<thead>
<tr>
<th>( m_{h_0} ) (GeV)</th>
<th>( m_{\pi_v} ) (GeV)</th>
<th>Excluded Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>20</td>
<td>0.50 &lt; c( \tau ) &lt; 20.65 m</td>
</tr>
<tr>
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The LHC: 2012 and Beyond

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 2012)

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*Only a selection of the available mass limits on new states or phenomena shown.
The LHC: 2012 and Beyond
The LHC: 2012 and Beyond

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: March 2012)

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<th>Mass [TeV]</th>
<th>ATLAS Preliminary</th>
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<tr>
<td>3.2</td>
<td>$M_D$ ($\delta=2$)</td>
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<tr>
<td>3.6</td>
<td>$M_D$ (GRW cut-off)</td>
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<tr>
<td>1.22</td>
<td>Compact scale 1/R (SPS8)</td>
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<tr>
<td>1.95</td>
<td>Graviton mass</td>
</tr>
<tr>
<td>2.16</td>
<td>Graviton mass</td>
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<td>845 GeV</td>
<td>$M_S$ (KK gluon mass)</td>
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<td>10.2</td>
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*Only a selection of the available mass limits on new states or phenomena shown.
## The LHC: 2012 and Beyond

<table>
<thead>
<tr>
<th></th>
<th>2012 performance</th>
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<tbody>
<tr>
<td>Colliding bunches</td>
<td>1331</td>
<td>2808</td>
</tr>
<tr>
<td>Energy</td>
<td>4 TeV x 4 TeV</td>
<td>7 TeV x 7 TeV</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>50 ns</td>
<td>25 ns</td>
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<tr>
<td>Luminosity</td>
<td>$6.8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
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<tr>
<td>Pile-up interactions</td>
<td>~35</td>
<td>~25</td>
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</table>

![Colliding bunches diagram](image-url)
The LHC: 2012 and Beyond

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<td>~25</td>
</tr>
</tbody>
</table>

**ATLAS**

**CMS**

Colliding bunches: 1331 vs. 2808

- Energy: 4 TeV x 4 TeV vs. 7 TeV x 7 TeV
- Bunch spacing: 50 ns vs. 25 ns
- Luminosity: $6.8 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ vs. $10^{34}$ cm$^{-2}$ s$^{-1}$
- Pile-up interactions: ~35 vs. ~25

**ATLAS Online Luminosity**

- $\sqrt{s} = 8$ TeV
- Total Delivered: 1.06 fb$^{-1}$
- Total Recorded: 0.98 fb$^{-1}$

**Total Integrated Luminosity [fb$^{-1}$]**

- Day in 2012:
  - 26/03
  - 02/04
  - 09/04
  - 16/04
  - 23/04
  - 30/04
  - 07/05

**Univ. of Massachusetts**
### The LHC: 2012 and Beyond

#### 2012 performance vs. Design performance

<table>
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<tr>
<th>Parameter</th>
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<th>Design performance</th>
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<tr>
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<tr>
<td>Pile-up interactions</td>
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<td>~25</td>
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#### ATLAS Online Luminosity

- **LHC Delivered**: 1.06 fb\(^{-1}\)
- **ATLAS Recorded**: 0.98 fb\(^{-1}\)

### W.J. Stirling, private communication

- ratios of LHC parton luminosities: 8 TeV / 7 TeV, 10 TeV / 7 TeV and 14 TeV / 7 TeV

---

### Graph

- **g\(g\)**
- **\(\Sigma qq\)**

---

**MSTW2008NLO**