10. Other Extensions of the Standard Model

10.1 Introduction to Grand Unified Theories

10.2 Leptoquarks

10.3 Additional Gauge bosons, $W'$ and $Z'$ searches

10.4 Compositeness and excited quarks

10.5 Extra Space dimensions
Why Physics Beyond the Standard Model?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accommodated

3. Many open questions in the Standard Model
   - Hierarchy problem: \( m_W \) (100 GeV) \( \rightarrow \) \( m_{\text{Planck}} \) (10\(^{19}\) GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

All this calls for a more fundamental theory of which the Standard Model is a low energy approximation \( \rightarrow \) New Physics

Candidate theories: Supersymmetry
Extra Dimensions
New gauge bosons
……..

Many extensions predict new physics at the TeV scale !

Strong motivation for LHC, mass reach \( \sim 3 \) TeV
10.1 Introduction to Grand Unified Theories (GUT)

- The $SU(3) \times SU(2) \times U(1)$ gauge theory is in impressive agreement with experiment.

- However, there are still three gauge couplings ($g$, $g'$, and $\alpha_s$) and the strong interaction is not unified with the electroweak interaction.

- Is a unification possible?

Is there a larger gauge group $G$, which contains the $SU(3) \times SU(2) \times U(1)$? Gauge transformations in $G$ would then relate the electroweak couplings $g$ and $g'$ to the strong coupling $\alpha_s$.

For energy scales beyond $M_{GUT}$, all interactions would then be described by a grand unified gauge theory (GUT) with a single coupling $g_G$, to which the other couplings are related in a specific way.
Gauge couplings are energy-dependent, $g_2$ and $g_3$ are asymptotically free, i.e. their value decreases with energy, $g_1$ increases with energy.

Figure suggests that for some large energy scale $Q = M_X$ the three couplings merge into a single grand unified coupling $g_G$:

For $Q > M_X$: \[ g_i(Q) = g_G(Q) \]
• Assuming that there exists unification, the known / measured values of the coupling constants at low energy, i.e. at an energy scale \( m \), can be used to estimate the Grand Unification Mass scale \( M_X \).

• The energy dependence of the three couplings is theoretically known, from the renormalization group equations.

Example: running of the strong coupling constant \( \alpha_s \):

\[
\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f) \log(Q^2/\mu^2)}.
\]

This can be written in the form:

\[
\frac{1}{g_3^2(\mu)} = \frac{1}{g_3^2(Q)} + 2b_3 \log \frac{Q}{\mu},
\]

where:

\[
\alpha_s(Q) = \frac{g_3^2(Q)}{4\pi}
\]

and

\[
b_3 = \frac{1}{(4\pi)^2} \left( \frac{2}{3} n_f - 11 \right)
\]
• For $Q = M_X$ and $g_3 = g_G$ follows ($i = 3$):

\[
\frac{1}{g_i^2(\mu)} = \frac{1}{g_G^2} + 2b_i \log \frac{M_X}{\mu}
\]

This relation is valid also for the SU(2) and U(1) gauge groups ($i = 1, 2$). The $b_i$ terms for these gauge couplings are given by (see textbooks):

\[
b_1 = \frac{1}{(4\pi)^2} \left( \frac{4}{3} n_g \right),
\]

\[
b_2 = \frac{1}{(4\pi)^2} \left( -\frac{22}{3} \right) + b_1,
\]

\[
b_3 = \frac{1}{(4\pi)^2} (-11) + b_1,
\]

where $n_g$ is the number of generations
• From these relations and the experimental measurements of the couplings, the mass scale $M_X$ can be calculated.

• Within the Standard Model a mass scale of $M_X \sim 10^{15}$ GeV is obtained, however, the coupling unification is not possible.

…. in contrast to the Supersymmetric extension of the Standard Model assuming a SUSY mass scale at the TeV-scale

for SUSY scenarios: $M_X \sim 10^{16}$ GeV
The SU(5) Model (Georgi, Glashow, ~1980):

• Georgi and Glashow have shown that SU(5) is the smallest gauge group that can contain the SU(3) x SU(2) x U(1) as subgroups (this is also possible for larger gauge groups)

• In SU(5) quarks and leptons are assigned to one multiplet
e.g. in the Standard Model we have 15 left handed states:

\[(u,d)_L, (\nu_e, e^-)_L \text{ (ubar, dbar)_L } e^+_L\]

They are arranged in SU(5) multiplets: \((\text{dbar, } \nu_e, e^-)\) and \((e^+, u, d, \text{ubar})\)

• Transitions between SU(5) multiplets are mediated by new gauge bosons, X and Y

• There should be 24 gauge bosons in total \((N^2 -1)\), i.e. 12 X and Y bosons in addition to the 8 gluons, and 4 el.weak gauge bosons \((W^+, W^-, Z, \gamma)\)

These gauge bosons carry weak isospin, electric charge and colour charge
The SU(5) Model (Georgi, Glashow, ~1980) (cont):

• Transitions mediated by X and Y bosons violate lepton number and baryon number conservation;

\[ u + u \rightarrow X \rightarrow e^+ \bar{d} \bar{u} \]

• At energies \( Q > M_X \) the strong colour force merges with the electroweak force and the sharp separation of particles into coloured quarks and colourless leptons disappears. This leads to lepton / baryon number-violating interactions.

(similar to the unification of the weak and electromagnetic interaction for energy scales \( Q > m_W \), see HERA results on charged and neutral currents)

• This has profound implications: The proton is predicted to decay!
The model has several nice features, among them: it predicts equality of electron and proton charge:

- Charge in each multiplet must be zero

\[ 3 Q_{\text{d bar}} + Q_v + Q_{\text{e-}} = 0 \quad \Rightarrow \quad Q_d = \frac{1}{3} Q_{\text{e-}} \]

2\textsuperscript{nd} multiplet: \( Q_u = -2 Q_d \)

The combined result resolves the mystery of why \( Q_p = -Q_e \)
Can proton decay be detected?

- Similar to the muon lifetime (which depends on $m_W$), the proton lifetime can be estimated:

Estimated lifetime: $M_X = 10^{14}$ GeV $\rightarrow \tau (p) \sim 10^{30}$ years

in SUSY models, lifetime is significantly longer (higher mass scale) $> 10^{32}$ years
Results of experimental searches for proton decay:

(i) Large mass calorimeter detectors

<table>
<thead>
<tr>
<th></th>
<th>KGF</th>
<th>NUSEX</th>
<th>Fréjus</th>
<th>Soudan II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{tot}}$ [t]</td>
<td>140</td>
<td>150</td>
<td>912</td>
<td>1000</td>
</tr>
<tr>
<td>$M_{\text{eff}}$ [t]</td>
<td>60</td>
<td>113</td>
<td>550</td>
<td>600</td>
</tr>
<tr>
<td>Tiefe [m]</td>
<td>2300</td>
<td>1850</td>
<td>1780</td>
<td>760</td>
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<tr>
<td>Wasseräquivalent [m]</td>
<td>7600</td>
<td>5000</td>
<td>4850</td>
<td>1800</td>
</tr>
<tr>
<td>Vertexauflösung [cm]</td>
<td>10</td>
<td>1</td>
<td>0.5</td>
<td>~ 0.5</td>
</tr>
<tr>
<td>Ort</td>
<td>Kolar-Goldmine</td>
<td>Mont-Blanc-Tunnel</td>
<td>Fréjus-Tunnel</td>
<td>Soudan-Erzmine</td>
</tr>
</tbody>
</table>

(ii) Large mass water Cherenkov detectors

<table>
<thead>
<tr>
<th></th>
<th>Kam I (II)</th>
<th>IMB I, III</th>
<th>HPW</th>
<th>Superkam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{tot}}$ [t]</td>
<td>3000</td>
<td>8000</td>
<td>680</td>
<td>50000</td>
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<tr>
<td>$M_{\text{eff}}$ [t]</td>
<td>880 (1040)</td>
<td>3300</td>
<td>420</td>
<td>22000</td>
</tr>
<tr>
<td>Tiefe [m]</td>
<td>825</td>
<td>600</td>
<td>525</td>
<td>825</td>
</tr>
<tr>
<td>Wasseräquivalent [m]</td>
<td>2400</td>
<td>1600</td>
<td>1500</td>
<td>2400</td>
</tr>
<tr>
<td>Vertexauflösung [cm]</td>
<td>100 (20)</td>
<td>100</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Ort</td>
<td>Kamioka-Erzmine</td>
<td>Thielkol-Salzbergwerk</td>
<td>King-Silbermine</td>
<td>Kamioka-Erzmine</td>
</tr>
</tbody>
</table>
Overview on locations of proton decay experiments:
Results:
- so far no evidence for proton decay detected
- limits on lifetime in the order of $10^{32}$ years
  → simple SM + GUT models ruled out
  SUSY + GUT models still alive

<table>
<thead>
<tr>
<th>Proton lifetime lower bounds ($10^{30}$ years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mesonic $\Delta S = 0$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ \pi^0$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+ \pi^0$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \bar{\nu} \pi^+$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ \eta$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+ \eta$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ \rho^0$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+ \rho^0$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \bar{\nu} \rho^+$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ \omega$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+ \omega$</td>
</tr>
<tr>
<td>mesonic $\Delta S \neq 0$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ K^0_S$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ K^0_L$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+ K^0_S$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+ K^0_L$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \bar{\nu} K^+$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ K^0*(892)$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ K^{++}(892)$</td>
</tr>
<tr>
<td>inclusive</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+$ anything</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+$ anything</td>
</tr>
<tr>
<td>radiative</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+ \gamma$</td>
</tr>
<tr>
<td>$p^+ \rightarrow \mu^+ \gamma$</td>
</tr>
<tr>
<td>multi-body</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+e^-e^+$</td>
</tr>
<tr>
<td>$p^+ \rightarrow e^+\pi^0\pi^0$</td>
</tr>
</tbody>
</table>
Results:
- so far no evidence for proton decay detected
- limits on lifetime in the order of $10^{32}$ years
  → simple SM + GUT models ruled out
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The Super-Kamiokande detector began operating in 1996, more than half a mile underground in a zinc mine in Kamioka, Japan. Japanese and American scientists erected a huge tank of water 138 feet tall to hunt for neutrinos and proton decay. The walls, ceiling, and floor of the 12.5-million-gallon tank are lined with 11,242 light-sensitive phototubes. These pick up and measure bluish streaks of light called Cherenkov radiation. Super-Kamiokande detects neutrinos that nuclear interactions in the sun and atmosphere produce.
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10.2 The Search for Leptoquarks

- Leptoquarks are particles that couple to leptons and quarks, motivated by Grand Unified Theories (or any theory that “unifies” quarks and leptons in the same particle multiplet)

- They carry colour charge, weak isopin and electric charge, and are bosons (spin-0 or spin-1)

Example: X and Y bosons in GUTs

- Generalization: Leptoquarks LQ (see classification)
  
  | Bosons:    | spin-0 or spin-1 |
  | el. charge:| -5/3, -4/3, -2/3, -1/3, 1/3, 2/3 |
  | weak isospin: | 0, ½, 1 |

Lepton .and. baryon number ≠ 0
## Leptoquark classification

(Buchmüller, Rückl, Wyler)

### TABLE 1  Leptoquark classification according to electroweak quantum numbers

<table>
<thead>
<tr>
<th>Type</th>
<th>$Q$</th>
<th>Coupling</th>
<th>$\beta$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_0$</td>
<td>$-1/3$</td>
<td>$\lambda_L(e_Lu)$, $-\lambda_L(v_\nu d)$</td>
<td>$1/2$</td>
<td>$2$</td>
</tr>
<tr>
<td>$S_0$</td>
<td>$-1/3$</td>
<td>$\lambda_R(e_Ru)$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
<tr>
<td>$S_0^R$</td>
<td>$-4/3$</td>
<td>$\lambda_R(e_Rd)$</td>
<td>$1$</td>
<td>$2$</td>
</tr>
<tr>
<td>$S^L$</td>
<td>$-4/3$</td>
<td>$\sqrt{2}\lambda_L(e_Ld)$</td>
<td>$1$</td>
<td>$2$</td>
</tr>
<tr>
<td>$S^L$</td>
<td>$-1/3$</td>
<td>$-\lambda_L(e_Lu)$, $-\lambda_L(v_\nu d)$</td>
<td>$1/2$</td>
<td>$2$</td>
</tr>
<tr>
<td>$S^L$</td>
<td>$+2/3$</td>
<td>$\sqrt{2}\lambda_L(v_\nu u)$</td>
<td>$0$</td>
<td>$2$</td>
</tr>
<tr>
<td>$V^L_{1/2}$</td>
<td>$-4/3$</td>
<td>$\lambda_L(e_Ld)$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
<tr>
<td>$V^L_{1/2}$</td>
<td>$-1/3$</td>
<td>$\lambda_L(v_\nu d)$</td>
<td>$0$</td>
<td>$2$</td>
</tr>
<tr>
<td>$V^R_{1/2}$</td>
<td>$4/3$</td>
<td>$\lambda_R(e_Rd)$</td>
<td>$1$</td>
<td>$2$</td>
</tr>
<tr>
<td>$V^R_{1/2}$</td>
<td>$1/3$</td>
<td>$\lambda_R(e_Ru)$</td>
<td>$1$</td>
<td>$2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$S = $ Skulachev LQ

$V = $ Vichi-LQ

$F = $ Fermion Zahl

$F = L + 3B$

$\beta = BR (LQ \rightarrow \chi^\pm q)$

gel. Lepton spec. Modell: $0, 1/2, 1$

i.allg. $0 \leq \beta \leq 1$
Leptoquarks at the electroweak scale?

- Leptoquarks may also be light, with masses on the electroweak scale; (consistent with proton lifetime, if baryon and lepton number are separately conserved)

  allowed decays: \( \text{LQ} \left( -\frac{1}{3} \right) \rightarrow e^- u \), or \( \text{LQ} \left( -\frac{4}{3} \right) \rightarrow e^- d \)
  \( \text{LQ} \left( -\frac{1}{3} \right) \rightarrow \nu_e d \)

  Decays proceed always as: \( \text{LQ} \rightarrow \text{lepton} + \text{quark} \)

Branching ratio \( \beta \):

\[
\beta = \frac{\text{BR} \left( \text{LQ} \rightarrow l q \right)}{\text{charged lepton decay}}
\]

\[
1 - \beta = \frac{\text{BR} \left( \text{LQ} \rightarrow \nu q \right)}{\text{neutral lepton decay}}
\]

\( \beta \) is a free parameter \( (0 \leq \beta \leq 1) \), in general not fixed by the theory

- Leptoquarks (in general form) may enhance flavour-changing neutral currents to suppress these contributions: require that leptoquarks only couple to one generation of fermions

\( \rightarrow \text{LQs \ of \ 1^{st}, 2^{nd}, \ and \ 3^{rd} \ generation} \)
Search for Scalar Leptoquarks (LQ)

- **Production:**
  - pair production via QCD processes (qq and gg fusion)

- **Decay:** into a lepton and a quark

\[ \beta = \text{LQ branching fraction to charged lepton and quark} \]

\[ N = \text{Generation index} \]

Leptoquarks of 1., 2., and 3. generation

- **Experimental Signatures:**
  - Two high \( p_T \) isolated leptons + jets .OR.
  - One isolated lepton + \( E_T^{\text{miss}} \) + jets .OR.
  - \( E_T^{\text{miss}} \) + jets
Results from the ATLAS and CMS searches for leptoquarks

• Require two high $P_T$ leptons and two high $P_T$ jets (ll qq channel)
  .or. one high $P_T$ lepton, $E_T^{\text{miss}}$, and two high $P_T$ jets (l$\nu$ qq channel)

• Additional kinematic requirements:

<table>
<thead>
<tr>
<th>eejj and $\mu\mu jj$</th>
<th>evjj</th>
<th>$\mu\nu jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{ll}$ $&gt;$ 120 GeV</td>
<td>$M_T$ $&gt;$ 200 GeV</td>
<td>$M_T$ $&gt;$ 160 GeV</td>
</tr>
<tr>
<td>$M_{LQ}^{\text{all}}$ $&gt;$ 150 GeV</td>
<td>$M_{LQ}^T$ $&gt;$ 180 GeV</td>
<td>$M_{LQ}^T$ $&gt;$ 150 GeV</td>
</tr>
<tr>
<td>$p_T^{\text{all}}$ $&gt;$ 30 GeV</td>
<td>$M_{LQ}^T$ $&gt;$ 180 GeV</td>
<td>$M_{LQ}^T$ $&gt;$ 150 GeV</td>
</tr>
<tr>
<td>$S_T^\ell$ $&gt;$ 450 GeV</td>
<td>$S_T^{\nu}$ $&gt;$ 410 GeV</td>
<td>$S_T^{\nu}$ $&gt;$ 400 GeV</td>
</tr>
</tbody>
</table>

where $S_T$ is the total scalar sum of the transverse momenta (two leptons and two jets)

• Data, backgrounds and signal expectation (36 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Source</th>
<th>eejj</th>
<th>evjj</th>
<th>$\mu\mu jj$</th>
<th>$\mu\nu jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V+$jets</td>
<td>0.50 ± 0.28</td>
<td>0.65 ± 0.38</td>
<td>0.28 ± 0.22</td>
<td>2.6 ± 1.4</td>
</tr>
<tr>
<td>Top</td>
<td>0.51 ± 0.23</td>
<td>0.67 ± 0.39</td>
<td>0.52 ± 0.23</td>
<td>1.6 ± 0.9</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.03 ± 0.01</td>
<td>0.10 ± 0.03</td>
<td>0.04 ± 0.01</td>
<td>0.10 ± 0.03</td>
</tr>
<tr>
<td>QCD</td>
<td>0.02 ± 0.03</td>
<td>0.06 ± 0.01</td>
<td>0.00 ± 0.01</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>1.1 ± 0.4</td>
<td>1.4 ± 0.5</td>
<td>0.8 ± 0.3</td>
<td>4.4 ± 1.9</td>
</tr>
<tr>
<td>Data</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>LQ(250 GeV)</td>
<td>38 ± 8</td>
<td>9.6 ± 2.1</td>
<td>45 ± 10</td>
<td>13 ± 3</td>
</tr>
<tr>
<td>LQ(300 GeV)</td>
<td>17 ± 4</td>
<td>5.1 ± 1.1</td>
<td>21 ± 5</td>
<td>6.4 ± 1.4</td>
</tr>
<tr>
<td>LQ(350 GeV)</td>
<td>7.7 ± 1.7</td>
<td>2.6 ± 0.6</td>
<td>9.4 ± 2.1</td>
<td>3.0 ± 0.7</td>
</tr>
<tr>
<td>LQ(400 GeV)</td>
<td>3.5 ± 0.8</td>
<td>—</td>
<td>4.4 ± 1.0</td>
<td>—</td>
</tr>
</tbody>
</table>
Example: results of the search for second generation leptonquarks
Final states: \(\text{LQ LQ} \rightarrow \mu \mu j j\)

Left: invariant mass of \(m(\mu_1, j_1), m(\mu_2, j_2)\)

Right: \(S_T := p_T(\mu_1) + p_T(\mu_2) + E_T(j_1) + E_T(j_2)\) scalar sum
Excluded cross sections:

\[ \beta = 1.0 \]
\[ m_{LQ} > 685 \, \text{GeV} \, \text{(95\% C.L.)} \]

\[ \beta = 0.5 \]
\[ m_{LQ} > 594 \, \text{GeV} \, \text{(95\% C.L.)} \]
Excluded regions of parameter space:

\[ \beta = \text{BR}(LQ \rightarrow \mu q) \]

\[ LQ \overline{LQ} \rightarrow \mu\mu jj + \nu\nu jj \]

\[ \int Ldt = 1.03 \text{ fb}^{-1} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ m_{LQ} \text{ [GeV]} \]

ATLAS

\[ \mu\mu jj + \nu\nu jj \text{ (Exp.)} \]

\[ \mu\mu jj + \nu\nu jj \text{ (Obs.)} \]

\[ D0 \text{ (1.0 fb}^{-1}) \]

\[ CMS \text{ (34 pb}^{-1}) \]
## Current mass limits for 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> generation Leptoquarks

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (Run II)</td>
<td>235 GeV/c²</td>
<td>224 GeV/c²</td>
<td>129 GeV/c²</td>
</tr>
<tr>
<td>D0 (Run I + II)</td>
<td>282 GeV/c²</td>
<td>200 GeV/c²</td>
<td></td>
</tr>
<tr>
<td>HERA</td>
<td>699 GeV/c² (λ = 0.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>606 GeV/c² (1 fb⁻¹)</td>
<td>594 GeV/c² (1 fb⁻¹)</td>
<td>534 GeV/c² (4.7 fb⁻¹)</td>
</tr>
<tr>
<td>CMS</td>
<td>845 GeV/c² (19.6 fb⁻¹)</td>
<td>785 GeV/c² (19.6 fb⁻¹)</td>
<td>550 GeV/c² (19.7 fb⁻¹)</td>
</tr>
</tbody>
</table>

\[ \beta = 0.5 \]
LHC reach for other BSM Physics
(expected discovery sensitivity for 30 and 100 fb$^{-1}$ @ 14 TeV)

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>30 fb$^{-1}$</th>
<th>100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excited Quarks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q^* \rightarrow q\gamma$</td>
<td>$M(q^*) \sim 3.5$ TeV</td>
<td>$M(q^*) \sim 6$ TeV</td>
</tr>
<tr>
<td><strong>Leptoquarks</strong></td>
<td>$M(LQ) \sim 1$ TeV</td>
<td>$M(LQ) \sim 1.5$ TeV</td>
</tr>
<tr>
<td>$Z' \rightarrow \ell\ell, j j$</td>
<td>$M(Z') \sim 3$ TeV</td>
<td>$M(Z') \sim 5$ TeV</td>
</tr>
<tr>
<td>$W' \rightarrow \ell \nu$</td>
<td>$M(W') \sim 4$ TeV</td>
<td>$M(W') \sim 6$ TeV</td>
</tr>
<tr>
<td><strong>Compositeness</strong></td>
<td>$\Lambda \sim 25$ TeV</td>
<td>$\Lambda \sim 40$ TeV</td>
</tr>
</tbody>
</table>

(from Di-jet)
10.3 Additional Gauge Bosons: $W'$ and $Z'$
Search for new, high-mass di-lepton resonances

- Additional neutral Gauge Boson $Z'$
- Randall-Sundrum narrow Graviton resonances decaying to di-lepton

appear in Extra Dim. Scenarios

- Identical final state (two leptons), same analysis, interpretation for different theoretical models
- Main background process: Drell-Yan production of lepton pairs
Event display of the selected event with the highest di-muon invariant mass in the ATLAS experiment. The highest momentum muon has a $p_T$ of 653 GeV and an $\eta$ of 0.99. The subleading muon has a $p_T$ of 646 GeV and an $\eta$ of -0.85. The invariant mass of the pair is 1844 GeV.
Search for New Resonances in High Mass Di-leptons

Data are consistent with background from SM processes. No excess observed.

Detailed numbers on signal and background for the ee channel:

<table>
<thead>
<tr>
<th>$m_{e^+e^-}$ [GeV]</th>
<th>70-110</th>
<th>110-200</th>
<th>200-400</th>
<th>400-800</th>
<th>800-3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY</td>
<td>258482 ± 410</td>
<td>5449 ± 180</td>
<td>613 ± 26</td>
<td>53.8 ± 3.1</td>
<td>2.8 ± 0.1</td>
</tr>
<tr>
<td>$tt$</td>
<td>218 ± 36</td>
<td>253 ± 10</td>
<td>82 ± 3</td>
<td>5.4 ± 0.3</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>Diboson</td>
<td>368 ± 19</td>
<td>85 ± 5</td>
<td>29 ± 2</td>
<td>3.1 ± 0.5</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>W+jets</td>
<td>150 ± 100</td>
<td>150 ± 26</td>
<td>43 ± 10</td>
<td>4.6 ± 1.8</td>
<td>0.2 ± 0.4</td>
</tr>
<tr>
<td>QCD</td>
<td>332 ± 59</td>
<td>191 ± 75</td>
<td>36 ± 29</td>
<td>1.8 ± 1.4</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Total</td>
<td>259550 ± 510</td>
<td>6128 ± 200</td>
<td>803 ± 40</td>
<td>68.8 ± 3.9</td>
<td>3.4 ± 0.4</td>
</tr>
<tr>
<td>Data</td>
<td>259550</td>
<td>6117</td>
<td>808</td>
<td>65</td>
<td>3</td>
</tr>
</tbody>
</table>

Drell-Yan background can be normalized in the Z peak region, 70-110 GeV
Development with more data: from 1.1 fb\(^{-1}\) to 20 fb\(^{-1}\)

**Di-electron invariant mass**

\[
\int L \, dt = 1.08 \text{ fb}^{-1}
\]

\[
\sqrt{s} = 7 \text{ TeV}
\]

---

**2011:**

\[L = 1.1-1.2 \text{ fb}^{-1}\]

**Di-muon invariant mass**

\[
\int L \, dt = 1.21 \text{ fb}^{-1}
\]

\[
\sqrt{s} = 7 \text{ TeV}
\]

---

**2012:**

\[L = 20 \text{ fb}^{-1}\]
Search for New Resonances in High Mass Di-leptons

Data are still consistent with background from SM processes (no excess).

Detailed numbers on signal and background for the ee channel:

<table>
<thead>
<tr>
<th>$m_{ee}$ [GeV]</th>
<th>110 - 200</th>
<th>200 - 400</th>
<th>400 - 800</th>
<th>800 - 1200</th>
<th>1200 - 3000</th>
<th>3000 - 4500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^*$</td>
<td>119000 ± 8000</td>
<td>13700 ± 900</td>
<td>1290 ± 80</td>
<td>68 ± 4</td>
<td>9.8 ± 1.1</td>
<td>0.008 ± 0.005</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>7000 ± 800</td>
<td>2400 ± 400</td>
<td>160 ± 60</td>
<td>2.5 ± 0.6</td>
<td>0.11 ± 0.04</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Diboson</td>
<td>1830 ± 210</td>
<td>660 ± 160</td>
<td>93 ± 33</td>
<td>4.8 ± 0.8</td>
<td>0.79 ± 0.26</td>
<td>0.005 ± 0.004</td>
</tr>
<tr>
<td>Dijet, W + jet</td>
<td>3900 ± 800</td>
<td>1260 ± 310</td>
<td>230 ± 110</td>
<td>8.6 ± 2.4</td>
<td>0.9 ± 0.6</td>
<td>0.004 ± 0.006</td>
</tr>
<tr>
<td>Total</td>
<td>131000 ± 8000</td>
<td>18000 ± 1100</td>
<td>1780 ± 150</td>
<td>84 ± 5</td>
<td>11.6 ± 1.3</td>
<td>0.017 ± 0.009</td>
</tr>
<tr>
<td>Data</td>
<td>133131</td>
<td>18570</td>
<td>1827</td>
<td>98</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Drell-Yan background can be normalized in the Z peak region, 70-110 GeV.
Z’ models used in the interpretation

(i) Sequential Standard Model Z’

- Z’ has the same couplings to fermions as the Standard Model Z, width of the Z’ increases proportional to its mass

(ii) Models based on the E6 grand unified symmetry group

- Broken into SU(5) and two additional U(1) groups, leading to two new neutral gauge fields, denoted Ψ and χ. The particles associated with the additional fields can mix to form the Z’ candidates

\[ Z' = Z'_\Psi \cos \theta_{E6} + Z'_\chi \sin \theta_{E6} \]

- The pattern of symmetry breaking and the value of \( \theta_{E6} \) determine the Z’ couplings to fermions
  (several choices are considered)
Interpretation in the SSM:

Resulting mass limits: \( ee + \mu\mu \)

95\% C.L., \( \sqrt{s} = 8 \) TeV, \( L = 20 \) fb\(^{-1}\)

Sequential SM: \( m_{Z'} > 2.90 \) TeV

E\(_6\) models: \( m_{Z'} > 2.43 - 2.73 \) TeV

Summary of 95\% C.L. SSM exclusion limits from various experiments:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \sqrt{s} ) (TeV)</th>
<th>( L ) (fb(^{-1}))</th>
<th>ee lower limit (TeV)</th>
<th>( \mu\mu ) lower limit (TeV)</th>
<th>( Z'_\text{SSM} ) lower limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF / D0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>1.1 / 1.2</td>
<td>0.96</td>
<td>0.83</td>
<td>1.07</td>
</tr>
<tr>
<td>ATLAS</td>
<td>8</td>
<td></td>
<td>1.70</td>
<td>1.61</td>
<td>1.83</td>
</tr>
<tr>
<td>ATLAS</td>
<td></td>
<td>20</td>
<td>2.79</td>
<td>2.53</td>
<td>2.90</td>
</tr>
</tbody>
</table>
Interpretation in the Randall-Sundrum models: Graviton resonances: $G \rightarrow \Pi$

(Kaluza-Klein modes)

Limits as a function of the coupling strength $k/M'_{Pl}$

$k : = \text{space-time curvature in the extra dimension}$

$M'_{Pl} = M_{Pl} / \sqrt{8\pi}$ (reduced Planck scale)

Resulting mass limits: $ee + \mu\mu$

95% C.L.

$k/M'_{Pl} = 0.10$: $m_{Z'} > 2.47$ TeV
Resulting mass limits: ee + μμ 95% C.L. from the CMS analyses

Sequential SM: $m_{Z'} > 2.96$ TeV

$E_6$ models: $m_{Z'\psi} > 2.60$ TeV
Search for W’ → lν

- W’: additional charged heavy vector boson

- Appears in theories based on the extension of the gauge group
e.g. Left-right symmetric models: SU(2)_R ↔ W_R

- Assume ν from W’ decay to be light and stable, and W’ to have the same couplings as in the SM (“Sequential Standard Model, SSM”)

Signature: high p_T electron + high E_t^{miss}

→ peak in transverse mass distribution
Search for New Resonances in High Mass $\ell\nu$ events

Transverse mass ($e, E_T^{\text{miss}}$)

Transverse mass ($\mu, E_T^{\text{miss}}$)

![Graphs showing event distributions for different processes like SSM $W' \rightarrow e\nu$, $W \rightarrow (e,\tau)\nu$, HNC Cl $\rightarrow e\nu$, $t\bar{t}$, single $t$, QCD, $\gamma + \text{jets}$, $\mu$, $E_T^{\text{miss}}$, $\nu$, $W \rightarrow (\mu,\tau)\nu$, $t\bar{t}$, single $t$, QCD, $\gamma + \text{jets}$, $\mu$, $E_T^{\text{miss}}$, $\nu$ with CMS logo and 19.7 fb$^{-1}$ at 8 TeV.]
Interpretation in the Sequential SM

Resulting mass limits: $e\nu + \mu\nu$
95% C.L. from the CMS analyses

Sequential SM: $m_{W'} > 3.35$ TeV
Search for WW, WZ, and ZZ resonances

Fully hadronic final state
Use jet substructure techniques

subjet momentum balance
mass $m_j$ of the groomed jet
Search for WW, WZ, and ZZ resonances
Search for WW, WZ, and ZZ resonances

Fully hadronic final state
Use jet substructure techniques

[Graphs showing the product of cross section and branching fraction (σ × B) for WW and ZZ resonances as a function of resonance mass.]
10.4 Search for substructure / compositeness of quarks

• Substructure of quarks would lead to contact interactions at high energy scales between the constituents

• Such interactions would lead to deviations from the expected QCD scattering behaviour, which would be most visible in:
  - the inclusive jet cross section at high $p_T$
  - the di-jet invariant mass distribution
    (traditional variables, but very sensitive to uncertainties on the jet energy measurement, i.e. jet energy scale)
  - the di-jet angular distributions of jets in the parton-parton centre-of-mass system

• Parametrize effects by using an effective Lagrangian, in addition to the QCD terms

\[
L_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda^2} \psi_q^L \gamma^\mu \psi_q^L \psi_q^L \gamma^\mu \psi_q^L
\]

where \( \frac{g^2}{4\pi} = 1 \)

\( \xi = \pm 1 \), interference parameter, relative phase between QCD terms and contact terms

\( \Lambda = \) scale parameter of new interaction, to be determined in experiment

\[
\psi_q^L \gamma^\mu \psi_q^L = \frac{g^2}{4\pi} \psi_q^L \gamma^\mu \psi_q^L
\]
Measured inclusive jet $p_T$ spectrum from CMS (full 2010 dataset)
Di-jet angular distributions

- Reduced sensitivity to Jet energy scale
- Sensitivity to higher order QCD corrections preserved

Good agreement with next-to-leading order QCD predictions
Search for compositeness:

Measurements of the di-jet angular distributions with early ATLAS data \((L_{\text{int}} = 3.1 \text{ pb}^{-1})\)

In QCD: gluon exchange diagrams dominate, have the same angular dependence as Rutherford scattering; essentially flat in the variable

\[ \chi = e^{y_1 - y_2} \]

\(y_1, y_2 = \) rapidities of the two jets

This variable (angular measurement) is less sensitive to the syst. uncertainties on the jet energy measurement (jet energy scale) than the di-jet invariant mass spectrum
Search for compositeness:

Measurements of the di-jet angular distributions with full ATLAS data \((L_{\text{int}} = 17.3 \text{ fb}^{-1}; \text{lower than } 20 \text{ due to trigger pre-scales})\)

In QCD: gluon exchange diagrams dominate, have the same angular dependence as Rutherford scattering; essentially flat in the variable

\[ \chi = e^{|y_1 - y_2|} \]

\(y_1, y_2 = \) rapidities of the two jets

95% C.L. Limits on composite scale \(\Lambda\) :
- 8.1 TeV (destructive interference)
- 12.0 TeV (constructive interference)

This variable (angular measurement) is less sensitive to the syst. uncertainties on the jet energy measurement (jet energy scale) than the di-jet invariant mass spectrum.
Results on $\chi$ measurement from the CMS experiment based on full dataset

95% C.L. Limits on composite scale $\Lambda$:
- 9.0 TeV (destructive interference)
- 11.7 TeV (constructive interference)
\[ F_\chi(m_{jj}) \equiv \frac{dN_{\text{central}}}{dN_{\text{total}}} \frac{d \chi}{d m_{jj}} \]

\[ \int L dt = 4.8 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \]

- QCD Prediction
- Theoretical uncertainties
- Total Systematics
- data
- Contact Interaction: \( \Lambda = 7.5 \text{ TeV} \)
- QBH (n=6) : \( M_D = 4.0 \text{ TeV} \)
- \( q^* : m_{q^*} = 2.5 \text{ TeV} \)
- Lower boundary of search region
Search for Resonances in the di-jet mass distribution

Many extensions of the Standard Model predict the existence of new massive objects that couple to quarks (q) and gluons (g) and result in resonances in the di-jet mass spectrum:

Some examples searched for by ATLAS and CMS:

- **Excited quarks** $q^*$, which decay to $qg$, predicted if quarks are composit objects
- **Axial-vector particles** called **axigluons** ($A$), which decay to $qq$, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $SU(3)_L \times SU(3)_R$
- **New gauge bosons** ($W'$ and $Z'$), which decay into $qq$, predicted by models that include new gauge symmetries; the $W'$ and $Z'$ are assumed to have Standard Model couplings
- **Randall-Sundrum (RS) gravitons** ($G$), which decay to $qq$ and $gg$, predicted in the RS model of extra dimensions; the value of the dimensionless coupling $k/M'_P$ is chosen to be 0.1.

......
ATLAS search in data corresponding to $L_{\text{int}} = 20.3$ fb$^{-1}$

- Search for resonance / bump in the invariant dijet mass spectrum
- Assume smooth functional form of the QCD mass spectrum
- No evidence for a resonance $\rightarrow$ exclusion limits

95% C.L. Limits (ATLAS, $L = 20.3$ fb$^{-1}$):
Excited quarks: $m_{q^*} > 4.06$ TeV
10.5 Extra space dimensions

- Introduction

- Search for escaping gravitons at the LHC

- Search for Black Hole Production
Time is the fourth Dimension

Time:

1. Required by relativity to be a dimension

2. Required, along with three spatial dimensions, to specify the location of an event

- Space-time is four dimensional: $x$, $y$, $z$, and $t$

- Universal constant “$c$”, which relates measurements of space to measurements of time
The Polish mathematician T. Kaluza showed in 1919 that gravity and electromagnetism could be unified in a single theory with 5 dimensions – using Einstein’s theory of gravity.

“The idea of achieving a unified theory by means of a five-dimensional world would never have dawned on me...At first glance I like your idea tremendously”
The fifth dimension

- The Swedish physicist O. Klein proposed in 1926 that the fifth dimension was real, but too tiny to be observed.
- Computed to be of a size of $10^{-30}$ cm to unify gravity with electromagnetism.

"Klein’s paper is beautiful and impressive"
Compactified Extra Dimensions

Extra dimensions are too small for us to observe
⇒ they are ‘curled up’ and compact

Tightrope walker sees only one dimension
Ant can also go "around the circle"
Every point in space-time has curled up extra dimensions associated with it.

One extra dimension is a circle.

Two extra dimensions can be represented by a sphere.

Six extra dimensions can be represented by a Calabi-Yau space.
Newtonian inverse-squared law of gravity is modified with extra dimensions

- Example: 2 extra dimensions of size $R$
- Distances $r > R$
  \[ F \sim \frac{1}{r^2} \]
- Distances $r < R$
  \[ F \sim \frac{1}{r^4} \]
Creators of New Extra-Dimensional Ideas!

Lisa Randall
Harvard

Raman Sundrum
Johns Hopkins

Savas Dimopoulos
Stanford

Nima Arkani-Hamed
Princeton

Gia Dvali
New York Univ.

Raman Sundrum
Johns Hopkins
Large Extra Dimensions & the ADD Model

- Assume that there are \( n \) compactified extra space dimensions, with size \( r \).
- Only gravity can propagate in the extra dimensions;

Relation between Planck mass \( M_{\text{Pl}} \) in 4 and \((4+n)\) dimensions \( M_D \):

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

- The Standard Model interactions and all matter particles are confined to our 3-dimensional world.
Experimental Signature: Mono-jets from graviton production

Signal: single jet, $E_T^{\text{miss}}$

A nice candidate event: 1 jet with $p_T = 602$ GeV
$E_T^{\text{miss}} = 523$ GeV
Experimental Signature: Monojets

Signal: single jet, $E_T^{\text{miss}}$

Physics background:
- $Z + \text{jet}, Z \rightarrow \nu \nu$ (irreducible)
- $W^+ \text{jet}, W \rightarrow l \nu, l$ not detected
- QCD jet background, jet mis-measured

In addition, there could be a sizeable “instrumental / non-physics” background:

- Calorimeter noise, coherent noise in one region of the calorimeter
- Beam induced background
- Background from cosmic rays
  (e.g. high energy muon showers)
Typical selection: ATLAS, 2012 data, $L_{\text{int}} = 20.3 \text{ fb}^{-1}$

- require strict vertex cuts (five tracks associated to a primary vertex) suppresses beam-related background and cosmic ray backgrounds

- apply tight cuts on the shape of the calorimeter energy depositions, i.e. fraction of el.magn. energy, timing cuts, … (to suppress jets from “correlated noise in the calorimeter”)

- Require 1 jet with $p_T > 120 \text{ GeV}$ in the central detector region, $|\eta| < 2.0$
No further jets in the event with $p_T > 30 \text{ GeV}$ within $|\eta| < 4.5$

- $\Delta \phi \ (\text{jet, } E_T^{\text{miss}}) > 1.0$

- $E_T^{\text{miss}} > 150 \text{ GeV, 200 GeV, 250 GeV, 300 GeV, 350 GeV, 400 GeV, 500 GeV, 600 GeV, 700 GeV}$

- Lepton veto: reject all events with an identified lepton, electrons with $p_T > 20$ or muons with $p_T > 10 \text{ GeV}$
**W/Z + jet background estimate from data:**

- Control sample, require one or two identified leptons (disjoint to the signal sample); all other cuts identical; done separately for the electron and the muon channels

These control sample contain contributions from $Z \to \ell \ell$ (two leptons), as well as $W \to \ell \nu$, and $W \to \tau \nu$ (one lepton), plus some pollution by $t\bar{t}$ background; the latter one is subtracted using the theory prediction (Monte Carlo)

- Normalize the NNLO MC background cross section in each signal region separately according to the ratio found in the individual data/MC control regions

---

$W \to \mu\nu$ control region  
$Z \to \mu\mu$ control region to constrain $Z \to \nu\nu$
Numbers of observed events in data in comparison to expectations from Standard Model background for most sensitive signal regions:

Table 5: Data and SM background expectation in the signal region for the SR6–SR9 selections. For the SM expectations both the statistical and systematic uncertainties are included. In each signal region, the individual uncertainties for the different background processes can be correlated, and do not necessarily add in quadrature to the total background uncertainty.

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>Observed events</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM expectation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR6 3813</td>
</tr>
<tr>
<td></td>
<td>SR7 1028</td>
</tr>
<tr>
<td></td>
<td>SR8 318</td>
</tr>
<tr>
<td></td>
<td>SR9 126</td>
</tr>
<tr>
<td>$Z(\rightarrow \nu \bar{\nu})$</td>
<td>4000 ± 160</td>
</tr>
<tr>
<td>$W(\rightarrow \tau \nu)$</td>
<td>1030 ± 60</td>
</tr>
<tr>
<td>$W(\rightarrow e \nu)$</td>
<td>310 ± 30</td>
</tr>
<tr>
<td>$W(\rightarrow \mu \nu)$</td>
<td>97 ± 14</td>
</tr>
<tr>
<td>$Z/\gamma^* (\rightarrow \mu^+ \mu^-)$</td>
<td>740 ± 60</td>
</tr>
<tr>
<td>$Z/\gamma^* (\rightarrow \tau^+ \tau^-)$</td>
<td>240 ± 30</td>
</tr>
<tr>
<td>$t\bar{t}$, single top</td>
<td>30 ± 20</td>
</tr>
<tr>
<td>Dibosons</td>
<td>65 ± 35</td>
</tr>
<tr>
<td>Multijets</td>
<td>6 ± 6</td>
</tr>
</tbody>
</table>


Agreement between data and expectations for the $p_T(jet)$ and $E_T^{\text{miss}}$ spectra:
Constraints on the ADD model parameters:

Cross sections as a function of $M_D$
for $n=2$, $n=4$, and $n=6$ extra dimensions
(cutoff for $s^\ast < M_D^2$)
Use same analysis to also constrain Dark Matter production cross sections
Microscopic Black Holes at the LHC?
• New physics, scale of gravity $M_D$, can appear at the TeV-mass scale, i.e. accessible at the LHC

• Extra dimensions are compactified on a torus or sphere with radius $r$; 
Relation between Planck mass in 4 and (4+n) dimensions (fundamental scale $M_D << M_{Pl}$):

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

• Black hole formation at energies greater than $M_D$, (above a threshold mass, $M_{th}$)

Production cross section can be in the order of 100 pb for $M_D \sim 1$ TeV (large model dependence)

• Once produced, the black hole is expected to decay via Hawking radiation, democratically to all Standard Model degrees of freedom (quarks and gluons dominant, 75%, because $N_{C}=3$)

$\rightarrow$ multijet events with large mass and total transverse energy

• However, near production threshold, quantum effects play a role (quantum black holes); democratic decay is not valid any more
CMS search for events with high jet multiplicity and large transverse energy

Candidate events exist....

event with high multiplicity of jets, high mass....

all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?
Discriminating variables between QCD background and black hole signals:

- jet multiplicity $N_J$
- total transverse momentum/energy (scalar sum) in the event, $\Sigma p_T =: S_T$

Results of an ATLAS Monte Carlo simulation:

QCD multijet “background”

Black hole signal events with Planck scale $M_D = 1$ TeV and $n = 2$, threshold production mass 4.3 TeV
ATLAS analysis with 20.3 fb$^{-1}$ at 8 TeV:

- One or more high-$p_T$ lepton (electron or muon), plus 2 or more leptons or jets
- Total transverse momentum/energy (scalar sum) in the event, $\Sigma p_T =: S_T$

Shape of $S_T$ distribution cannot be reliably calculated in Monte Carlo simulation.

Problem: high jet multiplicities
Extrapolate each background individually with a fit to data from low-$S_T$ to high-$S_T$ region
ATLAS analysis with 20.3 fb\(^{-1}\) at 8 TeV:

- One or more high-\(p_T\) lepton (electron or muon), plus 2 or more leptons or jets
- Total transverse momentum/energy (scalar sum) in the event, \(\Sigma p_T =: S_T\)

Shape of \(S_T\) distribution cannot be reliably calculated in Monte Carlo simulation. Problem: high jet multiplicities
Extrapolate each background individually with a fit to data from low-\(S_T\) to high-\(S_T\) region
ATLAS analysis with 20.3 fb^{-1} at 8 TeV:

- One or more high-p_T lepton (electron or muon), plus 2 or more leptons or jets
- Total transverse momentum/energy (scalar sum) in the event, \( \Sigma p_T =: S_T \)

→ No evidence for the formation of micro Black Holes… limits
However, near production threshold, quantum effects play a role (quantum black holes); democratic decay is not valid any more

- Use production threshold $M_{\text{th}} > M_D$ above which semi-classical approximations work
- Between $M_{\text{th}}$ and $M_D$, quantum-gravitations effects become important and evaporation by emission of Hawking radiation is no longer a suitable model

→ No evidence for the formation of micro Black Holes… limits
Total transverse energy $S_T$ for events with $N > 3$, 5, 10 objects

No evidence for excess above the QCD expectations

$\rightarrow$ No evidence for the formation of micro Black Holes
Literature

Available on the web:


• T. Rizzo, „Pedagogical Introduction to Extra Dimensions“, hep-ph/0409309


• G. Landsberg, „Black Holes at Future Colliders and Beyond“, hep-ph/0607297

Books (popular science):

### Summary of results on searches for Physics Beyond the Standard Model in ATLAS

#### ATLAS Exotics Searches* - 95% CL Exclusion

**Status:** March 2015

\[
\mathcal{L} \, dt = (1.0 - 20.3) \, \text{fb}^{-1} \quad \sqrt{s} = 7, 8 \, \text{TeV}
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>(\ell, \gamma)</th>
<th>Jets</th>
<th>(E_{\text{miss}}^T) [fb]</th>
<th>(M_{\text{limit}}) [TeV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD G(_{1})K + g/q</td>
<td>(2,\ell)</td>
<td>-</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>5.25 TeV</td>
</tr>
<tr>
<td>ADD non-resonant (\ell\ell)</td>
<td>(2,\ell)</td>
<td>-</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>4.7 TeV</td>
</tr>
<tr>
<td>ADD QBG</td>
<td>(1,\ell)</td>
<td>2j</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>ADD BH high (N_{B})</td>
<td>1, (\mu)</td>
<td>2j</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>5.82 TeV</td>
</tr>
<tr>
<td>ADD BH high (\sum PT)</td>
<td>(2,\mu) (SS)</td>
<td>-</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>4.7 TeV</td>
</tr>
<tr>
<td>ADD BH high multiplet</td>
<td>(2,\ell)</td>
<td>-</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>5.8 TeV</td>
</tr>
<tr>
<td>RS1 G(_{1})K + (\ell\ell)</td>
<td>(2,\ell)</td>
<td>-</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>2.68 TeV</td>
</tr>
<tr>
<td>RS1 G(_{1})K + (\gamma\gamma)</td>
<td>(2\gamma)</td>
<td>-</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>2.66 TeV</td>
</tr>
<tr>
<td>Bulk RS G(_{1})K (\rightarrow Z\ell\ell)</td>
<td>(2,\ell)</td>
<td>2j/1j</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>740 GeV</td>
</tr>
<tr>
<td>Bulk RS G(_{1})K (\rightarrow WW\rightarrow q\bar{q}l\ell)</td>
<td>(1,\ell)</td>
<td>2j/1j</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>700 GeV</td>
</tr>
<tr>
<td>Bulk RS G(_{1})K (\rightarrow HH\rightarrow b\bar{b}b\bar{b})</td>
<td>(1,\ell)</td>
<td>1b</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>590-710 GeV</td>
</tr>
<tr>
<td>Bulk RS G(_{1})K (\rightarrow \ell\ell)</td>
<td>(1,\ell)</td>
<td>1b, 1/2j</td>
<td>20.3</td>
<td>(M_{\phi})</td>
<td>2.2 TeV</td>
</tr>
</tbody>
</table>

**2UED / RPP**

- SSM \(\rightarrow \ell\ell\)
- \(Z\) mass
- 2.9 TeV

**Extra dimensions**

- \(Z\) mass
- 2.02 TeV
- 3.24 TeV

**Gauge bosons**

- \(Z\) mass
- 1.52 TeV
- 1.59 TeV
- 1.47 TeV

**Scalar LQ**

- \(M_{\phi}\)
- 660 GeV
- 534 GeV
- 680 GeV
- 534 GeV

**Scalar LQ**

- \(M_{\phi}\)
- 974 GeV
- 870 GeV
- 840 GeV

**Scalar LQ**

- \(M_{\phi}\)
- 660 GeV
- 585 GeV
- 4.35 TeV

**DM**

- \(M_{\phi}\)
- 660 GeV
- 534 GeV

**LO**

- \(M_{\phi}\)
- 974 GeV
- 585 GeV
- 4.35 TeV

**Heavy quarks**

- \(M_{\phi}\)
- 785 GeV
- 735 GeV
- 640 GeV
- 840 GeV

**Excited fermions**

- \(M_{\phi}\)
- 660 GeV
- 5.8 TeV
- 3.5 TeV
- 4.09 TeV

**LQ + \(t\) quark**

- \(M_{\phi}\)
- 660 GeV
- 534 GeV
- 680 GeV
- 840 GeV

**Other**

- \(M_{\phi}\)
- 660 GeV
- 585 GeV

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*Only a selection of the available mass limits on new states or phenomena is shown.*
End of lectures