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
- 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_{\ell^+\ell^-} \text{ [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>(t\bar{t})</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**

\[ \int L \, dt = 1.08 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

**Di-muon invariant mass**

\[ \int L \, dt = 1.21 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

2011:
\[ L = 1.1–1.2 \text{ fb}^{-1} \]

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>$Z/\gamma$</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>$t\bar{t}$</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>Diboson</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 E$_6$ grand unified symmetry group
- Broken into SU(5) and two additional U(1) groups, leading to two
  new neutral gauge fields, denoted $\Psi$ and $\chi$.
  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)
Summary of 95% C.L. SSM exclusion limits from various experiments:

<table>
<thead>
<tr>
<th>95% C.L. limits (SM couplings)</th>
<th>ee</th>
<th>(\mu\mu)</th>
<th>ll combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF / D0 (5.3 \text{ fb}^{-1})</td>
<td>0.96 TeV</td>
<td>(0.83 \text{ TeV})</td>
<td>1.07 TeV</td>
</tr>
<tr>
<td>ATLAS (0.036 \text{ fb}^{-1})</td>
<td>1.70 TeV</td>
<td>(1.61 \text{ TeV})</td>
<td>1.05 TeV</td>
</tr>
<tr>
<td>ATLAS (\sqrt{s}=7 \text{ TeV}, L=1.1/1.2 \text{ fb}^{-1})</td>
<td>2.79 TeV</td>
<td>(2.48 \text{ TeV})</td>
<td>1.83 TeV</td>
</tr>
<tr>
<td>ATLAS (\sqrt{s}=8 \text{ TeV}, 20 \text{ fb}^{-1})</td>
<td>(\mu\mu)</td>
<td>(\mu\mu)</td>
<td>2.86 TeV</td>
</tr>
<tr>
<td>CMS (1.1 \text{ fb}^{-1})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Resulting mass limits: ee + \(\mu\mu\) 95% C.L., \(\sqrt{s}=8 \text{ TeV}, L=20 \text{ fb}^{-1}\)

Sequential SM: \(m_{Z'} > 2.86 \text{ TeV}\)

\(E_6\) models: \(m_{Z'} > 2.38 - 2.54 \text{ TeV}\)
Interpretation in the Randall-Sundrum models: Graviton resonances: $G \to \ell \ell$ (Kaluza-Klein modes)

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

$k : = $ space-time curvature in the extra dimension

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

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

95% C.L.

$k/M'_\text{Pl} = 0.10: \ m_{Z'} > 2.47$ TeV
Resulting mass limits: $e^+e^- + \mu^+\mu^-$
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 $W' \rightarrow l\nu$

- $W'$: additional charged heavy vector boson

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

- Assume $\nu$ 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 $E_t^{\text{miss}}$

$\rightarrow$ peak in transverse mass distribution
Search for New Resonances in High Mass $l\nu$ events

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

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

CMS Preliminary

$\int L \, dt = 20 \, fb^{-1}$

$\sqrt{s} = 8 \, TeV$

Events / 20 GeV

Events / 1 GeV

$M = 2500 \, GeV$

$M = 500 \, GeV$

CMS Preliminary

$\int L \, dt = 20 \, fb^{-1}$

$\sqrt{s} = 8 \, TeV$

Ratio data/MC
Interpretation in the Sequential SM

Resulting mass limits: $e\nu + \mu\nu$

95% C.L. from the CMS analyses

Sequential SM: $m_{W'} > 3.35 \text{ TeV}$
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 \(\frac{g^2}{4\pi} = 1\)

corresponds to a 4-fermion interaction (analogue to Fermi theory) ;
\(\xi = \pm 1\), interference parameter, relative phase between QCD terms and contact terms
\(\Lambda = \) scale parameter of new interaction, to be determined in experiment
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
\( F_\chi (m_{jj}) \equiv \frac{dN_{\text{central}}/dm_{jj}}{dN_{\text{total}}/dm_{jj}} \)

**Figure:**

- **QCD Prediction**
- **Theoretical uncertainties**
- **Total Systematics**
- **Data**
- **Contact Interaction:** \( \Lambda = 7.5 \text{ TeV} \)
- **QBH (n=6):** \( M = 4.0 \text{ TeV} \)
- **q*:** \( m_{q^*} = 2.5 \text{ TeV} \)
- **Lower boundary of search region**

**ATLAS**

\[ \int L dt = 4.8 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \]
Results on $\chi$ measurement from the CMS experiment based on full 2010 dataset, 36 pb$^{-1}$

95% C.L. Limits on scale $\Lambda$:

**ATLAS:** $4.8 \text{ fb}^{-1}$ $\Lambda > 7.6 \text{ TeV}$

**CMS:** $5 \text{ fb}^{-1}$ $\Lambda > 9.9 \text{ TeV}$
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 compositied 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 $k/M'_\text{Pl}$ is chosen to be 0.1.

- ......
ATLAS search in data corresponding to $L_{\text{int}} = 4.8 \text{ fb}^{-1}$

- 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, $L = 4.8 \text{ fb}^{-1}$):

**Excited quarks:** $m_{q^*} > 2.83 \text{ TeV}$

**Axigluons:** $m_A > 1.68 \text{ TeV}$
10.5 Extra space dimensions

- Introduction
- Search for escaping gravitons at the LHC
- Search for Black Hole Production

Microscopic-Black Hole Events at the LHC?
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"
“Visualizing” Extra Dimensions

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.
Modifications of Newton’s Law of Gravity

- 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

Nima Arkani-Hamed
Princeton

Savas Dimopoulos
Stanford

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 \( M_{Pl} \) in 4 and (4+n) dimensions \( M_D \):

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

• 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, 2011 data, \( L_{\text{int}} = 1.0 \text{ fb}^{-1} \)

- 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 \( p_T > 120 \text{ GeV} \) (low \( p_T \)), \( 250 \text{ GeV} \) (high \( p_T \)), \( 350 \text{ GeV} \) (very high) in the central detector region, \(|\eta| < 2.0\)

  No further jets in the event with \( p_T > 30 \text{ GeV} \) within \(|\eta| < 4.5\)

- \( E_T^{\text{miss}} > 120 \text{ GeV} \) (low), \( 220 \text{ GeV} \) (high) and \( 300 \text{ GeV} \) (very high) and \( \Delta\phi \) (jet, \( E_T^{\text{miss}} \)) \( > 0.5 \)

- Lepton veto: reject all events with an identified lepton, electrons with \( p_T > 20 \) or muons with \( p_T > 10 \) GeV

\[ \Rightarrow 15750, 965 \text{ and } 167 \text{ events observed in ATLAS data for the low, high and very high selections, respectively} \]
W/Z + jet background estimate from data:

- Control sample, require an identified lepton (disjunct with the signal sample); all other cuts identical; done separately for the electron and the muon channels

This control sample contains contributions from $Z \rightarrow ll$, $W \rightarrow lv$, and $W \rightarrow \tau\nu$, as well as some pollution by $tt$ background; the latter one is subtracted using the theory prediction (Monte Carlo)

- Total sum is normalized to the data; normalization factors found are: e.g. low $p_T$ selection: $0.95 \pm 0.02$ (muons) and $0.90 \pm 0.04$ (electrons) (on top of the NNLO theory prediction for inclusive W/Z cross section)

After normalization: very good agreement between data and Monte Carlo simulation

![Graphs showing comparison between data and Monte Carlo for muon and electron control regions.](image)
Estimate of multijet background from data:

- Control sample: give up veto on 2nd jet and $\Delta \phi$ (jet, $E_T^{miss}$) requirement ("fake" $E_T^{miss}$ will most likely result from a mis-measured second jet)

- Look at the $\Delta \phi$ distribution for the second jet:
  (for physics backgrounds the same normalization factors as determined before are used)

Good description of data, except in low $\Delta \phi$ region $\rightarrow$ QCD background component from data
**Numbers of observed events in data in comparison to expectations from Standard Model background:**

<table>
<thead>
<tr>
<th>Background</th>
<th>LowPt Selection</th>
<th>HighPt Selection</th>
<th>veryHighPt selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z (\rightarrow \nu \bar{\nu})$+jets</td>
<td>$7700 \pm 90 \pm 400$</td>
<td>$610 \pm 27 \pm 47$</td>
<td>$124 \pm 12 \pm 15$</td>
</tr>
<tr>
<td>$W (\rightarrow \tau \nu)$+jets</td>
<td>$3300 \pm 90 \pm 220$</td>
<td>$180 \pm 16 \pm 22$</td>
<td>$36 \pm 7 \pm 8$</td>
</tr>
<tr>
<td>$W (\rightarrow e \nu)$+jets</td>
<td>$1370 \pm 60 \pm 90$</td>
<td>$68 \pm 10 \pm 8$</td>
<td>$8 \pm 1 \pm 2$</td>
</tr>
<tr>
<td>$W (\rightarrow \mu \nu)$+jets</td>
<td>$1890 \pm 70 \pm 100$</td>
<td>$113 \pm 14 \pm 9$</td>
<td>$18 \pm 4 \pm 2$</td>
</tr>
<tr>
<td>Multi-jets</td>
<td>$360 \pm 20 \pm 290$</td>
<td>$30 \pm 6 \pm 11$</td>
<td>$3 \pm 2 \pm 2$</td>
</tr>
<tr>
<td>$Z/\gamma^* (\rightarrow \tau^+ \tau^-)$+jets</td>
<td>$59 \pm 3 \pm 4$</td>
<td>$2.0 \pm 0.6 \pm 0.2$</td>
<td>-</td>
</tr>
<tr>
<td>$Z/\gamma^* (\rightarrow \mu^+ \mu^-)$+jets</td>
<td>$45 \pm 3 \pm 2$</td>
<td>$2.0 \pm 0.6 \pm 0.1$</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma+\text{jet}$</td>
<td>$17 \pm 1 \pm 3$</td>
<td>$1.7 \pm 0.3 \pm 0.3$</td>
<td>-</td>
</tr>
<tr>
<td>$Z/\gamma^* (\rightarrow e^+ e^-)$+jets</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Non-collision Background</td>
<td>$370 \pm 40 \pm 170$</td>
<td>$8.0 \pm 3.3 \pm 4.1$</td>
<td>$4.0 \pm 3.2 \pm 2.1$</td>
</tr>
<tr>
<td>Total Background</td>
<td>$15100 \pm 170 \pm 680$</td>
<td>$1010 \pm 37 \pm 65$</td>
<td>$193 \pm 15 \pm 20$</td>
</tr>
<tr>
<td>Events in Data (1.00 fb$^{-1}$)</td>
<td>15740</td>
<td>965</td>
<td>167</td>
</tr>
</tbody>
</table>
Agreement between data and expectations for the $p_T$($\text{jet}$) and $E_T^{\text{miss}}$ spectra:

**Low $p_T$ selection:**

**Very high $p_T$ selection:**
Constraints on the ADD model parameters:

Cross sections as a function of $M_D$ for $n=2$ and $n=4$ extra dimensions (cutoff for $s^2 < M_D^2$)

Excluded $M_D$ values (95% C.L.):

<table>
<thead>
<tr>
<th>$n$</th>
<th>LowPt selection [TeV]</th>
<th>HighPt selection [TeV]</th>
<th>veryHighPt selection [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.20</td>
<td>3.16</td>
<td>3.39</td>
</tr>
<tr>
<td>3</td>
<td>1.76</td>
<td>2.50</td>
<td>2.55</td>
</tr>
<tr>
<td>4</td>
<td>1.54</td>
<td>2.15</td>
<td>2.26</td>
</tr>
<tr>
<td>5</td>
<td>1.37</td>
<td>1.89</td>
<td>1.90</td>
</tr>
<tr>
<td>6</td>
<td>1.24</td>
<td>1.68</td>
<td>1.58</td>
</tr>
</tbody>
</table>
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:

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

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

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 particles (quarks and gluons dominant, 75%) → multijet events with large mass and total transverse energy
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
Background model / “calibration” of QCD multijet background

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

problem: high jet multiplicities

→ Fit a smooth QCD model to data in low $S_T$ region, determine parametrization (functional form) at low multiplicities ($n=2$)
Total transverse energy $S_T$ for events with $N > 3, 5, 7$ objects

No evidence for excess above the QCD expectations

→ No evidence for the formation of micro Black Holes
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 in ATLAS

<table>
<thead>
<tr>
<th>Mass (TeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.37</td>
<td>[1210.6604]</td>
</tr>
<tr>
<td>7.6</td>
<td>[1109.1150]</td>
</tr>
<tr>
<td>8.4</td>
<td>[1209.6593]</td>
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*Only a selection of the available mass limits on new states or phenomena shown*
End of lectures