I give a summary of BSM searches performed by the ATLAS and CMS experiments with a focus on heavy gauge bosons, extra dimensions and quantum black holes. The presented results use data collected during 2012 when the LHC operated at an center of mass energy of $\sqrt{s} = 8$ TeV.

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1 Introduction

The Large Hadron Collider (LHC) operated at a center of mass energy of $\sqrt{s} = 8\text{ TeV}$ during 2012 and the multi-purpose particle detectors ATLAS [2] and CMS [1] recorded data with an integrated luminosity of $20\text{ fb}^{-1}$. The recorded data presents a unique opportunity to search for physics beyond the standard model (BSM) and both experiments have interpreted their measurements in terms of a variety of theories.

This work aims to briefly summarize search results in the dilepton (same and opposite flavor), lepton+$\not{E_T}$, dijet and ditop channel for a selected set of related BSM theories which predict the existence of heavy gauge bosons $Z'$ and $W'$, extra dimensions or quantum black holes.

2 Theories

**Extra dimension models** summarized in the following describe extensions of our spacetime with additional compactified dimension. The related theories may lower the fundamental Planck mass $M_D$ to the TeV region, and thus solve the higgs mass hierarchy problem. This summary focuses on the most popular theories: Randall Sundrum (RS)[3] and the Arkani-Hamed, Dimopoulos, Dvali (ADD) [4, 5] models. Both models provide no fundamental theory of quantum gravity, but are built as effective field theories based on classical assumptions. They use parts of the mathematical framework which was developed in string theory, or more precisely brane physics to confine SM particles to a (3+1) dimensional subspace of the (3 + 1 + n) dimensional space-time[6]. Extra dimension theories predict a spectrum of Graviton modes (Kaluza-Klein towers) or a spectrum of heavier copies of SM particles if they are able to propagate in the compactified additional dimensions.

The ADD model assumes a flat spacetime. The model parameter under study depends on the production process. The direct production cross section depends directly on $M_D$, while the virtual graviton exchange is only able to probe the UV cut-off $M_s$, which can be argued to be close to $M_D$.

The RS model assumes a warped space-time represented by an exponential term in the metric $ds^2 = e^{-2k\phi}g_{\mu\nu}dx^\mu dx^\nu + r_c d\phi^2$. The cross section in these models depends on the ratio $k$ of the warp factor $k$ and $M_D$. Several extensions of this model exist, most notably the Bulk RS1 scenario [7]. Here the fermion and boson fields localized near to a TeV or a Planck brane respectively. This allows solving the flavor puzzle and the higgs mass hierarchy problem without introducing an additional hierarchy.

**Heavy Gauge Bosons** $W', Z'$ refer to heavier versions of the weak gauge bosons and are predicted in several classes of theories. The most studied scenario is the sequential standard model (SSM) [8] where $W'$ and $Z'$ bosons carry exactly the same
quantum numbers and interfere with their SM counterparts. The $Z'$ is expected to decay flavor violating in several theories. Relevant with respect to the presented searches are generic extensions of the SSM with additional flavor violating couplings, which are expressed as ratios $Q_{ij}$ ($i, j = e, \mu, \tau$) of the SSM same flavor coupling [9] or extra dimensions where the mass hierarchy among SM families is explained by the overlap of the particle wave functions if fermions and the higgs are localized on a higher dimensional brane [10]. Technicolor models which suggest additional gauge couplings are of special interest in decay channels with tops where the color singlet $Z'$ is leptophobic and couples only to first and third generation quarks[11].

Quantum Black Holes (QBH) may be produced if LHC collisions take place above a lowered fundamental Planck scale. All discussed models assume either the ADD or the RS model as their starting point, but include different sets of additional assumptions. The main parameters to control the signal shape and cross section are the additional number of dimensions and the threshold mass $M_{th}$, which is necessary to produce a QBH. The presented models are often referred to by the generator which implements it. The generators used for the summarized searches are:

- CalcHEP for flavor violating QBH decays [12].
- QBH which uses a generic description of gravitational bound two-body states with an non thermal QBH decay [13].
- BLACKMAX includes a wide range of black hole theories but most relevant for the presented analyses are models comparable to the QBH generator with additional model assumptions [14].

QBH theories share an important limitation: black hole production is expected at scales where gravity becomes strong, and one hopes that the extrapolation from the classical domain holds.

3 Selected Searches with the CMS and ATLAS Experiments

3.1 Dilepton (same flavor)

The dilepton channel is theoretical well understood and has been studied by both experiments [15] [16] [17]. Both analyses try to use a model unspecific selection which aims to reliably select well reconstructed and isolated pairs of electrons or muons. No significant deviation from the SM was observed and two distinct limit strategies have been used to set limits for resonant and non-resonant BSM signals.
The resonant searches fit smooth functions to both data and background prediction. A set of signal shape templates with different $Z'$ mass is used to construct a background + signal hypothesis, which is compared to both data and the background only hypothesis. The resulting limit on the cross section times efficiency for a SSM $Z'$ dependent on the resonance mass is shown in fig. [1]. Both experiments report observed limits of 2.9 TeV on the $Z'_{SSM}$ mass. The technique to derive these results differs between both experiments. The ATLAS collaboration uses the complete spectrum with a binned likelihood approach, this allows gaining additional sensitivity for the studied SSM by including interference effects outside the resonance. The CMS collaboration has chosen a more general strategy using an unbinned likelihood approach with a narrow width approximation. The results may be reinterpreted for any model with comparable acceptance by simply applying a cross section ratio for the SSM $Z'$ and the model under investigation within a mass window of $\pm 5\% \sqrt{s}$. This difference explains stronger fluctuations for CMS results in fig. [1].

Possible signals from the lightest Kaluza-Klein Graviton mode in RS models serve as a benchmark model for spin 2 resonances with a modified signal acceptance. The ATLAS results show exclusion limits in the $k - M_{Pl}$ plane, while CMS chose to present results similar to the $Z'$ interpretation, see figure [2]. The comparison of both CMS limit plots show that differences in cross section between $Z'$ and RS Gravitons are only visible for small resonance masses.

QBHs are expected to create an edge like resonance structure in the dilepton mass range close above the production threshold mass $M_{th}$. The ATLAS search uses the resonant search strategy to derive 95% CL exclusion limits on $M_{th}$ of 3.65 TeV for a signal based on an ADD scenario ($n = 6$) and 2.24 TeV for a RS based scenario ($n = 1$) using the QBH generator.

Both experiments performed non-resonant searches using a single bin counting

Figure 1: 95% CL limits on the cross section $\times$ branching ratio $\times$ efficiency dependent on the resonance mass for the ATLAS [15] (left) and CMS [17] (right) searches.

\[\text{Figure 1: 95\% CL limits on the cross section} \times \text{branching ratio} \times \text{efficiency dependent on the resonance mass for the ATLAS [15] (left) and CMS [17] (right) searches.}\]
Figure 2: 95% CL exclusion limits in the $k - M_{Pl}$ plane as reported by the ATLAS collaboration [15] (left) 95% CL exclusion limits on the cross section times efficiency depending on the resonance mass for spin-2 RS Gravitons by CMS [17] (right).

experiment above a lower mass threshold, which was optimized for the best exclusion limits on the ADD UV cut-off $M_s$ at different number of extra dimensions as shown in fig. 3 the observed limits reach from 4.9 TeV to 3.3 TeV for 3 to 7 additional dimensions.

### 3.2 Dilepton (mixed flavor)

Dilepton events with opposite flavor were studied by both experiments in the $e\mu$ channel. ATLAS has performed additional searches in $e\tau$ and $\mu\tau$ channels. Lepton flavor decays are of special interest because of the good mass resolution and only small SM background contributions to the final states.

Both experiments searched for $Z'$ bosons with additional lepton flavor violating couplings. The ATLAS search chose the coupling $Z' \rightarrow e\mu, e\tau, \mu\tau$ to be equal to SSM $Z'$ same flavor coupling. A binned likelihood approach was used to derive limits on the $Z'$ mass of 2.5 TeV ($e\mu$), 2.2 TeV ($e\tau$) and 2.2 TeV ($\mu\tau$) at 95% CL. The CMS analysis studied an extra dimension inspired model where the coupling is set to match existing strong bounds from $K_L \rightarrow e\mu$ decays. This search concluded to be not sensitive to the $Z'$ model under investigation.

The quantum gravitational nature of QBHs suggest the existence of lepton flavor violating decays. The CMS experiment has interpreted its measurements in terms of several QBH models implemented in CalcHEP where the threshold mass is set to be equal to the reduced Planck mass. Limits at 95% CL were set on $M_{th}$ of 2.4 TeV in a RS based scenario ($n = 1$) and 3.15 TeV to 3.63 TeV for 2 to 6 extra dimensions in an ADD based scenario.
3.3 Lepton+\vec{E}_T

Both experiments published results for final states with one high \(p_T\) lepton and a significant amount of missing momentum in the transverse plane \(\vec{E}_T\) \cite{21, 22}. The high mass tails for this signature are dominated by off-shell SM \(W\) production. Single lepton triggers with transverse momentum thresholds for electrons (muons) of \(p_T > 120\, \text{GeV} (p_T > 40\, \text{GeV})\) and \(p_T > 80\, \text{GeV} (p_T > 40\, \text{GeV})\) have been used by ATLAS and CMS respectively. Events with additional well reconstructed same flavor leptons with \(p_T > 20\, \text{GeV}\) are discarded in the ATLAS analysis while CMS uses \(p_T > 35\, \text{GeV}\) for electrons and \(p_T > 25\, \text{GeV}\) for muons. The transverse mass \(M_T = \sqrt{2p_T\vec{E}_T \left(1 - \cos[\Delta \phi(p_T^l, \vec{E}_T)]\right)}\) is used as the main observable for \(W'\) searches.

Additional final state specific kinematic cuts distinguish both searches: ATLAS adjusts the lower threshold for \(\vec{E}_T\) to the trigger \(p_T\) thresholds for each flavor; CMS applies a back-to-back cut \(\Delta \phi(l, \vec{E}_T) > 2.5\) and requirements on the \(p_T/\vec{E}_T\) ratio: \(0.4 < p_T/\vec{E}_T < 1.5\), both cuts should reflect that BSM paricles are produced in a balanced recoil at leading order.

ATLAS and CMS report lower limits of 3.2\,\text{TeV} and 3.3\,\text{TeV} on the \(W'\) mass at 95\%CL. Different statistical procedures were used to derive the limits; ATLAS uses a single bin counting experiment above a varying lower threshold on \(M_T\). Cross section limits are calculated based on an optimized threshold for each considered \(W'\) mass, see fig. \ref{fig:limits}. The CMS analysis used an shape based template fit similar to the resonant

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{limits.png}
\caption{Comparison of 95\% CL exclusion limits on the UV cutoff \(M_s\) depending on the number of additional dimensions for different searches by ATLAS \cite{15}, CMS \cite{17-19} and D0 \cite{20}.

Figure 3: Comparision of 95\% CL exclusion limits on the UV cutoff \(M_s\) depending on the number of additional dimensions for different searches by ATLAS \cite{15}, CMS \cite{17-19} and D0 \cite{20}.

\end{figure}
ATLAS search in the dilepton channel, see fig. 4. CMS has also reported limits based on single bin counting experiments above varying mass thresholds but did not use this approach for the $W'$ interpretation. 

Figure 4: 95% CL exclusion limits on branching ratio times cross section depending on the $W'$ mass for ATLAS [21] (left) and CMS [22] (right)

3.4 Dijet

Final states with two high-$p_T$ jets profit from a large cross section at hadron colliders like the LHC and enough events were collected to extract shape information up to several TeV. Both experiments add additional requirements on the dijet event kinematics in their search [23, 24]. A separation in (pseudo)-rapidity between the jets with the highest $p_T$ of $\Delta y < 0.6$ and $\Delta \eta < 0.65$ is used by ATLAS and CMS respectively. ATLAS used so called pre-scaled triggers where only a fixed fraction of all events is saved. This allows collecting data with lowered trigger requirements and decreases the lower limit for searches in the dijet mass distribution to $m_{jj} > 250$ GeV compared to the CMS analysis with $m_{jj} > 890$ GeV. Both experiments use smooth fit function to estimate the background expectation from data and compare it to signal templates using a binned likelihood approach. Lower limits on particle masses for SSM $Z'$, $W'$ and Kaluza-Klein Gravitons in the RS model with $n = 1$ are listed in table 1.

Dijet events also represent the most sensitive channel for QBH searches, and many QBH models predict that the produced BH decays primarily to dijet pairs [25]. Lower limits on $M_{th}$ were set by both experiments using the model implemented in the QBH generator. ATLAS has set $M_D = M_{th}$ and reported 5.7 TeV while CMS kept both variables as free parameters and found a limit of 5.8 TeV for $M_{pl} = 5$ TeV. Additional
\[
\begin{array}{|c|ccc|}
\hline
 & W' & Z' & G_{KK} (RS) \\
\hline
\text{ATLAS} & 2.5 & & \\
\text{CMS} & 2.2 & 1.7 & 1.6 \\
\hline
\end{array}
\]

Table 1: 95\% CL lower mass limits on the SSM \(W'\), \(Z'\) and \(G_{KK}\) (RS \(n = 1\)) as reported by ATLAS \cite{23} and CMS \cite{24} for the dijet channel.

bounds on a related model implemented in \texttt{BLACKMAX} were set by the ATLAS experiment of \(M_{th} < 5.6\,\text{TeV}\) where \(M_{th}\) is again set to be equal to the reduced Planck mass \(M_D\).

### 3.5 Ditop

![Graphical representation of the possible decay modes for a single top quark.](image)

Figure 5: Graphical representation of the possible decay modes for a single top quark.

The analysis of ditop final states by ATLAS and CMS \cite{26, 27} has significantly increased its sensitivity by employing new analysis strategies for the reconstruction of boosted top decays, and the subsequent top identification via so called top-tagging techniques. Each of the two tops decays either leptonically or hadronically; the hadronic decays can be further split into a resolved and boosted topology, see fig. 5. The combination of these decay modes for both tops results in the ditop decay modes: leptonic-leptonic, leptonic-hadronic, leptonic-hadronic(boosted), hadronic-hadronic hadronic(boosted)-hadronic(boosted). ATLAS restricted its analysis to the most sensitive combination with one leptonic and one hadronic decay for the models under investigation, CMS analyzed all possible decay modes and combined the measurements for the final result.

Limits have been set on the \(Z'\) mass based on topcolor models as described in \cite{11} where the coupling to lighter quarks is suppressed: ATLAS and CMS found lower limits of 1.8\,\text{TeV} and 2.4\,\text{TeV} with a width of 1.2\% and 1\% of the \(Z'\) mass respectively, see figure 6.
The Bulk RS1 model expects a suppression in production and decay for lighter quarks. This leaves $t\bar{t}$ final states as the most promising channel to probe the production of Kaluza-Klein gluons $g_{KK}$ at the LHC [7]. ATLAS and CMS report lower limits on the mass of the lightest Kaluza-Klein mode of the gluon $g_{KK}$ of 2.2 TeV and 2.8 TeV respectively.

Figure 6: 95% CL exclusion limits on the branching ratio $\times$ cross section dependent on the $Z'$ mass for ATLAS [26] (left) and CMS [27] (right)

4 Conclusion

ATLAS and CMS have both performed a large number of searches for the presented theories and it should be emphasized that this summary reports only on a small subset of all searches. No significant evidence for physics beyond the standard model has been reported. A comprehensive list of all searches for new physics related to this talk are constantly updated online (ATLAS: ExoticsPublicResults CMS: PhysicsResultsEXO, PhysicsResultsB2G). The reach for most of the presented analysis is limited by the probable phase space. The recent restart of the LHC at a center of mass energy of $\sqrt{s} = 13$ TeV will increase the discovery reach for most theories with a fraction of the recorded integrated luminosity at 8 TeV.

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