Searches for new exotic phenomena at the LHC

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for the ATLAS and CMS collaborations
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Introduction

The Standard Model has so far done remarkably well at withstanding experimental tests

- Higgs discovery of 2012 marked last piece of the SM
- No meaningful deviations from SM predictions observed by end of Run I

But many questions indicate there must still be new physics beyond the Standard Model!

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<tr>
<th>Dark matter</th>
<th>What is it? Is it a particle?</th>
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<td>Hierarchy problem</td>
<td>Why is gravity so weak? Can extra dimensions explain it?</td>
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<td>Gauge unification</td>
<td>Is there a unified theory connecting fundamental forces?</td>
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<td>Higgs fine-tuning</td>
<td>How do we account for large, fine-tuned Higgs mass corrections?</td>
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<td>Why 3 generations? Why 4 forces? Matter-antimatter asymmetry?</td>
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</table>
Searching for BSM physics with ATLAS and CMS

- Two all-purpose detectors at the LHC allow examination of any high-energy final state
- Enormous overlap between models and signatures, with each final state corresponding to numerous theories and vice versa
- To ensure we don’t miss anything, focus on signatures in broad classes of analyses and search for any signs of deviation from a SM prediction

- Select signatures motivated by one or more theories
- Use handful of benchmark models to define limits on mass or cross section of possible new particles
- Today: searches for (non-SUSY) physics beyond the Standard Model in 13 TeV data
The 2015 data-taking period

**Integrated luminosity** delivered: 4.2/fb

- ATLAS Recorded: 3.9/fb (IBL on: 3.2/fb)
- CMS Recorded: 3.8/fb (toroid on: 2.7/fb)

Since cross-section increase over Run I corresponds to dramatic increase in parton luminosities at high mass, sensitivity to exotic signatures improves even with much less than the 20/fb of luminosity used in 2012.
Enormous number of exotic limits at the end of Run I...

Where to next?
Black hole searches

• Models assuming a higher-dimensional universe allow strong gravity on the same scale as the other fundamental forces

• Consequence is production of microscopic black holes above fundamental gravity scale $M_D$

• Decays of semiclassical microscopic black holes are “democratic”: equally likely to produce any particle, and give high multiplicity final states

• Decays of quantum black holes are dominated by 2-body final states, especially jets at the LHC

• Primary backgrounds: QCD multijet production. Secondary: V+jets, $\gamma+$jets, $tt$
Black holes in multi-particle final states

- Discriminating variable: $S_T = \Sigma p_T (\Sigma E_T)$ of all objects. Include jets, e, $\mu$, ($\gamma$, MET in CMS) > 60/50 GeV
- Selection: $S_T > 2$ TeV. CMS accepts any event of mult. $\geq 2$; ATLAS requires $\geq 1$ lepton, mult. $\geq 3$
- Background estimation
  - ATLAS: W/Z+jets dominant with ttbar, di-boson, single-top contribs. Estimate from MC.
  - CMS: dominated by QCD multijets.
    Since shape of $S_T$ dist. constant, scale from fit to dijet events with low $S_T$

CMS PAS EXO-15-007
ATLAS CERN-EP-2016-109
Black holes in multi-particle final states

- ATLAS covers non-leptonic states with multiplicity \( \geq 3 \) by fit extrapolated in \( H_T \)
- Evaluate in exclusive luminosity steps to ensure low contamination of CR & VR
- 10 fit functions examined in data and MC.
  - Baseline = highest performing
  - Uncertainty = envelope of other acceptable function predictions

Limits

Semi-classical BH, n=6

CMS (non-rotating), @ MD = 4 TeV: 8.7 TeV using all final states

ATLAS (rotating), @ MD = 5 TeV:
- 7.4 TeV for lepton+jets
- 9 TeV for multijets

ATLAS

\[
\int L \, dt = 3.0 \, fb^{-1}
\]

\( \sqrt{s} = 13 \, TeV \)

\( n_{jet} \geq 3 \)

Step 4

Data 2015

- \( f_5(x) = p_x (1-x)^\alpha (1+x)^\beta x^\gamma \)
- \( f_6(x) = p_x (1-x)^\alpha (1+x)^\beta x^\gamma \)
- \( f_7(x) = p_x (1-x)^\alpha (1+x)^\beta x^\gamma \)
- \( f_8(x) = p_x (1-x)^\alpha (1+x)^\beta x^\gamma \)
- \( f_9(x) = p_x (1-x)^\alpha (1+x)^\beta x^\gamma \)
- \( f_{10}(x) = p_x (1-x)^\alpha (1+x)^\beta x^\gamma \)

Rejected in validation region

\( H_T \) [TeV]
Black holes decaying to different-flavour leptons

- Quantum black holes favour **two-body production** and often support **flavour violation**.
- Selection: exactly 1 e and 1 mu (**new** ATLAS analysis also covers $\mu\tau$, $\mu\tau$!)
- Low SM background to mixed lepton flavours.
- $t\bar{t}$bar dominant dilepton background; single-top, Drell-Yann, diboson also contribute. Take from MC. In ATLAS, use fit to top and diboson backgrounds to extend shape where stats are low
- $W$+jet and multijet processes with a fake electron: use data-driven estimation

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**Limits**

ADD QBH, $n=6$:
4.5 TeV for both ATLAS, CMS
Comparison: dijet analysis sets limits at 8.1 TeV

**CMS PAS EXO-16-001**
ATLAS EXOT-2015-20

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**Figures**

Data/SM Bkg

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

$\mu\tau$ channel

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**Table**

<table>
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<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
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<td>Top Quarks</td>
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<tr>
<td>Drell-Yan</td>
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<td>Diboson</td>
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<td>QTBH RS 1.5 TeV</td>
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<td>RPV $\tau$, 1.5 TeV</td>
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<td>Z' 1.5 TeV</td>
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**Graphs**

- Plot of $M_{\mu\tau}$ (GeV) vs. Events/GeV
- Plot of $m_{\mu\tau}$ (GeV) vs. Events
Vector-like quarks, leptoquarks, simple SM extensions

- Compositeness models remain among the few naturally motivated models not yet excluded. One prediction is **vector-like quarks**
  - Couple to 3rd generation quarks
  - Permit flavour-changing neutral current decays
- Second potential consequence (also consequence of GUTs) is **leptoquarks**
  - Essentially fill in the holes of the SU(5) matrix. Mediate interactions between leptons & quarks of same generation.
  - Pair-produced at LHC; decay gives lq
- Another GUT consequence is additional standard-model like **heavy vector bosons**, W' and Z'
  - Simplest are “sequential standard model” SSM: same couplings as SM W and Z with larger masses
**VLQ to lepton+jets**

- **Model**: pair production of up-type vector quarks $T$ to $Wb$, $Zt$, and $Ht$
  - **One lepton**, high MET, and **plenty of jet activity** including several $b$-tagged jets from $H\rightarrow bb$
  - Also sensitive to SM $tttt$ production
- Selection: isolated leptons, all objects’ $p_T > 30$ GeV. Sort by $N(\text{jets})$, $N(\text{b-tagged jets})$, and number of large-$R$ jets passing $n$-subjet requirements (and in some cases jet mass cuts). Define 11 search channels with $\geq 6$ $\text{j}$ and 9 validation channels with exactly 5 $\text{j}$
- Backgrounds: mainly $tt + \text{bosons or jets incl. heavy flavour}$, also $W/Z+\text{jets}$, single top, diboson
- Uncertainties: $tt$ cross section, generator choice, ISR/FSR, normalisation uncertainties
VLQ to lepton+jets, cont’d

- **CMS analysis** of VLQ pair production: T to Wb, Zt, and Ht
  - One lepton, high MET, ≥ 3 high-pT jets
  - Divide into regions by lepton flavour, N(b-tagged jets), N(W-tagged large-R jets). 16 signal regions.
  - Same background contributions as ATLAS
  - Uncertainties: reweighting of MC distributions to match data add additional uncertainty to background
  - Analyses give **results** sorted by **BR assumption**. Nominal assumption used in CMS limit plot: B(T->bW) = 0.5, B(T->tH) = 0.25, B(T->tZ) = 0.25

CMS-PAS-B2G-16-002
Leptoquarks at ATLAS and CMS

- **LQ pair production**: 2 leptons (ATLAS: exactly 2 e or \( \mu \), CMS: \( \geq 2 \mu \)) and \( \geq 2 \) jets

- Backgrounds: \( tt \), Drell-Yann+jets, diboson, \( W+t \)

- Systematics: JES, lumi, MC shape and norm. (CMS), PDF acceptance & cross section, showering & hadronisation (ATLAS)

- Signal regions **cut in** \( m_{ll} \) and \( S_T \)
  Discriminating variable: **minimum** \( m_{\text{LQ}} \), pairs chosen for smallest mass difference

- CMS also searches in hadronic tau channel.

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**Limits**

Observed limits, \( \beta=1 \)
LQ1 to 1100 GeV (ATLAS)
LQ2 to 1165 GeV (CMS)
LQ3 to 740 GeV (CMS)

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**ATLAS CERN-EP-2016-074**
CMS PAS EXO-16-007
CMS PAS EXO-16-016
W’ to lepton + MET

- Kinematic variable:
  \[ m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi_{\ell\nu})} \]

- Selection: exactly 1 e > 55 (53) GeV or µ > 55 (130) GeV
- ATLAS ensures MET > 55 GeV, \( m_T > 110 \) GeV
- CMS requires \( 0.4 < p_T/\text{MET} < 1.5 \), lepton and MET back-to-back
- Backgrounds: W->lν, Drell-Yann, tt, single-top, diboson. Estimated using MC. Fake lepton contrib. estimated from data
- Systematics: muon scale factors, pT/E scales, MET uncertainties, K factors, PDF

**Limits**

SSM W’

- 4.07 TeV (ATLAS)
- 4.4 TeV (CMS)
Dark matter searches: mono-X

- **EFT** uses contact operators for DM to SM vertex
- Harmonisation of WIMP models a big focus of CMS and ATLAS for Run II. **Dark Matter Forum** targets include (arXiv:1507.00966v1, arXiv:1506.03116v3):
  - Unify simplified models and implementations between analyses
  - Ensure effective field theory models only used within valid regimes (very heavy mediators)
  - Help LHC results to complement direct detection searches

• **Search for DM mediator to MET plus any object on which to trigger**

• **Simplified model** uses mediator explicitly. Usually SM object produced in conjunction with mediator or as ISR

**New physics!**
Jet + MET signatures

- **Lead jet pT > 250** (100) GeV, up to 4 jets (ATLAS), MET > 250 (200) GeV isolated from 4 lead jets.

- **Leptons vetoed.** CMS rejects events with b-jets.

- Z(νν)/W(lν)+jets contributions calculated from simultaneous fit to control regions.

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**Limits**

Mediator mass

1.3 TeV, g_q=1, 90% CL (CMS)
1 TeV, g_q=0.25, 95% CL (ATLAS)

**Top and diboson backgrounds** taken from simulation

**Systematics:** normalisation/ factorisation σ effects, PDF unc., NLO correction, MET, lumi, selection/background estimation uncertainties
Photon + MET

- Leading isolated photon with \( p_T > 150 \) (175) GeV, MET > 150 (170) GeV and not near photon. **Leptons vetoed.**

- ATLAS vetoes if > 1 jet, or jet is near photon.

- CMS rejects if photon near any of 4 leading jets

- Backgrounds: ATLAS takes Z/W+\( \gamma \) from simultaneous fit to control regions; CMS directly from MC. \( \gamma \)+jets from MC. Fake photons estimated from data.
Heavy boson + MET signatures

- **(ATLAS) W/Z hadronic + MET**
  - 1 large-R jet, high MET, no leptons

- **(CMS) Multijet (W/Z hadronic) + MET** includes the above + mono-jet channel

- **Higgs + MET** (ATLAS)
  - H(bb) High MET, no leptons, two small or one large jet, 2 b-tags
  - Also H(γγ), H to four leptons. See ATLAS-CONF-2016-011, ATLAS-CONF-2015-059
General resonance searches

Heavy particles with short lifetimes appear as **narrow resonances**

\[ f(E') = \frac{k}{(E^2 - m^2)^2 + M^2 \Gamma^2} \]

where \( M \) is resonance mass and \( \Gamma \) is decay width.

This appears as a **bump** on a smooth, well-understood background:

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**Discriminating variable**

- **Events**
  - SM
  - **New physics!**

**Arbitrary scale**

**Dijet invariant mass [GeV]**

**CMS Simulation Preliminary**

(13 TeV)
Dijet resonance search

- Search dijet events above unprescaled trigger turn-on
  - **Resonance analysis** uses invariant mass \( m_{jj} \)
  - **Angular analysis** uses rapidity difference in jet CMF

- ATLAS: \( \geq 2 \) jets, \( |y^*| < 0.6 \) (\( \chi < 30 \)), \( m_{jj} > 1 \) (2.5) TeV

- CMS: \( \geq 2 \) jets, \( |\Delta \eta_{jj}| < 1.3 \) (\( \chi < 16 \)), \( m_{jj} > 1.2 \) (1.9) TeV. Uses wide jets to account for gluon FSR

- Background estimate taken from smooth parameterised fit (resonance) or from MC (angular)

- ATLAS also explores \( m_{jj} \) with \( \geq 1 \) b-tag

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**Limits**

- \( q^* \)
  - CL \( n_{LL} = +1 \)
  - 5.2 TeV (ATLAS) 12.0 TeV (ATLAS)
  - 5.0 TeV (CMS) 12.1 TeV (CMS)
Dijets at low masses

- Challenge in dijet analysis below 1 TeV is strong trigger prescales
- Wish to access this region for low-cross section, low-mass signals (Z')
- Solution 1: look for dijet + ISR (jet or γ) events and trigger on the ISR object

- Solution 2: “Trigger level analysis”. Save only partial event data to increase statistics.
  - Challenging! Requires special jet calibration for jets with only calorimeter level information
  - CMS used same strategy in 8 TeV

See Garabed’s talk for more details!
DM including dijet limits: where do we stand?

Limits on simplified DM are filling in remaining holes

Most limits dramatically improved from 8 TeV!
Di-lepton final states

- Models: **SSM Z'**, six narrow E6 gauge group model Z's

- Selection:
  - ATLAS: $\geq 2$ same-flavour isolated leptons, $p_T > 30$ GeV; opposite-sign if $\mu$. Select highest scalar sum-$p_T$ lepton pair

- Systematics: $Z/\gamma$ cross-section (PDF etc), lepton energy scale, trigger, reco., isolation efficiencies, MC stats. Data driven bkg estimation in ee.

- CMS also publishes analysis in di-$\tau$ channel

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### Limits

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<th>$Z'_\psi$</th>
<th>$Z'_{SSM}$</th>
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<tr>
<td>2.8 TeV (ATLAS)</td>
<td>3.4 TeV (ATLAS)</td>
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<tr>
<td>2.6 TeV (CMS)</td>
<td>3.15 TeV (CMS)</td>
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</table>
Resonances in diboson final states

- **W(lν)+jj, Z(ll)+jj, Z(vv)+jj** final states reconstructed by using single large-R jet plus isolated, high pT leptons and/or large MET.

- **W/Z→qqqq** reconstructed as 2 large-R boson-tagged jets

Benchmark heavy vector triplet (W', Z')

- Backgrounds for semileptonic channels: SM diboson and W/Z+jets, ttbar, mis-ID’d jets and photons.

- Estimate qqqq bkg with **dijet fit** to data

- Estimate semileptonic backgrounds by combined fit of **MC** across control regions

Other heavy diboson signatures

- \( Z+\gamma \) sets limits on generic signals of varying widths
  - \( Z(\text{ee,}\mu\mu) \). CMS includes \( Z(\tau\tau) \) analysis, ATLAS includes \( Z(\text{qq}) \).
  - Background taken from fit
- \( W/Z+h \) constrains \( W' \) and \( Z' \) models plus generic resonances
- \( X\rightarrow hh\rightarrow(bb)(bb) \) constrains KK gravitons
  - Resolved analysis: \( \geq 4 \) b-tagged jets in two nearby, high-pT dijet pairs. Boosted analysis: \( \geq 2 \) large-R jets with 3 or 4 b-tags
The diphoton final state

• Caused a great deal of fervour in the community with these results!

• Pairs of isolated photons passing cleaning cuts are parameterised by a smooth fit

  • In CMS, divide into separate spectra by detector region
  • In ATLAS, fits include signal template and therefore 2 distinct results

  • Constrain spin-0, spin-2 RS gravitons

  • Excess at 750 GeV has global significance 2.1σ in ATLAS and 1.6σ in CMS. Require 2016 data to confirm or deny the presence of interesting physics!
... and a whole host of other exotic searches
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The exotic landscape at 13 TeV

Empty and desolate, yet still fun to explore!

Does the diphoton analysis offer excitement on the horizon?
Backup
W/Z hadronic + MET

- Selection
  - 1 large-R jet, MET > 250 GeV isolated from all small-R jets, no leptons
  - Large-R jets reclustered, selected by jet mass and $D_2$ substructure variable
- Systematics:
  - Dominant: modelling of large-R jet parameters ($D_2$, mass, energy)
  - Other: small-R JES, lumi, reconstruction and ID efficiency for leptons
- Backgrounds: ttbar, W+jets, Z+jets, single-top

ATLAS-CONF-2015-080
Multijet + MET

- ≥ 2 jets and high MET. Lepton veto. MET is kinematic variable
  - For mono-V look at AKT8 jets with n-subjettiness cut
  - Includes mono jet (top left) and mono-vector boson hadronic (top right) signatures
- Backgrounds: Z(νν)+jets, W(νl)+jets dominant & taken from data control regions. Top and diboson subdominant and taken from MC.
- Systematics: V-tagging in large-R jets, normalisation of top & diboson background, luminosity, b jet veto efficiency
- Consider vector, axial-vector simplified models

Limits

Vector, axial-vector mediators @ 90% CL: 1.3 TeV
Higgs + MET

- All s-channel vector mediators Z' with higgs as ISR/FSR
- **H(bb)+MET**: High MET, no leptons, resolved (2 small-R jets) and boosted (large-R jet with 2 ass. track jets) channels
- **H(γγ)+MET**: 2 central isolated photons. High MET. Modelled with fit; count number of events with myy in Higgs mass window.
- **H(llll)+MET**: reinterpretation of measurement results extended to high-MET region
Monojet further information I: limit vs. coupling

95% CL upper limit on $\sigma/\sigma_{\text{theory}}$

- **observed**
- **median ($\pm 1\sigma$)**

Axial Vector Mediator
- $m_\chi = 150$ GeV, $m_A = 1$ TeV
- $g = g_\chi = g_q$

**ATLAS**
- $\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

$g$
Monojet further information II: WIMP-proton scattering cross-section limits

CMS Preliminary

\( g_{\text{DM}} = g_{\text{SM}} = 1 \)

Vector

\( \sigma_{\text{SI}} (\text{cm}^2) \)

Median Expected 90% CL
Observed 90% CL
8TeV - Median Expected 90% CL
8TeV - Observed 90% CL
LUX

\( m_{\text{DM}} (\text{GeV}) \)

\( \sigma_{\text{SD}} (\chi\text{-proton}) [\text{cm}^2] \)

ATLAS
\( \sqrt{s} = 13 \text{ TeV, 3.2 fb}^{-1} \)

90% CL limits
XENON100
LUX
PICO-2L
PICO-60
Axial Vector Mediator
Dirac Fermion DM
\( g_q = 0.25, g_\chi = 1.0 \)
The jet+γ final state

- ATLAS uses jet+γ events to set limits on excited quarks, RS1 and ADD quantum black holes, generic resonances.
- Selection: at least 1 each of an isolated photon and a jet, both pT > 150 GeV, |Δη| < 1.6 between the lead jet and photon, and photon is not near any jet.
- Data-driven background estimate from fit.
  - Fit above 1 TeV for all signals but ADD QBH
  - Fit for ADD QBH from 2 TeV
- Systematics: jet and γ energy scales, γ trigger, ID, and isolation efficiencies, function choice.
  - Here function choice modelled by testing spurious signal for each mass point and range of MC settings, taking result as uncertainty.

Limits
- q* 4.4 TeV
- RS1 QBH 3.8 TeV
- ADD QBH 6.2 TeV
Z+γ search

- Z(ee) or Z(μμ) + photon
- Require exactly 2 opposite-sign leptons, at least 1 photon isolated from leptons and with significant fraction of energy in Zγ system
- Search in m_{Zγ} > 200 GeV for localised excesses. Background described by parametric fit.
- Signal shape is generic based on the crystal ball function
W/Z+higgs final state

- Signature: Z(ll), W(lν), or Z(νν) plus h(bb)

- Reconstruct higgs candidate with large-R jet associated to b-tagged track jets and within selected mass window

- Use simplified model of heavy vector triplets as benchmark: V couples to higgs and SM bosons

- Use transverse mass as discriminant in 0-lepton channel; m_{VH} in other channels

- Background modelling taken from MC

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**ATLAS CERN-EP-2016-142**
X->hh->bbbb

- Resolved analysis: search for 4 b-tagged small-R jets. Reconstruct as 2 dijet pairs with small ΔR within pair.

- Boosted: 2 large-R jets each with associated b-tagged track jets (3 or 4 tags overall).

- Switch at resonance masses of 1100 GeV.

- Compare dijet/fatjet masses to top quark mass and higgs mass using probability variable. Use for ttbar veto and to define signal region near Higgs mass.

ATLAS EXOT-2015-18