Search for heavy resonances with the ATLAS detector

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On behalf of the ATLAS Collaboration

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PRiSMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

ATLAS EXPERIMENT

Outline

Motivation

- Standard Model (SM) still most successful and comprehensive theory to describe the microcosm
- Some open questions remain:
  - 19 arbitrary parameters
  - Lightness of Higgs boson (mass hierarchy)
  - Grand unification (GUT)
  - Dark matter
  - ...

LHC run-1 provided opportunity to search in totally unexplored regions

- pp collisions, $\sqrt{s}$ =8 TeV, L_{int} ≈20 fb^{-1} (in 2012)

Search strategy

Analysis channels

- Lepton+E_T^{miss}
- Dilepton
- Dijet
- Dihiggs$\rightarrow$4b
- Lepton+jet
- Photon+jet
- Multi-Object (leptons, jets)
- WZ $\rightarrow$ talk of Liv Wiik-Fuchs

Models

- Heavy vector gauge bosons
  $\rightarrow$ E_6 gauge group, chiral bosons..
- Randall-Sundrum Graviton
- Minimal Walking Technicolor
- ADD and Quantum black holes (QBH)
- Microscopic black holes
- Contact interactions and large extra dimensions (non-resonant search)

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New spin-1 resonances

- Leptonic final states
- Hadronic final states

Heavy vector gauge bosons

Use Sequential Standard Model (SSM) as benchmark model

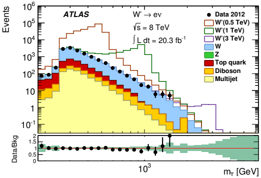
- Heavy vector gauge bosons with spin 1 outside the SM (W′, Z′)
- Couplings to fermions identical to those of SM bosons
- Interference between SM and new gauge bosons neglected
- Small intrinsic width of the resonance compared to detector resolution ($\frac{\Gamma_{W'}}{m_{W'}} \approx 3.6\%$)

Extension to chiral bosons (W^*, Z^*):

- Electroweak doublet spin 1 vector boson
- Main theoretical motivation: Hierarchy problem
- Predicted by at least three approaches for explaining the relative lightness of the Higgs doublets
- Anomalous magnetic moment type couplings
$\rightarrow$ significantly different kinematic distributions

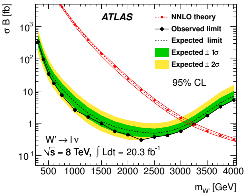
Charged vector gauge bosons

- Select events with high energy leptons (p_T^e >125 GeV) and large missing transverse energy (E_T^{miss} >125 GeV)
- Use transverse mass $m_T = \sqrt{p_T E_T^{miss}(1 - \cos\phi_{l\nu})}$ as signal discriminant → falls sharply at boson mass



Background processes

- W boson decays $W \to l\nu$
- Dibosons (WW, WZ, ZZ), top pair and single top production
- Z boson decays
- QCD (mainly multijet) → estimated from data



Limits

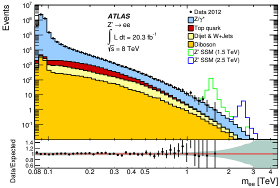
- Large off-shell production for higher pole masses

	m_{exp}	m_{obs}
W′	3.17	3.24
W*	3.12	3.21

95% CL lower mass limit (in TeV)
arXiv:1407.7494

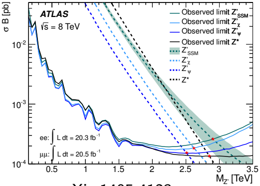
Neutral vector gauge bosons

- Final states with two isolated leptons
- Background scaled to data ($80< m_{ll} <110\,\text{GeV}$)
- MC templates used to set limits
  $\rightarrow$ actual signal shape on reconstruction level taken into account
- Systematics dominated by PDF variation & choice



Additional models:

E6 Z'_χ and Z'_ψ $\rightarrow$ GUT motivated

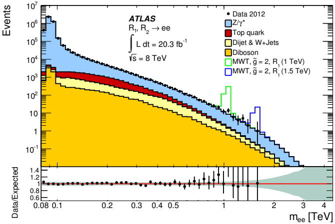


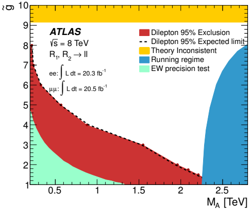
arXiv:1405.4123

- Large off-shell production for higher pole masses
- For lower pole masses, limits become stronger with decreasing width (small effect only)

Minimal Walking Technicolor

- Minimal Walking Technicolor with composite Higgs
  $\rightarrow$ bound by (strong force) technicolor
- Technimesons decaying to dilepton final states
- Narrow resonances with masses of a few hundred GeV



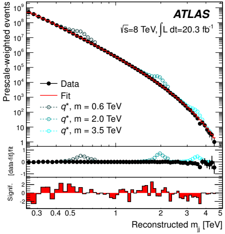


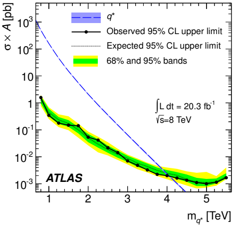
arXiv:1405.4123

Dijet resonances

- Search for resonances in the invariant dijet-mass spectrum (q^* as benchmark model)
- Make use of prescaled triggers and delayed data stream $\rightarrow$ possible to enlarge mass range (0.25-4.5 TeV)
- Background estimation by fitting the data: $f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x}$

No significant excess observed $\rightarrow$ $m(q^*) >$4.09 TeV (95% CL.)





arXiv:1407.1376

Dijet resonances

Model-dependent interpretations:

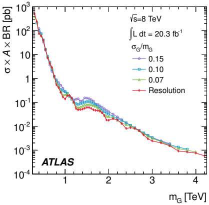
- Excited quarks (q^*)
- Color-octet scalar ("s8")
- SSM W′, charged chiral bosons (W*)
- Quantum black holes (QBH)

model	decay	Obs.	Exp.
q^*	qg	4.09	3.99
s8	gg	2.72	2.83
W′	$q\bar{q}'$	2.45	2.51
W*	$q\bar{q}'$	1.75	1.93
QBH	q, g	5.82	5.82

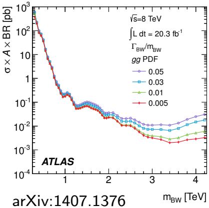
95% CL lower mass limit (in TeV)

Model-independent interpretations:

- Gaussian shape



- Breit-Wigner
  - Γ/M=0.5-5 %
  - qq, qg, gg, $q\bar{q}$ initial states



arXiv:1407.1376

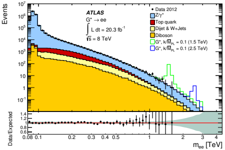
Extra dimensions

- Randall-Sundrum Graviton
- ADD and Quantum Black Holes
- Microscopic Black Holes

Randall-Sundrum Graviton

Randall-Sundrum model:

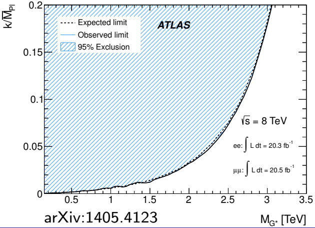
- One warped extra dimension (ED)
- Contains two 4-dimensional branes: TeV brane and Planck brane
- Gravity originates from Planck brane
- SM particles confined to TeV brane



Lightest Kaluza-Klein (KK) excitation mode (G*)

- Coupling strength $k/\bar{M}_{Pl}$,
  with k as warp factor of the ED, reduced Planck mass $\bar{M}_{Pl} = M_{Pl}/\sqrt{8\pi}$
  $\rightarrow$ G* resonance narrow for $k/\bar{M}_{Pl} < 0.2$
- Intrinsic width proportional to $(k/\bar{M}_{Pl})^2$
- Produced via $q\bar{q}$ annihilation and gluon fusion
  $\rightarrow$ decays to SM fermions and bosons

Search for spin-2 resonances
$\rightarrow$ Dilepton final states still sensitive

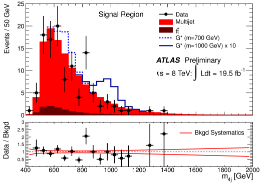


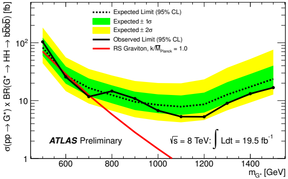
arXiv:1405.4123

Resonant Higgs-pair production

- Decay of SM Higgs boson reconstructed from pair of b-tagged jets (anti-k$_t$, R=0.4)
  $\rightarrow$ dijet system with $p_T > 200\,\mathrm{GeV}$, $m_{jj} \approx m_H$
- Bulk Randall-Sundrum model (one warped extra dimension, $k/\bar{M}_{Pl} = 1$) as benchmark model
  $\rightarrow$ SM fermion and boson fields free to propagate into extra dimension
- Natural width of G* resonance smaller than m_{4j} resolution ($\approx$15%)

Background dominated by multi-jet events (estimated out of data)
$t\bar{t}$ (shape MC, normalization from data), Z+jets (MC)





ATLAS-CONF-2014-005

ADD and Quantum Black Holes (QBH)

ADD: Arkani-Hamed, Dimopoulos, Dvali

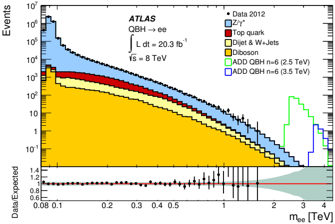
- Motivated by hierarchy problem
- $n \geq 1$ additional flat extra dimensions (gravity only)
- Planck scale M_{th} lowered to TeV scale M_D by introducing extra spatial dimensions
  $\rightarrow$ Quantum Black Holes produced if collision energy $\geq M_D$

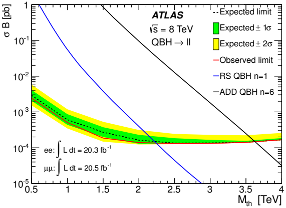
QBH

- Predicted by low scale quantum gravity models
- QBH with masses above M_D $\rightarrow$ decay to two particles
- Model assumption: total angular momentum, color and charge conserved

QBH - dilepton final states

- QBH decay to dileptons
- QBH with neutral charge
- gg or $q\bar{q}$ production

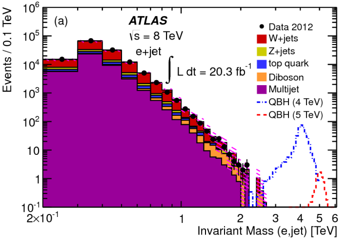


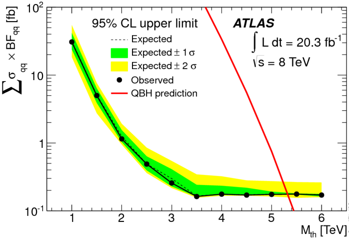


arXiv:1405.4123

QBH - lepton plus jet

- Lepton $p_{T,l} > 130\,\mathrm{GeV}$
- Jet $p_{T,jet} > 130\,\mathrm{GeV}$ (anti-k_t, R=0.4)
- Data control regions ($440 < m_{e,jet} < 900\,\mathrm{GeV}$) used for normalisation of MC (EW) and data-driven (multijet) background estimates
- Background estimation to higher masses via fits to data
- Systematics dominated by fit and PDF uncertainties

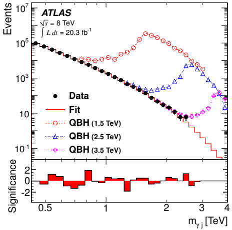


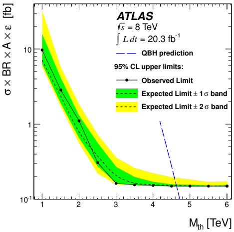


PRL 112, 091804 (2014)

QBH - photon plus jet

- Photon $p_{T,l} > 125\,\text{GeV}$
- Jet $p_{T,jet} > 125\,\text{GeV}$ (anti-k_t, R=0.6)
- Background estimation by fitting the data ($m_{\gamma j}$ spectrum): $f(x) = p_1(1-x)^{p_2} x^{-(p_3+p_4 \ln x)}$

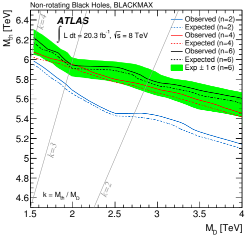


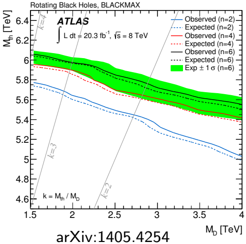


PLB 728, 562 (2013)

BH - semi-classical production

- $M_{th} > M_D$ (higher dimensional gravitational scale)
- Loss of mass and angular momentum by Hawking radiation
- Decay to ensemble of (high-energy) particles





arXiv:1405.4254

Use $S_T = \sum E_T$ (E_T >50 GeV) as signal discriminant (including E_T^{miss})
$\rightarrow$ independent of particle multiplicity

Dominant backgrounds

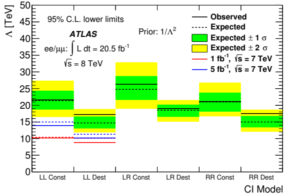
Z+jets, W+jets, $t\bar{t}$

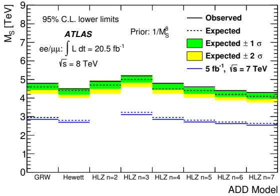
$\rightarrow$ define control regions with constraints on dilepton mass or E_T^{miss}

Contact interactions (CI) and large extra dimensions (LED)

1. Four-fermion contact interactions:
    - Energy scale Λ corresponds to binding energy between fermion constituents (quark and lepton compositeness)
    - Use dilepton forward-backward asymmetry $\rightarrow$ sensitive to chiral structure of interaction
    - Interference between DY and CI dominant for higher values of Λ
2. ADD model:
    - Planck scale M_D can be in TeV range $\rightarrow$ small mass differences in KK modes
    - Sum over KK modes up to string scale $M_S = 2\sqrt{\pi}[\Gamma(\frac{n}{2})]^{1/(n+2)}M_D$
    - Small interference effects only

Non-resonant search in dilepton final states:





arXiv:1407.2410

Summary & Outlook

- LHC run-1 explored new regions with higher centre-of-mass-energies and significant higher luminosities than previous experiments
  $\rightarrow$ But: no new physics observed yet
- SM still most consistent theory
- New data with $\sqrt{s}$ up to 14 TeV eagerly expected:
  $\rightarrow$ search for higher masses, smaller couplings

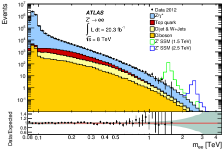
Results with 8 TeV:

new!

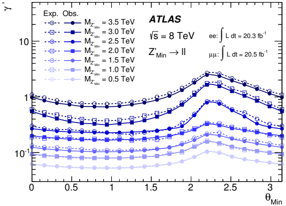
- New Spin-1 resonances:
  - Lepton + E_T^{miss} (arXiv:1407.7494)
  - Dilepton (arXiv:1405.4123)
  - Dijet (arXiv:1407.1376)
  - WZ (arXiv:1406.4456) → talk of Liv Wiik-Fuchs
- Extra-Dimensions (ED): Randall-Sundrum
  - Dilepton (arXiv:1405.4123)
  - Dihiggs→4b (ATLAS-CONF-2014-005)
  - Contact interactions and large ED (arXiv:1407.2410)
- Extra-Dimensions: (Quantum) Black Holes
  - Dilepton (arXiv:1405.4123)
  - Lepton + jet (PRL 112, 091804 (2014))
  - Photon + jet (PLB 728, 562 (2013))
  - Multi-Object (leptons, jets) (arXiv:1405.4254)
- Composite Higgs in Minimal Walking Technicolor
  - Dilepton (arXiv:1405.4123)

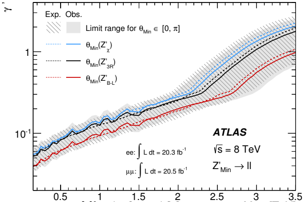
Backup

Minimal Z′ model



- Three characteristic parameters: mass of Z'_{min}, γ' (coupling strength relativ to SM Z), θ_{min} (mixing between generators of weak hypercharge Y and (B-L) gauge groups (θ_{Min}))
- Interference with SM Z/γ^* included
- Varying width of Z'_{min} (varies with coupling) included
- Couplings to hypothetical right-handed neutrinos and to W boson pairs not included





arXiv:1405.4123

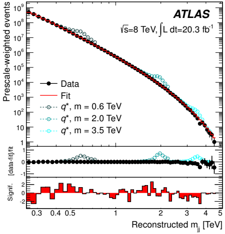
Dijet resonances

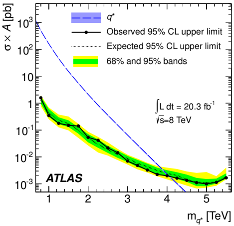
Search for resonances in the invariant dijet-mass spectrum in the context of a q^* benchmark model

- Assumption: quarks have substructure
- Excited quarks have same couplings than SM quarks
- Decay into SM quarks and leptons

Background estimation by fitting the data: $f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x}$

No significant excess observed $\rightarrow$ $m(q^*) >$4.09 TeV (95% CL.)





arXiv:1407.1376

Data driven background - QCD

- Hard to simulate due to high suppression by selection cuts (even so it is a process with high cross-section)
- Use matrix method to determine amount of fake electrons (jets) that pass selection criteria
- Calculate N_{QCD} based on the probability that a real / fake electron fulfills loose or tight criteria

tight	Standard selection
loose	Standard selection but "looser" electron identification (e.g. no isolation..)
Real rate ϵ_R	Probability that real "loose" electrons also pass tight criteria (derived using MC)
Fake rate ϵ_F	Probability that fake loose electrons also pass tight criteria (derived using data)

Matrix method

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_R & \epsilon_F \\ 1-\epsilon_R & 1-\epsilon_F \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}$$

- Wanted truth quantities (not measurable):
  N_R (true number of electrons) and
  N_F (true number of fake electrons)
- Measurable observables:
  N_T (electron candidates that fulfill tight criteria) and
  N_L (electron candidates that fulfill loose but not tight criteria)
- Use first line only: $N_T = \epsilon_R N_R + \epsilon_F N_F$

  N_{QCD}
- And invert the matrix above:
  $N_{QCD} = \epsilon_F N_F = \frac{\epsilon_F}{\epsilon_R - \epsilon_F}(\epsilon_R(N_L + N_T) - N_T)$