

Search for heavy resonances with the ATLAS detector

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On behalf of the ATLAS Collaboration

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and Research



Outline

Motivation

Analyses

Summary

References

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, $\sqrt{s} = 8 \text{ TeV}$, $L_{int} \approx 20 \text{ fb}^{-1}$ (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
→ significantly different kinematic distributions

Charged vector gauge bosons

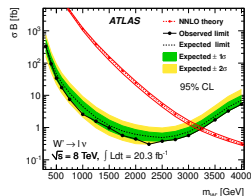
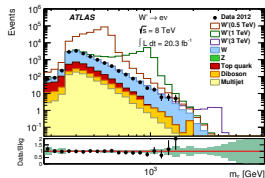
- ▶ Select events with high energy leptons ($p_T^e > 125$ GeV) and large missing transverse energy ($E_T^{miss} > 125$ GeV)
- ▶ Use transverse mass $m_T = \sqrt{p_T E_T^{miss} (1 - \cos \phi_{l\nu})}$ as signal discriminant \rightarrow falls sharply at boson mass

Background processes

- ▶ W boson decays $W \rightarrow l\nu$
- ▶ Dibosons (WW, WZ, ZZ), top pair and single top production
- ▶ Z boson decays
- ▶ QCD (mainly multijet) \rightarrow 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

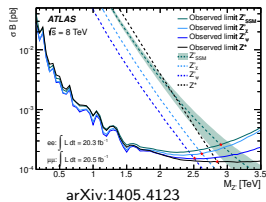
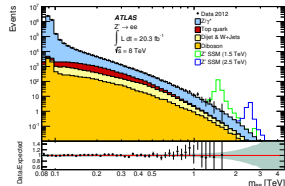
Neutral vector gauge bosons

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

Additional models:

E6 Z'_χ and Z'_ψ → GUT motivated

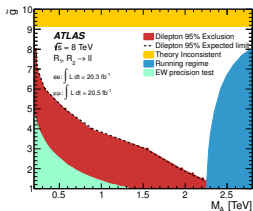
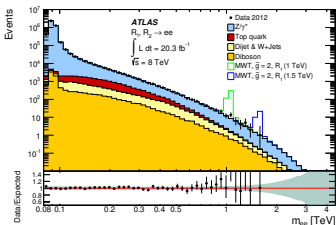
- ▶ Large off-shell production for higher pole masses
- ▶ For lower pole masses, limits become stronger with decreasing width (small effect only)



arXiv:1405.4123

Minimal Walking Technicolor

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

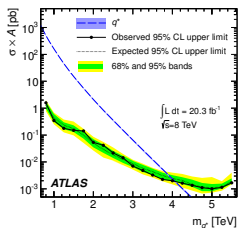
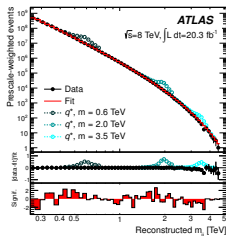


arXiv:1405.4123

Dijet resonances

- ▶ Search for resonances in the invariant dijet-mass spectrum (q^* as benchmark model)
- ▶ Make use of prescaled triggers and delayed data stream
→ 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 → $m(q^*) > 4.09$ TeV (95% CL.)



arXiv:1407.1376

Dijet resonances

Model-dependent interpretations:

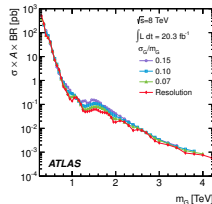
- ▶ Excited quarks (q^*)
- ▶ Color-octet scalar ("s8")
- ▶ SSM W' , charged chiral bosons (W^*)
- ▶ Quantum black holes (QBH)

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)

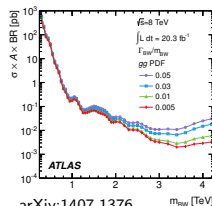
Model-independent interpretations:

- ▶ Gaussian shape



- ▶ Breit-Wigner

- ▶ $\Gamma/M = 0.5-5\%$
- ▶ qq, qg, gg, $q\bar{q}$ initial states

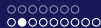


arXiv:1407.1376



Extra dimensions

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



Randall-Sundrum Graviton

Randall-Sundrum model:

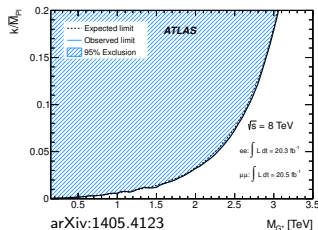
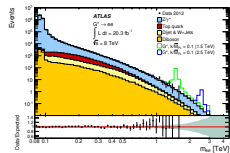
- ▶ One warped extra dimension (ED)
- ▶ Contains two 4-dimensional branes: TeV brane and Planck brane
- ▶ Gravity originates from Planck brane
- ▶ SM particles confined to TeV brane

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

- ▶ Coupling strength k/\bar{M}_{Pl} ,
with k as warp factor of the ED, reduced Planck mass $\bar{M}_{Pl} = M_{Pl}/\sqrt{8\pi}$
→ 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
→ decays to SM fermions and bosons

Search for spin-2 resonances

→ Dilepton final states still sensitive



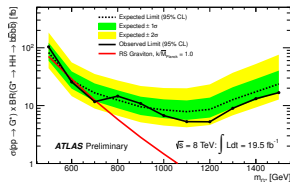
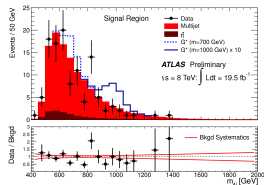


Resonant Higgs-pair production

- ▶ Decay of SM Higgs boson reconstructed from pair of b-tagged jets (anti- k_t , $R=0.4$)
→ dijet system with $p_T > 200$ GeV, $m_{jj} \approx m_H$
- ▶ Bulk Randall-Sundrum model (one warped extra dimension, $k/\bar{M}_{Pl} = 1$) as benchmark model
→ 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
→ Quantum Black Holes produced if collision energy $\geq M_D$

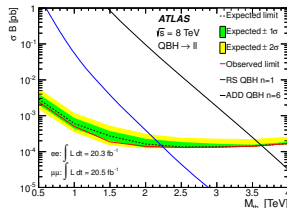
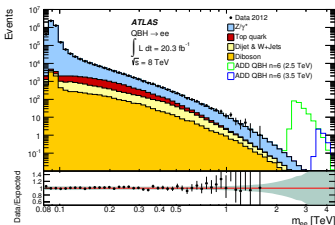
QBH

- ▶ Predicted by low scale quantum gravity models
- ▶ QBH with masses above M_D → 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

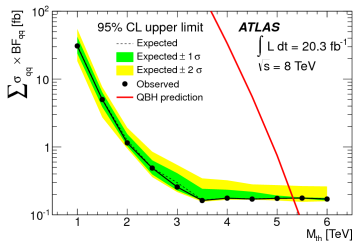
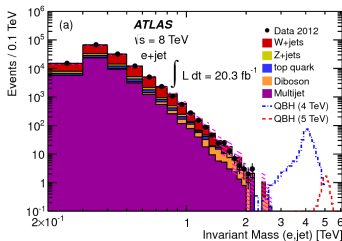


arXiv:1405.4123



QBH - lepton plus jet

- ▶ Lepton $p_{T,l} > 130$ GeV
- ▶ Jet $p_{T,jet} > 130$ GeV (anti- k_t , $R=0.4$)
- ▶ Data control regions ($440 < m_{e,jet} < 900$ 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



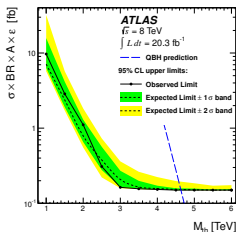
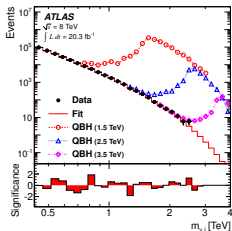
PRL 112, 091804 (2014)



QBH - photon plus jet

- ▶ Photon $p_{T,l} > 125$ GeV
- ▶ Jet $p_{T,jet} > 125$ 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

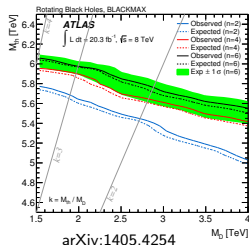
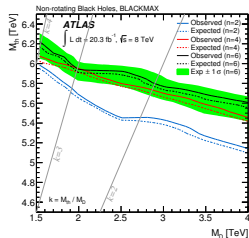
Use $S_T = \sum E_T$ ($E_T > 50$ GeV) as signal discriminant (including E_T^{miss})

→ independent of particle multiplicity

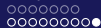
Dominant backgrounds

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

→ define control regions with constraints on dilepton mass or E_T^{miss}



arXiv:1405.4254



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

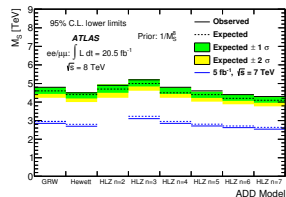
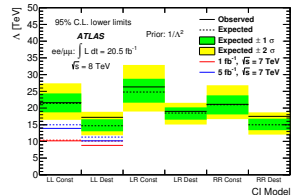
1. Four-fermion contact interactions:

- ▶ 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
→ But: no new physics observed yet
- ▶ SM still most consistent theory
- ▶ New data with \sqrt{s} up to 14 TeV eagerly expected:
→ search for higher masses, smaller couplings

Results with 8 TeV:



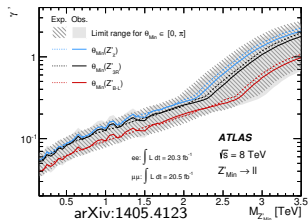
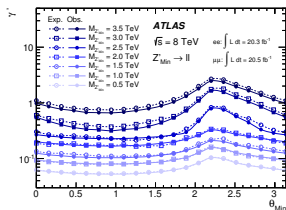
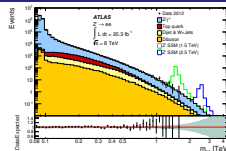
new!

- ▶ 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



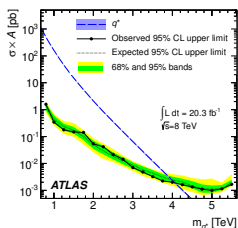
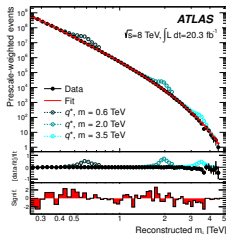
Dijet resonances

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: $N_T = \epsilon_R N_R + \epsilon_F N_F$
- ▶ And invert the matrix above:


 N_{QCD}

$$N_{QCD} = \epsilon_F N_F = \frac{\epsilon_F}{\epsilon_R - \epsilon_F} (\epsilon_R (N_L + N_T) - N_T)$$