# SEARCHES FOR NON-SUSY EXOTICS IN ATLAS



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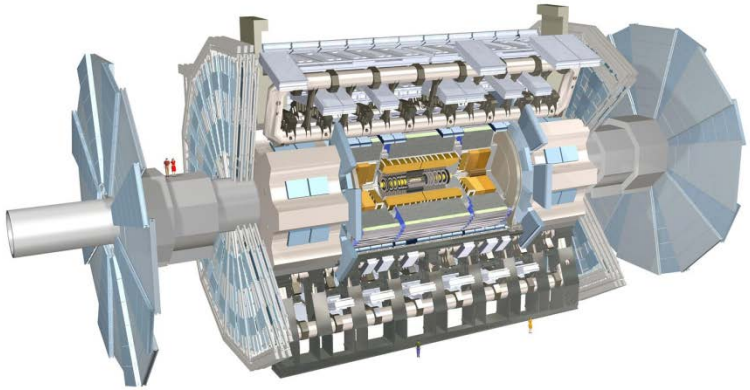
University of Victoria

# MOTIVATION



- **Standard Model (SM) has generally given excellent agreement with experimental observation**
- **Discovery of Higgs boson provides an important missing piece**
- **Questions remain…**
  - Dark matter, naturalness, unification with gravity…

- **SUSY is one route to answering many questions**
- **But we can look for much with ATLAS data that is not SUSY…**

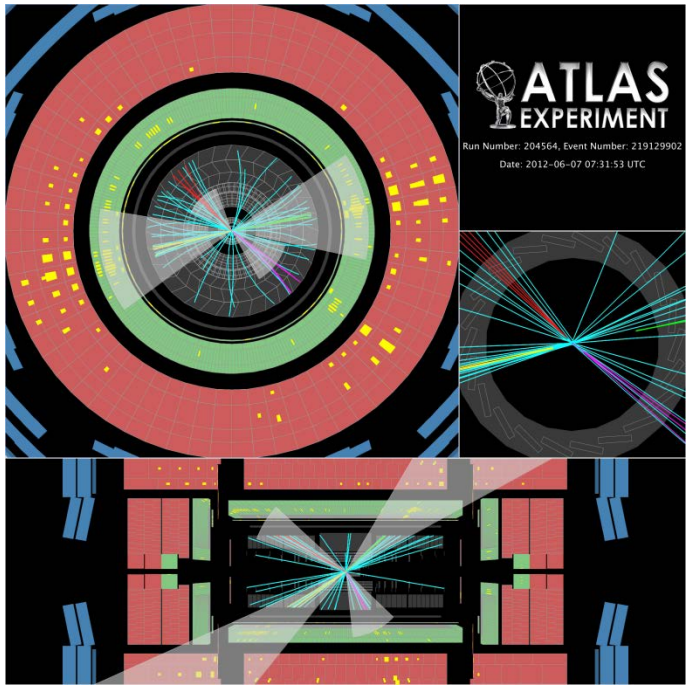


# OVERVIEW OF EXOTIC RESULTS



- **New Heavy Bosons**
  - Z', W', G*
- **Searches at High Energy Scales**
  - **Contact Interactions**
  - Black Holes
  - Excited electrons
  - **Dijet resonances**
- **Unique Signatures**
  - Long-lived particles

NEW!



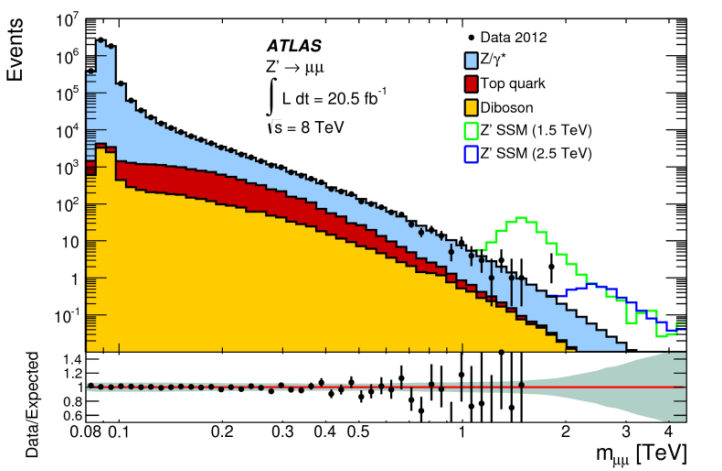

- ***Some recent* searches for non-SUSY new physics**
  - No significance evidence for new physics
  - 2012 data using ~20 fb-1
  - Limits set on a wide set of predictions for Exotics extensions

# SEARCHES FOR NEW HEAVY BOSONS

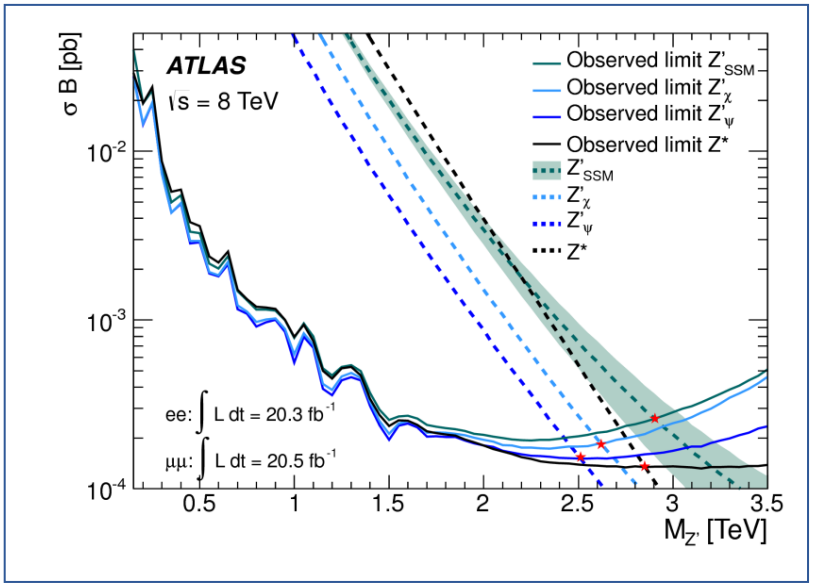


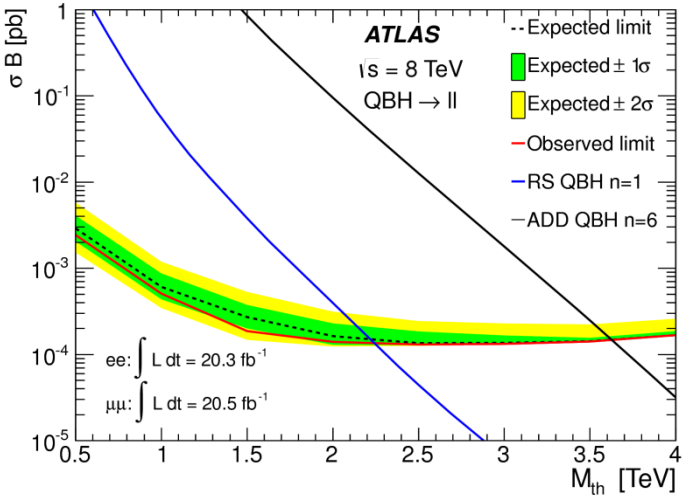
- **Searches for new strong dynamics or for extra dimensions**
- **Provide non-SUSY explanation for electroweak symmetry breaking**
- **Signature based searches provide more model independence, but various benchmark models used**

# HIGH-MASS DILEPTON RESONANCES



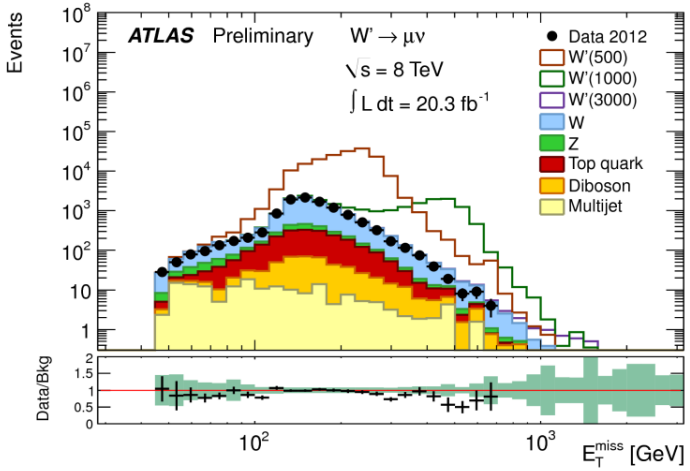

- **Invariant mass isolated muon or electron pairs**
- **Dominant background is Z/γ* → ll**
- **Data-driven estimation of di-jet and W+jet backgrounds**
- **Limits set of various models with no excess above SM background:**
  - SSM Z', E6 Z' , Z*
  - Minimal models, Walking Technicolor
  - RS-Graviton, Quantum Black Holes

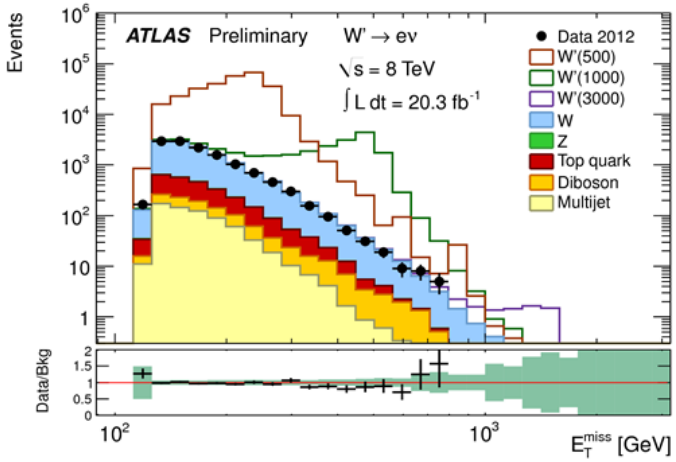



arXiv:1405.4123

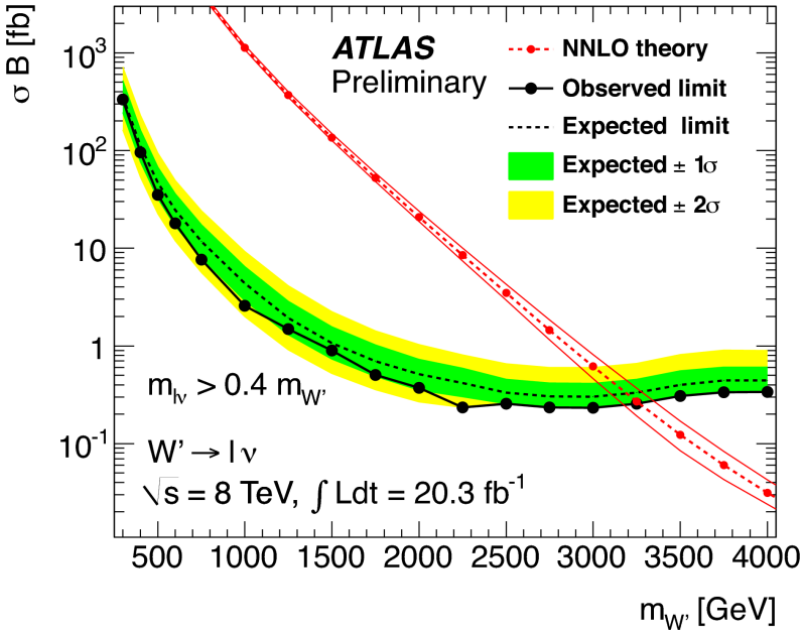
# LEPTON + $E_T^{MISS}$ HIGH-MASS STATES




[ATLAS-CONF-2014-017]

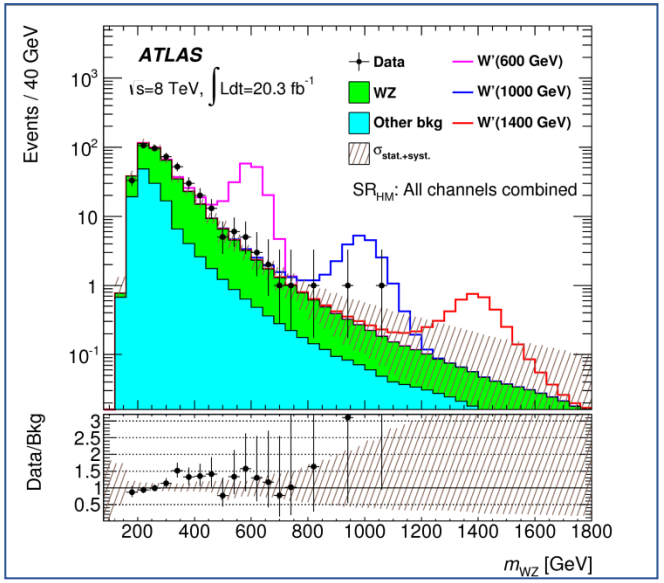
- **W' / W* → lυ**
- **Isolated high-$P_T$ lepton + missing transverse energy are selected**
- **W is main background**
- **Combined limit (~3.2 TeV) from muon and electron channels**
  - Also dark matter interpretation

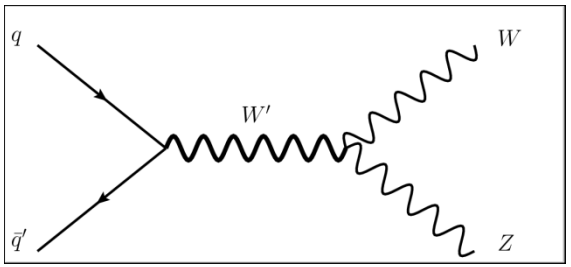


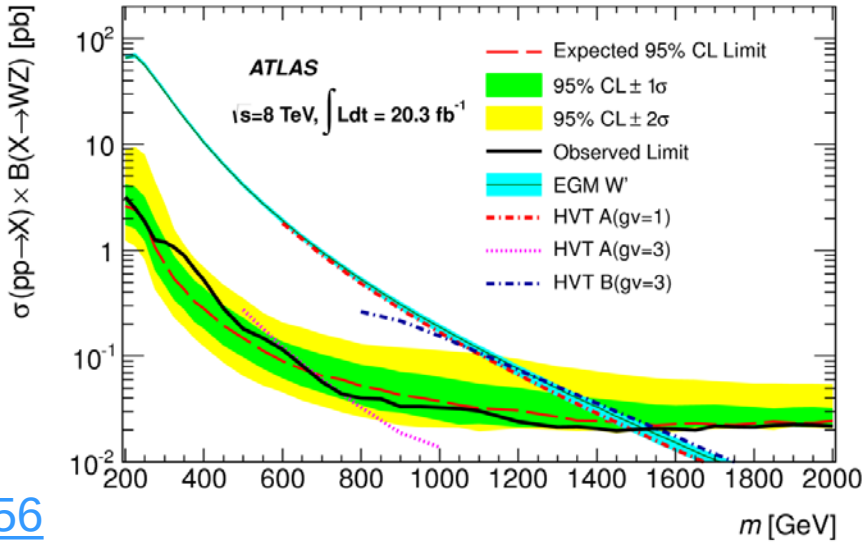
# WZ RESONANCES TO LEPTONS

- **W'→ WZ →3l+υ**
- **Exactly 3 charged leptons are selected**
  - eυee, μυee, eυμμ, μυμμ
- **Dominant background is SM WZ production, consistent with data**
- **95% C.L. limits are set combining 4 decay channels**
  - Extended gauge model W'
  - Heavy Vector Triplet



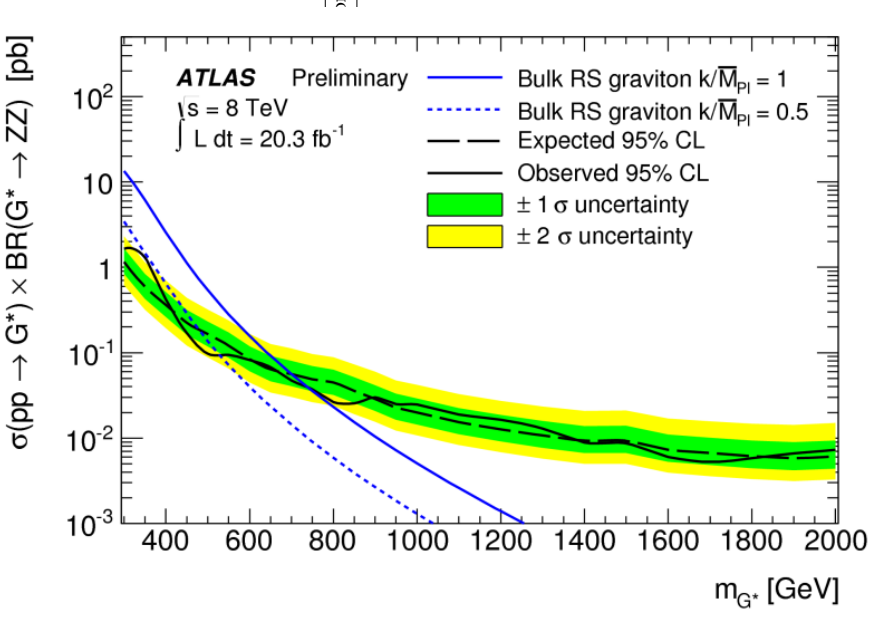


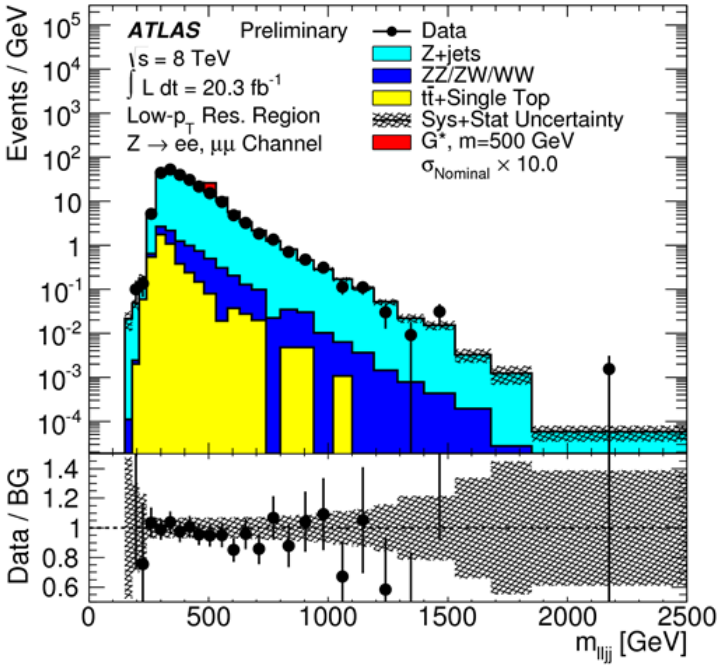




arXiv:1406.4456

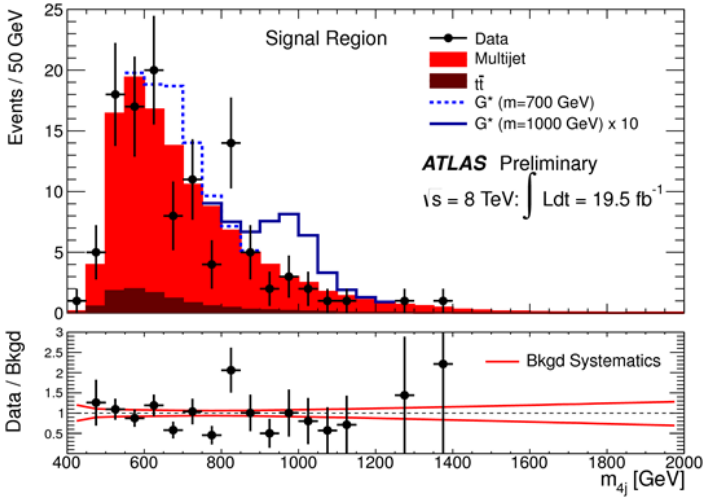
# RESONANT DIBOSON PRODUCTION TO LEPTONS AND QUARKS

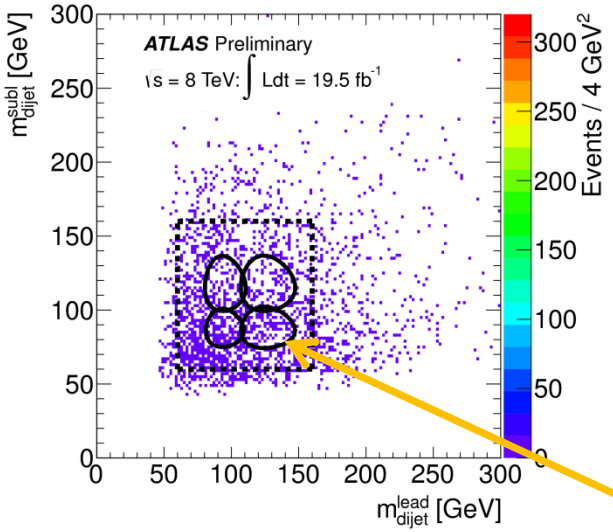



- **ZZ or ZW → llqq**
- **Mass of dijet, dilepton system reconstructed in 3 regions**
  - High and low $P_T$ regions where jets are resolved and merged-jet regions
- **Z+jet dominant background is corrected with data from sidebands**
- **Upper limits set on σ x BR of Kaluza–Klein gravitons predicted by Randall–Sundrum and EGM W'**

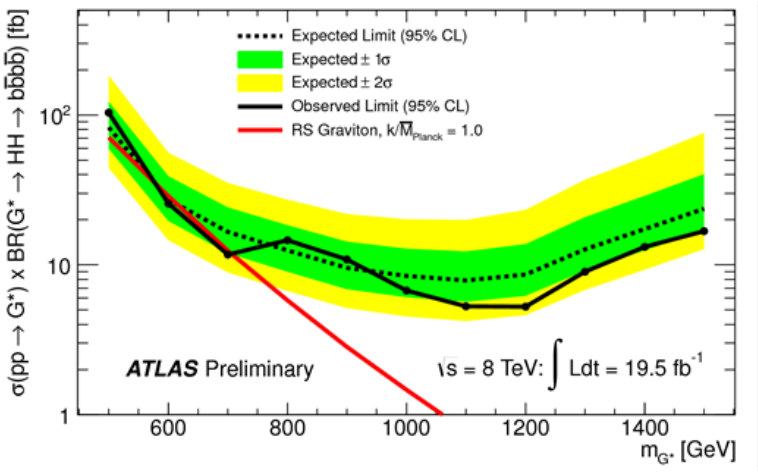
# RESONANT HIGGS-PAIR PRODUCTION → 4B




ATLAS-CONF-2014-005

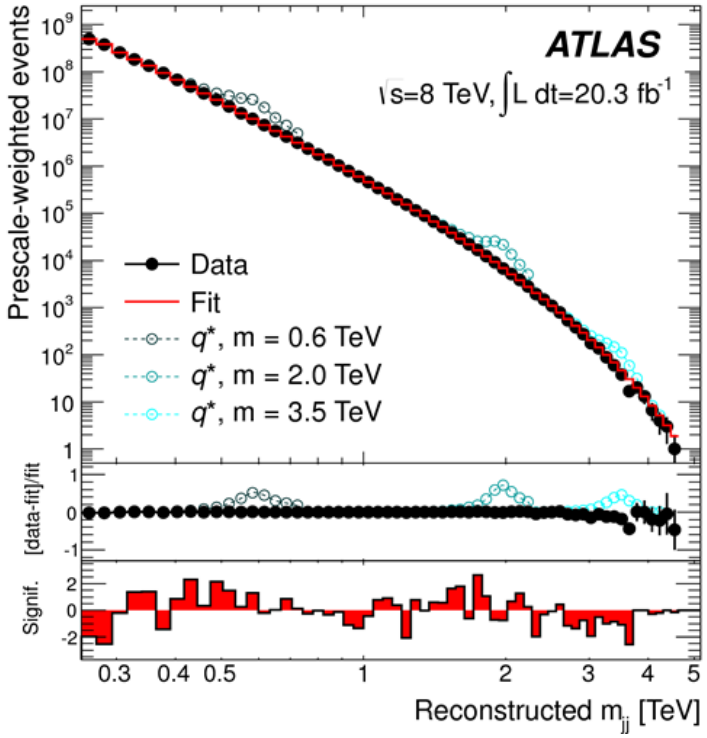
- **Search for Kaluza-Klein excitation of RS graviton**
  - G* → HH → 4b (~3% BR)
- **Invariant mass of 4 b-jets with $P_T$ > 40 GeV**
- **Two pair of b-tagged jets with dijet invariant mass ~ $M_H$**
- **No excess observed**
  - Observed upper limits on σxBR ranges from 100 fb at 500 GeV to 7 fb at 1 TeV
  - Limits on KK G* in warped (RS) ED 590 to 710 GeV

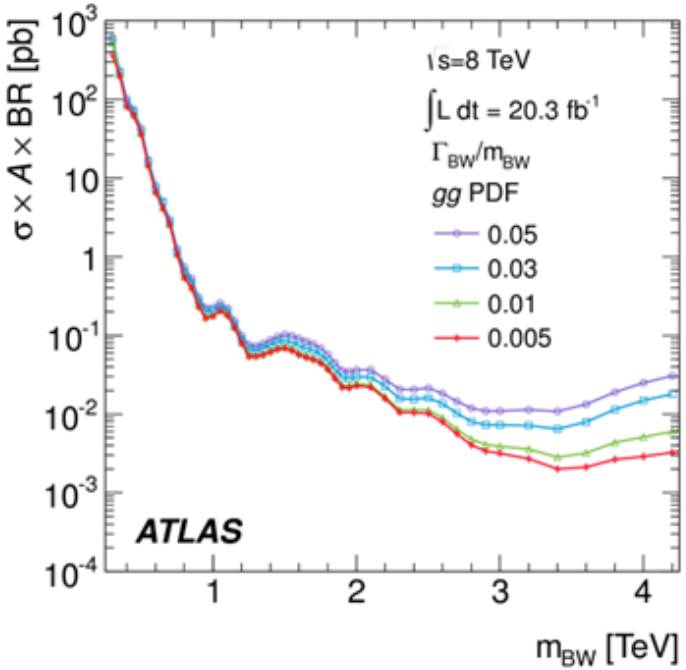



**Signal, ZZ and ZH Regions**

# SEARCHES AT HIGH ENERGY SCALES

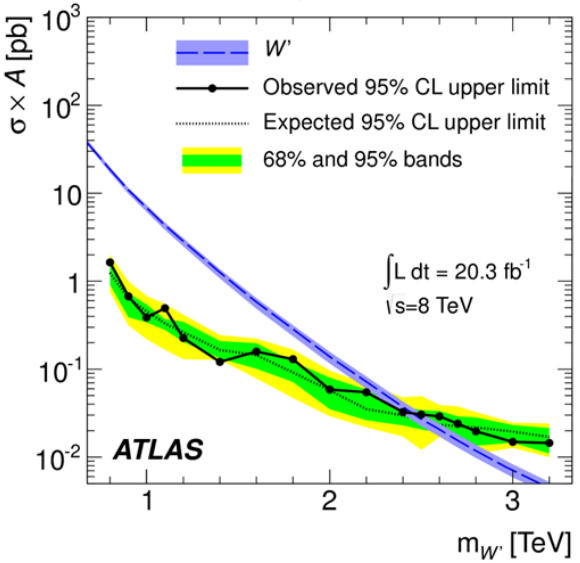
# DIJET MASS RESONANCES



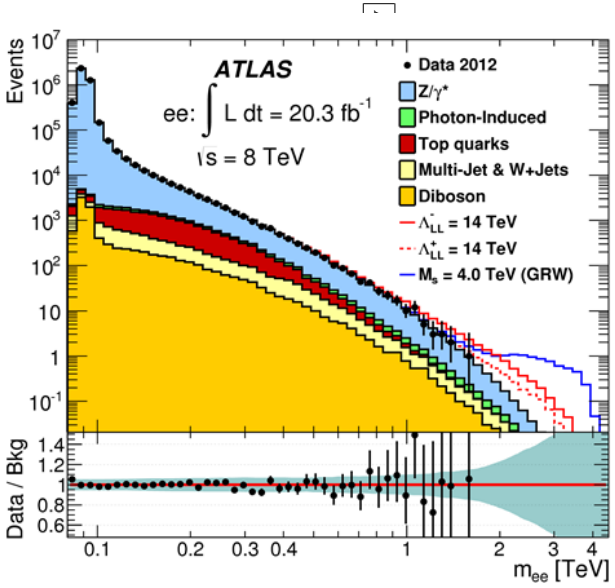




arXiv:1407.1376

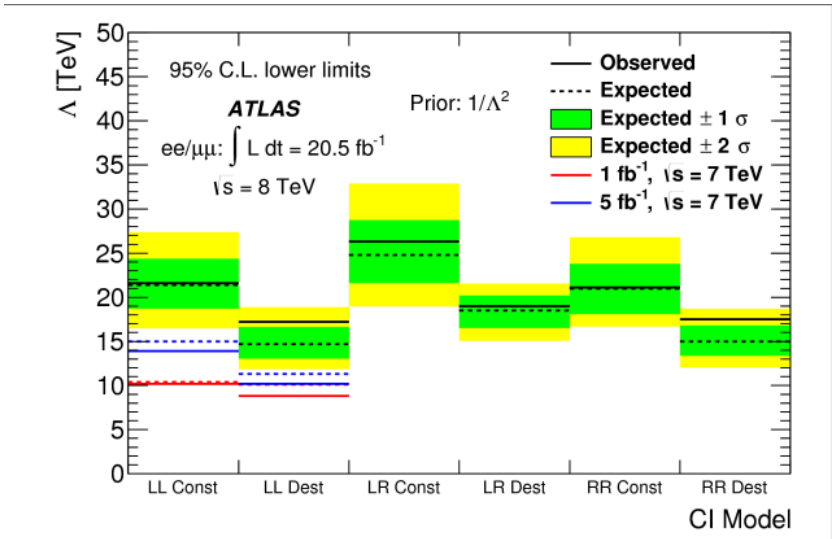
- **Dijet masses up to about 4.5 TeV are probed (down to 250 GeV using prescaled/delayed stream triggers)**
- **No resonance-like features are observed in the dijet mass spectrum**
- **Limits on σ × A for a simple Gaussian resonance or a Breit-Wigner narrow resonance decaying to dijets**
- **Specific models: excited quarks, color-octet scalars, W', W*, BH, and ED**

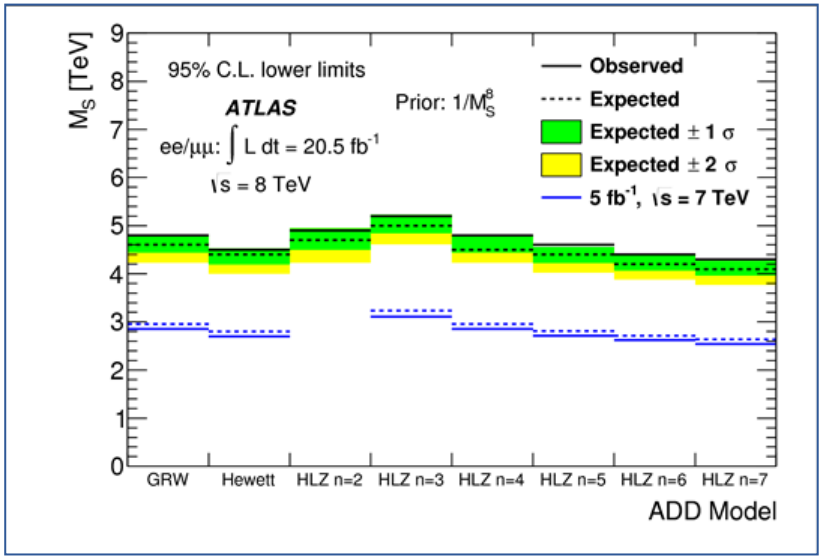


# SEARCH FOR CONTACT INTERACTIONS AND LARGE EXTRA DIMENSIONS




- **Complementary search to dilepton resonance search (non-resonant)**
- **Contact interactions (CI) and Arkani-Hamed, Dimopoulos and Dvali model (ADD) with large extra dimensions**
- **Limits are set on**
  - CI scale, Λ, 15.4 - 26.3 TeV
  - ED string scale, $M_S$, 4.1 - 6.1 TeV

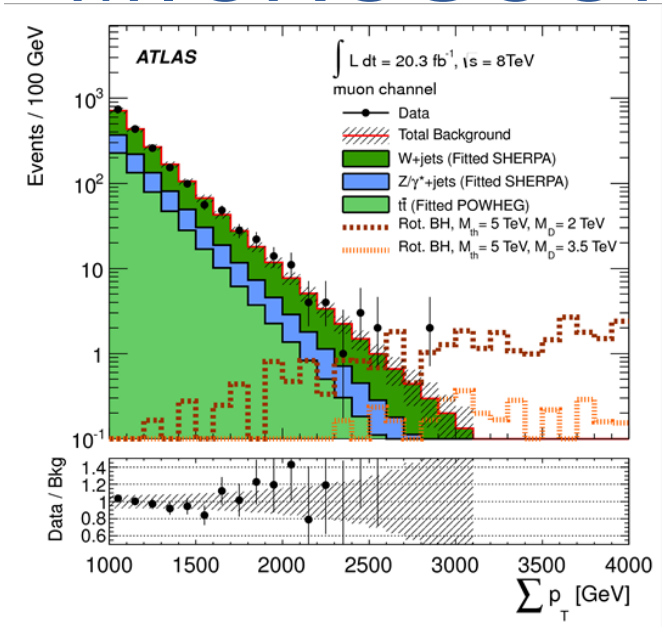


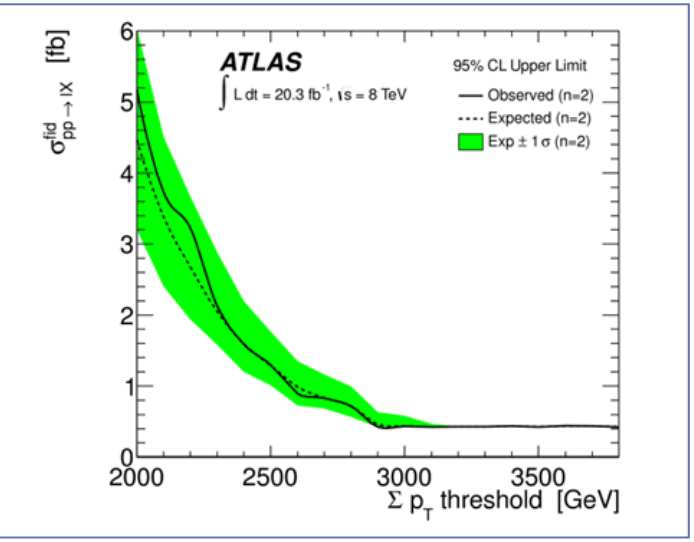


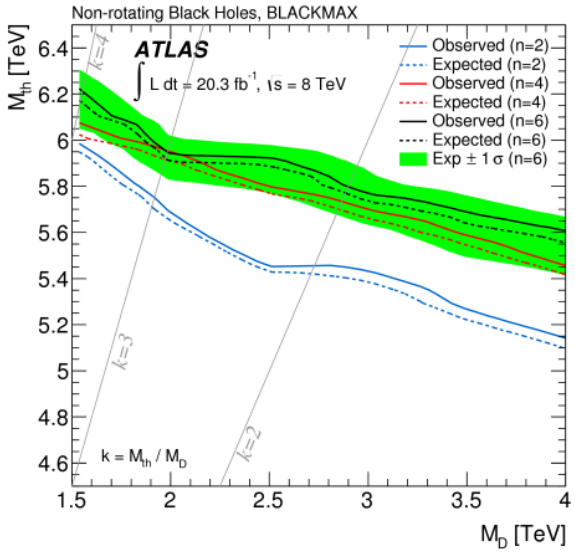

arXiv:1407.2410

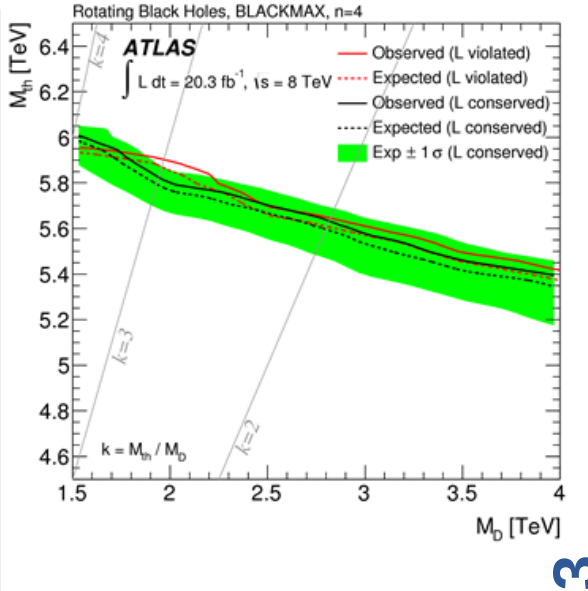
# MICROSCOPIC BLACK HOLES




- **Search for high-$P_T$ leptons + jets**
  - At least one isolated muon or electron
  - At least two additional leptons or jets
- **ADD 2, 4, and 6 ED models:**
  - Scale in extra dim.: $M_D$
  - Production threshold: $M_{th}$

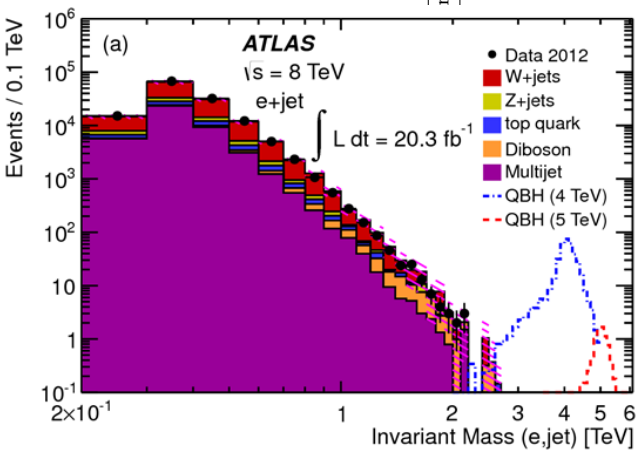


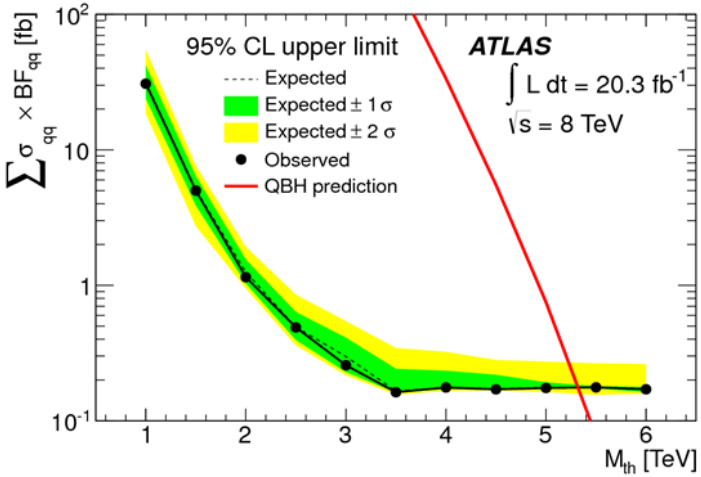




arXiv:1405.4254

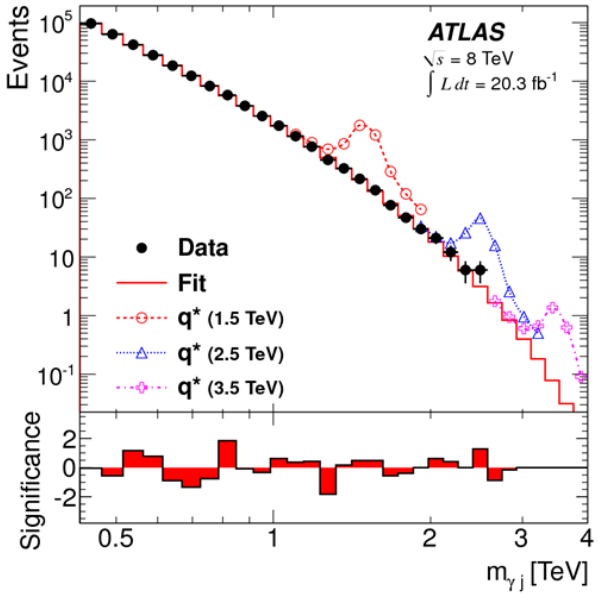
# QUANTUM BLACK-HOLE PRODUCTION

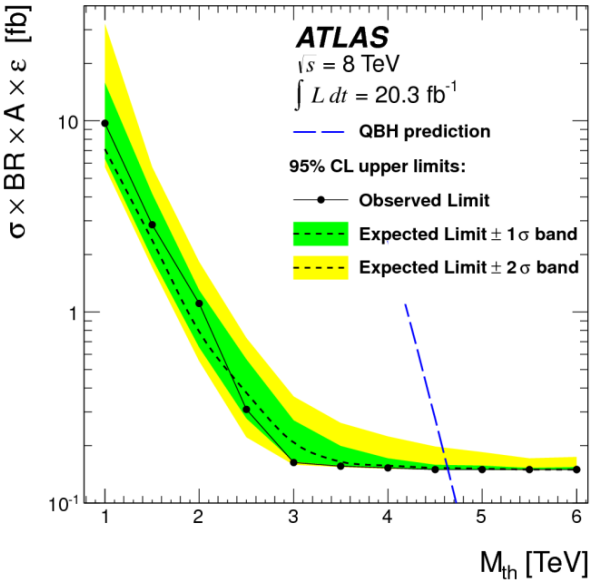



[arXiv:1311.2006](arXiv:1311.2006)

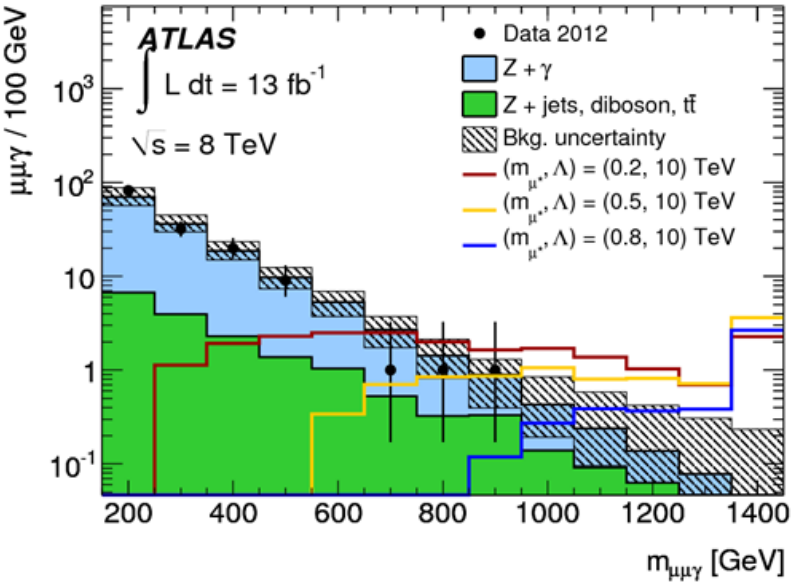
- **Lepton+jet and Photon+jet final states**
- **Invariant mass of trigger object (γ, e, μ) and high $P_T$ jet**
- **Limits of 5.3 and 4.6 TeV respectively**
- **Photon+jet also limits excited quarks**

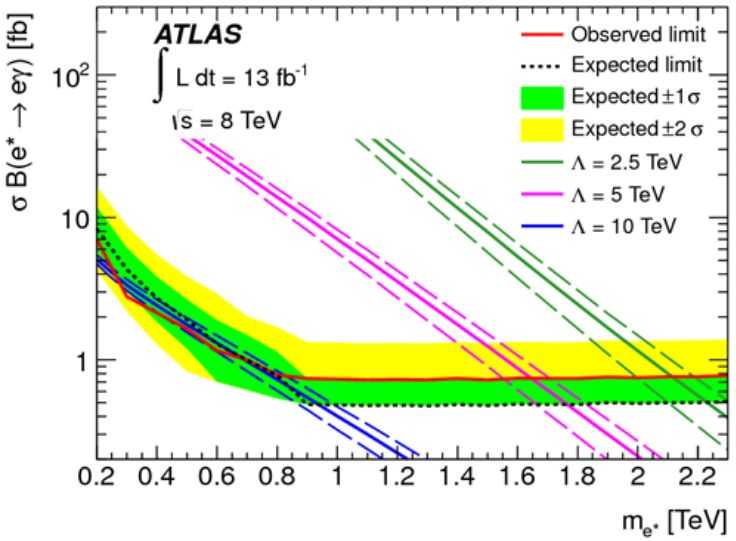


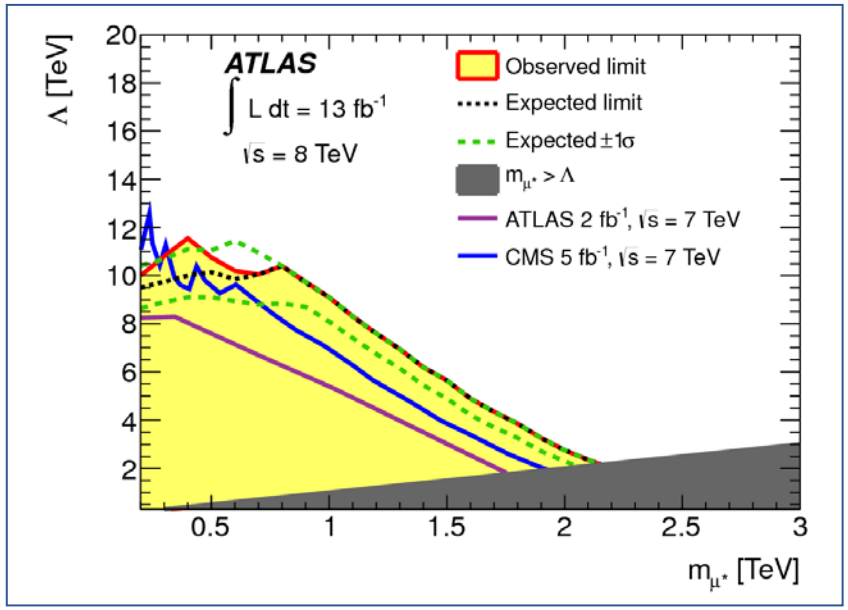




[Phys. Lett. B 728C (2014) 562-578]

# EXCITED LEPTONS



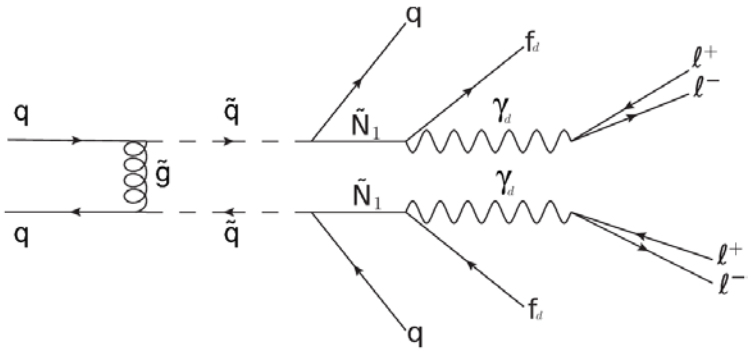

- **Excited leptons:**
- **ll* → llγ**
- **Strong or weak production**
- **Model-independent searches**

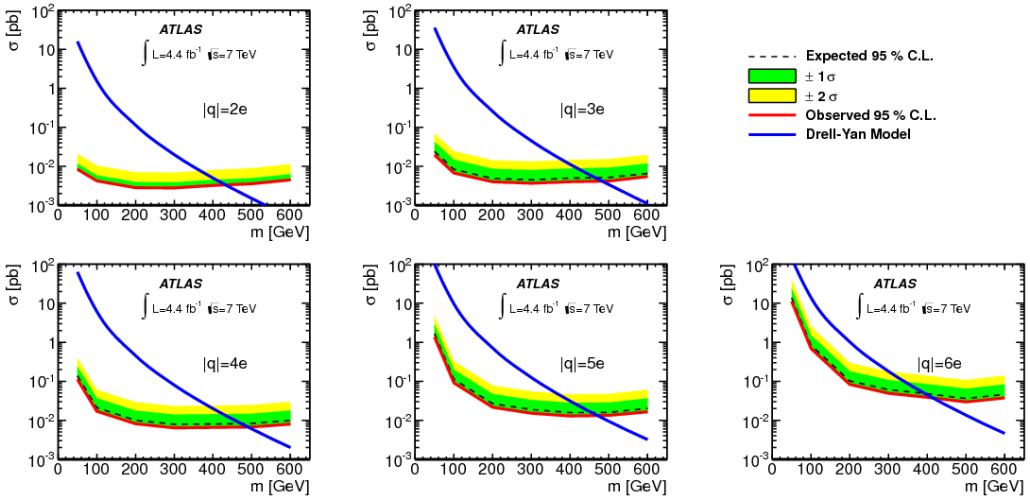
NJP 15 (2013) 093011

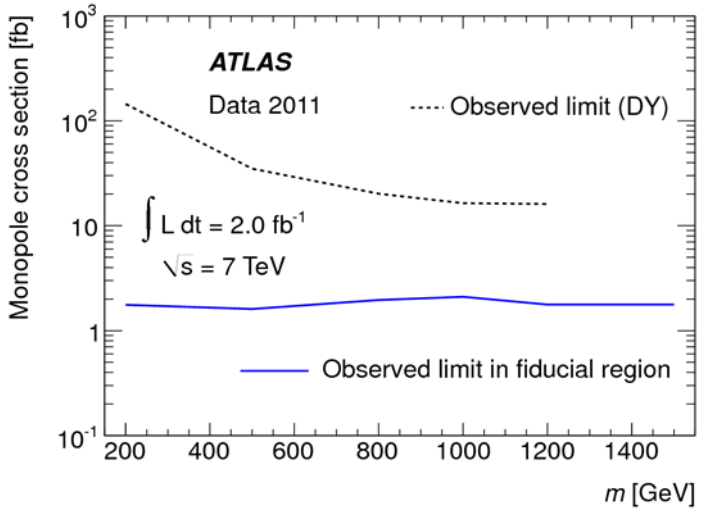
# UNIQUE SIGNATURES

- **Long-lived Particles utilize special signatures that may require custom triggers or reliance on associated production**
- **Examples:**
  - Lepton Jets
  - Multi-charge particles
  - Monopoles
- **One brand new result with 20 fb^-1**
- **More updates coming very soon!**





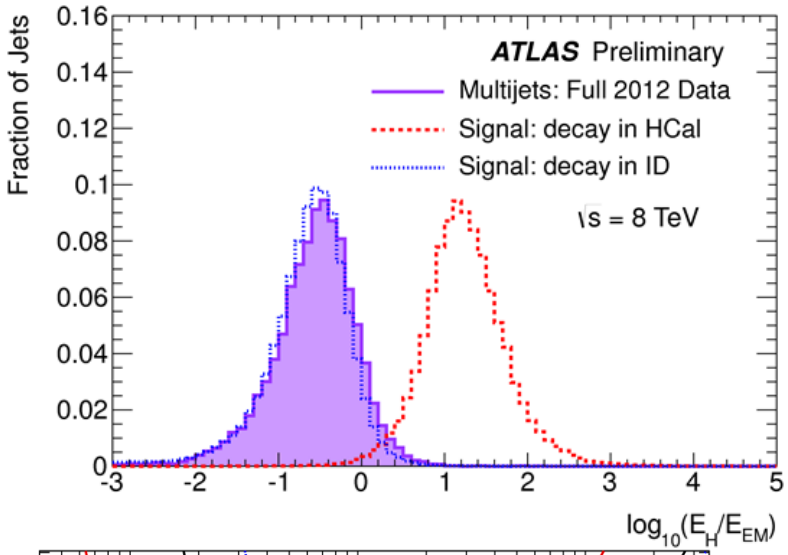



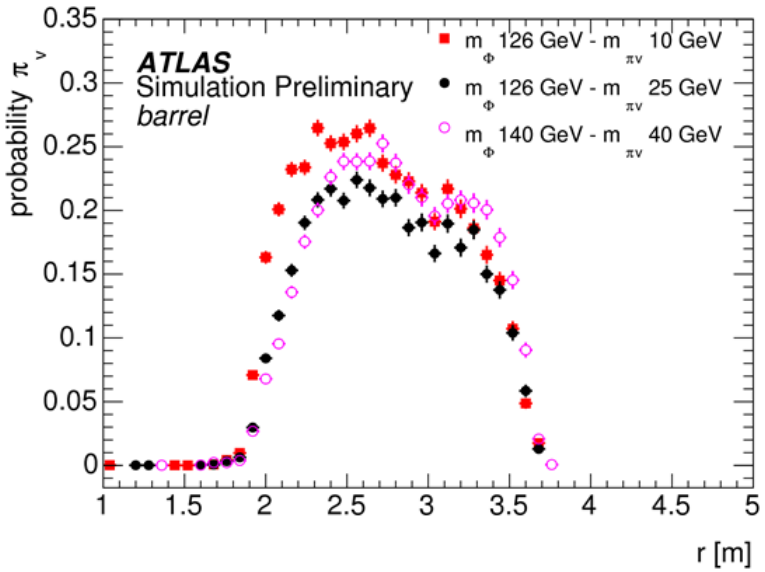



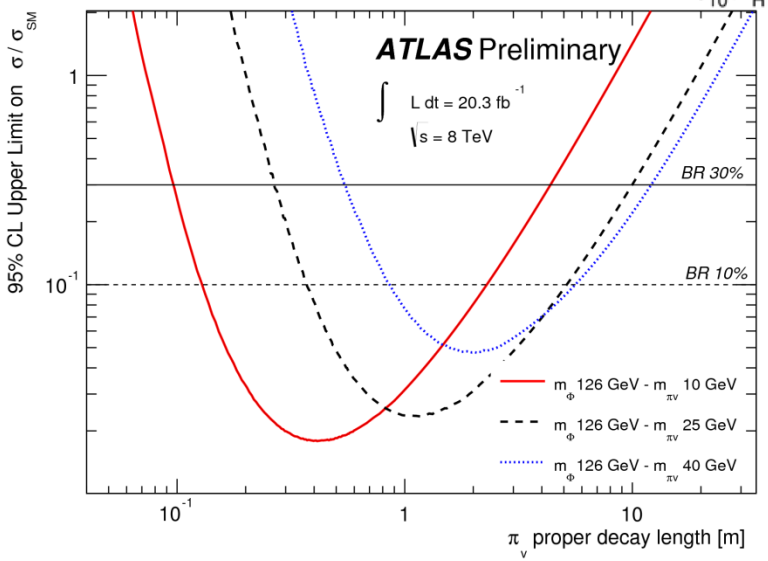
# LIGHT HIGGS BOSON DECAYING TO LONG-LIVED WEAKLY-INTERACTING PARTICLES



- **Higgs boson decays to two long-lived neutral particles ($\pi_v$)**
  - Then $\pi_v \rightarrow b\bar{b}$, $c\bar{c}$ or $\tau\tau$
- **Events are selected using the specialized Cal-ratio trigger**
  - Jet with high had/EM calorimeter energy ratio and $E_T > 60$ GeV
- **Jets must have**
  - $\log10(E_H/E_{EM}) > 1.2$
  - No good tracks in ID with $P_T$>1GeV
- **Main background SM QCD jets**




ATLAS-CONF-2014-041

# CONCLUSIONS



- **Exotic searches provide an alternative to SUSY in answering remaining questions in particle physics**
- **Many searches for non-SUSY new physics performed with 2012 ATLAS data**
- **No evidence for new phenomena, but strong limits placed on many theoretical models of new physics in Run I**
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- **Looking forward to Run II**
  - More energy, larger dataset
  - Tools developed and lessons learned from Run I
  - Improved triggering for unique signatures

# ATLAS Exotics Searches* - 95% CL Exclusion

*Status: ICHEP 2014*

**ATLAS** Preliminary

$\int \mathcal{L}\, dt$ = (1.0 - 20.3) fb$^{-1}$ $\sqrt{s}$ = 7, 8 TeV

| | Model | $\ell, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt$[fb$^{-1}$] | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | – | 1-2 j | Yes | 4.7 | $M_D$ 4.37 TeV | $n = 2$ | 1210.4491 |
| | ADD non-resonant $\ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $M_S$ 5.2 TeV | $n = 3$ HLZ | ATLAS-CONF-2014-030 |
| | ADD QBH $\rightarrow \ell q$ | 1 $e, \mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| | ADD QBH | – | 2 j | – | 20.3 | $M_{th}$ 5.82 TeV | $n = 6$ | to be submitted to PRD |
| | ADD BH high $N_{trk}$ | 2 $\mu$ (SS) | – | – | 20.3 | $M_{th}$ 5.7 TeV | $n = 6$, $M_D = 1.5$ TeV, non-rot BH | 1308.4075 |
| | ADD BH high $\sum p_T$ | $\geq 1$ $e, \mu$ | $\geq 2$ j | – | 20.3 | $M_{th}$ 6.2 TeV | $n = 6$, $M_D = 1.5$ TeV, non-rot BH | 1405.4254 |
| | RS1 $G_{KK} \rightarrow \ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $G_{KK}$ mass 2.68 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1405.4123 |
| | RS1 $G_{KK} \rightarrow WW \rightarrow \ell\nu\ell\nu$ | 2 $e, \mu$ | – | Yes | 4.7 | $G_{KK}$ mass 1.23 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1208.2880 |
| | Bulk RS $G_{KK} \rightarrow ZZ \rightarrow \ell\ell qq$ | 2 $e, \mu$ | 2 j / 1 J | – | 20.3 | $G_{KK}$ mass 730 GeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2014-039 |
| | Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ | – | 4 b | – | 19.5 | $G_{KK}$ mass 590-710 GeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2014-005 |
| | Bulk RS $g_{KK} \rightarrow t\bar{t}$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 14.3 | $g_{KK}$ mass 2.0 TeV | BR = 0.925 | ATLAS-CONF-2013-052 |
| | $S^1/Z_2$ ED | 2 $e, \mu$ | – | – | 5.0 | $M_{KK} \approx R^{-1}$ 4.71 TeV | | 1209.2535 |
| | UED | 2 $\gamma$ | – | Yes | 4.8 | Compact. scale $R^{-1}$ 1.41 TeV | | ATLAS-CONF-2012-072 |
| Gauge bosons | SSM $Z' \rightarrow \ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $Z'$ mass 2.9 TeV | | 1405.4123 |
| | SSM $Z' \rightarrow \tau\tau$ | 2 $\tau$ | – | – | 19.5 | $Z'$ mass 1.9 TeV | | ATLAS-CONF-2013-066 |
| | SSM $W' \rightarrow \ell\nu$ | 1 $e, \mu$ | – | Yes | 20.3 | $W'$ mass 3.28 TeV | | ATLAS-CONF-2014-017 |
| | EGM $W' \rightarrow WZ \rightarrow \ell\nu\,\ell'\ell'$ | 3 $e, \mu$ | – | Yes | 20.3 | $W'$ mass 1.52 TeV | | 1406.4456 |
| | EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$ | 2 $e, \mu$ | 2 j / 1 J | – | 20.3 | $W'$ mass 1.59 TeV | | ATLAS-CONF-2014-039 |
| | LRSM $W'_R \rightarrow t\bar{b}$ | 1 $e, \mu$ | 2 b, 0-1 j | Yes | 14.3 | $W'$ mass 1.84 TeV | | ATLAS-CONF-2013-050 |
| | LRSM $W'_R \rightarrow t\bar{b}$ | 0 $e, \mu$ | $\geq 1$ b, 1 J | – | 20.3 | $W'$ mass 1.77 TeV | | to be submitted to EPJC |
| CI | CI $qqqq$ | – | 2 j | – | 4.8 | $\Lambda$ 7.6 TeV | $\eta = +1$ | 1210.1718 |
| | CI $qq\ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $\Lambda$ 21.6 TeV | $\eta_{LL} = -1$ | ATLAS-CONF-2014-030 |
| | CI $uutt$ | 2 $e, \mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 14.3 | $\Lambda$ 3.3 TeV | $\lvert C \rvert = 1$ | ATLAS-CONF-2013-051 |
| DM | EFT D5 operator (Dirac) | 0 $e, \mu$ | 1-2 j | Yes | 10.5 | $M_*$ 731 GeV | at 90% CL for $m(\chi) < 80$ GeV | ATLAS-CONF-2012-147 |
| | EFT D9 operator (Dirac) | 0 $e, \mu$ | 1 J, $\leq 1$ j | Yes | 20.3 | $M_*$ 2.4 TeV | at 90% CL for $m(\chi) < 100$ GeV | 1309.4017 |
| LQ | Scalar LQ 1$^{st}$ gen | 2 $e$ | $\geq 2$ j | – | 1.0 | LQ mass 660 GeV | $\beta = 1$ | 1112.4828 |
| | Scalar LQ 2$^{nd}$ gen | 2 $\mu$ | $\geq 2$ j | – | 1.0 | LQ mass 685 GeV | $\beta = 1$ | 1203.3172 |
| | Scalar LQ 3$^{rd}$ gen | 1 $e, \mu$, 1 $\tau$ | 1 b, 1 j | – | 4.7 | LQ mass 534 GeV | $\beta = 1$ | 1303.0526 |
| Heavy quarks | Vector-like quark $TT \rightarrow Ht + X$ | 1 $e, \mu$ | $\geq 2$ b, $\geq 4$ j | Yes | 14.3 | T mass 790 GeV | T in (T,B) doublet | ATLAS-CONF-2013-018 |
| | Vector-like quark $TT \rightarrow Wb + X$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 14.3 | T mass 670 GeV | isospin singlet | ATLAS-CONF-2013-060 |
| | Vector-like quark $TT \rightarrow Zt + X$ | 2/$\geq$3 $e, \mu$ | $\geq$2/$\geq$1 b | – | 20.3 | T mass 735 GeV | T in (T,B) doublet | ATLAS-CONF-2014-036 |
| | Vector-like quark $BB \rightarrow Zb + X$ | 2/$\geq$3 $e, \mu$ | $\geq$2/$\geq$1 b | – | 20.3 | B mass 755 GeV | B in (B,Y) doublet | ATLAS-CONF-2014-036 |
| | Vector-like quark $BB \rightarrow Wt + X$ | 2 $e, \mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 14.3 | B mass 720 GeV | B in (T,B) doublet | ATLAS-CONF-2013-051 |
| Excited fermions | Excited quark $q^* \rightarrow q\gamma$ | 1 $\gamma$ | 1 j | – | 20.3 | $q^*$ mass 3.5 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1309.3230 |
| | Excited quark $q^* \rightarrow qg$ | – | 2 j | – | 20.3 | $q^*$ mass 4.09 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | to be submitted to PRD |
| | Excited quark $b^* \rightarrow Wt$ | 1 or 2 $e, \mu$ | 1 b, 2 j or 1 j | Yes | 4.7 | $b^*$ mass 870 GeV | left-handed coupling | 1301.1583 |
| | Excited lepton $\ell^* \rightarrow \ell\gamma$ | 2 $e, \mu$, 1 $\gamma$ | – | – | 13.0 | $\ell^*$ mass 2.2 TeV | $\Lambda = 2.2$ TeV | 1308.1364 |
| Other | LSTC $a_T \rightarrow W\gamma$ | 1 $e, \mu$, 1 $\gamma$ | – | Yes | 20.3 | $a_T$ mass 960 GeV | | to be submitted to PLB |
| | LRSM Majorana $\nu$ | 2 $e, \mu$ | 2 j | – | 2.1 | $N^0$ mass 1.5 TeV | $m(W_R) = 2$ TeV, no mixing | 1203.5420 |
| | Type III Seesaw | 2 $e, \mu$ | – | – | 5.8 | $N^\pm$ mass 245 GeV | $\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0 | ATLAS-CONF-2013-019 |
| | Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ | 2 $e, \mu$ (SS) | – | – | 4.7 | $H^{\pm\pm}$ mass 409 GeV | DY production, BR($H^{\pm\pm} \rightarrow \ell\ell$)=1 | 1210.5070 |
| | Multi-charged particles | – | – | – | 4.4 | multi-charged particle mass 490 GeV | DY production, $\lvert q \rvert = 4e$ | 1301.5272 |
| | Magnetic monopoles | – | – | – | 2.0 | monopole mass 862 GeV | DY production, $\lvert g \rvert = 1 g_D$ | 1207.6411 |

$\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 8 TeV

$10^{-1}$ 1 10 **Mass scale [TeV]**

**Only a selection of the available mass limits on new states or phenomena is shown.*