Searches with boosted bosons in ATLAS

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Why "boosted"?

- "Boosted" refers to particles with $\sim$ energies $\geq$ twice their masses
- For decays of W/Z/H/top $\rightarrow$ decay products reconstructed as single "fat-jet"
- Many interesting ideas developed to explore this kinematic regime
- Further our understanding of the SM
- Search for new physics!

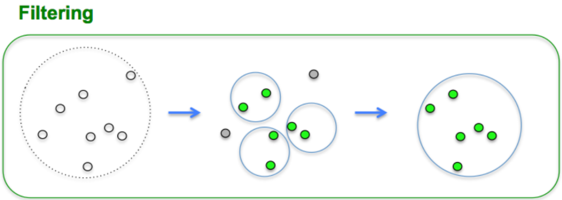
Overview of searches covered:

- Mono-hadronic W/Z decays
- Vector-like quarks
- Exotic di-boson searches
- Boosted Higgs

Jet substructure and grooming

Used to remove pileup and underlying event (UE) effects, and to help identify boosted objects

- **Trimming:** divide large-radius jets into subjets, then remove soft components
- **Pruning:** removes soft components, additional veto on wide-angle radiation
- **Filtering:** like trimming, but also discard jet if insufficient subjets remain



Improves mass resolution of hadronically decaying boosted objects!

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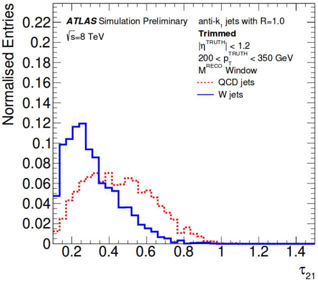
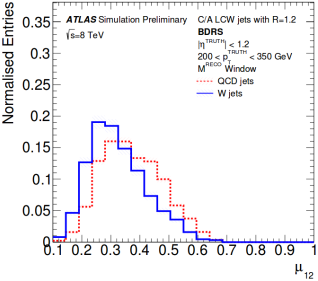
More jet substructure

Many variables which help to distinguish different kinds of jets, e.g. ...

- **N-subjettiness:** τ_N, expresses how likely jet is to have N or less sub-jets
- **Mass-drop:** defined at last stage of recombination (two 'proto-jets' combining to form one jet), μ_{12} is fraction of mass carried by most massive proto-jet

ATL-PHYS-PUB-2014-004

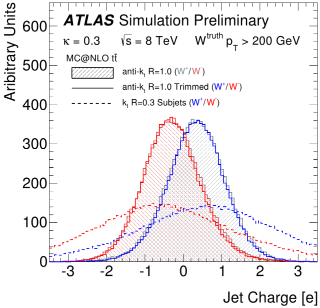




Boosted W/Z identification

Specifically for boosted W/Z can use in addition:

- **τ_N:** Better discrimination with ratios e.g. τ_1/τ_2 for W/Z
- **Jet charge:** sensitive to charge of hadronically decaying heavy particles
- Take large-radius jet, in order to capture all decay products (cone of $\Delta R \sim 1.0$ usually sufficient for boosted W/Z)
- Cut on the 'groomed mass', in a window around m_W (m_Z)



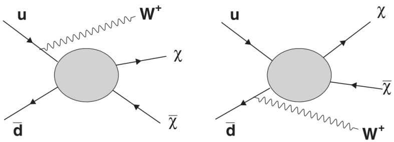
Validated in data and simulation for various W processes

ATLAS-CONF-2013-086

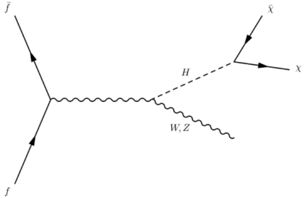
Mono-hadronic W/Z decays

Dark matter (DM) pair production in association with W/Z e.g.

DM searches with W/Z



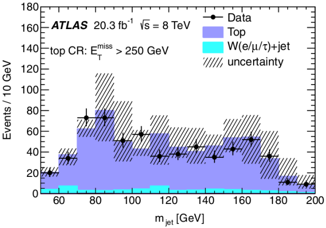
Associated Higgs production with Higgs→invisible

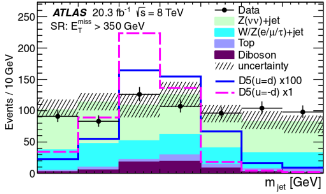


- Boosted W/Z jets reconstructed with C/A ($R = 1.2$)
- Mass drop + substructure to identify fat-jet: $p_T > 250$GeV, $|\eta| < 1.2$, $50 < m_J < 120$GeV
- Veto events with extra narrow jets - suppress $t\bar{t}$, multijet bkgs

PRL 112, 041802 (2014)

DM searches with W/Z bosons



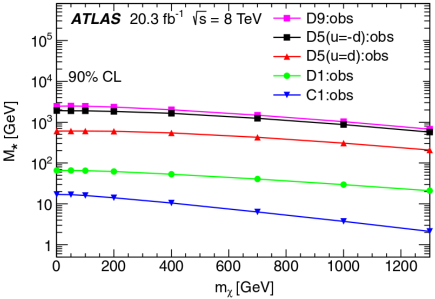


*only D5 constructive and destructive cases shown here, scaled

PRL 112, 041802 (2014)

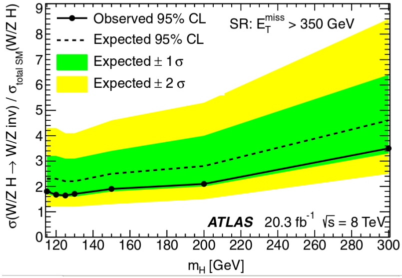
- TopCR used to validate large-R jet
- Signal regions: $E_T^{miss} > 350(500)\text{GeV}$
- 20.3fb^{-1} at 8TeV

For various models, derived 90% C.L. exclusion limits on the effective theory mass scale M_*



Associated Higgs production with Higgs→invisible

Limits on simple DM production theory, with a light mediator (the Higgs)



20.3fb^{-1} at 8TeV

For $m_H = 125\text{GeV}$:

- Upper limit on xsec: 1.3pb at 95% C.L.
- Compare to SM NLO prediction for associated production xsec: 0.8pb
- $E_T^{miss} > 350\text{GeV}$ - one signal region only

PRL 112, 041802 (2014)

Vector-like Quarks (VLQ)

Vector-like $\rightarrow$ left and right-handed components transform in same way under $SU(3) \otimes SU(2) \otimes U(1)$

SM quarks - only left-handed charged currents (V-A)
VLQ - both left and right-handed charged currents (V)

- Can have same charge as b, t-quarks (B', T')
- Exotic charges also allowed in some models e.g. $T_{\frac{5}{3}}$
- Arranged in weak isospin singlets/doublets/triplets
- Assume usually only interactions with 3rd-gen. quarks

Vector-like Quarks (VLQ)

Can appear in:

- Composite Higgs models - excited resonances of bound states which produce SM particles
- Warped or extra dimensions - excited partners of SM particles
- "Little Higgs" models - partners of SM fermions in larger group representation
- Gauged flavour group - required to cancel anomalies in the gauged flavour symmetry
- Non-minimal SUSY extensions - introduced to increase Higgs mass corrections without affecting EW precision tests

Search for VLQs in ATLAS

Search for pair produced heavy top-like quarks $T\bar{T}$:

- dominant decay mode $T \rightarrow Wb$, if T is isospin singlet
- Zt, Ht also sizable in this case

Investigate also limits on Y quark:

- Isospin partner of B quark - arranged in isospin doublet
- Electric charge -4/3
- Decays exclusively $Y \rightarrow W^{-}b$
- Experimentally indistinguishable from chiral fourth generation T quark

ATLAS-CONF-2013-060

Search for VLQs in ATLAS

- Look at lepton+jets, exactly one e/μ, ≥ 4 anti-k_t 0.4 jets
- Substantial boost of W - small angular separation between W decay products
- Heavy $T \rightarrow$ highly energetic W and b, with large angular separation
- Split according to hadronic decay products of W:
  - Both jets are reconstructed separately, $p_T^{jj} > 200\text{GeV}$
  - Single, large, high p_T jet, $p_T > 250\text{GeV}$ (boosted Ws)
  - Require $60 < m_J/m_{jj} < 120\text{GeV}$

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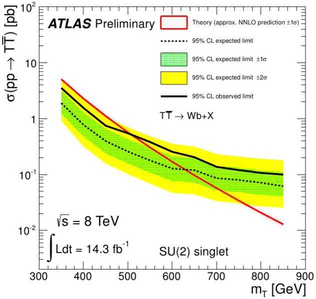
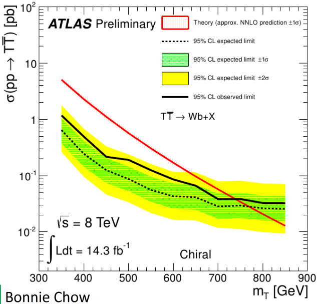
Search for VLQs in ATLAS





Observed exclusion limits at 95%C.L.

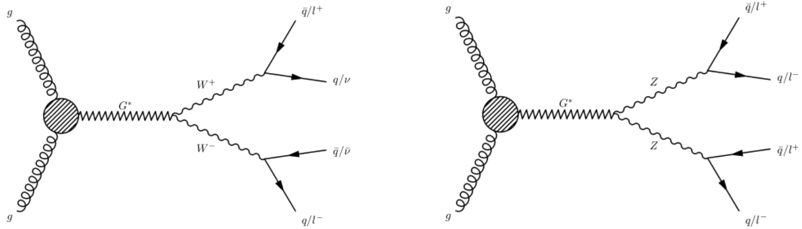
- 14.3fb^{-1}at 8TeV
- **T quark:** $m_T > 505\text{GeV}$
- Combining with previous ATLAS search ($T\bar{T} \to Ht + X, with\ H \to b\bar{b}$): $m_T > 670\text{GeV}$
- **Y quark:** $m_Y > 740\text{GeV}$

ATLAS-CONF-2013-060

*for VLQ search in Z b/t + X channel: ATLAS-CONF-2014-036

Di-boson searches

Various SM extensions predict heavy resonances decaying to pairs of EW bosons (warped extra dimensions, GUTs...etc)



Only public results for semi-leptonic search in ATLAS
$\rightarrow$ lepton requirement helps suppress multijet bkg

(also have WZ resonance searches in leptonic channel)

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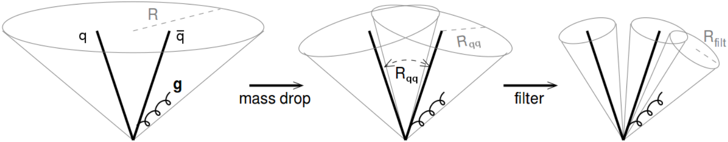
Resonant diboson production $\rightarrow l^+l^-q\bar{q}$

Spin-2 (Bulk Randall-Sundrum) Kaluza-Klein gravitons $G^* \rightarrow ZZ$

Spin-1 gauge boson $W' \rightarrow ZW$ from Sequential SM with modified coupling to ZW[1]

- Boosted W/Z jets reconstructed with C/A ($R = 1.2$)
- Other narrow jets as anti-k_t 0.4, $p_T > 30$GeV
- Improve acceptance of highly boosted Zs ($p_T > 800$GeV) - optimised isolation for dilepton objects
- Use substructure techniques to identify boosted bosons

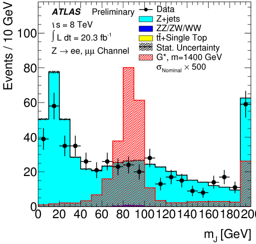


[1] G. Altarelli, B. Mele, and M. Ruiz-Altaba, Z. Phys. C 45 , 109 (1989)

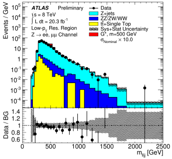
ATLAS-CONF-2014-039

Resonant diboson production $\rightarrow l^+l^-q\bar{q}$

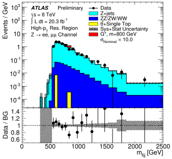
- Split into three exclusive regions by boson and jet p_T
- $70 < m_J/m_{jj} < 110$GeV for hadronically decaying W/Z



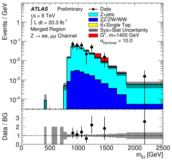
$p_T^{ll} > 100$GeV, $p_T^{jj} > 100$GeV

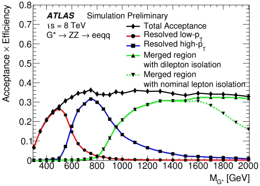


$p_T^{ll} > 250$GeV, $p_T^{jj} > 250$GeV



$p_T^{ll} > 400$GeV, $p_T^{J} > 400$GeV





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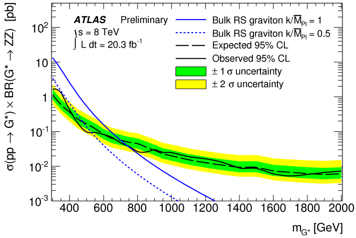
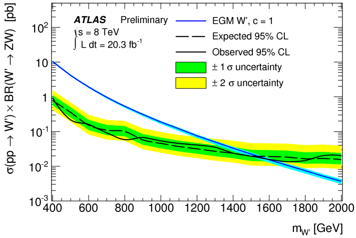
Resonant diboson production $\rightarrow l^+l^-q\bar{q}$

95% C.L. upper limits for production $\sigma \times$ branching fraction:





Exclusion of mass values (lower limits 95% C.L.):

- 20fb^{-1} at 8TeV
- 740GeV for KK graviton
- 1590GeV for W' boson

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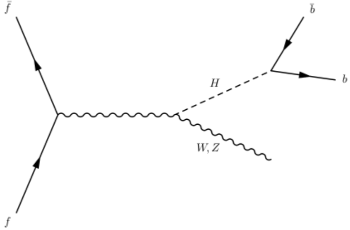
Associated Higgs production with H→ $b\bar{b}$

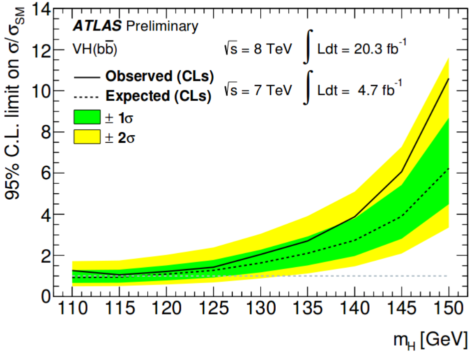


- Higgs not boosted enough at 8TeV→no need to use substructure
- Even for $p_T > 200$GeV, b-jets usually distinguishable

- anti-k_t 0.4 jets (2 b-tagged, additionally ≤ 1 jet
- Split channels by lepton multiplicity:
  - 0l: various E_T^{miss} cuts to suppress multijet bkg
  - 1l: $m_T^W < 120$ GeV
  - 2l: $83 < m_{ll} < 99$GeV

ATLAS-CONF-2013-079

Associated Higgs production with H→ $b\bar{b}$



No significant gain for 8TeV dataset in using boosted techniques

Work ongoing to investigate new methods for RunII, at 14TeV - e.g. Higgs tagger

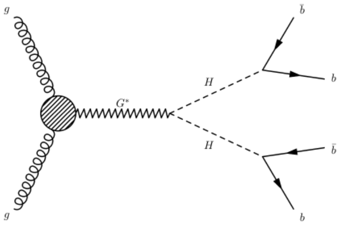
$m_H = 125$GeV, 95% C.L. upper limit:

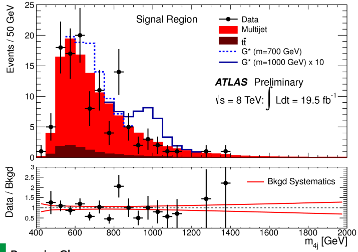
- 1.4×SM expectation on production σ
- 20.3fb^{-1} at 8TeV , 4.7fb^{-1} at 7TeV

ATLAS-CONF-2013-079

Resonant Higgs-pair prod $\rightarrow b\bar{b}b\bar{b}$

Spin-2 KK graviton $G^* \rightarrow HH \rightarrow b\bar{b}b\bar{b}$
(Bulk Randall-Sundrum, with warped extra dimension)

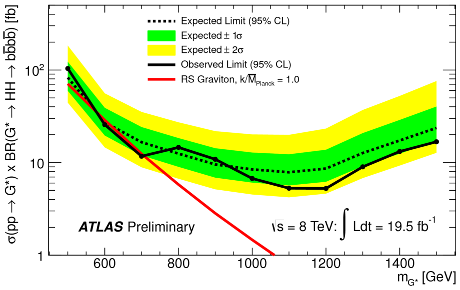




- Assumes SM Higgs, $m_H = 125\text{GeV}$
- Coupling $k/\bar{M}_{Pl} = 1.0$, corresponds to first KK excitation of G^*
- ≥ 4 MV1 b-tagged jets (anti-k_t 0.4)
- Form two unique dijet systems, $p_T > 200\text{GeV}$, $\Delta R < 1.5$

ATLAS-CONF-2014-005

Resonant Higgs-pair prod $\to b\bar{b}b\bar{b}$



No evidence for new resonances, search used to set limits for this scenario

Currently no public results for boosted topology - however already in the pipeline

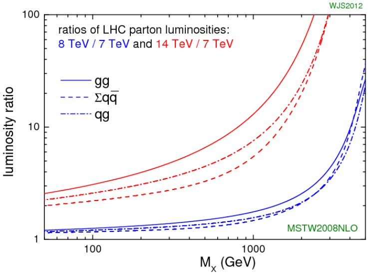
ATLAS-CONF-2014-005

95% C.L. limits:

- 19.5fb^{-1} at 8TeV
- KK graviton mass: $590 < m_{G^*} < 710\text{GeV}$
- $\sigma(pp \to G^*) \times BR(G^* \to HH \to b\bar{b}b\bar{b})$: 7fb for $m_{G^*} = 1\text{TeV}$

RunII prospects

More data!
Higher energy+higher luminosity →higher pile up



*Lumi plot from CMS-NOTE-13-002

ATL-PHYS-PUB-2012-004

- Boosted bosons increasingly important
- New production modes will become accessible, e.g. for some singly produced VLQ
- "Higgs factory" - precision measurements, observation of Higgs self-coupling?
- Search for new physics

Summary

- Wide variety of techniques developed for boosted objects
- Help to identify boosted bosons, improve mass resolution
- Will become especially interesting as the centre-of-mass energy increases
- Extend current limits on searches
- New physics may become accessible

Thank you! And stay tuned for more!

Backup...

Jet substructure variable definitions

- **Mass-drop:** μ_{12} defined at last stage of recombination, where two 'proto-jets' are combined to form one 'fat-jet'. μ_{12} is the mass fraction of the heavier proto-jet:
  $\mu_{12} = \frac{max(m_1, m_2)}{m_{12}}$
- **N-subjettiness:** Describes how similar the jet substructure of a given jet is, to N or fewer subjets:
  $\tau_N = \frac{\sum_k p_{T,k}(min[\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k}])^\beta}{\sum_k p_T(R_0)^\beta}$
  where β is an angular weighting, R_0 is the characteristic jet radius

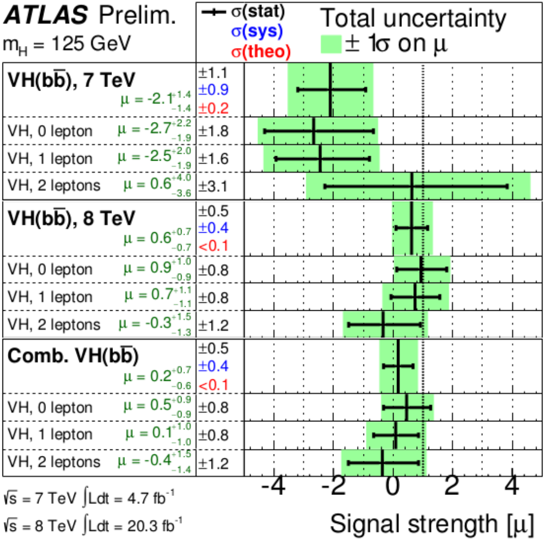
Search for VLQs in ATLAS - selection

Selection	Requirements
Preselection	One electron or muon
	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV
	≥ 4 jets, ≥ 1 b-tagged jets
loose selection	Preselection
	≥ 1 W_{had} candidates
	$H_{\mathrm{T}} > 800$ GeV
	$p_{\mathrm{T}}(b_1) > 160$ GeV, $p_{\mathrm{T}}(b_2) > 80$ GeV
	$\Delta R(\ell, \nu) < 1.2$
tight selection	*loose* selection
	$\min\Delta R(\ell, b) > 1.4$, $\min\Delta R(W_{\mathrm{had}}, b) > 1.4$

Associated Higgs production with H$\to b\bar{b}$ - selection

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_{\mathrm{T}}^{\mathrm{jet}_1} > 45$ GeV $p_{\mathrm{T}}^{\mathrm{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \boldsymbol{p}_{\mathbf{T}}^{\mathbf{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, b\bar{b}) > 2.8$	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ Gev	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

Associated Higgs production with H$\rightarrow b\bar{b}$ - μ



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