



1

Recent results of searches for beyond Standard Model physics in ATLAS

Leonid Serkin

(INFN Gruppo Collegato di Udine and ICTP Trieste)

on behalf of the ATLAS Collaboration

14-18 November 2016

- Busy last months for the ATLAS Collaboration
 - Culminating in a multitude of results shown at ICHEP2016 and Top2016 Conferences
- I will present <u>a subset of recent results</u> from the Higgs and Exotics physics group
- Apologies if your favourite BSM search is not shown in this talk!
- Focus on <u>BSM physics and top quark</u>, which plays a prominent role in many BSM scenarios
- Look for new phenomena in high jet multiplicity final states:
 - search for heavy charged Higgs
 - search for vector-like quarks
- Listing of public ATLAS Higgs and Exotics group results:

http://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults http://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults • LHC 2016 proton-proton physics run came to an end, and we have about <u>10 times</u> more data in 2016 than in 2015!



• Results today cover the 2015 dataset (3.2 fb⁻¹) and the "ICHEP2016" dataset (13.2 fb⁻¹)

• ATLAS experimental challenges:



- <u>Strategy</u> for new physics searches (for example, in the case of Higgs boson):
 - <u>Indirectly</u>, by looking for non-standard properties of light Higgs (spin, CP, couplings...)
 - <u>Directly</u>, by explicit search for BSM objects
 - additional Higgs bosons (neutral and charged, decays to SM particles,..)
 - Higgs boson decays to BSM states (light scalar resonances, invisible decays,..)

• In the case of direct searches, define <u>selection</u> based on signal signatures/acceptance and background kinematics

• <u>Compare</u> observed data to Standard Model background (Monte Carlo and data-driven) and MC signal predictions

• Split into control and signal regions, <u>extrapolation checked</u> before unblinding (validation)



• In the case of no evidence for new physics: set <u>limits</u> on cross-section times branching ratio

• Comparisons provided for specific models, but usually possible to constrain additional models

Charged Higgs boson

- No <u>charged scalar bosons</u> exist in SM: many BSM models predict extended Higgs sectors containing charged Higgs bosons (2HDM, Higgs triplets...)
- Example: two-Higgs-doublet model (2HDM) adds 5 physical states (h, H, A, H[±])
- 4 types depending on which fermion couples to which doublet (tan $\beta = \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$)
 - Minimal Supersymmetric SM is a special case of type II 2HDM, often used as benchmark
- At high H[±] mass, the <u>main production mode</u> of heavy charged Higgs boson at the LHC is in association with a top quark, and H[±] \rightarrow tb is the dominant <u>decay mode</u>
- Focus on final state (4FS): t (\rightarrow Wb) b H[±] (\rightarrow tb), dominant background is top pairs + jets



Search for charged Higgs boson in the $H \rightarrow tb$ decay



- Split into <u>4 signal</u> and <u>4 control</u> regions based on number of jets and b-tagged jets
- <u>Dominant</u> background is top quark pair + heavy flavour jets

Single lepton with $p_T > 25$ GeV, ≥ 4 jets with $p_T > 25$ GeV and at least 2 b-tagged jets

ATLAS-CONF-2016-089 (08/16)



 Maximum likelihood fit to all regions based scalar sum of jet p_T in control and boosted decision trees (BDT) output in signal regions as discriminants



- tt+jets production:
 - split into light/heavy flavour based on extra jets tt+light, tt +≥1c, tt+≥1b
- <u>Rely on MC</u> (Powheg+Pythia6) to describe tt+jets
 - tt+≥1b kinematics reweighted to dedicated NLO Sherpa+OpenLoops prediction
 - tt+light and tt+ \geq 1c reweighted to NNLO prediction for p_T^{tt} and p_T^{top} (arxiv:1606.03350)
 - Normalisation of tt +≥1c and tt+≥1b contributions freely floating in the fit
- <u>BDT</u> trained against:
 - tt+ \geq 1b for $m_{H^{\pm}}$ < 500 GeV, reduces syst. correlation
 - all the backgrounds for $m_{H^{\pm}} > 500 \text{ GeV}$
- Sources of systematic uncertainty:
 - luminosity measurement
 - reconstruction of physics objects
 - signal/background modelling
 - affect normalisation and/or shapes

ATLAS-CONF-2016-089 (08/16)



Search for charged Higgs boson in the $H \rightarrow tb$ decay



ATLAS-CONF-2016-089 (08/16)

 Signal and control region normalisation and shape well described after fit

No significant excess observed

Search for charged Higgs boson in the $H \rightarrow tb$ decay

- Observed cross-section times branching ratio limits of the order of 1.1 - 0.18 pb for m(H⁺) range of 300 GeV - 1 TeV
- Unlike Run I, no broad excess
 - observe 2.1σ excess at 600 GeV
- Exclude high values of tan β for m(H⁺) < 380 GeV









- <u>Chiral 4th quark generation</u> excluded by Higgs boson measurements
- <u>Vector-like quarks</u> (VLQ): spin ½, coloured, charged LH and RH coupling to charged currents
- Arise in little Higgs, composite Higgs, extra dimensions, and GUTs models, naturalness would require m₀ ≤ 2 TeV
- **Production**:
 - <u>strong pair production</u> (less model dependent)
 - single via EW (mixing angles model dependent)





	VLQ	Q [e]	Т3
singlets	(T) (B)	+2/3 -1/3	0
doublets	(X,T) (T,B) (B,Y)	+5/3, +2/3 +2/3, -1/3 -1/3, -4/3	± 1/2
triplets	(X,T,B) (T,B,Y)	+5/3, +2/3, -1/3 +2/3, -1/3, -4/3	+1, 0, -1







✓ Single-lepton + jets targeting TT \rightarrow WbWb (ATLAS-CONF-2016-102)



✓ Single-lepton + jets targeting TT \rightarrow tZtZ (ATLAS-CONF-2016-101)

Contour plane of $BR(T \rightarrow Ht)$ versus $BR(T \rightarrow Wb)$



✓ Same-sign leptons targeting TT \rightarrow tZtZ and TT \rightarrow tHtH (ATLAS-CONF-2016-032)

ATLAS-CONF-2016-104 (09/16)

- We can target at once several <u>signal scenarios</u>:
 - ✓ VLQ TT pair production (TT→HtHt, HtZt, HtWb, ZtZt, ZtWb)
 - ✓ 4-top quarks production (SM, 2UED-RPP, EFT)
 - ✓ BSM Higgs (bbH/A(\rightarrow tt), ttH/A (\rightarrow tt), tbH⁺(\rightarrow tb)
- Orthogonal 1-lepton and 0-lepton analyses <u>probe different</u> <u>corners</u> of branching ratio plane





- Analysis pre-selection similar to charged Higgs:
 - 1-lepton channel: 1 lepton with $p_T > 25$ GeV, \geq 5 jets with p_T > 25 GeV, out of which \geq 2 b-tags
 - 0-lepton channel: MET trigger, ≥ 6 jets with ≥ 2 b-jets, cut on MET > 200 GeV
- Split by <u>number of jets</u> $(5, \geq 6)$, <u>number of b-jets</u> $(2, 3, \geq 4)$ and <u># of mass-tagged jets</u> $(0, 1, \geq 2)$
 - reclustered from calibrated small-R jets with anti-kT R=1.0, M > 100 GeV, and p_T > 300 GeV
- Signal discrimination based on shape of effective <u>mass</u> $m_{eff} = \Sigma p_T^{jets} + p_T^{lepton} + MET$ used in a profile likelihood fit performed across signal regions
- Enhance further S/B:
 - <u>1-lepton channel</u>: high $m_{hh}^{min\Delta R}$ increases sensitivity to signals with $H \rightarrow bb$ in final state
 - <u>O-lepton channel</u>: cut on m_{T. min}^b (min. transv. mass between MET and leading 3 b-jets)



ATLAS-CONF-2016-104 (09/16)

16



ATLAS-CONF-2016-104 (09/16)

- Total of 8 (12) <u>search regions and</u>
 6 (9) <u>validation regions in 1(0)</u>lepton channel
 - regions with ≥ 6 (7) jets are search regions and with exactly 5(6) jets are validation regions

- Different phase-spaces covered by each channel
- Complex top-quark pair background model (low to high signal purity)



ATLAS-CONF-2016-104 (09/16)

 Shape of effective mass distribution is well described by background-only hypothesis

- No significant excess observed
- Limits sets on several signal models

- VLQ scenarios extended sensitivity of previous searches by ~200-300 GeV wrt to previous search
- Model-independent limits on 2D BR plane with good coverage obtained from combination
- 95% CL lower limits on T quark mass [GeV] Search $BR(T \rightarrow Ht) = 1$ $BR(T \rightarrow Zt) = 1$ Doublet Singlet 1-lepton channel 1180(1120)740(820)1060(1000)900 (880) 0-lepton channel 1090(1070)1060(1010)1090(1060)950(890)Combination 1200(1160)1100(1040)1160(1110)1020(960)Previous ATLAS $T\bar{T} \rightarrow Ht + X$ searches (1-lepton) Ref. Run 2 (3.2 fb⁻¹) 900(980)700(740)800 (900) 750 (780) [24]Run 1 950(880)750(690)860 (820) 760 (720) [18]



 Complimentarity of 0-lepton and 1-lepton analyses evident

ATLAS-CONF-2016-104 (09/16)



- ATLAS-CONF-2016-104 (09/16)
- Extended Higgs sector in 2HDM model, H/A to top-quarks pair decay is dominant for $m_{H/A} > 2m_{top}$
- Type-II 2HDM model: probing masses from 400 GeV to 1 TeV
- Sensitivity in HBSM ttH(tt): excluding tan β < 0.2
- First limits on bbH(tt): current analysis not optimal for bbH/A(→tt) due to low acceptance of b-quarks
- Sensitivity in 0.3 < $m_{\rm H^+}$ < 1 TeV about twice worse than dedicated H+ analysis, also sensitive to $m_{\rm H^+}$ > 1 TeV





20

• Several new searches for BSM phenomena with 13 TeV probe a varied range of BSM signals

• Lots of recent results on searches for new states or phenomena:

		c 3 -	30/	ᅂᄔ	Exclusion			AILA	S Preliminar
Status: August 2016							∫£ d	$t = (3.2 - 20.3) \text{ fb}^{-1}$	\sqrt{s} = 8, 13 TeV
Model	<i>ℓ</i> , γ	Jets†	E ^{miss} T	∫£ dt[fb	-1]	Limit	-		Reference
$\begin{array}{c} \text{ADD } G_{KK} + g/q \\ \text{ADD non-resonant } (\ell \\ \text{ADD } \text{OBH} \rightarrow (q \\ \text{ADD } \text{OBH} \rightarrow (q \\ \text{ADD } \text{OBH} \rightarrow (l \\ \text{ADD } \text{OBH} \rightarrow (l \\ \text{ADD } \text{OBH} \rightarrow (l \\ \text{ADD } \text{BH } \text{Injh})_{2} \rho_T \\ \text{Bergen } \text{ADD } \text{BH } \text{Injh})_{2} \rho_T \\ \text{Bergen } \text{ADD } \text{BH } \text{Injh})_{2} \rho_T \\ \text{Bergen } \text{ADD } \text{BH } \text{Injh})_{2} \rho_T \\ \text{Bergen } \text{BSI } G_{KK} \rightarrow (l \\ \text{Buik } \text{RS } G_{KK} \rightarrow (H \\ \text{Buik } \text{RS } G_{KK} \rightarrow (H \\ \text{ADD } \text{Buik } \text{RS } G_{KK} \rightarrow (H \\ \text{ADD } \text{Buik } \text{RS } G_{KK} \rightarrow (H \\ \text{ADD } \text{Buik } \text{RS } G_{KK} \rightarrow (H \\ \text{ADD } \text{ADD } \text{Buik } \text{RS } \text{Bree } \text{If } \text{ADD } $	$2 e, \mu \\ 1 e, \mu \\ - \\ 2 e, \mu \\ 2 y \\ 1 e, \mu \\ $	$\geq 1 j$ - 1 j 2 j $\geq 2 j$ $\geq 3 j$ - 1 J 4 b $\geq 1 b, \geq 1 J J$ $\geq 2 b, \geq 4$	Yes - - - Yes 2j Yes j Yes	3.2 20.3 15.7 3.2 3.6 20.3 3.2 13.2 13.3 20.3 3.2	Mg Mg Mg Mg Mg Mg Mg Mg Mg Mg Mg Mg Mg M	1.24 360-860 GeV 1	6,58 TeV 4,7 TeV 5,2 TeV 8,7 8,7 8,7 8,7 8,7 8,7 9,5 9,5 9,5 9,5 9,5 9,5 9,5 9,5 9,5 9,5	$\begin{array}{l} n=2 \\ n=3 \ \text{HZ} \\ n=6 \\ \hline \textbf{6V} & n=6 \\ M & n=6, \ M_D=3 \ \textbf{TeV}, \ \textbf{rot} \ \textbf{BH} \\ \textbf{5TeV} & n=6, \ M_D=3 \ \textbf{TeV}, \ \textbf{rot} \ \textbf{BH} \\ \textbf{K} & \overline{M}_B=0.1 \\ \textbf{K} & \overline{M}_B=0.1 \\ \textbf{K} & \overline{M}_B=0.1 \\ \textbf{K} & \overline{M}_B=1.0 \\$	1604.07773 1407.2410 1311.2006 ATLAS-CONF-2016-069 1606.02265 1512.02566 1405.4123 1606.03833 ATLAS-CONF-2016-062 ATLAS-CONF-2016-063 ATLAS-CONF-2016-013
$\begin{array}{ccc} \mathrm{SSM} \ Z' \to \mathcal{U}(\\ \mathrm{SSM} \ Z' \to \tau \\ \mathrm{Constraint} \ \mathcal{C} \to \tau \\ \mathrm{SSM} \ \mathcal{W}' \to \psi \\ \mathrm{SSM} \ \mathcal{W}' \to \psi \\ \mathrm{HVT} \ \mathcal{W}' \to \mathcal{W} \\ \mathrm{HSM} \ \mathcal{W}'_R \to \psi \\ \mathrm{LRSM} \ \mathcal{W}'_R \to \psi \\ \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ - \\ 1 \ e, \mu \\ \text{del A} 0 \ e, \mu \\ \text{del B} - \\ \text{multi-channe} \\ 1 \ e, \mu \\ 0 \ e, \mu \end{array}$	– 2b – 1J 2J el 2b,0-1j ≥1b,1J	- Yes Yes - Yes -	13.3 19.5 3.2 13.3 13.2 15.5 3.2 20.3 20.3	2' mass Z' mass Z' mass W' mass W' mass V' mass W' mass W' mass		4.05 TeV 2.02 TeV 1.5 TeV 2.4 TeV 3.0 TeV 3.0 TeV 1.92 TeV 1.92 TeV 1.92 TeV	$g_V = 1$ $g_V = 3$ $g_V = 3$	ATLAS-CONF-2016-045 1502.07177 1603.08791 ATLAS-CONF-2016-061 ATLAS-CONF-2016-082 ATLAS-CONF-2016-055 1607.05621 1410.4103 1408.0886
Cl qqqq Cl llqq Cl uutt	2 e, µ 2(SS)/≥3 e,j	2j _ µ≥1b,≥1j	– – Yes	15.7 3.2 20.3	Λ Λ Λ		4.9 TeV	19.9 TeV $\eta_{LL} = -1$ 25.2 TeV $\eta_{LL} = -1$ $ C_{RR} = 1$	ATLAS-CONF-2016-069 1607.03669 1504.04605
Axial-vector mediator (Dirac D Axial-vector mediator (Dirac D ZZ _{XX} EFT (Dirac DM)	M) 0 e, μ M) 0 e, μ, 1 γ 0 e, μ	≥1j 1j 1J,≤1j	Yes Yes Yes	3.2 3.2 3.2	m _A m _A M _*	1.0 Te ⁱ 710 GeV 550 GeV	V	$\begin{array}{l} g_{\rm q}{=}0.25,g_{\chi}{=}1.0,m(\chi)<250~{\rm GeV}\\ g_{\rm q}{=}0.25,g_{\chi}{=}1.0,m(\chi)<150~{\rm GeV}\\ m(\chi)<150~{\rm GeV} \end{array}$	1604.07773 1604.01306 ATLAS-CONF-2015-080
Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	2 e 2 μ 1 e,μ	≥ 2 j ≥ 2 j ≥1 b, ≥3 j	– – Yes	3.2 3.2 20.3	LQ mass LQ mass LQ mass	1.1 T 1.05 Te 640 GeV	eV_ ₽V	$egin{array}{c} eta = 1 \ eta = 1 \ eta = 1 \ eta = 0 \end{array}$	1605.06035 1605.06035 1508.04735
$\begin{array}{c} \text{VLQ }TT \rightarrow Ht + X\\ \text{VLQ }YY \rightarrow Wb + X\\ \text{VLQ }BB \rightarrow Hb + X\\ \text{VLQ }BB \rightarrow Zb + X\\ \text{VLQ }BB \rightarrow Zb + X\\ \text{VLQ }QQ \rightarrow WqWq\\ \text{VLQ }T_{5/3}T_{5/3} \rightarrow WtWt \end{array}$	1 e, μ 1 e, μ 1 e, μ 2/≥3 e, μ 1 e, μ 2(SS)/≥3 e, j	$\geq 2 \text{ b}, \geq 3$ $\geq 1 \text{ b}, \geq 3$ $\geq 2 \text{ b}, \geq 3$ $\geq 2/\geq 1 \text{ b}$ $\geq 4 \text{ j}$ $\mu \geq 1 \text{ b}, \geq 1 \text{ j}$	j Yes j Yes j Yes - Yes Yes	20.3 20.3 20.3 20.3 20.3 3.2	T mass Y mass B mass B mass Q mass T _{5/3} mass	855 GeV 770 GeV 735 GeV 755 GeV 690 GeV 990 GeV	,	T in (T.B) doublet Y in (B,Y) doublet isospin singlet B in (B,Y) doublet	1505.04306 1505.04306 1505.04306 1409.5500 1509.04261 ATLAS-CONF-2016-032
Excited quark $q^* \rightarrow q\gamma$ Excited quark $q^* \rightarrow qg$ Excited quark $b^* \rightarrow bg$ Excited quark $b^* \rightarrow bg$ Excited quark $b^* \rightarrow Wt$ Excited lepton t^*	1 γ - 1 or 2 e, μ 3 e, μ 3 e, μ, τ	1 j 2 j 1 b, 1 j 1 b, 2-0 j - -	- - Yes -	3.2 15.7 8.8 20.3 20.3 20.3	q* mass q* mass b* mass b* mass t* mass v* mass		4.4 TeV 5.6 TeV 2.3 TeV 1.5 TeV 3.0 TeV 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $f_g = f_L = f_R = 1$ $\Lambda = 3.0$ TeV $\Lambda = 1.6$ TeV	1512.05910 ATLAS-CONF-2016-069 ATLAS-CONF-2016-060 1510.02664 1411.2921 1411.2921
LSTC $a_T \rightarrow W\gamma$ LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow ee$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ Multi-charged particles Magnetic monopoles	$1 e, \mu, 1 \gamma$ 2 e, μ 2 e (SS) 3 e, μ, τ 1 e, μ	- 2 j - 1 b - -	Yes Yes 	20.3 20.3 13.9 20.3 20.3 20.3 7.0	a⊤ mass N ^e mass H ^{4±} mass spin-1 invisible particle mass multi-charged particle mass monopole mass	960 GeV 570 GeV 400 GeV 657 GeV 785 GeV 1.:	2.0 TeV	$\begin{split} m(W_R) &= 2.4 \text{ TeV}, \text{no mixing} \\ DY \text{ production, } BR(H_1^{\pm\pm} \to ee) = 1 \\ DY \text{ production, } BR(H_2^{\pm\pm} \to (\tau) = 1 \\ a_{20,cres} = 0.2 \\ DY \text{ production, } q = 5e \\ DY \text{ production, } g = 1g_0, \text{ spin } 1/2 \end{split}$	1407.8150 1506.06020 ATLAS-CONF-2016-051 1411.2921 1410.5404 1504.04188 1509.08059

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded. † Small-radius (large-radius) jets are denoted by the letter j (J).

• Still ~33 fb⁻¹ of data to analyse ahead of us - let's see...

Muchas gracias por su atención!

Back-up

Search for charged Higgs boson in the $H \rightarrow tb$ decay

The variables entering the BDT training are :

- The leading jet $p_{\rm T}$.
- The mass of the *bb* pair with smallest ΔR .
- The $p_{\rm T}$ of the fifth jet, with the jets ordered by transverse momentum with the *b*-tagged jets first and then the non-*b*-tagged jets.
- The second Fox-Wolfram moment calculated using all jets and leptons.
- The average ΔR of all *bb* pairs.
- The ΔR of the lepton and the *bb* pair with smallest ΔR .
- The mass of the untagged jet pair with smallest ΔR .
- The scalar sum of $E_{\rm T}$ calculated using all jets.
- The mass of the *bb* pair with largest $p_{\rm T}$.
- The mass of the *bb* pair with largest mass.
- The mass of the jet triplet with largest $p_{\rm T}$.
- The centrality, defined as the ratio of the scalar sum of the $p_{\rm T}$ of all jets and leptons over the total visible energy.

Search regions $(\geq 6 \text{ jets})$				Search regions (≥ 7 jets)				
Mass-tagged jet multiplicity	<i>b</i> -jet multiplicity	$m_{bb}^{\min\Delta R}$	$m_{ m eff}$	Channel name	Mass-tagged jet multiplicity	<i>b</i> -jet multiplicity	$m^b_{\mathrm{T,min}}$	Channel name
0	3	_	$> 400 {\rm GeV}$	0J. >6i. 3b	0	2	-	0J, \geq 7j, 2b
0	>4	_	> 400 GeV	0J. > 6i. > 4b	0	3	-	$0J, \geq 7j, 3b$
1	2	< 100 GeV	> 700 GeV	11 > 6i 3h LM	0	≥ 4	-	$0J, \geq 7j, \geq 4b$
1	0	< 100 GeV	> 700 GeV	$15, \ge 05, 50, 100$	1	2	-	$1J, \geq 7j, 2b$
1	3	> 100 GeV	> 700 GeV	$1J, \geq 0J, 3D, HM$	1	3	< 160 GeV	$1J, \ge 7j, 3b, LM$
1	≥ 4	< 100 GeV	> 700 GeV	$1J, \geq 6J, \geq 4b, LM$	1	3	> 160 GeV	$1J, \geq 7j, 3b, HM$
1	≥ 4	> 100 GeV	$> 700 { m ~GeV}$	$ $ 1J, $\geq 6j$, $\geq 4b$, HM	1	≥ 4	< 160 GeV	$1J, \geq 7j, \geq 4b, LM$
≥ 2	3	-	-	$\geq 2J, \geq 6j, 3b$	1	≥ 4	> 160 GeV	$1J, \geq 7j, \geq 4b, HM$
>2	>4	-	-	>2J, >6j, >4b	≥ 2	2	-	$\geq 2J, \geq 7j, 2b$
					≥ 2	3	$< 160~{\rm GeV}$	$\geq 2J, \geq 7j, 3b, LM$
Validation regions (5 jets)					≥ 2	3	> 160 GeV	$\geq 2J, \geq 7j, 3b, HM$
Mass-tagged jet multiplicity	<i>b</i> -iet multiplicity	$m_{ii}^{\min\Delta R}$	m g	Channel name	≥ 2	≥ 4	-	$\geq 2J, \geq 7j, \geq 4b$
	o jet materprietty	11666	> 400 C V		Validation regions (6 jets)			
0	3	-	> 400 GeV > 400 CeV	[0J, 5], 3D	Mass-tagged jet multiplicity	<i>b</i> -jet multiplicity	$m^b_{\rm T}$ min	Channel name
0	<u>_4</u>	-	> 400 GeV	[0, 0], 2], 240		0	1,1111	
1	3	-	> 700 GeV	1J, 5J, 3D	0	2	-	0J, 0J, 2D
1	≥ 4	-	$> 700 { m GeV}$	$1J, 5j, \geq 4b$	0	3	-	0J, 0J, 3D
≥ 2	3	-	-	≥ 2 J, 5j, 3b	0	$\frac{\geq 4}{2}$	-	$0J, 0J, \ge 40$
≥ 2	≥ 4	-	-	$\geq 2J, 5j, \geq 4b$	1	2	-	1J, 0J, 2D
					1	3	-	1J, 6J, 3D
					1	≥ 4	-	$[1J, 0], \geq 40$
					<u>≥2</u>	2	-	$\geq 2J, 6J, 2b$
					<u>≥2</u>	3	-	$\geq 2J, 6J, 3b$
					≥ 2	≥ 4	-	$ \geq 2J, 6j, \geq 4b$

Preselection requirements					
Requirement	1-lepton channel	0-lepton channel			
Trigger Leptons Jets b-tagging $E_{\rm T}^{\rm miss}$ Other $E_{\rm T}^{\rm miss}$ -related	Single-lepton trigger =1 isolated e or μ ≥ 5 jets $\geq 2 b$ -tagged jets $E_{\rm T}^{\rm miss} > 20 \text{ GeV}$ $E_{\rm T}^{\rm miss} + m_{\rm T}^W > 60 \text{ GeV}$	$E_{\rm T}^{\rm miss} \text{ trigger}$ =0 isolated <i>e</i> or μ ≥ 6 jets $\geq 2 b$ -tagged jets $E_{\rm T}^{\rm miss} > 200 \text{ GeV}$ $\Delta \phi_{\rm min}^{4j} > 0.4$			