Search for heavy gluon and vector-like quark in the 4b final state at 8 TeV

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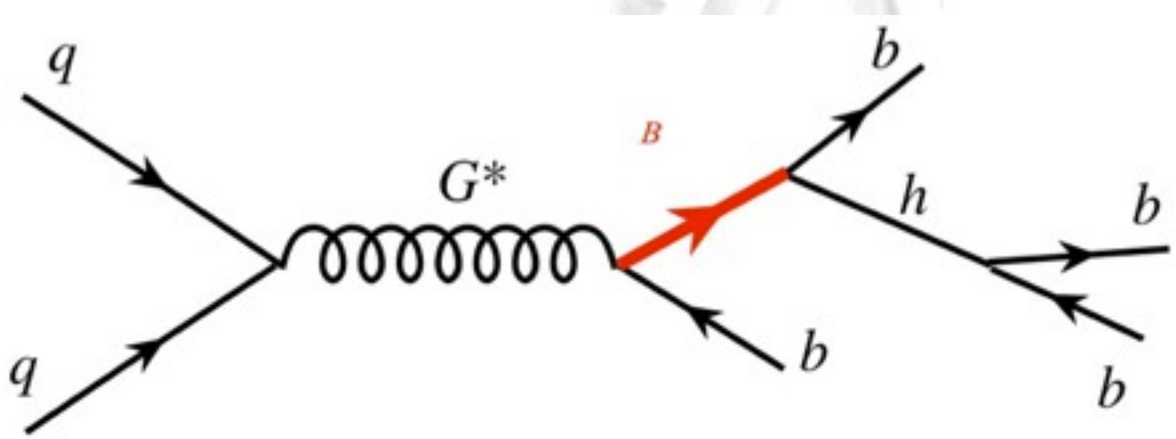
Model

- Hbb production in Composite Higgs Models : 1305.1940
  - new strong dynamics for EWSB
  - SM particles are considered elementary (except for the Higgs)
  - new particles belong to the composite sector
  - composite fermions mix with elementary sector → partial compositeness
- Single production of bottom partners (B_H) : $pp \to G^* \to B_H b \to H(\to bb)bb$
  - exchange of heavy gluons (G^*) via the s-channel
  - decay to Higgs boson ($H \to bb$) + SM bottom quarks
  - cross sections not large enough for γγ and ZZ channels



Backgrounds

- Largest background is QCD
  - estimated with data-driven technique (discussed later)
- Other backgrounds are estimated with the following MC

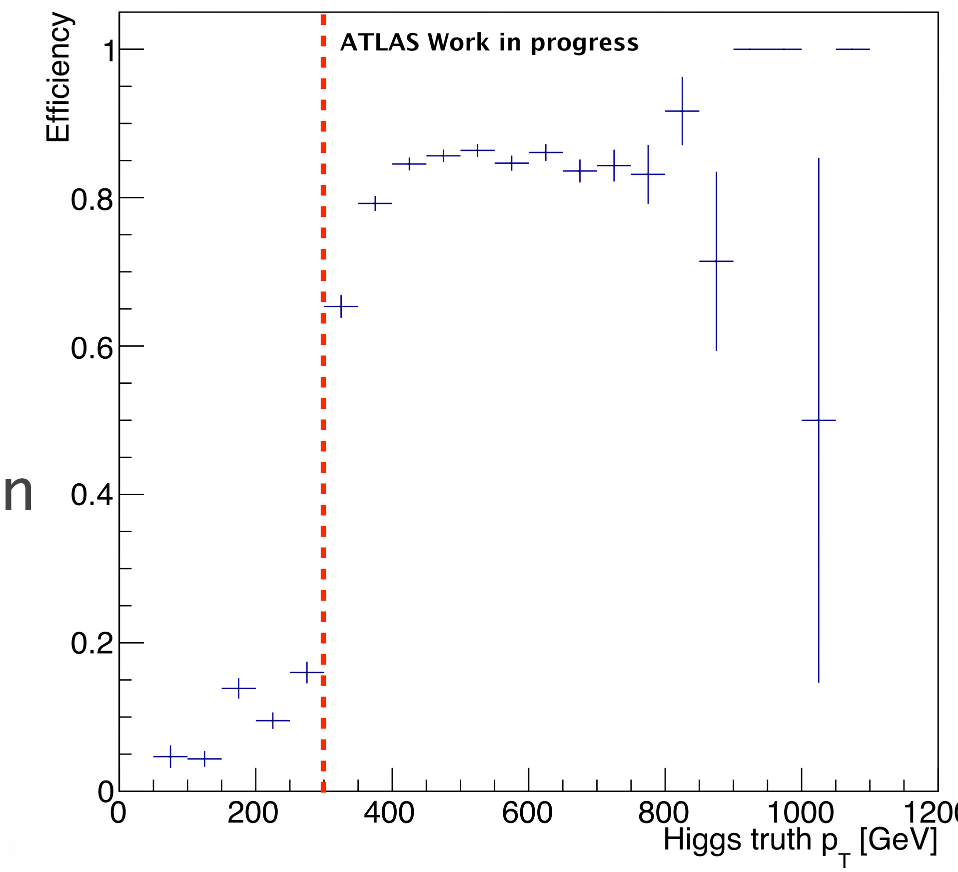
Process	Generator	$\sigma \times$ BR [pb]	N_{events}
top quark			
$t\bar{t}$	Powheg+Pythia	238.06	25M
t-channel	Powheg+Pythia	26.92	10M
s-channel	Powheg+Pythia	1.64	6M
Wt-channel	Powheg+Pythia	32.38	3M
$t\bar{t} + Z$	Pythia	0.068	400k
$t\bar{t} + H(\to b\bar{b})$	Pythia	0.034	50k
Diboson			
WW	Powheg+Pythia	55.43	2.5M
WZ	Powheg+Pythia	22.69	250k
$66 < m_{\ell\ell} < 116$ GeV			
ZZ	Powheg+Pythia	7.697	1M
$66 < m_{\ell\ell} < 116$ GeV			
W/Z+jets			
$W \to \ell\nu$	Sherpa 1.4.1	10.97	168M
$Z/\gamma^* \to \ell\ell$	Sherpa 1.4.1	1.24	42M
$m_{\ell\ell} > 40$ GeV			
$Z/\gamma^* \to \nu\nu$	Sherpa 1.4.1	6.71	77M
$m_{\nu\nu} > 5$ GeV			
$Z \to b\bar{b}$	Sherpa 1.4.1	140.55	6M

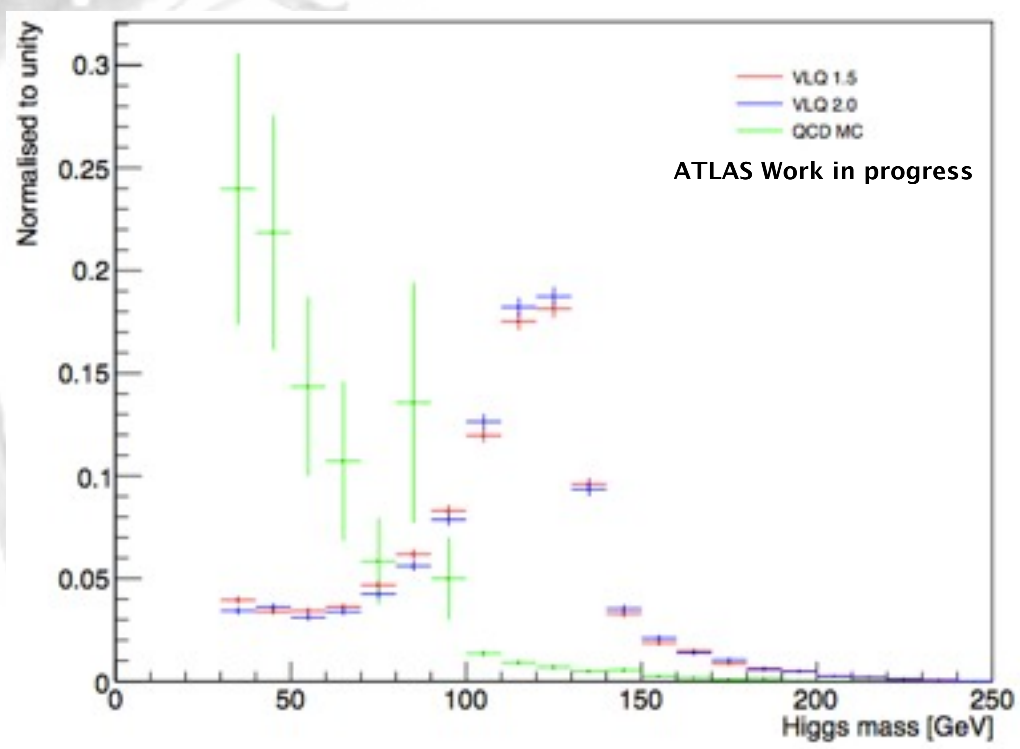
Object definition

- **Jets** :
  - AntiKt R=0.4 LCTopo, $p_T > 50$ GeV, $|\eta| < 2.5$
  - b-tagging : MV1 at 70% efficiency
- **Fat jets** :
  - AntiKt R=1.0 (trimmed)
- **Electron veto** :
  - $p_T > 10$ GeV, $|\eta| < 2.7$ and medium ++
  - ptcone20/$p_T < 0.15$
  - Etcone20/$E_T < 0.14$
- **Muon veto** :
  - $p_T > 10$ GeV
  - track_cone_pt20/$p_T < 0.1$
- No overlap between jets and isolated leptons

Signal Region – merged

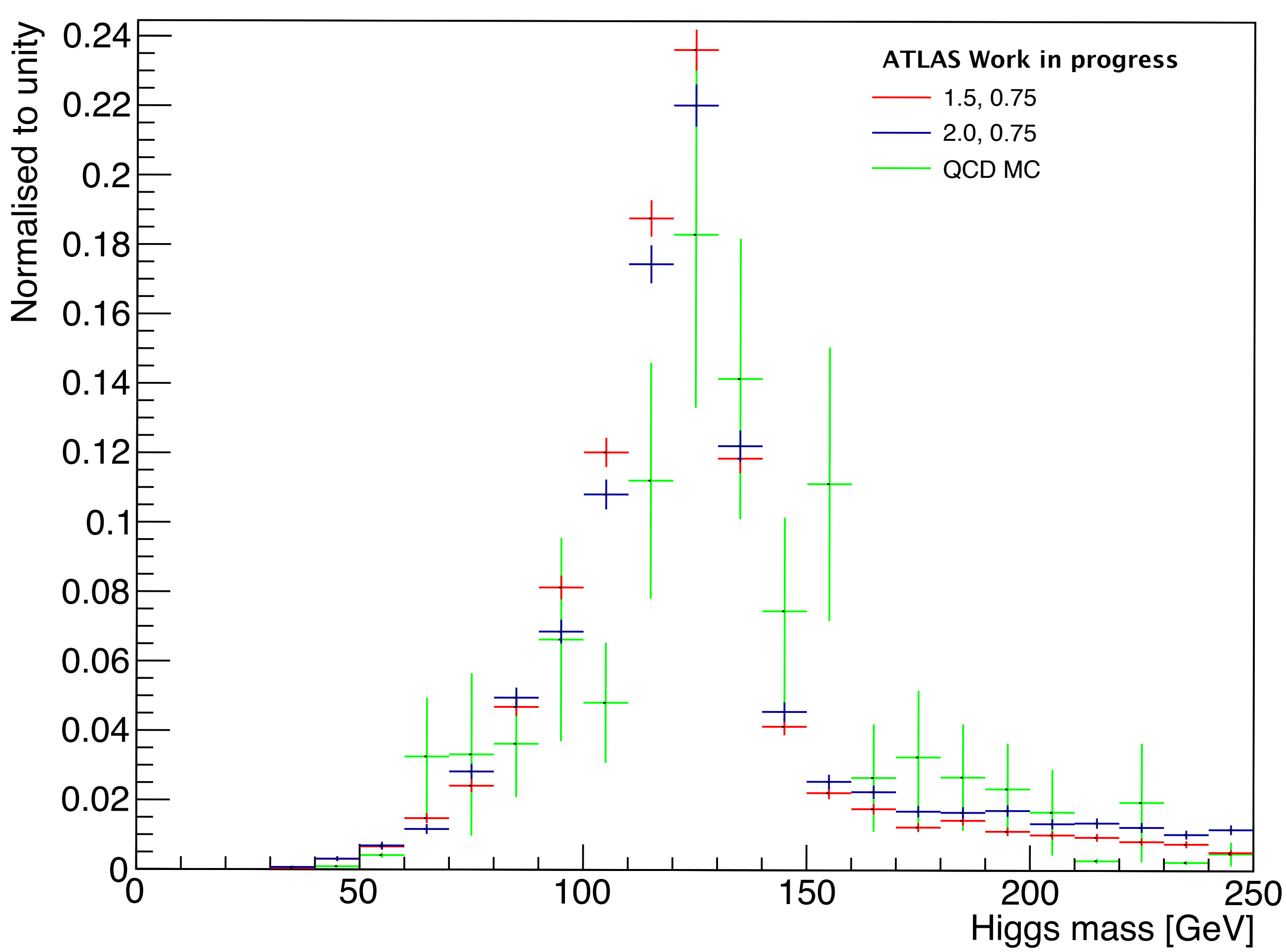
- **Higgs jet**
  - fat jet with mass closest to the Higgs mass (126 GeV)
  - $p_T > 300$ GeV, $|\eta| < 2.0$
  - at least one AntiKt4 b-tagged jet has to be within the Higgs fat jet ($\Delta R(h,b) < 1$)
  - AntiKt1.0 → $90 < M(J) < 140$ GeV
- Two highest p_T jets away from the Higgs ($\Delta R(h,b) > 1.4$) are used to reconstruct B and G*
  - both jets are b-tagged in the SR
- **B_H** : 4-vector sum of the higgs fat jet and either the leading or next-to-leading b-tagged jet away from the Higgs (depends on the G*-B mass spliting)
- **G*** : 4-vector sum of the higgs fat jet and the two b-tagged jets away from Higgs





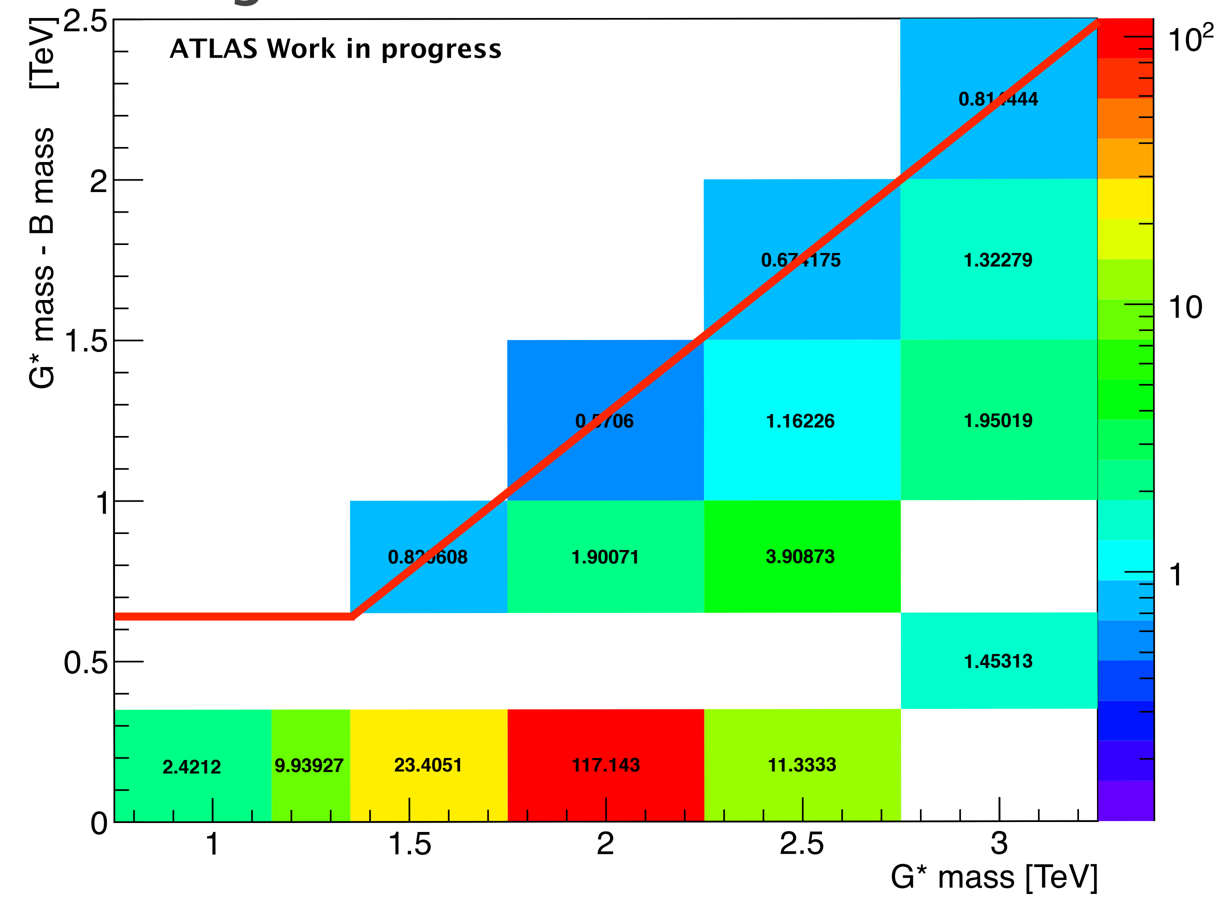
Signal Region - resolved

- Exactly 4 AntiKt4 LCTopo jets with p_T > 50 GeV and $|\eta|$ < 2.5
- **Higgs** : 2 jets which form the closest mass to the Higgs'
  - 90 < M(jj) < 140 GeV
- **B_H** : 4-vector sum of the Higgs of either the leading or next-to-leading jet away from the Higgs (depends on the G*-B mass spliting)
- **G*** : 4-vector sum of the 4 jets
- Resolved and merged analysis are **orthogonal** to each other
  - if event doesn't pass merged criteria → try resolved case

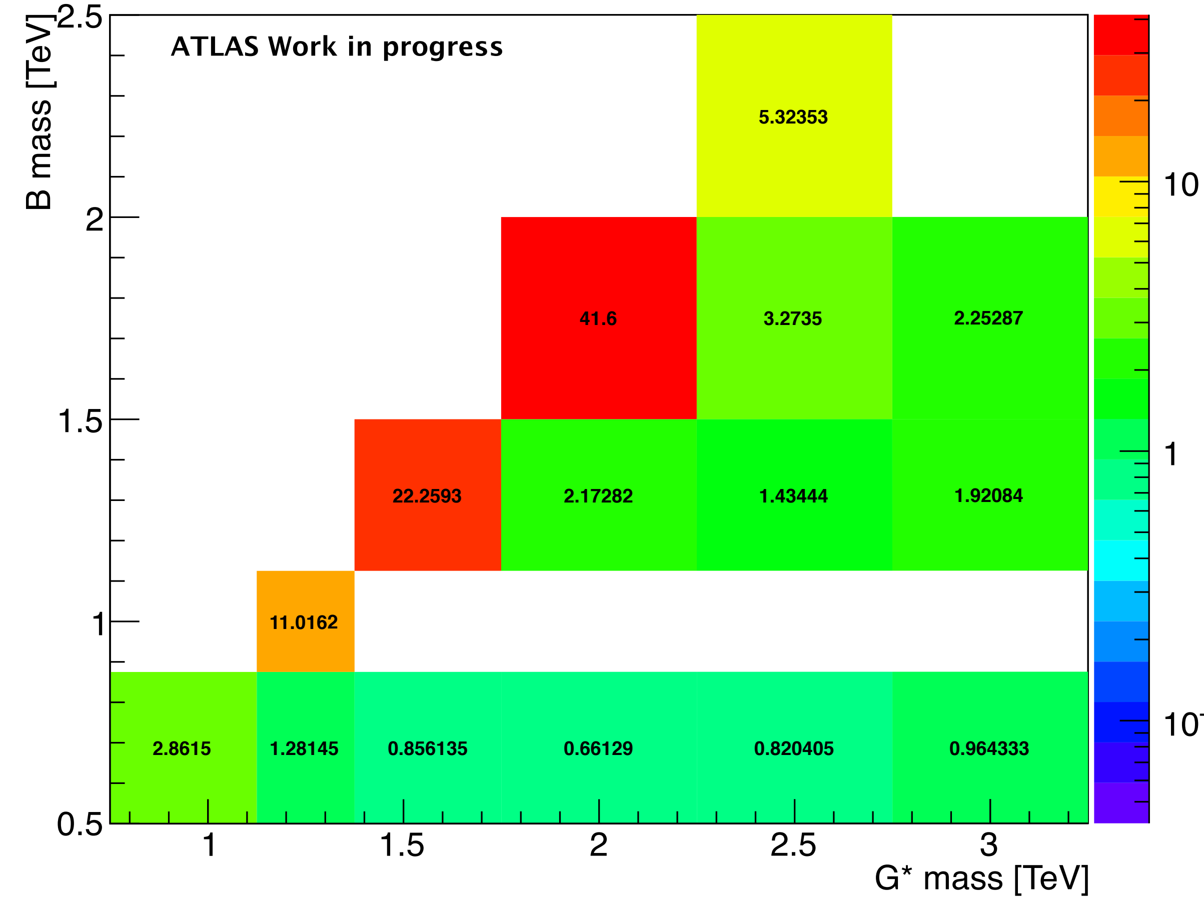


Categories, SR1-SR5

Merged



Resolved



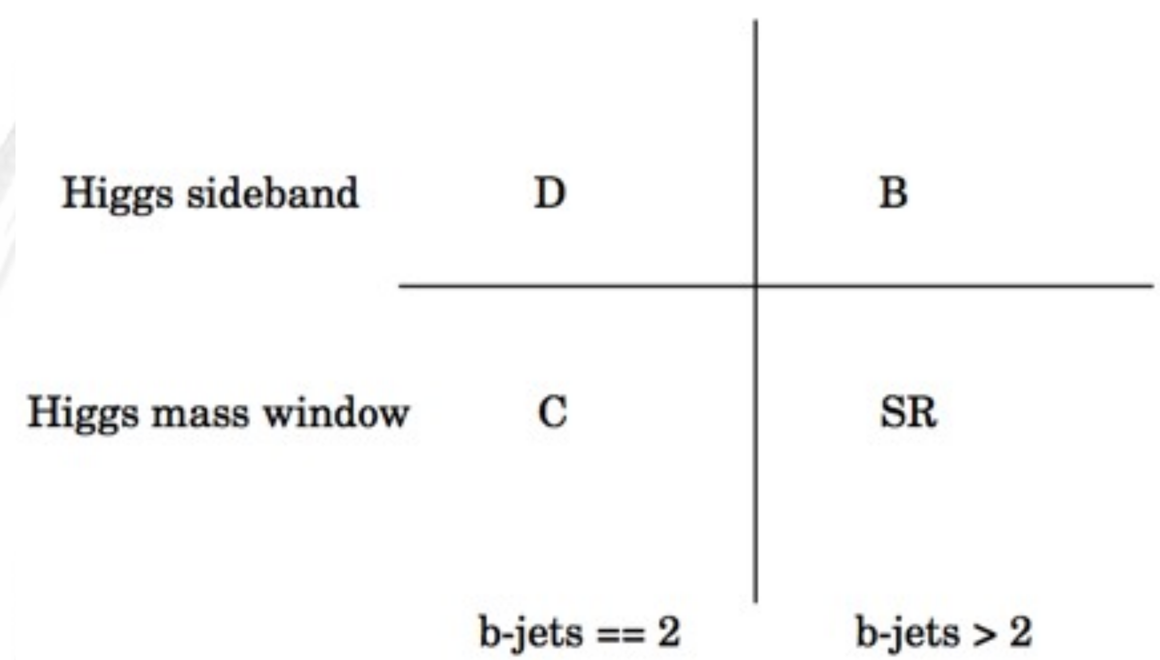
	Category 1		Category 2		
	SR1	**SR2**	**SR3**	**SR4**	**SR5**
Lower cuts on (G*, B) mass [TeV]	(1.0, 0.5)	(1.3, 0.5)	(0.8, 0.5)	(1.5, 0.5)	(1.8, 1.0)

- ratio of leading efficiency over next-to-leading efficiency ($r = \varepsilon_L/\varepsilon_{NL}$)
  - efficiency is defined as the ratio of events passing all the SR cuts + B mass window cut (± 200 GeV of the nominal mass) over the events passing all the SR cuts
- **Category 1 :** next-to-leading jet is assumed to be from B decay ($r < 1$)
- **Category 2 :** leading jet is assumed to be from B decay ($r > 1$)

QCD Background

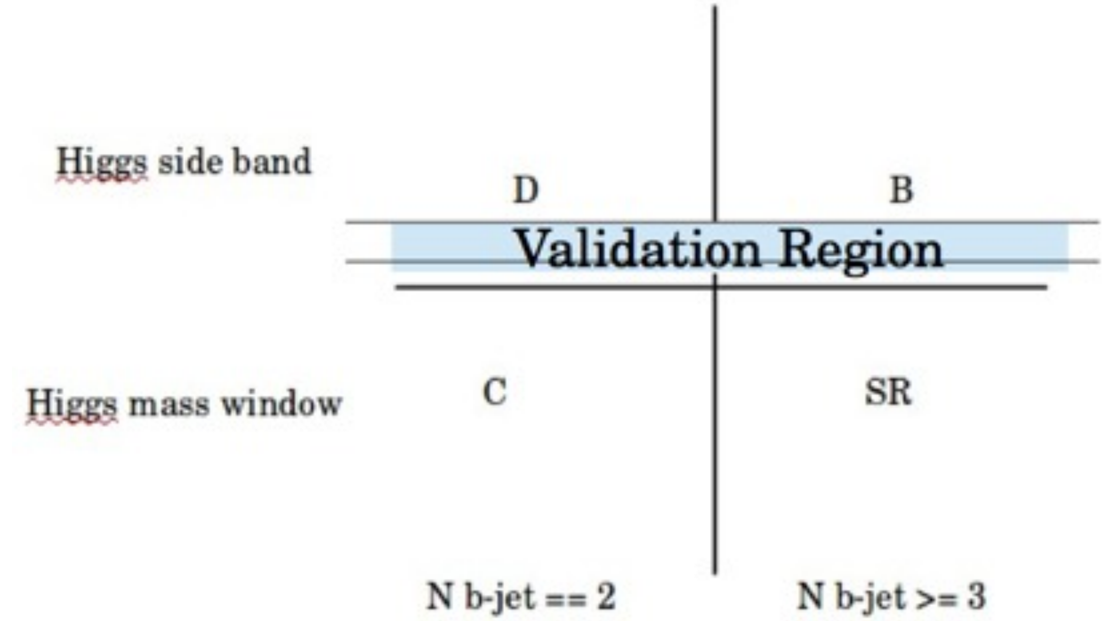
- Largest background is QCD multijet
- Estimated with an ABCD data-driven technique
- 3 orthogonal control regions
- Higgs sideband region (== 2 or >2 b-tagged jets) (B&D)
- Higgs window with exactly 2 b-tagged jets (C)
- # events in the SR → $N_{\mathrm{SR}}^{\mathrm{QCD}} \times N_{\mathrm{D}} = N_{\mathrm{B}} \times N_{\mathrm{C}}$

- ttbar, single-top, diboson and V+jets BG are removed from each of the CR (using MC)
- this estimation is done separately in each of the 5 SRs
- M(J) > 30 GeV



Validation of multijet BG

- Validation region defined in the sidebands of the Higgs mass
- Region C' is now [75,90] and [140,155] GeV (b-tag = 2)
- Regions B' and D' : 30 < M(J) < 75 GeV && M(J)> 155 GeV (B' : b-tag = 2, D' b-tag ≥ 3)
- non-QCD BG removed
- ⇒ compare estimated nb. of events to observed nb. of events in VR



CR	VR	SR	VR	CR
[30, 75]	[75, 90]	[90, 140]	[140, 155]	> 155

QCD multijet yields

SR1

Algorithm	Number of events					
	B	C	D	VR (exp.)	VR (obs.)	SR (exp.)
Merged	1753.4	15080.8	24314.8	529 ± 18	529 ± 24	1088 ± 30
Resolved	4510.8	31503.5	68883.7	1127 ± 22	1101 ± 34	2063 ± 34

SR2

Algorithm	Number of events					
	B	C	D	VR (exp.)	VR (obs.)	SR (exp.)
Merged	670.67	7018.24	12105.7	198 ± 10	183 ± 14	389 ± 17
Resolved	1754.28	11033.7	28858.6	362 ± 11	341 ± 19	671 ± 18

SR3

Algorithm	Number of events					
	B	C	D	VR (exp.)	VR (obs.)	SR (exp.)
Merged	4808.24	43668.8	63420.9	1560 ± 32	1589 ± 42	3311 ± 55
Resolved	11488.1	126851.	162491.	3949 ± 51	4088 ± 65	8968 ± 91

SR4

Algorithm	Number of events					
	B	C	D	VR (exp.)	VR (obs.)	SR (exp.)
Merged	445.88	5281.06	9404.36	126 ± 8	134 ± 12	250 ± 13
Resolved	1128.71	9276.13	19223.2	257 ± 10	253 ± 16	545 ± 18

SR5

Algorithm	Number of events					
	B	C	D	VR (exp.)	VR (obs.)	SR (exp.)
Merged	147.86	1786.85	3211.56	42 ± 5	38 ± 6	82 ± 8
Resolved	339.92	2415.65	5439.96	67 ± 5	70 ± 9	151 ± 9

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- Observed number of events in control and validation regions
- Non-QCD backgrounds are removed from CR, VR (obs.) and SR

Systematic uncertainties

- Stat. uncert. of the data in CRs
- Non-closure of the VR (syst. uncert. due to the difference between observed and predicted numbers in the validation region) : $r = N_{obs}/N_{exp}$
  - if r is consistent with 1 (within 1σ) → Δr
  - otherwise |r−1| is the relative uncert.
- Dectector syst. uncert. of the MC-based backgrounds (JES : components leading to an upper (lower) yield are added in quadrature to JESUp (JESDown)

Merged

systematic uncertainty	SR1	SR2	SR3	SR4	SR5
VR non-closure	5.1%	7.5%	3.%	10.2%	18.9%
Jet Energy Resolution	+0.87%	+0.26%	-1.53%	0.01%	-1.70%
JES AntiKt4	+0.49% -0.61%	+0.41% -0.76%	+0.62% -0.72%	+0.69% -0.76%	+0.29% -0.72%
JES AntiKt10	+0.58% -1.09%	+0.63% -1.41%	+1.32% -1.17%	+0.82% -1.21%	+0.39% -0.76%
Mass AntiKt10	+0.11% -0.07%	+0.19% -0.42%	+0.06% -0.23%	+0.08% -0.40%	+0.18% -0.30%
b-tagging SFs - Total	0.23% 0.32%	0.32% 0.32%	0.05% 0.40%	0.40% 0.05%	0.31% -1.14%
b-tagging SFs - high p_T	0.45% 0.11%	0.69% 0.05%	0.28% 0.22%	0.57% -0.04%	0.33% -1.10%
Luminosity	0.26%	0.24%	0.30%	0.23%	0.22%
data/MC statistical (CR)	2.50%	4.02%	1.49%	4.83%	9.20%
MC/QCD statistical (SR)	2.75%	4.73%	1.57%	5.95%	10.34%
Total (stat.)	2.75%	4.73%	1.57%	5.95%	10.34%
Total (syst.)	5.91%	8.71%	4.03%	11.41%	21.18%

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Resolved

systematic uncertainty	SR1	SR2	SR3	SR4	SR5
VR non-closure	3.5%	5.9%	3.2%	7.%	14.4%
Jet Energy Resolution	+1.64%	+1.41%	+0.11%	-0.19%	-0.62%
JES AntiKt4	+0.70% -0.52%	+0.84% -0.46%	+0.22% -0.28%	+0.52% -0.20%	+0.28% -0.24%
b-tagging SFs - Total (up/down)	0.09% 0.78%	0.09% 0.72%	-0.06% 0.71%	-0.09% 0.48%	-0.0006% 0.75%
b-tagging SFs - high p_T (up/down)	0.43% 0.50%	0.40% 0.46%	0.33% 0.38%	0.24% 0.19%	0.42% 0.40%
Luminosity	0.14%	0.13%	0.17%	0.15%	0.11%
data/MC statistical (CR)	1.59%	2.60%	0.98%	3.18%	5.92%
MC/QCD statistical (SR)	2.14%	3.73%	1.01%	4.04%	7.69%
Total (stat.)	2.14%	3.73%	1.01%	4.04%	7.69%
Total (syst.)	4.34%	6.71%	3.46%	7.73%	15.61%

BG yields in SRs

- Non-QCD BG contributions to the different signal regions is estimated with MC
- Stat. uncert. only for individual BG
  - stat. + syst. uncert. for total BG

Merged

Background	SR1	SR2	SR3	SR4	SR5
multi-jet	1088 ± 30	389 ± 17	3311 ± 55	250 ± 13	82 ± 8
$t\bar{t}$	$89. \pm 3.8$	25.05 ± 2.05	334.5 ± 7.3	14.7 ± 1.6	3.9 ± 0.9
single top	6.8 ± 1.5	2.76 ± 0.97	17.7 ± 2.1	1.41 ± 0.71	—
di-boson	—	—	—	—	—
W/Z($\rightarrow \ell\nu$) + jets	8.2 ± 1.8	2.9 ± 1.2	2.7 ± 0.9	0.51 ± 0.54	0.5 ± 0.5
$t\bar{t} - H$	0.49 ± 0.06	0.17 ± 0.04	2.01 ± 0.12	0.05 ± 0.03	0.01 ± 0.01
$t\bar{t} - W$	0.10 ± 0.02	0.013 ± 0.010	0.50 ± 0.05	0.013 ± 0.008	0.008 ± 0.006
$t\bar{t} - Z$	0.17 ± 0.02	0.05 ± 0.01	0.77 ± 0.05	0.014 ± 0.007	0.005 ± 0.005
Z($\rightarrow b\bar{b}$) + jets	8.05 ± 0.60	3.51 ± 0.42	24.92 ± 0.94	1.85 ± 0.32	0.33 ± 0.09
Total BG	$1200 \pm 33 \pm 71$	$423 \pm 20 \pm 37$	$3694 \pm 58 \pm 149$	$269 \pm 16 \pm 31$	$87 \pm 9 \pm 18$

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Resolved

Background	SR1	SR2	SR3	SR4	SR5
multi-jet	2063 ± 34	671 ± 18	8968 ± 91	545 ± 18	151 ± 9
$t\bar{t}$	59.80 ± 3.08	16.7 ± 1.7	330.16 ± 7.2	13.8 ± 1.6	2.99 ± 0.67
single top	2.21 ± 0.57	0.29 ± 0.16	14.6 ± 1.8	0.61 ± 0.25	—
di-boson	0.05 ± 0.05	—	0.05 ± 0.03	—	—
W/Z($\rightarrow \ell\nu$) + jets	3.9 ± 2.1	1.3 ± 0.5	40.4 ± 5.5	3.7 ± 1.8	0.1 ± 0.1
$t\bar{t} - H$	0.09 ± 0.03	0.02 ± 0.01	0.47 ± 0.06	0.02 ± 0.01	—
$t\bar{t} - W$	0.04 ± 0.02	0.02 ± 0.01	0.24 ± 0.03	—	—
$t\bar{t} - Z$	0.04 ± 0.01	0.01 ± 0.01	0.33 ± 0.03	0.01 ± 0.01	0.002 ± 0.002
Z($\rightarrow b\bar{b}$) + jets	23.1 ± 1.1	8.20 ± 0.61	90.3 ± 2.0	6.37 ± 0.46	2.16 ± 0.28
Total BG	$2152 \pm 46 \pm 93$	$697 \pm 26 \pm 47$	$9408 \pm 95 \pm 326$	$569 \pm 23 \pm 44$	$156 \pm 12 \pm 24$

Upper limits on signal yields

Merged

Region	Expected	Exp. with cont.	Observed
SR1	109^{+60}_{-34}	108^{+60}_{-34}	**Blinded**
SR2	103^{+69}_{-33}	100^{+67}_{-32}	
SR3	247^{+149}_{-82}	245^{+148}_{-81}	
SR4	76^{+70}_{-26}	74^{+68}_{-25}	
SR5	56^{+221}_{-24}	52^{+203}_{-22}	

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Resolved

Region	Expected	Exp. with cont.	Observed
SR1	181^{+74}_{-51}	179^{+74}_{-51}	**Blinded**
SR2	104^{+42}_{-29}	103^{+42}_{-29}	
SR3	667^{+284}_{-191}	661^{+282}_{-190}	
SR4	66^{+31}_{-20}	66^{+31}_{-19}	
SR5	46^{+22}_{-14}	45^{+22}_{-14}	

- upper limits on signal yields for merged and resolved assuming no signal contmination
- effect of signal contamination in the CRs
  - in each CRs, substract c_X from N_X where $c_X = f_X \cdot y_{limit}/1.64$
    - f_X : ratio of # signal events in CR X over # signal events in SR, y_{limit} is the 95% CL limit

Expected sensitivity

signal cross section (fb)/expected combined limit (fb)

M_B \ M_{G*}	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
2.0						SR5 5.2/14.9	SR5 4.8/13.7	SR5 2.9/14.2	SR5 1.5/21
1.75					SR5 16/20	SR5 13.4/14.	SR5 7.8/13.3	SR5 3.8/13.4	SR5 1.7/15.0
1.50				SR4 47/21	SR4 38/34	SR5 21/17.3	SR5 9.6/14.5	SR5 4.3/14.3	SR5 1.9/15.3
								SR5 4.5/14.8	
1.25			SR3 148/58	SR4 105/21	SR4 54/9.9	SR5 24/15.4	SR5 10.5/		
						SR5 25/16.0			
1.0		SR3 475/55	SR3 291/51	SR4 159/15.7	SR4 58/17.8				
				SR2(1) 137/26.9					
0.75	SR3 1449/84	SR3 746/59	SR1(1) 310/30.1						

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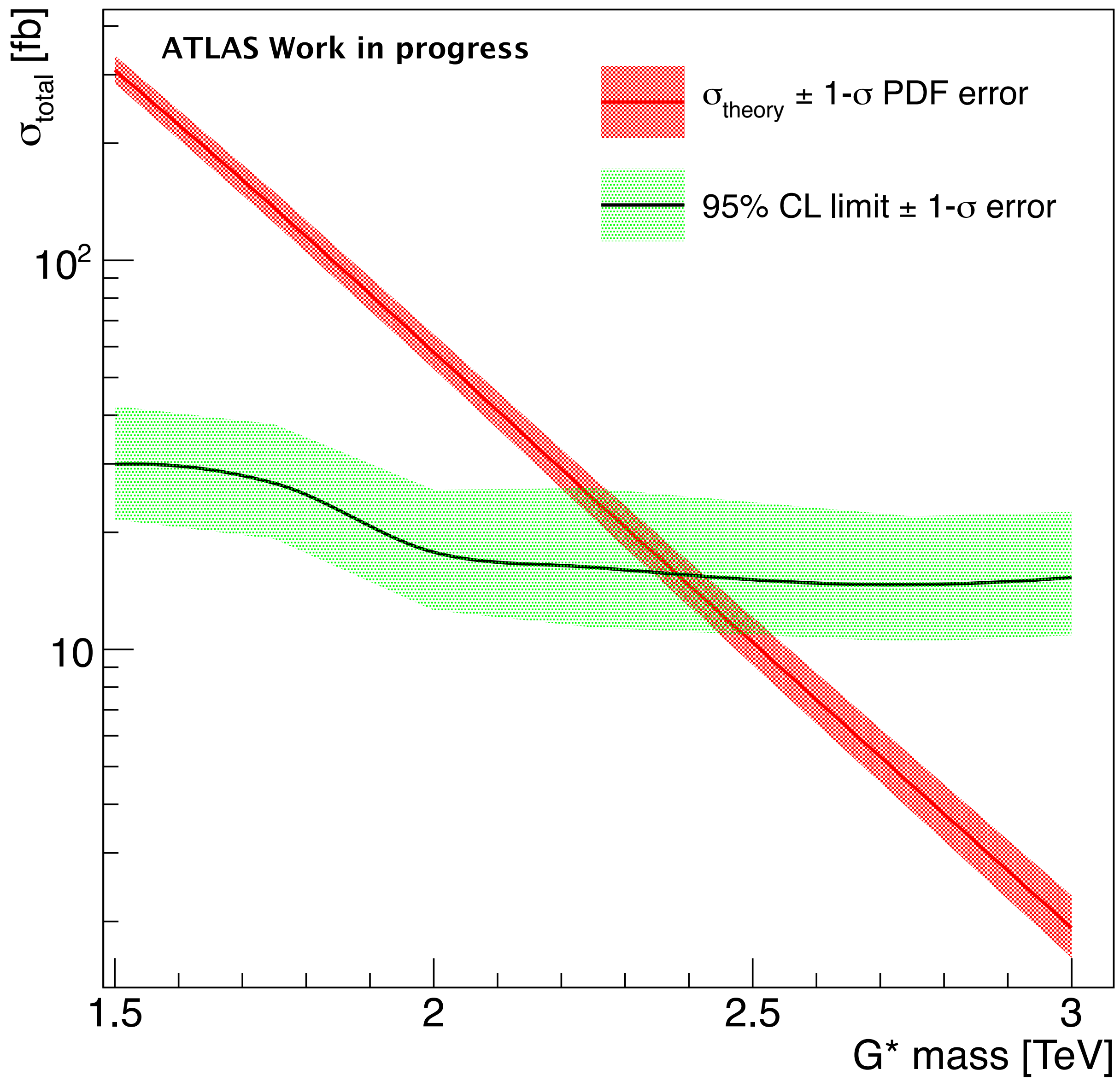
- Sensitivity : signal cross section compared to expected combined exclusion limit at 95% C.L.
- Red cells are expected to be excluded

Combined limit



Preliminary results

- Expected limit as a function of M(G*) for M(B) = M(G*)/2
- Green : combined upper limit on the total cross section
- Red : theory cross section with PDF uncertainty

Summary

- Composite Higgs models among the leading candidates to explain EWSB
  - VLQ predicted by many CH models
- 1st search for VLQ via heavy gluon in ATLAS
  - other searches via weak interactions
- Good sensitivity is expected
- Results later in the summer