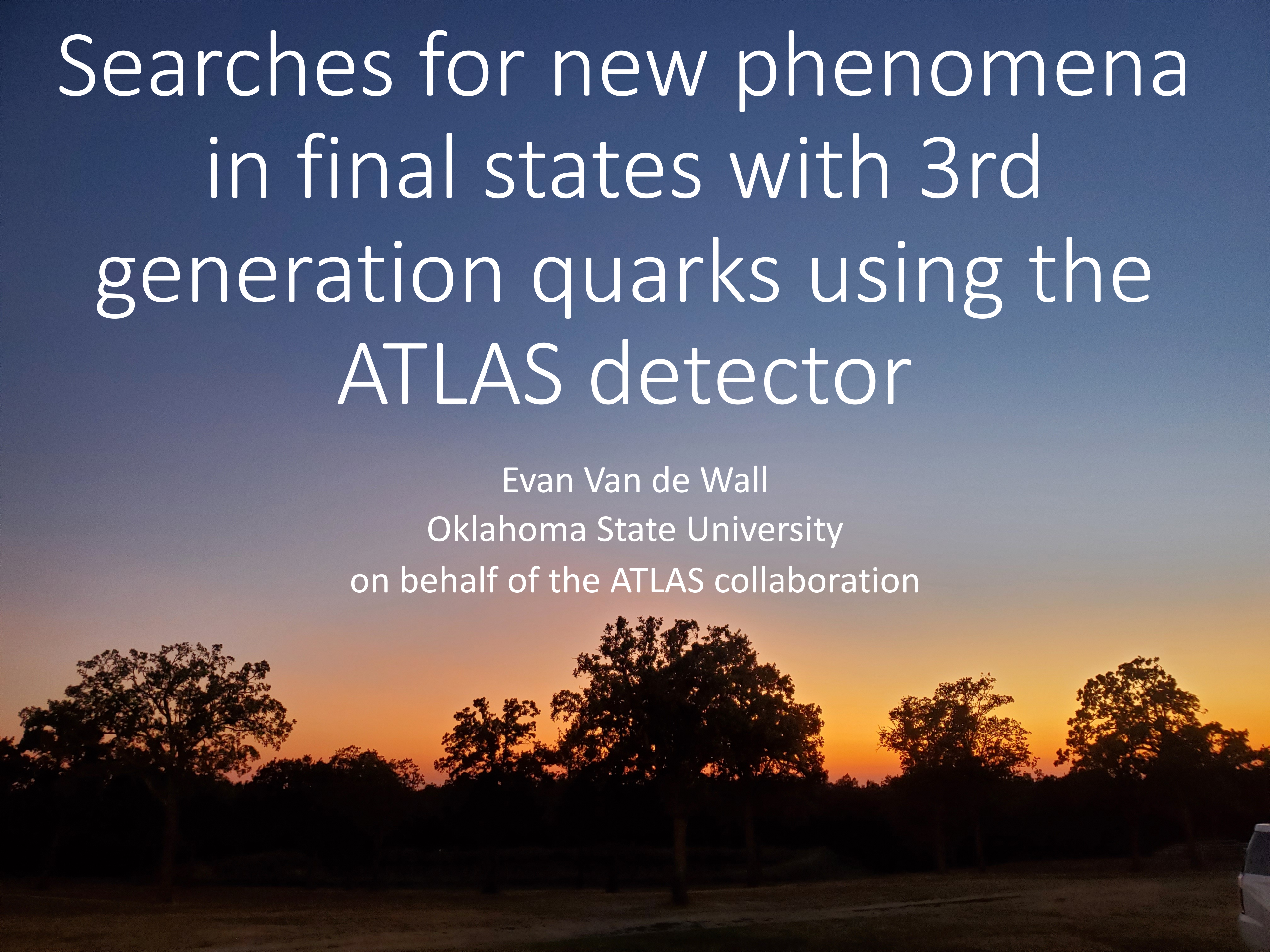


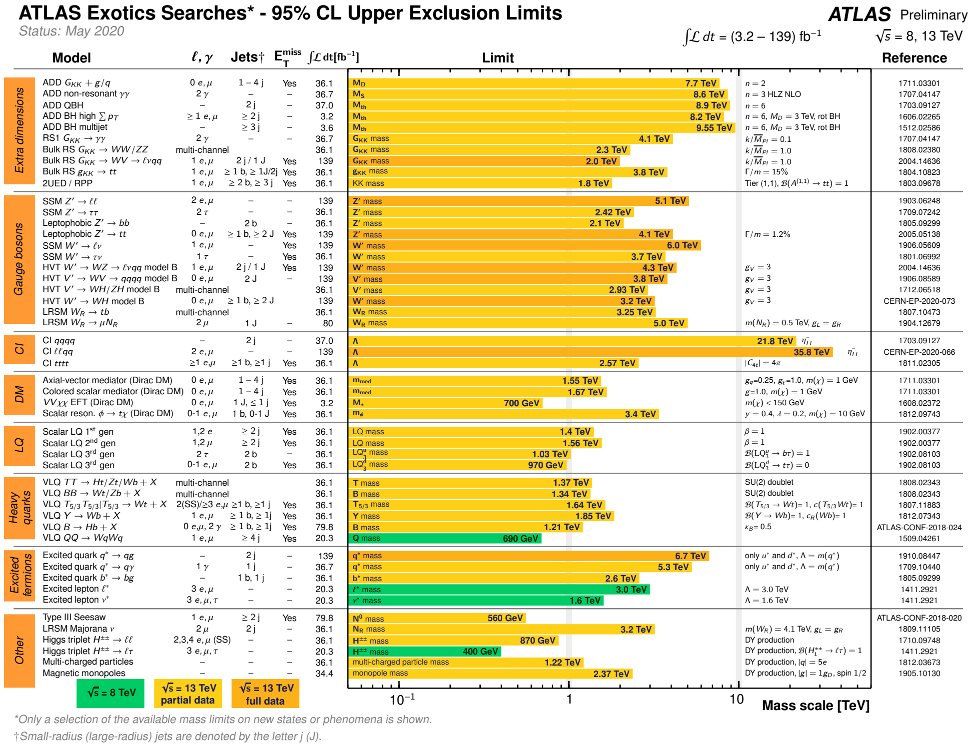
Searches for new phenomena in final states with 3rd generation quarks using the ATLAS detector

Evan Van de Wall
Oklahoma State University
on behalf of the ATLAS collaboration

Why 3^{rd} generation quarks

Third generation Quarks

- Unique signature
    - Use of taggers
    - Suppress Standard Model processes
- Large mass
    - Large coupling to Higgs Boson



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	$1\ e, \mu$	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	$0\ e, \mu$	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η^-_{LL}	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ 35.8 TeV	η^-_{LL}	CERN-EP-2020-066
	CI $tttt$	$\geq 1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1^{st} gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2^{nd} gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3^{rd} gen	$2\ \tau$	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3^{rd} gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	$0\ e,\mu, 2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

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

†Small-radius (large-radius) jets are denoted by the letter j (J).

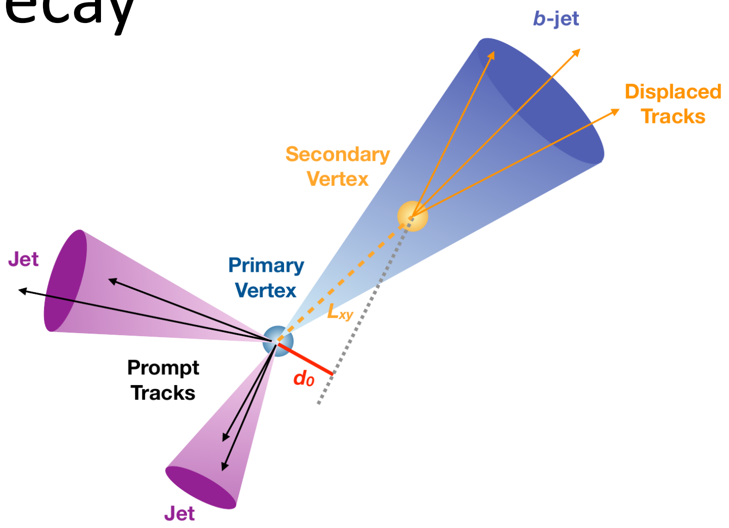
Analyses Discussed

- Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$
- Search for single vector-like quark
    - $T \to Ht$
- Search for invisible + single top
- Search for pair production of leptoquarks

3^{rd} Generation Quark Identification (Bottom Quarks)

- b-quarks hadronized and then decay

- Unique properties of decays
  - Longer lifetime
    - Displaced decay vertex
  - Large track multiplicity
  - Large mass

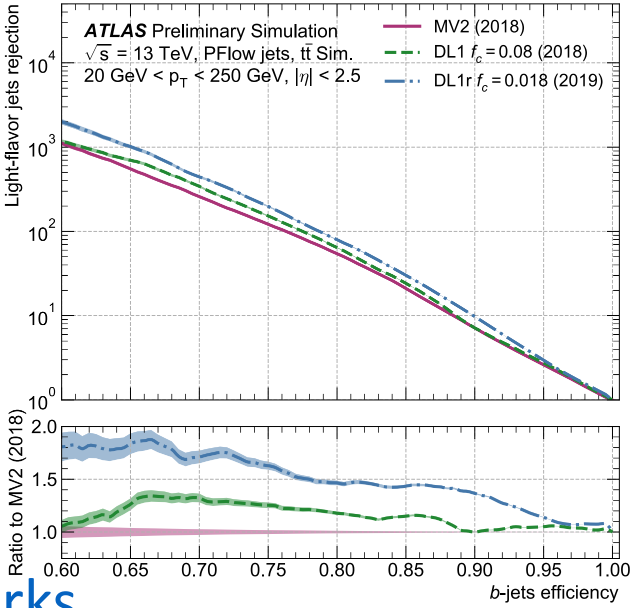


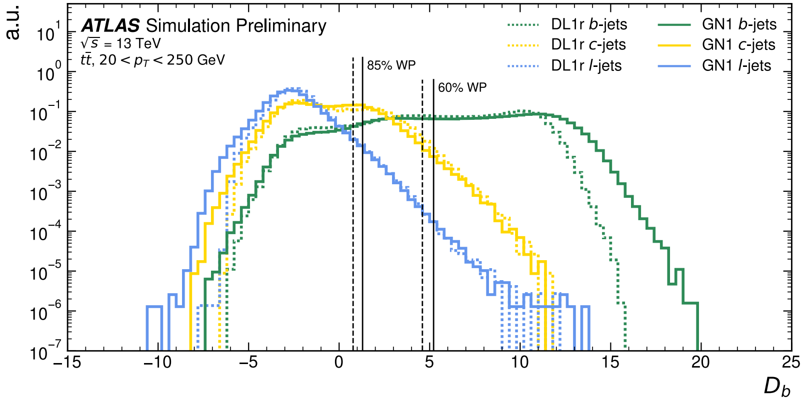
- These properties are used to create a b-tagger

ATLAS-FTAG-2019-005

3rd Generation Quark Identification (Bottom Quarks)

- Many versions of b-taggers
  - MV2 – Boosted Decision Tree
  - DL1 – Deep Neural Network
  - DL1r – Recurrent Neural Network
- Each showed better performance
- Development still ongoing
  - Investigating graphical nueral networks



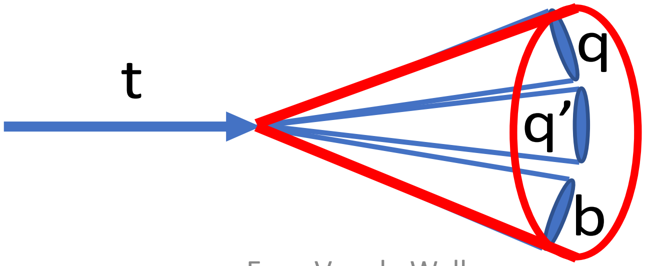


3^{rd} Generation Quark Identification (Top Quarks)

- top quarks decay before they hadronized
  - Branching Ratio ~100% for $t \rightarrow Wb$

- Many searches are for heavy particles
  - top quark is boosted

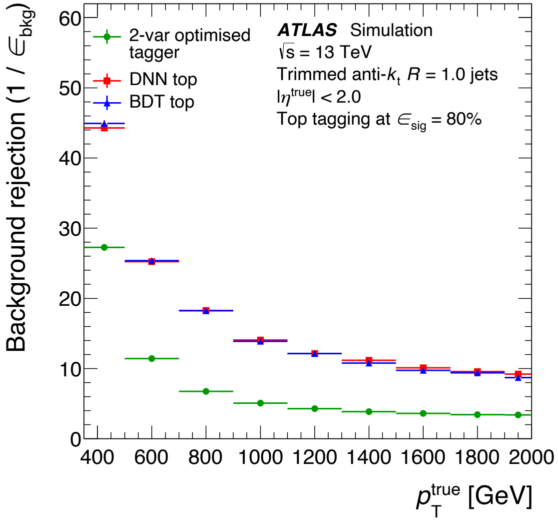
- Boosted top quarks result in collimated jet
  - Captured by a large-R jet



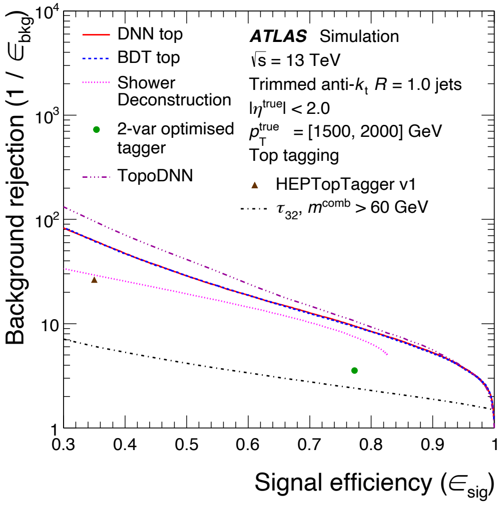
arXiv:1808.07858

3rd Generation Quark Identification (Top Quarks)

- Compared BDT to DNN
  - Used low level variables
    - p_{T}, mass, N-subjetiness, etc.
  - Results are similar



- Trained a DNN with high level variables
  - Topoclusters
- Slight increase in background rejection



ATLAS-CONF-2022-008

Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

Motivation

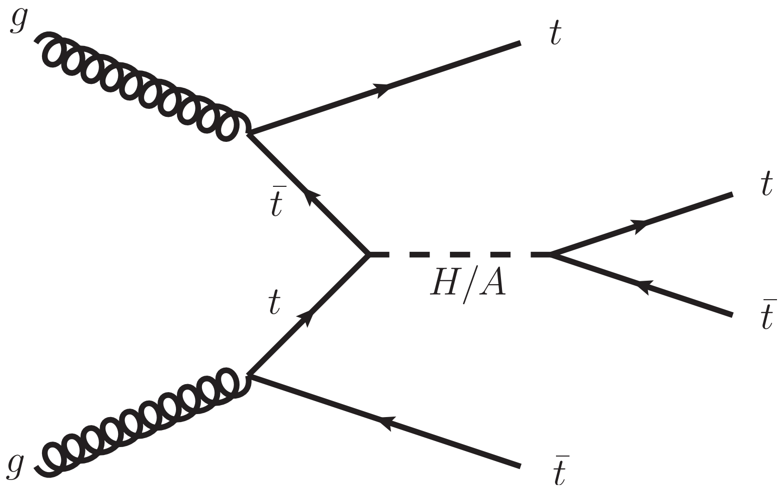
- Extension to the Standard Model Higgs
  - Popular in different models such as MSSM
  - Targets 2HDM type-II in the limit that $\sin(\beta - \alpha) \rightarrow 1$

Decay Channel

- Same-Sign Multilepton
  - 2 leptons with the same sign
  - $\geq$ 3 leptons

Object Tagging

- DL1r 77% WP for b-tagging

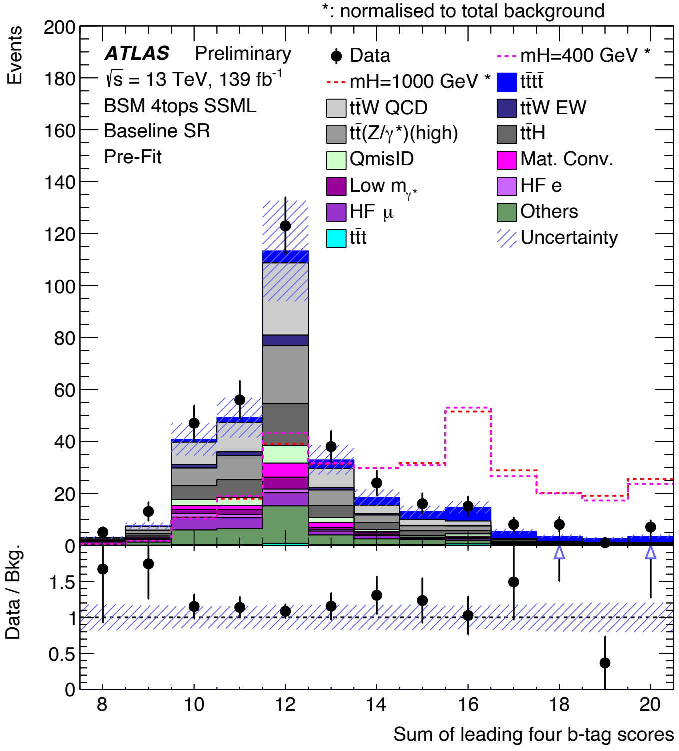


ATLAS-CONF-2022-008

Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

Backgrounds

- Irreducible
  - Standard Model $t\bar{t}t\bar{t}$
  - $t\bar{t}W/Z/H/\gamma^{*}$
- Reducible
  - Fake leptons
  - Charge misidentification



Analysis Strategy

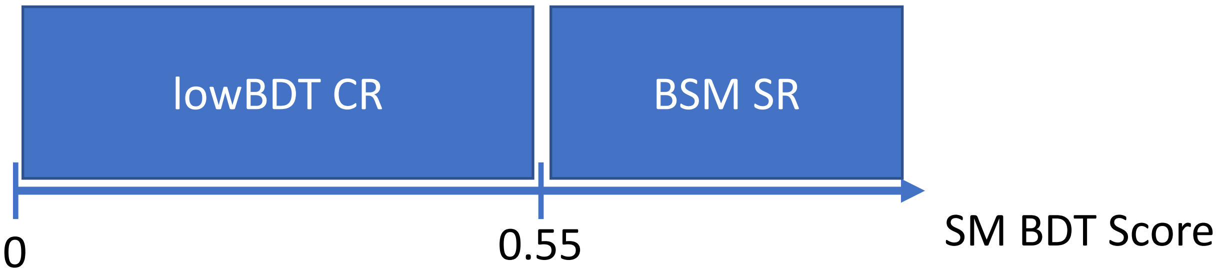
- Constrain background in dedicated Control Regions (CR)
- BDT separates SM $t\bar{t}t\bar{t}$ from other SM processes (SM BDT)
  - This BDT will also be sensitive to signal
- BDT separates signal from all SM processes (BSM pBDT)

ATLAS-CONF-2022-008

Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

Signal Regions (SR)

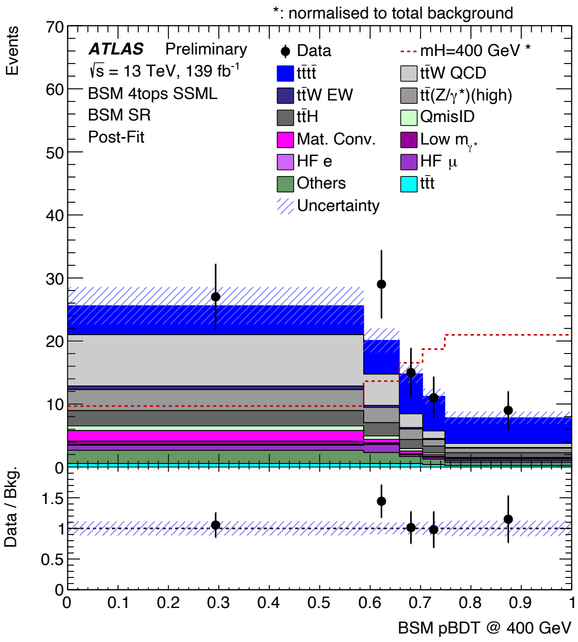
- Baseline SR
  - $H_T = \sum p_T^{jets} + \sum p_T^{leptons} > 500\ \text{GeV}$
  - ≥ 6 jets
  - ≥ 2 b-tags
- BSM SR
  - SM BDT score > 0.55



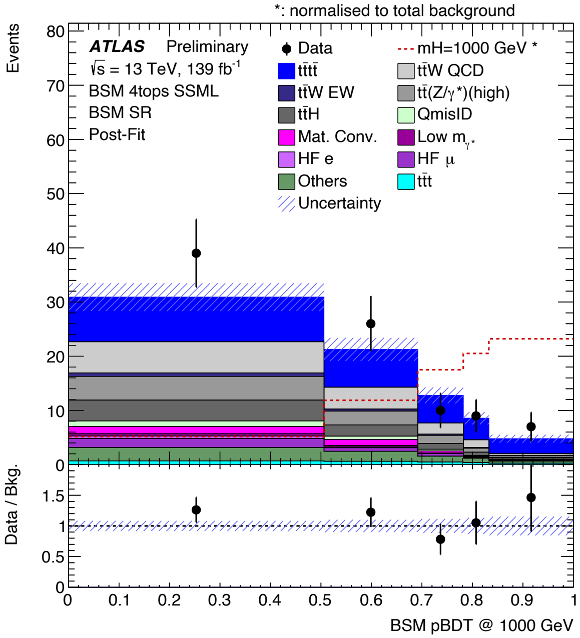
ATLAS-CONF-2022-008

Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

Post Fit (m=400 GeV)



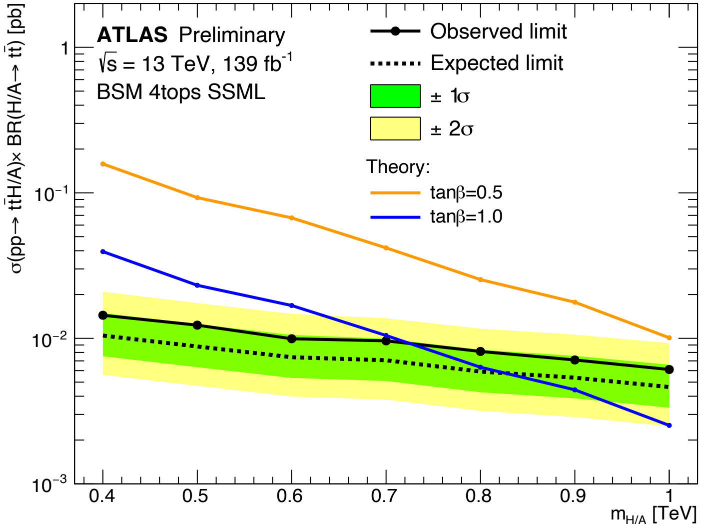
Post Fit (m=1000 GeV)

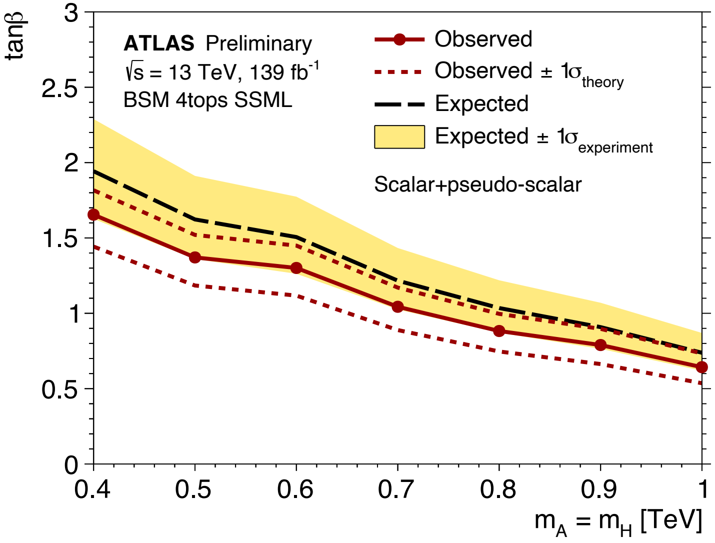


- Fit in all regions
- No excess observed

ATLAS-CONF-2022-008

Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$





- Fit in all regions
- No excess observed
- Limit set in 2 planes
  - σ vs Mass
  - $\tan\beta$ vs Mass

arXiv:2201.07045

Search for single Vector-Like Quark $T \rightarrow Ht$

Motivation

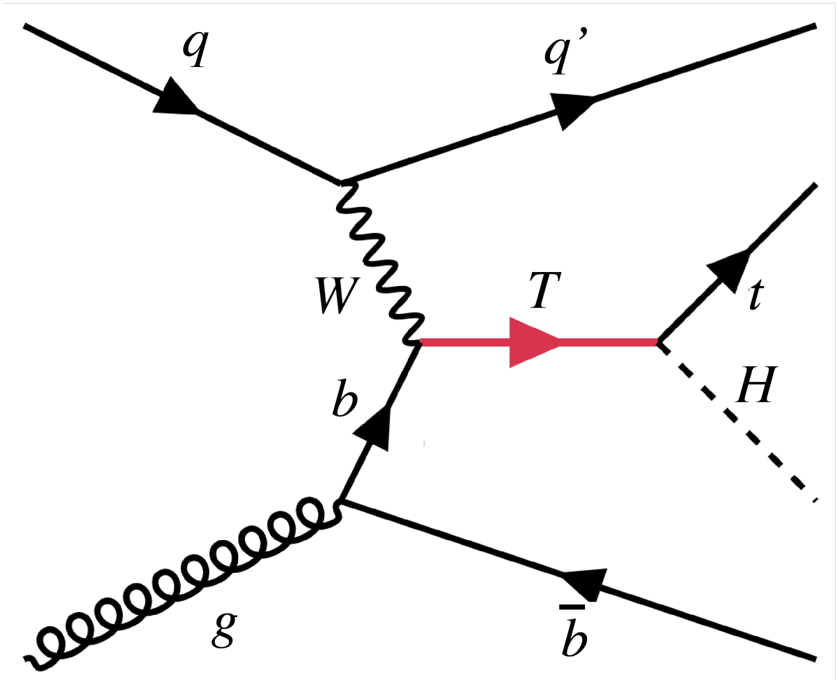
- Can address the Hierarchy Problem
- Single production dominates at high mass

Decay Channel

- All hadronic
  - $H \rightarrow b\bar{b}$
  - $t \rightarrow Wb$
    - $W \rightarrow qq'$

Tagged Objects

- DL1 70% WP for b-tagging
- Boosted top-tagger 80% WP

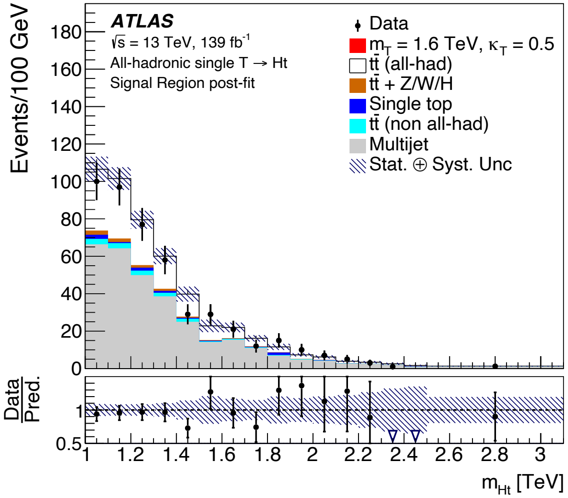


arXiv:2201.07045

Search for single Vector-Like Quark $T \rightarrow Ht$

Backgrounds

- Multijet and $t\bar{t}$
- Single top, $tW/Z/H$



Analysis Strategy

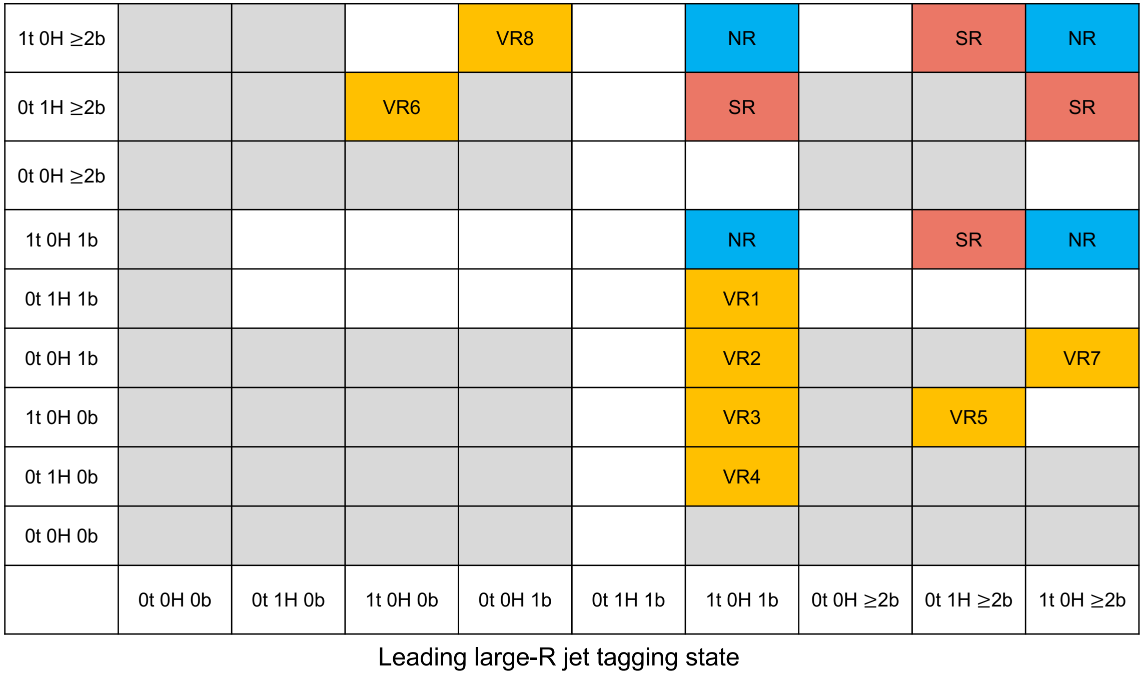
- Categorize data by leading and sub leading large-R jets tagging
    - Number of Higgs/top tags
    - b-tags in the jet substructure
- Estimate multijet using a data-driven method
- Fit dijet invariant mass

arXiv:2201.07045

Search for single Vector-Like Quark $T \rightarrow Ht$

Regions

- Defined by large-R jet tagging

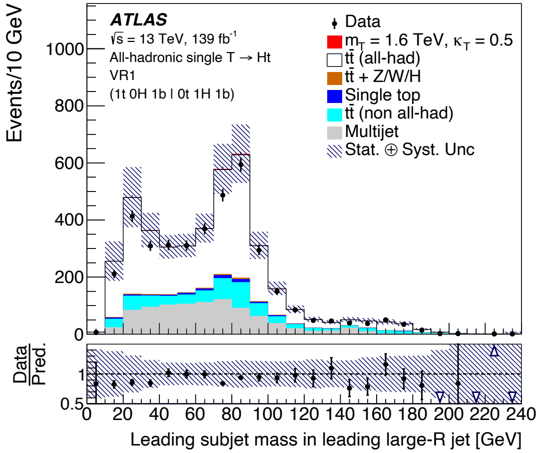


Second-leading large-R jet tagging state

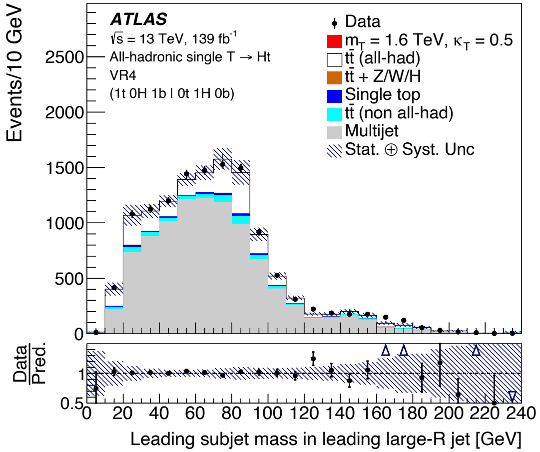
1t 0H ≥2b				VR8		NR		SR	NR
0t 1H ≥2b			VR6			SR			SR
0t 0H ≥2b									
1t 0H 1b						NR		SR	NR
0t 1H 1b						VR1			
0t 0H 1b						VR2			VR7
1t 0H 0b						VR3		VR5	
0t 1H 0b						VR4			
0t 0H 0b									
	0t 0H 0b	0t 1H 0b	1t 0H 0b	0t 0H 1b	0t 1H 1b	1t 0H 1b	0t 0H ≥2b	0t 1H ≥2b	1t 0H ≥2b

Leading large-R jet tagging state

- Validate multijet in VRs



VR1



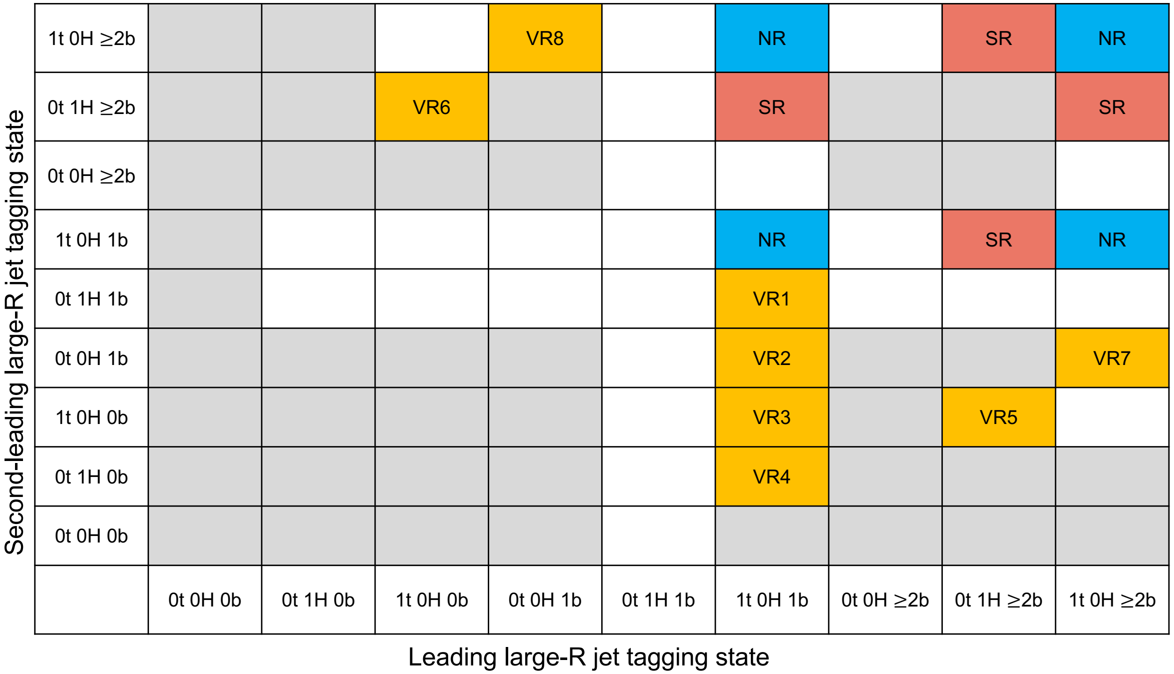
VR4

arXiv:2201.07045

Search for single Vector-Like Quark $T \rightarrow Ht$

Regions

- Defined by large-R jet tagging



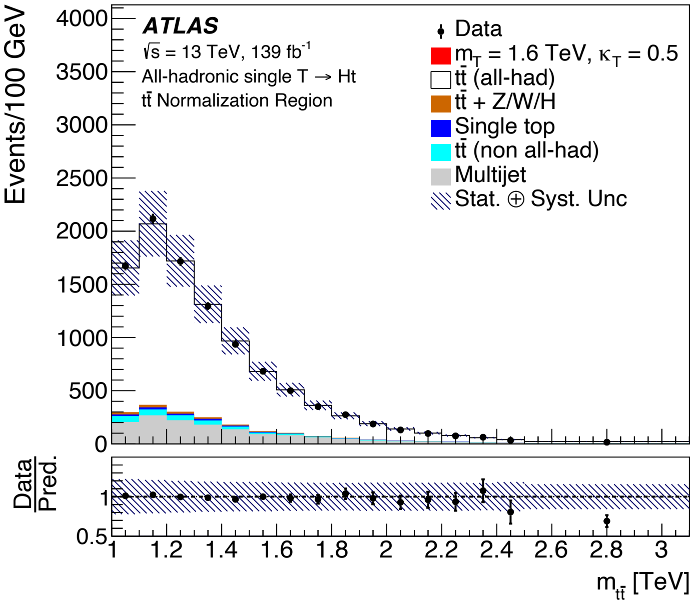
1t 0H ≥2b				VR8		NR		SR	NR
0t 1H ≥2b			VR6			SR			SR
0t 0H ≥2b									
1t 0H 1b						NR		SR	NR
0t 1H 1b						VR1			
0t 0H 1b						VR2			VR7
1t 0H 0b						VR3		VR5	
0t 1H 0b						VR4			
0t 0H 0b									
	0t 0H 0b	0t 1H 0b	1t 0H 0b	0t 0H 1b	0t 1H 1b	1t 0H 1b	0t 0H ≥2b	0t 1H ≥2b	1t 0H ≥2b

Second-leading large-R jet tagging state

Leading large-R jet tagging state

- Normalize $t\bar{t}$ in NR
  - Used in fit to constrain $t\bar{t}$

NR



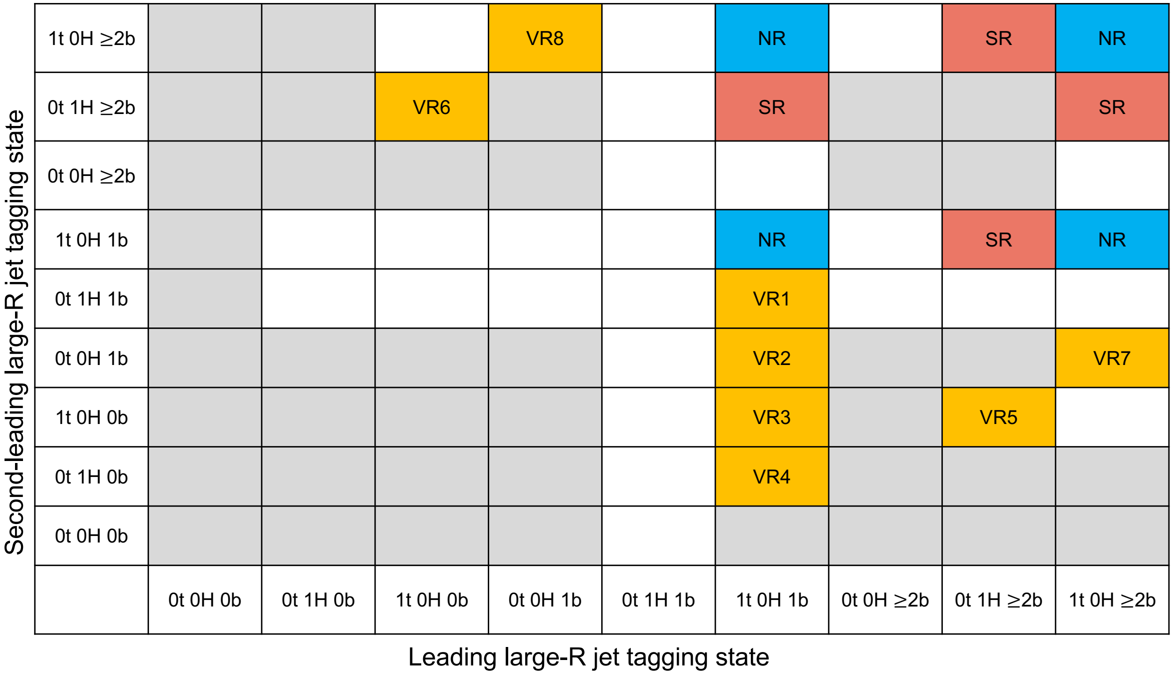
[arXiv:2201.07045](https://arxiv.org/abs/2201.07045)

Search for single Vector-Like Quark $T \rightarrow Ht$

Regions

- Defined by large-R jet tagging

- Enriched in signal SR

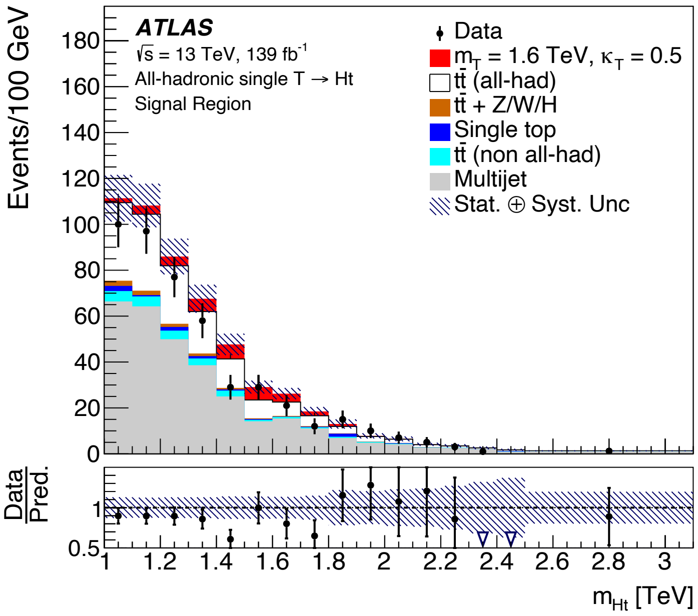


1t 0H ≥2b				VR8		NR		SR	NR
0t 1H ≥2b			VR6			SR			SR
0t 0H ≥2b									
1t 0H 1b						NR		SR	NR
0t 1H 1b						VR1			
0t 0H 1b						VR2			VR7
1t 0H 0b						VR3		VR5	
0t 1H 0b						VR4			
0t 0H 0b									
	0t 0H 0b	0t 1H 0b	1t 0H 0b	0t 0H 1b	0t 1H 1b	1t 0H 1b	0t 0H ≥2b	0t 1H ≥2b	1t 0H ≥2b

Second-leading large-R jet tagging state

Leading large-R jet tagging state

SR

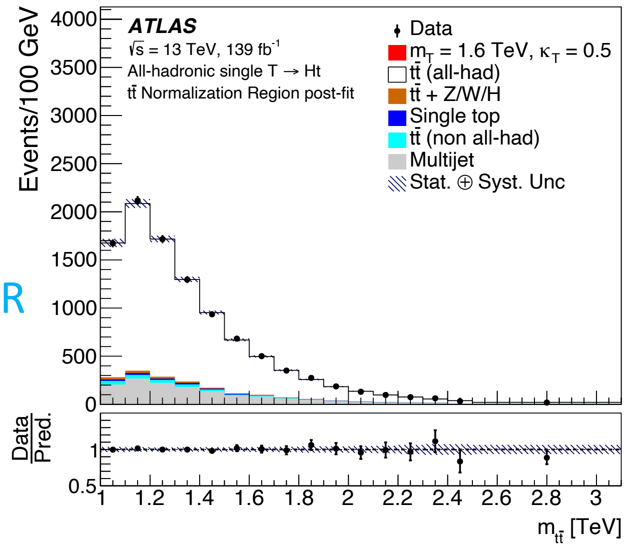


[arXiv:2201.07045](https://arxiv.org/abs/2201.07045)

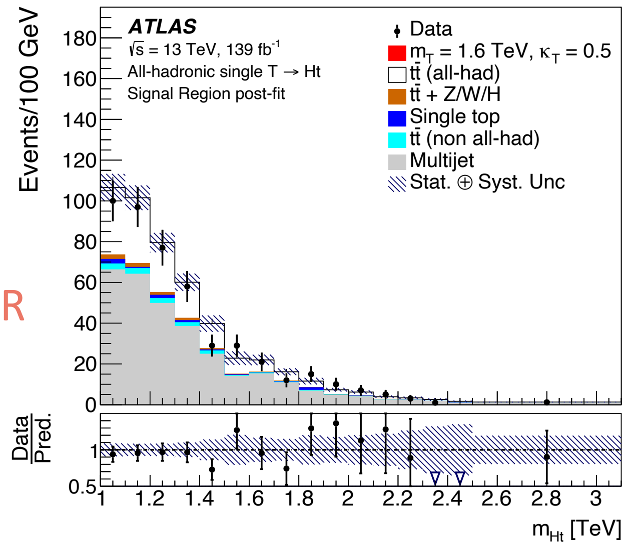
Search for single Vector-Like Quark

$T \rightarrow Ht$

Postfit

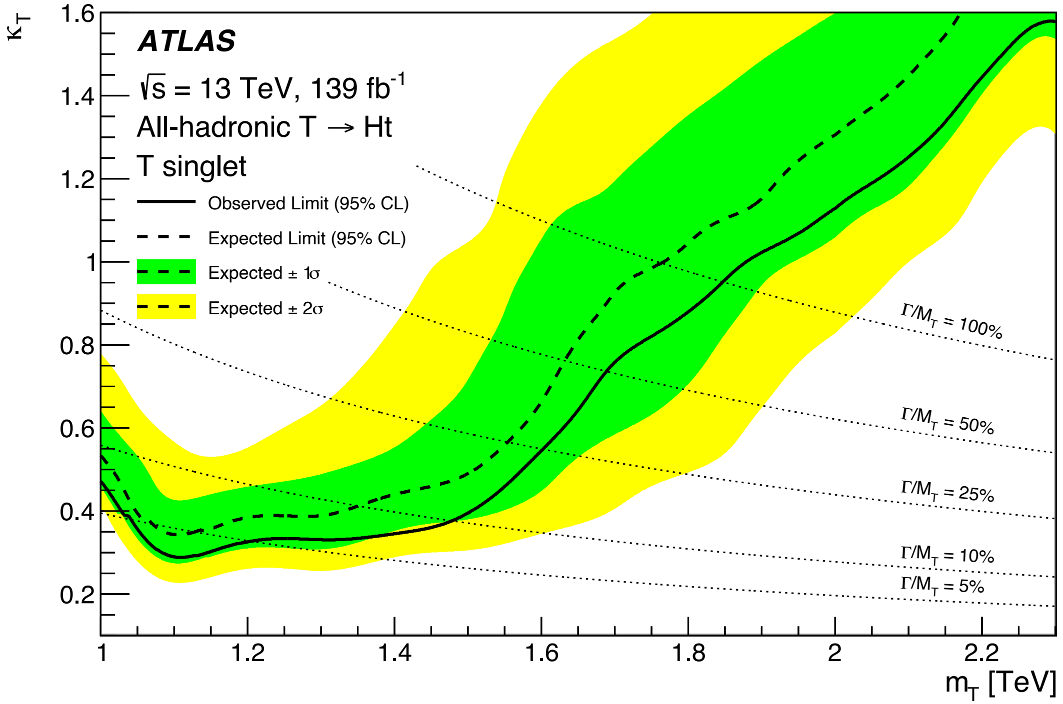


NR



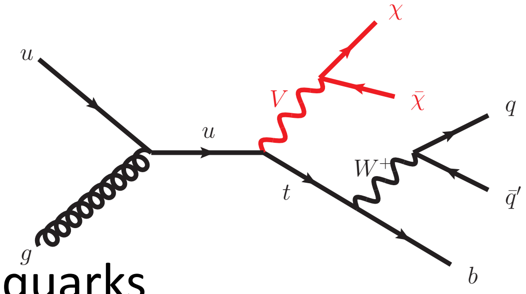
SR

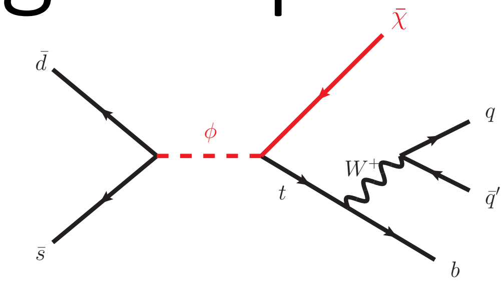
- Simultaneous fit in NR and SR
- No excess observed
- Set limit on σ vs Mass and κ



ATLAS-CONF-2022-036

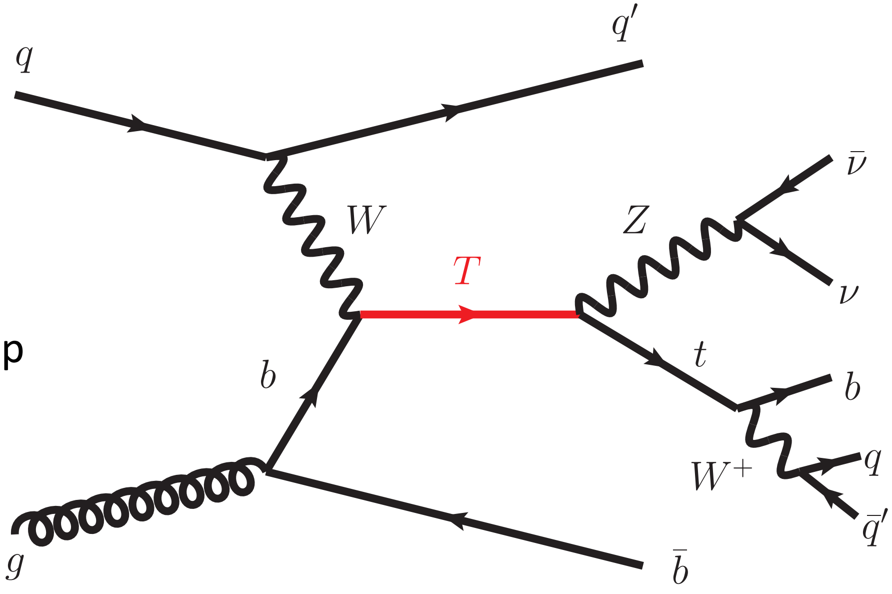
Search for Invisible + Single top





Motivation

- Search for DM
- Sensitivity for vector-like quarks
  - $T \rightarrow Zt$



Decay Channel

- Non-Resonant DM
  - New vector boson V decays to DM
- Resonant DM
  - New scalar Ø decays to DM and top
- Vector-Like Quark
  - Z decays to neutrinos

Tagged Objects

- DL1r 77% WP for b-tagging
- Boosted top-tagger 50% WP

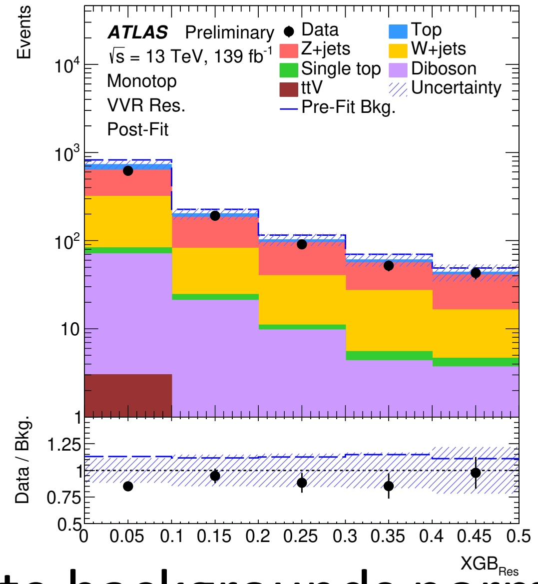
ATLAS-CONF-2022-036

Search for Invisible + Single top

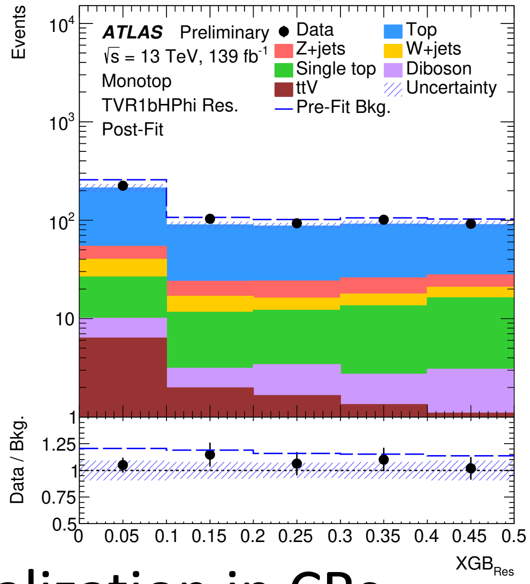
Backgrounds

- $t\bar{t}$ and V+Jets
- Single top

0 b-tags



1 b-tags



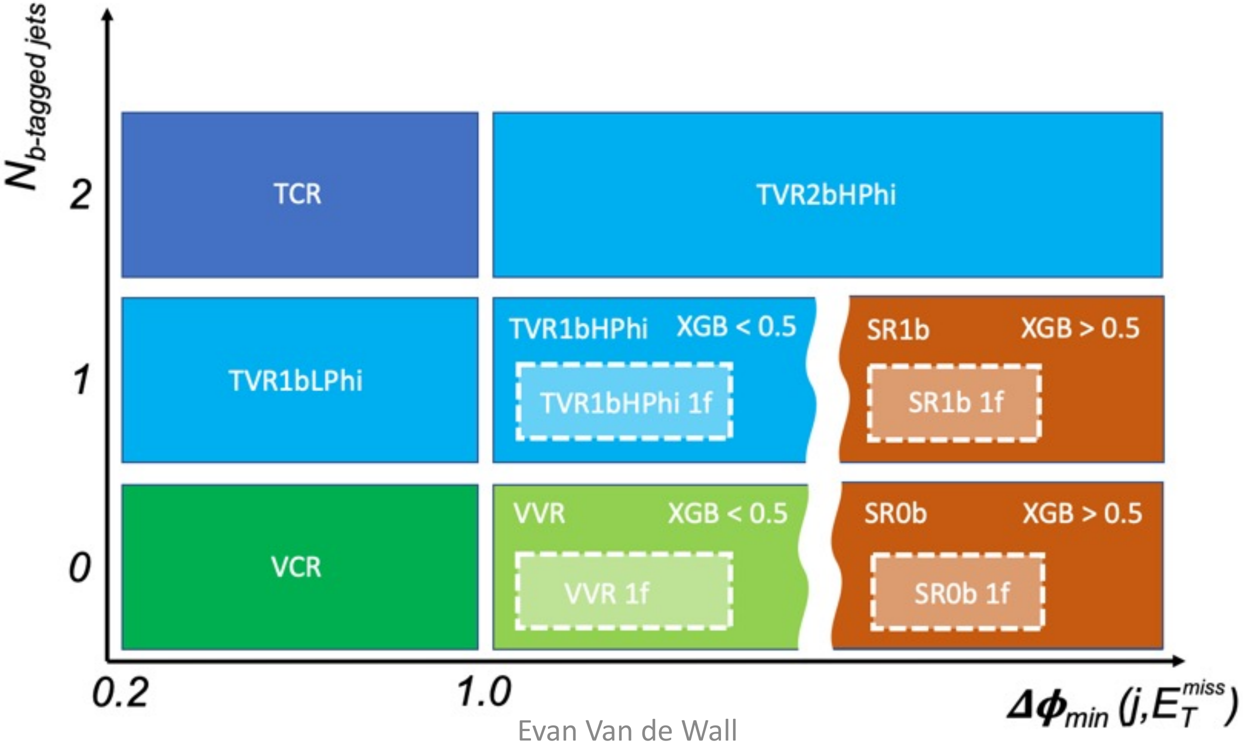
Analysis Strategy

- Constrain dominate backgrounds normalization in CRs
- Validate normalizations in validation regions
- XGBoost (XGB) classifiers constructs signal regions for the 3 models
  - 1 SR with 0 b-tags
  - 1 SR with 1 b-tag

Search for Invisible + Single top

Regions

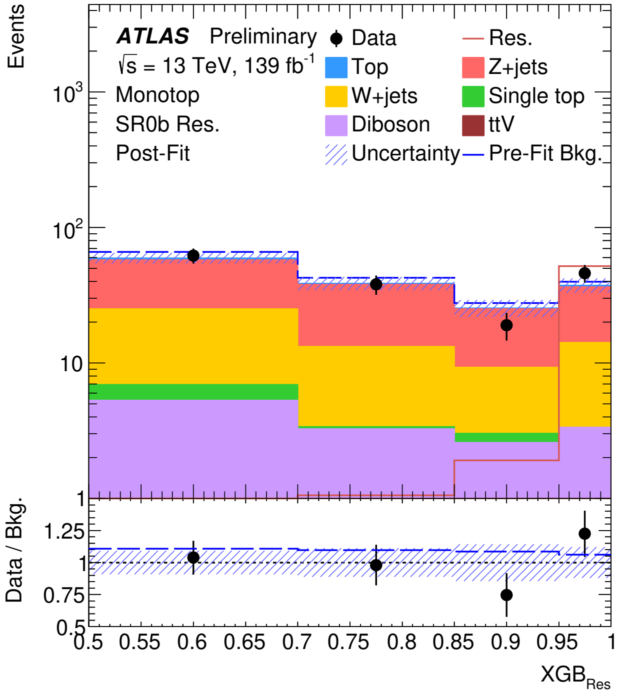
- Regions split on b-tags and $\Delta\emptyset_{\min}(\mathrm{j},\ \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}})$
- XGB is trained for each model



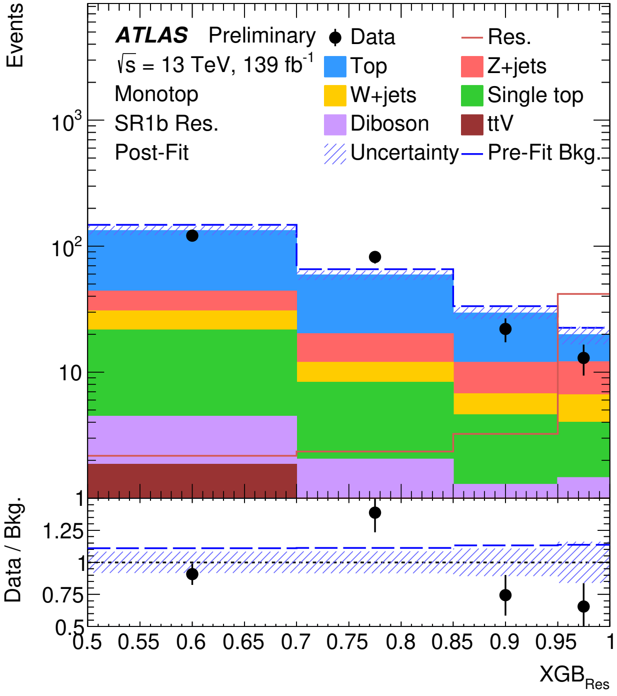
ATLAS-CONF-2022-036

Search for Invisible + Single top

0 b-tags



1 b-tags

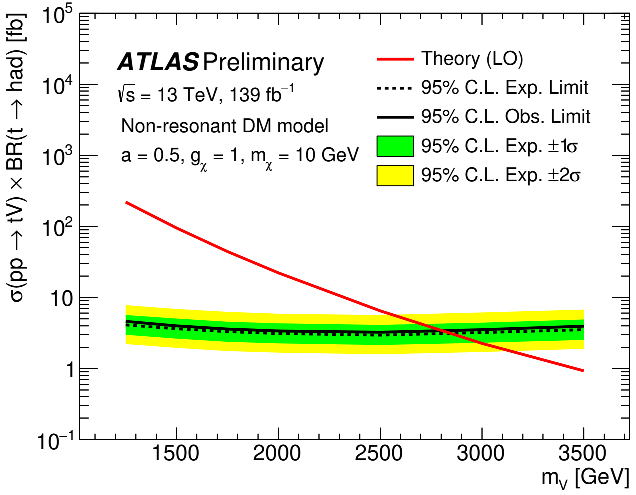


- Fit XGB for each model
- No excess observed

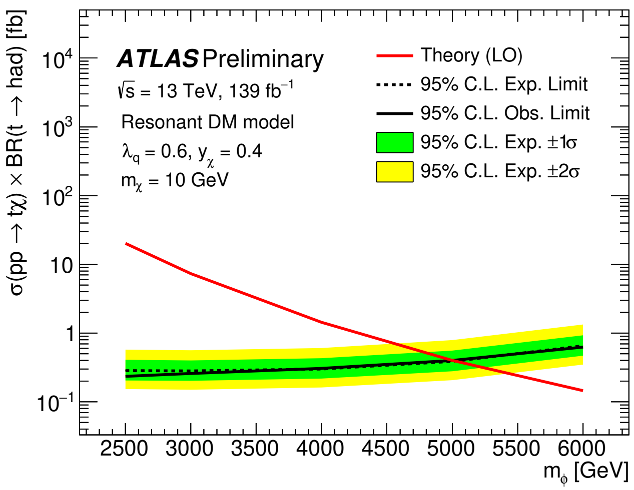
ATLAS-CONF-2022-036

Search for Invisible + Single top

Non-Resonant

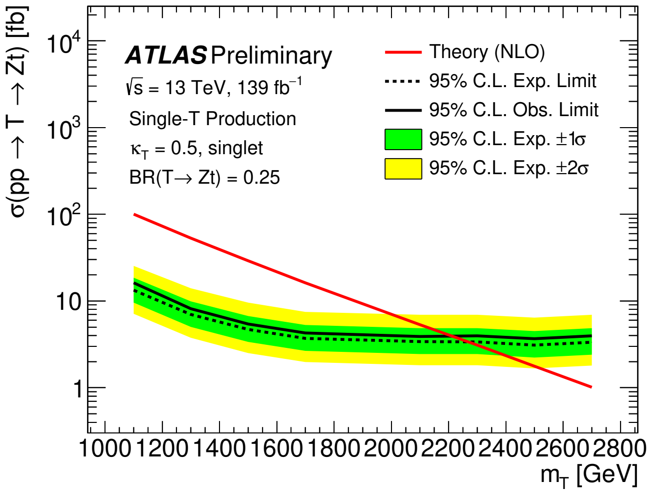


Resonant



- Fit XGB for each model
- No excess observed
- Set limit on σ vs Mass

VLQ



ATLAS-CONF-2022-052

Search for Leptoquarks

Motivation

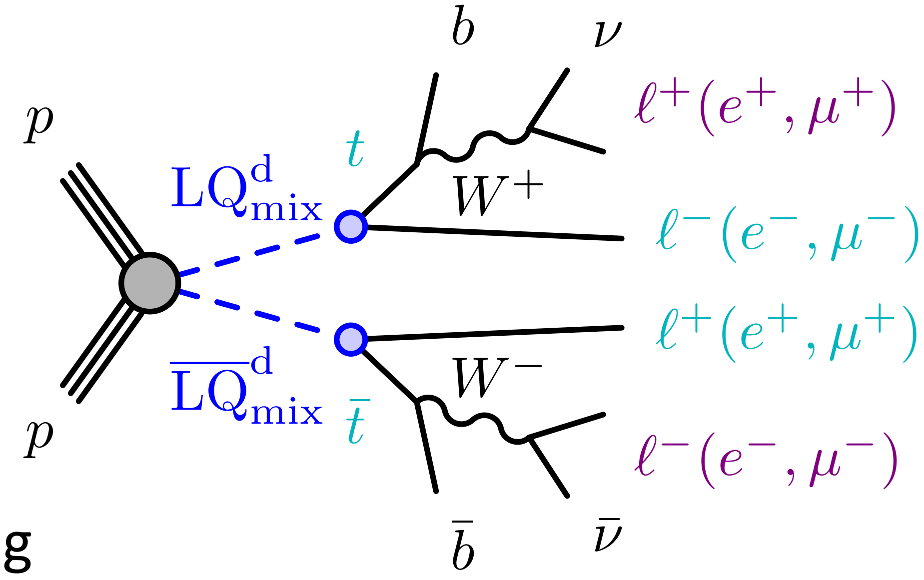
- Account for anomalous muon magnetic moment
- Explain violation in lepton flavor universality
  - B-meson decays

Decay Channel

- Same-sign Mutilepton

Tagged Objects

- DL1r 85% WP for b-tagging

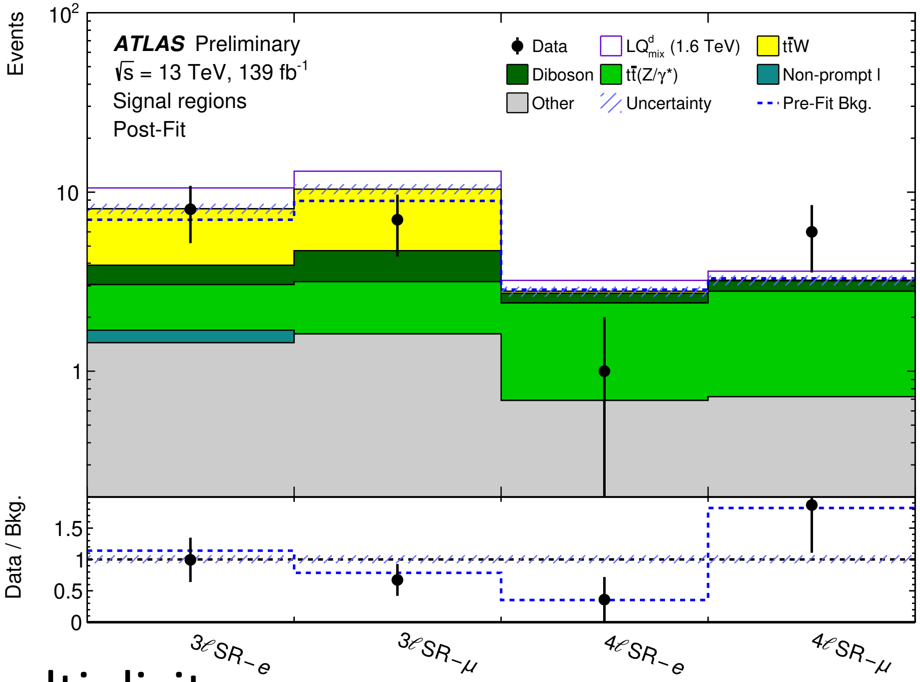


ATLAS-CONF-2022-052

Search for Leptoquarks

Backgrounds

- Irreducible
  - $t\bar{t}W/Z/\gamma^*$ and diboson
- Reducible
  - Non-prompt leptons
  - Charge misidentification



Analysis Strategy

- Split data based on lepton multiplicity
- Define CRs to constrain dominate backgrounds
- Confirm corrections in validation regions
- Fit $m_{\text{eff}} = \sum p_{\text{T}}^{\text{jets}} + \sum p_{\text{T}}^{\text{leptons}} + E_{\text{T}}^{\text{miss}}$ in CRs and SRs

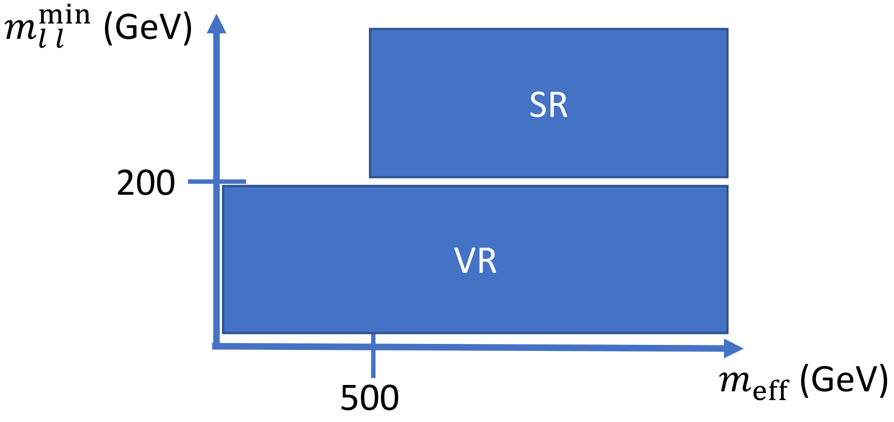
ATLAS-CONF-2022-052

Search for Leptoquarks

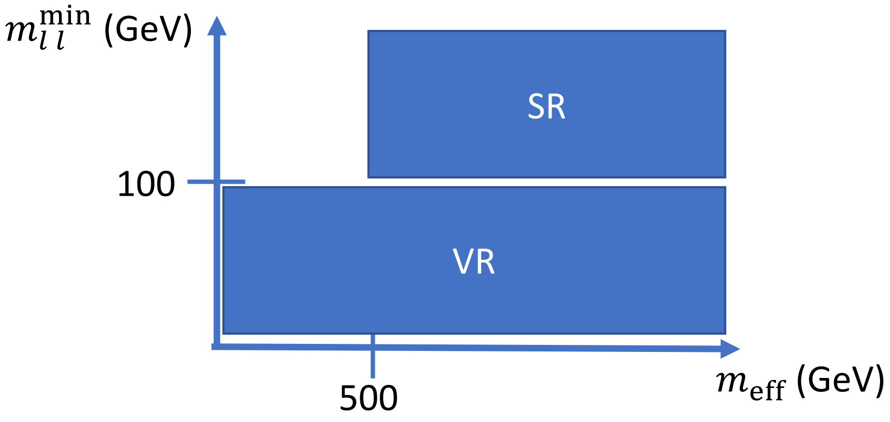
Region

- 2 leptons – 3 CRs
- 3 leptons – 4 CRs, 1 VRs, 2 SRs
- 4 leptons – 1 VR and 2 SR

3 leptons



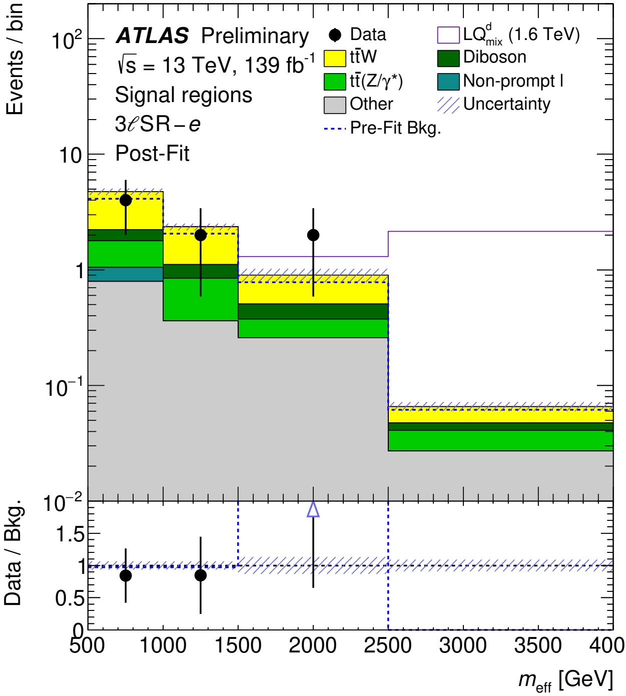
4 leptons



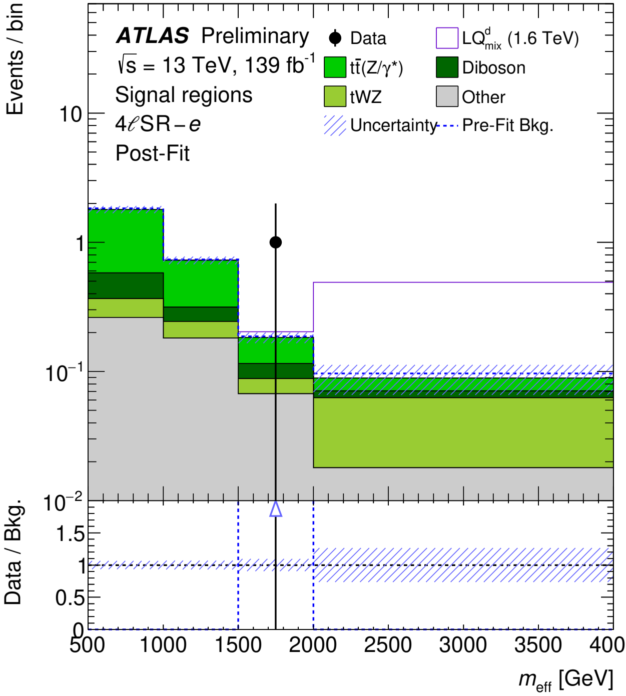
ATLAS-CONF-2022-052

Search for Leptoquarks

Electron 3 lepton fit



Electron 4 lepton fit



- Electron and muon fit separately

- No excess observed

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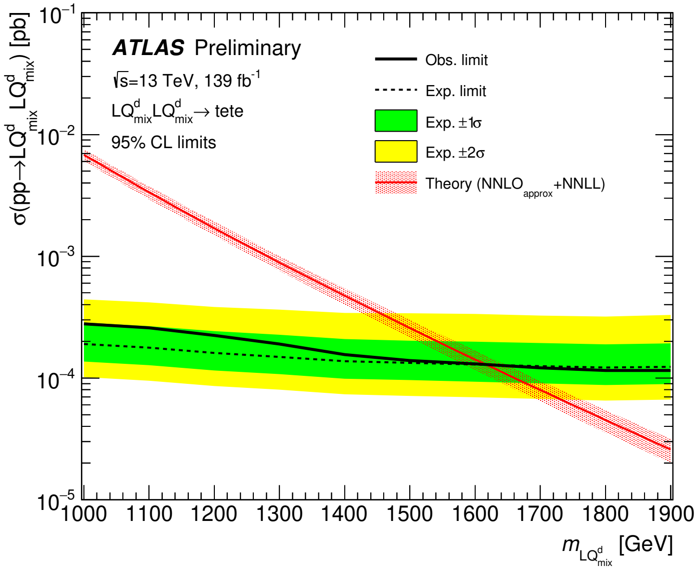
Search for Leptoquarks



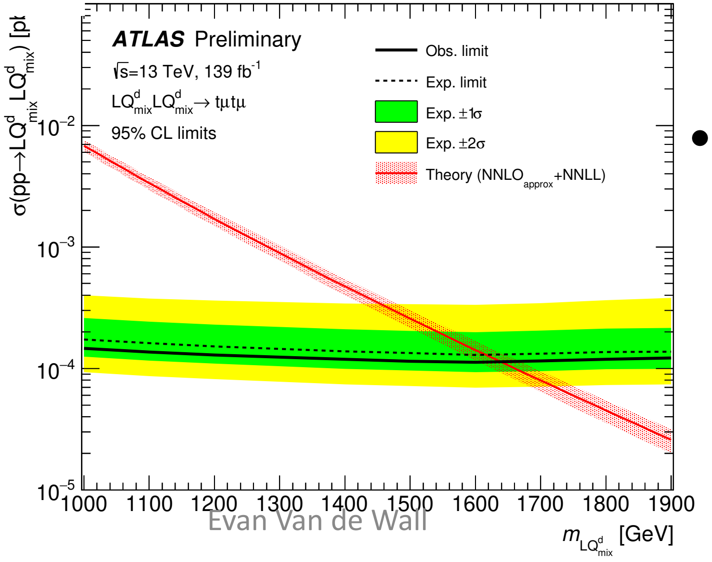
Electron Limit

- Electron and muon fit separately

- No excess observed

- Set limit on σ vs Mass

Muon Limit



Conclusions

- Broad search for new particles coupling to 3rd generation quarks
- 3rd generation quarks have unique signatures
  - Allow for tagging
  - Suppress standard model background
- Tagging is continued to be improved

- Presented 3 ATLAS results
  - Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$
  - Search for single vector-like quark $T \rightarrow Ht$
  - Search for invisible + single top
  - Search for pair production of leptoquarks
- No excess from the SM prediction were observed
- Continue to search and push the limits
- Run 3 data collection has started!

Thank You!

Thank you for listening!

Thank you to the organizers!

Thank you to ATLAS!

Thank you to the DOE for financial support!