Search for Vector-Like Quarks in the ATLAS Experiment

Romain Madar
on behalf of the ATLAS Collaboration

Laboratoire de **P**hysique de **C**lermont (CNRS/UCA)
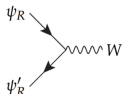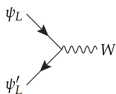Clermont-Ferrand – France

SUSY Conference – Barcelona (SP)

– 25th of July 2018 –

Why searching for Vector-like quarks (VLQs)?

1. What? Spin-1/2 fermions having ψ_L and ψ_R in the same SU(2) representation.

$$SU(3)_c \times SU(2) \times U(1)_Y$$

$$\mathcal{L}_{\text{mass}} = M_Q \ (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

Gauge-invariant mass term
(*impossible* to have for SM fields)

Why searching for Vector-like quarks (VLQs)?

1. **What?** Spin-1/2 fermions having ψ_L and ψ_R in the same SU(2) representation.

2. **Why?** Fermions predicted in many theories addressing naturalness

Why searching for Vector-like quarks (VLQs)?

1. What? Spin-1/2 fermions having ψ_L and ψ_R in the same SU(2) representation.

2. Why? Fermions predicted in many theories addressing naturalness

- Based on general assumptions, mostly 7 possible SU(2) representations heavily constraining the dynamics

> X,Y : exotic charges
> → **no mixing** with SM fields

(singlets) $\longrightarrow$ $T_{L,R}^0$, $B_{L,R}^0$

(doublets) $\longrightarrow$ $(X\,T^0)_{L,R}$, $(T^0\,B^0)_{L,R}$, $(B^0\,Y)_{L,R}$

(triplets) $\longrightarrow$ $(X\,T^0\,B^0)_{L,R}$, $(T^0\,B^0\,Y)_{L,R}$

Why searching for Vector-like quarks (VLQs)?

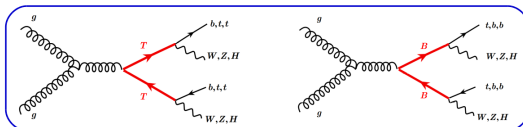**1. What?** Spin-1/2 fermions having ψ_L and ψ_R in the same SU(2) representation.

2. Why? Fermions predicted in many theories addressing naturalness

- Based on general assumptions, mostly 7 possible SU(2) representations heavily constraining the dynamics
- Modify observable physics via a mixing with SM quarks (3rd generation)

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^u_{L,R} & -\sin\theta^u_{L,R}e^{i\phi_u} \\ \sin\theta^u_{L,R}e^{-i\phi_u} & \cos\theta^u_{L,R} \end{pmatrix} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix}$$

Propagating states   Mixing matrix   SU(2) states
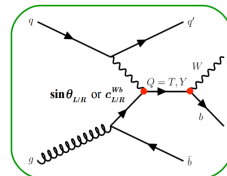
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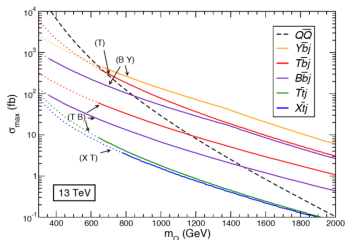**3. How?** Rich phenomenology at the LHC based on t, b, H, W, Z **signature**

Motivations
●○

The ATLAS search program
○○

Pair production
○○○○

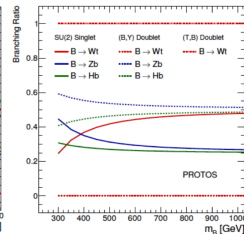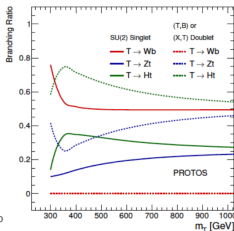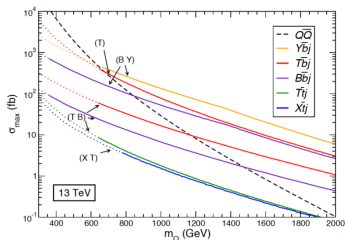Single production
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Conclusion
○

Why searching for Vector-like quarks (VLQs)?

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3. How? Rich phenomenology at the LHC based on t, b, H, W, Z signature

Pair production (model **independent** – driven by QCD)

Single production / decay (model **dependent** – driven by EW)

Why searching for Vector-like quarks (VLQs)?

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The ATLAS search program
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Pair production
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Single production
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Example of search strategy: $pp \rightarrow TT$

Branching ratio (BR) not known *a priori* except for
- VLQ with exotic charge $|q| > 1$ (only one possible decay)
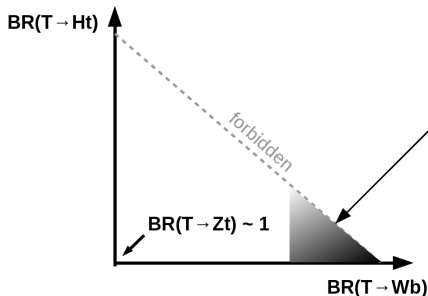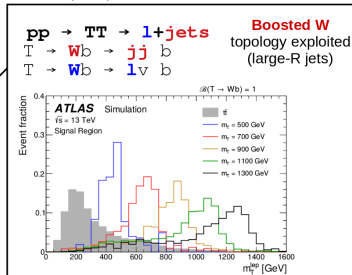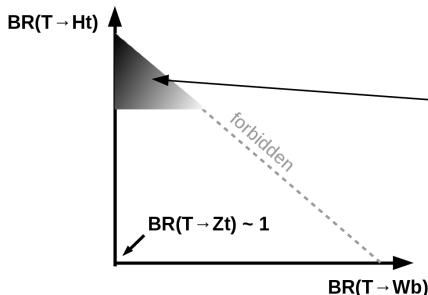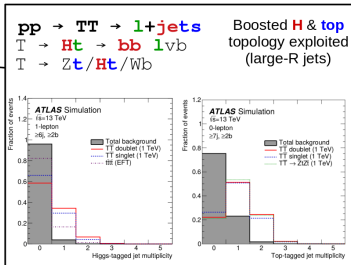- SU(2) singlet (BR independant from the mixing at the first order)
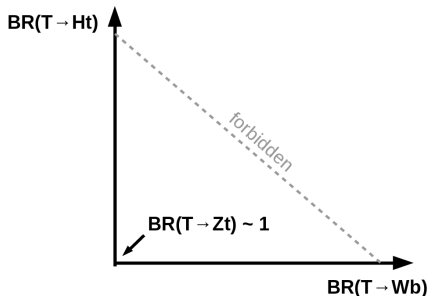
Example of search strategy: $pp \to TT$

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Example of search strategy: $pp \rightarrow TT$

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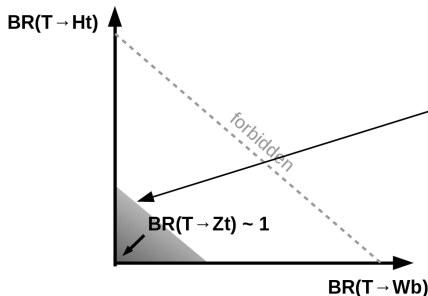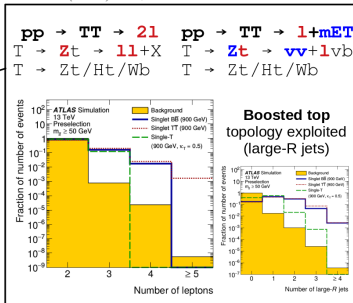
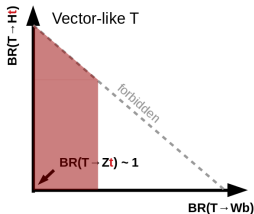| Analysis		Vector-Like Top T			Vector-Like Bottom B			$X_{+5/3}$	$Y_{-4/3}$
name	ref.	Ht	Zt	Wb	Hb	Zb	Wt	$W^+ t^{+2/3}$	$W^- b^{-1/3}$
specific, boosted									
ℓ+jets / $0\ell + E_T^{\mathrm{miss}}$ (boosted H/t)	JHEP 07 (2018) 089	PP	PP	-	-	-	-	-	-
ℓ+jets (boosted W/t)	arXiv:1806.01762	-	-	-	-	-	PP	-	-
ℓ+jets (boosted W)	JHEP 10 (2017) 141	-	-	PP	-	-	-	-	-
specific, ℓ's and γ's									
ℓ+jets	ATLAS-CONF-2016-072	-	-	SP	-	-	-	-	SP
ℓ+jets+E_T^{miss}	JHEP 08 (2017) 052	-	PP	-	-	-	-	-	-
$bH(\to \gamma\gamma)$	ATLAS-CONF-2018-024	-	-	-	SP	-	-	-	-
os2ℓ/3ℓ	arXiv:1806.10555	-	PP/SP	-	-	PP/SP	-	-	-
$\approx$ generic									
ss2ℓ/3ℓ	CERN-EP-2018-171	PP	PP	-	-	-	PP	SP/PP	-
full had (boosted $H/W/Z$)	CERN-EP-2018-176	PP	PP	PP	PP	PP	PP	-	-
combination	ATLAS-CONF-2018-032	PP	PP	PP	PP	PP	PP	-	-

PP $\equiv$ Pair Production, SP $\equiv$ Single Production, red $\equiv$ new results $\equiv$ presented today

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| Motivations | The ATLAS search program | Pair production | Single production | Conclusion |
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Generic decays

Covering many decay chains with ss2ℓ/3ℓ + b-jets
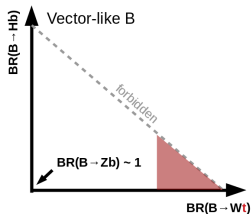
CERN-EP-2018-171

- $B\bar{B} \to W^- t W^+ \bar{t} \to W^- W^+ b W^+ W^- \bar{b}$
- $B\bar{B} \to W^- t Z\bar{b} \to W^- W^+ b Z \bar{b}$
- $T\bar{T} \to Zt Z\bar{t} \to ZW^+ b ZW^- \bar{b}$
- $T\bar{T} \to Zt H\bar{t} \to ZW^+ b HW^- \bar{b}$

Strategy: exploit b-jets together with same-sign leptons pair (or 3l)
    → *very low SM background*

Final states:
Ht / Ht / Wt

Covering many decay chains with ss2ℓ/3ℓ + b-jets
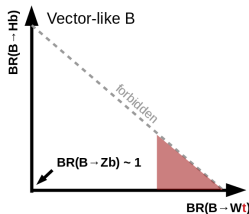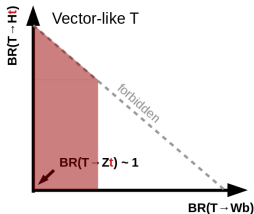
CERN-EP-2018-171

- $B\bar{B} \rightarrow W^-tW^+\bar{t} \rightarrow W^-W^+bW^+W^-\bar{b}$

- $B\bar{B} \rightarrow W^-t Z\bar{b} \rightarrow W^-W^+bZ\bar{b}$

- $T\bar{T} \rightarrow Zt Z\bar{t} \rightarrow ZW^+bZW^-\bar{b}$

- $T\bar{T} \rightarrow Zt H\bar{t} \rightarrow ZW^+bHW^-\bar{b}$

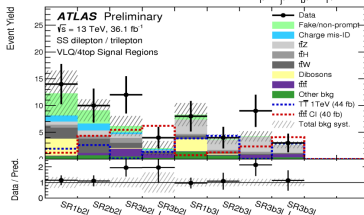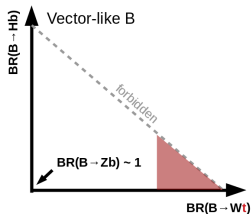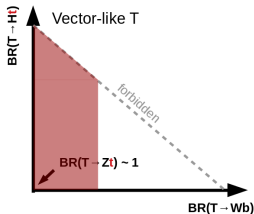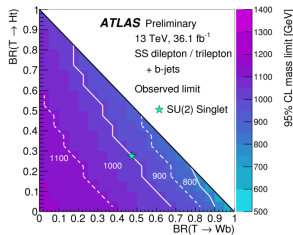**Strategy:** exploit b-jets together with same-sign leptons pair (or 3l)
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6 VRs based on N_l, N_j, N_b, H_T, mET

Final states:
Ht / Ht / Wt

Main backgrounds:
physics: $t\bar{t}$ + W, $t\bar{t}$ + Z,
Instrumental: fake/non-prompt lepton, Qmis-ID

Main systematics:
statistically limited

Covering many decay chains with ss2ℓ/3ℓ + b-jets

CERN-EP-2018-171
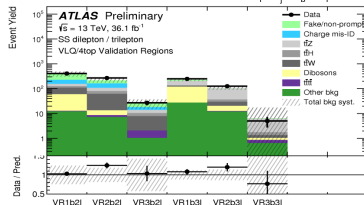
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Strategy: exploit b-jets together with same-sign leptons pair (or 3l)
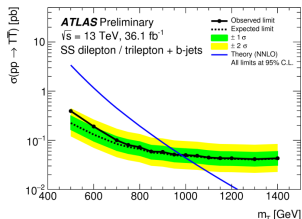→ *very low SM background*

8 SRs based on N_l, N_j, N_b, H_T, mET

Final states:
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CERN-EP-2018-171

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CERN-EP-2018-171

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- $T\bar{T} \to ZtH\bar{t} \to ZW^+b HW^-\bar{b}$

Final state also sensitive to many other signals such as
$t\bar{t}t\bar{t}$, 2HDM, extra-dimensions or top-coupled dark matter
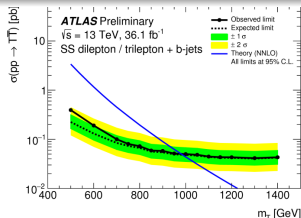
talk on $t\bar{t}t\bar{t}$

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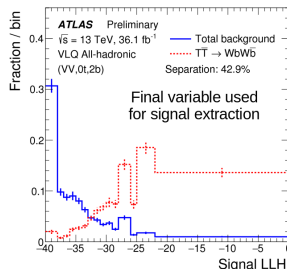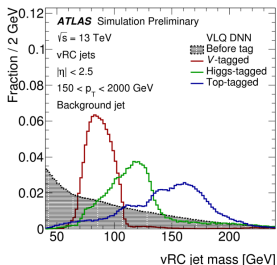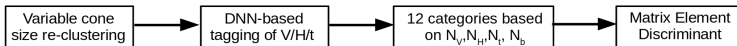
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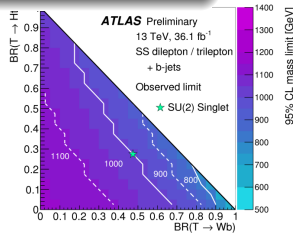
Boson and top tagging with full hadronic mode

CERN-EP-2018-176

Overall strategy:
- exploit *jet sub-structure* to tag **W, Z, H and t** using advanced technics
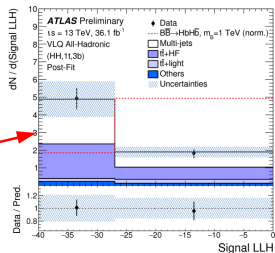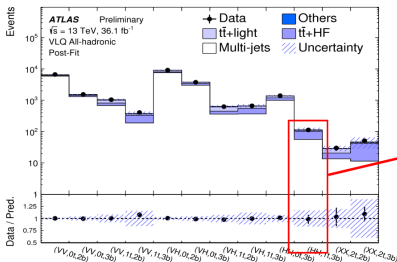- keep *multijet background* under control, requiring moderate mET

| Variable cone |
| size re-clustering |

cone size optimized for
- capturing boosted structures
- minimizing overlap between objects (quite busy events)

Generic decays

Boson and top tagging with full hadronic mode

CERN-EP-2018-176

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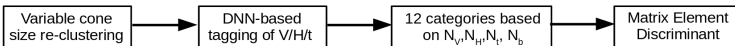- keep *multijet background* under control, requiring moderate mET

Motivations
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The ATLAS search program
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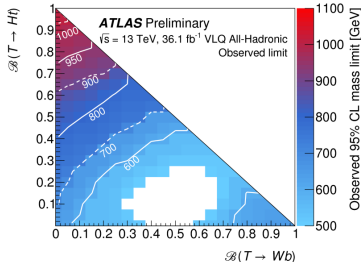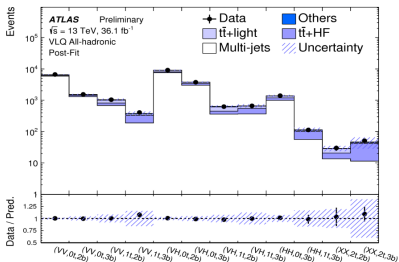
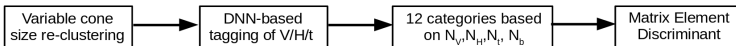Pair production
○○●○

Single production
○○

Conclusion
○

Generic decays

Boson and top tagging with full hadronic mode
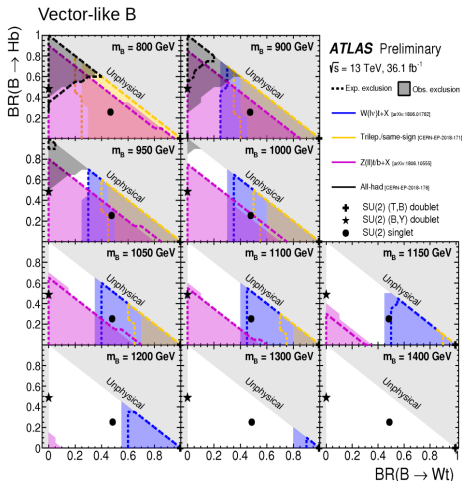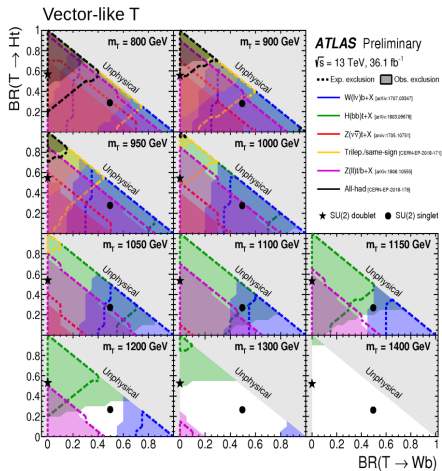
CERN-EP-2018-176

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```
┌──────────────────┐    ┌──────────────────┐    ┌──────────────────┐    ┌──────────────────┐
│ Variable cone    │ →  │ DNN-based        │ →  │ 12 categories    │ →  │ Matrix Element   │
│ size re-clustering│    │ tagging of V/H/t │    │ based on N_V,N_H,N_t, N_b │    │ Discriminant     │
└──────────────────┘    └──────────────────┘    └──────────────────┘    └──────────────────┘
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Motivations	The ATLAS search program	Pair production	Single production	Conclusion
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Generic decays

Boson and top tagging with full hadronic mode

CERN-EP-2018-176

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└─────────────────┘   └─────────────────┘   └─────────────────┘   └─────────────────┘
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Boson and top tagging with full hadronic mode

CERN-EP-2018-176

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Variable cone  →  DNN-based      →  12 categories based  →  Matrix Element
size re-clustering  tagging of V/H/t   on $N_V, N_H, N_t, N_b$   Discriminant
```

Motivations
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Pair production
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Single production
○○

Conclusion
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Combination

Putting everything together ...

Overlay of all channels

ATLAS-CONF-2018-032

Putting everything together ...

Full statistical combination

ATLAS-CONF-2018-032
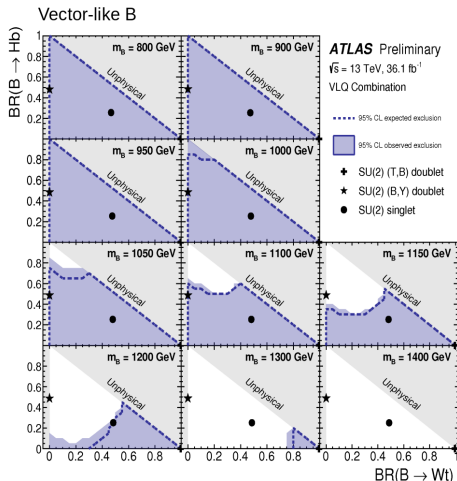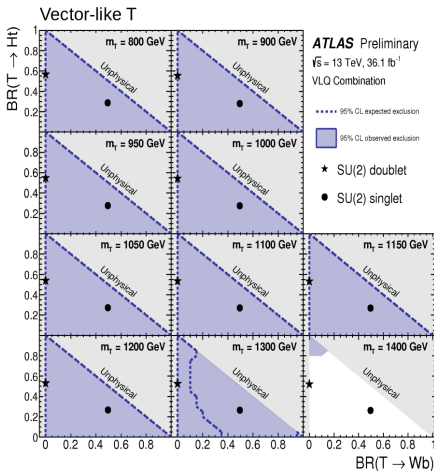
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○

B with $H \to \gamma\gamma$
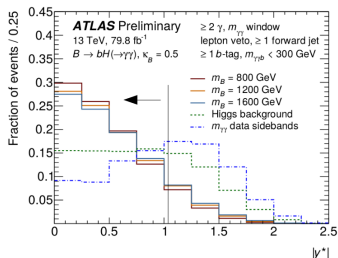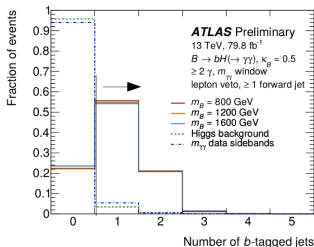
Singly-produced B with $H \to \gamma\gamma$

ATLAS-CONF-2018-024

Single production
- depends on mixing parameters
- potentially reach higher masses
- signature: presence of a forward jet

Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
●○

Conclusion
○

B with $H \to \gamma\gamma$

Singly-produced *B* with $H \to \gamma\gamma$

ATLAS-CONF-2018-024

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B → Hb → γγb strategy
- clean and reconstructible final state
- background estimate using side bands
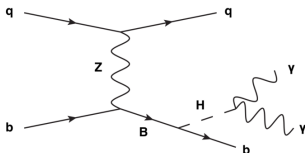
B with $H \rightarrow \gamma\gamma$

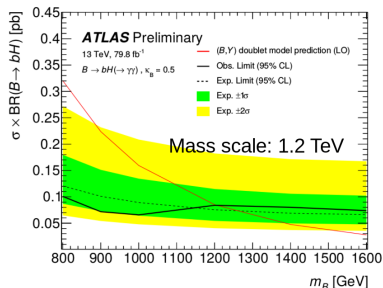# Singly-produced B with $H \rightarrow \gamma\gamma$
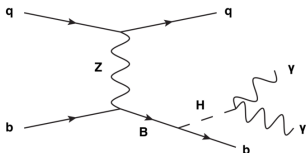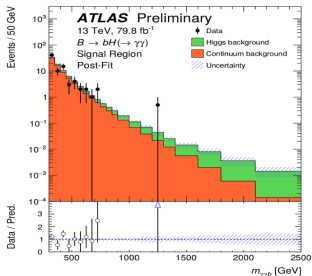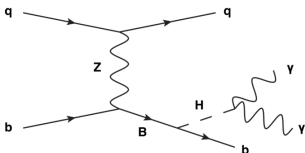
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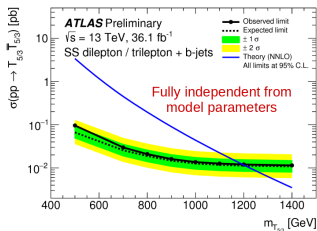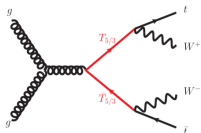
$B \rightarrow Hb \rightarrow \gamma\gamma b$ strategy
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Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
●○

Conclusion
○

B with H → γγ

Singly-produced B with H → γγ

Single production
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B → Hb → γγb strategy
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Singly- and pair-produced $X_{5/3}$ with ss2$\ell + b$-jets

CERN-EP-2018-171

Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
○●

Conclusion
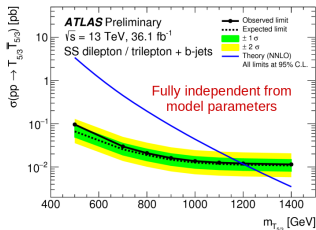○

B with $H \rightarrow \gamma\gamma$

Singly- and pair-produced $X_{5/3}$ with ss2ℓ + *b*-jets

CERN-EP-2018-171

Identify the exotic charge >1 only if
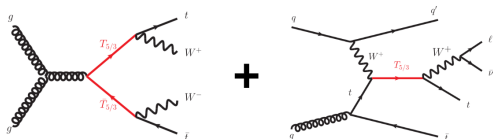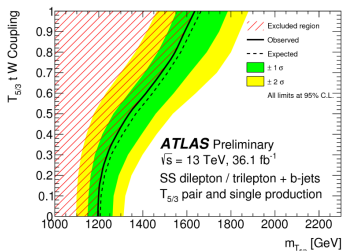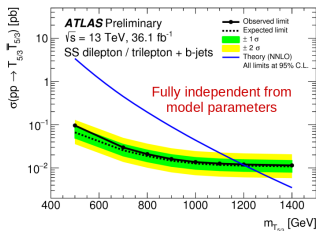- single production
- same-sign dilepton final state

Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
○●

Conclusion
○

B with $H \to \gamma\gamma$

Singly- and pair-produced $X_{5/3}$ with ss2ℓ + b-jets

CERN-EP-2018-171

Identify the exotic charge >1 only if
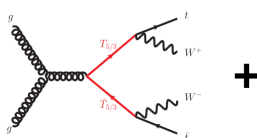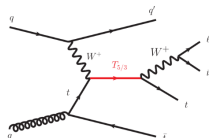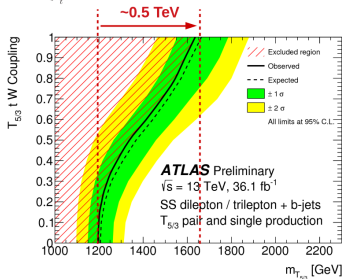- single production
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Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
○●

Conclusion
○

B with $H \to \gamma\gamma$

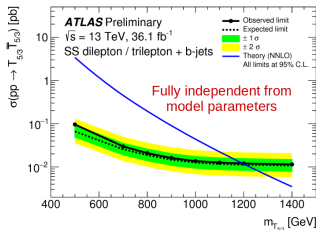# Singly- and pair-produced $X_{5/3}$ with ss2ℓ + *b*-jets

CERN-EP-2018-171

Identify the exotic charge >1 **only if**
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Table of content

Take-home messages

Vector-like quarks appear in a large number of Standard Model extensions

extremely rich final states involving combination of H, W, Z, t, b

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facing background difficult to model (e.g. $t\bar{t}$+H.F. or $t\bar{t}V$+H.F.)

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Take-home messages

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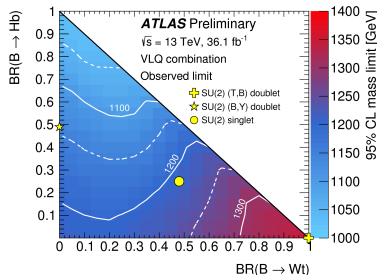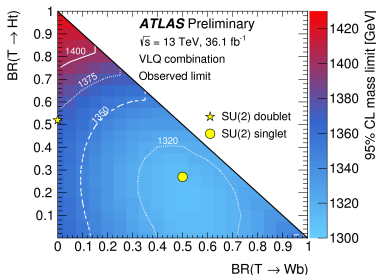 extremely rich final states involving combination of H, W, Z, t, b

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Combining all channels excludes T (B) with masses up to 1.4 (1.3) TeV

Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
○○

Conclusion
○

Backup Slides

Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
○○

Conclusion
○

Targeting Ht: $\ell+$jets / $0\ell + E_T^{\text{miss}}$ with boosted H/t

arXiv:1803.09678

Final states:
Ht Ht / Ht Zt / Ht Wb

Main background:
$t\bar{t}$ + H.F.

Main systematics:
$t\bar{t}$ + H.F. profiled and
validated using dedicated regions
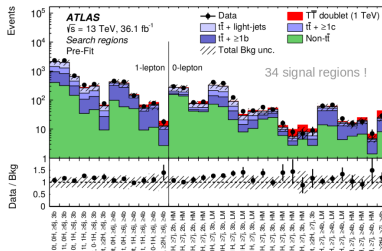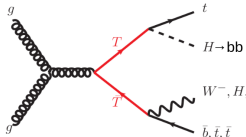
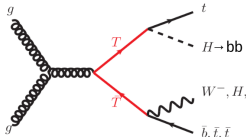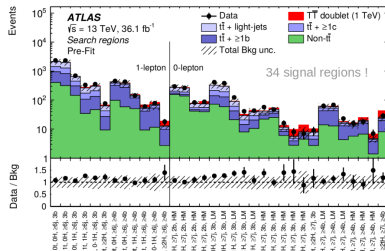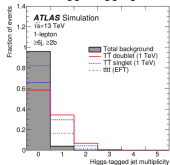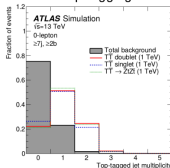| High N_b, high N_j, jet sub-structure	
1 lep	Leptonic decay of V
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Tagging based on **re-clustered small-R jets**:
- after overlap removal / PU-corrected
- good control of systematics

Top-tagged:
pT>300 GeV, 2 sub-jets, m>140 GeV

Higgs-tagged:
2 sub-jets (or more depending on pT), 105>m>140 GeV

Motivations
○○

The ATLAS search program
○○

Pair production
○○○○

Single production
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Conclusion
○

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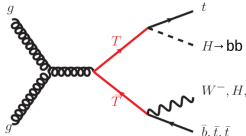
arXiv:1803.09678

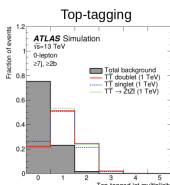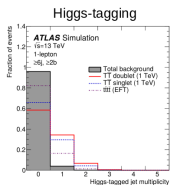**Final states:**
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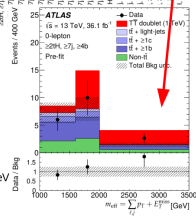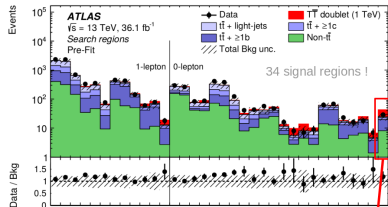| High N_b, high N_j, jet sub-structure	
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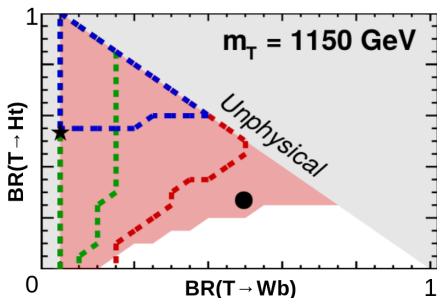- good control of systematics

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Pair production
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Single production
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Conclusion
○

Targeting Ht: $\ell+$jets / $0\ell + E_T^{miss}$ with boosted H/t

ATLAS

$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1} arXiv:1803.09678

- - - Exp. 1-lepton limit
- - - Exp. 0-lepton limit
- - - Exp. combination limit
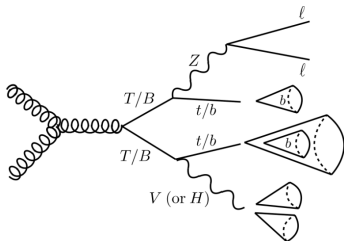▨ Obs. combination limit
★ SU(2) doublet   ● SU(2) singlet

95% CL lower limits on T quark mass [TeV]				
Search	$\mathcal{B}(T \to Ht) = 1$	$\mathcal{B}(T \to Zt) = 1$	Doublet	Singlet
1-lepton channel	1.47 (1.30)	1.12 (0.91)	1.36 (1.16)	1.23 (1.02)
0-lepton channel	1.11 (1.20)	1.12 (1.17)	1.12 (1.19)	0.99 (1.05)
Combination	**1.43 (1.34)**	**1.17 (1.18)**	**1.31 (1.26)**	**1.19 (1.11)**

Exploiting $Z \rightarrow \ell\ell$ from the decay chain: os2ℓ

arXiv:1806.10555

pT[ll] > 200 GeV

At least 2
b jets

0 or 1
large-R jets

Final states:
Zt V[t,b] / Zb V[t,b]

Main background:
Z+jets

Main systematics:
statistically limited

Motivations
○○

The ATLAS search program
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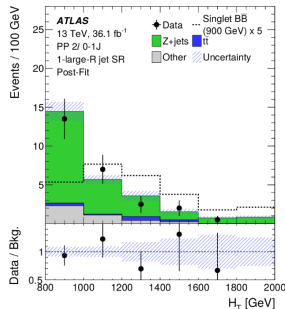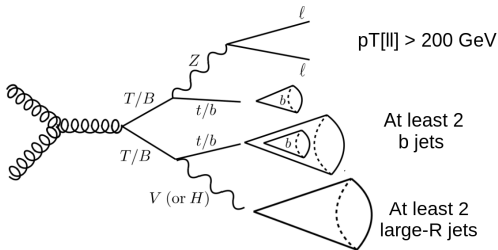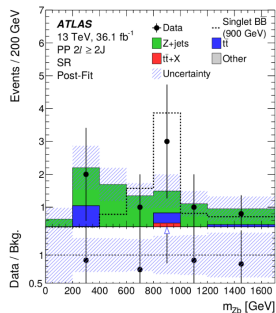
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At least 2
b jets

At least 3
leptons

Final states:
Zt V[t,b] / Zb V[t,b]

Main background:
$t\bar{t}$ + Z

Main systematics:
statistically limited

Motivations
○○

The ATLAS search program
○○

Pair production
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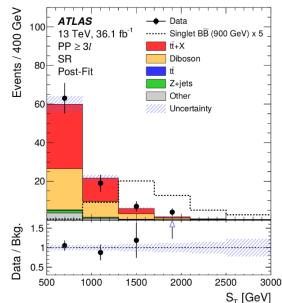
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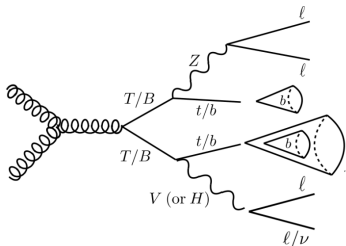Zt V[t,b] / Zb V[t,b]

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