Top quarks and exotics at ATLAS and CMS

Leonid Serkin

for the ATLAS and CMS Collaborations

INFN Gruppo Collegato di Udine and ICTP Trieste

Motivation for exotic Top BSM searches (non-SUSY)

- Many extensions of the SM (exotic models) predict new particles usually coupled preferentially to 3rd generation quarks (top, bottom)

- Basic phenomenology of exotic Top BSM (non-SUSY):
  - new heavy gauge bosons (to unitarise fully the *VV* scattering):

    DY produced *Z', W',..*
  - new fermionic resonances (alter radiative corrections to H from top):
    top/b partners (vector-like quarks)
  - simplified models of WIMP dark matter produced at the LHC

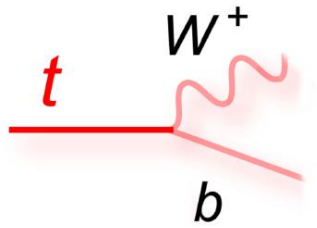
- Latest results (Summer 18) from both ATLAS EXPERIMENT and CMS Collaborations:

1. Searches for heavy resonances decaying into 3rd gen. quarks
2. Searches for vector-like quarks
3. Searches for dark-matter with top quarks

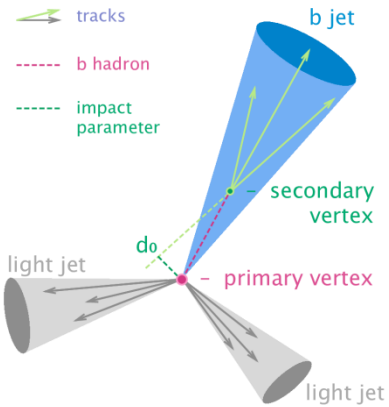
- Apologies if your preferred search is not included due to lack of time

Experimental signatures: top and bottom as probes

- Top quarks almost exclusively decaying to Wb:
  - $W \rightarrow lv$ (~ 30%) / qq' (~ 70%)

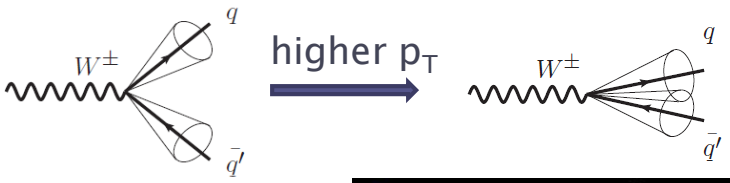


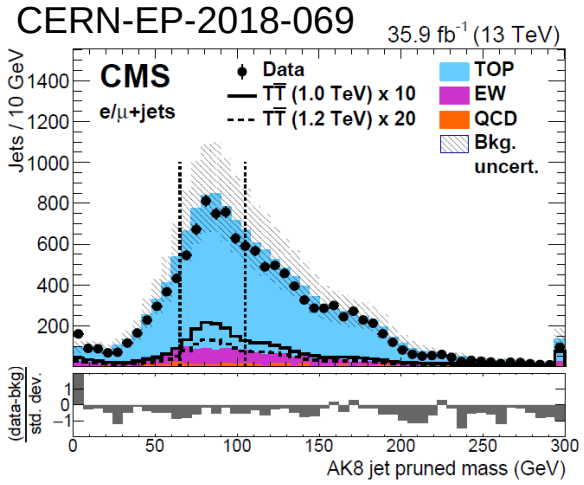
- Very peculiar experimental signature
  - jets and *b*-jets, charged leptons, MET (neutrino)

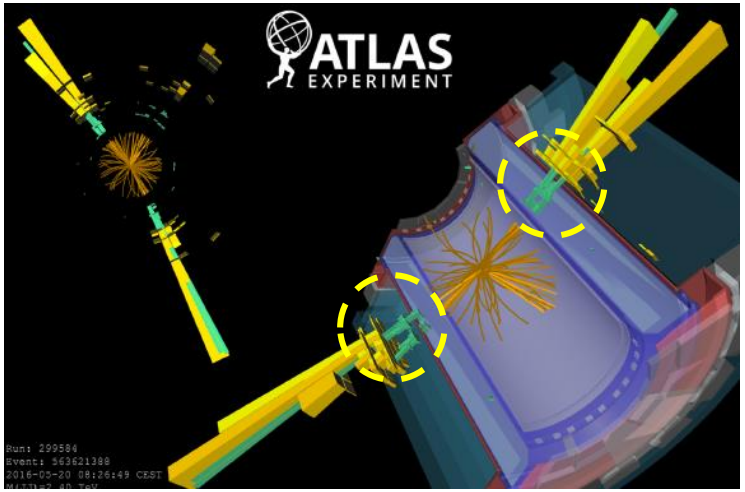


- Algorithms built to identify b-jets
  - based on secondary vertex and jet shape information
  - multivariate discriminant used to discriminate *b*-, *c*- and *light*-jets

- Boosted object tagging:

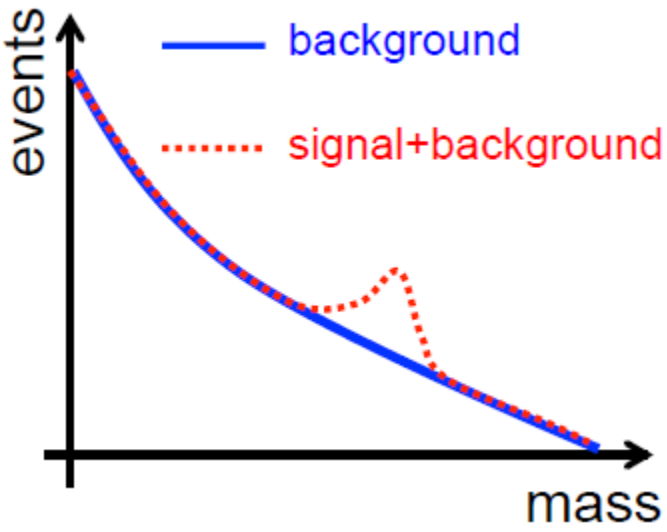


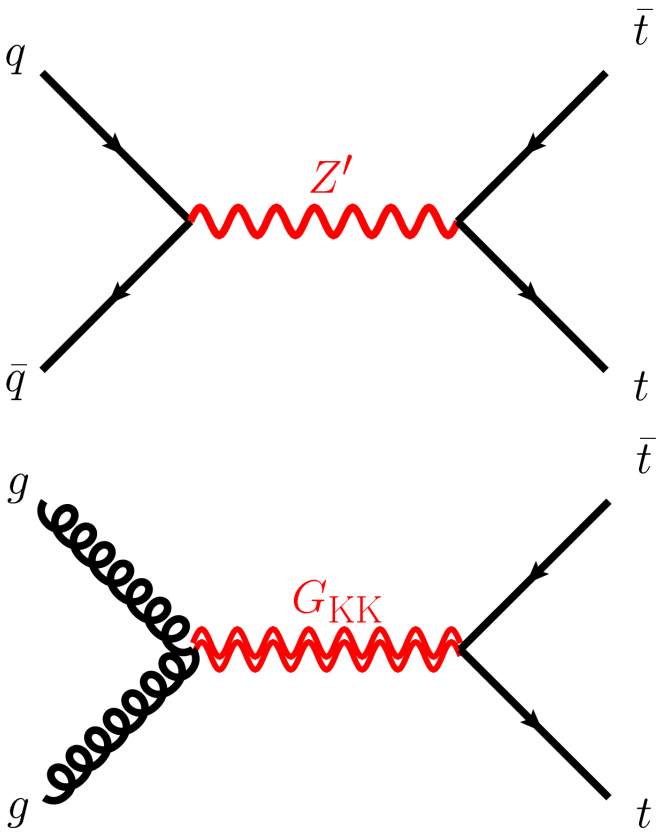




Resonances decaying into 3rd generation quarks

- Resonance search:
  - spin 1(2) heavy particles decaying to a pair of top quarks
  - several benchmark models: heavy *Z'*-boson, KK-gluons or gravitons





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- Single lepton, MET and jet activity compatible with hadronic top-quark decay

- Split into resolved and boosted channels based on hadronic activity

- Discriminant: invariant mass of top-pair system (χ^2-recontruction)

- Observed (expected) limits (95 % C.L.) m(*Z'*) < **2.6** (**3.0**) **TeV**, width = 1%

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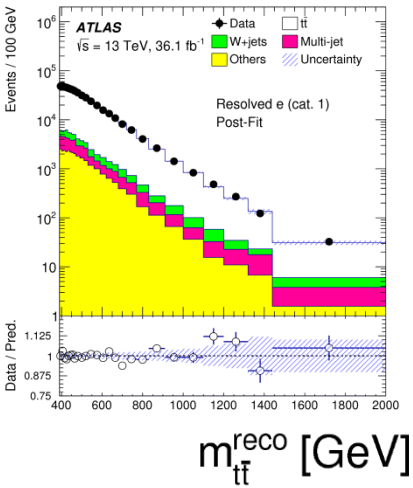
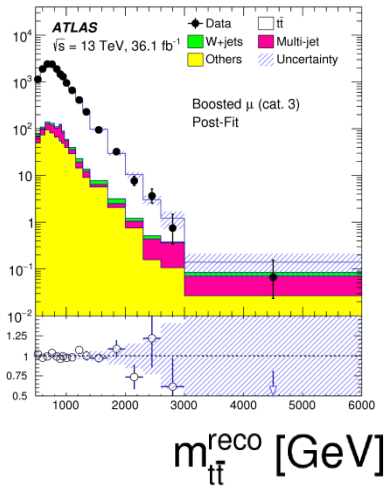
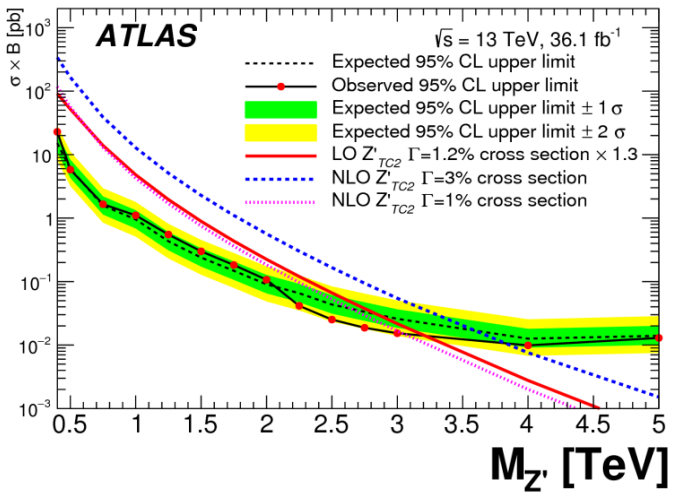
resolved



boosted





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- First interpretation using top-pair decay channel for the DM-mediators mass m(*Z'*) < **1.2 - 1.4 TeV**

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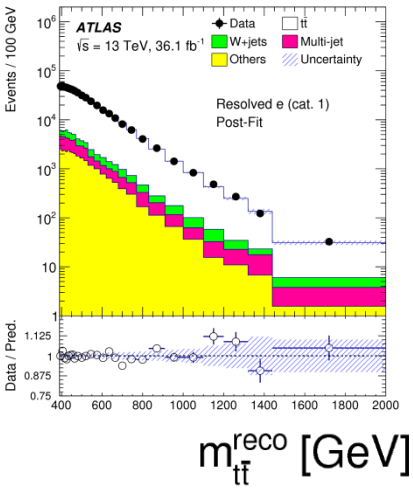

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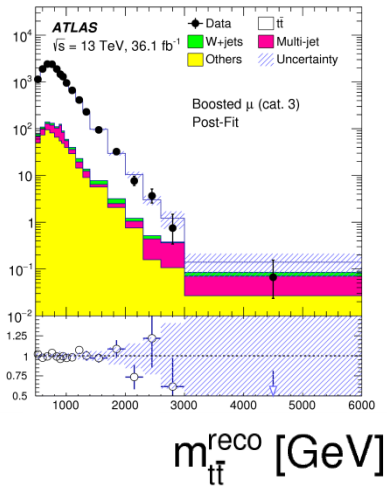
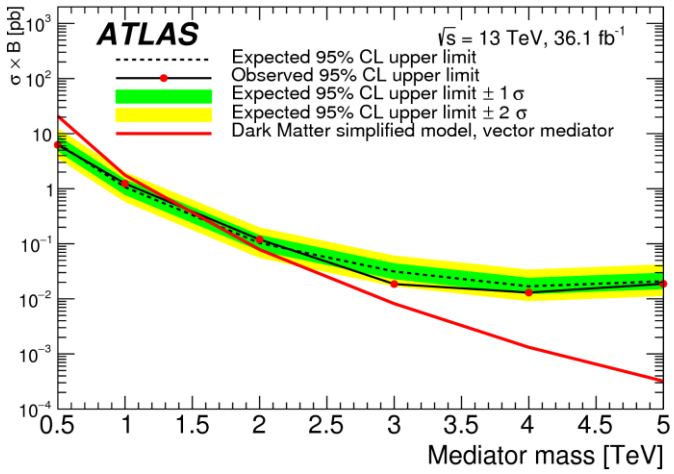




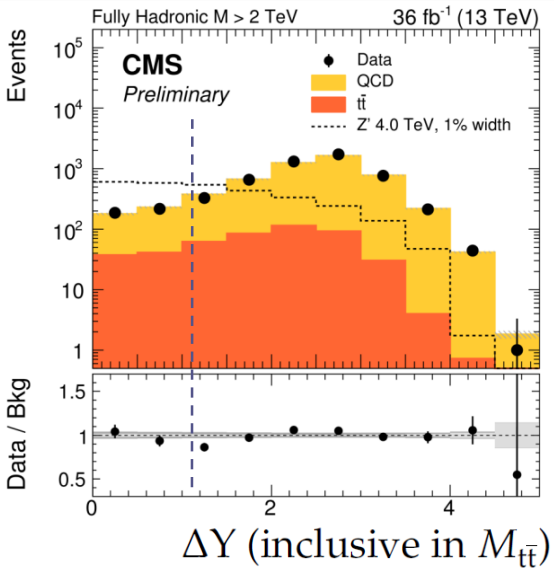
Resonances decaying into 3rd generation quarks

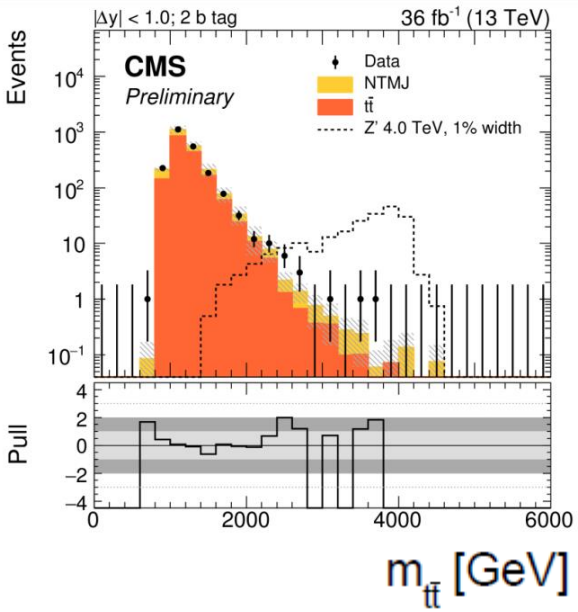
- Search for heavy *Z'* resonance in 3 final states: single lepton, dilepton and fully hadronic

- Reconstruction techniques optimized for top quarks with high Lorentz boosts, requiring the use of non-isolated leptons and jet substructure

- All hadronic channel:
  - 2 high p_T top-tagged jets, 6 signal regions (rapidity difference and b-subjet)
  - data-driven estimation of QCD via anti-tag and probe procedure

CMS-PAS-B2G-17-017





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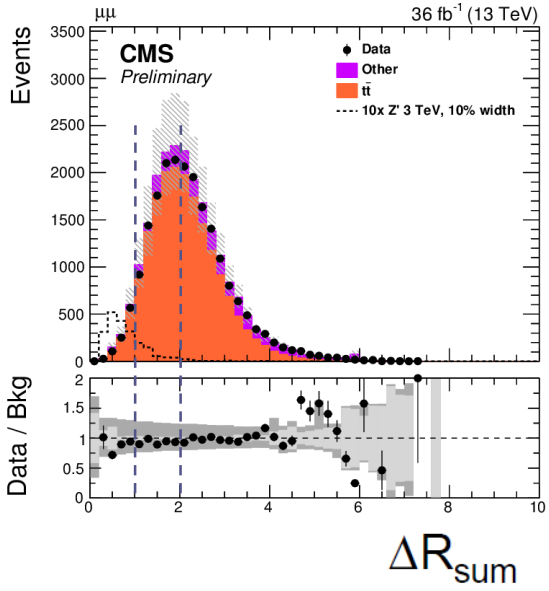
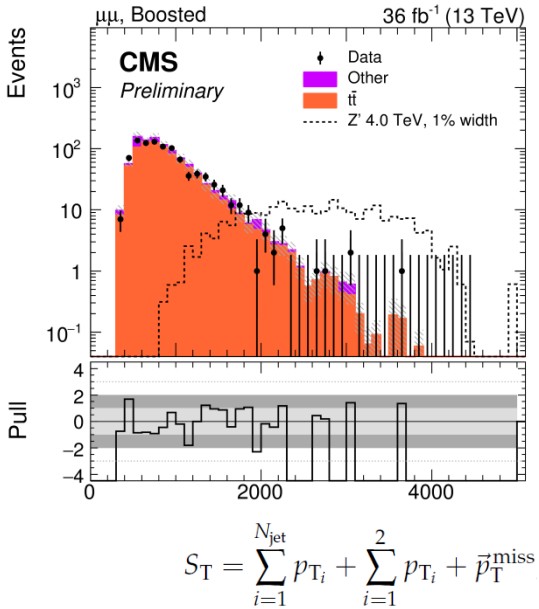
- Dilepton channel: define: ΔR_{sum} to categorize events: $\Delta R_{\text{sum}} = \Delta R_{\text{min}\,0}(\ell 1, j) + \Delta R_{\text{min}\,1}(\ell 2, j)$
  - boosted: $\Delta R_{sum} < 1$
  - resolved: $1 < \Delta R_{sum} < 2$
  - background CR: $\Delta R_{sum} > 2$
- S_T variable used in 6 signal and 3 bgd regions

CMS-PAS-B2G-17-017





$$S_{\text{T}} = \sum_{i=1}^{N_{\text{jet}}} p_{\text{T}_i} + \sum_{i=1}^{2} p_{\text{T}_i} + \vec{p}_{\text{T}}^{\,\text{miss}}$$

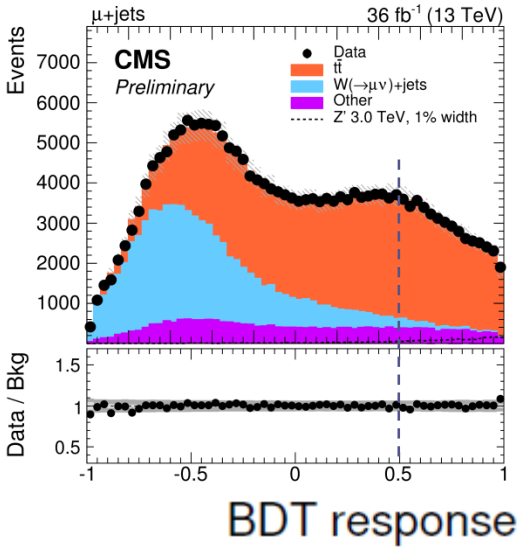
Resonances decaying into 3rd generation quarks

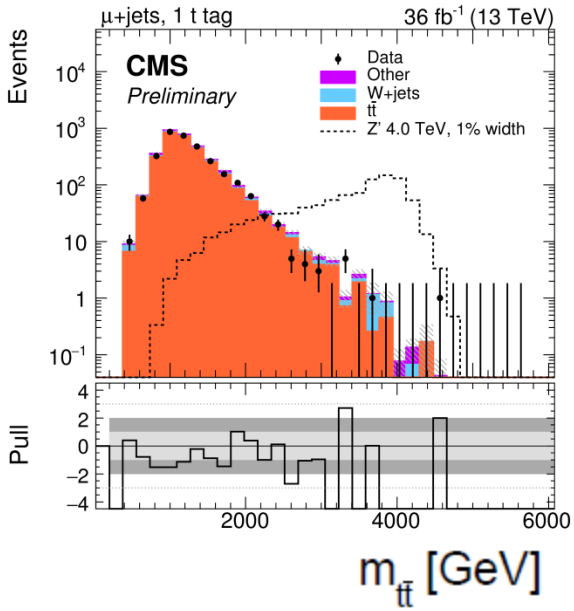
- Search for heavy *Z'* resonance in 3 final states: single lepton, dilepton and fully hadronic

CMS-PAS-B2G-17-017

- Reconstruction techniques optimized for top quarks with high Lorentz boosts, requiring the use of non-isolated leptons and jet substructure

- Single lepton channel: 1 non-isolated high p_T lepton and at least 2 high p_T jets
  - BDT to suppress W+jets background
  - SR require top-tagged large-R jet
  - χ^2 -reconstruction of the top-pair system





Resonances decaying into 3rd generation quarks

• Search for heavy *Z'* resonance in 3 final states: single lepton, dilepton and fully hadronic

CMS-PAS-B2G-17-017

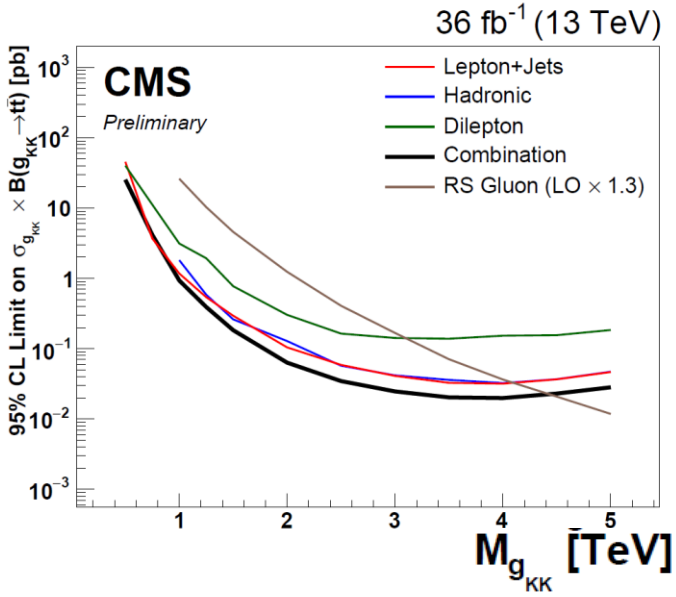
• Reconstruction techniques optimized for top quarks with high Lorentz boosts, requiring the use of non-isolated leptons and jet substructure

✓ All hadronic channel: reduction in the uncertainty on multijet bkg estimate

✓ Single lepton channel: improved W+jets rejection via BDT

✓ Inclusion of dilepton channel in the combination

• All hadronic and single lepton channels provide most of the sensitivity for high-mass, dilepton contributes in the low-mass range



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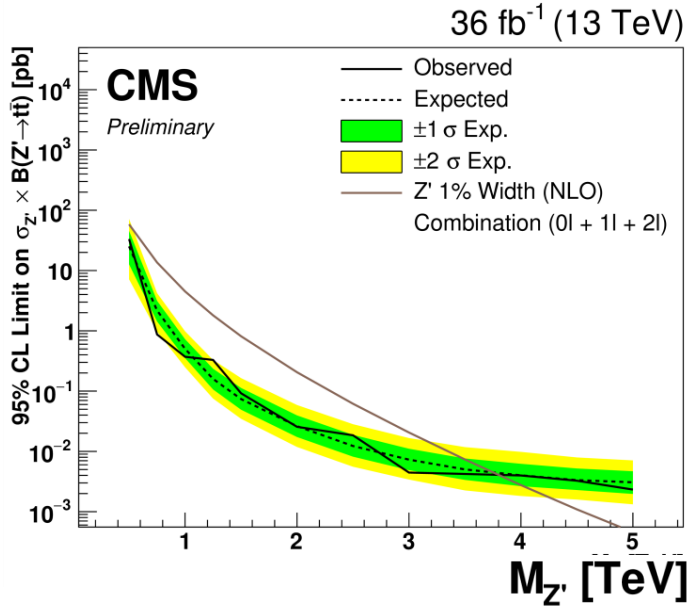
• Observed (expected) limits (95 % CL)

m(Z') < **3.8** (**3.75**) **TeV**, width = 1%



Resonances decaying to top and bottom

- Search for a heavy *W'* resonance decaying to a top and bottom quarks in the semileptonic decay channel

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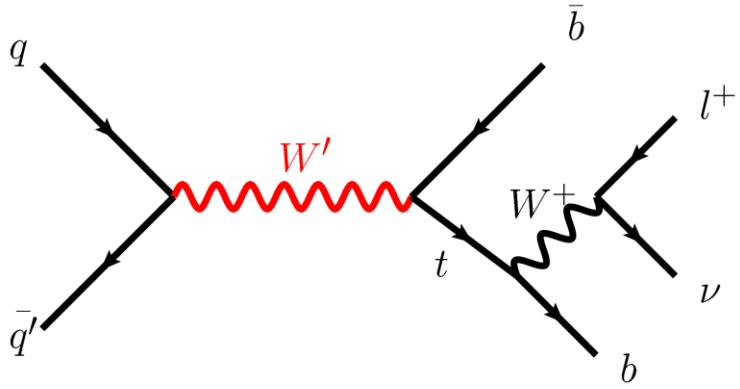
Phys. Lett. B 777 (2018) 39

- Complementary to searches for $W' \rightarrow lv$ and $W' \rightarrow WZ$, with a single lepton, MET and central jet activity, sensitive to $m_{W'}$ of 1 - 4 TeV



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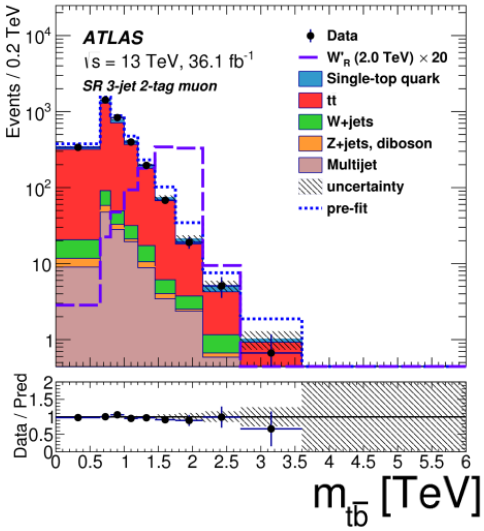
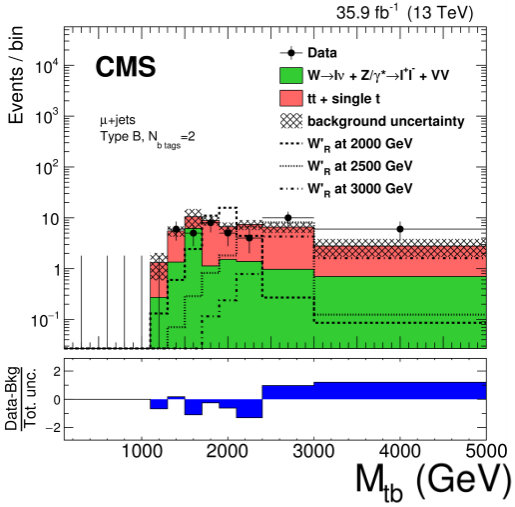
Phys. Lett. B 777 (2018) 39

- Complementary to searches for $W' \rightarrow l\nu$ and $W' \rightarrow WZ$, with a single lepton, MET and central jet activity, sensitive to $m_{W'}$ of 1 - 4 TeV
  - ATLAS: kinematic categorisation based on lepton type and number of (*b*-) jets
  - CMS: hight p_T non-isolated leptons, and categories on top and jets p_T
- Syst. uncert. dominated by *b*-tagging efficiency and top-pair generator/showering
- Combined ATLAS single lepton + fully hadronic final state search: $m(W'_R) <$ **3.25 TeV**, similar to CMS single lepton exclusion of $m(W'_R) <$ **3.4 TeV**





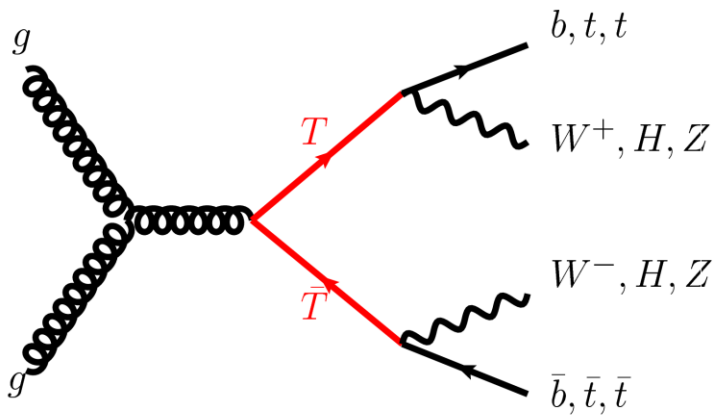
Searching for vector-like quarks (VLQs)

- VLQs predicted in many BSM models that address the naturalness
  - coloured, fractionally-charged fermions, left- and right-handed components have same weak isospin (“vector-like")

- Both fractional (-1/3, 2/3) and “exotic” (-4/3, 5/3) charges possible

  B **T** **($B^{-4/3}$, Y)** **($T^{5/3}$, X)**

- Pair (single) production via QCD (EW) interactions
  - Single: model dependent (EW coupling), dominate high-mass
  - Pair: model independent (QCD), typically leading low mass

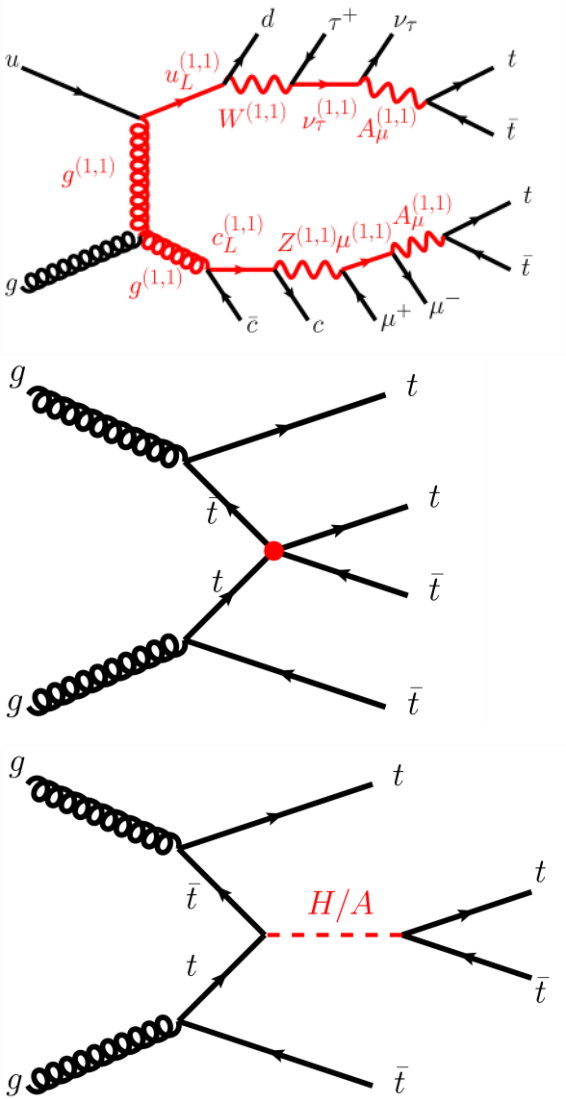


- Most searches assume:
  - VLQs couple only to SM particles
  - VLQs decay always to a boson (*W,Z,H*) and 3rd generation quarks

- Rich phenomenology at the LHC based on *t, b, H, W, Z* signature

- Wide search for new phenomena
  - vector-like quark, exotic four-top-quark, 2HDM and top-coupled DM production

CERN-EP-2018-171



- Wide search for new phenomena
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- Cut & count in 6 (8) validation (signal) regions with selection on MET, HT, number of leptons, jets and *b*-jets: achieve very low SM background

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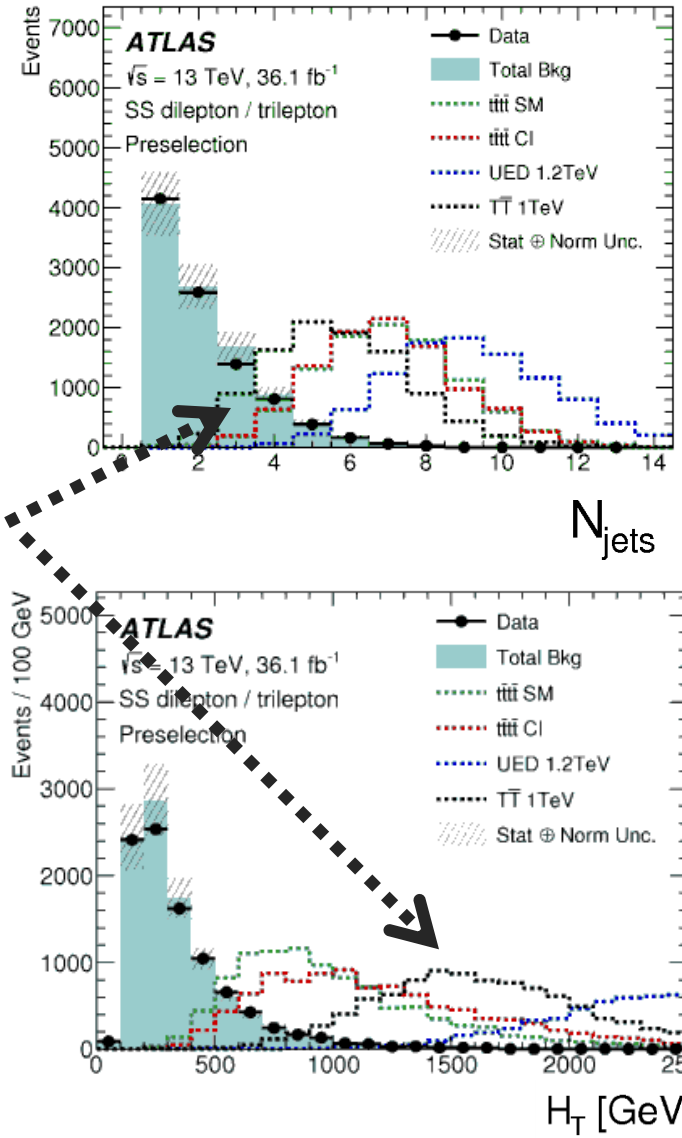

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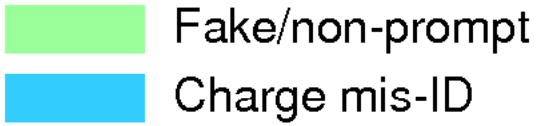
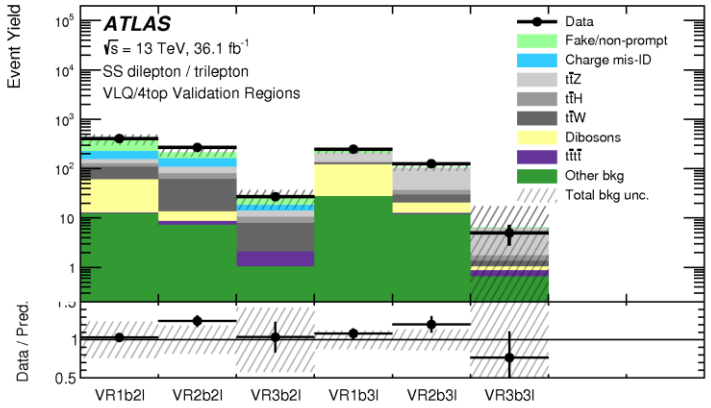
- Data-driven backgrounds:
  - ✓ Fake/non-prompt *e/μ* backgrounds estimated using a matrix method
  - ✓ Charge mis-ID backgrounds (for same-sign dilepton events) estimated via rate measured in data





validation regions

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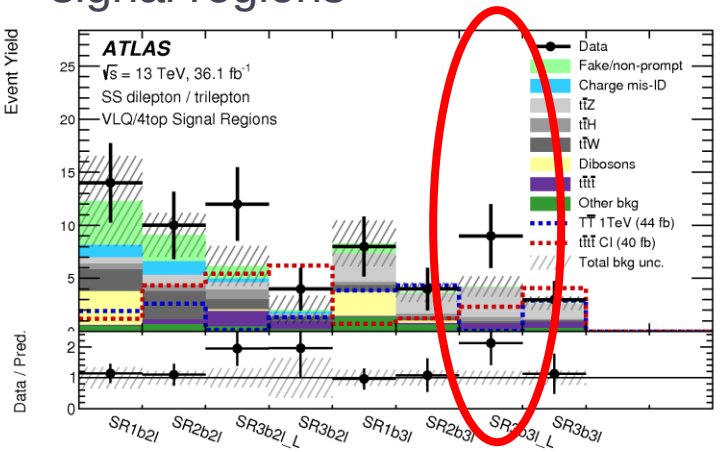

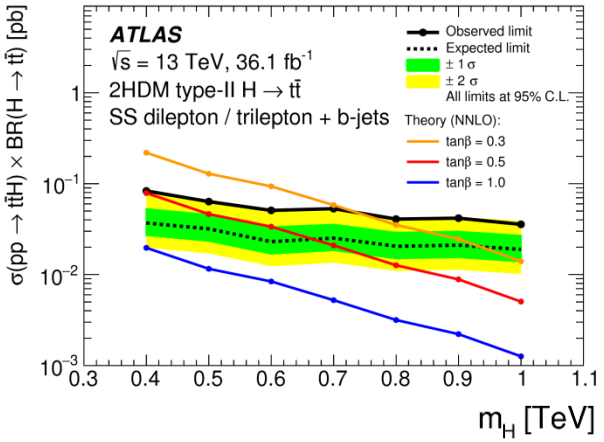

- Constrain T (B) masses at 95% C.L. at around **1 TeV** in the singlet scenario
- Limits in the 2HDM interpretation: probing masses from 0.4 - 1 TeV

TT/BB→1 lepton, 2 SS and 3 leptons

- Generic search for TT/BB decaying to jets and one, two same-sign and three leptons
- Heavy VLQs decay products often merged: quantify jet internal structure with N-prong hypothesis
- Single lepton: 16 categories of events with/without *H/W*-jets (~60% efficiency) and *b*-jets
- Event yield in the 2SS dilepton and S_T in 4 trilepton categories based on lepton flavour
- MC simulation-based (data-driven) for prompt (instrumental) backgrounds
- Exclude T (B) quarks at 95% C.L. with masses below **1200** (**1170**) **GeV** in the singlet and **1280** (**940**) **GeV** in the doublet branching fraction scenario

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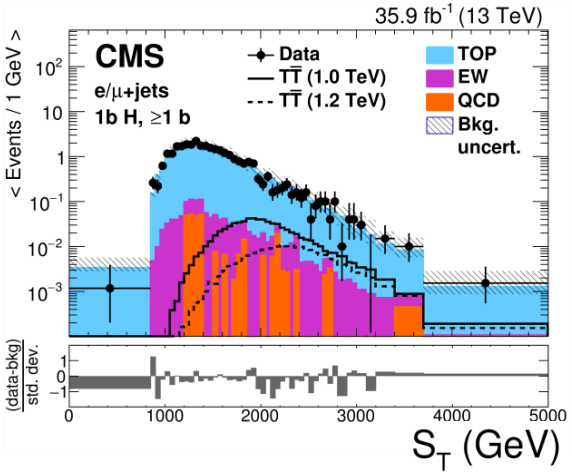
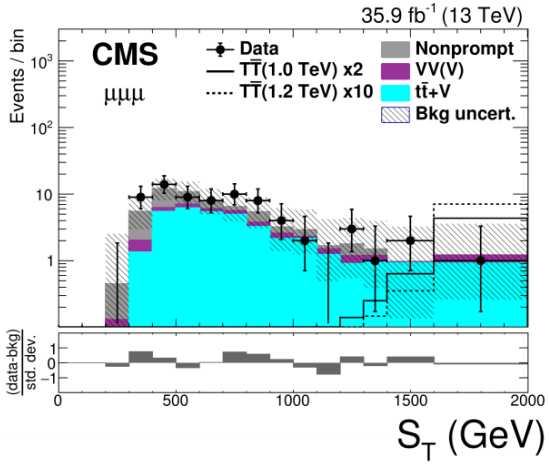
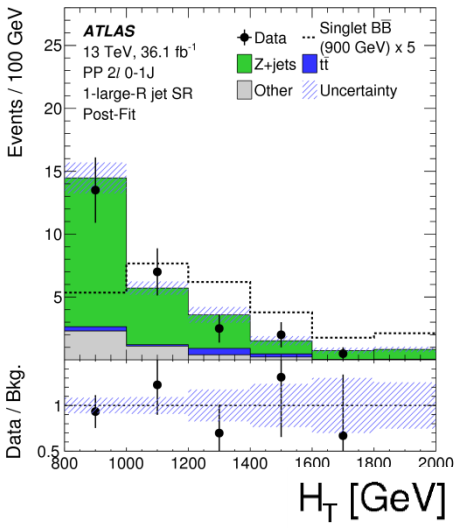


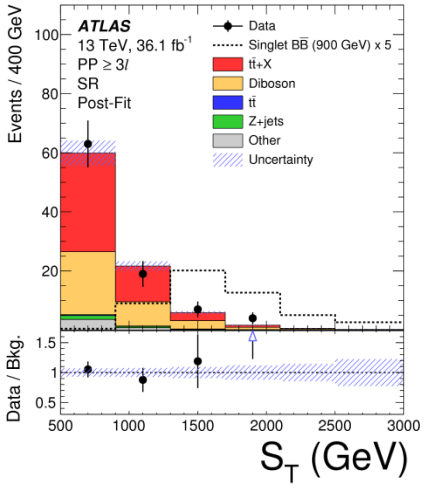


TT/BB→Z(→ll)t/b+X

CERN-EP-2018-145

- Search for VLQs which targets their decays into a *Z*-boson and a 3rd generation quark
- ≥2 *e/μ*, with one pair consistent with *Z-boson* decay, ≥2 jets and ≥1 *b*-tagged jets
- four signal regions defined:
  - 3 dilepton signal regions with 0 / 1 or ≥2 large-radius jets
  - 1 trilepton signal region with ≥1 b-tagged jets
- Backgrounds from MC, corrected in the fit using specific CRs for *tt/Z*+jets, *tt*+X and diboson
- Final discriminants: HT, mass of Zb-system and scalar sum of small-R jet and lepton transverse momenta (S_T)
- Exclude T (B) quarks at 95% C.L. with masses below **1030** (**1010**) **GeV** in the singlet and **1210** (**1140**) **GeV** in the doublet branching fraction scenario





TT/BB→fully hadronic

- Search for VLQs which targets targets all decay modes of T/B with 0 leptons
- Uses high-pT variable-radius reclustered (vRC) jets
- vRC-jets are tagged as *V, H*, or top, based on a multi-class DNN-tagger.
- *V-, H- (VV,VH,HH), t-*, and *b*-tagged multiplicity defines the 12 signal regions
- Multi-jet Backgrounds: “ABCD” method, top from MC with floating normalisation
- Discriminant: “Signal LLH” matrix element of VLQ signal likelihood in 12 signal regions
- Exclude B quarks at 95% C.L. with masses below ~**1 TeV** in the singlet and doublet BRs scenarios

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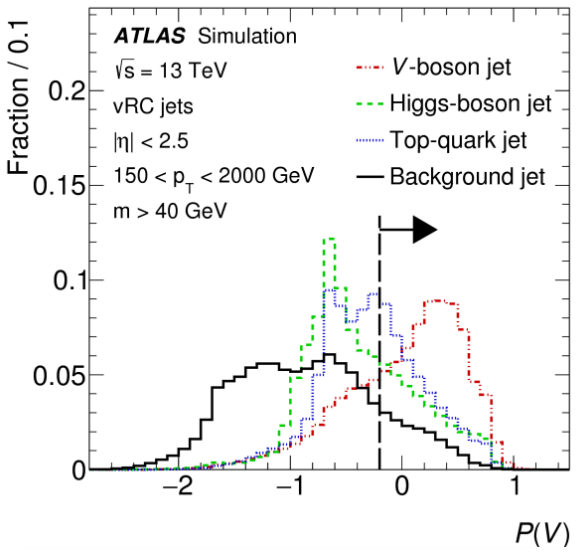
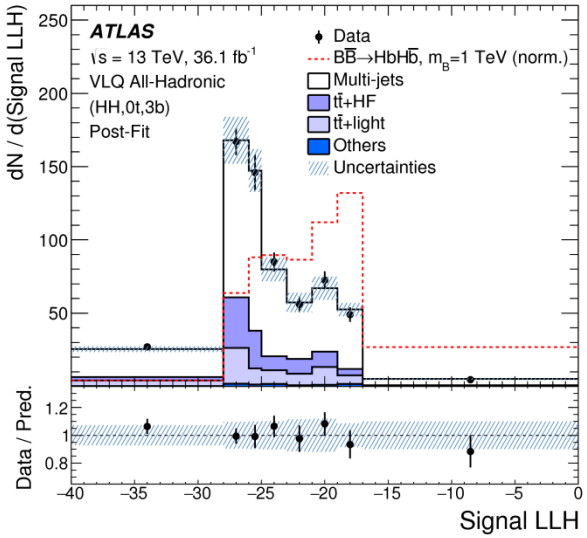


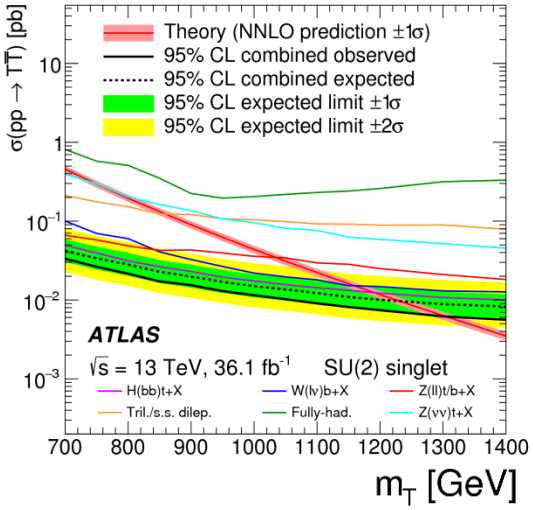


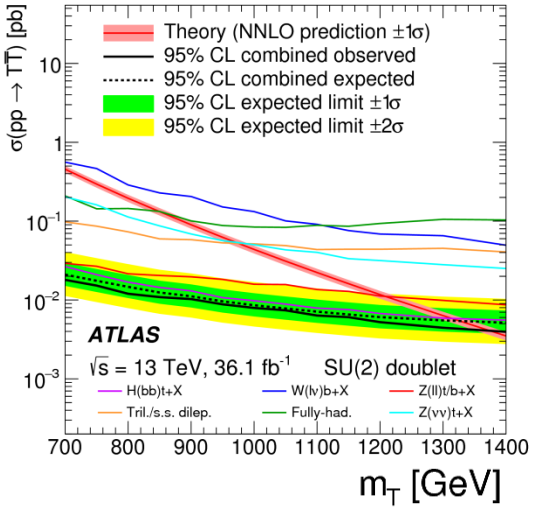
Combination of VLQ searches

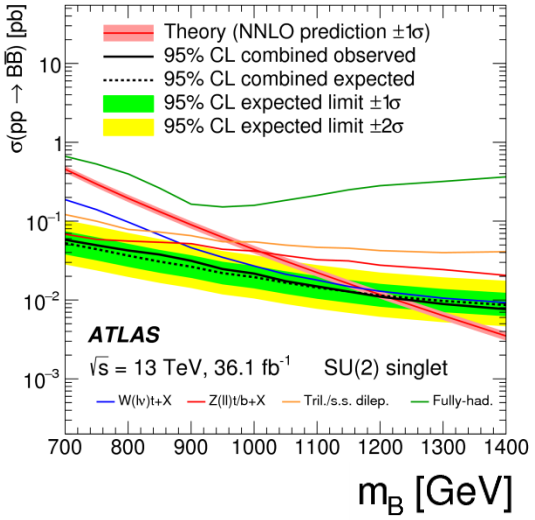
- Combination of seven pair-production searches at 13 TeV using 36.1 fb^{-1}
- Significantly extends the reach of individual searches
- Singlet T (B) quarks at 95% C.L. excluded for masses below **1.31** (**1.22**) **TeV** and $m_{T(B)}$ < **1.37** (**1.37**) **TeV** in the doublet scenario

CERN-EP-2018-205

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$	$HtH\bar{t}$	-
$W(\ell\nu)b + X$	$WbW\bar{b}$	-
$W(\ell\nu)t + X$	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$	$ZtZ\bar{t}$	$ZbZ\bar{b}$
tril./s.s. dilepton	$HtH\bar{t}$	$WtW\bar{t}$
fully-hadronic	$HtH\bar{t}$	$HbH\bar{b}$

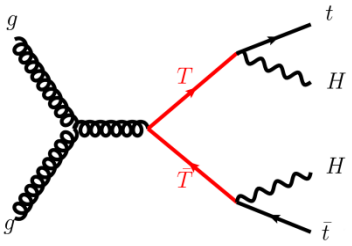




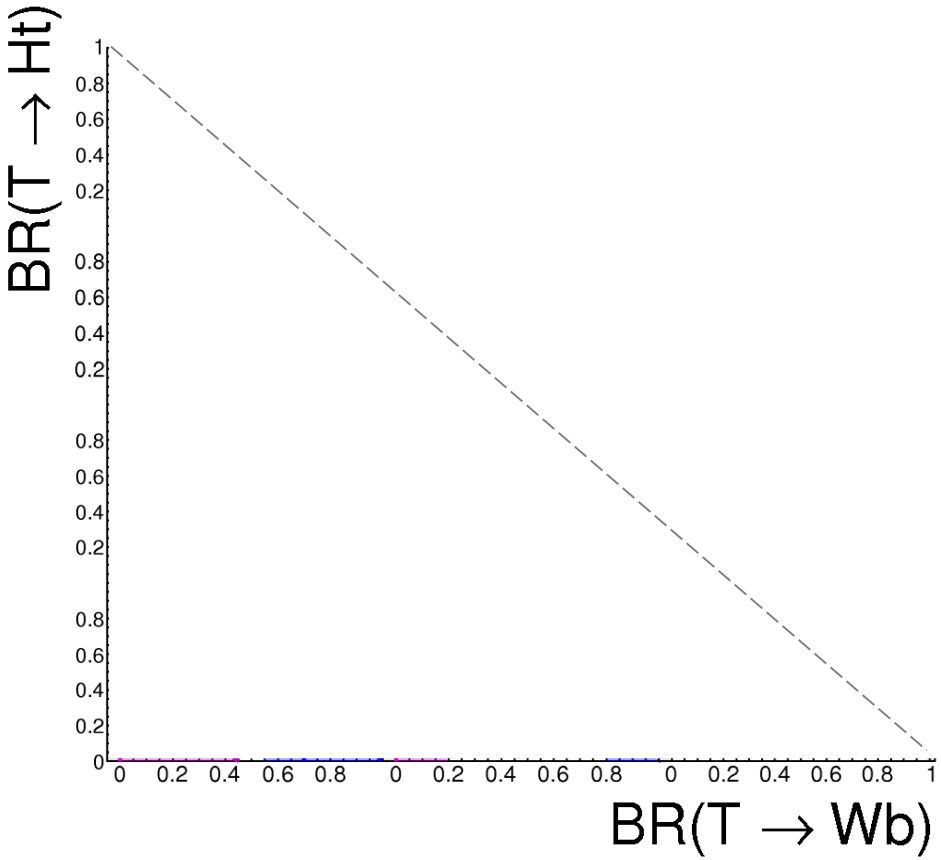


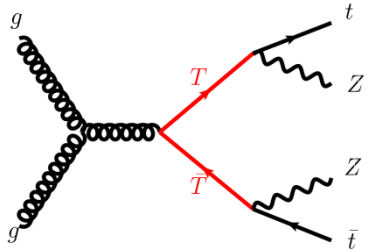
- Combination of seven pair-production searches at 13 TeV using 36.1 fb^{-1}

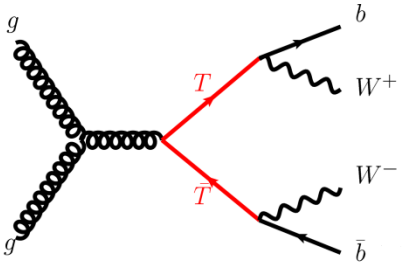
CERN-EP-2018-205



vector-like T







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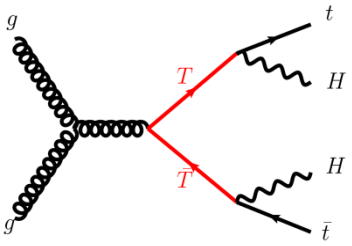
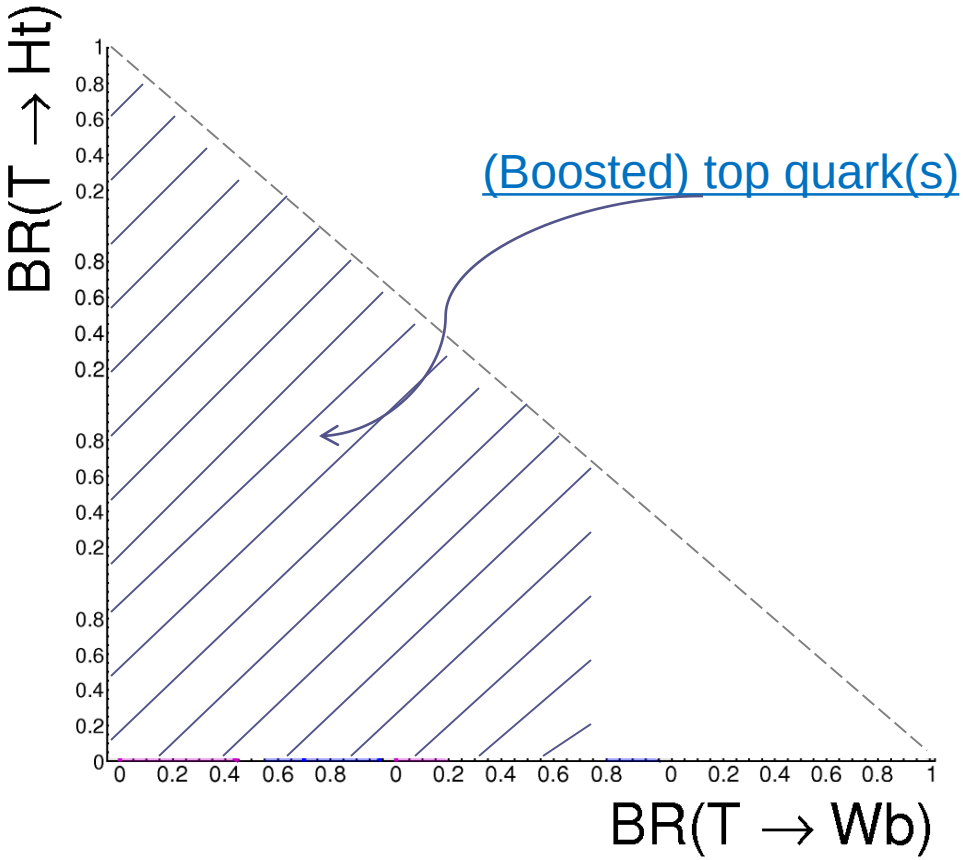
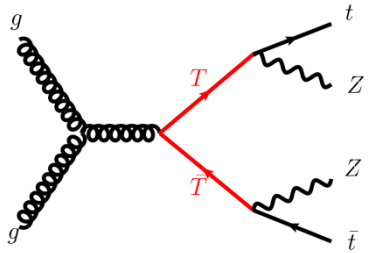
CERN-EP-2018-205

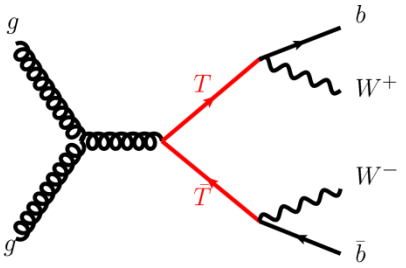


vector-like T

(Boosted) top quark(s)







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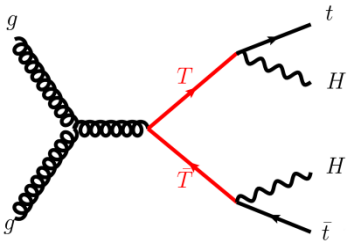
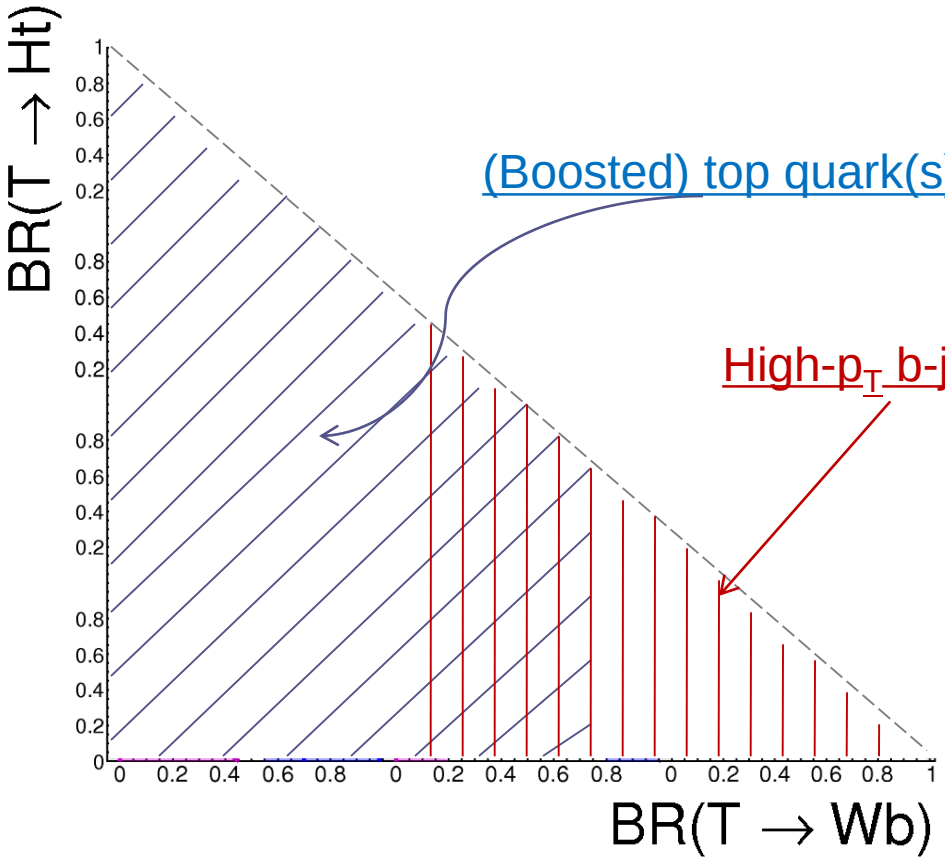
CERN-EP-2018-205

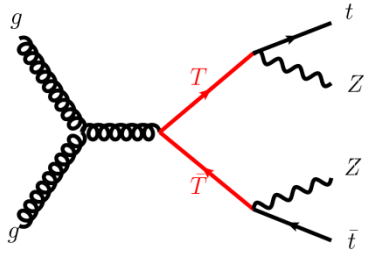


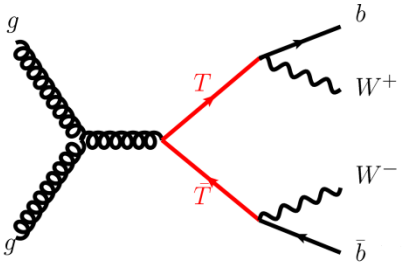
vector-like T

(Boosted) top quark(s)

High-p_T b-jet(s)

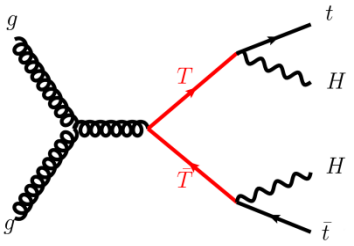






- Combination of seven pair-production searches at 13 TeV using 36.1 fb^{-1}

CERN-EP-2018-205



Exp. exclusion Obs. exclusion

W(lν)b+X [arXiv:1707.03347]

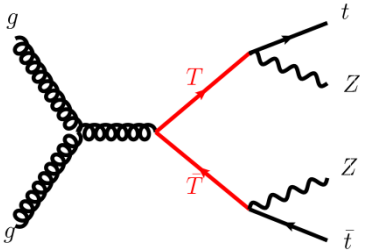
H(bb)t+X [arXiv:1803.09678]

Z(νν̄)t+X [arxiv:1705.10751]

Trilep./same-sign [CERN-EP-2018-171]

Z(ll)t/b+X [arXiv:1806.10555]

All-had [CERN-EP-2018-176]



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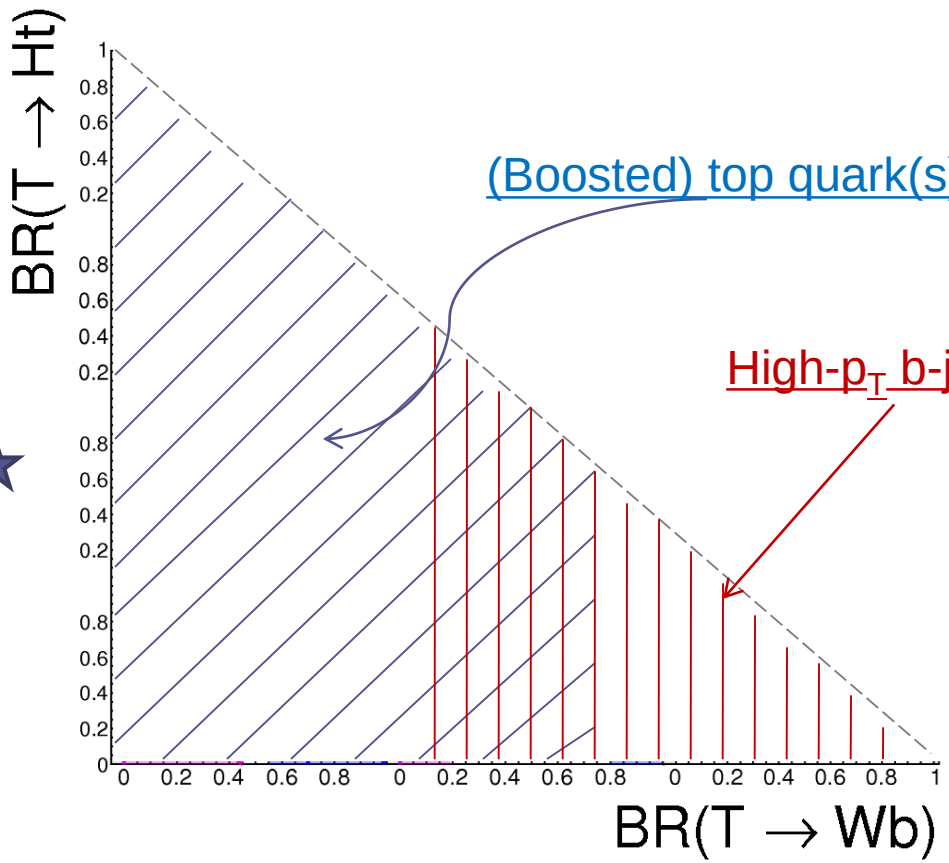

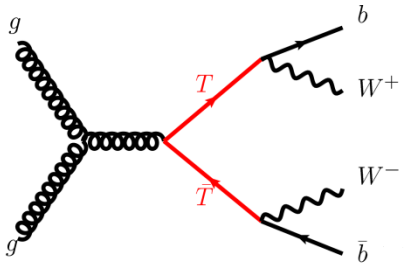

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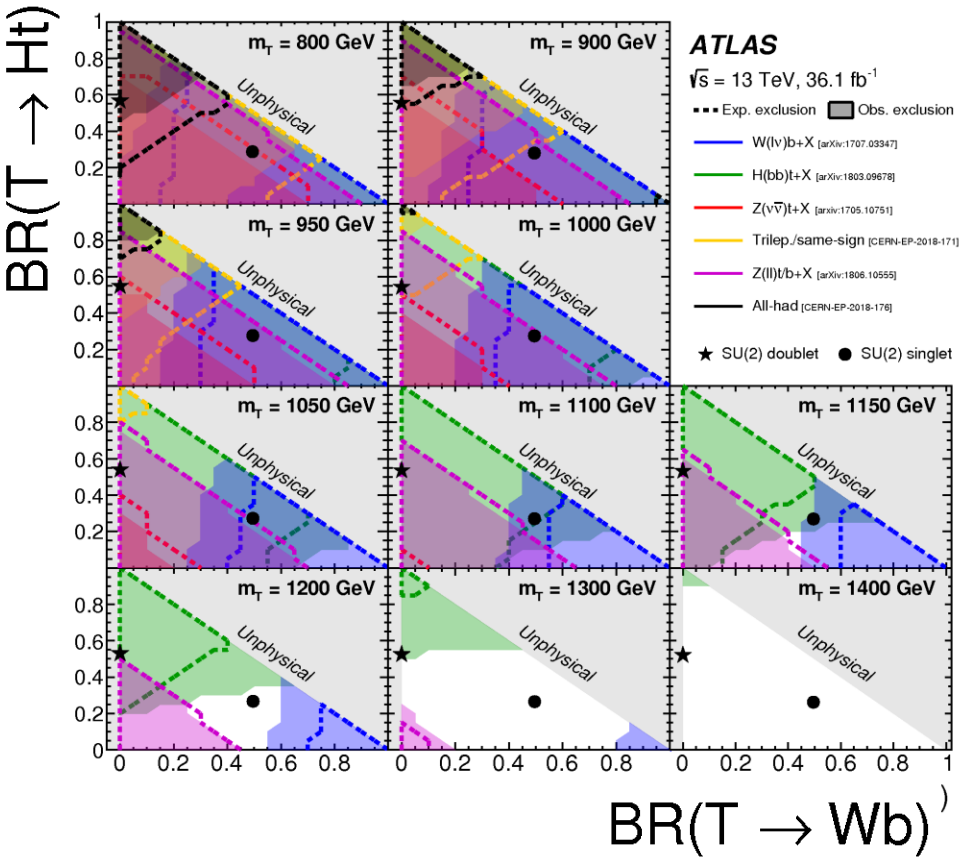
CERN-EP-2018-205

vector-like T



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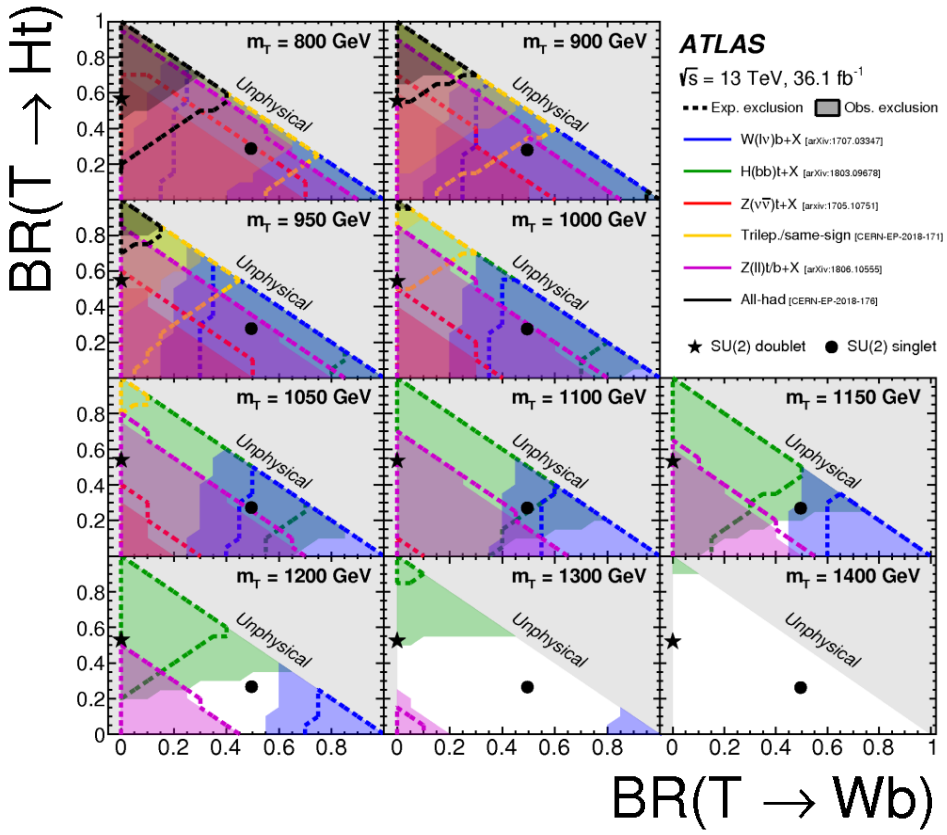
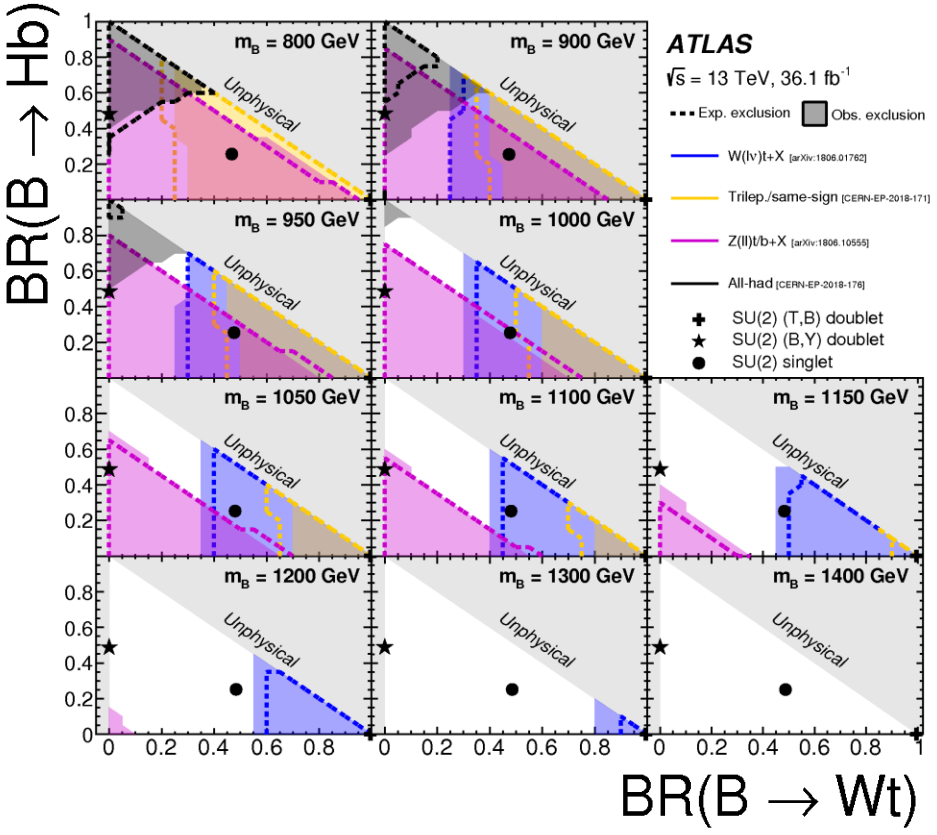
CERN-EP-2018-205

vector-like T



vector-like B

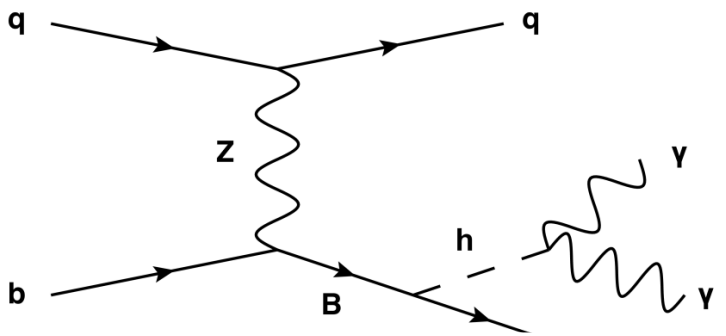


single VLQ: B→bH(→γγ)

- Search for single B →Hb in the diphoton decay mode using 2015+2016 and 2017 data (79.8 fb^{-1})

ATLAS-CONF-2018-024

- *t*-channel production characteristic: 2 photons, forward jet and high p_T b-jet



single VLQ: B→bH(→γγ)

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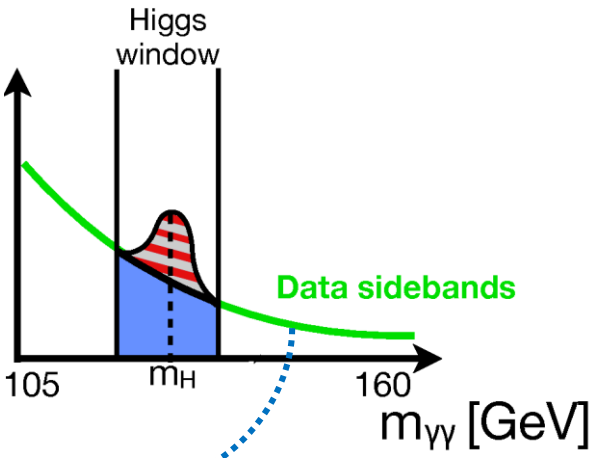
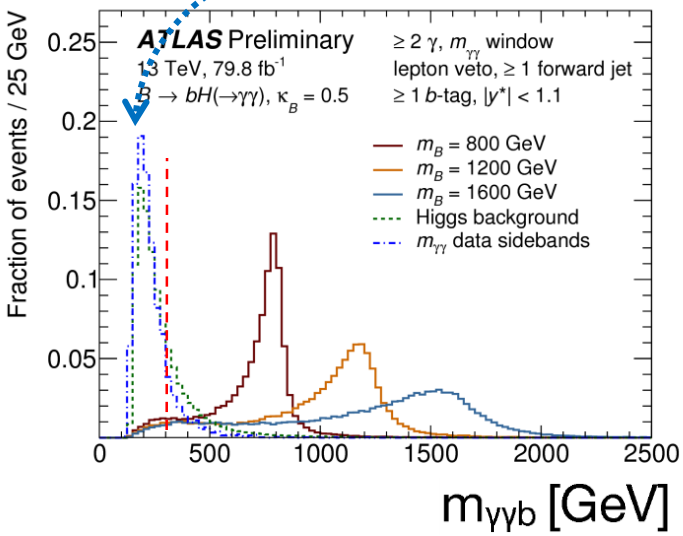
- Higgs backgrounds from MC, non-resonant continuum (*γγ*+jet) from data-driven estimate
- Shape of discriminant $m_{\gamma\gamma b}$ of continuum is estimated from $m_{\gamma\gamma}$ data sidebands

ATLAS-CONF-2018-024





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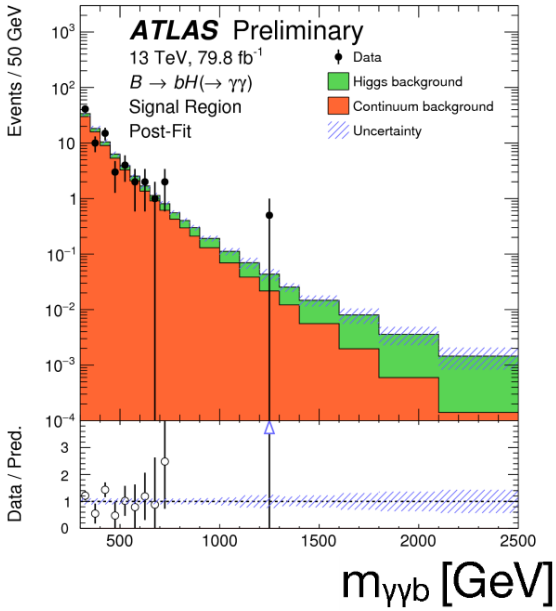
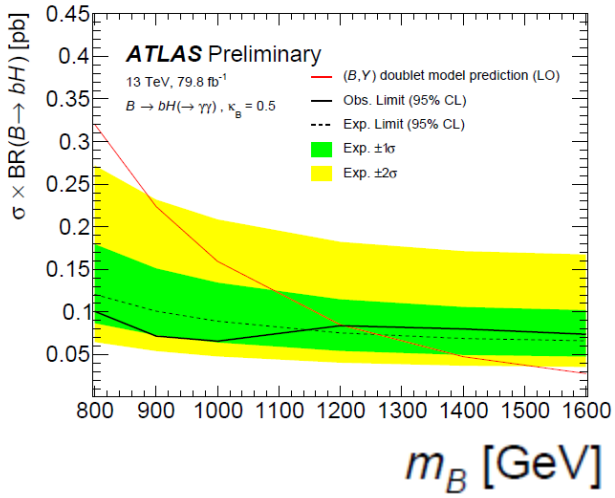
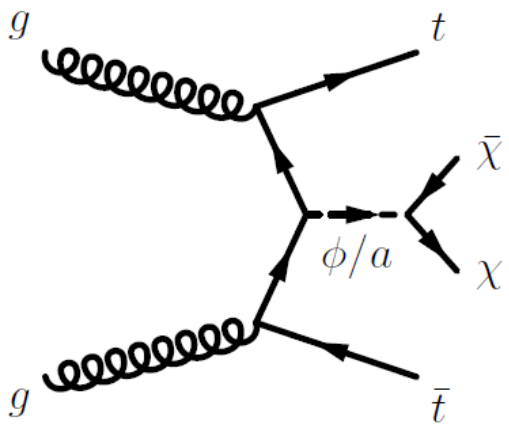
- Shape of discriminant $m_{\gamma\gamma b}$ of continuum is estimated from $m_{\gamma\gamma}$ data sidebands
- Using a generalized coupling value κ=0.5 and doublet BRs of 50% for B→Hb(Zb), vector-like B quarks with m_B< **1210 GeV** are excluded

ATLAS-CONF-2018-024





- In a large class of models, DM consists of stable WIMPs (χ) which may be pair-produced at LHC with a spin-0 scalar (ϕ) or pseudo-scalar (a) mediator produced in assocation with top quarks
  - Probing mediator mass within 10-500 GeV
  - Coupling between mediator and DM set to 1



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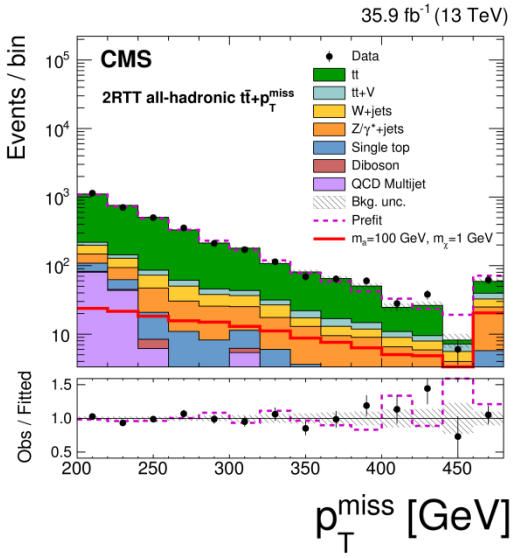
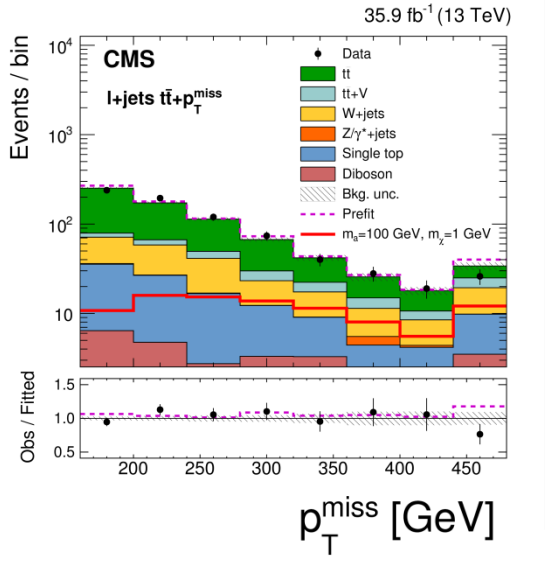
- Search for top+DM (tt + $\chi\chi$) covering all top-pair decay modes: all-hadronic, lepton+jets and dileptonic final states
- Dedicated CRs to constrain tt,W/Z+jets for each p_T^{miss} bin
  - all-hadronic: categorisation based on MVA "Resolved Top Tagger" that identifies top → 3 jets
  - lepton+jets: CRs in order to control Z($\nu\nu$)/W($l\nu$)+jets, cuts to suppress dileptonic decays

CERN-EP-2018-183





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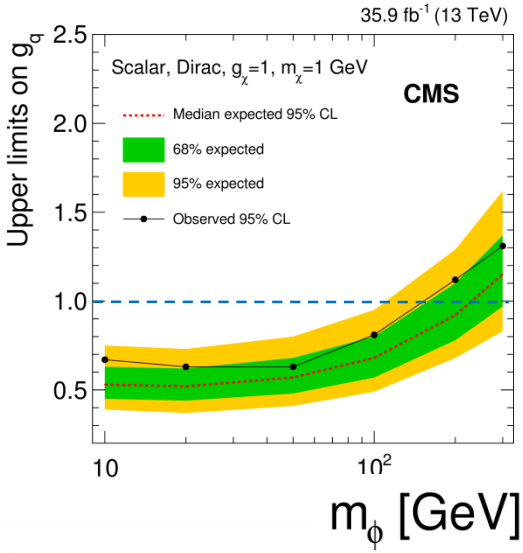
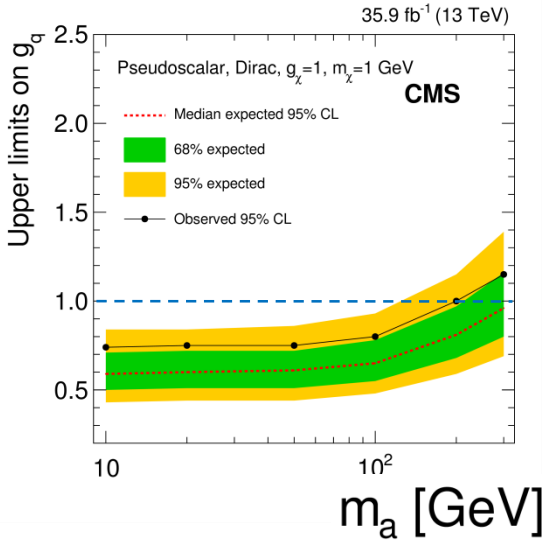
  - lepton+jets: CRs in order to control $Z(\nu\nu)/W(l\nu)$+jets, cuts to suppress dileptonic decays
- Exclude (pseudo-) scalar DM mediator with masses of **160** (**220**) **GeV** (assuming m_χ=1 GeV)
- Better sensitivity for spin-0 mediators than DM+jets (considered the most sensitive signature!)

CERN-EP-2018-183





Conclusions

- Top quark: ideal to probe several new theories extending the Standard Model

- Both ATLAS and CMS have a broad search program using top/b-quarks with many public results in the last months: no evidence for new physics has yet emerged

- Challenging and rare decay modes are exploited:
  - generic searches using all possible top-quark pair final states
  - dedicated resolved/boosted channels
  - jet substructure and jet reclustering
  - event categorisation/background rejection using MVAs
  - combination of searches and various interpretations of the results

- Looking forward to new results using 2017/18 data thanks to LHC great performance

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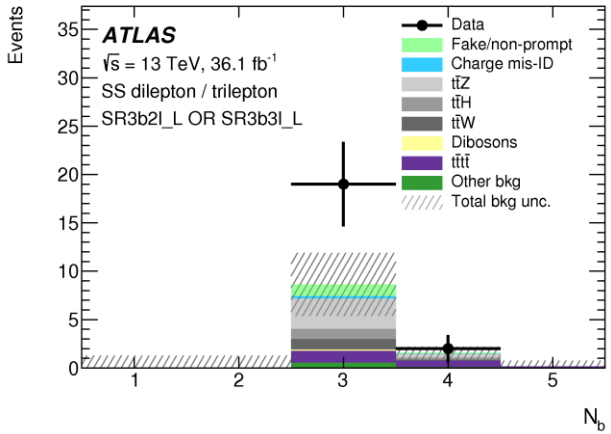
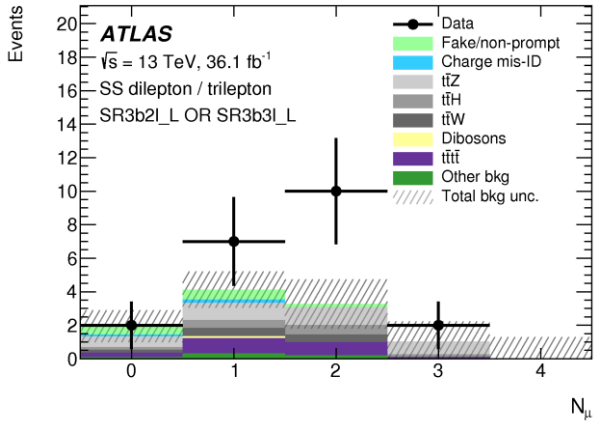
- Looking forward to new results using 2017/18 data thanks to LHC great performance and thank you for your attention!

BACK-UP

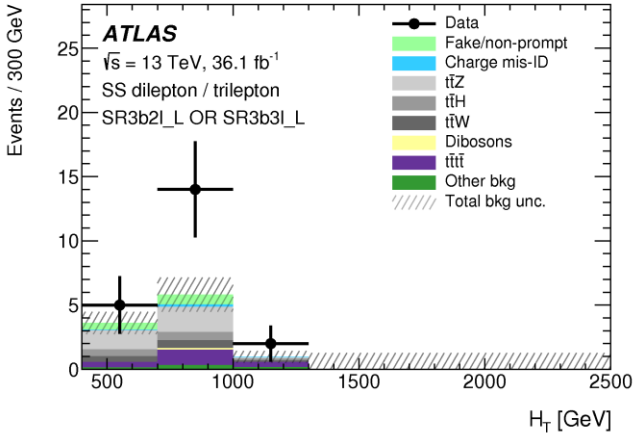
- Excess info: More than half of the excess is observed in events with two muons, three b-tagged jets and HT around 700 GeV.

- the kinematic properties of the events were compared with the expectations from the BSM four-top-quark production benchmark models, and found to agree poorly with all of them, particularly in the b-tagged jet multiplicity





Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	++ or −−	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 40$ GeV
VR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$400 < H_T < 1400$ GeV or $E_T^{miss} < 40$ GeV
SR3b2ℓ_L	≥ 7	≥ 3	2	++ or −−	$500 < H_T < 1200$ GeV and $E_T^{miss} > 40$ GeV
SR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR1b3ℓ	≥ 1	1	3	any	$400 < H_T < 2000$ GeV or $E_T^{miss} < 40$ GeV
SR1b3ℓ	≥ 1	1	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 140$ GeV
VR2b3ℓ	≥ 2	2	3	any	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 400$ GeV
SR3b3ℓ_L	≥ 5	≥ 3	3	any	$500 < H_T < 1000$ GeV and $E_T^{miss} > 40$ GeV
SR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 40$ GeV

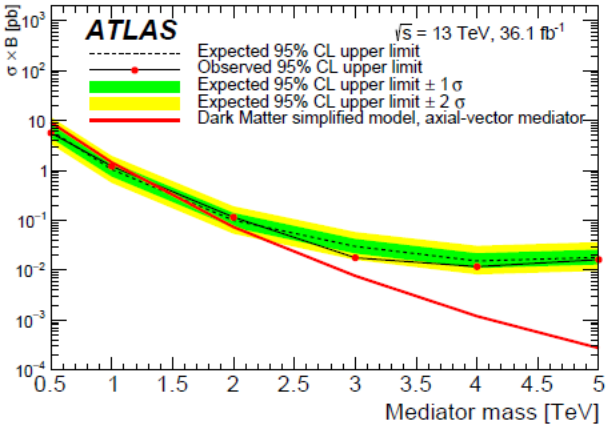


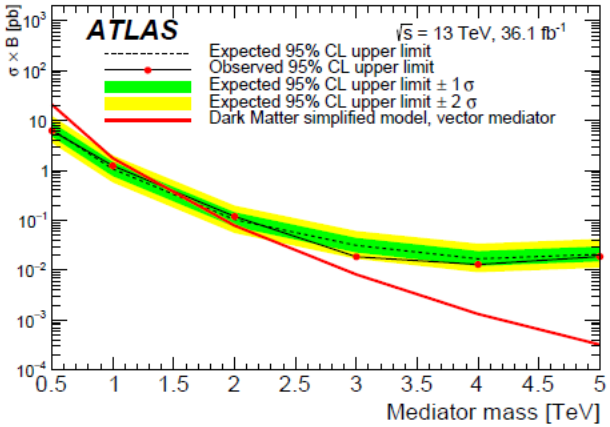
Resonances with the 3rd generation quarks

Eur. Phys. J. C 78 (2018) 565

Interactions between dark matter and normal matter may be mediated by weakly coupled TeV-scale particles. This search considers an axial-vector mediator, $Z'_{\mathrm{DM,ax}}$ and a vector mediator, $Z'_{\mathrm{DM,vec}}$, within a framework of simplified models proposed by the LHC Dark Matter Working group [7]. There are five free parameters for these mediators: the coupling to quarks (g_q), the coupling to leptons (g_ℓ), the coupling to dark matter (g_{DM}), the dark-matter mass (m_{DM}) and the mediator mass. The mediator mass is varied between 0.5 TeV and 5 TeV with the other parameters set to $g_q = 0.25$, $g_\ell = 0$, $g_{\mathrm{DM}} = 1$, and $m_{\mathrm{DM}} = 10$ GeV following the benchmarks A1 and V1 defined in Ref. [7]. The width of $Z'_{\mathrm{DM,ax}}$ and $Z'_{\mathrm{DM,vec}}$ are 5.6% of their masses, with the $Z'_{\mathrm{DM,ax}}$ width kinematically limited to 5.3% at 0.5 TeV.

[7] A. Albert et al., *Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels*, (), arXiv: 1703.05703 [hep-ex].



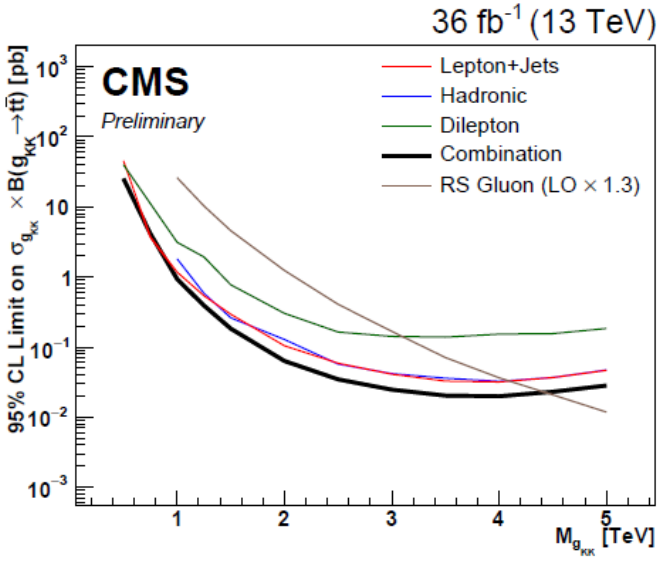


Resonances decaying into 3rd generation quarks

CMS-PAS-B2G-17-017

Uncertainty		Channel		
Source	Prior	Dilepton	Single Lepton	Hadronic
b tag efficency	± 1 s.d.(p_T, η)	✓		✓
b mistag rate	± 1 s.d.(p_T, η)	✓		✓
Parton distribution functions	± 1 s.d.	✓	✓	✓
CSV shape	± 1 s.d.		✓	
Diboson cross section	15%	✓		
Electron trigger	± 1 s.d.(p_T, η)	✓	✓	
Electron identification	± 1 s.d.(p_T, η)	✓	✓	
Jet energy scale	± 1 s.d.(p_T, η)	✓	✓	✓
Jet energy resolution	± 1 s.d.(η)	✓	✓	✓
Luminosity measurement	2.7%	✓	✓	✓
NTMJ modified mass procedure	± 1 s.d.			✓
NTMJ estimate closure test	± 1 s.d.			✓
Muon trigger	± 1 s.d.(p_T, η)	✓	✓	
Muon identification	± 1 s.d.(η)	✓	✓	
Pileup reweighting	± 1 s.d.	✓	✓	✓
Q^2 scale ($t\bar{t}$ pair production)	± 1 s.d.	✓	✓	✓
Single top quark cross section	15%	✓		
t tagging efficiency	unconstrained		✓	✓
t tagging mistag rate (Fully hadronic)	± 1 s.d.(p)			✓
t tagging mistag rate (Single Lepton)	± 1 s.d.		✓	
Top quark pair cross section	3%	✓	✓	✓
Top quark p_T reweighting	± 1 s.d.	✓	✓	✓
W+jets cross section	8%	✓	✓	
Z+jets cross section	20%	✓	✓	

Table 1: Sources of systematic uncertainty that affect the $M_{t\bar{t}}$ distribution in each analysis channel. For uncertainty sources that apply to multiple channels, the corresponding nuisance parameter is fully correlated across these channels if the symbol ✓ appears in the same row of the table. For normalization uncertainties, the size of the effect on the prior distribution is shown. Shape uncertainties have pirors of one standard deviation (s.d.), and the dependence on kinematic quantities is shown.



The discriminant function P for a V boson, Higgs boson and top quark is given by

$$P(V) = \log_{10}\left(\frac{D^{V}_{\mathrm{DNN}}}{0.9 \cdot D^{\mathrm{background}}_{\mathrm{DNN}} + 0.05 \cdot D^{t}_{\mathrm{DNN}} + 0.05 \cdot D^{H}_{\mathrm{DNN}}}\right),$$

$$P(H) = \log_{10}\left(\frac{D^{H}_{\mathrm{DNN}}}{0.9 \cdot D^{\mathrm{background}}_{\mathrm{DNN}} + 0.05 \cdot D^{V}_{\mathrm{DNN}} + 0.05 \cdot D^{t}_{\mathrm{DNN}}}\right) \text{ and}$$

$$P(t) = \log_{10}\left(\frac{D^{t}_{\mathrm{DNN}}}{0.9 \cdot D^{\mathrm{background}}_{\mathrm{DNN}} + 0.05 \cdot D^{H}_{\mathrm{DNN}} + 0.05 \cdot D^{V}_{\mathrm{DNN}}}\right),$$

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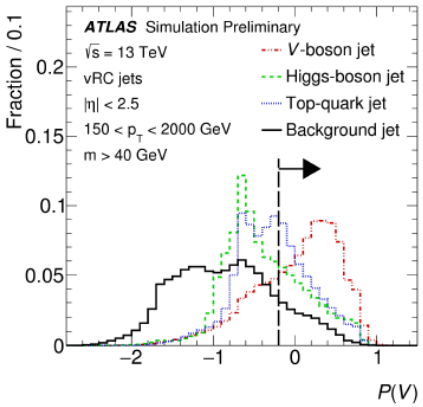

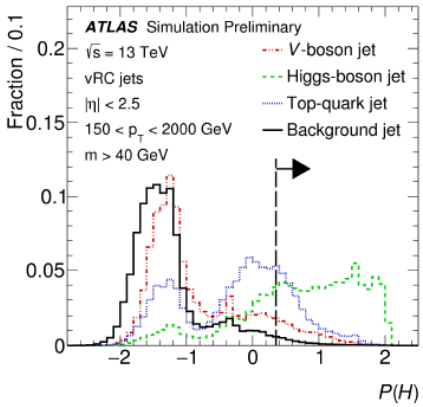

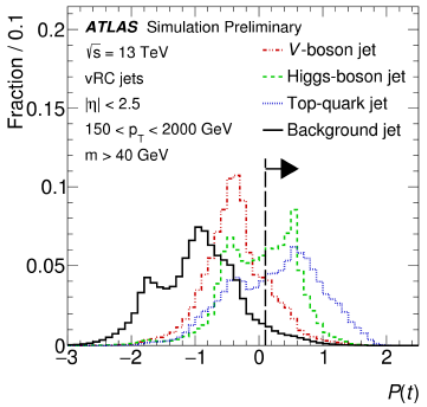

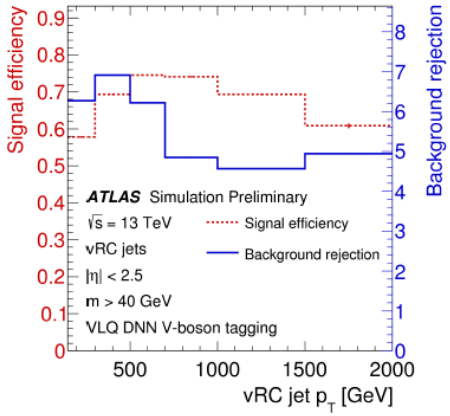

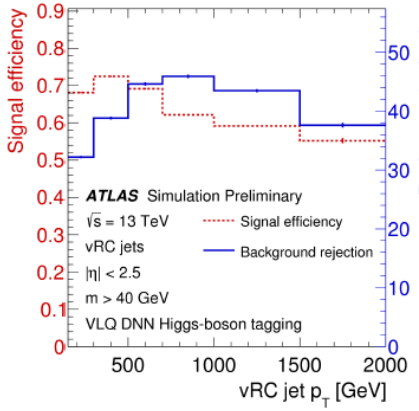

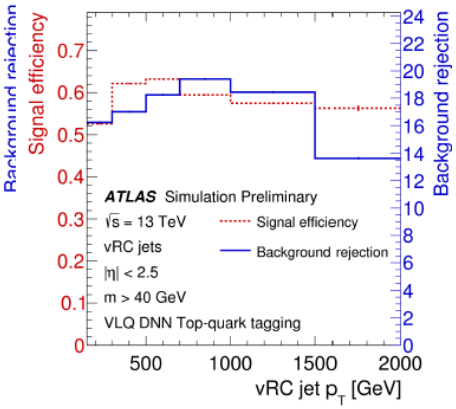

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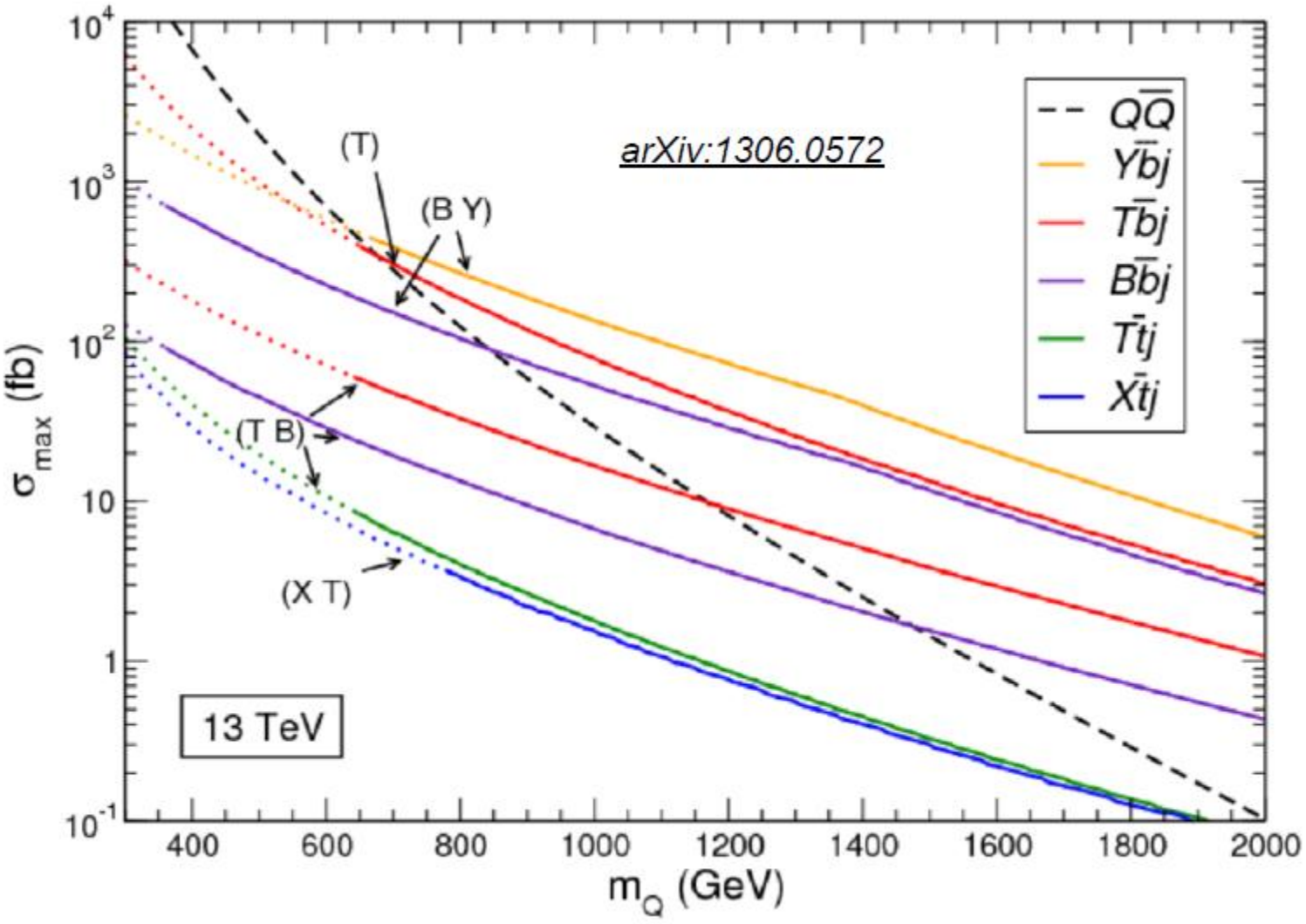
The signal is simulated using simplified models of dark matter production [43]. The dominant mechanism is s-channel production of the mediator via gluon fusion, with the mediator then decaying to a pair of dark matter particles. The dark matter particles are assumed to be Dirac fermions, and the mediators are spin-0 particles with scalar (ϕ) or pseudoscalar (a) interactions. The couplings between the mediator and standard model quarks are $g_{qq} = g_q y_q$, where $y_q = \sqrt{2} m_q / v$ are the standard model Yukawa couplings, m_q is the quark mass, and $v = 246\,\text{GeV}$ is the Higgs boson field vacuum expectation value. The g_q parameter is assumed to be unity for all quarks. The direct coupling strength of the mediators to dark matter is denoted by g_χ. The model does not take into account possible mixing between ϕ and the standard model Higgs boson [44]. The $t\bar{t}+\chi\overline{\chi}$ signal is generated at LO using MADGRAPH with up to one additional parton, and the mediator is forced to decay to a pair of dark matter fermions. The mediator width is computed according to partial-width formulas in Ref. [45] and assuming no additional interactions beyond those described here. The relative width of the scalar (pseudoscalar) mediator varies between 4–6% (4–8%) for masses in the range of 10–500 GeV. The signal is normalized to the cross section computed at NLO in QCD.


arXiv:1306.0572
(T)
(B Y)
(T B)
(X T)
13 TeV
$Q\bar{Q}$
$Y\bar{b}j$
$T\bar{b}j$
$B\bar{b}j$
$T\bar{t}j$
$X\bar{t}j$
σ_{max} (fb)
m_Q (GeV)
10^4
10^3
10^2
10
1
10^{-1}
400
600
800
1000
1200
1400
1600
1800
2000