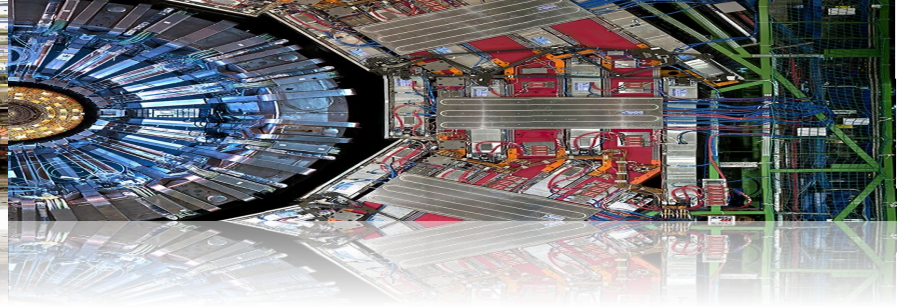


VLQ (Vector-Like Quarks)
ATLAS & CMS

Dalia Lucero Ramírez Guadarrama
on behalf of the ATLAS & CMS Collaborations

1 Vector-Like Quarks

2 Pair Production

3 Single Production

4 Conclusions

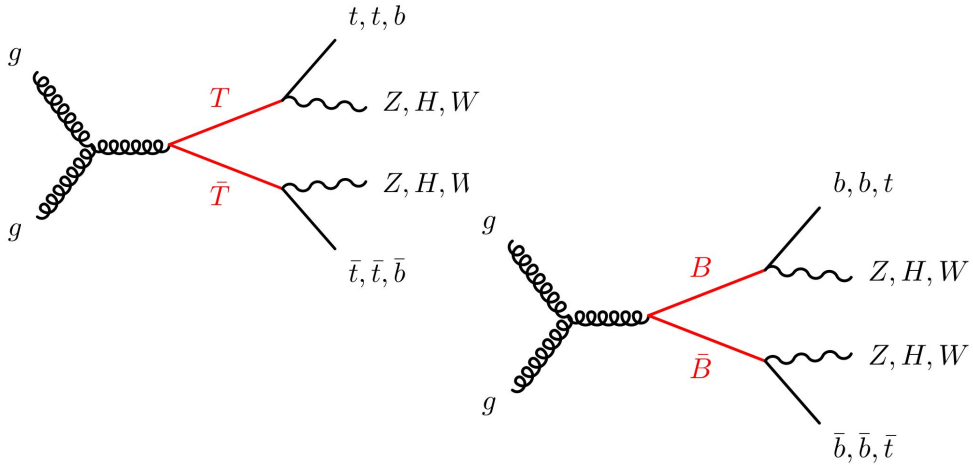
1 Vector-Like Quarks

Vector-Like Quarks

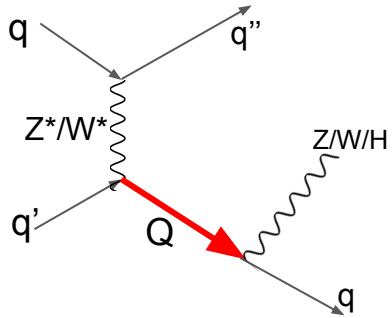
- Spin 1/2.
- Left and right-handed chiralities transform in the same way under the SM gauge group.
- Decay to qZ, qW or qH where q = { t, b }

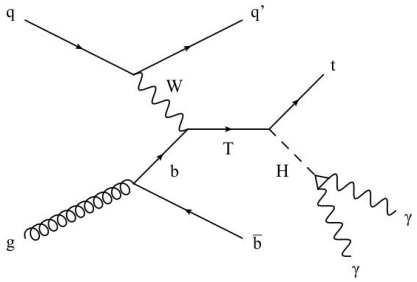
Vector-Like Quarks X, Y, T & B

- **Pair production**
  - Model Independent production cross section



- **Single production**
  - Dependent on qQ coupling (constraints from flavor physics and EW precision tests)
  - Becomes dominant at high energies



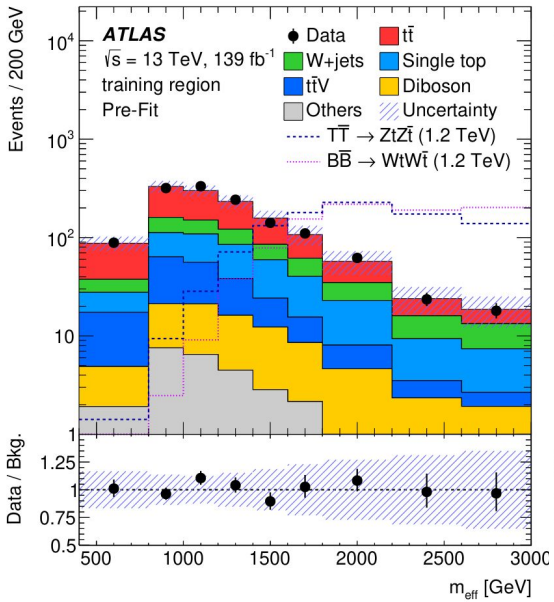


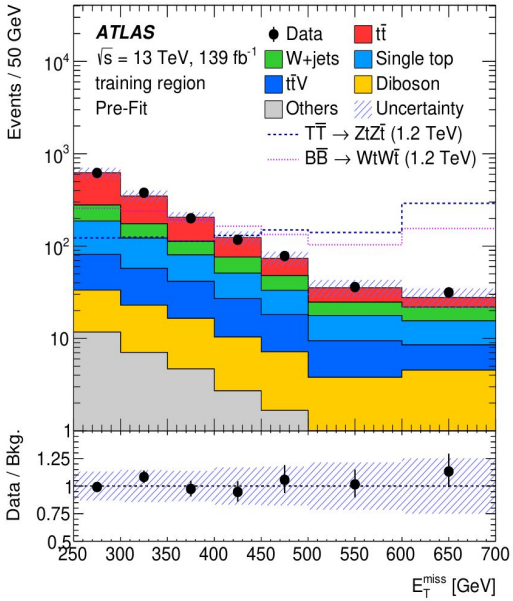
2 Pair Production

$T\bar{T}$ & $B\bar{B}$ production

2212.05263

- For masses of the VLQs above 800 GeV
- Branching Ratios $\mathcal{B}$:
  - T: $\mathcal{B}(Zt, Ht, Wb) \approx (0.25, 0.25, 0.5)$
  - B: $\mathcal{B}(Zb, Hb, Wt) \approx (0.25, 0.25, 0.5)$
- Final state signature:
  - High missing transverse momentum $E_T^{miss} > 250$ GeV
  - One lepton ℓ (e or μ) (veto for a second lepton)
  - At least 4 jets including a b-tagged jet
- Dominant Bkg: $t\,t^-$ and W+jets
  - "Others": $t\,t^-$H, tWZ and Z+jets
- Neural Networks (NN) covering sections of the $\mathcal{B}$ plane
  - For TT 4 NN: (0.8, 0.1, 0.1), (0.2, 0.4, 0.4), (0.4, 0.1, 0.5), (0.4, 0.5, 0.1).
  - For BB 3 NN: (0.1, 0.1, 0.8), (0.4, 0.1, 0.5), and (0.1, 0.4, 0.5).





- Systematic Uncertainties
  Resolution and scale of:
  - $t\,t^-$ bkg
  - Jet mass
  - Efficiency of lepton identification, isolation, reconstruction and energy.

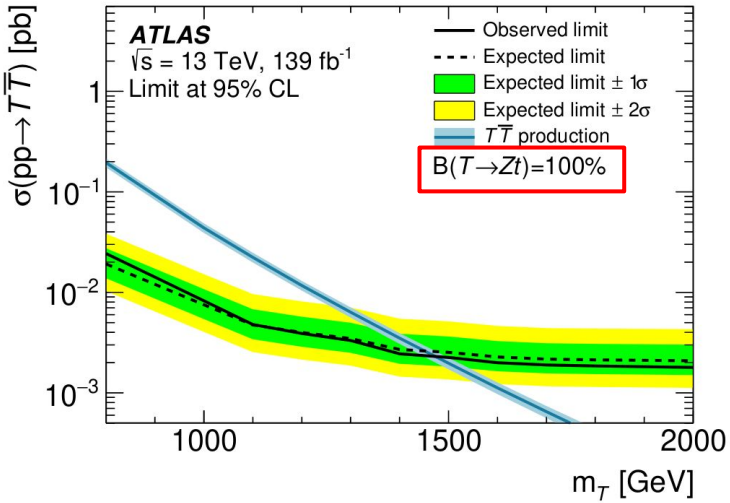
- more sensitive to T'→ Zt, B'→Wt

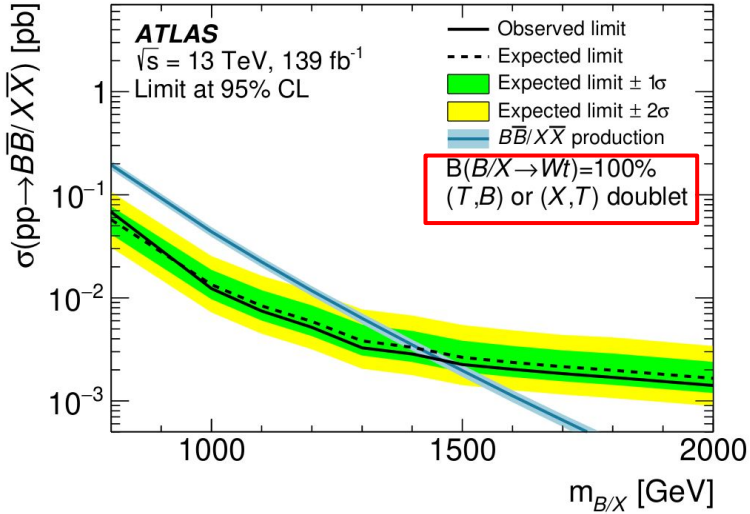
$T\bar{T}$ & $B\bar{B}$ production

2212.05263

- Expected and observed upper limits on the signal cross-section

VLQ	Scenario	Exp. limit [TeV]	Obs. limit [TeV]
T	$\mathcal{B}(T \to Zt) = 100\%$	1.45	1.47
T	singlet	1.33	1.26
T	(T,B) or (X,T) doublet	1.41	1.41
B	singlet	1.30	1.33
B/X	$\mathcal{B}(B/X \to Wt) = 100\%$ or $(T,B)/(X,T)$ doublet	1.42	1.46
$T/B/X$	(T,B) or (X,T) doublet, mass degenerate	1.56	1.59

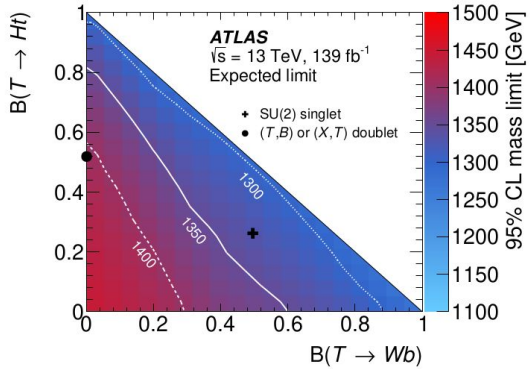


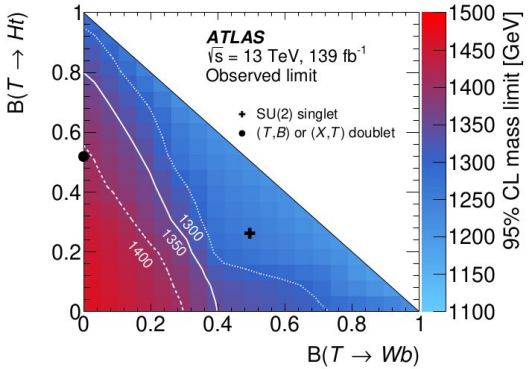


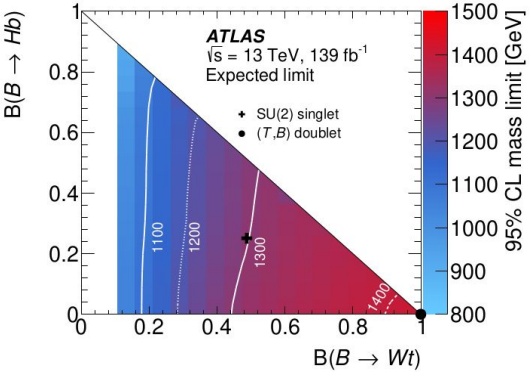
$T\bar{T}$ & $B\bar{B}$ production

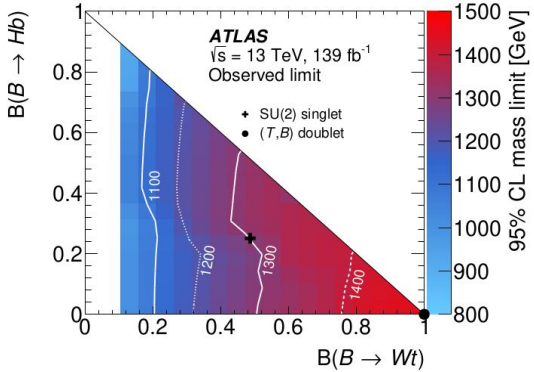
2212.05263

- Expected and observed mass limits as a function of the T' and B' branching ratios
- The highest sensitivity is found in the regions near
  - $\mathcal{B}$(T'→ Zt) = 100%
  - $\mathcal{B}$(B'→ Wt) = 100%
- The strongest lower limits on the masses are 1.59 TeV corresponding to the weak-isospin doublet model
- 1.47 TeV (1.46 TeV) for exclusive T->Zt (B/X->Wt) decays
- Lower limits on the T and B quark masses are derived for all possible branching ratios.







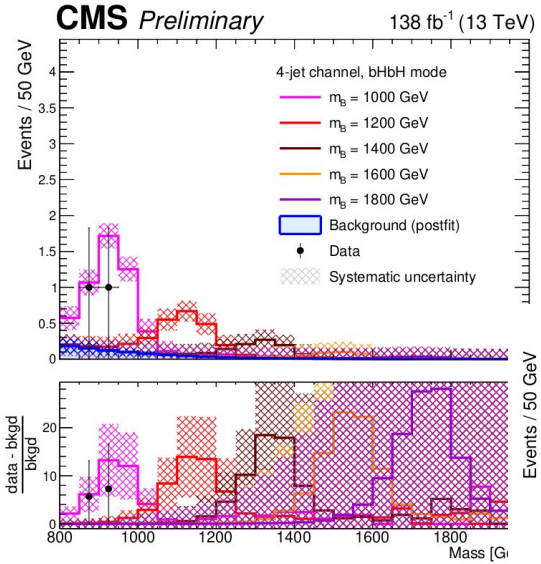


$B\,\bar{B}$ production (full hadronic and leptonic)

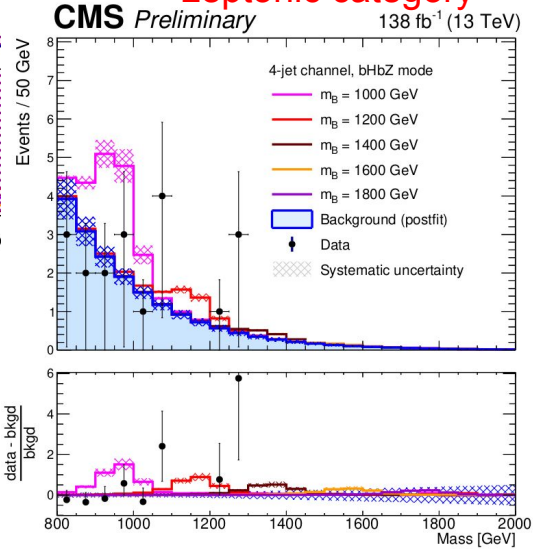
B2G-20-014

- For masses of the VLQs from 1000 to 1800 GeV
- Branching Ratios $\mathcal{B}$:
  - Leptonic: $\mathcal{B}$ (Zb, Hb, Wt)
  - Hadronic: $\mathcal{B}$ (Zb, Hb)
- Fully hadronic category:
  - At least 4 (<=6) AK4 jets P_T > 50 GeV $|\eta|$ < 2.4, H_T > 1350 GeV
  - No isolated e or μ P_T > 50 GeV
  - Bkg: SM jets produced through the strong interaction (QCD multijet events).
- Leptonic category:
  - At least 3 (<=5) AK4 jets P_T > 50 GeV and $|\eta|$ < 2.4
  - At least one pair of leptons 80 < m$\ell\ell$ < 102 GeV
  - Bkg: Drell-Yan dilepton production in association with jets
- Systematic uncertainties:
  - Integrated luminosity, trigger, dilepton Z boson efficiency, scale factors...

Hadronic category



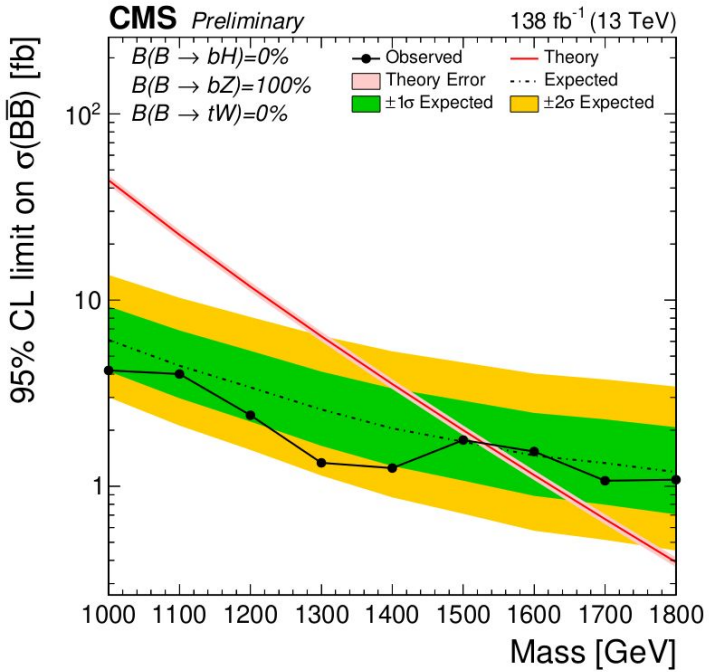
Leptonic category



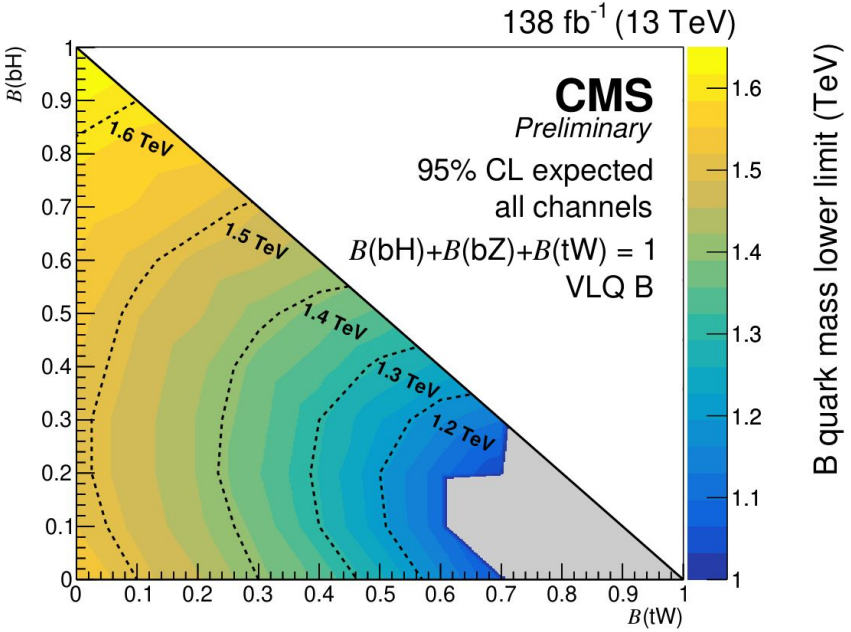
$B\,\bar{B}$ production (full hadronic and leptonic)

B2G-20-014

- Expected and observed limits on the cross section at 95% CL



- Expected exclusion limits on the VLQ mass at 95% CL as a function of the branching fractions



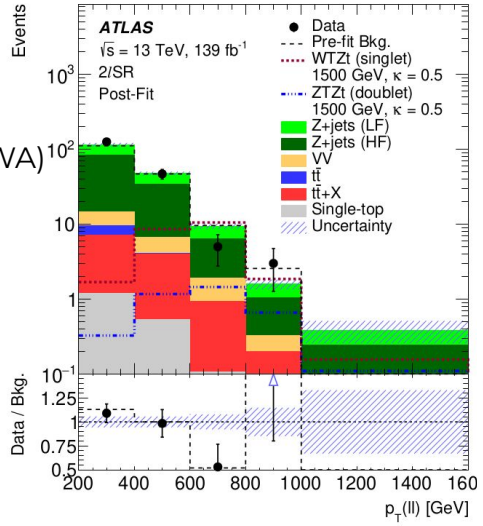
- The limits on the VLQ mass have been increased from 1390 to 1540 GeV in the 100% B->bZ doublet case. These represent the current world best limits on B VLQs in pair production.

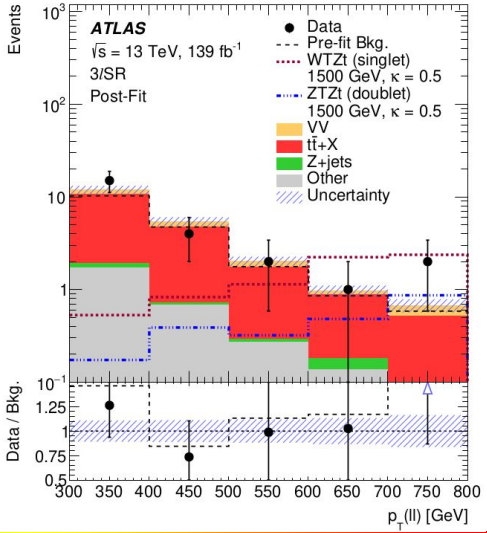
3 Single Production

T’→ Zt (multileptonic)

2307.07584

- For masses of the VLQs from 1 TeV to 2 TeV
- Relative strength coupling ξ
  - ξ: (ξW, ξZ, ξH) ≈ (0.5, 0.25, 0.25)
  - Signal samples normalized to NLO cross-section (NWA)
- Final state signature 2ℓ:
  - Z boson: $|m_{(\ell\ell)} - m_Z| < 10$ GeV
  - $P_{T\,(\ell\ell)} > 200$ GeV
  - $H_T > 300$ GeV
  - $H_T + E_T^{miss} < m_{\ell\ell J}$
  - 1 FWD jet; at least 1 b-jet & 1 top-tagged jet
- Final state signature 3ℓ:
  - 3 leptons passing the preselection
  - At least 1 FWD jet, 1 b-tagged jet
  - Z boson candidate $P_T(\ell\ell) > 300$ GeV
  - Leading lepton $P_T(\ell) > 200$ GeV
  - $H_T \cdot n(\text{jets}) < 6$ TeV
- Main Backgrounds:
  - 2ℓ: Z+jets, minor contributions from VV and $t\bar{t}$ processes
  - 3ℓ: Diboson processes and tt+Z and other small contributions from tt+W and tttt



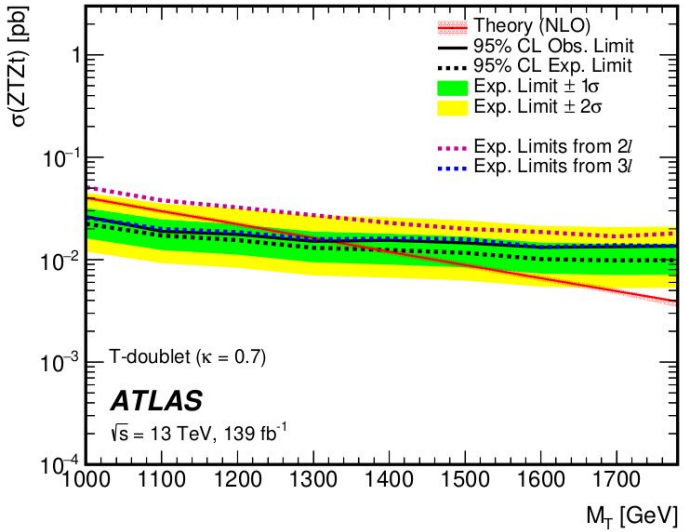


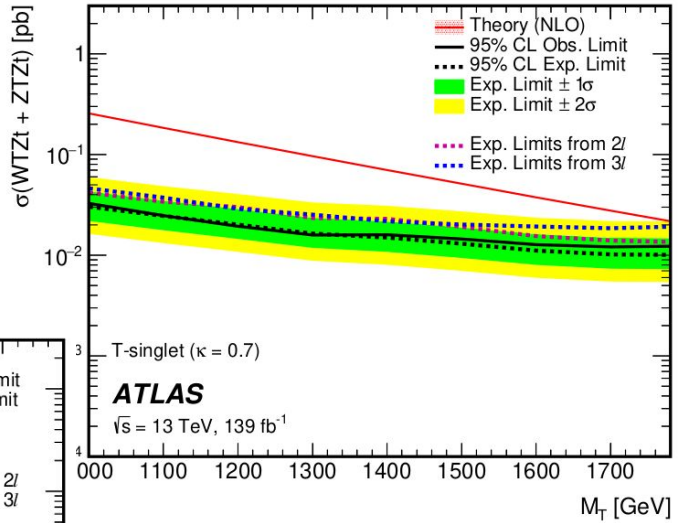
T'→ Zt (multileptonic)

2307.07584

- Systematic uncertainties
  - Experimental sources:
    - electron energy scale and resolution
    - muon momentum scale and resolution
    - flavor tagging, jet energy scale and resolution…
  - Theoretical sources:
    - cross section
    - other modeling uncertainties for all background samples
  - Jets misidentified as leptons

- Observed and Expected limits at 95% on total cross-section
  - k=0.7
  - Singlet representation
  - Doublet representation





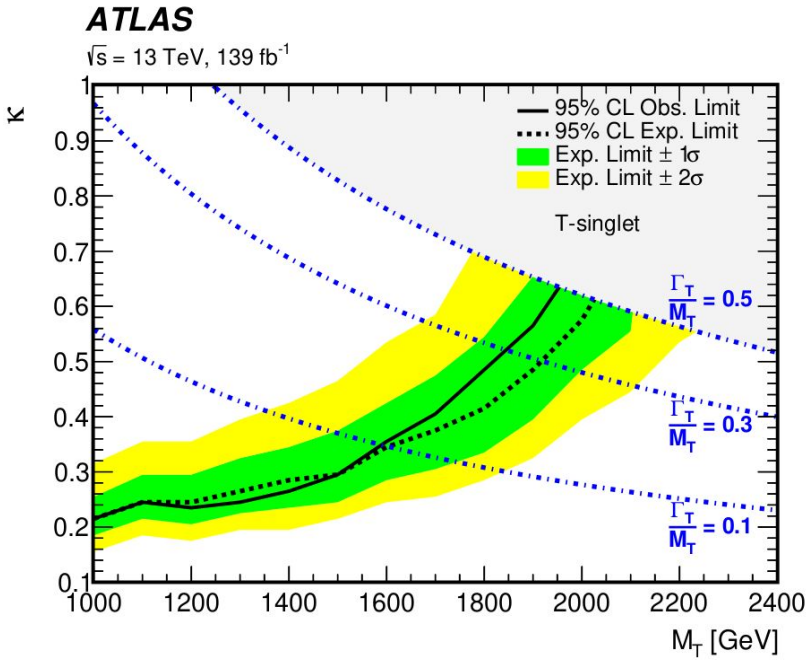
T'→ Zt (multileptonic)

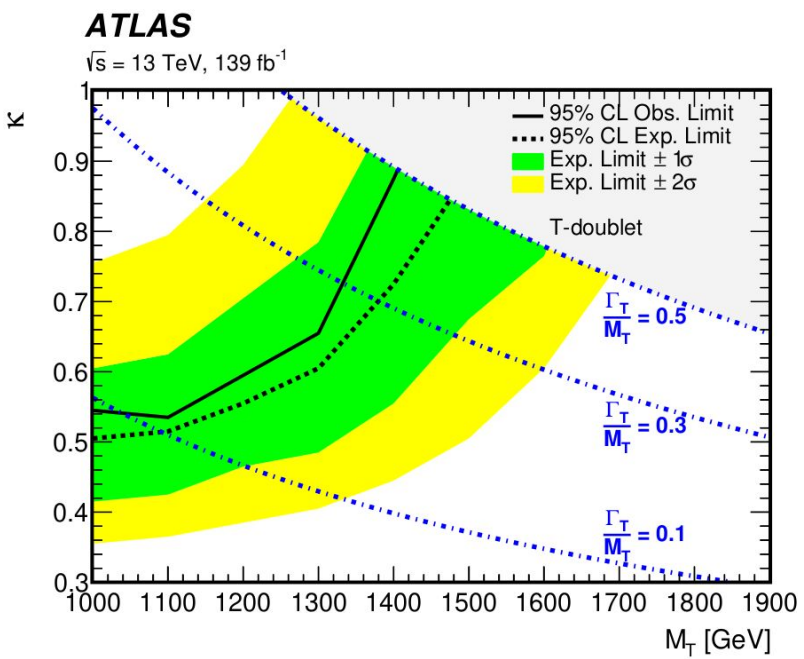
2307.07584

1-lepton channel

B->bH (bb)

- Observed and expected limits at 95% CL on the top partner coupling as a function of the T mass



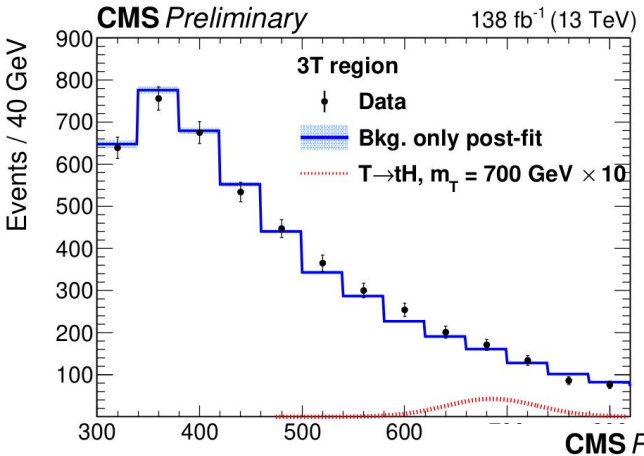


- The strongest exclusion is observed for singlet representation with ξ_W approx 0.5 where masses up to 1975 GeV are excluded at relative decay width of Γ_T/M_T=0.5 for the top partner.

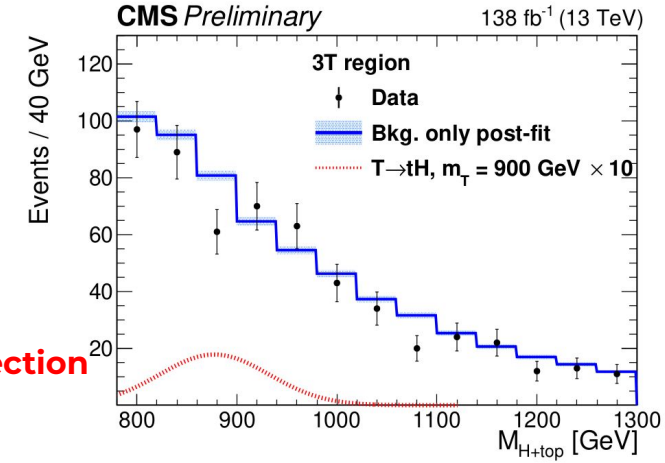
T' → Ht / Zt

B2G-19-001

- For masses of the VLQs from 600 - 1200 GeV
- Branching Ratios $\mathcal{B}$:
  - T': $\mathcal{B}$ (Zt, Ht, Wb) ≈ (0.25, 0.25, 0.5)
- Final state signature:
  - 5 jets, single production 2 additional jets
    3 of them b-jets
  - P_T > 400 GeV (2016)
  - P_T > 300 GeV (2017 & 2018)
  - m_T up to 700 GeV (low-mass selection)
    m_T above 800 GeV (high-mass selection)
- Main Bkg process:
  - multijet
  - tt+ jets
- Systematic Uncertainties
  - Trigger efficiency
  - Jet energy and resolution uncertainties
  - b tagging efficiency scale factor for jets
- Invariant mass reconstructed from 5 jets is used as the main discriminating variable



Low-Mass selection
designed to avoid distorting the 5-jet invariant mass distribution and producing artificial peaks (see backup).

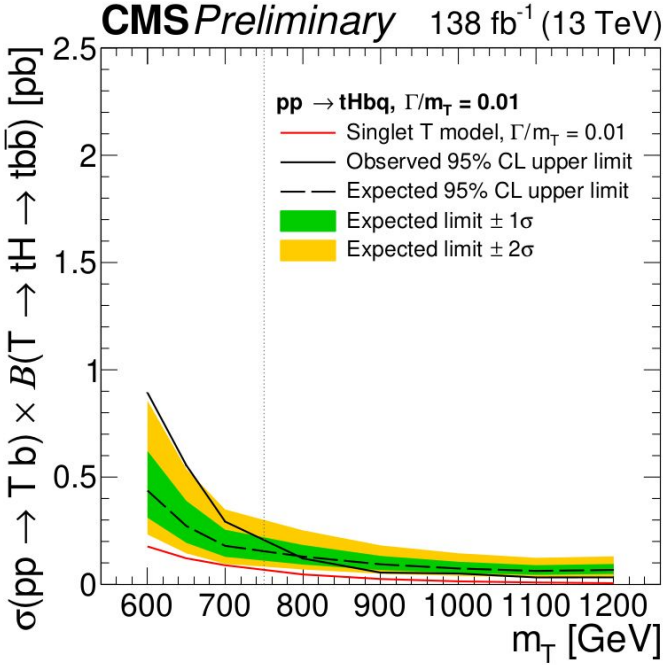


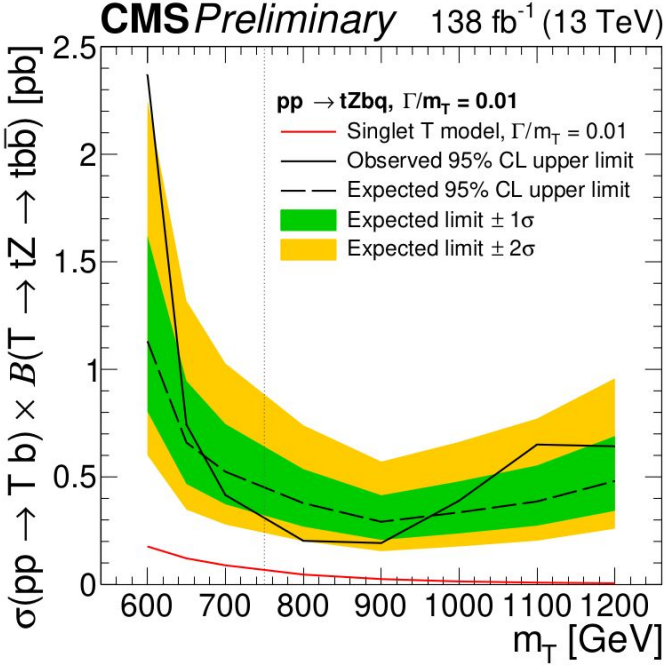
High-Mass selection

T' → Ht / Zt

B2G-19-001

- Expected and Observed 95% CL upper limits on the cross-section for associated production with a b for final states tHbq and tZbq, for T masses from 600 - 1200 GeV.





- Excess in the tH final state found in [1909.04721], is not observed with a larger dataset. The limits are stronger than those in the previous search by at least a factor of three.

4 Conclusions

Conclusions

- Several studies were performed by ATLAS and CMS
- No significant deviations from the SM predictions are observed
  Mass ranges have been excluded at 95% CL.
- Many more searches in other decay channels are in progress
- The search of VLQs conducted by ATLAS & CMS continues to explore, improve and innovate for all the possible decay channels
- This is just the tip of the iceberg. Both ATLAS and CMS have huge programs on searches of VLQs.

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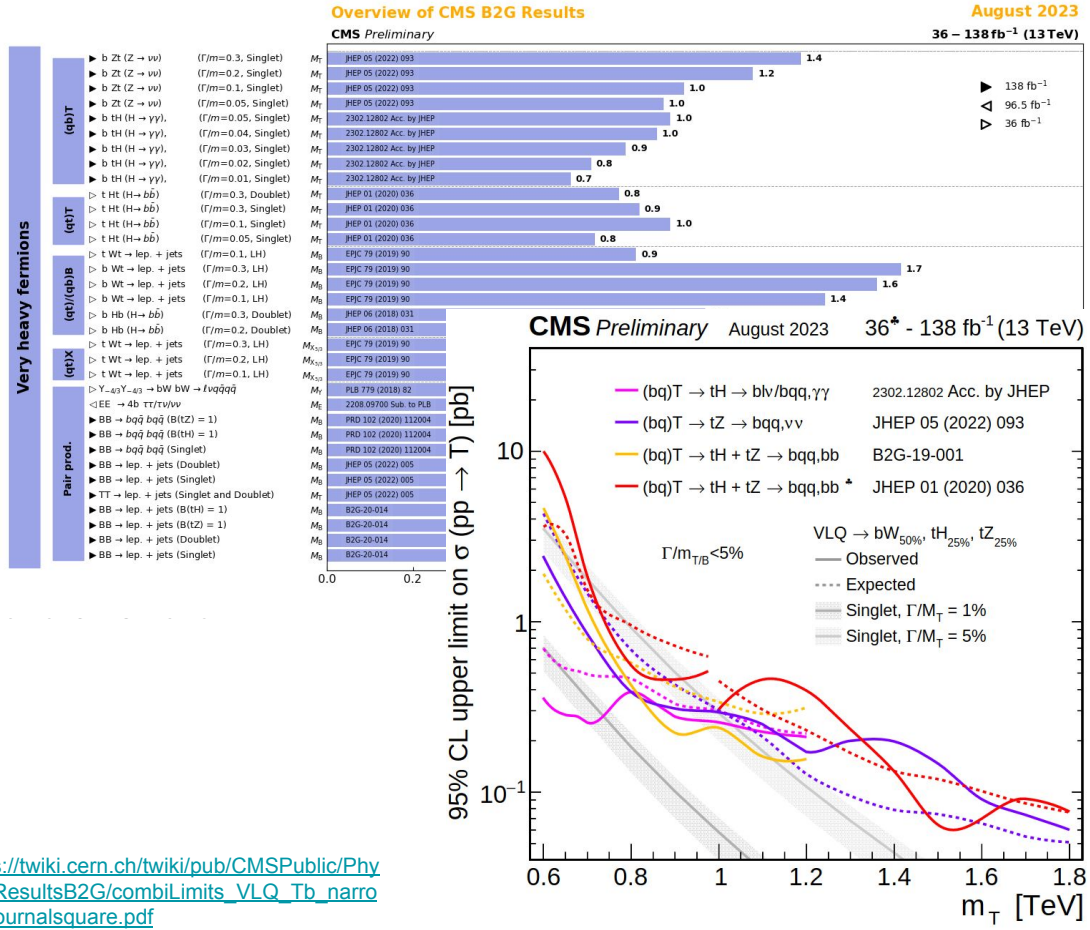

https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsB2G/combiLimits_VLQ_Tb_narrow_Journalsquare.pdf

Conclusions

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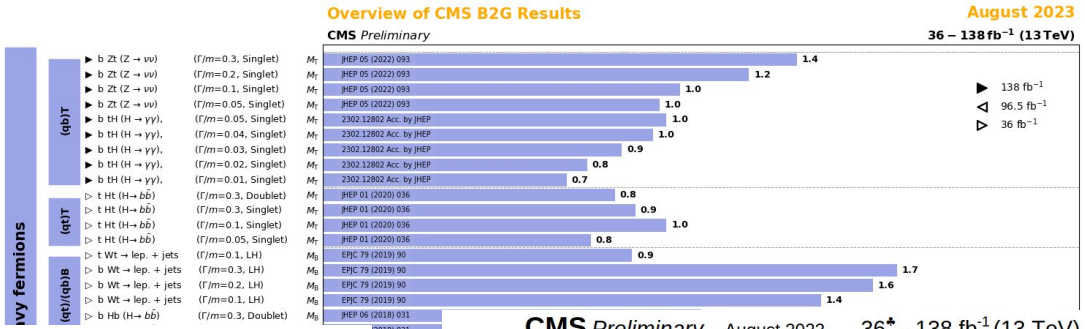
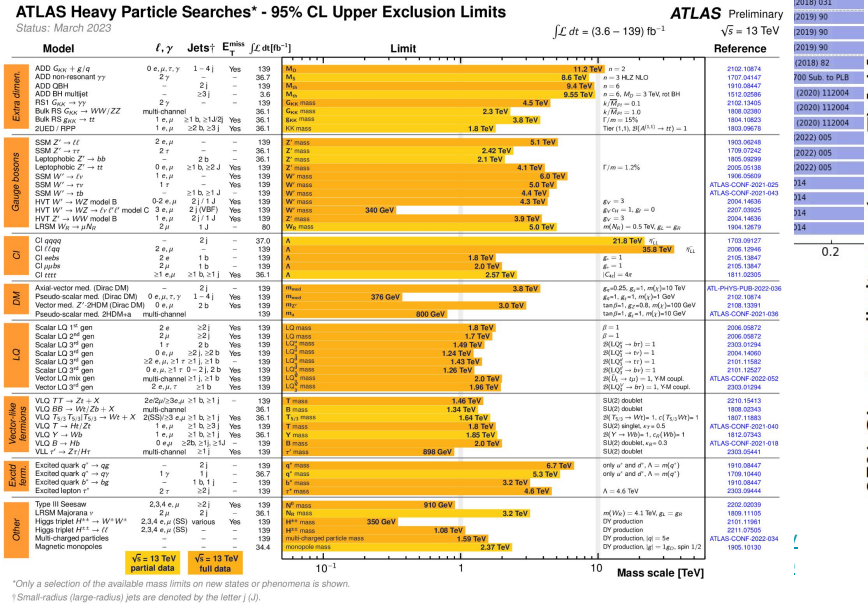
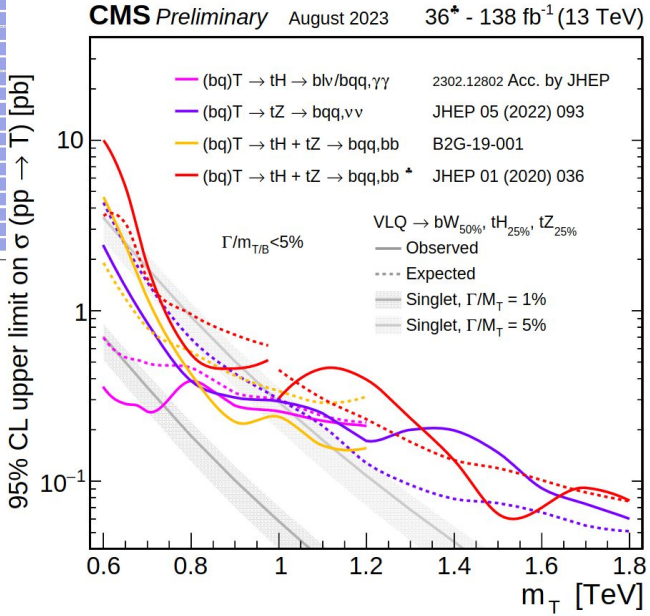
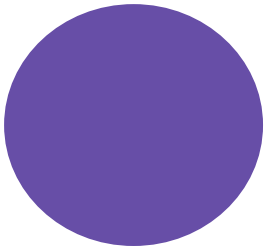






https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-008/


thank
you

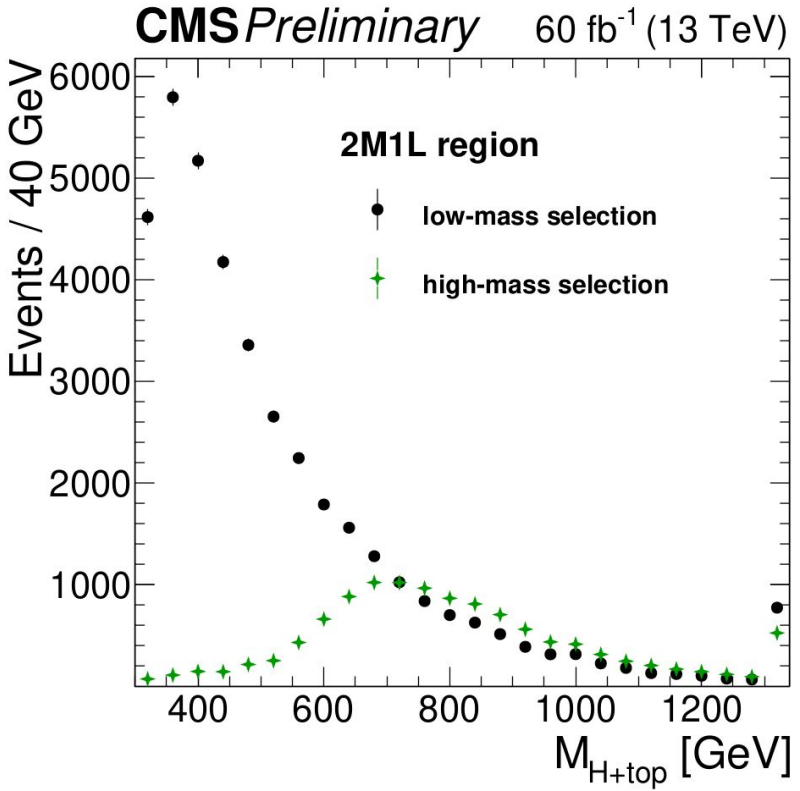


Backup

T’ → Ht / Zt

B2G-19-001

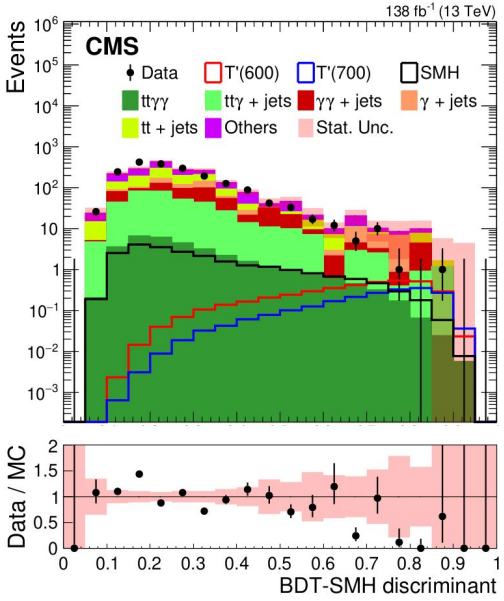
- Low mass requirements are chosen to avoid distorting the five-jet invariant mass distribution and producing artificial peaks.
- The five-jet invariant mass distribution in the 2M1L region after the high-mass and low-mass selections in 2018 dataset.
- The low-mass selection results in a mass distribution that is smoothly falling, unlike the high-mass selection.



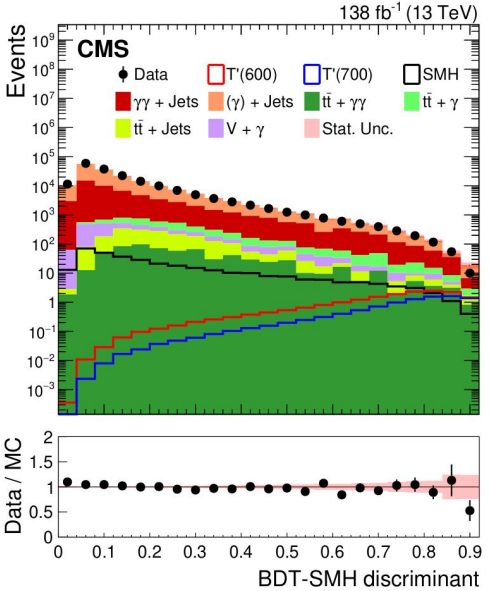
T' → Ht (H → $\gamma\gamma$)

2302.12802

- For masses of the VLQs from 600 - 1200 GeV
- Branching Ratios $\mathcal{B}$:
  - T': $\mathcal{B}$ (Zt, Ht, Wb) ≈ (0.25, 0.25, 0.5)
- Final state signature:
  - At least 2 γ:
    $P_T(\gamma 1)$ > 30 Gev ; $P_T(\gamma 2)$ > 18 or >22 GeV
  - $m_{\gamma\gamma}$ > 90 GeV
  - Jet candidates P_T > 25 GeV and $|\eta|$ < 4.5
  - Photons and leptons well separated
- Leptonic Category:
  - 2 photons
  - 1 lepton at least
  - 1 b-tagged jet
  - Bkg: QCD, γ+jets and $\gamma\gamma$+jets 25% of the bkg yield
- Hadronic Category:
  - 3 jets
  - 1 b-tagged jet
  - Bkg: $t\,t^{-}$H with H -> $\gamma\gamma$



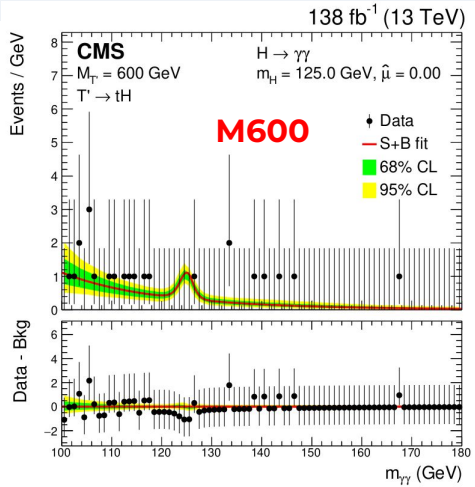
Boosted Decision Trees (BDT) used to separate signal from the SM Higgs boson backgrounds

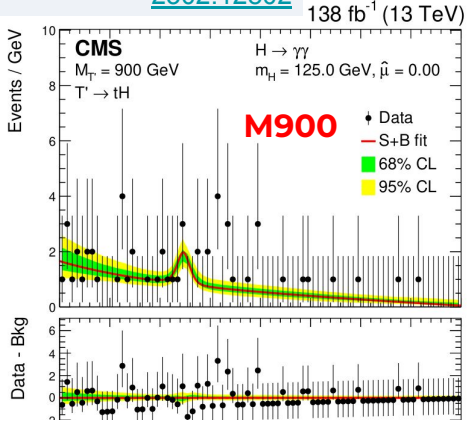


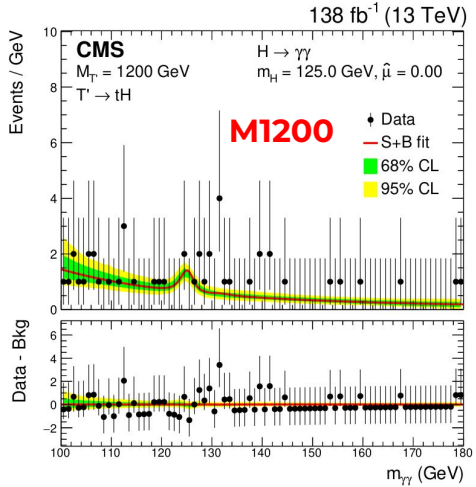
T' → Ht (H → γγ)

2302.12802

- Uncertainties associated are less than 5% on the final parameter of interest
- Data distributions and the corresponding signal+bkg model fits to mgg
  - $M_{T'}$ = 600 GeV
  - $M_{T'}$ = 900 GeV
  - $M_{T'}$ = 1200 GeV



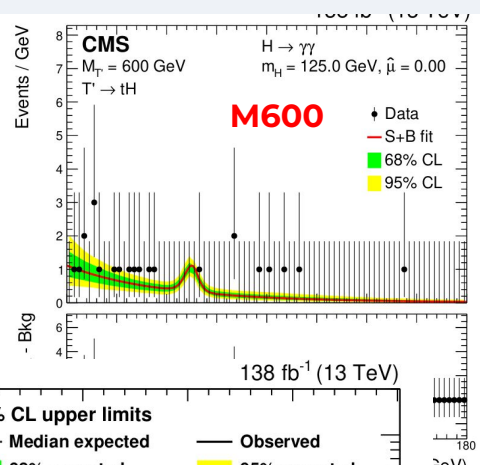


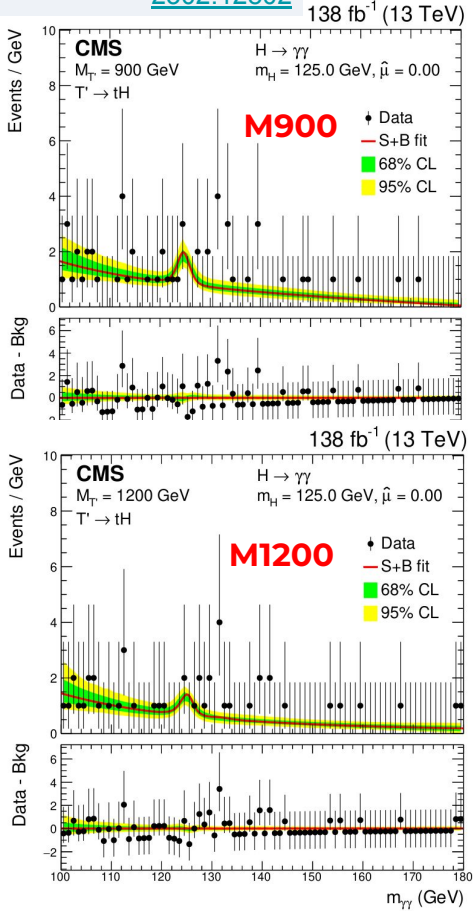


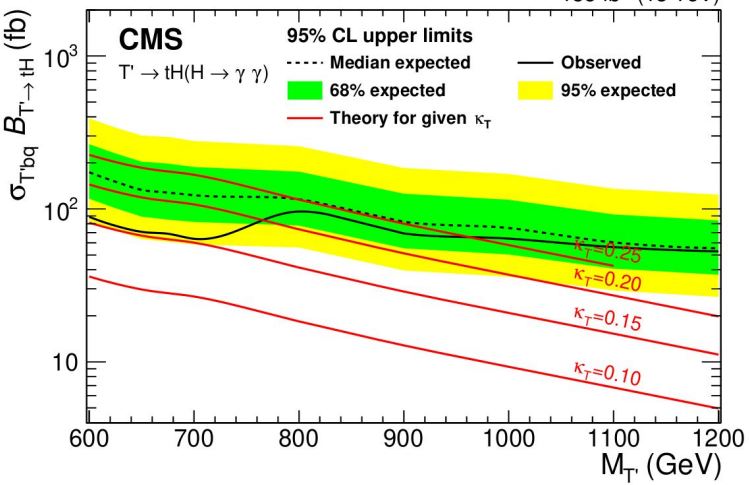
T' → Ht (H → γγ)

2302.12802

- Uncertainties associated are less than 5% on the final parameter of interest
- Data distributions and the corresponding signal+bkg model fits to mgg
  - $M_{T'}$ = 600 GeV
  - $M_{T'}$ = 900 GeV
  - $M_{T'}$ = 1200 GeV
- Combined upper limits 95% CL on $\sigma_{T'bq}\,\mathcal{B}_{T'\to tH}$ as a function of $M_{T'}$.
- This technique leads to an increased sensitivity to T' mass values up to 1 TeV with respect to the previous searches



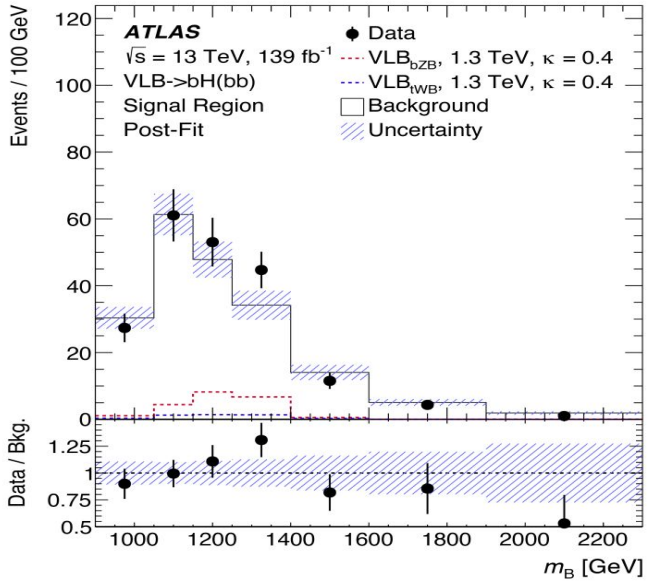


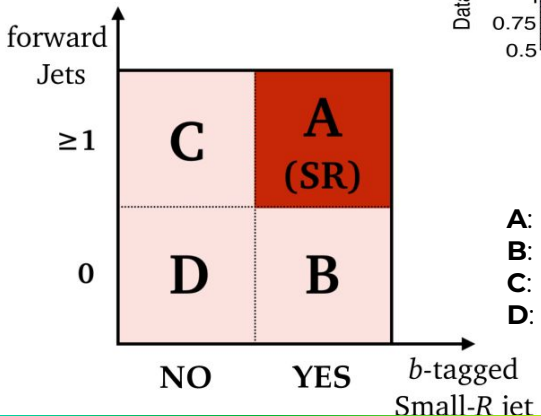


B' → bH ($b\,\bar{b}$)

2308.02595

- For masses of the VLQs from 1 TeV to 2 TeV
- Branching Ratios $\mathcal{B}$:
  - B: $\mathcal{B}$ (Zb, Hb, Wt) ≈ (0.25, 0.25, 0.5)
- Final state signature:
  - High P_T Higgs boson decaying into $b\,b^-$
    P_T > 480 GeV, $|\eta|$ > 2.0
  - Energetic jet from the b-quark from VLB
  - Softer forward jet from the spectator quark
  - Veto over leptons (e or μ).
- Dominant Bkg: Multijet production
  - "Others": $t\,t^-$ shows small contributions
- Systematic uncertainties
  - Signal and Bkg uncertainties



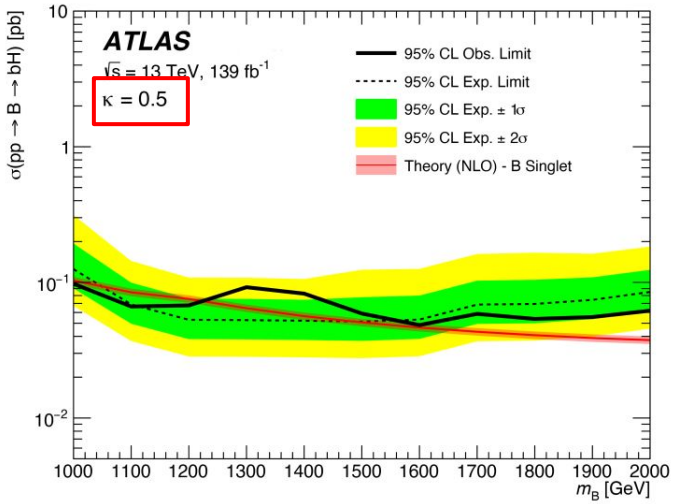


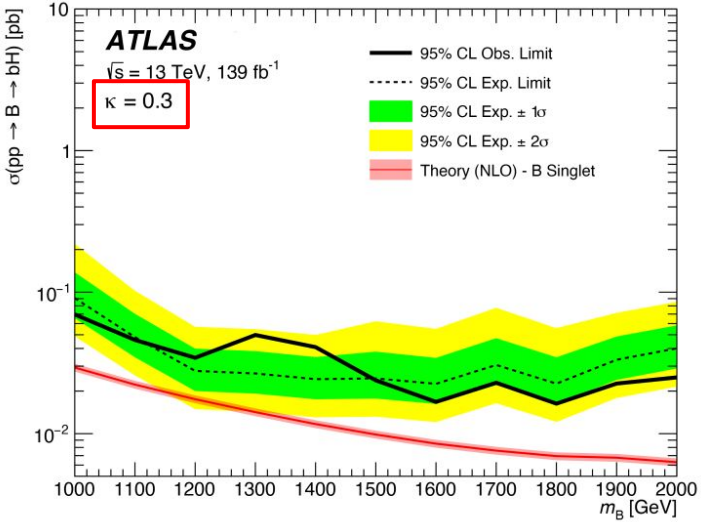
A: Events passing the full selection
B: Events lacking fwd jet
C: Events lacking b-tagged jet
D: Events lacking both fwd and b-tagged jets

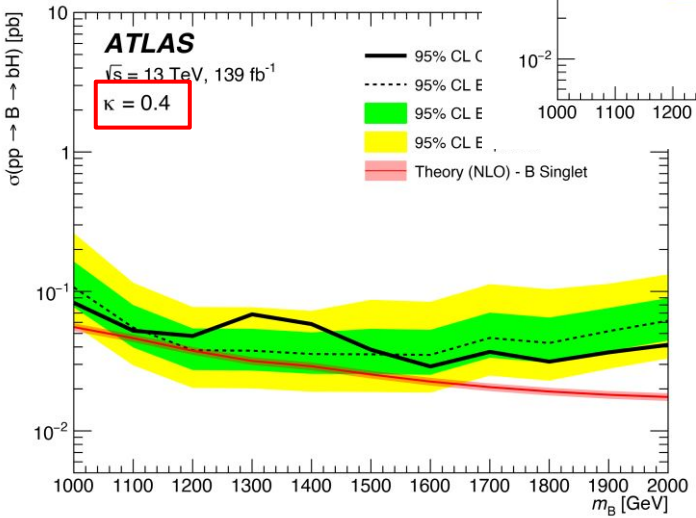
B' → bH ($b\,\bar{b}$)

2308.02595

- Expected and Observed 95% CL exclusion limits on the cross-section for single VLB production
- Higgs decay mode in the B' singlet
- Limits presented for three values of the coupling strength κ : 0.3, 0.4 and 0.5



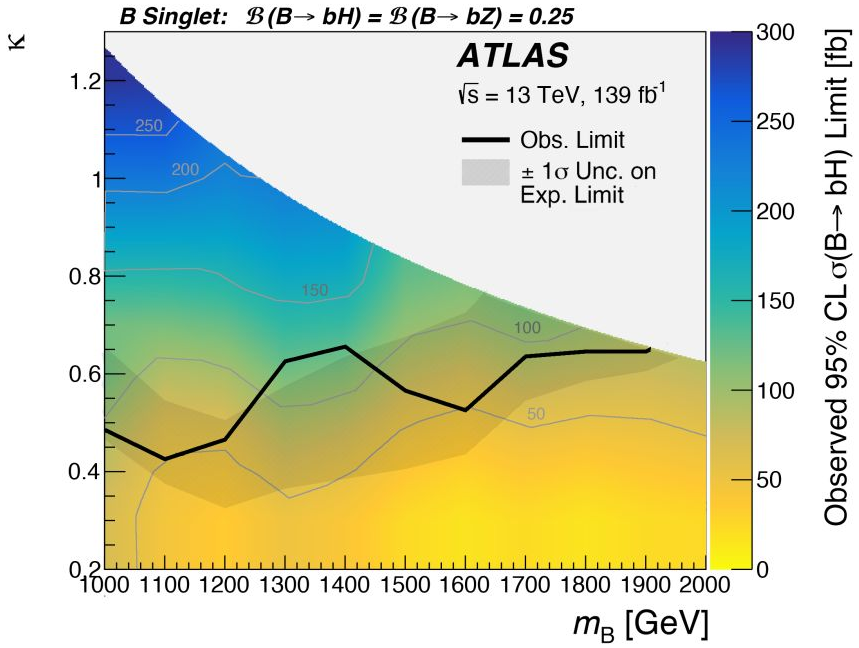


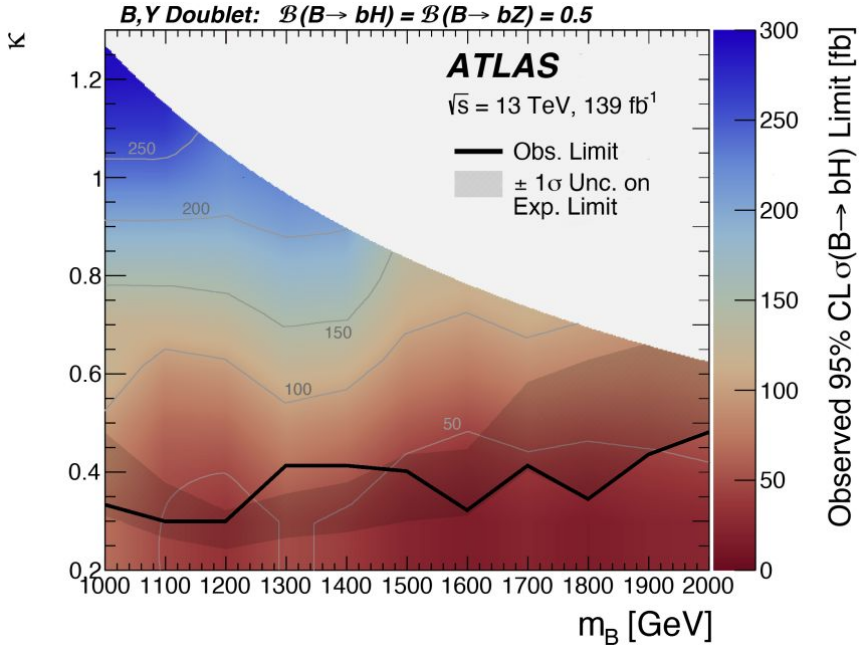


B' → bH ($b\,\bar{b}$)

2308.02595

- Expected and Observed exclusion limits on $\sigma(p\,p \to B' \to bH)$, as a function of the resonance mass and coupling strength κ and relative width in the isospin-singlet and doublet scenarios.





- Improvement by significantly expanding the region of the VLQ theoretical phase space explored and excluded by collider experiments.