Search for Single Production of a Vector-like *T* Quark Decaying into a Higgs Boson and Top Quark with Fully Hadronic Final States using the ATLAS Detector

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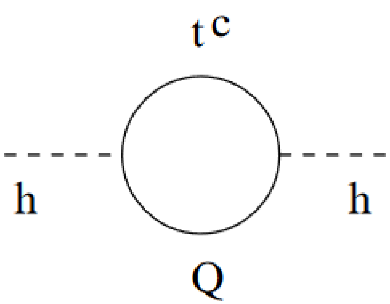
Outline

- Motivation
- Previous Limits (CMS)
- Analysis Description
  - Event Selection
  - Background Calculation
  - Systematics
- Results
- Summary

Motivation

- Vector-like quarks → Colour gauge, spin-½, left- and right-handed chiralities transform similarly under SM gauge groups
  - VLQ mass not from Higgs → Unconstrained by existing Higgs coupling measurements → only surviving massive quark model
- Quadratic divergences in Higgs mass “naturally” cancelled out by additional VLQ diagrams
  - Useful tool in many BSM models (ex. Little/Composite Higgs, GUTs)
- Four possible VLQs: X, T, B, Y
  - Focused on T, the VLQ analog to SM top

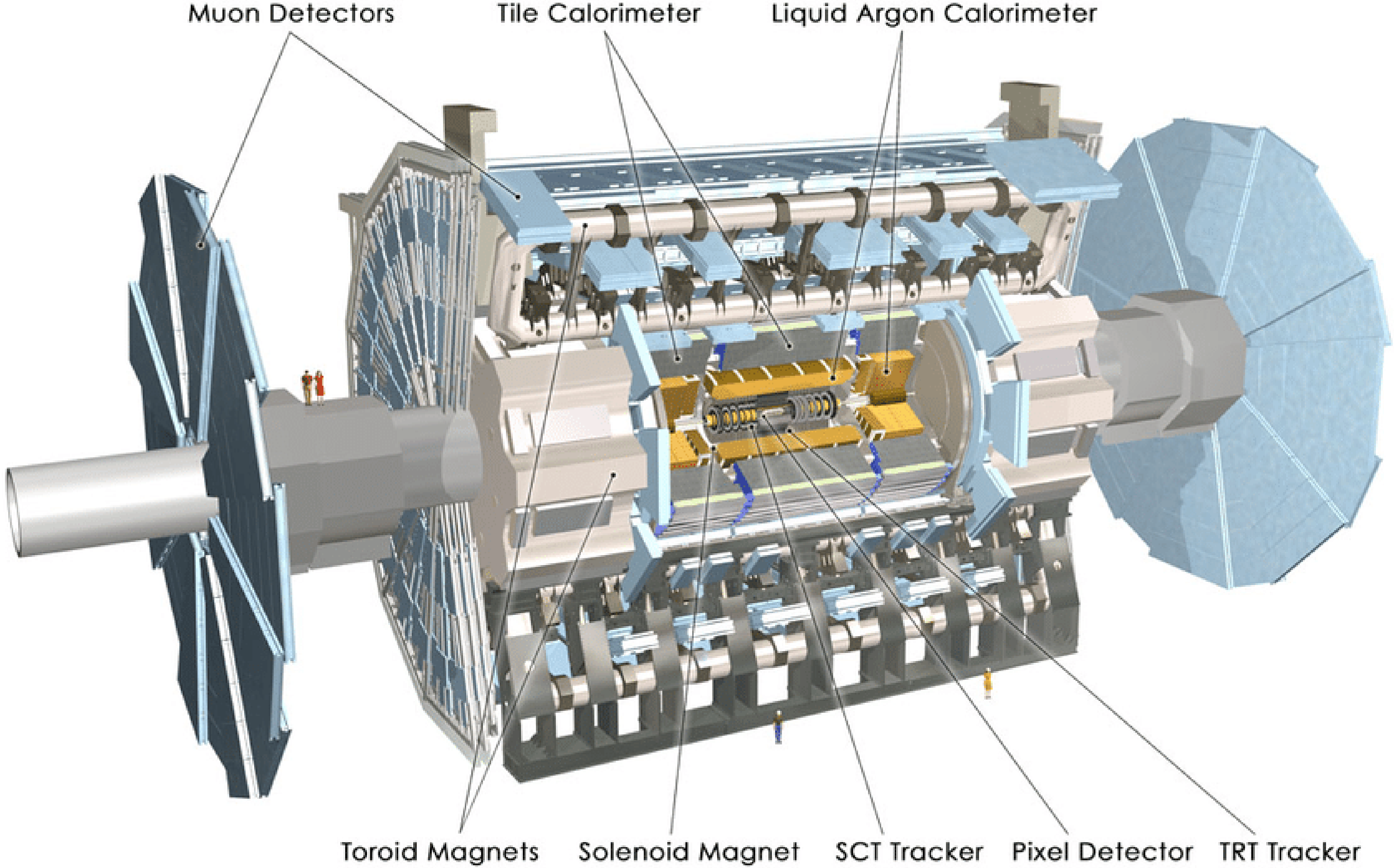
Q[e]	VLQs: singlets		VLQs: doublets			VLQs: triplets	
$5/3$			X			X	
$2/3$	(T)		T	T		T	T
$-1/3$		(B)		B	B	B	B
$-4/3$					Y		Y



arXiv:hep-ph/0502182

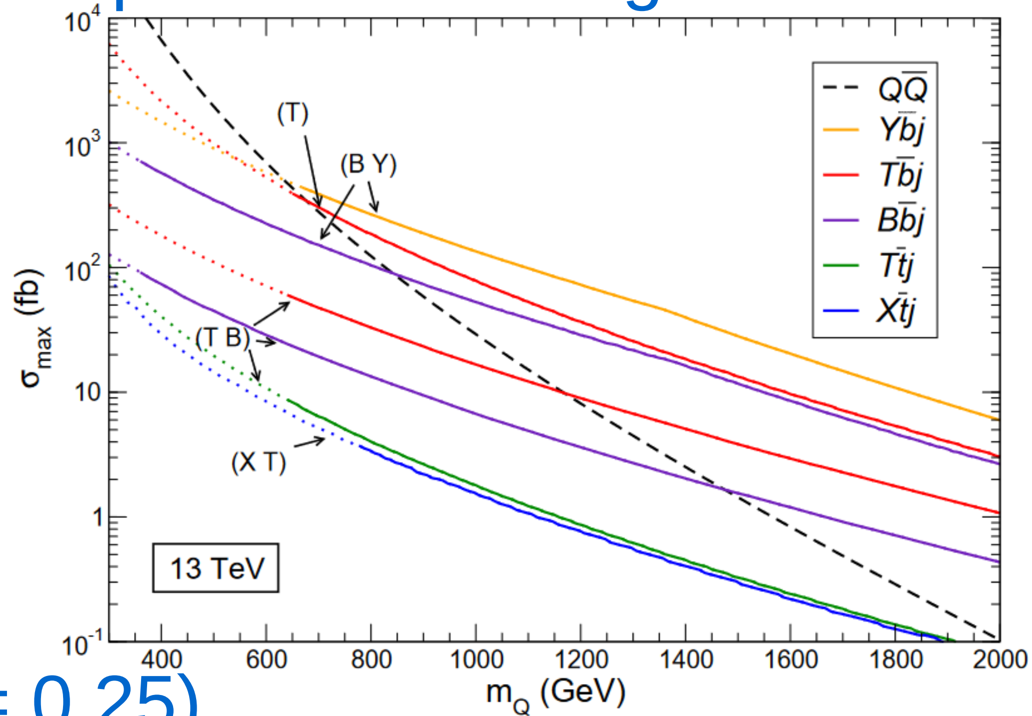
ATLAS

- Full Run 2 dataset: 139 fb^{-1} (Data taking period 2015 – 2019)
- $\sqrt{s}$ = 13 TeV



Analysis Outline

- Single production overtakes pair production at higher mass
  - For T, occurs at m > 700 GeV
- Phase space:
  - VLQ mass (1.0 to 2.3 TeV)
  - Coupling to SM (κ) (0.1 to 1.6)



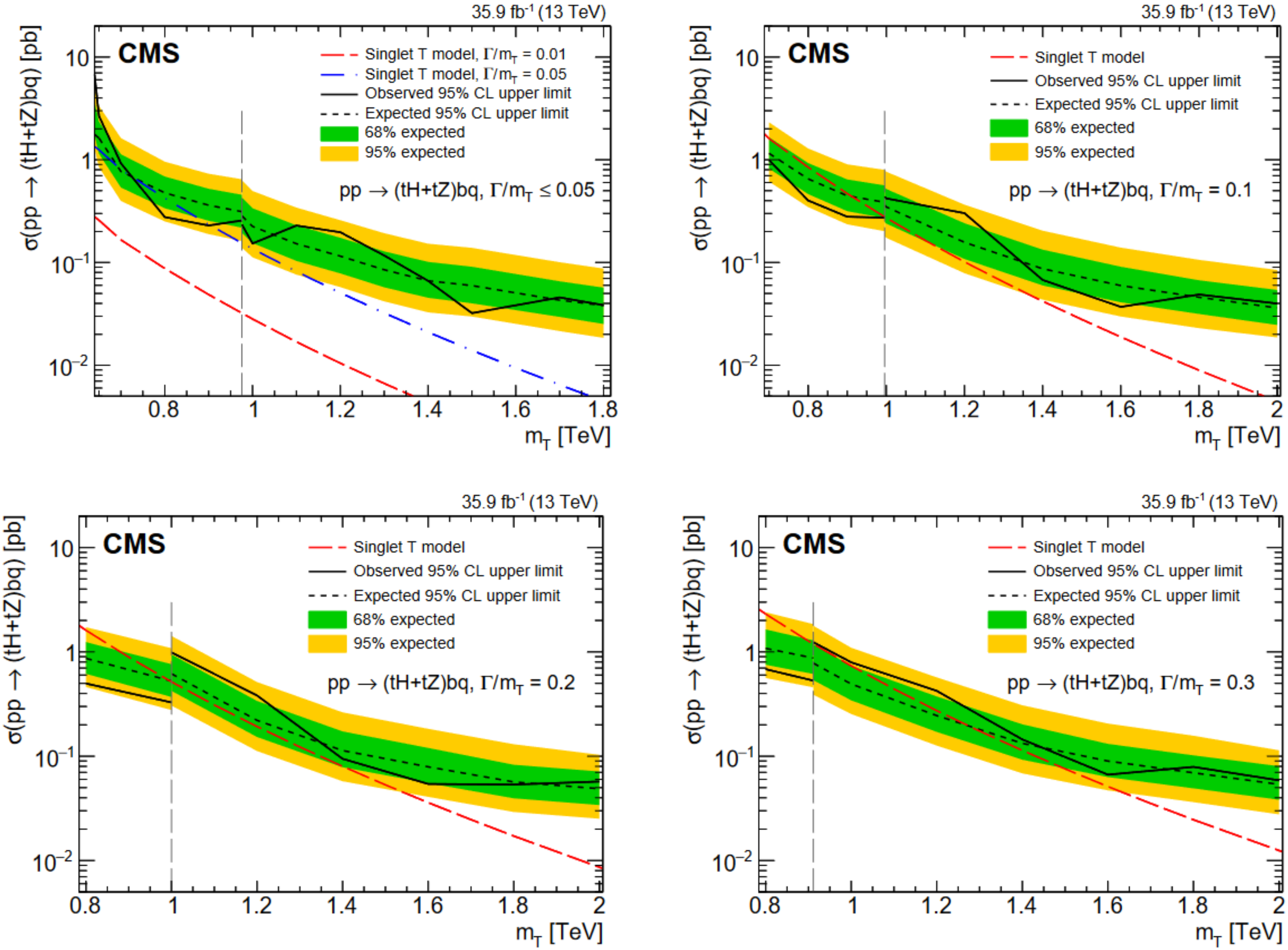
arXiv:1306.0572 [hep-ph]

- T → Ht (Asymptotic limit BR = 0.25)
  - H → bb, t → qq'b
  - Previous search:

CMS Collaboration, "Search for electroweak production of a vector-like T quark using fully hadronic final states," JHEP, vol. 01, p. 036, 2020.

Previous Limits (CMS)

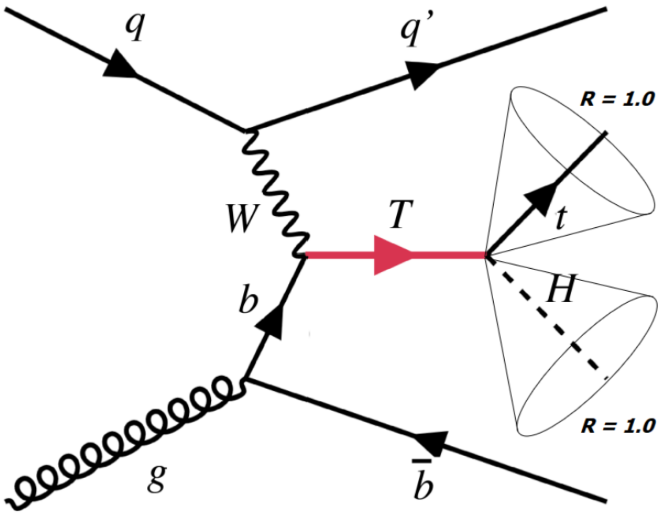
The previous all-hadronic search by CMS was unable to exclude higher mass ranges (>1.28 TeV) for models with Γ/m_T up to 0.3



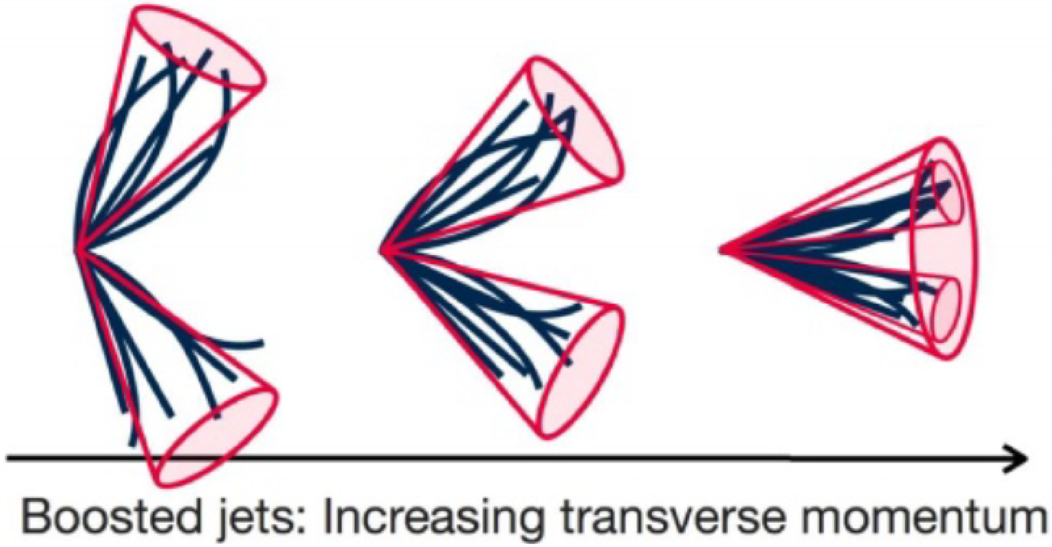
arXiv:1909.04721 [hep-ex]

Event Selection

- Lepton veto
- 2 large-R jets (2 body decay from massive (>1 TeV) object means decay products are "boosted")
  - High p_T requirements (>500 GeV, >350 GeV)
  - Mass requirement of 100 – 225 GeV for each



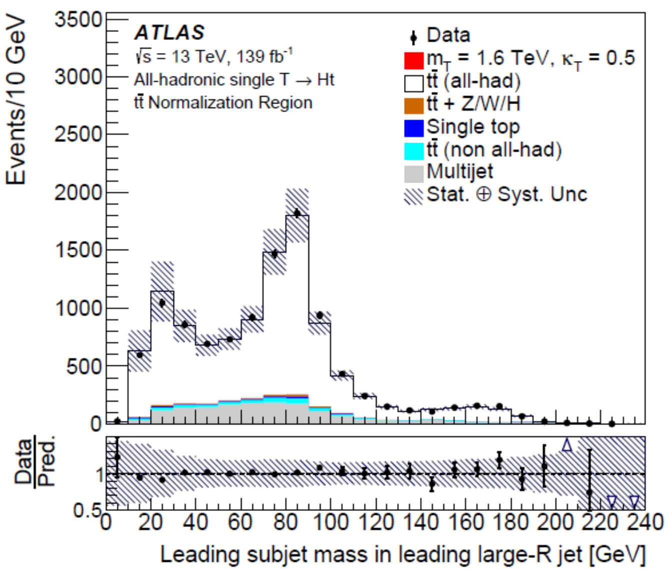
arXiv:2201.07045 [hep-ex]

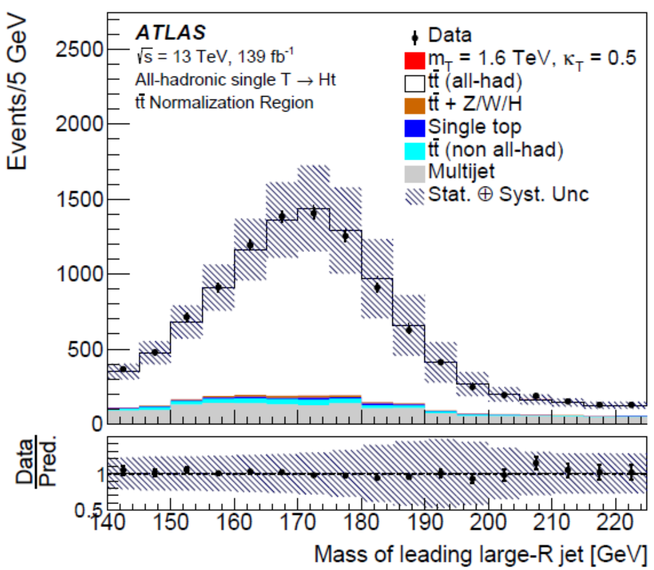


F.A. Dias: Searches for high-mass resonances at the LHC (2016)

Tagging Algorithms

- Top: Deep Neural Net tagger at 80% W.P.
  - Explicit mass window of 140 – 225 GeV
- Higgs: Mass window + τ_{21} jet substructure cut
  - Mass window is 100 – 140 GeV
- B-tag: Deep Neural Net tagger (DL1) at 70% W.P. using Variable Radius track jets





Both diagrams correspond to a large-R jet which is top-tagged with one b-tagged subjet.

arXiv:2201.07045 [hep-ex]

Background

- Background events can be considered as one of two categories:
  - Multi-jet background; the main contributor
    - Use data-driven ABCD method to estimate
  - Top-related Standard Model backgrounds
    - These are: ttbar, tt+W/Z/H, single top
    - Estimated using Powheg+Pythia8 MC

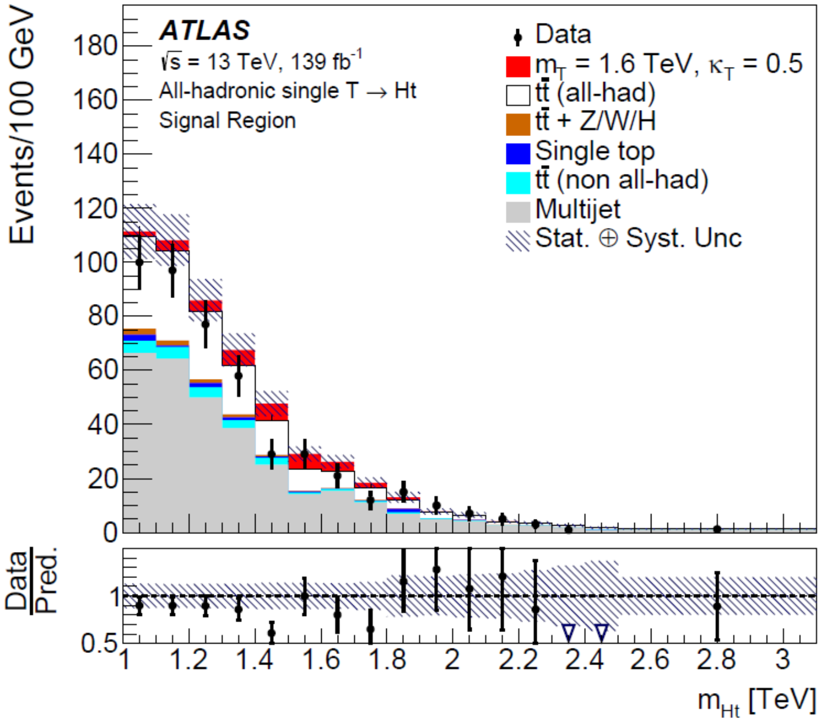
Region	$t\bar{t}$ Normalization Post-Fit			Ht Signal Region Post-Fit		
$t\bar{t}$ all-hadronic	8366	±	216	147	±	17
$t\bar{t}$ non-all-hadronic	189	±	133	14	±	10
Single top-quark	92	±	49	8	±	6
$t\bar{t}$+$W/Z/H$	117	±	25	9	±	2
Multijet events	1452	±	57	316	±	9
Signal events (m_T = 1.6 TeV, κ_T = 0.5)				−9	±	21
Predicted background	10 216	±	150	494	±	22
Data (139 fb^{-1})	10 231			471		

arXiv:2201.07045 [hep-ex]

Signal Fitting

- Signal Region: 1 top + >1 b, 1 Higgs + >2 b
- All-hadronic decay channel -> reconstruct the VLQ candidate mass (*dijet invariant mass distribution)*
  - Fitted using binned profile-likelihood fit function to search for a mass resonance

$$\mathcal{L}(\mu, \hat{\theta}; S, B, n, h) = \prod_{i=1}^{N_b} \text{Poiss}(n_i; \mu S_i + B_i) \cdot \text{Poiss}(h_i; \gamma_i) \prod_{j=1}^{N_p} \text{Gauss}(\theta_j, \sigma_j)$$



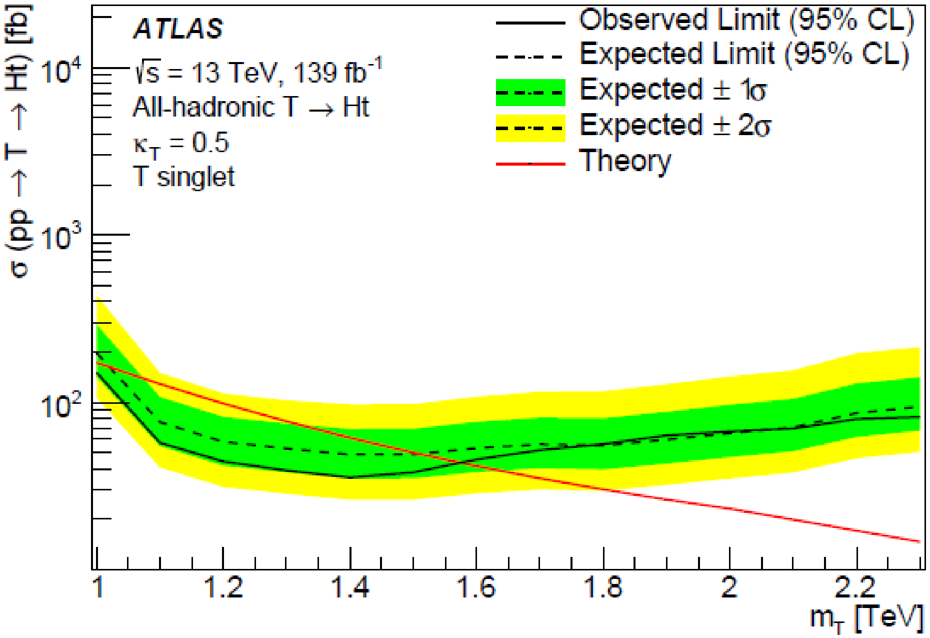
arXiv:2201.07045 [hep-ex]

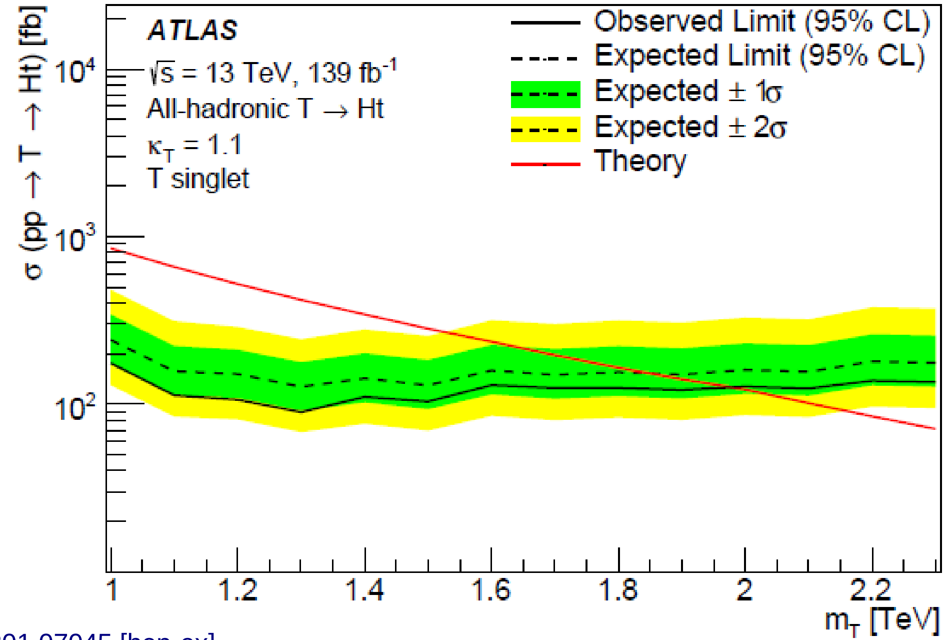
Limits

- Signal samples with mass points range from 1.0 to 2.3 TeV in 100 GeV steps
- Coupling parameter κ from 0.1 to 0.5 in 0.05 steps, 0.5 to 1.6 in 0.10 steps
- Limits are set using the CL(s) method to determine 95% Confidence Level on the upper limit of signal strength

Limits

- Upper Limit vs. Mass for κ = 0.5 (left) and κ = 1.1 (right)

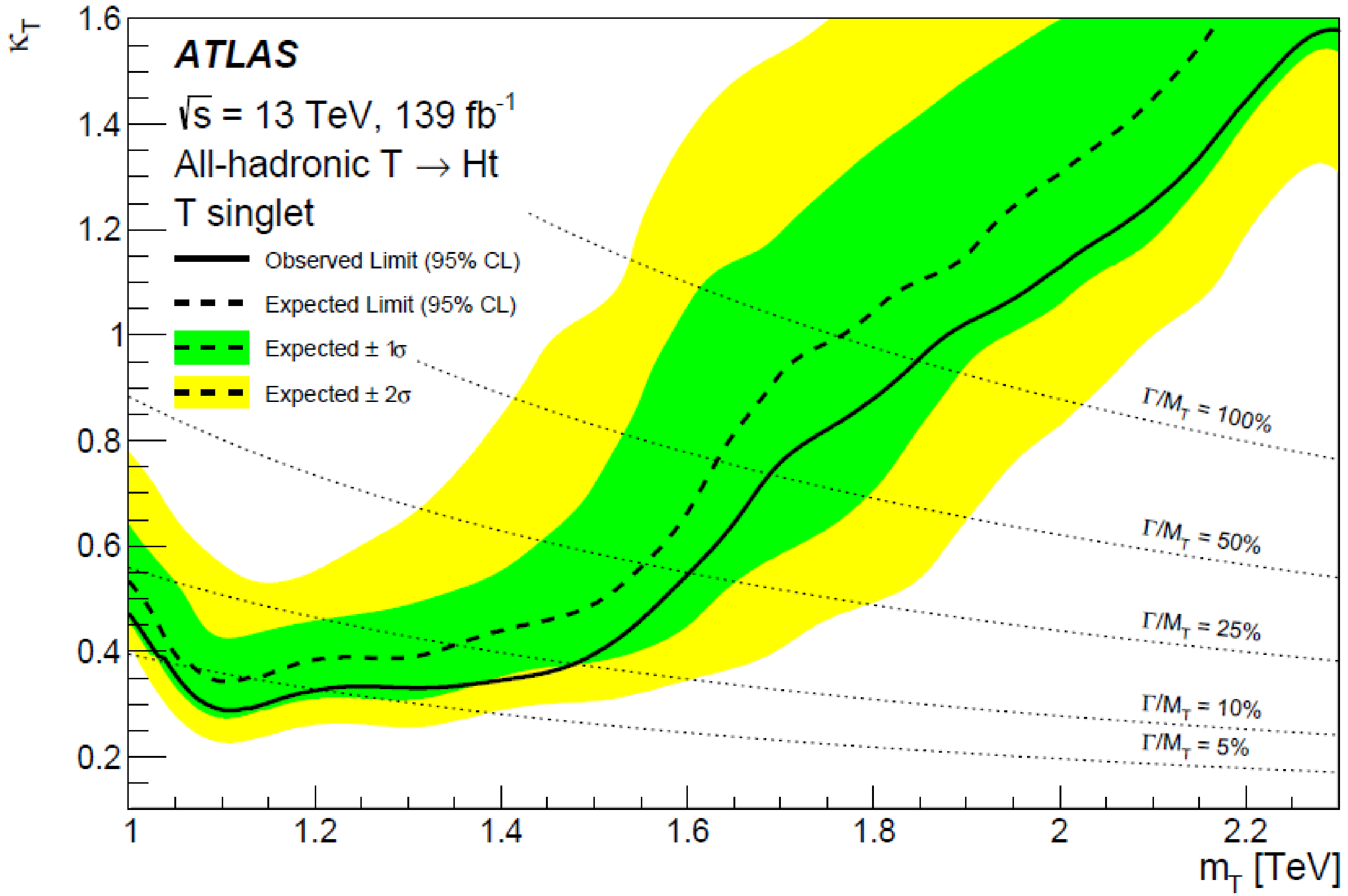




arXiv:2201.07045 [hep-ex]

Limits

- 2D Limit plot for κ vs. Mass
- Regions above the observed limit are excluded



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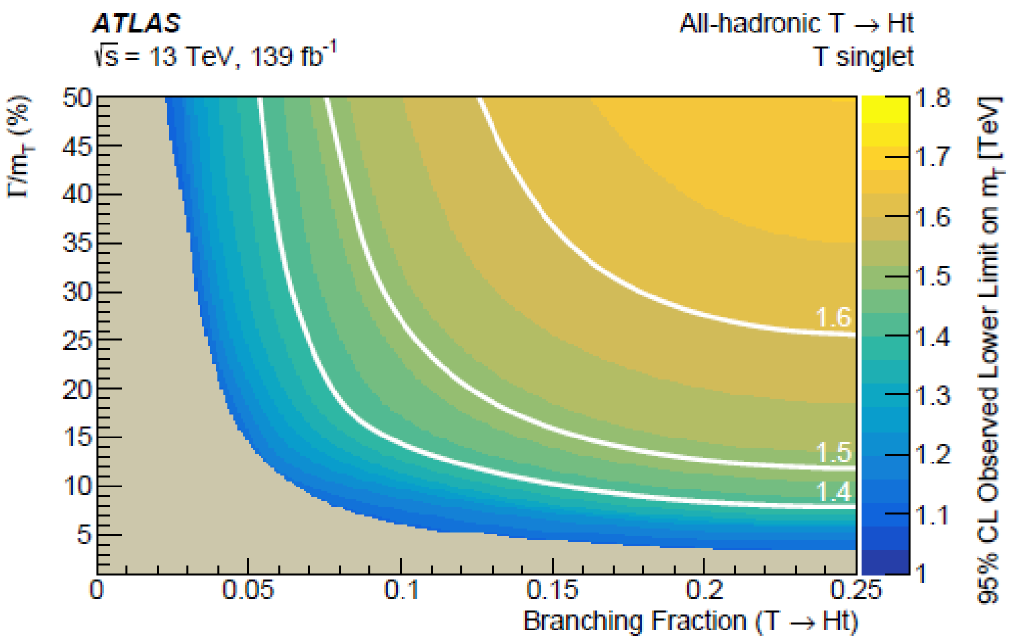
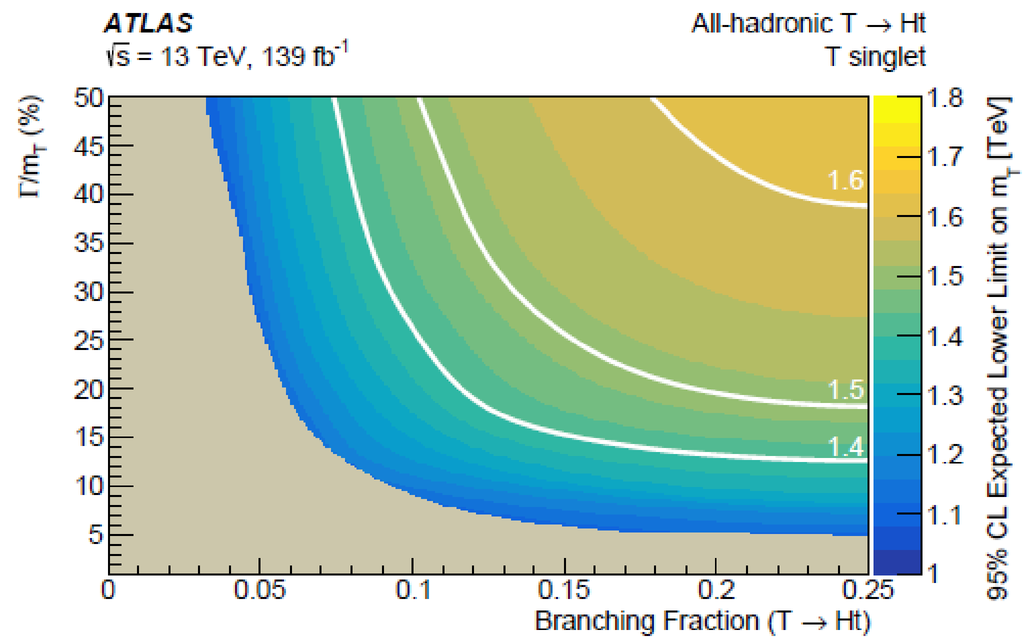
Limits

- Branching fraction of T -> Ht versus width-to-mass ratio Γ/m_T
- Observed Limit (left) and Expected Limit (right)





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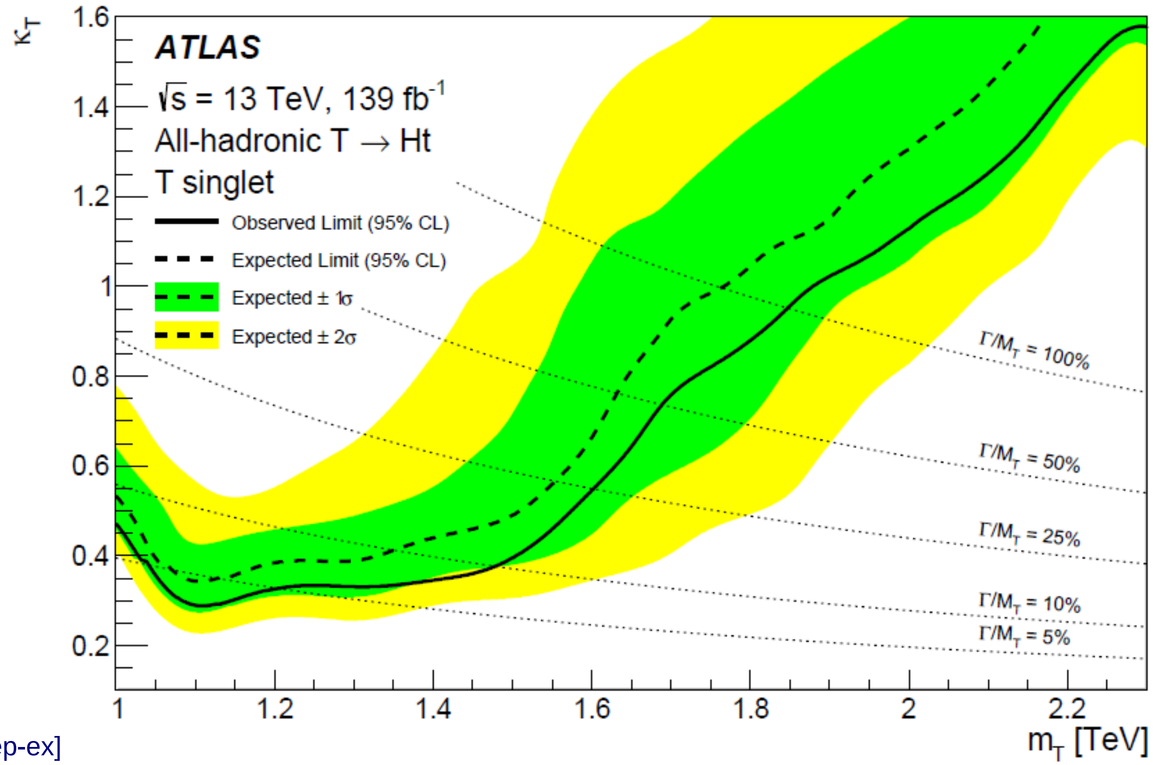
Summary

- Models with following parameters excluded at 95% C.L.:
  - κ > 0.5 and m < 1.48 TeV, rising to κ > 1.1 for m < 1.82 TeV
  - κ > 1.6 and m < 2.2 TeV
  - κ > 0.35 with 1.1 < m < 1.35 TeV, with excluded κ region increasing at higher m, e.g. κ > 1.2 excluded for m < 2.0
- Not sensitive to low κ region, improvements can be made here for future analyses



arXiv:2201.07045 [hep-ex]

Current Status

- First of many ATLAS VLQ searches using Full Run 2 data
  - A VLQ combination analysis is planned when more searches are completed
  - Ht/Zt + X (1-lepton), $B \rightarrow H(bb)b$, $B \rightarrow H(\gamma\gamma)b$, $Z(\nu\nu)t$ + X, $T/Y \rightarrow Wb$, OS ML (pair + single), $TT \rightarrow Wb$ + X, $TT \rightarrow BSM$, VLQ E6 pair to HqZq
- Submitted to PRD, published May 25, 2022
  - Phys. Rev. D **105**, 092012
  - arXiv:2201.07045 [hep-ex]

Backup

All-had ttbar Background

- Iterative formula for *α* defined (used in ABCD calculation):

$$\alpha_{n+1} = \frac{N_{\text{Data}} - N_{\text{Multijet},n} - N_{\text{top-related}}}{N_{t\bar{t}\ MC}}$$

- Value from iteration is *α* = 0.814 +/- 0.01 (stat.)
- Then floated as a fit parameter in TRexFitter
- Fit to data value is *α* = 0.80 ± 0.01 (stat.) ± 0.12 (syst.)
  - Systematic uncertainty from constraining *α* with modelling/detector systematics

Analysis Regions

Second-leading large-R jet tagging state	0t 0H 0b	0t 1H 0b	1t 0H 0b	0t 0H 1b	0t 1H 1b	1t 0H 1b	0t 0H ≥2b	0t 1H ≥2b	1t 0H ≥2b
1t 0H ≥2b				VR8		NR		SR	NR
0t 1H ≥2b			VR6			SR			SR
0t 0H ≥2b									
1t 0H 1b						NR		SR	NR
0t 1H 1b						VR1			
0t 0H 1b						VR2			VR7
1t 0H 0b						VR3		VR5	
0t 1H 0b						VR4			
0t 0H 0b									

Leading large-R jet tagging state

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ABCD Calculation Method

- Subtract all MC estimated backgrounds from data before calculation, leaving only multi-jet
- 1^{st} order ABCD (assume no correlations) e.g. B = (D*A)/C
- Then correlations:
  - In principle, 6 correlation factors (e.g. 1t1b, 1H2b)
  - 1t vs 1b, 1t vs 1H, 1t vs 2b
  - 1H vs 2b, 1H vs 1b
  - 1b vs 2b
- Correlations are calculated from data
- All of this (ABCD + Correlations) are done bin-by-bin

A	B
C	D

Systematics

- Systematic uncertainties arising from the fit
- For m_T = 1.6 TeV, κ_T = 0.5

Category	Uncertainty in σ $(pp \to T + X \to Ht + X)$ [fb]
Detector Uncertainties	
b-jet tagging	6.1
Top-quark jet tagging	5.9
Jet mass resolution	3.0
Jet mass scale	2.3
Jet energy scale	1.8
Jet energy resolution	1.7
Higgs-boson tagging	1.6
Other detector uncertainties	0.3
Modeling Uncertainties	
Other $t\bar{t}$ modeling uncertainties	4.9
$t\bar{t}$ parton shower and hadronization	1.9
$t\bar{t}$ matrix element	2.4
Background uncertainty	7.3
Signal MC statistical uncertainty	4.9
$t\bar{t}$ normalization (α^{fit})	1.5
Other top-quark-background theory uncertainties	1.8
Total Uncertainties	
Total statistical uncertainty	19
Total systematic uncertainty	15
Total uncertainty	25

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Similar uncertainties for different mass and kappa hypotheses