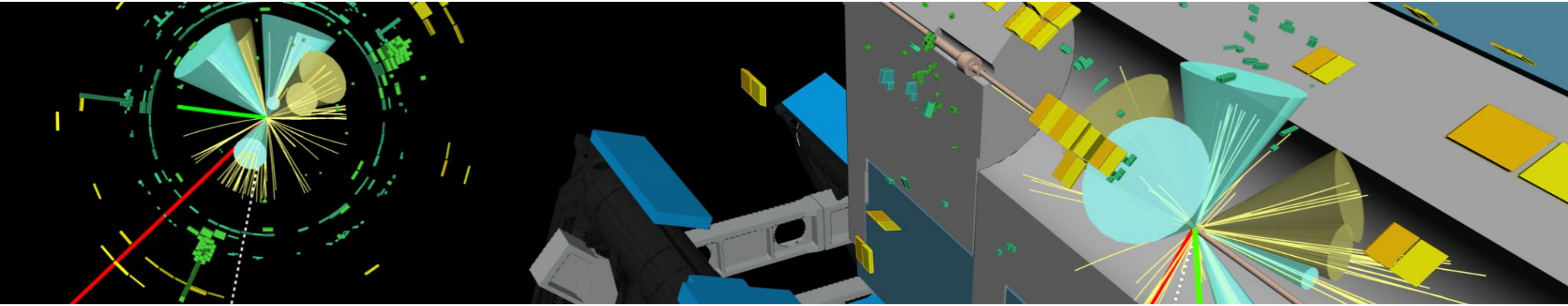
Search for heavy resonances in four-top-quark final states in pp collisions at √s=13 TeV with the ATLAS detector



14th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"

Philipp Gadow (DESY) | 23.11.2021

CLUSTER OF EXCELLENCE
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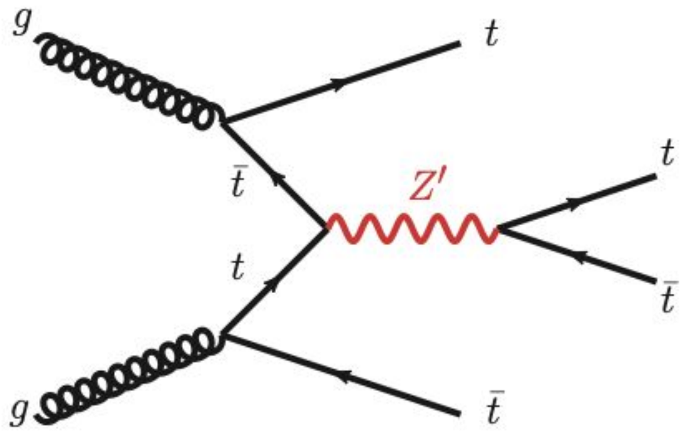
Motivation

- The large Yukawa coupling of the top quark to the Higgs boson motivates various top-quark-based resonance searches.
- Many theories for Beyond-Standard-Model phenomena (e.g. composite Higgs models) predict vector resonances coupling more strongly to top quarks than to the light quarks.
- Typical resonance searches with top quarks target resonances produced in qq annihilation. Top-philic resonances require associated ttZ' production leading to four-top-quark final states.



First search for heavy resonances in four-top-quark final states of its kind at the LHC, motivated by recent evidence for SM four-top-quark production.

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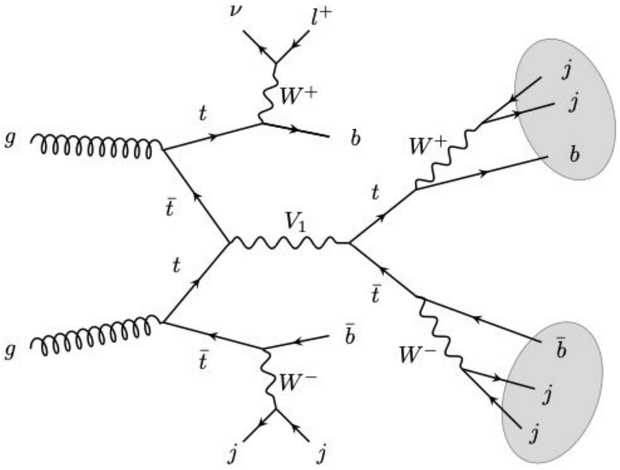
Benchmark signal model

$$\mathcal{L}_{int} = \bar{t}\gamma_\mu(c_L P_L + c_R P_R)\, t\, V_1^\mu$$
$$= \boxed{c_t}\,\bar{t}\gamma_\mu(\boxed{\cos\theta} P_L + \boxed{\sin\theta} P_R)\, t\, \boxed{V_1^\mu},$$

where $P_{R/L} = (1 \pm \gamma_5)/2$, $c_t = \sqrt{(c_L)^2 + (c_R)^2}$ and $\tan\theta = \frac{c_R}{c_L}$ are the projection operators, coupling of the vector singlet with the top quarks and tangent of the chirality angle respectively.

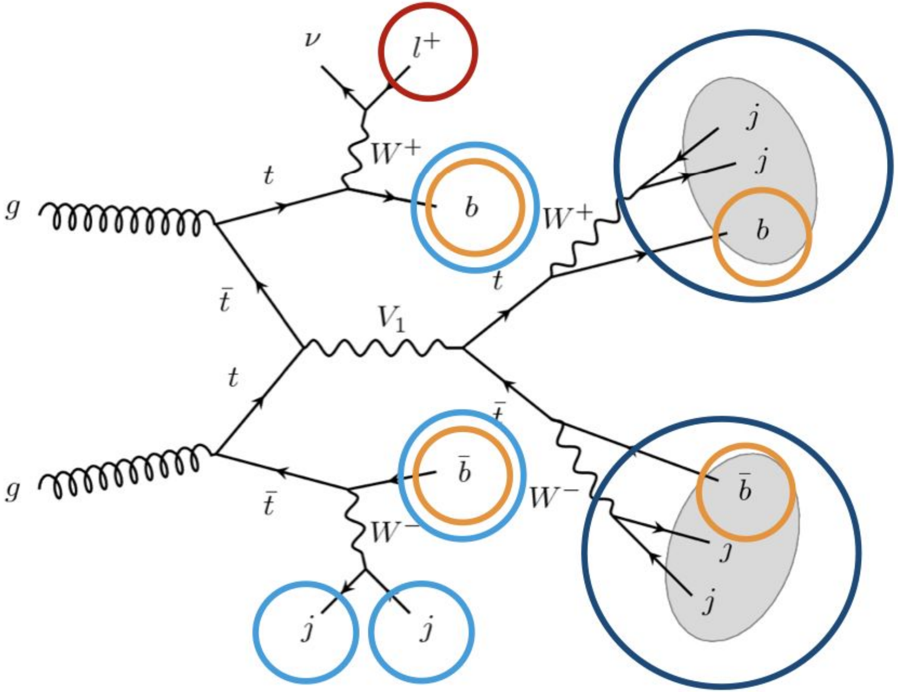


- bottom-up approach: minimal extension of Standard Model particle content
  - consequentially, focus on tree-level processes
- free signal parameters
  - resonance mass: $m_{Z'}$ = [1 TeV, 1.25 TeV, 1.5 TeV, 2 TeV, 2.5 TeV, 3 TeV]
  - coupling to top quarks: consider c_t = 1 (corresponds to 4% relative width)
  - chirality parameter: θ = π/4 (ttZ' production insensitive to θ)

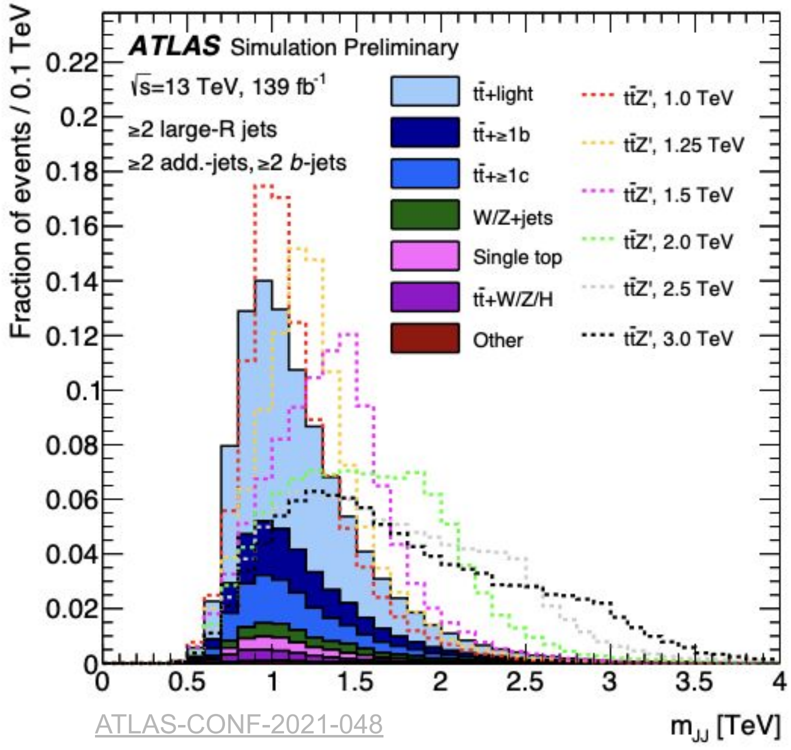
Event selection

1 lepton channel

- 1 lepton with p_T > 28 GeV, no additional leptons
- ≥ 2 reclustered (RC) R=1.0 jets with p_T > 300 GeV, m > 100 GeV and 2 or more constituents
- ≥ 2 R=0.4 PFlow jets outside of the RC jets ("additional jets")
- ≥ 2 b-tagged PFlow jets (DL1r using 77% efficiency WP)



Analysis strategy



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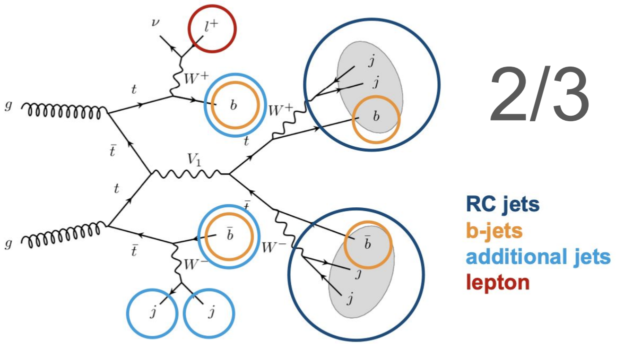
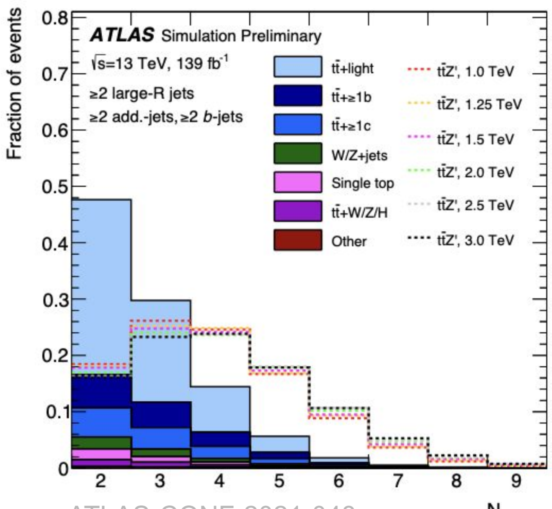
- Main discriminant: invariant mass of top quark candidate RC jets m_{JJ}
- Signal distributions peak above smoothly falling background
- Mass resolution affected by:
  - natural width of resonance
  - inefficiencies in using large-radius jets to capture full top quark decay
  - semi-leptonic decays of top quarks originating from Z' boson decay

Analysis strategy



Region definition based on number of additional jets
and number of b-jets to enhance sensitivity:

- Signal regions with large signal contribution used for search
- Source region used for data-driven background estimate



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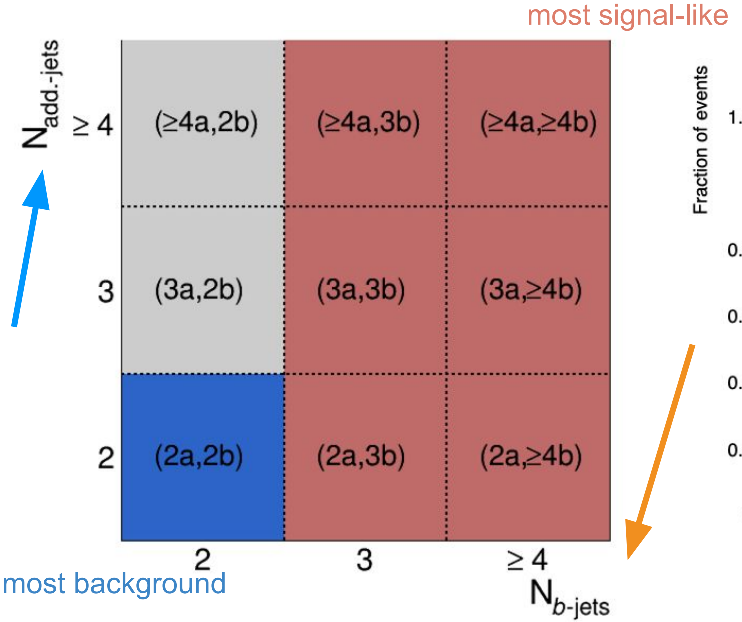

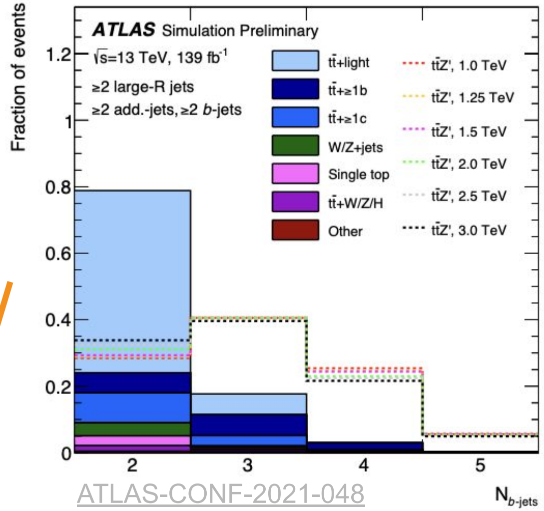

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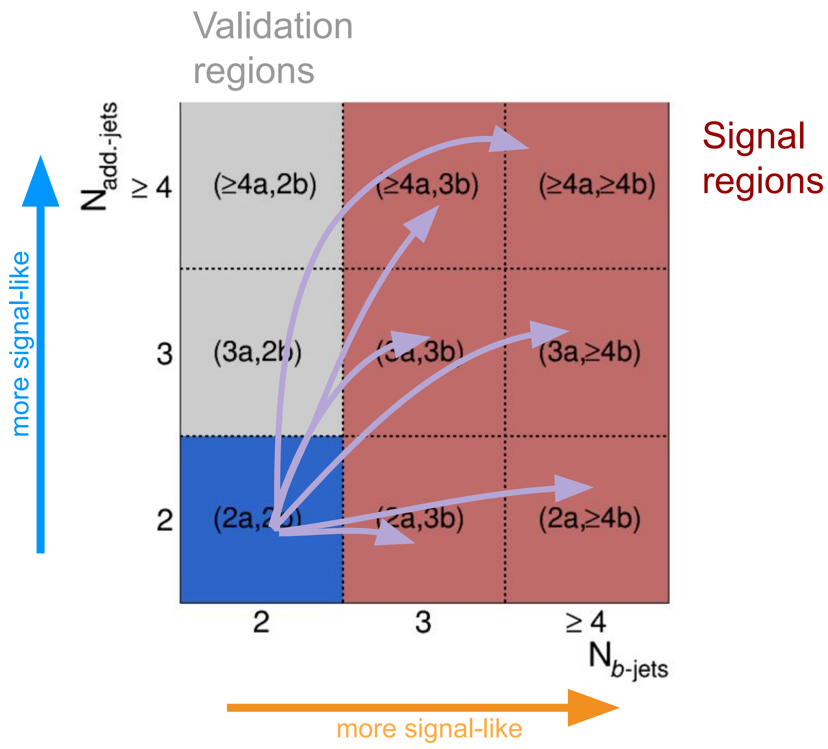
Analysis strategy

Region definition based on number of additional jets and number of b-jets also foundational for data-based background estimate.

Background prediction B^{reg} in signal region from functional form fit to source region data and MC-based extrapolation functions $C^{source \rightarrow reg}$

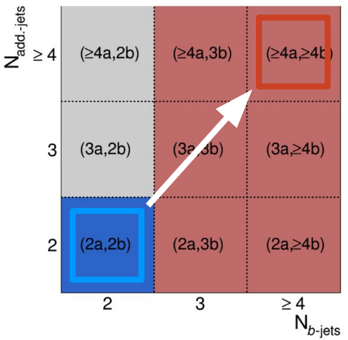
$$B^{\mathrm{reg}}(m_{t\bar{t},i}) = f(m_{t\bar{t},i}) \times C^{\mathrm{source}\rightarrow\mathrm{reg}}(m_{t\bar{t},i})$$

background prediction for bin i of mtt distribution

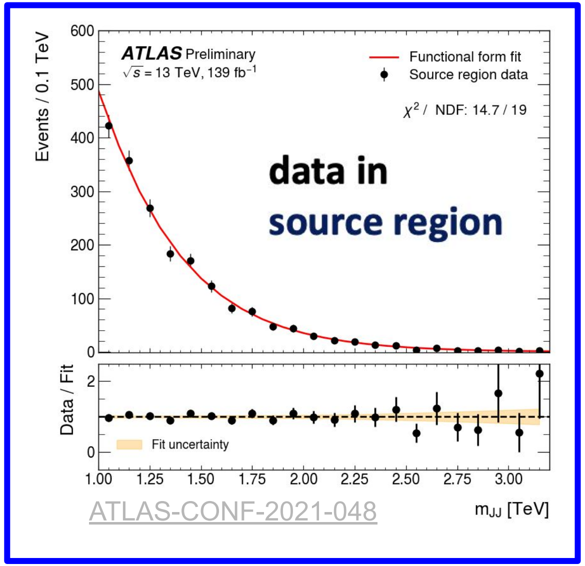


Background estimate

Background prediction B^{reg} in signal region from functional form fit to source region data and MC-based extrapolation functions $C^{source \rightarrow reg}$



$$B^{reg}(m_{JJ}) =$$



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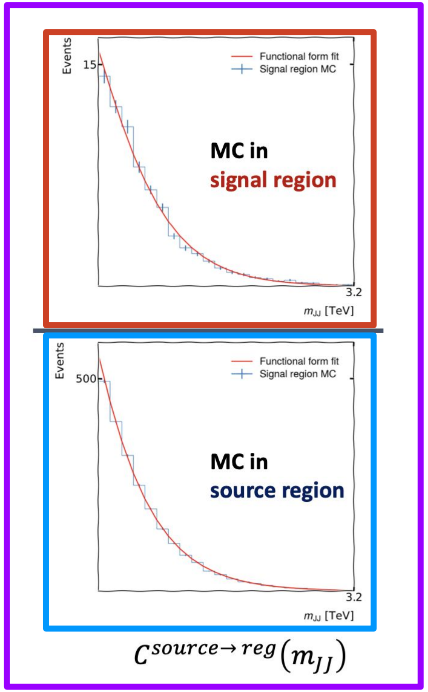

Functional form used in background fit:

$$f\left(\frac{m_{JJ}}{\sqrt{s}}\right) = \left(1 - \frac{m_{JJ}}{\sqrt{s}}\right)^{p_1} \times \left(\frac{m_{JJ}}{\sqrt{s}}\right)^{-p_2 - p_3 \ln\left(\frac{m_{JJ}}{\sqrt{s}}\right)} \text{ with } \sqrt{s} = 13 \text{ TeV}$$

Sketch by Alicia Wongel

Systematic uncertainties

Uncertainty categories	Relative contribution to the total uncertainty [%]	
	1.5 TeV	3 TeV
$t\bar{t}$+jets modeling	68	50
Signal bias	45	25
Functional fit and extrapolation	34	33
Jet energy scale and resolution	29	18
Single-top-quark modeling	9.4	7.7
Flavor tagging	8.7	3.6
Minor backgrounds modeling	5.1	5.6
Other uncertainties	0.4	2.0
Luminosity	0.3	0.1
Total systematic uncertainty	92	74
Statistical uncertainty	39	67

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Largest impact on total uncertainty:

- tt+jets modelling
- uncertainties related to background estimate (spurious signal bias and functional form fit)
- jet-related uncertainties

Results

1/2

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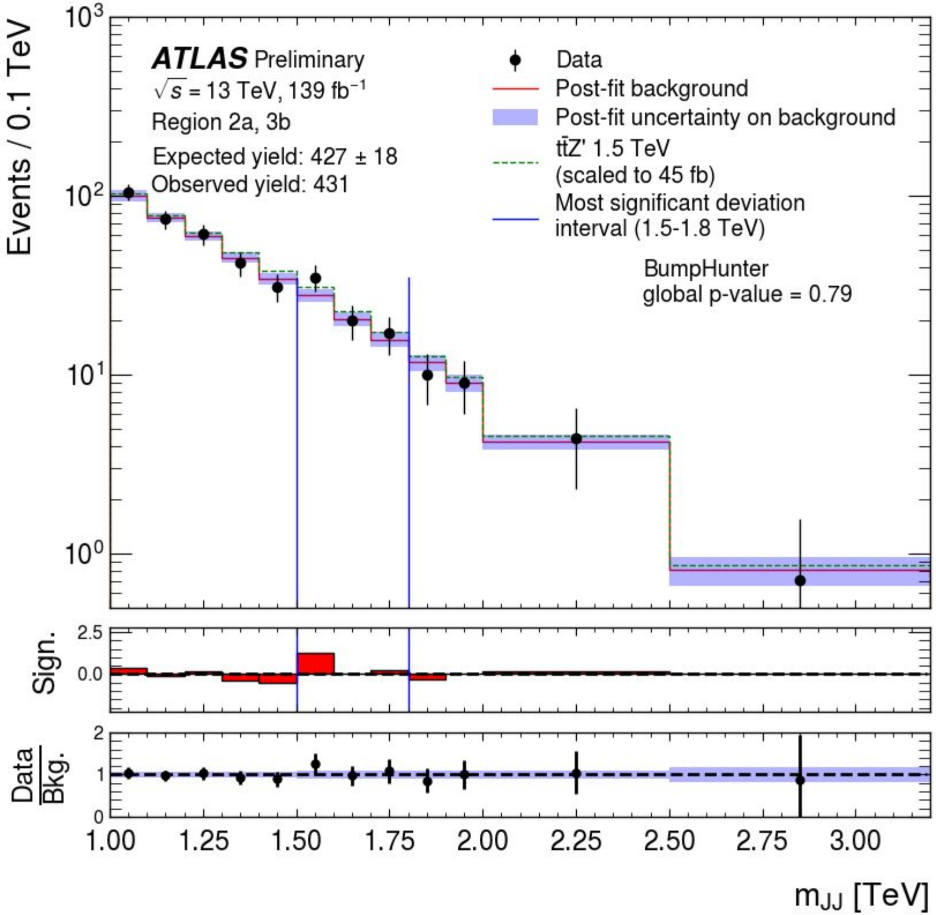
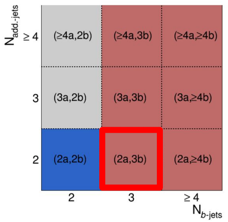
BumpHunter algorithm flags most significant deviations from background: model-independent approach



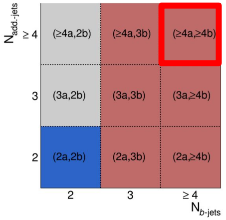


ratio of data over SM bkg

BumpHunter: locates the most significant local deviations from the bkg-only null hypothesis H_0, provides a p-value accounting for trials factor which corresponds to the Type I error probability

(see additional material for more details)

Results 2/2



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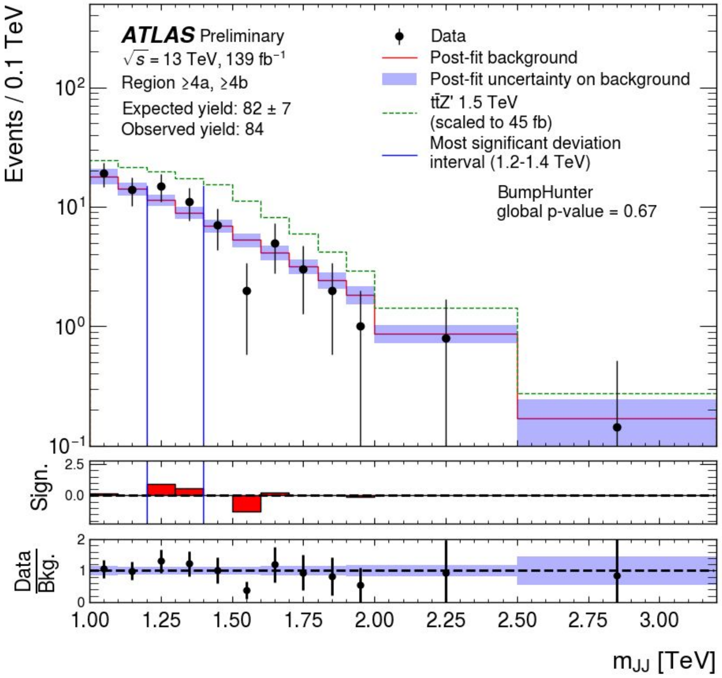

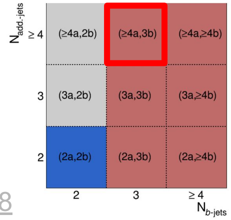

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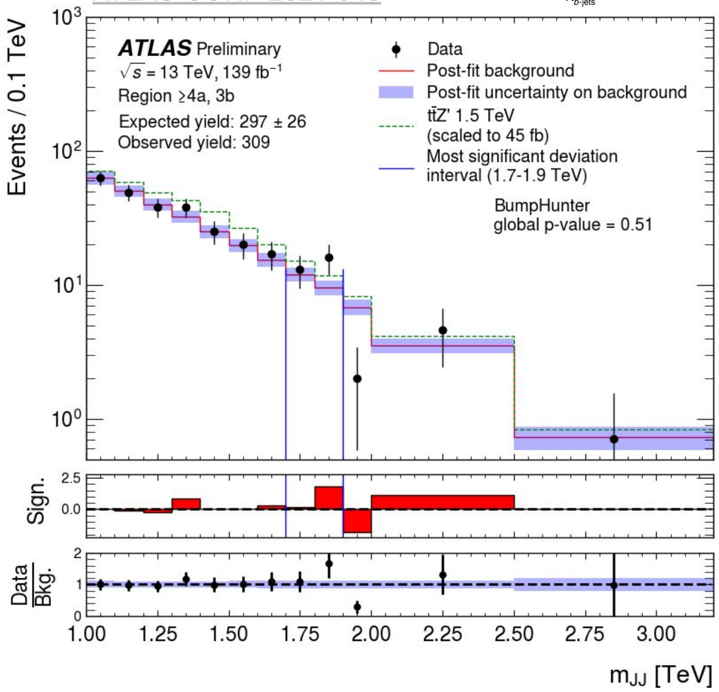
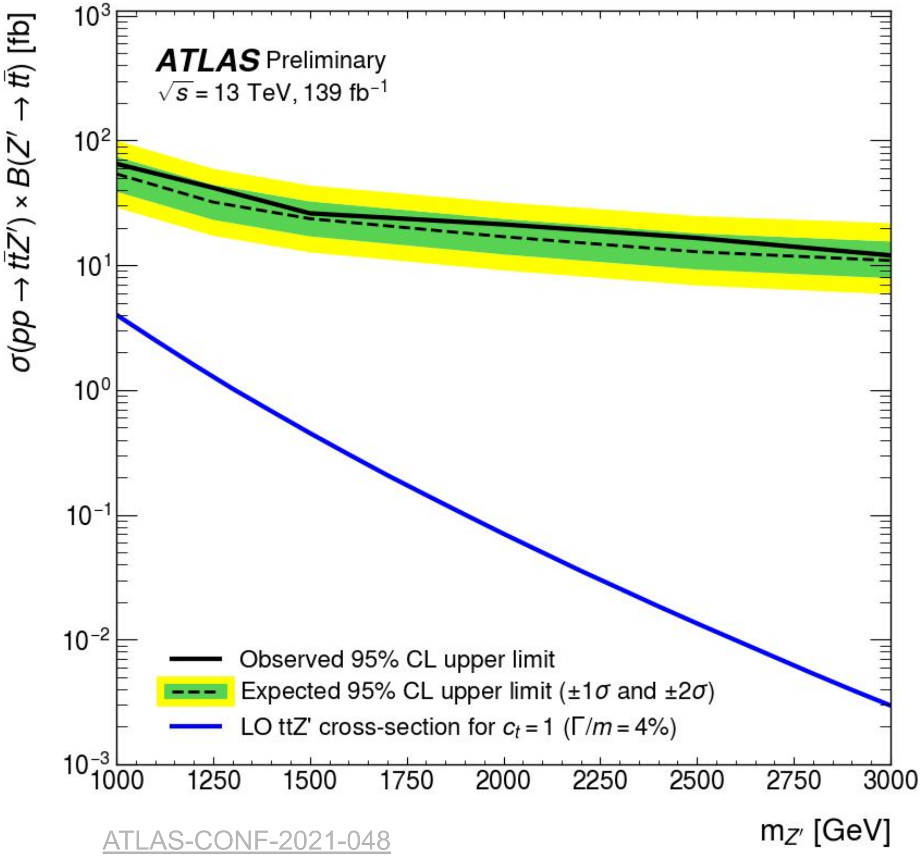


Search approach with minimal model dependence: combined bkg-only profile likelihood fit of all signal regions to data.
Post-fit distributions in good agreement with data, no significant deviations flagged by BumpHunter algorithm.

Interpretation

Model-dependent interpretation in terms of simplified top-philic resonance model:

- observed 95% CL upper limit on ttZ’ production cross-section for narrow width (Γ/m ≈ 4%) resonance
- LO theory cross-section prediction for resonance-top-quark coupling ct = 1



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released for TOP2021 in September 2021:
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Summary

- A search for heavy top-philic resonances in the four-top-quark final state is presented. In contrast to existing four-top-quark searches, a resonance is explicitly reconstructed using reclustered large-radius jets.
- The background is estimated using a data-driven method to mitigate MC mismodelling in the high jet multiplicity regime.
- Results are interpreted using both a BumpHunter method with minimal model dependence and a model-dependent approach.
- No excess was found in data, limits were set on a simplified model for production of top-philic spin-1 Z' resonances as a function of mass $m_{Z'}$ for a relative width of $\Gamma/m \approx 4\%$.

Additional material

MC Simulation of background processes

Process	Generator + fragmentation/hadronisation	Tune	PDF set	Cross-section order
$t\bar{t}$	POWHEG BOX v2 + PYTHIA 8.230	A14	NNPDF3.0	NNLO+NNLL
W+ jets	SHERPA 2.2.1	Default	NNPDF3.0	NNLO
Wt-single-top	POWHEG BOX v2 + PYTHIA 8.230	A14	NNPDF3.0	NNLO+NNLL
Z + jets	SHERPA 2.2.1	Default	NNPDF3.0	NNLO
s/t-single-top	POWHEG BOX v2 + PYTHIA 8.230	A14	NNPDF3.0	NNLO+NNLL
Dibosons	SHERPA 2.2.1/2.2.2	Default	NNPDF3.0	NLO
$t\bar{t} + W/Z$	aMC@NLO 2.3.3 + PYTHIA 8.210	Default	NNPDF2.3	NLO
$t\bar{t} + H$	POWHEG BOX v2 + PYTHIA 8.230	A14	NNPDF3.0	NLO
$t\bar{t}\,t\bar{t}$	aMC@NLO 2.6.2 + PYTHIA 8.230	A14	NNPDF3.1	NLO
tZ	aMC@NLO 2.3.3 + PYTHIA 8.212	A14	NNPDF3.0	LO

What is BumpHunter?

arXiv: [1101.0390v2](https://arxiv.org/abs/1101.0390v2)

Run BumpHunter algorithm on background prediction after conditional μ=0 profile likelihood fit to obtain model-agnostic results.

BumpHunter: locates the most significant local deviations from the bkg-only null hypothesis H_0, provides a p-value accounting for trials factor which corresponds to the Type I error probability

1. generate large number of pseudo-data following H_0 and for each dataset
2. compute BumpHunter test statistic
   - scan with sliding window and report test statistic $t = -\log p\text{-}value_{min}$ based on window with smallest p-value
3. calculate p-value of the test based on observed data and *t*-distribution of pseudo-experiment