Searches for New Phenomena in Final States with 3rd Generation Quarks using the ATLAS Detector

Joseph Haley
Oklahoma State Universtiy

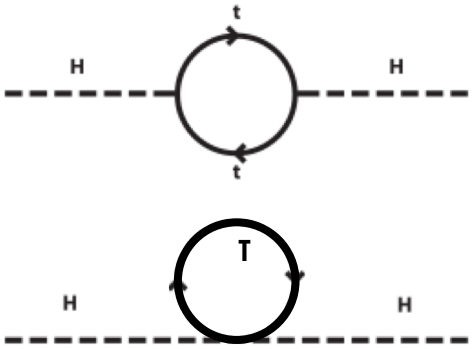
Lake Louise Winter Institute 2022
20–26 Feb 2022
Chateau Lake Louise

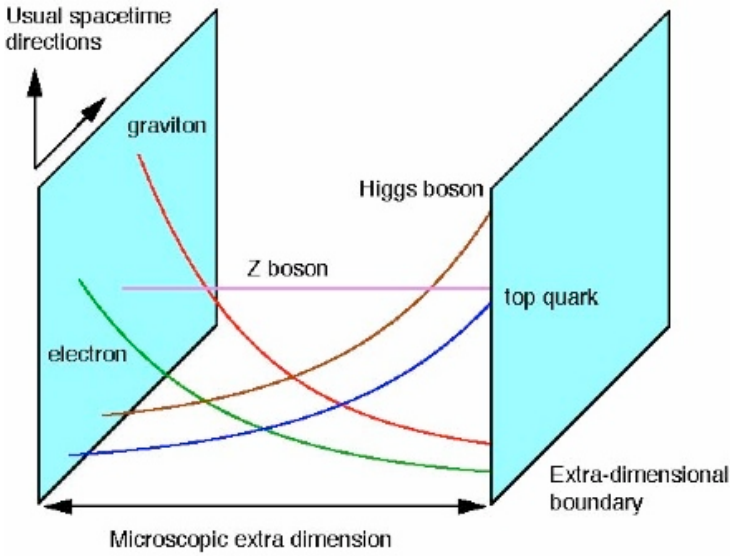
Supported by the U.S. Department of Energy

Probing New Physics with 3rd Generation Quarks

Top and bottom quarks are like gold

- Heavy ⇒ Very large Yukawa coupling
- Precious ⇒ Many BSM model predict enhanced coupling to 3rd generation
  - Heavy mediators (*W'*, *Z'*, *H/A*, g_{KK}, G_{KK})
  - Top partners (Vector-like quarks)





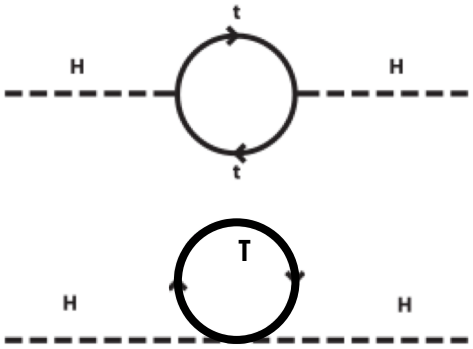
I will highlight the **most recent** searches (with some personal bias)

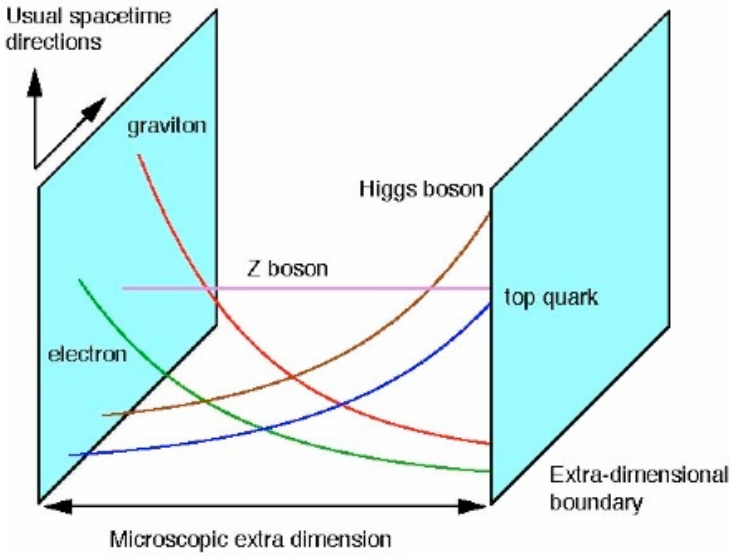
- Data from *pp* collisions with √s = 13 TeV recorded by ATLAS during **Run 2 (2015-2018)**
- See also searches with associated tops in Nedaa-Alexandra's talk on Monday

Probing New Physics with 3rd Generation Quarks

Top and bottom quarks are like gold

- Heavy ⇒ Very large Yukawa coupling
- Precious ⇒ Many BSM model predict enhanced coupling to 3rd generation
  - Heavy mediators (*W'*, *Z'*, *H/A*, g_{KK}, G_{KK})
  - Top partners (Vector-like quarks)





I will highlight the **most recent** searches (with some personal bias)

- Data from *pp* collisions with √s = 13 TeV recorded by ATLAS during **Run 2 (2015-2018)**
- See also searches with associated tops in Nedaa-Alexandra's talk on Monday

Identification of 3rd Generation Quarks

All analyses in this talk rely on the identification of jets from **top** or **bottom** quarks

⇒ Critical for separating from multijet events

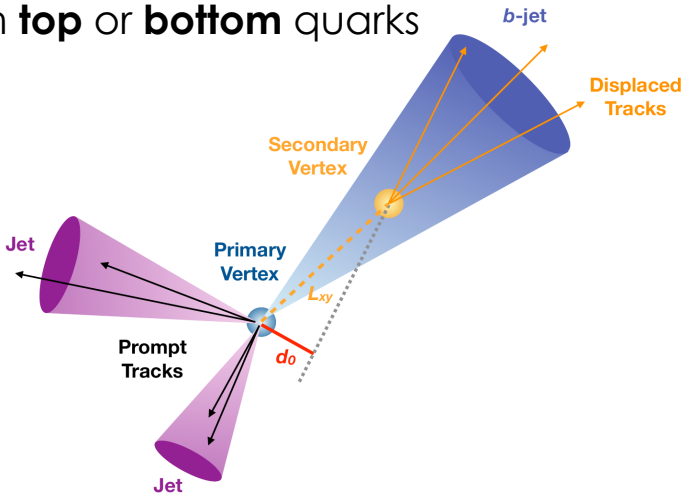
High-p_T **bottom** quarks

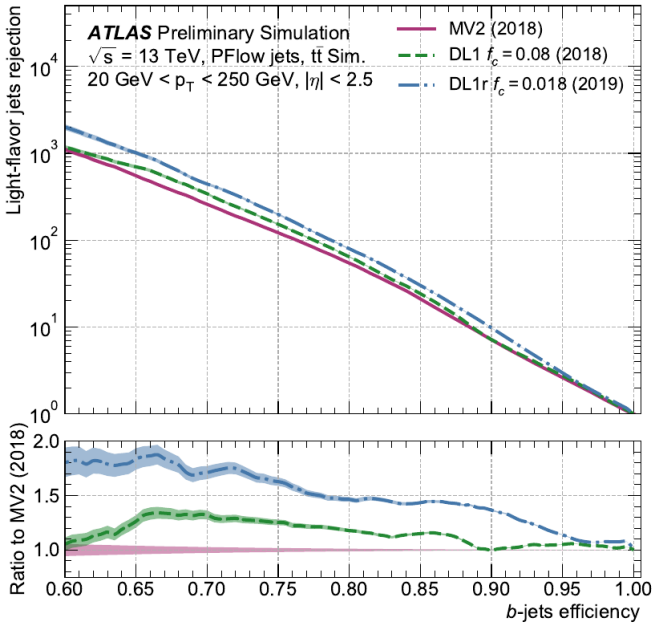
- Small-R jet with displaced secondary vertex, high mass, and high track multiplicity

⇒ Train Deep Neural Network (DNN) b-tagger

- Uses all previous inputs, plus *recurrent neutral network* to exploit correlations between different tracks
- >50% better rejection w.r.t. Boosted Decision Tree

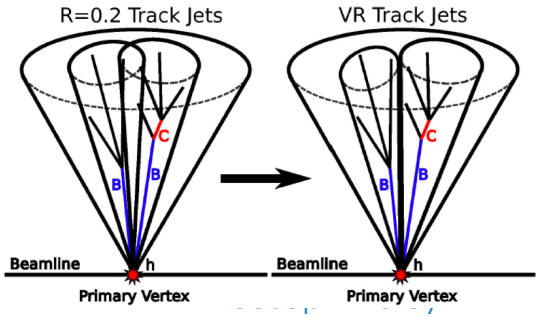
Dedicated b-taggers for new particle-flow and variable radius track jet reconstruction algorithms





Variable-radius track jets:

$$R \longrightarrow R_{\text{eff}}(p_T) = \frac{\rho}{p_T}$$



Identification of 3rd Generation Quarks

All analyses in this talk rely on the identification of jets from **top** or **bottom** quarks

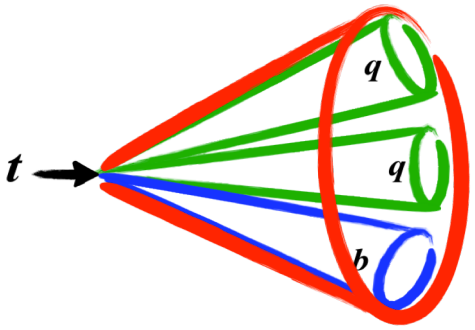
⇒ Critical for separating from multijet events

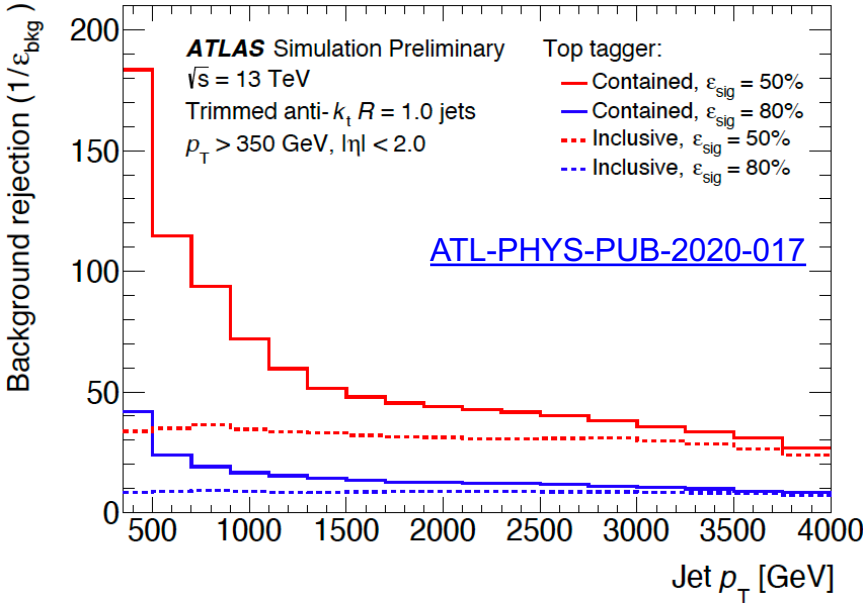
High-p_T **top** quarks ("boosted-top")

- Large-radius jet with highly collimated sub-jets, including one b-jet
- Discriminate from QCD jets using kinematics (jet mass, p_T, etc.) and dispersion of jet constituents (N-subjettiness, splitting scales, and energy correlation functions)

Official DNN top-taggers defined for 50% and 80% efficiency

Some analyses define custom top-taggers (more later)





Vector-Like Quarks (VLQs)

Both chiralities transform the same under SM gauge groups ⇒ "Vector-like"

- Avoids constraints from Higgs measurements

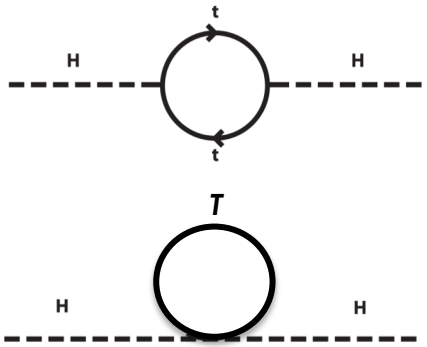
SM *V-A* current	VLQ current
$(\bar{q}\gamma^{\mu}(1-\gamma^{5})q')$	$(\bar{Q}\gamma^{\mu}Q')$

VLQs can cancel quadratic divergence in Higgs mass

⇒ Show up in many BSM models

(Little/Composite Higgs, Topcolor, GUTs, …)

- Naturalness requires VLQ mass ~TeV



Can mix with SM quarks

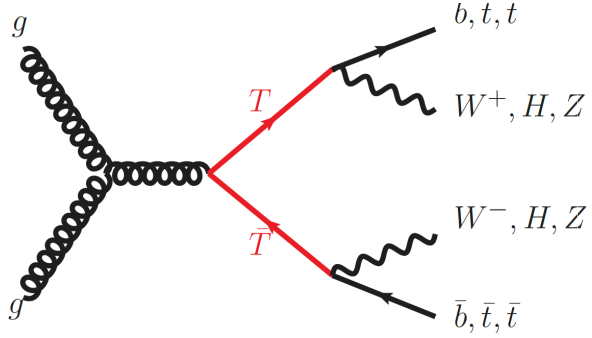
- Naturalness + FCNC constraints prefer mixing with 3rd generation

Top partner →
Bottom partner →

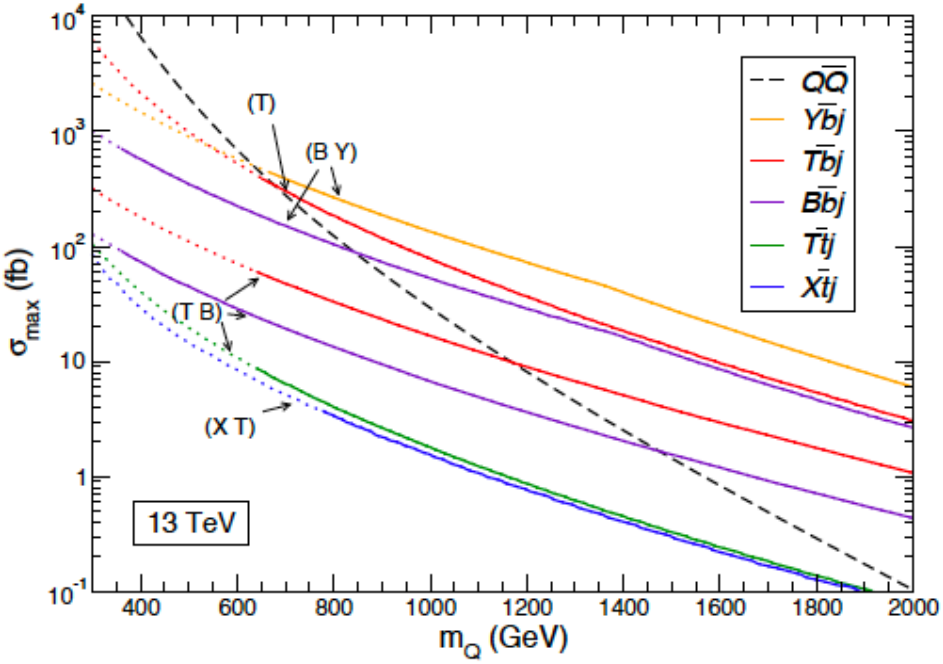
Q[e]	VLQs: singlets	doublets	triplets
5/3		$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$
2/3	(T)	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
−1/3	(B)	$\begin{pmatrix} B \\ Y \end{pmatrix}$	
−4/3			

What do we look for?

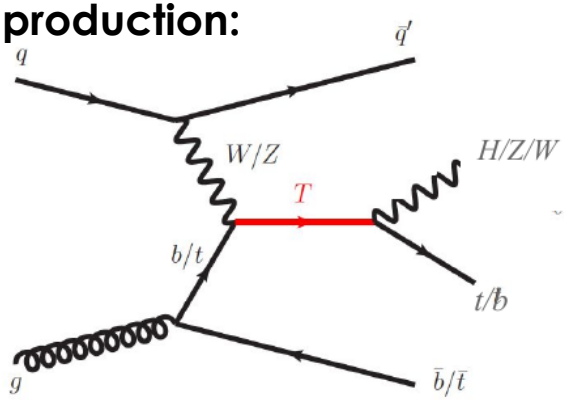
Pair Production:



- Via QCD ⇒ Depends only on VLQ mass (**Model-independent**)



Single production:



- Via mixing with SM quarks ⇒ Depends on mass and coupling (κ)
- **Could dominate** for large VLQ masses

Decays:

- Dictated by quantum numbers

$T \rightarrow Wb,\ Zt,\ Ht$

$B \rightarrow Wt,\ Zb,\ Hb$

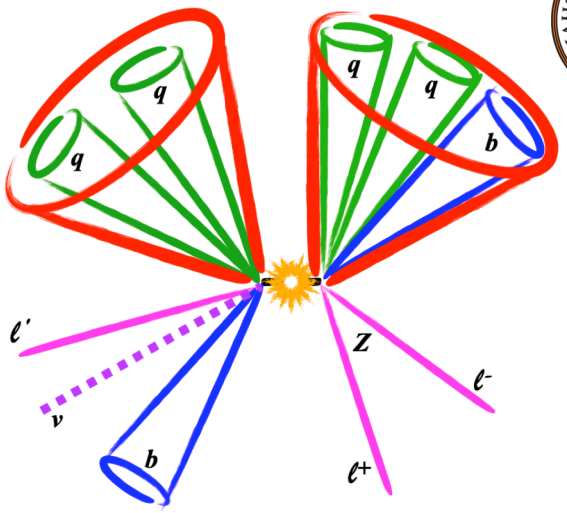
ATLAS-CONF-2021-024

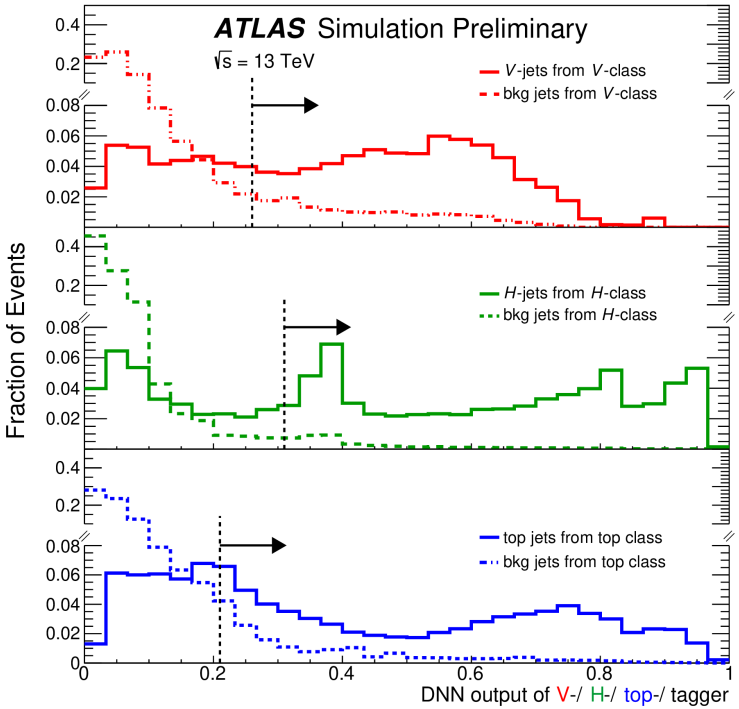
$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$

Independently optimized for dilepton and trilepton final states

DNN "multi-class boosted object tagger" (MCBOT) trained to identify large-R jets from hadronically decaying top, V, H

Example of trilepton decay:



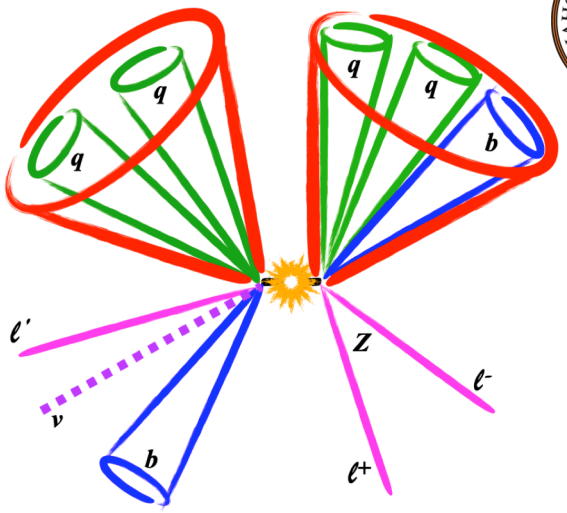


$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$

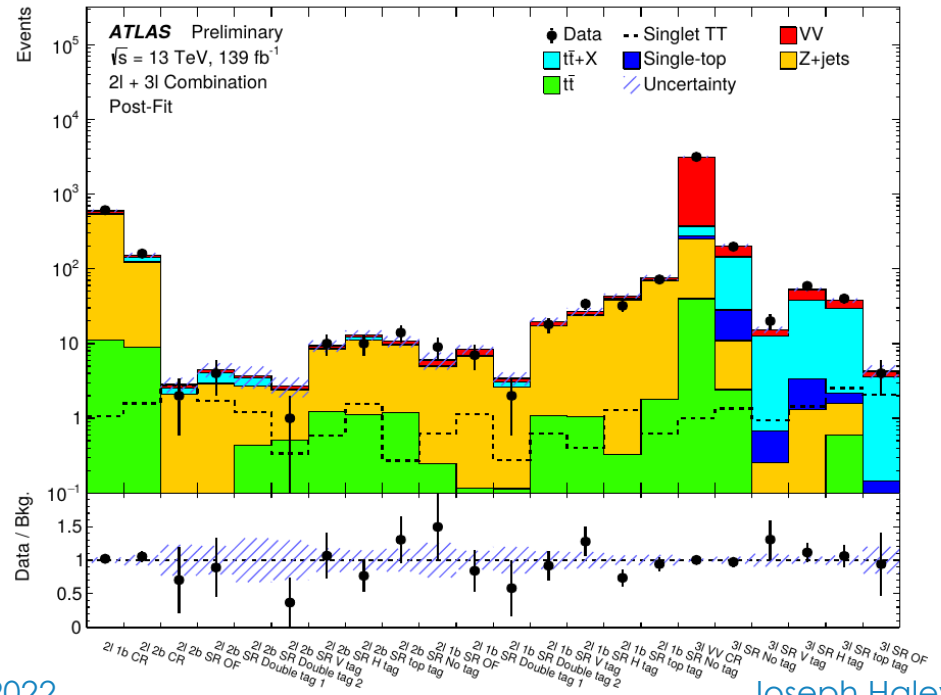
Independently optimized for dilepton and trilepton final states

DNN "multi-class boosted object tagger" (MCBOT) trained to identify large-R jets from hadronically decaying top, V, H

Example of trilepton decay:



Define 22 exclusive categories based on kinematic properties, b-tag and MCBOT

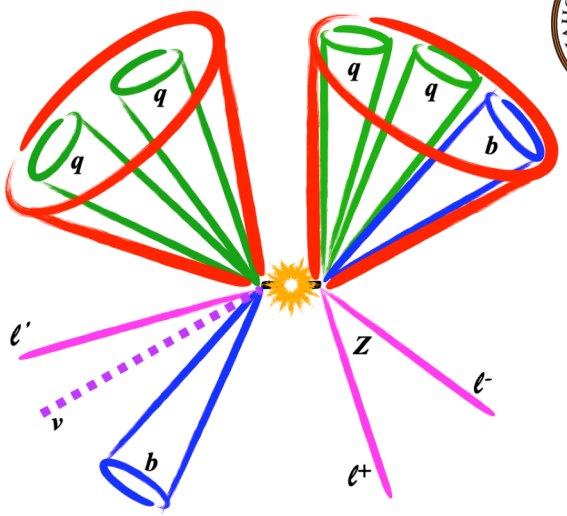


$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$

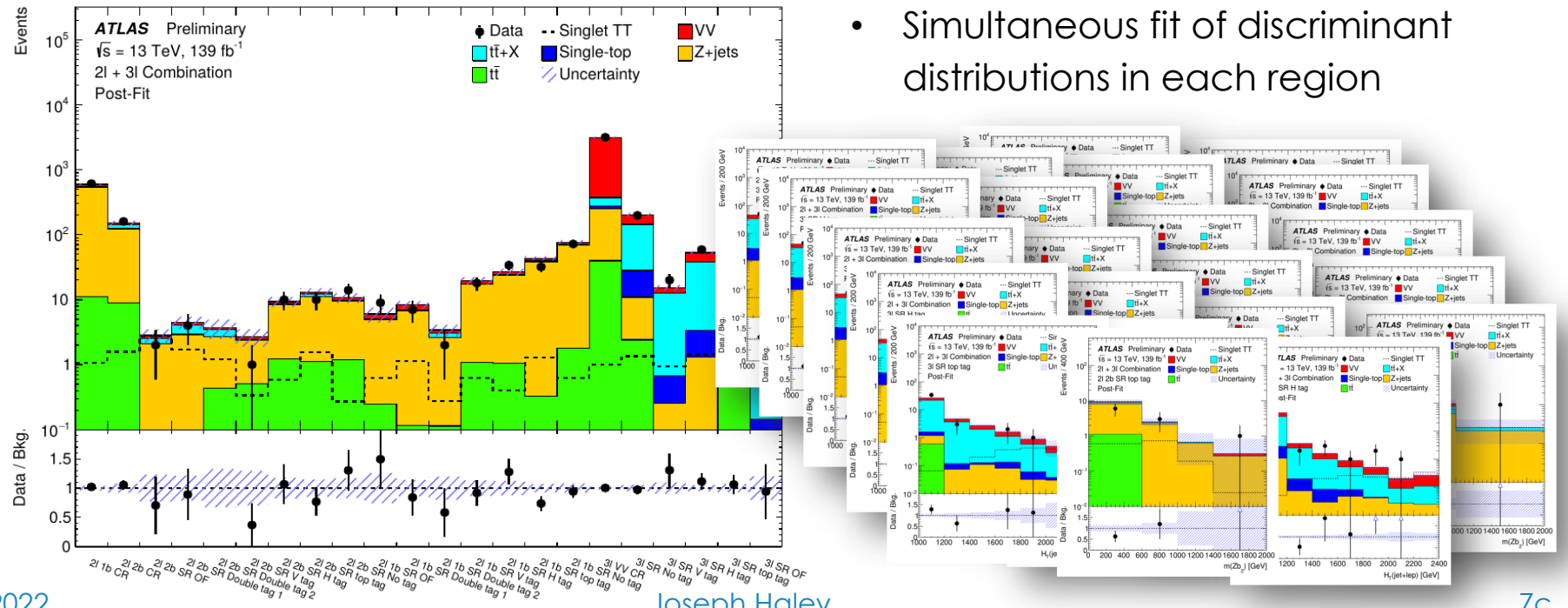
Independently optimized for dilepton and trilepton final states

DNN "multi-class boosted object tagger" (MCBOT) trained to identify large-R jets from hadronically decaying top, V, H

Example of trilepton decay:

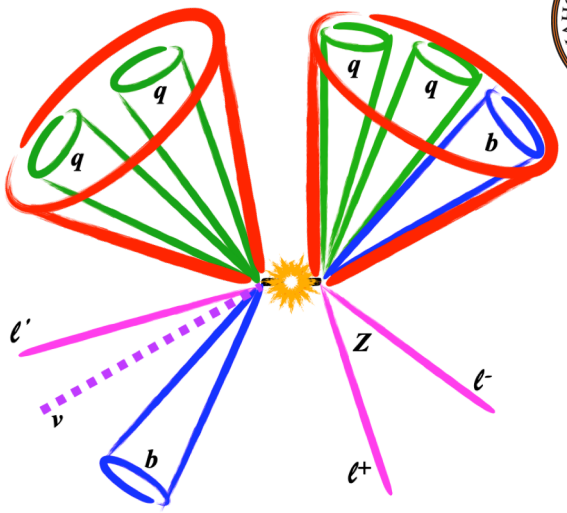


Define 22 exclusive categories based on kinematic properties, b-tag and MCBOT



- Simultaneous fit of discriminant distributions in each region

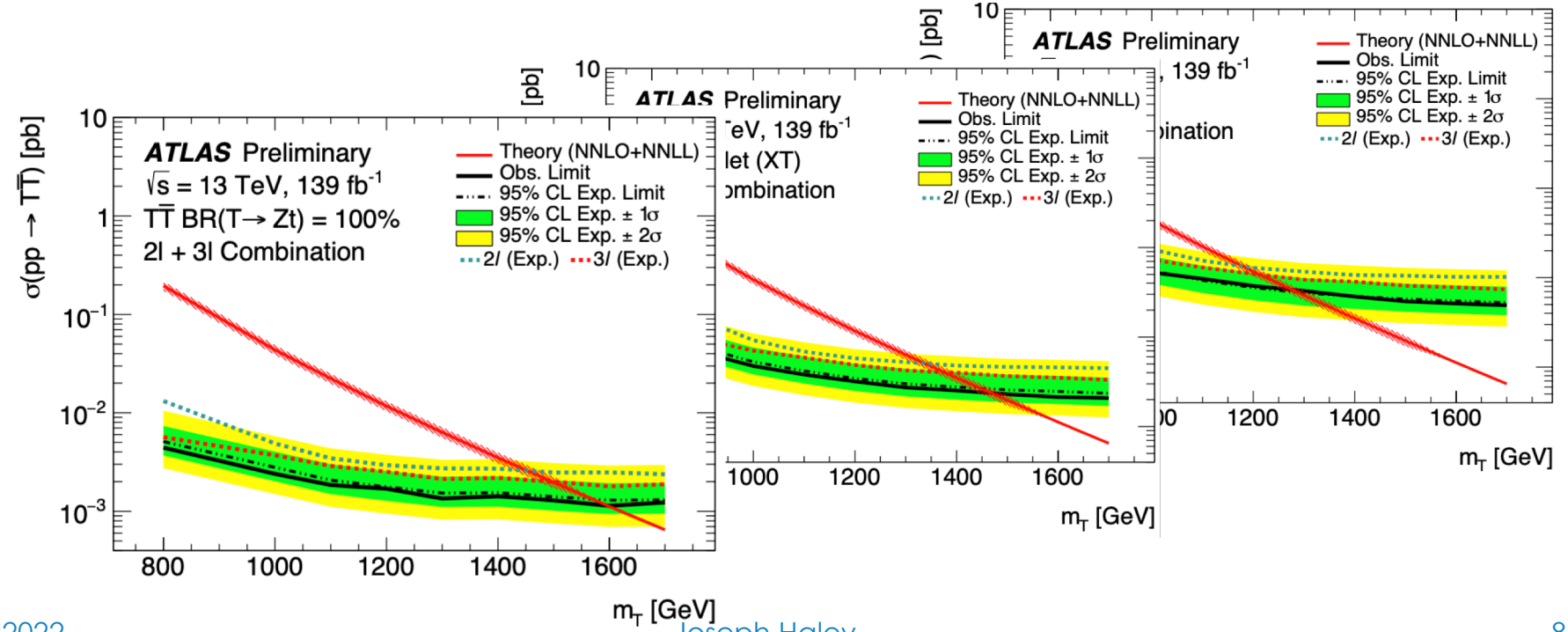
$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$



Analyze full Run 2 ATLAS dataset (139fb-1)

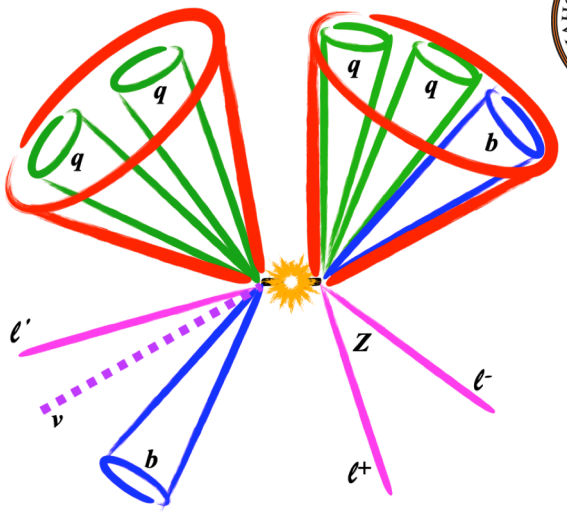
- Sensitivity limited by statistical uncertainties
- No deviations from the background-only model observed

⇒ Limits on cross-section vs. VLQ mass for **benchmark** scenarios



ATLAS-CONF-2021-024

$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$

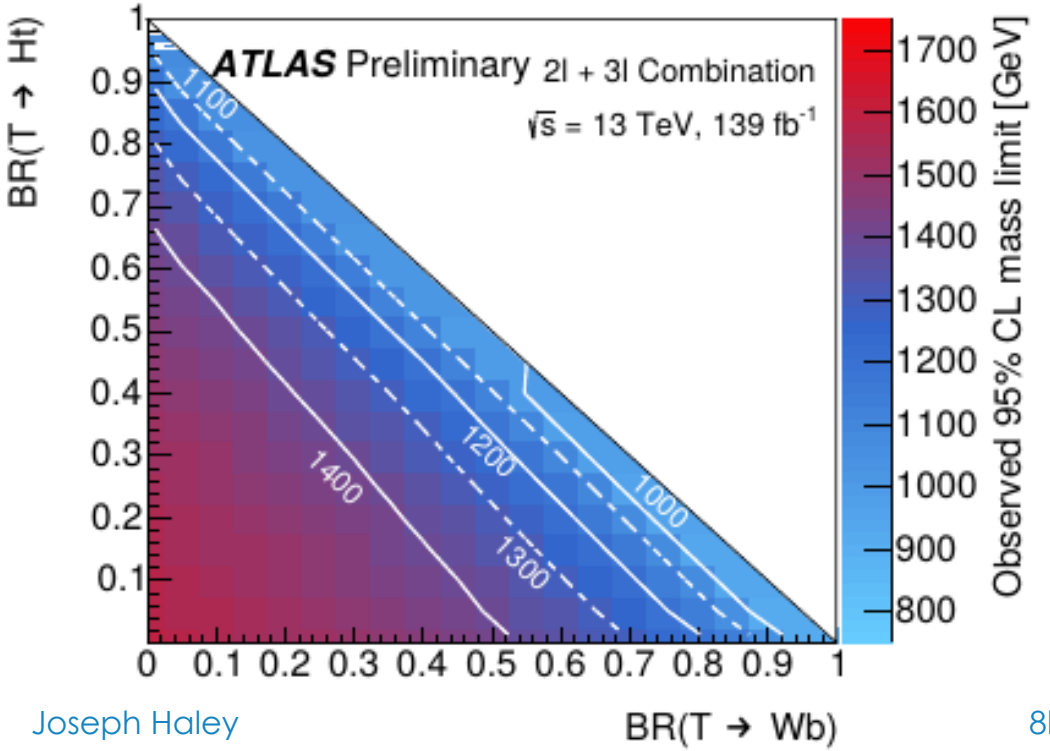


Analyze full Run 2 ATLAS dataset (139fb-1)

- Sensitivity limited by statistical uncertainties
- No deviations from the background-only model observed

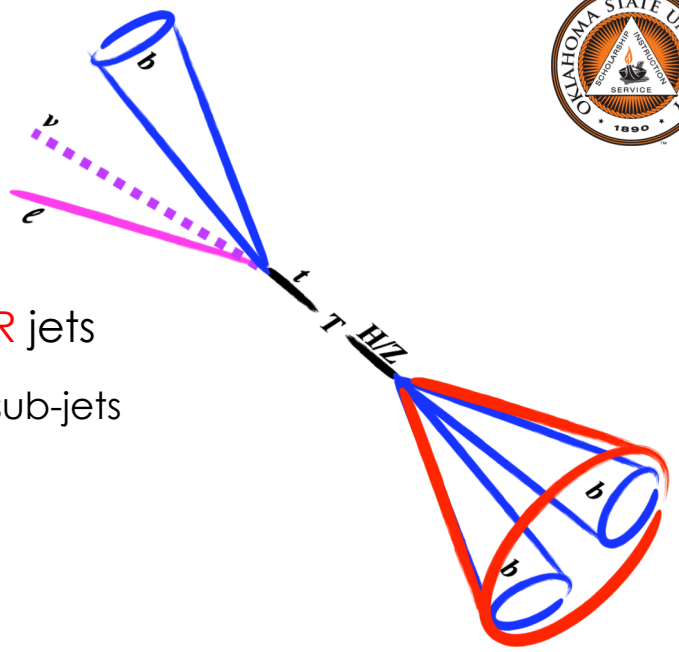
⇒ Limits on cross-section vs. VLQ mass for **benchmark** scenarios

⇒ **Model-independent limits** on VLQ mass vs. branching ratio:



Extends the excluded B & T mass limits by more than 200 GeV compared to previous analysis using 2015+16 data (36fb^{-1})

$T \rightarrow Ht/Zt$, with $t \rightarrow lvb$



Leptonic top: High-pT e/μ + E_T^{miss} + b-jet

Boosted H or Z: Small-R jets "re-clustered" into Large-R jets

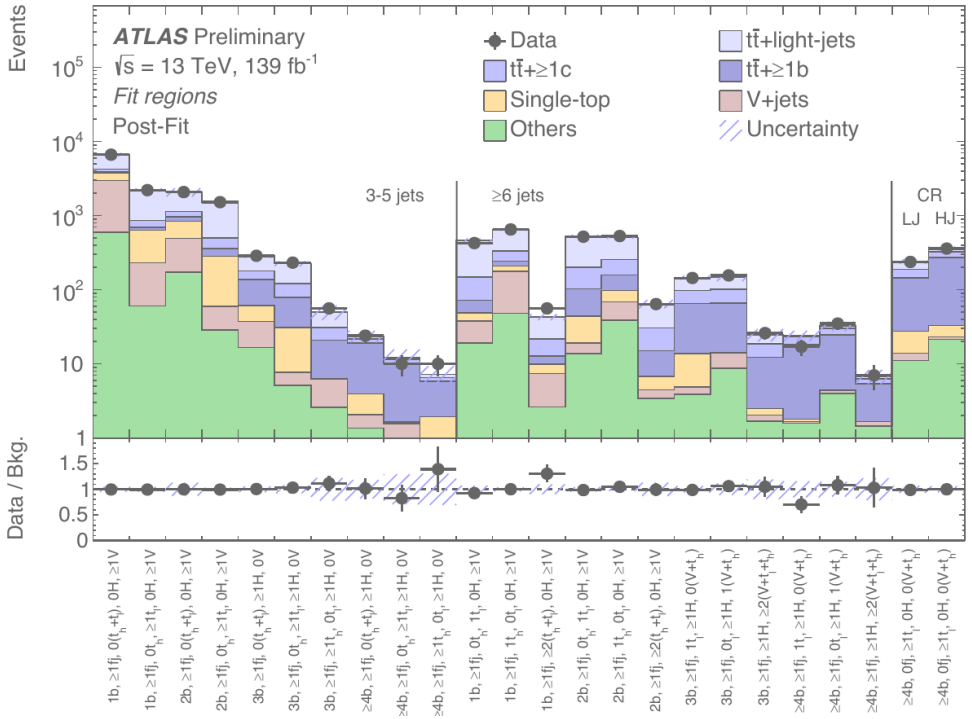
- Tag as H, V, or top based on jet mass, p_T and number of sub-jets

Sensitivity limited by modeling uncertainties on dominant tt and single top backgrounds

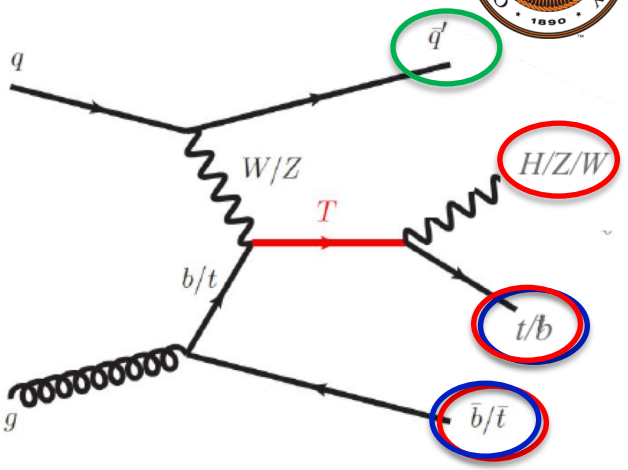
- Data-driven kinematic reweighting for tt&tW and V+jets

Divide events into 24 regions based on number of jets, b-tags, H, V, & top-tags

Perform combined fit to discriminating variable in all regions



$T \rightarrow Ht/Zt$, with $t \rightarrow lvb$



Leptonic top: High-pT e/μ + E_T^{miss} + b-jet

Boosted H or Z: Small-R jets "re-clustered" into Large-R jet

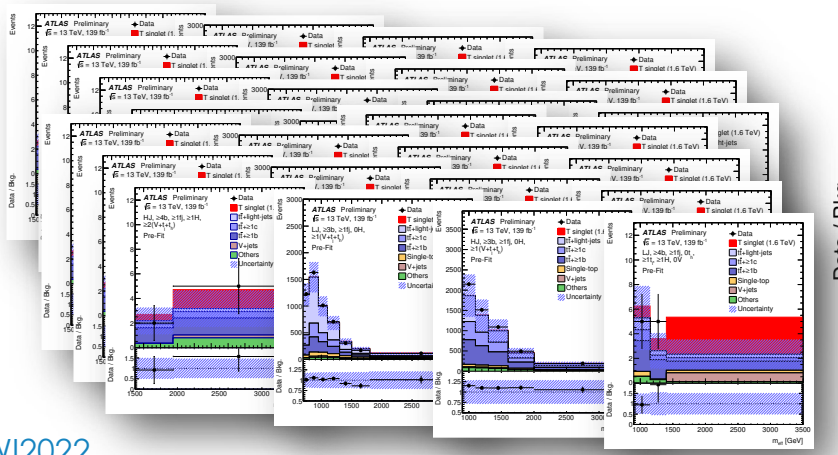
- Tag as H, V, or top based on jet mass, p_T and number of sub-j

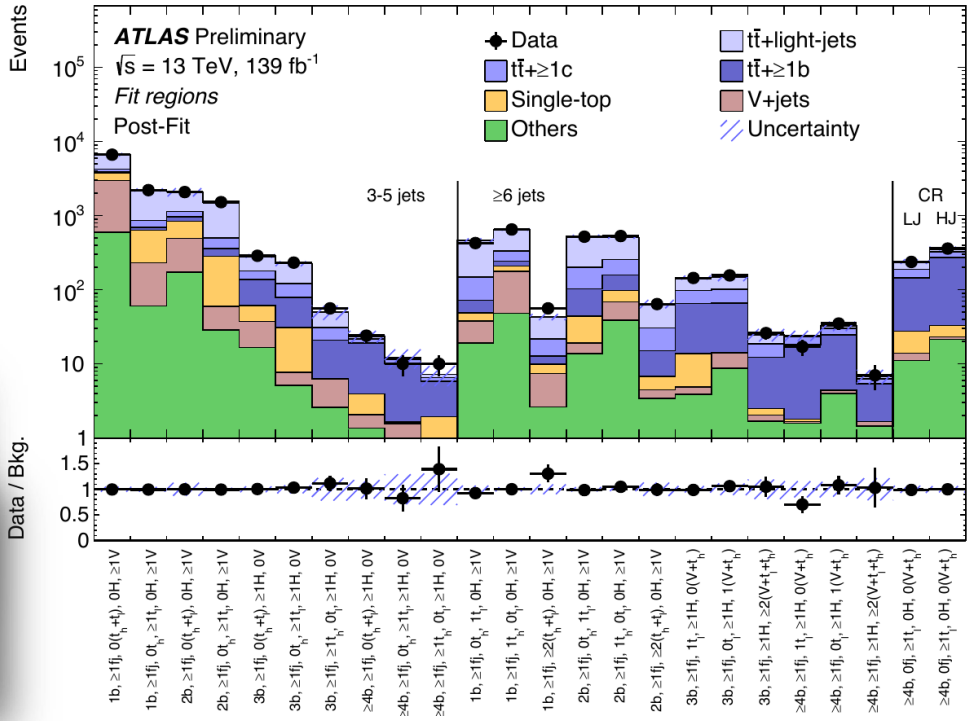
Sensitivity limited by modeling uncertainties on dominant tt and single top backgrounds

- Data-driven kinematic reweighting for tt&tW and V+jets

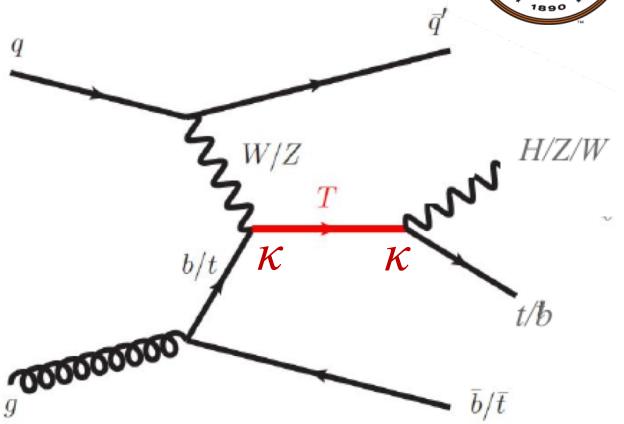
Divide events into 24 regions based on number of jets, b-tags, H, V, & top-tags

Perform combined fit to discriminating variable in all regions





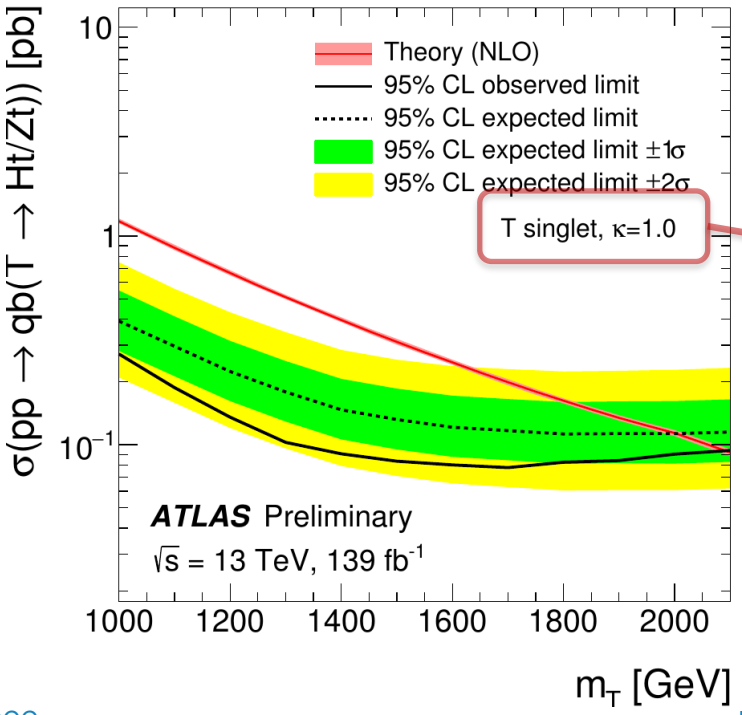
$T \rightarrow Ht/Zt$, with $t \rightarrow lvb$

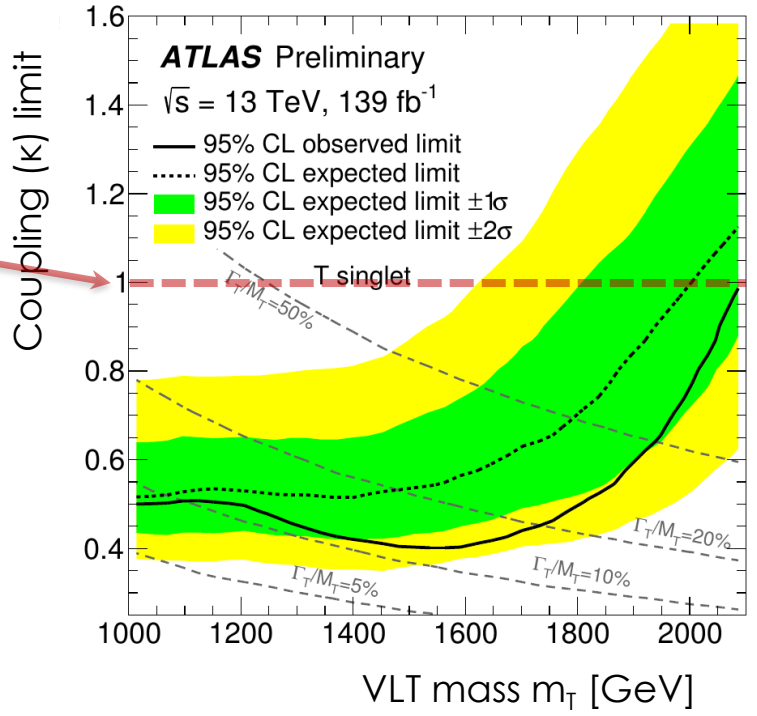


Analyze full Run 2 ATLAS data set (139 fb-1)

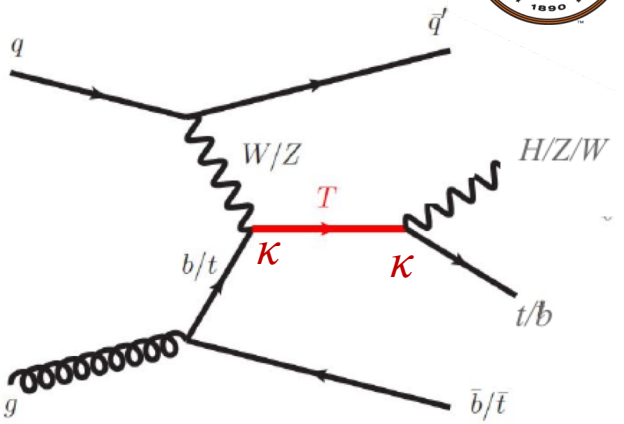
No deviation from the background-only hypothesis

⇒ Set limits on singlet T as a function of mass m_T and coupling constant κ





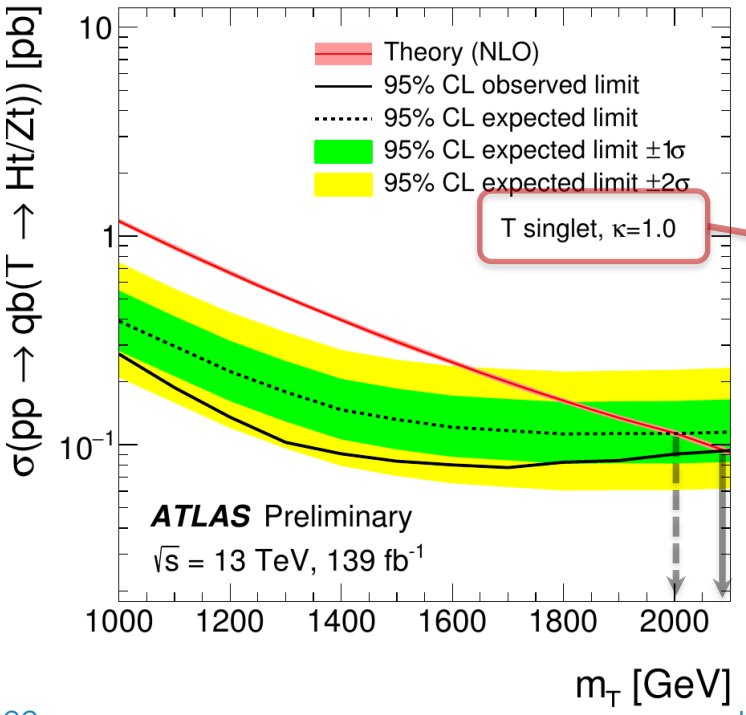
$T \rightarrow Ht/Zt$, with $t \rightarrow lvb$

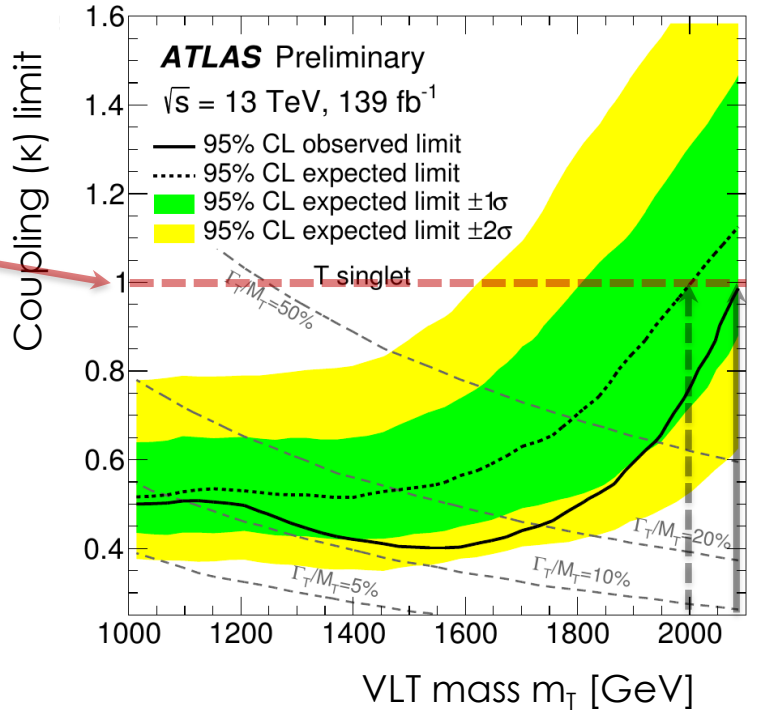


Analyze full Run 2 ATLAS data set (139 fb-1)

No deviation from the background-only hypothesis

⇒ Set limits on singlet T as a function of mass m_T and coupling constant κ





CERN-EP-2021-249 *Submitted to PRD January 18!*

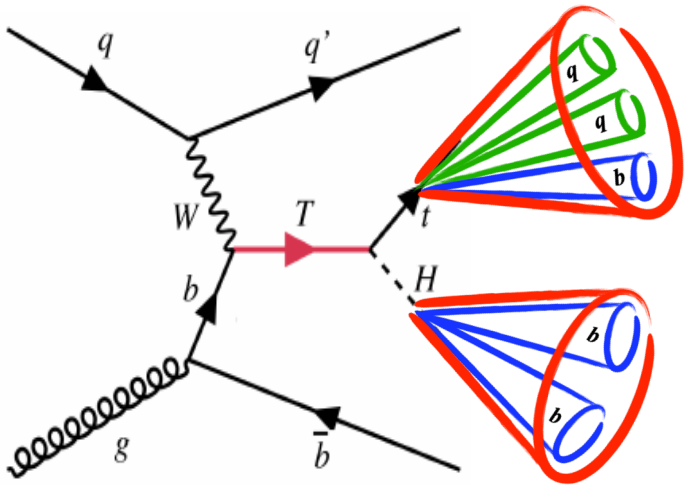
$T \rightarrow Ht$ with hadronic final state

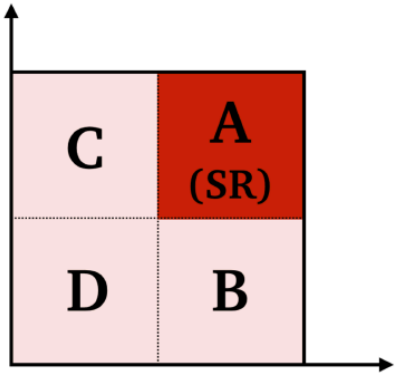
T→Ht with H→bb and t→qqb

- 2 high-pT large-R jets with b-subjets

Dominant background from QCD multijet events

- Estimate from data using an extension of the "ABCD" method
- 2D grid based on the tagging state of the two large-R jets
  - Higgs or top tag
  - Number of b-tagged VRTrack jets inside large-R jet





$$N_A = N_B \times \frac{N_C}{N_D}$$

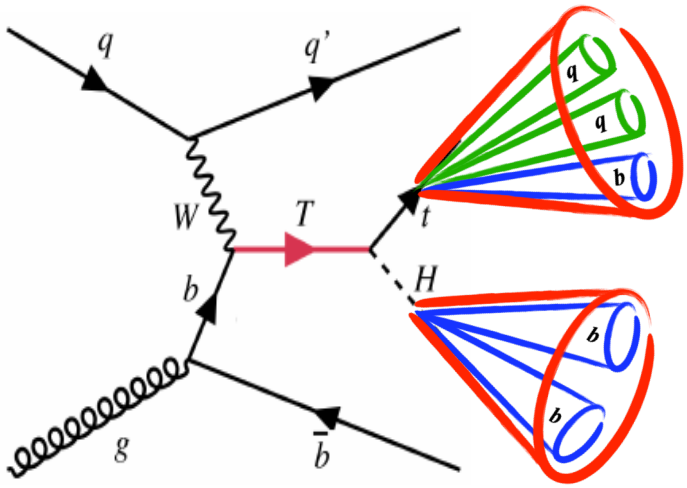
$T \rightarrow Ht$ with hadronic final state

T→Ht with H→bb and t→qqb

- 2 high-pT large-R jets with b-subjets

Dominant background from QCD multijet events

- Estimate from data using an extension of the "ABCD" method
- 2D grid based on the tagging of the two large-R jets
  - Higgs or top tag
  - Number of b-tagged VRTrack jets inside large-R jet



Second-leading large-R jet tagging state \ 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									

CERN-EP-2021-249 *Submitted to PRD January 18!*

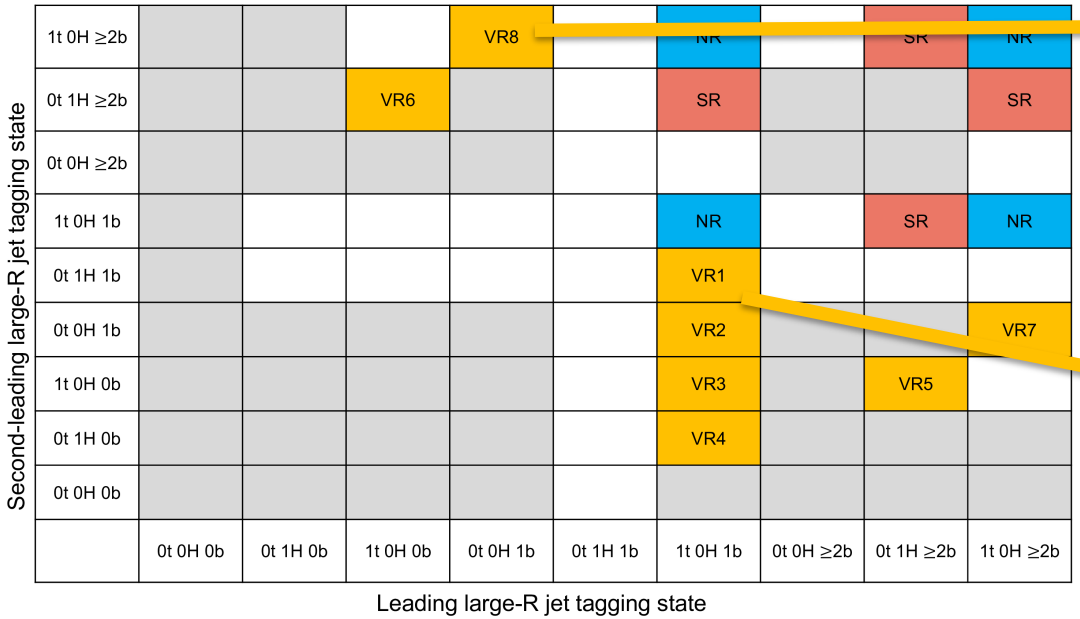
$T \rightarrow Ht$ with hadronic final state

T→Ht with H→bb and t→qqb

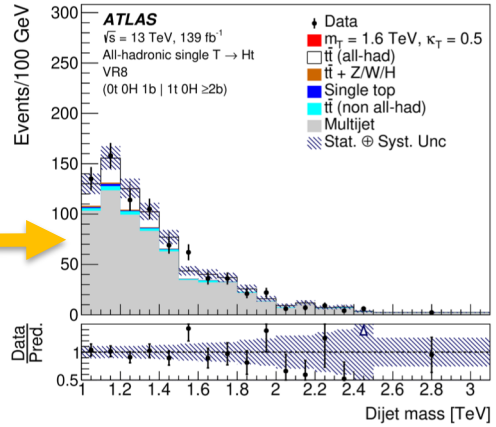
- 2 high-pT large-R jets with b-subjets

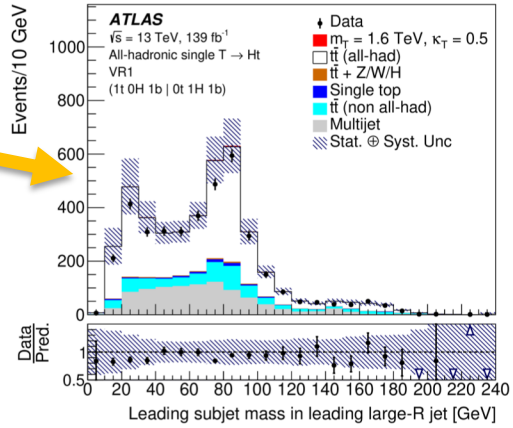
Dominant background from QCD multijet events

- Estimate from data using an extension of the "ABCD" method
- 2D grid based on the tagging of the two large-R jets
  - Higgs or top tag
  - Number of b-tagged VRTrack jets inside large-R jet



- Validation Regions (VRs) enhanced in backgrounds → Validate background modeling





CERN-EP-2021-249 *Submitted to PRD January 18!*

$T \rightarrow Ht$ with hadronic final state

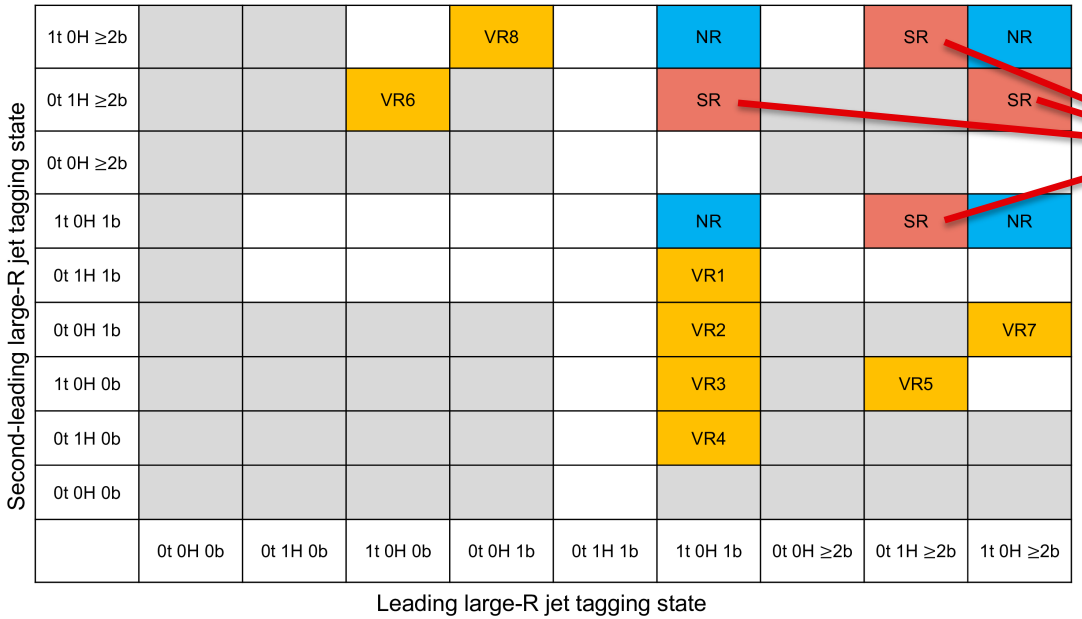
T→Ht with H→bb and t→qqb

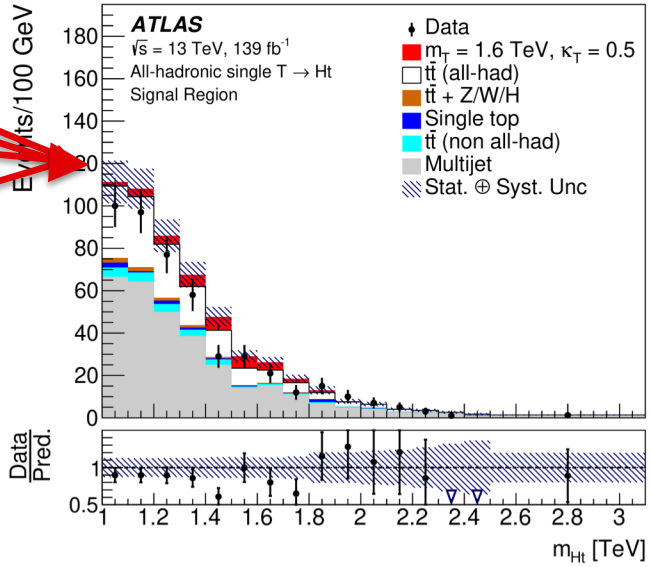
- 2 high-pT large-R jets with b-subjets

Dominant background from QCD multijet events

- Estimate from data using an extension of the "ABCD" method
- 2D grid based on the tagging of the two large-R jets
  - Higgs or top tag
  - Number of b-tagged VRTrack jets inside large-R jet

- Validation Regions (VRs) enhanced in backgrounds → Validate background modeling
- Signal Region (SR) enhanced in signal → Sensitive to T→Ht





CERN-EP-2021-249 *Submitted to PRD January 18!*

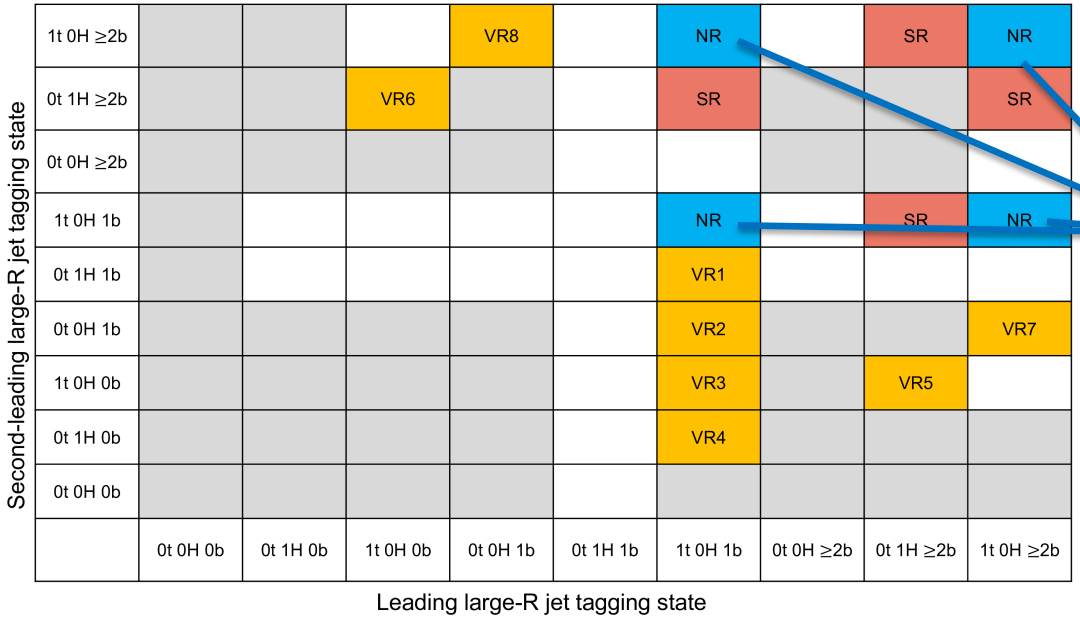
$T \rightarrow Ht$ with hadronic final state

T→Ht with H→bb and t→qqb

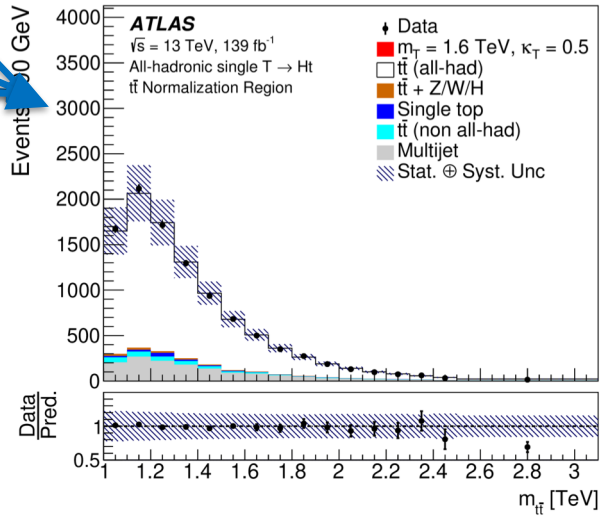
- 2 high-pT large-R jets with b-subjets

Dominant background from QCD multijet events

- Estimate from data using an extension of the "ABCD" method
- 2D grid based on the tagging of the two large-R jets
  - Higgs or top tag
  - Number of b-tagged VRTrack jets inside large-R jet



- Validation Regions (VRs) enhanced in backgrounds
  → Validate background modeling
- Signal Region (SR) enhanced in signal
  → Sensitive to T→Ht
- Normalization Region (NR) enhanced in ttbar
  → Use in fit to constrain ttbar



CERN-EP-2021-249 *Submitted to PRD January 18!*

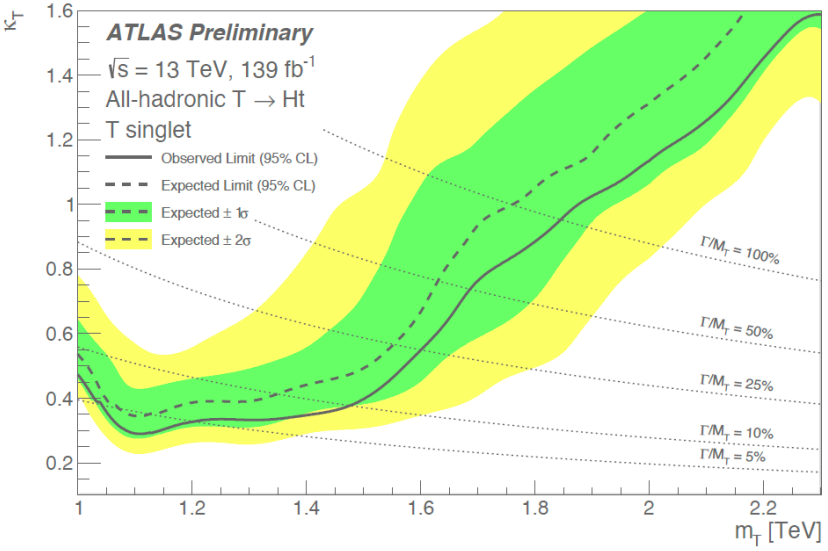
$T \rightarrow Ht$ with hadronic final state

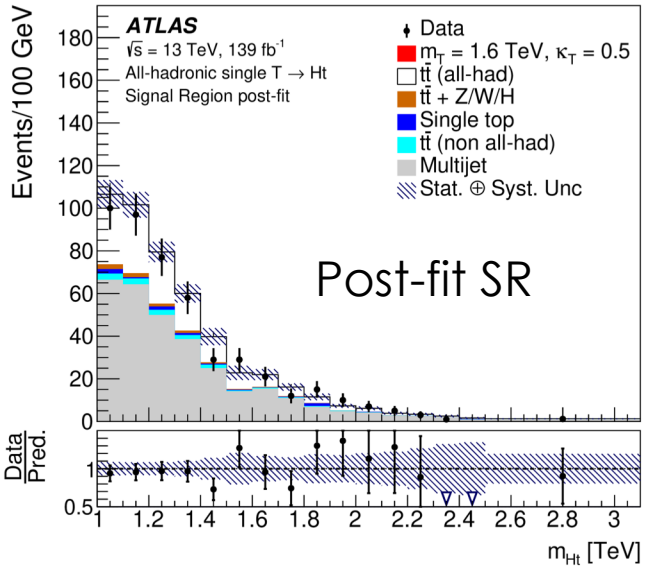
Simultaneous fit of dijet mass distribution in SR and NR

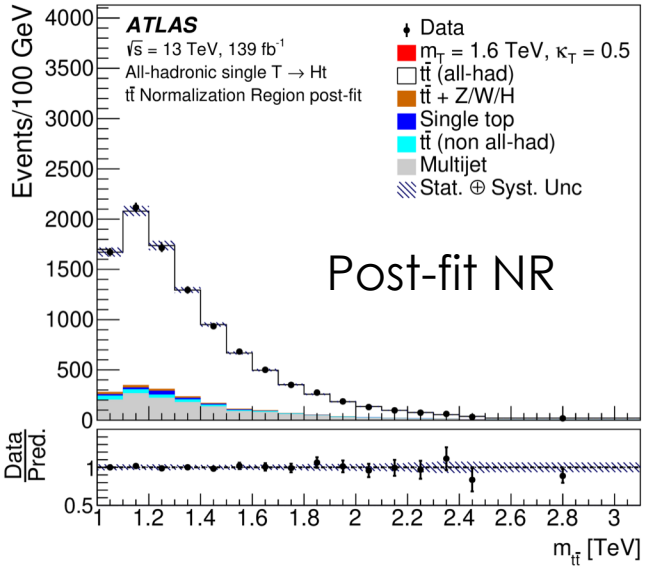
- Fit of signal cross section and normalization of tt background

Set limit as a function of the T mass m_T and coupling κ

⇒ Exclude couplings above $\kappa \simeq 0.4$ for low VLQ masses ($m_T \lesssim 1.5$ TeV)







CERN-EP-2021-249 *Submitted to PRD January 18!*

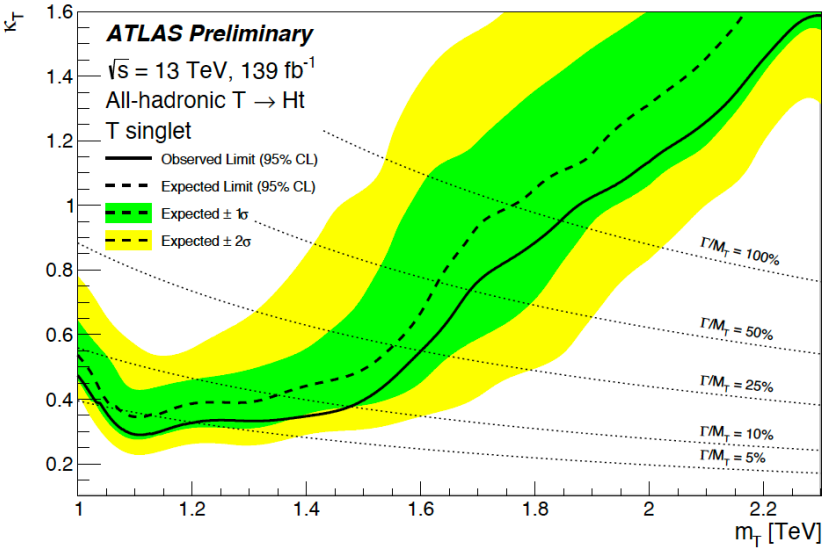
$T \rightarrow Ht$ with hadronic final state

Simultaneous fit of dijet mass distribution in SR and NR

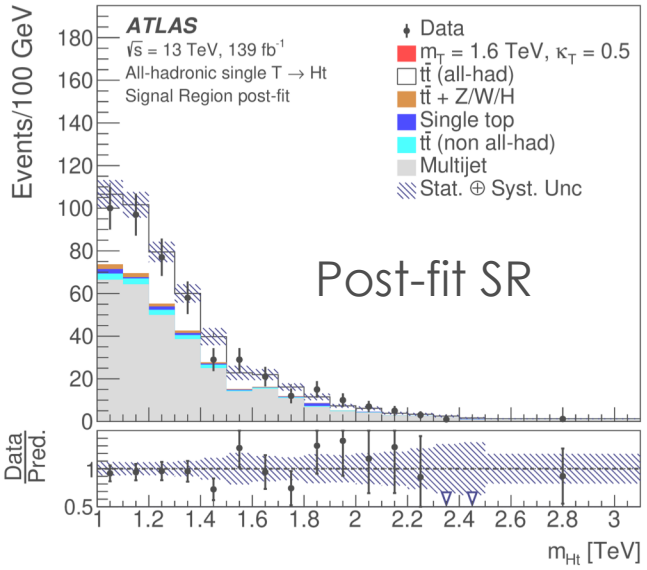
- Fit of signal cross section and normalization of tt background

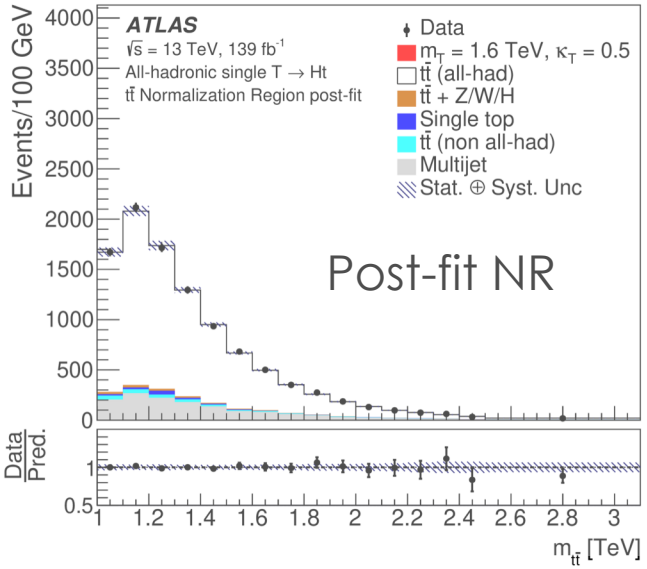
Set limit as a function of the T mass m_T and coupling κ

⇒ Exclude couplings above $\kappa \simeq 0.4$ for low VLQ masses ($m_T \lesssim 1.5$ TeV)

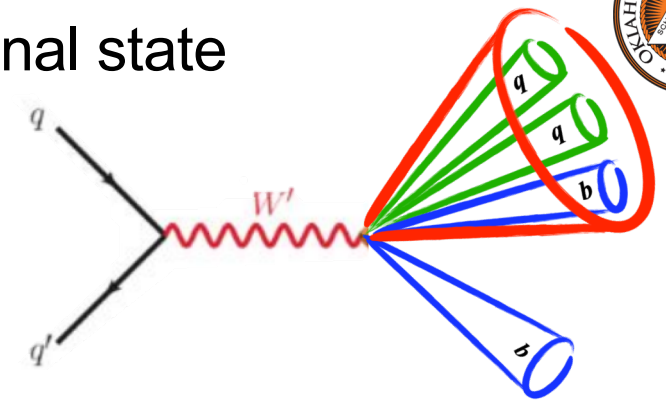


Sensitivity gains from improved multijet estimation, jet tagging, and exploitation of boosted topologies.





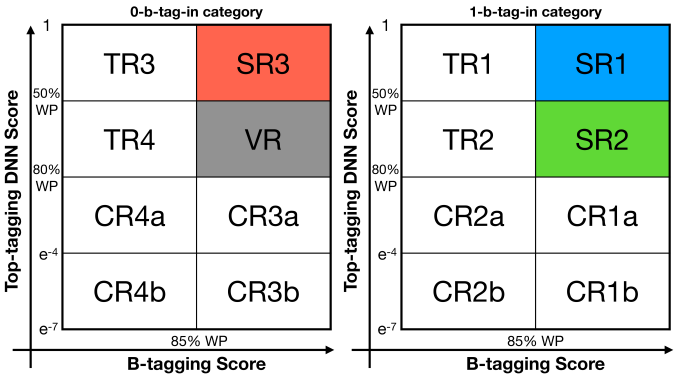
W'→tb with hadronic final state

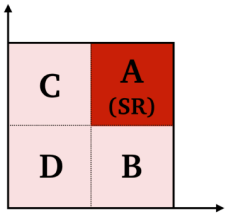


New heavy gauge bosons (W', Z') could explain the lepton-flavor universality deviations in recent LHCb & Belle results

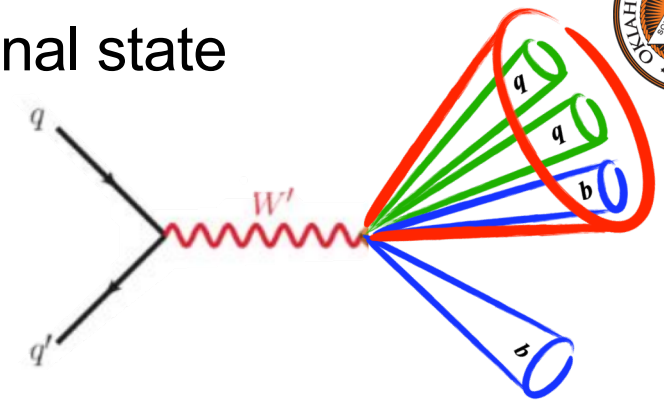
Heavy W' decaying to boosted top and b-quark

- Classify events by:
  - DNN top tag category
  - b-tag from W' decay
  - b-tagged jet in large-R jet
- Data-driven ABCD method to estimate for dominant multijet background
- Significant improvement from top and b-tagging and improved multijet estimate





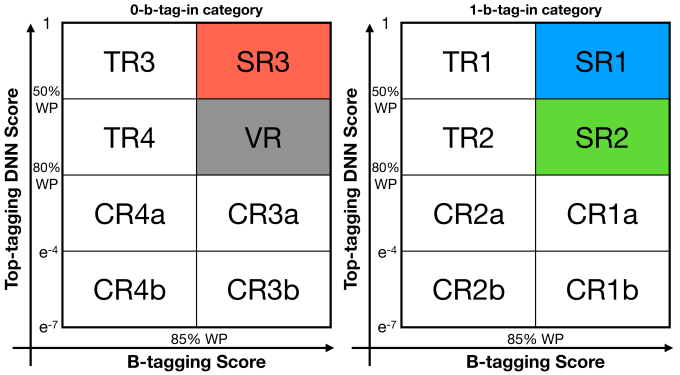
W'→tb with hadronic final state

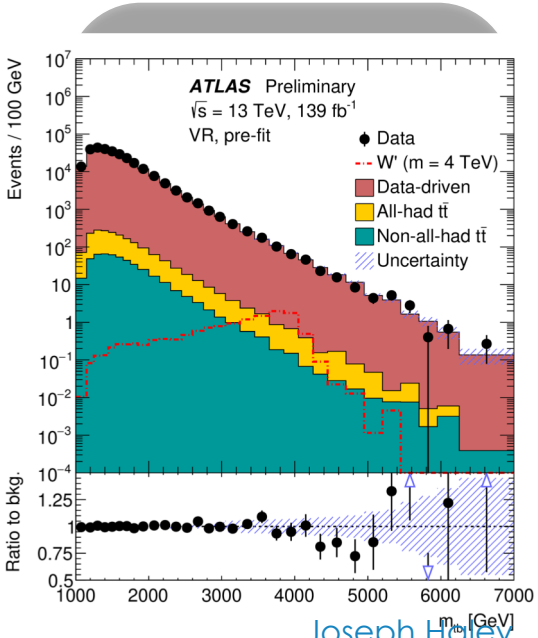


New heavy gauge bosons (W', Z') could explain the lepton-flavor universality deviations in recent LHCb & Belle results

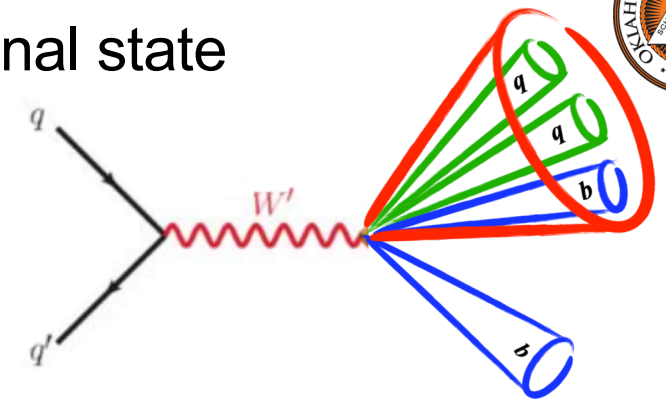
Heavy W' decaying to boosted top and b-quark

- Validate background modeling in VR





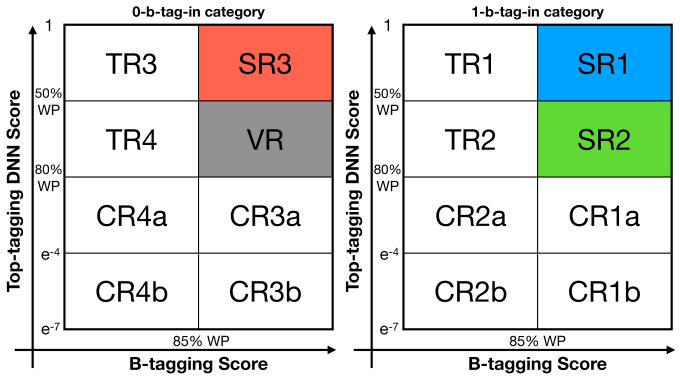
W'→tb with hadronic final state

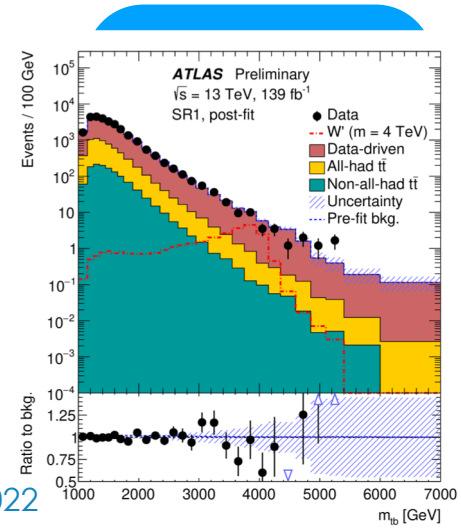


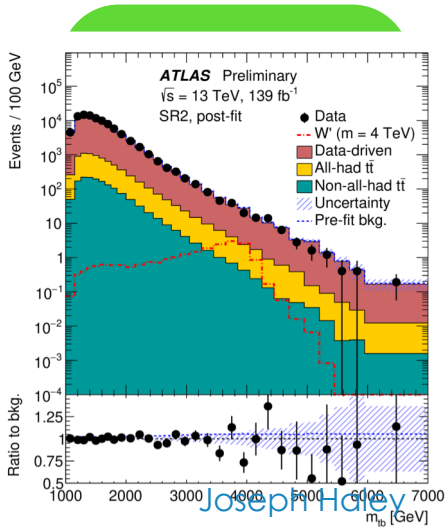
New heavy gauge bosons (W', Z') could explain the lepton-flavor universality deviations in recent LHCb & Belle results

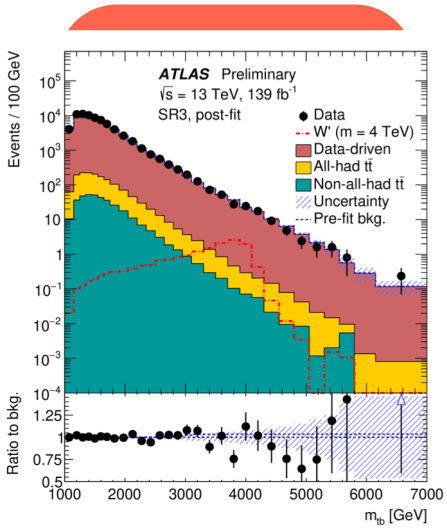
Heavy W' decaying to boosted top and b-quark

- Combined fit in SR1, SR2, SR3
  - Consistent with background-only

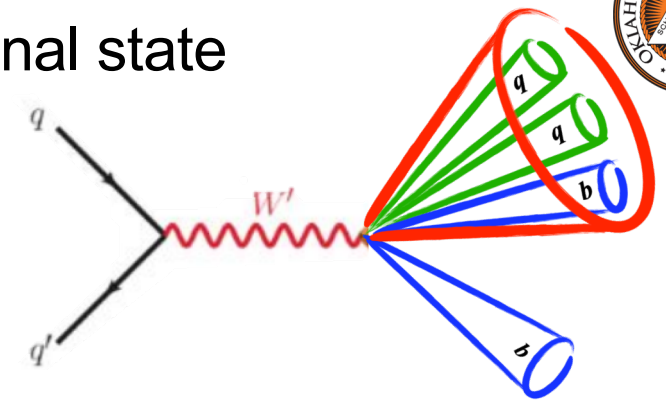








W'→tb with hadronic final state

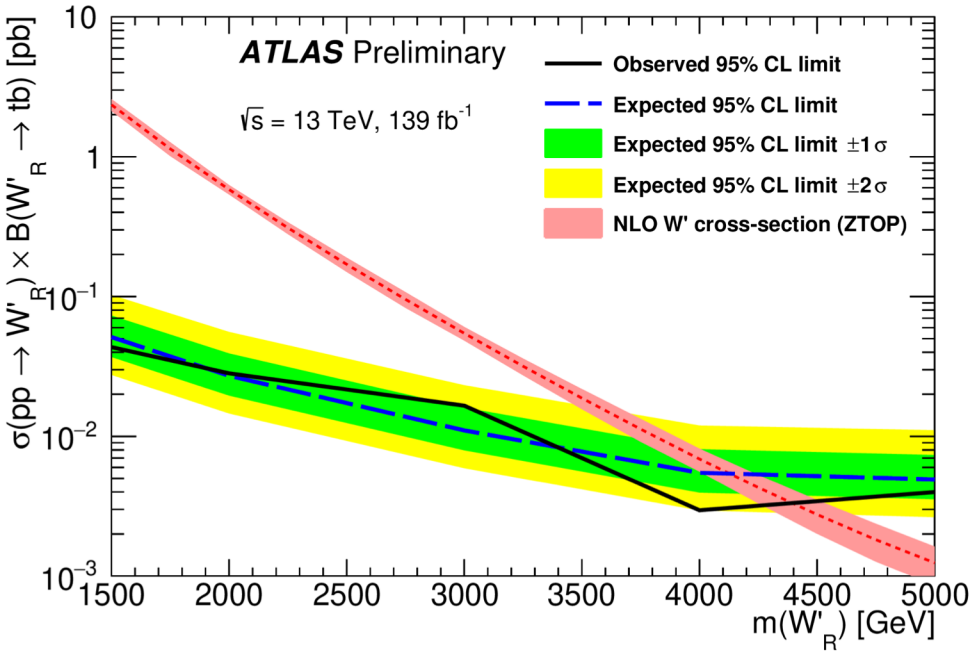


New heavy gauge bosons (W', Z') could explain the lepton-flavor universality deviations in recent LHCb & Belle results

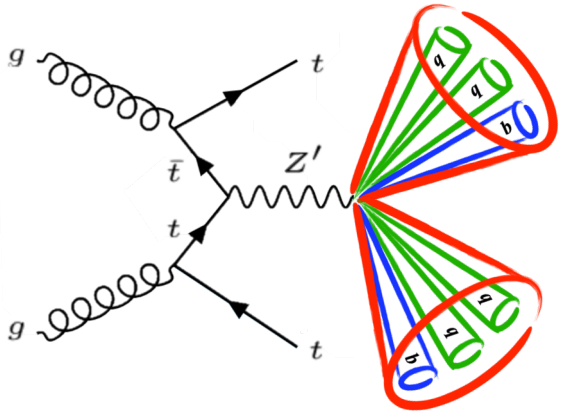
Heavy W' decaying to boosted top and b-quark

- Combined fit in SR1, SR2, SR3
  - Consistent with background-only
- Set limits on cross-section
  - Exclude W' with right-handed coupling for masses below 4.4TeV
  - Sensitivity limited by statistical uncertainty

Improvement in mass limit by 1TeV w.r.t previous result using 2015+2016 data (36fb^{-1})



Z'tt→tttt



Search for *top-philic* resonance

- Can only be produced in association with tt
- Reconstructed Z' from large-R jets with cuts on jet mass, pT, and number of subjets
- Suppress multijet background by requiring one lepton from associate tt

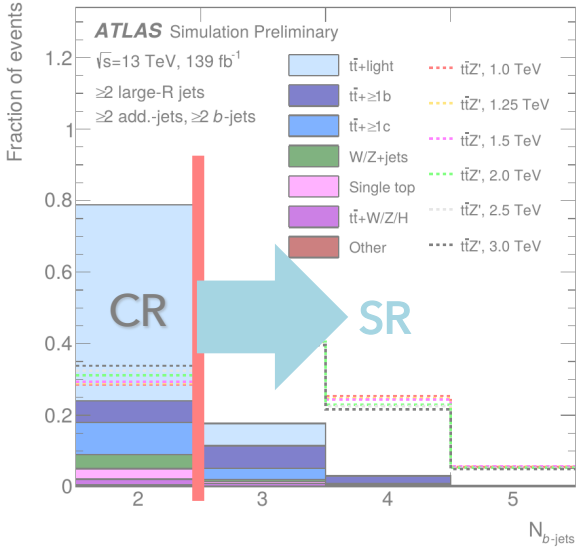
Define signal and control regions by multiplicities of additional jets and b-jets

(Mostly) data-driven background estimate

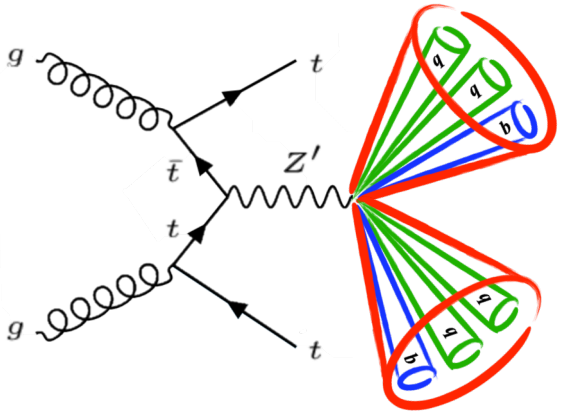
- Shape of background determined in control regions and extrapolated to signal regions
- Extrapolation factors derived from simulation

Scan m_{tt} spectrum in signal regions (BumpHunter)

⇒ No significant excesses (set limits)



Z'tt→tttt



Search for *top-philic* resonance

- Can only be produced in association with tt
- Reconstructed Z' from large-R jets with cuts on jet mass, pT, and number of subjets
- Suppress multijet background by requiring one lepton from associate tt

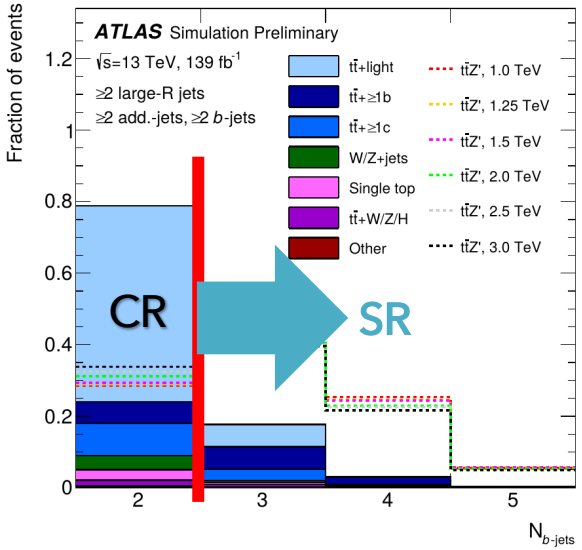
Define signal and control regions by multiplicities of additional jets and b-jets

(Mostly) data-driven background estimate

- Shape of background determined in control regions and extrapolated to signal regions
- Extrapolation factors derived from simulation

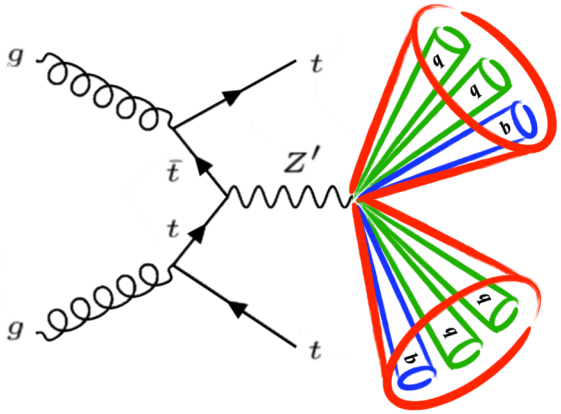
Scan m_{tt} spectrum in signal regions (BumpHunter)

⇒ No significant excesses (set limits)



ATLAS-CONF-2021-048

Z'tt→tttt



Search for *top-philic* resonance

- Can only be produced in association with tt
- Reconstructed Z' from large-R jets with cuts on jet mass, pT, and number of subjets
- Suppress multijet background by requiring one lepton from associate tt

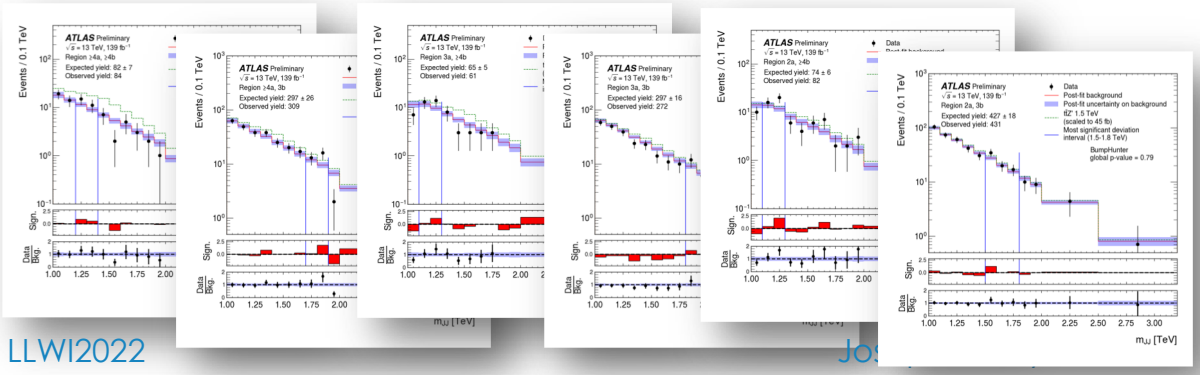
Define signal and control regions by multiplicities of additional jets and b-jets

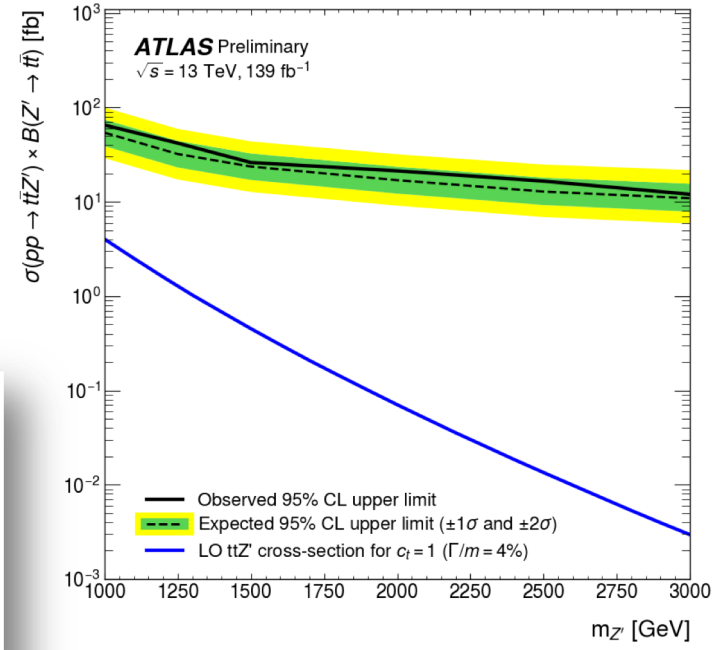
(Mostly) data-driven background estimate

- Shape of background determined in control regions and extrapolated to signal regions
- Extrapolation factors derived from simulation

Scan m_{tt} spectrum in signal regions (BumpHunter)

⇒ No significant excesses (set limits)





Phys. Rev. D 105 (2022) 012001

Z'bb→bbbb

Reconstruct Z' from two highest-p_T b-jets

Require one or two additional b-jets to reduce dominant multijet background

- Not required in previous searches

New trijet trigger with asymmetric p_T thresholds

- Added in 2017 ⇒ 103 fb^{-1} of data

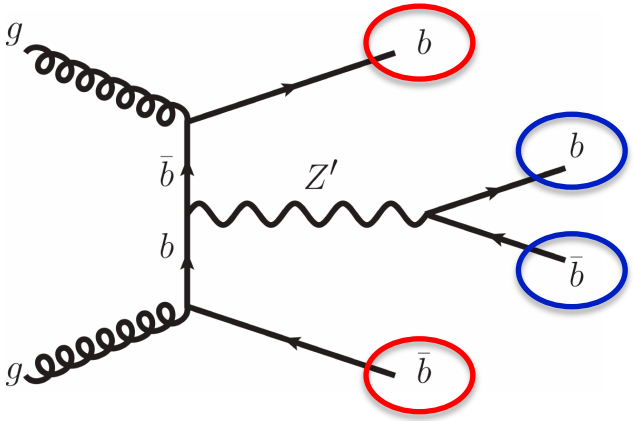
Data-driven estimate using functional decomposition (FD)

- Background spectrum given by series of orthonormal exponential basis functions

$$\Omega(z) = \sum_{n=1}^{N} c_n E_n(z)$$

Scan dijet mass spectrum (BumpHunter)

⇒ No significant excesses (set limits)



Phys. Rev. D 105 (2022) 012001

Z'bb→bbbb

Reconstruct Z' from two highest-p_T b-jets

Require one or two additional b-jets to reduce dominant multijet background

- Not required in previous searches

New trijet trigger with asymmetric p_T thresholds

- Added in 2017 ⇒ 103 fb^{-1} of data

Data-driven estimate using functional decomposition (FD)

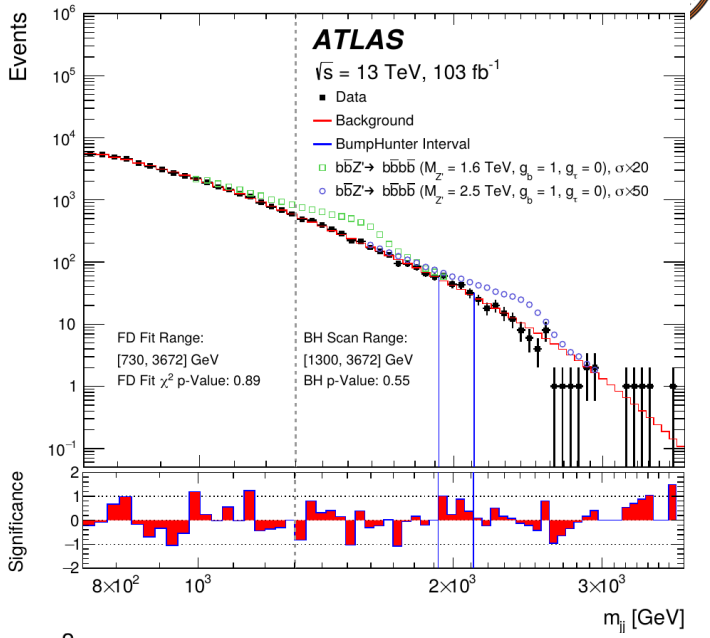
- Background spectrum given by series of orthonormal exponential basis functions

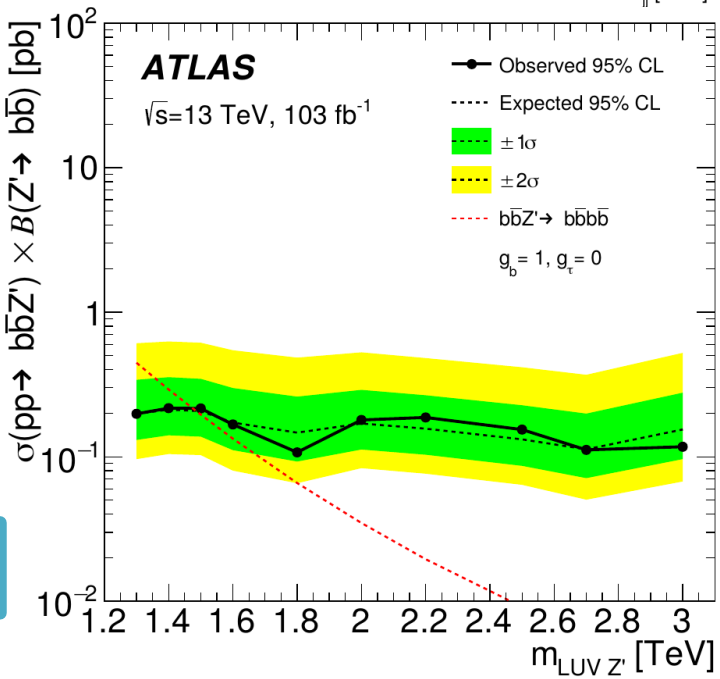
$$\Omega(z) = \sum_{n=1}^{N} c_n E_n(z)$$

Scan dijet mass spectrum (BumpHunter)

⇒ No significant excesses (set limits)

20-50% improvement from additional b-jet requirement!

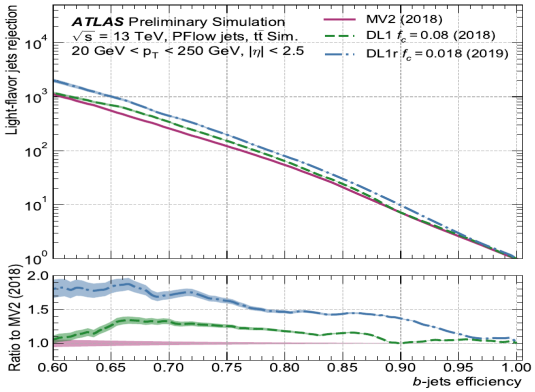




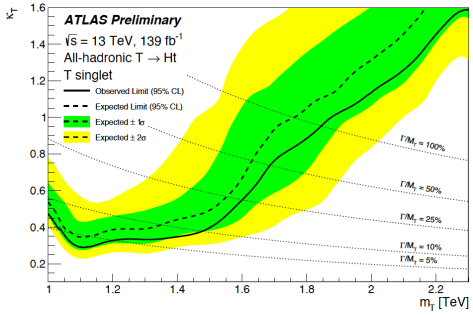
Conclusion

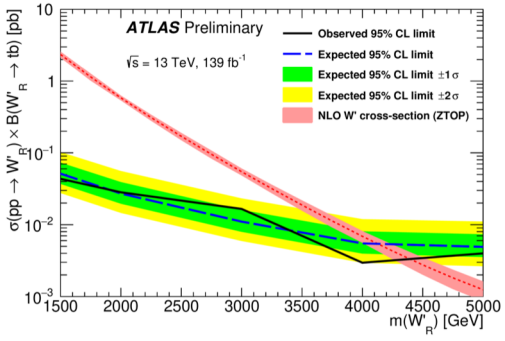
Many recent results from searches for new particles that decay to top and bottom quarks using ATLAS Run 2 data

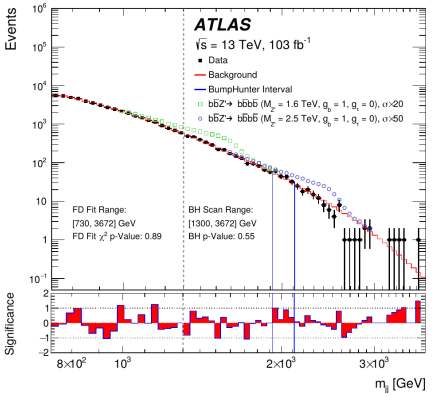
- Significant improvements in sensitivity provided by new b- and top-tagging techniques
- Also improved background modeling



Unfortunately, still no signs of new physics…







But more Run 2 analyses coming soon!

… And Run 3 just around the corner!!!

Thank you!

(Time for lunch!)

List of presented analyses

- Search for pair-production of vector-like quarks in *pp* collision events at √s =13 TeV with at least one leptonically-decaying *Z* boson and a third-generation quark with the ATLAS detector (ATLAS-CONF-2021-024)
- Search for single production of vector-like *T* quarks decaying to *Ht* or *Zt* in *pp* collisions at √s =13 TeV with the ATLAS detector (ATLAS-CONF-2021-040)
- Search for single Vector-Like *B* -quark production and decay via $B \rightarrow bH(bb)$ in pp collisions at √s =13 TeV with the ATLAS detector (ATLAS-CONF-2021-018)
- Search for vector boson resonances decaying to a top quark and a bottom quark in hadronic final states using *pp* collisions at √s =13 TeV with the ATLAS detector (ATLAS-CONF-2021-043)
- Search for heavy resonances in four-top-quark final states in *pp* collisions at √s=13 TeV with the ATLAS detector (ATLAS-CONF-2021-048)
- Search for heavy particles in the *b*-tagged dijet mass distribution with additional *b*-tagged jets in proton-proton collisions at √s=13 TeV with the ATLAS experiment (arXiv:2108.09059)
- Search for a vector-like quark produced in 13 TeV proton-proton collisions and decaying into a Higgs boson and top quark with a fully-hadronic final state at ATLAS (EXOT-2019-07)

B → bH(bb)

Identification of 3 b-jets important for dominant (90%) multijet background suppression

Identify boosted H➞bb as large-R jet with mass ≈ m_H, 2-pronged substructure, jand associated b-tagged variable-radius track jets (VRtrack jets)

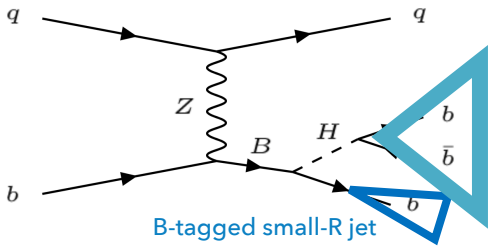
Purely data-driven background estimate using several orthogonal auxiliary regions ("ABCD method")

- Extrapolate background from control region (B) to search region (A) using transfer functions measured in neighboring regions (C/D)

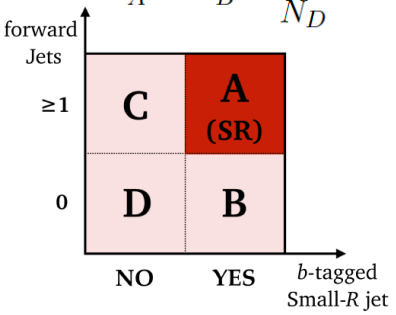
Binned maximum-likelihood fit to reconstructed VLB mass distribution m_B

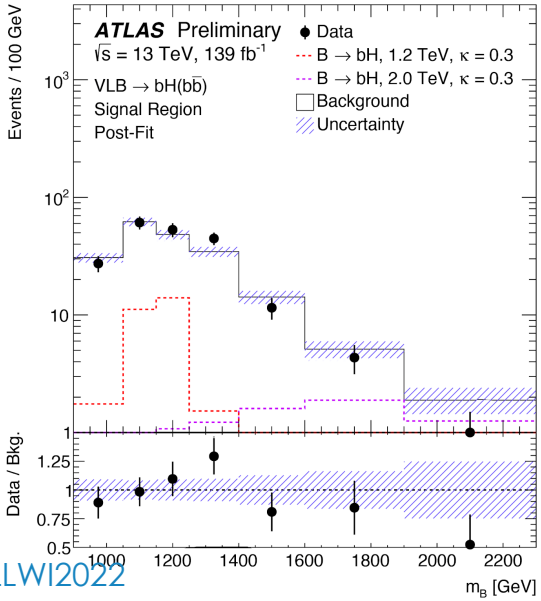
No significant excesses found in full Run 2 dataset
⇒ Set limits on coupling and as a function of the VLB mass:

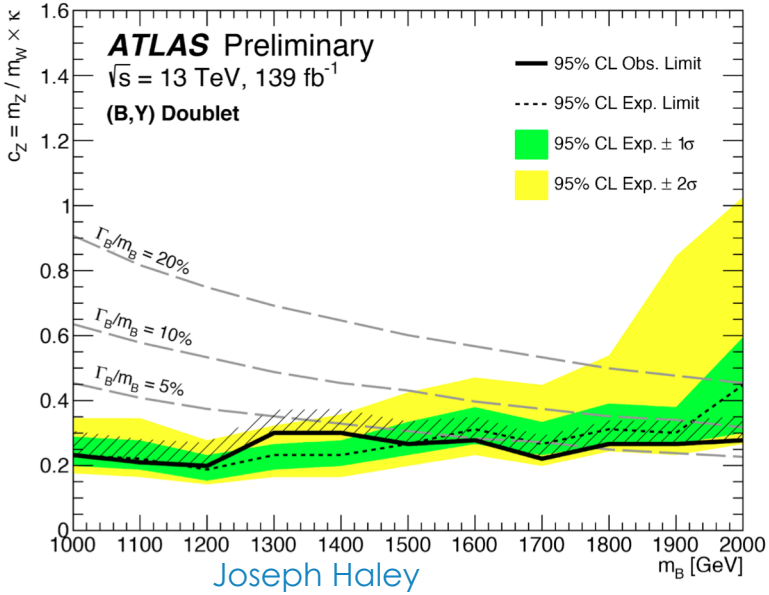
Reclustered large-R jet with two matched b-tagged VRtrack jets



$$N_A = N_B \times \frac{N_C}{N_D}$$







Significantly extended VLB parameter space being probed (previous limits: for (B,Y) doublet scenario @1.2TeV)