Searches for vector-like quarks with the ATLAS detector

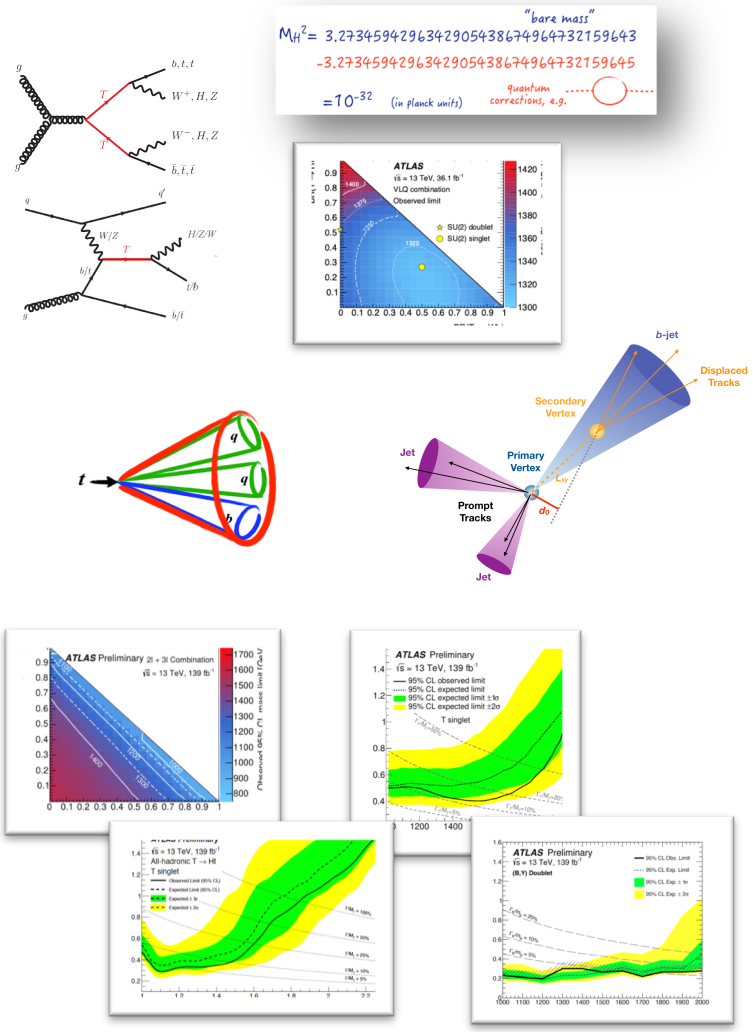
Joe Haley
Oklahoma State Universtiy

BEACH 2022

XIV INTERNATIONAL CONFERENCE ON BEAUTY, CHARM AND HYPERON HADRONS

5-11 June 2022 AGH-UST Kraków, Poland

Overview



Vector-like quarks

- What are they?
- Why should you care?
- What do they look like?
- Previous Results (36.1 fb^{-1})

Improved techniques

- Top-Tagging
- b-Tagging

Results using Full Run 2 Dataset (139 fb^{-1})

- TT→Zt+X, with Z→ℓℓ
- T→Ht/Zt, with t→lνb
- T→Ht with hadronic final state
- B→Hb, with H→bb

Conclusion

Vector-like Quarks

"Quarks": Color-triplet, spin-½ particles

"Vector-like": Left and right chiralities have the same weak isospin

- Weak current is vector-like:

VLQs: $(\bar{Q}\gamma^\mu Q')$ SM quarks: $(\bar{q}\gamma^\mu(1-\gamma^5)q')$

- Can have bare VLQ mass term
  ⇒ Avoids constraints from Higgs measurements

Couple to SM through mixing with SM quarks
Naturalness + FCNC constraints ⇒ mixing mostly with 3rd generation

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

Vector-like Quarks

"Quarks": Color-triplet, spin-½ particles

"Vector-like": Left and right chiralities have the same weak isospin

- Weak current is vector-like:

VLQs: $(\bar{Q}\gamma^{\mu}Q')$ SM quarks: $(\bar{q}\gamma^{\mu}(1-\gamma^{5})q')$

- Can have bare VLQ mass term
  ⇒ Avoids constraints from Higgs measurements

Couple to SM through mixing with SM quarks
Naturalness + FCNC constraints ⇒ mixing mostly with 3rd generation

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

Vector-like Quarks

"Quarks": Color-triplet, spin-½ particles

"Vector-like": Left and right chiralities have the same weak isospin

- Weak current is vector-like:

VLQs: $(\bar{Q}\gamma^{\mu}Q')$ SM quarks: $(\bar{q}\gamma^{\mu}(1-\gamma^{5})q')$

- Can have bare VLQ mass term
  ⇒ Avoids constraints from Higgs measurements

Couple to SM through mixing with SM quarks
Naturalness + FCNC constraints ⇒ mixing mostly with 3rd generation

Top-partner T →
Bottom-partner B →

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			

Naturalness

What is naturalness?

If X is an observable that depends on n independent inputs, a_i:

$$X = a_1 + a_2 + \ldots + a_n$$

It would be unnatural to have some $|a_i| >> |X|$

Natural:

$a_1 = 4$

$a_2 = 2{,}098{,}572{,}309{,}800$

$a_3 = -1{,}099{,}785$

$\Rightarrow X = 2{,}098{,}571{,}210{,}019$

Unnatural:

$a_1 = 4$

$a_2 = 2{,}098{,}572{,}309{,}800$

$a_3 = -2{,}098{,}572{,}309{,}885$

$\Rightarrow X = -81$

Naturalness

What is naturalness?

If X is an observable that depends on n independent inputs, a_i:

$X = a_1 + a_2 + \ldots + a_n$

It would be unnatural to have some $|a_i| \gg |X|$

Natural:

$a_1 = 4$
$a_2 = 2{,}098{,}572{,}309{,}800$
$a_3 = -1{,}099{,}785$

$\Rightarrow X = 2{,}098{,}571{,}210{,}019$

Unnatural:

$a_1 = 4$
$a_2 = 2{,}098{,}572{,}309{,}800$
$a_3 = -2{,}098{,}572{,}309{,}885$

$\Rightarrow X = -81$

The "Hierarchy Problem"

The mass (squared) of the Higgs gets quantum corrections from interacting with other particles: $M_H^2 = 2\mu^2 + (\delta m_1)^2 + (\delta m_2)^2 + \ldots$

The most significant correction comes from top quarks, which causes a quadratic divergence!

- If the SM is correct up to the Planck scale

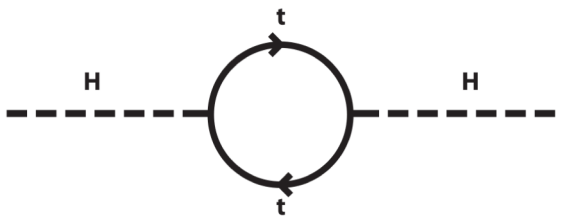
"bare mass"

$M_H^2 = 3.27345942963429054386749647321596 43$

$-3.27345942963429054386749647321596 45$

$= 10^{-32}$ (in planck units)

quantum corrections, e.g.



from Roni Harnik

Having vector-like quarks could naturally cancel the divergent top correction!

- Adding a ~400 GeV vector-like top (T):

$M_H^2 \sim 10 - 9 = 1$ (in units of ~100 GeV squared)

- Thus, VLQs show up in many BSM scenarios
  - Little/Composite Higgs, Topcolor, GUTs, …
- **And naturalness requires mass ~1 TeV ⇒ Accessible at the LHC!**

The "Hierarchy Problem"

The mass (squared) of the Higgs gets quantum corrections from interacting with other particles: $M_H^2 = 2\mu^2 + (\delta m_1)^2 + (\delta m_2)^2 + \ldots$

The most significant correction comes from top quarks, which causes a quadratic divergence!

- If the SM is correct up to the Planck scale

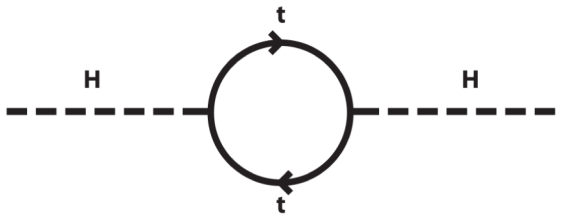
"bare mass"

$M_H^2 = 3.27345942963429054386749647321596 43$

$-3.27345942963429054386749647321596 45$

$= 10^{-32}$ (in planck units)

quantum corrections, e.g.

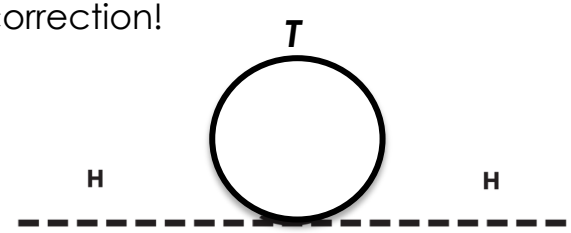


from Roni Harnik

Having vector-like quarks could naturally cancel the divergent top correction!

- Adding a ~400 GeV vector-like top (T):

$M_H^2 \sim 10 - 9 = 1$ (in units of ~100 GeV squared)



- Thus, VLQs show up in many BSM scenarios
  - Little/Composite Higgs, Topcolor, GUTs, …
- **And naturalness requires mass ~1 TeV ⇒ Accessible at the LHC!**

The "Hierarchy Problem"

The mass (squared) of the Higgs gets quantum corrections from interacting with other particles: $M_H^2 = 2\mu^2 + (\delta m_1)^2 + (\delta m_2)^2 + \ldots$

The most significant correction comes from top quarks, which causes a quadratic divergence!

- If the SM is correct up to the Planck scale

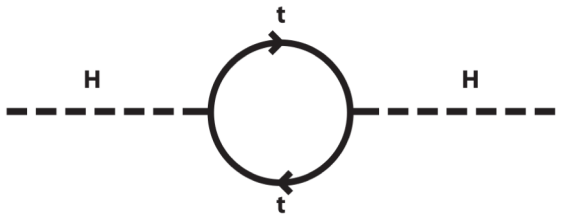
"bare mass"

$M_H^2 = 3.27345942963429054386749647321596 43$

$-3.27345942963429054386749647321596 45$

$= 10^{-32}$ (in planck units)

quantum corrections, e.g.

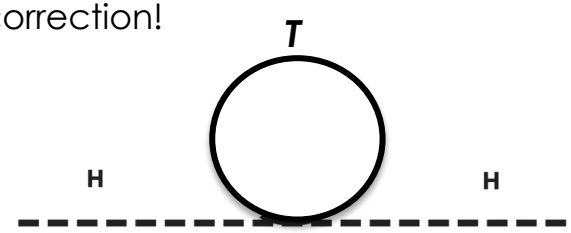


from Roni Harnik

Having vector-like quarks could naturally cancel the divergent top correction!

- Adding a ~400 GeV vector-like top (T):

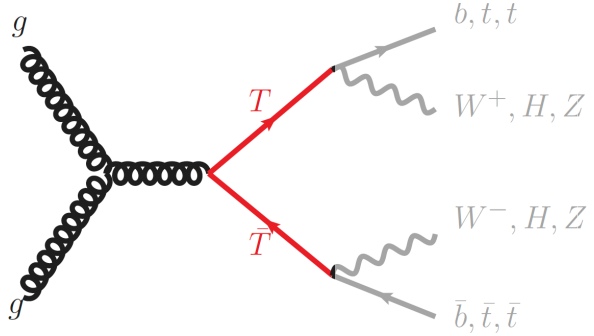
$M_H^2 \sim 10 - 9 = 1$ (in units of ~100 GeV squared)



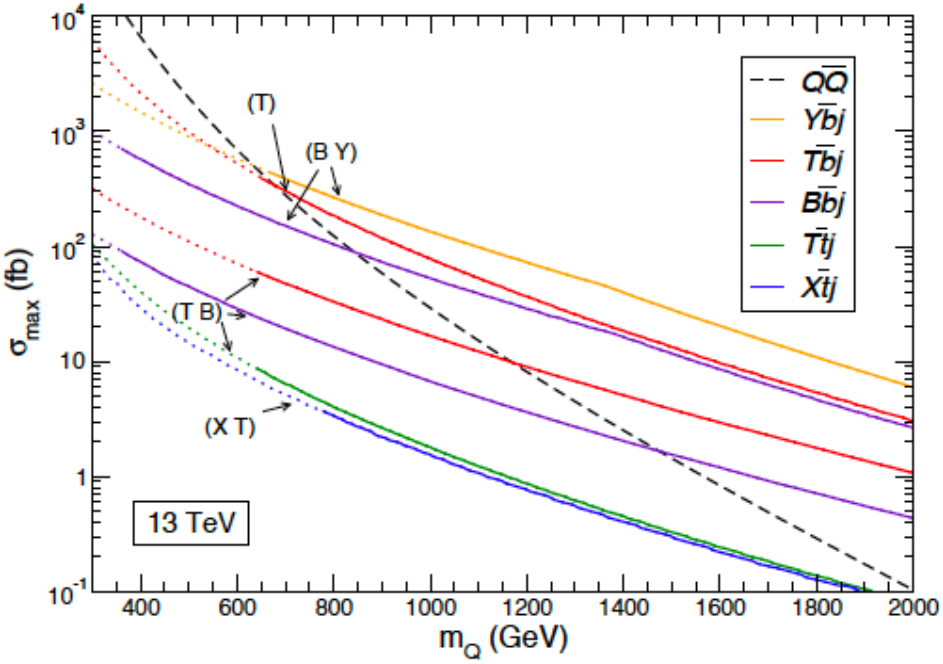
- Thus, VLQs show up in many BSM scenarios
  - Little/Composite Higgs, Topcolor, GUTs, …
- **And naturalness requires mass ~1 TeV ⇒ Accessible at the LHC!**

What do we look for?

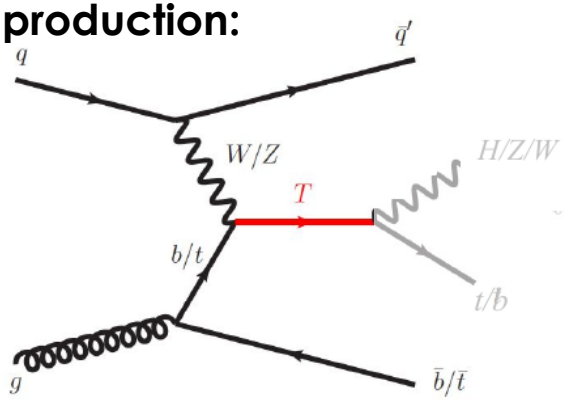
Pair Production:



- 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

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

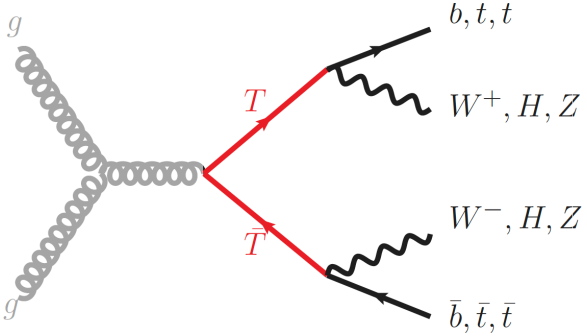
  $B \rightarrow Wt,\ Zb,\ Hb$

- Branching ratios depend on model/representation

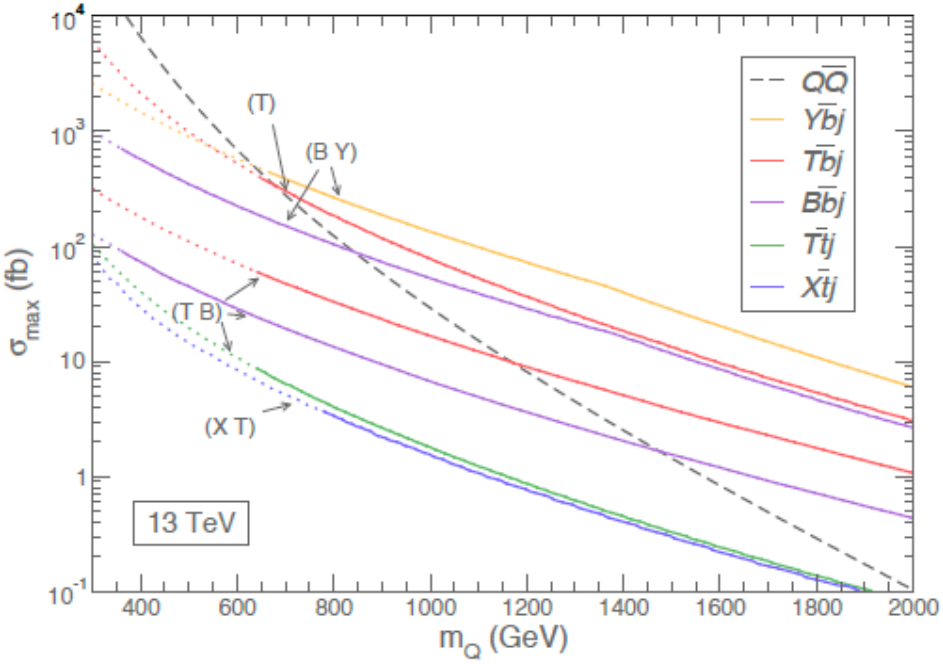
  $(T),\ (T,B),\ (X,T),\ (X,T,B),$ etc.

What do we look for?

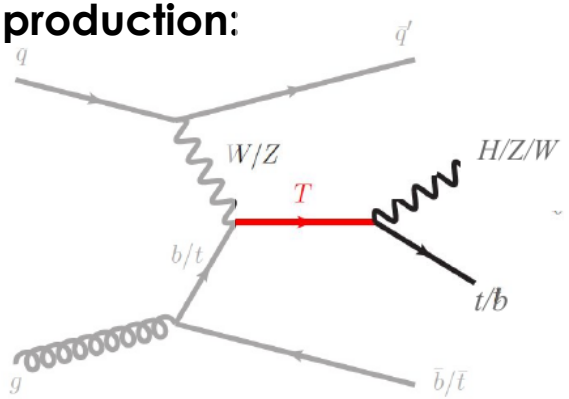
Pair Production:



- 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

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

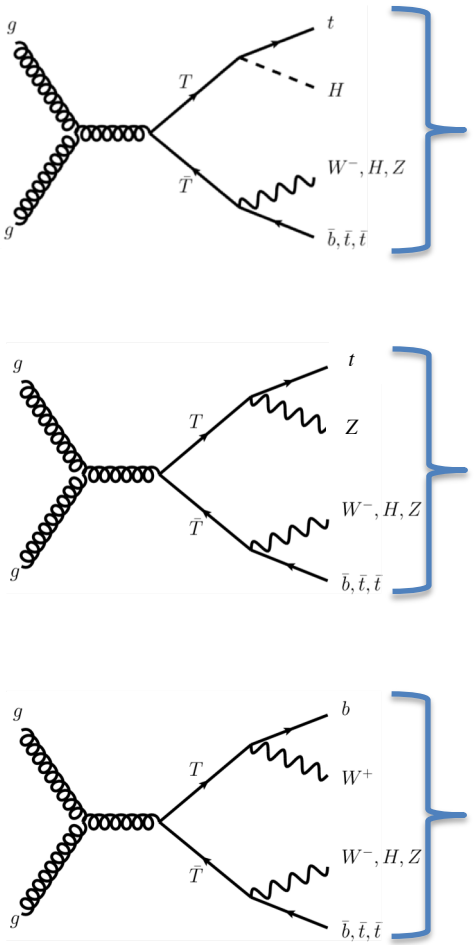
  $B \rightarrow Wt,\ Zb,\ Hb$

- Branching ratios depend on model/representation

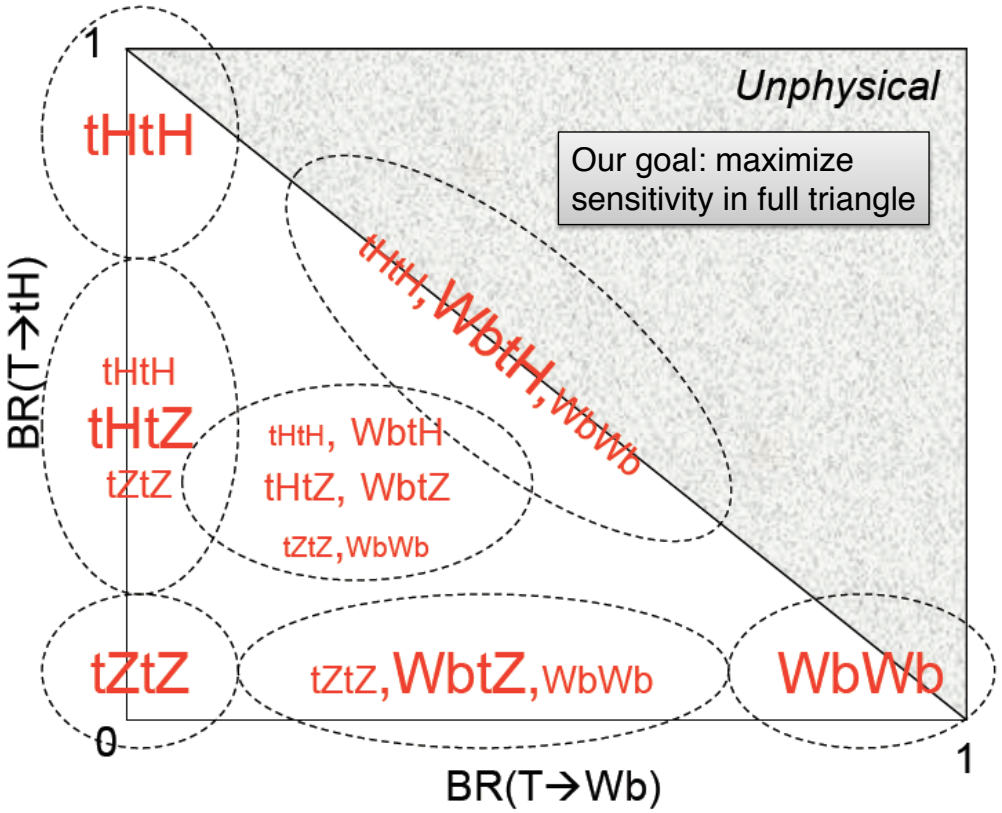
  $(T),\ (T,B),\ (X,T),\ (X,T,B),$ etc.

General Strategy

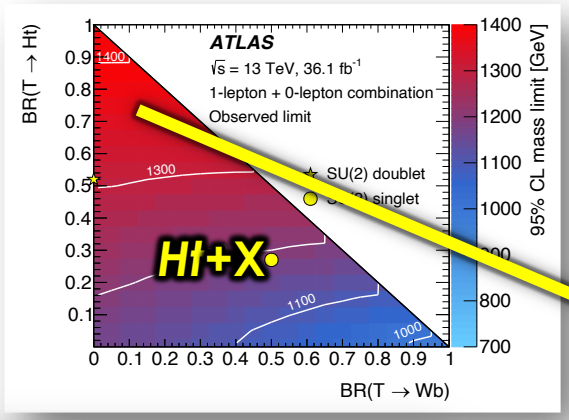
Multiple analyses to target each decay:

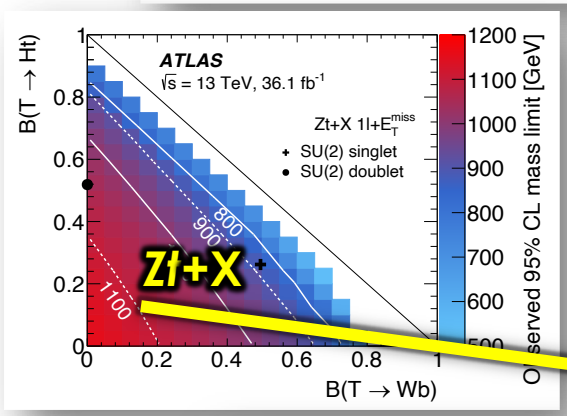


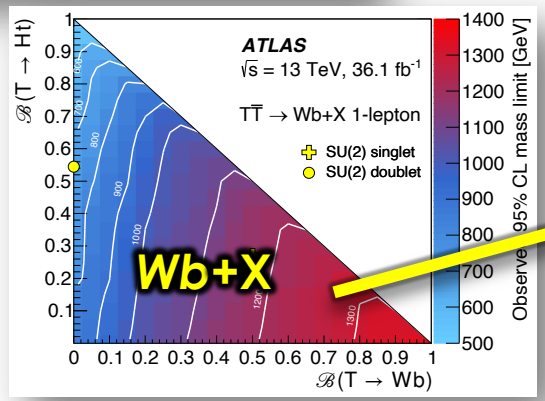
Test all possible branching ratios:

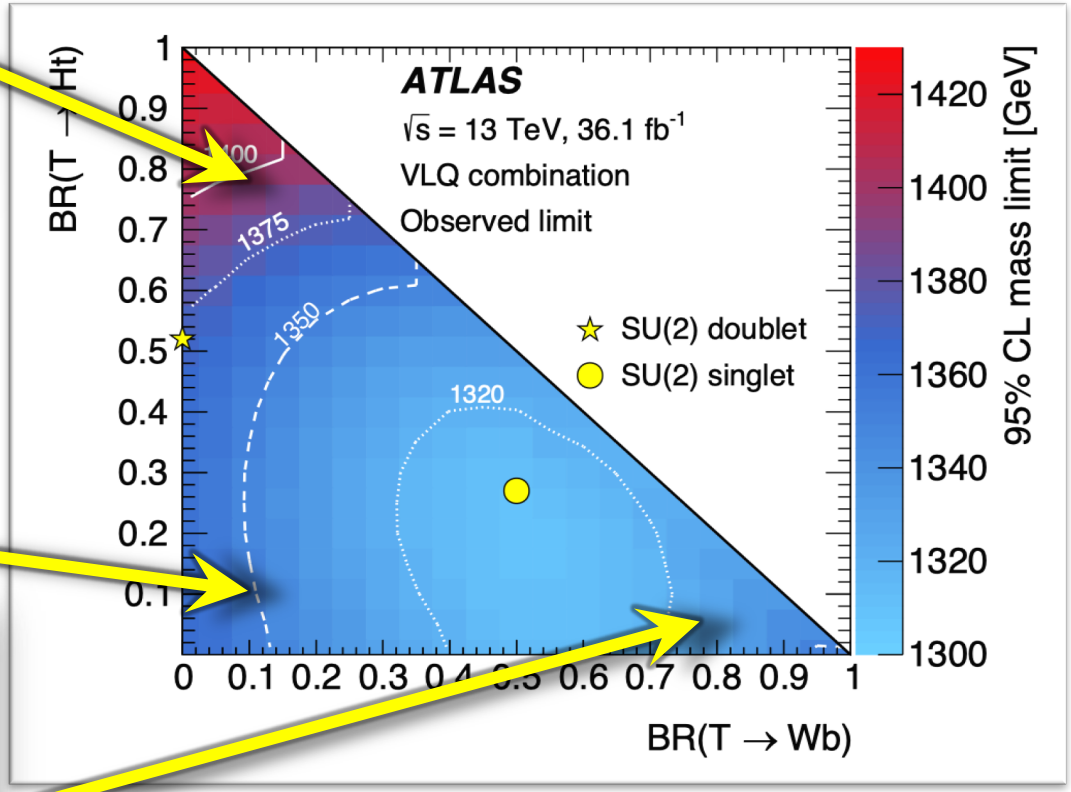


Previous Results (36.1 fb^{-1})



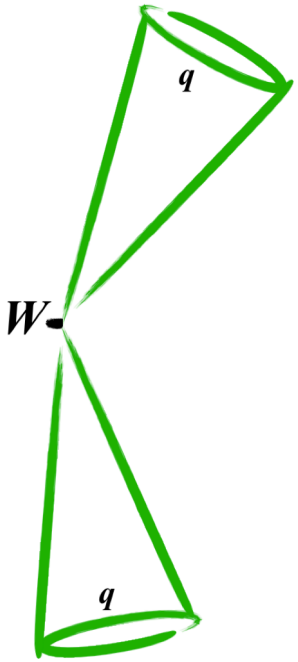


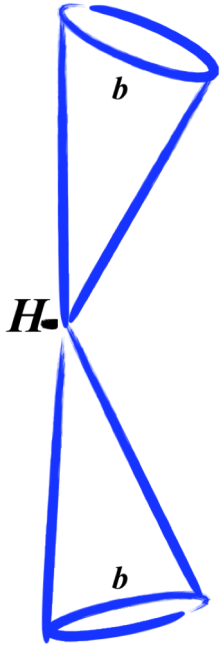


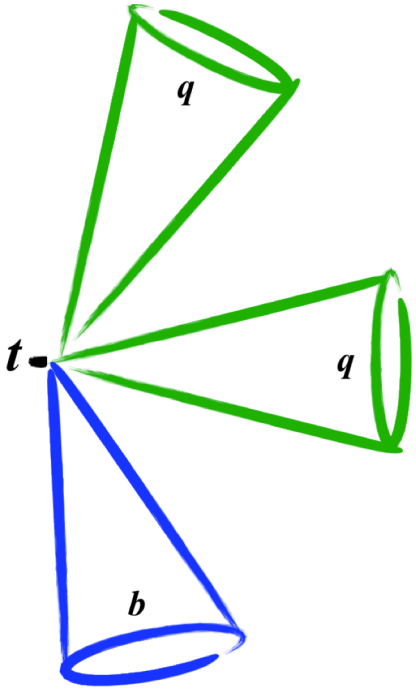


Heavy Objects

With low-p_T:



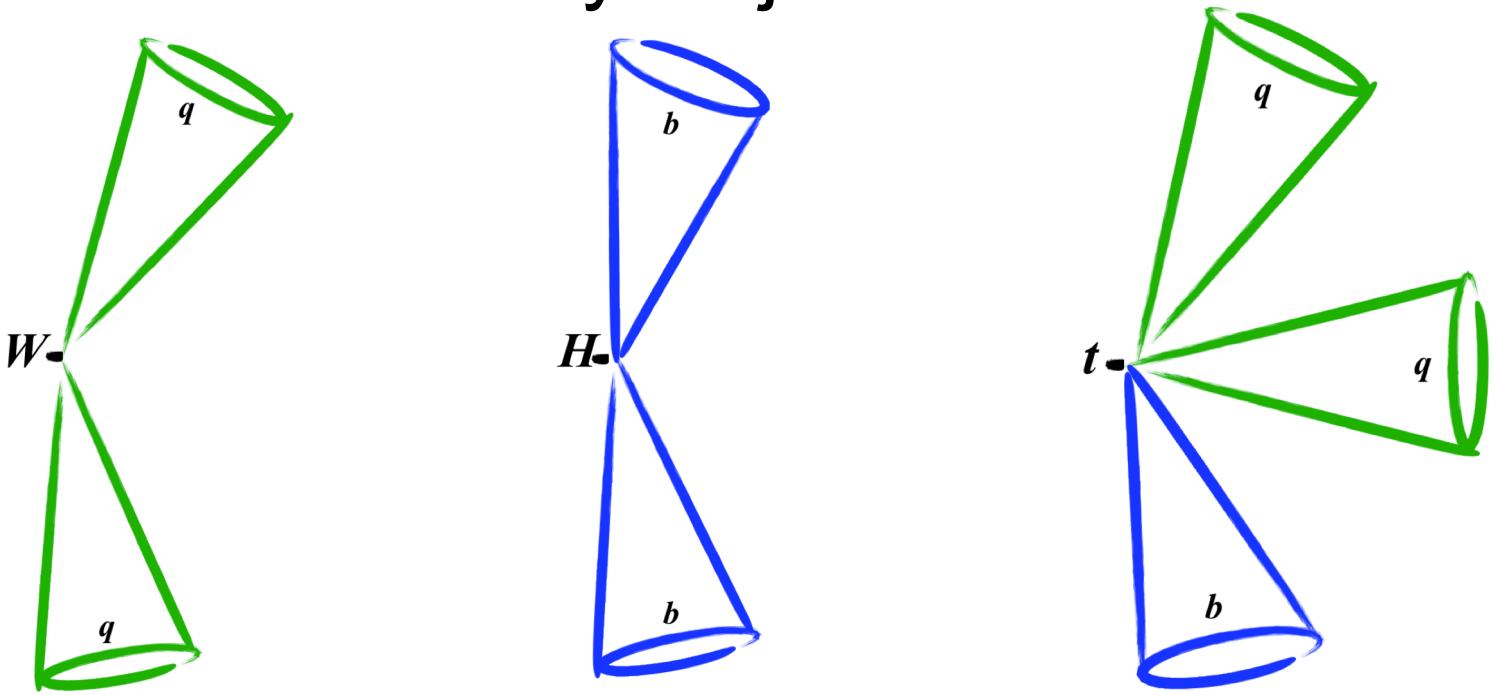




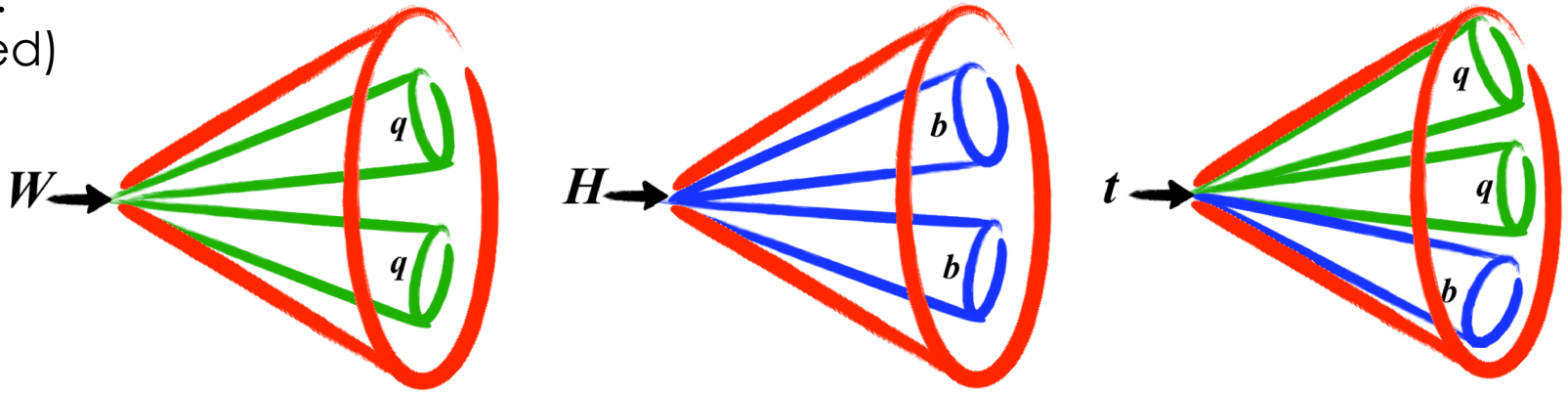
high-p_T: (boosted)

Heavy Objects

With low-p_T:



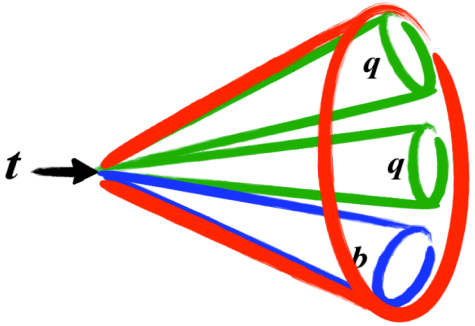
high-p_T: (boosted)



top-tagging

Identify high-p_T **top** quarks ("boosted-tops")

- Large-radius jet with highly collimated sub-jets, including one b-jet



⇒ Deep Neural Network top-tagger

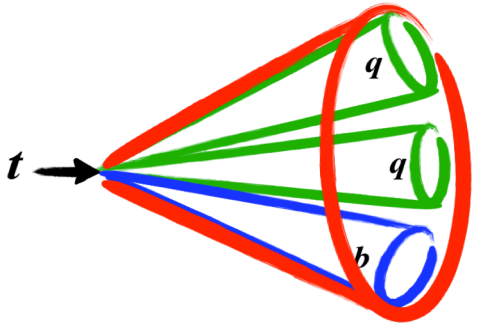
- Uses kinematics (jet mass, p_T, etc.) and dispersion of jet constituents (N-subjettiness, splitting scales, and energy correlation functions)

Inclusive top-tagger allows some of decay productions to fall outside large-R jet

top-tagging

Identify high-p_T **top** quarks ("boosted-tops")

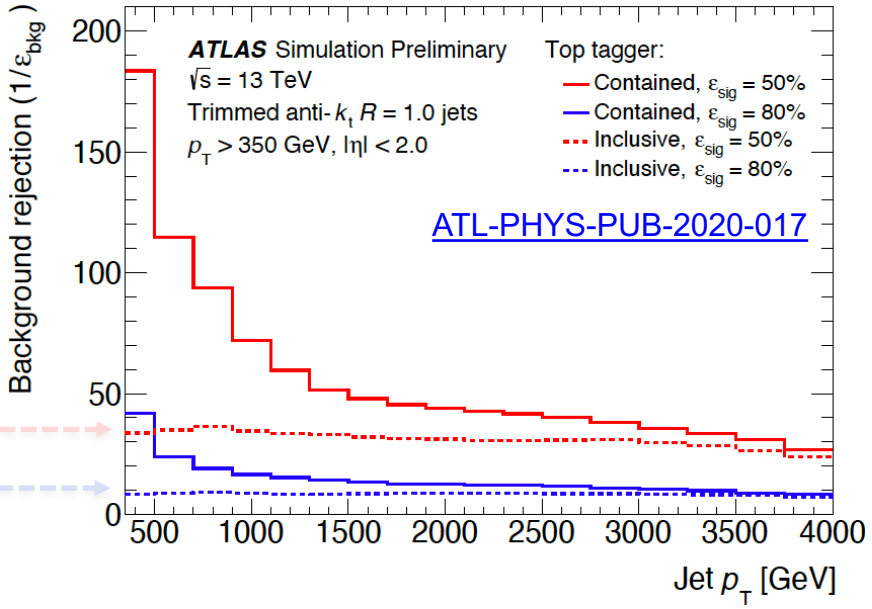
- Large-radius jet with highly collimated sub-jets, including one b-jet



⇒ Deep Neural Network top-tagger

- Uses kinematics (jet mass, p_T, etc.) and dispersion of jet constituents (N-subjettiness, splitting scales, and energy correlation functions)

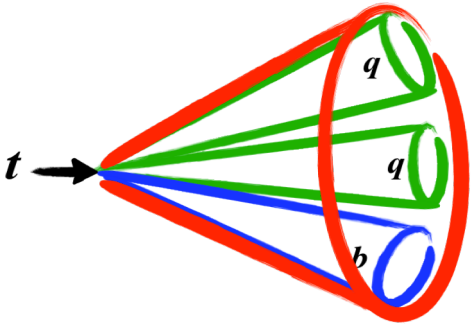
Inclusive top-tagger allows some of decay productions to fall outside large-R jet



top-tagging

Identify high-p_T **top** quarks ("boosted-tops")

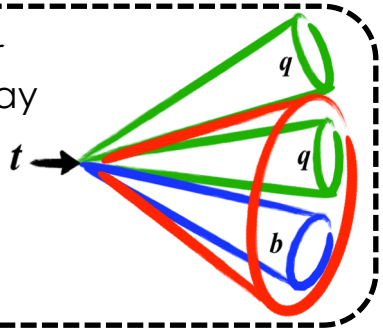
- Large-radius jet with highly collimated sub-jets, including one b-jet

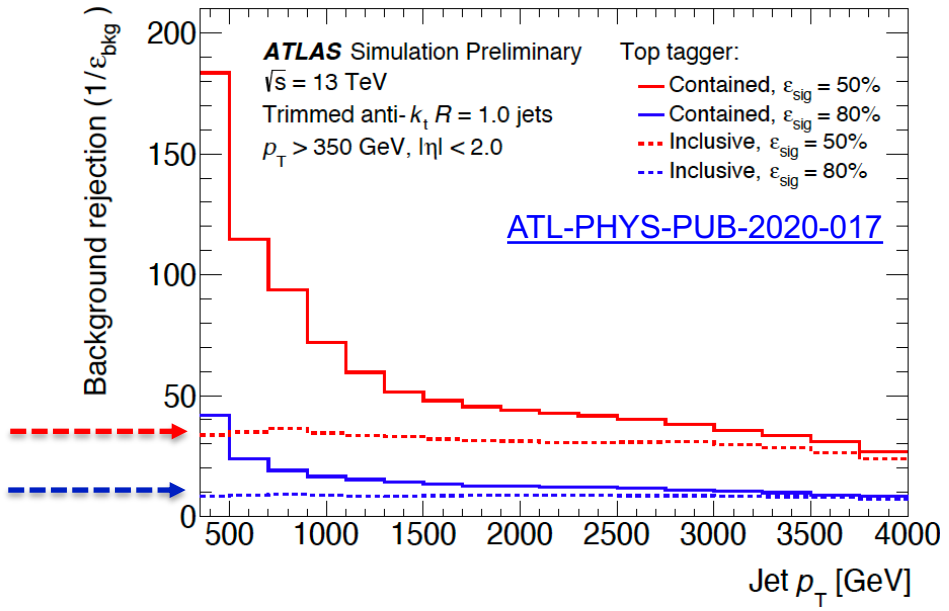


⇒ Deep Neural Network top-tagger

- Uses kinematics (jet mass, p_T, etc.) and dispersion of jet constituents (N-subjettiness, splitting scales, and energy correlation functions)

Inclusive top-tagger allows some of decay productions to fall outside large-R jet





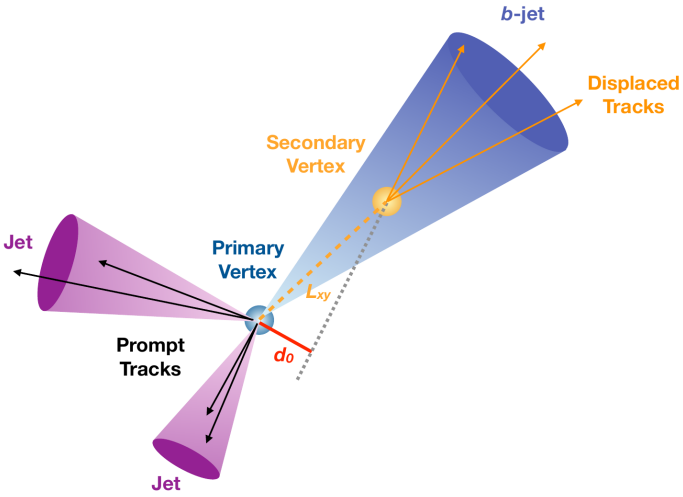
(Some analyses define their own custom taggers, but idea is the same)

b-tagging

Final states with (multiple) **bottom** quarks

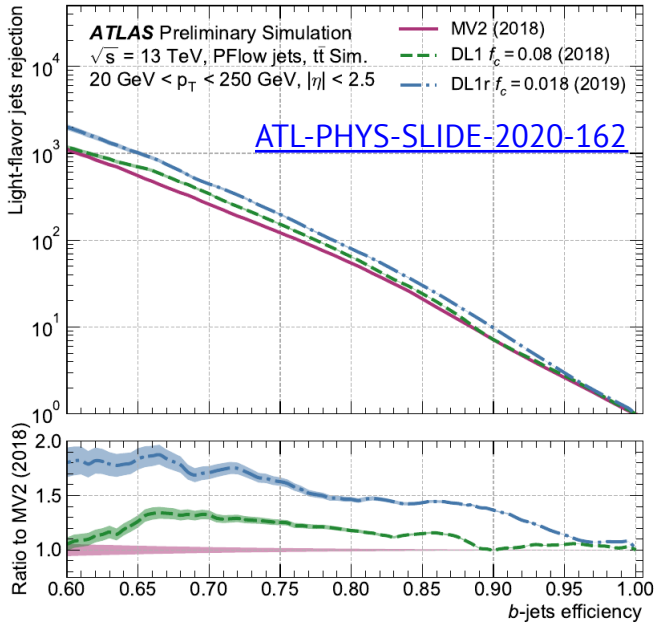
Small-R jet with displaced secondary vertex, high mass, and high track multiplicity

⇒ Train Deep Neural Network b-tagger

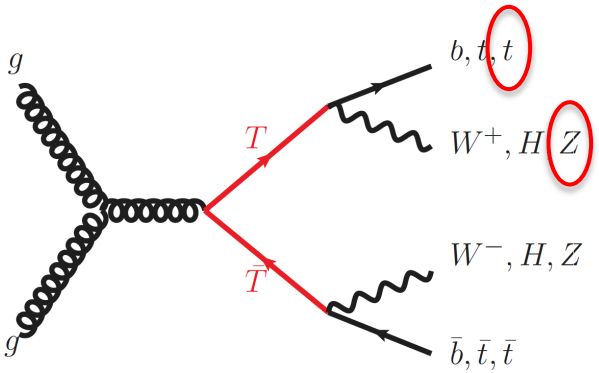


- Dedicated b-taggers for different jet reconstruction algorithms
  - Particle Flow Jets
  - Variable-Radius Track Jets

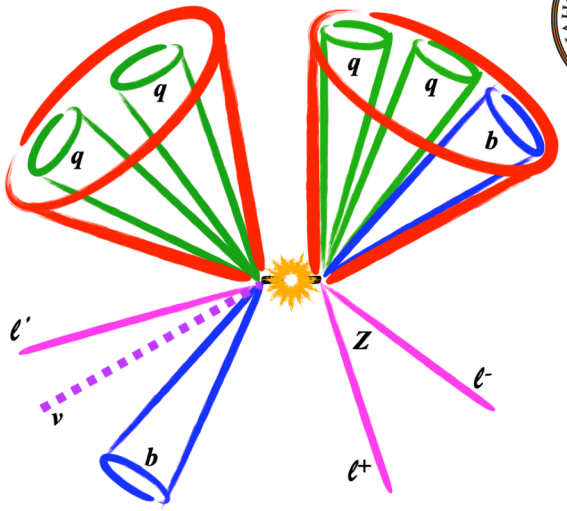
- Uses previous inputs, plus *recurrent neutral network* to *exploit correlations* between tracks
  - >50% better rejection w.r.t. Boosted Decision Tree



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



Example of trilepton decay:

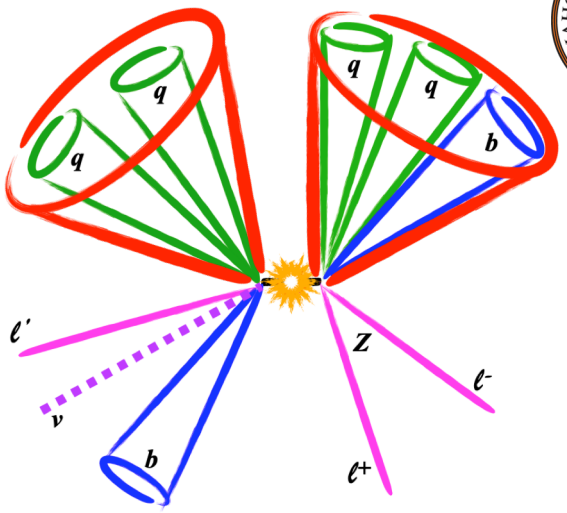


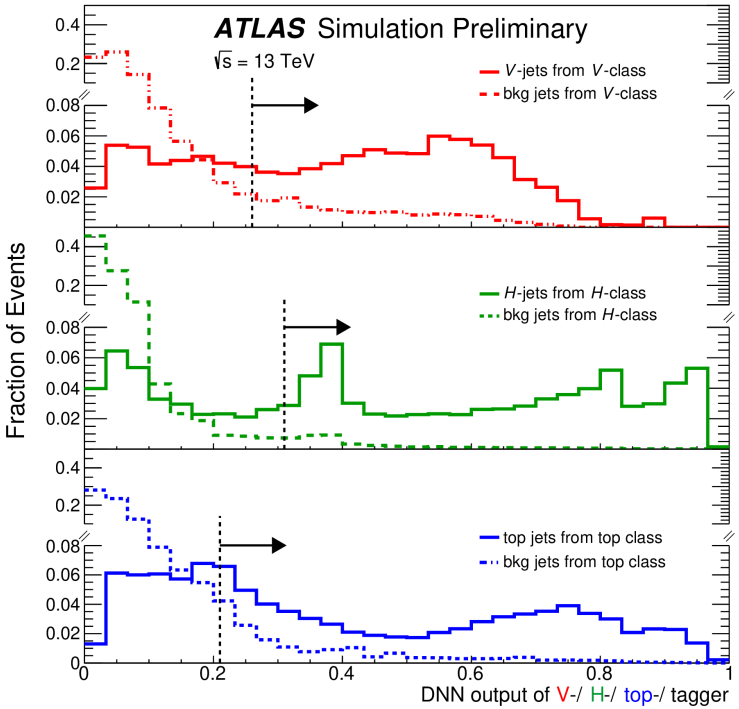
$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$

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:



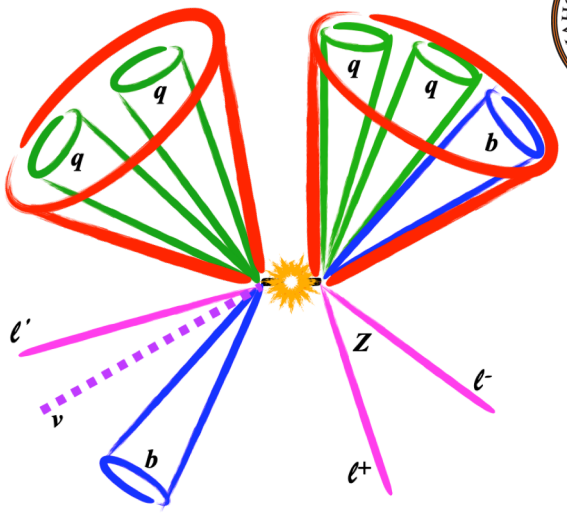


$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$

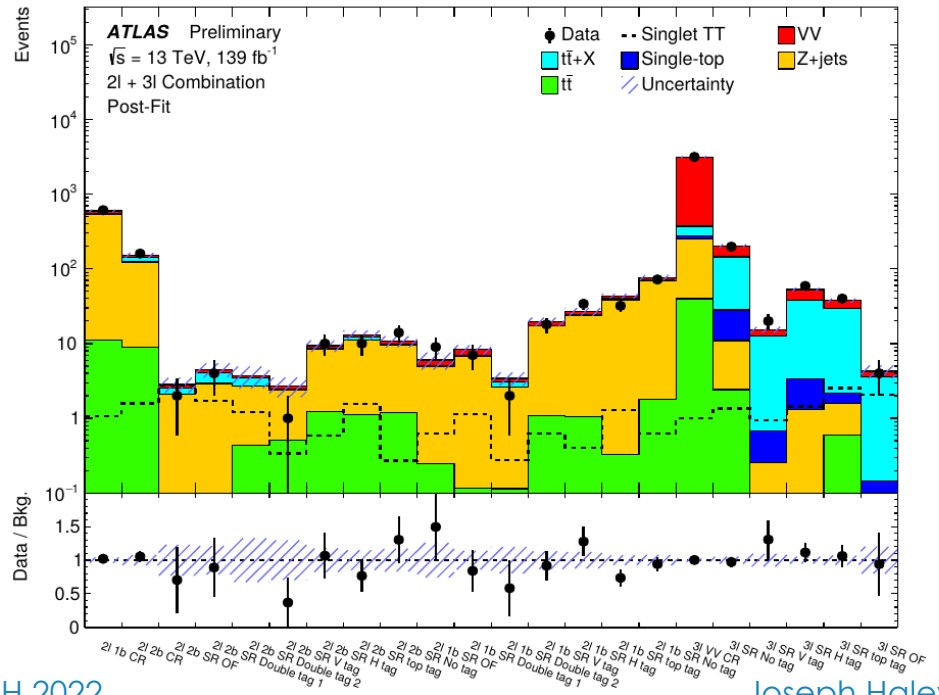
Independently optimized for dilepton and trilepton final states

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

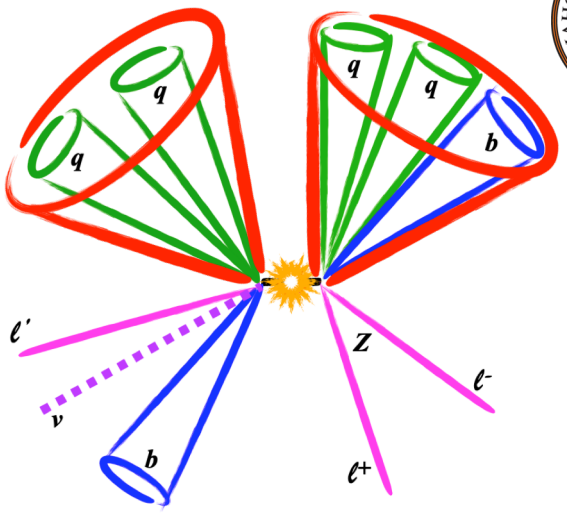


$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$

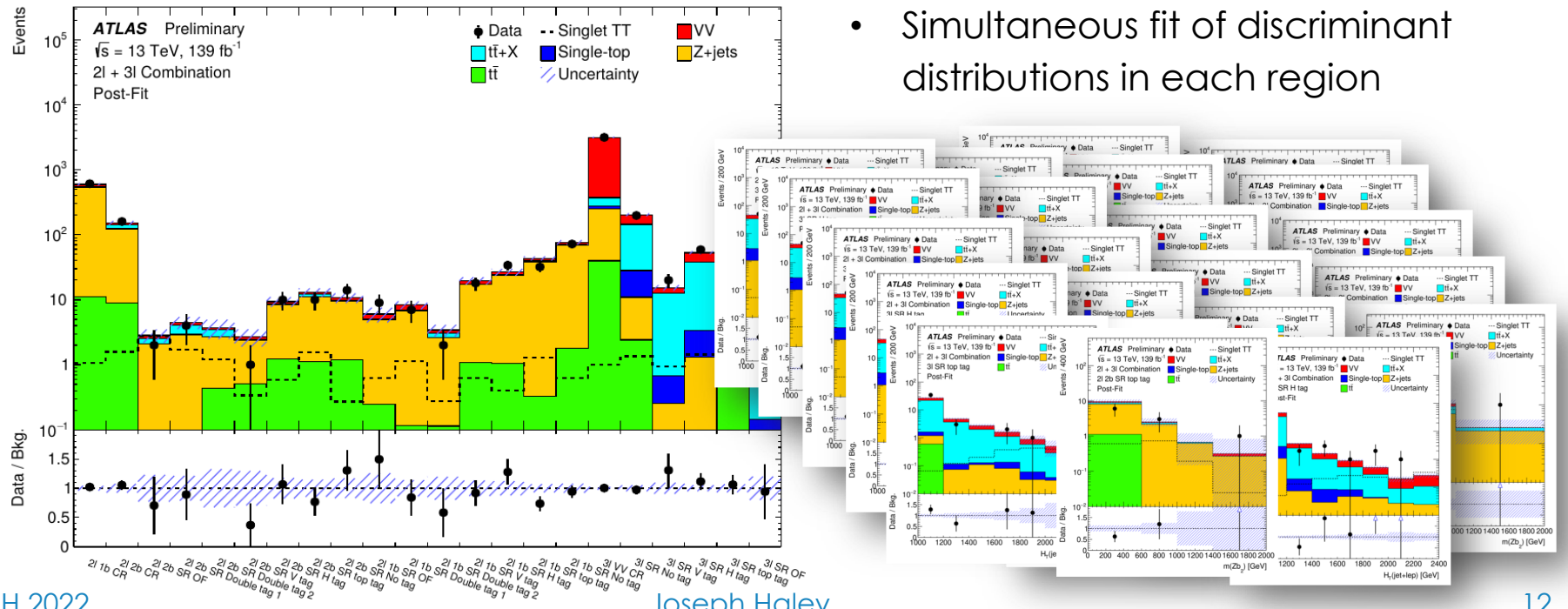
Independently optimized for dilepton and trilepton final states

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

Example of trilepton decay:



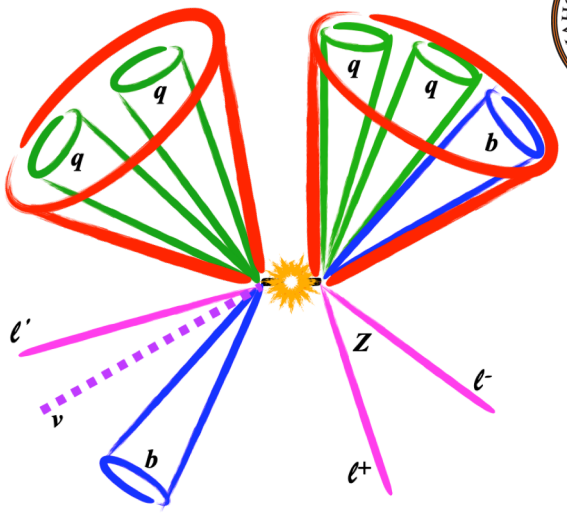
Define 22 exclusive categories based on kinematic properties, b-tag and MCBOT



- Simultaneous fit of discriminant distributions in each region

ATLAS-CONF-2021-024

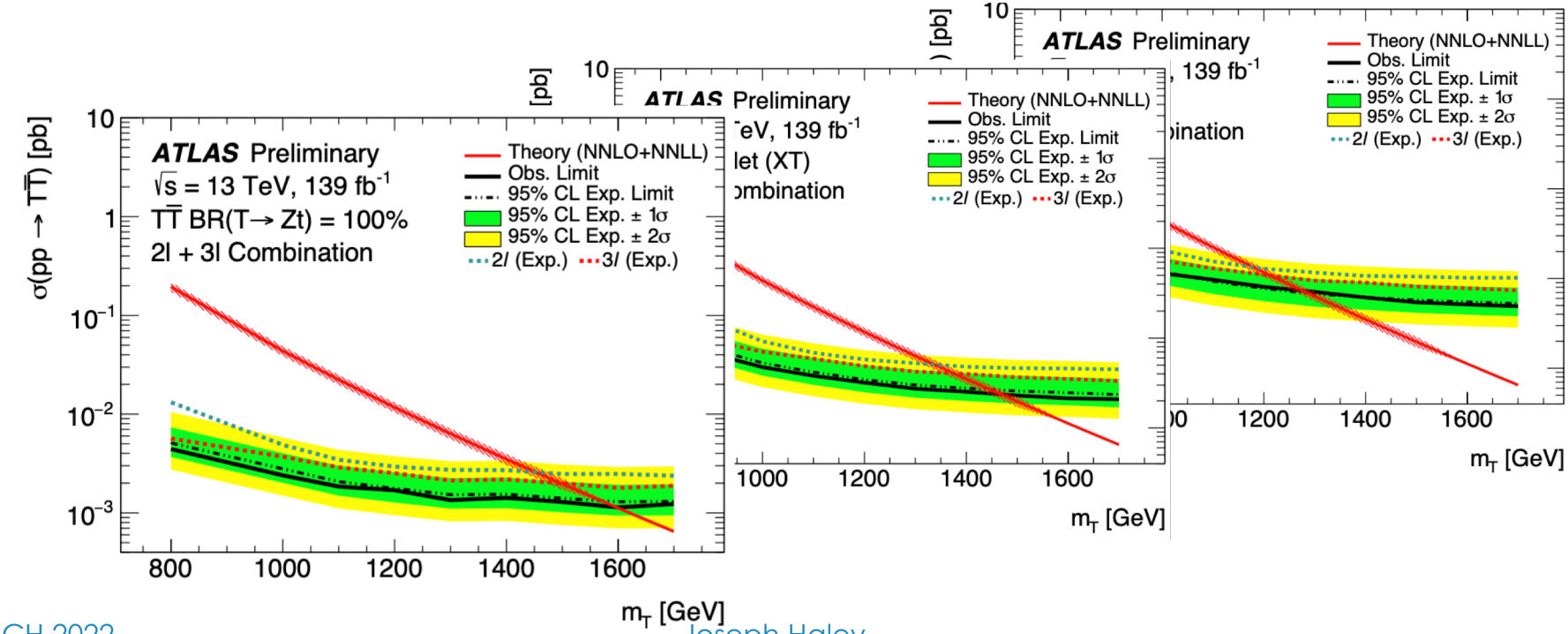
$TT \rightarrow Zt+X$, with $Z \rightarrow \ell\ell$



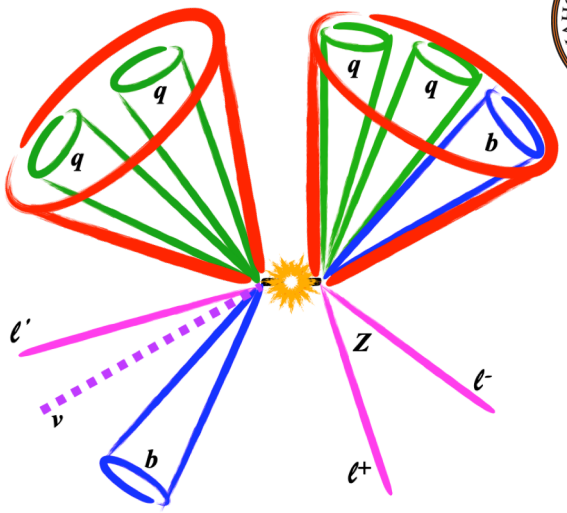
Analyze full Run 2 ATLAS dataset (139fb^{-1})

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

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



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

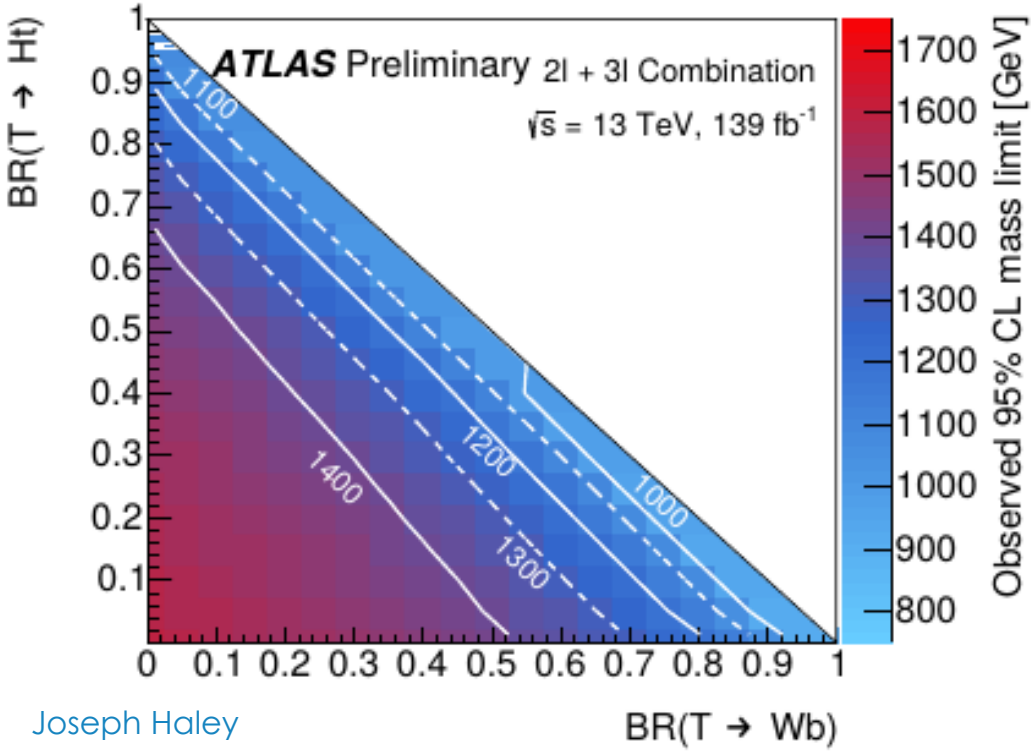


Analyze full Run 2 ATLAS dataset (139fb^{-1})

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

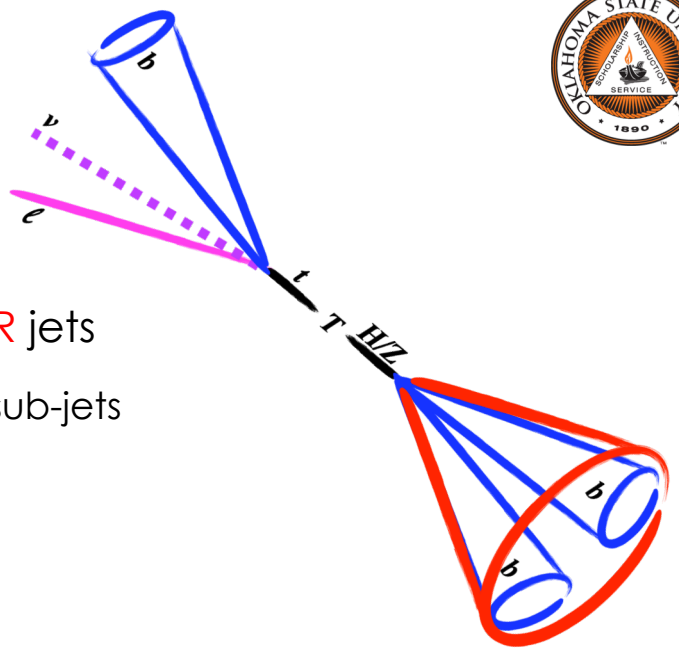
⇒ Limits on cross-section vs. VLQ mass for **benchmark** scenarios

⇒ **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

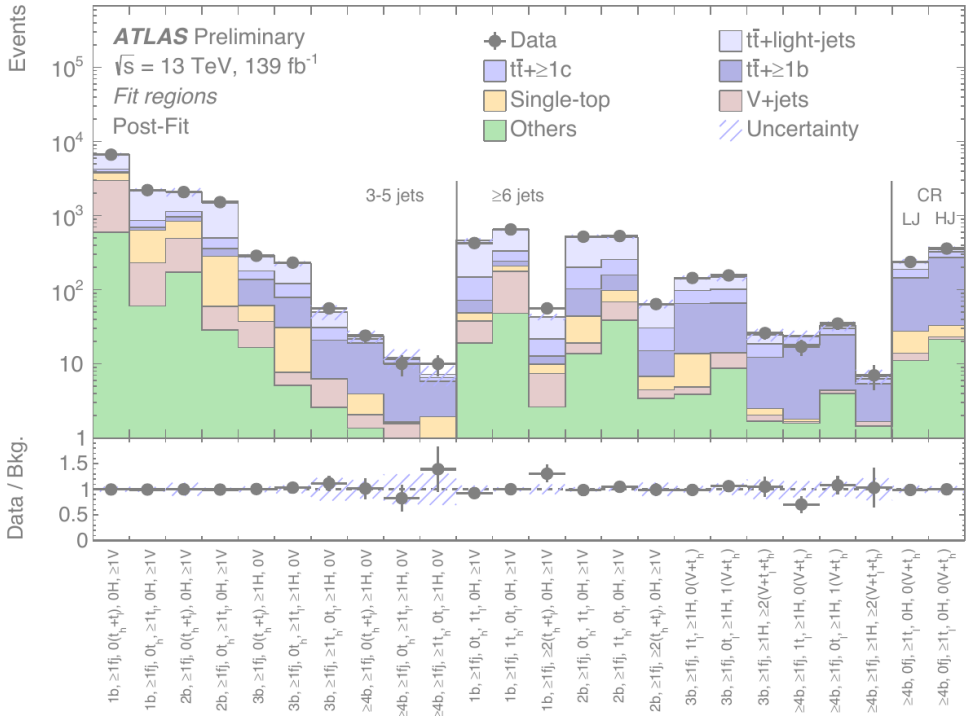
- Tag as H, V, or top based on jet mass, p_T and number of sub-jets

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

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

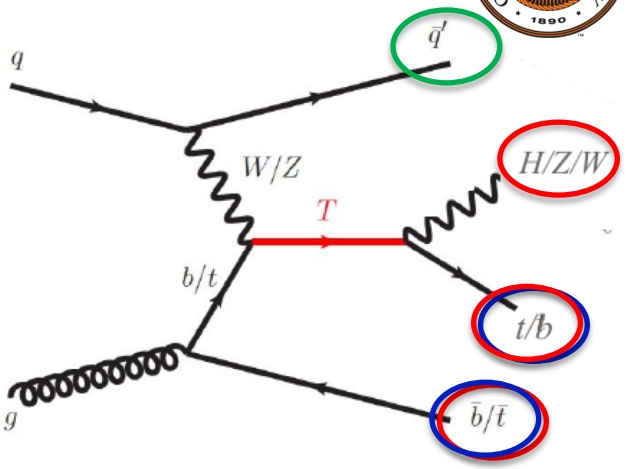
Divide events into 24 regions based on number of jets, b-tags, H, V, & top-tags

Perform combined fit to discriminating variable in all regions



ATLAS-CONF-2021-040

$T \rightarrow Ht/Zt$, 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

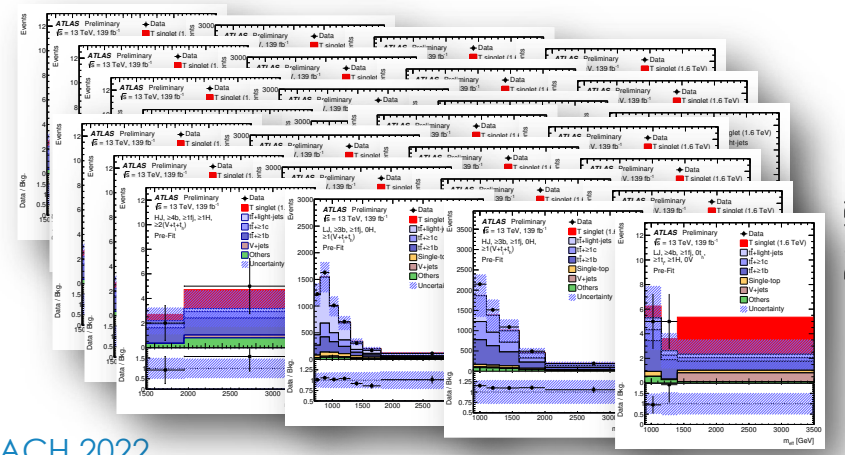
- Tag as H, V, or top based on jet mass, p_T and number of sub-j

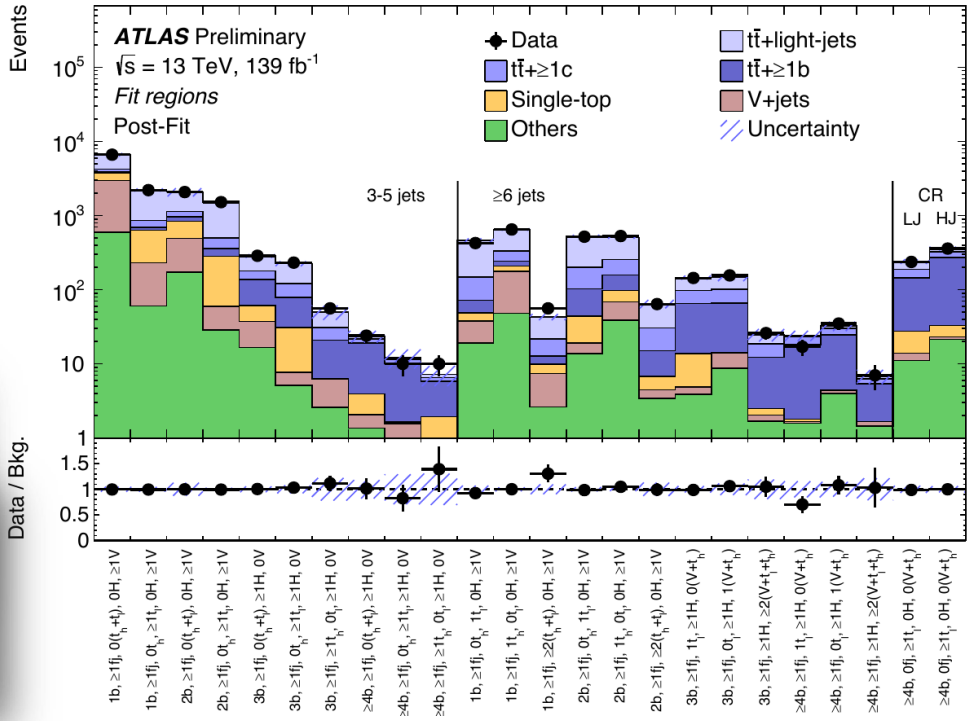
Sensitivity limited by modeling uncertainties on dominant tt and single top backgrounds

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

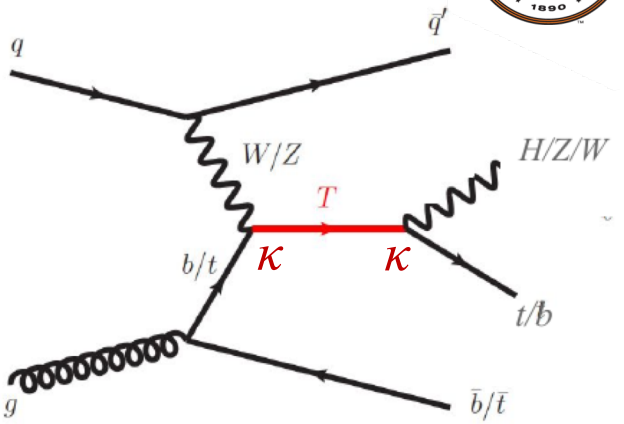
Divide events into 24 regions based on number of jets, b-tags, H, V, & top-tags

Perform combined fit to discriminating variable in all regions





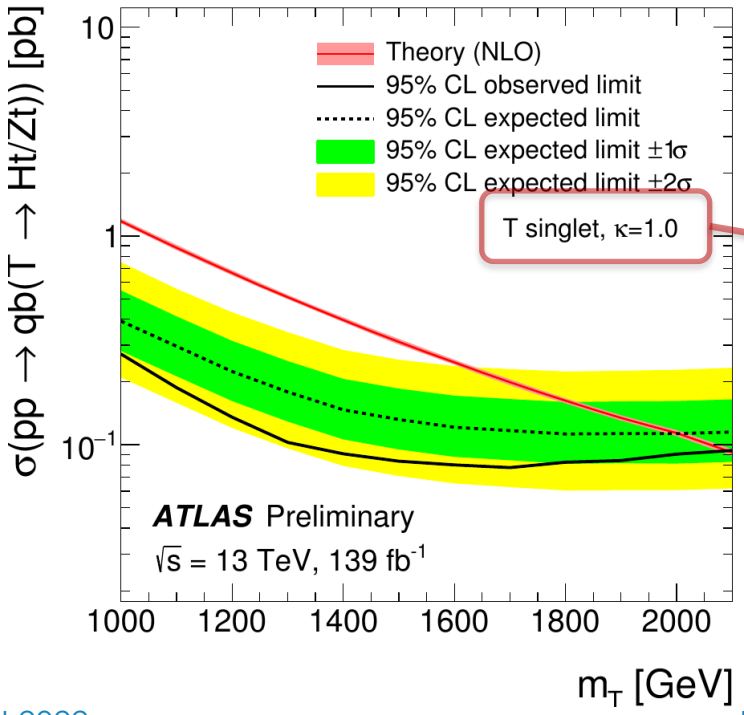
$T \rightarrow Ht/Zt$, with $t \rightarrow lvb$

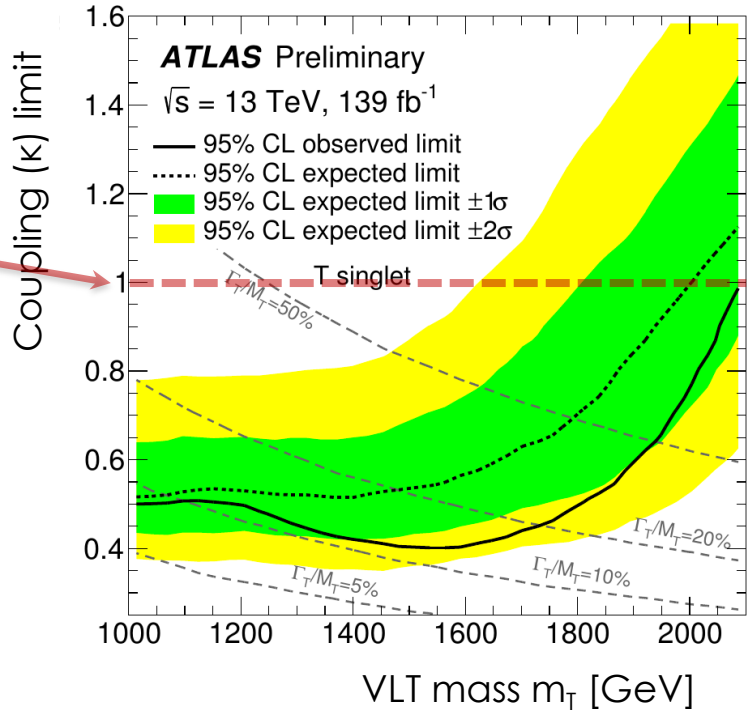


Analyze full Run 2 ATLAS data set (139 fb-1)

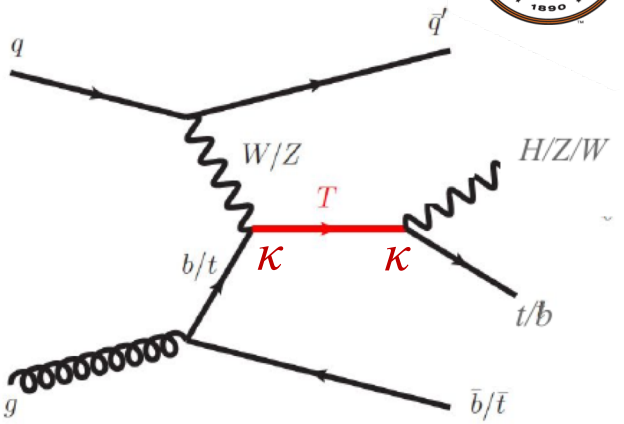
No deviation from the background-only hypothesis

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





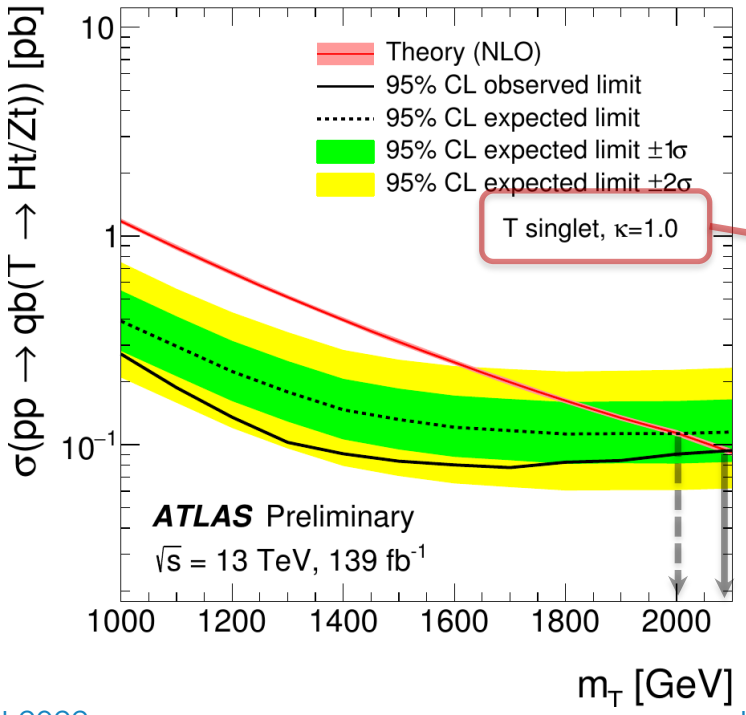
$T \rightarrow Ht/Zt$, with $t \rightarrow lvb$

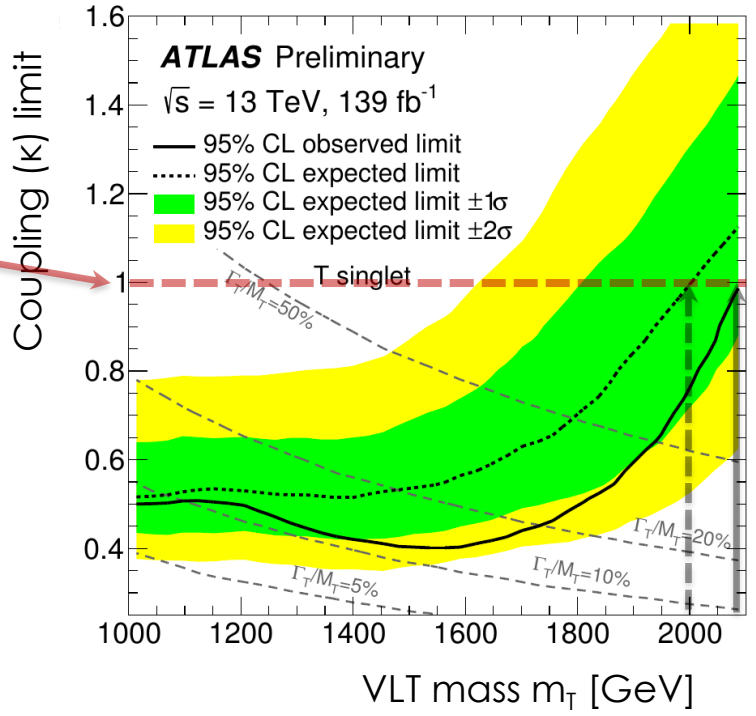


Analyze full Run 2 ATLAS data set (139 fb-1)

No deviation from the background-only hypothesis

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





Phys. Rev. D 105, 092012

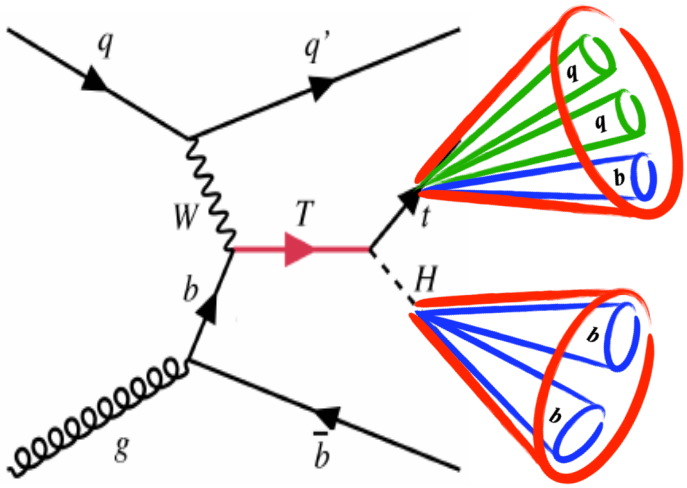
$T \rightarrow Ht$ with hadronic final state

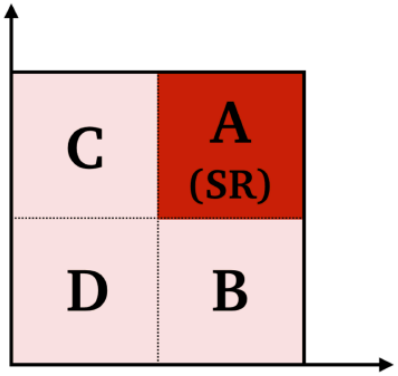
T→Ht with H→bb and t→qqb

- 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





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

Phys. Rev. D 105, 092012

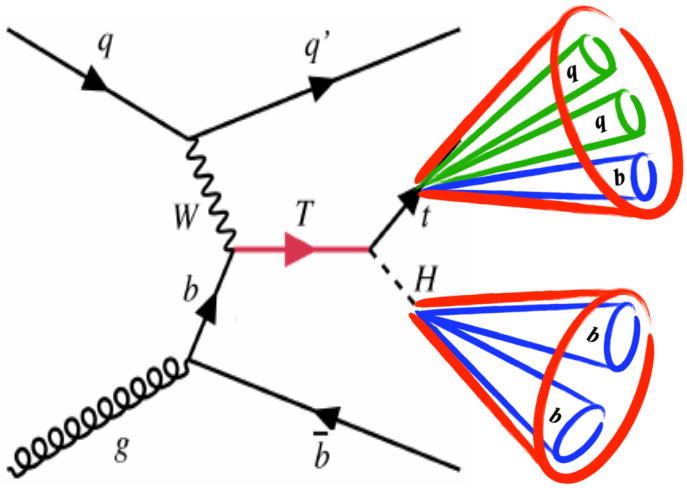
$T \rightarrow Ht$ with hadronic final state

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									

Phys. Rev. D 105, 092012

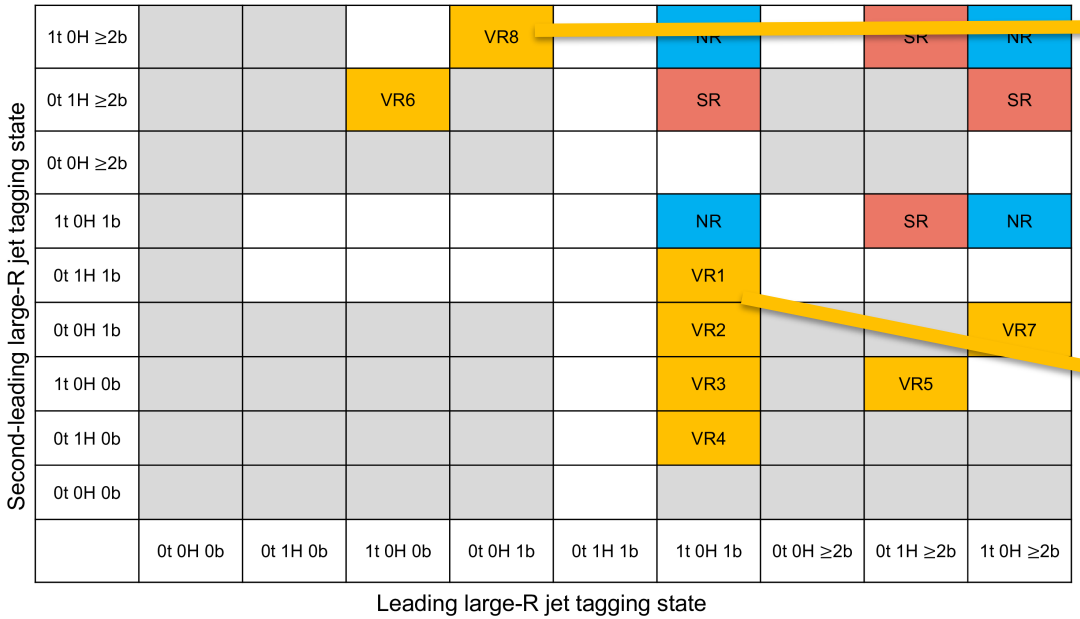
$T \rightarrow Ht$ with hadronic final state

T→Ht with H→bb and t→qqb

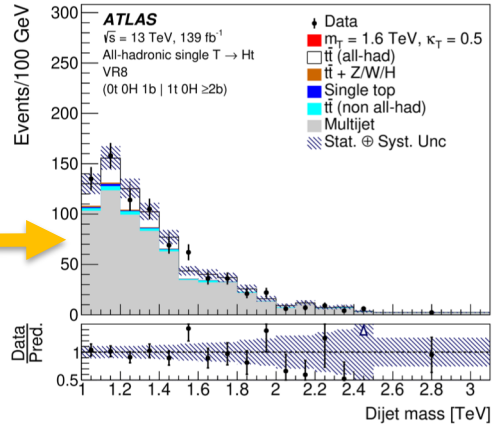
- 2 high-pT large-R jets with b-subjets

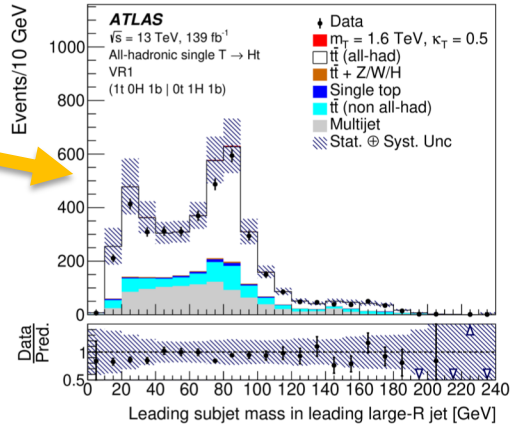
Dominant background from QCD multijet events

- 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





Phys. Rev. D 105, 092012

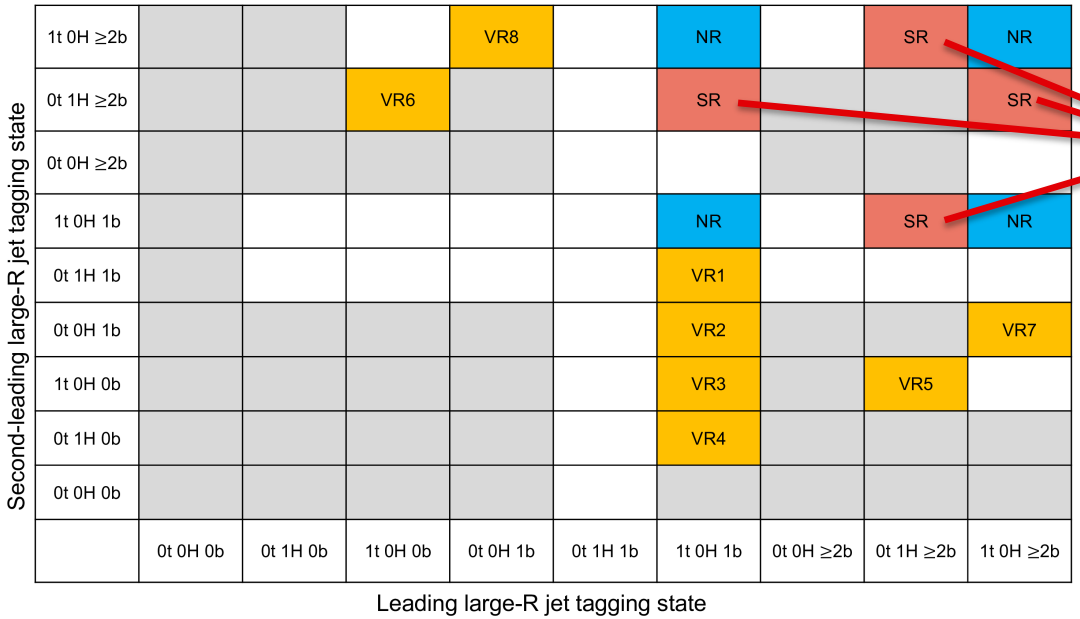
$T \rightarrow Ht$ with hadronic final state

T→Ht with H→bb and t→qqb

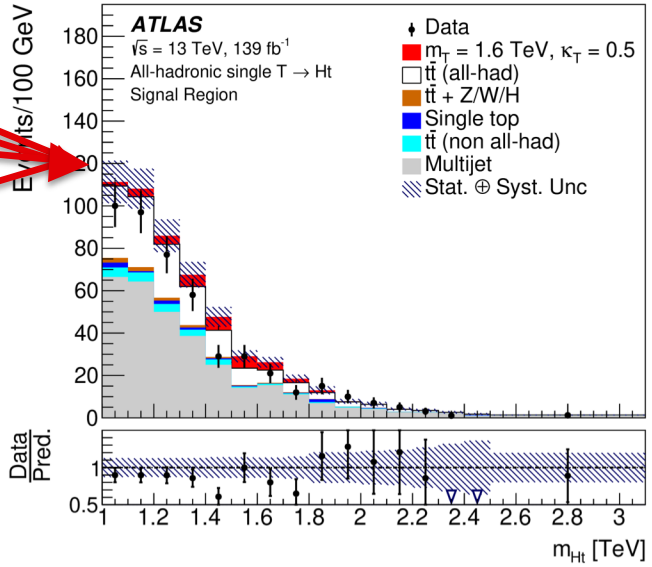
- 2 high-pT large-R jets with b-subjets

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



Phys. Rev. D 105, 092012

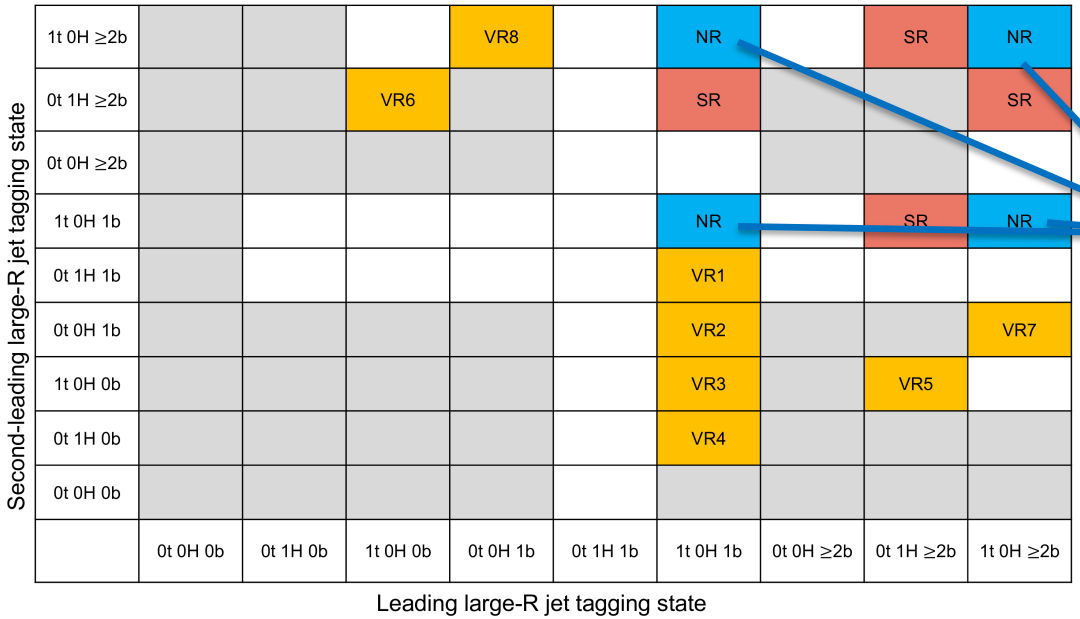
$T \rightarrow Ht$ with hadronic final state

T→Ht with H→bb and t→qqb

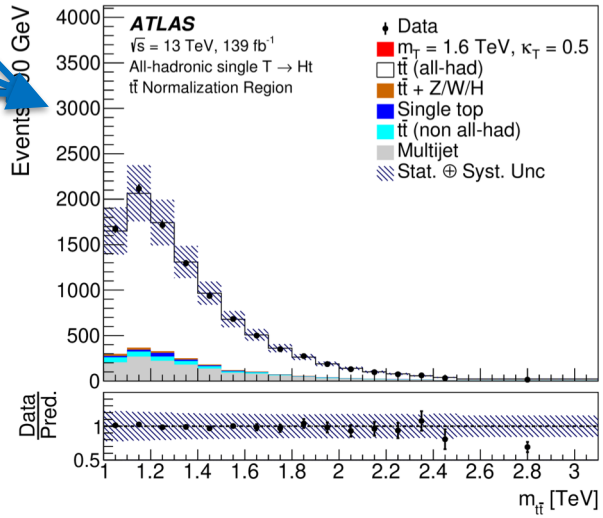
- 2 high-pT large-R jets with b-subjets

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



Phys. Rev. D 105, 092012

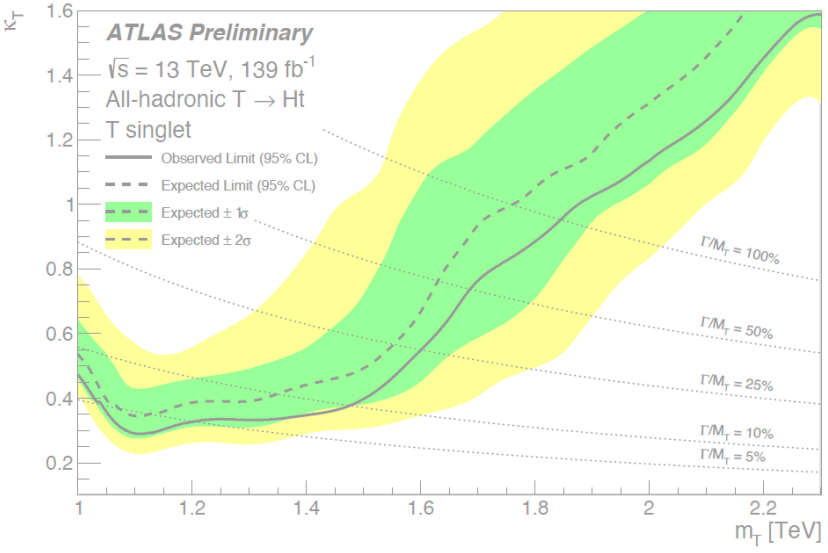
$T \rightarrow Ht$ with hadronic final state

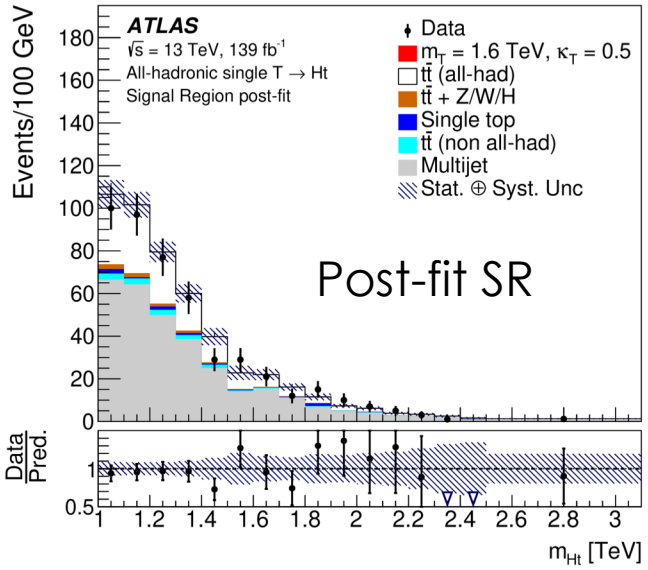
Simultaneous fit of dijet mass distribution in SR and NR

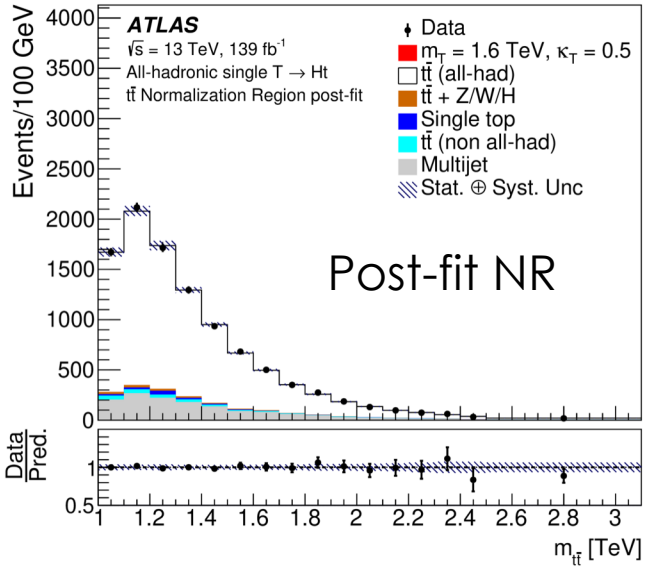
- Fit of signal cross section and normalization of tt background

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)







Phys. Rev. D 105, 092012

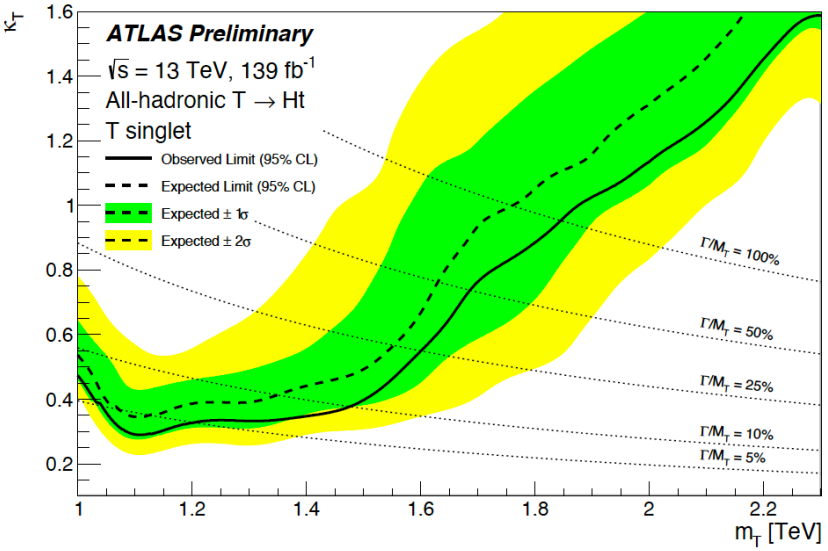
$T \rightarrow Ht$ with hadronic final state

Simultaneous fit of dijet mass distribution in SR and NR

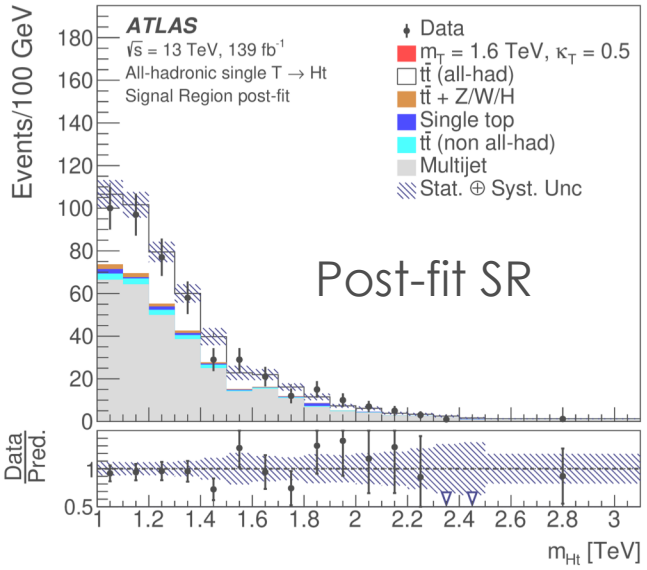
- Fit of signal cross section and normalization of tt background

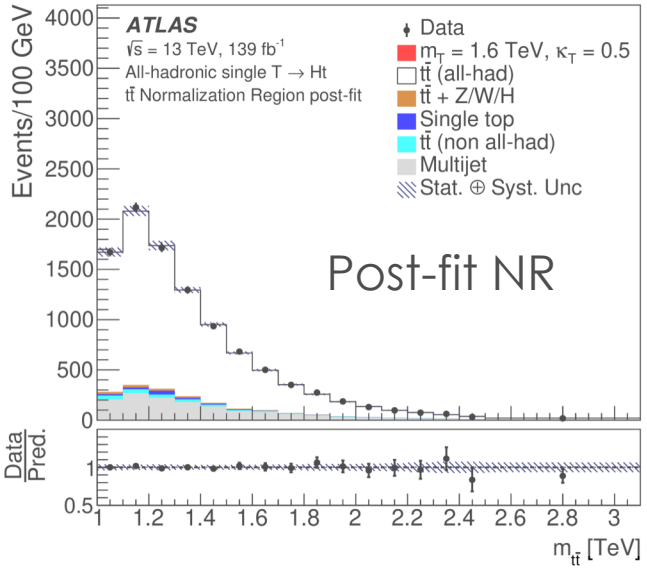
Set limit as a function of the T mass m_T and coupling κ

⇒ 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.





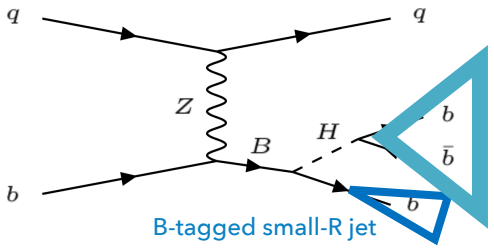
$B \rightarrow Hb$, with $H \rightarrow bb$

Require 3 b-tagged small-R jets

⇒ Critical to reduce dominant multijet background

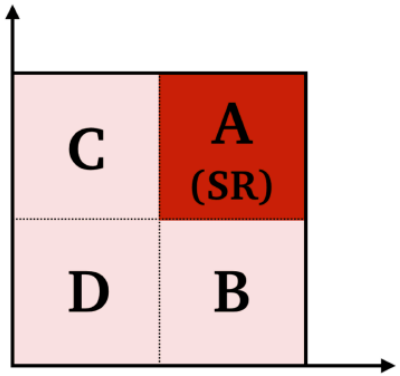
Identify boosted H→bb

⇒ Large-R jet with mass ≈ m_H & contains 2 b-tagged track jets



Purely data-driven background estimate using "ABCD" method

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



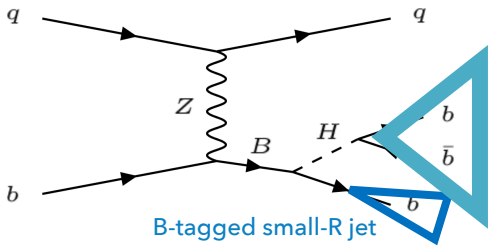
$$N_A = N_B \times \frac{N_C}{N_D}$$

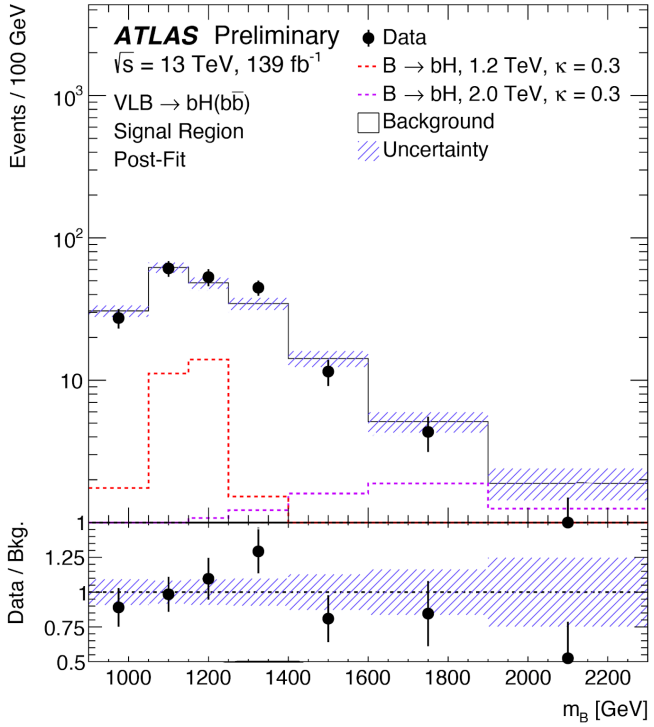
$B \rightarrow Hb$, with $H \rightarrow bb$

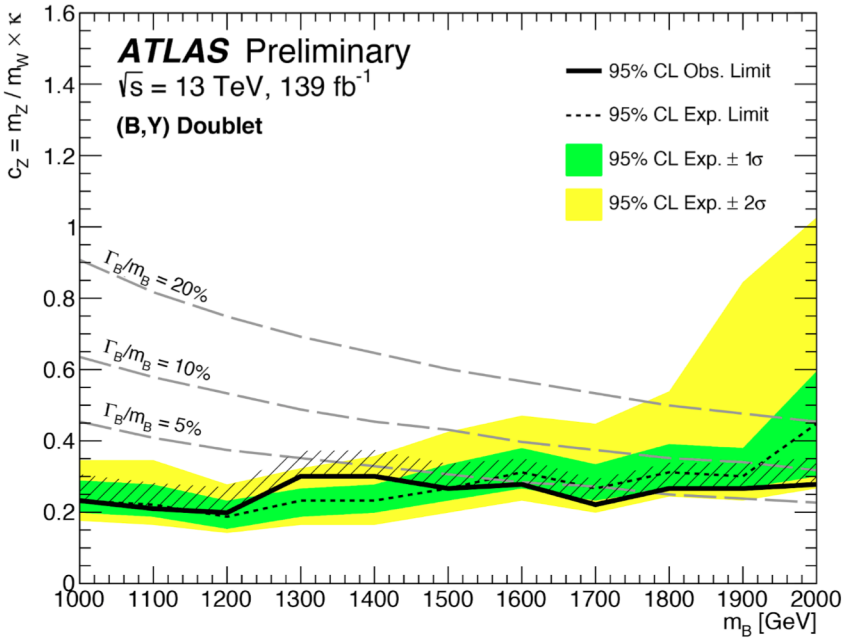
Binned maximum-likelihood fit to reconstructed B mass distribution m_B

No significant excesses found in full Run 2 dataset

⇒ Set limits on coupling and as a function of the VLB mass:





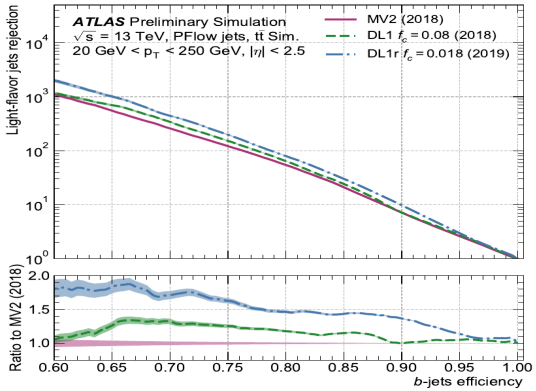


Significantly extended B parameter space being probed (previous limits: for (B,Y) doublet scenario @1.2TeV)

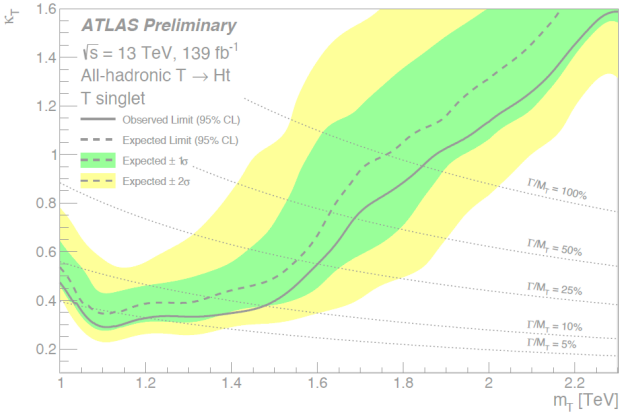
Conclusion

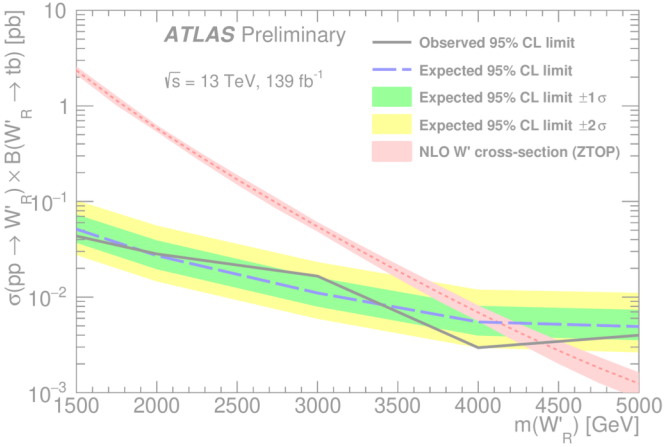
Many recent results from searches for vector-like partners to top and bottom quarks using ATLAS Run 2 data

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



Unfortunately, still no signs of new physics…





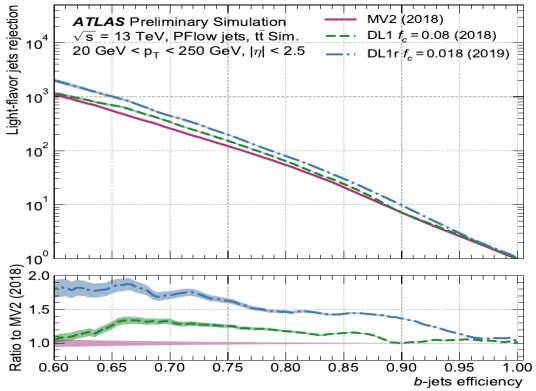
But more Run 2 analyses coming soon!

… And Run 3 just around the corner!!!

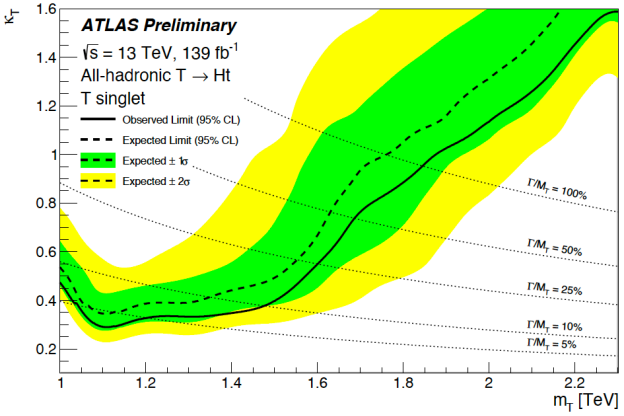
Conclusion

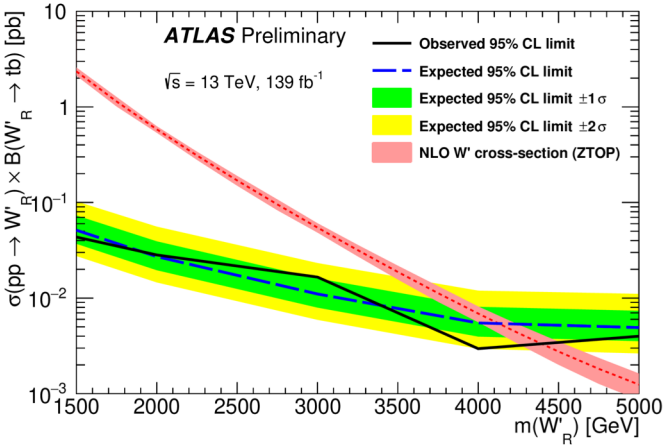
Many recent results from searches for vector-like partners to top and bottom quarks using ATLAS Run 2 data

- 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!

And special thanks to:

DOE for supporting this research

The ATLAS Collaboration

- Complete list of ATLAS exotic results: twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

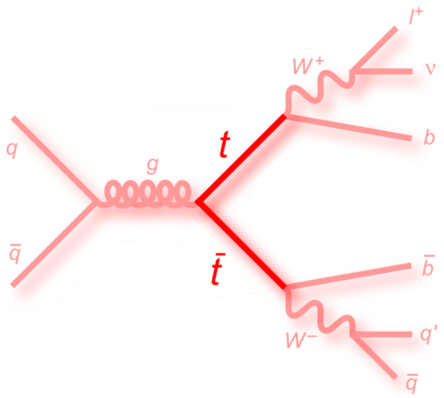
The BEACH 2022 Organizers!

List of presented analyses

- Search for pair-production of vector-like quarks in *pp* collision events at $\sqrt{s}$ =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 $\sqrt{s}$ =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 $\sqrt{s}$ =13 TeV with the ATLAS detector (ATLAS-CONF-2021-018)
- 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 (Phys. Rev. D 105, 092012)

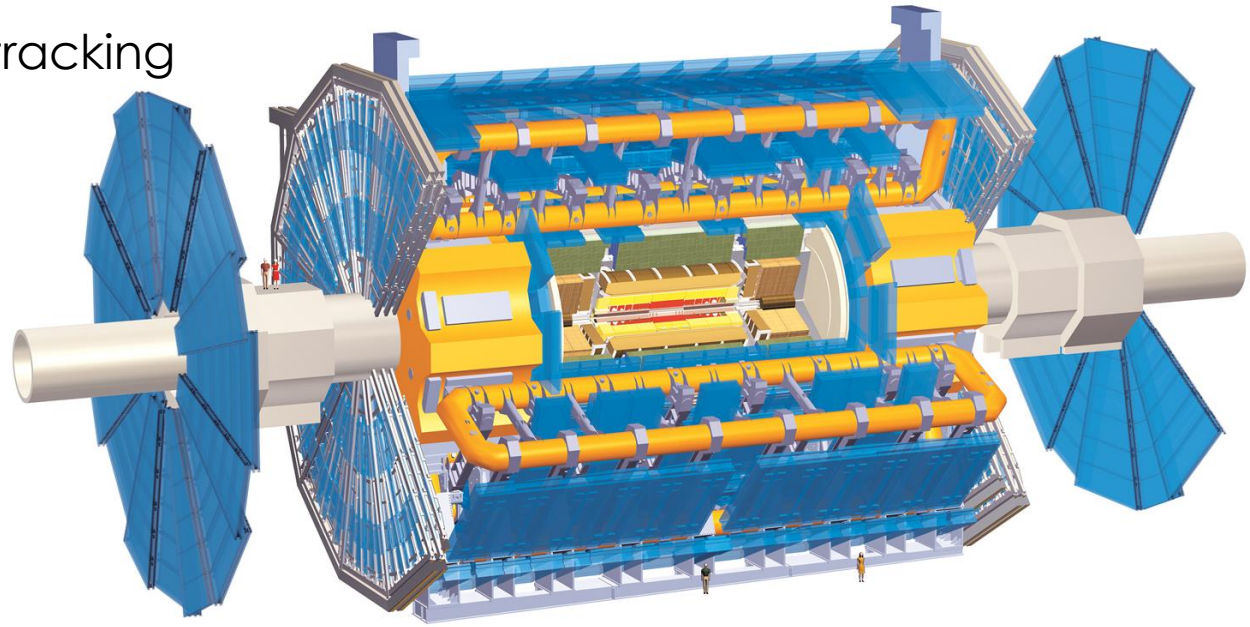
ATLAS Detector

The LHC is a "top factory" (~1 *tt*/second)



ATLAS is a "top detector"

- Efficient e/μ identification
- Nearly 4π coverage ⇒ E_T^{miss}
- High granularity tracking
- ⇒ *b*-tagging



All results using the ATLAS Run 2 data set (L = 139 fb^{-1}, √s = 13 TeV)