ATLAS EXPERIMENT

Vectorlike Quark Searches from ATLAS

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BCVSPIN Conference
Particle Physics and Cosmology in the Himalayas
9-13 Dec 2024
Kathmandu, Nepal

Overview

Vector-like quarks

- What are they?
- Why should you care?
- What do we look for?

Latest (and very complementary) results from ATLAS

- Pair-production Top-partner (with $T \to Wb$)
- Pair-production Light-partner (with $Q \to Wq$)
- Single-production Top-partner combination (with $T \to Ht/Zt$)

  All result using Full Run 2 data set (140/fb)

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		VLQs: doublets			VLQs: triplets	
	$^{5}/_{3}$			X			X	
Top-partner T →	$^{2}/_{3}$	(T)		T	T		T	T
Bottom-partner B →	$-^{1}/_{3}$		(B)		B	B	B	B
	$-^{4}/_{3}$					Y		Y

In the table, each doublet and triplet column is one multiplet in parentheses, running down the rows where its entries appear.

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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:

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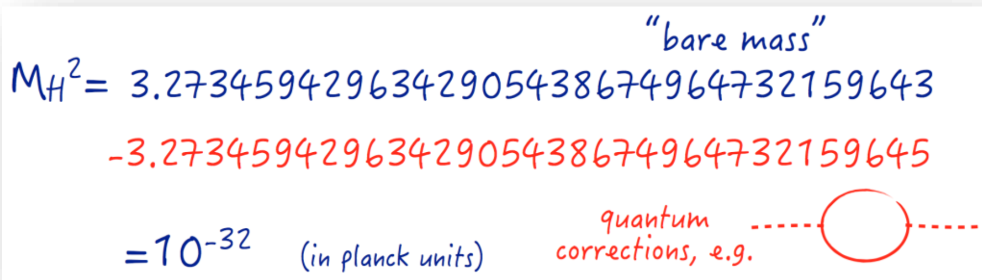
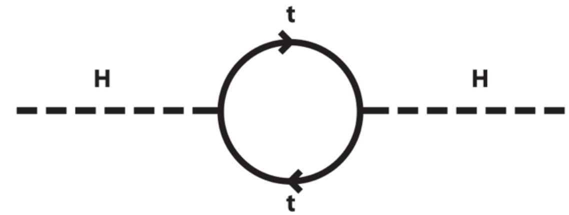
The “Hierarchy Problem”

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





from Roni Harnik

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

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

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

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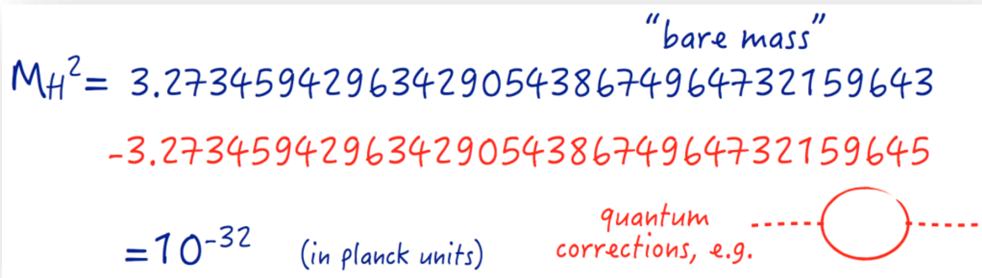

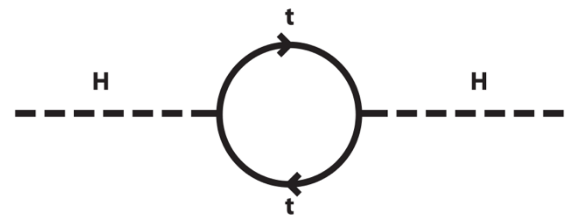

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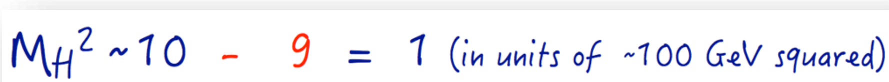

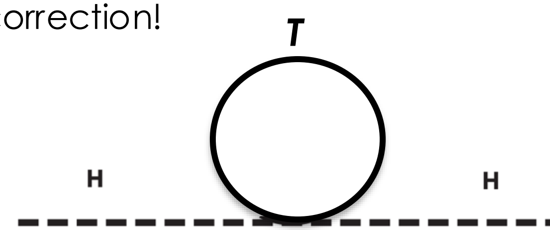

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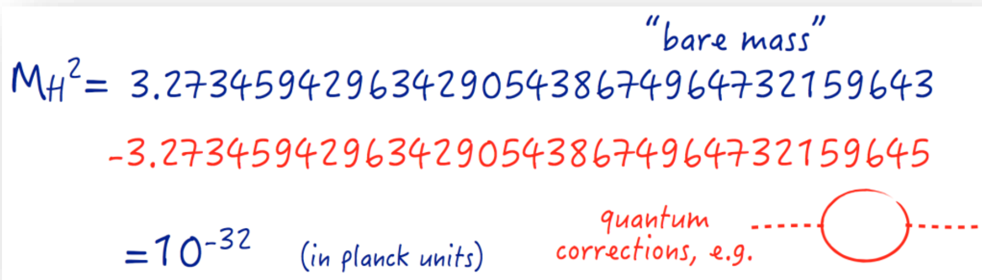

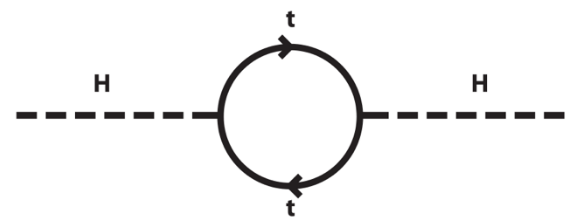

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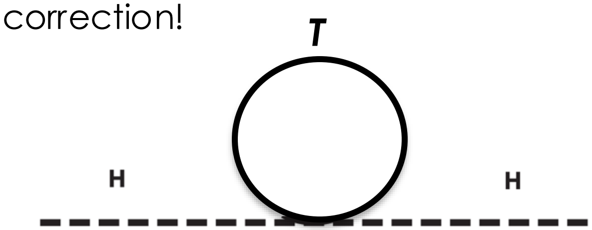
$M_H^2 \sim 10 - 9 = 1$ (in units of ~100 GeV squared)



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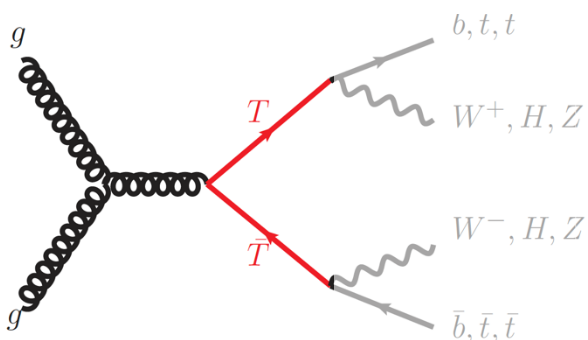
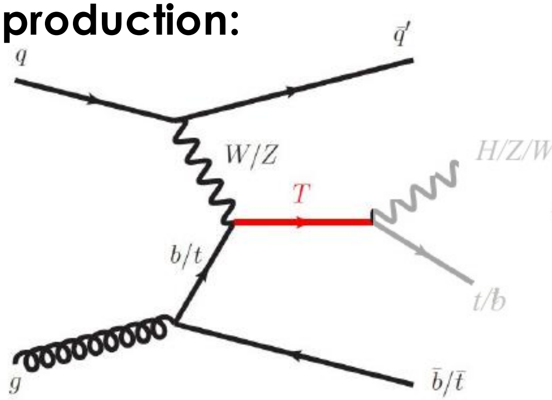
What do we look for?

Pair Production:

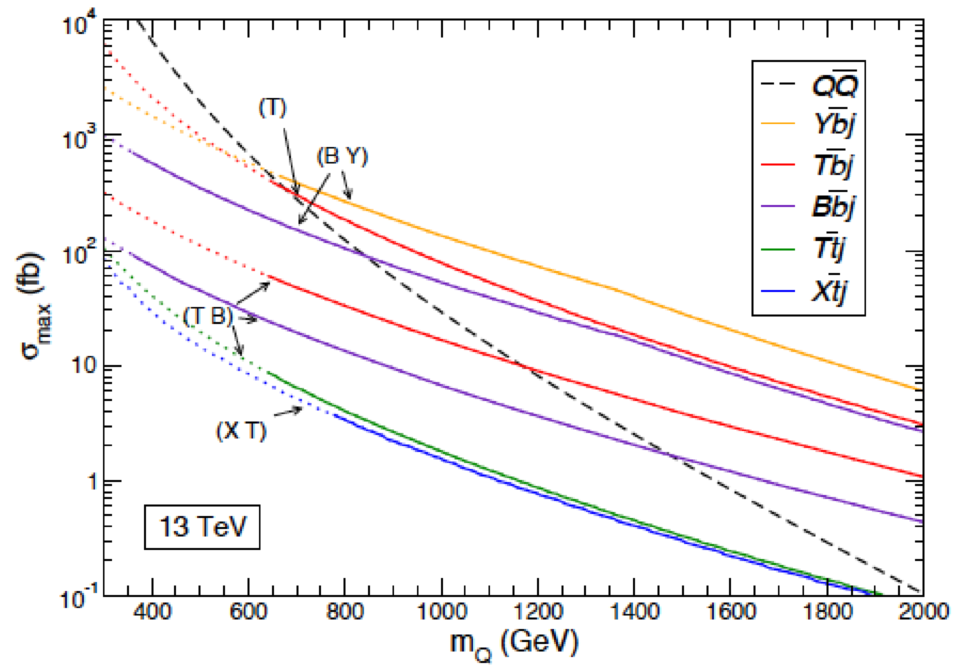


- Via QCD ⇒ Depends only on VLQ mass (**Model-independent**)

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.

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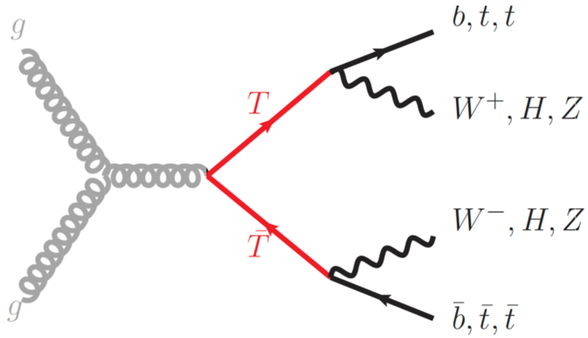

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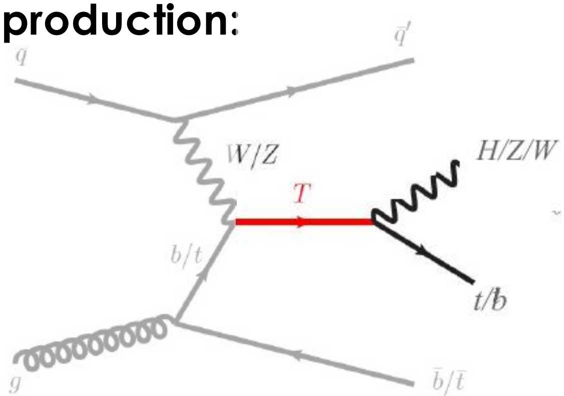

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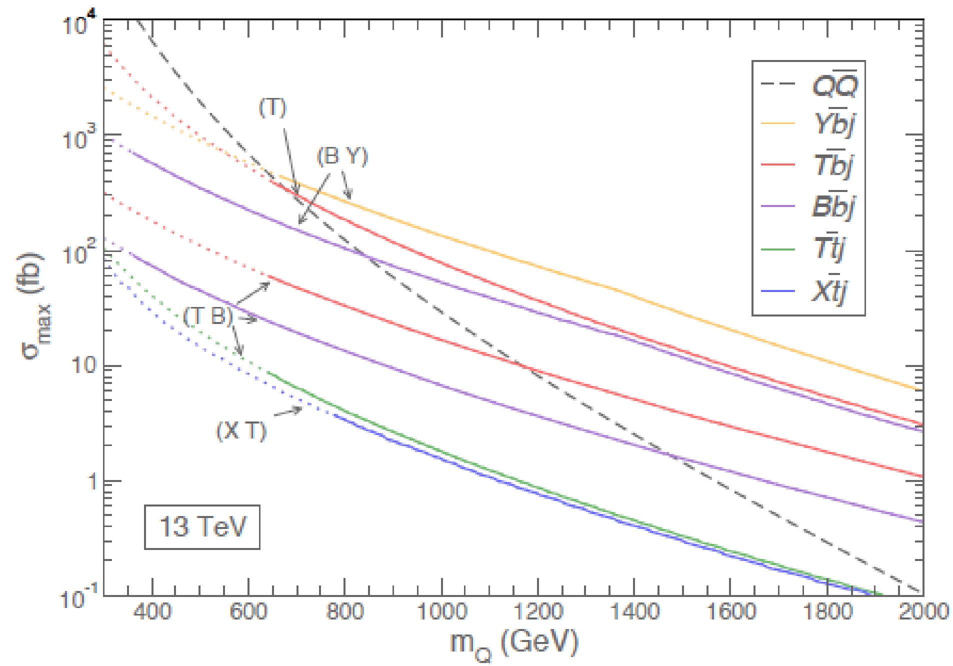

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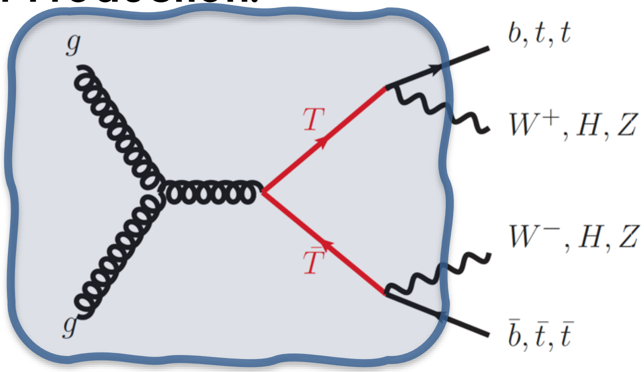

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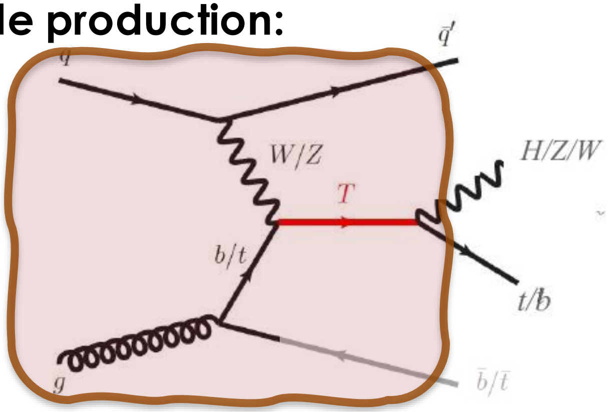

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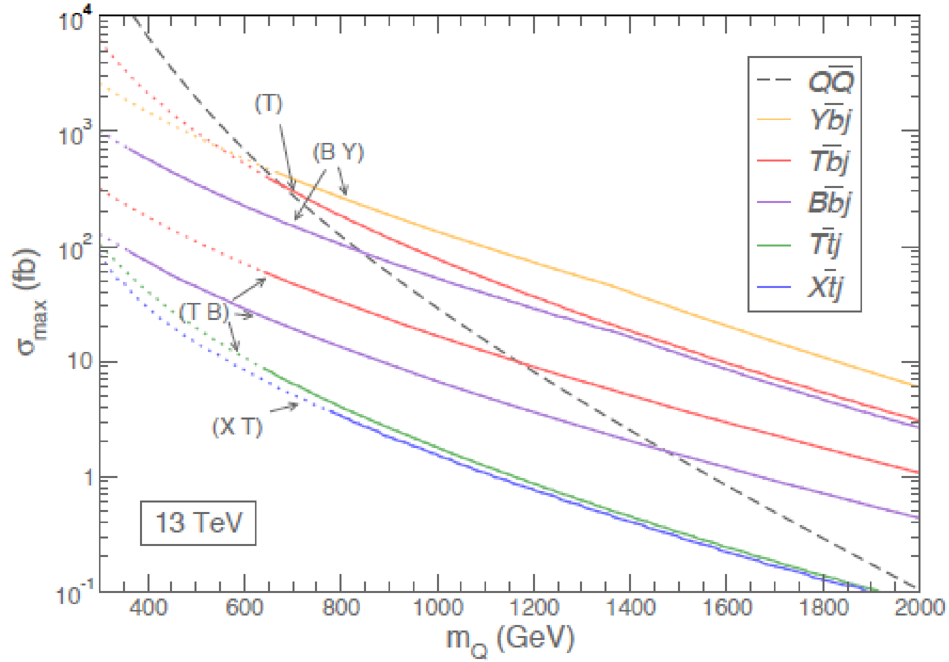

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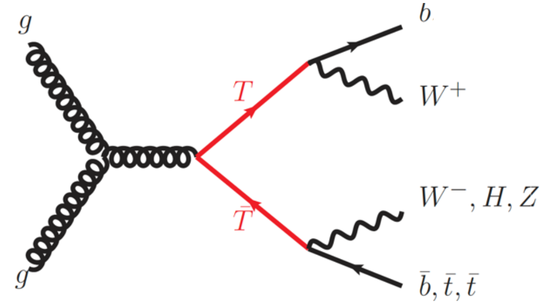
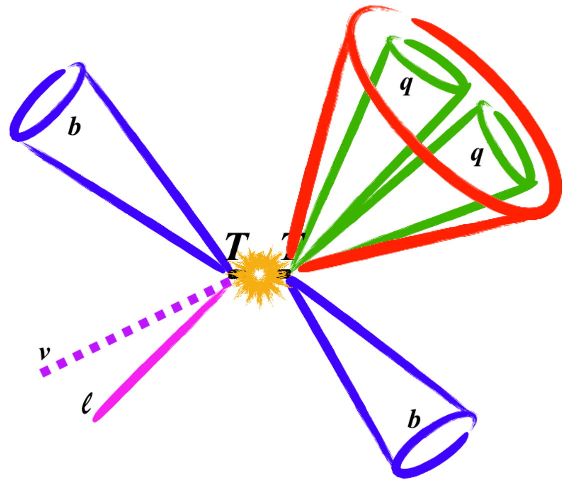
Phys. Lett. B 854 (2024) 138743

Top-Partner Pair-Produced : $TT \to Wb + X$



Optimized for $TT \to WbWb$, with $W \to \ell\nu$ and $W \to (qq)$

Primary event selection:



VLQ reconstruction:

- **Pair W_{had} and W_{lep} with b candidate** that gives smallest $\Delta m_{VLQ} = |m_T^{lep} - m_T^{had}|$

Final Signal Region requirements:

- $S_T = \sum_{jets,\ell,E_T^{miss}} |p_T| > 1900$ GeV
- $\Delta m_{VLQ} = |m_T^{lep} - m_T^{had}| < 500$ GeV

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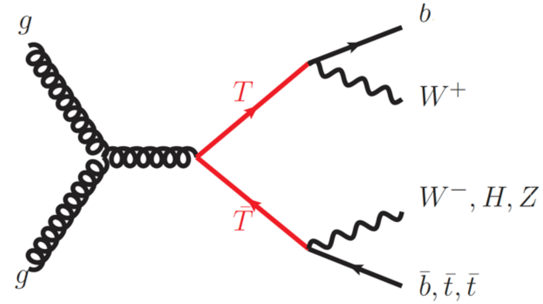
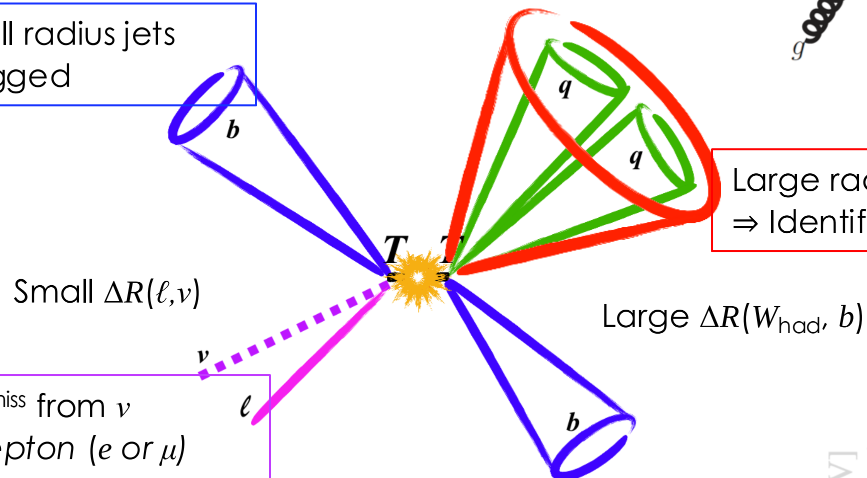


Optimized for $TT \to WbWb$, **with $W \to \ell\nu$ and $W \to (qq)$**

Primary event selection:

Multiple small radius jets with ≥1 b-tagged

Large radius jet with W-tag
⇒ Identified as $W_{had} \to qq$



Large E_T^{miss} from ν
& High-p_T *lepton* (e or μ)
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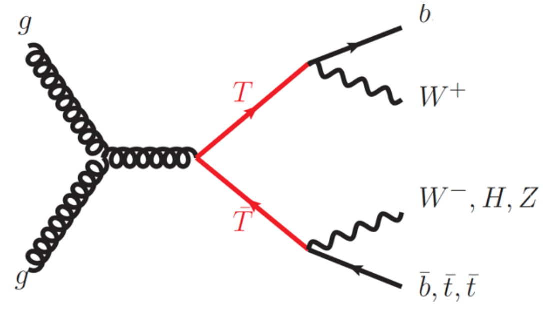

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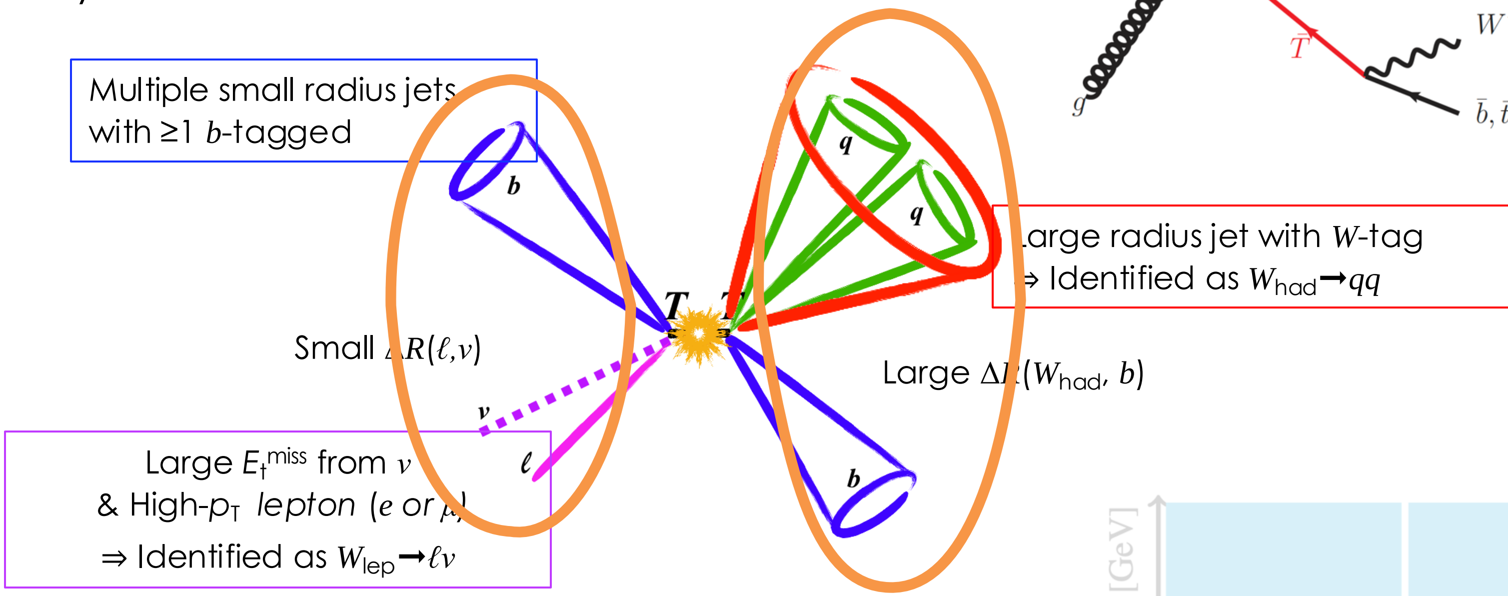

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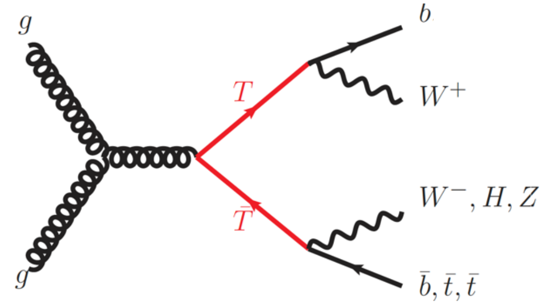

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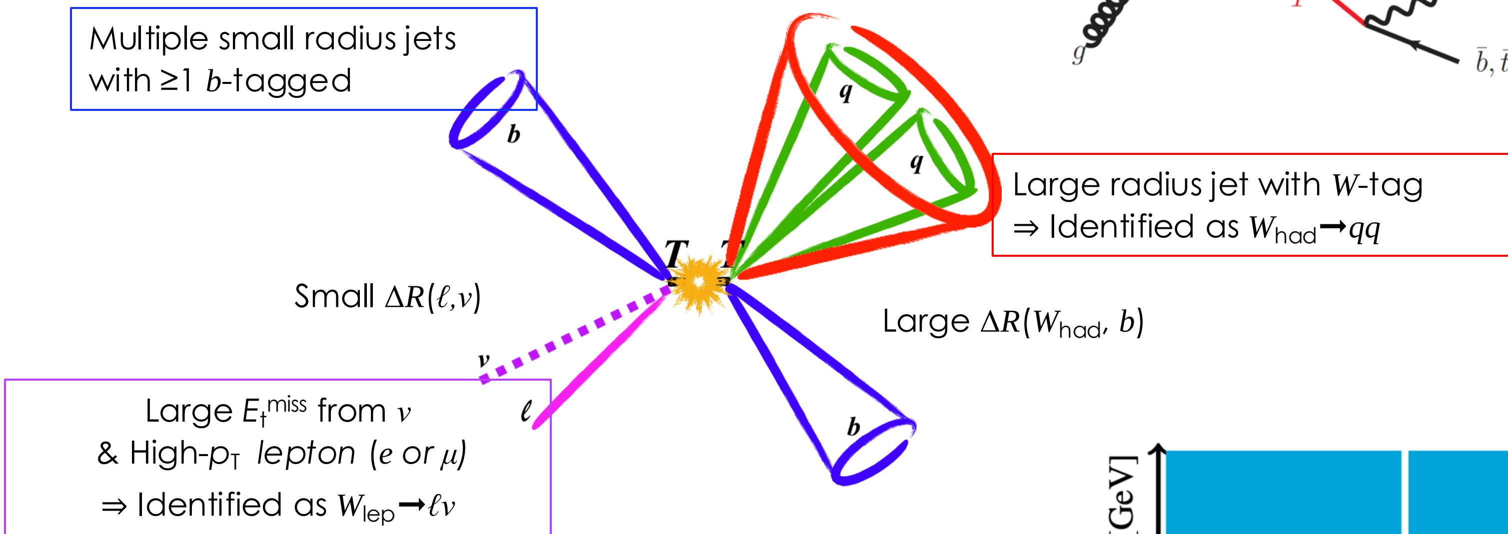

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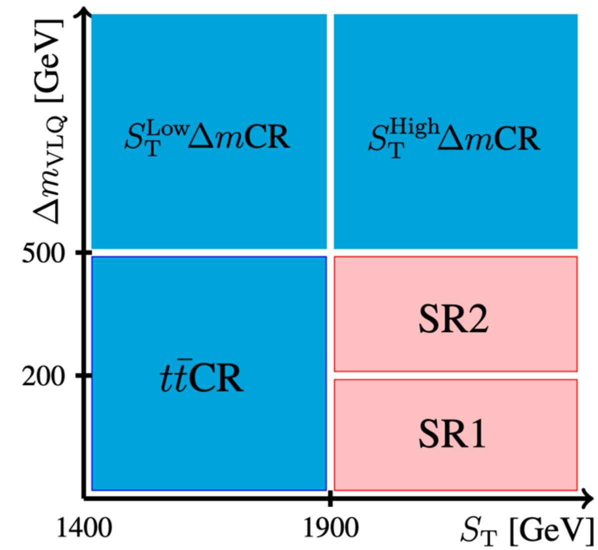

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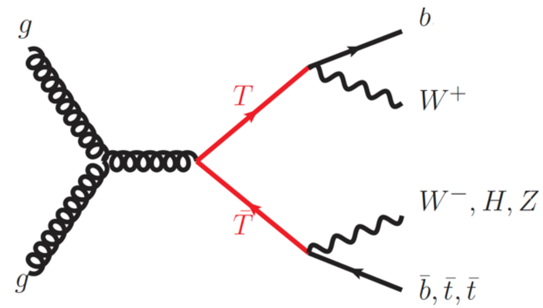
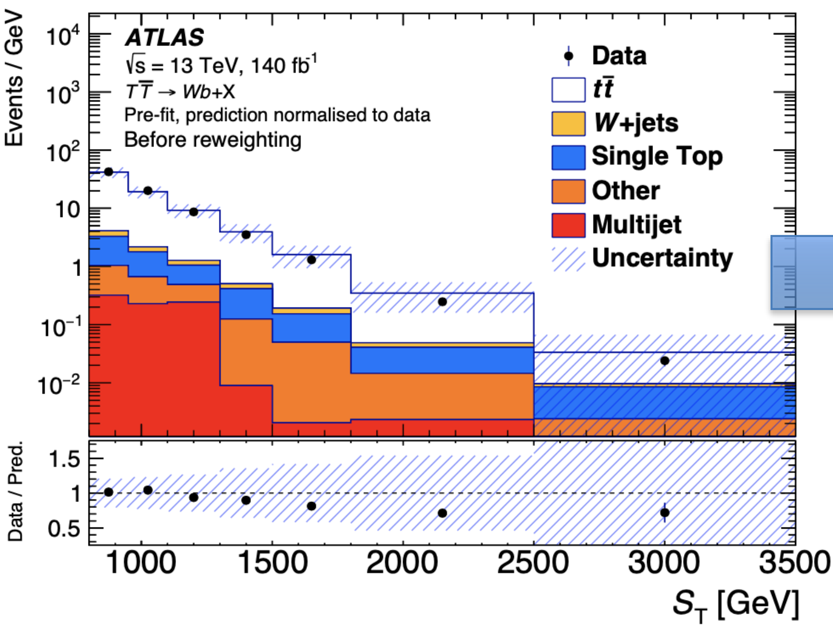
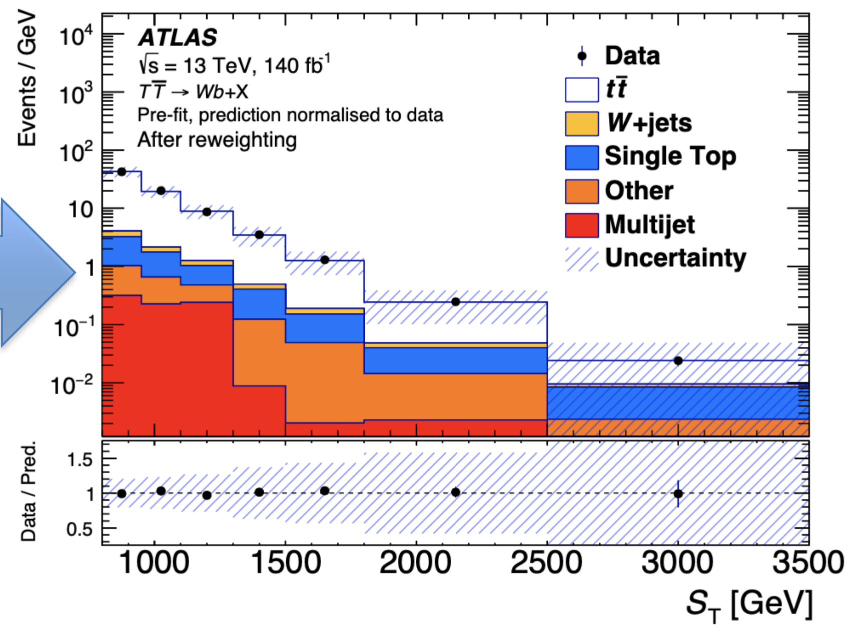


Background dominated by SM $t\bar{t}$

- Estimated with Monte Carlo simulation, but with data-driven correction to improve modeling
  - Derive S_T correction in "re-weighting region"
    - Similar kinematics to SRs, but low signal contamination

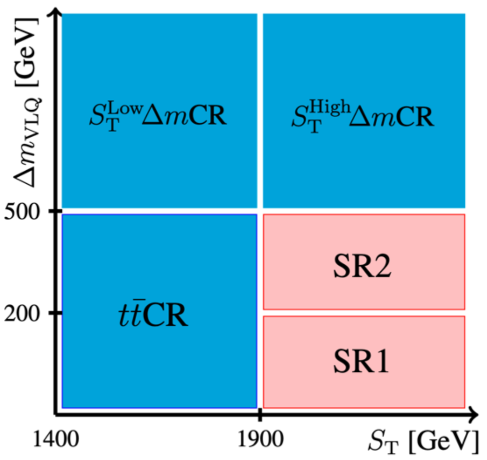




Top-Partner Pair-Produced : $TT \rightarrow Wb+X$

Perform simultaneous fit to data of reconstructed VLQ mass using:

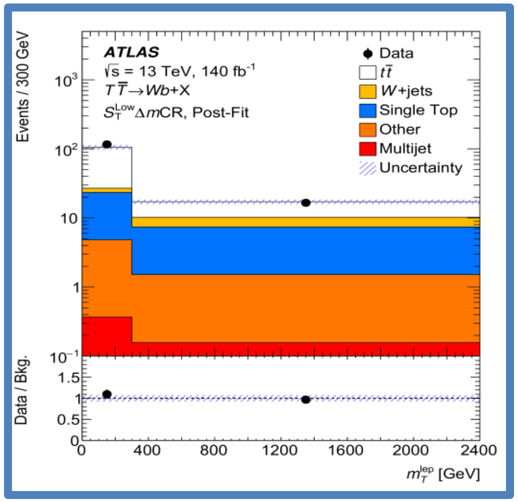
- **2 Signal Regions**
- **3 Control Regions**
  - ttCR: **Constrains** dominate tt background
  - ΔmCRs with Low and High S_T: **Provides extrapolation** between ttCR and SRs

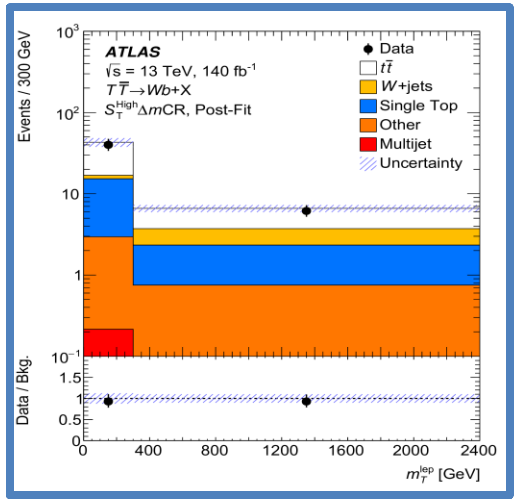


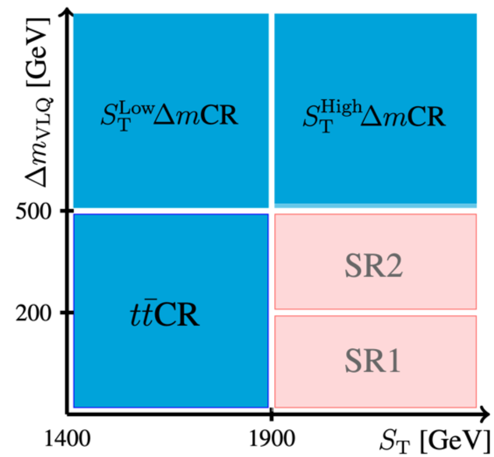
[Phys. Lett. B 854 (2024) 138743](https://doi.org/10.1016/j.physletb.2024.138743)

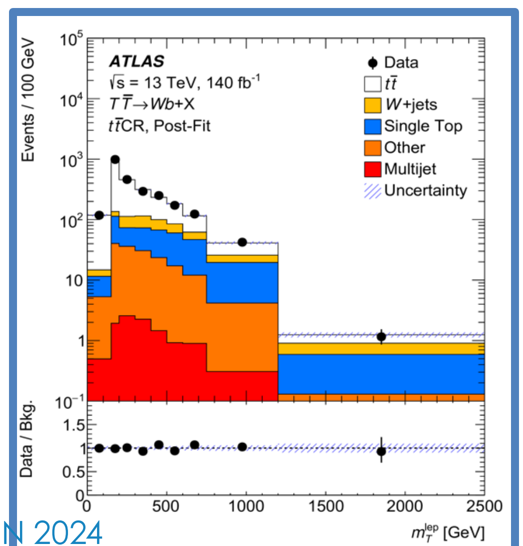
Top-Partner Pair-Produced : $TT \to Wb+X$

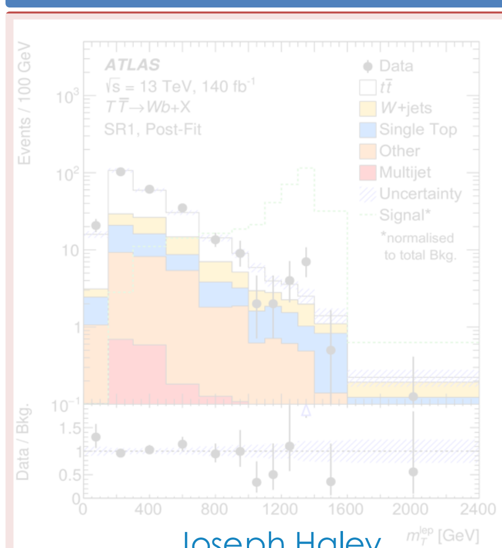
Perform simultaneous fit to data of reconstructed VLQ mass in **3 CRs**

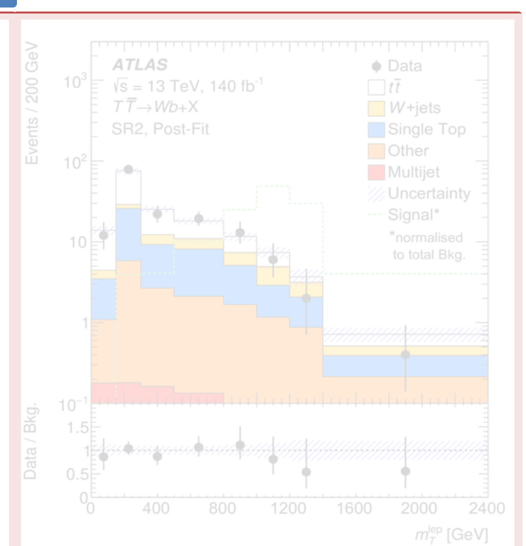












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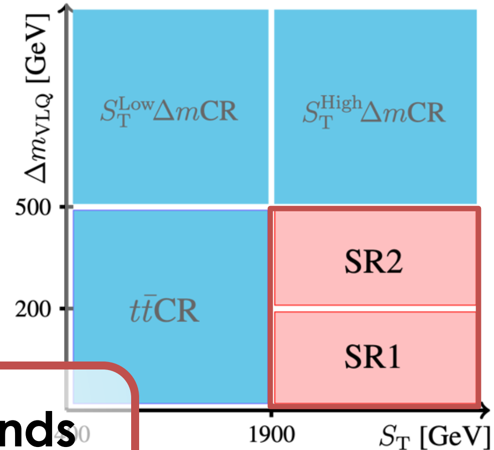
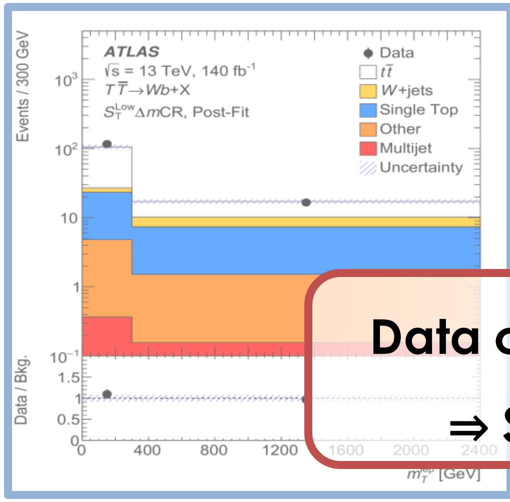
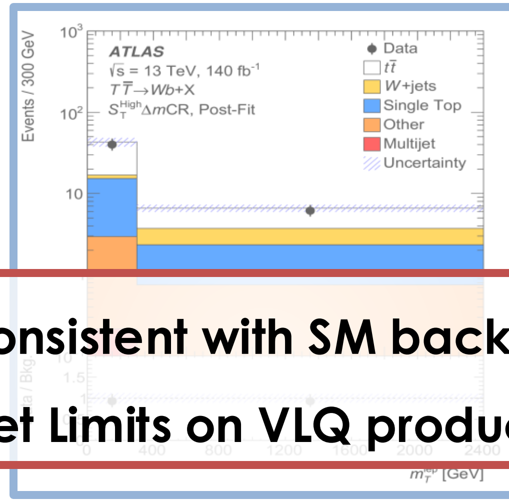
Top-Partner Pair-Produced : $TT \rightarrow Wb+X$

Perform simultaneous fit to data of reconstructed VLQ mass in **3 CRs** and **2 SRs**

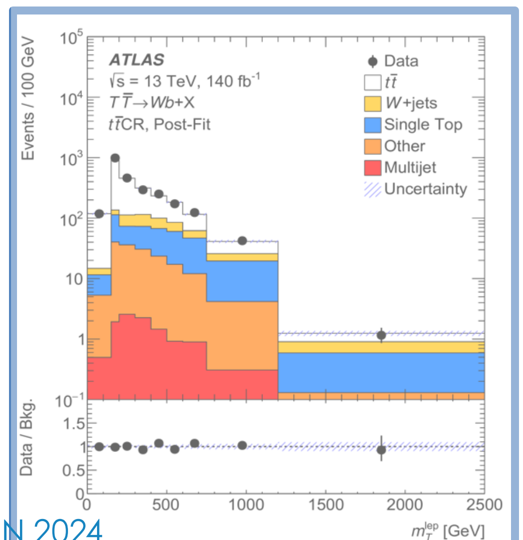


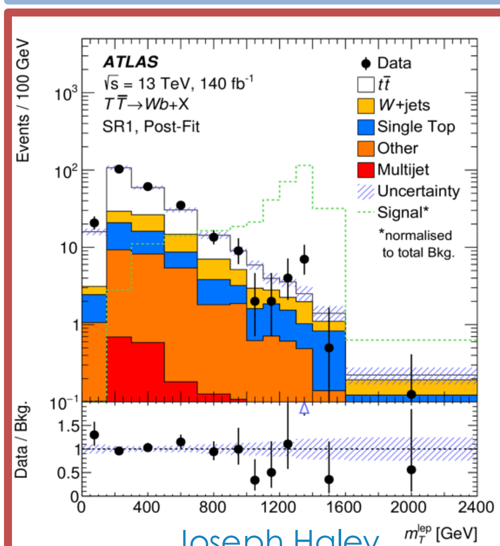


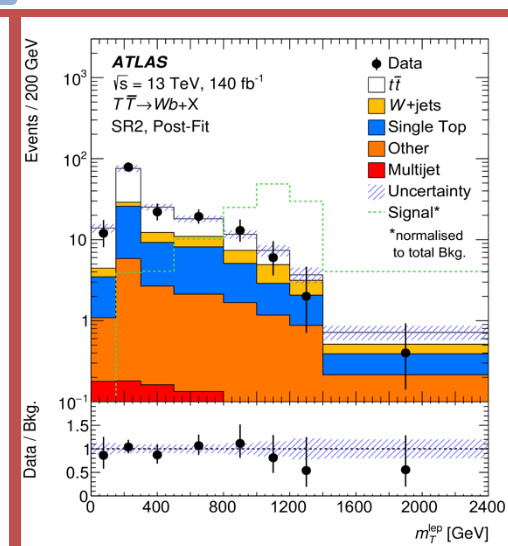


Data consistent with SM backgrounds

⇒ Set Limits on VLQ production







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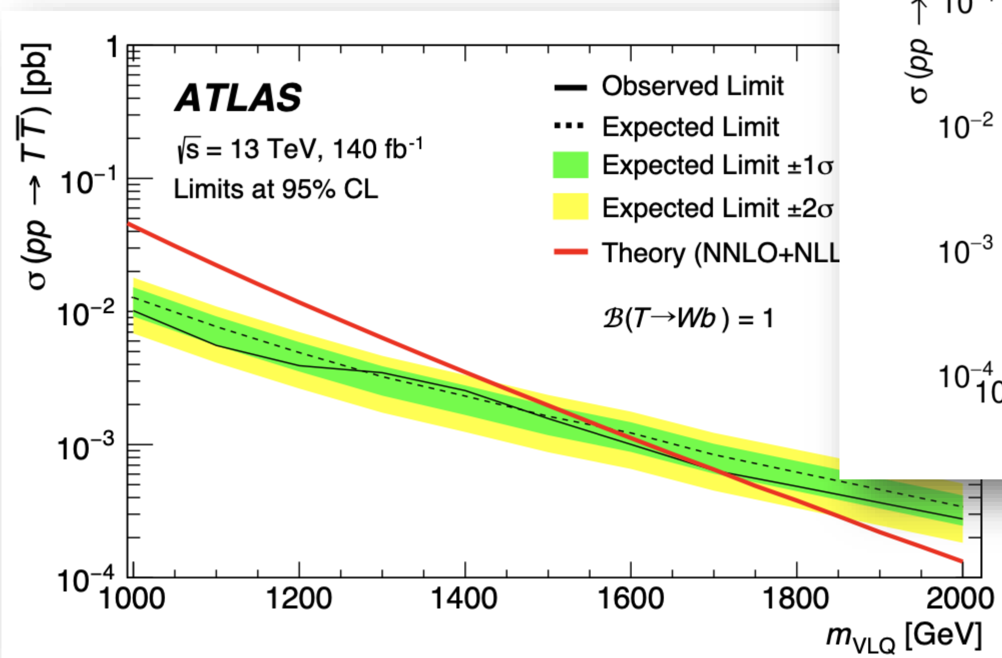
⇒ **Limits on cross-section vs. mass**

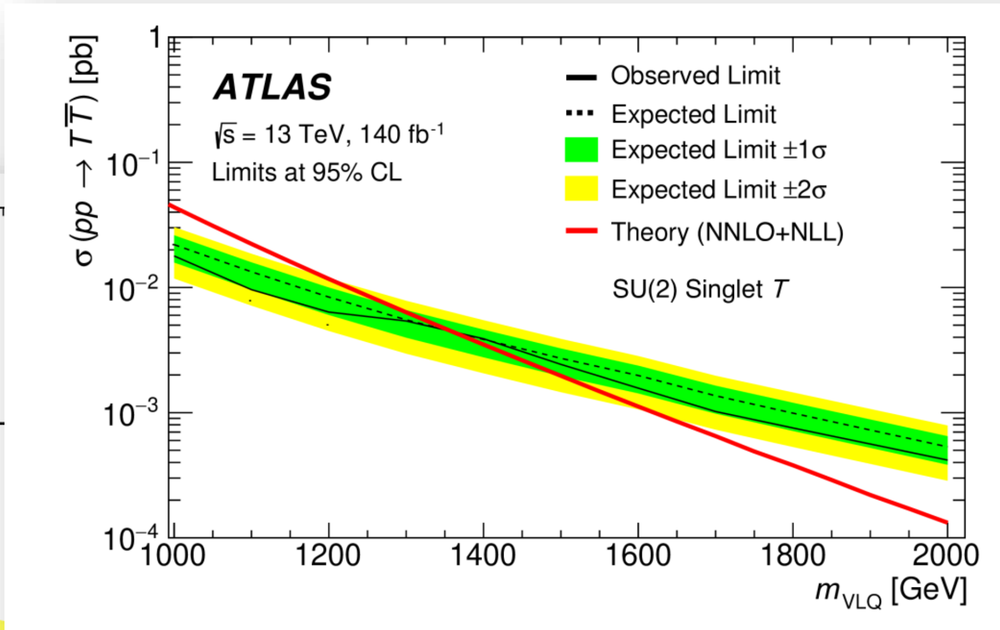
Electroweak Singlet T

⇒ $\mathcal{B}(T \rightarrow Wb : Ht : Zt) =$ ½ : ¼ : ¼

Pure $T\,T \rightarrow WbWb$

⇒ $\mathcal{B}(T \rightarrow Wb) = 1$





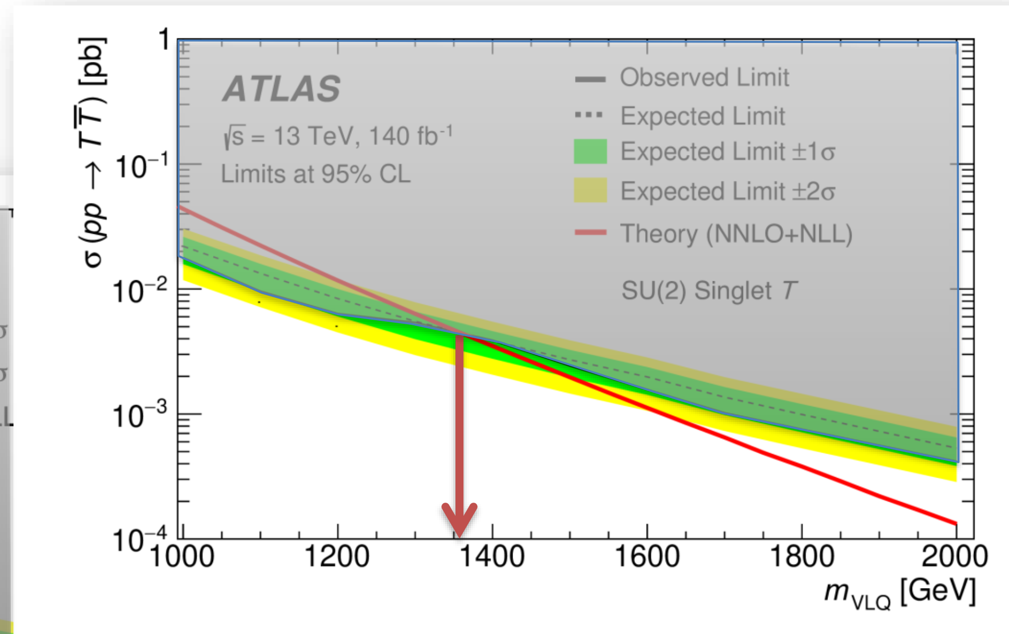
Phys. Lett. B 854 (2024) 138743

Top-Partner Pair-Produced : $TT \rightarrow Wb+X$

⇒ Limits on cross-section vs. mass

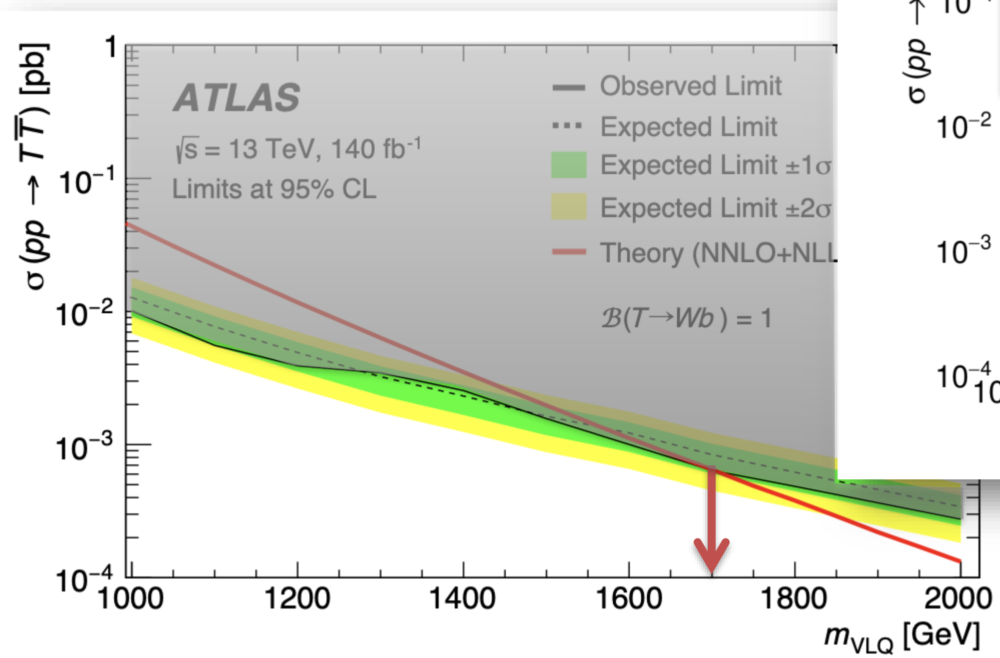
Electroweak Singlet T

⇒ $\mathcal{B}(T \rightarrow Wb : Ht : Zt) =$ ½ : ¼ : ¼



Pure $T\,T \rightarrow WbWb$

⇒ $\mathcal{B}(T \rightarrow Wb) = 1$

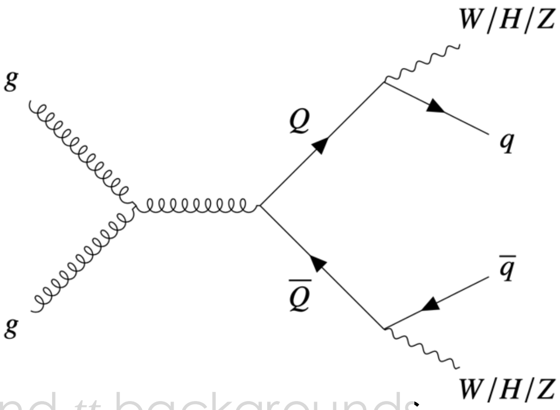


Singlet excluded for $m_{VLQ} \lesssim$ 1360 GeV

$\mathcal{B}(T \rightarrow Wb) = 1$ **excluded for $m_{VLQ} \lesssim$ 1700 GeV**

350 GeV increase from previous limit $m_{VLQ} \lesssim$ 1350 GeV

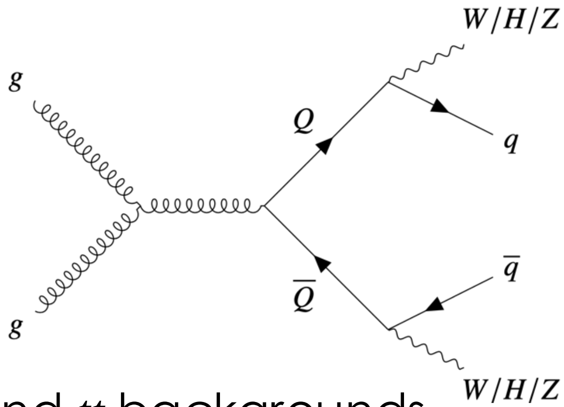
Light-Partners Pair-Produced : $QQ \rightarrow Wq+X$



Like $TT \rightarrow Wb+X$, but a few significant differences:

- Require **zero** b-tagged jets
- Background dominated by ***W*+jets**
  ⇒ Data-driven S_T correction for both W+jets and tt backgrounds

Light-Partners Pair-Produced : $QQ \rightarrow Wq+X$



Like $TT \rightarrow Wb$+X, but a few significant differences:

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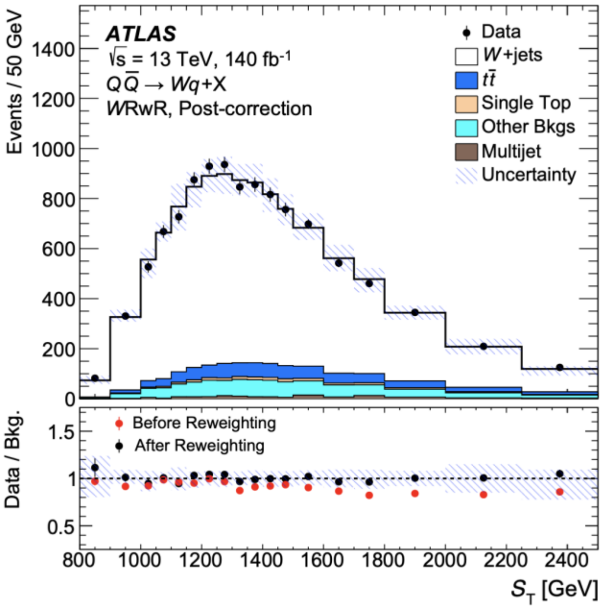
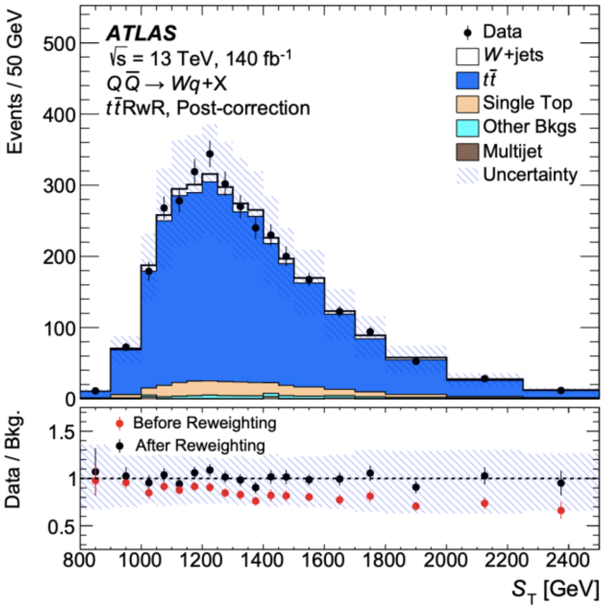
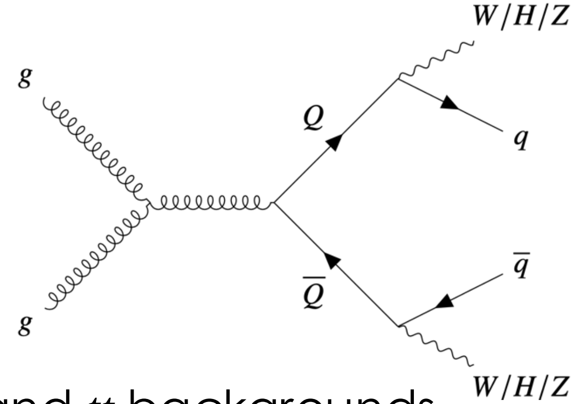


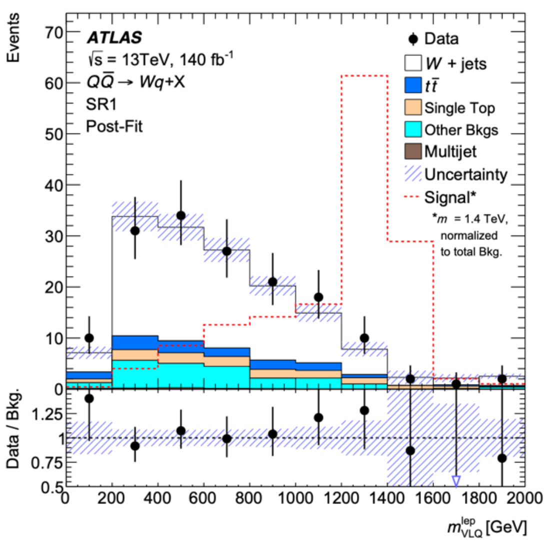


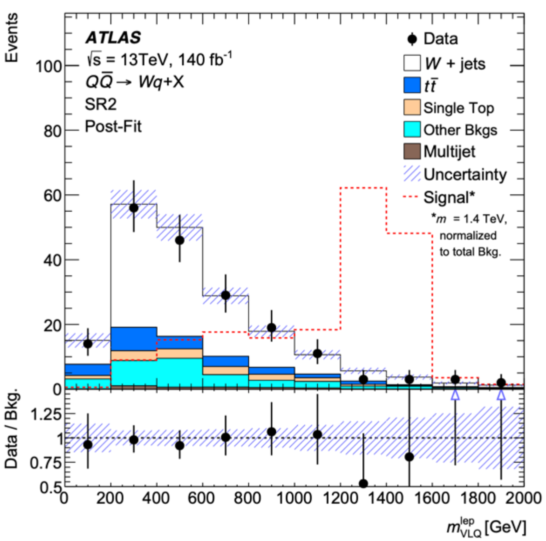
Light-Partners Pair-Produced : $QQ \rightarrow Wq+X$



Like $TT \rightarrow Wb$+X, but a few significant differences:

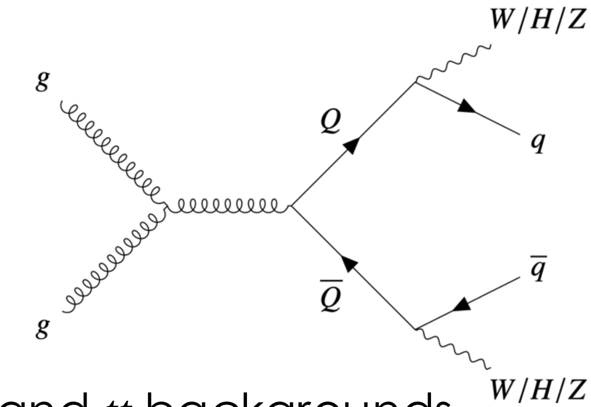
- Require zero b-tagged jets
- Background dominated by W+jets
  ⇒ Data-driven S_T correction for both W+jets and tt backgrounds
- Sensitivity limited by statistical uncertainty ⇒ **Only need to fit SRs**





EXOT-2021-35 Submitted to Phys Rev. D (*last Friday!*)

Light-Partners Pair-Produced : $QQ \rightarrow Wq+X$



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  ⇒ Data-driven S_T correction for both W+jets and tt backgrounds
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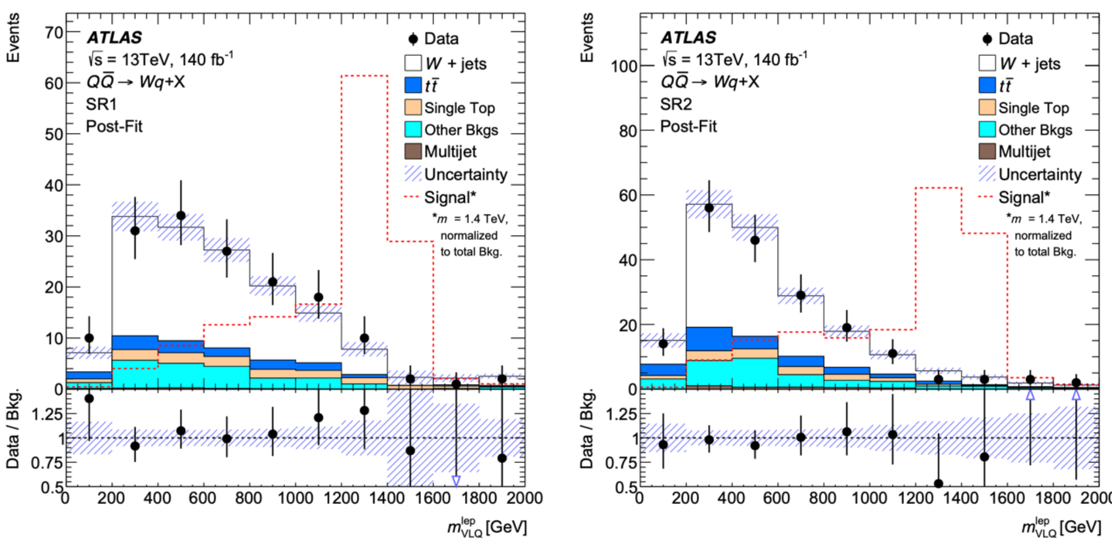


No signs of new physics

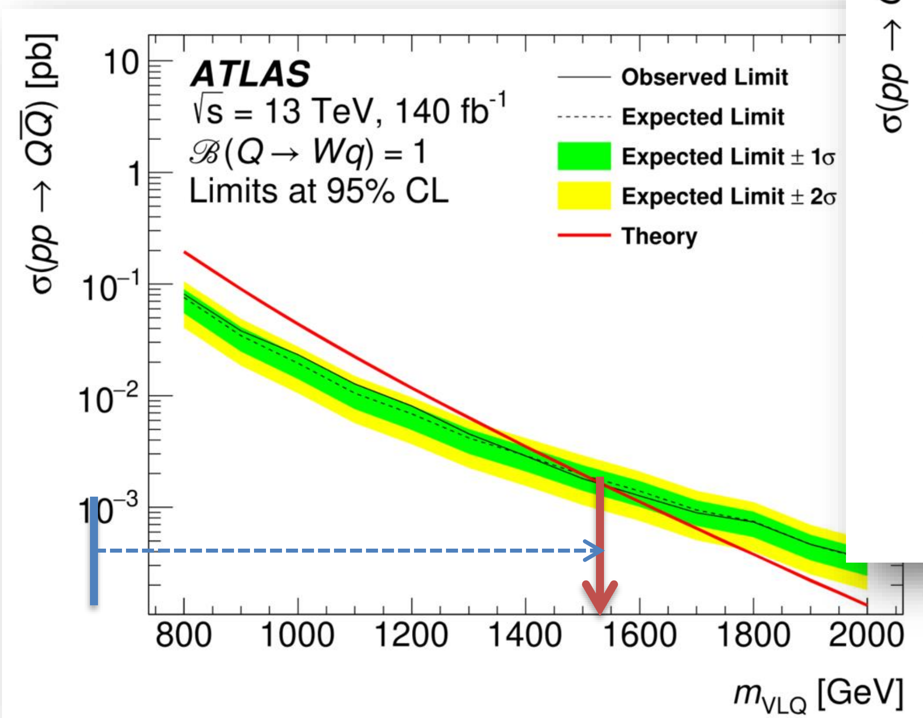
⇒ **Set limits**

EXOT-2021-35 Submitted to Phys Rev. D (*last Friday!*)

Light-Partners Pair-Produced : $QQ \rightarrow Wq+X$

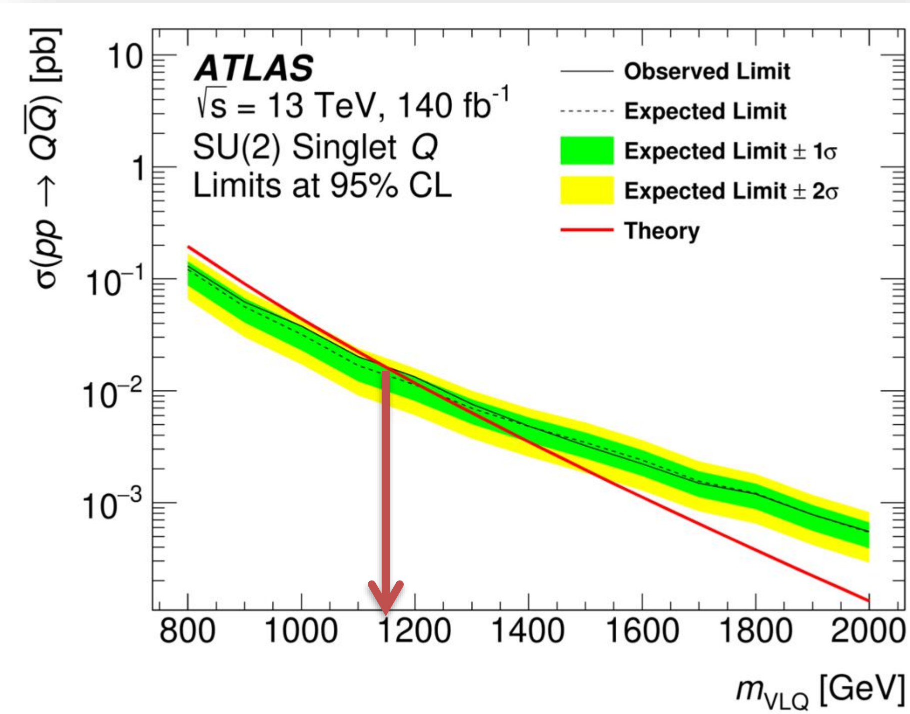
⇒ Limits on cross-section vs. mass for benchmark scenarios

Pure $QQ \rightarrow WqWq$



Excluded for $m_{VLQ} \leq$ **1530 GeV**

Electroweak Singlet Q

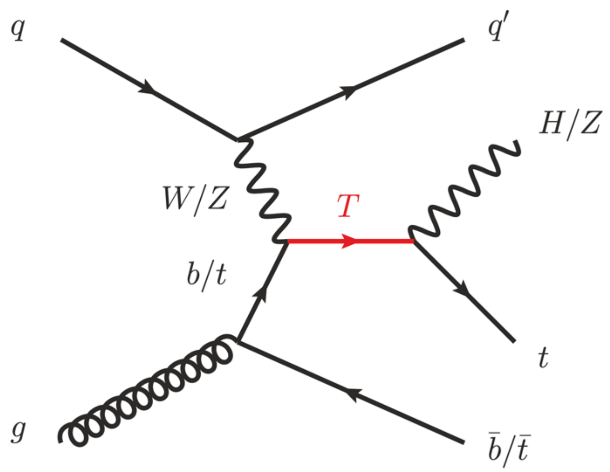


Excluded for $m_{VLQ} \leq$ **1150 GeV**

840 GeV increase from previous limit $m_{VLQ} \leq$ 690 GeV GeV

Top-partner Single-produced Combination

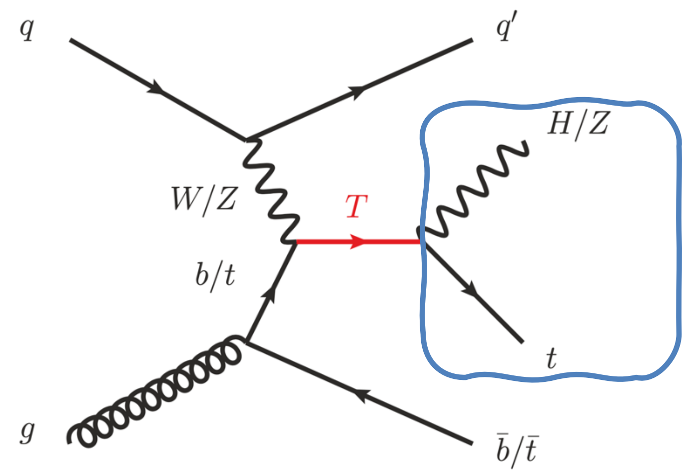
Statistical combination searches for single T production



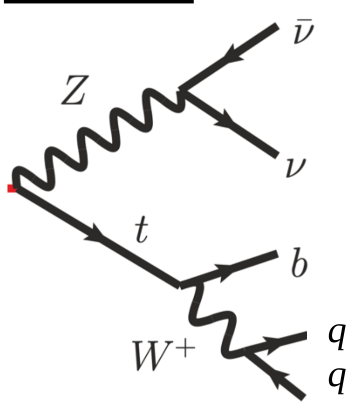
Top-partner Single-produced Combination

Statistical combination searches for single T production

⇒ Three input analyses with different numbers of leptons

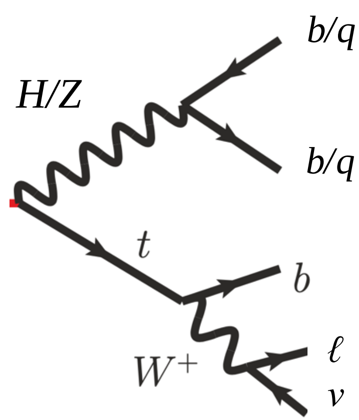


MonoTop



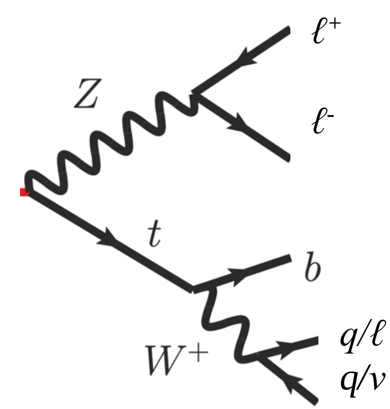
- $Z \rightarrow \nu\nu$: E_T^{miss} (0ℓ)
- Boosted $t \rightarrow bqq$

HtZt



- $t \rightarrow \ell\nu b$ (1ℓ)
- Boosted $H/Z \rightarrow qq/bb$

Osml

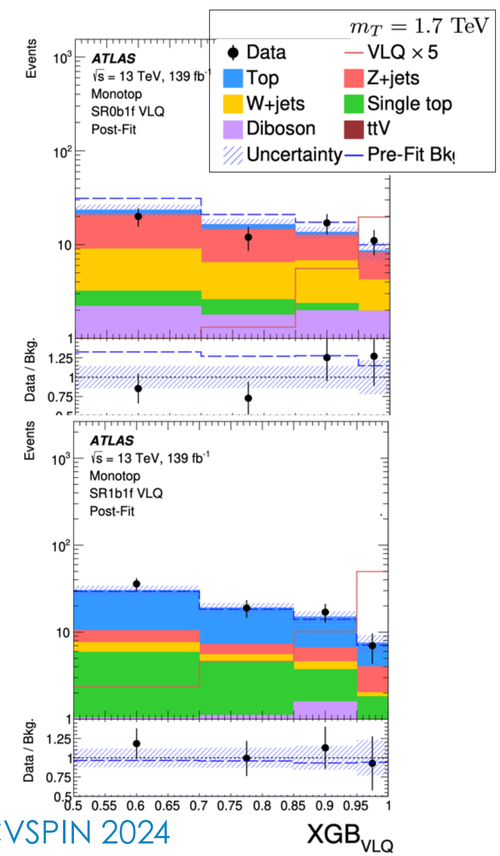


- $Z \rightarrow \ell^+\ell^-$ (2ℓ)
- $t \rightarrow qqb/\ell\nu b$

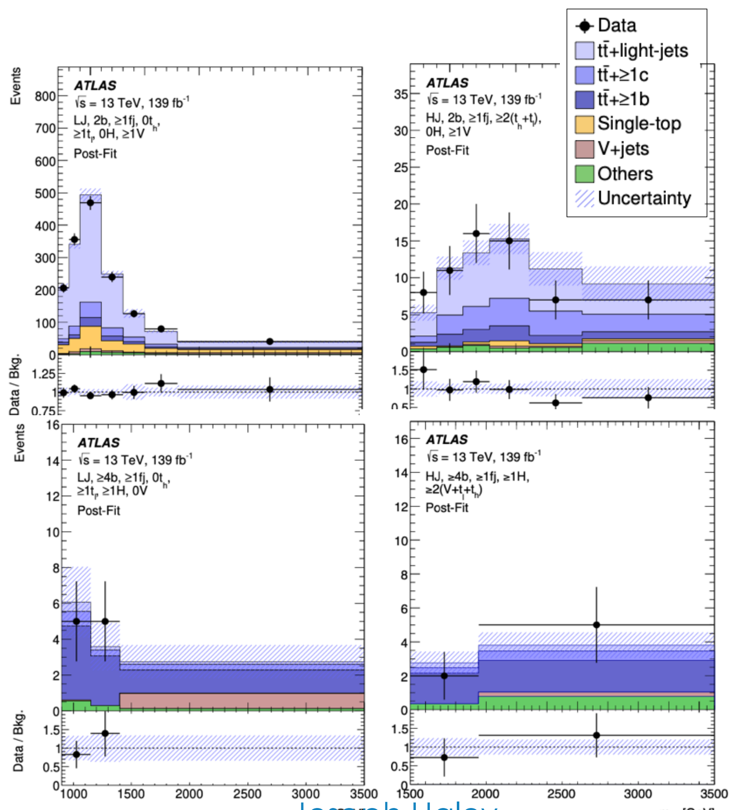
Single-Production Combination: Signal Regions

Analysis	Target signal	Decay channels	Discriminants
MONOTOP	$Wb/Zt \to T \to Zt$	$Zt \to \nu\nu bqq$ (0ℓ)	BDT score
HTZT	$Wb/Zt \to T \to Ht/Zt$	$Ht/Zt \to bbb\ell\nu/qqb\ell\nu$ (1ℓ)	m_{eff}
OSML	$Wb/Zt \to T \to Zt$	$Zt \to \ell\ell b\ell\nu$ (3ℓ), $Zt \to \ell\ell bqq$ (2ℓ)	Z boson p_{T}

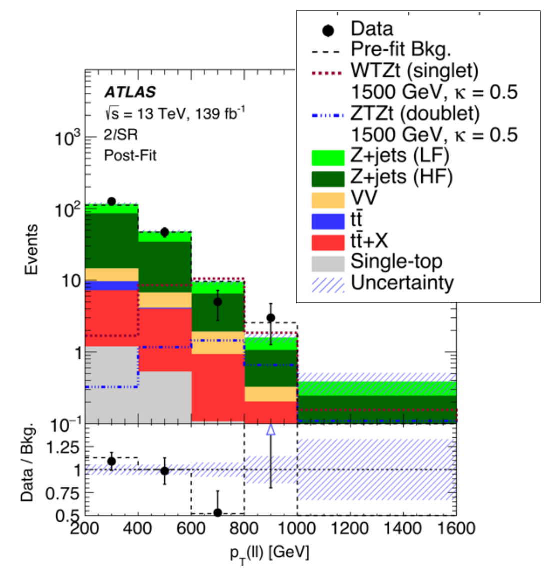
MonoTop



HtZt



Osml



All consistent with SM

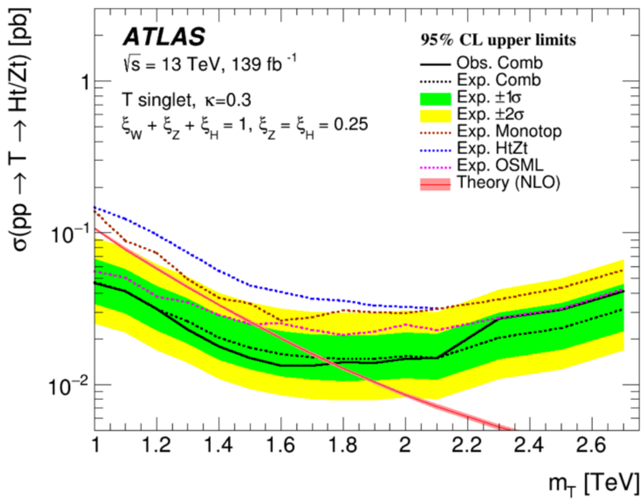
⇒ Set Limits

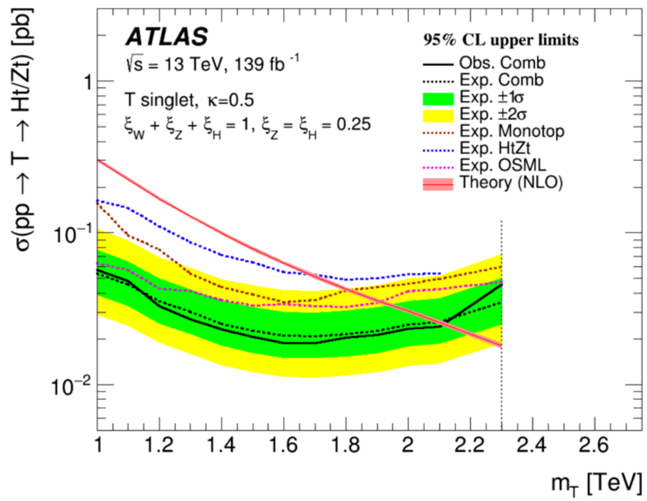
Single-Production Combination: Results

For a given model and κ, set **limits on cross-section vs. mass**

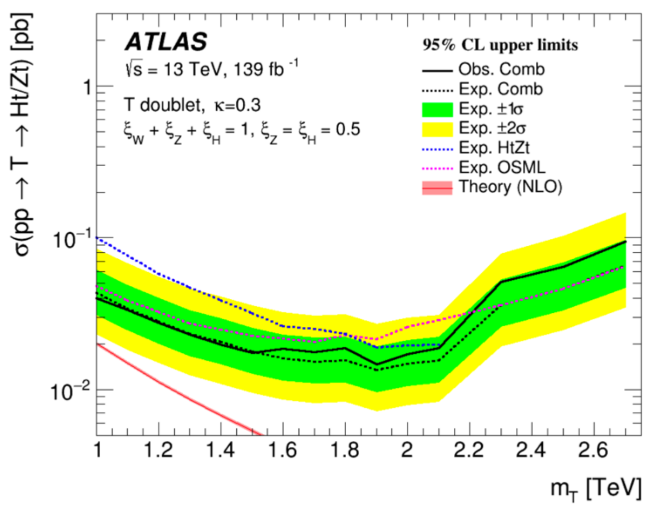
$\kappa = 0.3$ | $\kappa = 0.5$

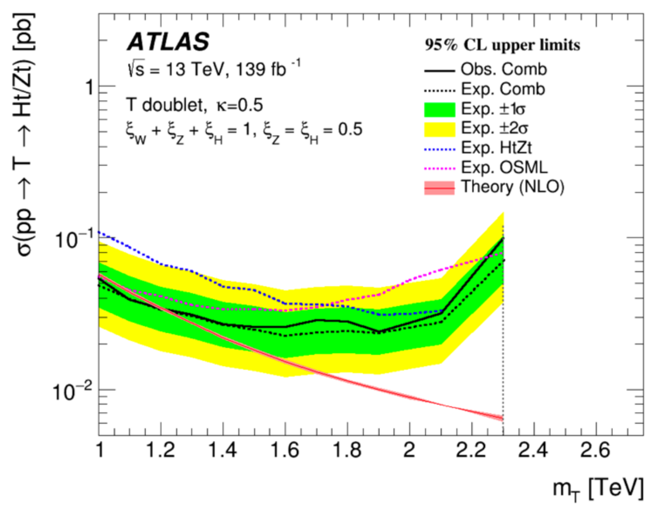
Singlet T





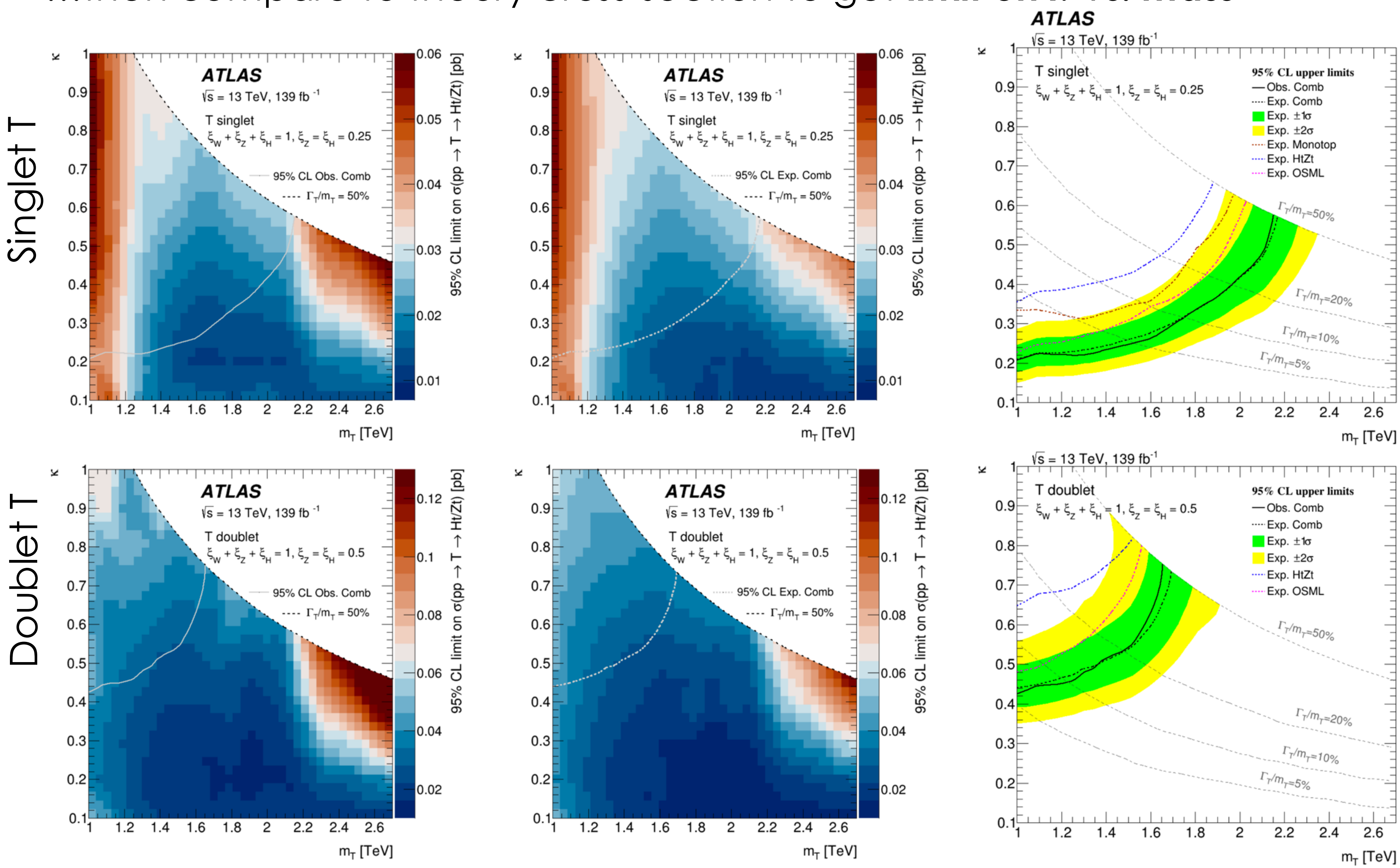
Doublet T





Single-Production Combination: Results

For a given model, set limit on **cross-section vs. (m, κ)**
…then compare to theory cross-section to get **limit on κ vs. mass**

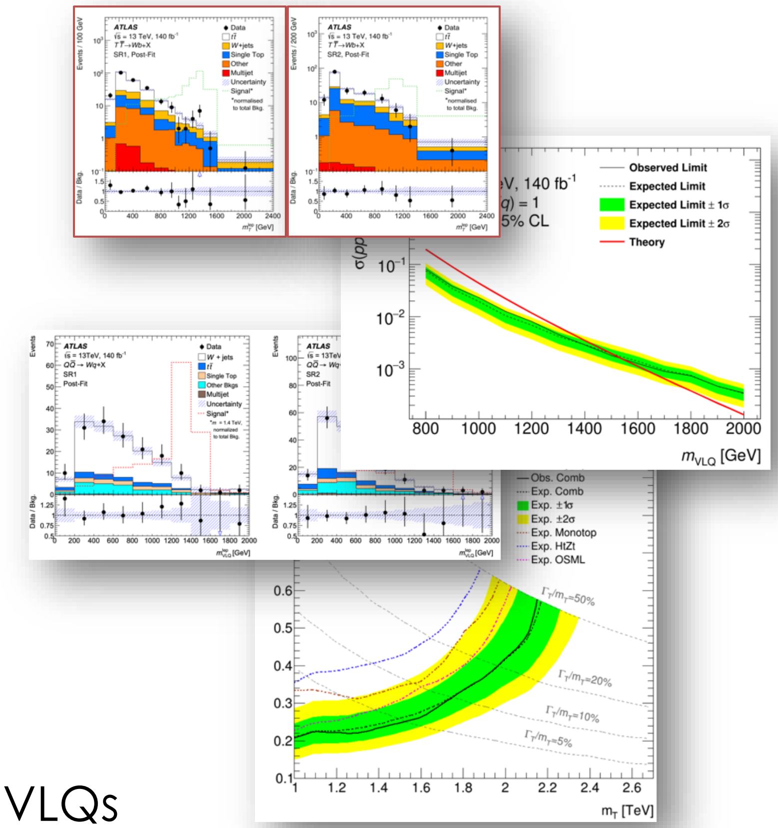


Conclusion

ATLAS has a wide range of searches for VLQs

- Significant gains in sensitivity
  - ➢ Using full Run 2 data set
  - ➢ Improved analysis techniques

    e.g. b-, W-, Higgs-, and top-tagging
  - ➢ Improved background modeling
  - ➢ Combination of single-VLQ searches
- Most results are best limits to date



- Unfortunately, still no direct signs of VLQs

  … but Run 3 is underway, bring much **more data**,

  … and even **more new searches**!

Thank you!

And special thank you to:

DOE for supporting this research

The ATLAS Collaboration

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

The BCVSPIN 2024 Organizers!

List of presented analyses

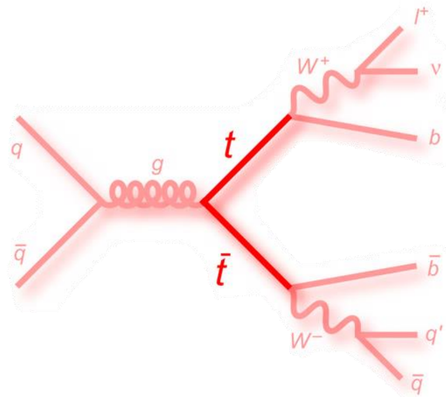
- Search for pair-production of vector-like quarks in lepton+jets final states containing at least one b-tagged jet using the Run 2 data from the ATLAS experiment (Phys. Lett. B 854 (2024) 138743)
- Search for pair-produced vector-like quarks coupling to light quarks in the lepton plus jets final state using 13 TeV pp collisions with the ATLAS detector (Phys. Rev. D 110 (2024) 052009)
- Combination of searches for singly produced vector-like top quarks in *pp* collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector (Submitted to Phys. Rev. D August 2024)

Backup:

- Search for single vector-like B -quark production and decay via B→bH(bb) in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector (JHEP11 (2023) 168)

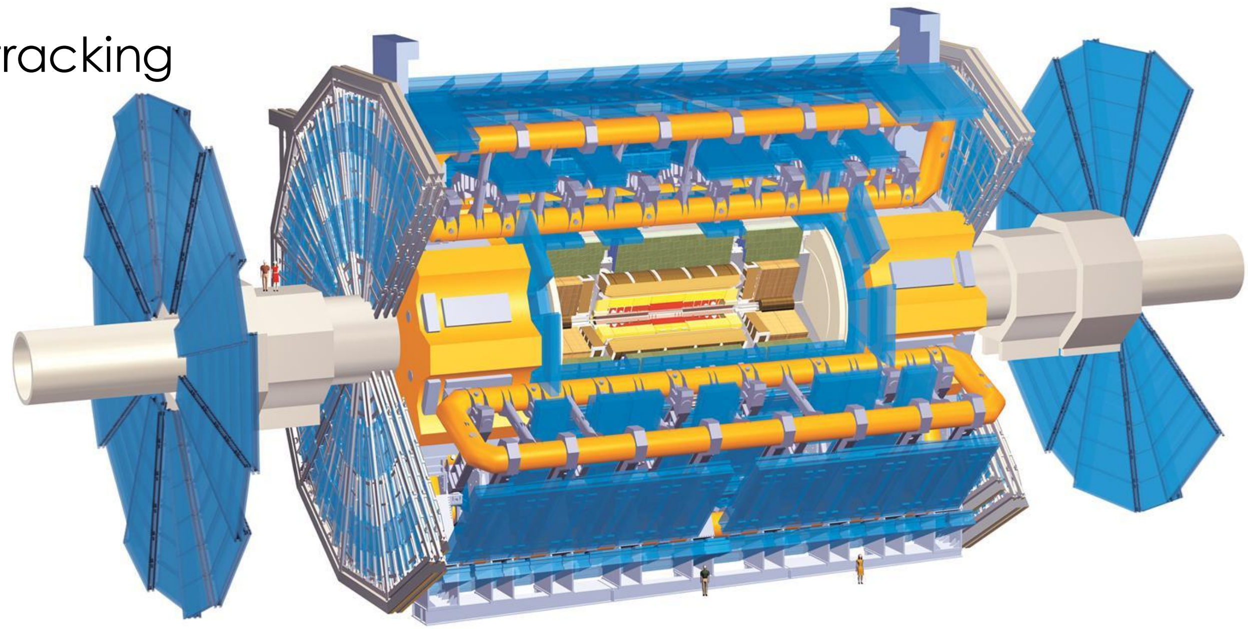
ATLAS Detector

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



ATLAS is a “top detector”

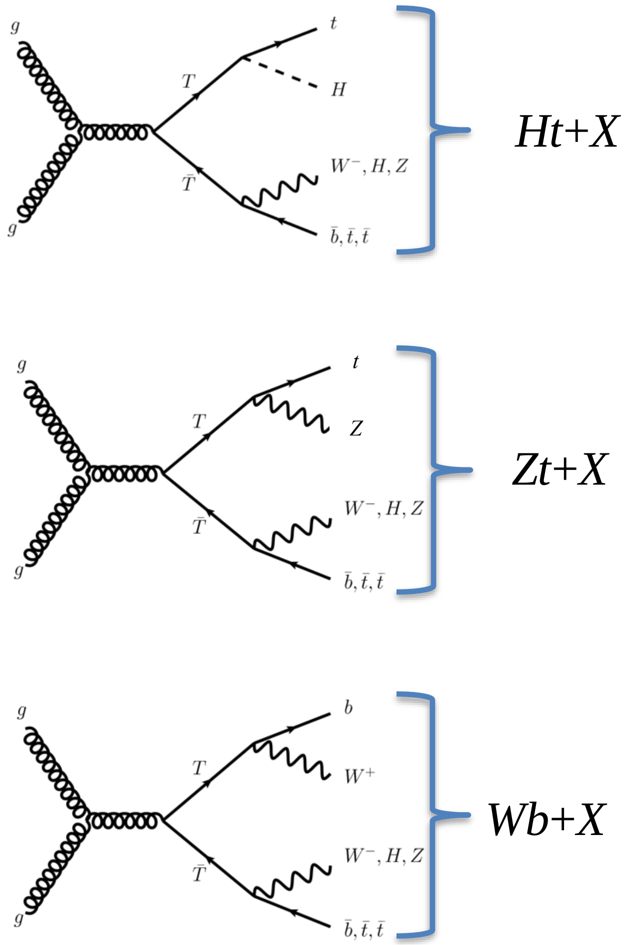
- Efficient e/μ identification
- Nearly 4π coverage ⇒ E_T^{miss}
- High granularity tracking
- ⇒ *b*-tagging



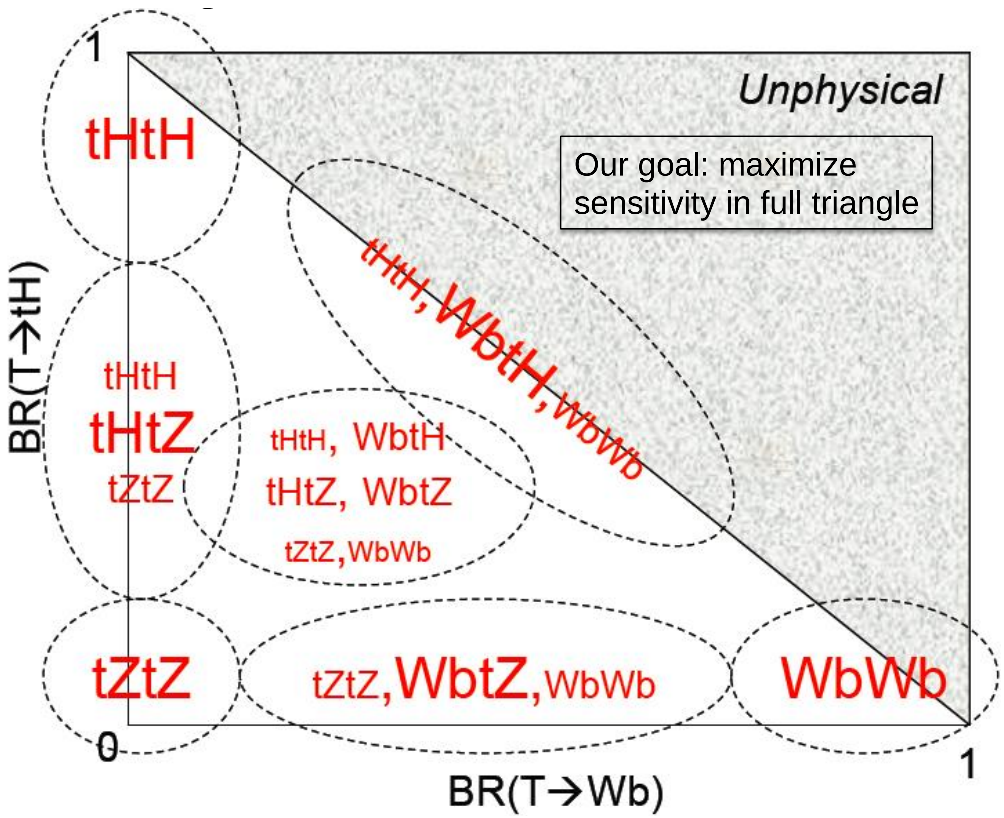
All results using the ATLAS Run 2 data set (L = 139 fb^{-1}, √s = 13 TeV)

General Strategy

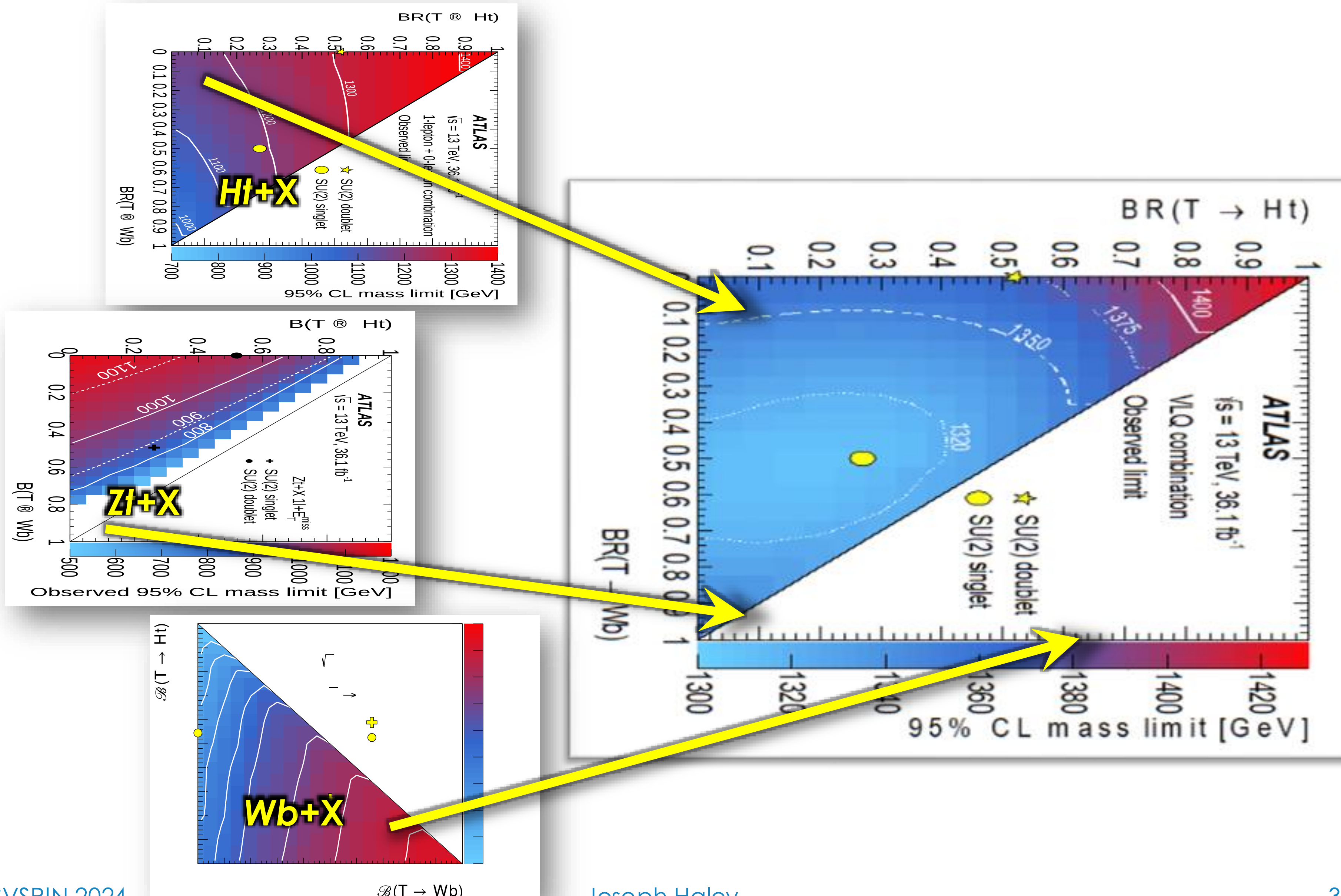
Multiple analyses to target each decay:



Test all possible branching ratios:



Previous Results (36.1 fb^{-1})



Top-Partner Pair-Produced : $TT \rightarrow Wb+X$

⇒ Limits on cross-section vs. mass

for benchmark scenarios

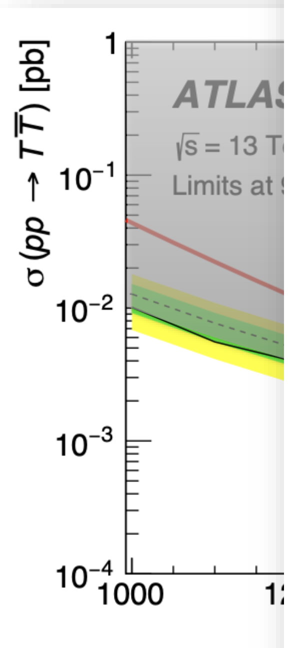
Electroweak Singlet T

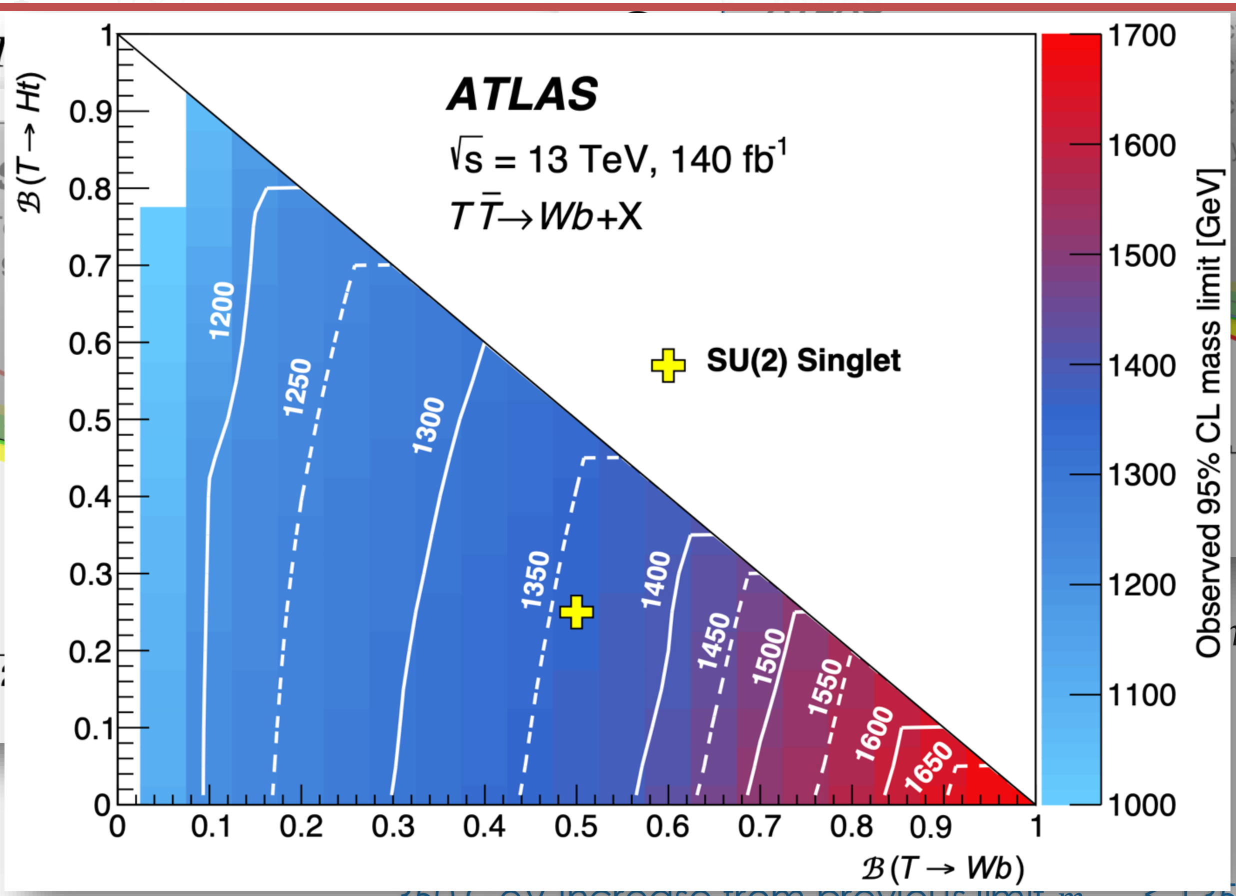
⇒ $\mathcal{B}(T \rightarrow Wb : Ht : Zt) = ½ : ¼ : ¼$

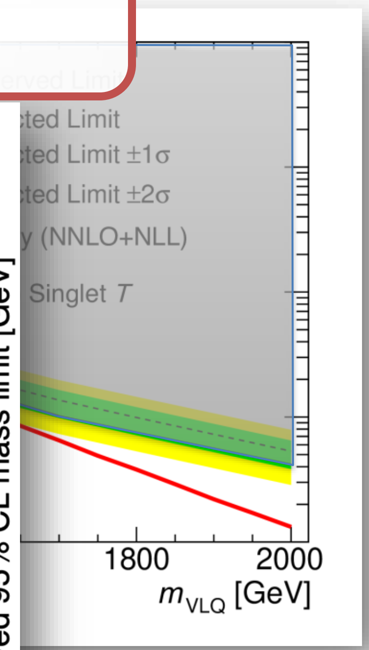
Pure $TT \rightarrow WbWb$

⇒ $\mathcal{B}(T$

⇒ Limits on T mass for any combination of branching ratios (assuming T decays to SM particles: $T \rightarrow Wb/Zt/Ht$)







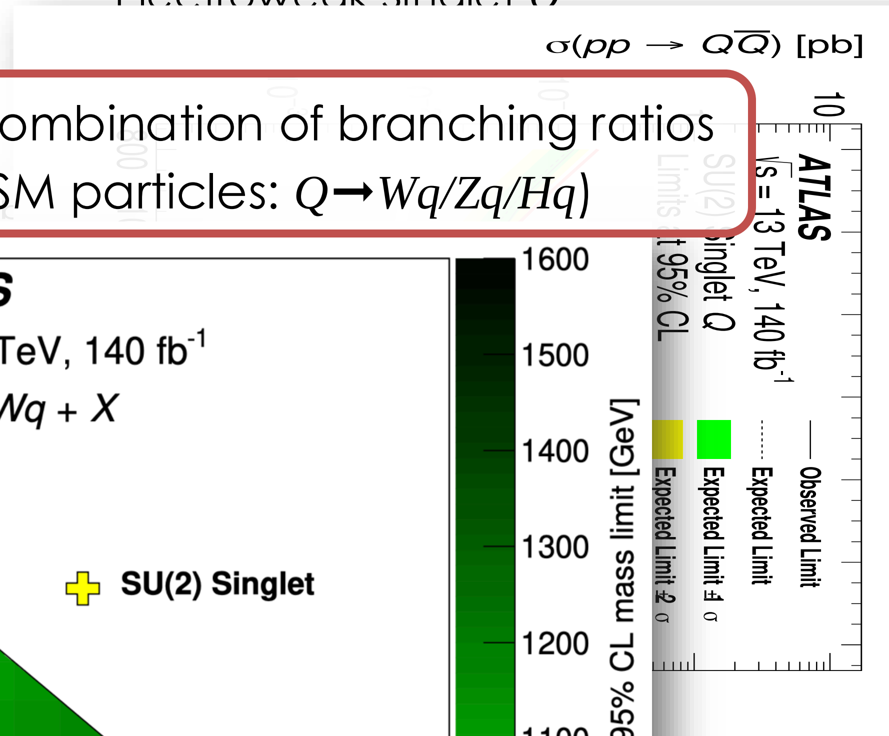
$m_{VLQ} \leq$ **1360 GeV**

350 GeV increase from previous limit $m_{VLQ} \leq 1350$ GeV

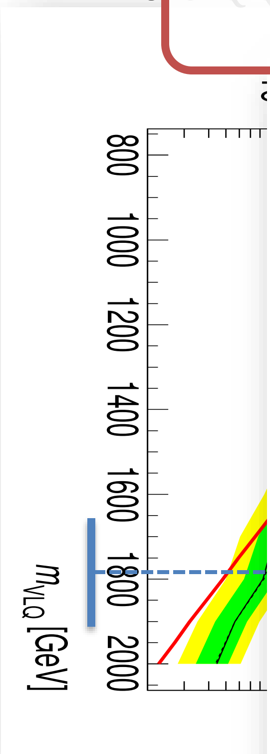
Light-Partners Pair-Produced : $QQ \rightarrow Wq+X$

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

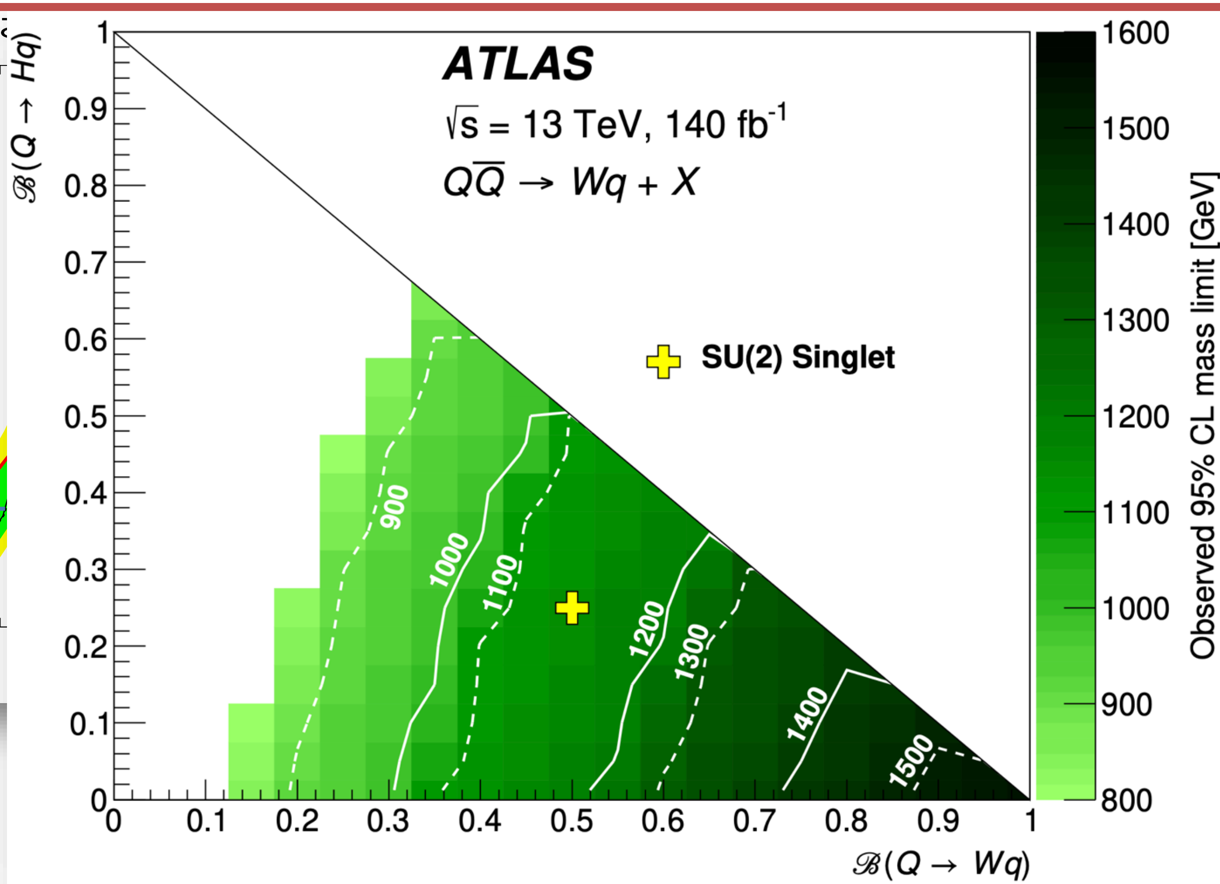
Electroweak Singlet Q



Pure $QQ \rightarrow WqWq$



⇒ Limits on Q mass for any combination of branching ratios (assuming Q decays to SM particles: $Q \rightarrow Wq/Zq/Hq$)



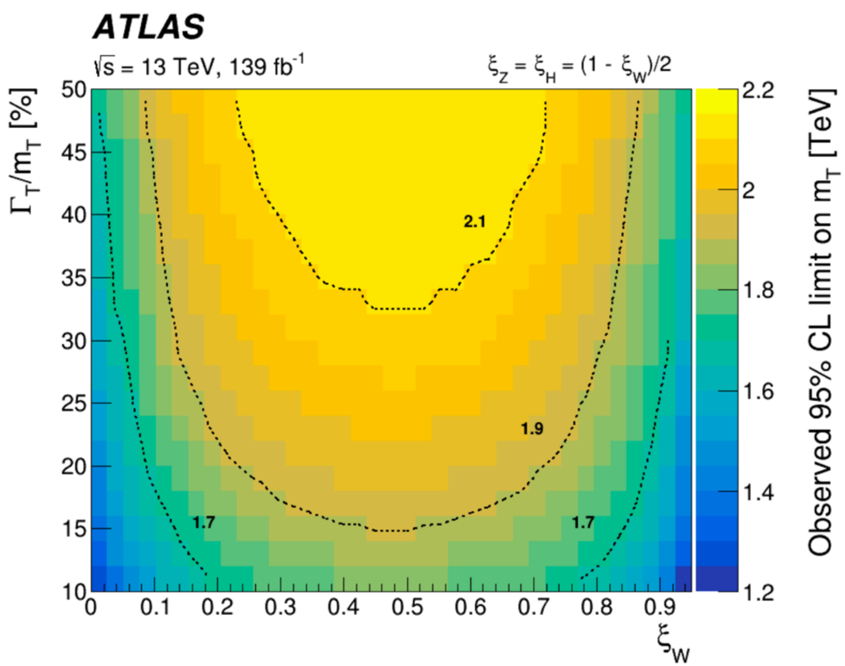
Q ≤ **1150 GeV**

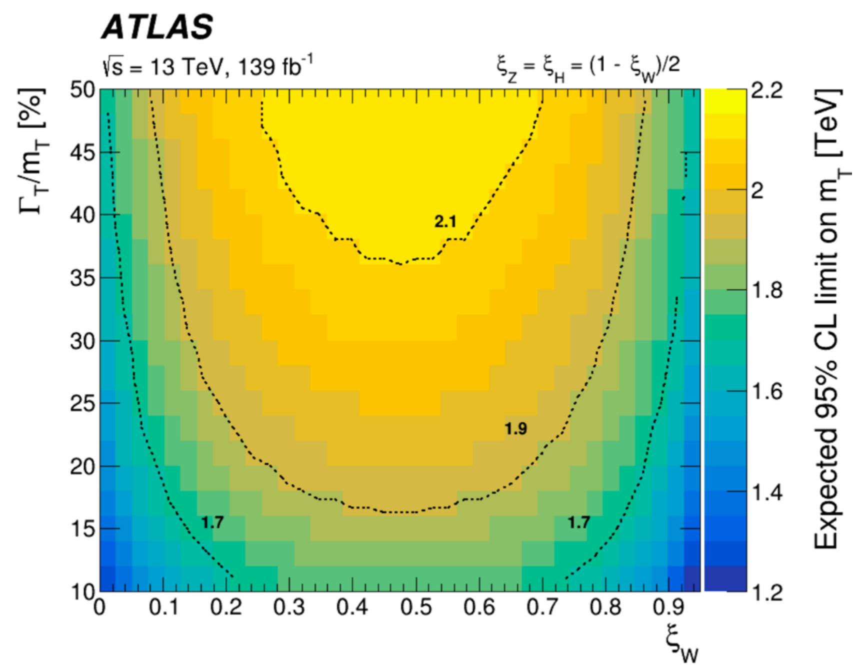
GeV

Singlet-Production Combination: Results

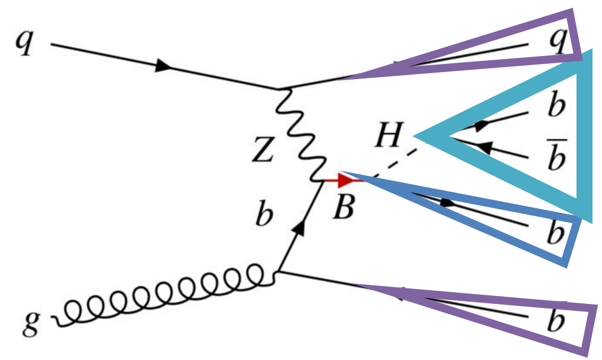
Limits on Singlet our Doublet

- Cross-section vs. mass for κ =0.3 or 0.5





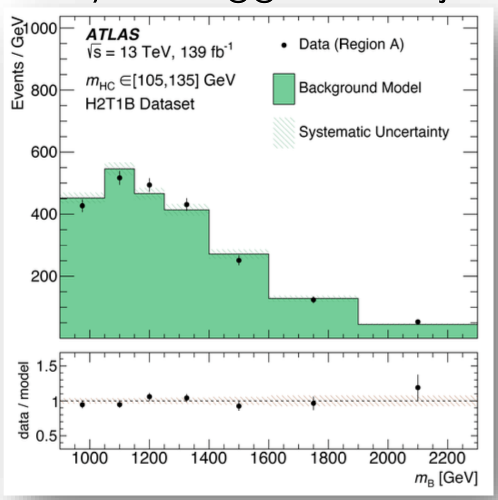
Single-produced Bottom-partner: $B \to Hb \to bbb$



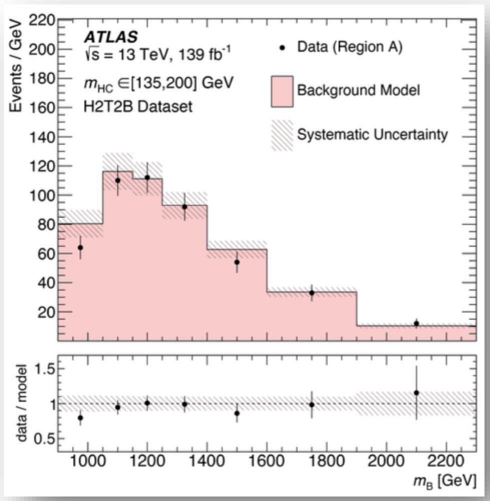
- **Large-R jet** with mass ≈ m_H & 2 b-tagged track jet
  - ⇒ Identified as boosted $H \to bb$
- High-p_T ***b*-tagged small-R jet** from $\boldsymbol{B}$ decay
  - ⇒ Critical to reduce huge multijet background
- At least one **"forward" jet** from spectator quarks

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)
- Validate by applying method in two orthogonal regions

Only 1 b-tagged track jet



Large-R jet mass sideband



J. High Energ. Phys. 2023, 168 (2023)

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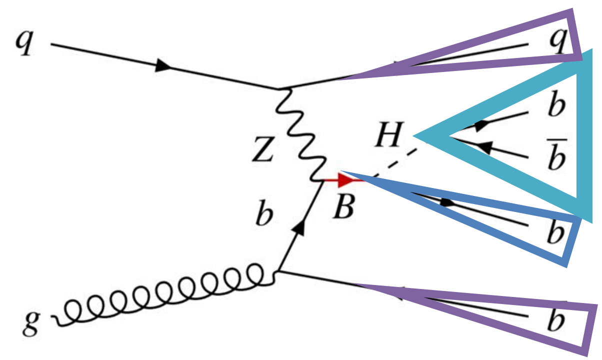

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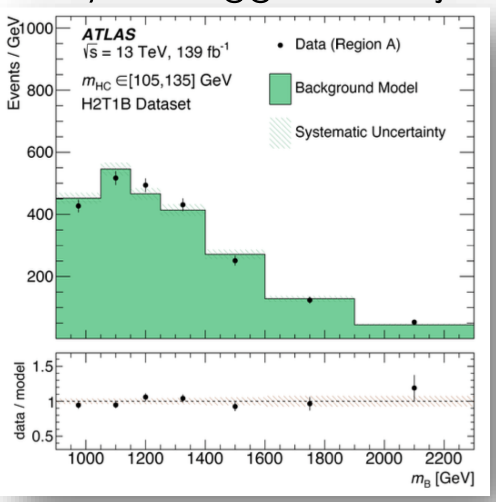
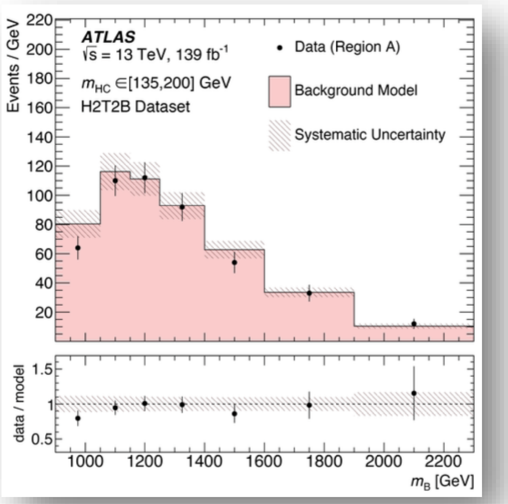


Large-R jet mass sideband



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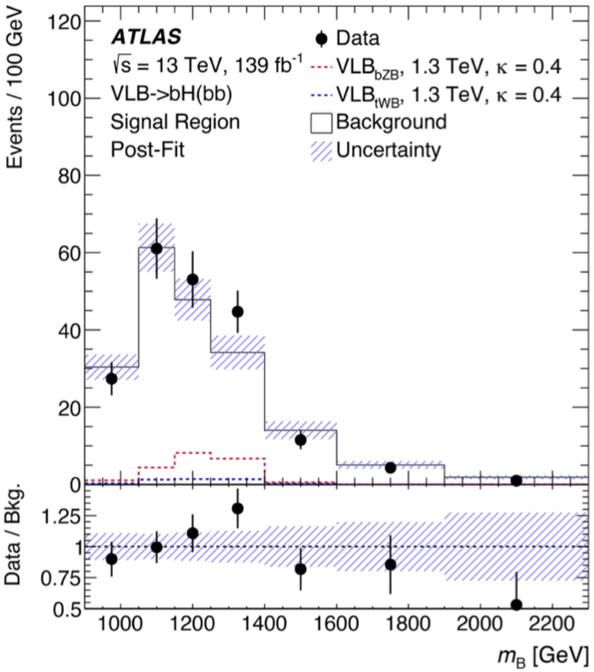
Single-produced Bottom-partner: $B \rightarrow Hb \rightarrow bbb$

Binned maximum-likelihood fit to reconstructed B mass distribution m_B

No significant excesses found in full Run 2 dataset

⇒ Set limits

- Limits on coupling κ as a function of the VLB mass for B singlet or (B,Y) doublet
- Lower bounds on VLB mass for given BR and width



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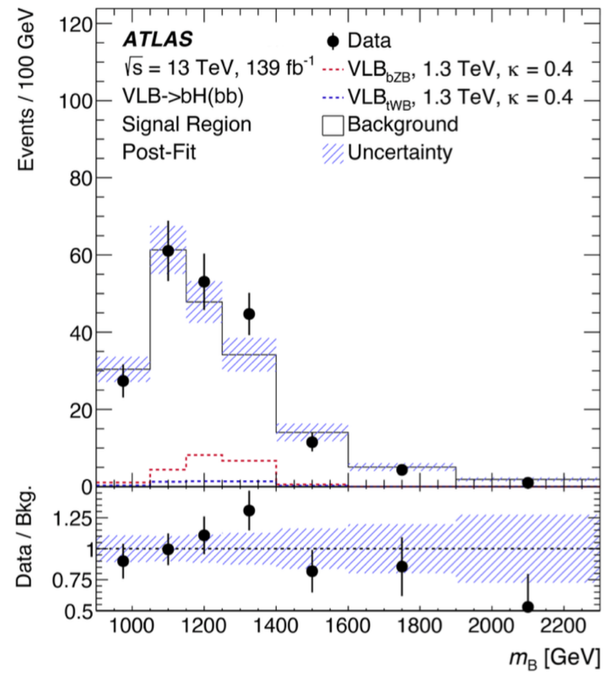

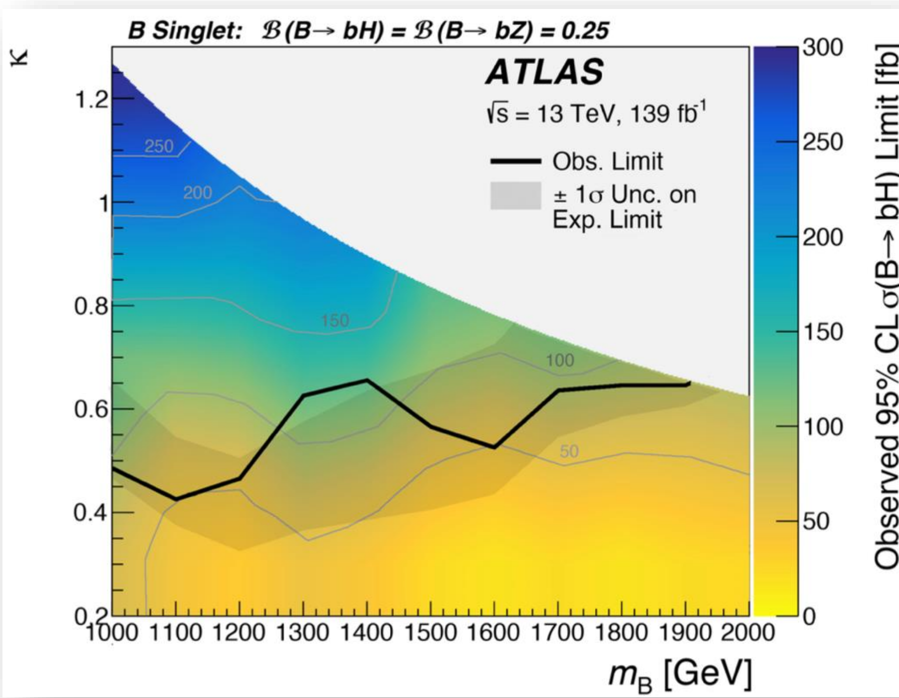

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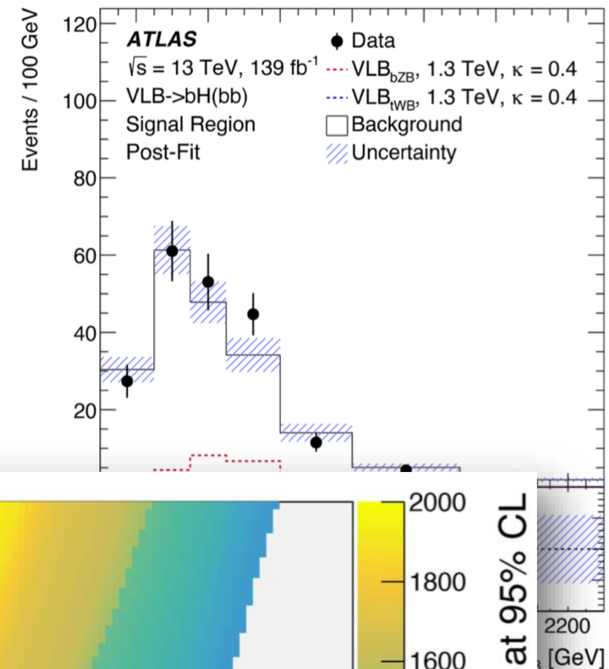
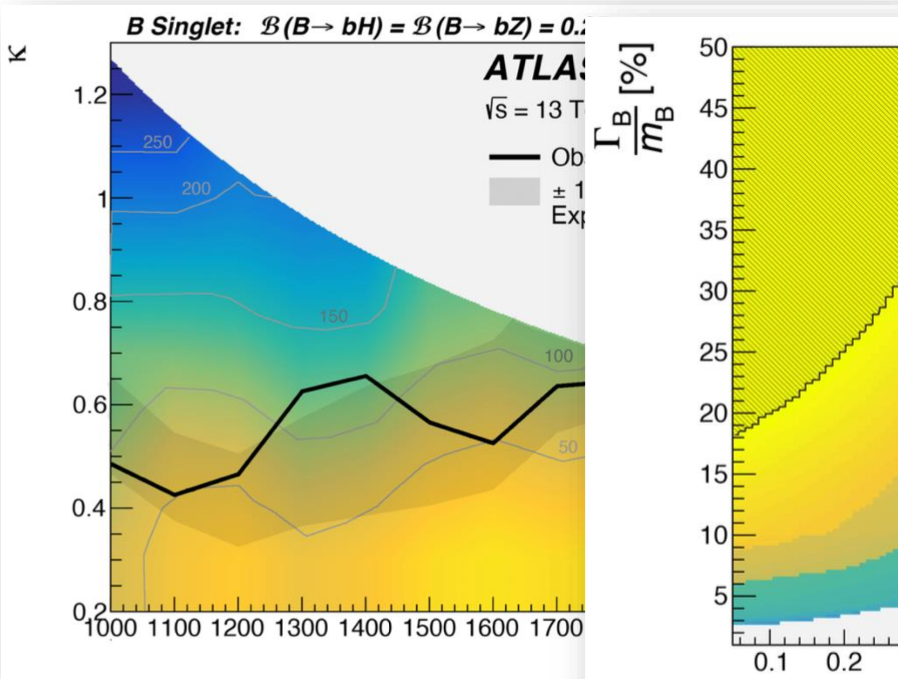
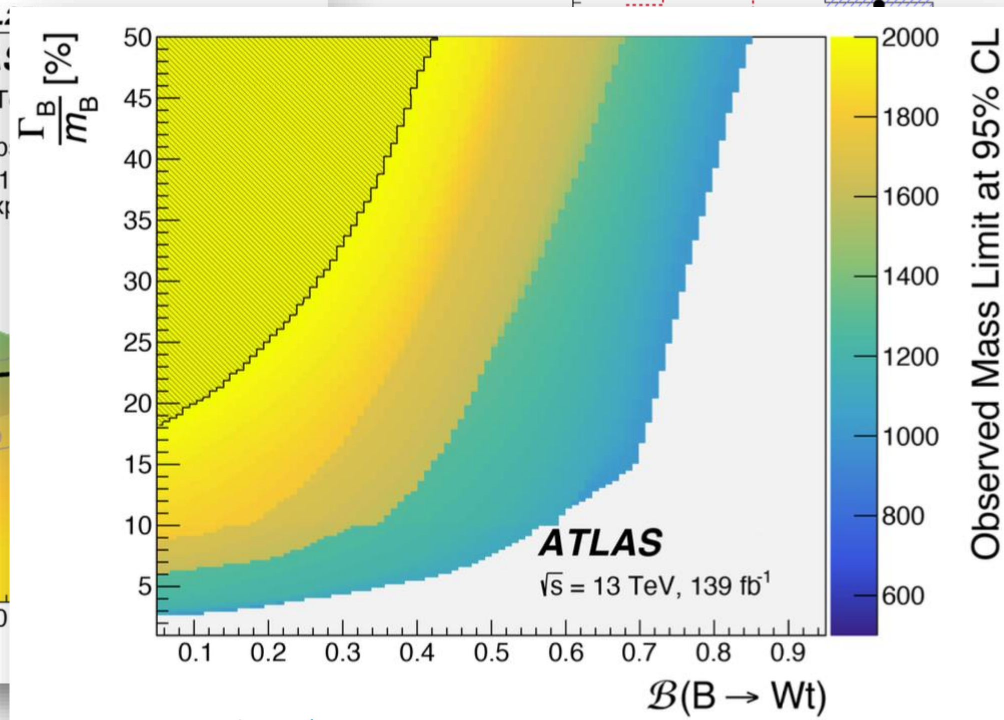
- Limits on coupling κ as a function of the VLB mass for B singlet or (B,Y) doublet
- Lower bounds on VLB mass for given BR and width

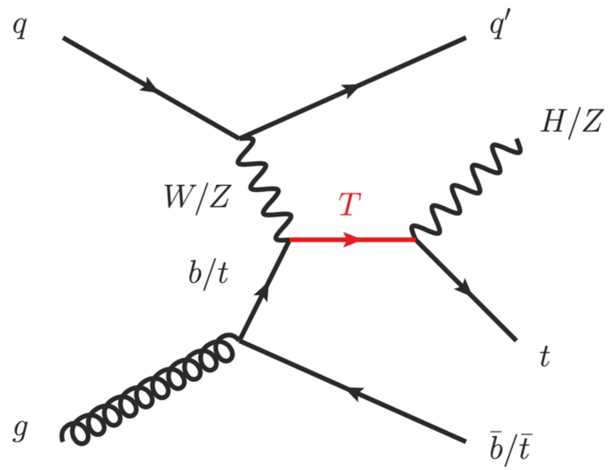






Single-produced Top-partner Combination

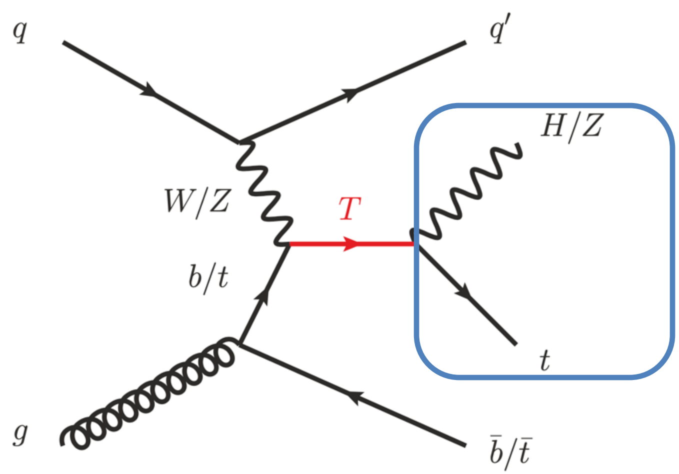
Statistical combination searches for single T production



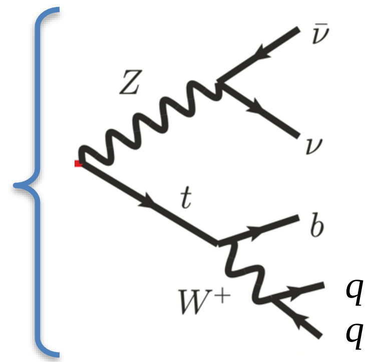
Single-produced Top-partner Combination

Statistical combination searches for single T production

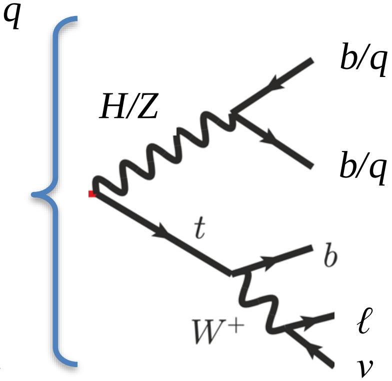
⇒ Three input analyses



MonoTop



HtZt



Osml