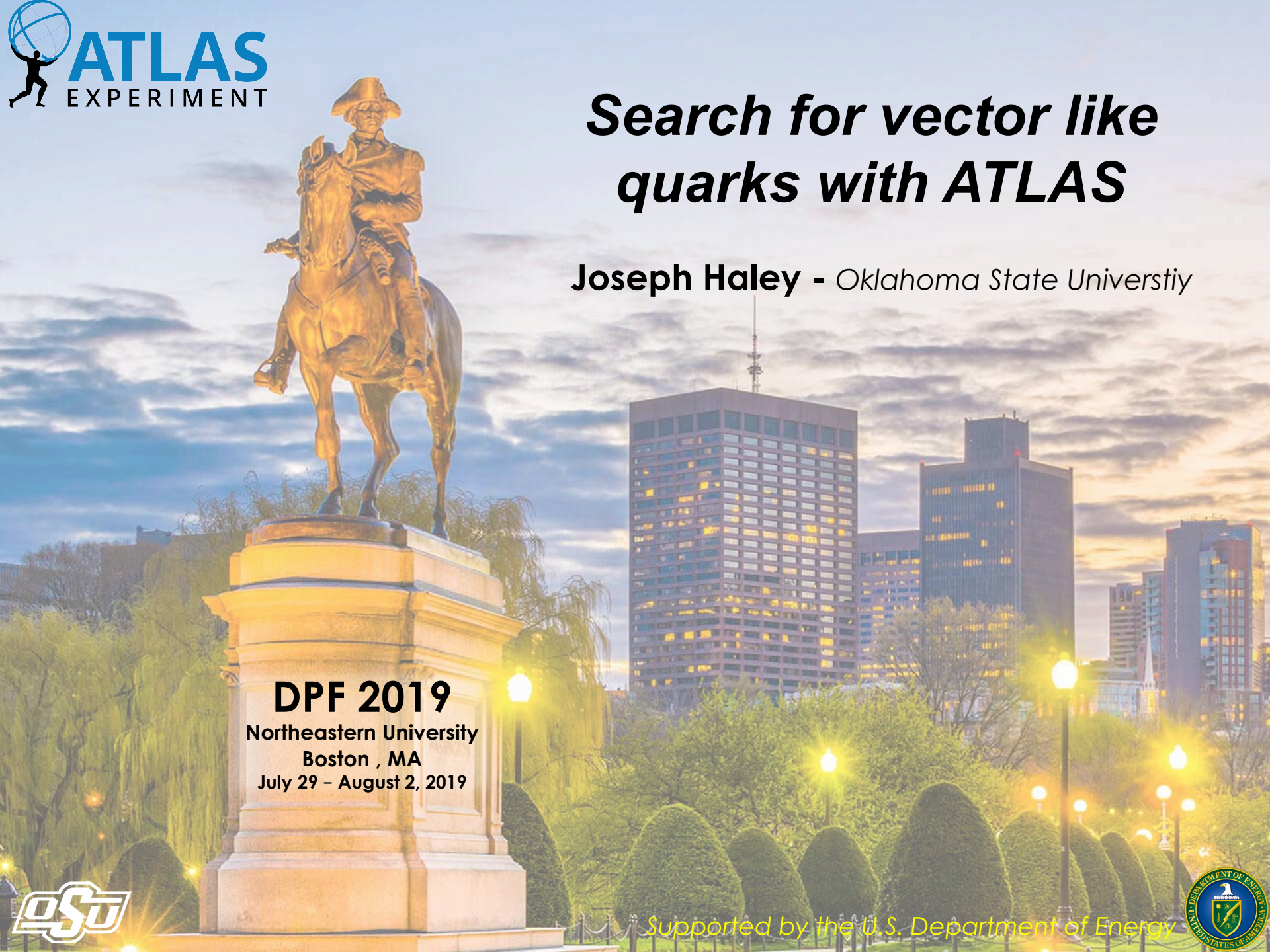


Search for vector like quarks with ATLAS

Joseph Haley - *Oklahoma State Universtiy*

DPF 2019
Northeastern University
Boston , MA
July 29 – August 2, 2019

Supported by the U.S. Department of Energy

Vector-Like Quarks - What and Why?

Colored, spin-½ particles ⇒ "Quarks"

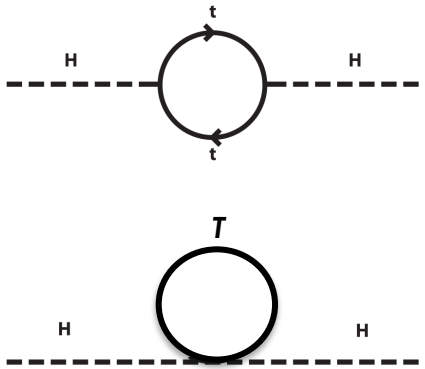
Both chiralities transform the same under SM gauge groups ⇒ "Vector-like"

- Avoids constraints from Higgs measurements

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

Higgs mass is quadratically divergent in the SM, but this can be naturally cancelled by VLQs

- As a result, VLQs show up in many BSM models (Little/Composite Higgs, Topcolor, GUTs, …)
- But naturalness requires VLQ mass ~TeV (Accessible at the LHC!)



Couple to SM through mixing with SM quarks

- Naturalness + FCNC constraints imply mixing with 3rd generation

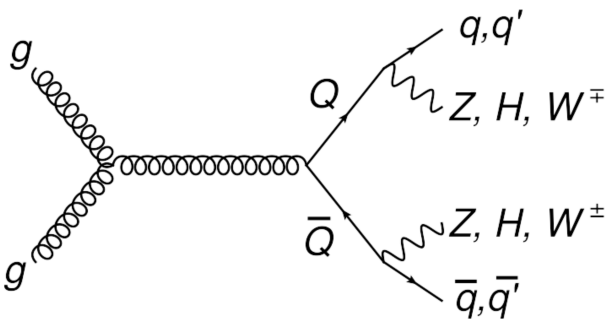
Top partner →
Bottom partner →

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?

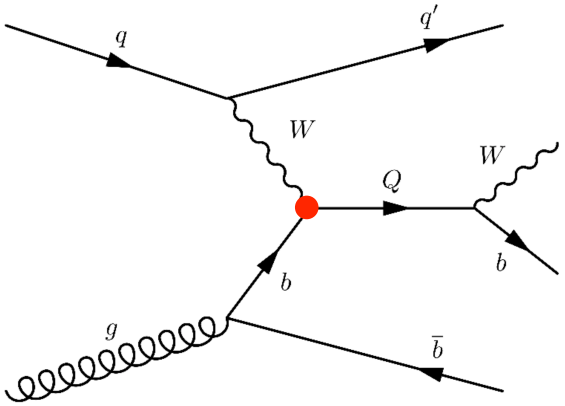
Pair Production via QCD

- Depends only on mass
  ⇒ ~Model-independent



Single production via EW boson

- Depends on mass and coupling



Decays dictated by quantum numbers:

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

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

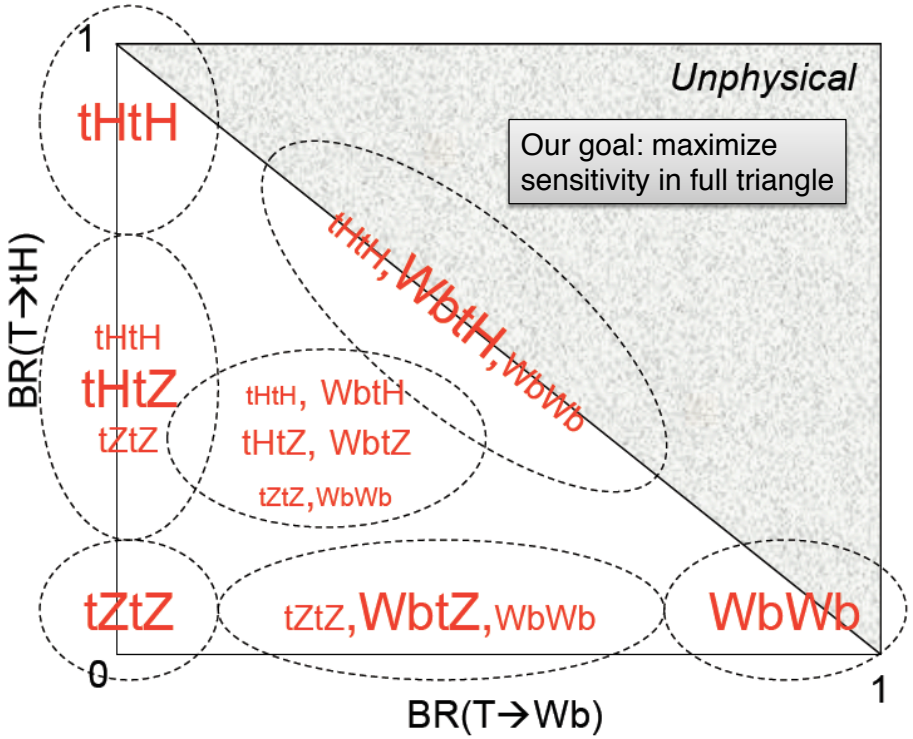
⇒ Rich phenomenology!

Branching ratios are model-dependent

- Constrained in some scenarios
  - "Singlet" scenario
  - "Doublet" scenario (assuming mixing only in up sector)
- **But best to test all possibilities!**

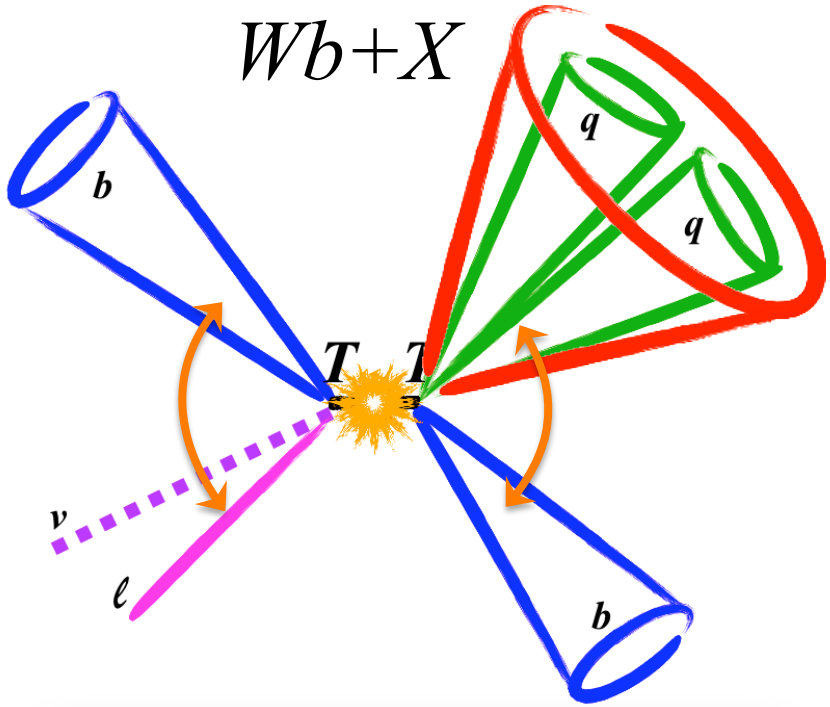
Pair Production: General Strategy

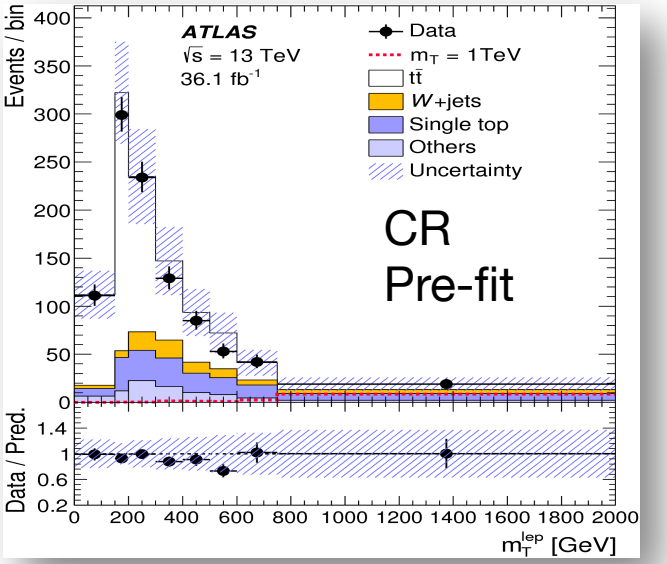
Set limits as a function of the branching ratios:

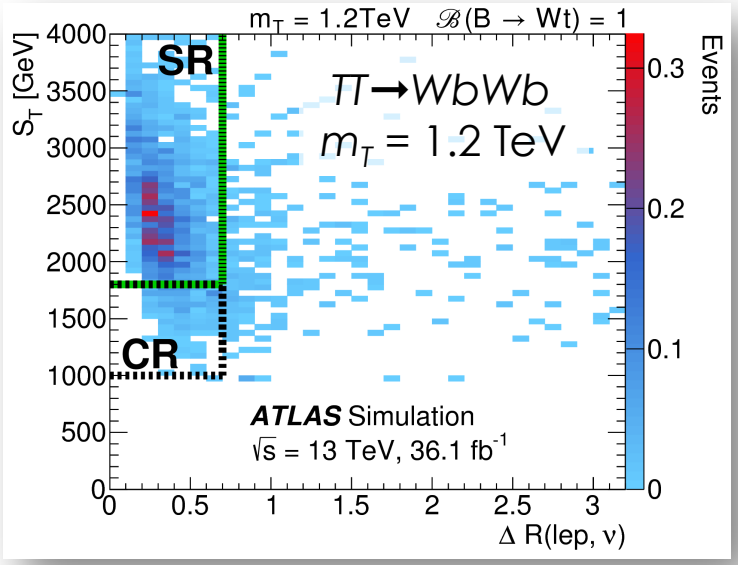


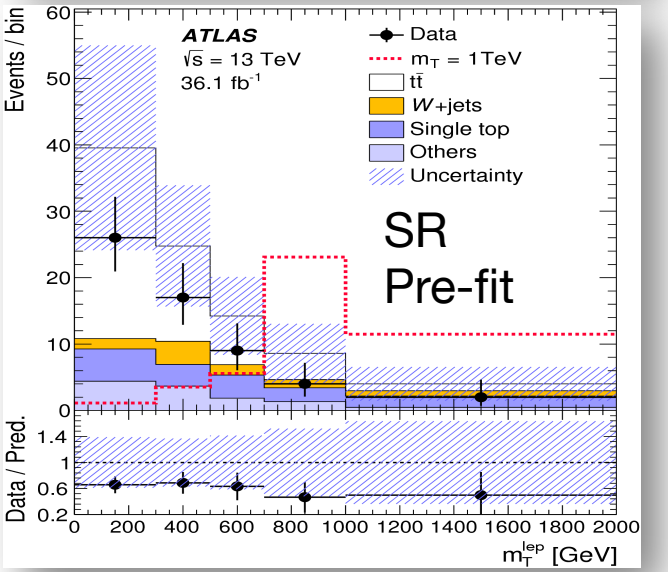
Perform multiple analyses to target different decays:

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$	$HtH\bar{t}$	-
$W(\ell\nu)b + X$	$WbW\bar{b}$	-
$W(\ell\nu)t + X$	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic	$HtH\bar{t}$	$HbH\bar{b}$









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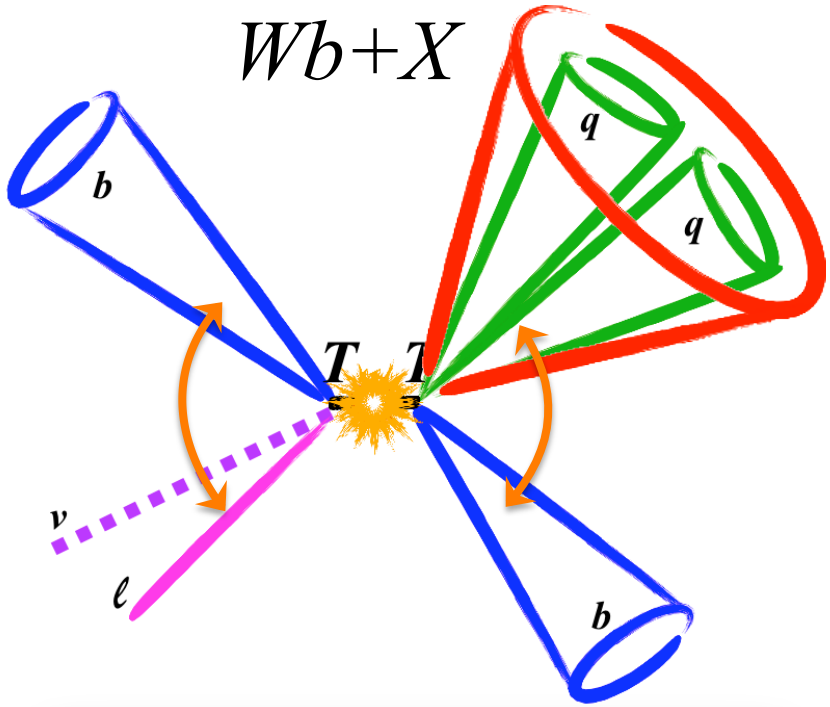

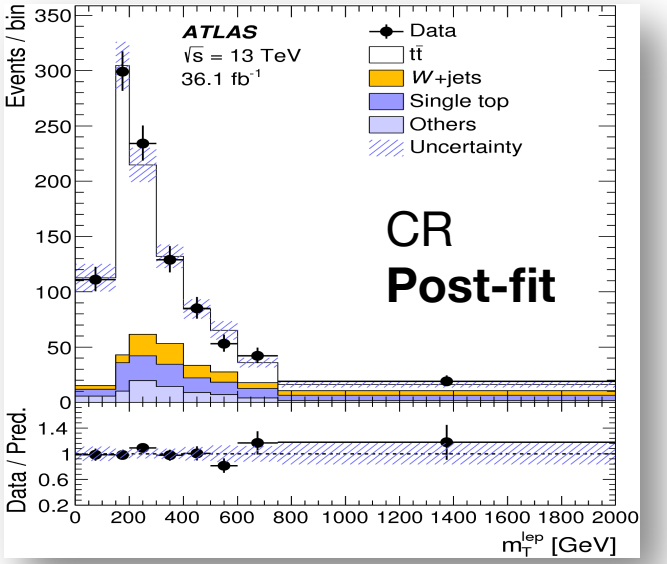

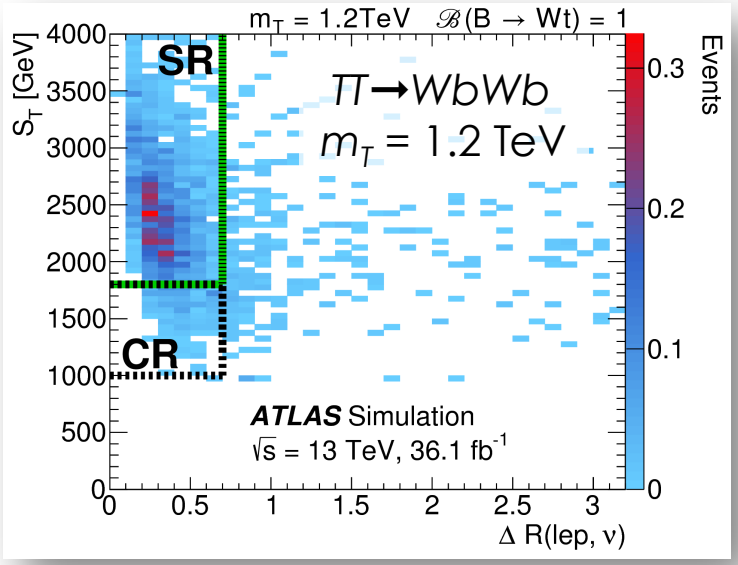

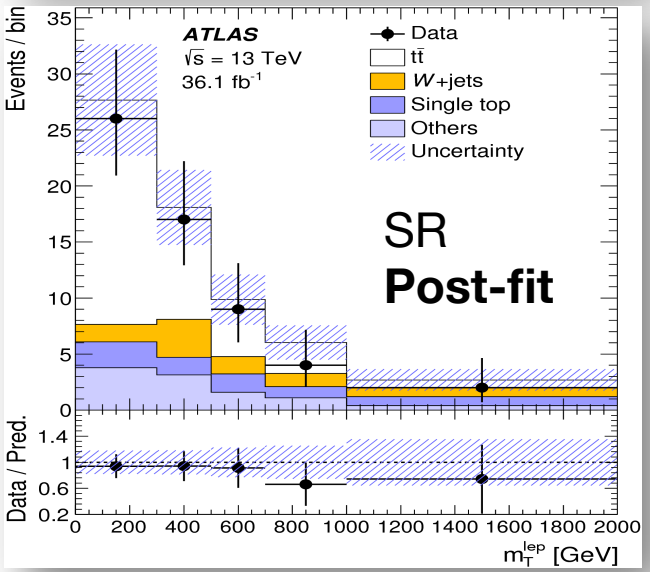

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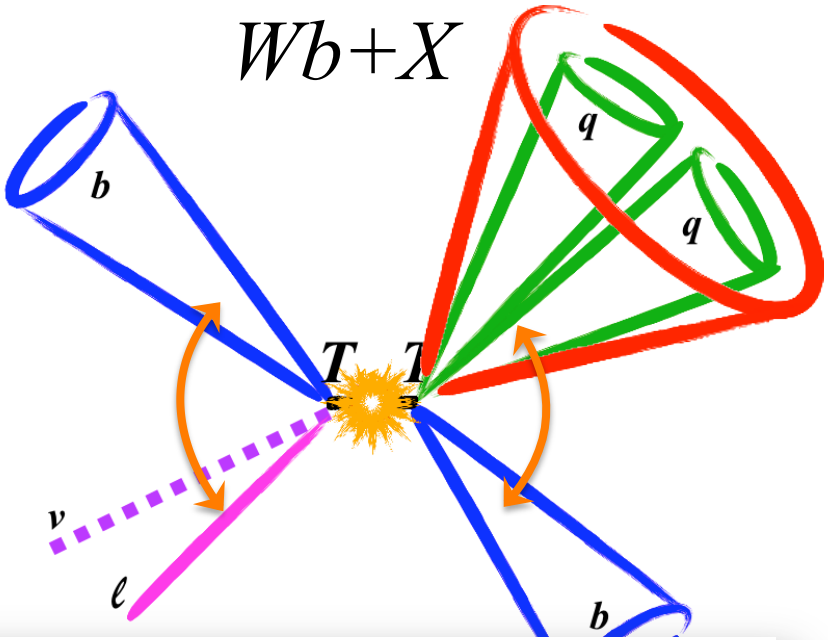

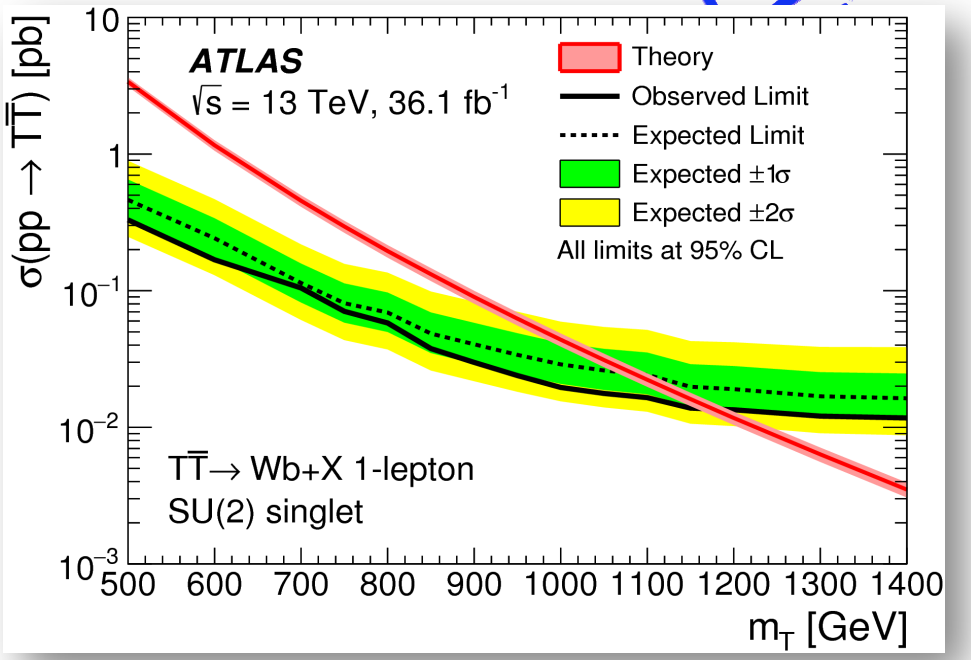

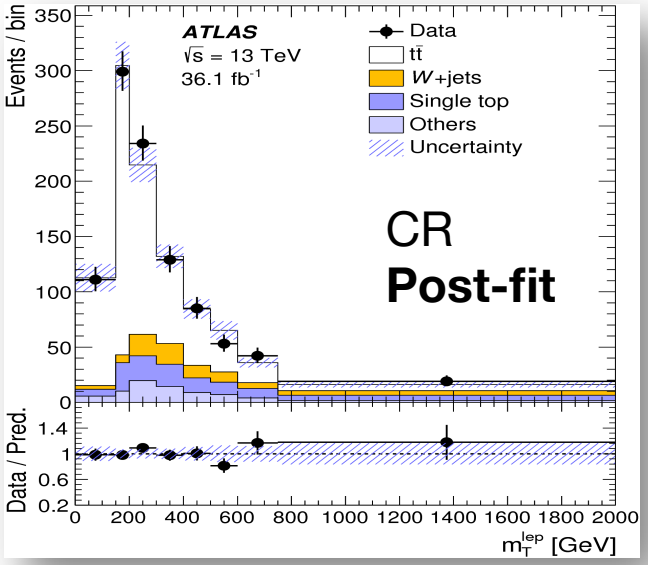

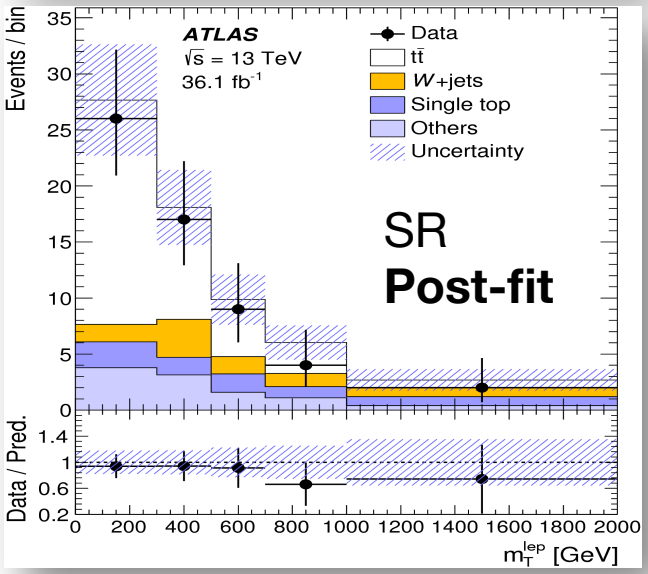

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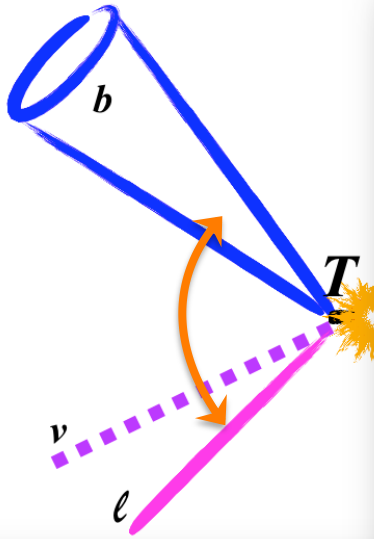
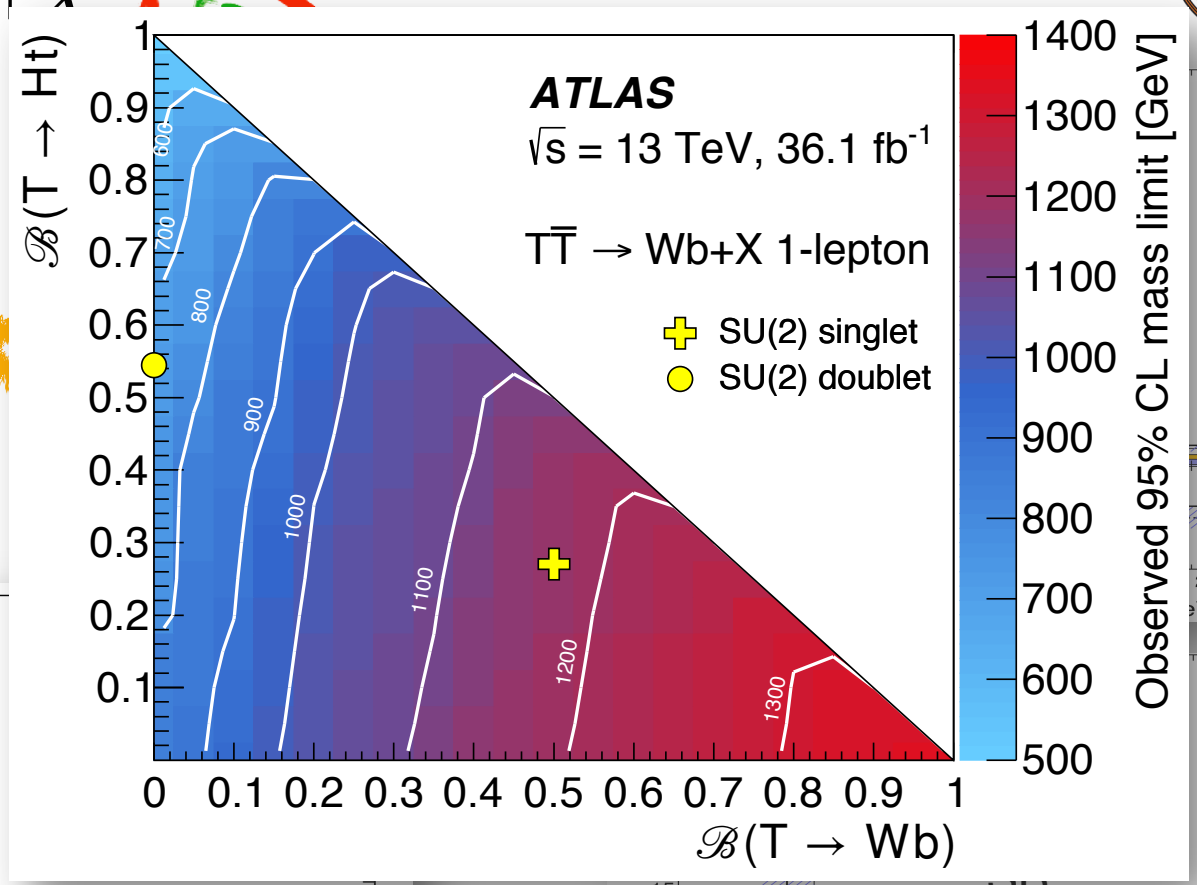
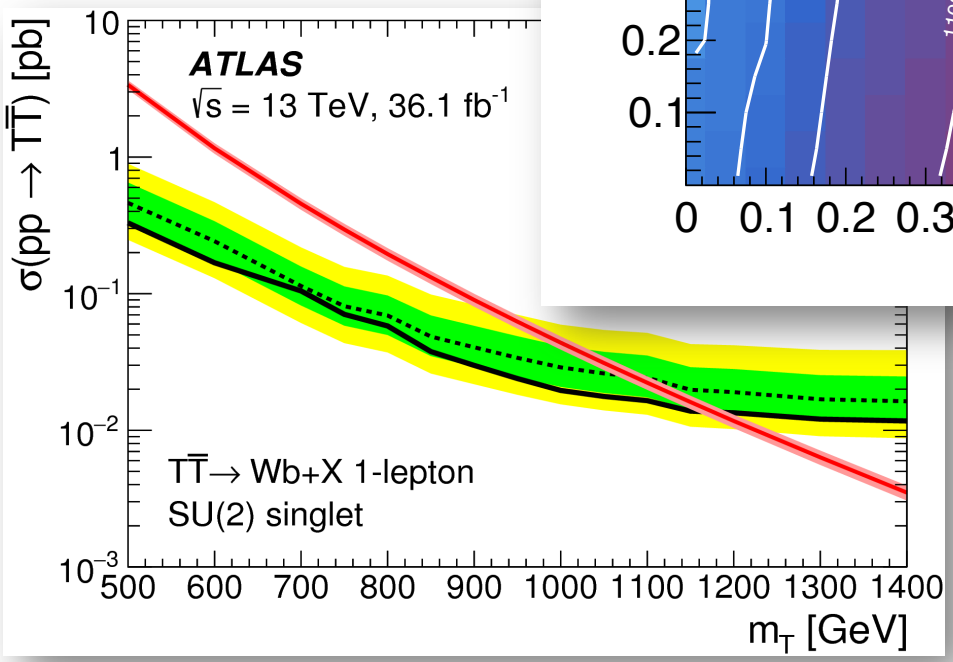
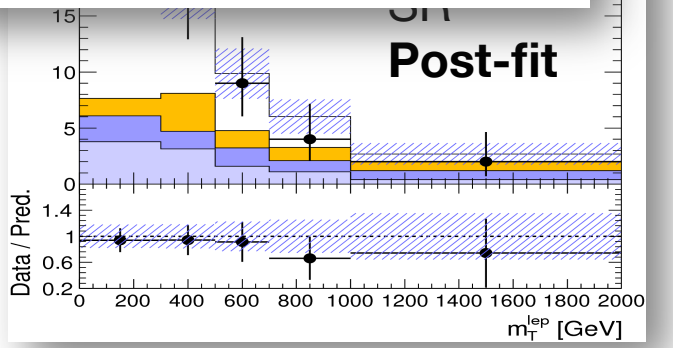
$Wb+X$









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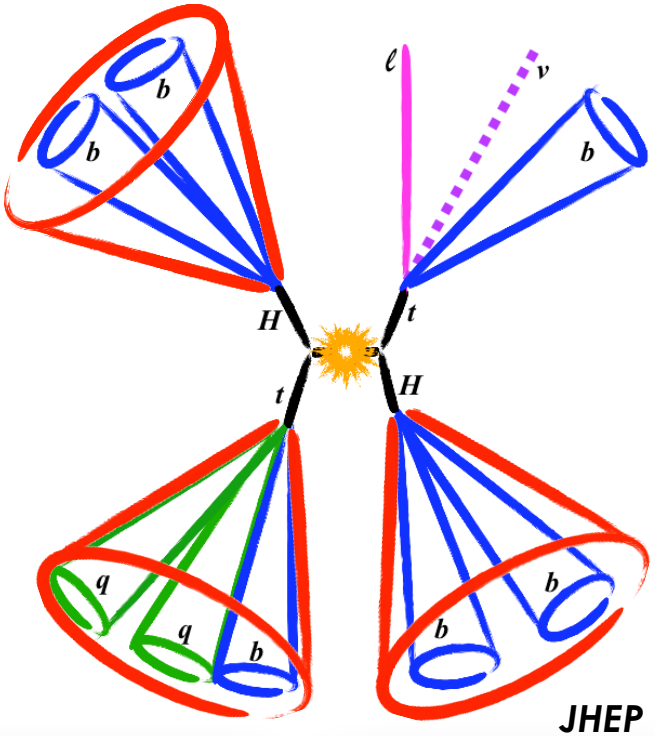
$Ht+X$

Split into 34 search regions based on:

- # leptons
- # small-R jets
- # *b*-tags
- # large-R jets



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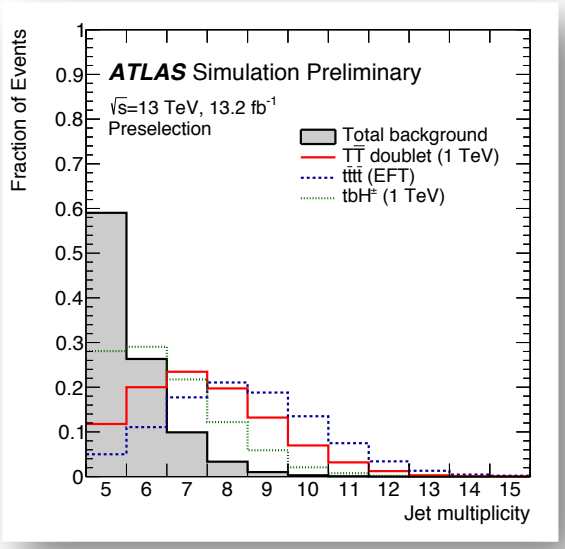
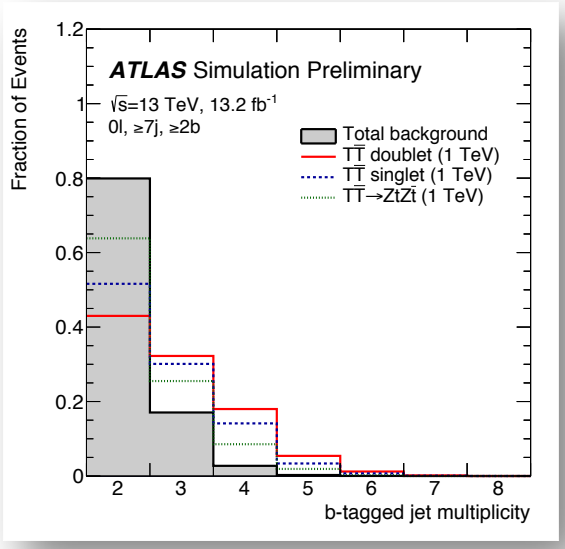
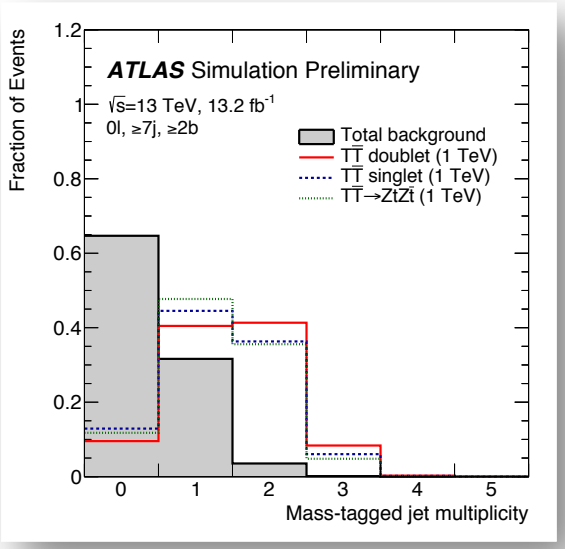
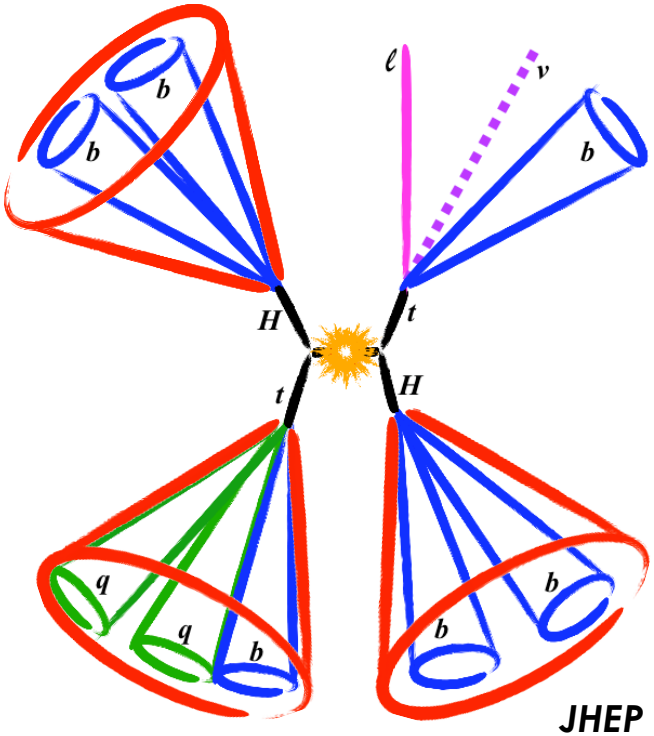






$Ht+X$



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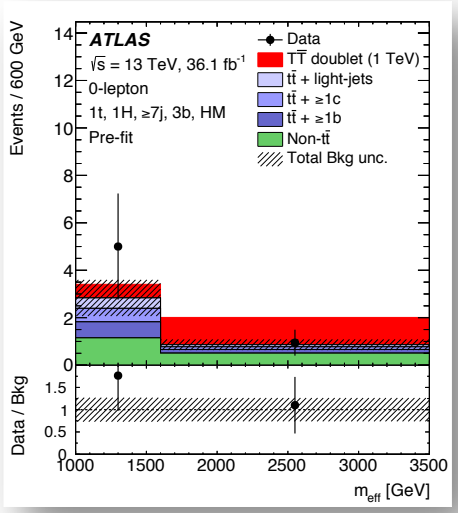
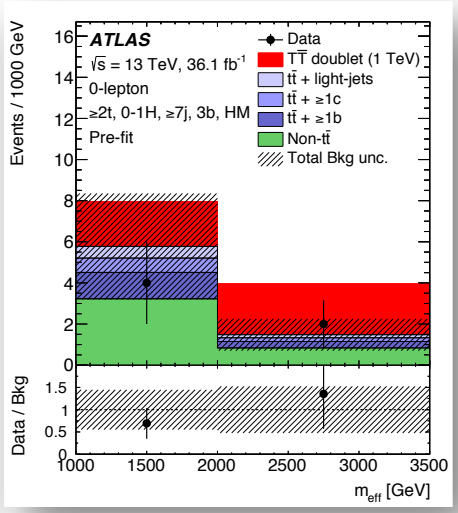
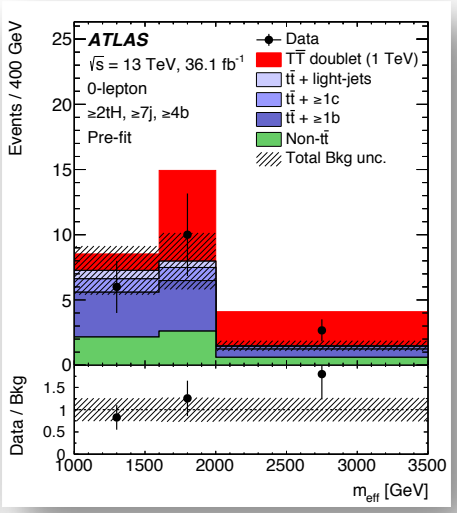
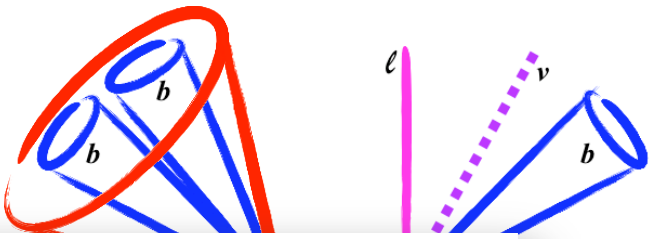
Most sensitive search regions:







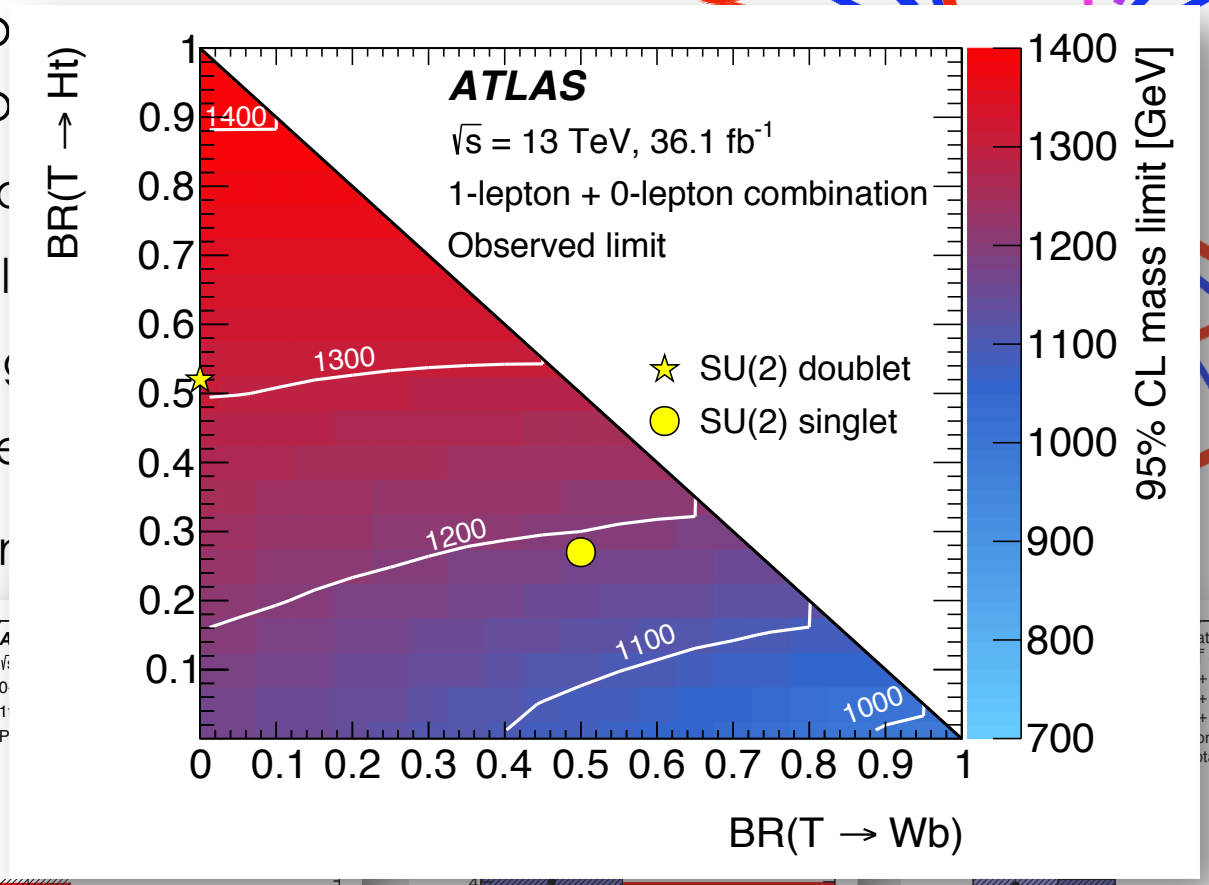
$Ht+X$

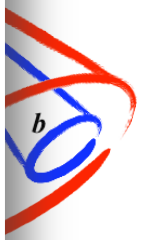


Split into
based o

- # lepto
- # smal
- # b-tag
- # large

Most sen





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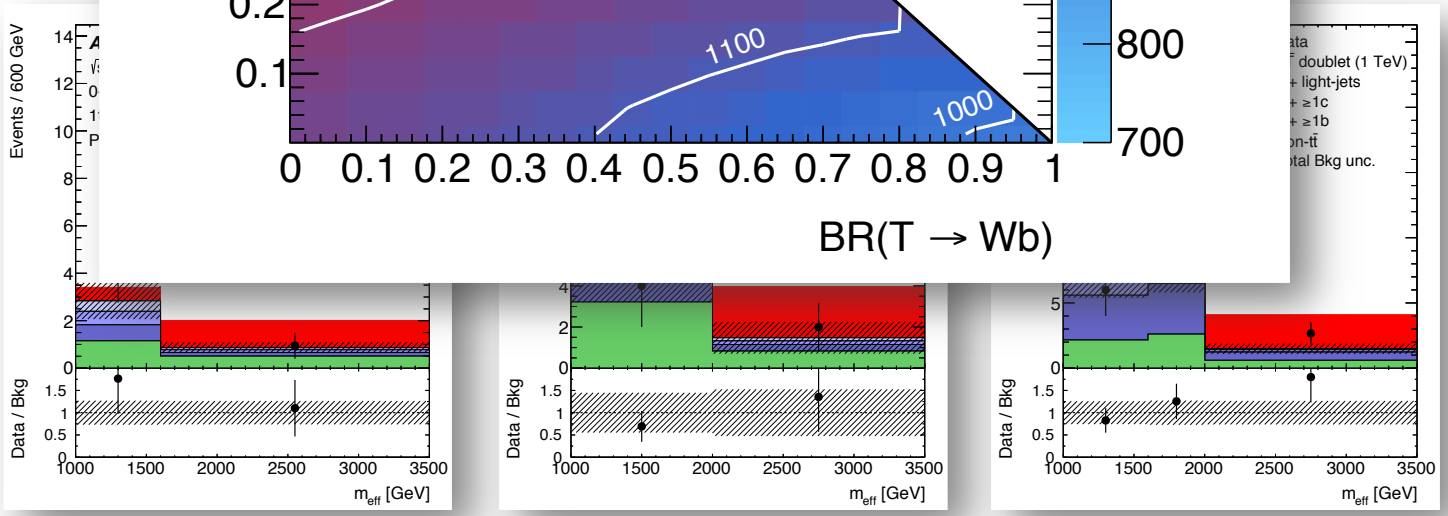
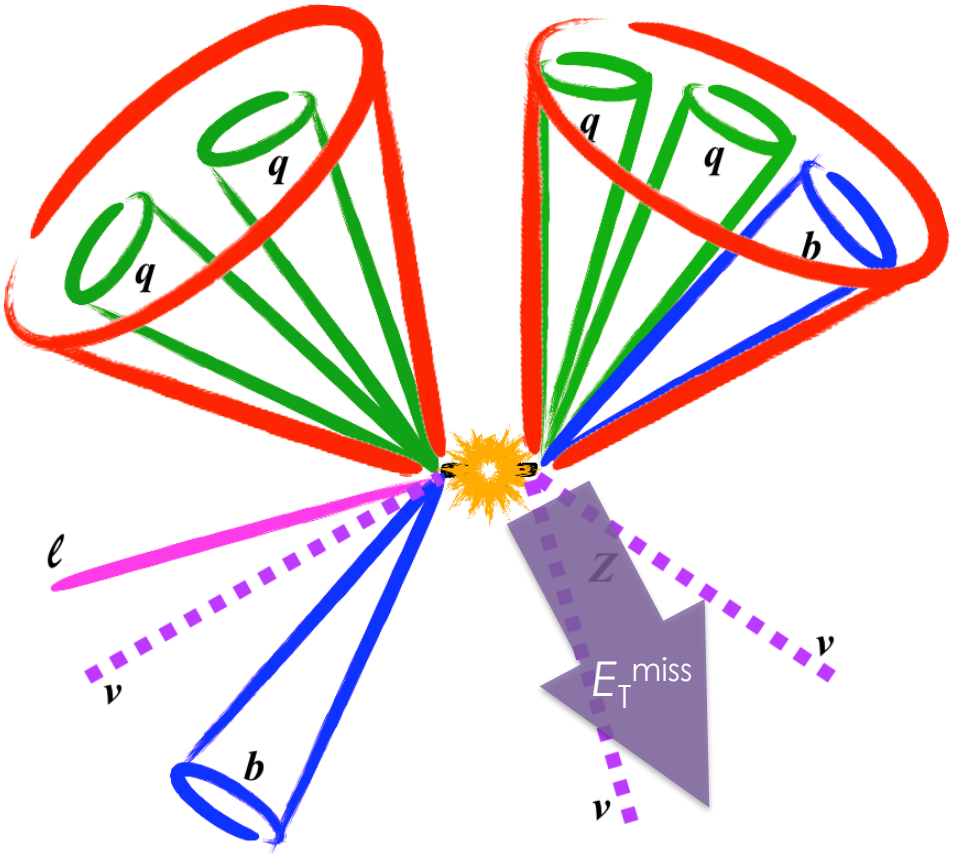


$Zt+X$



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Region	SR
Observed events	7
Fitted bkg events	6.1 ± 1.9
Fitted $t\bar{t}$ events	2.5 ± 1.7
Fitted W + jets events	1.1 ± 0.7
Fitted singletop events	1.1 ± 0.7
Fitted $t\bar{t} + V$ events	0.91 ± 0.20
Fitted diboson events	0.6 ± 0.6
MC exp. bkg events	6.5
Singlet (Doublet) T w/ m=1 TeV	5 (10)

Cut-and-count analysis

- Signal Region (Bin) – Kinematic cuts to optimize VLQ sensitivity
- Control Regions – To fit tt and W+jets normalizations
- Validation Regions – To check modeling of backgrounds

$Zt+X$

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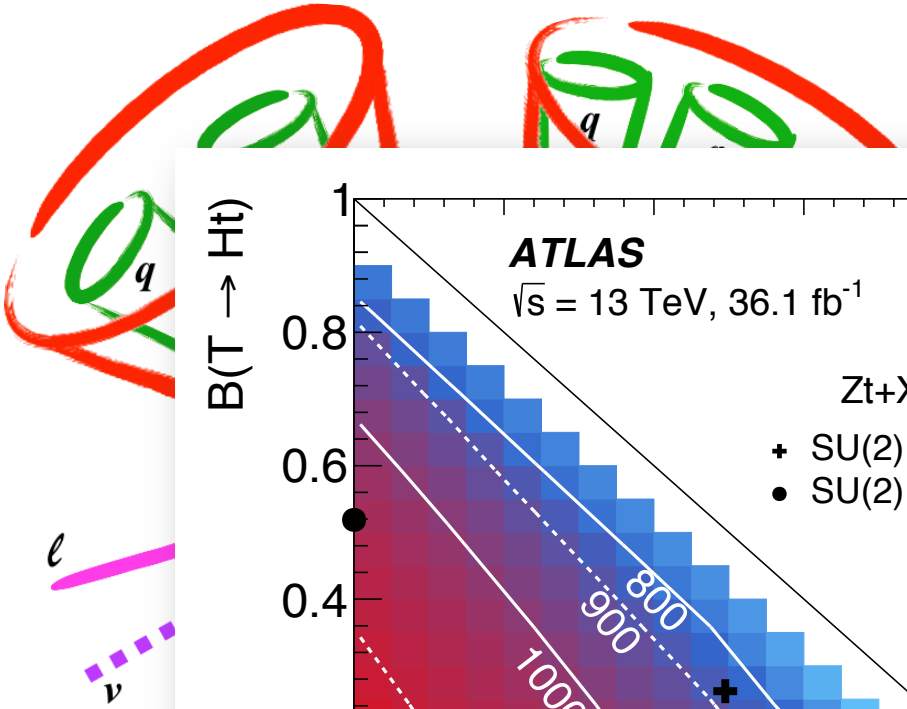

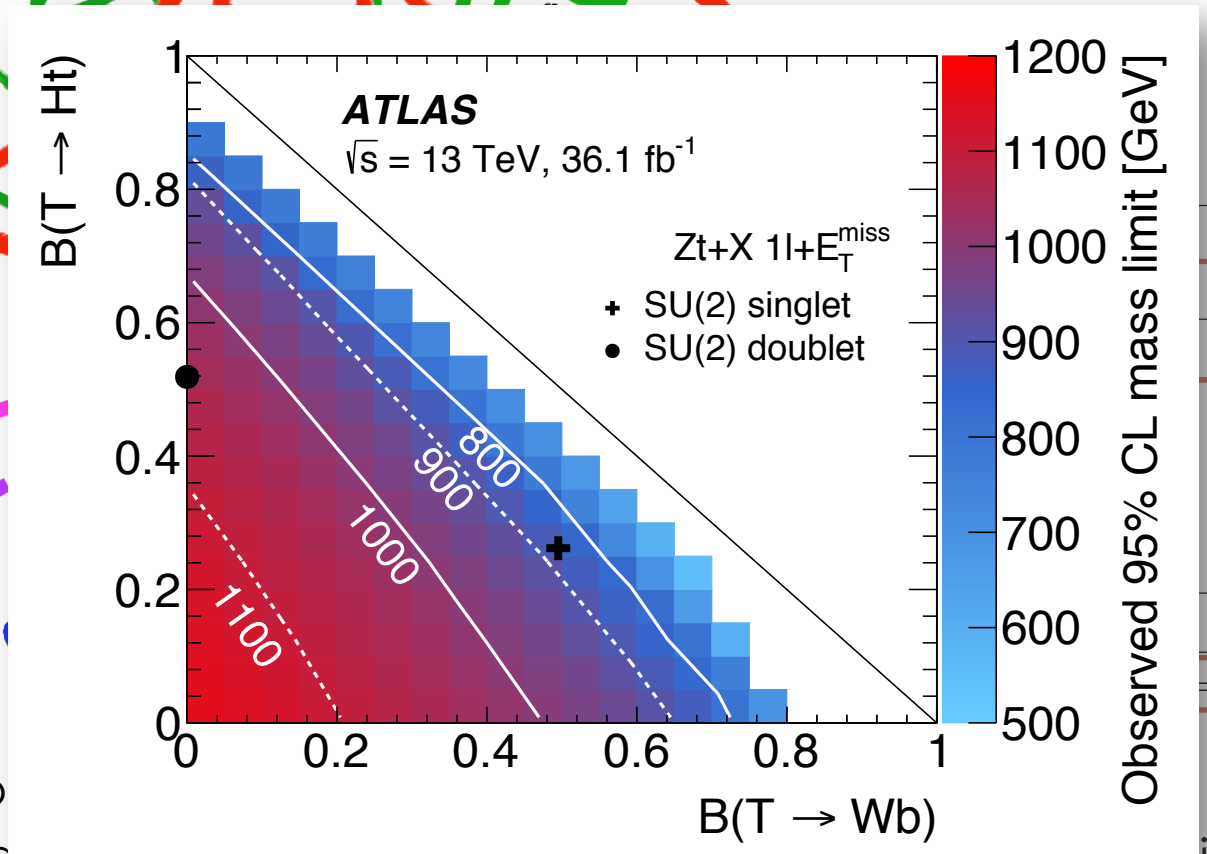

SR
7
6.1 ± 1.9
2.5 ± 1.7
1.1 ± 0.7
1.1 ± 0.7
0.91 ± 0.20
0.6 ± 0.6
6.5
=1 TeV 5 (10)

Cut-and-co

- Signal region (BIN) – kinematic cuts to optimize VLQ sensitivity
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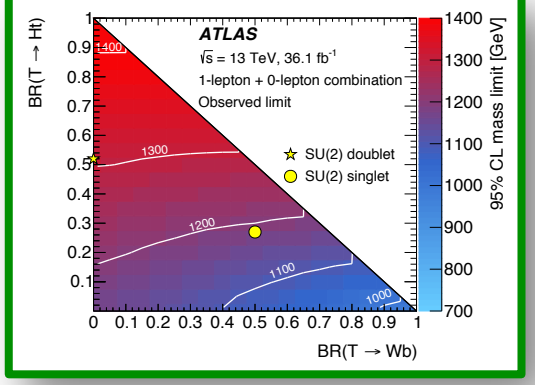

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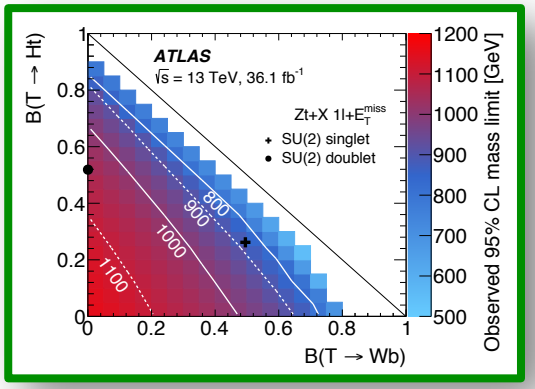

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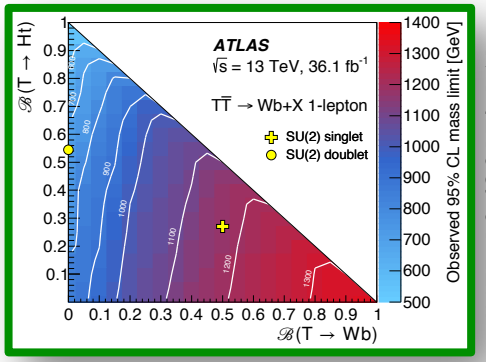

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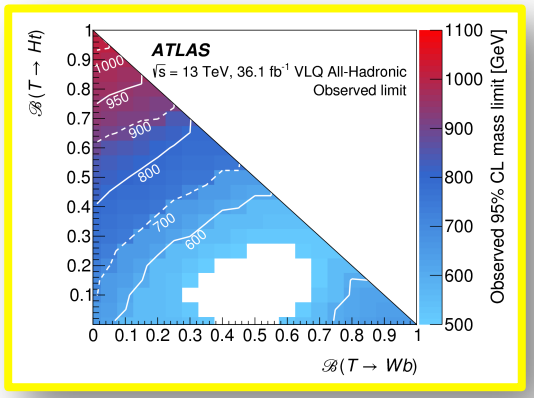
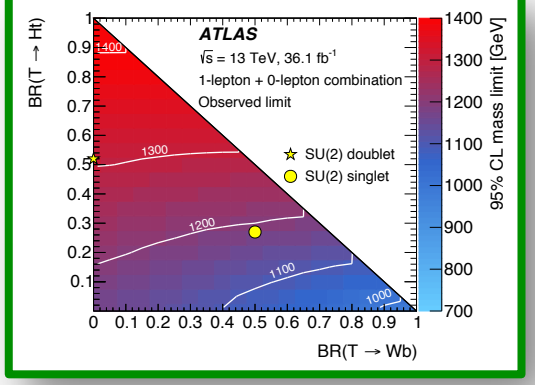


PRD 98, 092005 (2018)



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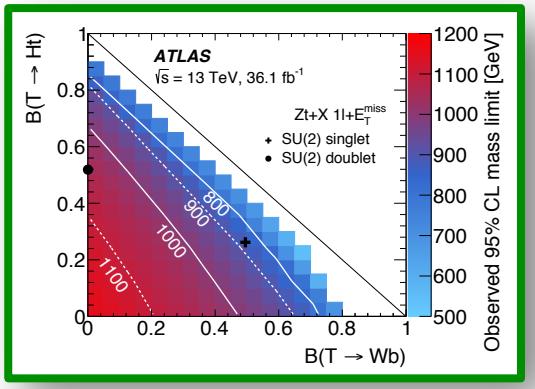

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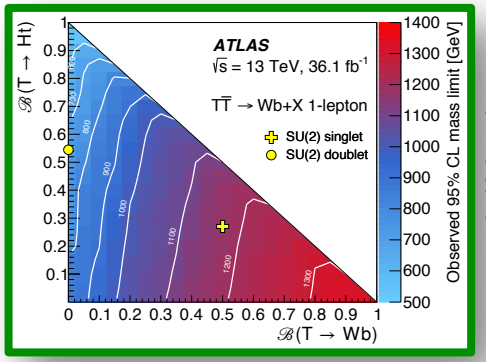

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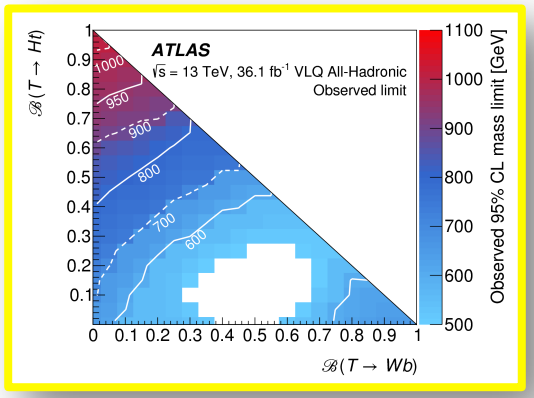

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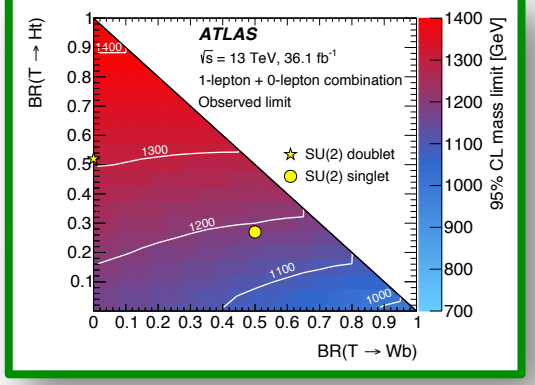

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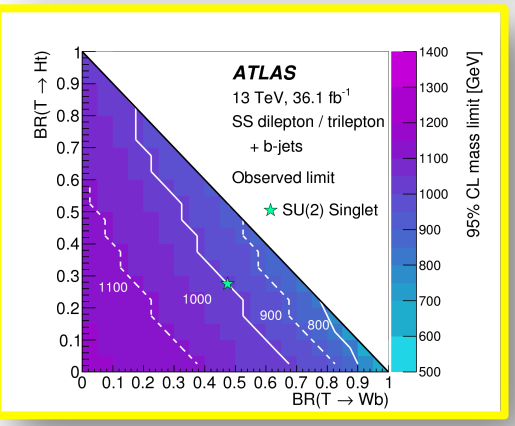

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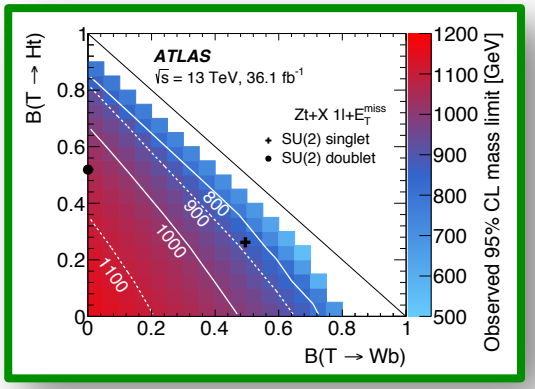
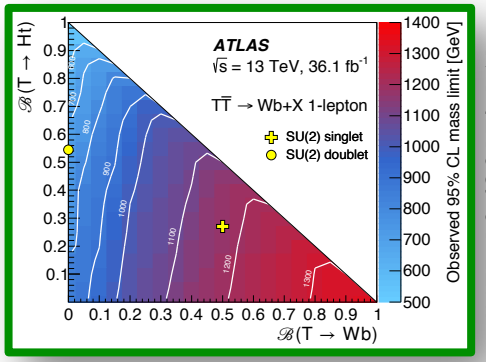
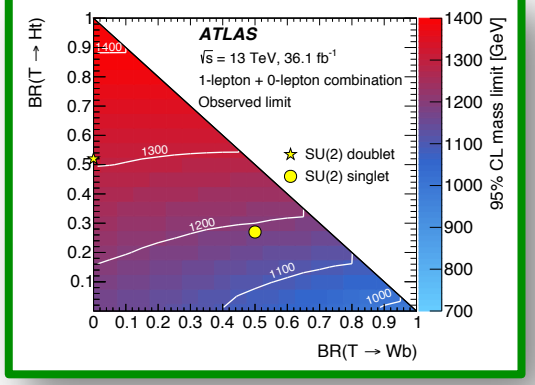


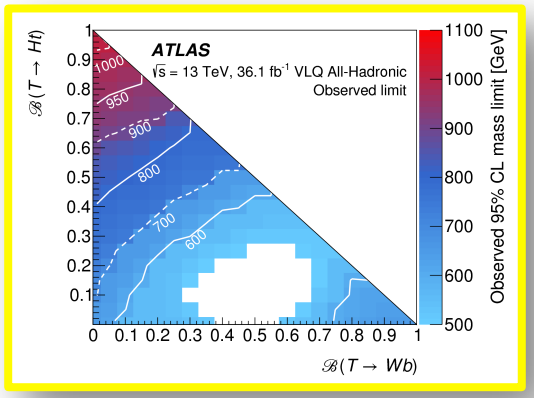
JHEP 08 (2017) 052



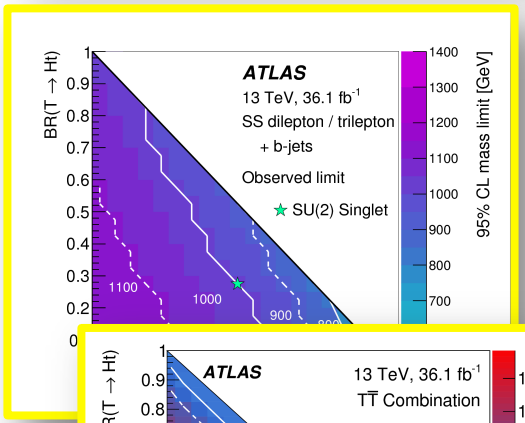
JHEP 10 (2017) 141



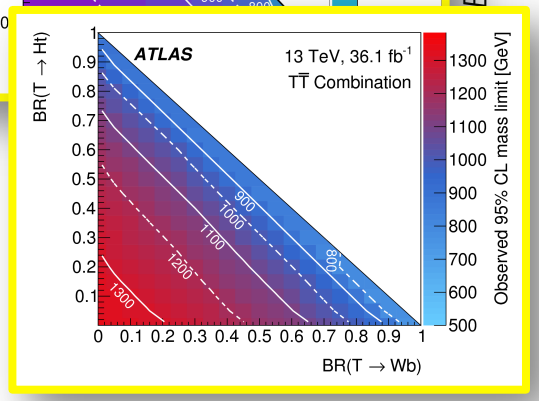
JHEP 07 (2018) 089



PRD 98, 092005 (2018)



EP 12 (2018) 039



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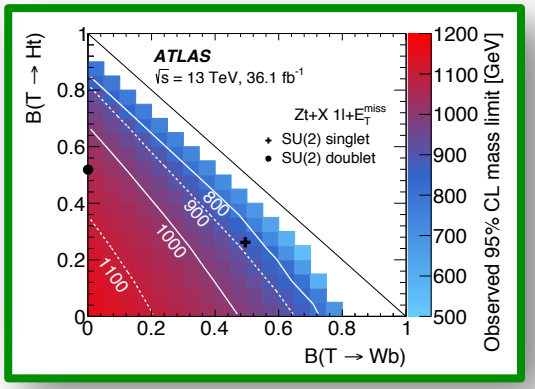
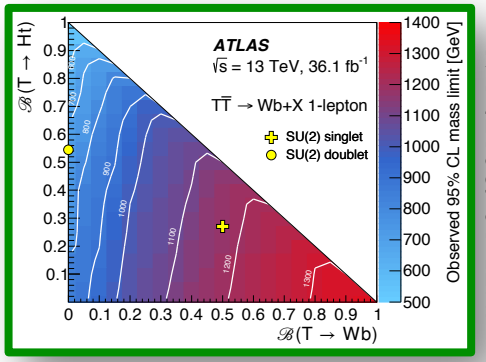
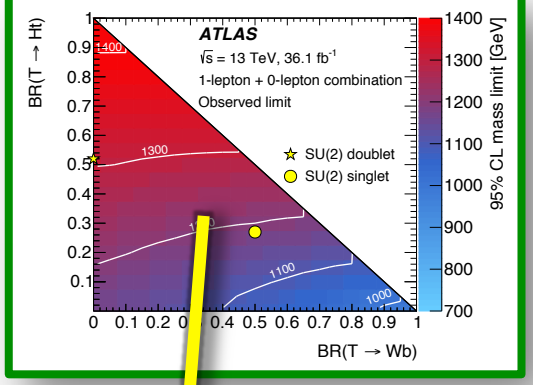


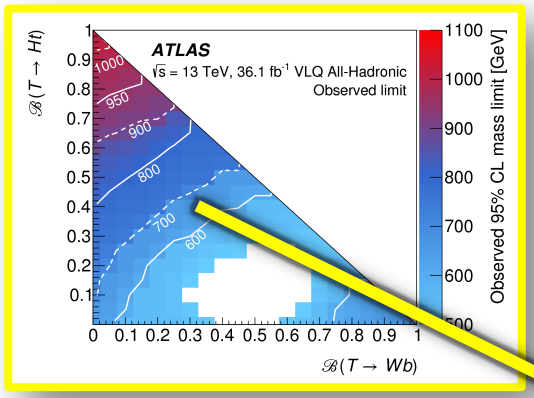
JHEP 08 (2017) 052

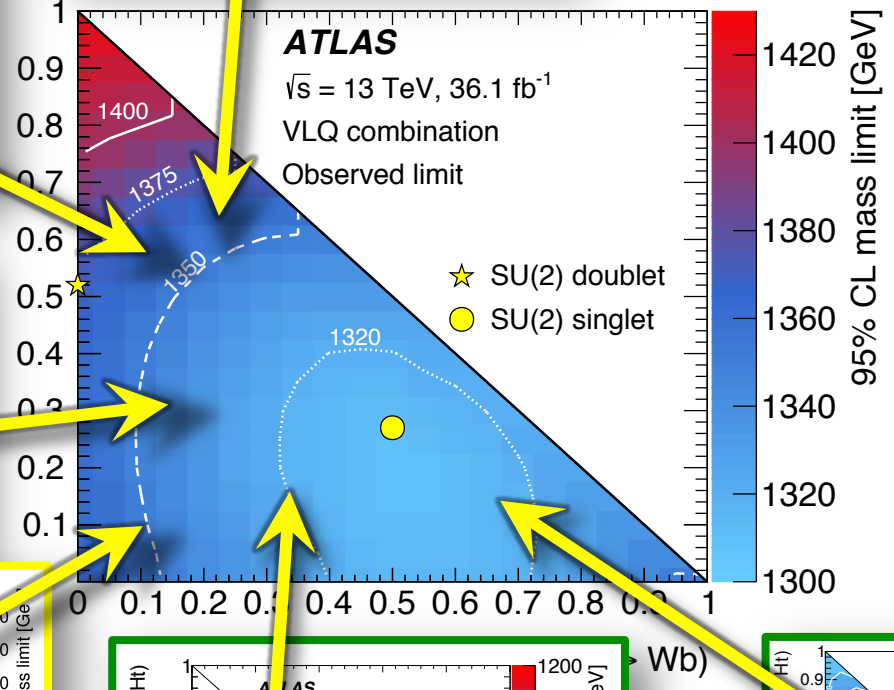


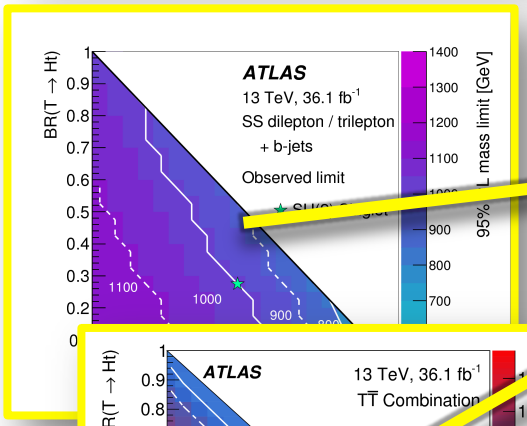
JHEP 10 (2017) 141

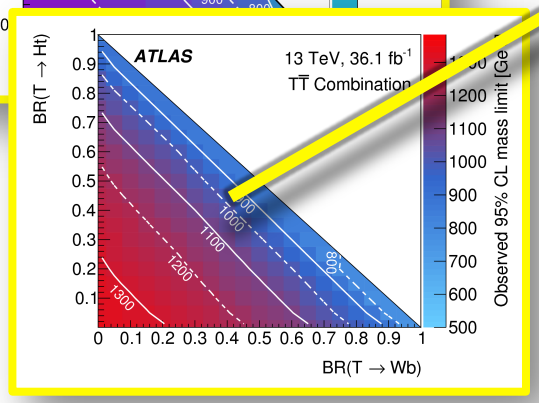
Combination!

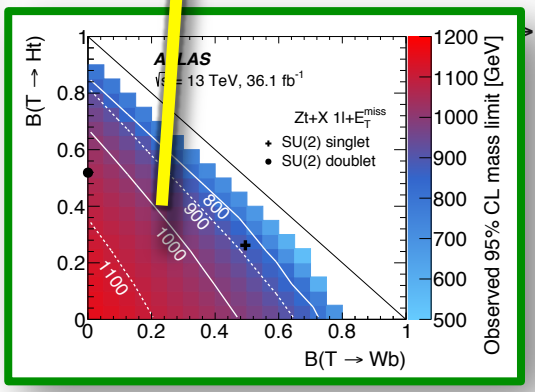


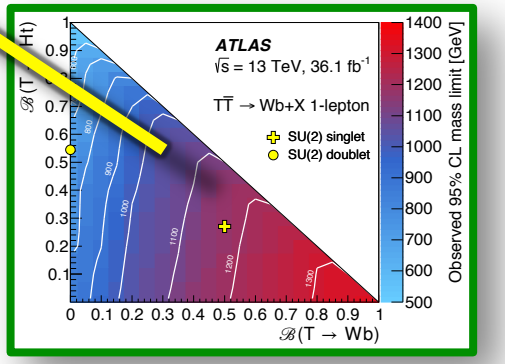










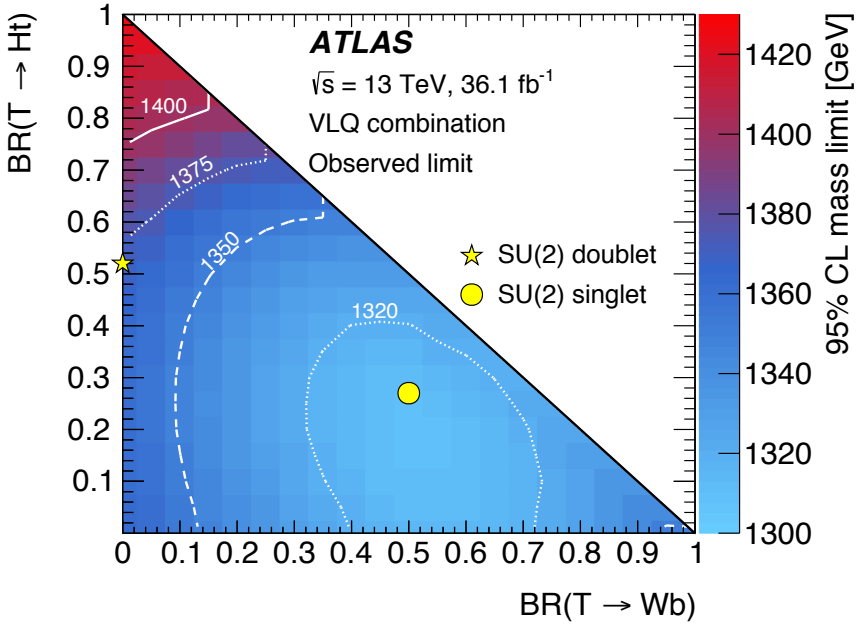


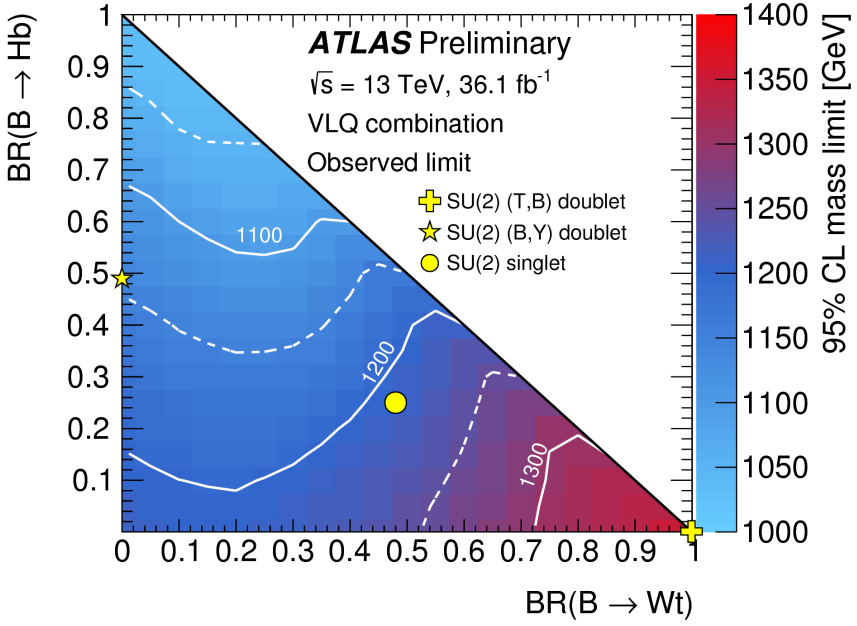
Phys. Rev. Lett. 121 (2018) 211801

Pair Production: Combination

Perform a statistical combination of all pair-production searches for both TT and BB production

Phys. Rev. Lett. 121 (2018) 211801



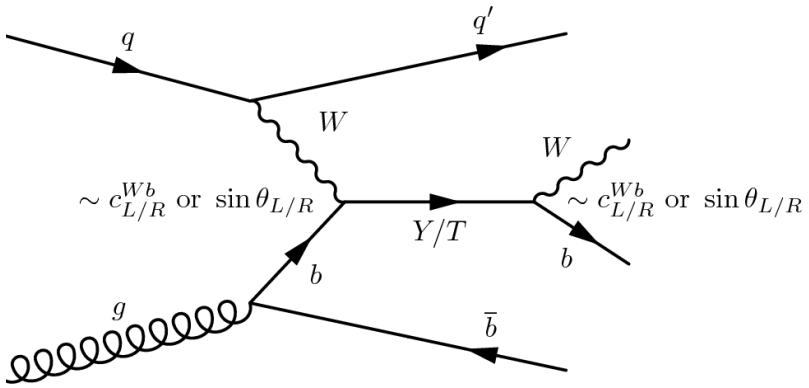


⇒ m_T **< 1.3 TeV excluded** for all Branching Ratios*

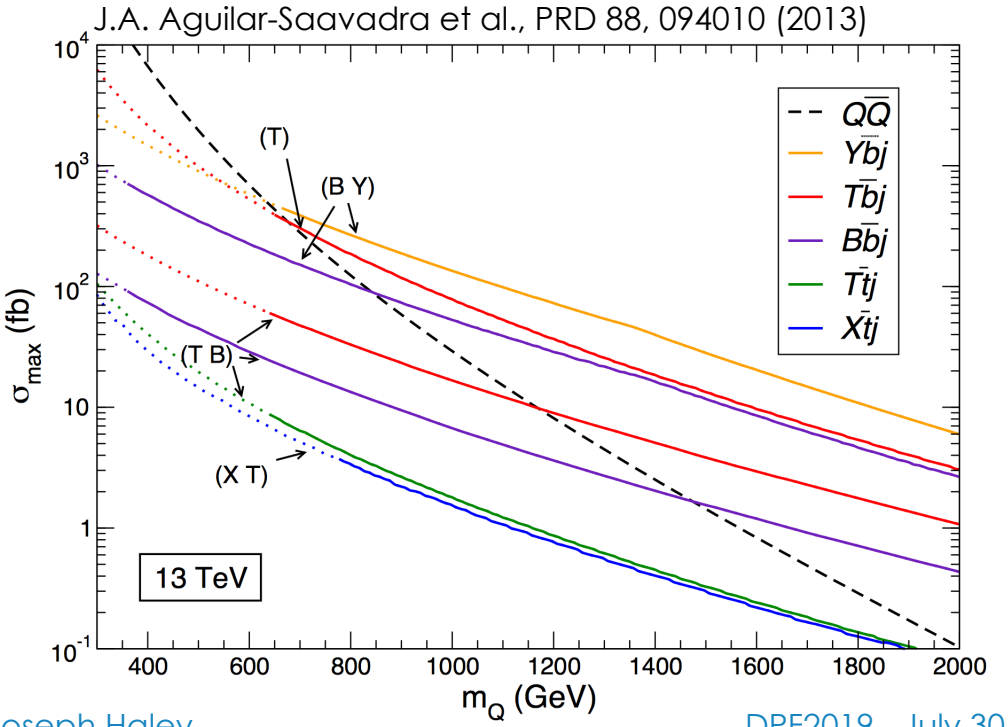
⇒ m_B **< 1.0 TeV excluded** for all Branching Ratios*

*Assuming it decays only to SM particles

Single Production



Depends on couplings to SM quarks

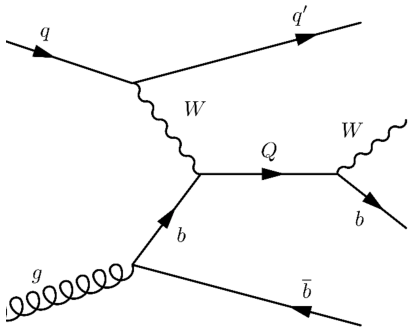


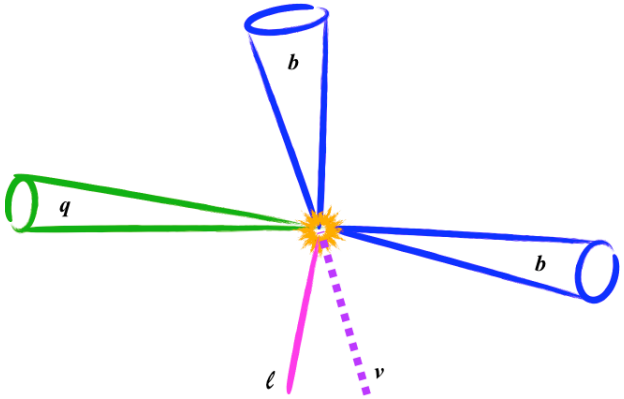
But could be the dominant production process for high VLQ masses

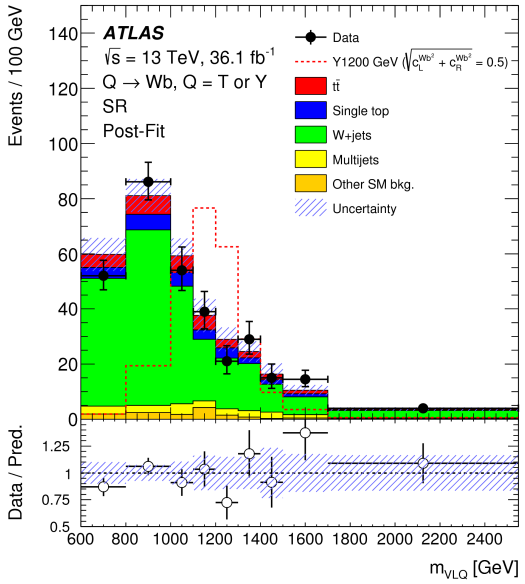
Single Production: T/Y → Wb

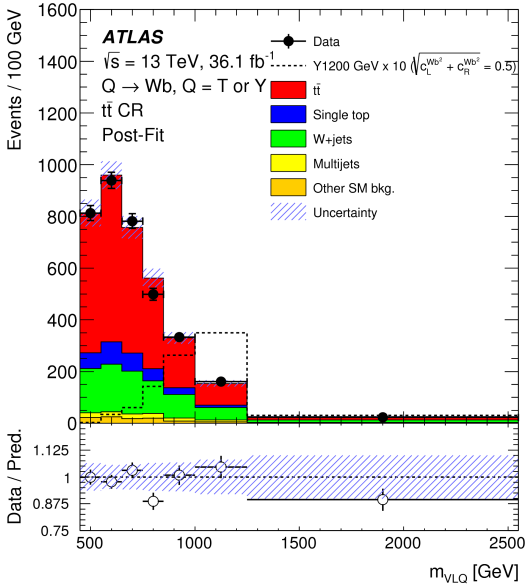
JHEP 05 (2019) 164

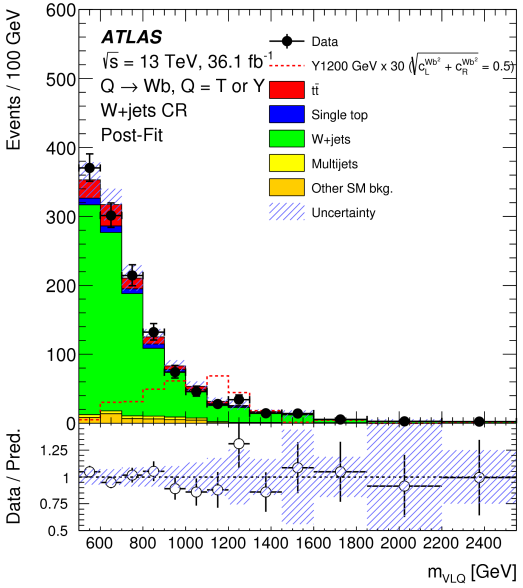
Perform fit to m_{VLQ} in signal region and two control regions









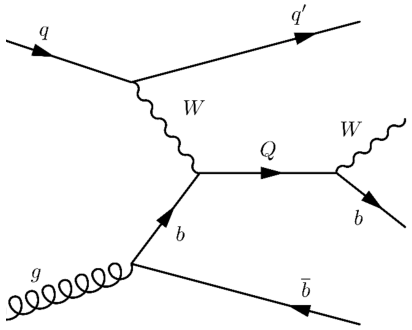


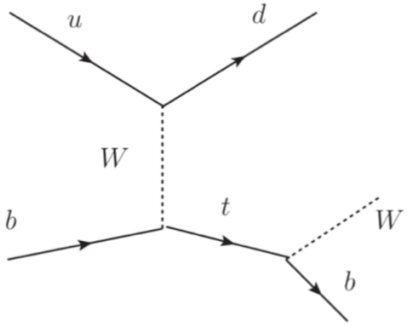
Single Production: T/Y → Wb

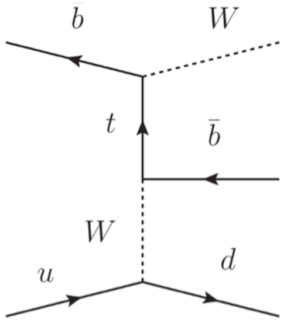
JHEP 05 (2019) 164

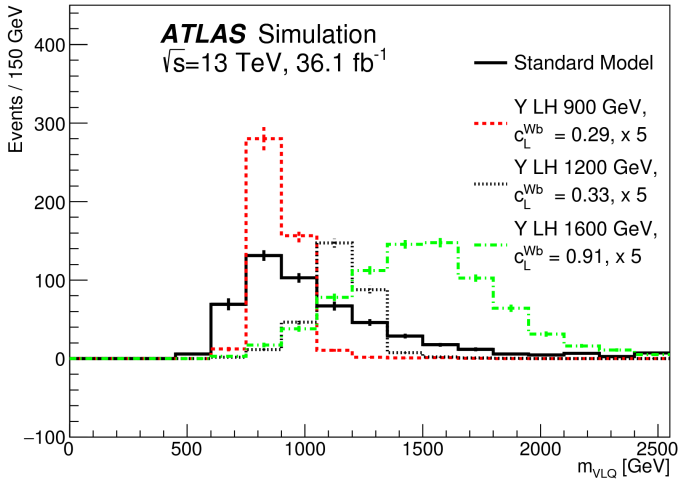
Perform fit to m_{VLQ} in signal region and two control regions

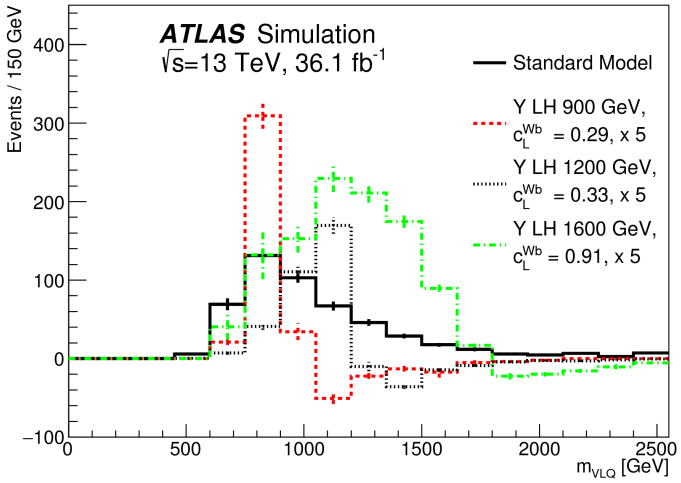
Signal prediction can have significant interference effects!











Single Production: T/Y → Wb

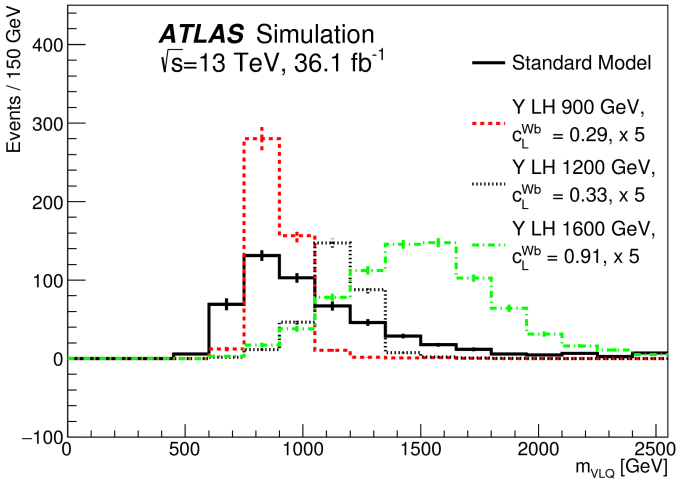
JHEP 05 (2019) 164

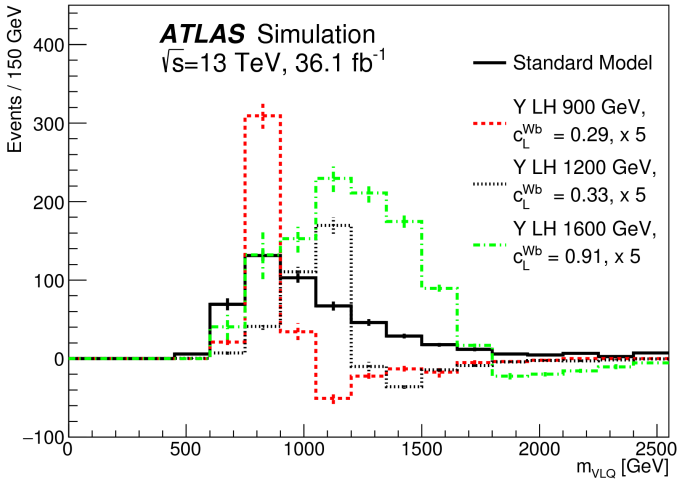
Perform fit to m_{VLQ} in signal region and two control regions

Signal prediction can have significant interference effects!

Iterative approach to determine coupling limit:

1. Pick coupling and make "signal" template
2. Set limit on "cross section"
3. Determine coupling corresponding to that cross section





Single Production: T/Y → Wb

JHEP 05 (2019) 164

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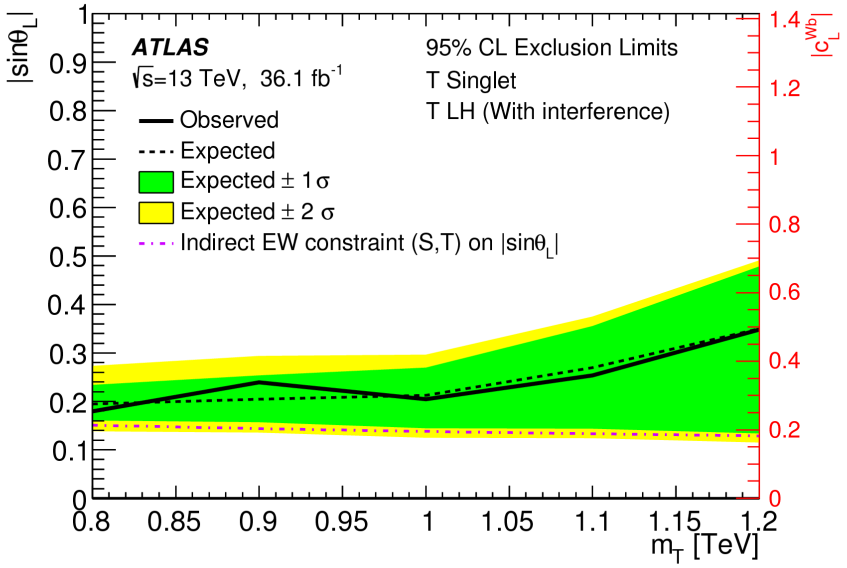
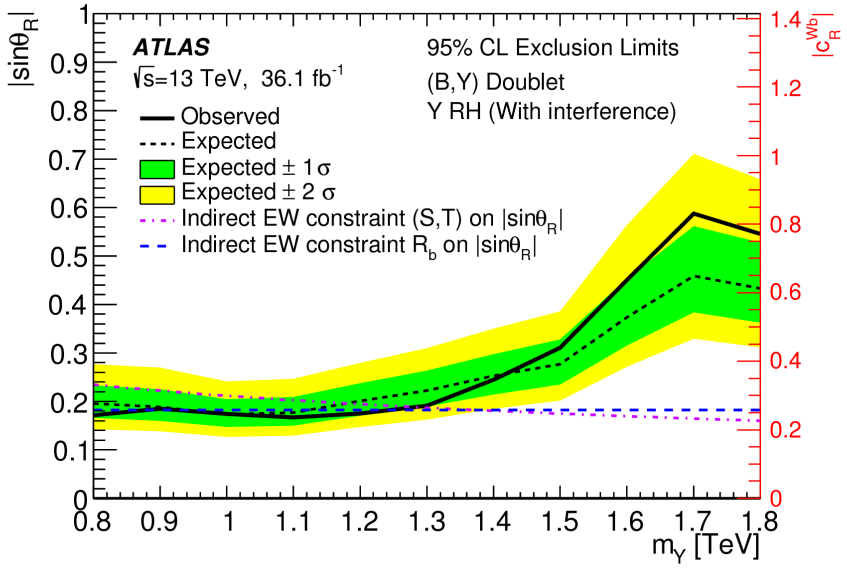
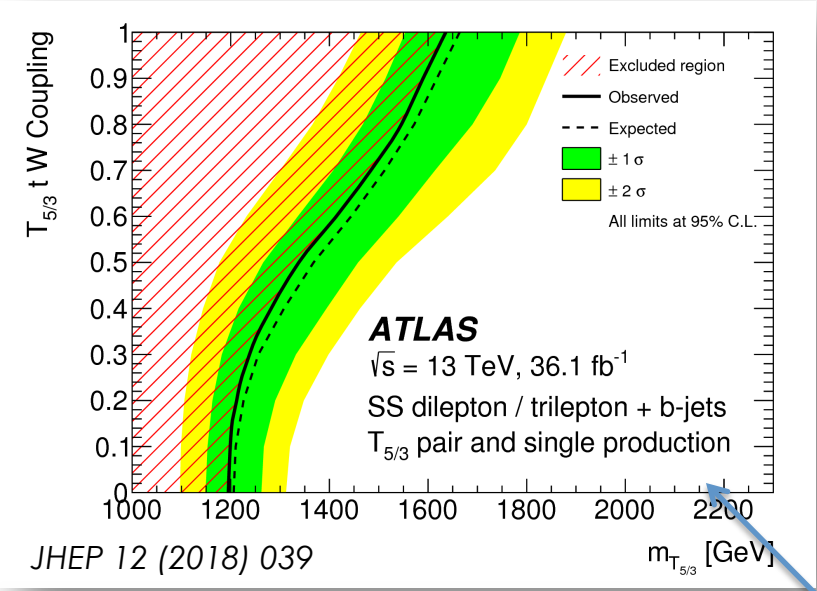
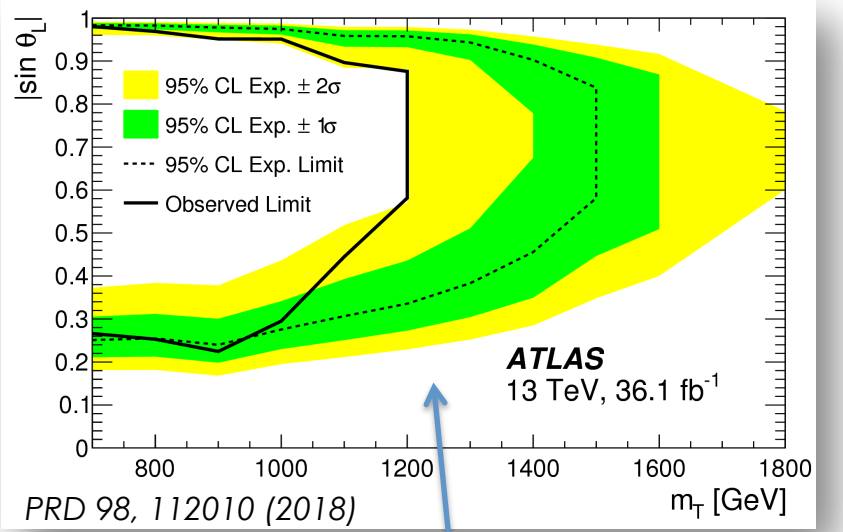
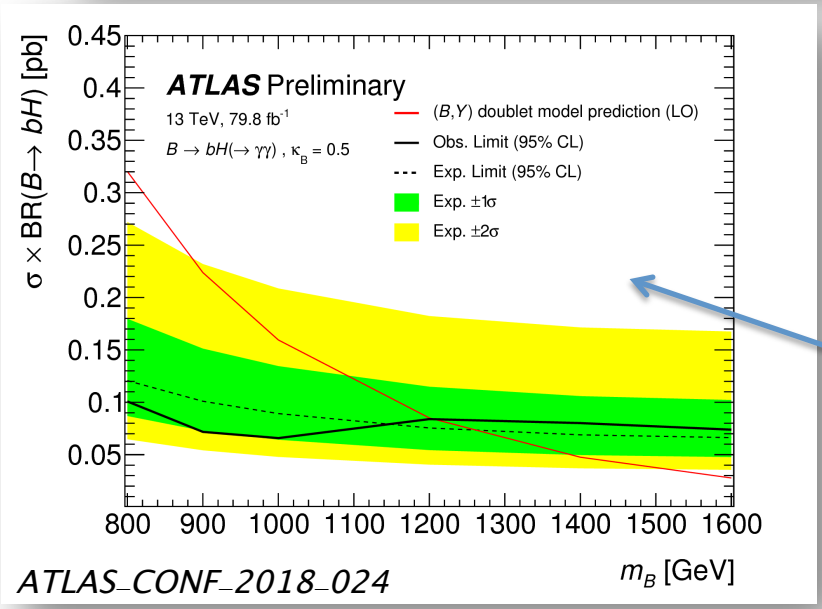




Single Production







$Z_{\ell\ell}+t$ analysis: Limits on T

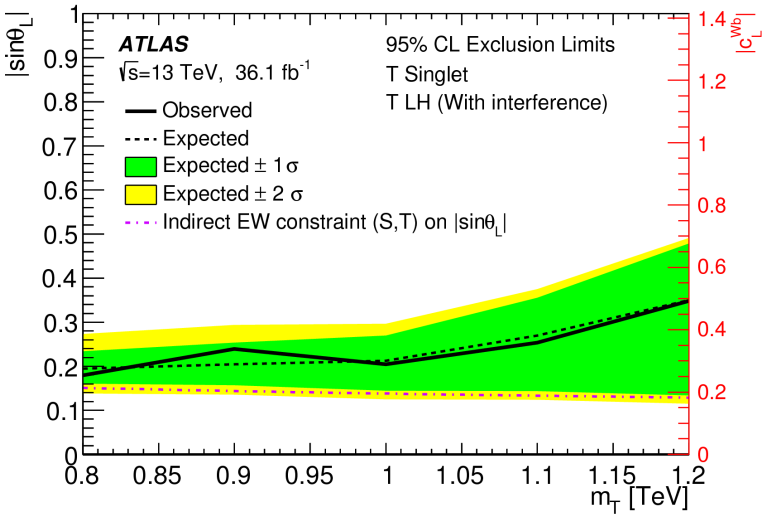
$\ell^{\pm}\ell^{\pm}/3\ell+b$ analysis: Limits on $X^{5/3}$

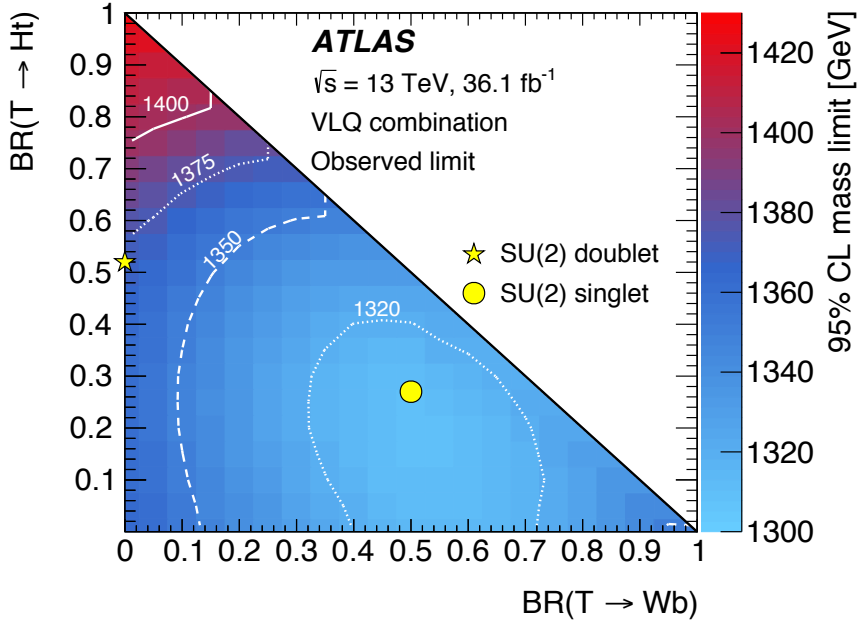
$H_{\gamma\gamma}+b$ analysis: Limits on B

Conclusions

- ATLAS has a broad VLQ program searching for pair and single-production
- VLQs can provide a natural solution to the hierarchy problem
  … if they are not too heavy
- So far, data appear to agree with SM
  - Combination of pair-production analyses:
    - $m_T > 1.3$ TeV
    - $m_B > 1.0$ TeV

    (Similar limits from CMS seaches)





Conclusions

- ATLAS has a broad VLQ program searching for pair and single-production
- VLQs can provide a natural solution to the hierarchy problem
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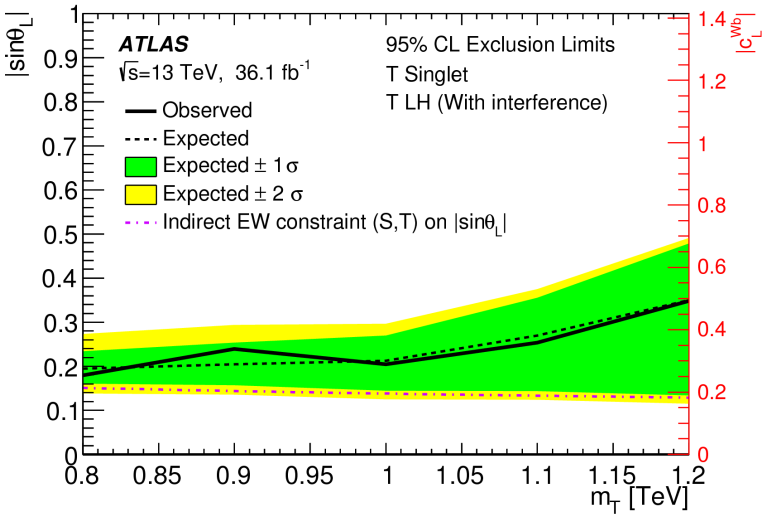
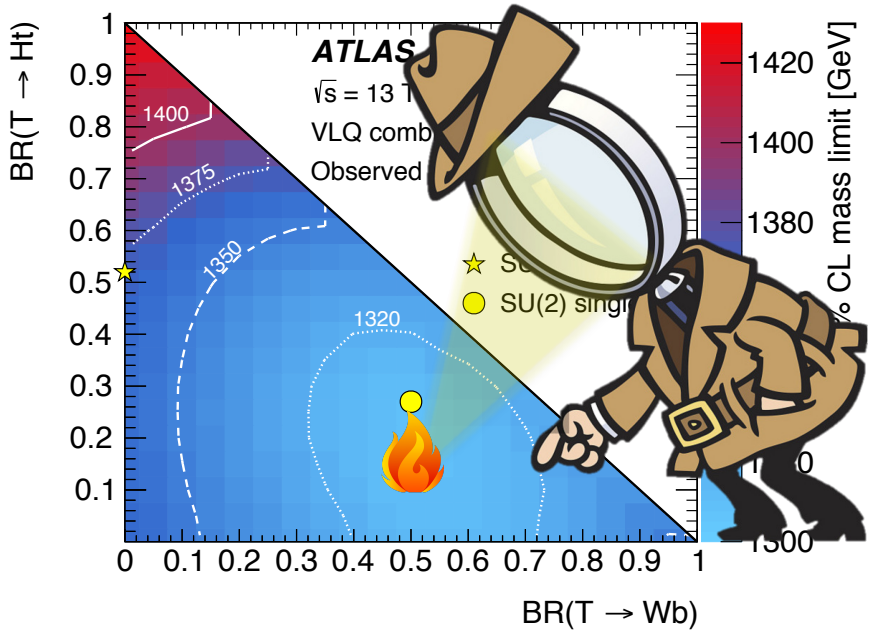
- So far, data appear to agree with SM
  - Combination of pair-production analyses:
    - $m_T > 1.3$ TeV
    - $m_B > 1.0$ TeV

    (Similar limits from CMS seaches)
- If VLQs solve the hierarchy problem, they are starting to feel the heat…

  … and we have 100/fb more data in the analysis pipeline!





Thank you

And special thanks to:

DOE for supporting this research

To the ATLAS Collaboration

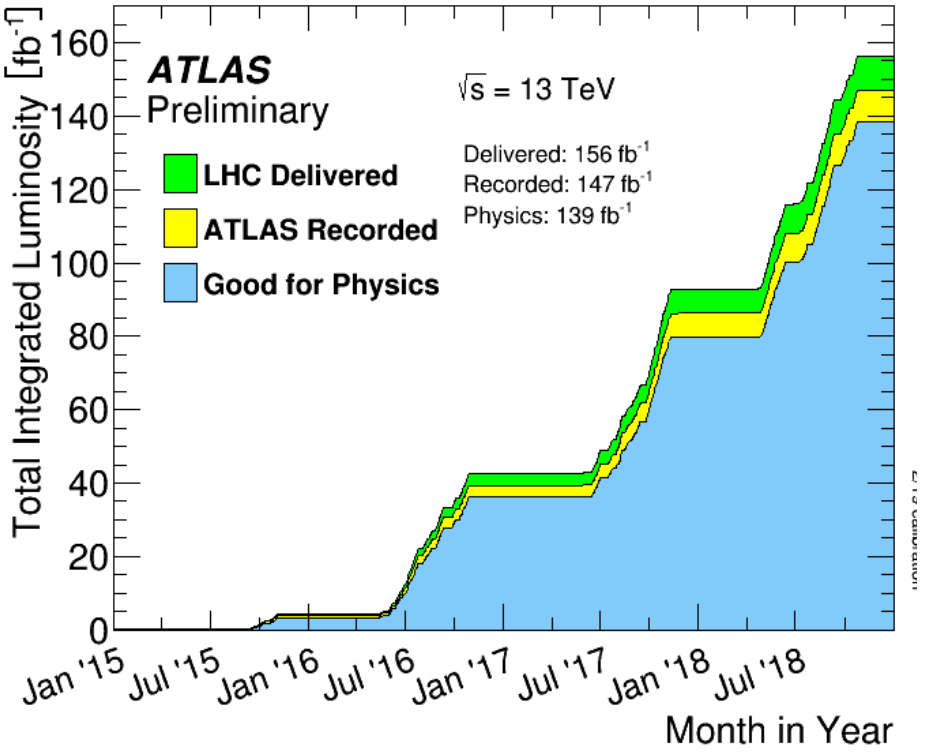
- Complete list of ATLAS exotic results: twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

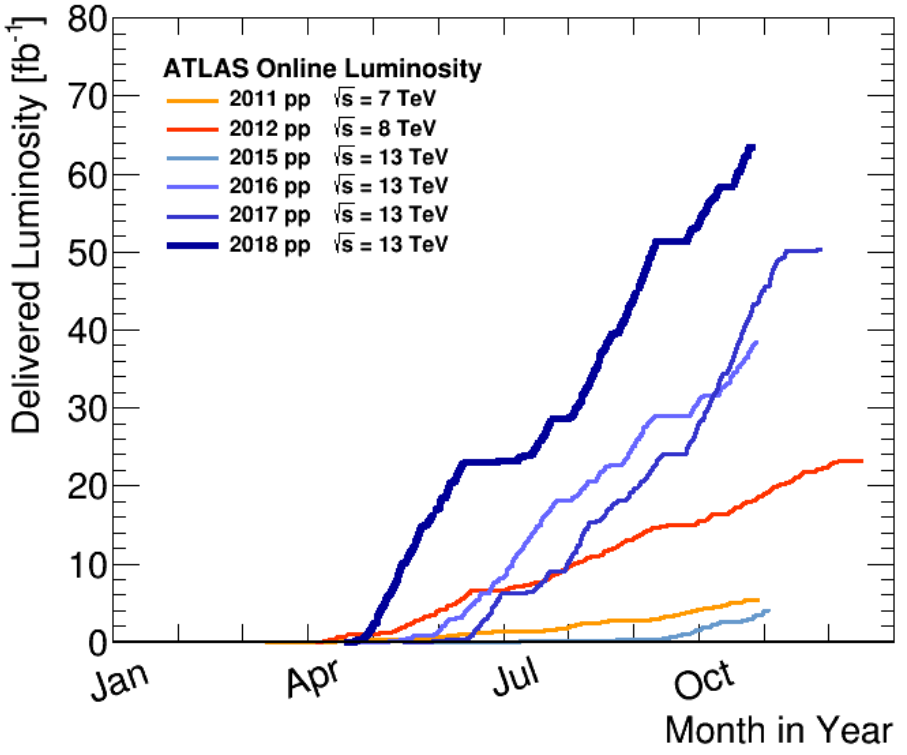
Run 2 Data

Results presented today use data from 2015-2016 (~36/fb)

In the process of analyzing full Run 2 data set (~136/fb)

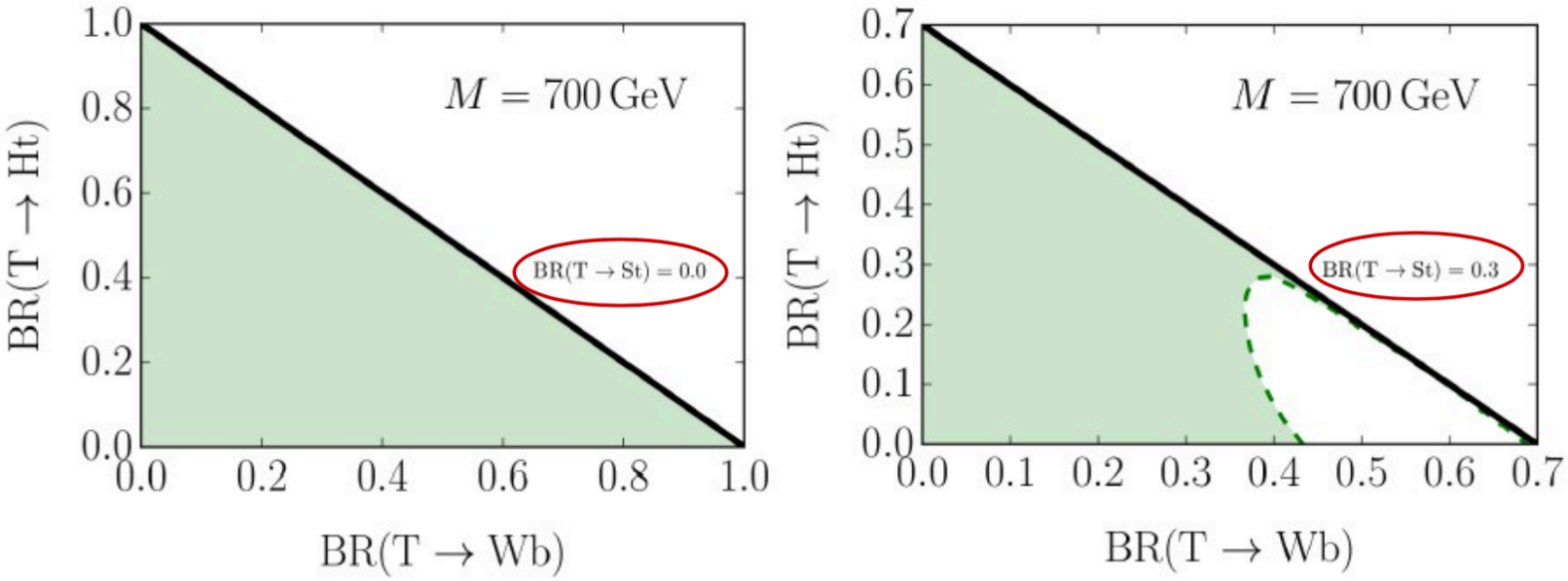
⇒ Thank you to LHC Operations!





Beyond B(T→Wb+Zt+Ht) = 1 Assumption

- In the triangular BR plots we assume that VLQs only decay to SM particles
  - This is not the case in most of the composite Higgs models (e.g. arXiv:1704.07388)



→ A non-negligible decay to a non-SM particle (e.g. the new scalar S) can significantly change the limits in the BR plane

[arXiv:1705.03013]

(Slide from Nuno Castro)

Beyond B(T→Wb+Zt+Ht) = 1 Assumption

- Depending on the model S can be ~ stable, evading detection, or decay e.g. to bb, tt, HH
  - Ideally we would have dedicated searches for these channels
  - Some of our current searches might even be (partially) sensitive to S, depending on its decay modes
    - We might even be able to tailor our analysis to increase the sensitivity to these additional final states
  - Nonetheless, providing the BR plane limits for relaxed Σ(BR) assumptions gives a conservative hint on the impact of S (i.e. gives us the maximum effect in the degradation of our results)
    - As long as we provide enough information and are very clear about the assumptions, this would fit well as a complementary result for our papers (in particular the combination one)

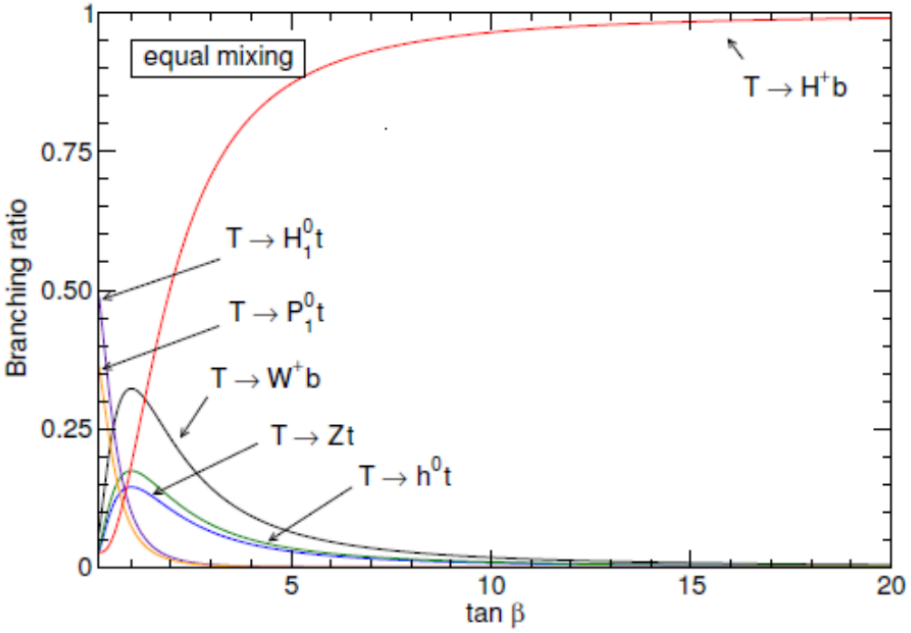
(Slide from Nuno Castro)

Beyond B(T→Wb+Zt+Ht) = 1 Assumption

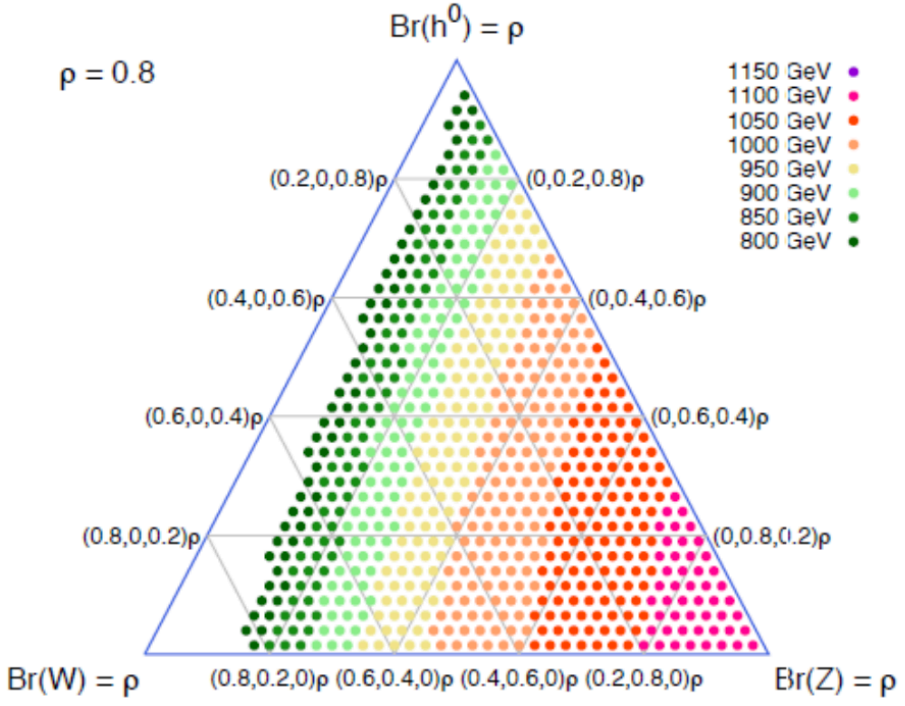
- Another recent proposal: arXiv:1705.02526

one example:

$$T \to H_k^0 t\,, \quad T \to P_k^0 t\,, \quad T \to H^+ b\,,$$



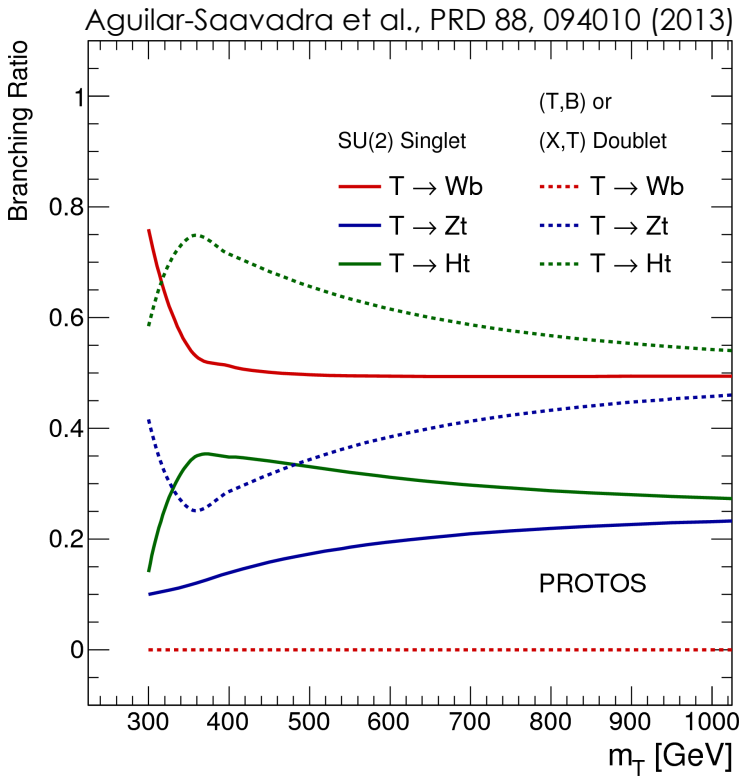
$$\mathrm{Br}(W) + \mathrm{Br}(Z) + \mathrm{Br}(h^0) \leq 1$$



$$\mathrm{Br}(W) + \mathrm{Br}(Z) + \mathrm{Br}(h^0) = \rho$$

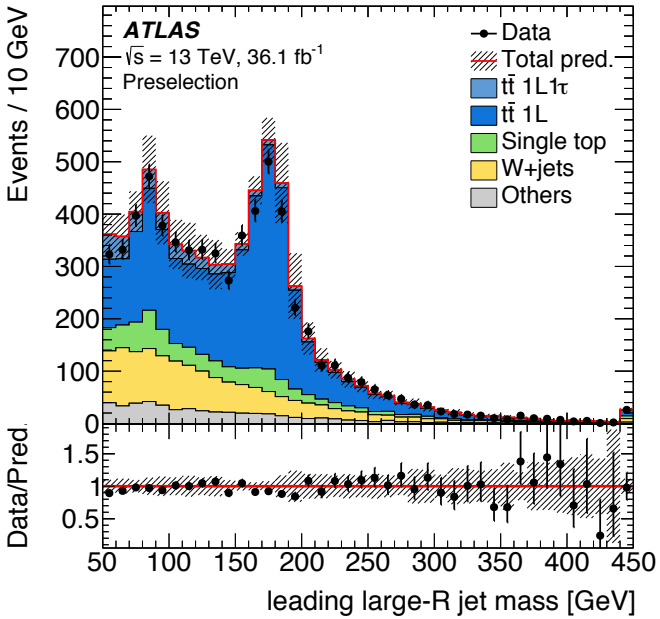
(Slide from Nuno Castro)

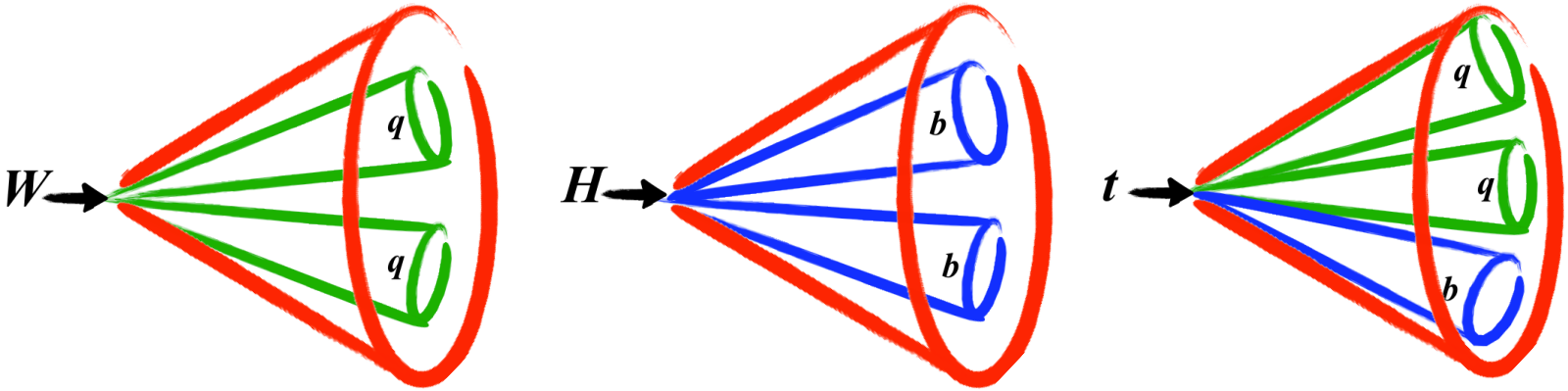
Branching Ratios



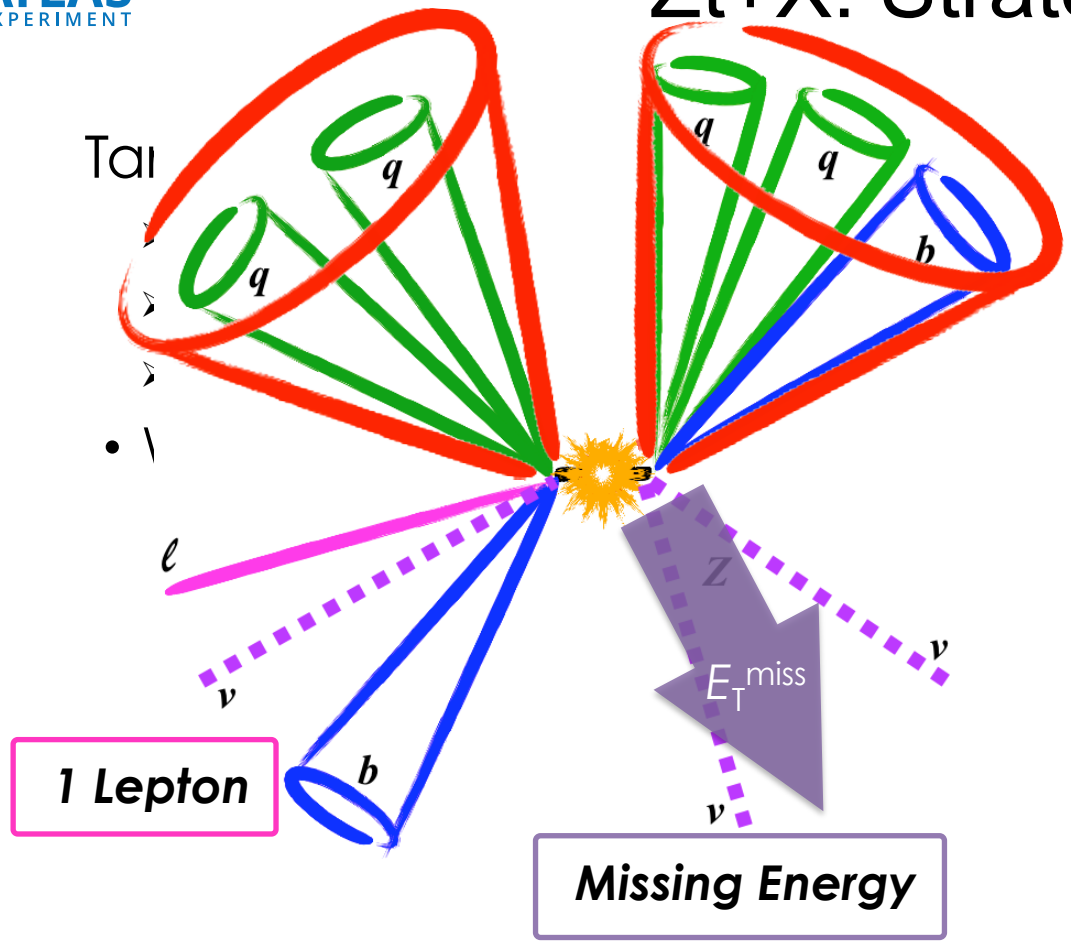
Heavy Objects

1) Large-R jets from calorimeter cells
   - R=1.0, C/A, trimmed jets
   - Dedicated calibrations and uncertainties
   - Use sub-structure to tag W bosons
2) Large-R "re-clustered" jets
   - Small-R jets are the input to R=1.0 clustering
   - Inherit calibration and uncertainties
   - Cut on large-R jet mass to "tag"





Zt+X: Strategy



1 Lepton

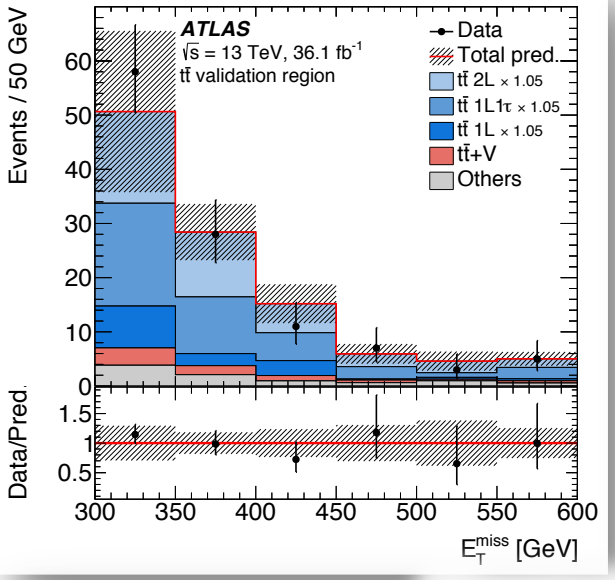
Missing Energy

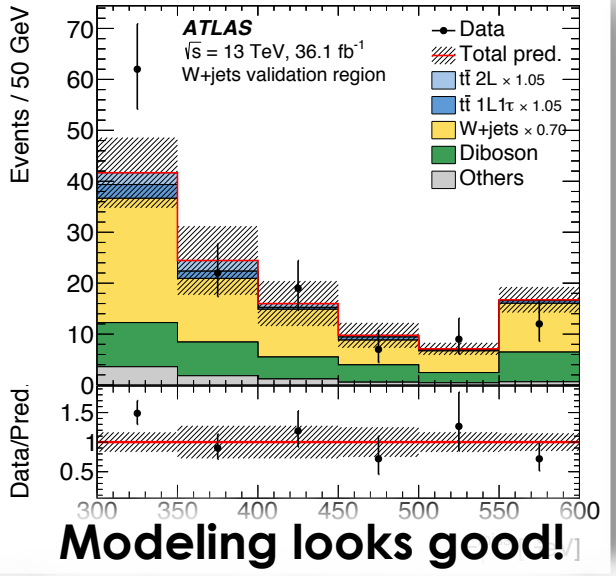
≥ 4 small-R jets
- ≥ 1 b-tagged

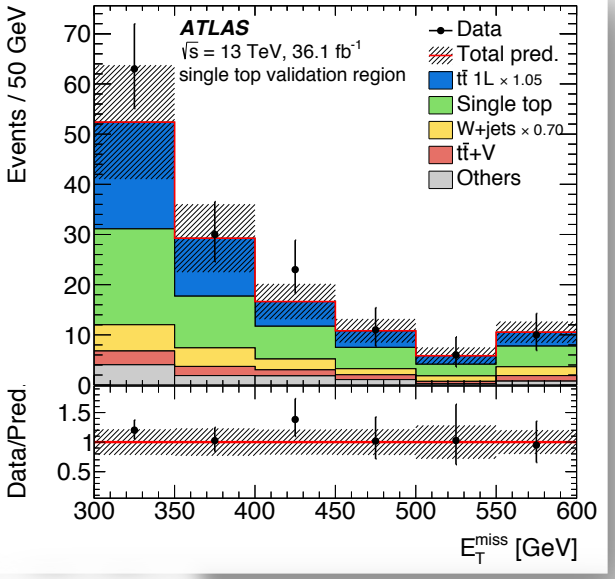
2 large-R jets

Cut-and-count analysis
- Signal Region (Bin) – Kinematic cuts to optimize VLQ sensitivity
- Control Regions – To fit *tt* and *W*+jets normalizations
- Validation Regions – To check modeling of backgrounds

Zt+X: Validation Regions

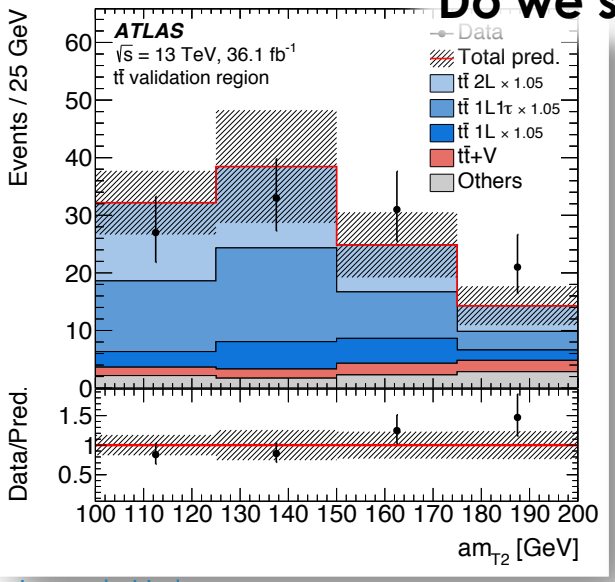


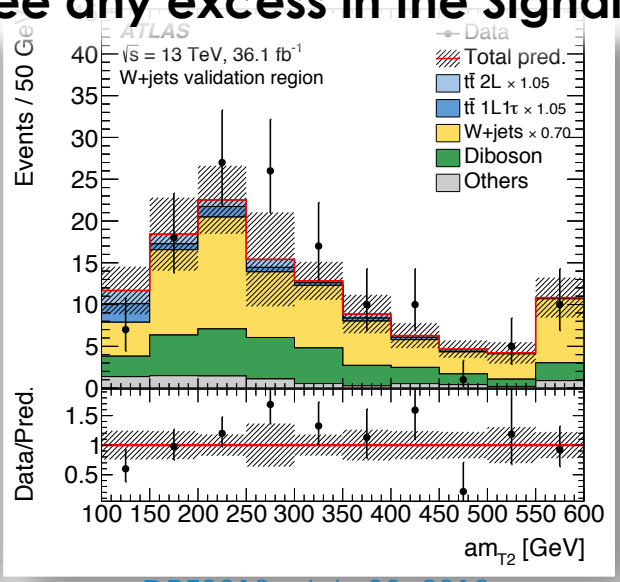


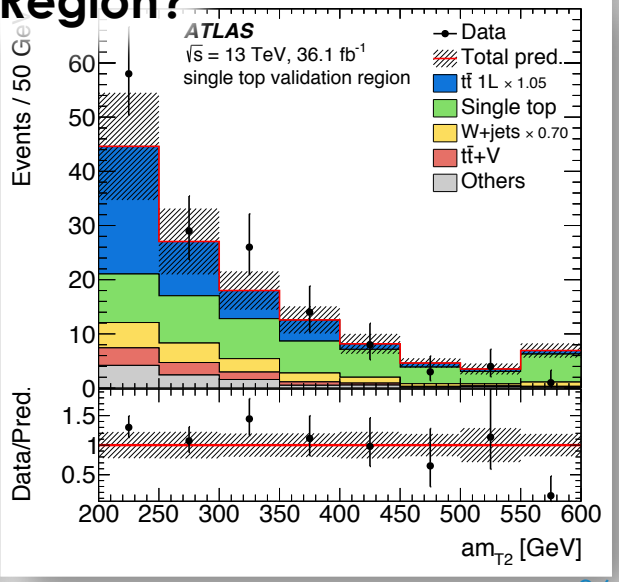


Modeling looks good!

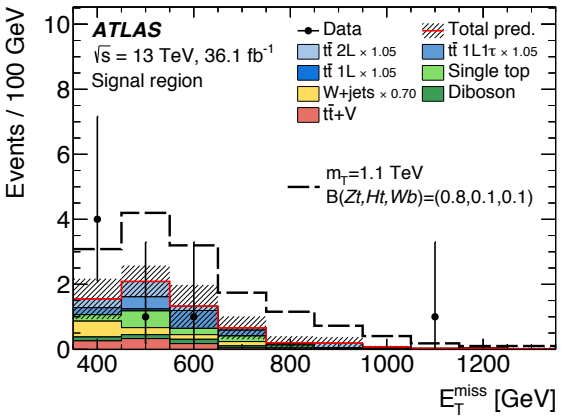
Do we see any excess in the Signal Region?

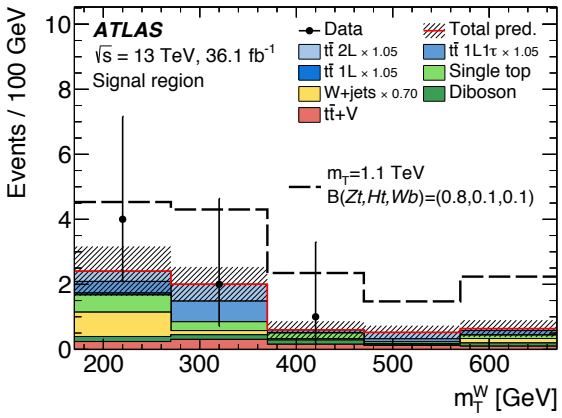


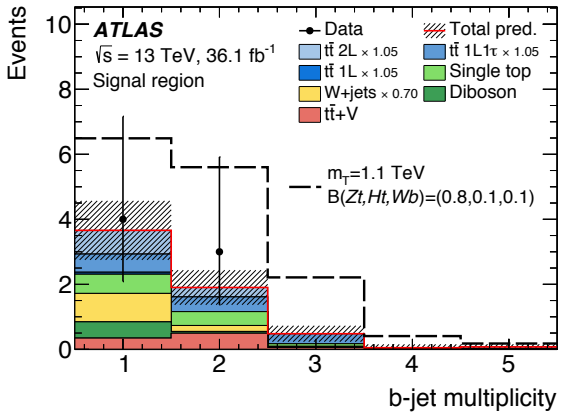




Zt+X: Signal Region







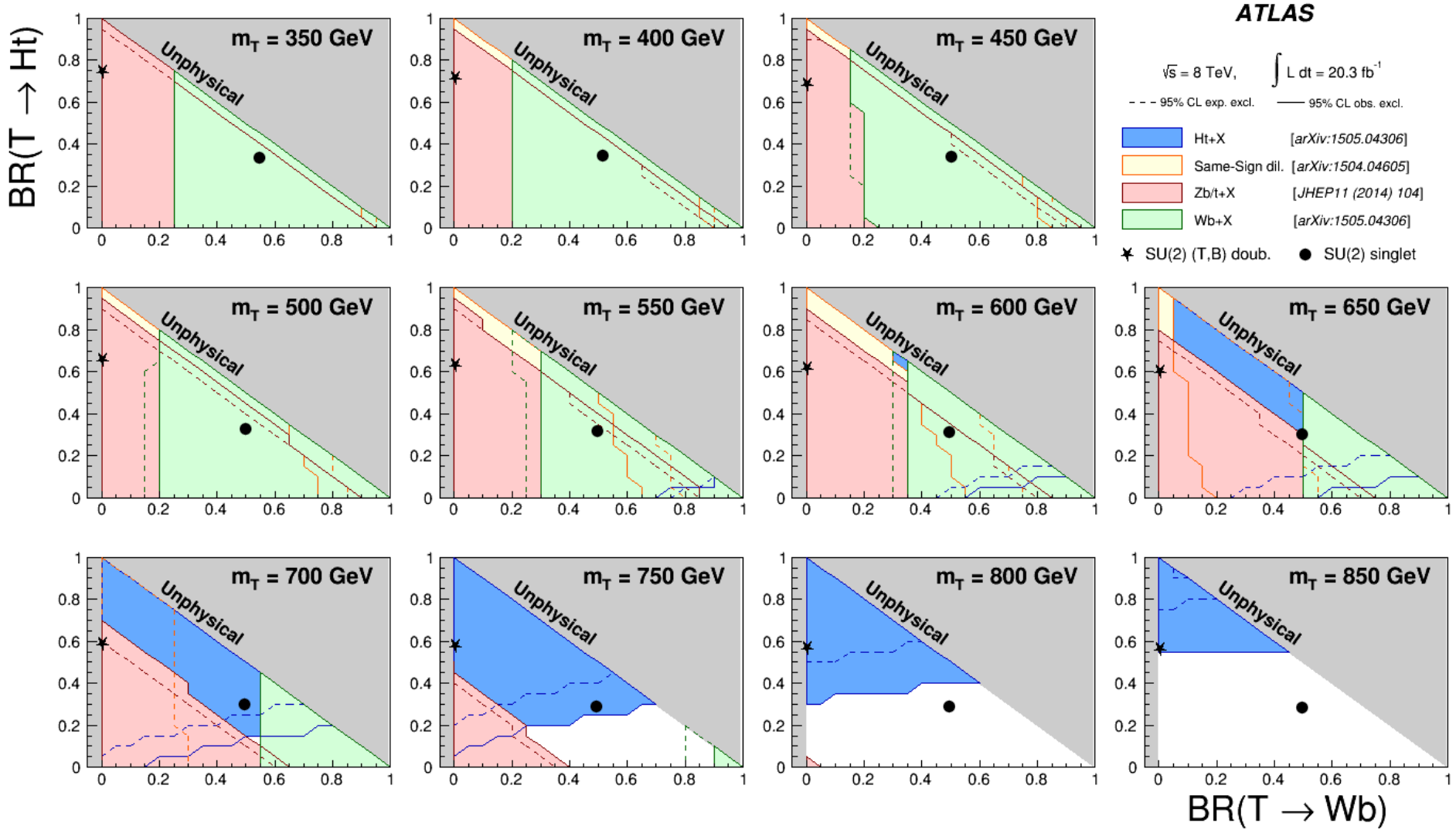
Region	SR	TCR	WCR	TVR	WVR	STVR
Observed events	7	437	303	112	131	143
Fitted bkg events	6.1 ± 1.9	437 ± 21	303 ± 17	109 ± 35	127 ± 31	125 ± 27
Fitted $t\bar{t}$ events	2.5 ± 1.7	280 ± 40	38 ± 15	90 ± 40	15 ± 8	53 ± 23
Fitted W + jets events	1.1 ± 0.7	70 ± 28	224 ± 27	3.5 ± 2.0	77 ± 30	15 ± 7
Fitted singletop events	1.1 ± 0.7	63 ± 24	10 ± 5	4.2 ± 2.6	$3.3^{+3.5}_{-3.3}$	46 ± 17
Fitted $t\bar{t} + V$ events	0.91 ± 0.20	9.7 ± 1.6	1.03 ± 0.30	7.0 ± 1.4	1.9 ± 0.7	8.3 ± 1.4
Fitted diboson events	0.6 ± 0.6	11 ± 5	30 ± 12	1.3 ± 1.3	31 ± 9	1.7 ± 1.1
MC exp. bkg events	6.5	450	398	106	160	129

Singlet (Doublet) *T* w/ *m*=1 TeV 5 (10)

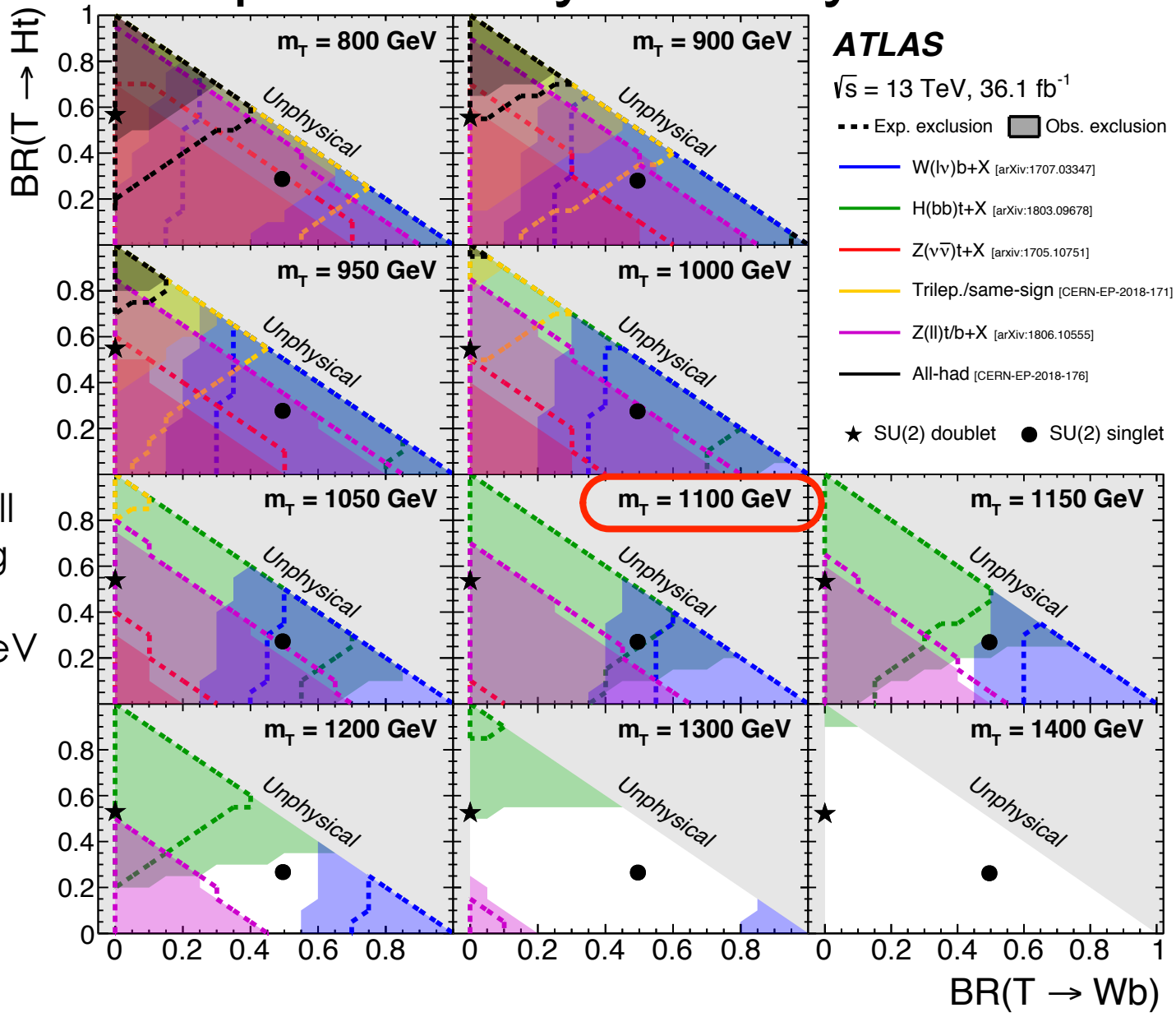
⇒ Also consistent with SM

arXiv:1505.04306

Run 1 Limits on TT

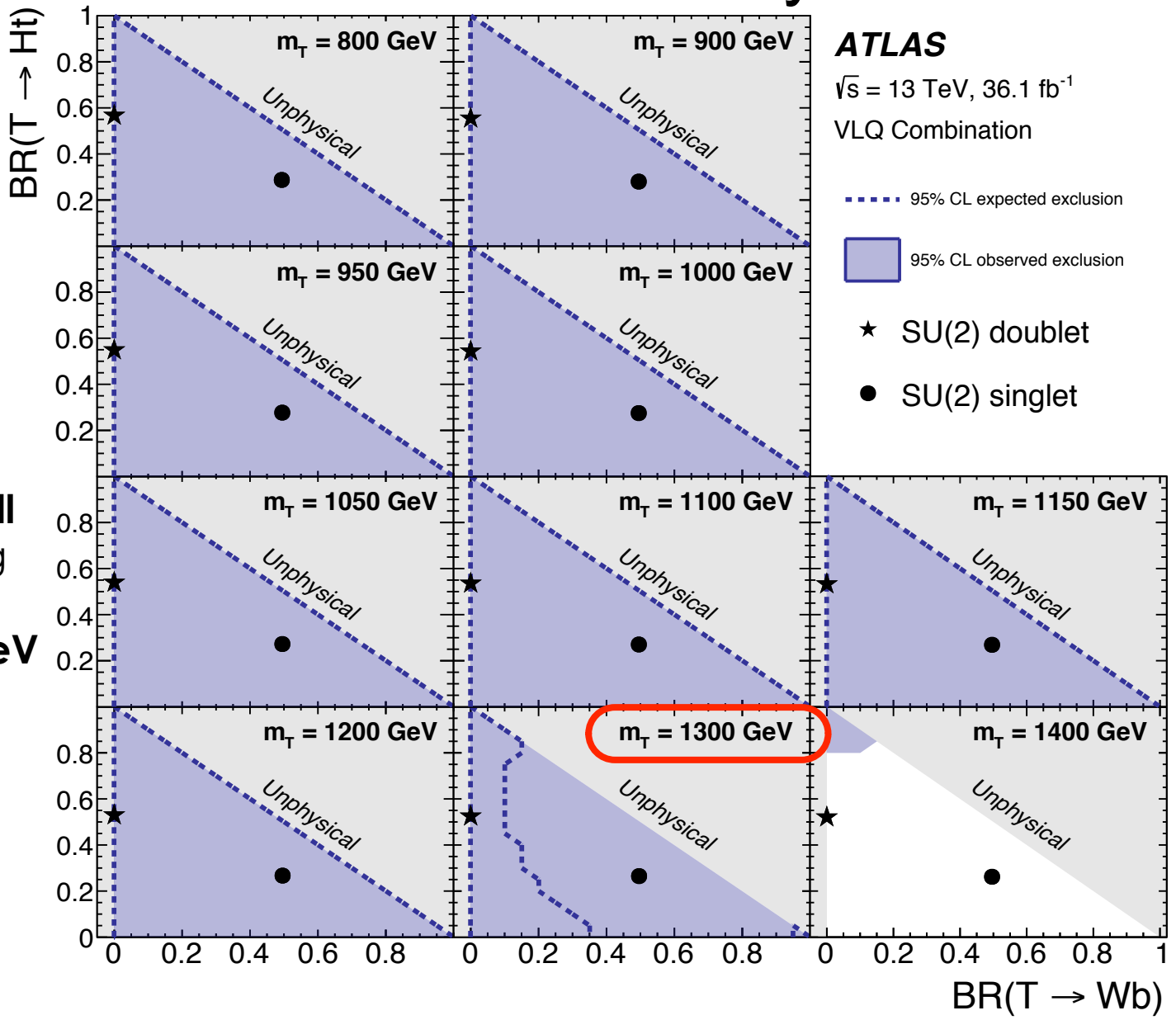


Simple Overlay of Analyses



Exclude all branching ratios for $m_T < 1.1$ TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

Combination of Analyses

Exclude **all** branching ratios for m_T < 1.3 TeV