ATLAS EXPERIMENT

Search for pair production of vector-like quarks in final states with a boosted W boson and b-jet

APS | DIVISION OF PARTICLES & FIELDS

DPF 2017

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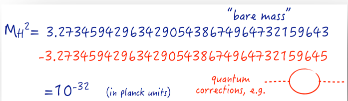
Oklahoma State Universtiy

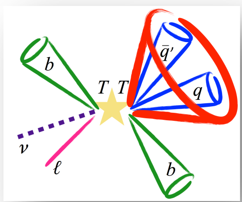
With support from

Outline



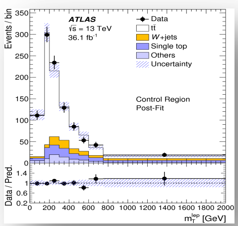
Background

- What are vector-like quarks (VLQs) and why should you care?



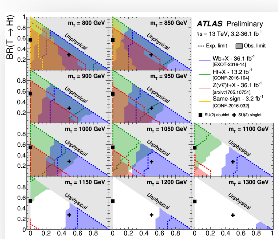
- VLQ phenomenology

Search for $T\bar{T} \rightarrow WbWb$



- Selection and Analysis strategy
- What do we see?

Other channels

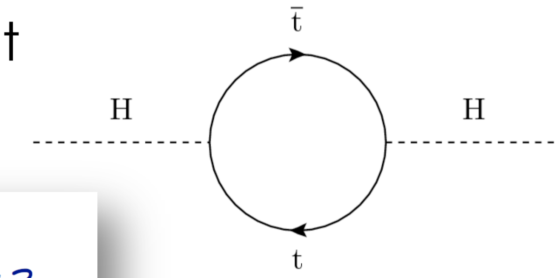


Conclusions

Hierarchy Problem

In the SM, Higgs mass is quadratically divergent

- Assuming no new physics until the Planck scale



"bare mass"

$$M_H^2 = 3.2734594296342905438674964732159643$$

$$-3.2734594296342905438674964732159645$$

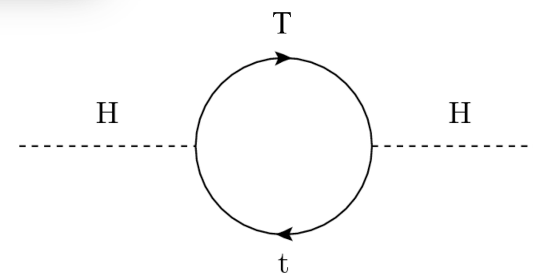
$$= 10^{-32} \quad \text{(in planck units)}$$

quantum corrections, e.g.

credit Roni Harnik

This can be *naturally* cancelled by VLQs!

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



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

VLQs show up in many BSM scenarios

- Little/Composite Higgs, Topcolor, GUTs, …
- **Naturalness requires mass ~1 TeV ⇒ Accessible at the LHC!**

Vector-like Quarks (VLQs)

Colored, spin-½ particles ⇒ "Quarks"

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

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

Can have bare VLQ mass term

- Avoids constraints from Higgs measurements

Couple to SM through mixing with SM quarks

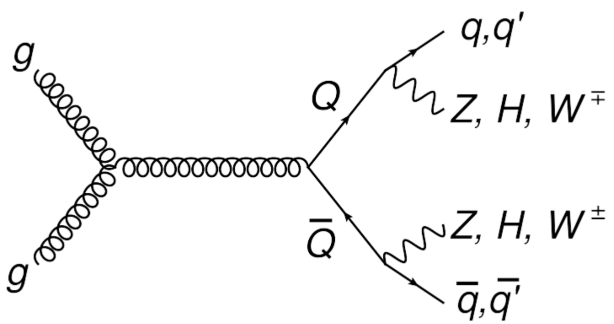
- Naturalness + FCNC constraints ⇒ mixing mostly with 3rd generation

	Q[e]	VLQs: singlets		doublets			triplets	
	$5/3$			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

Production and Decay

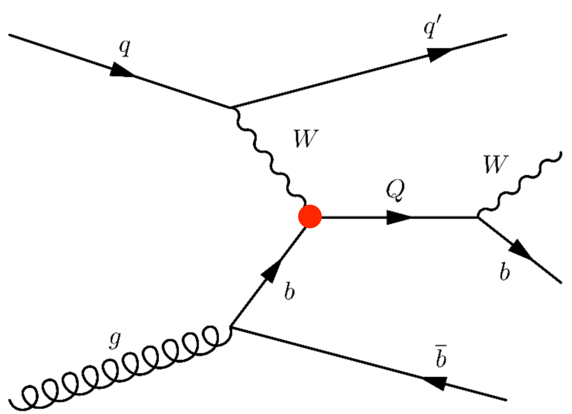
Pair Production (QCD)

- Depends only on mass



Single production (EW)

- Depends on coupling and mass

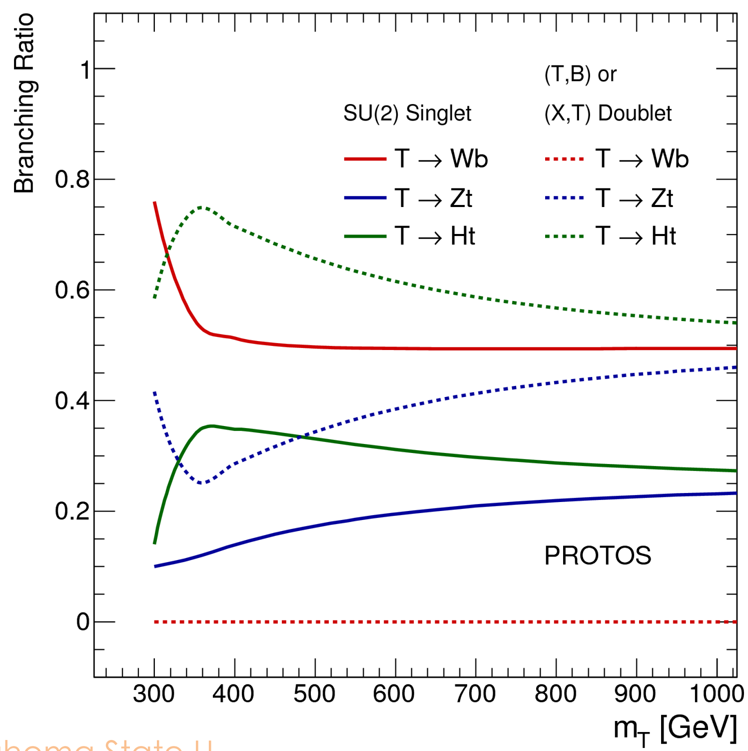


Possible decays dictated by quantum numbers

- $T \rightarrow Wb, Zt, Ht$
- $B \rightarrow Wt, Zb, Hb$

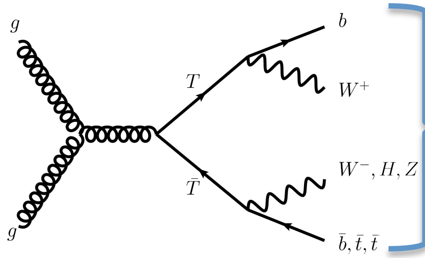
Branching ratios depend on model

- Constrained in some scenarios

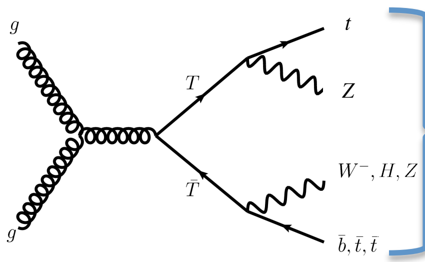


General Search Strategy

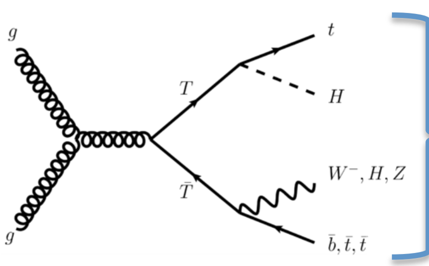
Multiple analyses to target each decay:



Wb+X

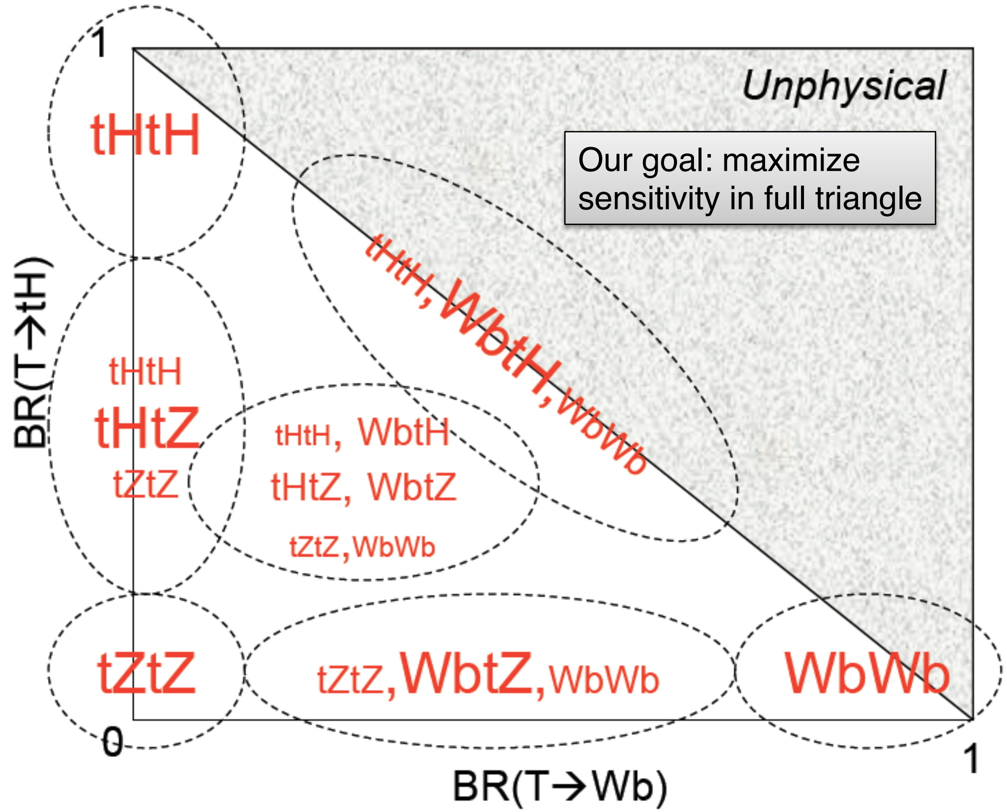


Zt+X



Ht+X

Set limits as a function of branching ratio



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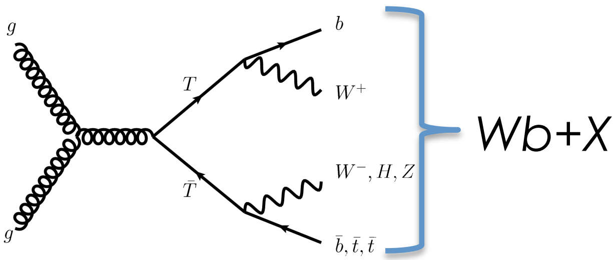

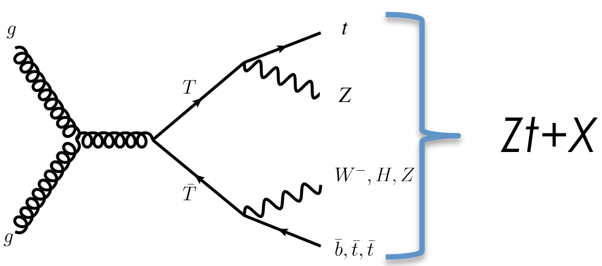

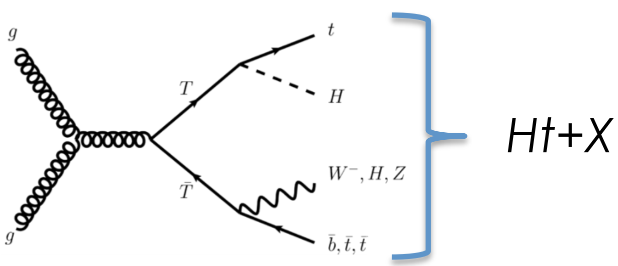

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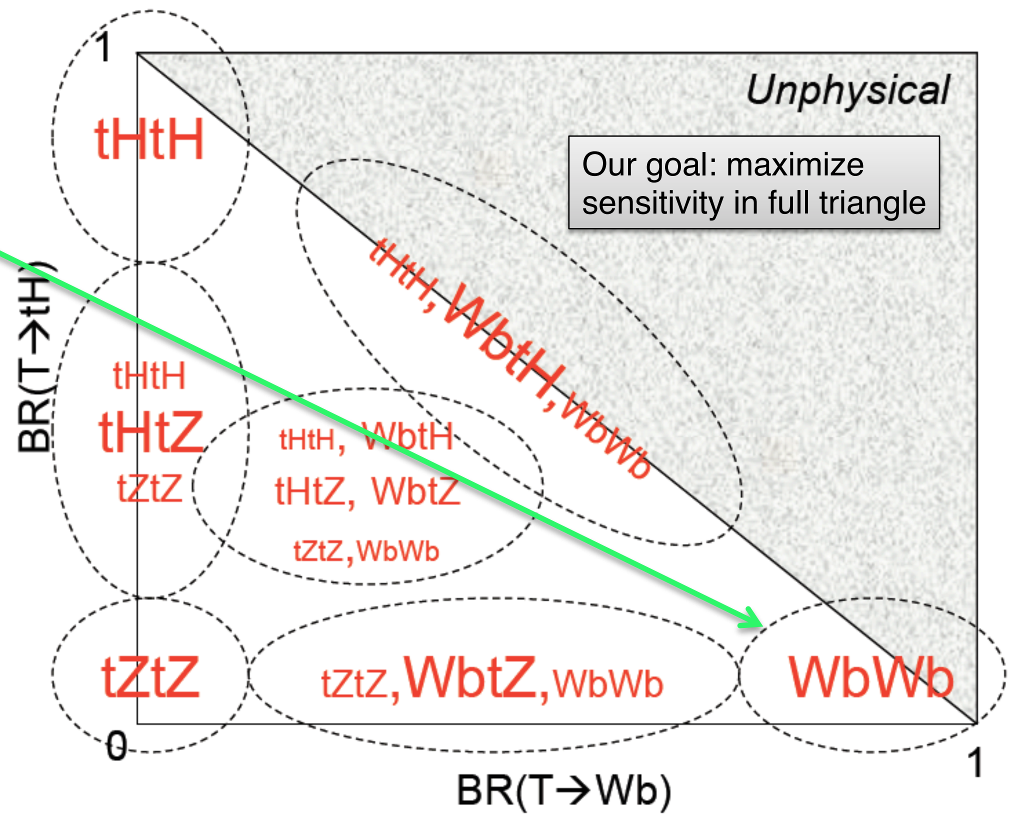
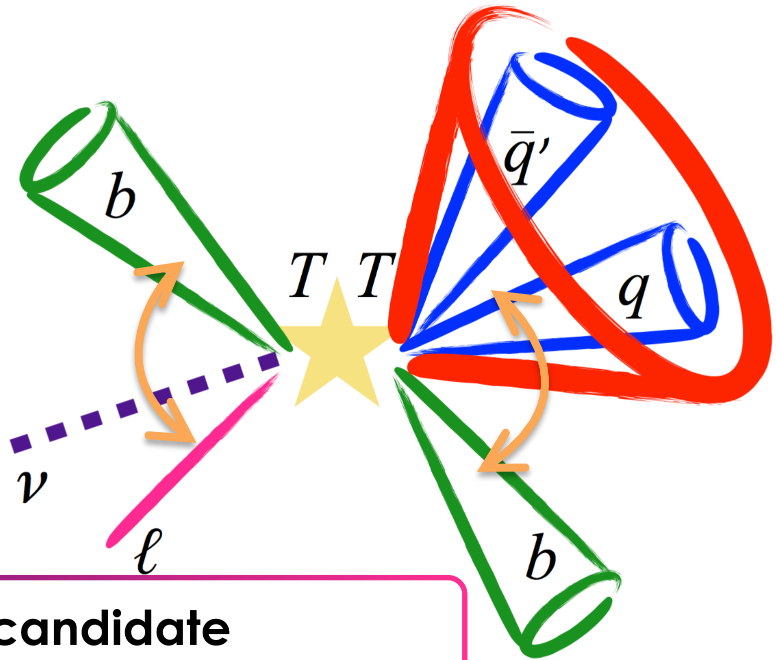


Submitted to JHEP [arXiv:1707.03347]

TT→*WbWb*: Basic Selection



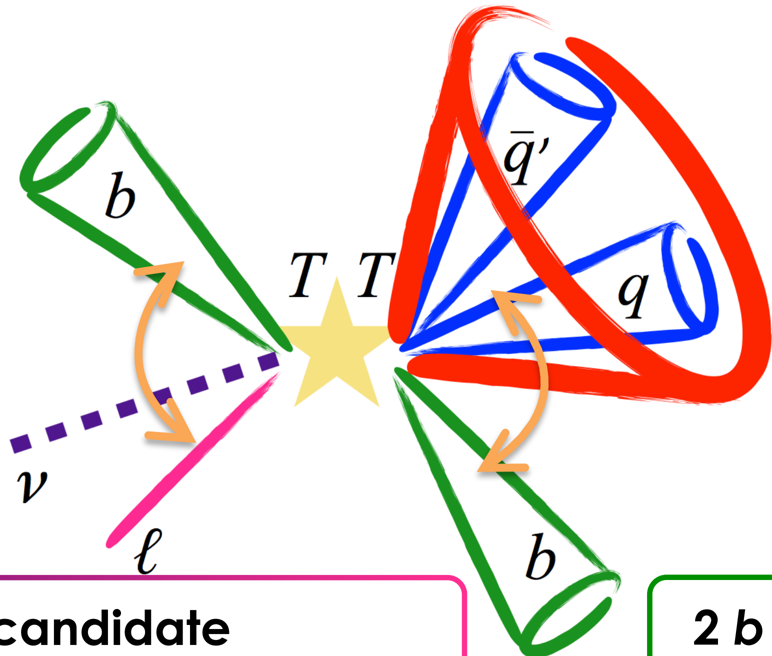
Boosted W_{had} candidate

- R=1.0, anti-k_t jet trimmed
- m > 50 GeV, p_T > 200 GeV
- Jet substructure *W*-tag (50% efficiency)

W_{lep} candidate

- e/μ with p_T > 30 GeV
- E_T^{miss} > 60 GeV
- Use m_W constraint to reconstruct neutrino

$TT \rightarrow WbWb$: Basic Selection



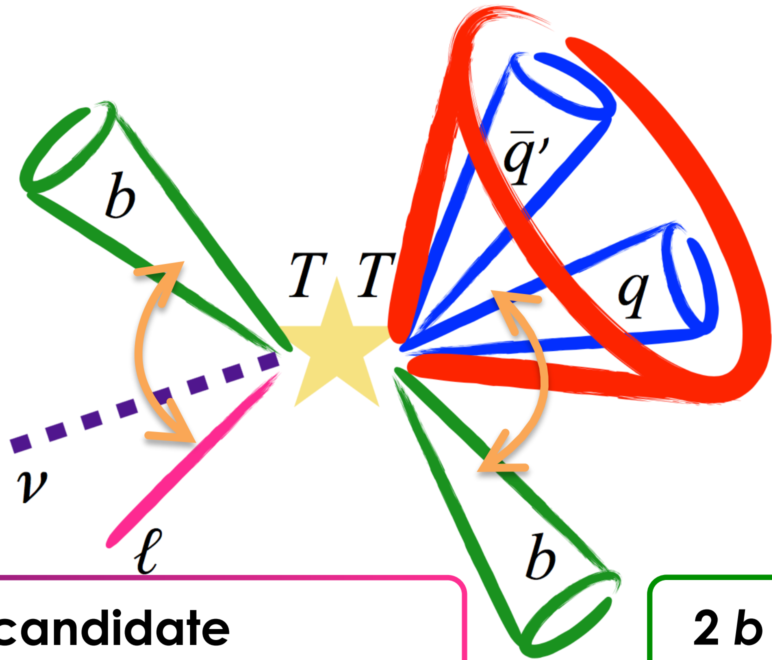
Boosted W_{had} candidate
- R=1.0, anti-k_t jet trimmed
- m > 50 GeV, p_T > 200 GeV
- Jet substructure W-tag (50% efficiency)

$\Delta R(W_{had}, b) > 1.0$
$\Delta R(\ell, b) > 1.0$

W_{lep} candidate
- e/μ with p_T > 30 GeV
- E_T^{miss} > 60 GeV
- Use m_W constraint to reconstruct neutrino

2 b candidates
- ≥ 2 additional R=0.4 jets
  - p_T > 25 GeV
  - Match to primary vertex
- ≥ 1 b-tagged (77% efficiency)

$TT \rightarrow WbWb$: Basic Selection



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2 *b* candidates
- ≥ 2 additional R=0.4 jets
  - p_T > 25 GeV
  - Match to primary vertex
- ≥ 1 *b*-tagged (77% efficiency)

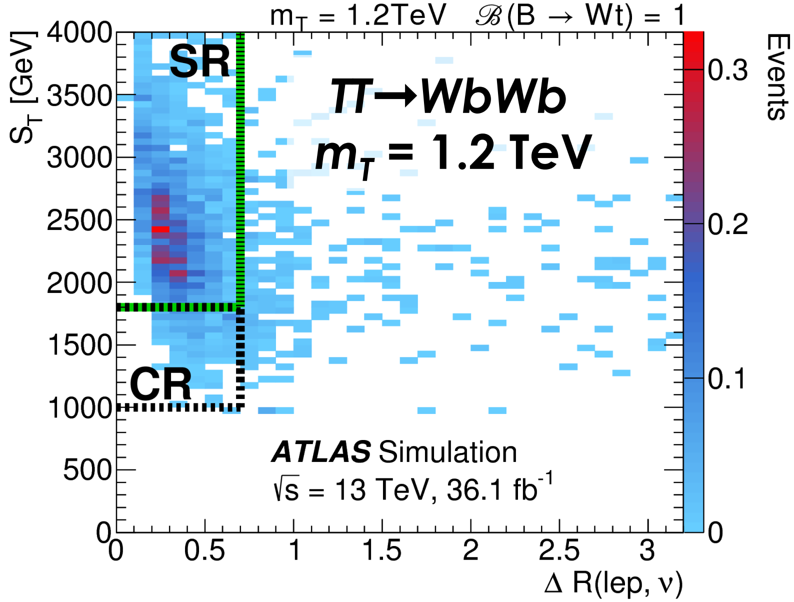
T_{had} and T_{lep} candidates
- Test all parings of *b* candidates with W_{had} or W_{lep}
- Pick combinaiton with smallest $|m_T^{lep} - m_T^{had}| < 300$ GeV

Final Selection

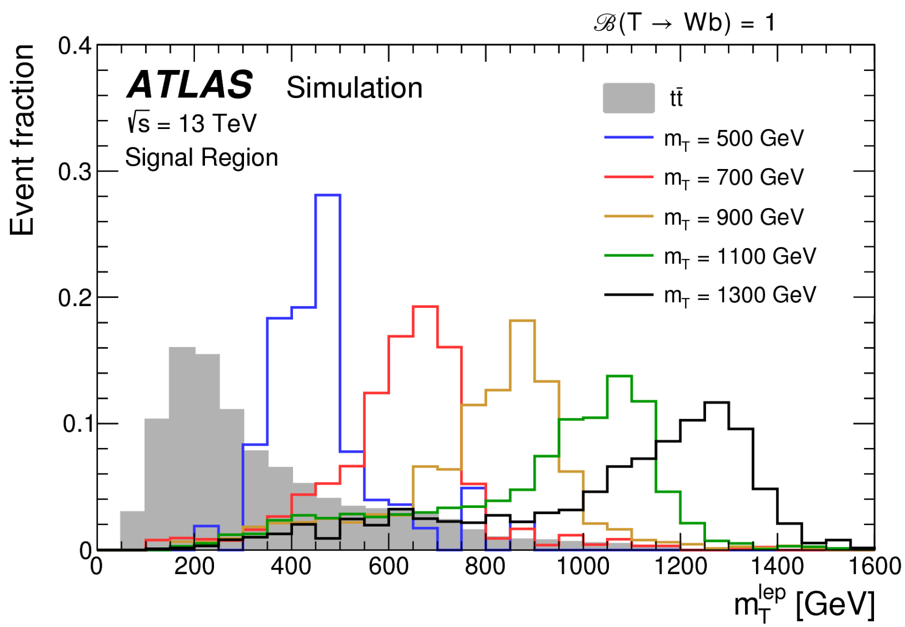
Signal Region (**SR**)

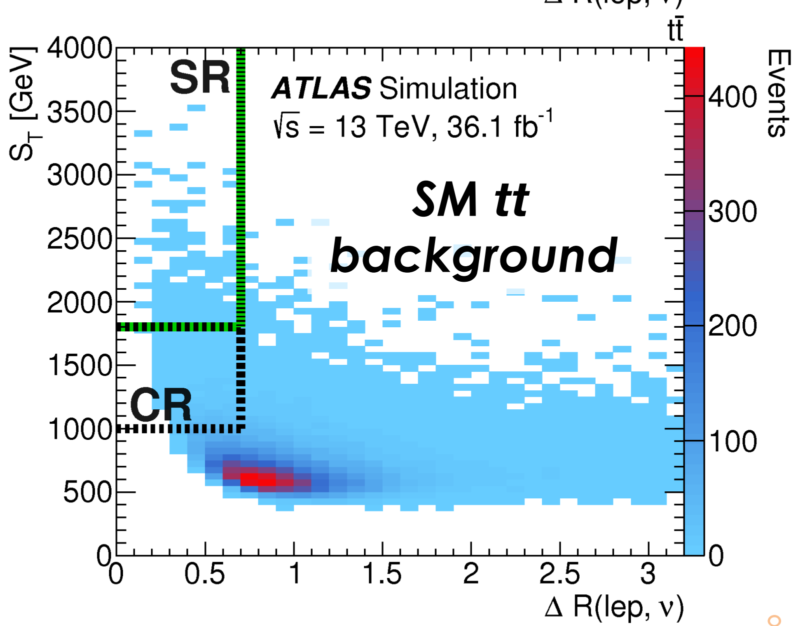
- Optimized for VLQ masses ≳ 1 TeV
  - ➢ **$\Delta R(\ell, \nu) < 0.7$**
  - ➢ **$S_T \equiv \sum p_T^{jets} + p_T^{\ell} + E_T^{miss} > 1200$ GeV**

Control Region (**CR**) to constrain *tt*

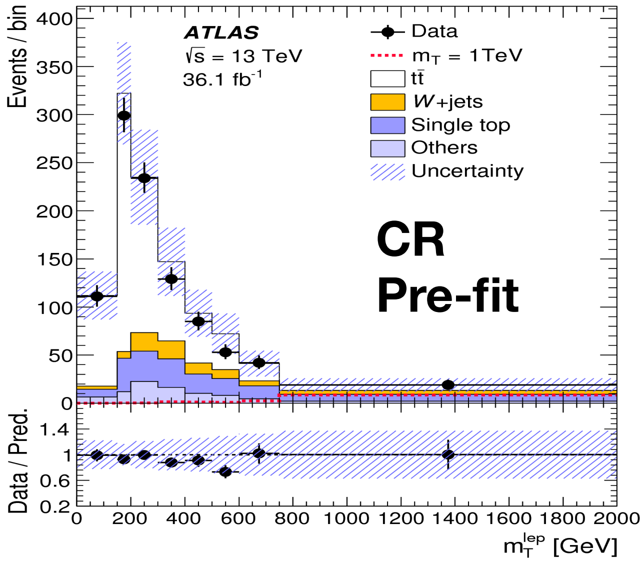


Final variable: m_T^{lep}





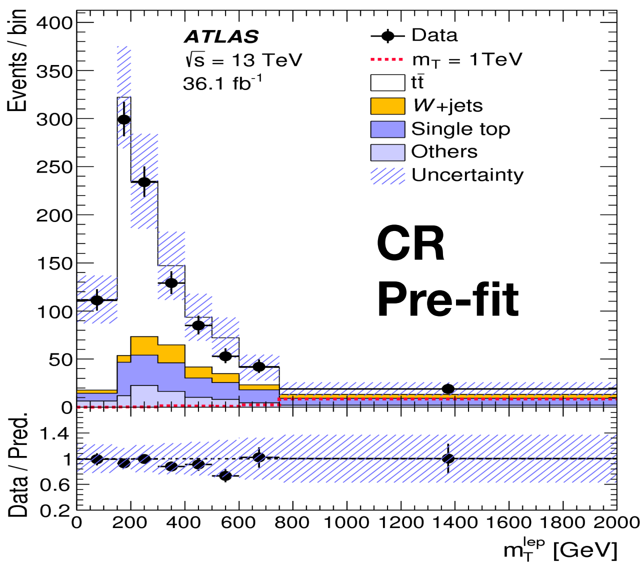
Backgrounds

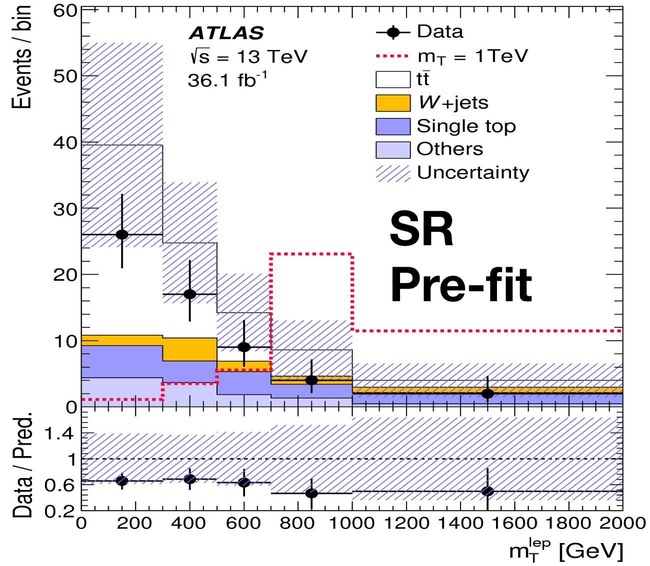


- Backgrounds estimated with MC simulations (expect multijet)
- Dominant uncertainties
  - Poisson uncertainty of data
  - Single top *Wt* removal scheme
  - *tt* parton shower and generator
  - Jet energy resolution

Sample	Signal region	Control region
$t\bar{t}$	55 ± 26	720 ± 130
W+jets	9 ± 4	78 ± 41
Single top	15 ± 15	160 ± 110
Others (Z+jets, diboson, ttV, multijet)	12 ± 10	82 ± 66
Total Background	91 ± 35	$1\,040 \pm 200$
Signal (m_T = 1 TeV, $T \to Wb$ = 100%)	45 ± 4	15 ± 2
Signal (m_T = 1 TeV, SU(2) singlet)	21 ± 2	8 ± 1

Backgrounds





No sign of VLQs

Sample	Signal region	Control region
$t\bar{t}$	55 ± 26	720 ± 130
W+jets	9 ± 4	78 ± 41
Single top	15 ± 15	160 ± 110
Others (Z+jets, diboson, ttV, multijet)	12 ± 10	82 ± 66
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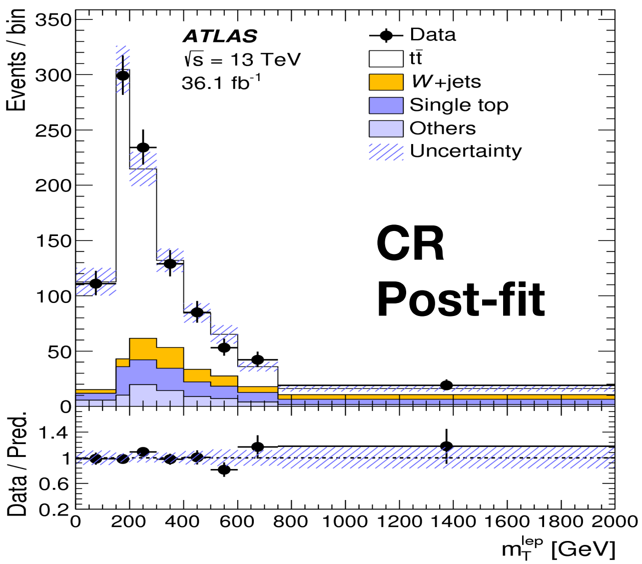
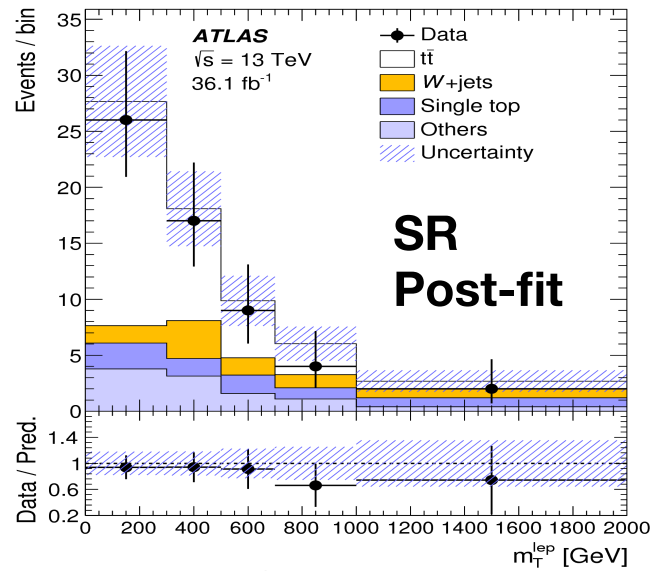
Submitted to JHEP [arXiv:1707.03347]

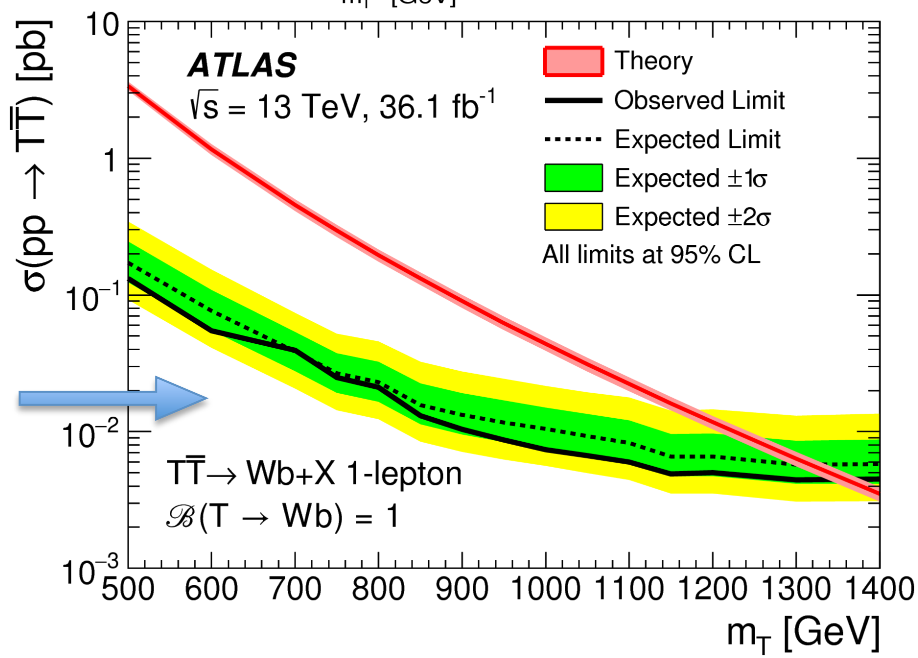
Limits on *TT* Production





Strongest limit!

- Data compatible with background-only fit
- Use CL_S method to set 95% CL limits on *TT* cross section
  - **For $\mathcal{B}(T\rightarrow Wb) = 1 \Rightarrow m_T > 1.35$ TeV**



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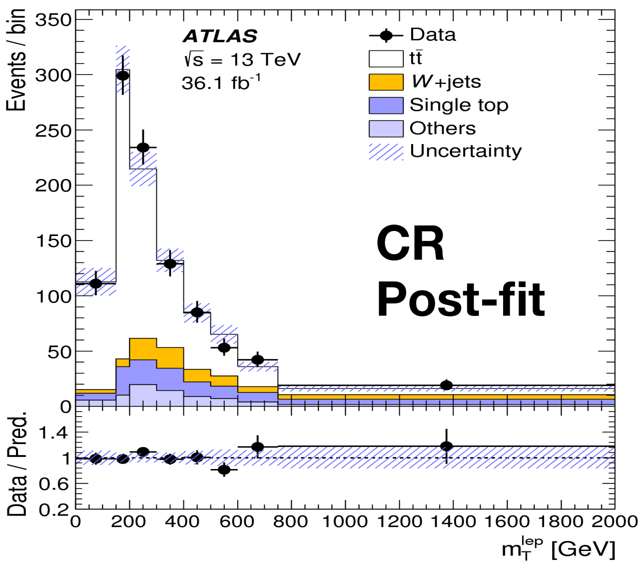
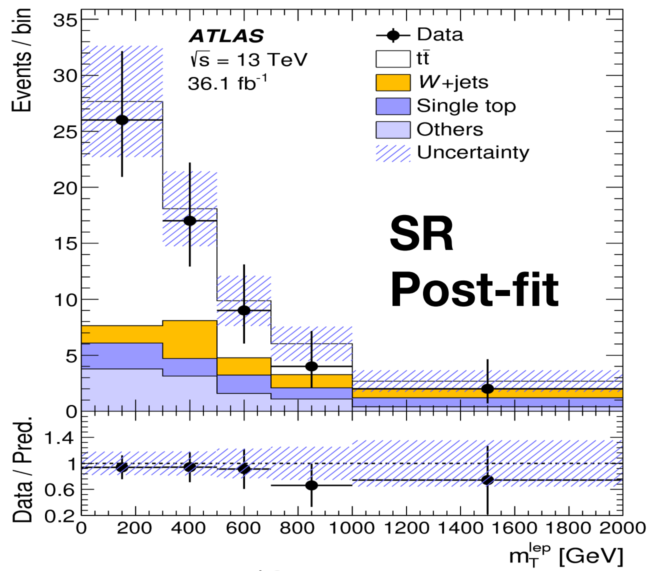
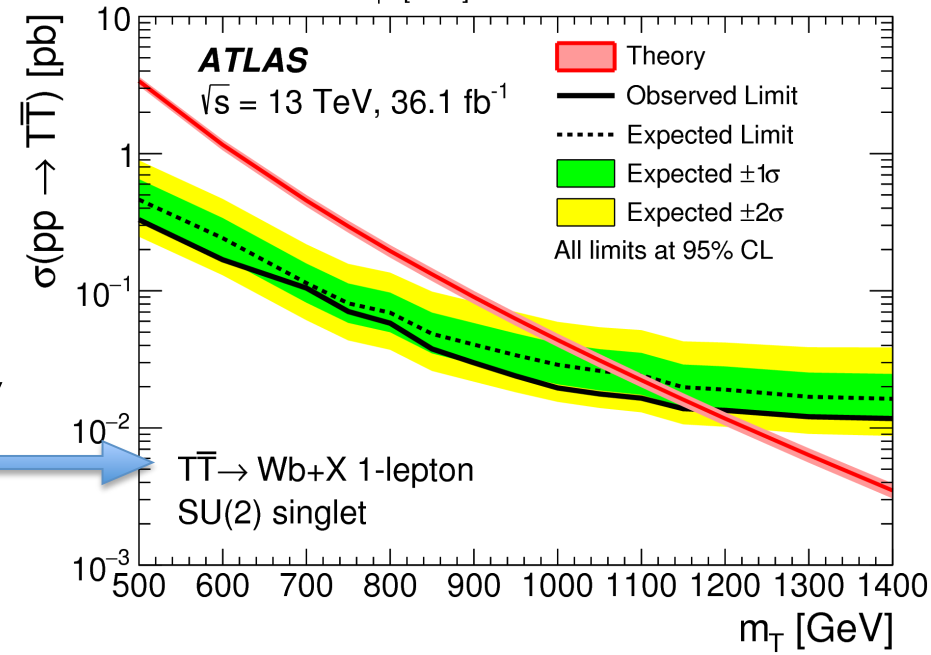
Limits on *TT* Production





Strongest Limit!

- Data compatible with background-only fit
- Use CL_S method to set 95% CL limits on *TT* cross section
  - For $\mathcal{B}(T \rightarrow Wb) = 1 \Rightarrow m_T > 1.35$ TeV
  - **For singlet *T* ⇒ m_T > 1.17 TeV**

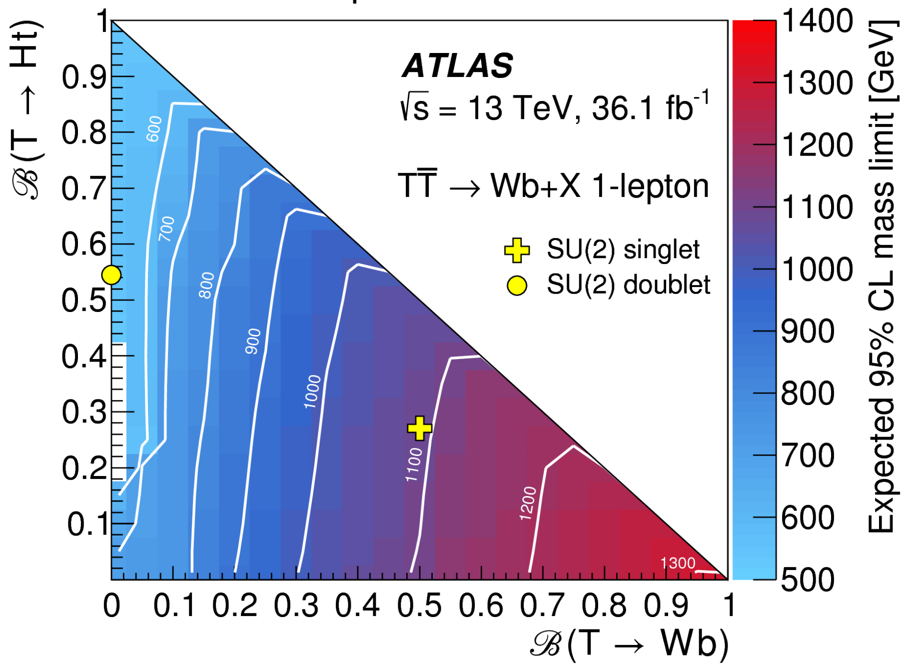


T Mass vs. Branching Ratio

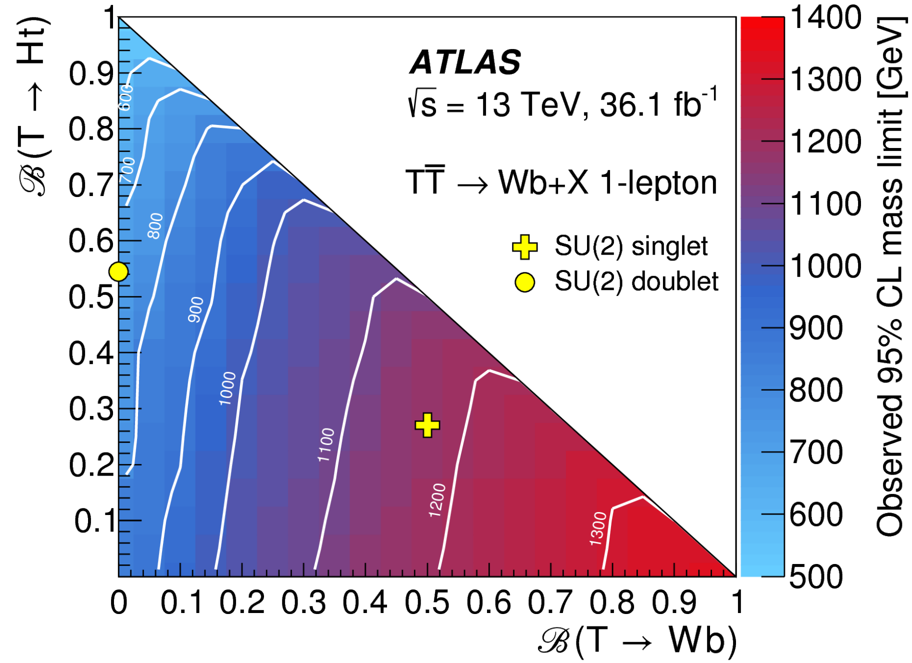
Model-independent limits for arbitrary branching ratios, assuming $\mathcal{B}(T\rightarrow Wb) + \mathcal{B}(T\rightarrow Zt) + \mathcal{B}(T\rightarrow Ht) = 1$

Minimum allowed VLQ mass:

Expected



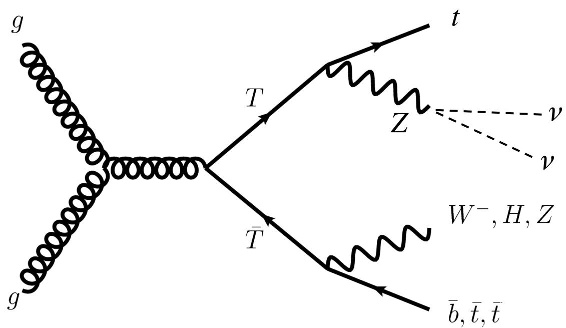
Observed

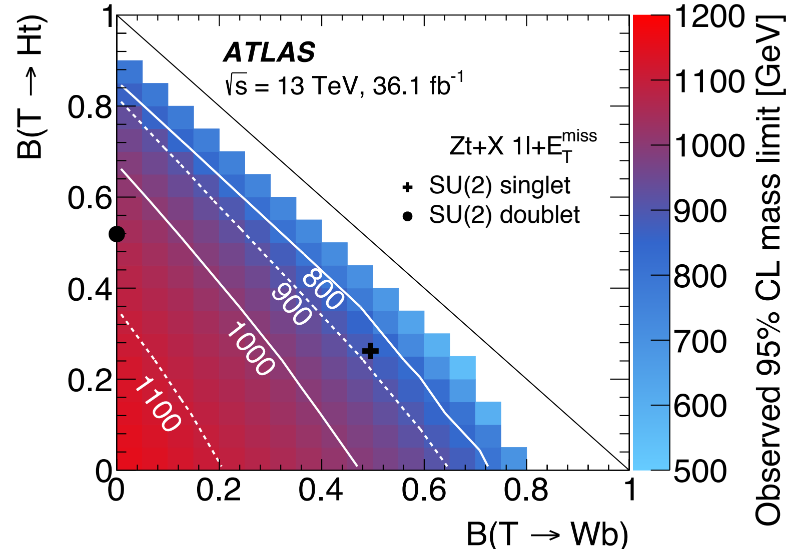


Stronger Together

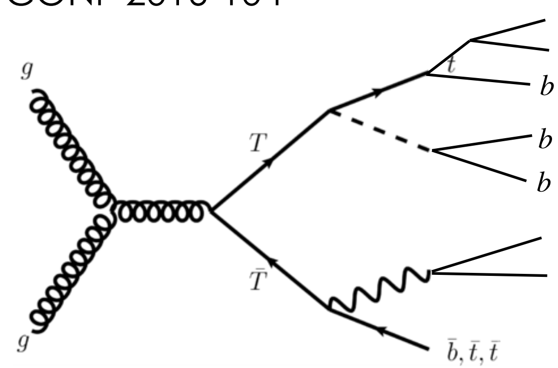
Many other analyses with complementary sensitivity

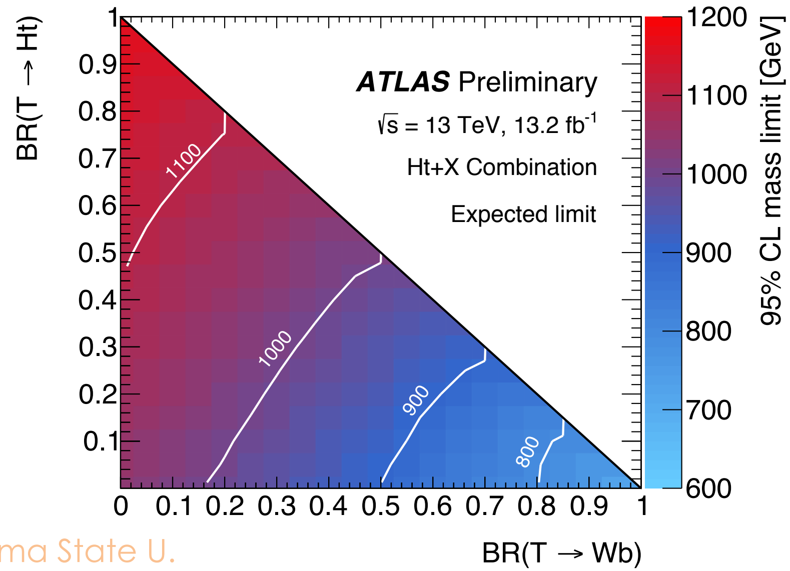
- $T\bar{T} \rightarrow Z(\nu\nu)t$+X$\rightarrow E_T^{miss}+\ell$ +jets
  Submitted to JHEP [arXiv:1705.10751]





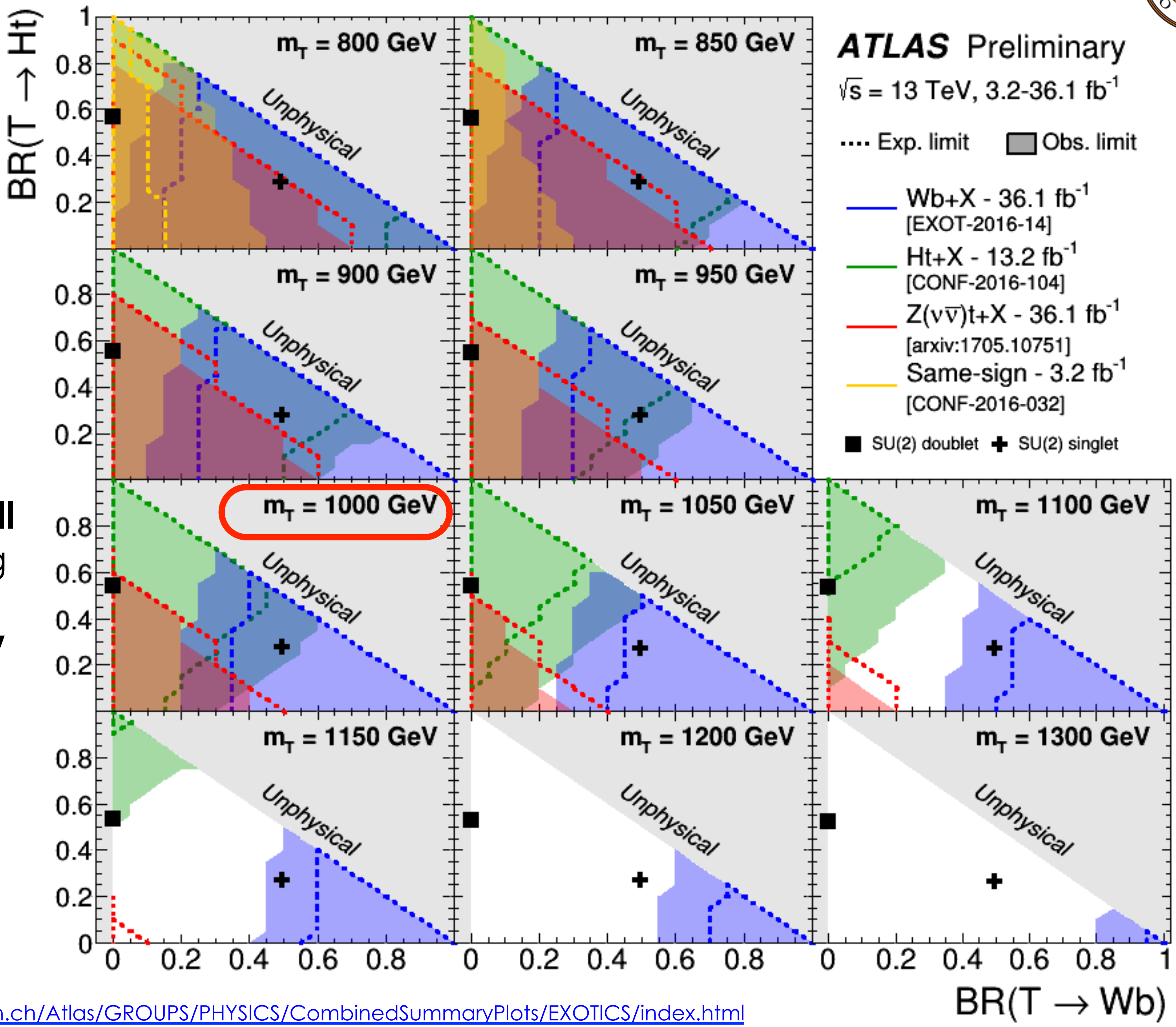
- $T\bar{T} \rightarrow Ht$+X$\rightarrow \ell + \geq 7j$ (2-4 *b*, 0-2 *W/t*)
  ATLAS-CONF-2016-104





- Plus others still in progress

Run 2 ATLAS Limits on *T*

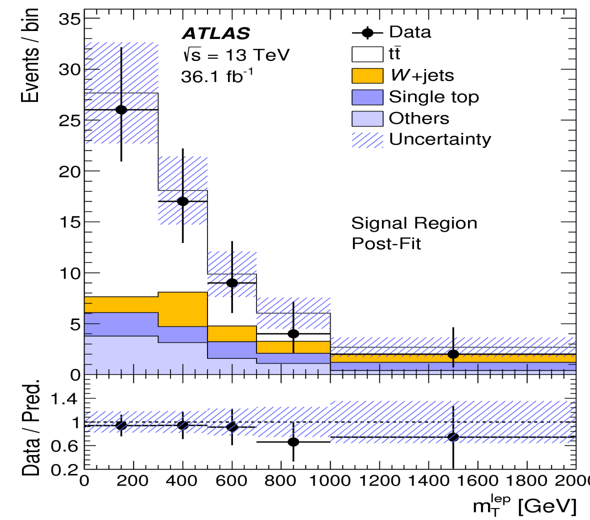


Exclude **all** branching ratios for ***m_T* < 1 TeV**

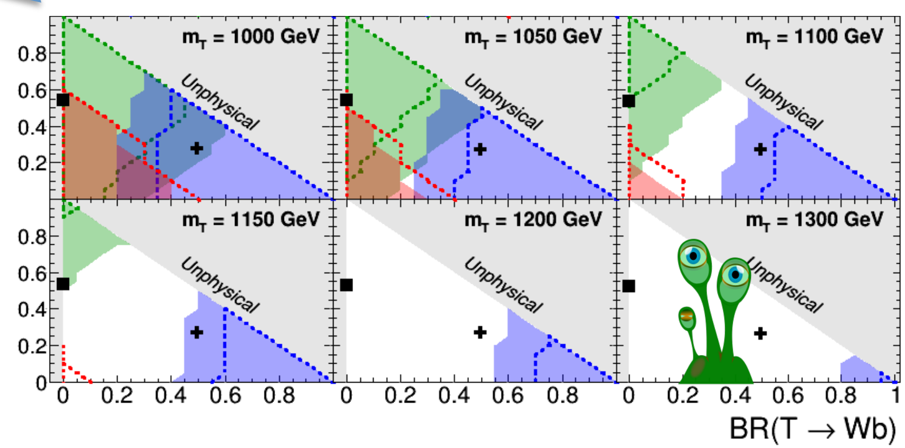
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

Conclusions

- VLQs can provide a natural solution to the hierarchy problem … but only if their mass is < 1-2 TeV

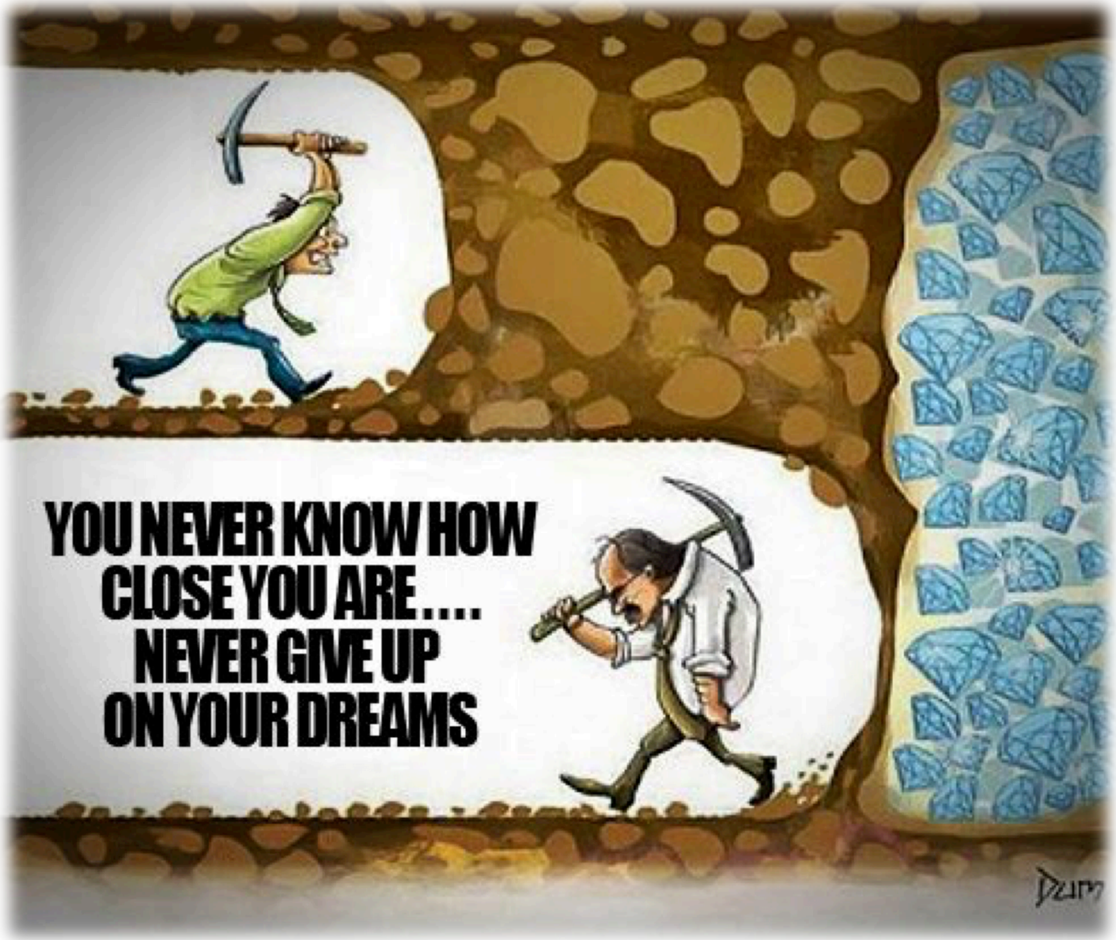


- Presented new ATLAS search for *TT*→*Wb*+*X*
  - Data consistent with background-only
  - Strongest limits for high $\mathcal{B}(T \rightarrow Wb)$
- With other channels, excluding masses up to 1 TeV for any branching ratios
  - Similar results from CMS



- If VLQs solve the hierarchy problem, they are starting to feel the heat of Run 2!

Thank you!

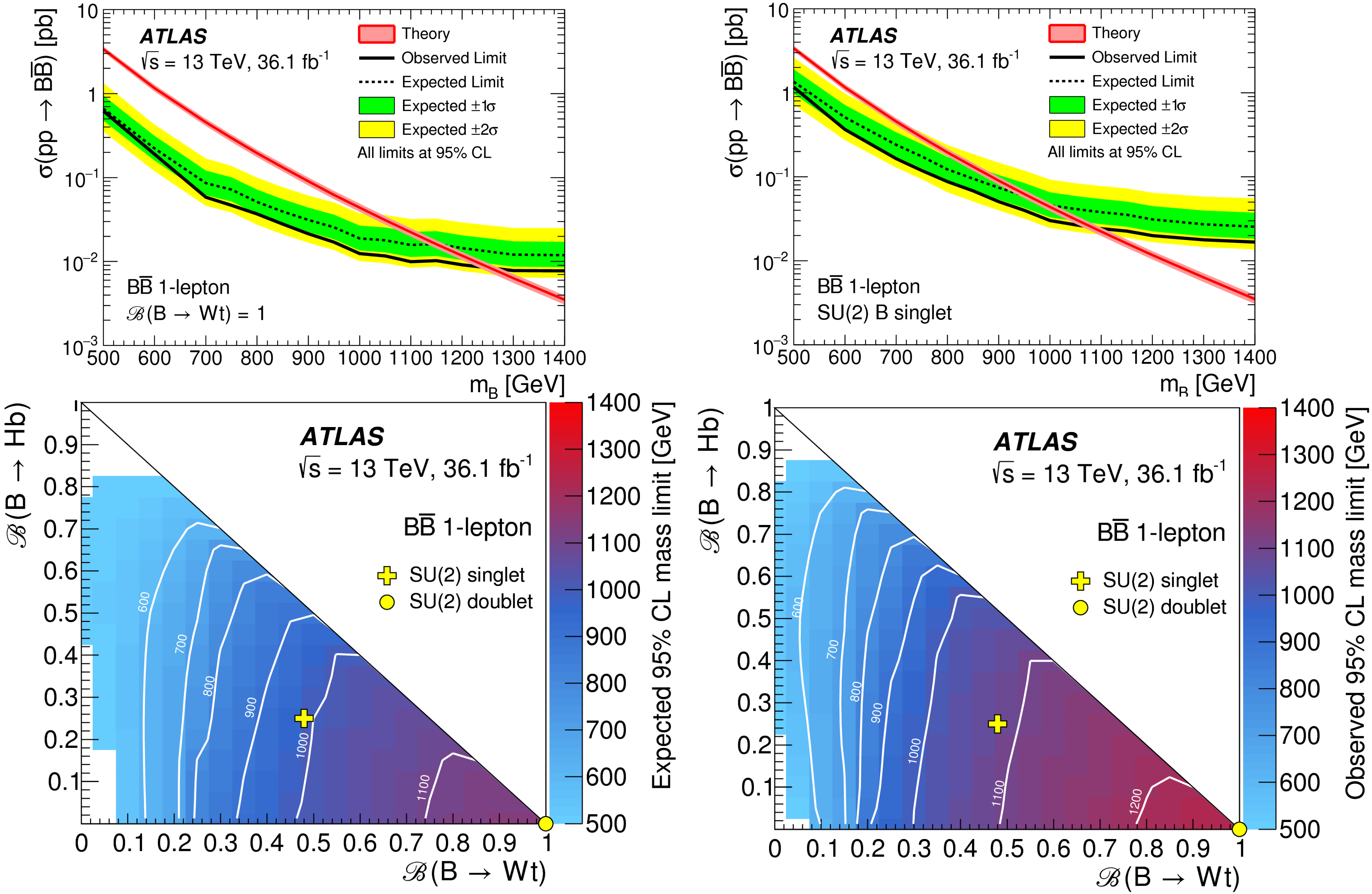


Complete list of ATLAS exotic results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

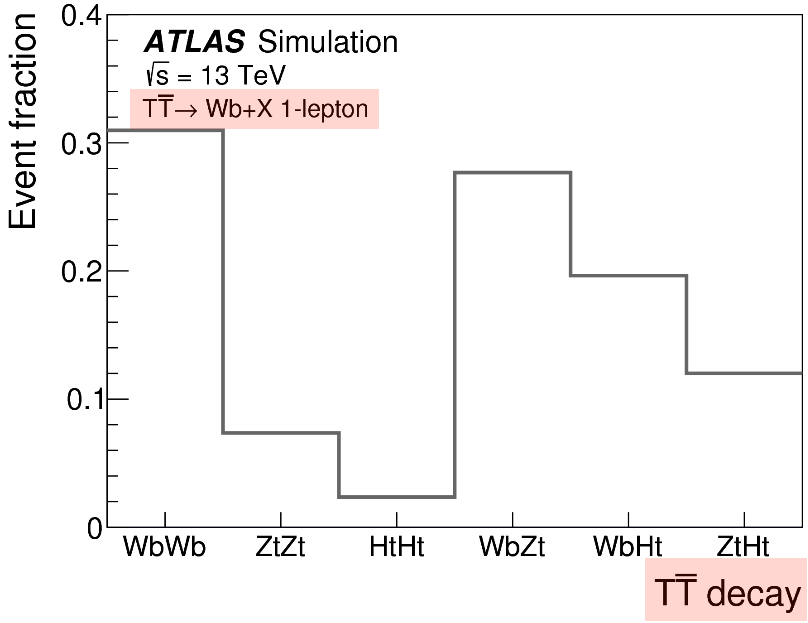
Submitted to JHEP [arXiv:1707.03347]

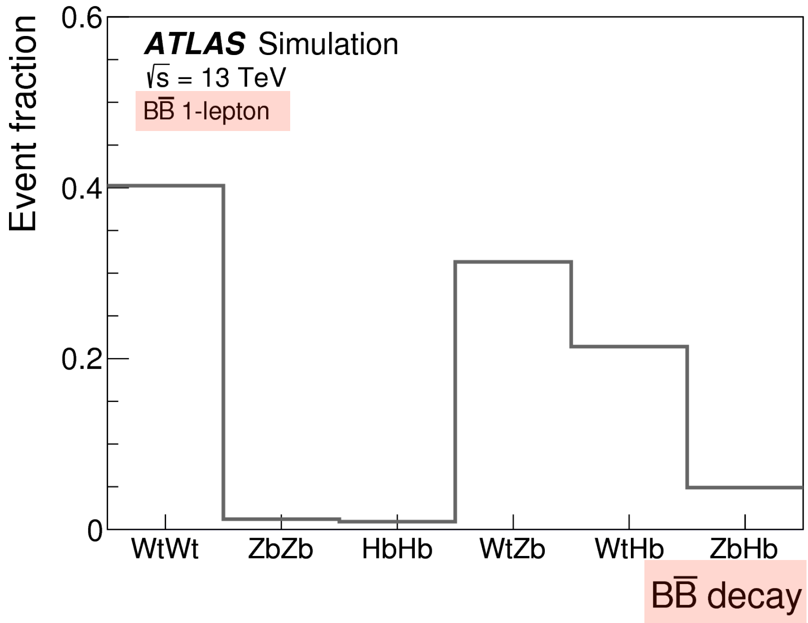
Also set limits on BB production



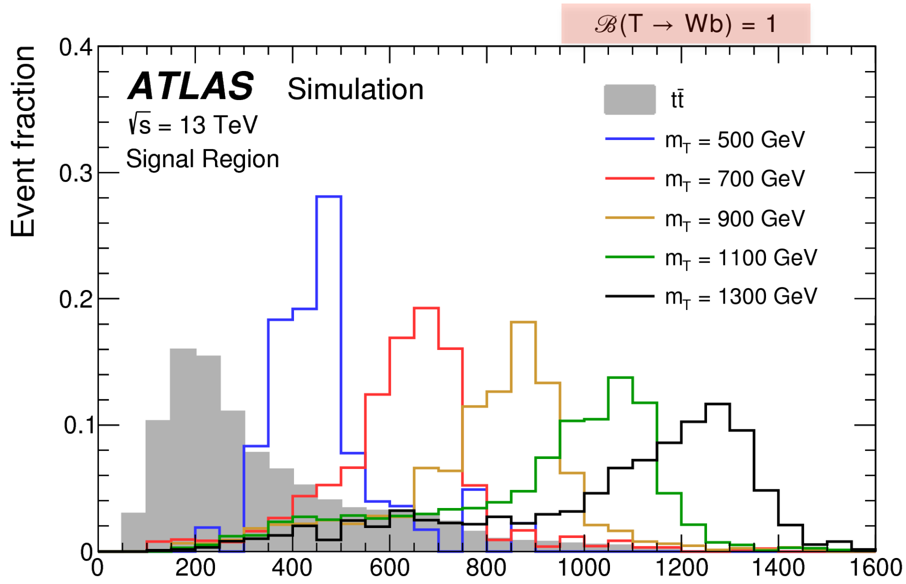
Acceptance

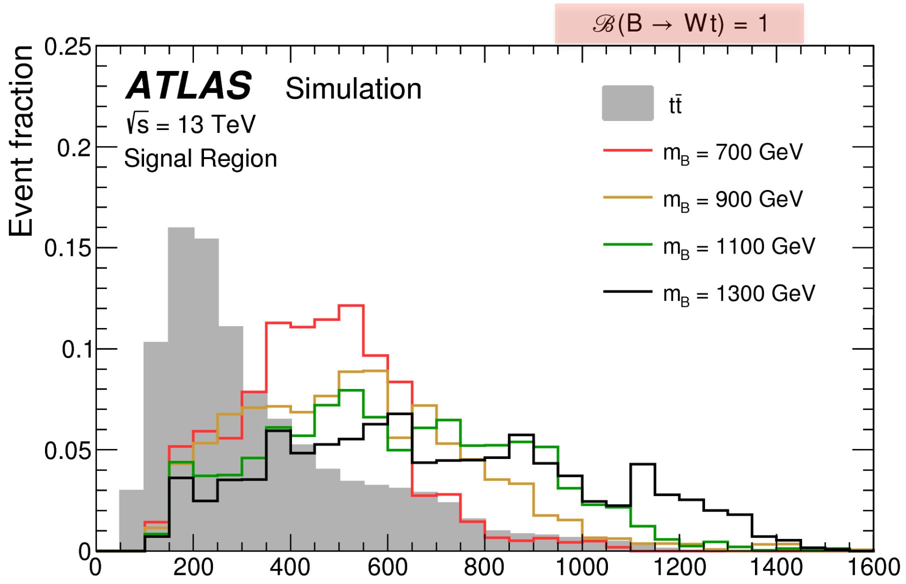
Selection criteria	$t\bar{t}$ [%]	Vector-like T: $\mathcal{B}(T \to Wb)$ =1 [%]	Vector-like T: SU(2) singlet [%]	Vector-like B: $\mathcal{B}(B \to Wt)$ =1 [%]	Vector-like B: SU(2) singlet [%]
Base selection	5.9	28	25	33	22
$\geq$ 1 W_{had} cand.	1.3	24	23	29	20
$E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV	66	94	68	92	91
$\geq$ 1b-tagged jet	74	80	85	89	88
$S_T \geq 1800$ GeV	0.6	71	68	64	64
$\Delta R(\mathrm{lep}, \nu) \leq 0.7$	71	90	75	72	68
$\lvert\Delta m\rvert < 300$ GeV	81	90	83	82	80
Total acceptance	$1.1 \cdot 10^{-4}$	2.9	1.4	3.0	1.2

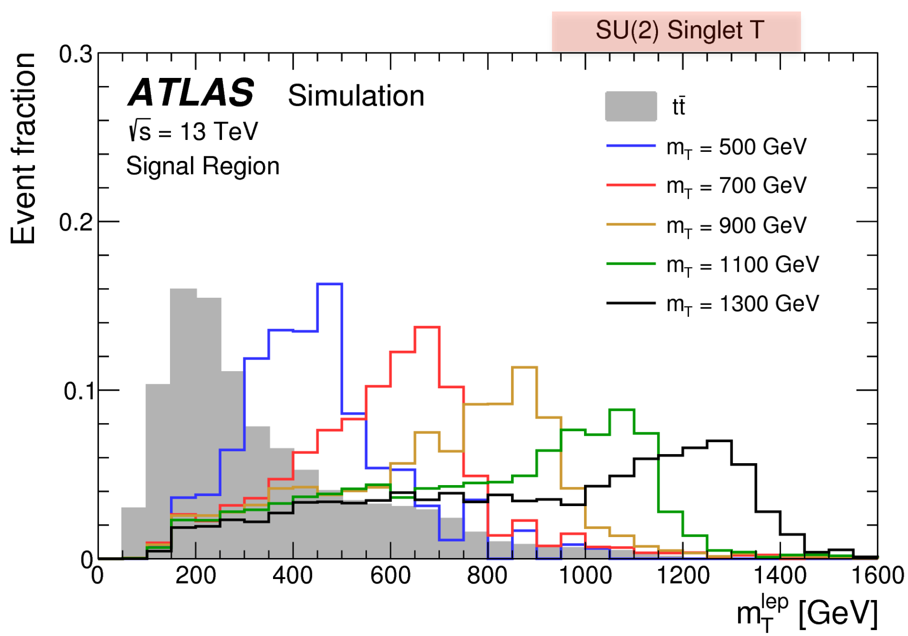


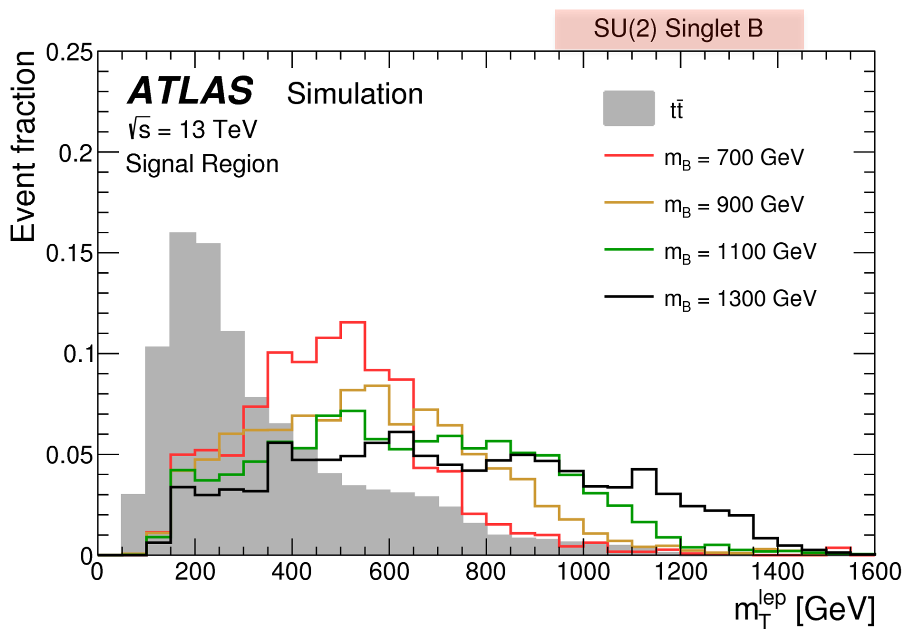


Signal Mass Distribution



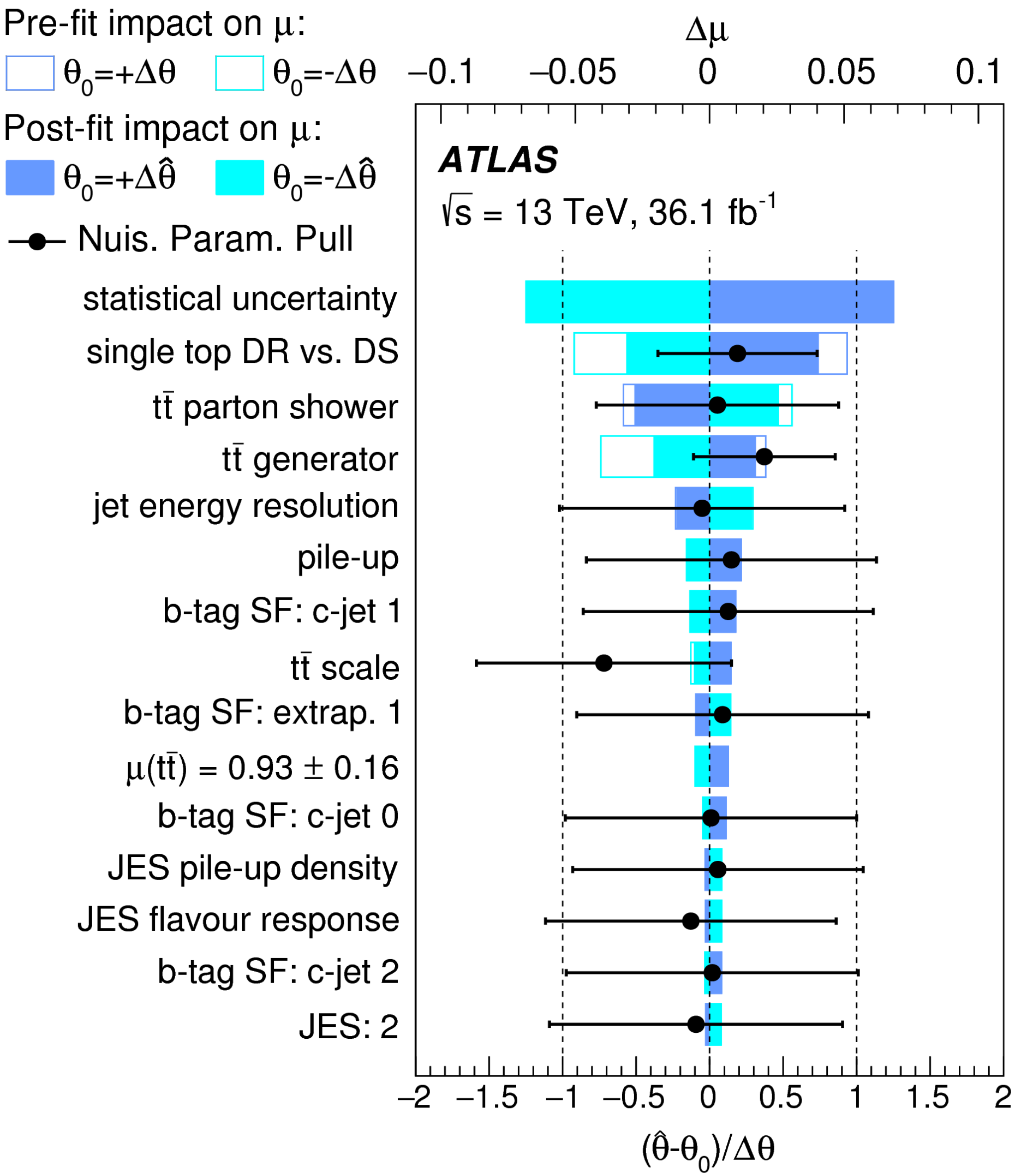






Submitted to JHEP [arXiv:1707.03347]

Uncertainties

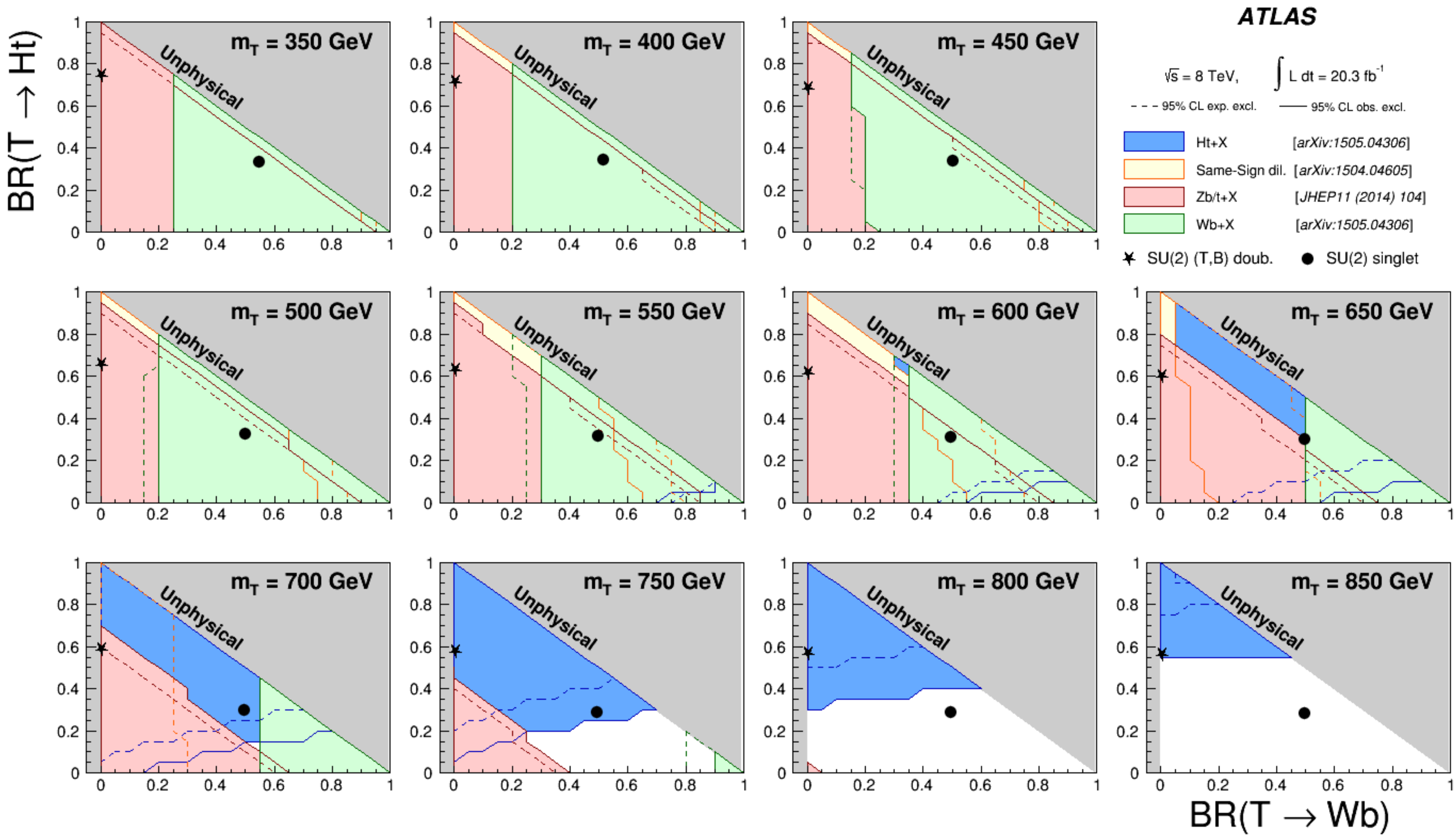


Post-fit

Sample	Signal region	Control region
$t\bar{t}$	39 ± 10	700 ± 70
W+jets	8 ± 4	78 ± 38
Single top	7 ± 4	110 ± 40
Others	10 ± 7	72 ± 48
Total background	64 ± 9	970 ± 50
Data	58	972

arXiv:1505.04306

Run 1 Limits on *T*



arXiv:1505.04306

Run 1 Limits on *B*