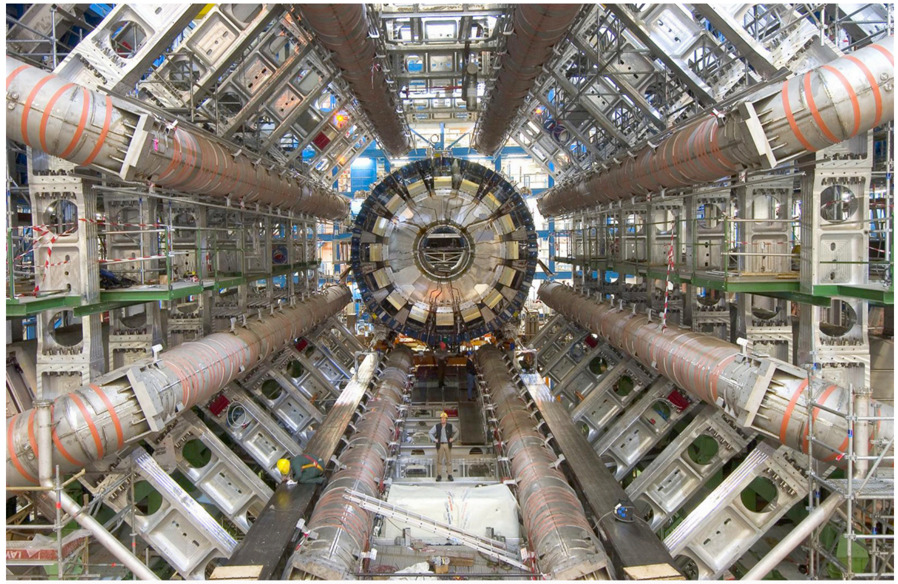


Searches for non-MSSM top/bottom quark partners with the ATLAS detector at the LHC

Jun Guo

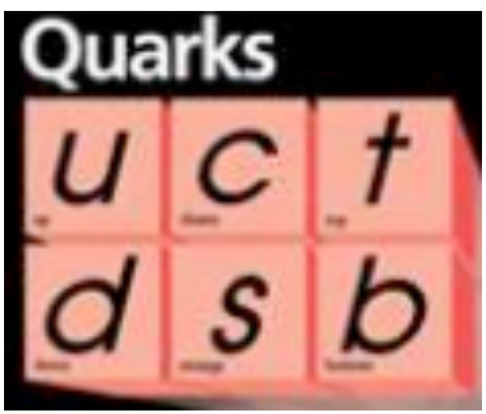
Shanghai Jiao Tong University

On behalf of the ATLAS Collaboration

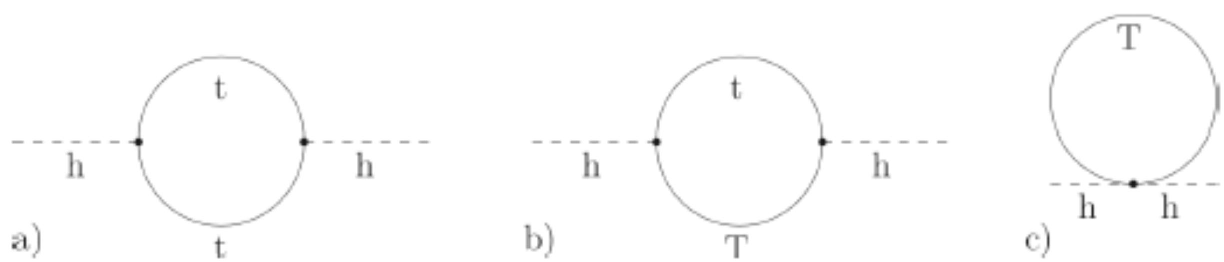
SUSY2015, Lake Tahoe, USA, 08/23 – 08/29/2015

Why search for Vector-like quarks?

- In addition to SUSY, some other new physics models provide natural solutions to hierachy problem, which predict the existence of Vector-like quarks(VLQ), to cancel quadratic divergences arising from radiative corrections of the Higgs mass
  - Predicted by Topcolor, Little Higgs and Composite Higgs, etc.
  - Colour-triplet, spin-1/2, both left- and right-handed components transform under the same SU(2)xU(1) group
  - Unlike Chiral 4th generation, VLQ avoid limits from Higgs measurement

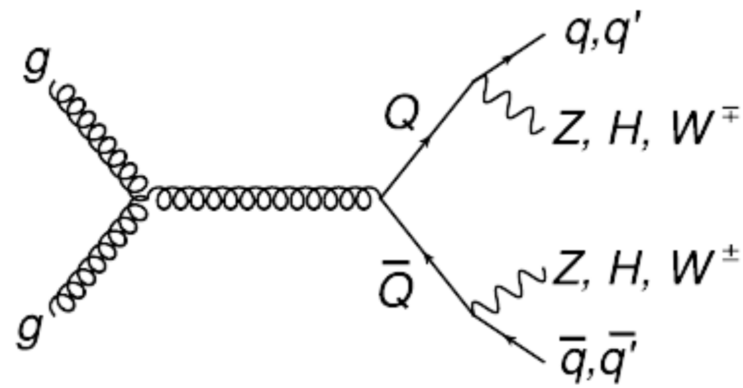


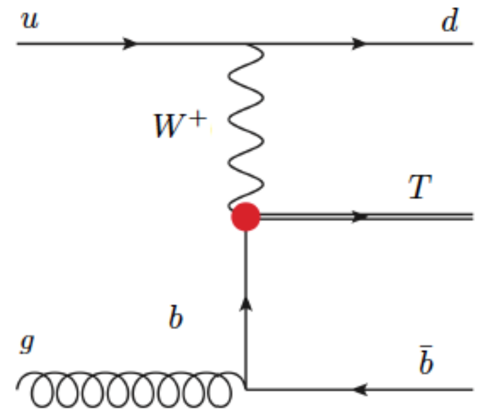
?
T
B

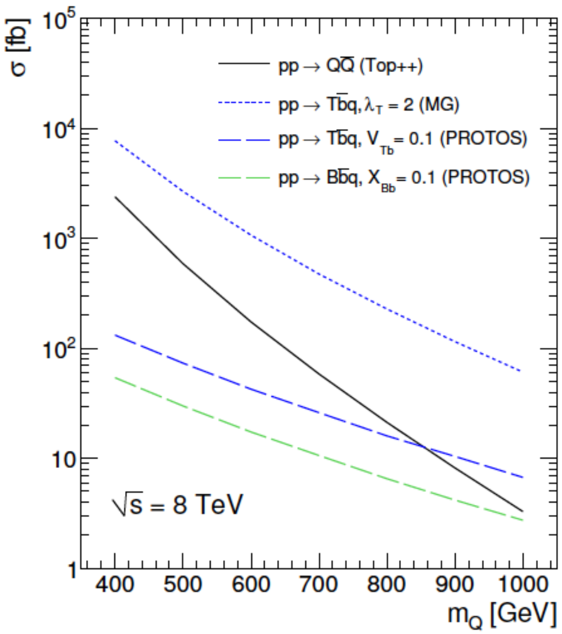


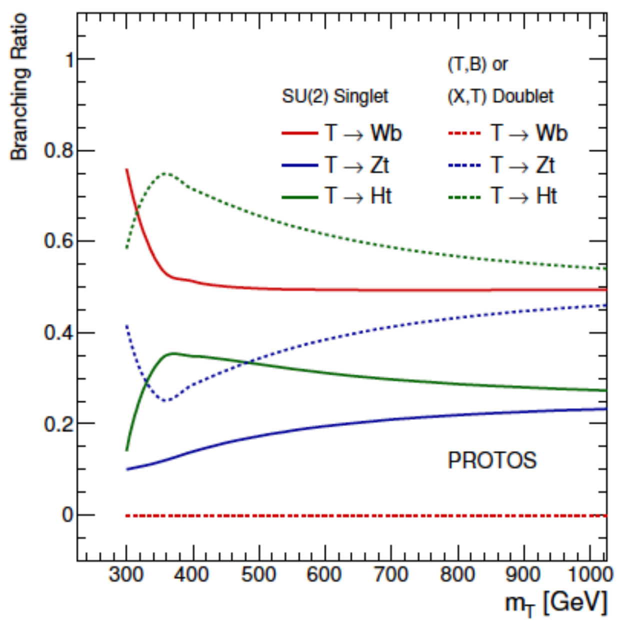
Vector-like Quarks

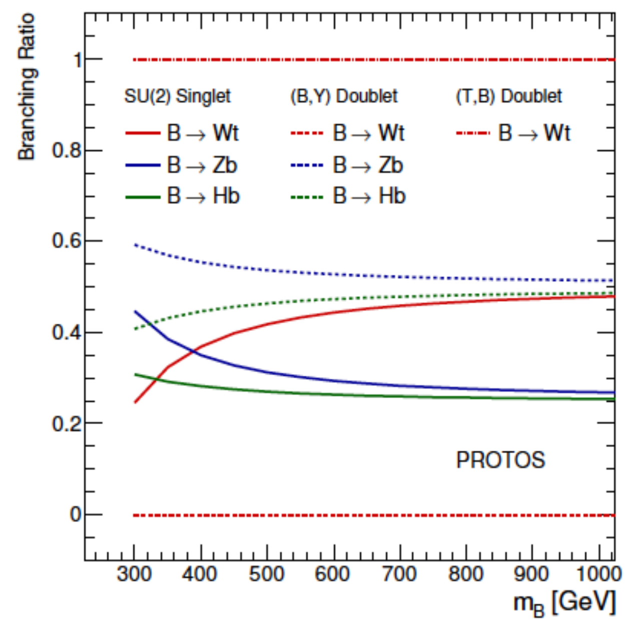
- **Production:**
  - Pair production: strong interaction, better sensitivity at lower mass, only depends on mass
  - Single production: weak interaction, more dominant at high mass, depends on mass, charge, coupling
- **Decay: large coupling with 3rd generation quarks; FCNC decays are allowed**
  - B->Wt, Zb, Hb
  - T->Wb, Zt, Ht
- Search strategy: based on final signatures











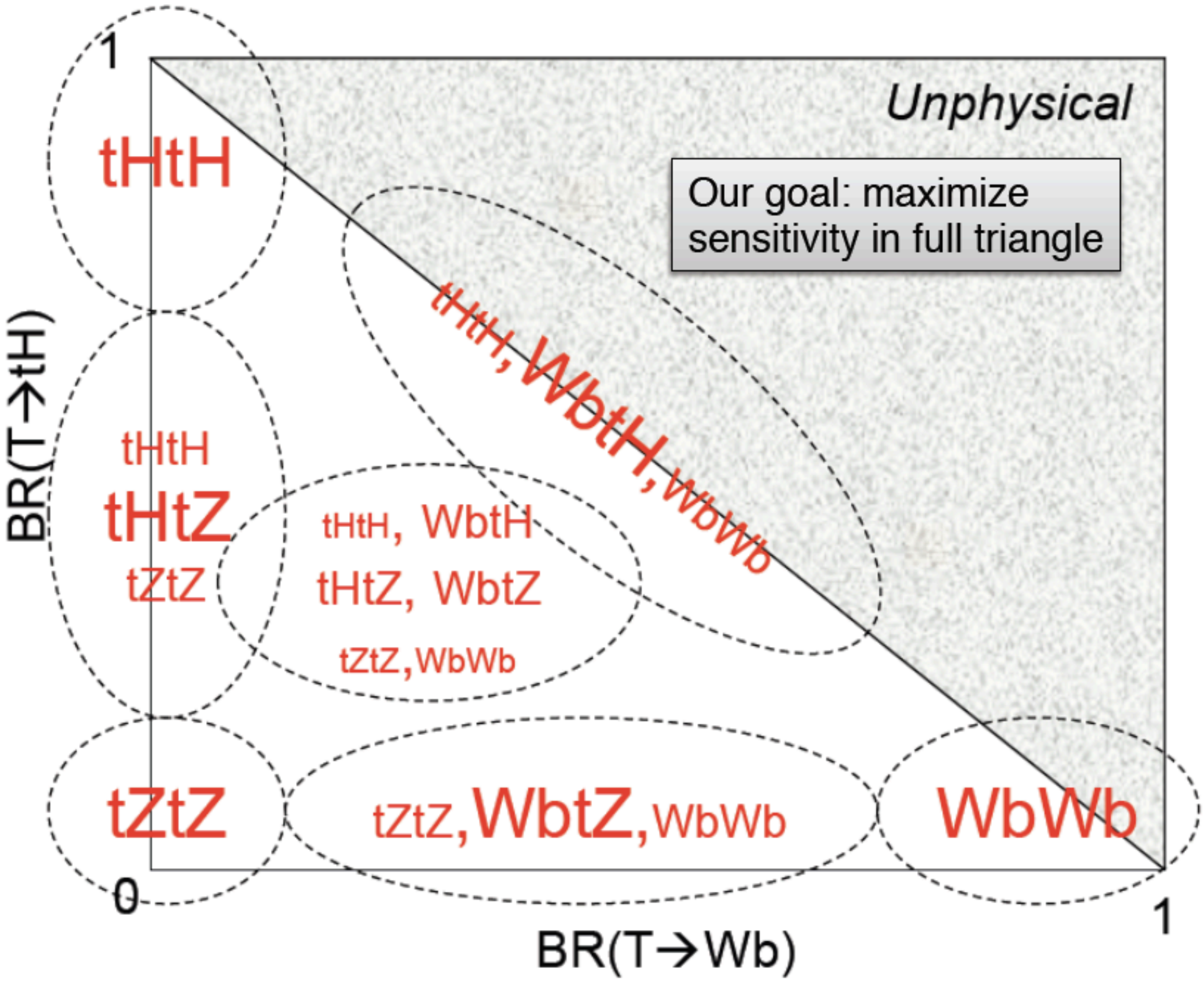
VLQ analyses at ATLAS

- **Pair production(couple with 3rd generation)**
  - **Lepton+jets:**
    - **Wt+X:** arxiv:1503.05425, PRD
    - **Wb+X:** arxiv:1505.04306, JHEP
    - **Ht/b+X:** arxiv:1505.04306, JHEP
  - **Zt/Zb+X: Z->dilepton,** arxiv:1409.5500, JHEP
  - **Same-Sign leptons:** arxiv:1504.04605, submitted to JHEP

- **VLQ pair->Wq+X:** just approved by ATLAS

- **Single VLQ:** arxiv:1409.5500, JHEP

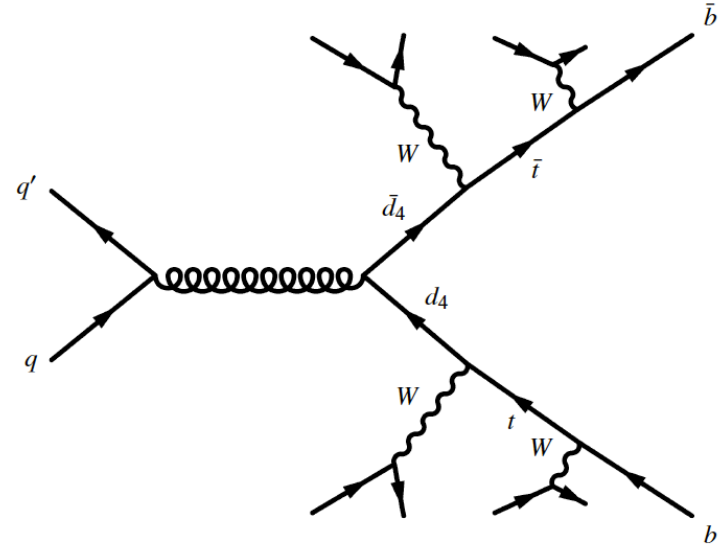
Strategy of VLQ pair production: $T\bar{T}$

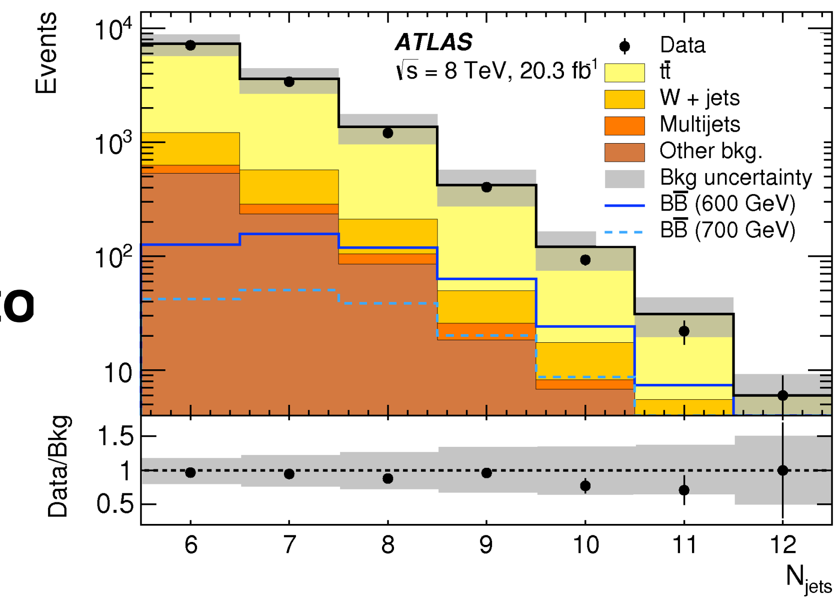


$B\bar{B}$->Wt+X

arxiv:1503.05425

- Search for vector-like heavy down-type quark B in pair production with 8TeV(20fb^{-1}):
  - $B\bar{B}$->tWtW->WWbWWb->lepton+ν+8jets
  - $B\bar{B}$->tWbZ->WWbZb->lepton+ν+6jets
- Selection:
  - High p_T isolated lepton(e/μ), jets
  - High E_t^{miss}, ……
  - Main variables: H_T, # of jets, # of hadronic W's
- Challenge:
  - Difficult to efficiently reconstruct "B" candidate
  - Dominant ttbar+jets background due to event topology close to signal
  - Modeling of high jet multiplicity
  - Large systematics: Jet energy scale, theory model, …
- Use Multi-variate technique: BDT

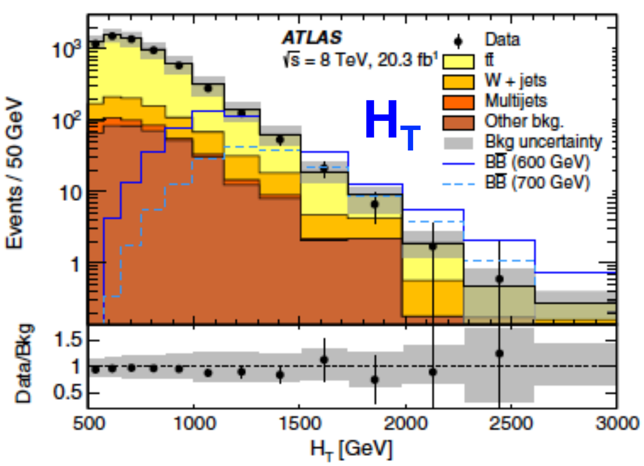


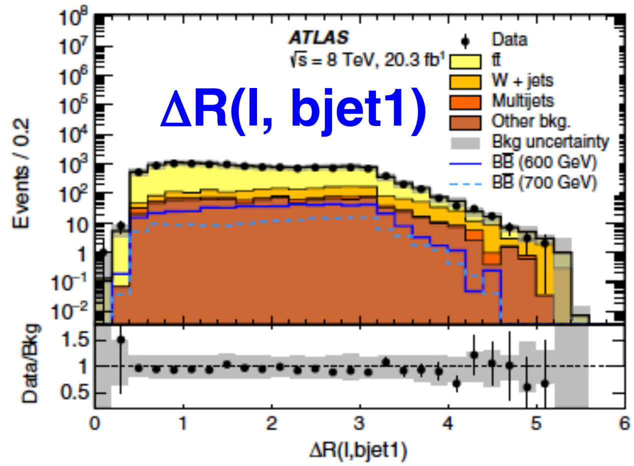


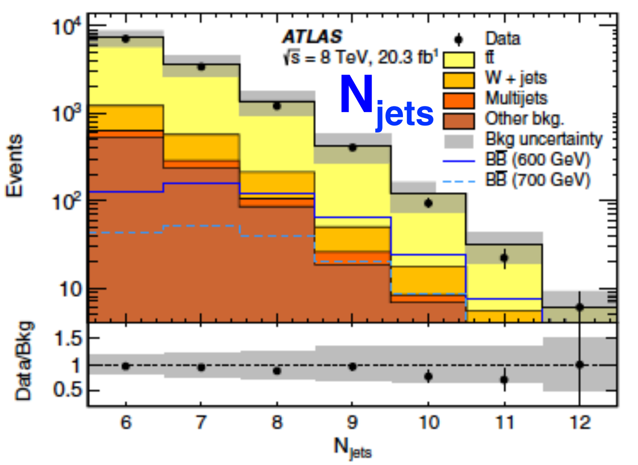
BDT input variables

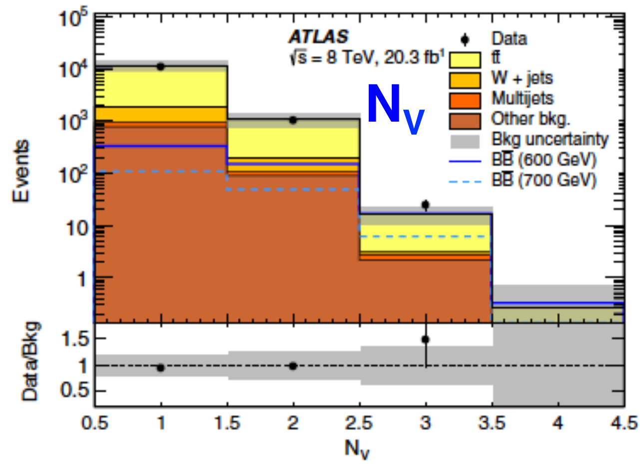
12 BDT input variables were chosen based on discrimination power :

➢ H_T, N_{jets}, N_V, pT(lepton), MET, …….

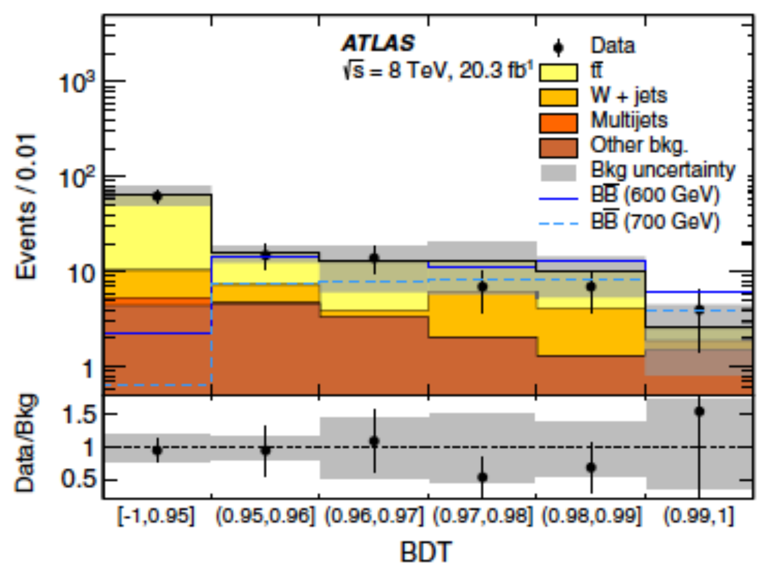








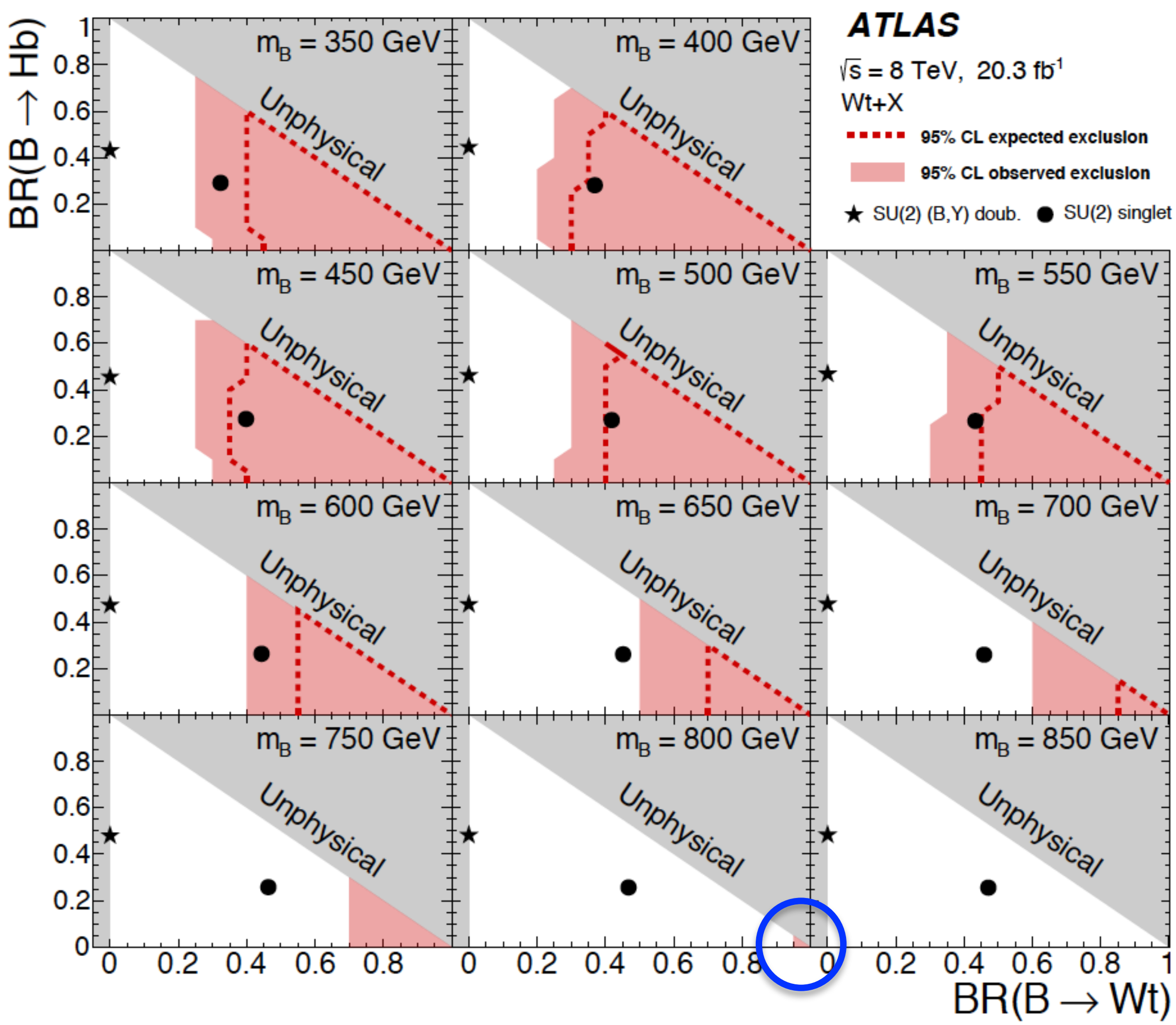
No signal observed! ☹

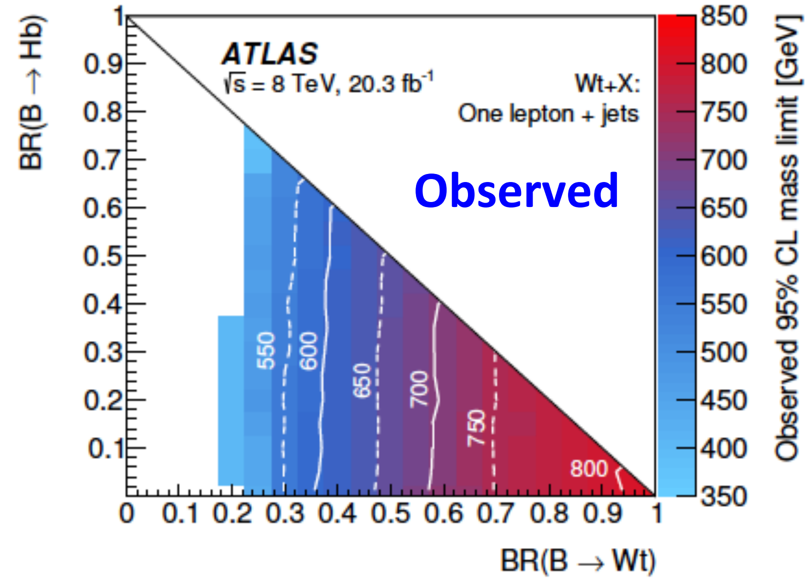


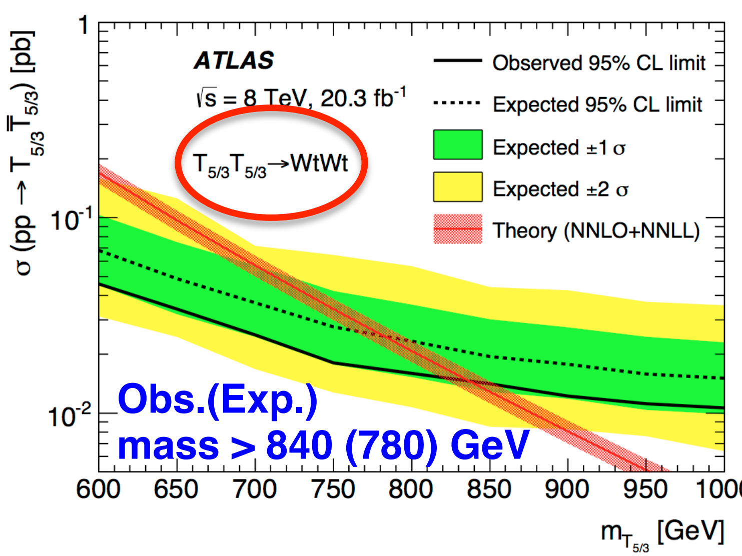
First bin from -1 to 0.95 is bkg enriched, used to constrain systematics

Result: Limit Setting

Mass limit vs Branching Ratios of VLQ B. The best mass limit is from BB->WtWt:
Obs.(Exp.) mass > 810 (760) GeV



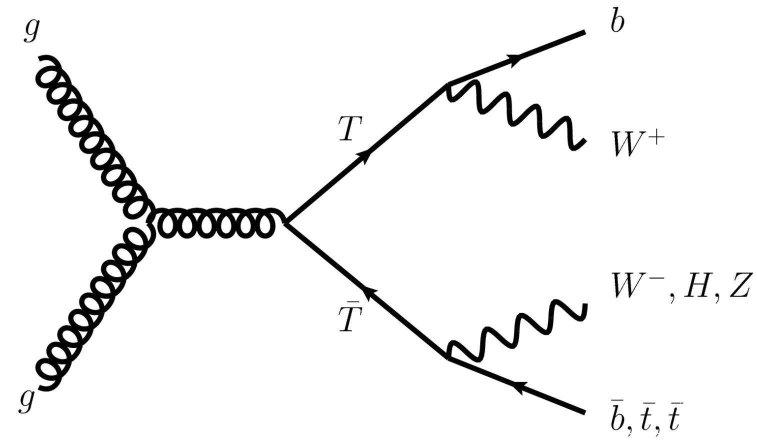


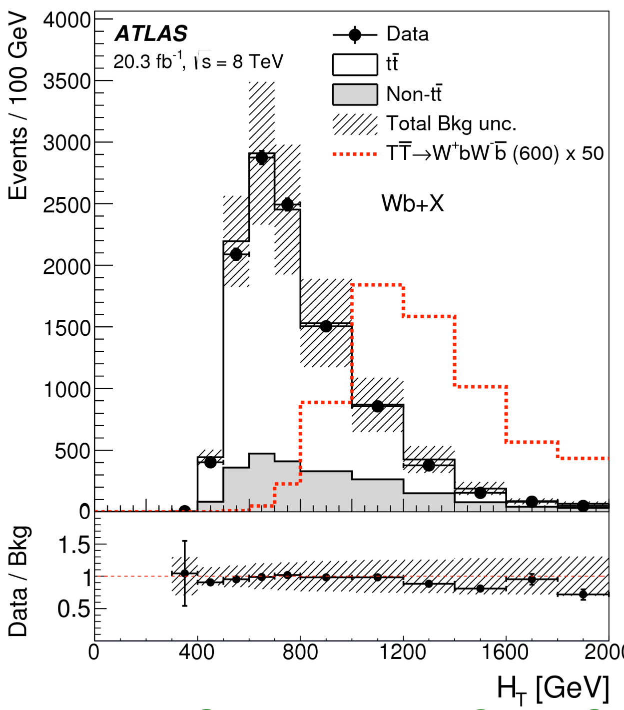


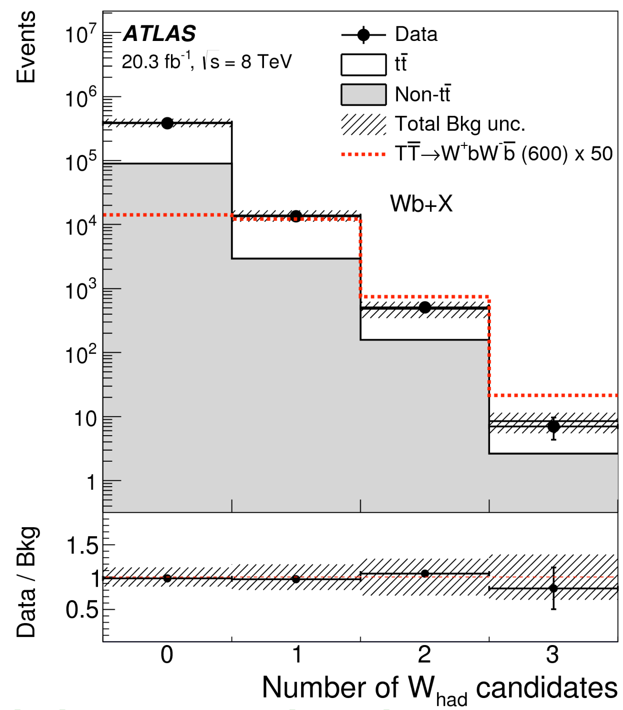
$T\bar{T}$->Wb+X

arxiv:1505.04306

- **Selection:**
  - **High p_T isolated lepton(e/μ) , high p_T jets**
  - **H_T > 800 GeV**
  - **$N_{jets} \geq 4$, $N_{bjets} \geq 2$**
- **Hadronic W reconstruction: W_{had}**
  - **Type-I: single jet, p_T>400 GeV**
  - **Type-II: di-jet, $\Delta R(j,j)$<0.8, p_T>250 GeV, 60<m<120 GeV**
- **Leptonic W reconstruction: W_{lep}**
  - **Use nominal W mass to constrain neutrino longitudinal momentum**



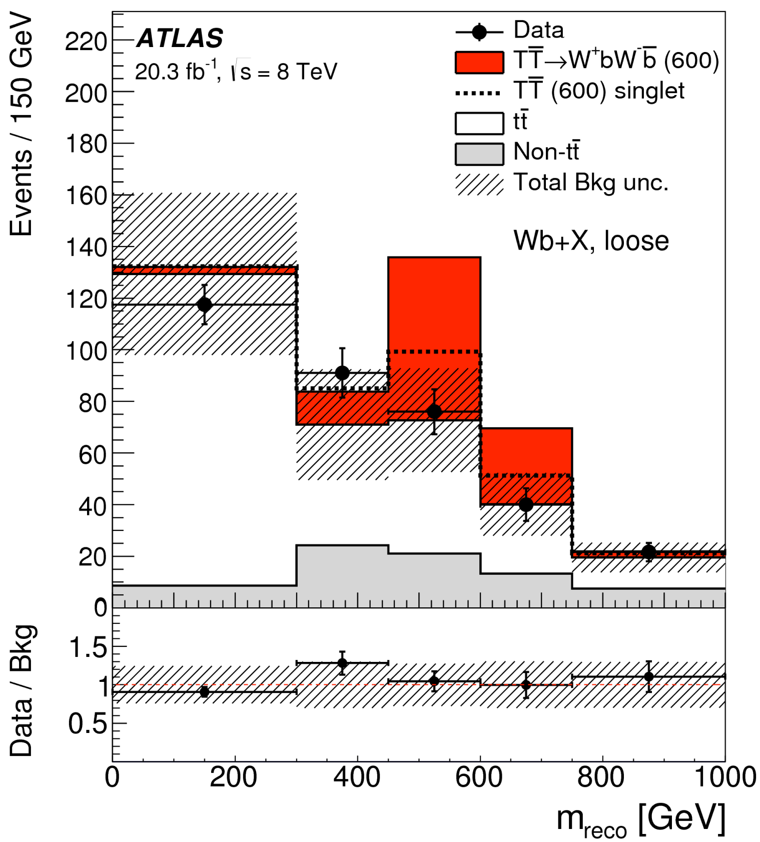


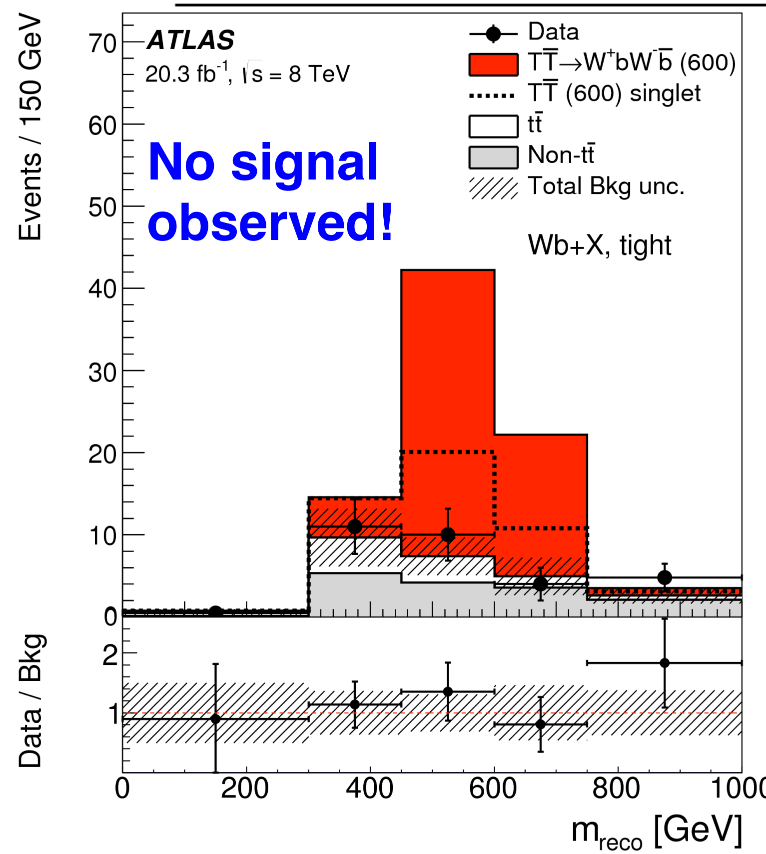


$T\bar{T}$->Wb+X

- **Final discriminant: m_{reco}**
  - **From W_{had} and one b-jet**
  - **Pairing $W_{had/lep}$ with b-jet to get the smallest absolute difference between the two reconstructed heavy quark masses**

	Loose selection	Tight selection
$T\bar{T}$ ($m_T = 600$ GeV)		
BR($T \to Wb$) = 1	115 ± 10	58.9 ± 5.9
Singlet	60.3 ± 5.1	24.5 ± 2.3
$t\bar{t}$	390 ± 110	10.7 ± 4.3
$t\bar{t}V$	6.5 ± 2.5	0.4 ± 0.2
$t\bar{t}H$	1.6 ± 0.4	0.10 ± 0.03
W+jets	38 ± 19	11.4 ± 6.2
Z+jets	1.5 ± 1.2	0.4 ± 0.4
Single top	36 ± 17	2.2 ± 1.5
Diboson	5.6 ± 1.4	1.5 ± 0.6
Multijet	0.3 ± 1.6	0.8 ± 0.7
Total background	480 ± 120	27.6 ± 8.6
Data	478	34

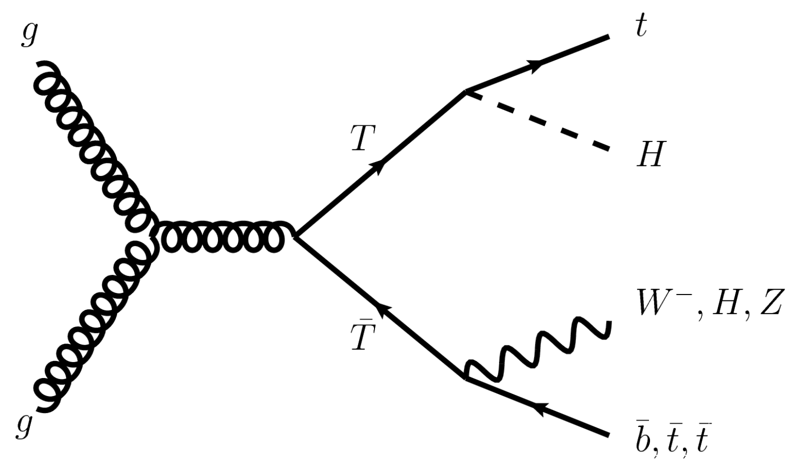


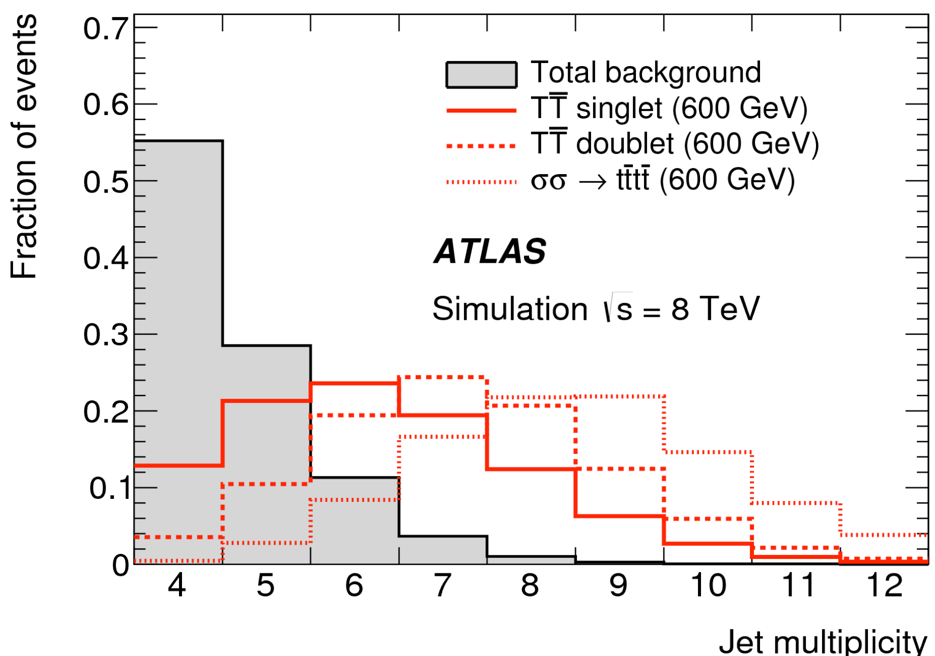


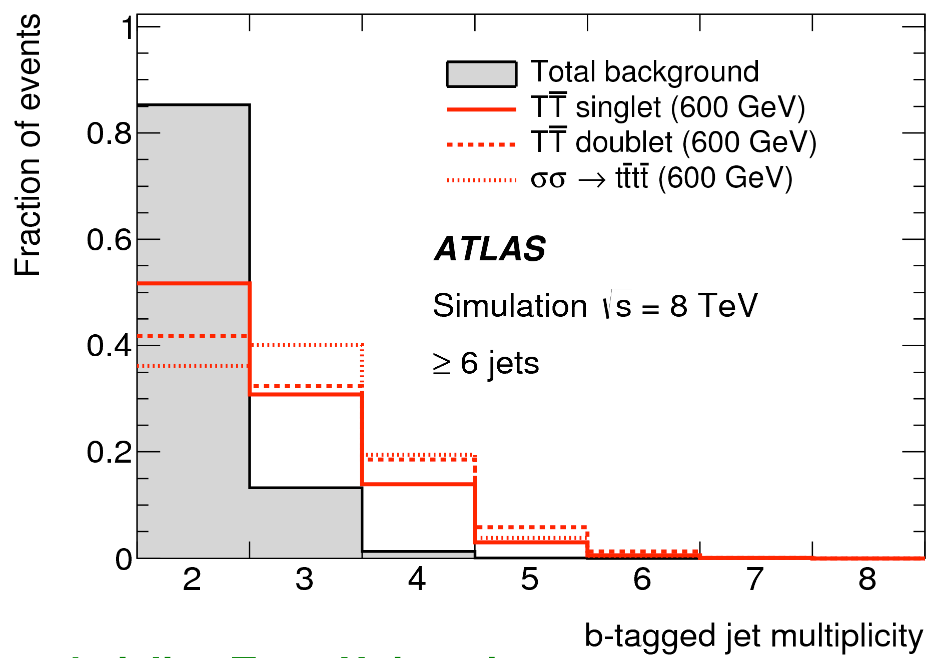
$T\bar{T}$->Ht+X

arxiv:1505.04306

- **Selection:**
  - **High p_T isolated lepton(e/μ) , high p_T jets**
  - **$N_{jets} \geq 5$**
  - **$N_{bjets} \geq 2$**
- **Discriminant:**
  - **H_T, independent from decay mode**
- **Main background:**
  - **ttbar+jets, largely affected by b tagging, jet energy scale, modeling of heavy-flavor content**

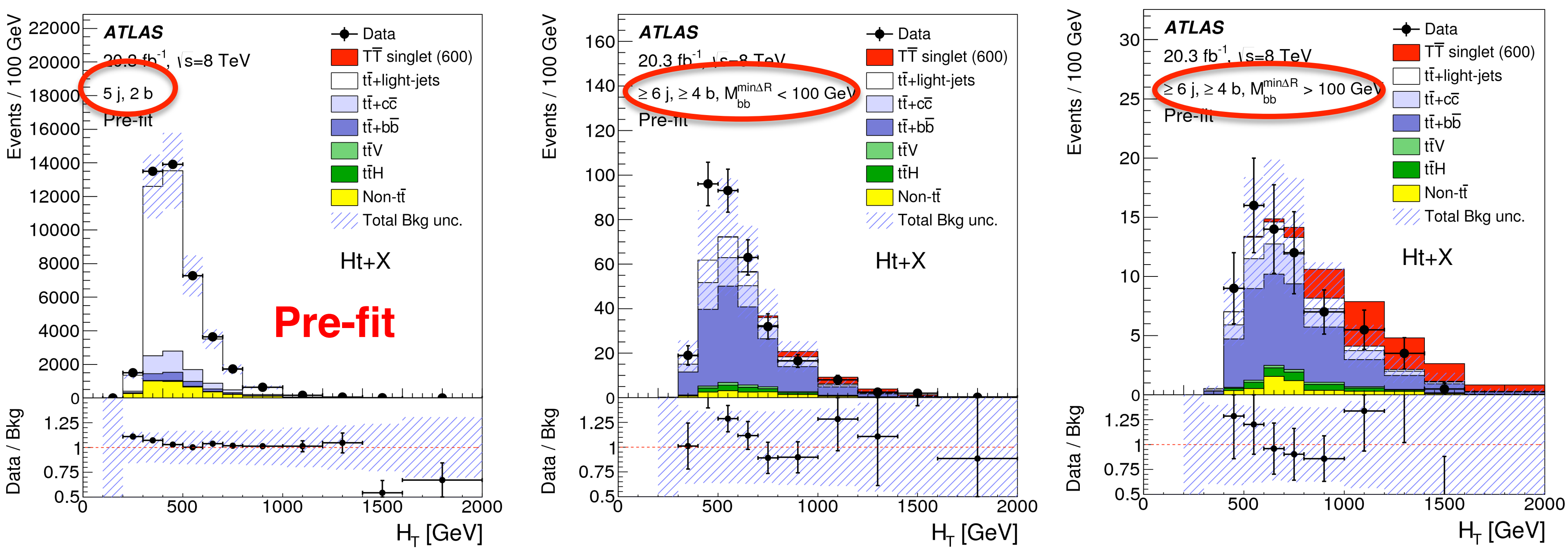






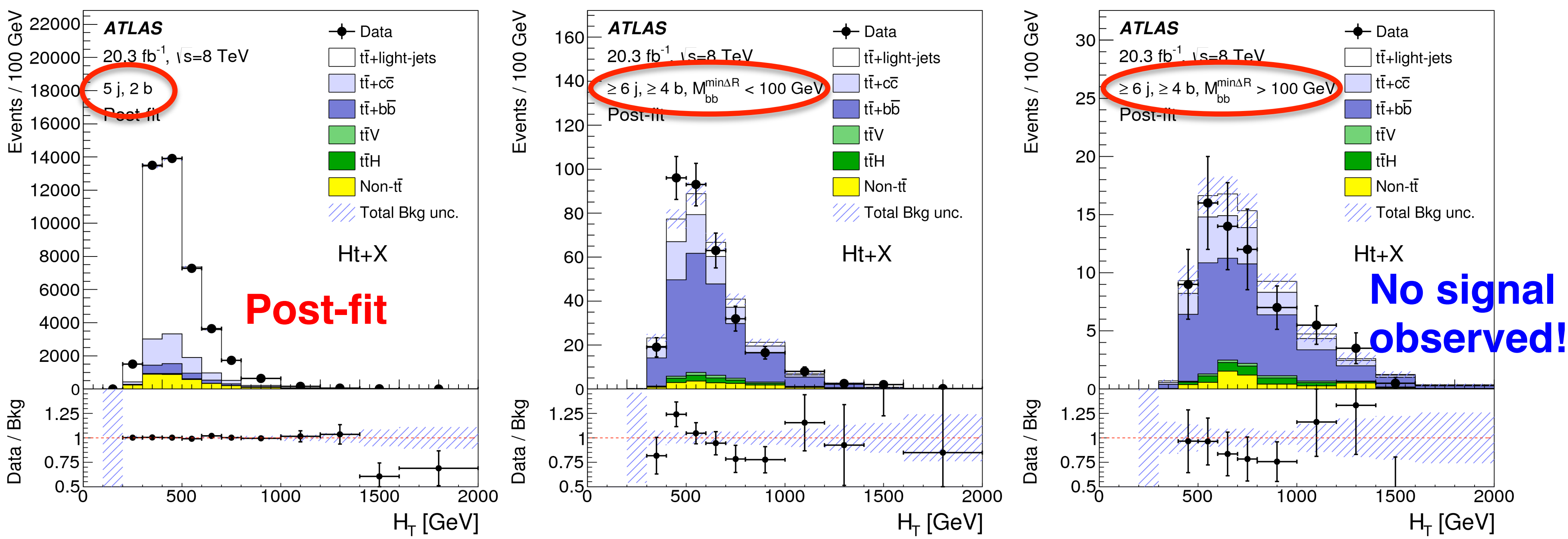
$T\overline{T}$->Ht+X

- **Split events into 6 channels based on number of jets & bjets to optimize sensitivity:**
  - N_{jets}: 5, ≥ 6
  - N_{bjets}: 2, 3, ≥ 4
- **Fit overall scaling factors to tt+light jets and tt+HF to "calibrate" background prediction to data and reduce impact of systematics:**
  - 2-bjets and 3-bjets channels play an important role



$T\bar{T}$->Ht+X

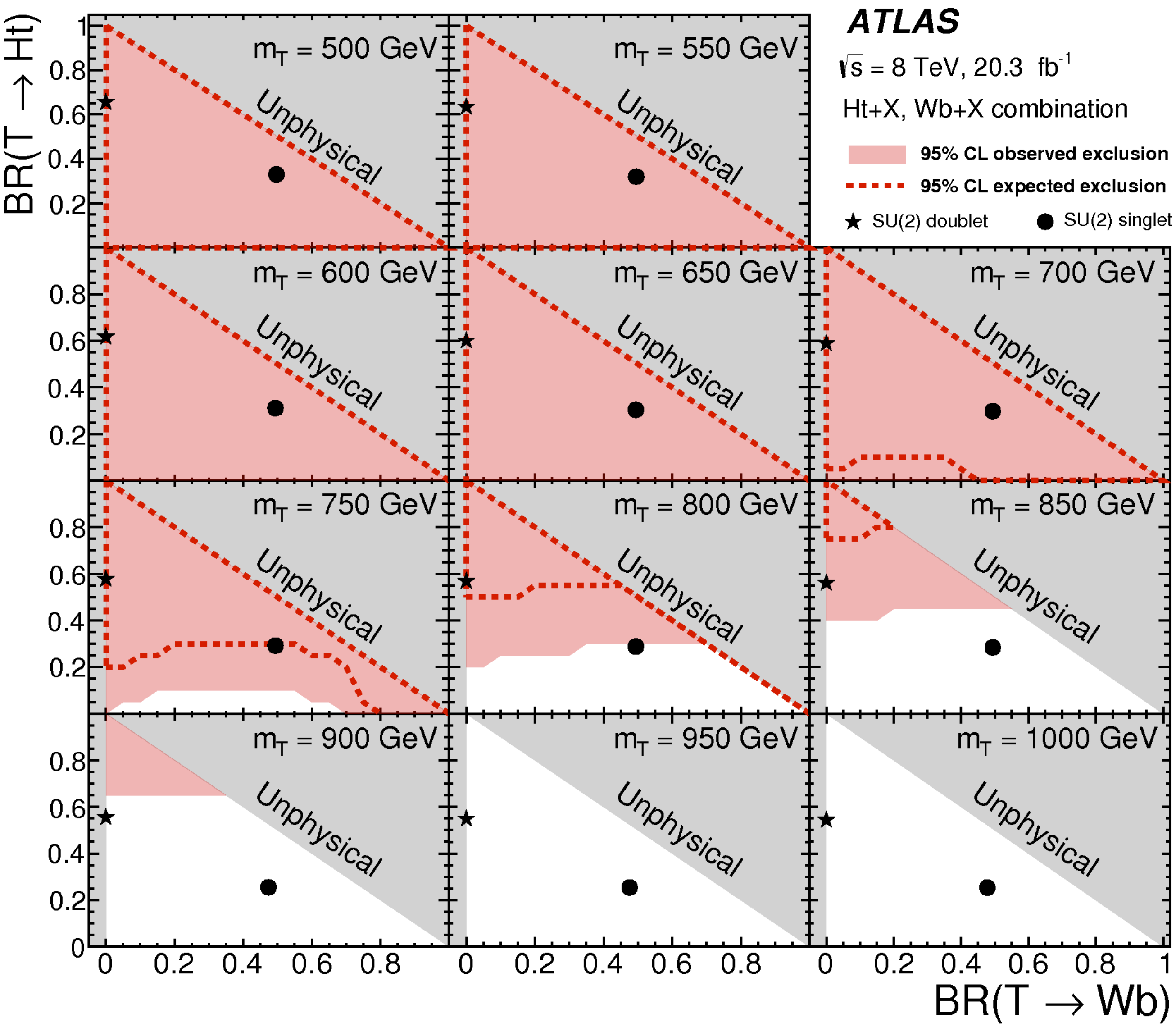
- **Split events into 6 channels based on number of jets & bjets to optimize sensitivity:**
  - **N_{jets}: 5, ≥ 6**
  - **N_{bjets}: 2, 3, ≥ 4**
- **Fit overall scaling factors to tt+light jets and tt+HF to "calibrate" background prediction to data and reduce impact of systematics:**
  - **2-bjets and 3-bjets channels play an important role**

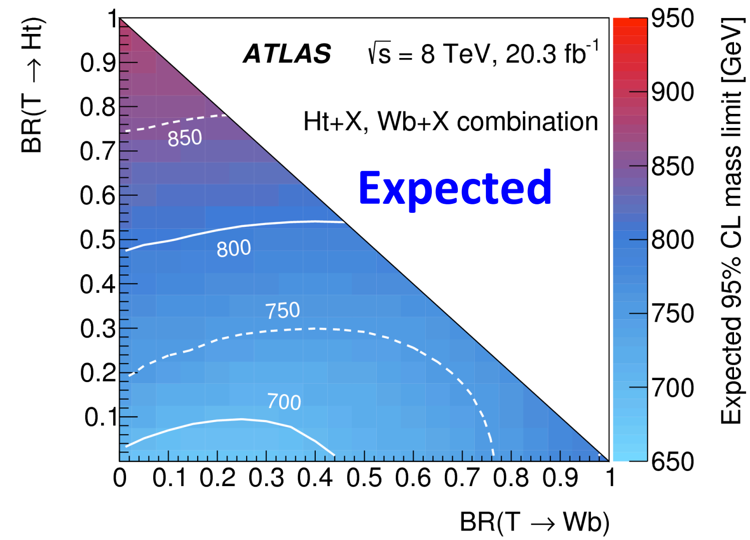


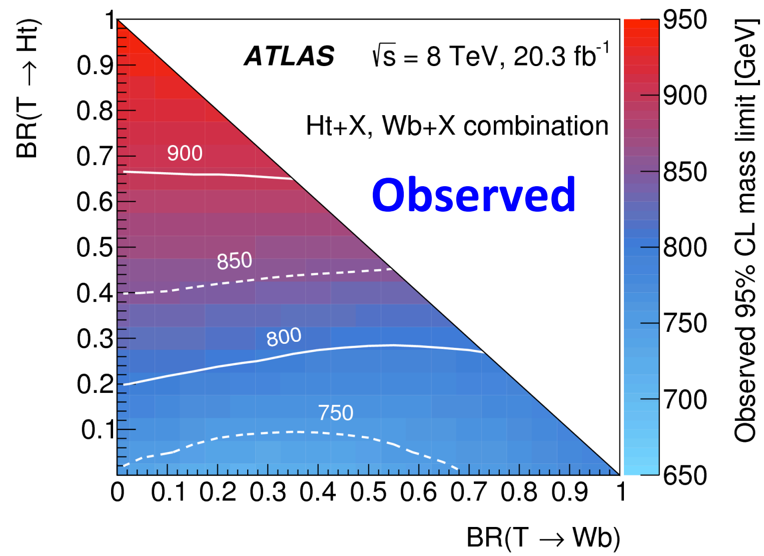
Wb/Ht+X result: $T\bar{T}$

Sensitivity is up to 900 GeV

arxiv:1505.04306

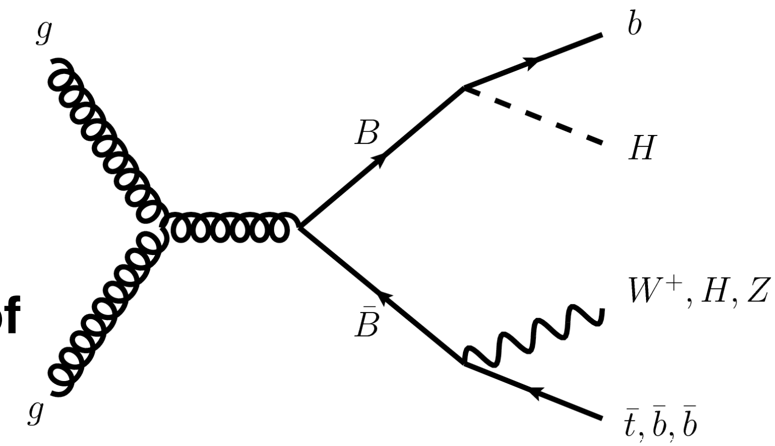




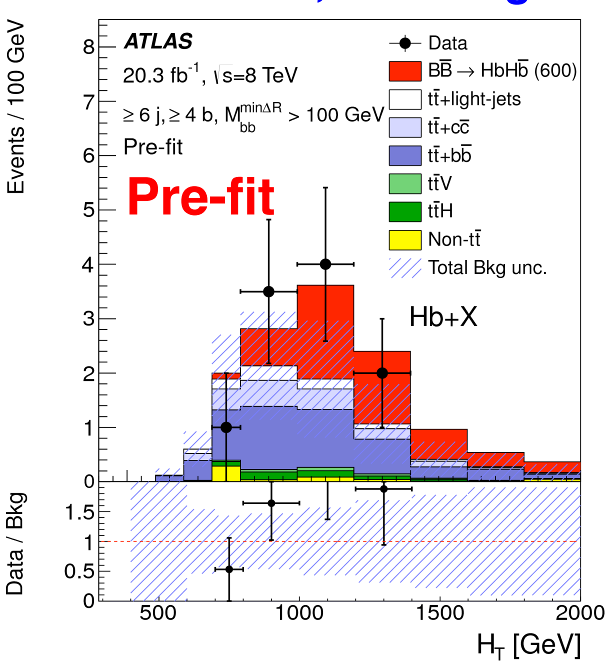


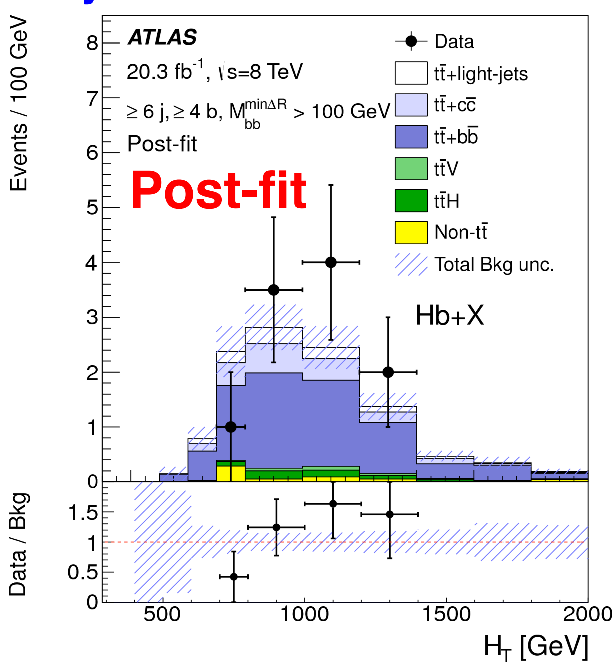
$T\bar{T}$->Hb+X

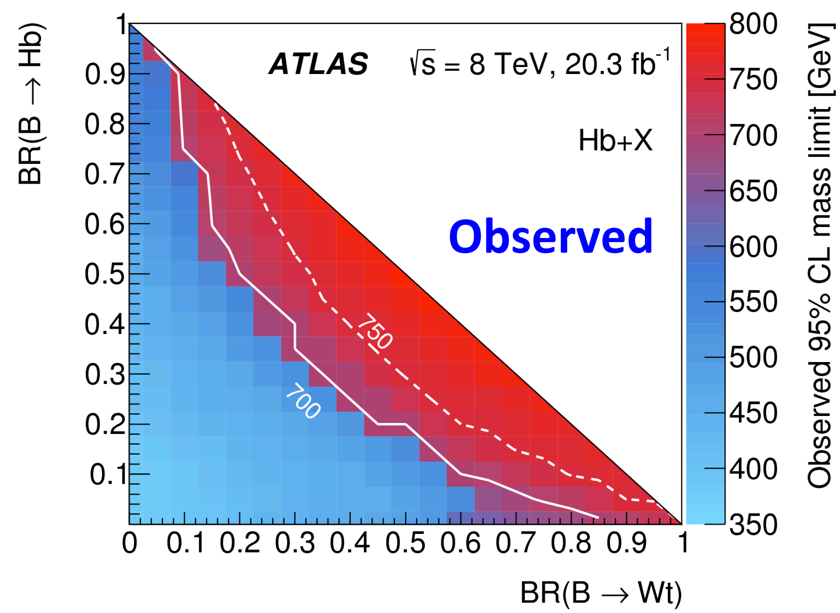
arxiv:1505.04306



- **Similar selection as for Ht+X, but with tighter 2 leading b-jets p_T cut(> 150 GeV):**
  - **High p_T isolated lepton(e/μ) , high p_T jets**
  - **N_{jets} ≥ 5**
  - **N_{bjets} ≥ 2**
- **Split events into 6 channels based on number of jets & bjets to optimize sensitivity:**
  - **N_{jets}: 5, ≥ 6**
  - **N_{bjets}: 2, 3, ≥ 4**
- **Main background:**
  - **ttbar+jets, largely affected by b tagging, jet energy scale, modeling of heavy-flavor content**





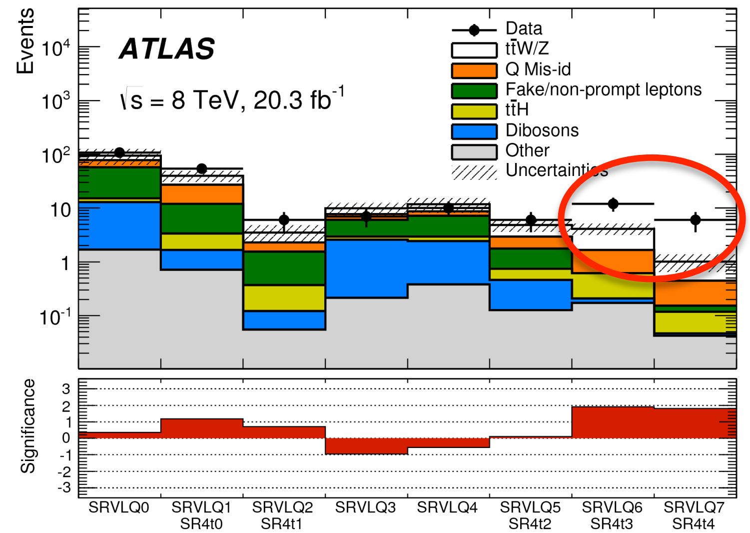


$T\bar{T}/B\bar{B}$->Same-Sign leptons

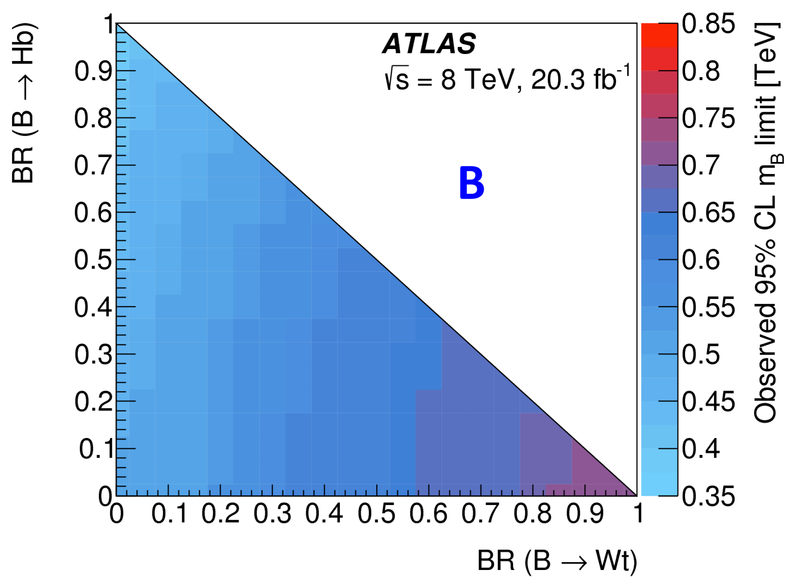
arxiv:1504.04605

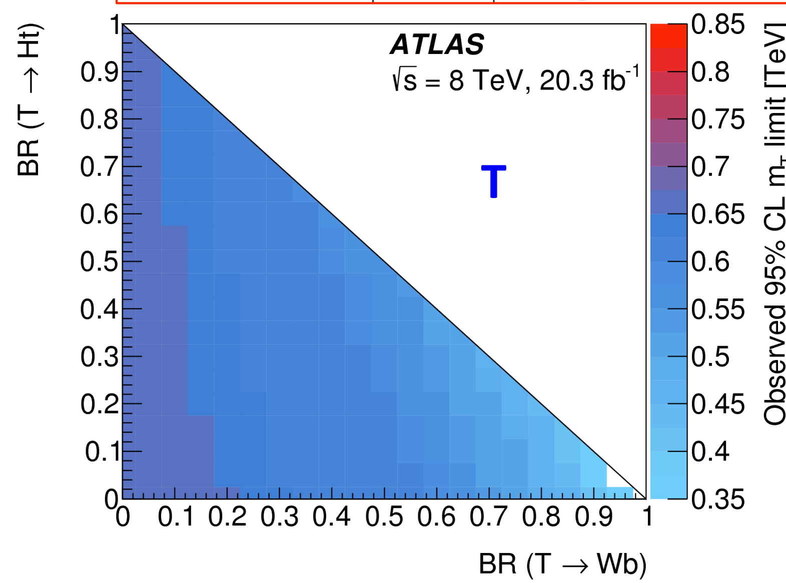
2.5σ is observed

- **Low SM backgrounds:**
  - **2 leptons with same charge**
  - **$N_{jets} \geq 2$, $N_{bjets} \geq 1$**
  - **Large MET(> 40 GeV)**
  - **Large H_T**
- **Eight orthogonal signal regions are defined by varying cuts on H_T, N_{bjets}, MET**
- **Dominant backgrounds:**
  - **Mis-identified leptons estimated from data-driven method**
  - **Charge mis-identification, determined from Z events**
  - **Irreducible diboson(VV), and ttbar+V**



$H_T \geq 700$ GeV	$N_b = 2$	$40 < E_T^{miss} < 100$ GeV	SRVLQ5
		$E_T^{miss} \geq 100$ GeV	SRVLQ6
	$N_b \geq 3$	$E_T^{miss} > 40$ GeV	SRVLQ7

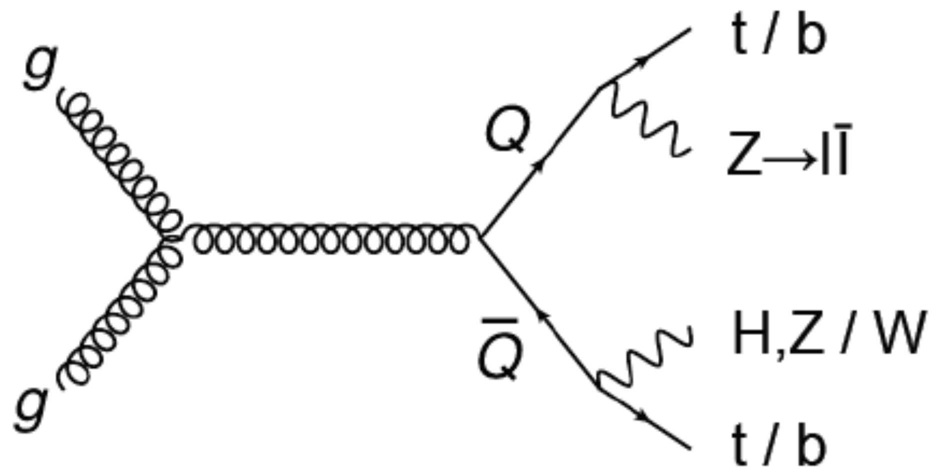


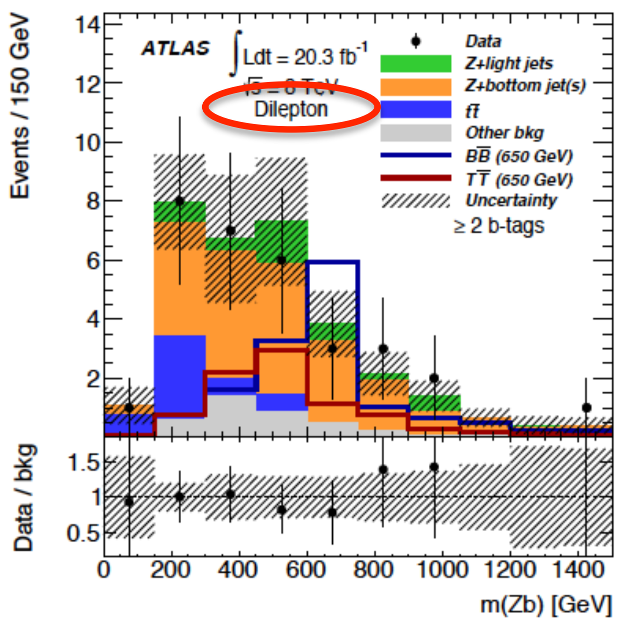


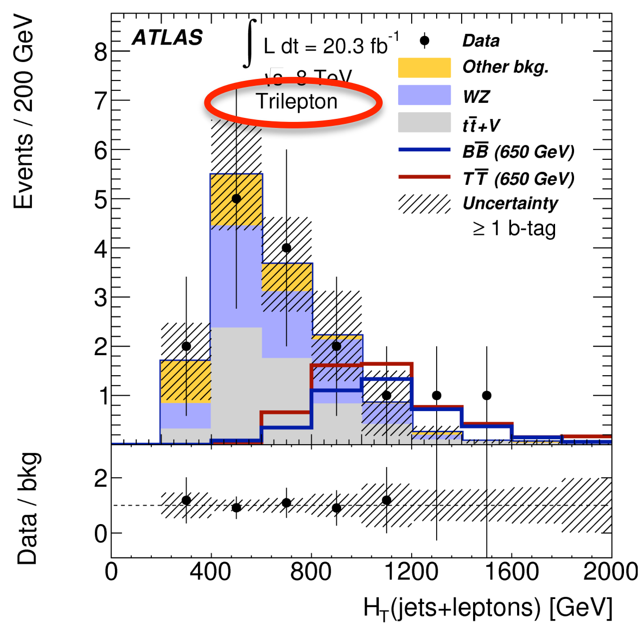
$T\overline{T}/B\overline{B}$->Zt/Zb+X

arxiv:1409.5500

- **Selection:**
  - **High p_T Z boson, which decays leptonically**
  - **$N_{bjets} \geq 2$**
  - **$p_T(Z) > 150$ GeV**
  - **$H_T > 600$ GeV**
- **Discriminant:**
  - **Dilepton: m(Zb)**
  - **Trilepton: H_T**





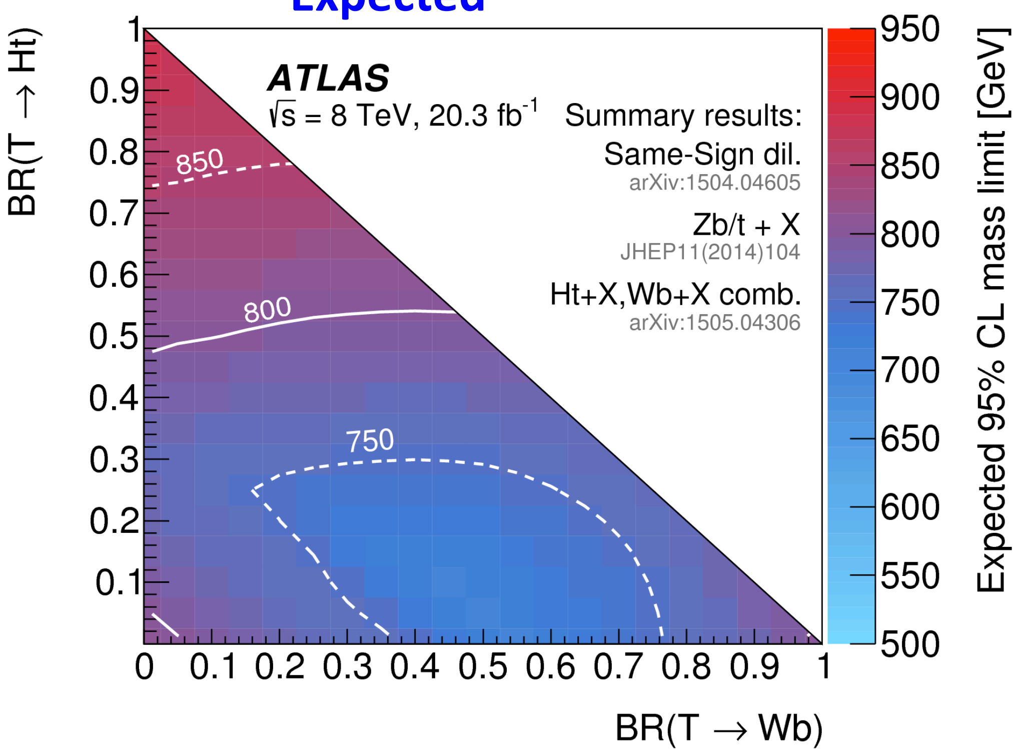


No signal observed!

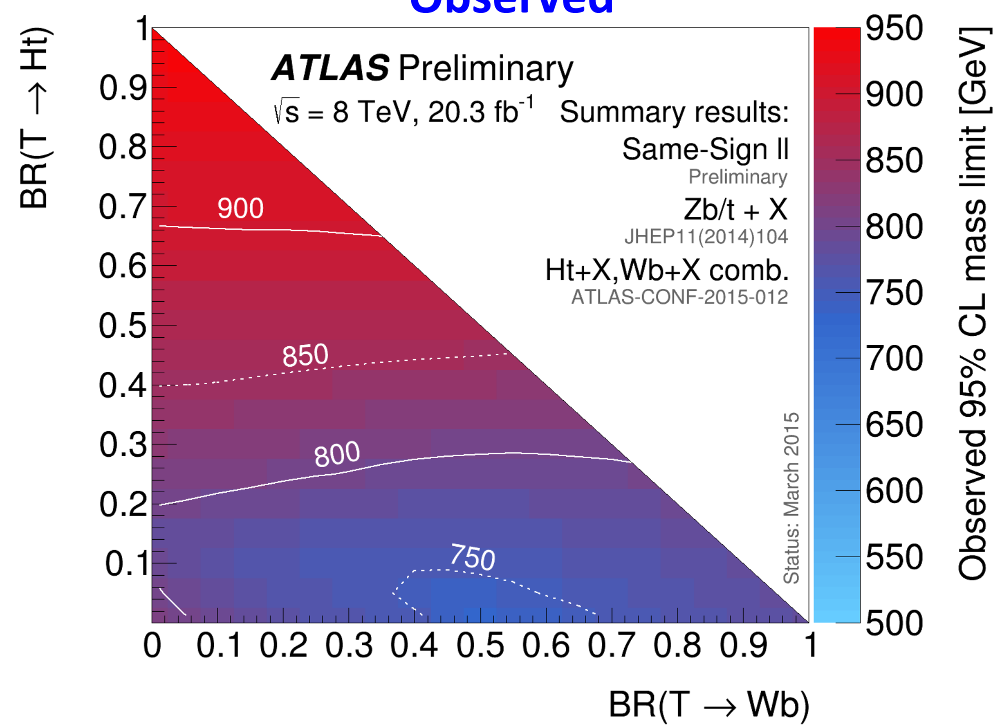
VLQ Mass Limits – T pair production

Summarize limits from various search channels

Expected



Observed

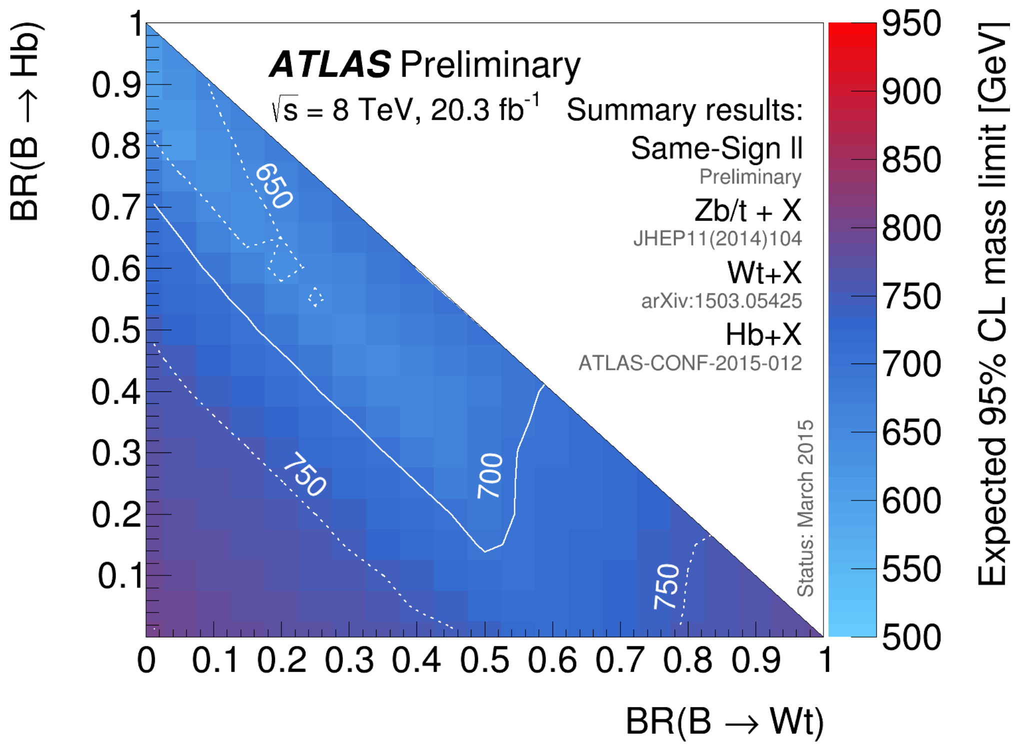


- **Observed(Expected) limit ranges between 730(715) GeV and 950(885) GeV**
- **Best sensitivity comes from T->Ht decay**

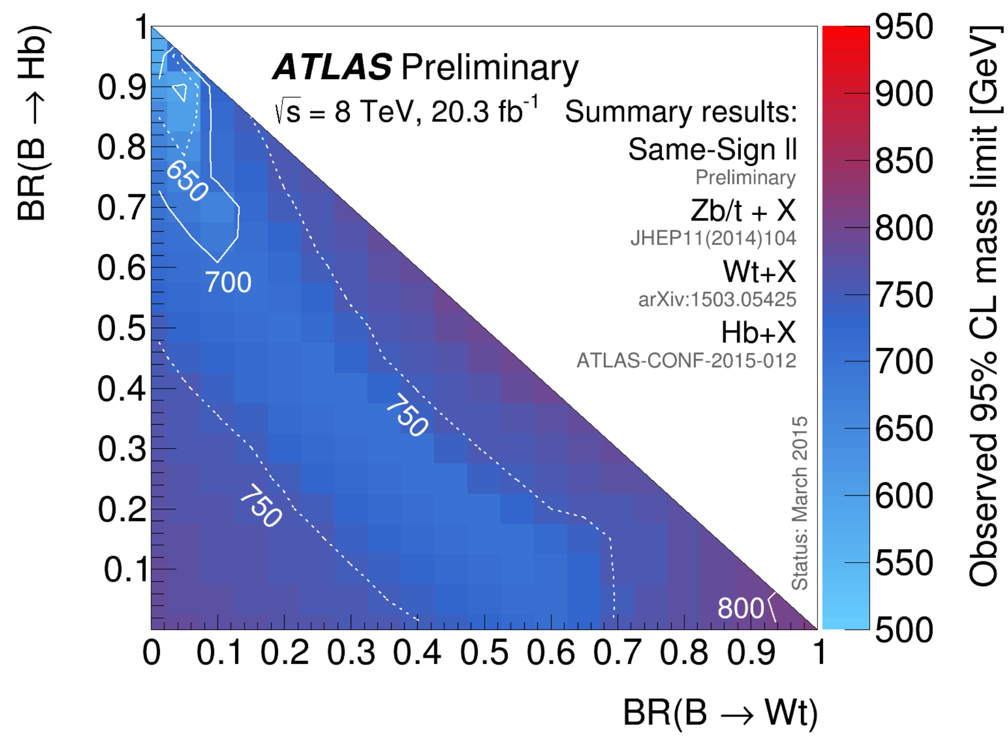
VLQ Mass Limits – B pair production

Summarize limits from various search channels

Expected



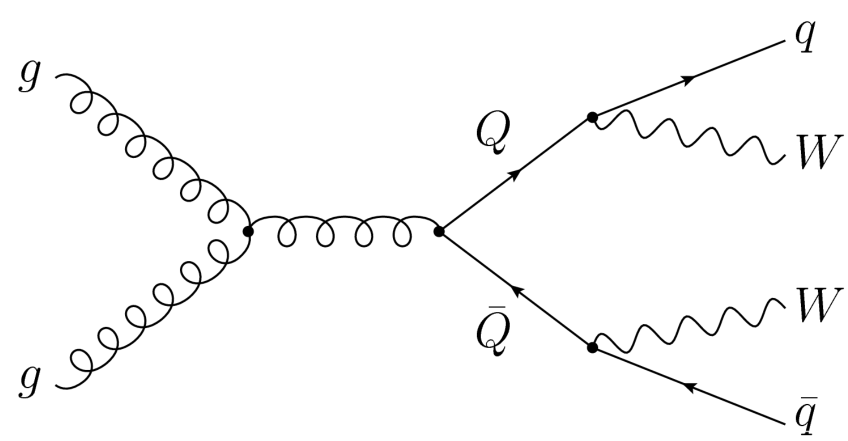
Observed

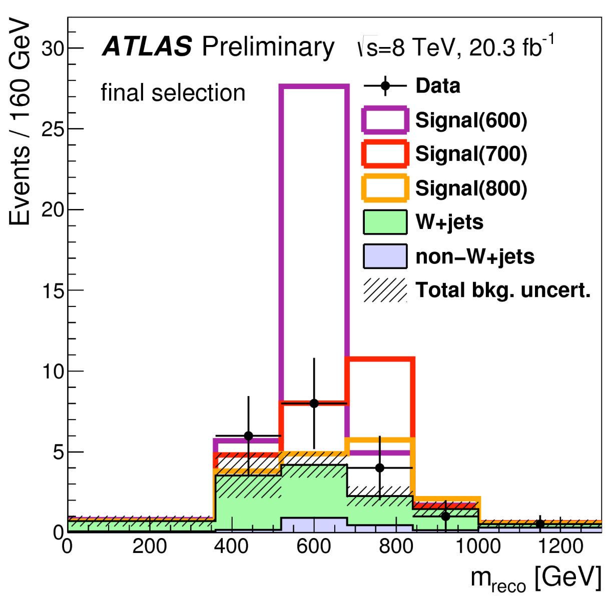


- **Observed(Expected) limit ranges between 575(615) GeV and 813(800) GeV**
- **Best sensitivity comes from B->Wt decay**

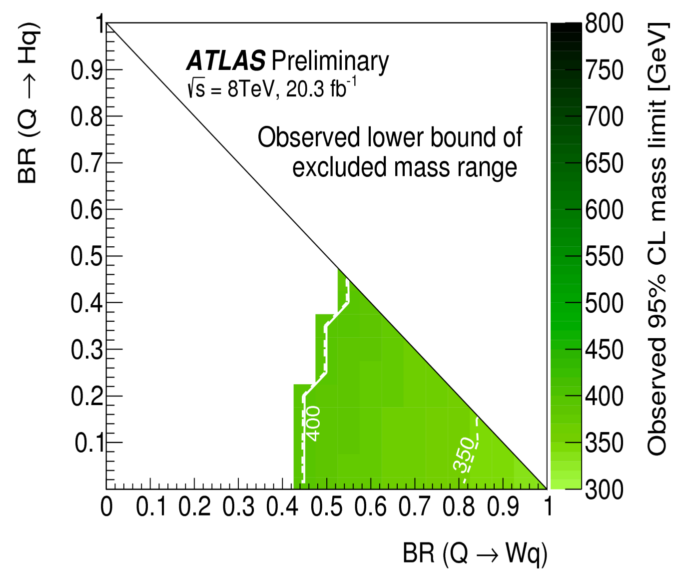
VLQ pair-> Wq+X

- In some models(LRMM, E6GUT, etc.), VLQ can decay to light quarks(u, d, s)
- Signatures explored: WWqq
  - Hadronic W & leptonic W
- No evidence for new physics observed so 95% CL limits were derived
- Limited sensitivity at low masses due to tight selection optimized for VLQ->Wq. Therefore set limit on both upper and lower mass bounds

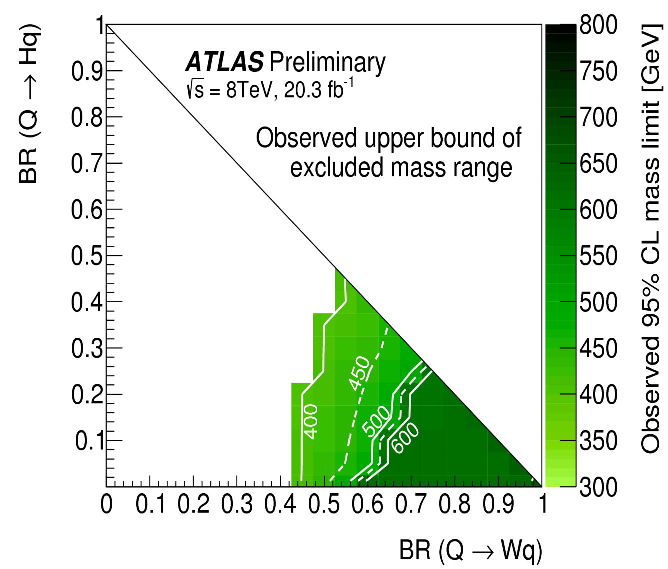




Lower bounds



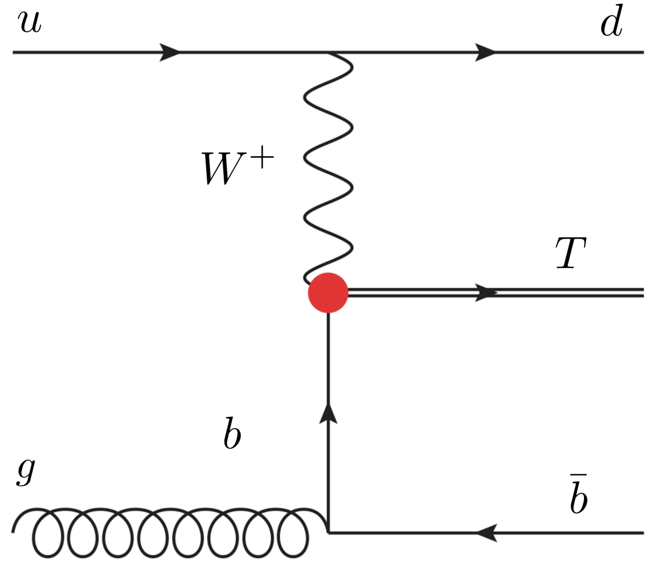
Upper bounds

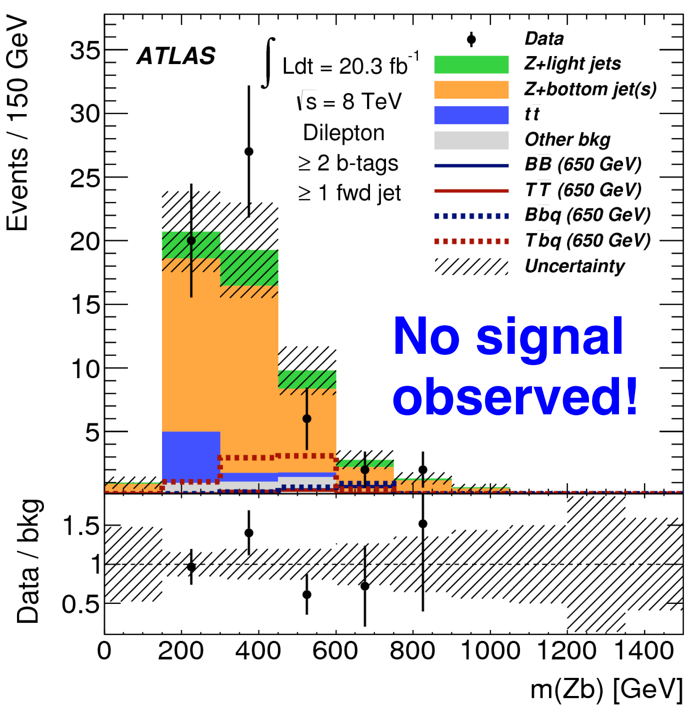


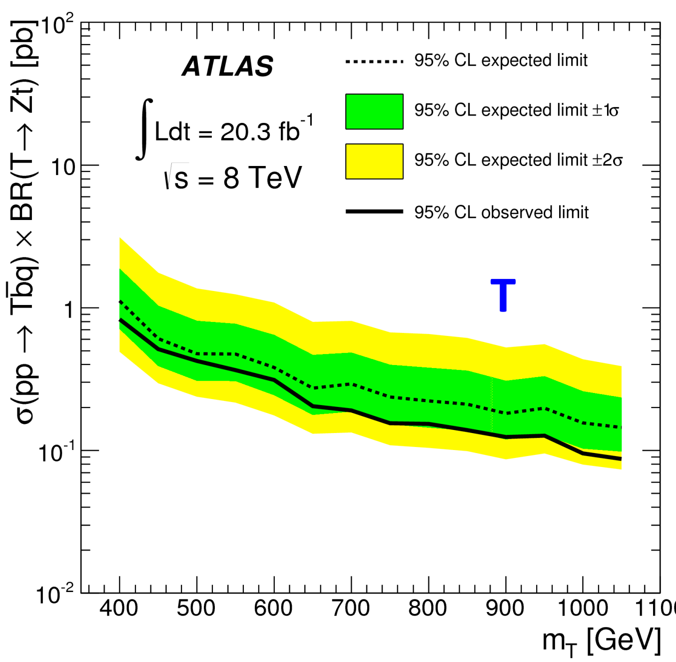
Single VLQ(T/B -> Zt/b)

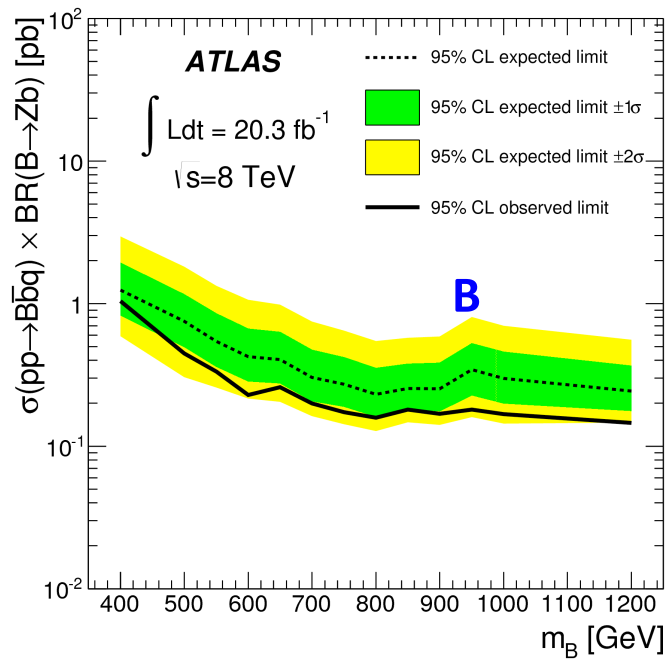
arxiv:1409.5500

- **Similar selection as for pair-production, but require energetic forward light-flavor jet produced in association**
- **For di-lepton channel, H_T requirement is removed**
- **Cross-section limits place limited constraints on the coupling with 3rd generation**









Summary

- **Searches for Vector-like Quarks were carried out in various channels(lepton+jets, multi-lepton, …) at ATLAS in Run I, including pair- and single-production.**

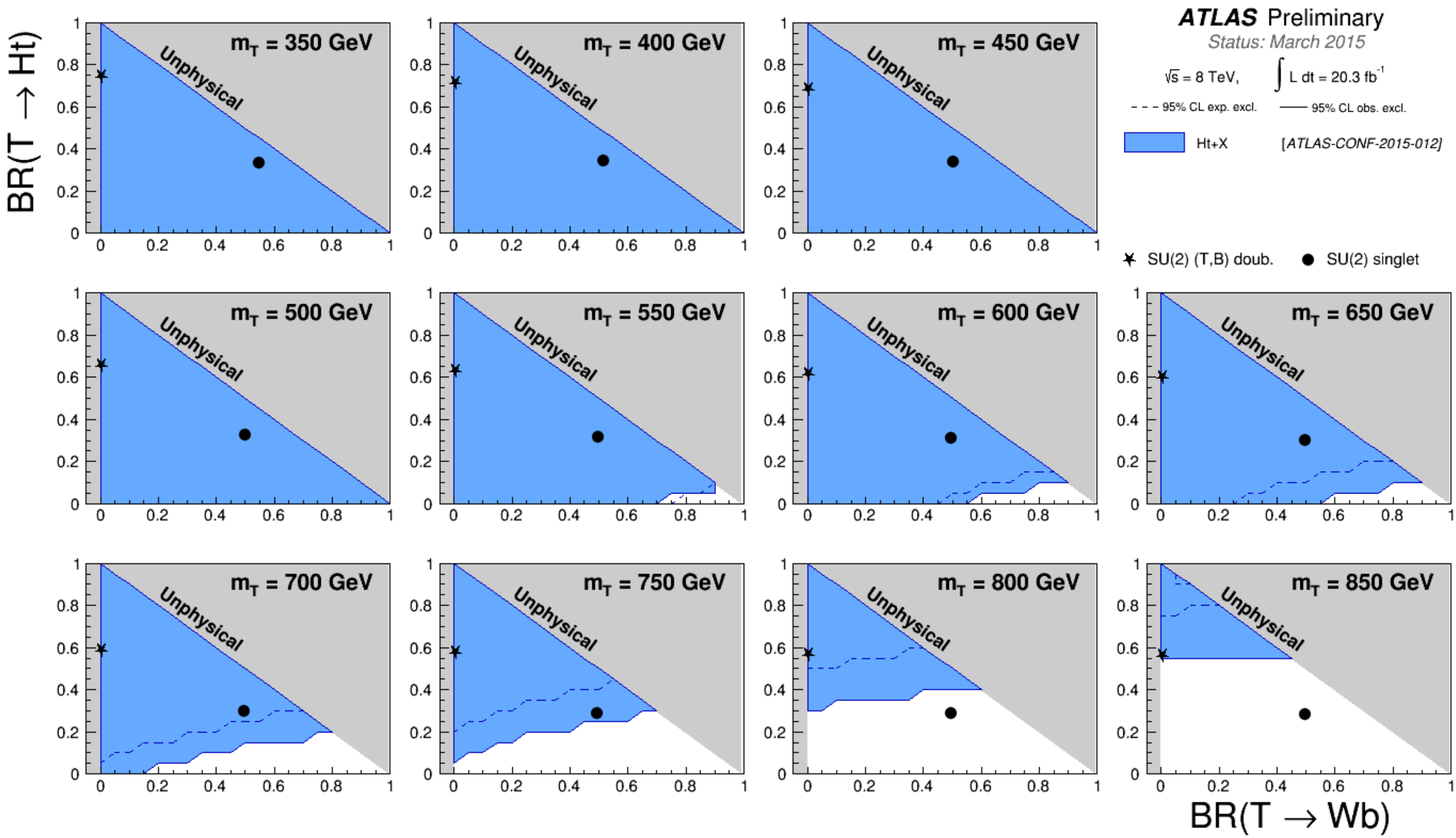
- **Search strategies were optimized independently for different channels. ATLAS results on heavy quarks have been published(or will soon) with 20fb^{-1} 8TeV data. No VLQ has been discovered so far ☹**

- **Current result mainly relies on VLQ pair-production. As mass limits reaching higher region, sensitivity of single production of VLQ will become more important, which also depends on the coupling with 3rd generation**

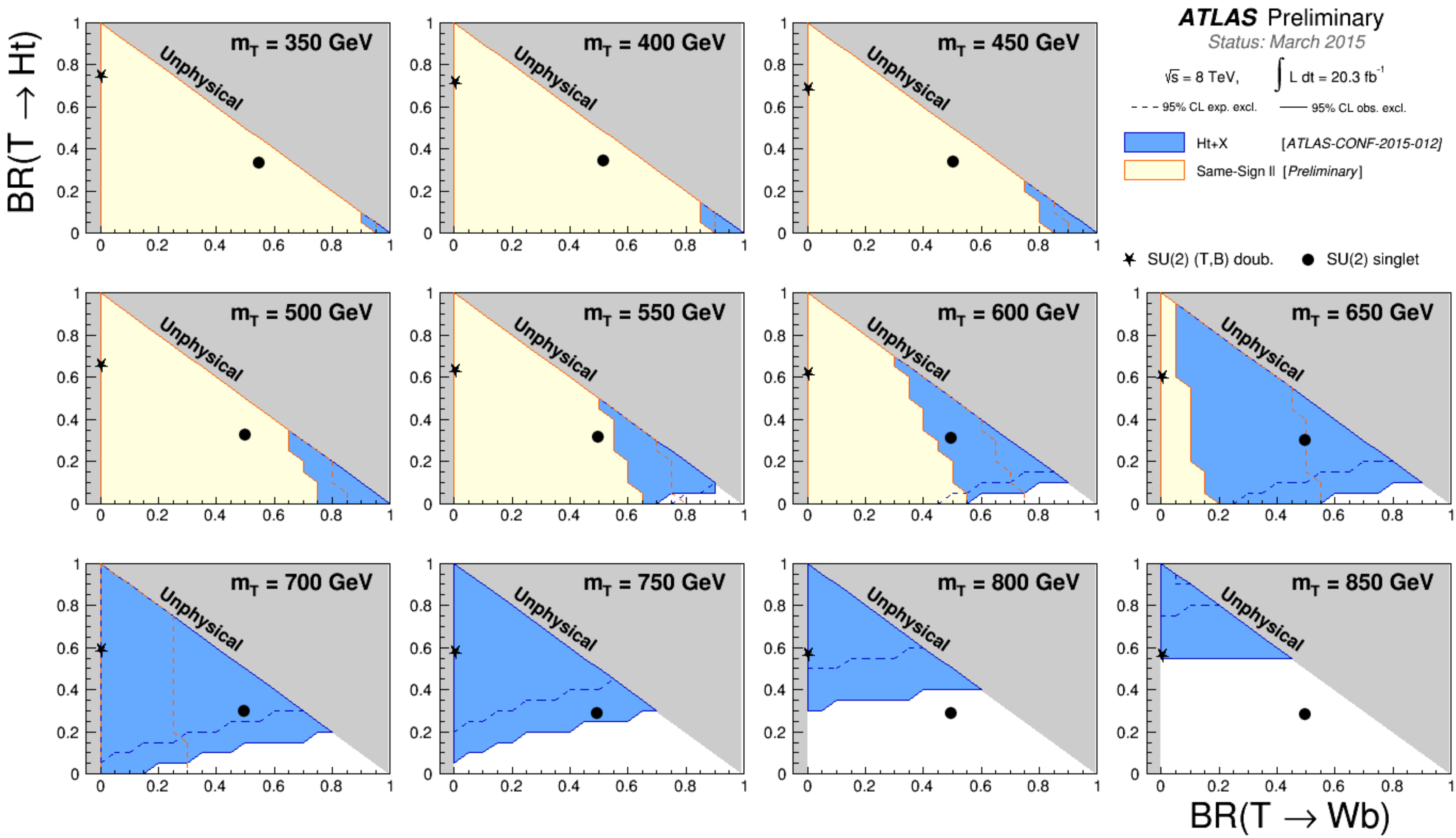
- **Run II @13 TeV data taking has begun. Stay tuned for more exciting physics!**

backup

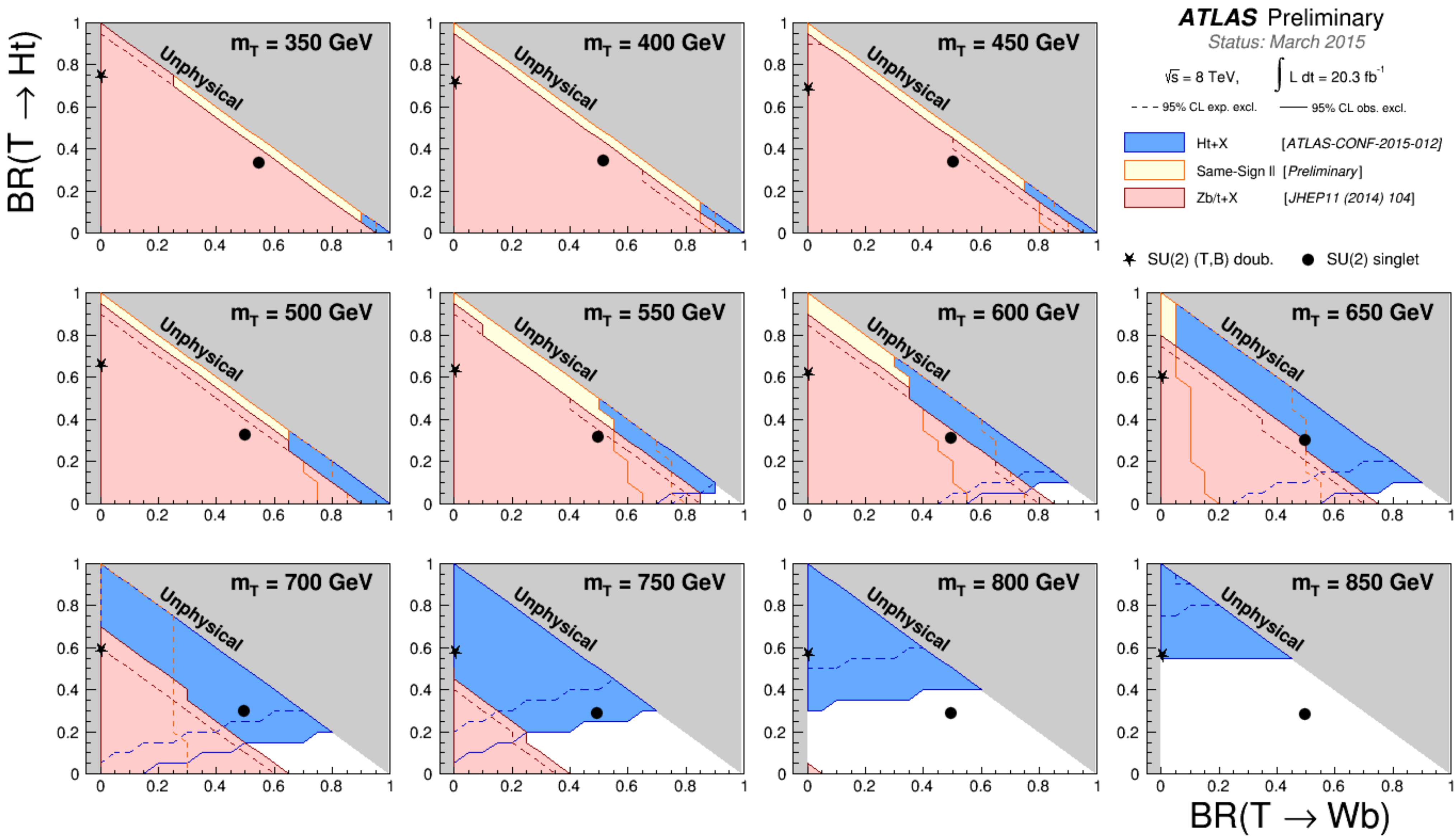
VLQ Limits – T pair production



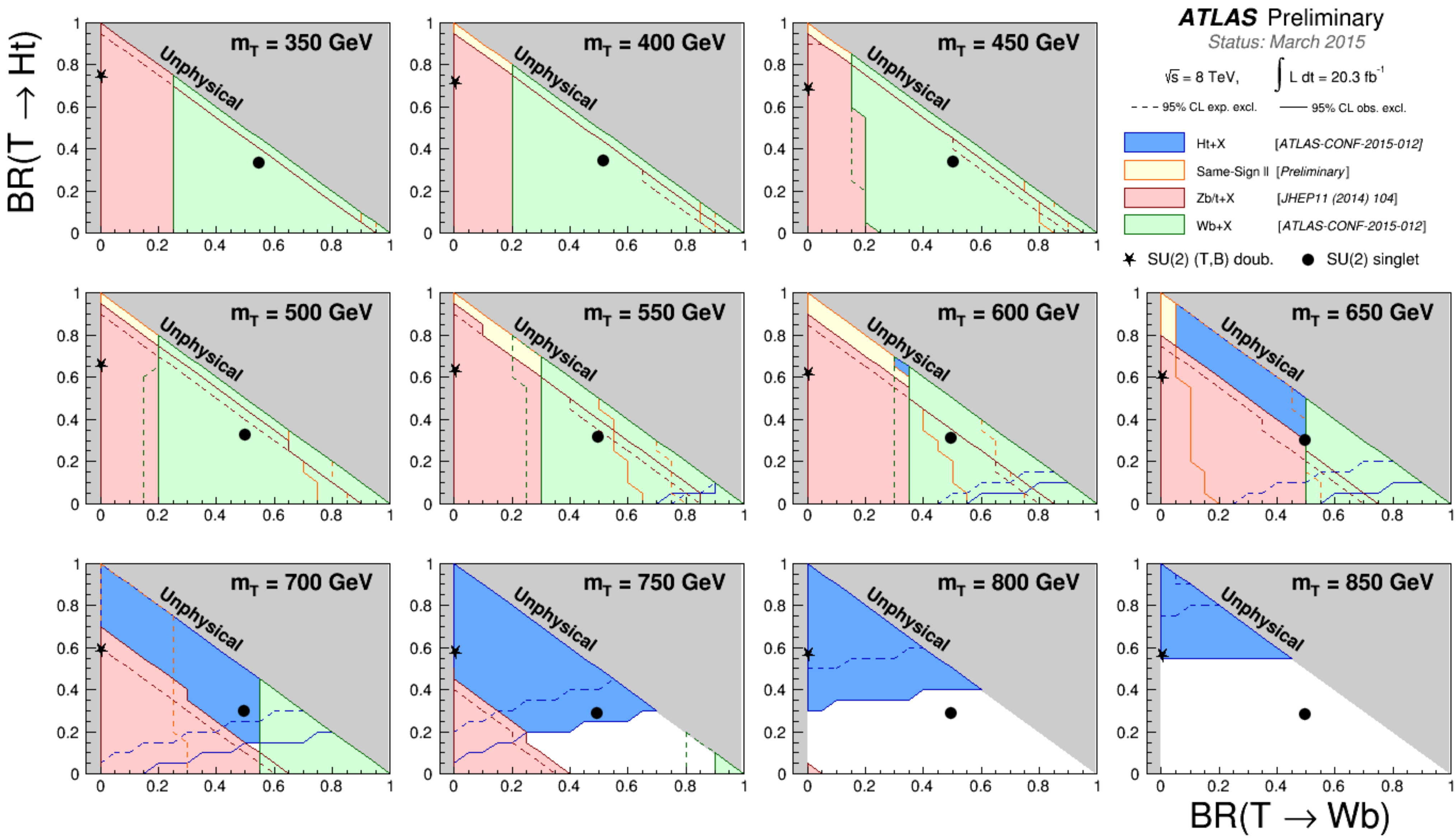
VLQ Limits – T pair production



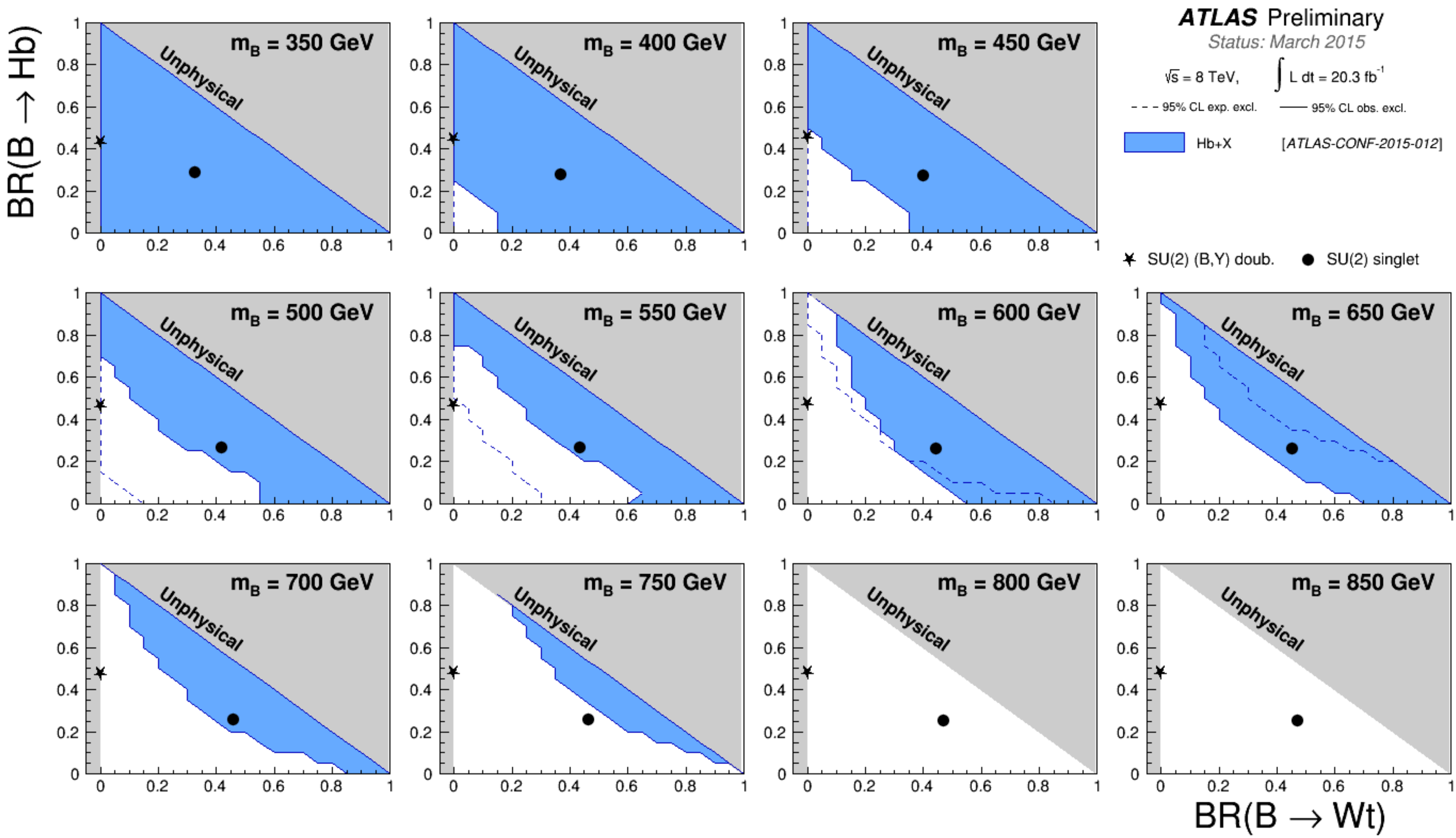
VLQ Limits – T pair production



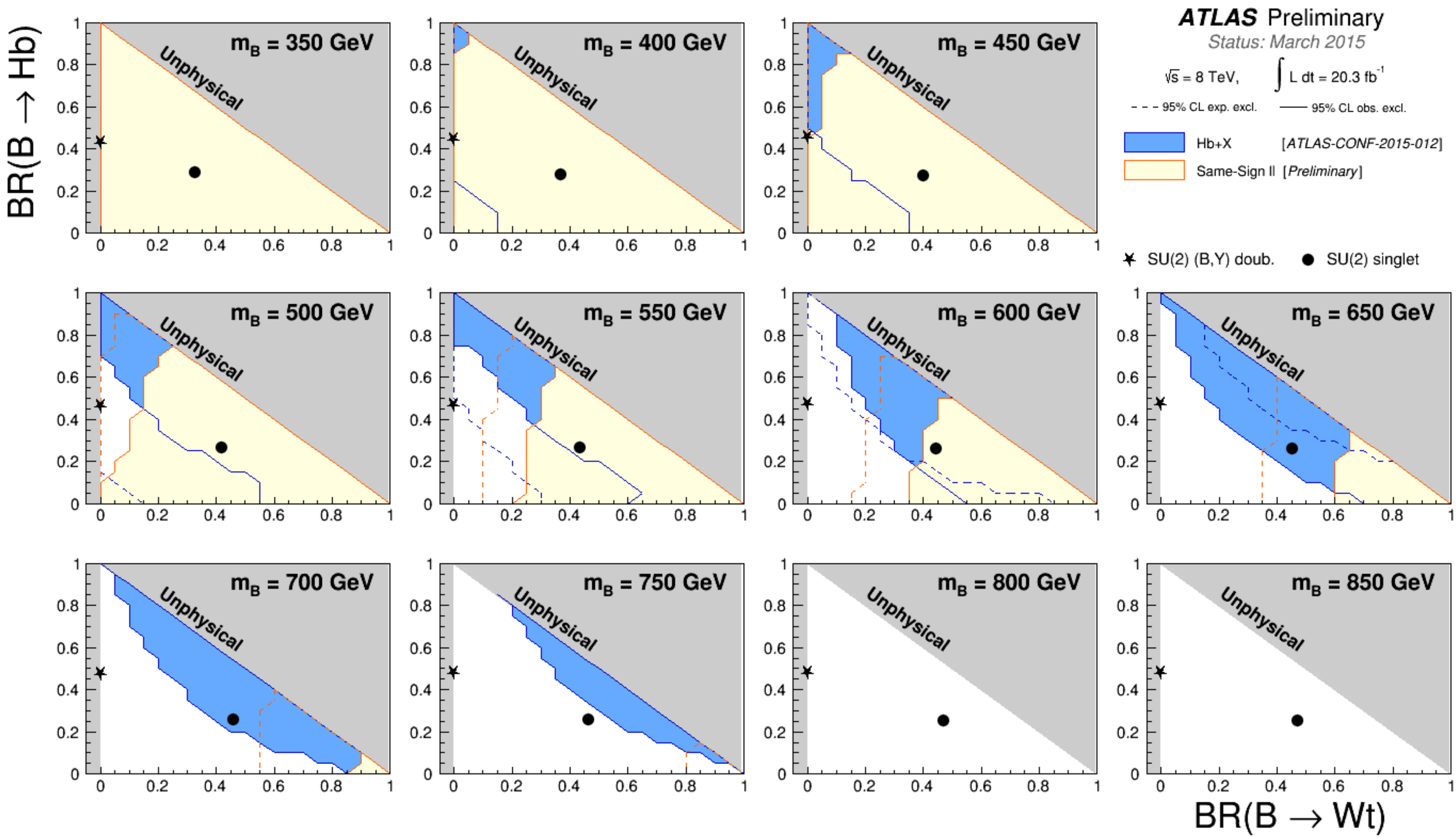
VLQ Limits – T pair production



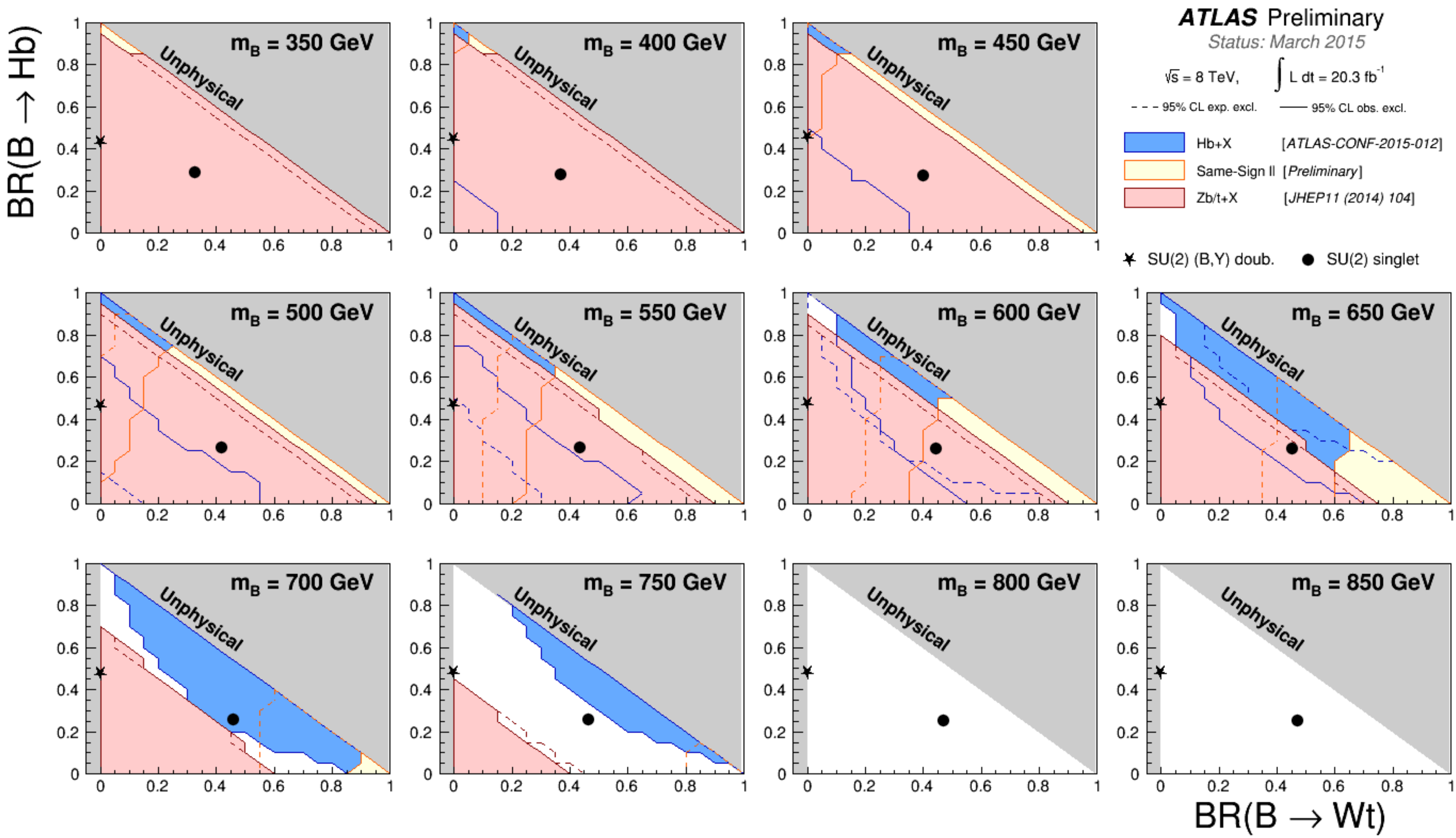
VLQ Limits – B pair production



VLQ Limits – B pair production



VLQ Limits – B pair production



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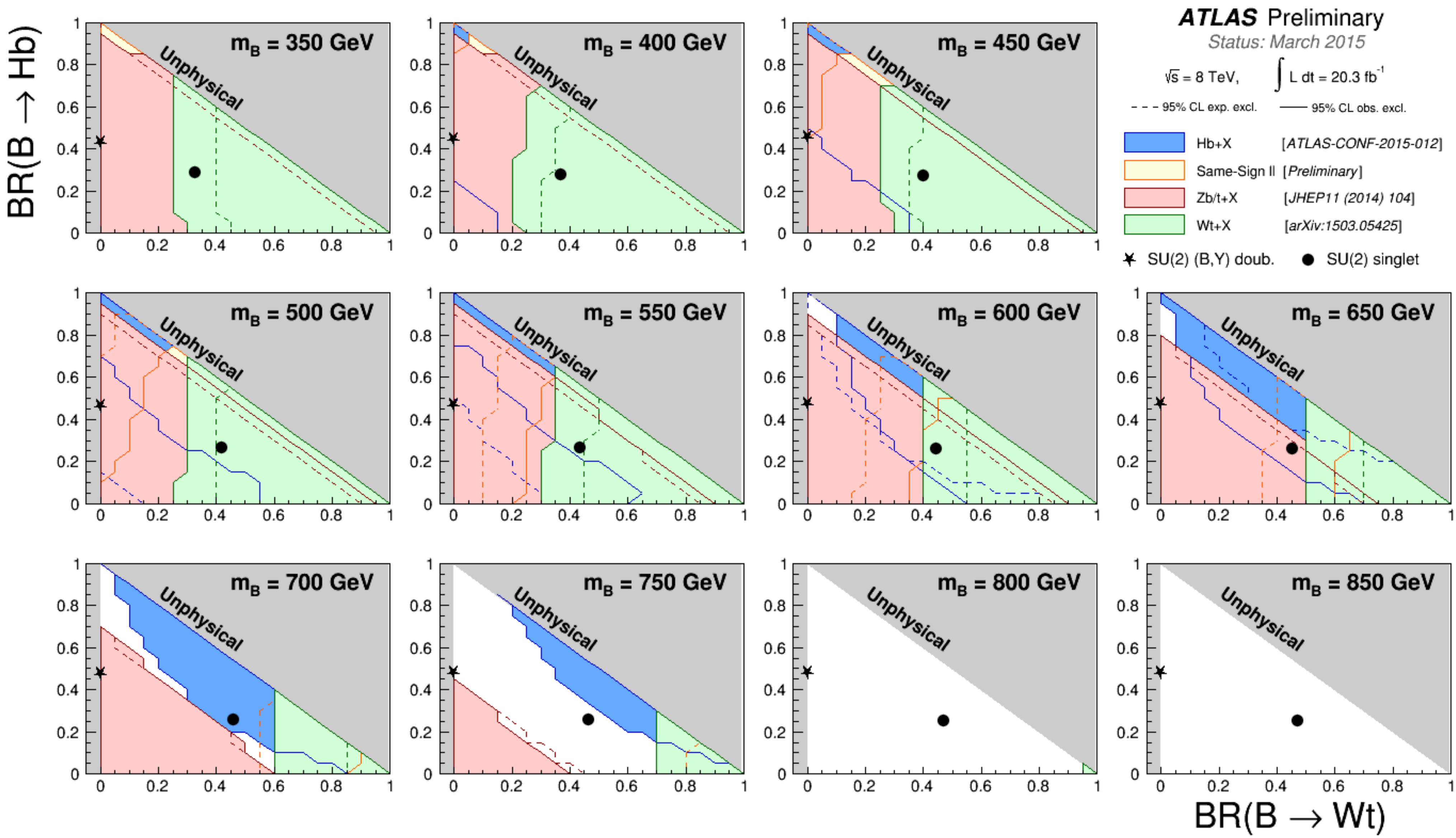
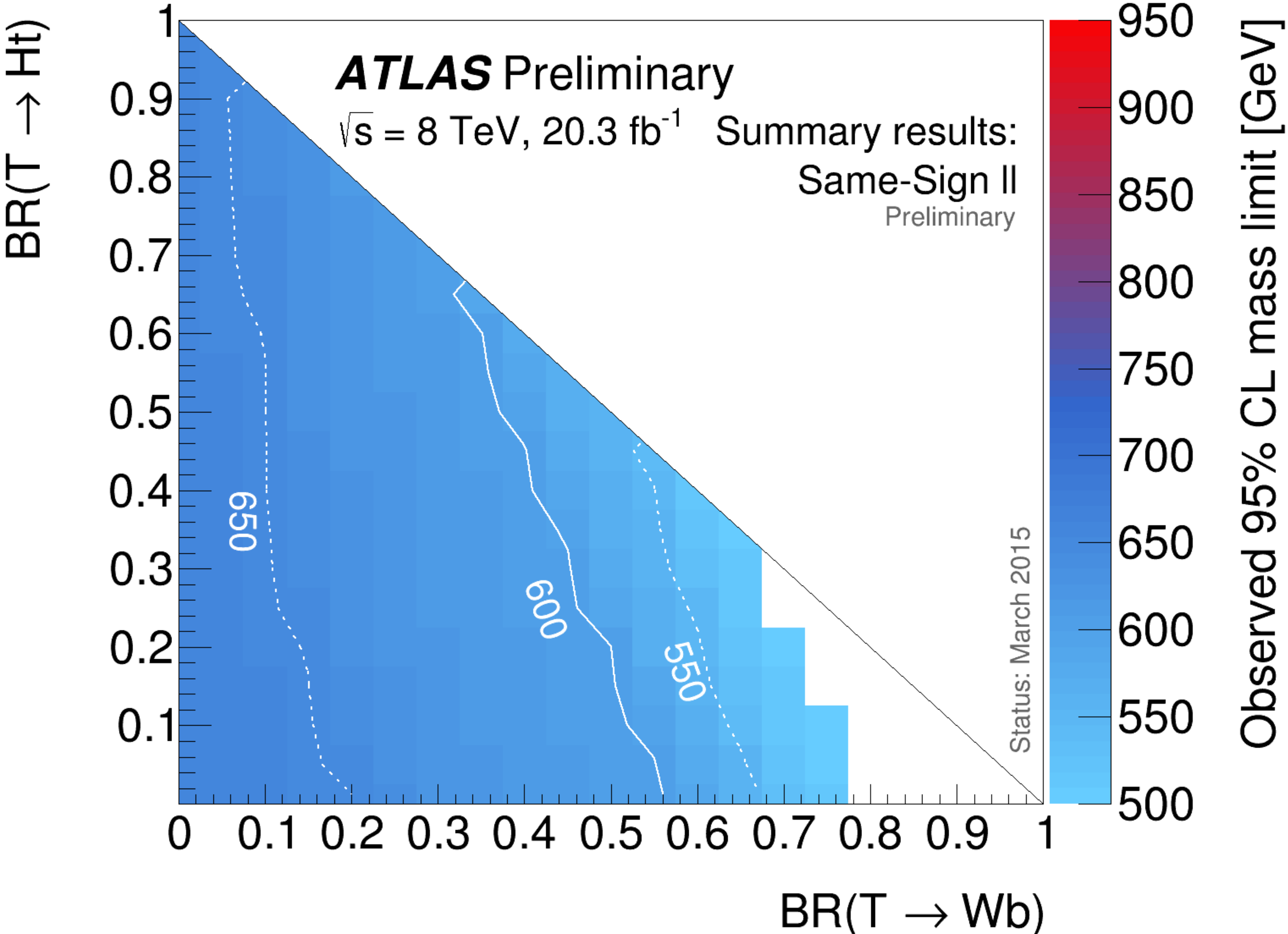
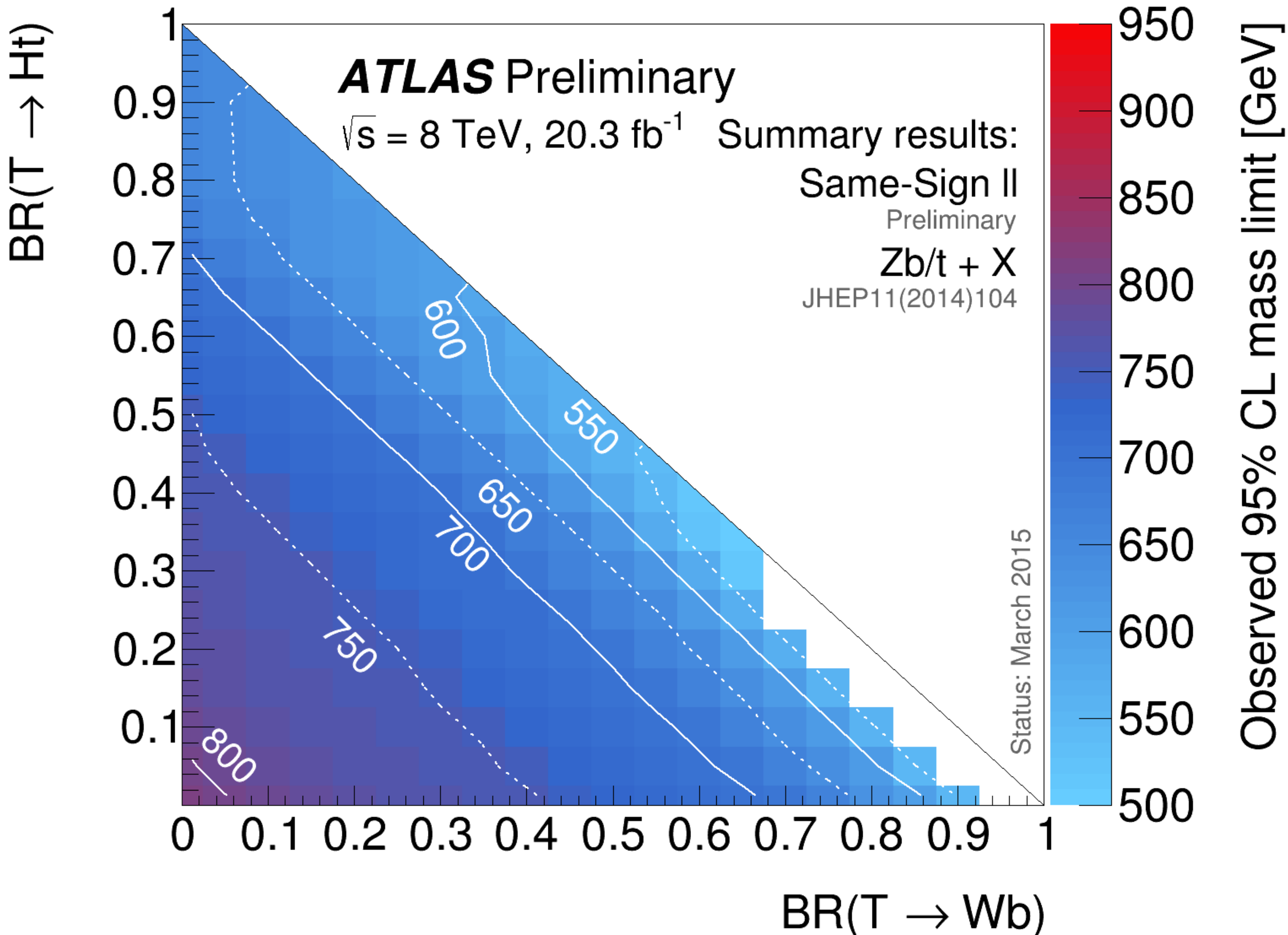


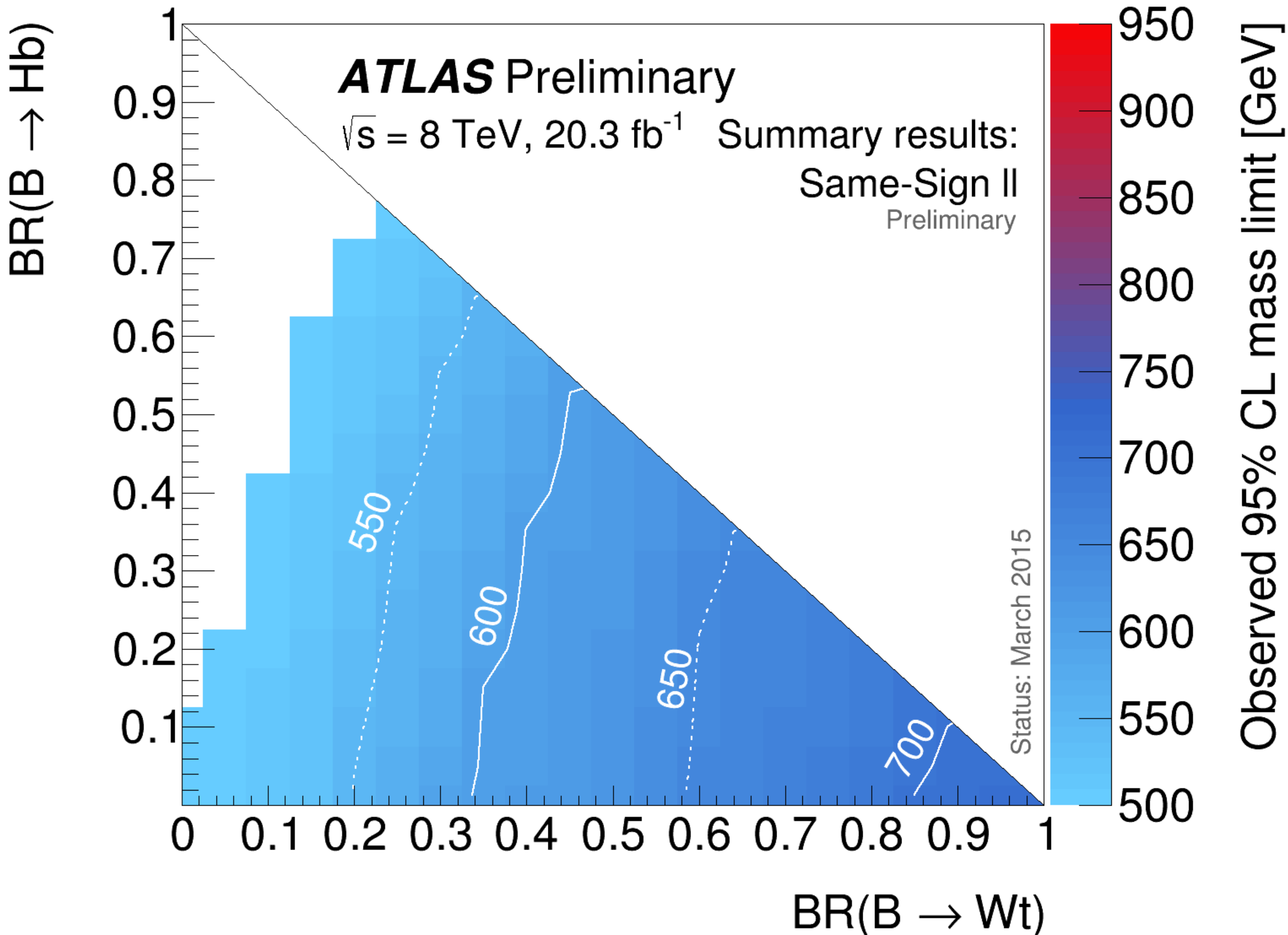
VLQ Limits – T pair production



VLQ Limits – T pair production



VLQ Limits – B pair production



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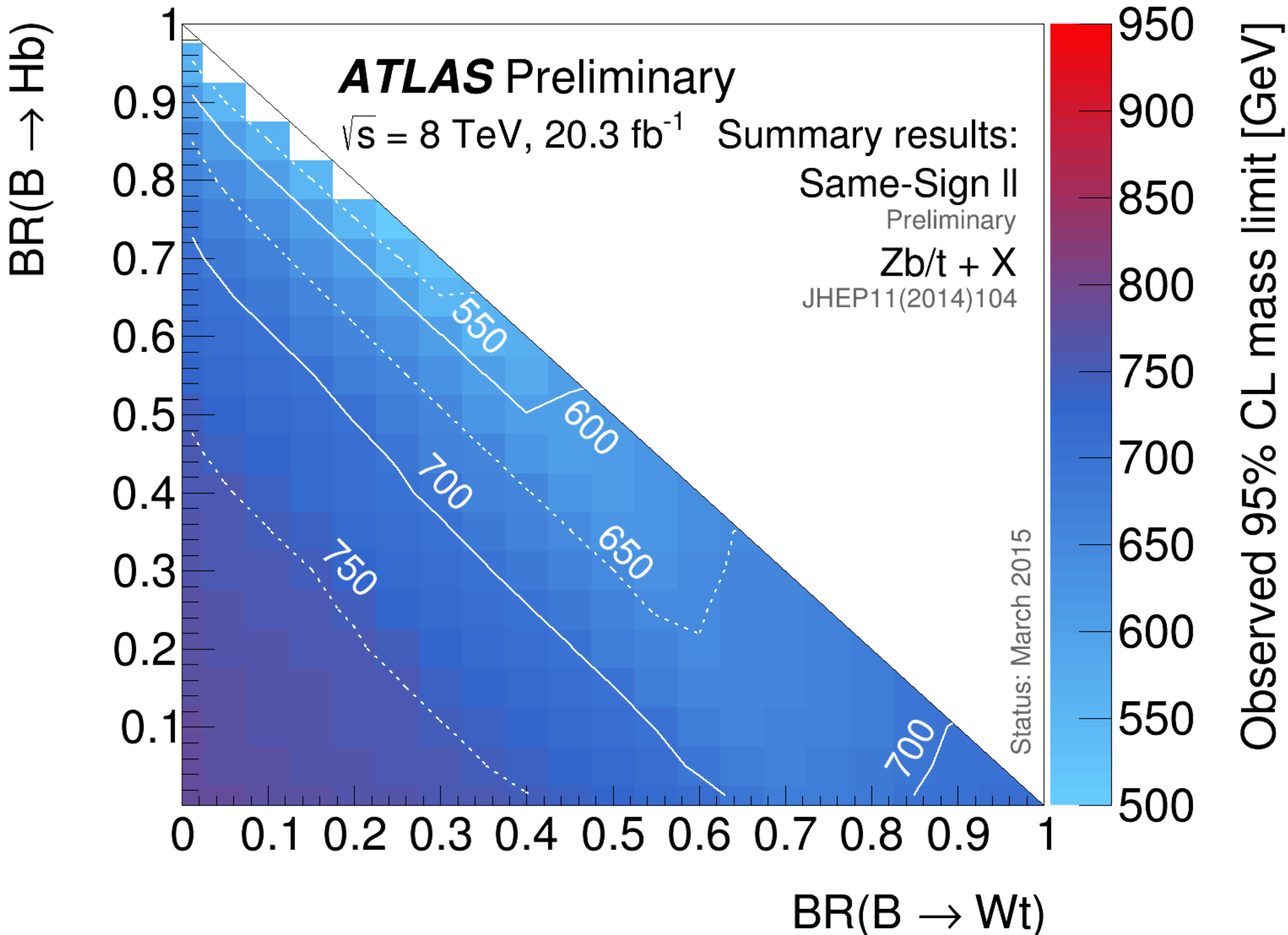
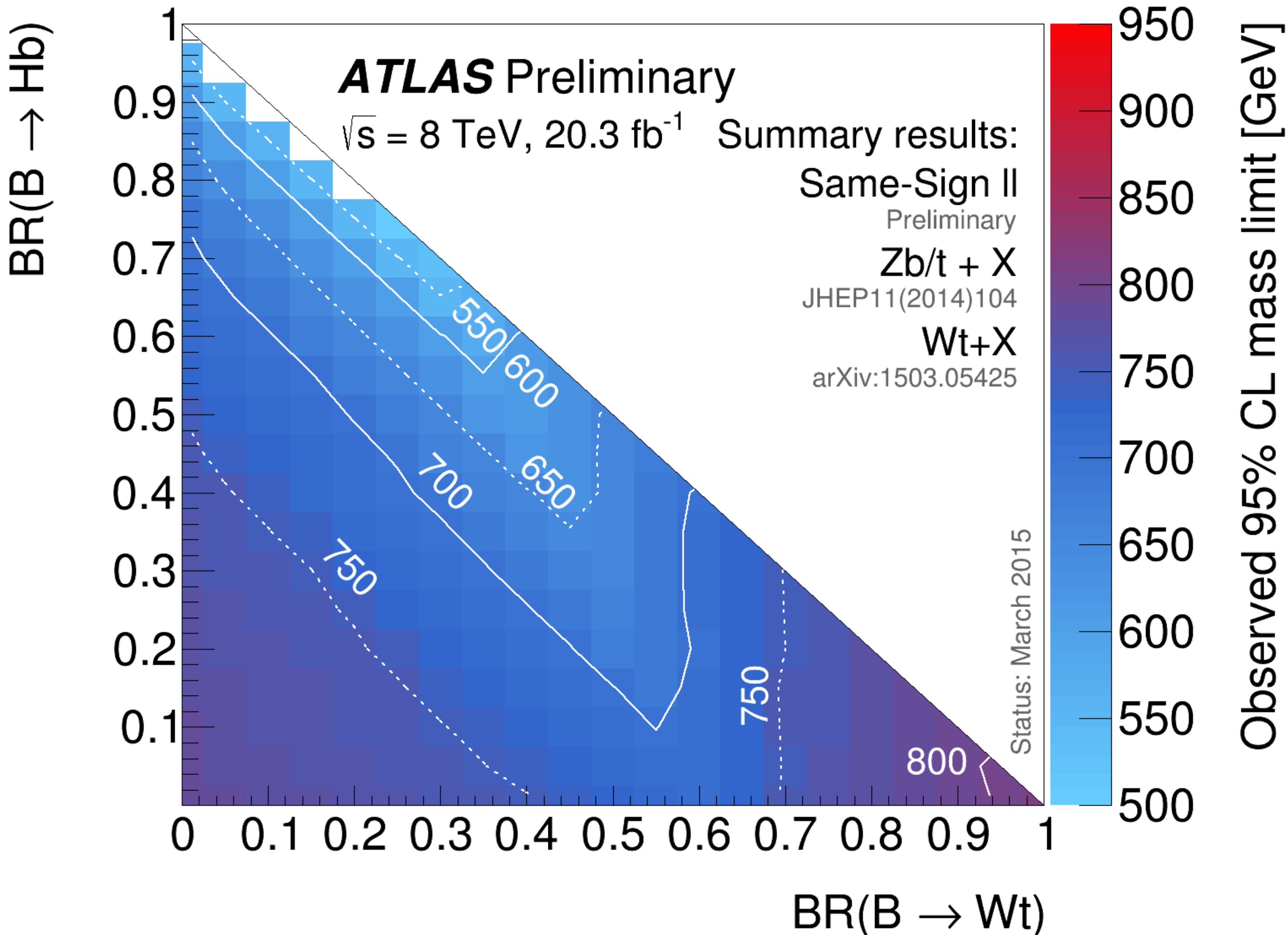
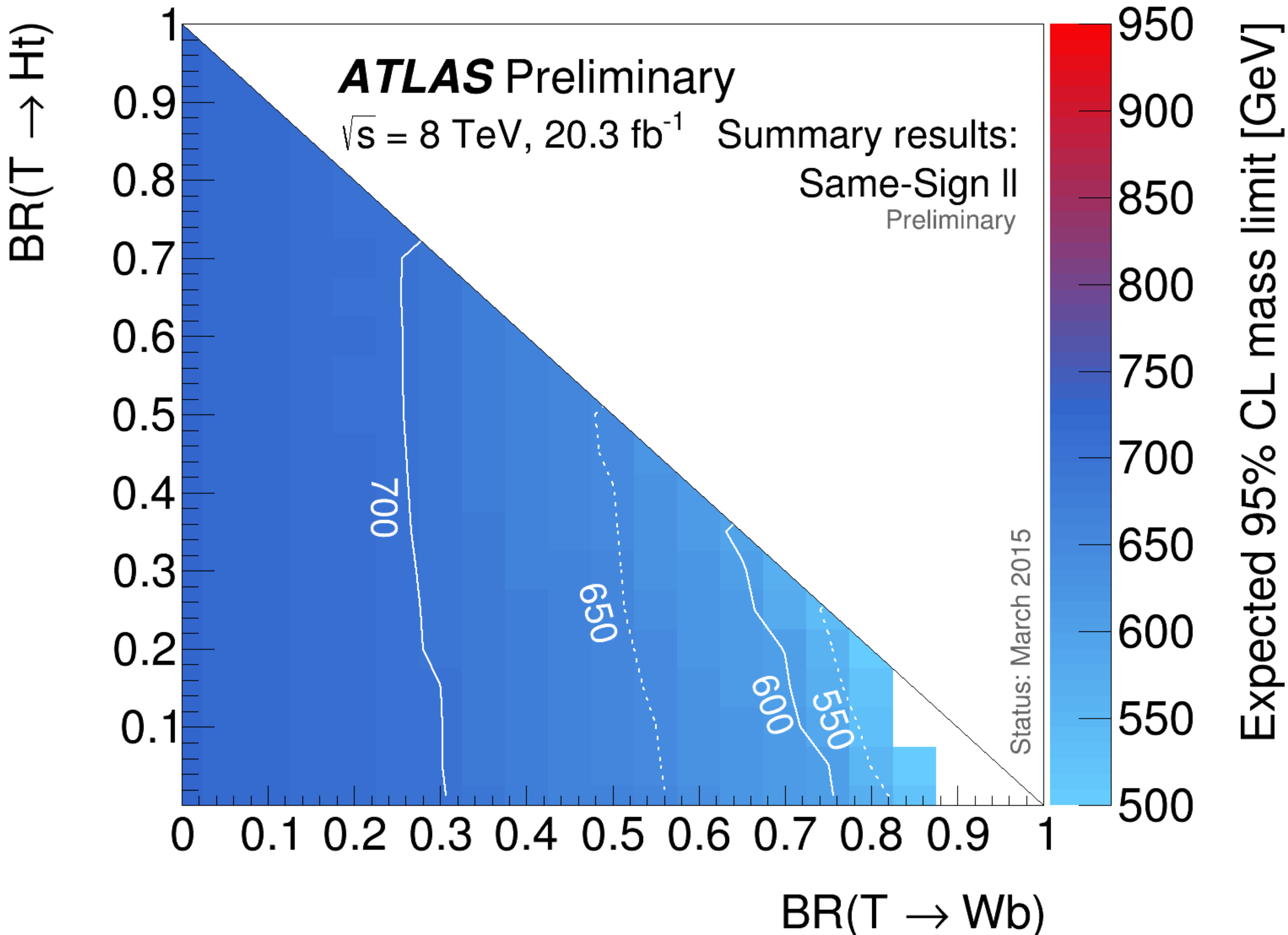


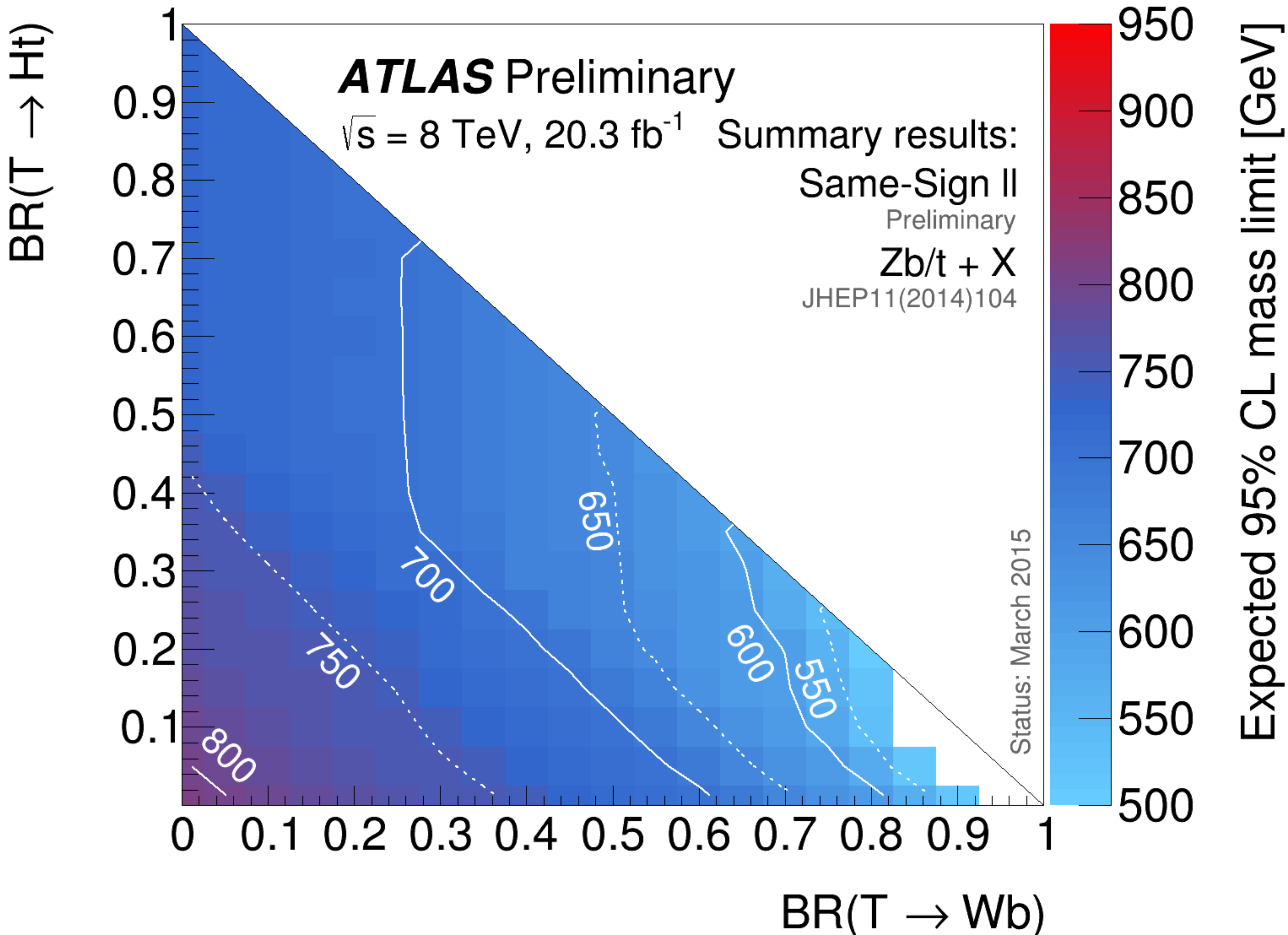
VLQ Limits – B pair production



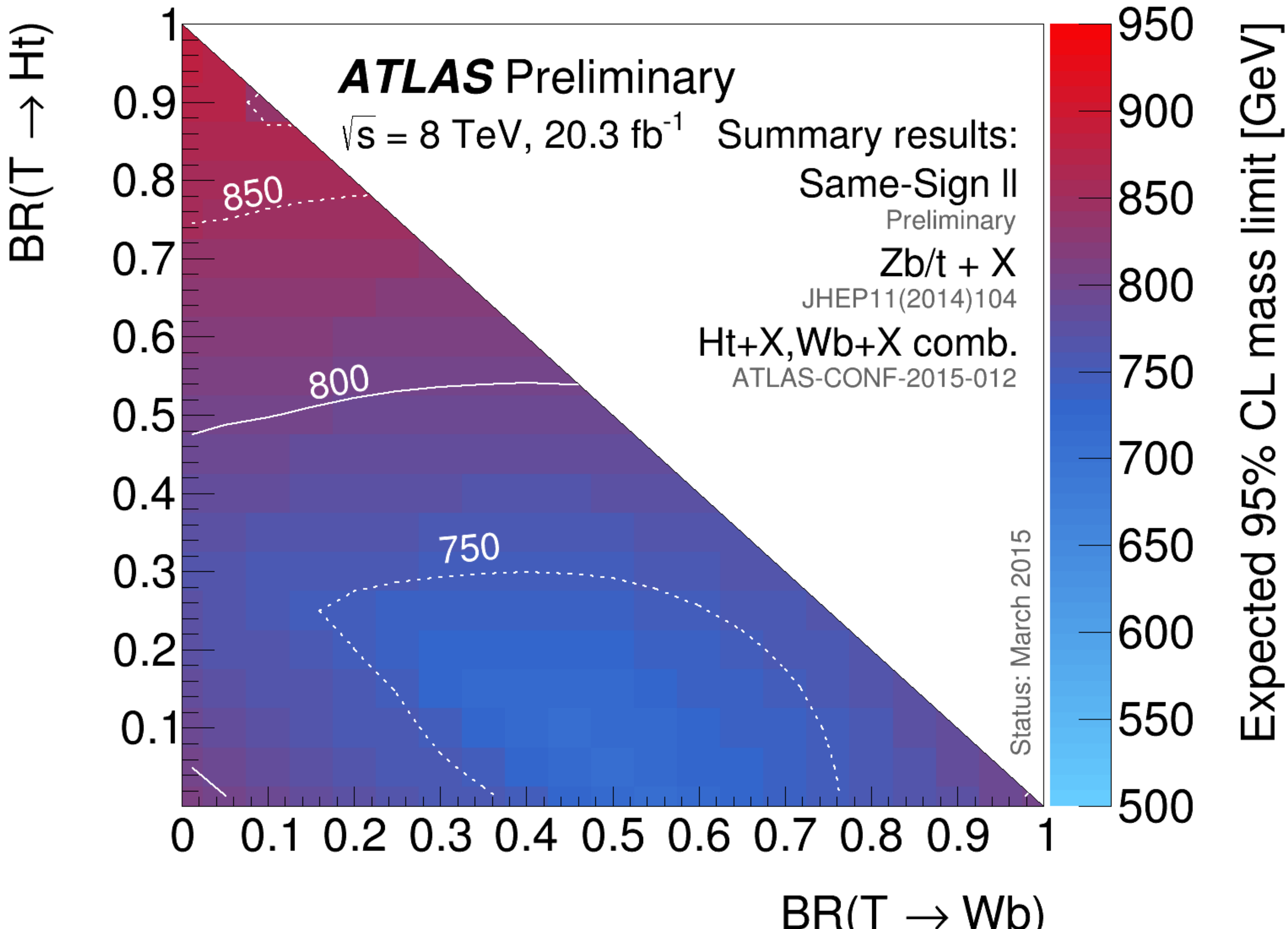
VLQ Limits – T pair production



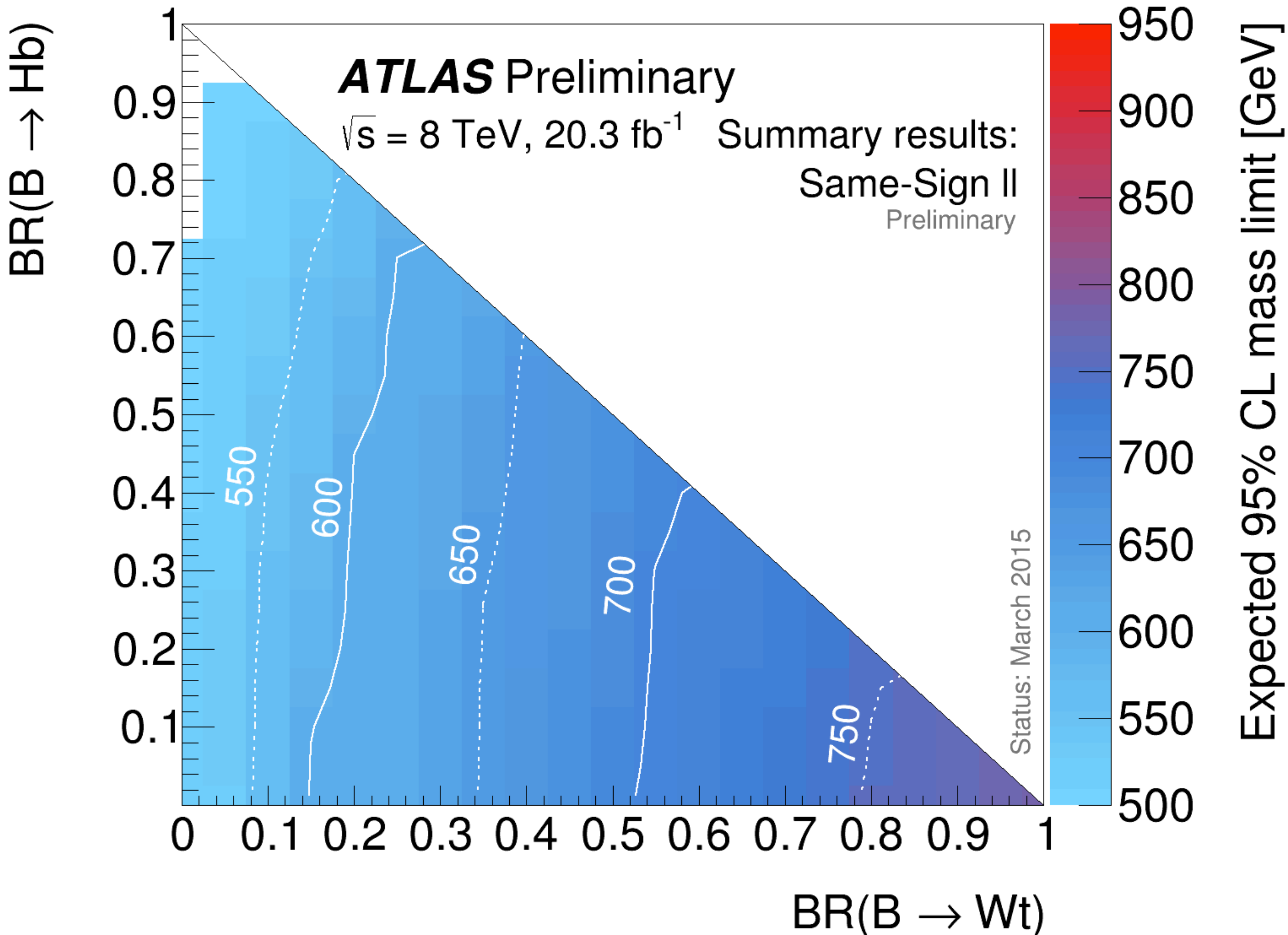
VLQ Limits – T pair production



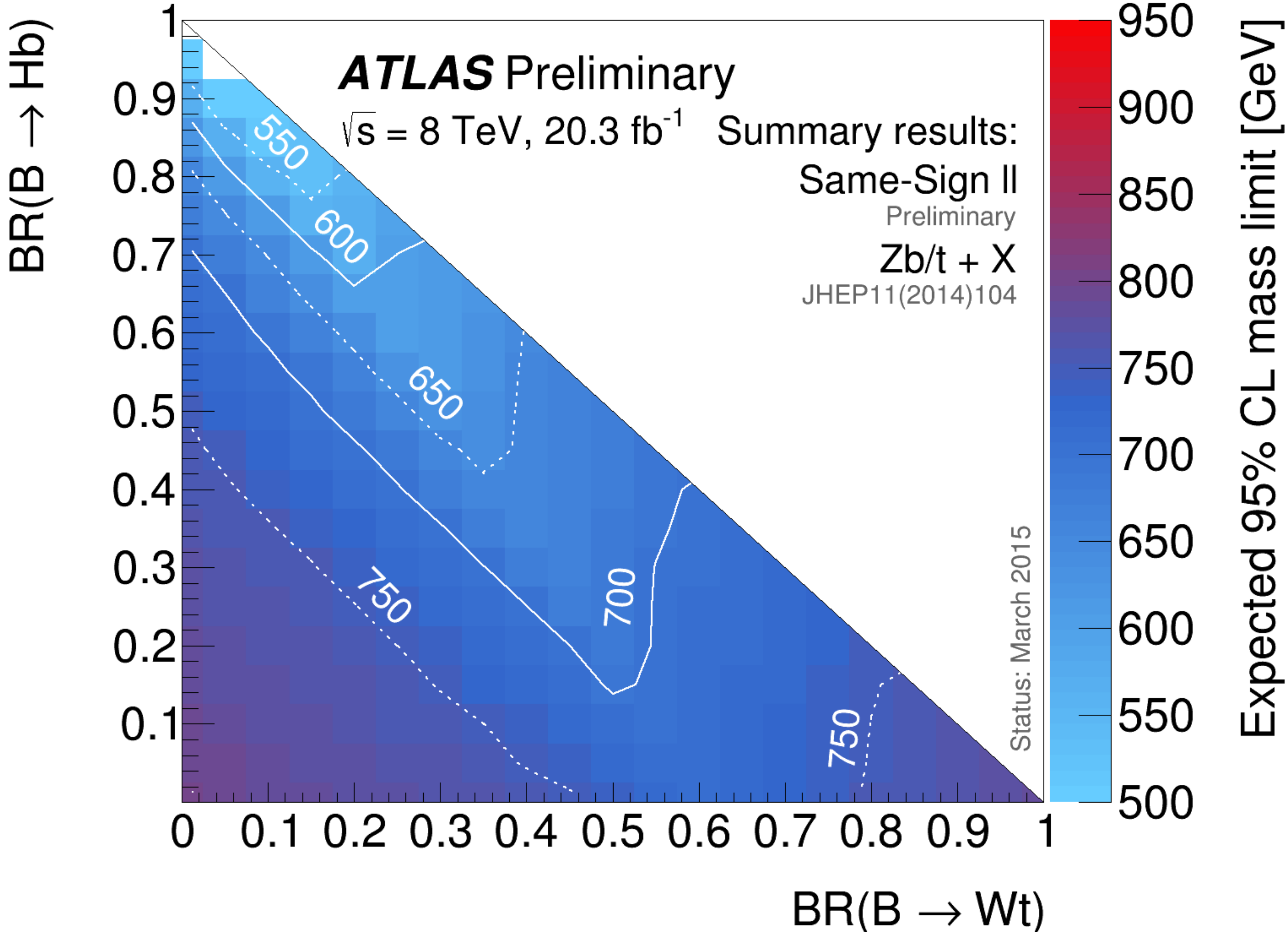
VLQ Limits – T pair production



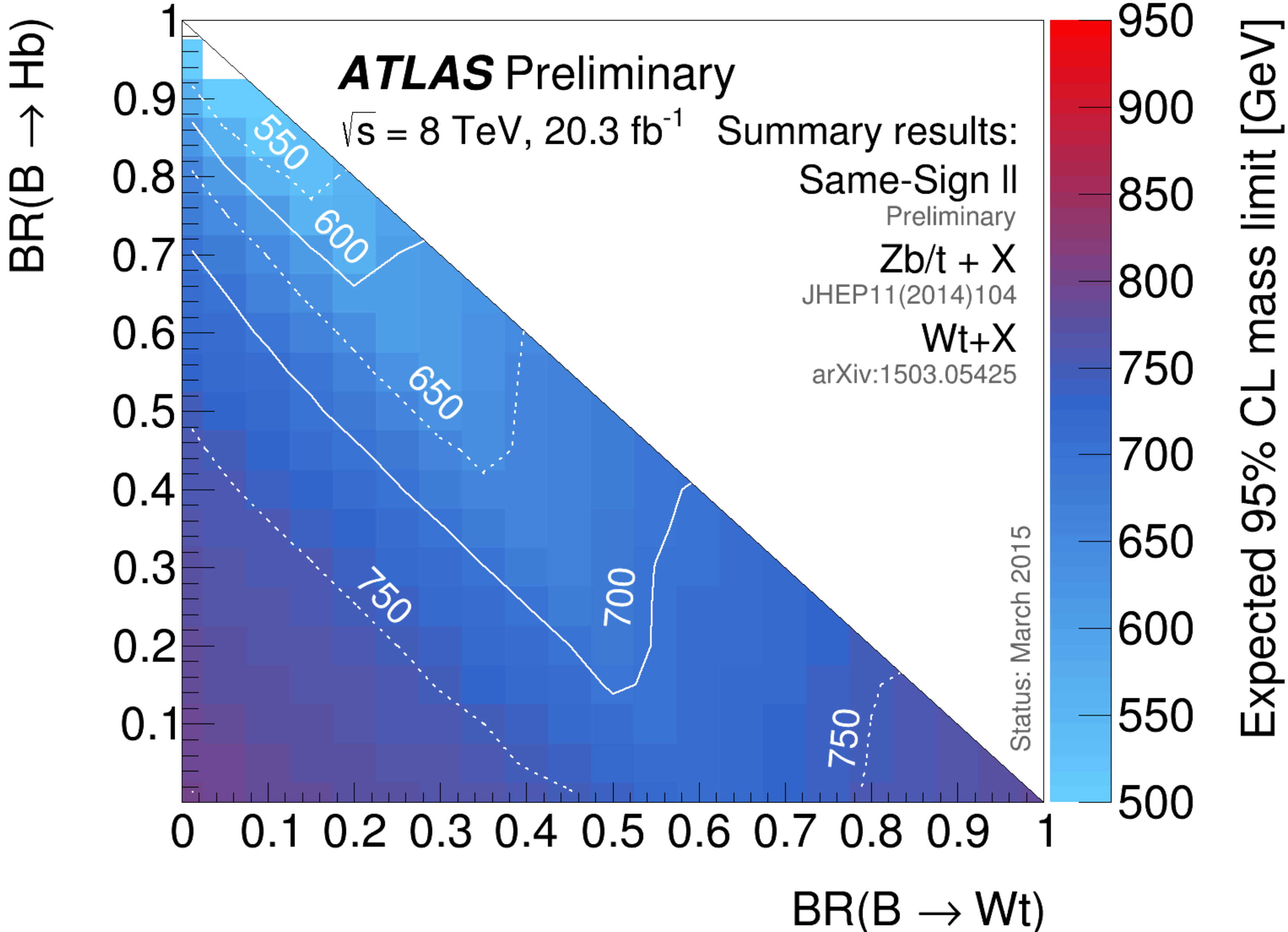
VLQ Limits – B pair production



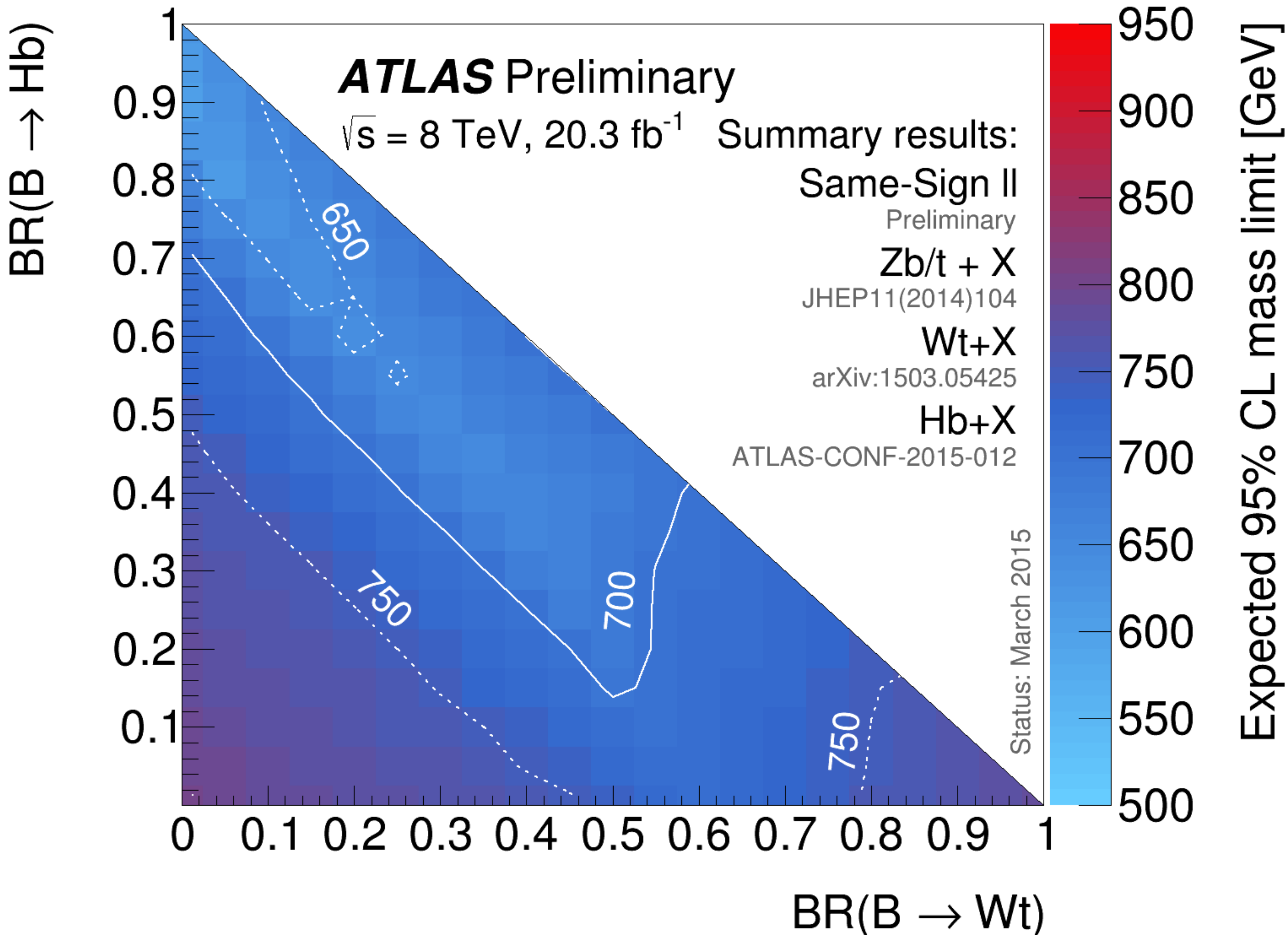
VLQ Limits – B pair production



VLQ Limits – B pair production

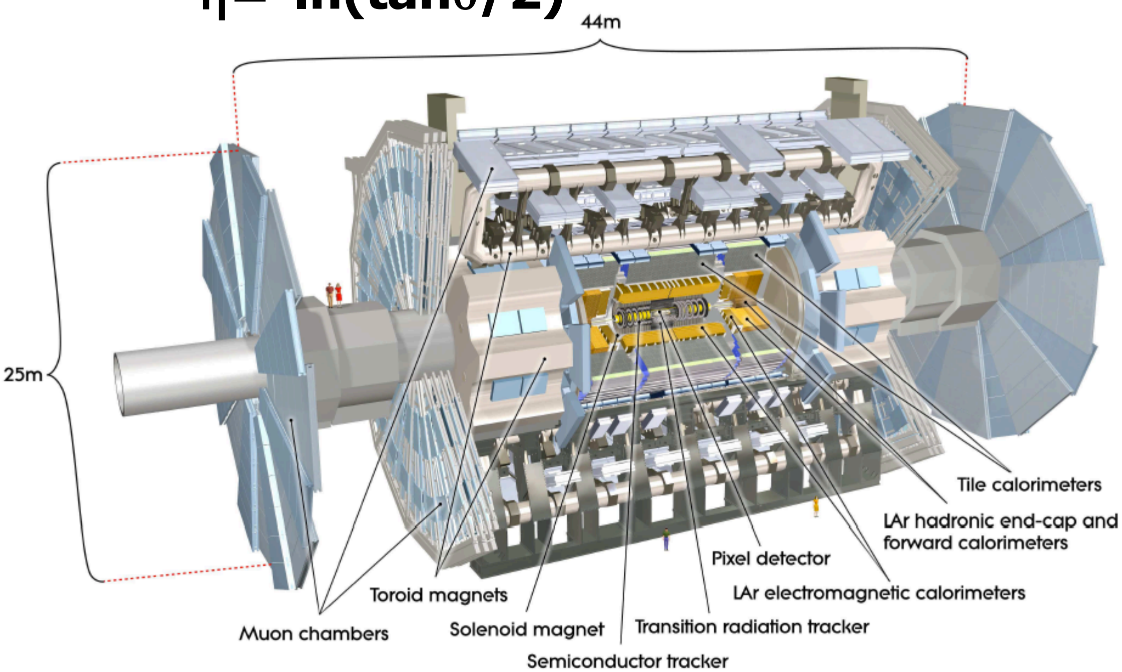


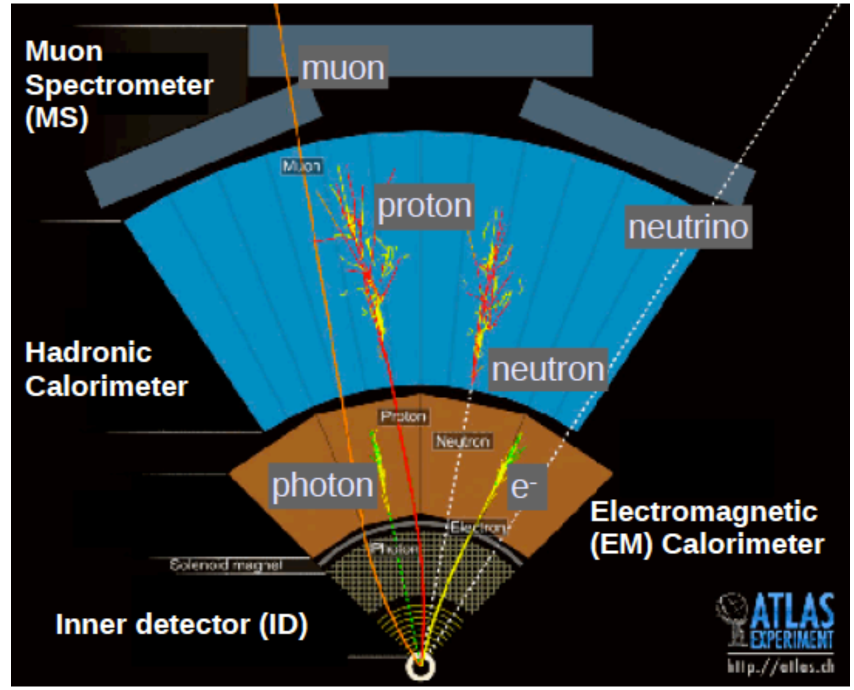
VLQ Limits – B pair production



ATLAS detector

$\eta = -\ln(\tan\theta/2)$



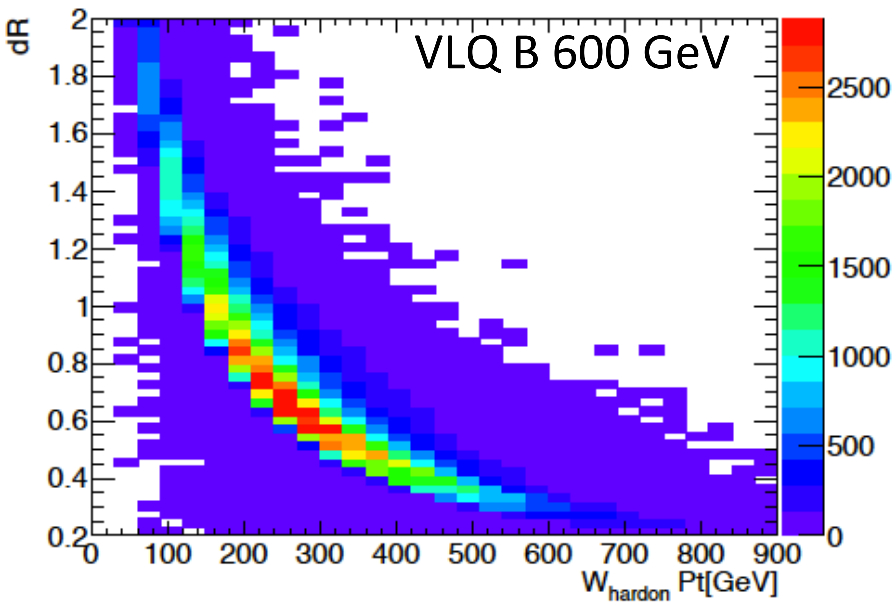


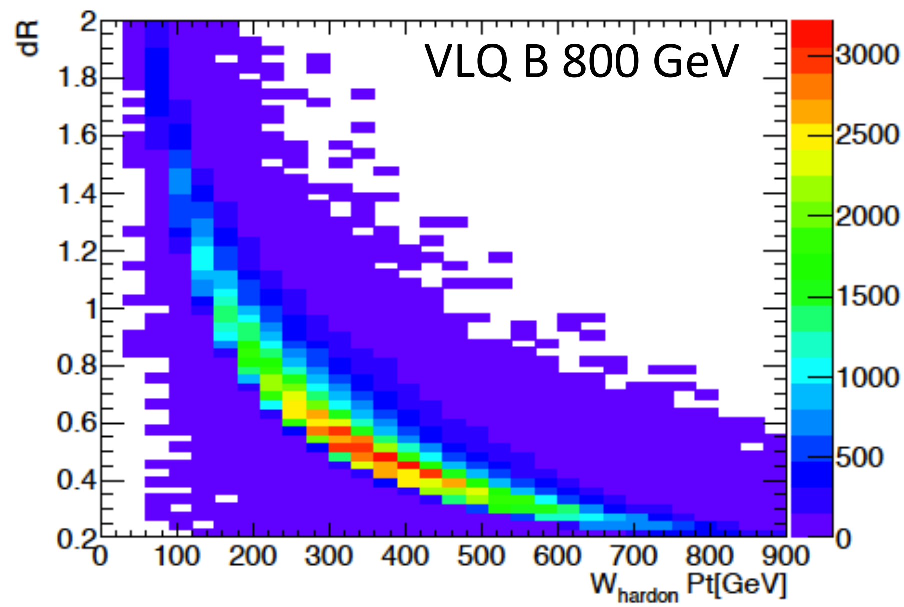
Challenge: search signatures at high p_T/E_T

- Electrons/photons: isolated energy in EM Calorimeter($|\eta|<2.47$)
- Muons: combined tracks from ID + MS ($|\eta|<2.0$)
- Neutrinos: total missing transverse energy of objects in calorimeter(with muon corrections)
- Jets: total transverse energy of objects in calorimeter

BB->Wt+X: W/Z boson tag

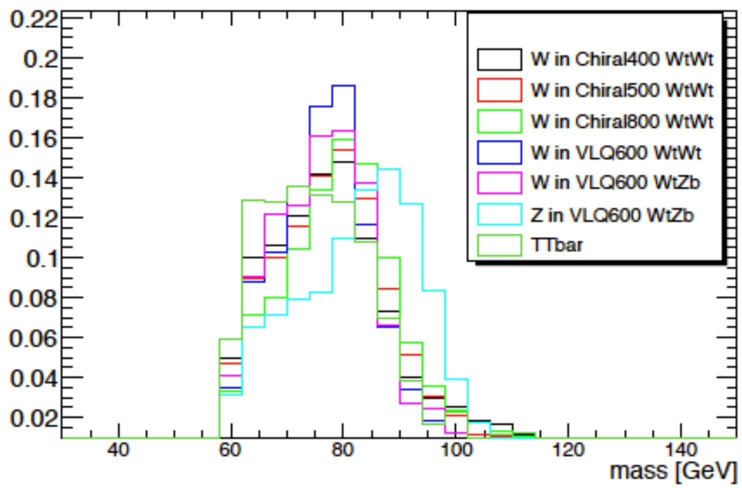
- Decay products from VLQ tend to have large transverse momentum
  - Decay products from W/Z could get collinear as $p_T(W/Z)$ gets large, or even merge into one single jet
  - $\Delta R(\text{jet, jet}) \approx 2 * m_W / p_T(W)$, $\Delta R = \text{sqrt}(\Delta\eta^2 + \Delta\phi^2)$

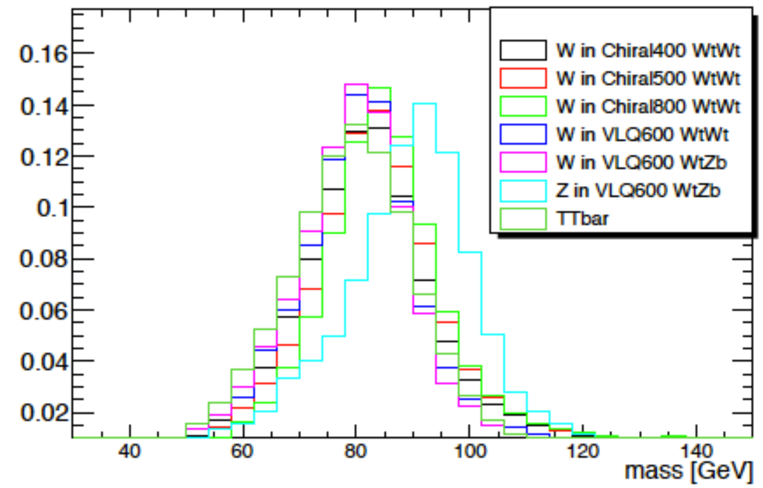


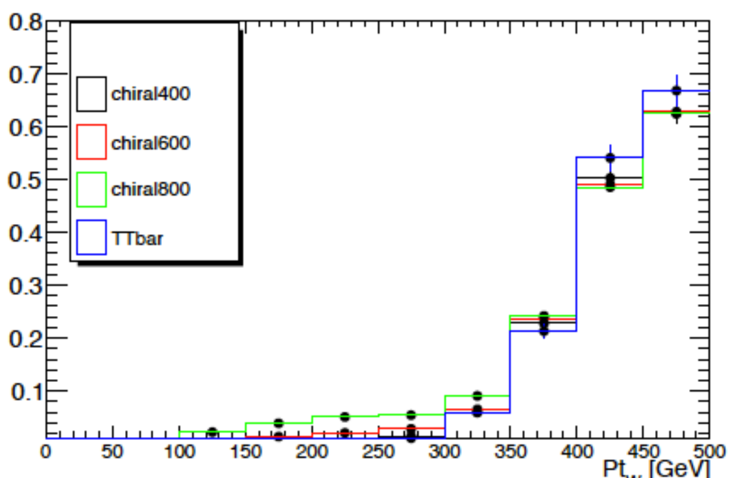


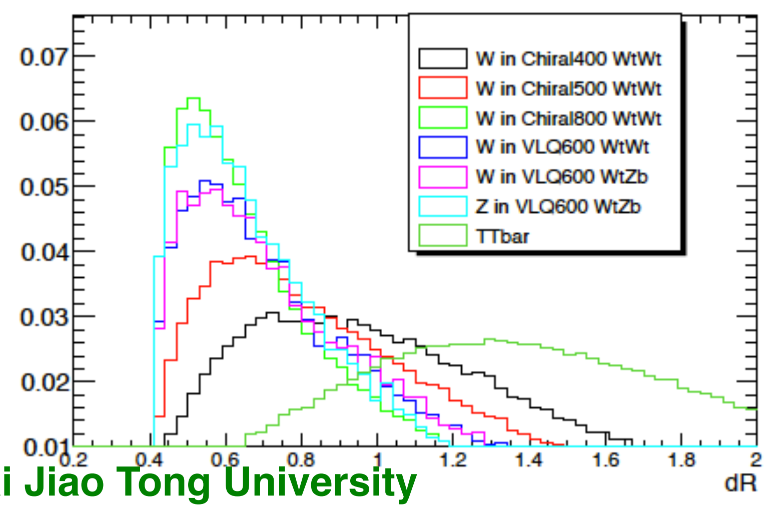
BB->Wt+X: W/Z boson tag

- **Single jet W: (had to drop it due to unavailable systematic error)**
  - p_T(antikt4) > 200 GeV
  - 60 GeV < mass(jet) < 110 GeV
- **Di-jet W:**
  - p_T(dijet) > 120 GeV
  - ΔR(dijet) < 1.0
  - 60 GeV < mass(dijet) < 110 GeV



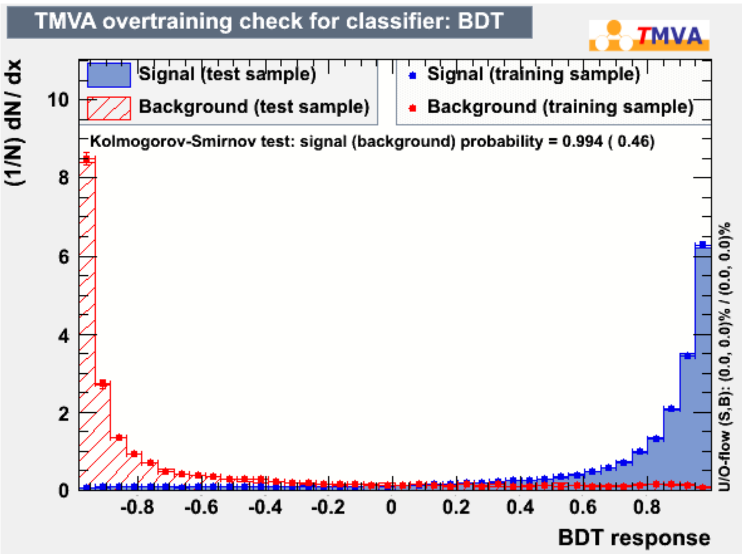


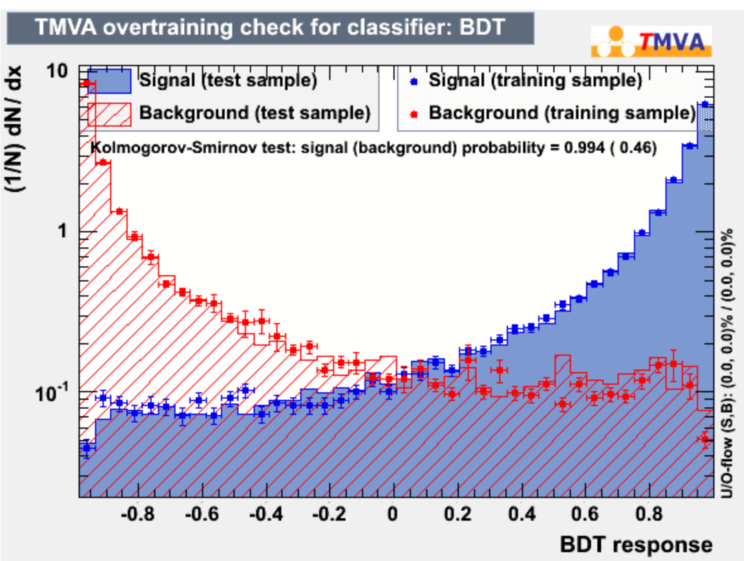


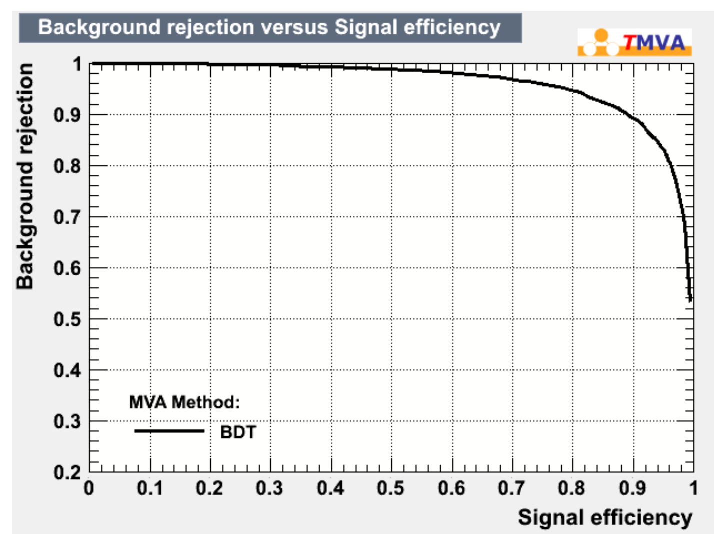


BB->Wt+X: BDT

- Selection: lepton, jet selection, triangle cut, HT>500 GeV, >=6 jets, >= 1 btag, >=1 W's
- Started with >30 variables and reduce to 12 variables that have high rankings and small correlation among them:
  - H_T
  - # of W's
  - # of jets
  - E of leading bjet
  - E_T^{miss}
  - p_T(lepton)
  - ΔR(lepton, leading b)
  - minΔR(lepton, hadronic W)
  - Average ΔR(jet, jet) from dijet W
  - pT of leptonic W
  - # of bjets
  - Mt of leptonic W

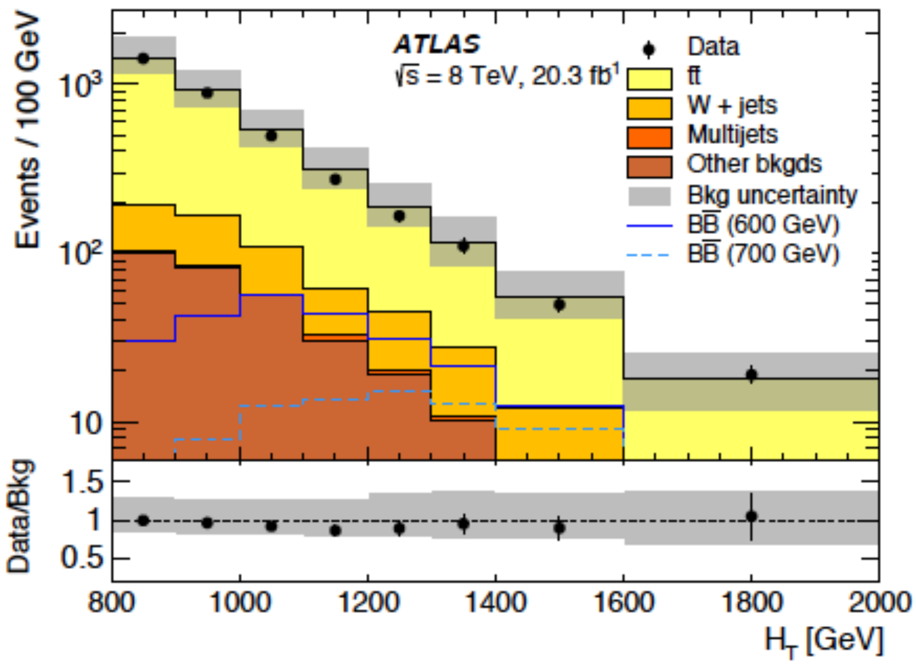




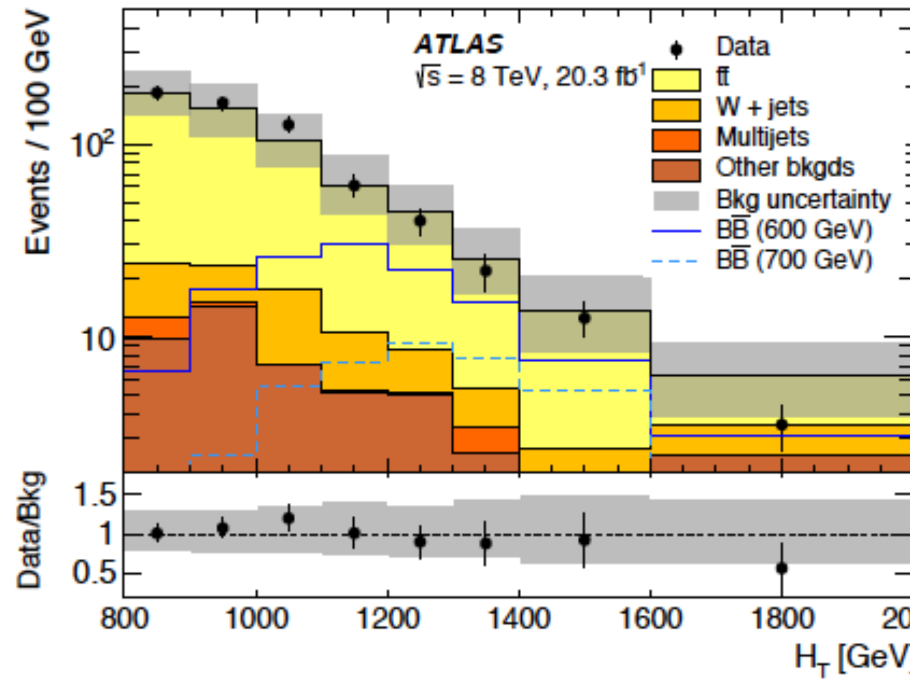


Signal region : cut-based

$N_W = 1$



$N_W \geq 2$



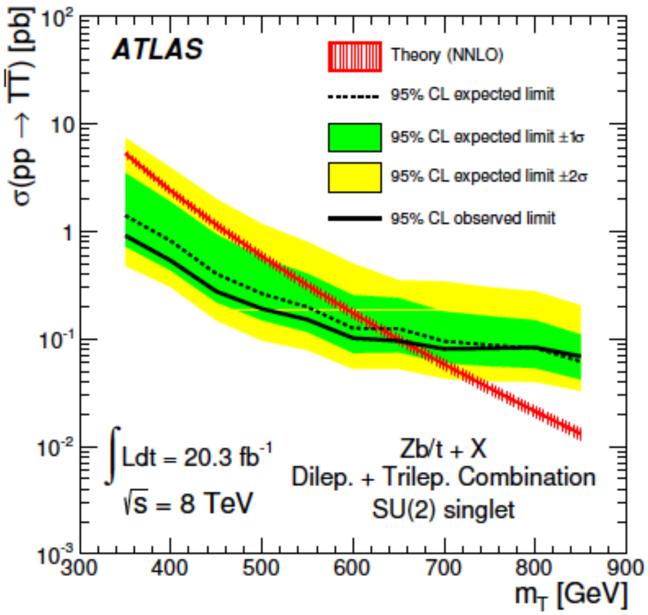
- These two H_T plots will be used to search for a signal and set limits
- The sensitivity mainly comes from $N_W \geq 2$, while $N_W = 1$ is more useful for constraining systematics

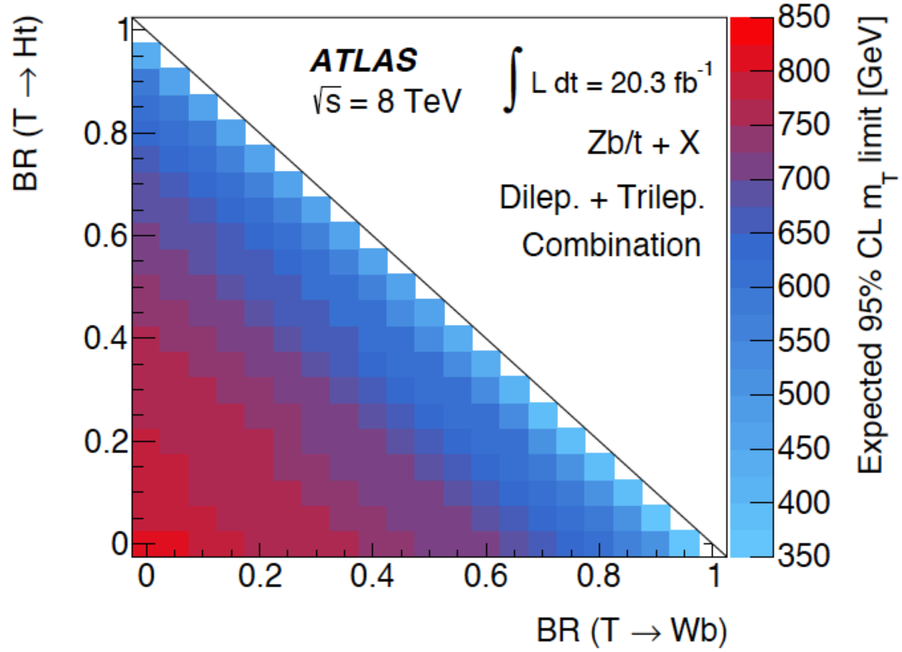
TT/BB->Zt/Zb+X

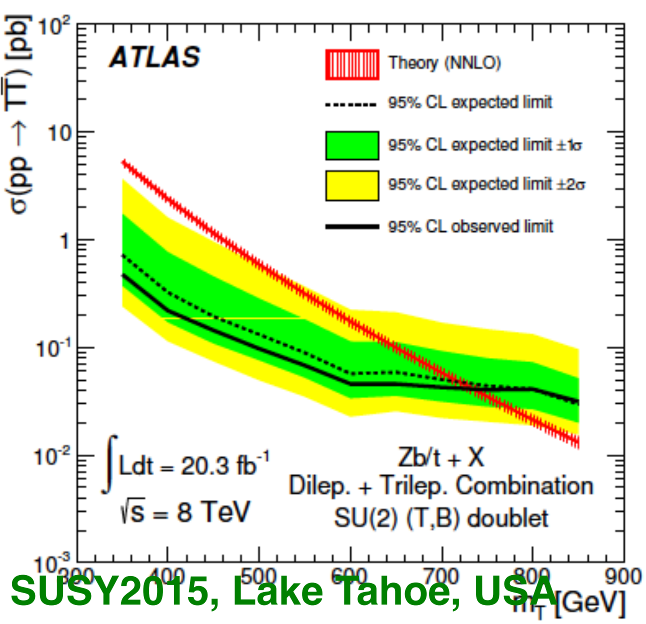
Observed(expected) limit at 95% CL:

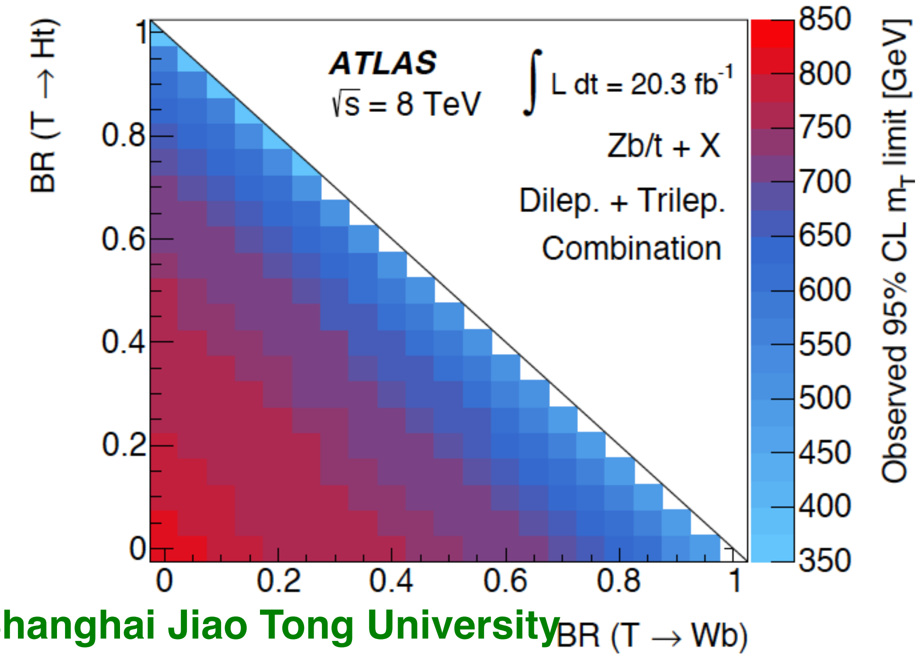
- **T singlet: m_T > 655(625) GeV**
- **T doublet: m_T > 735(720) GeV**

JHEP: http://arxiv.org/abs/1409.5500







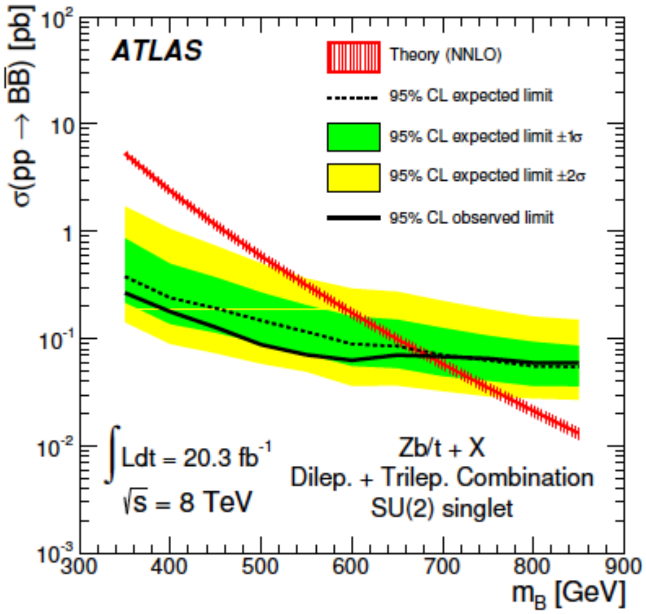


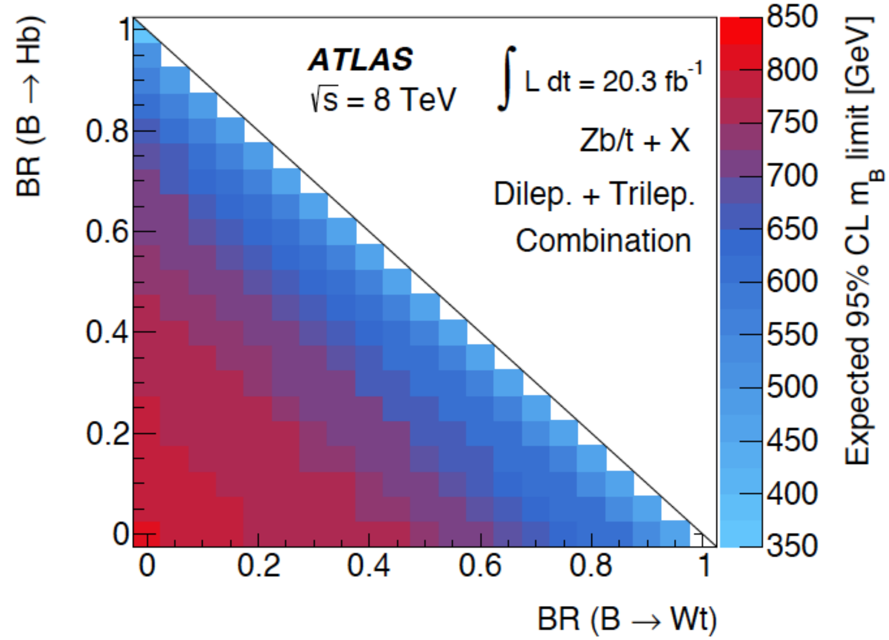
TT/BB->Zt/Zb+X

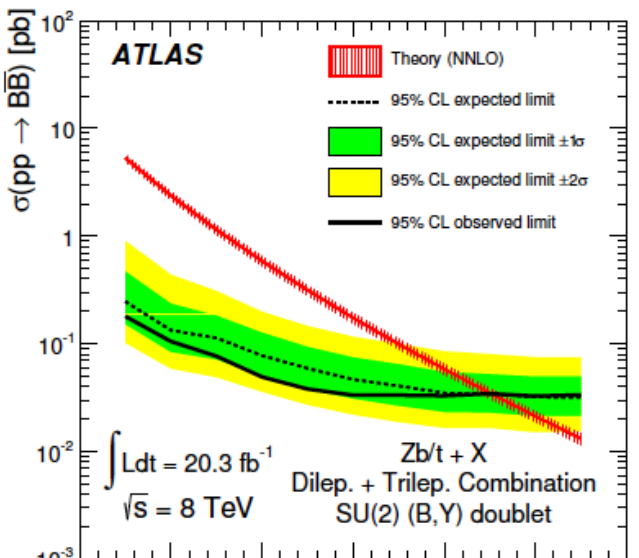
Observed(expected) limit at 95% CL:

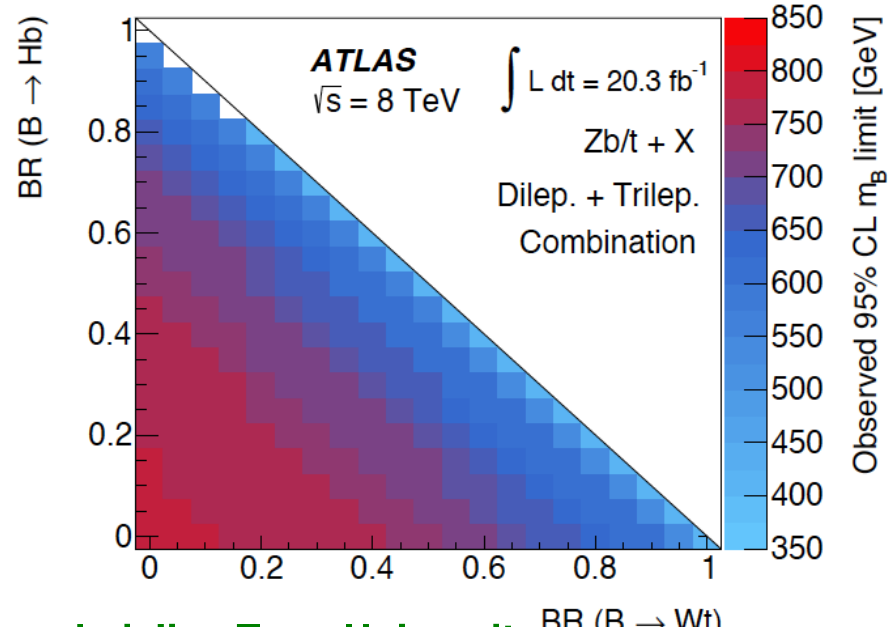
- **B singlet: m_B > 685(670) GeV**
- **B doublet: m_B > 755(755) GeV**

JHEP: http://arxiv.org/abs/1409.5500





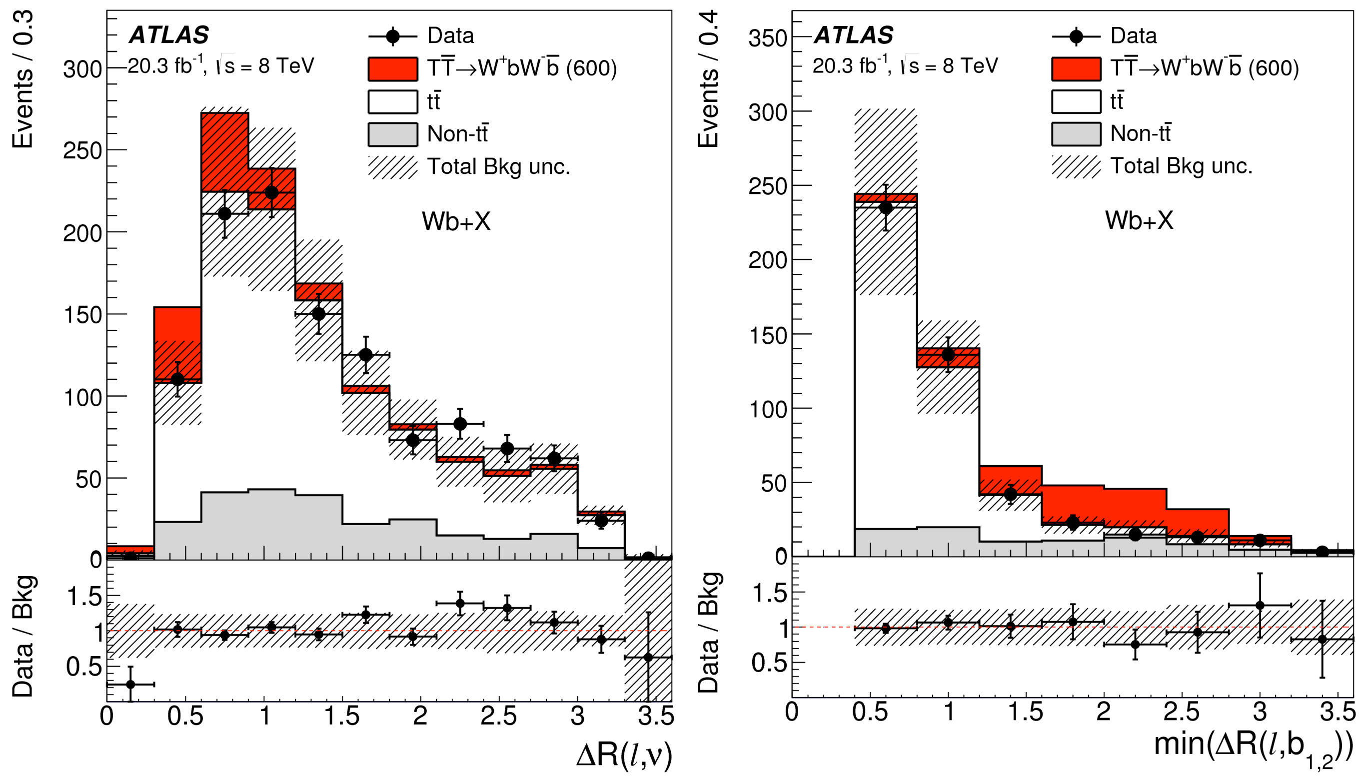




$T\bar{T}$->Wb+X

- **Further suppression of background using angular variables**
  - **ΔR(lepton,ν)<1.2**
  - **minΔR(lepton,$b_{1,2}$)>1.4**
  - **minΔR(W_{had},$b_{1,2}$)>1.4**

Selection	Requirements
Preselection	Exactly one electron or muon $E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T^W > 60$ GeV ≥4 jets, ≥1 b-tagged jets
Loose selection	Preselection ≥1 W_{had} candidate (type I or type II) $H_T > 800$ GeV $p_T(b_1) > 160$ GeV, $p_T(b_2) > 110$ GeV (type I) or $p_T(b_2) > 80$ GeV (type II) $\Delta R(\ell,\nu) < 0.8$ (type I) or $\Delta R(\ell,\nu) < 1.2$ (type II)
Tight selection	Loose selection $\min(\Delta R(\ell, b_{1,2})) > 1.4$, $\min(\Delta R(W_{had}, b_{1,2})) > 1.4$ $\Delta R(b_1,b_2) > 1.0$ (type I) or $\Delta R(b_1,b_2) > 0.8$ (type II) $\Delta m < 250$ GeV (type I) [see text for definition]



Same-sign leptons

Definition			Name	
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu,\ N_j \geq 2$				
$400 < H_{\mathrm{T}} < 700GeV$	$N_b = 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_{\mathrm{T}} \geq 700\ GeV$	$N_b = 1$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ3	
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100\ GeV$	SRVLQ4	
	$N_b = 2$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ5	SR4t2
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100\ GeV$	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ7	SR4t4
$e^{+}e^{+},\ e^{+}\mu^{+},\ \mu^{+}\mu^{+},\ N_j \in [2,4],\ \Delta\phi_{\ell\ell} > 2.5$				
$H_{\mathrm{T}} > 450\ GeV$	$N_b \geq 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40\ GeV$	SRttee, SRtt$e\mu$, SRtt$\mu\mu$	

Same-sign leptons

	SRVLQ0	SRVLQ1/SR4t0	SRVLQ2/SR4t1
$t\bar{t}W/Z$	$16.2 \pm 0.3 \pm 7.0$	$12.6 \pm 0.3 \pm 5.4$	$1.24 \pm 0.09 \pm 0.53$
$t\bar{t}H$	$2.5 \pm 0.1 \pm 0.3$	$1.8 \pm 0.1 \pm 0.2$	$0.26 \pm 0.03 \pm 0.05$
Dibosons	$11.2 \pm 0.6 \pm 2.8$	$0.95 \pm 0.19 \pm 0.25$	$0.07 \pm 0.12 \pm 0.05$
Fake/Non-prompt	$42.1 \pm 5.4 \pm 24.6$	$8.61 \pm 2.34 \pm 5.02$	$1.17 \pm 0.82 \pm 0.68$
Q mis-Id	$20.8 \pm 0.7 \pm 5.2$	$15.1 \pm 0.6 \pm 3.5$	$0.74 \pm 0.11 \pm 0.18$
Other bkg.	$1.76 \pm 0.13 \pm 0.17$	$0.75 \pm 0.04 \pm 0.10$	$0.10 \pm 0.08 \pm 0.03$
Total bkg.	$94.5 \pm 5.4 \pm 24.9$	$40.0 \pm 2.4 \pm 7.3$	$3.6 \pm 0.9 \pm 0.8$
Data	107	54	6
p-value	0.36	0.12	0.24

	SRVLQ3	SRVLQ4
$t\bar{t}W/Z$	$2.07 \pm 0.10 \pm 0.89$	$3.14 \pm 0.13 \pm 1.35$
$t\bar{t}H$	$0.40 \pm 0.04 \pm 0.07$	$0.57 \pm 0.05 \pm 0.07$
Dibosons	$2.36 \pm 0.29 \pm 0.61$	$2.03 \pm 0.25 \pm 0.49$
Fake/Non-prompt	$3.09 \pm 1.29 \pm 1.80$	$4.24 \pm 1.59 \pm 2.47$
Q mis-Id	$1.72 \pm 0.22 \pm 0.63$	$1.45 \pm 0.17 \pm 0.52$
Other bkg.	$0.22 \pm 0.08 \pm 0.03$	$0.41 \pm 0.10 \pm 0.06$
Total bkg.	$9.87 \pm 1.35 \pm 2.10$	$11.9 \pm 1.6 \pm 2.8$
Data	7	10
p-value	0.83	0.71

Same-sign leptons

	SRVLQ5/SR4t2	SRVLQ6/SR4t3	SRVLQ7/SR4t4
$t\bar{t}W/Z$	$1.87 \pm 0.09 \pm 0.80$	$2.46 \pm 0.11 \pm 1.06$	$0.57 \pm 0.05 \pm 0.25$
$t\bar{t}H$	$0.31 \pm 0.04 \pm 0.05$	$0.44 \pm 0.04 \pm 0.06$	$0.08 \pm 0.02 \pm 0.02$
Dibosons	$0.33 \pm 0.14 \pm 0.10$	$0.04 \pm 0.12 \pm 0.03$	$0.00 \pm 0.12 \pm 0.00$
Fake/Non-prompt	$1.03 \pm 0.97 \pm 0.60$	$0.00 \pm 1.02 \pm 0.28$	$0.04 \pm 0.83 \pm 0.24$
Q mis-Id	$1.17 \pm 0.16 \pm 0.38$	$1.09 \pm 0.14 \pm 0.34$	$0.30 \pm 0.09 \pm 0.10$
Other bkg.	$0.16 \pm 0.08 \pm 0.02$	$0.23 \pm 0.08 \pm 0.05$	$0.14 \pm 0.08 \pm 0.08$
Total bkg.	$4.9 \pm 1.0 \pm 1.0$	$4.3 \pm 1.1 \pm 1.1$	$1.1 \pm 0.9 \pm 0.4$
Data	6	12	6
p-value	0.46	0.029	0.036