Search for Heavy Quarks at ATLAS

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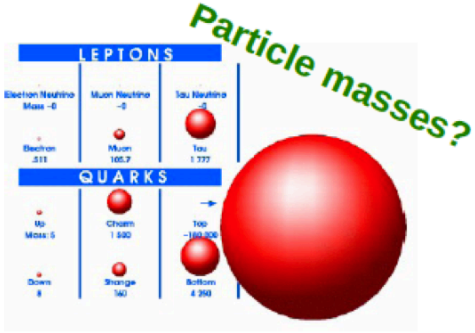
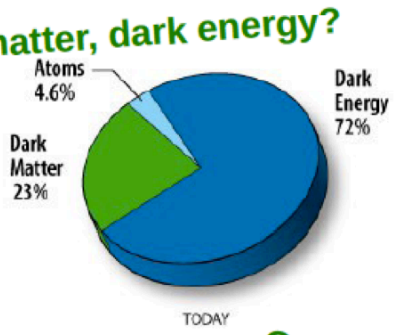
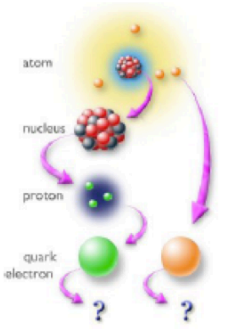
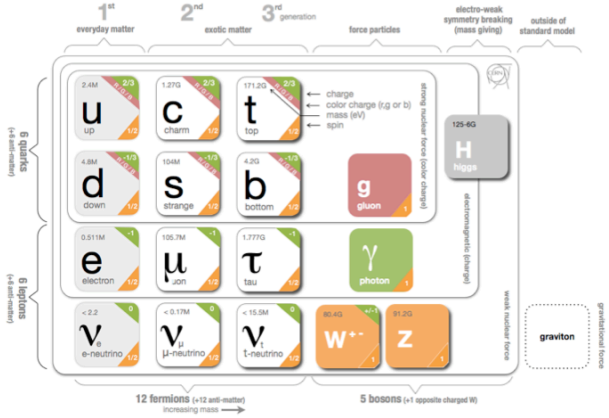
Introduction







- **The last missing piece of Standard Model(SM) - Higgs boson(125 GeV) was discovered. However, SM still can not explain some questions**
  - **Mass patterns of quarks and leptons**
  - **Dark matter and dark energy**
  - **Matter-antimatter asymmetry**
  - **Naturalness problem**
  - **……**



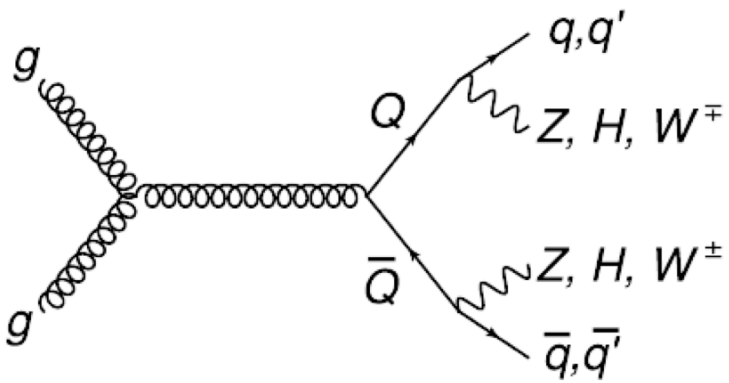
- **Many models beyond SM(BSM) predict heavy quarks:**
  - **Vector-like quarks(VLQ) are under study: left- and right-handed components transform identically under the $SU(2)_L$ weak isospin gauge symmetry**
  - **VLQ couples strongly to 3rd generation quarks**

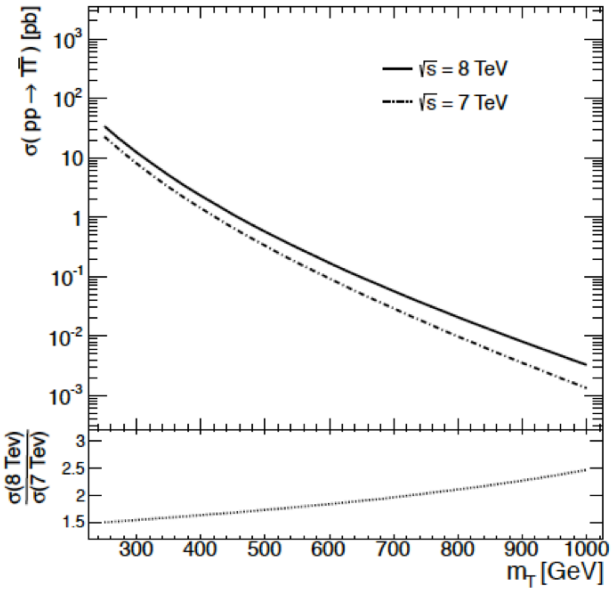
Vector-Like Quarks

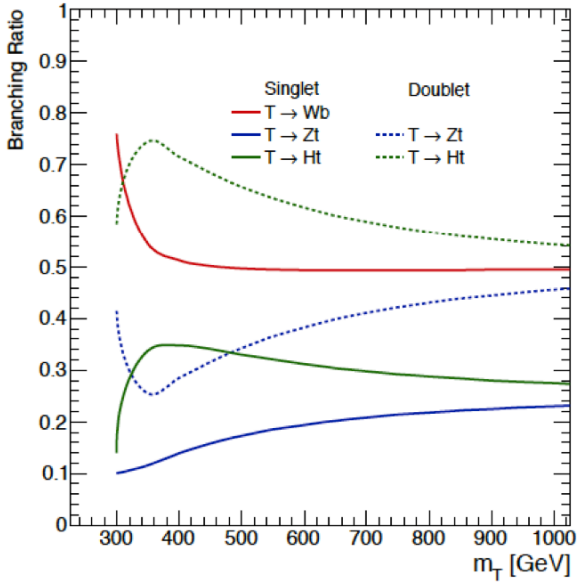
- **Chiral t', b' decay into Wb and Wt 100%, respectively, while VLQ quarks can have up to 3 decay modes**
  - **T -> Wb, Zt, or Ht**
  - **B -> Wt, Zb, or Hb**

- **Plan to cover all decays without assumption on Branching Ratios**
  - **TT -> WbWb, ZtZt, HtHt, WbZt, WbHt, ZtHt**
  - **BB -> WtWt, ZbZb, HbHb, WtZb, WtHb, ZbHb**

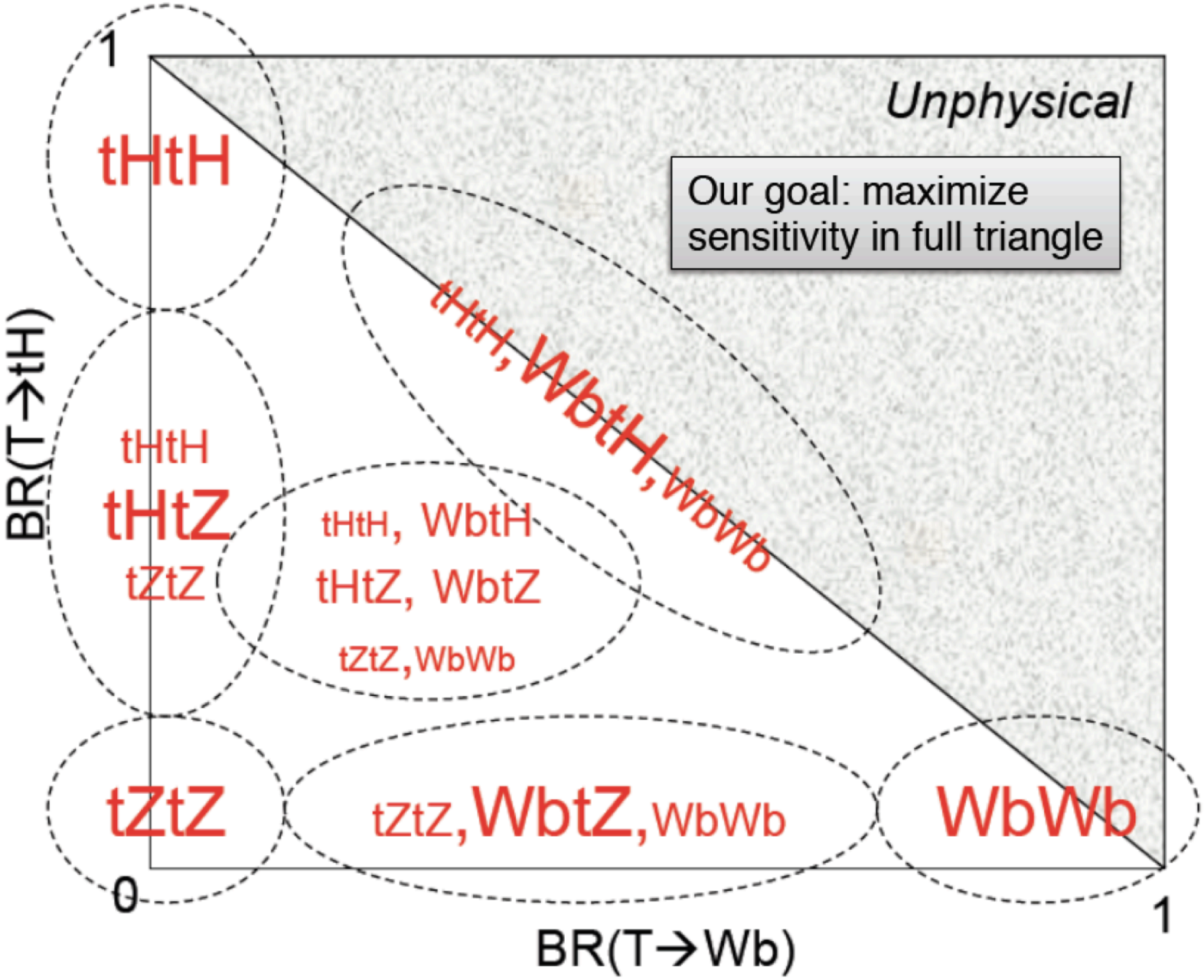
- **Various search channels that use final signatures containing exactly one lepton + jets**
  - **T T -> Ht+X**
  - **T T -> Wb+X**
  - **BB -> Wt+X**
  - **T T/BB -> Zt/Zb+X**







VLQ Pair production: T T



VLQ analyses(pair production) at ATLAS

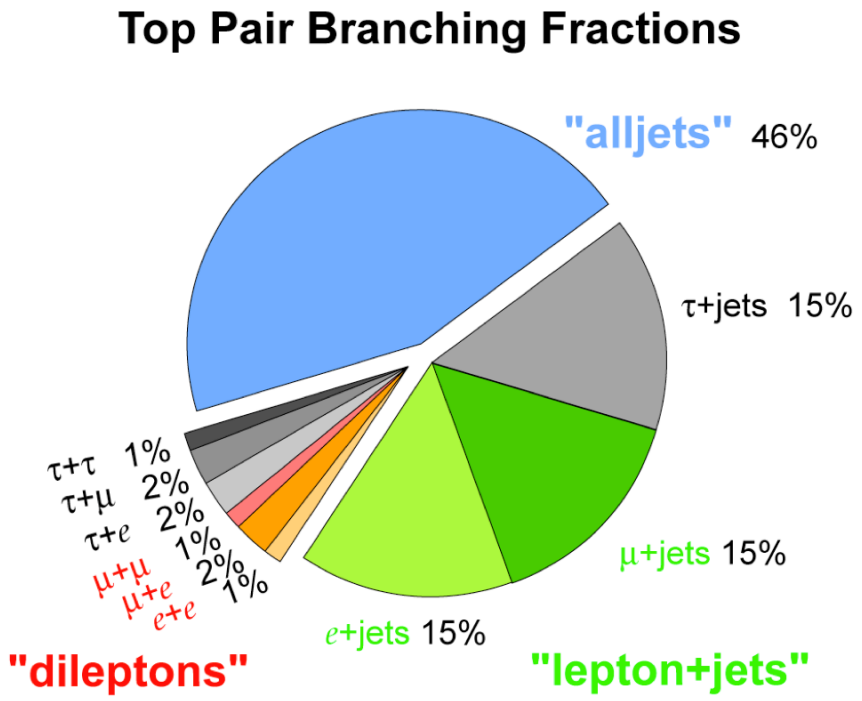
- **Lepton+jets:**
  - **Wt+X(what I am working on):**
    - Optimized for BB->WtWt->W(Wb)W(Wb)
      - 1 lepton + MET + ≥ 6-8 jets
    - Also sensitive to WtHb, WtZb
  - **Ht+X:**
    - Sensitive to HtHt, HtZt & HtWb
      - H->bb is dominant
  - **Wb+X:**
    - Optimized for TT->WbWb, the previous Chiral t' signature
    - 1 lepton + MET + ≥ 4 jets, ≥ 2 bjets
- **Zt/Zb+X**
- **Same-Sign leptons**

Final Signatures of Decay Modes

- **Dileptonic**
  - Very clear signature
  - Relatively low branching fraction
  - Ambiguity in invariant mass reconstruction due to two undetected neutrinos

- **Lepton+jets(semileptonic)**
  - Clear signature
  - High branching fraction

- **Fully hadronic(not probed so far)**
  - Busy environment: lots of jets
  - Huge QCD background
  - High branching fraction



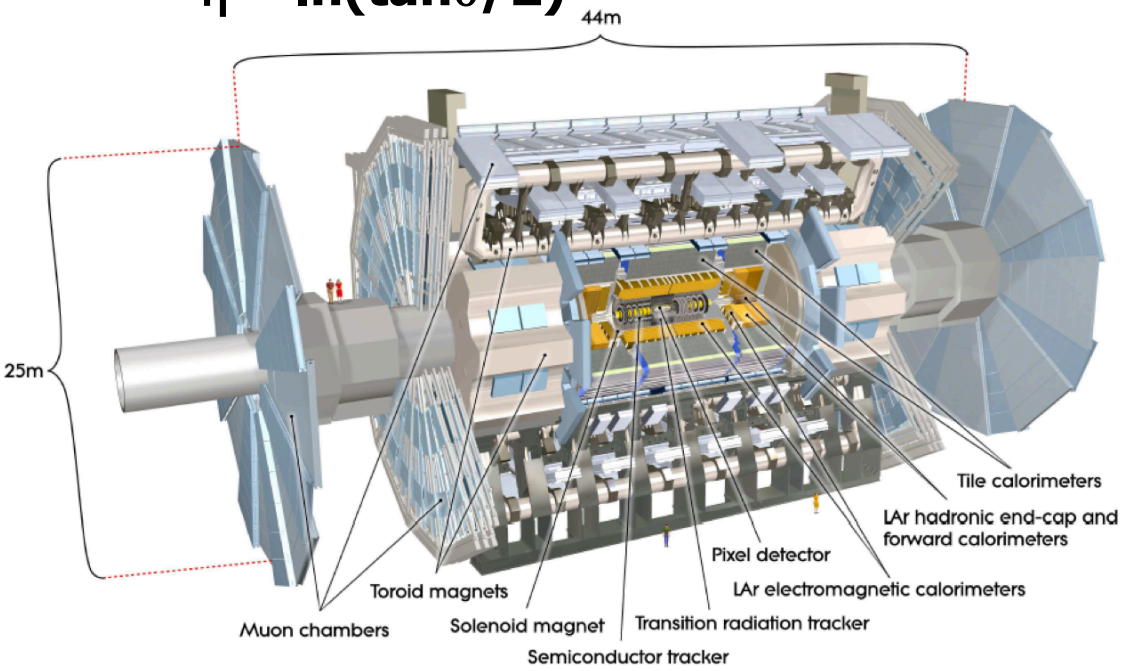
Large Hadron Collider(LHC)

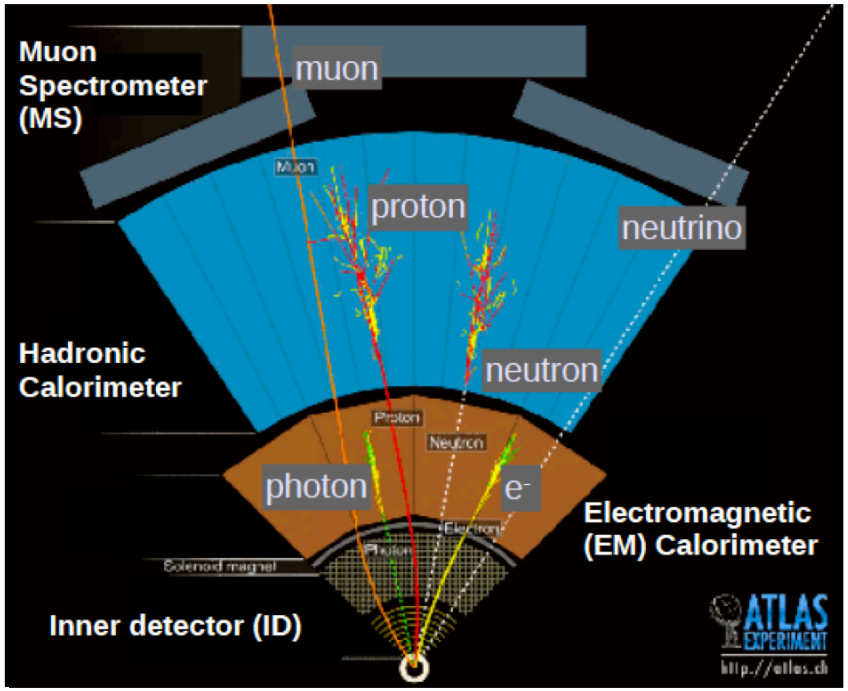
- **Proton-proton collider, with design collision energy = 14 TeV**
  - **Center-of-mass energy: 0.9TeV(2009), 7TeV(2010, 2011), 8TeV(2012)**
- **Six detectors, two of which are large general purpose detectors**
  - **ATLAS: balanced performance across sub-systems; excellent jet and E_T^{miss} resolution**
  - **CMS: high magnetic field(3.8T); excellent tracker and EM calorimeter**
- **Data collected**
  - **~5 fb^{-1} (2011), 7 TeV**
  - **~20 fb^{-1} (2012), 8TeV**

★: Where I used to live from 2009-2014, right next to ALICE

Introduction

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



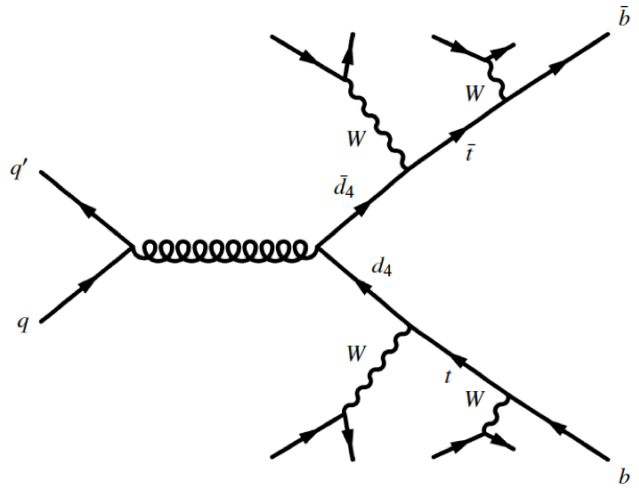


Challenge: search signatures at high p_T/E_T

- 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

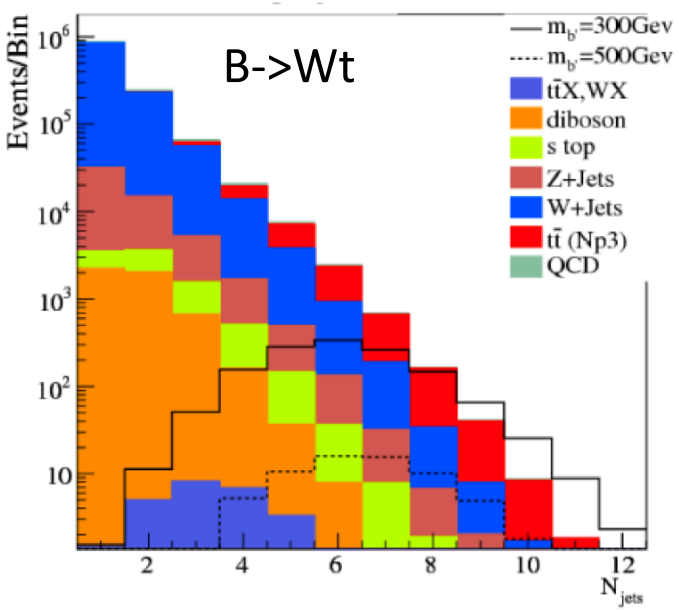
- Search for vector-like heavy down-type quark B in pair production with 8TeV(20fb^{-1}):
  - BB->tWtW->WWbWWb->lepton+ν+8jets
  - BB->tWbZ->WWbZb->lepton+ν+6jets



- **Selection:**
  - High p_T isolated lepton(e/μ) ; high p_T jets
  - High E_t^{miss}, ……
  - Main variables:
    - HT = p_T(lepton) + E_T^{miss} + p_T(selected jets), # of jets, # of W's

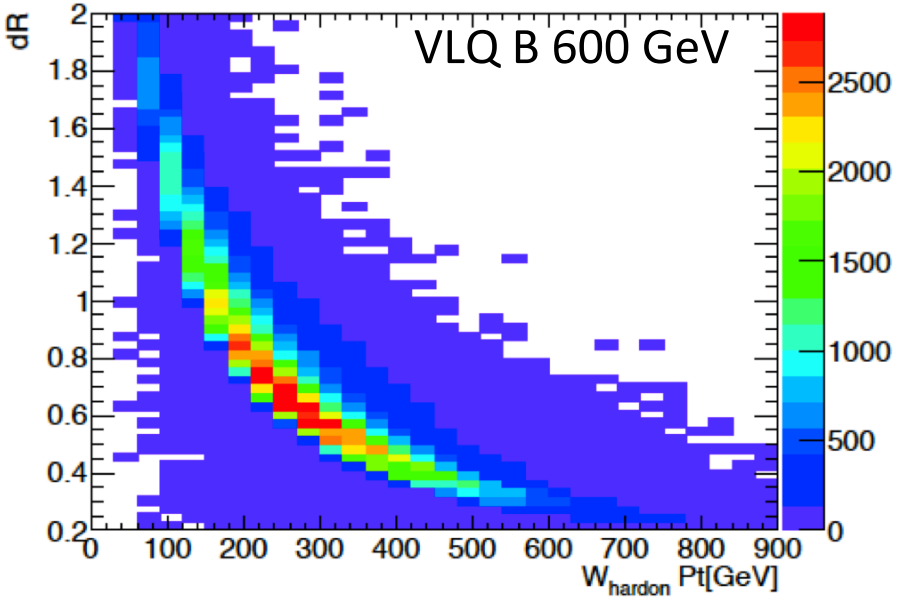
- **Challenge:**
  - Not easy to remove ttbar+jets due to event topology close to signal
  - Difficult to efficiently reconstruct b' candidate
  - Low xsection of signal: 0.33pb(500 GeV), 0.001(800 GeV)
  - Modeling of high jet multiplicity
  - Large systematics: Jet energy scale, theory model, …

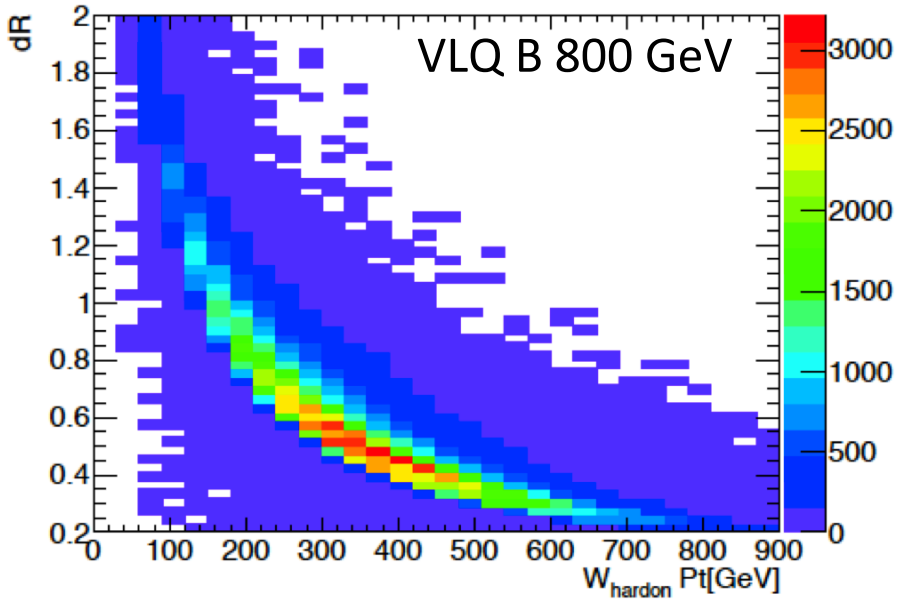
- **Two approaches:**
  - Cut-based
  - Using TMVA – BDT



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

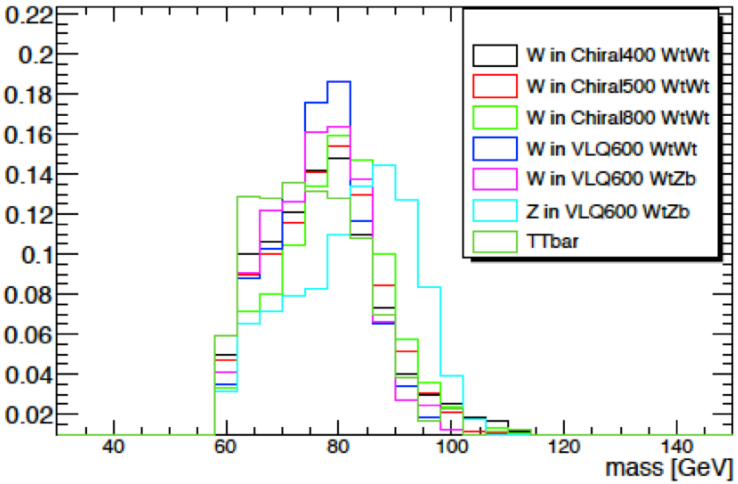
- **Decay products from VLQ tend to have large transverse momentum**
  - **Decay products from W/Z could get collinear as p_T(W/Z) gets large, or even merge into one single jet**
  - **$\Delta R(jet, jet) \approx 2*m_W/p_T(W)$, $\Delta R=sqrt(\Delta\eta^2+\Delta\phi^2)$**

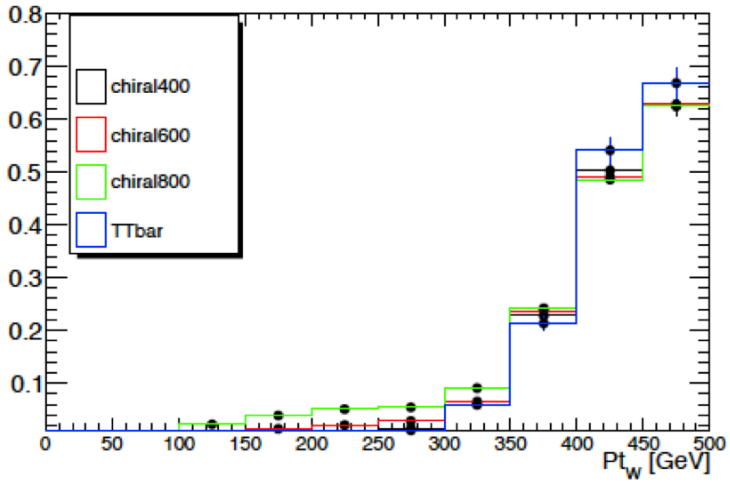




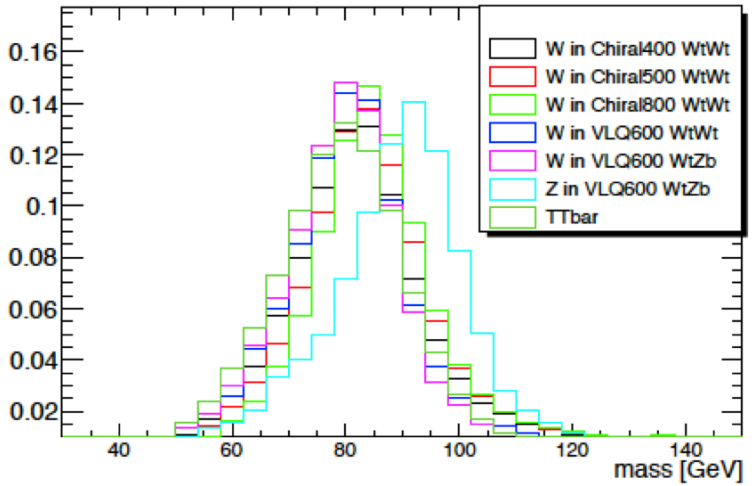
BB->Wt+X: W/Z boson tag

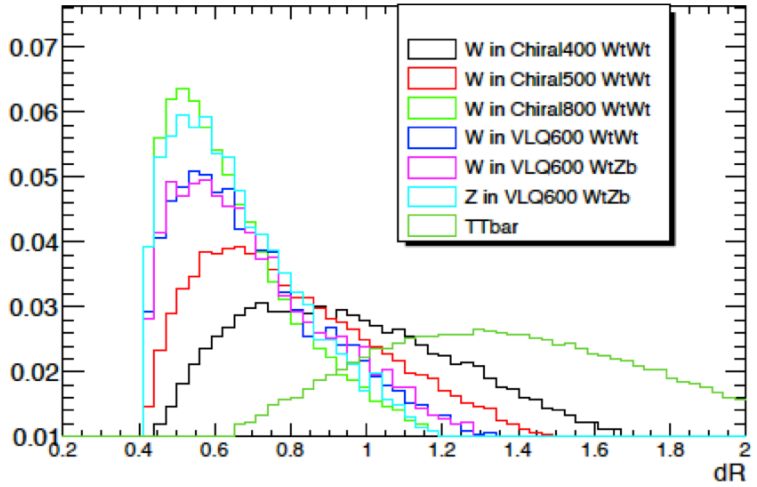
- **Single jet W: (decided to drop it, see later slide)**
  - p_T(antikt4) > 200 GeV
  - 60 GeV < mass(jet) < 110 GeV





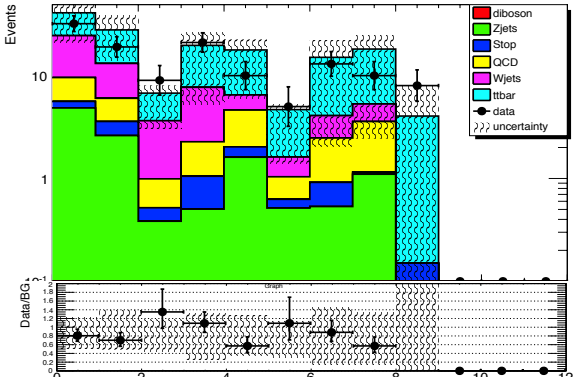
- **Di-jet W:**
  - p_T(dijet) > 120 GeV
  - ΔR(dijet) < 1.0
  - 60 GeV < mass(dijet) < 110 GeV





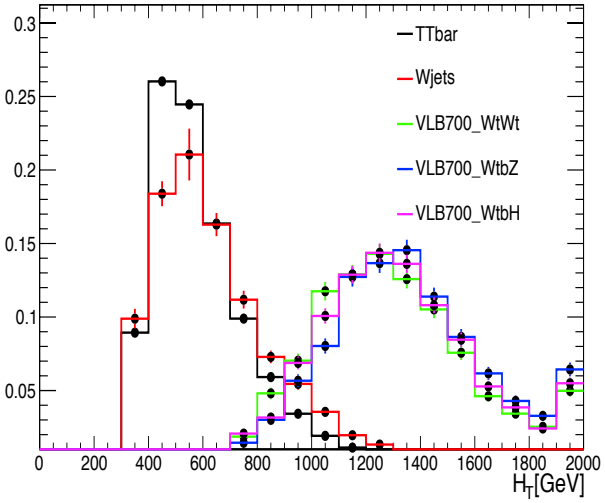
Optimization and Discriminant

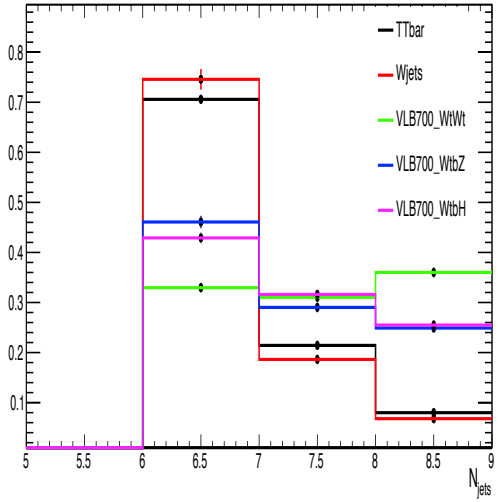
- N_{jets} vs N_W after selection(1 lepton; >=6 jets; >=1 bjet) was used in previous search
  - 9-bins was originally used as in the right-hand side plot
  - 12 and 6 bins were also tried
  - H_T cut was optimized for different binning choices
  - Cuts on other variables such as leptonic boson pT, objects relative angles were also tried as well to optimize signal/bkg

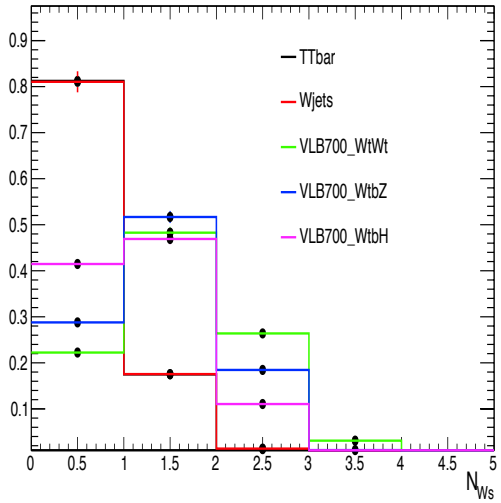


- H_T spectrum in different N_W bins(1, >=2) turns out very effective discriminant(expected sensitivity) from recent optimization
  - **Currently using H_T in 2 channels(1W, >=2 W's), H_T>800 GeV after trying different HT cuts and N_W binnings**

9bins:
6jets: 0W, 1W, >=2W's
7jets: 0W, 1W, >=2W's
>=8jets: 0W , 1W, >=2W's

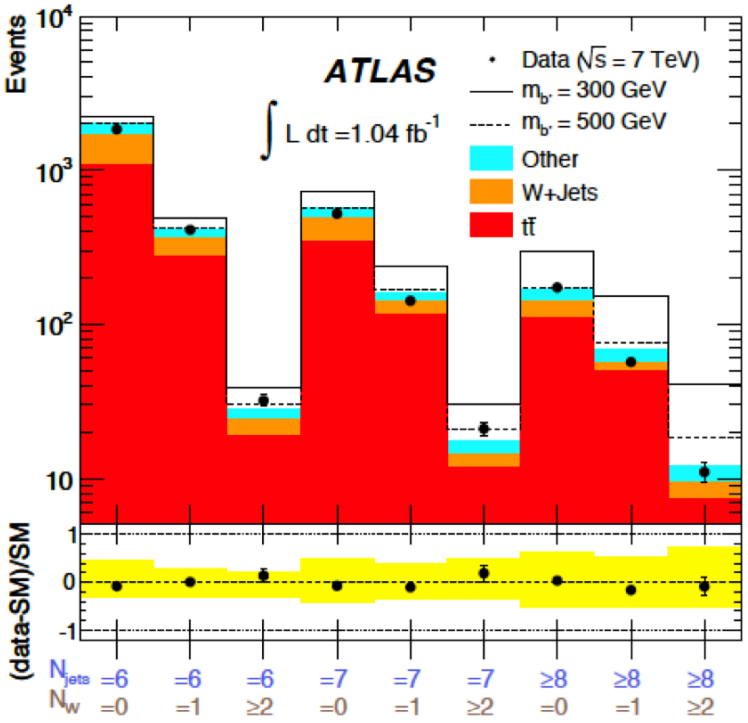


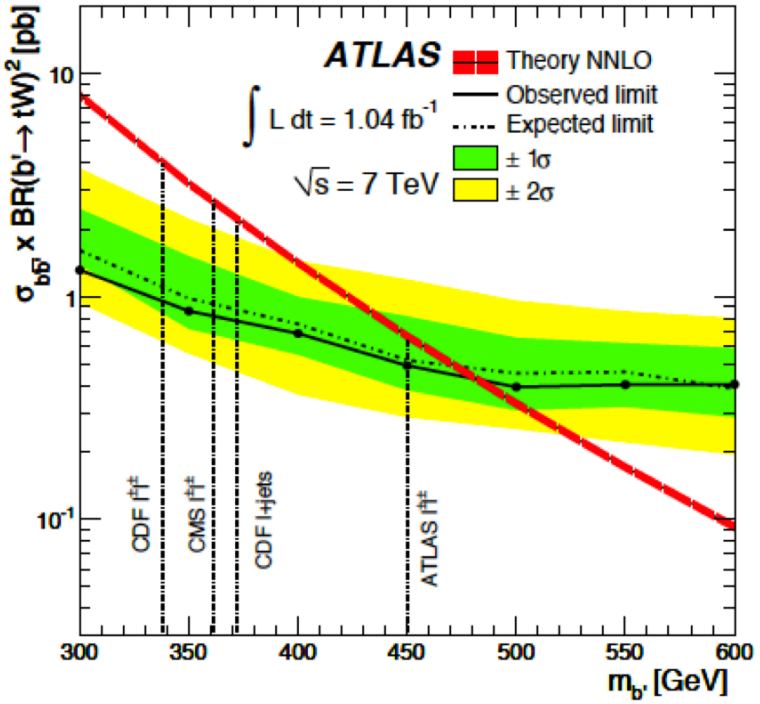




BB->Wt+X: Cut-based

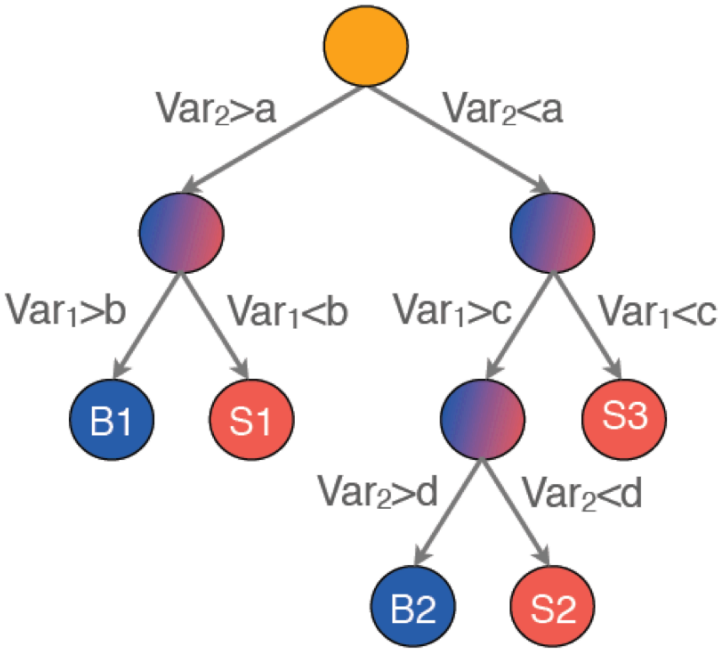
- **Previous result @7 TeV was for chiral b'->Wt->lepton+jets**
- **Discriminant: N_{jets} vs N_W**
- **Limit setting: CL_S, using LLR = $-2\log(L_{s+b}/L_b)$**
- **Observed(expected) limit at 95% CL:**
  - **Chiral: m_B > 480(470) GeV**





BB->Wt+X: BDT

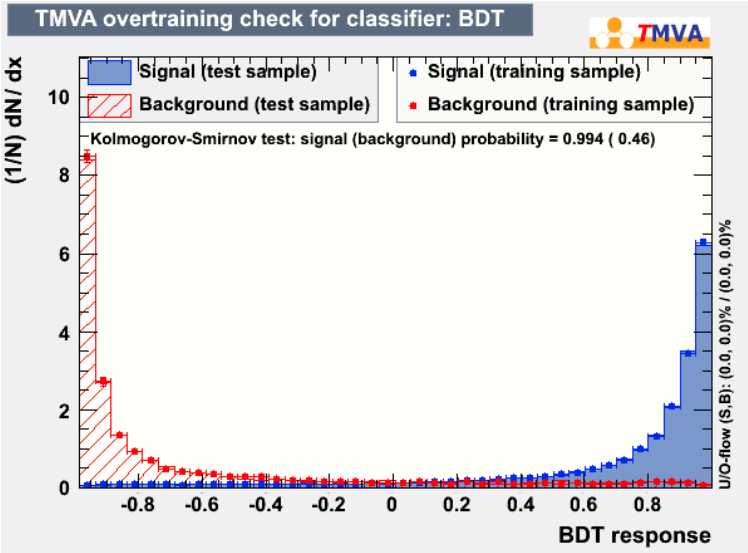
- B->Wt->WWb makes it extremely hard to reconstruct the invariant mass of B
  - Discrimination between signal and background using H_T, N_{jets}, N_W, etc. are not as good as using mass
- Turned to use Multi-Variate-Analysis(MVA), which combines info from a set of less powerful variables
  - Boosted Decision Tree(BDT) is used
    - Developed by Haijun Yang, Byron Roe and Ji Zhu

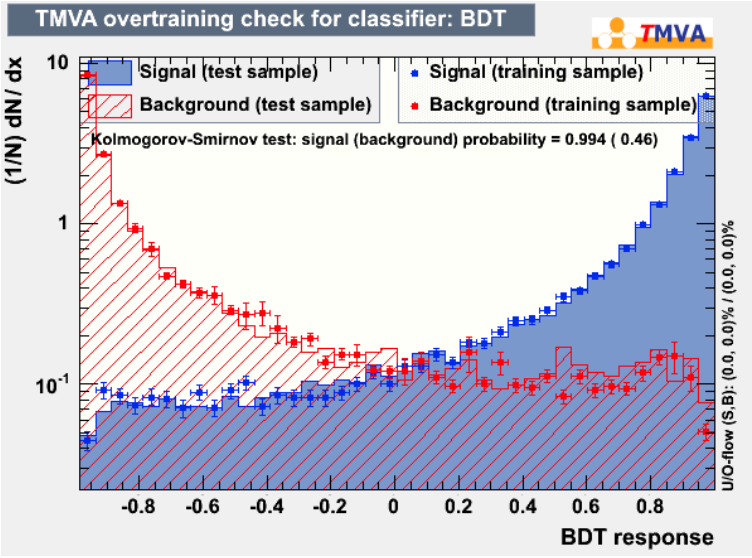


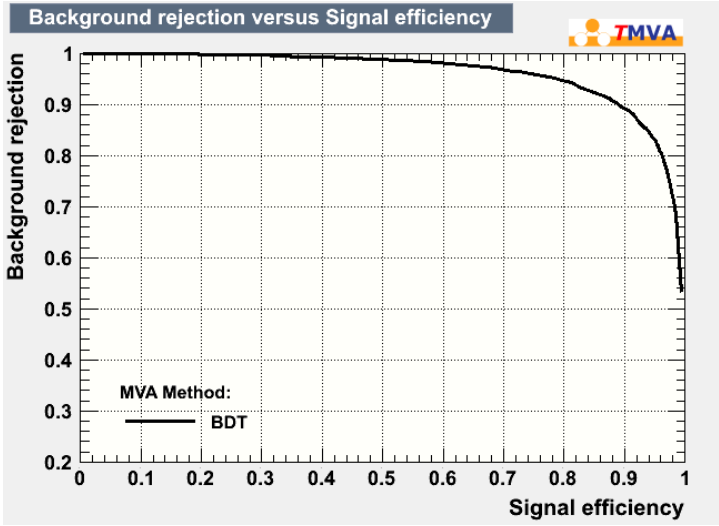
BB->Wt+X: BDT

- **Selection: lepton, jet selection, triangle cut, HT>500 GeV, >=6 jets, >= 1 btag, >=1 W's**

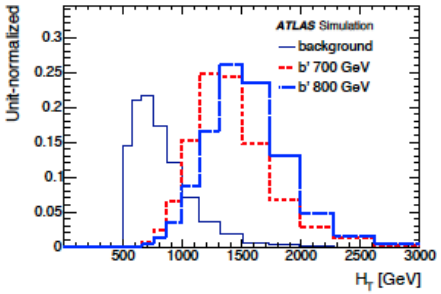
- **Started with >30 variables and reduce to 12 variables that have high rankings and small correlation among them:**
  - H_T
  - # of W's
  - # of jets
  - E of leading bjet
  - E_T^{miss}
  - p_T(lepton)
  - ΔR(lepton, leading b)
  - minΔR(lepton, hadronic W)
  - Average ΔR(jet, jet) from dijet W
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

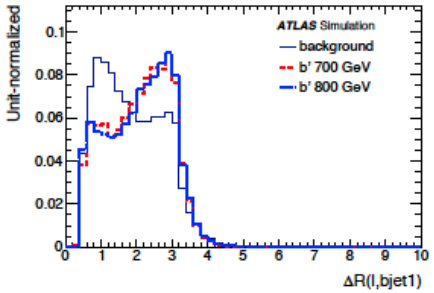


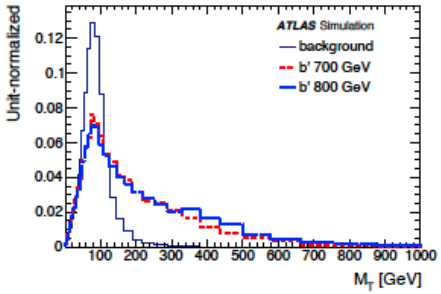


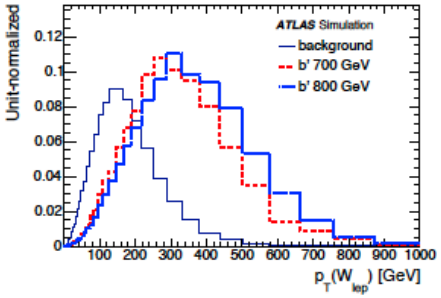


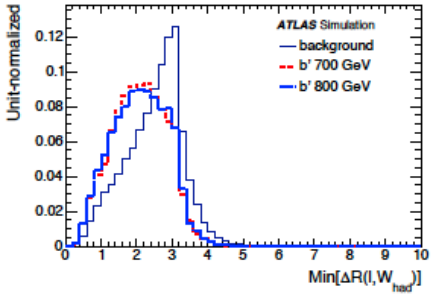
BDT training variables

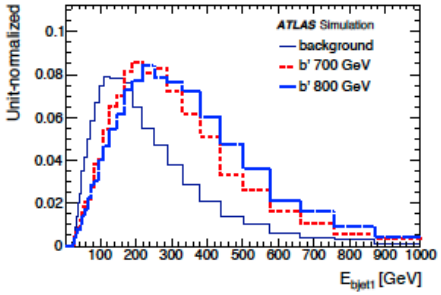


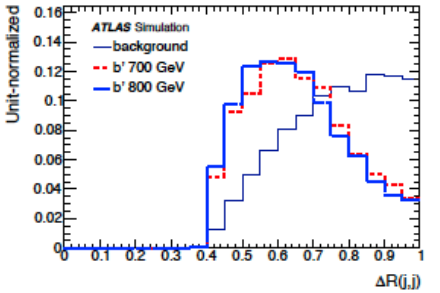


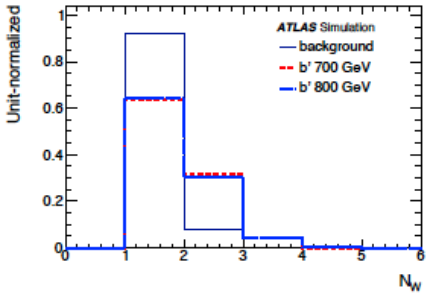


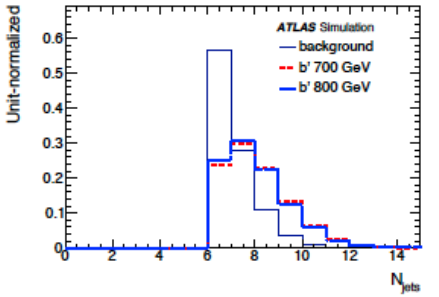


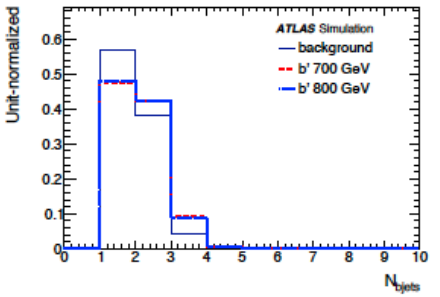


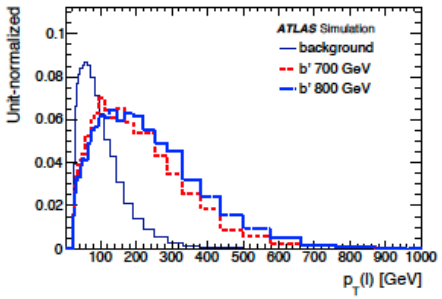


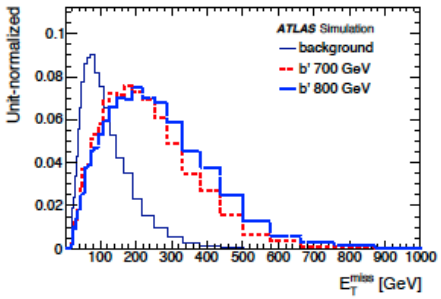




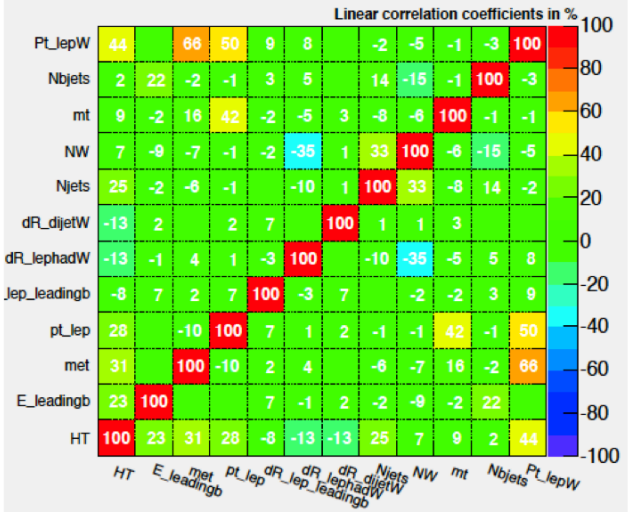




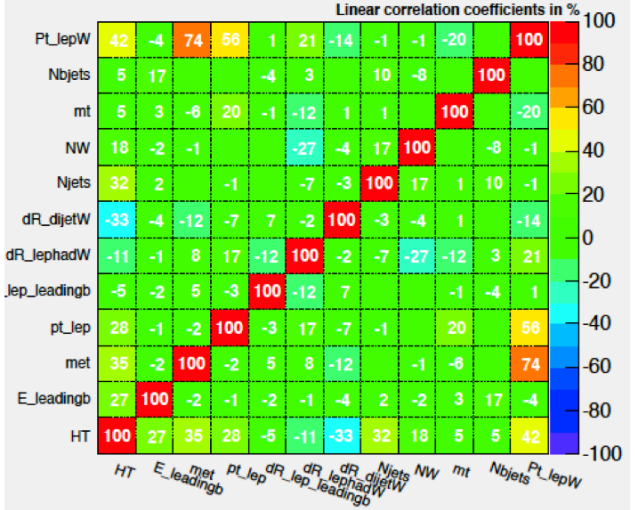




Correlation Matrix (signal)

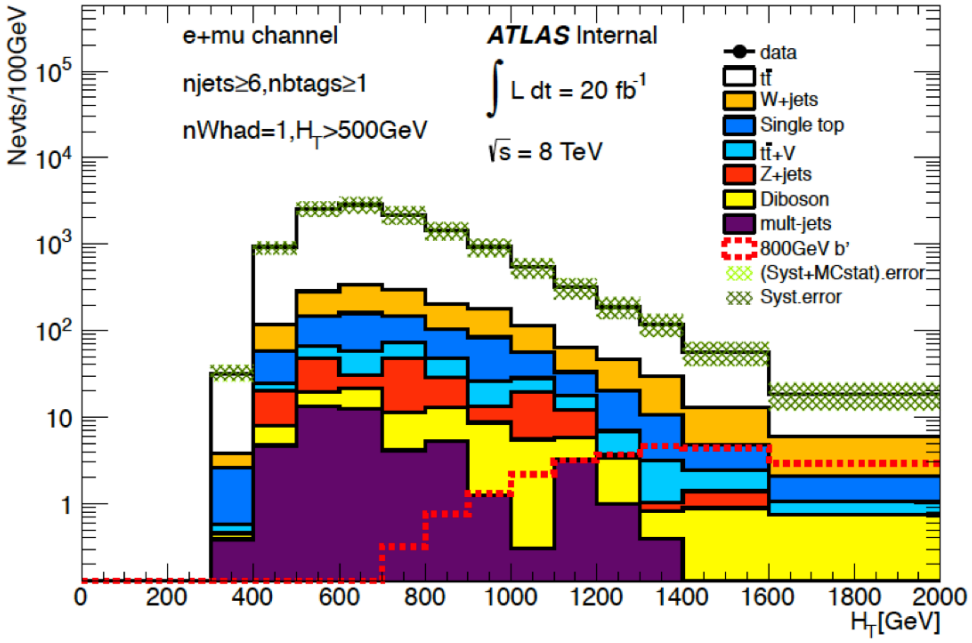


Correlation Matrix (background)

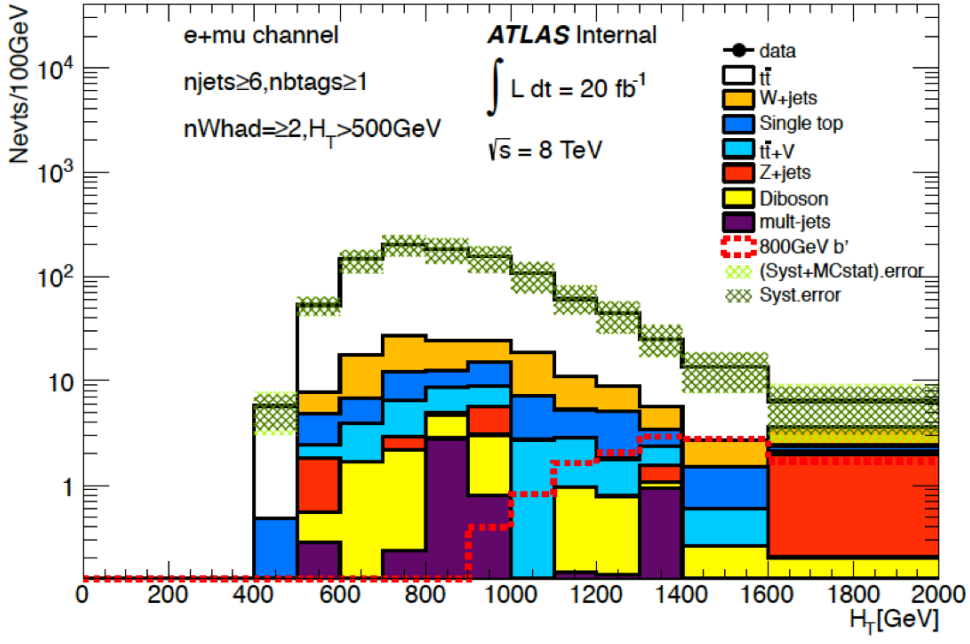


Signal region : cut-based

$N_W = 1$



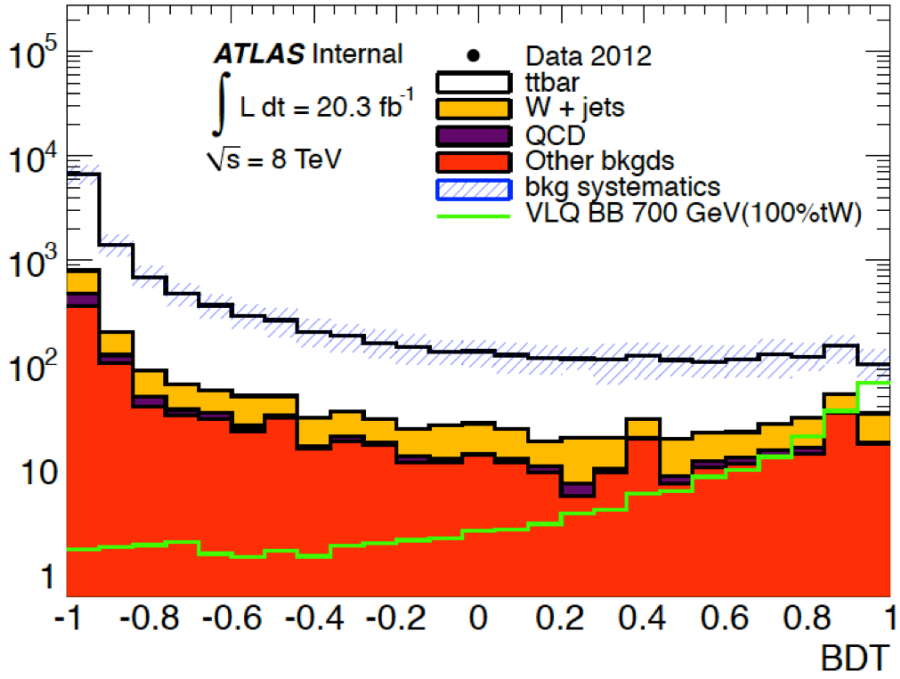
$N_W \geq 2$

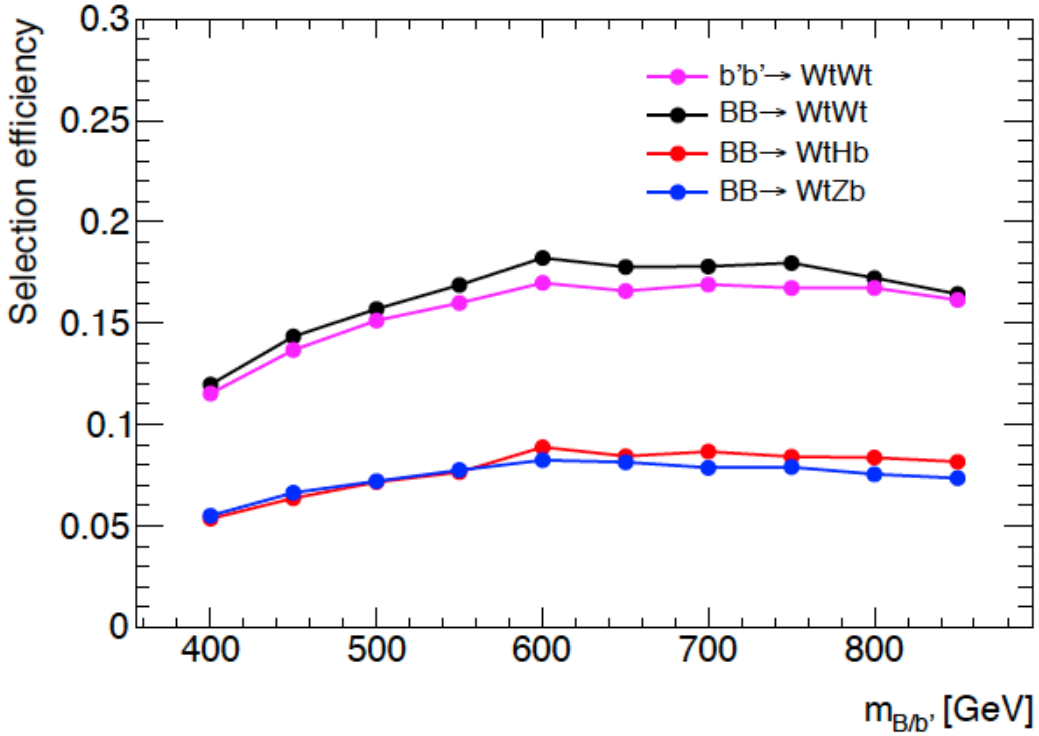


- These two H_T plots will be used to search for a signal and set limits
- The sensitivity mainly comes from $N_W \geq 2$, while $N_W = 1$ is more useful for constraining systematics

Signal region : BDT

$N_{jets} \geq 6$, $N_{bjets} \geq 1$, $N_W \geq 1$, HT > 500 GeV





- The BDT spectrum with optimized cut of BDT > 0.3 will be used to search a signal and set limits

- WtWt channel provides the main sensitivity

Systematics Table

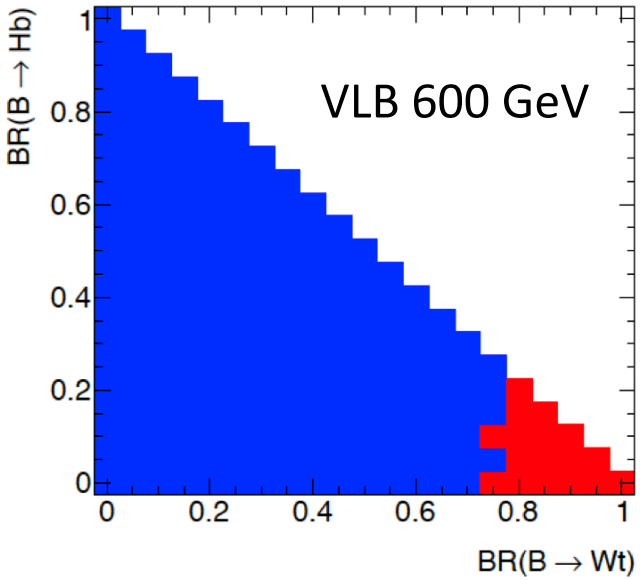
- Systematics impact common to both cut-based and BDT analyses
- Assume 100% uncorrelated among different systematics
- Total systematics impact: ~30%

Systematic	$t\bar{t}$	W+jets	Diboson	Z+jets	Single top	$t\bar{t}$V	QCD	Total bkg.	VLB 700 GeV
Luminosity	±2.8%	±2.8%	±2.8%	±2.8%	±2.8%	±2.8%	-	±2.8%	±2.8%
JES	±17	±19%	±11%	±15%	±15%	±12%	-	±17%	±4%
JER	±3%	±6%	±14%	±9%	±2%	±1%	-	±6%	±1%
JVF	±3%	±6%	±5%	±4%	±4%	±2%	-	±3%	±2%
b-tagging	±5%	±2%	±1%	±4%	±5%	±5%	-	±5%	±6%
MET	0	±1%	±2%	±4%	±1%	0	-	0	0
$t\bar{t}$ Theory	$^{+5\%}_{-6\%}$	-	-	-	-	-	-	+5%	-
$t\bar{t}$ reweighting	±16%	-	-	-	-	-	-	±13%	-
$t\bar{t}$ Parton Shower	±6%	-	-	-	-	-	-	±5%	-
$t\bar{t}$ PDF	+9%	-	-	-	-	-	-	±7%	-
W+jets norm	-	±59%	-	-	-	-	-	±6%	-
W+jets shape	-	±8%	-	-	-	-	-	±1%	-
Z+jets	-	-	-	±59%	-	-	-	±1%	-
Single Top	-	-	-	-	±48%	-	-	±3%	-
Diboson	-	-	±48%	-	-	-	-	±1%	-
$t\bar{t}$V	-	-	-	-	-	±30%	-	±1%	-
Multijet	-	-	-	-	-	-	±50%	±1%	-

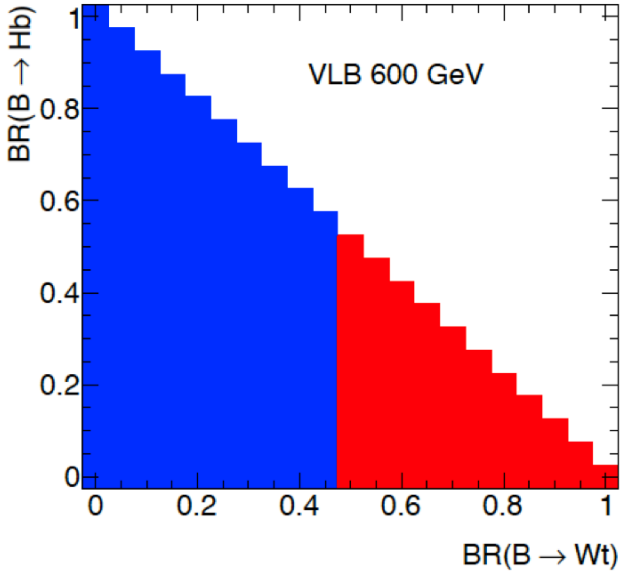
signal region: $N_{jets} \geq 6$, $N_{bjets} \geq 1$, $N_W \geq 1$, HT > 800 GeV

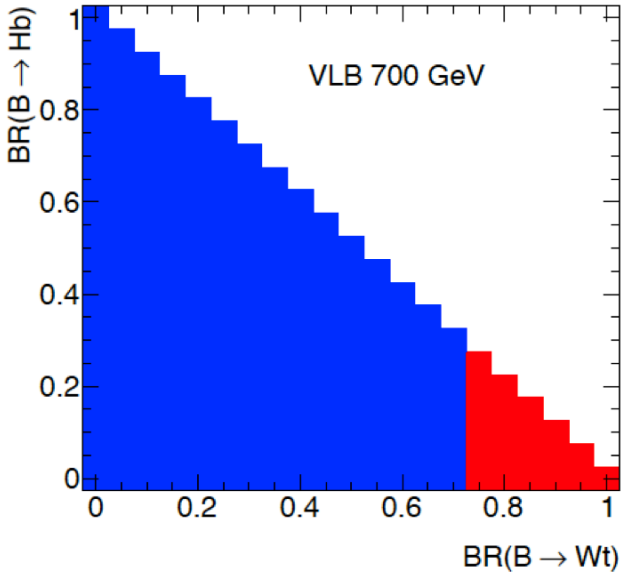
Expected Limits

Cut-based



BDT

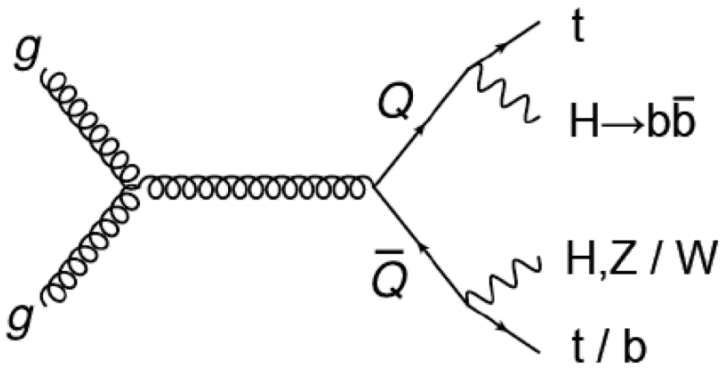


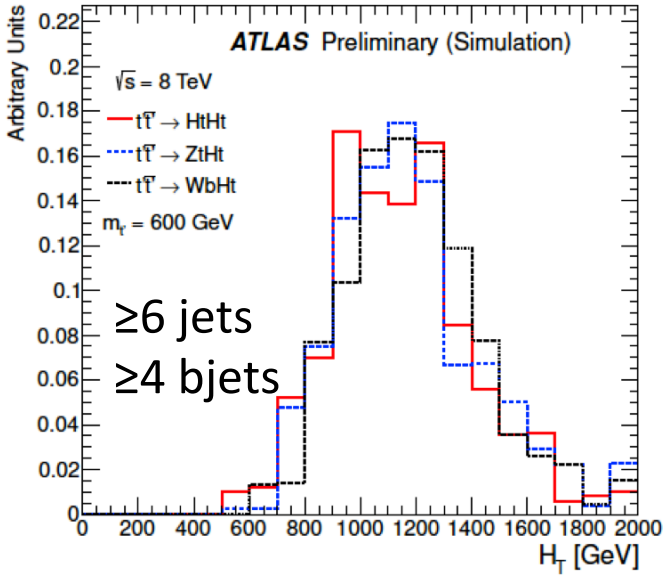


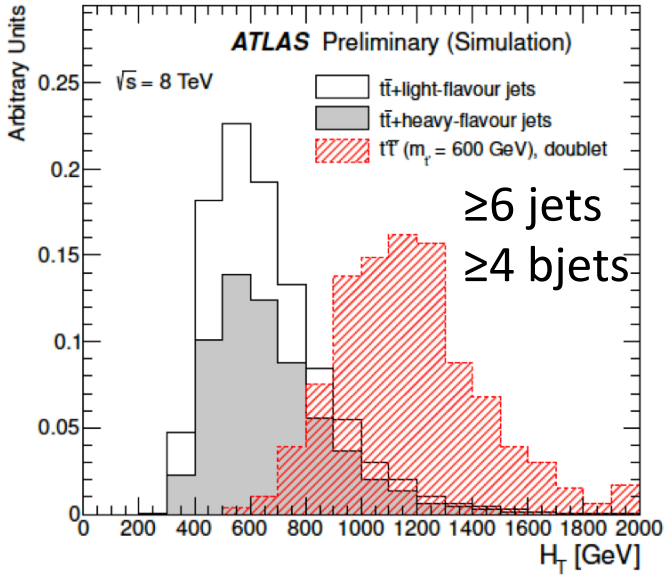
- **Limits are set considering different BRs of B->Wt, Hb, Zb, with the constraint that the BR sum of the 3 decays =1**
- **Red regions are expected exclusions for each signal mass**
- **BDT analysis has better sensitivity relative to cut-based**
- **The analysis just got approved last week by the ATLAS Exotics group. Paper draft is being prepared**

TT->Ht+X

- **Selection:**
  - **High p_T isolated lepton(e/μ) , high p_T jets**
  - **$N_{jets} \geq 6$**
  - **$N_{bjets} \geq 2$**
- **Discriminant:**
  - **H_T, independent from decay mode**
- **Main background:**
  - **ttbar+jets, largely affected by b tagging, jet energy scale, modeling of heavy-flavor content**





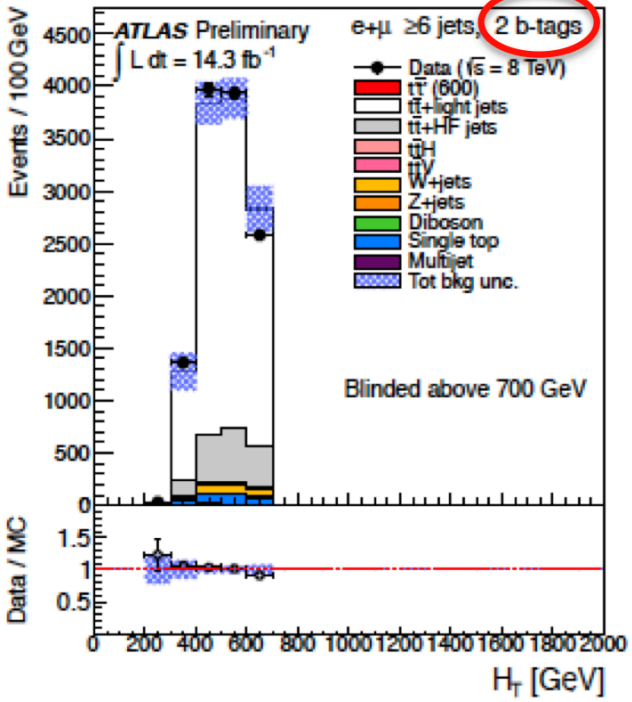


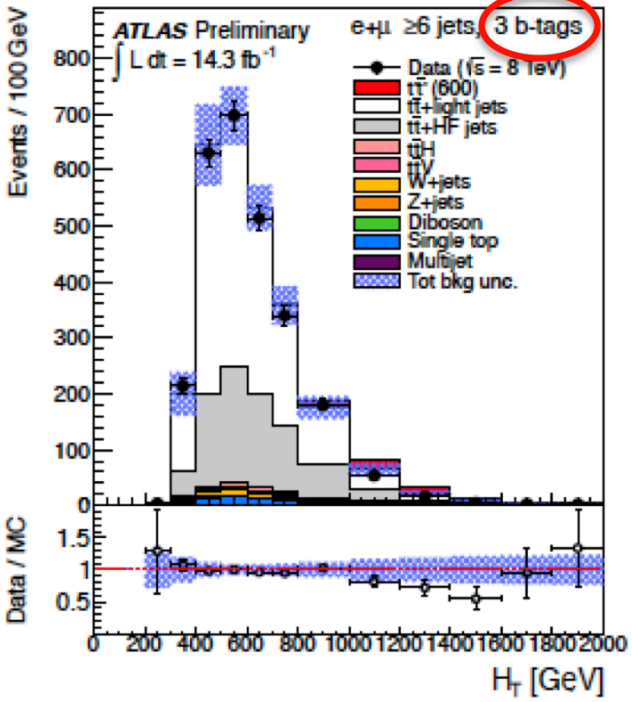
TT->Ht+X

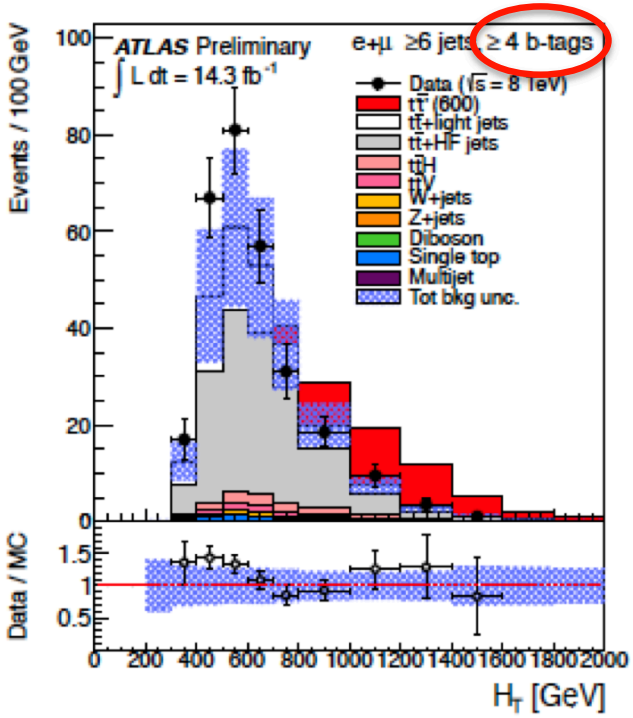
- **Split events into 3 channels based on number of bjets to optimize sensitivity:**
  - **N_{bjets}: 2, 3, ≥ 4**

- **Fit overall scaling factors to tt+light jets and tt+HF to "calibrate" background prediction to data and reduce impact of systematics:**
  - **2-tag and 3-tag channels play an important role**

Postfit (2-parameter fit)







TT->Ht+X

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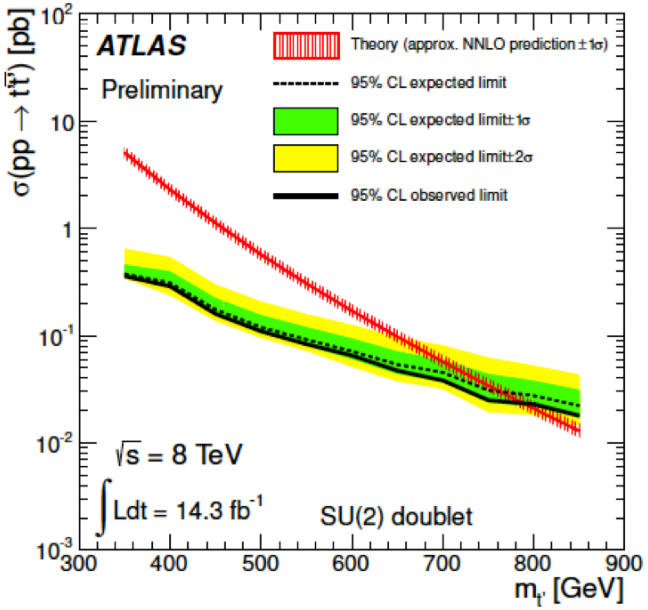
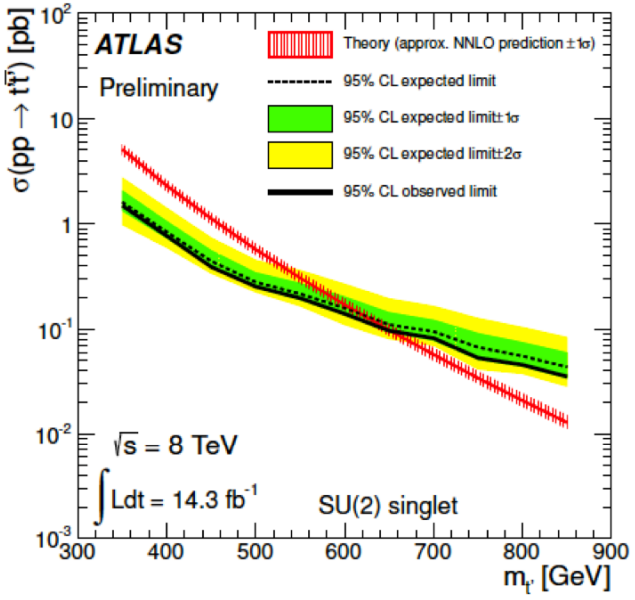
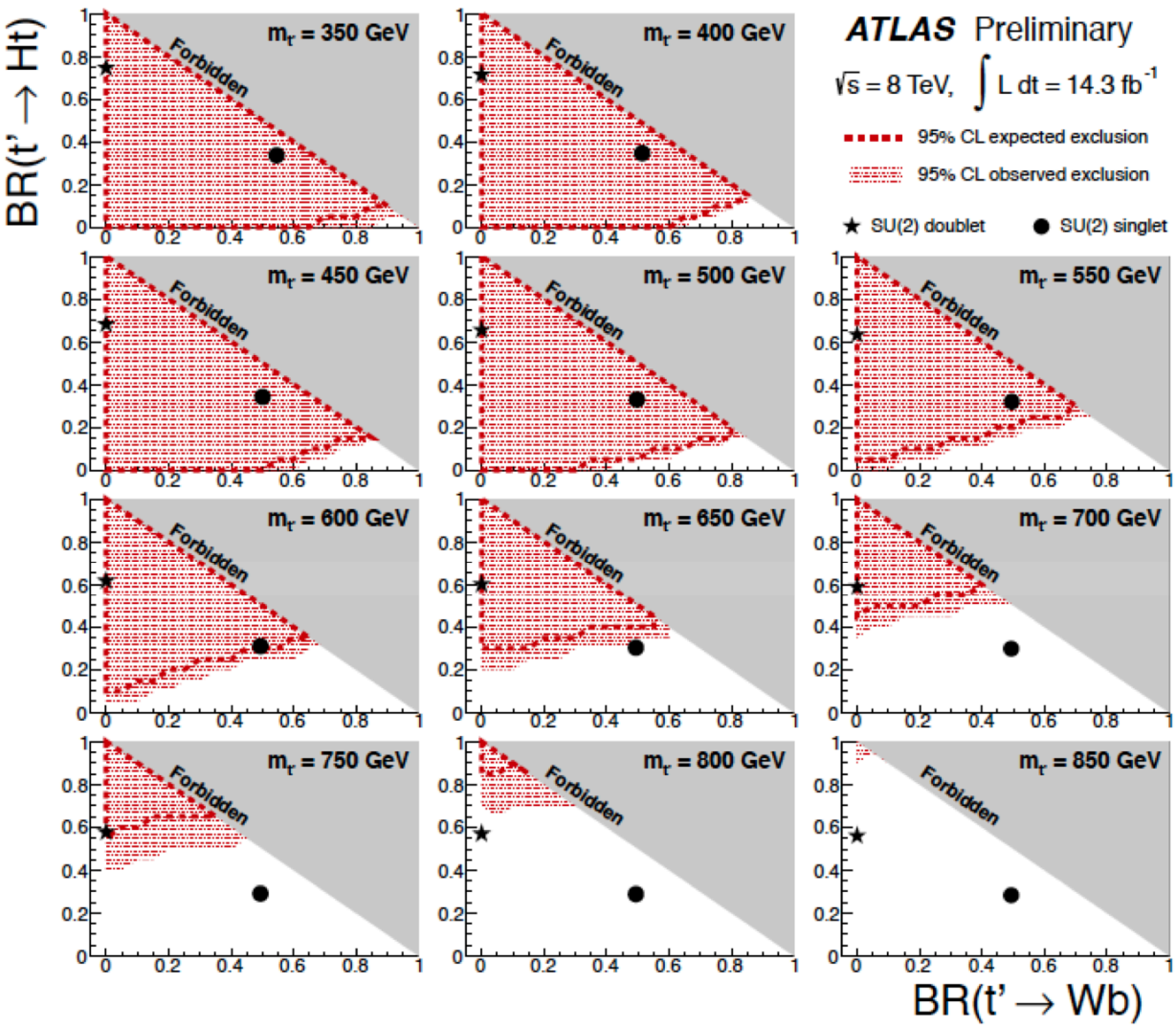




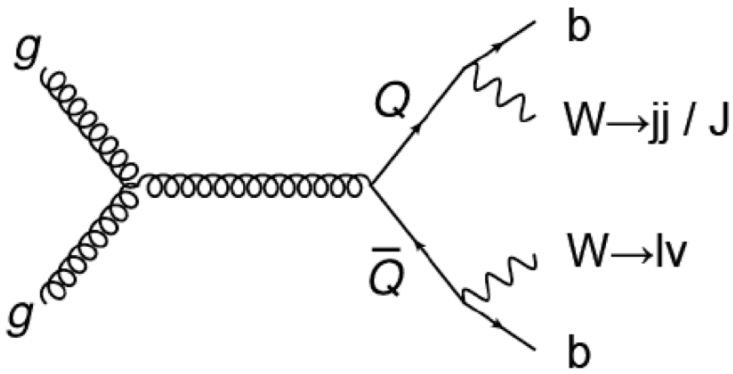


Observed (expected) 95% CL limit:

- **SU(2) doublet: m_T>790 (745) GeV**
- **SU(2) singlet: m_T>640 (615) GeV**

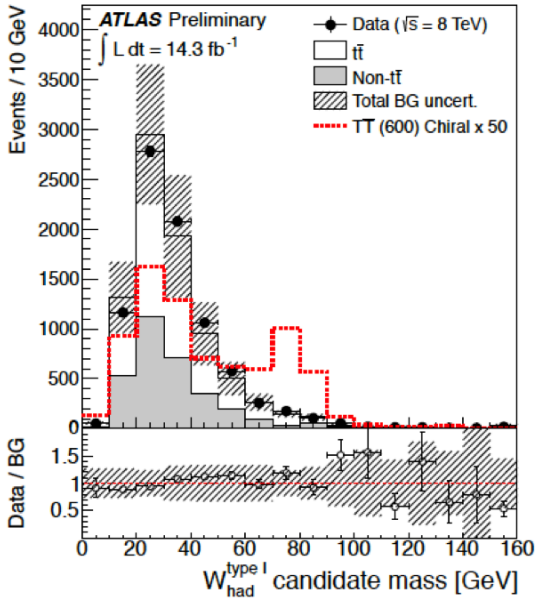
TT->Wb+X

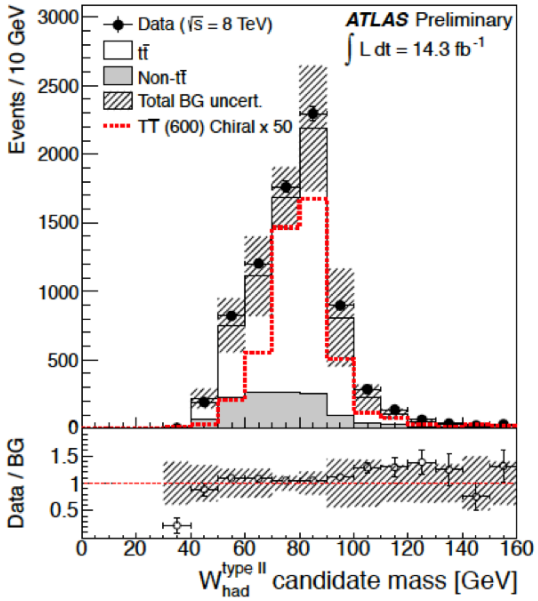
- **Selection:**
  - **High p_T isolated lepton(e/μ) , high p_T jets**
  - **$N_{jets} \geq 4$**
  - **$N_{bjets} \geq 2$**



- **Hadronic W reconstruction: W_{had}**
  - **Type-I: single jet, p_T>200 GeV, 60<m<120 GeV**
  - **Type-II: di-jet, ΔR(j,j)<0.8, p_T>200 GeV, 60<m<120 GeV**
  - **In case of multiple candidates, choose the one with highest p_T**

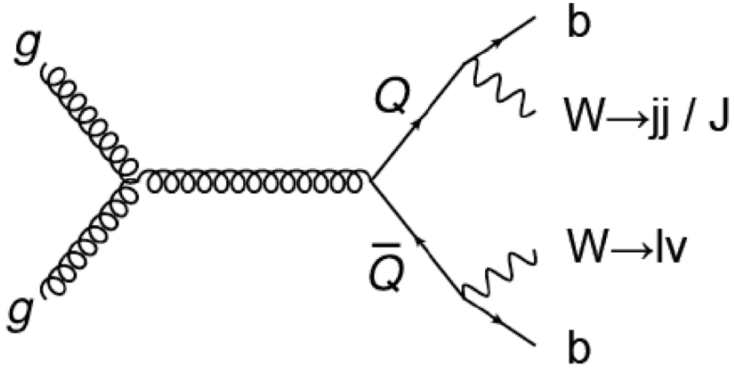
- **Leptonic W reconstruction: W_{lep}**
  - **Use nominal W mass to constrain neutrino longitudinal momentum**

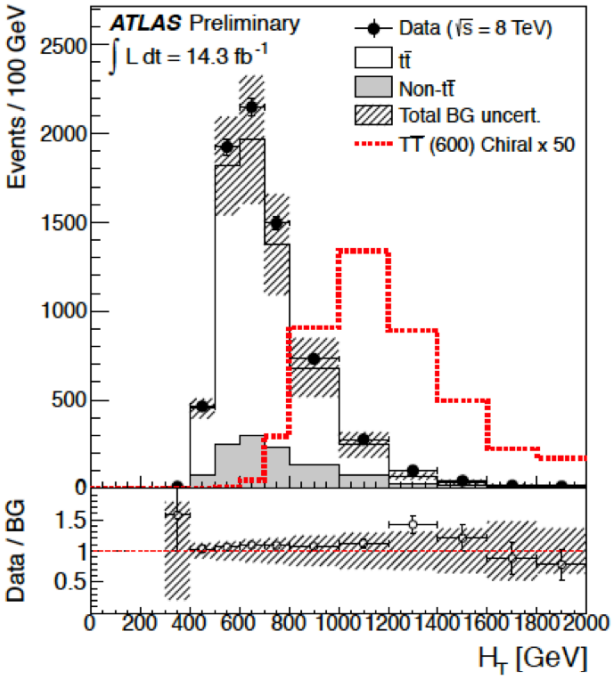


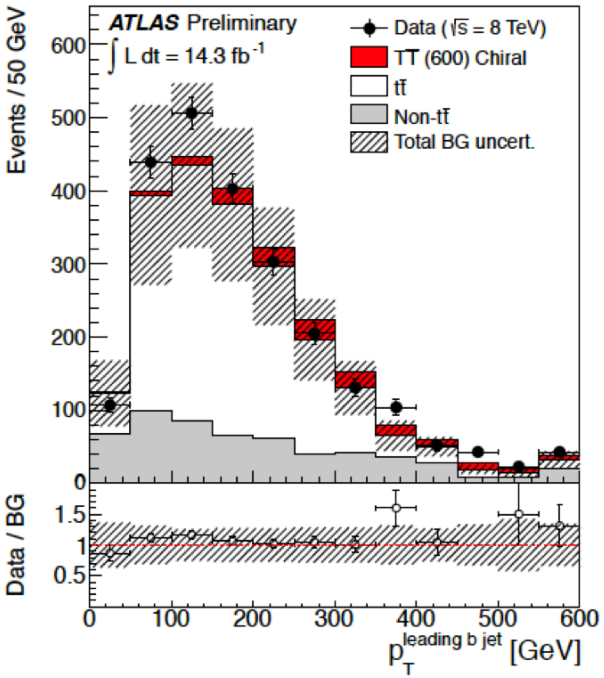


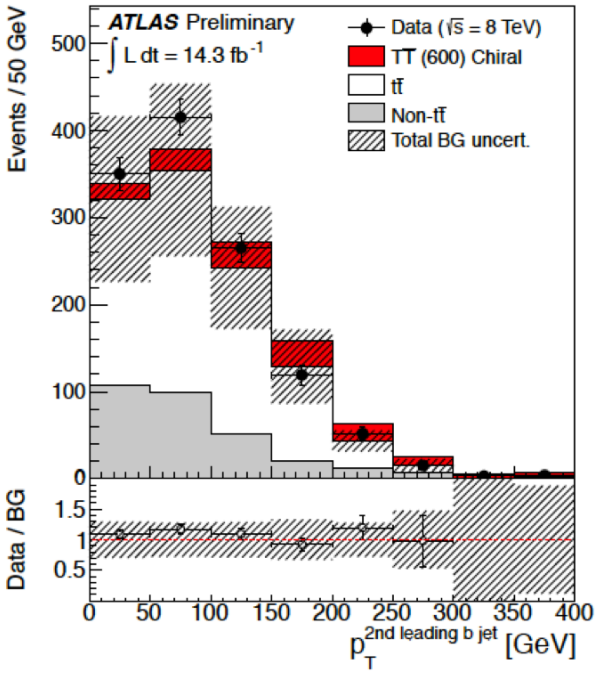
TT->Wb+X

- **Further suppression of background using kinematic variables**
  - H_T>800 GeV
  - $p_T(b_1)$>160 GeV
  - $p_T(b_2)$>80 GeV





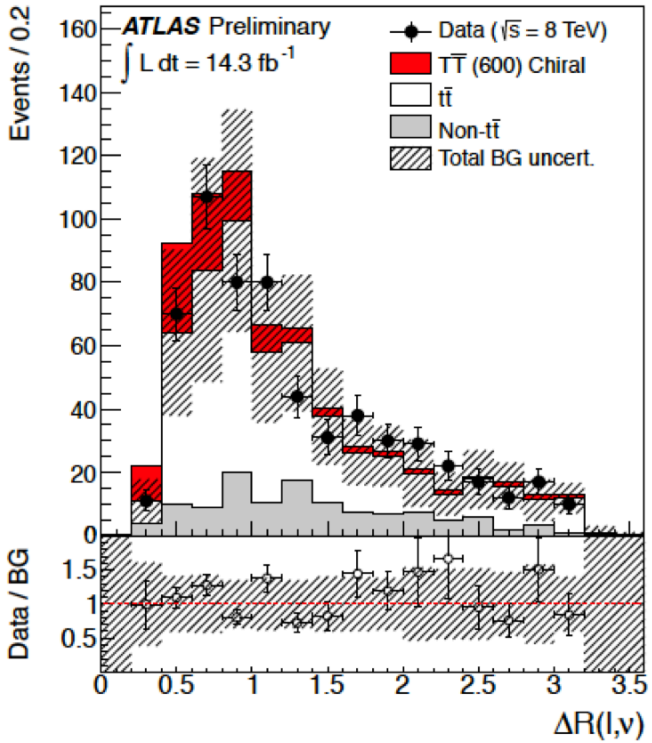


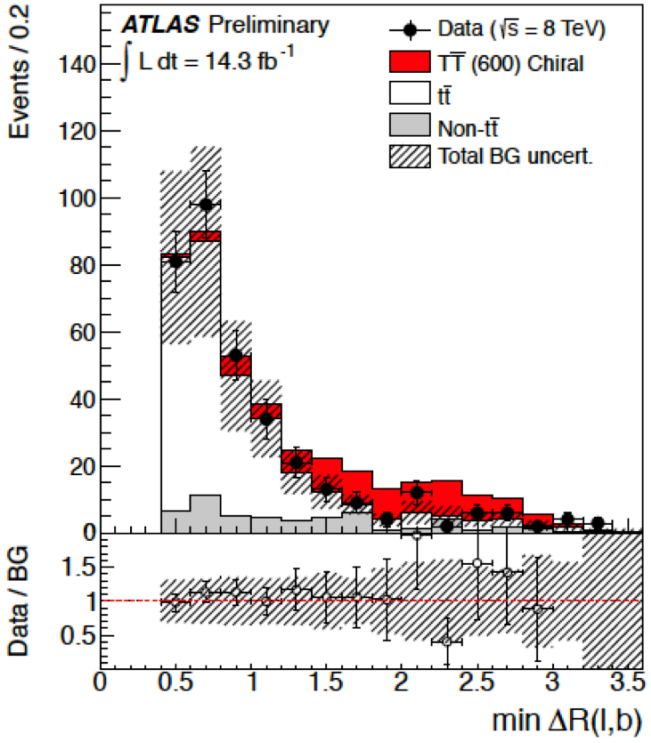


TT->Wb+X

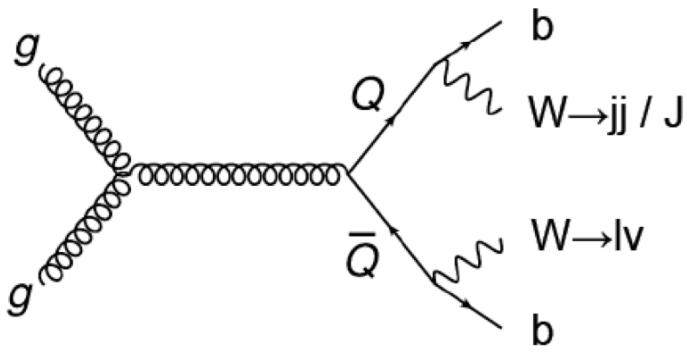
- **Further suppression of background using angular variables**
  - **$\Delta R(\text{lepton},\nu)<1.2$**
  - **$\min\Delta R(\text{lepton},b_{1,2})>1.4$**
  - **$\min\Delta R(W_{had},b_{1,2})>1.4$**

Selection	Requirements
Preselection	One electron or muon
	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV
	≥ 4 jets, ≥ 1 b-tagged jets
loose selection	Preselection
	≥ 1 W_{had} candidates
	$H_{\mathrm{T}} > 800$ GeV
	$p_{\mathrm{T}}(b_1) > 160$ GeV, $p_{\mathrm{T}}(b_2) > 80$ GeV
	$\Delta R(\ell, \nu) < 1.2$
tight selection	*loose* selection
	$\min\Delta R(\ell, b) > 1.4$, $\min\Delta R(W_{\mathrm{had}}, b) > 1.4$

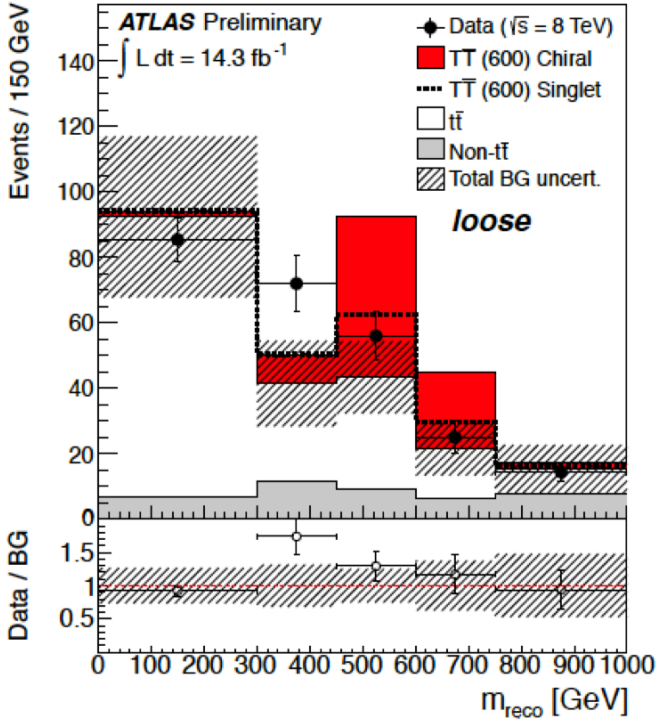


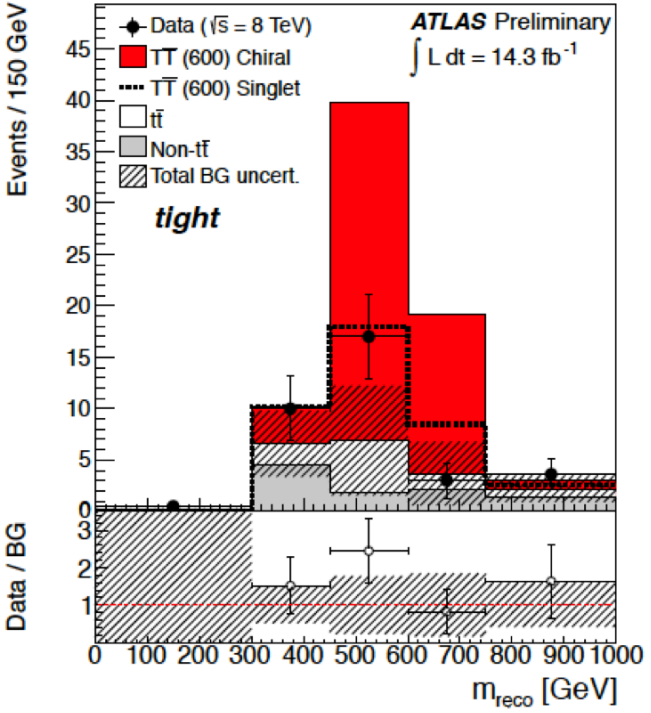


TT->Wb+X



- **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**





TT->Wb+X

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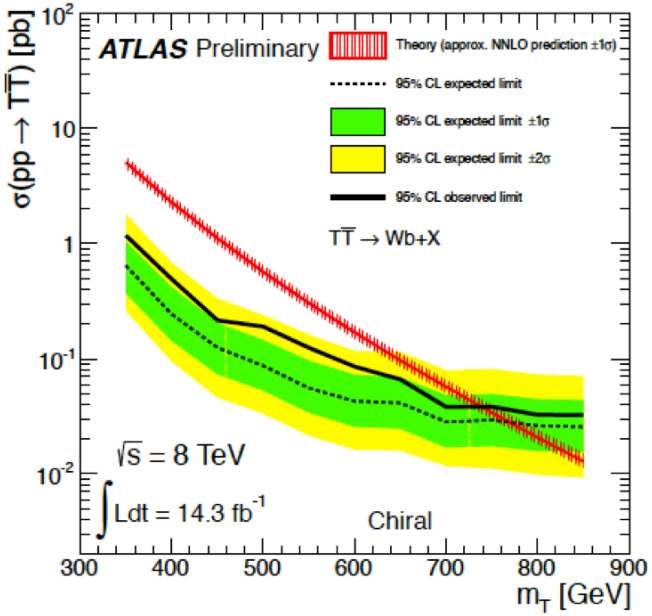
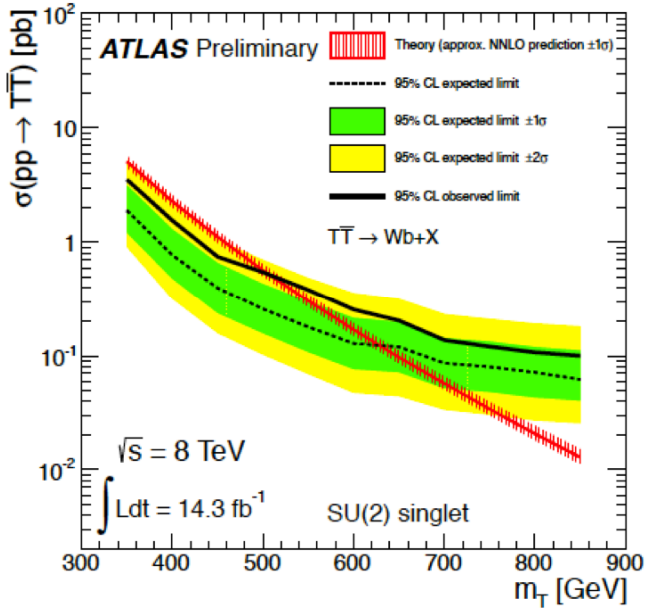
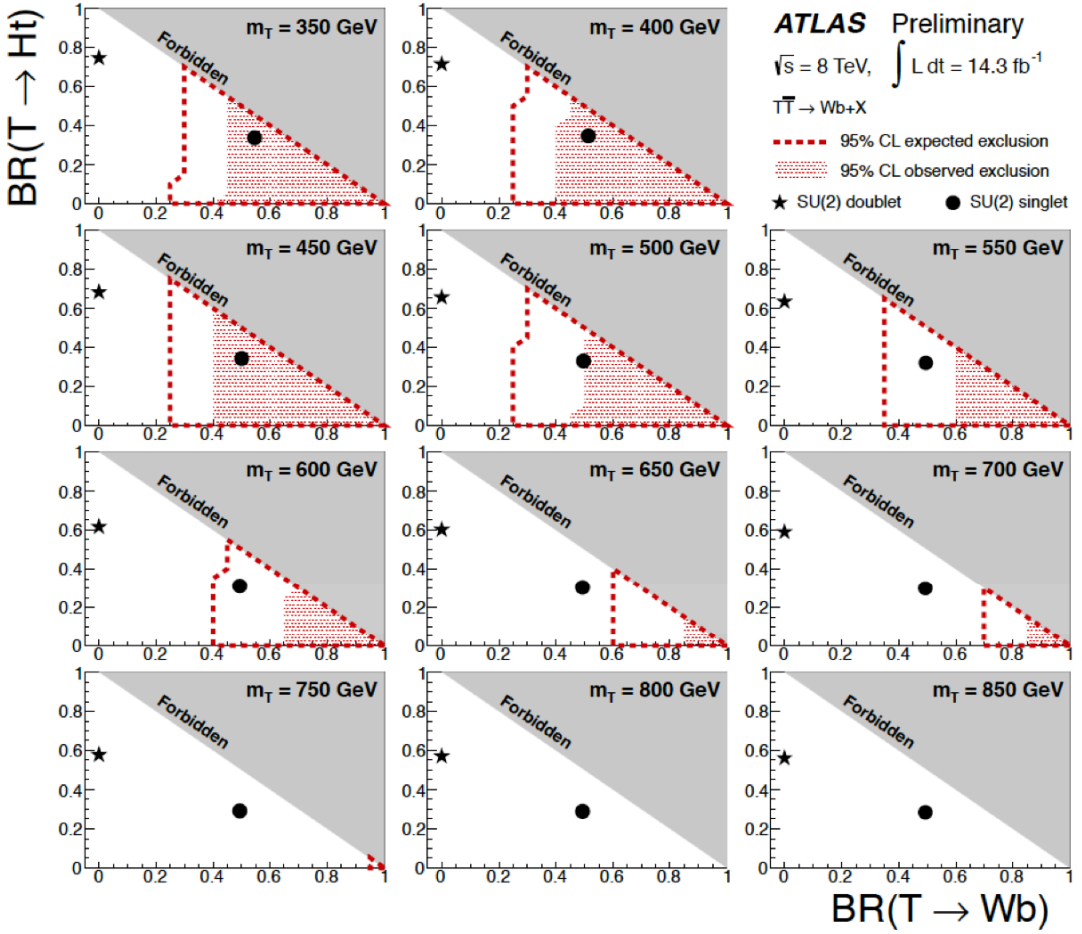




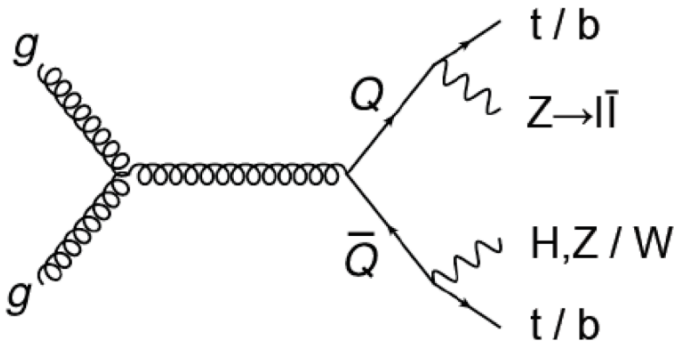


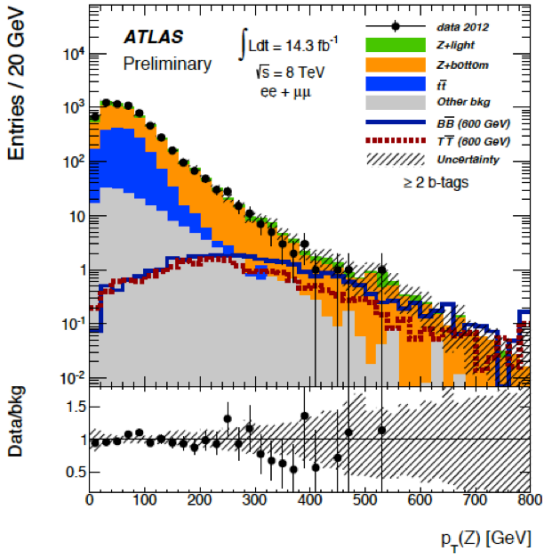
Observed(expected) limit at 95% CL:

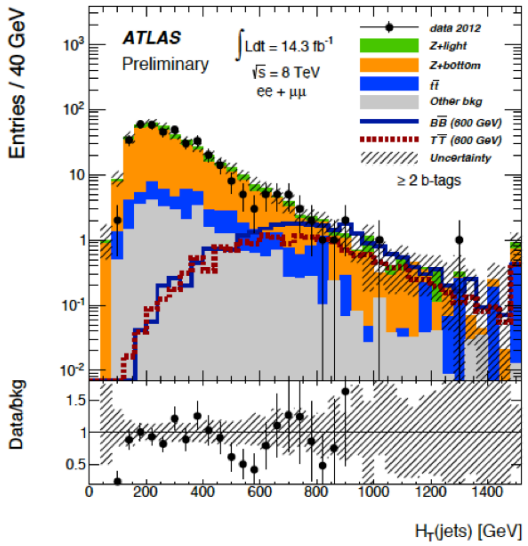
- **Chiral: m_T > 740(770) GeV**
- **Vector-like singlet T: m_T > 505(630) GeV**

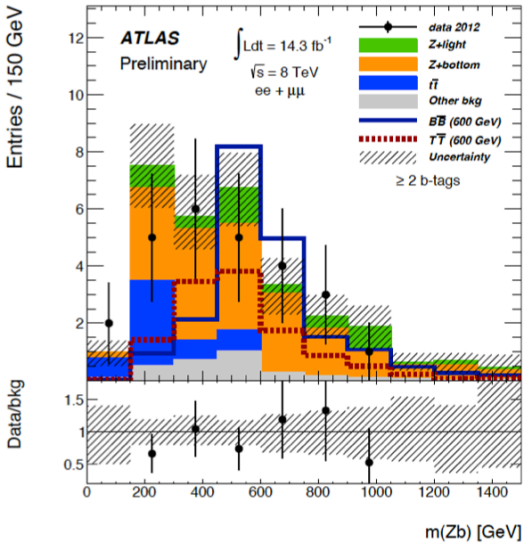
TT/BB->Zt/Zb+X

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









TT/BB->Zt/Zb+X

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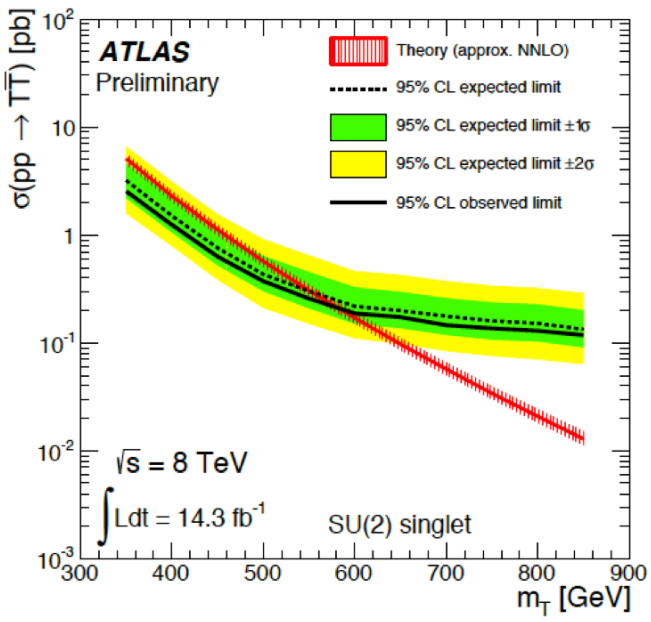

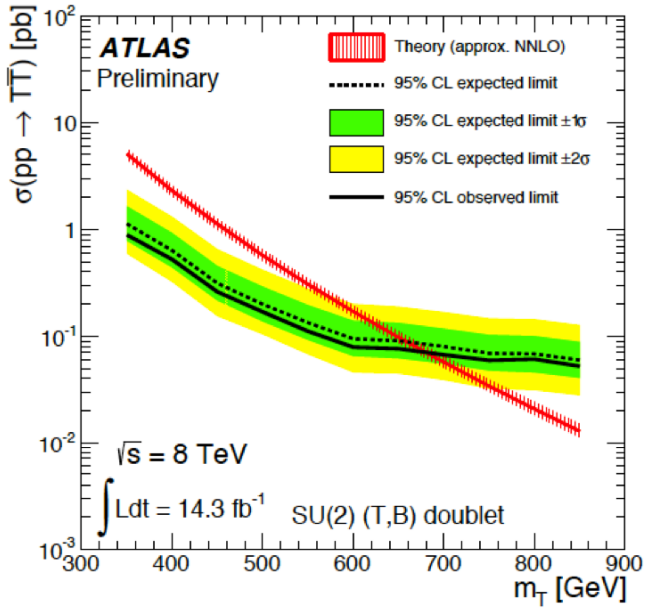

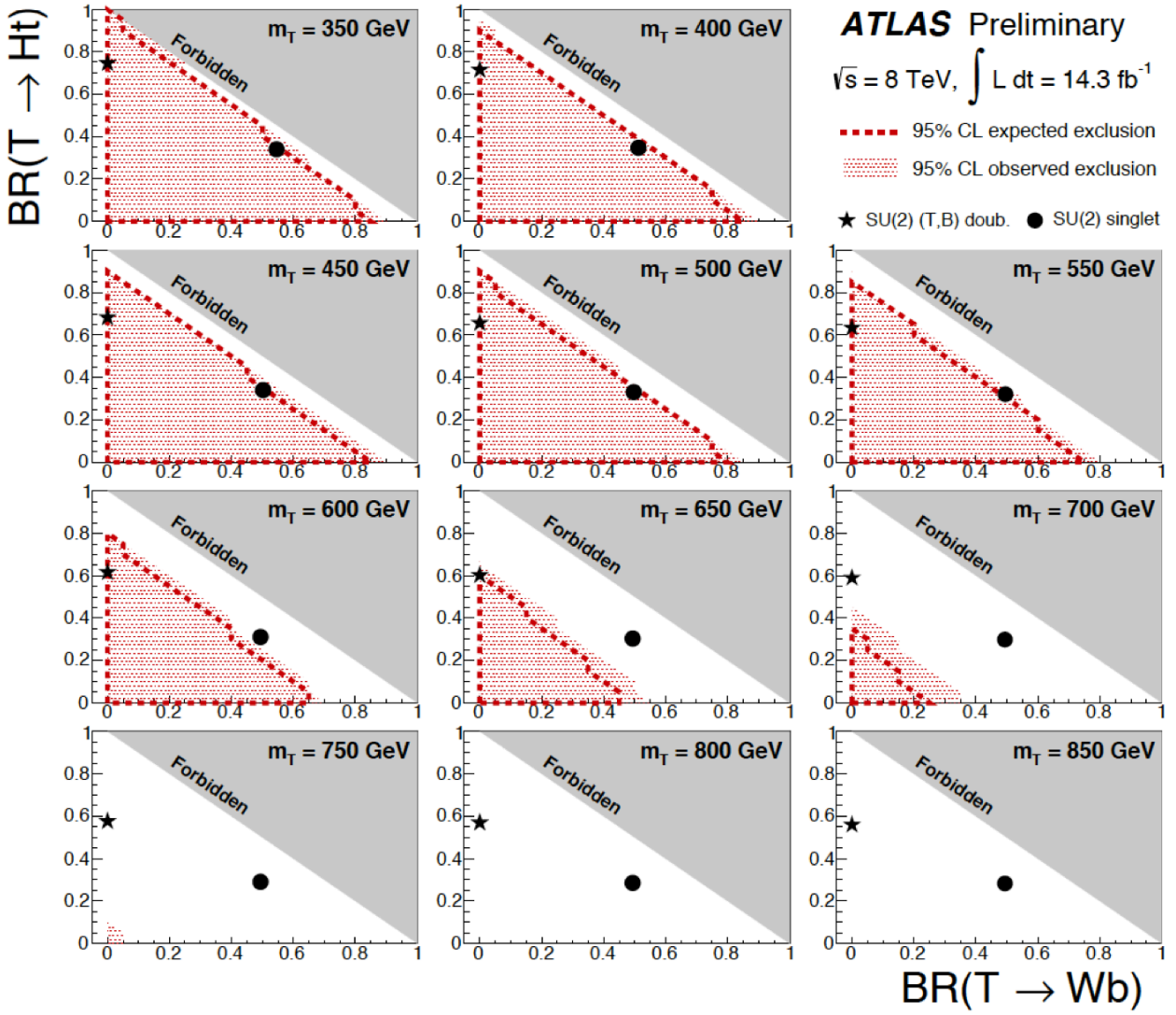

Observed(expected) limit at 95% CL:

- **T singlet: m_T > 585 GeV**
- **T doublet: m_T > 680 GeV**

TT/BB->Zt/Zb+X

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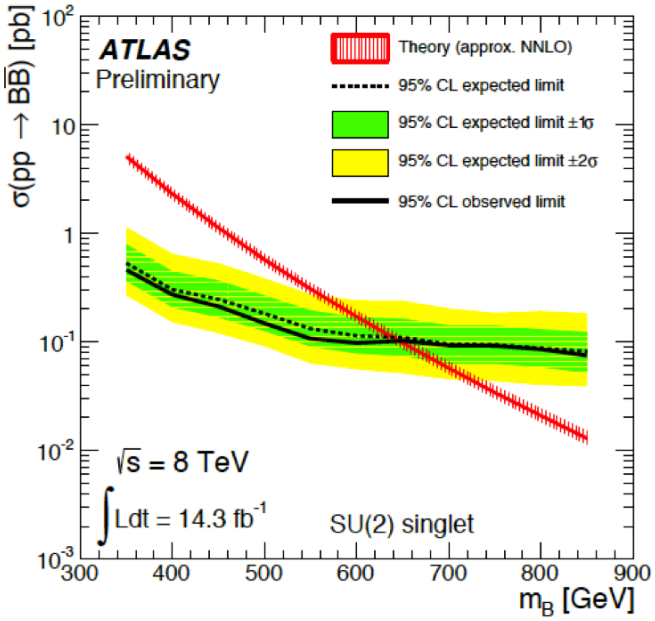
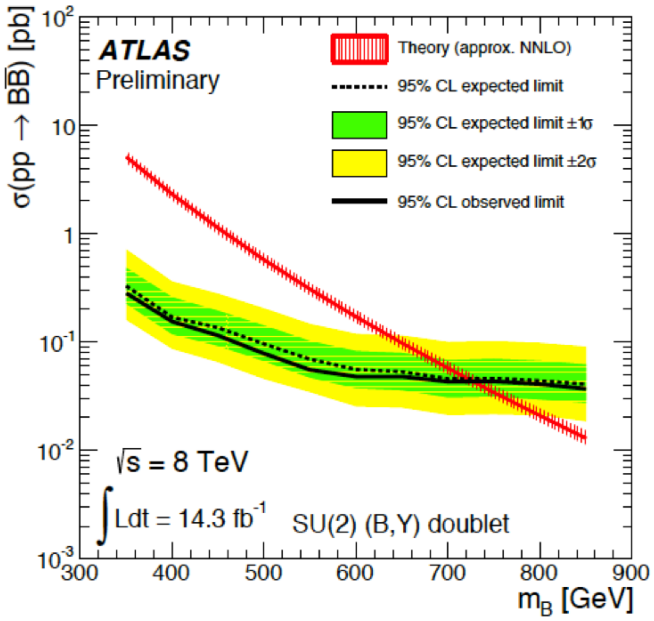
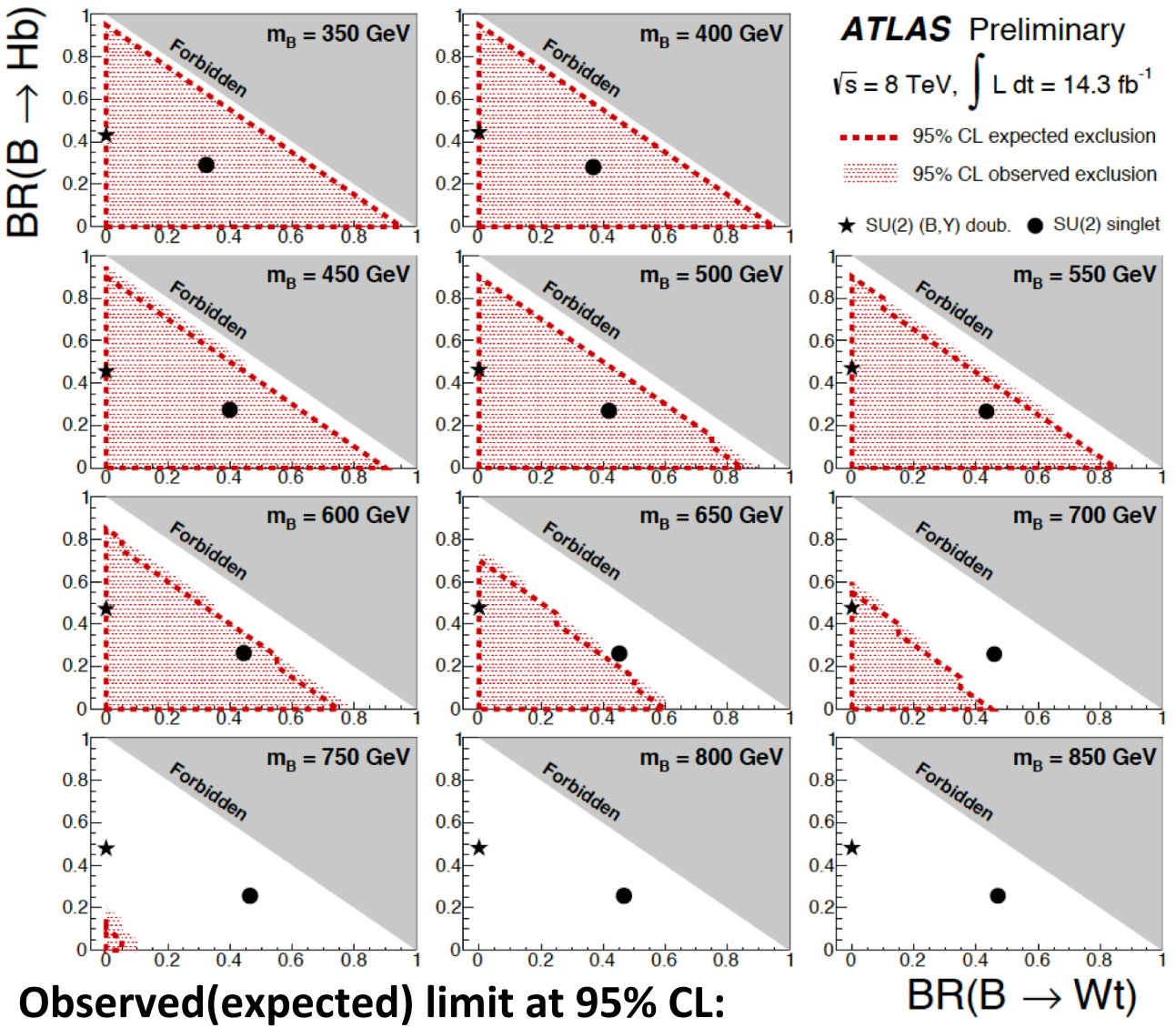






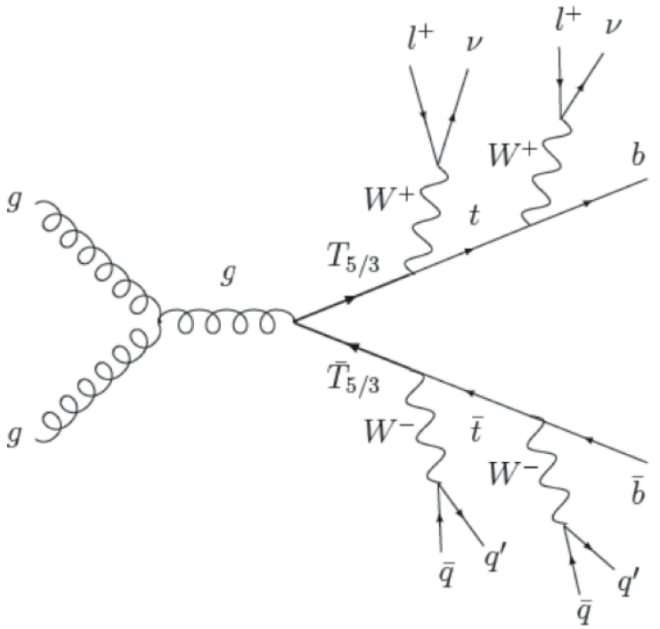
Observed(expected) limit at 95% CL:

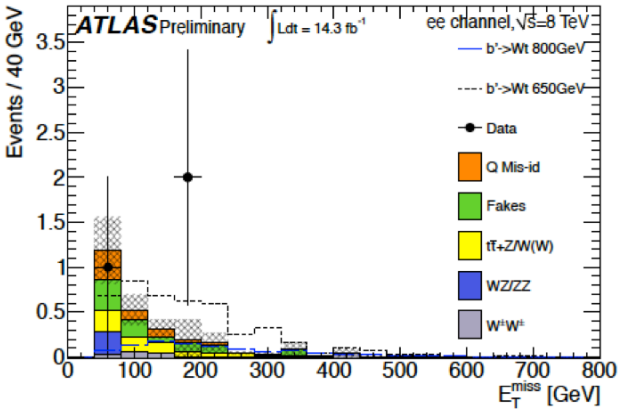
- **T singlet: m_T > 645 GeV**
- **T doublet: m_T > 725 GeV**

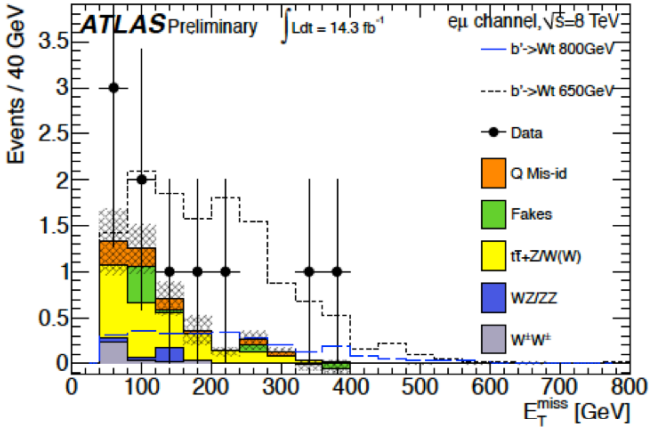
TT/BB->Same-Sign leptons

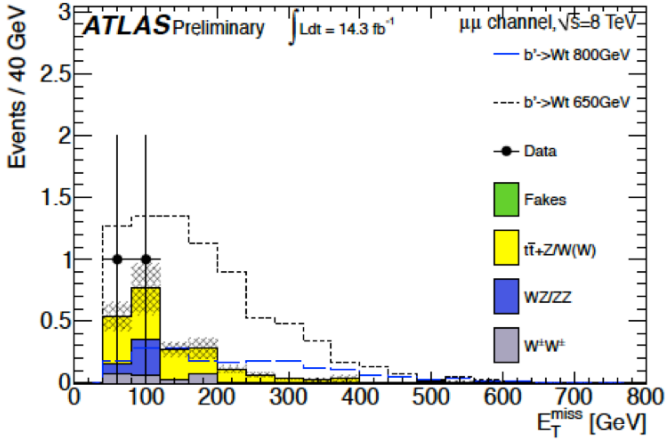
- **Low SM backgrounds:**
  - **2 leptons with same charge**
  - **$N_{bjets} \geq 2$**
  - **Large MET(> 40 GeV)**
  - **Large H_T**

- **Dominant background:**
  - **Faked leptons estimated from data-driven method**
  - **Charge mis-identification, determined from Z events**
  - **Irreducible diboson(VV), and ttbar+V**

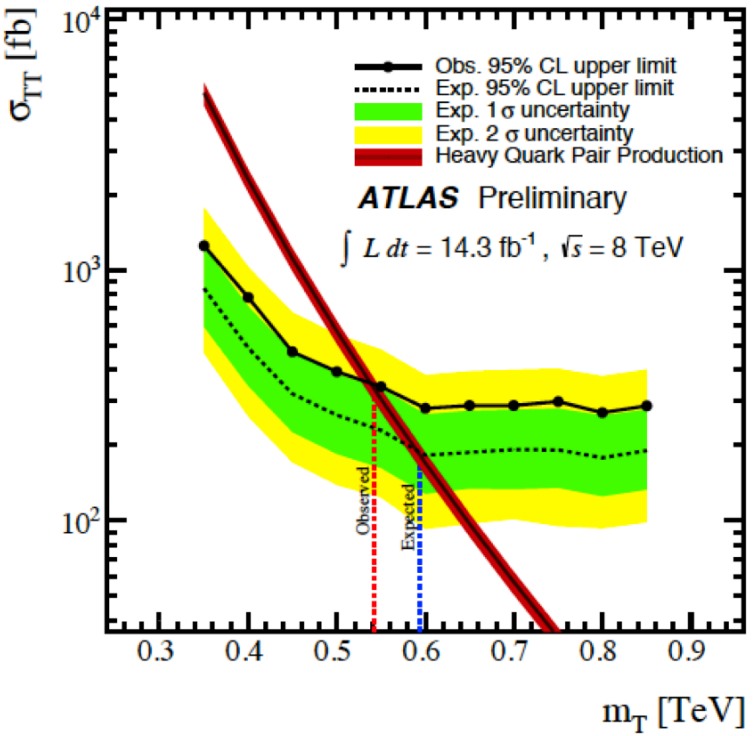


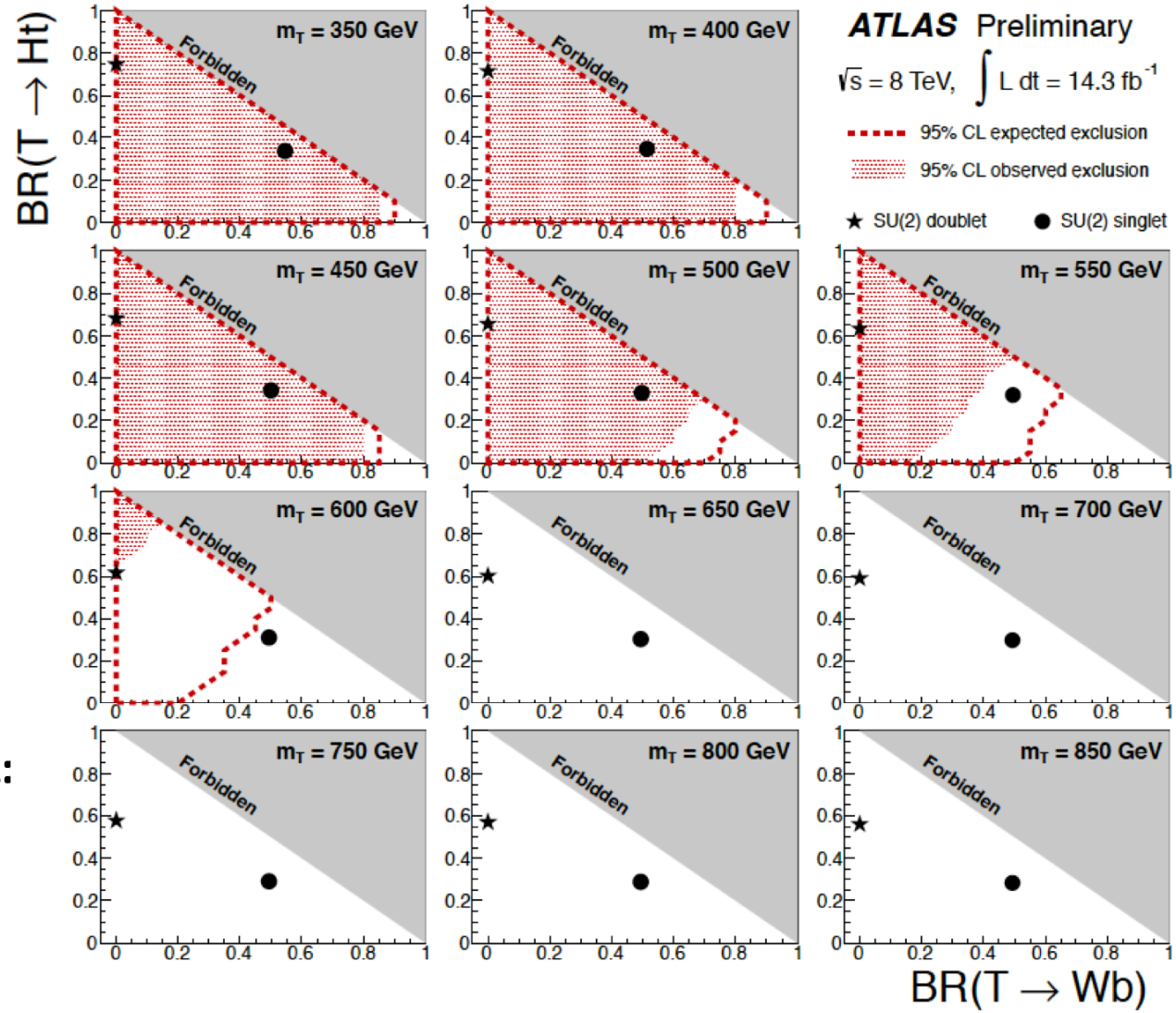






TT/BB->Same-Sign leptons





Observed(expected) limit at 95% CL:

- **T singlet: m_T > 540 GeV**

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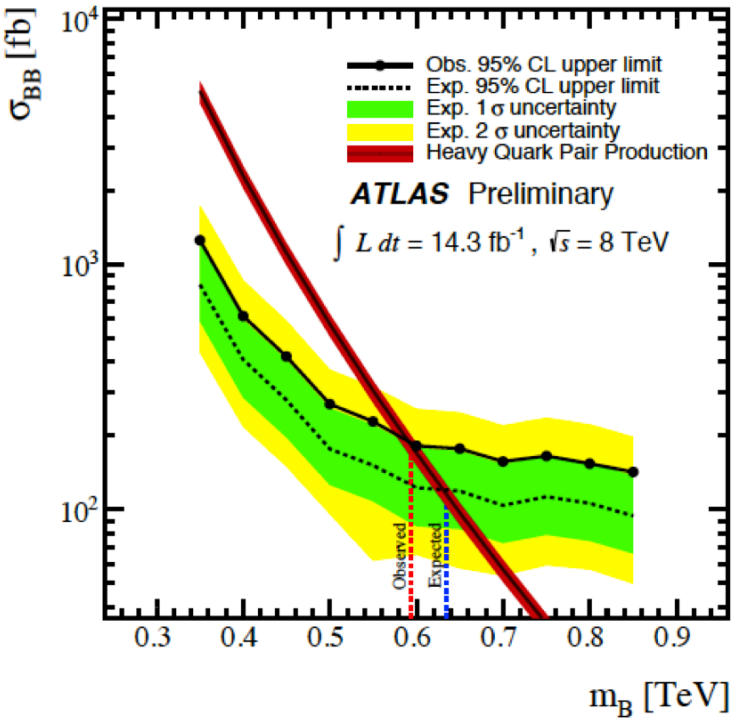
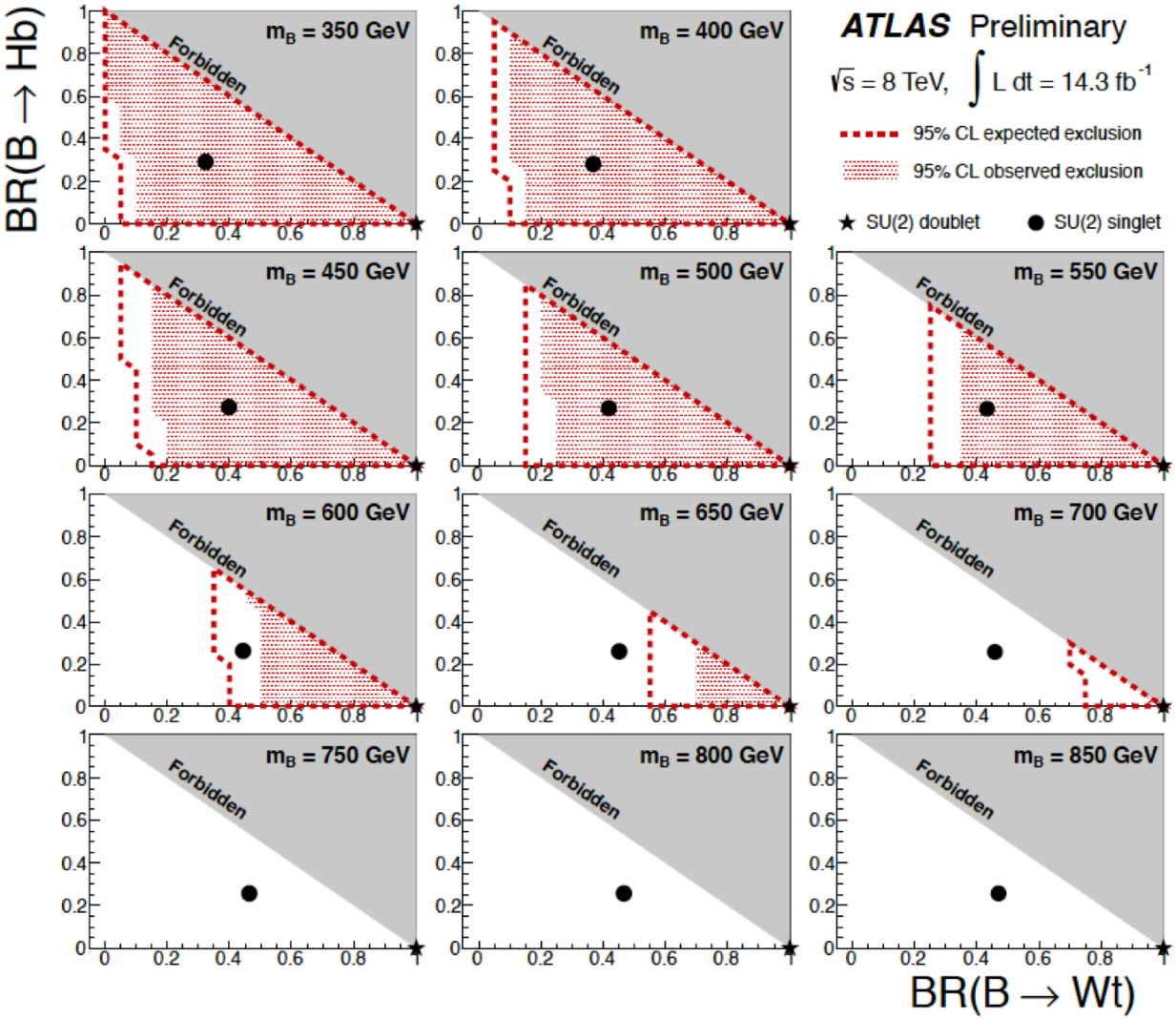
TT/BB->Same-Sign leptons





Observed(expected) limit at 95% CL:

- **B singlet: m_T > 590 GeV**

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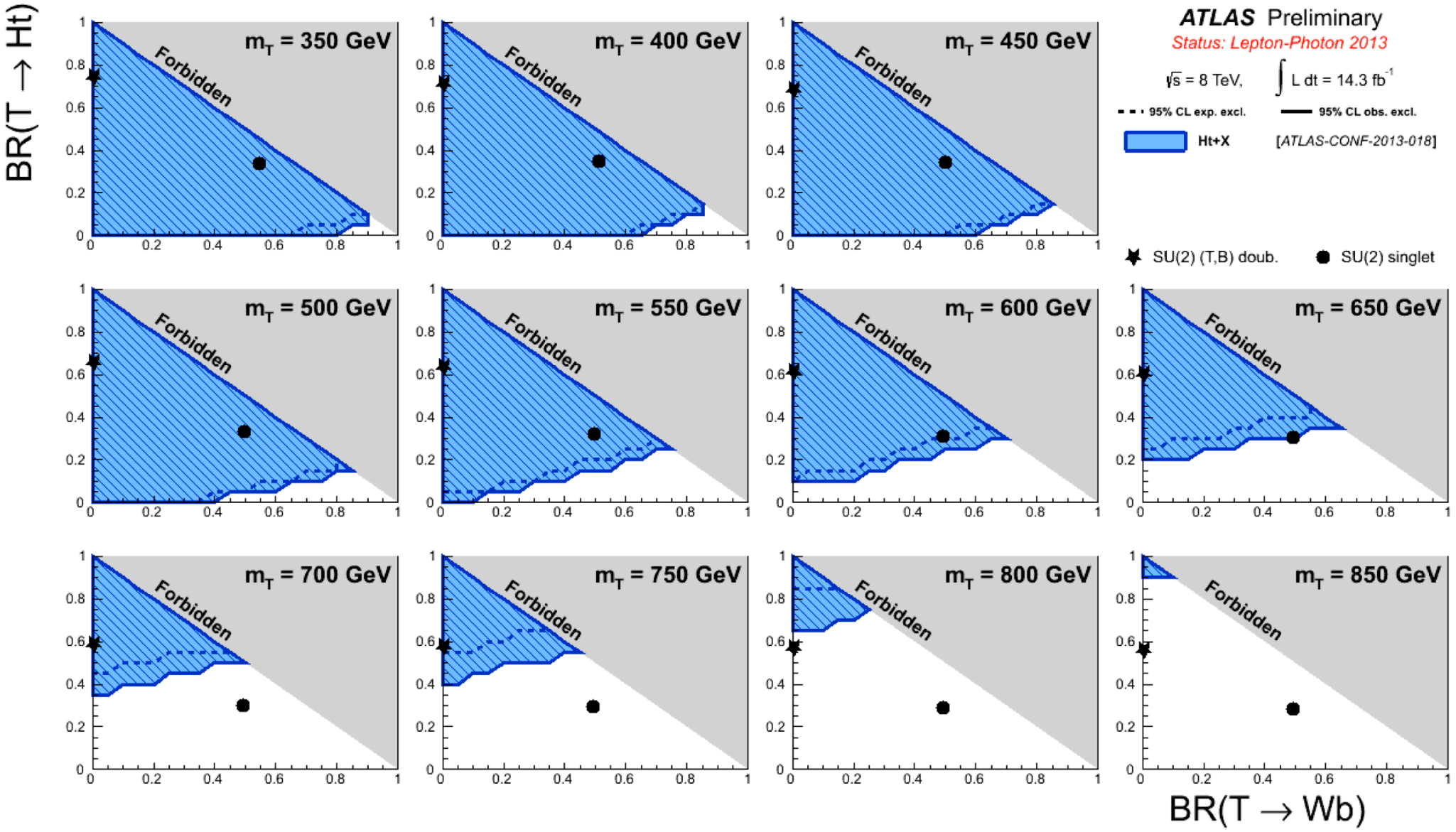
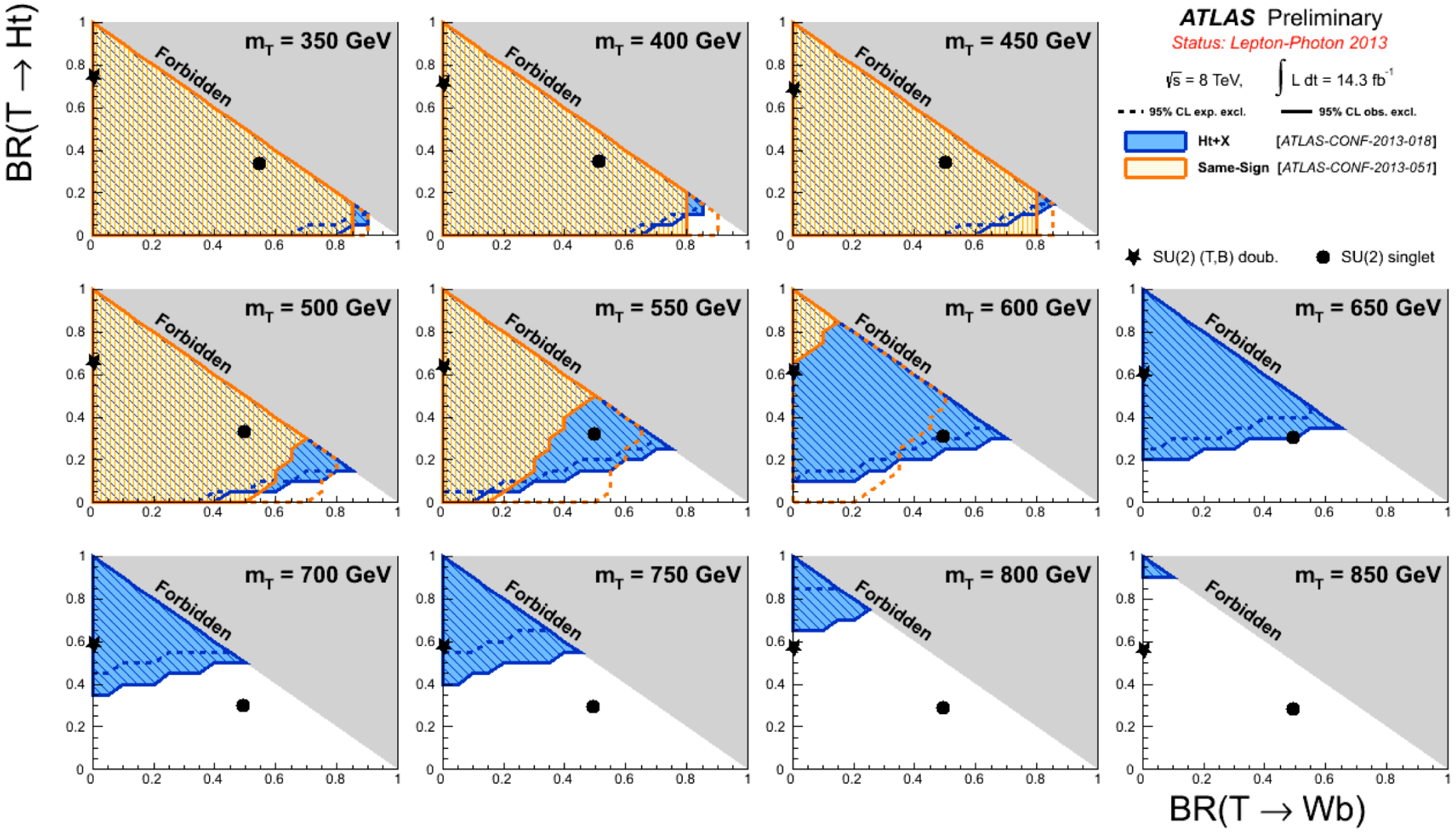
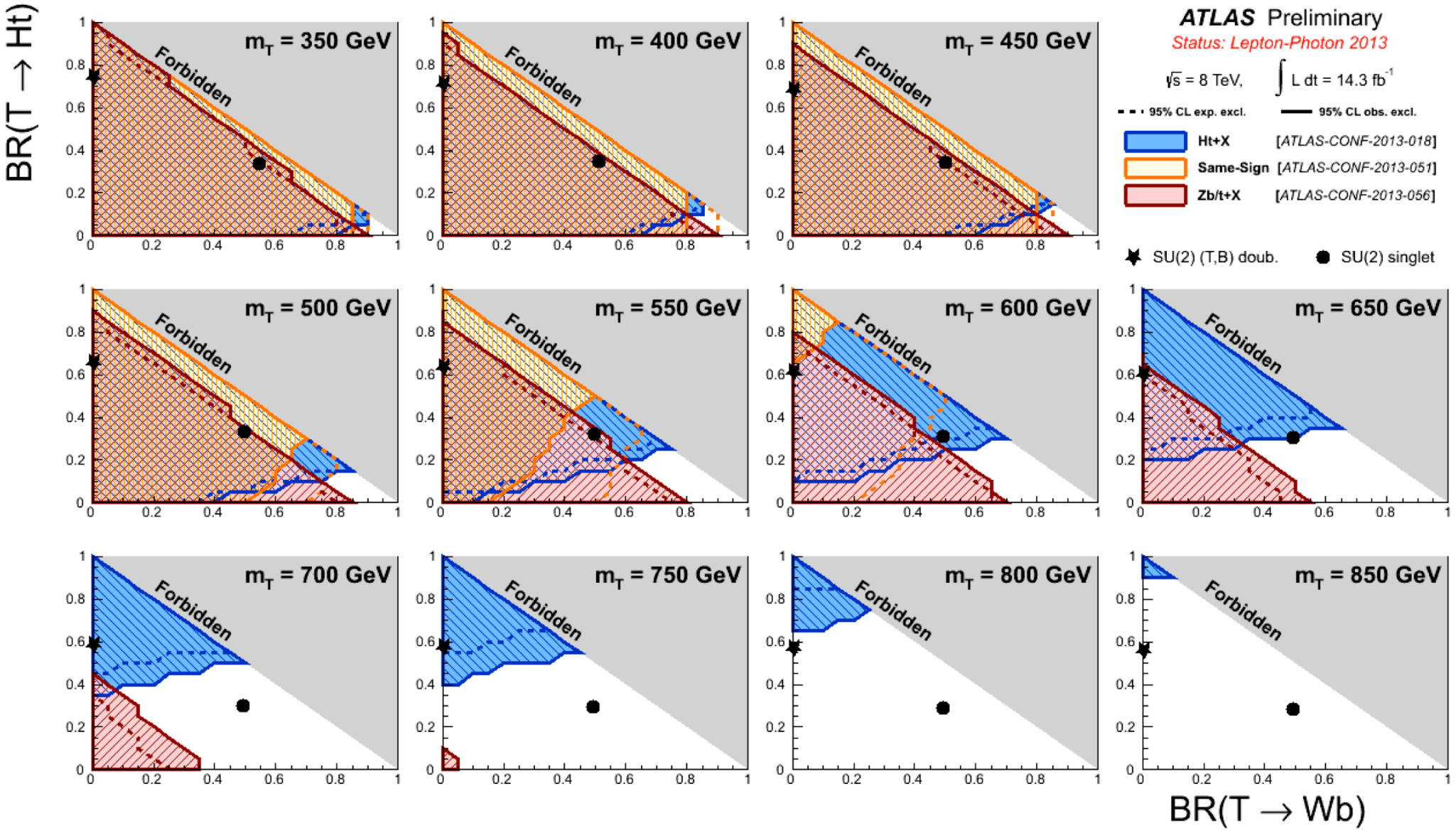
VLQ Limits – T pair production



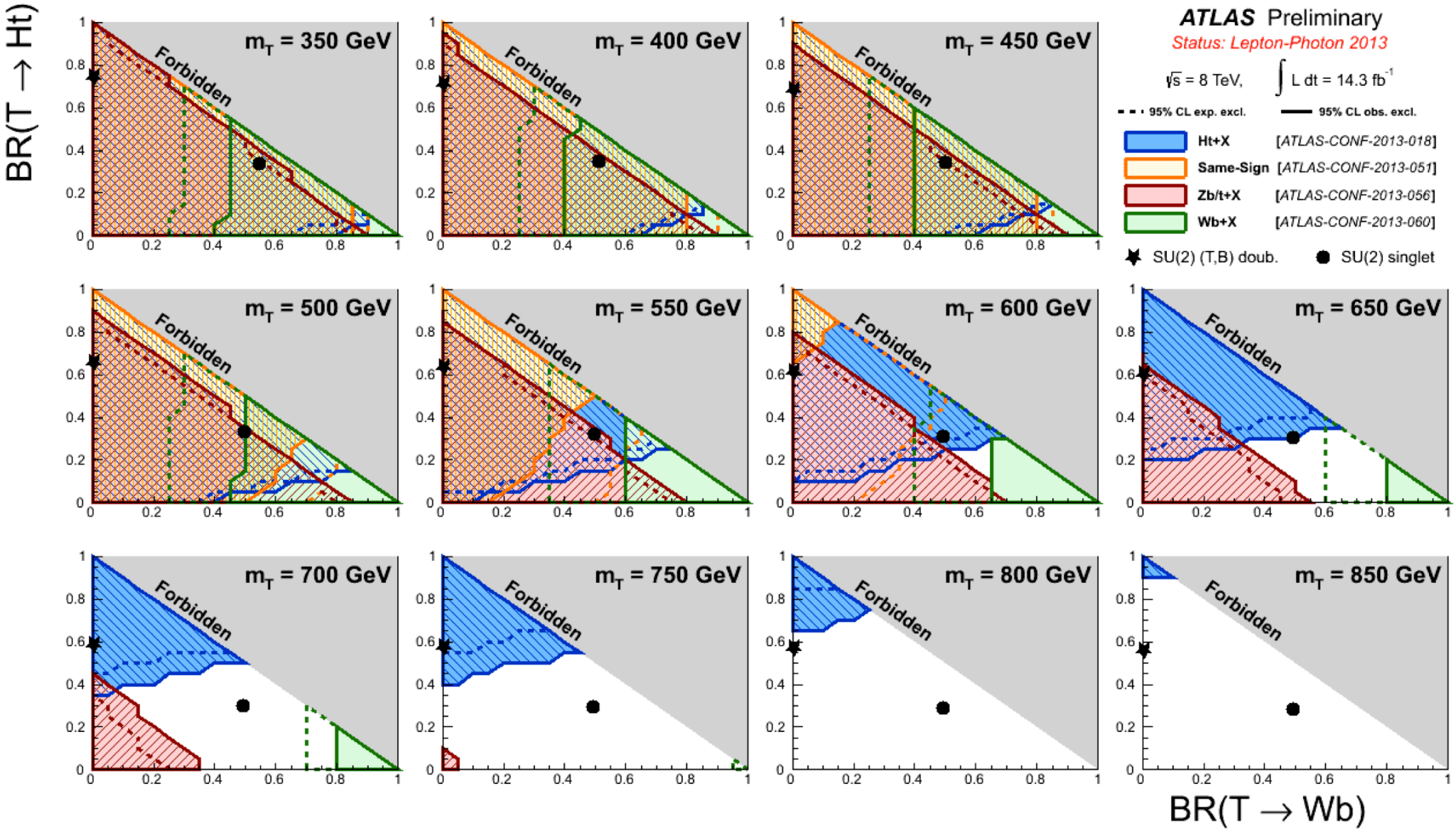
VLQ Limits – T pair production



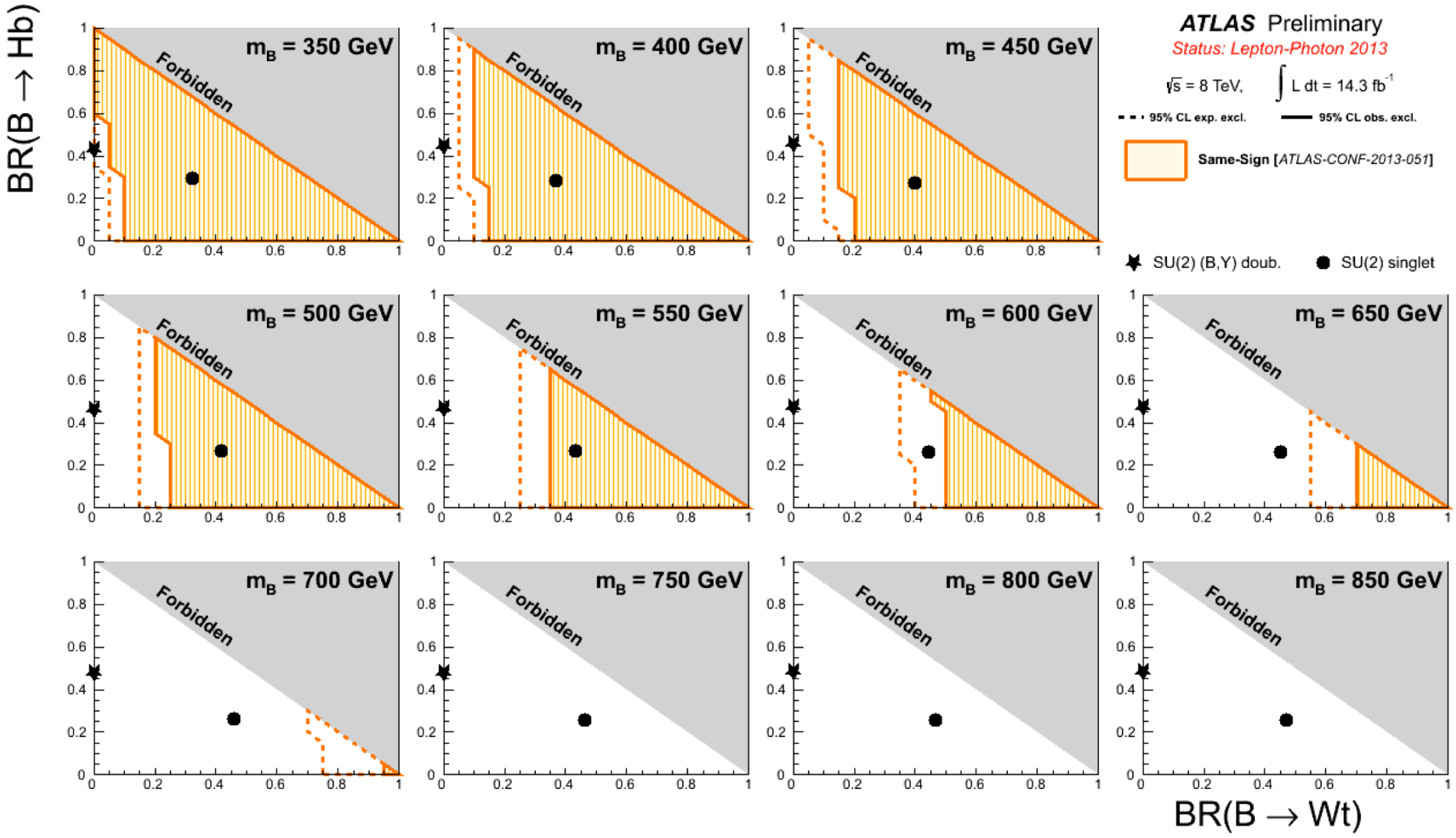
VLQ Limits – T pair production



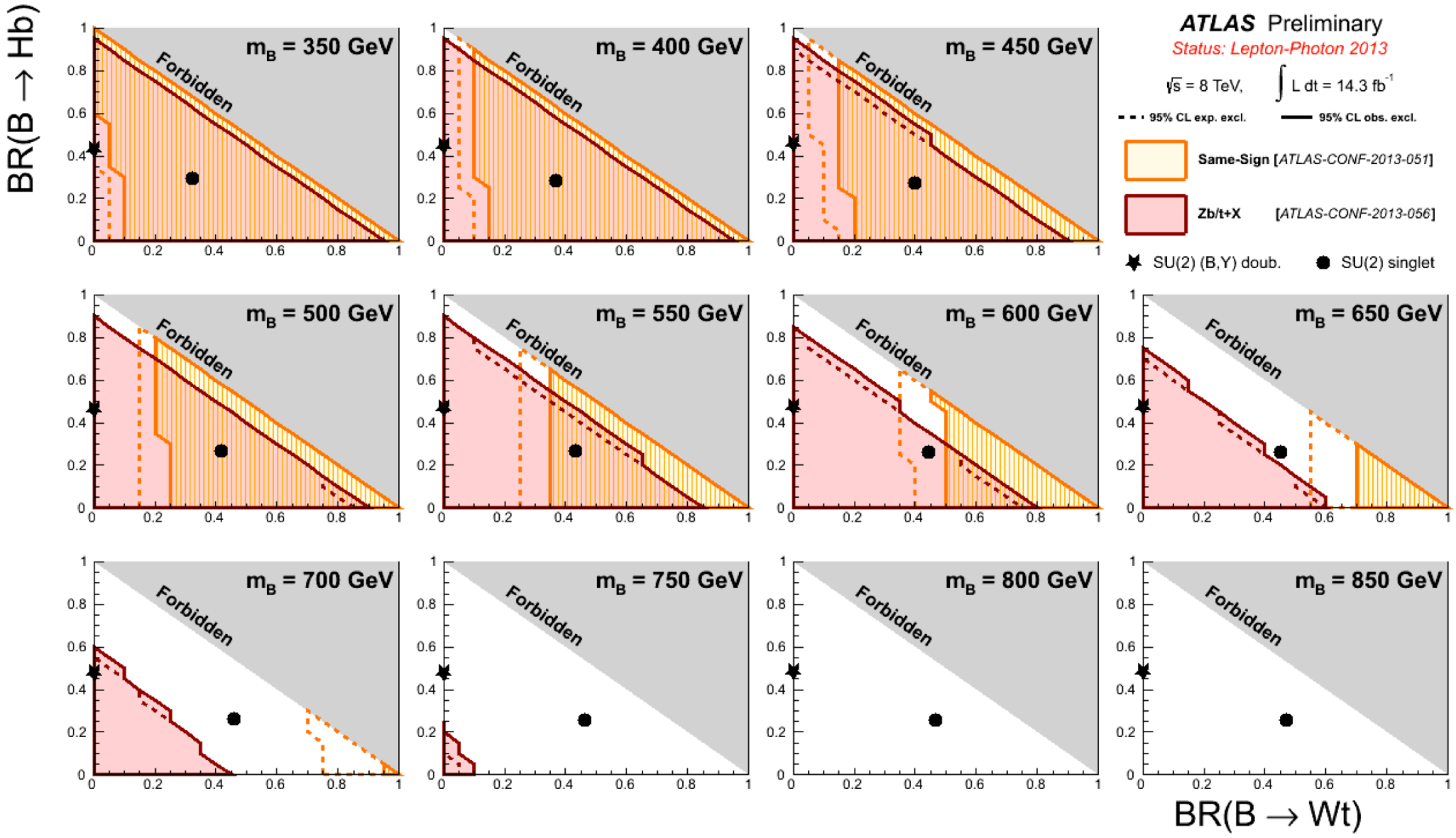
VLQ Limits – T pair production



VLQ Limits – B pair production



VLQ Limits – B pair production



Summary

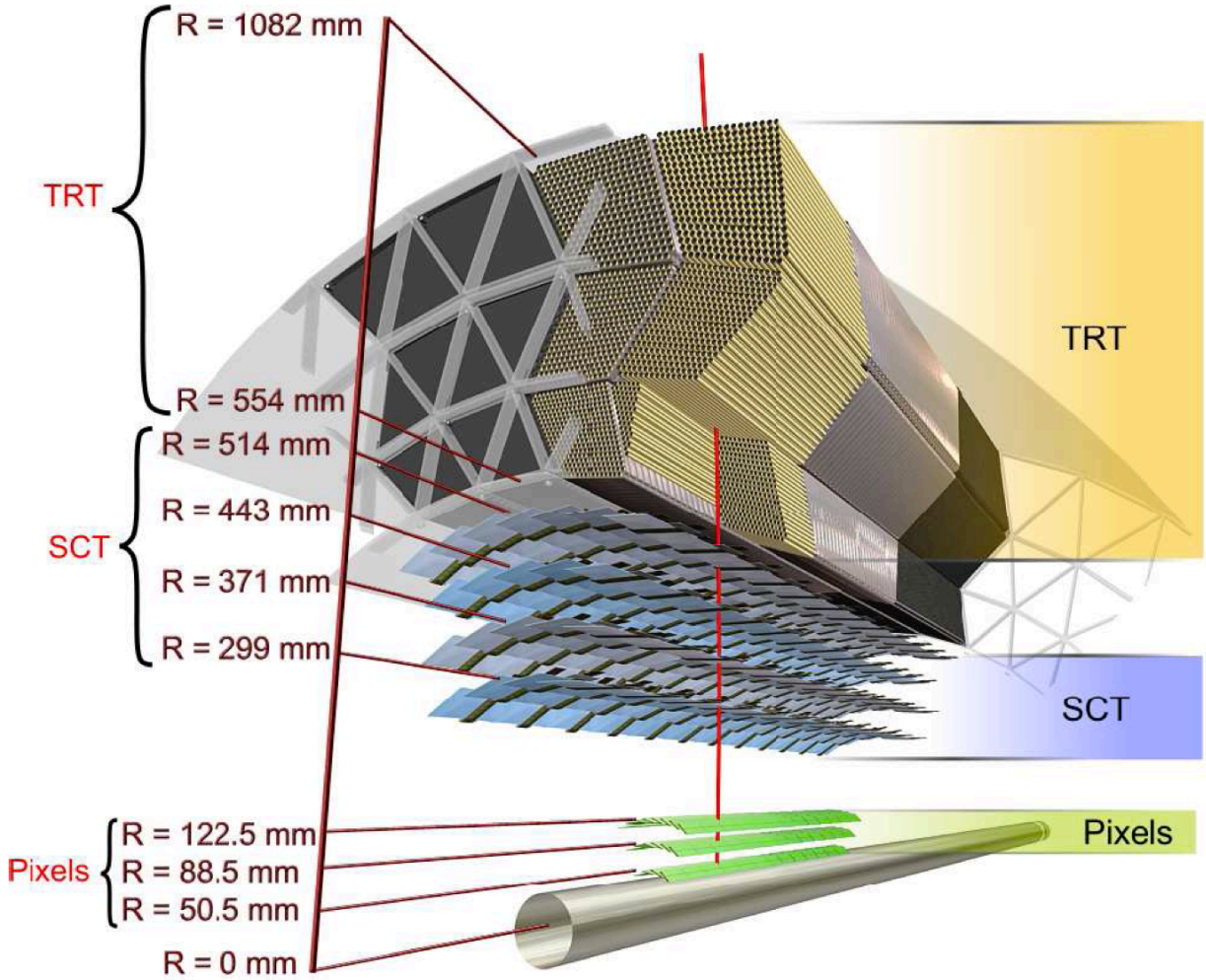
- Tremendous effort has been put into Vector-Like Quarks search in different channels at ATLAS in the last 2 years
- Search strategies are optimized independently for different channels
- Results are being updated with 20fb^{-1} 8TeV data
  - Wt+X: approved for paper publication
  - Ht+X: pre-approved, will open box soon
  - Zt/Zb+X: paper draft ready, soon to be published
  - Same-sign di-leptons: paper draft ready, soon to be published
- Gain a lot of experience from 7/8 TeV and ramp up for 13 TeV data in 2015

backup

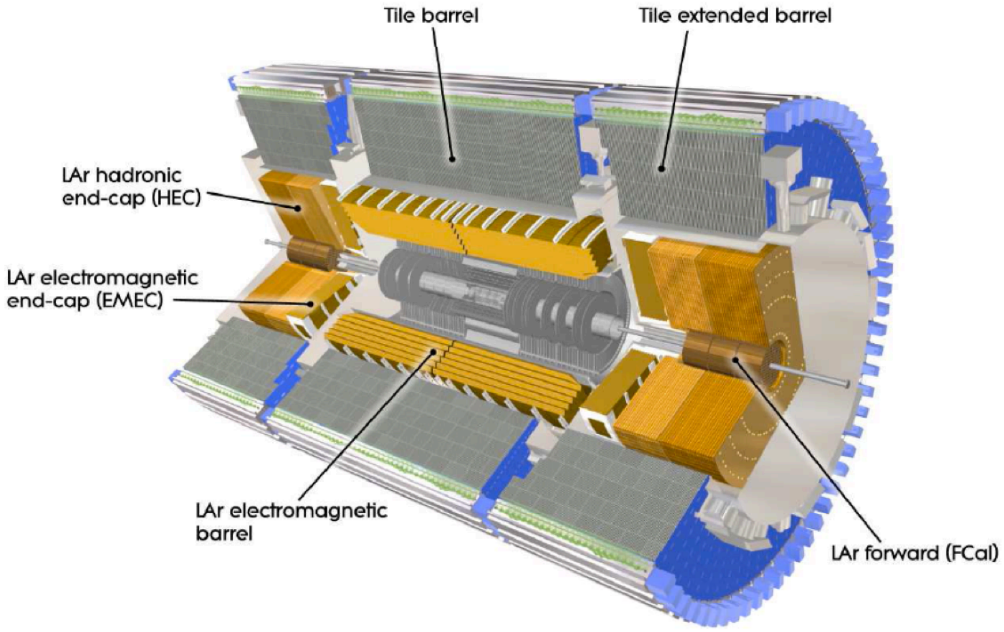
Inner Detector

Provide track measurement in both e and μ channels

- $|\eta| < 2.47$
- 3 layers of pixel
- 4 layers of silicon microstrip detectors(SCT) providing eight hits per track
- Transition radiation tracker(TRT) provides ~35 hits per track

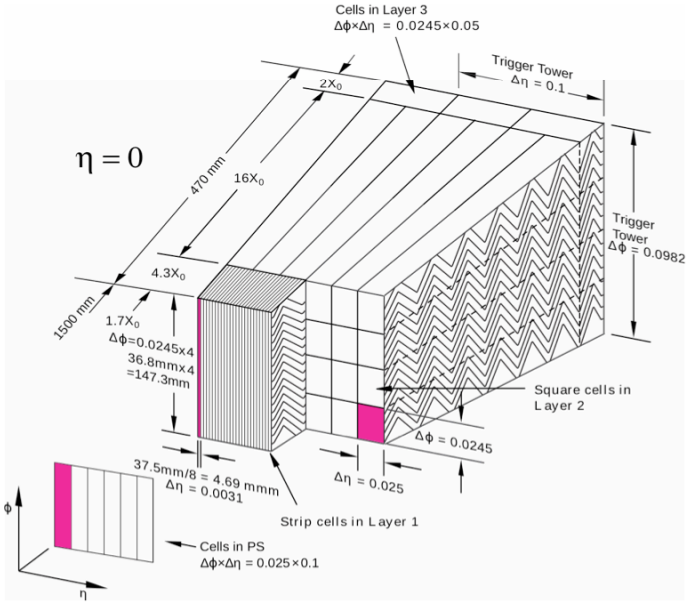


Calorimeter(Liquid Argon/Tile)



- Energy measurement and identification for electrons, photons and jets
- Barrel and Endcaps
- Electromagnetic and Hadronic

- Full coverage : $|\eta| < 4.9$
- Fine segmentation in lateral and longitudinal directions of showers(3 longitudinal sections in EM)



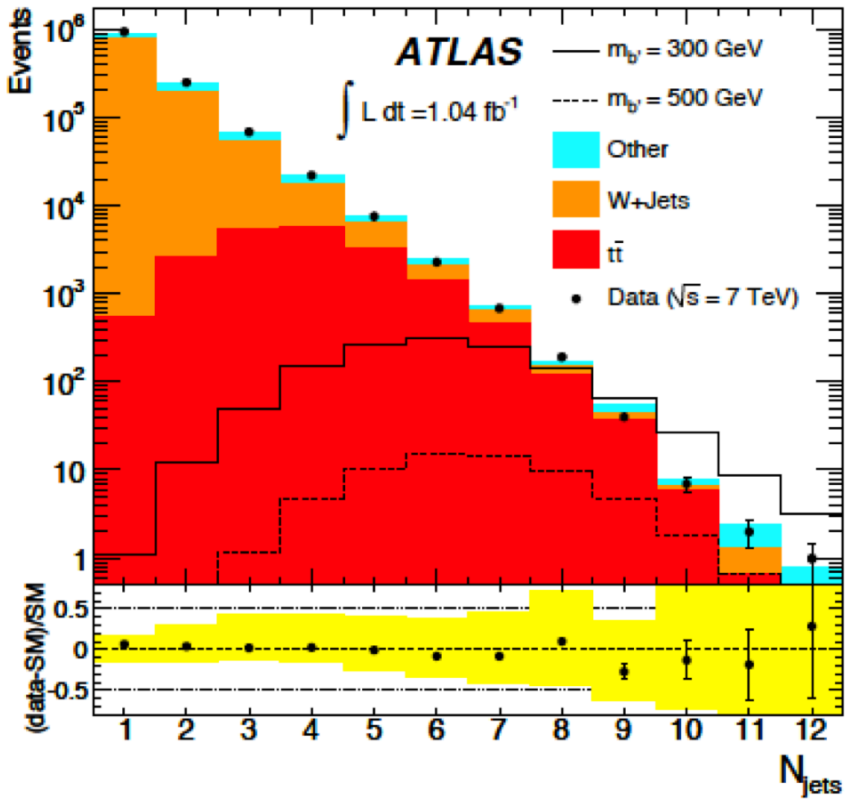
Backgrounds	Channel		
Samples	ee	$e\mu$	$\mu\mu$
Charge misidentification	$0.6 \pm 0.1 \pm 0.2$	$0.9 \pm 0.1 \pm 0.3$	—
Fakes	$0.8 \pm 0.4 \pm 0.3$	$0.2 \pm 0.4 \pm 0.1$	< 1.1
Diboson			
• WZ/ZZ+jets	$0.3 \pm 0.2 \pm 0.1$	$0.3 \pm 0.1^{+0.4}_{-0.2}$	$0.4 \pm 0.2 \pm 0.1$
• $W^{\pm}W^{\pm}$+2 jets	$0.17 \pm 0.09 \pm 0.05$	$0.3 \pm 0.2 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$
$t\bar{t} + W/Z$			
• $t\bar{t}W$(+jet(s))	$0.6 \pm 0.2 \pm 0.3$	$1.9 \pm 0.2 \pm 0.6$	$1.3 \pm 0.2 \pm 0.4$
• $t\bar{t}Z$(+jet(s))	$0.18 \pm 0.03 \pm 0.06$	$0.66 \pm 0.05 \pm 0.22$	$0.31 \pm 0.04 \pm 0.10$
• $t\bar{t}W^+W^-$	$0.024 \pm 0.003^{+0.010}_{-0.007}$	$0.072 \pm 0.005^{+0.028}_{-0.020}$	$0.055 \pm 0.004^{+0.022}_{-0.016}$
Total expected background	$2.7 \pm 0.5 \pm 0.4$	$4.4 \pm 0.5^{+0.9}_{-0.7}$	$2.3 \pm 1.2 \pm 0.5$
Observed	3	10	2

Process	Channel		
	ee	$e\mu$	$\mu\mu$
$b'(400\ \text{GeV}) \rightarrow Wt$	0.11 ± 0.01	0.39 ± 0.02	0.25 ± 0.02
$b'(600\ \text{GeV}) \rightarrow Wt$	0.30 ± 0.02	0.82 ± 0.03	0.53 ± 0.02
$b'(800\ \text{GeV}) \rightarrow Wt$	0.37 ± 0.02	1.02 ± 0.03	0.64 ± 0.02
$b'(1000\ \text{GeV}) \rightarrow Wt$	0.35 ± 0.02	1.11 ± 0.03	0.63 ± 0.02
$b'(400\ \text{GeV}) \rightarrow Wq$	0.024 ± 0.004	0.082 ± 0.007	0.060 ± 0.006
$b'(600\ \text{GeV}) \rightarrow Wq$	0.09 ± 0.01	0.25 ± 0.01	0.14 ± 0.01
$b'(800\ \text{GeV}) \rightarrow Wq$	0.13 ± 0.01	0.32 ± 0.01	0.19 ± 0.01
$b'(1000\ \text{GeV}) \rightarrow Wq$	0.10 ± 0.01	0.32 ± 0.02	0.20 ± 0.01

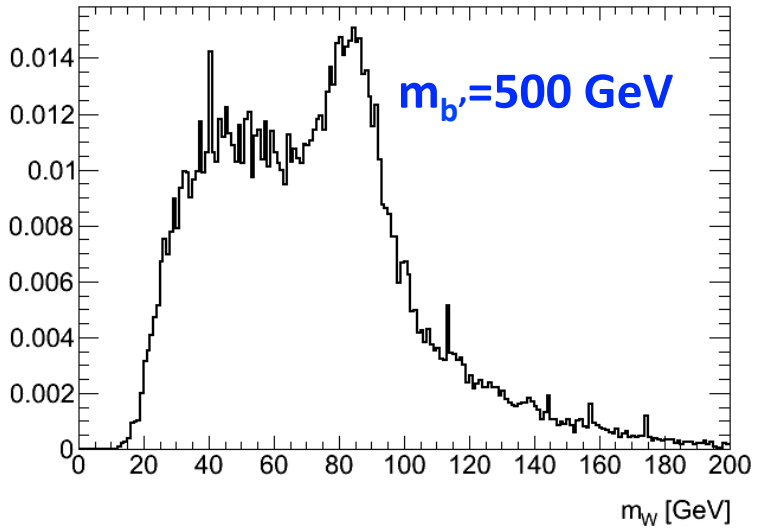
Jet Selection

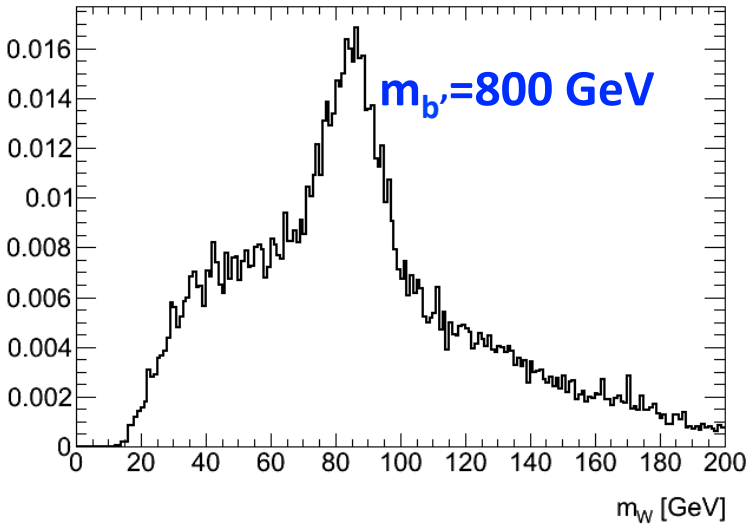
- Use AntiKt4 jet
- $|\eta| < 2.5$
- Pt > 25 GeV
- $|JVF| > 0.75$
- Remove jet overlapped with e candidate within $\Delta R < 0.2$
- Bad jet event removal

Jet multiplicity after Jet selection

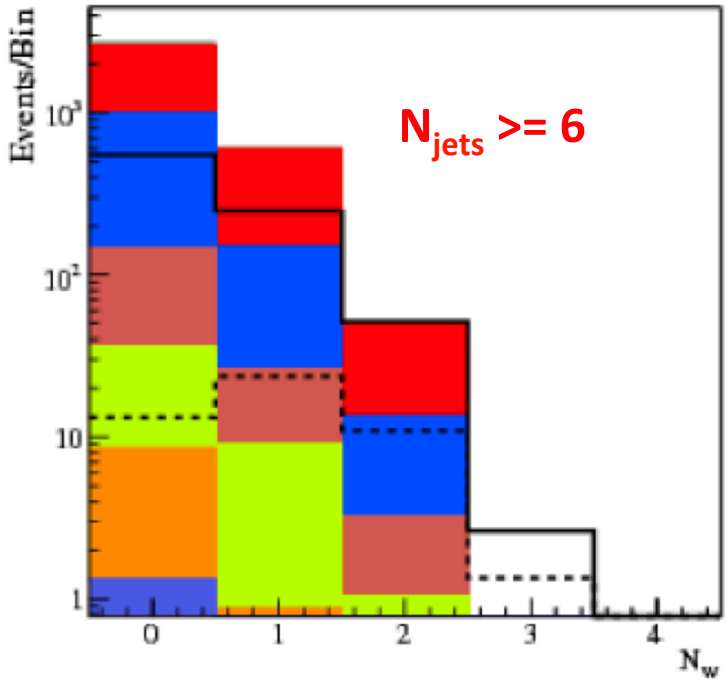


Event cuts





- Exactly one selected lepton
- Reject events with LAr noise burst
- Triangle cut(suppress QCD):
  - e: MET>30 GeV , W m_T>30 GeV
  - μ: MET>20 GeV, MET + W m_T > 60 GeV
- >=6 selected jets(signal region)
- Hadronic W reconstruction:
  - 2 jets within ΔR<1.0 (open angle : ~ $2*m_W/P_T$)
  - Di-jet mass within (70, 100)



Systematics

- **Dominant:**
  - **JES: 17%**
  - **ttbar reweighting(ttH recipe: 9 components): 17%**

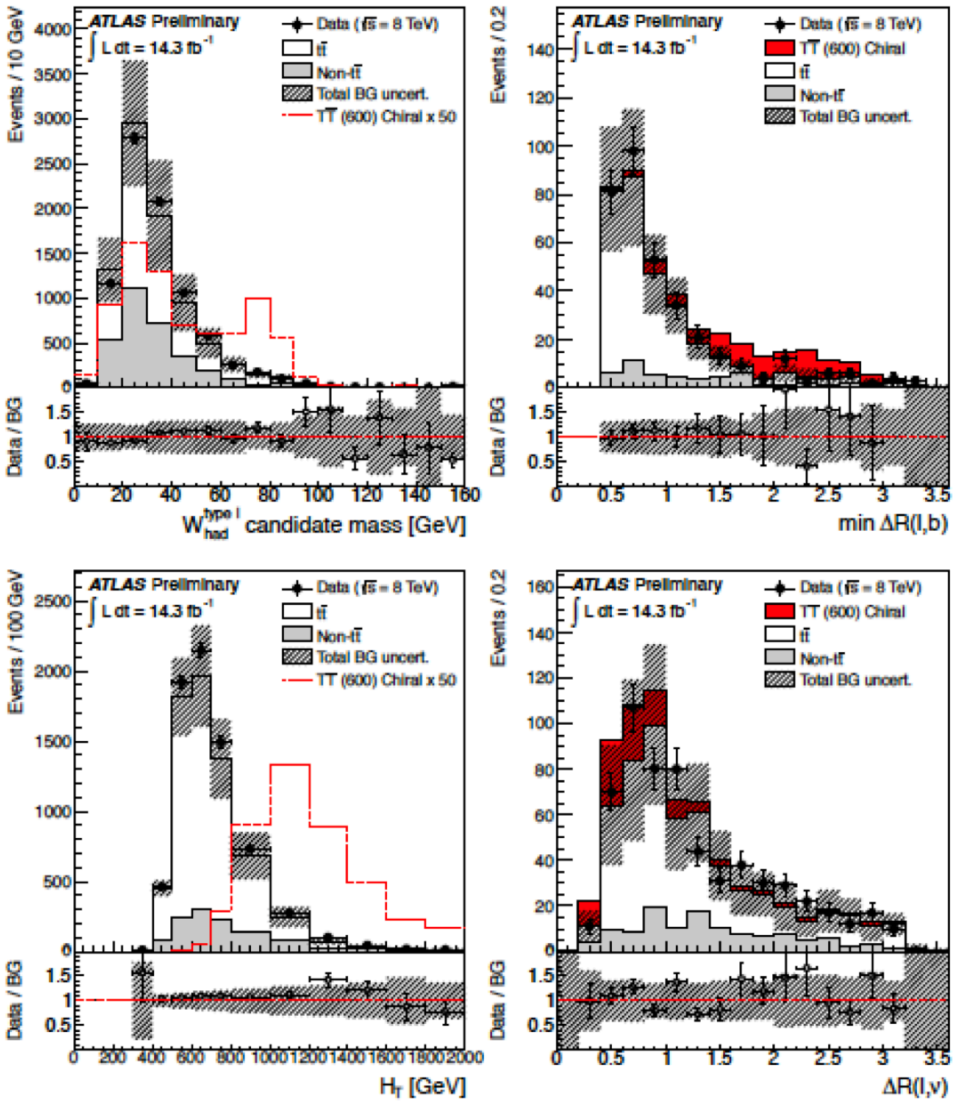
- **Other systs:**
  - **ttbar:**
    - **PDF: 9%**
    - **parton shower: Powheg+Pythia vs Powheg+Herwig, 6%**
  - **Lumi: 2.8%**
  - **JER: a few %**
  - **btag: a few %**
  - **QCD: quote conservative 50%**

- **Theoretical errors:**
  - **ttbar: +5%, -6%**
  - **Wjets, Zjets, diboson: 4 or 5% plus 24% for each additional jet**
  - **Single top: ~5%**
  - **ttbarV: 30%**

TT->Wb+X

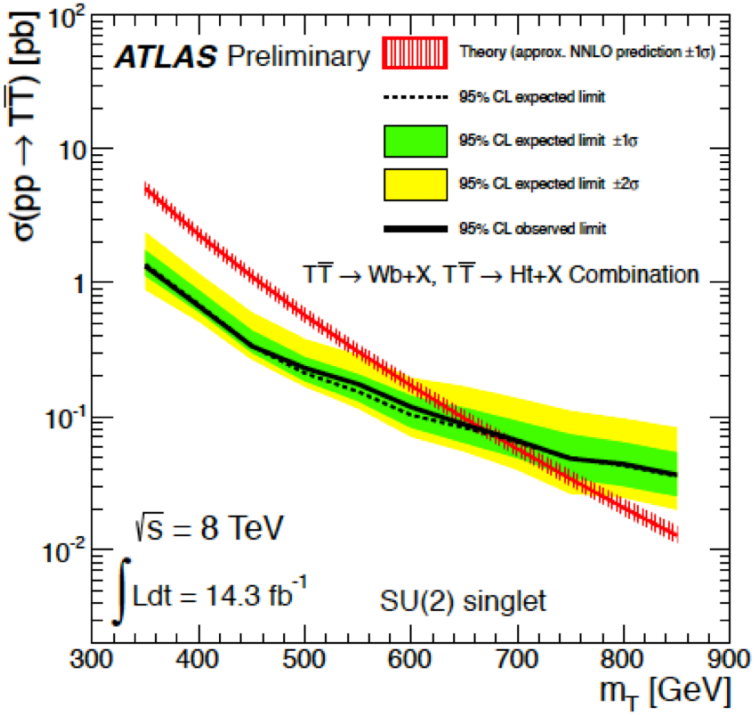
- W_{had}^{typeI}: single merged jet ($p_T > 250$ GeV, $m_j \in [60, 120]$ GeV)
- W_{had}^{typeII}: two close-by jets ($\Delta R(j,j) < 0.8$, $p_T > 200$ GeV, $m_{jj} \in [60, 120]$ GeV)

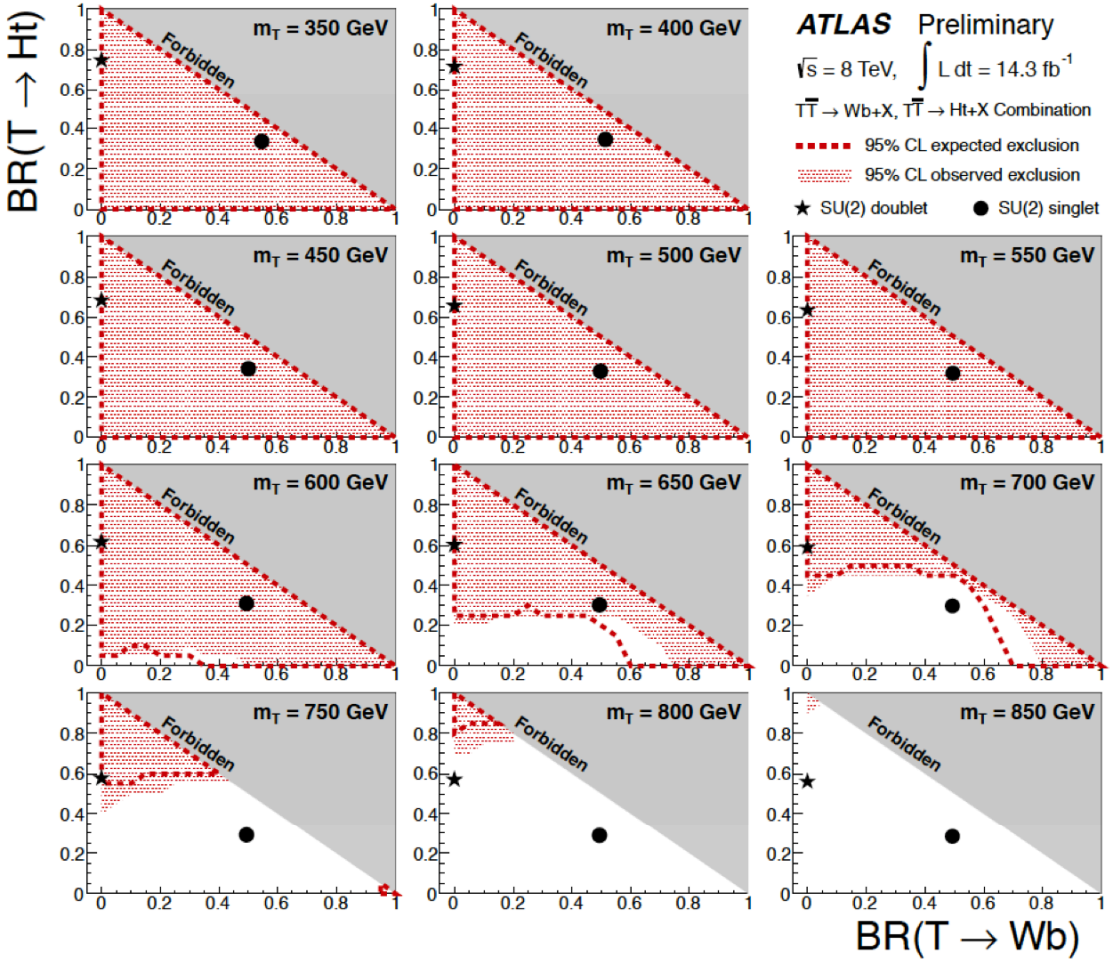
- one lepton (e or mu), E_T^{miss} >20 GeV, $E_T^{\text{miss}} + m_T(W)$ >60 GeV
- $\geq$4 jets AND (one W_{had}^{typeI} OR one W_{had}^{typeII})
- $\geq$ 1 $b$tagged jet (consider also the 2nd highest b-tag weight jet)
- $H_T^{(a)} > 800$ GeV
- $p_T(b_1) > 160$ GeV, $p_T(b_2) > 80$ GeV
- $\Delta R(l, \nu) < 1.2$
- $min(\Delta R(l, b_{1,2})) > 1.4$
- $min(\Delta R(W_{had}, b_{1,2})) > 1.4$



Define tight sample $^{(a)} H_T = p_T(j_1) + p_T(j_2) + p_T(j_3) + p_T(j_4) + p_T(l) + E_T^{\text{miss}}$

Combine Wb + X & Ht + X





Observed (expected) 95% CL limit:

- **SU(2) singlet: m_T>670 (675) GeV**
- **2D exclusion: completely exclude 350 – 550 GeV**

TT/BB->Same-Sign leptons

- Also set limit on other models:
  - b'->Wq_{light}
  - 2UED/RPP
  - 4-fermion Contact interaction
  - Sgluon pair production
  - ……