Searches for Vector-Like Quarks in the one lepton final state

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CERN

Signatures: 4th generation quarks

- 4thGeneration models have a restricted list of available signatures that simplify the search strategy: TT → WbWb, BB→tWtW → WbW WbW

			TB_d		
4l (0Z)			BB		
3l (0Z)			BB		
l^+l^- (0Z)			TT,BB		
$l^\pm l^\pm$			BB		
$l^\pm$ (4j)			TT		
$l^\pm$ (≥6j)			BB		

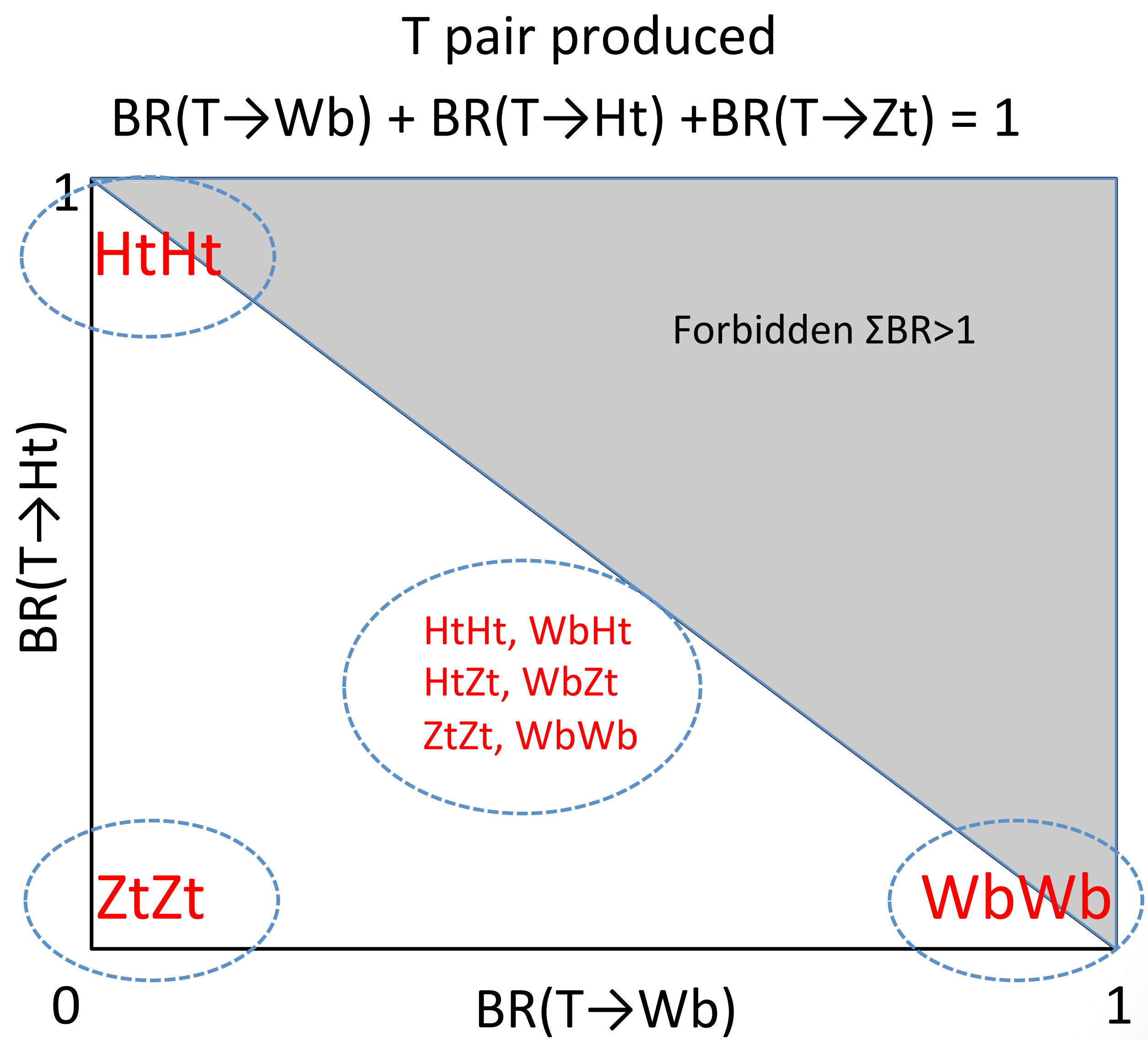
Vector-Like-Quarks

- If we consider VLQ models, there are many signatures that could be exploited, and which are ultimately needed to both enhance discovery potential and model discrimination.

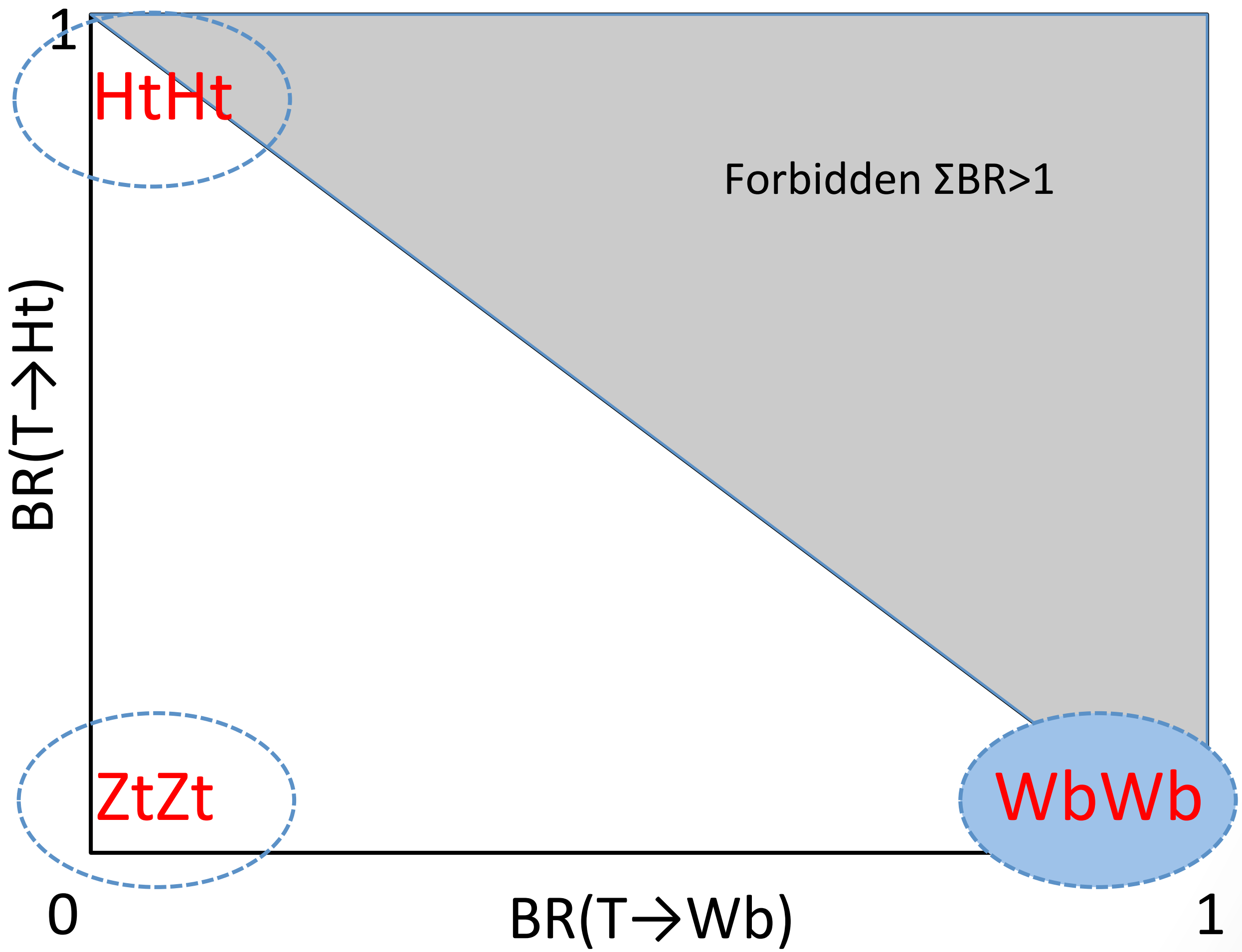
		T_s	B_s	TB_d	XT_d	BY_d
4 leptons	4l (2Z)	TT	BB	TT,BB	TT	BB
	4l (1Z)	TT	BB	TT,BB	TT	BB
	4l (0Z)	TT	BB	TT,BB	TT,XX	BB
3 leptons	3l (1Z)	TT	BB	TT,BB	TT	
	3l (0Z)	TT	BB	TT,BB	TT,XX	
OS leptons	l^+l^- (1Z)	TT	BB	TT,BB	TT	BB
	l^+l^- (0Z)	TT	BB	TT,BB	TT,XX	BB,YY
SS leptons	$l^\pm l^\pm$		BB	BB	XX	
L+jets	$l^\pm$ (4j)	TT		TT	TT	YY
	$l^\pm$ ($\geq$6j)	TT	BB	TT,BB	TT,XX	

Overall ATLAS strategy

Will not talk about B today as no 1 lepton VLQ interpretation has been made public yet…



7TeV, $1fb^{-1}$ Phys. Rev. Lett. 108, 261802 (2012)



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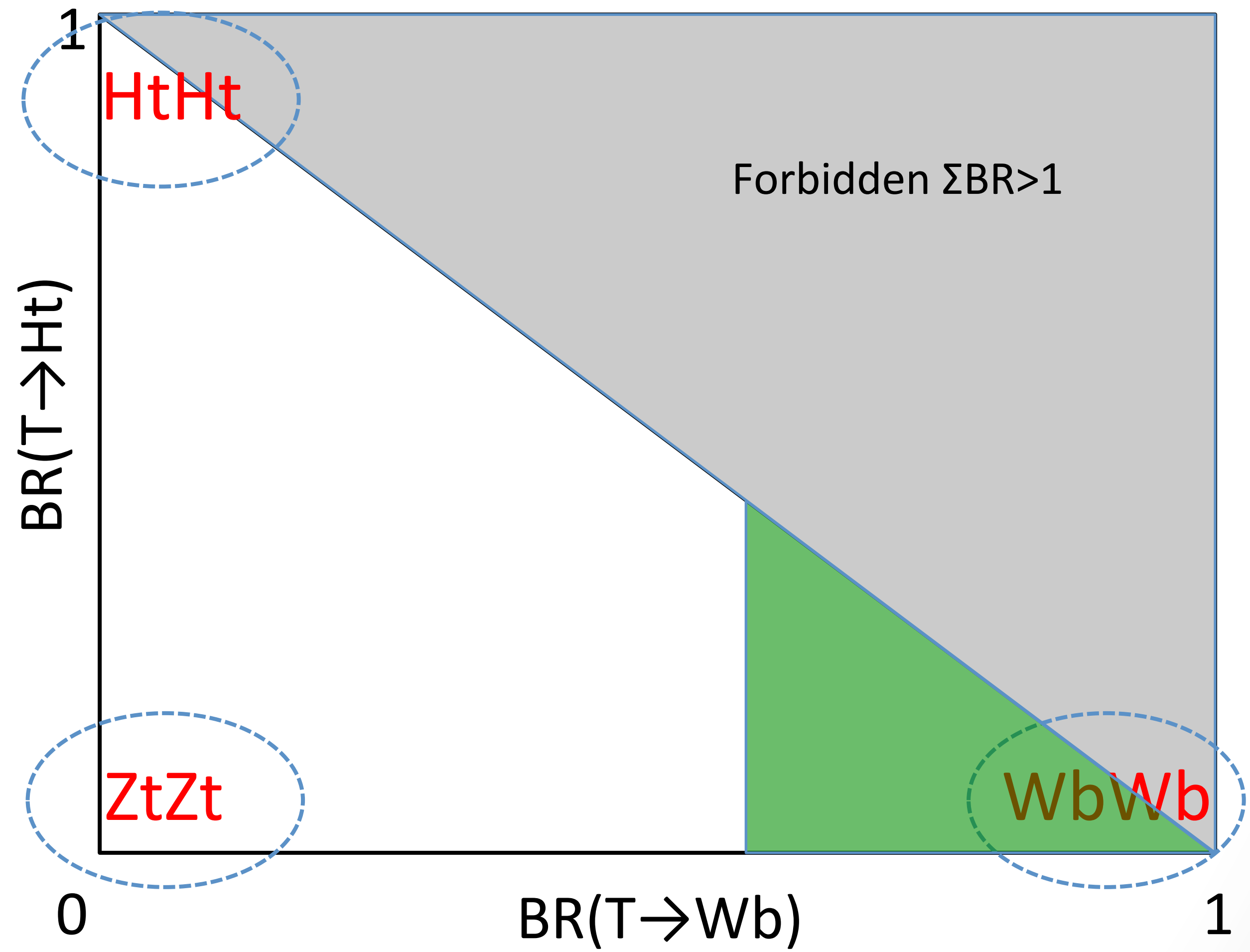

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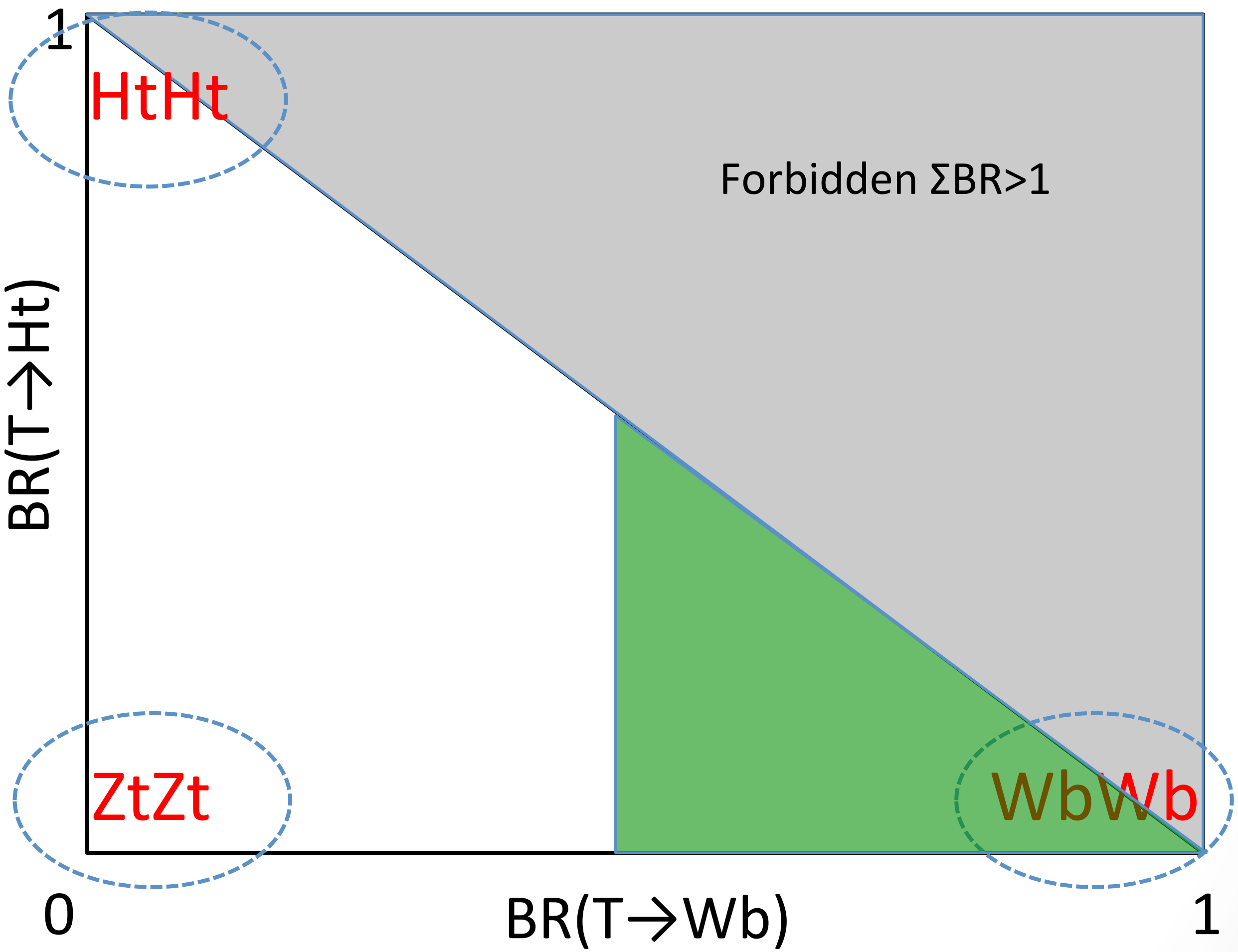
8TeV, $14.3fb^{-1}$ ATL-CONF-2013-060



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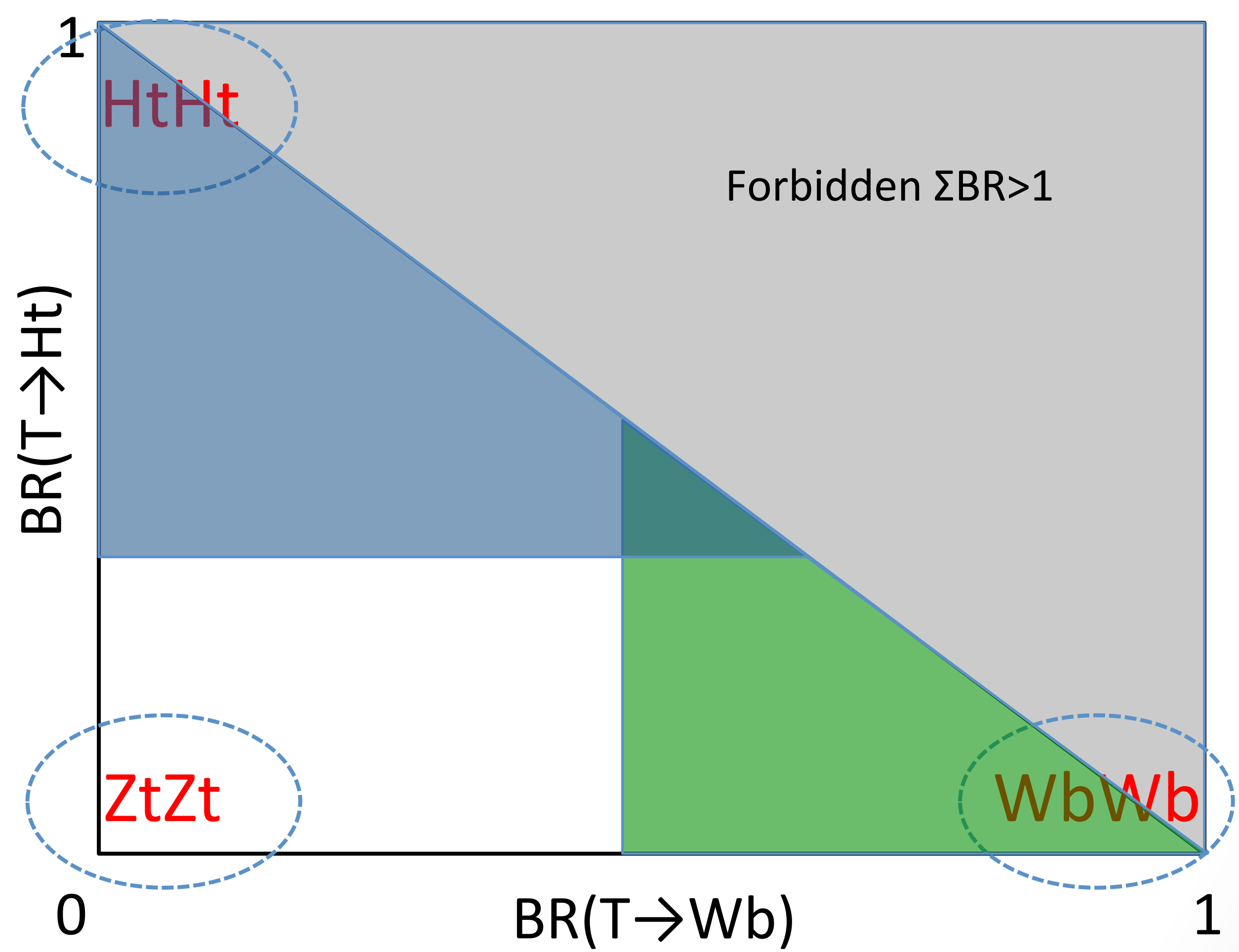

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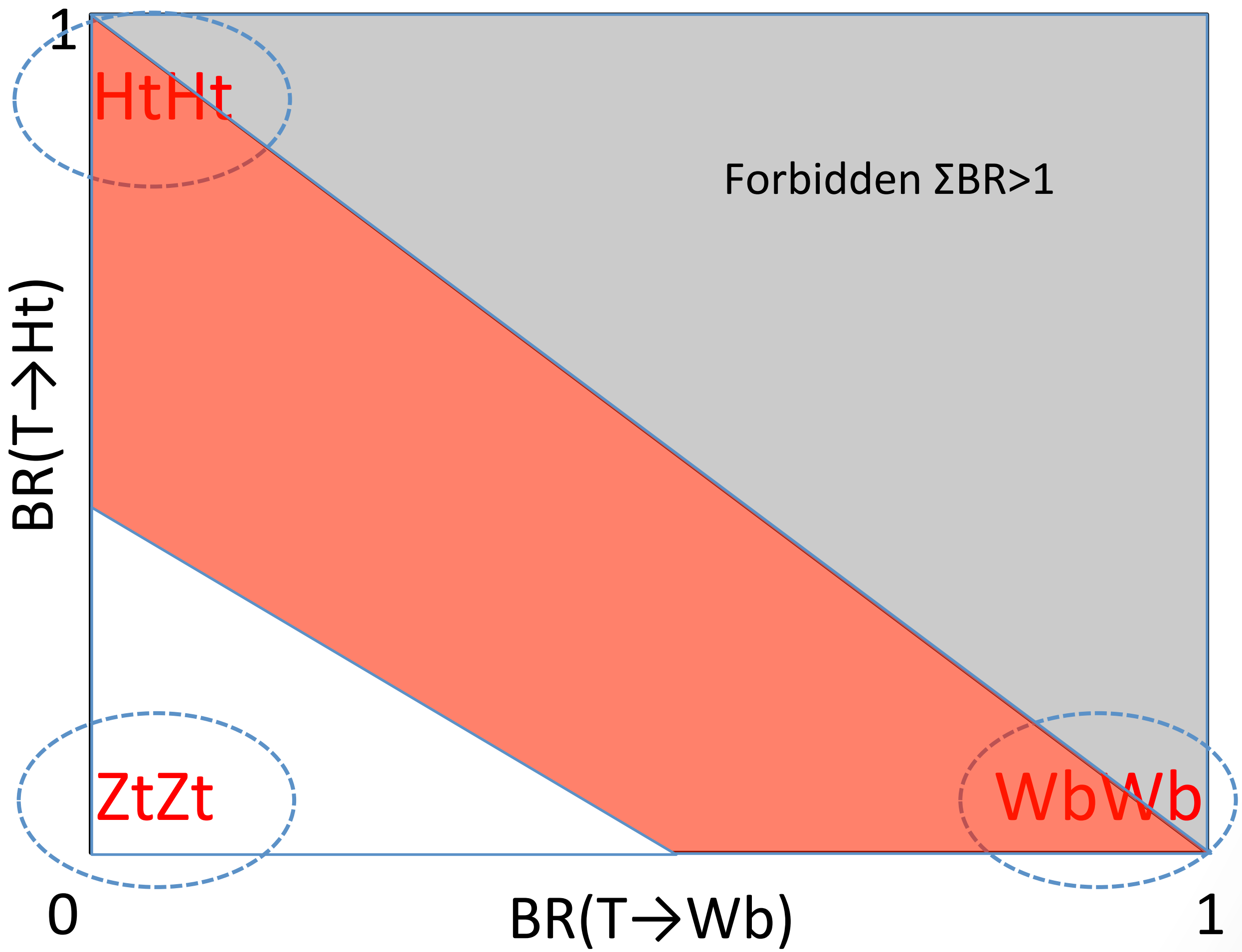
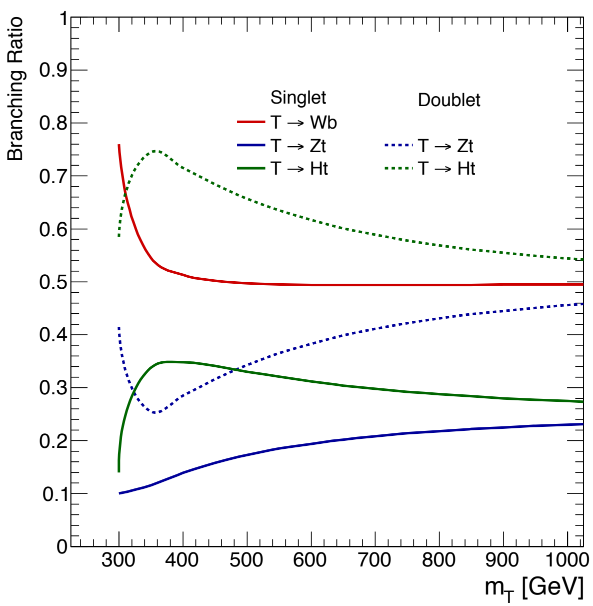
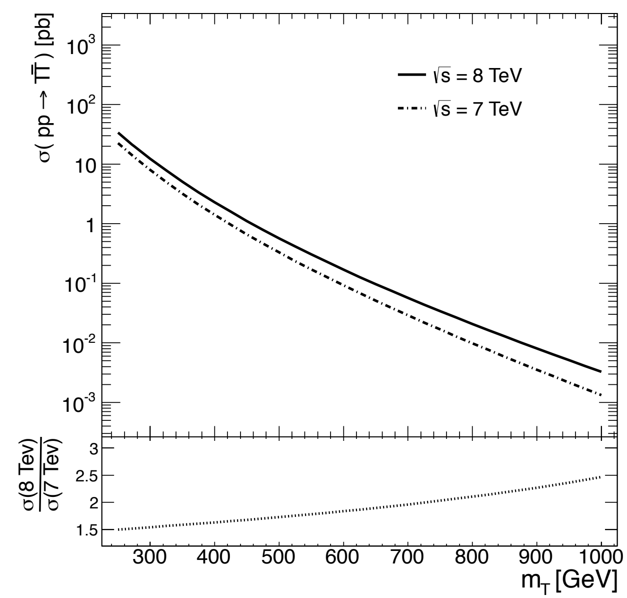


Signal samples

- Signal samples generated with PROTOS
  - Singlet model → checked that reweighting Singlet to Doublet BR is equivalent than generating Doublet (analysis not sensitive to chirality of the TWb coupling)
  - Masses 350-1100 GeV in steps of 50GeV
  - Original BR == 1/3 and apply a re-weighting procedure to achieve the desired BR

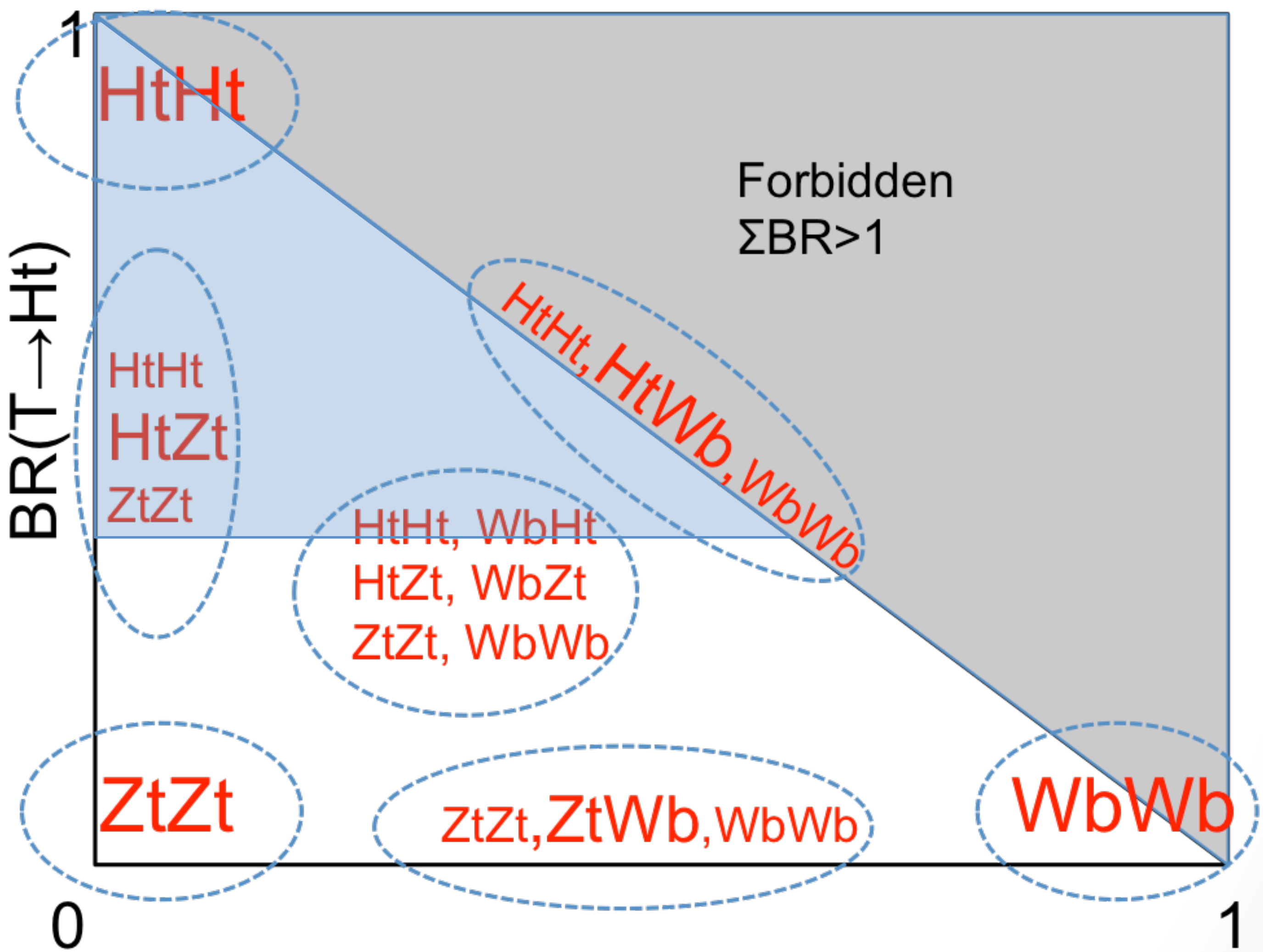




Common objects

- Jets:
  - p_T > 25GeV
  - $|\eta|$< 2.5
  - antik_T 0.4 cone
- B-tagging:
  - Multivariate algorithm
  - 70% efficiency to tag b-quark
  - Light rejection factor ~130
  - Charm rejection factor ~5
- Electron:
  - Single electron trigger
  - isolated
  - p_T> 25GeV
  - $|\eta|$<2.47 removing crack region [1.37, 1.52]
- Muon:
  - Single muon trigger
  - isolated
  - p_T > 25GeV; $|\eta|$< 2.5
- Topological
  - $M_T(W) + E_T^{Miss}$ > 60GeV
  - E_T^{Miss} > 20GeV

Ht+X

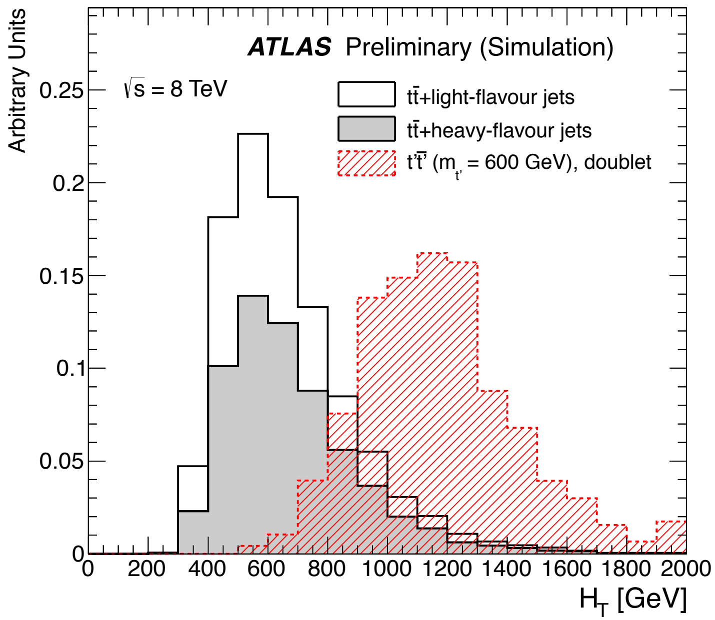

1
0
1
BR(T→Ht)
HtHt
Forbidden
ΣBR>1
HtHt
HtZt
ZtZt
HtHt, HtWb, WbWb
HtHt, WbHt
HtZt, WbZt
ZtZt, WbWb
ZtZt
ZtZt, ZtWb, WbWb
WbWb

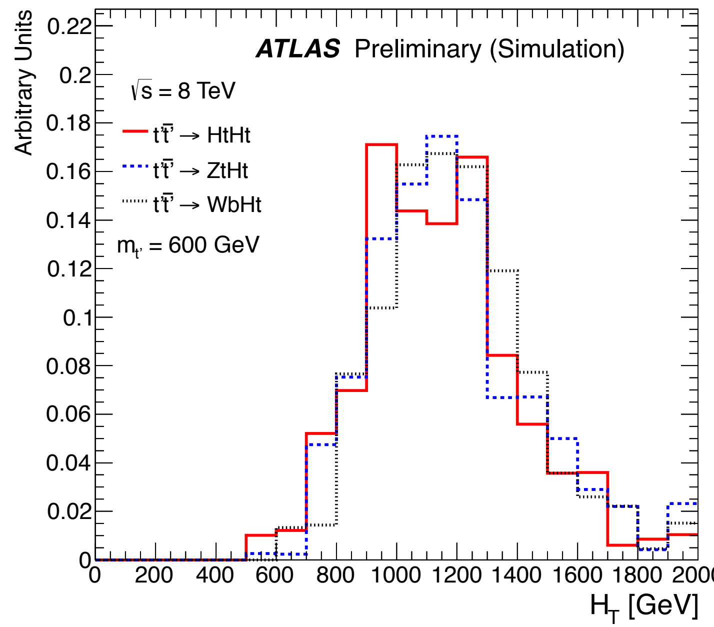
Overall strategy

- This analysis focuses on high multiplicities
  - ≥6 jets
  - ==2, ==3 and ≥4 b-jets
- Ht+X production with X=(Ht, Zt, Wb), always at least 2 b-jets
  - top → Wb ~100%
  - H(125) → bb ~58%
  - Z → bb ~20%
- Thus sensitive in the high b-jets multiplicities regions to
  - HtHt, HtZt, HtWb, ZtZt, ZtWb
- Use H_T as discriminant
  - Σjet p_T+ lepton p_T+ E_T^{Miss}
  - Model independent, same shape for the different decays

Strategy

≥6jets ≥4 tags selection





- H_T is a suitable discriminating variable between signal and background
  - Peaks at ~twice the signal mass
  - Expect a very good signal to background discrimination at high H_T!
- Different decay modes have the same H_T shape
  - Rather independent of the signal decay mode ☺
  - Not possible to discriminate between models ☹

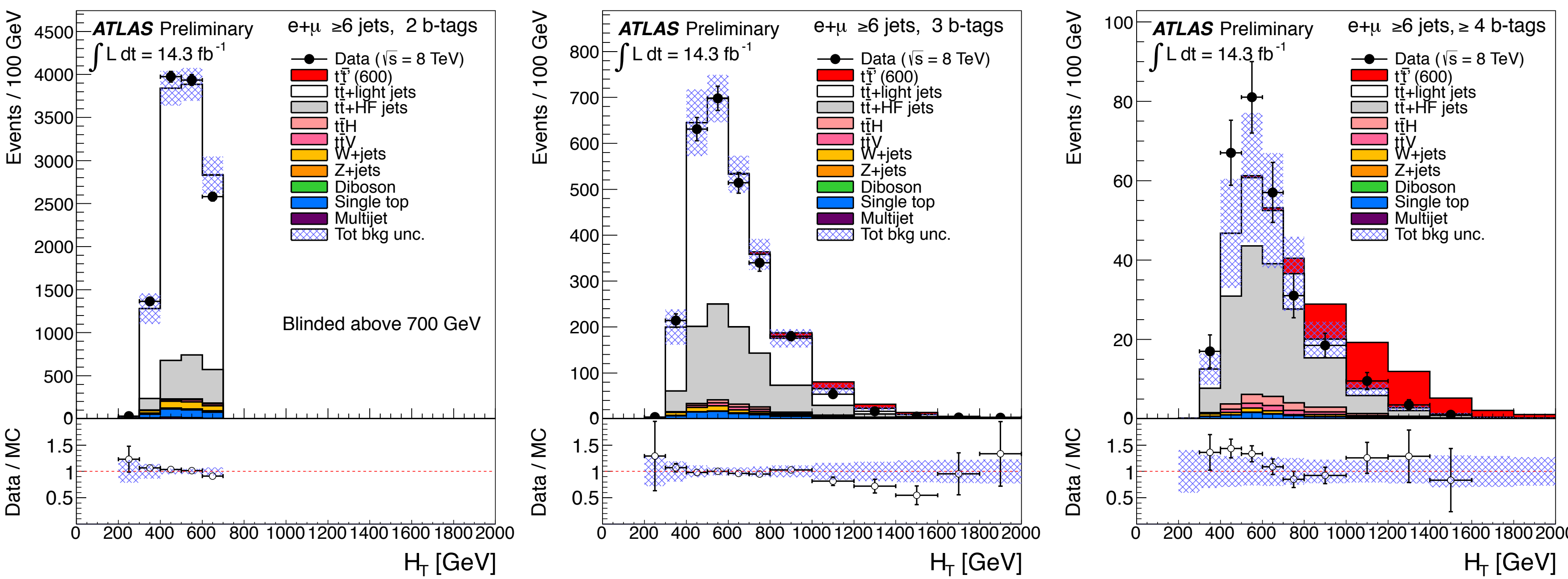
ttbar re-scaling

- Use the 3 channels with different ttbar composition:
  - ≥6 jets, ==2 tags (dominated by ttbar+light)
  - ≥6 jets, ==3tags (dominated by ttbar+light, with large fraction of ttbar+HF)
  - ≥6 jets, ≥4 tags (dominated by ttbar+HF)
- Consider 2 free parameters:
  - ttbar+HF scaling factor
  - ttbar+light scaling factor
- Perform a fit to data
  - ttbar+HF= 1.22 ± 0.08
  - ttbar+light= 0.88 ± 0.02
- Main purpose of this correction
  - Improve the modeling
  - Reduce the impact of systematic uncertainties on the background (fit is done during statistical analysis)

Signal region

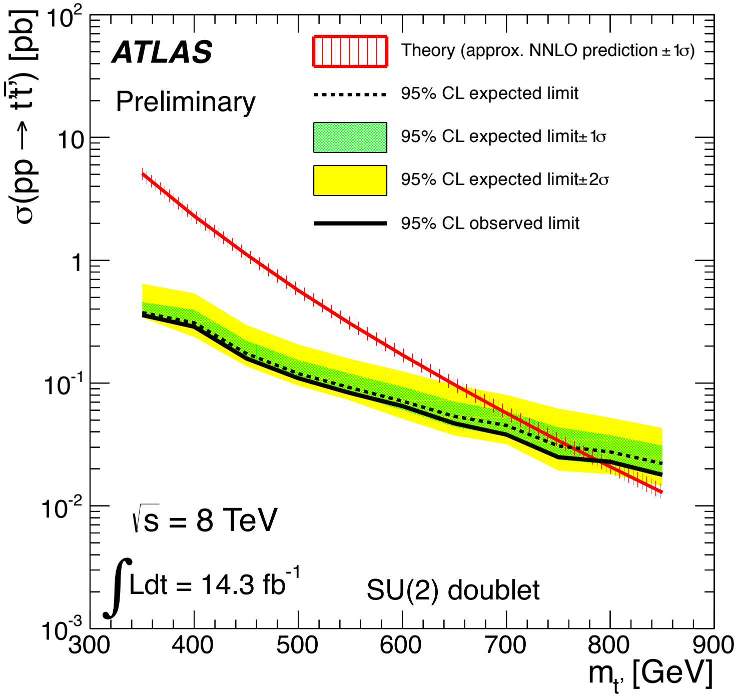
- Ttbar +HF and light are by far the main BG contribution
- Blind ≥6 jets, ==2 tags with H_T>800GeV for orthogonality with Wb+X

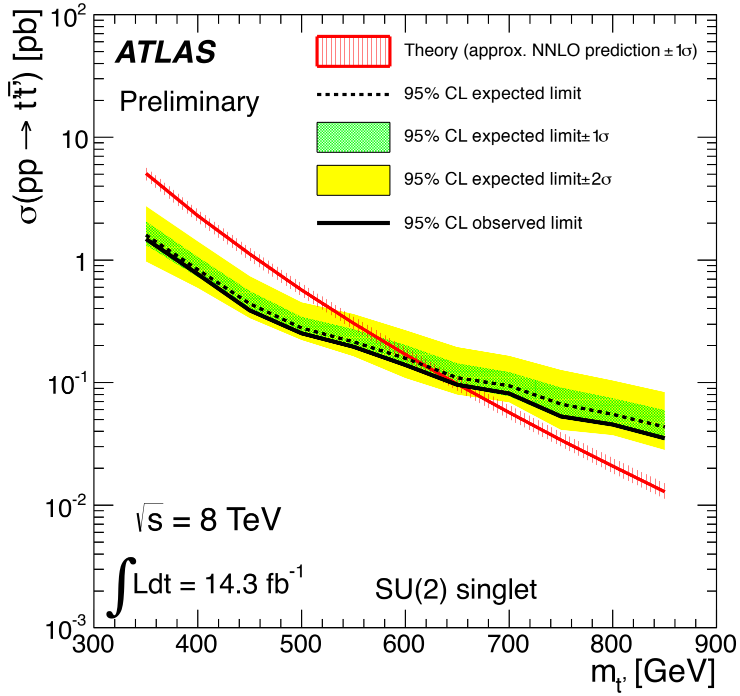
	≥ 6 jets, 2 *b*-tags	≥ 6 jets, 3 *b*-tags	≥ 6 jets, ≥ 4 *b*-tags
$t\bar{t}$+heavy-flavour jets	1500 ± 900	900 ± 400	170 ± 70
$t\bar{t}$+light-flavour jets	9600 ± 1000	1900 ± 350	75 ± 22
W+jets	250 ± 130	50 ± 30	5 ± 3
Z+jets	50 ± 40	9 ± 6	0.5 ± 0.9
Single top	300 ± 70	75 ± 18	7 ± 3
Diboson	1.7 ± 0.6	0.3 ± 0.1	0.03 ± 0.03
$t\bar{t}V$	70 ± 20	36 ± 12	7 ± 3
$t\bar{t}H$	28 ± 4	31 ± 6	12 ± 3
Multijet	49 ± 23	1.7 ± 0.8	0.15 ± 0.06
Total background	11860 ± 260	2990 ± 210	270 ± 60
Data	11885	2922	318
Doublet			
$t'\bar{t}'$(400)	550 ± 70	1100 ± 100	790 ± 160
$t'\bar{t}'$(600)	4.3 ± 1.2	94 ± 7	79 ± 18
$t'\bar{t}'$(800)	0.12 ± 0.05	10.7 ± 0.8	9.1 ± 2.1
Singlet			
$t'\bar{t}'$(400)	290 ± 30	650 ± 80	330 ± 70
$t'\bar{t}'$(600)	2.3 ± 0.4	61 ± 7	36 ± 9
$t'\bar{t}'$(800)	0.06 ± 0.01	6.9 ± 0.7	4.2 ± 1.1



Results versus mass

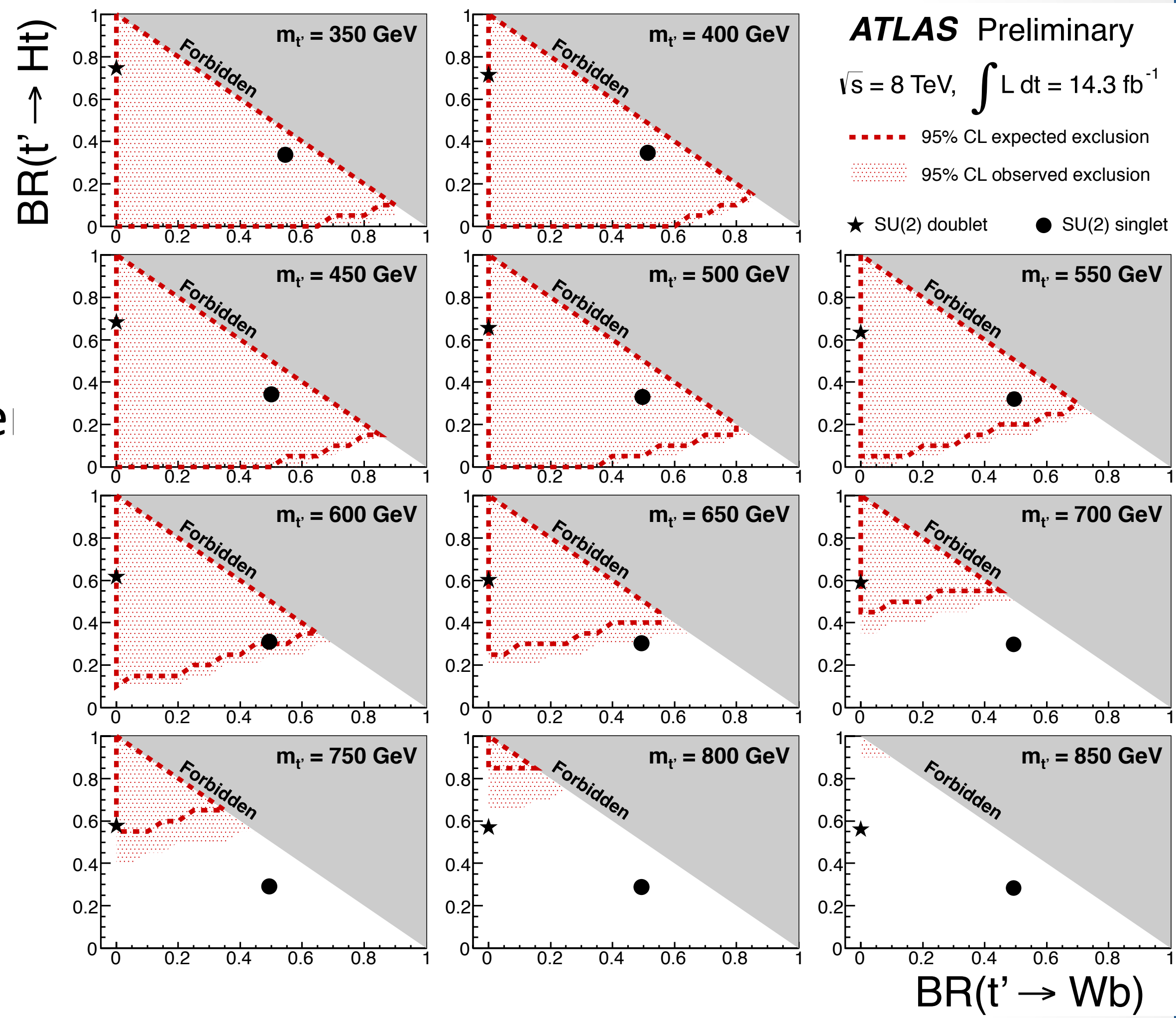
- Doublet m(t') > 790(745)GeV Obs(Exp)
- Singlet m(t') > 640(615)GeV Obs(Exp)





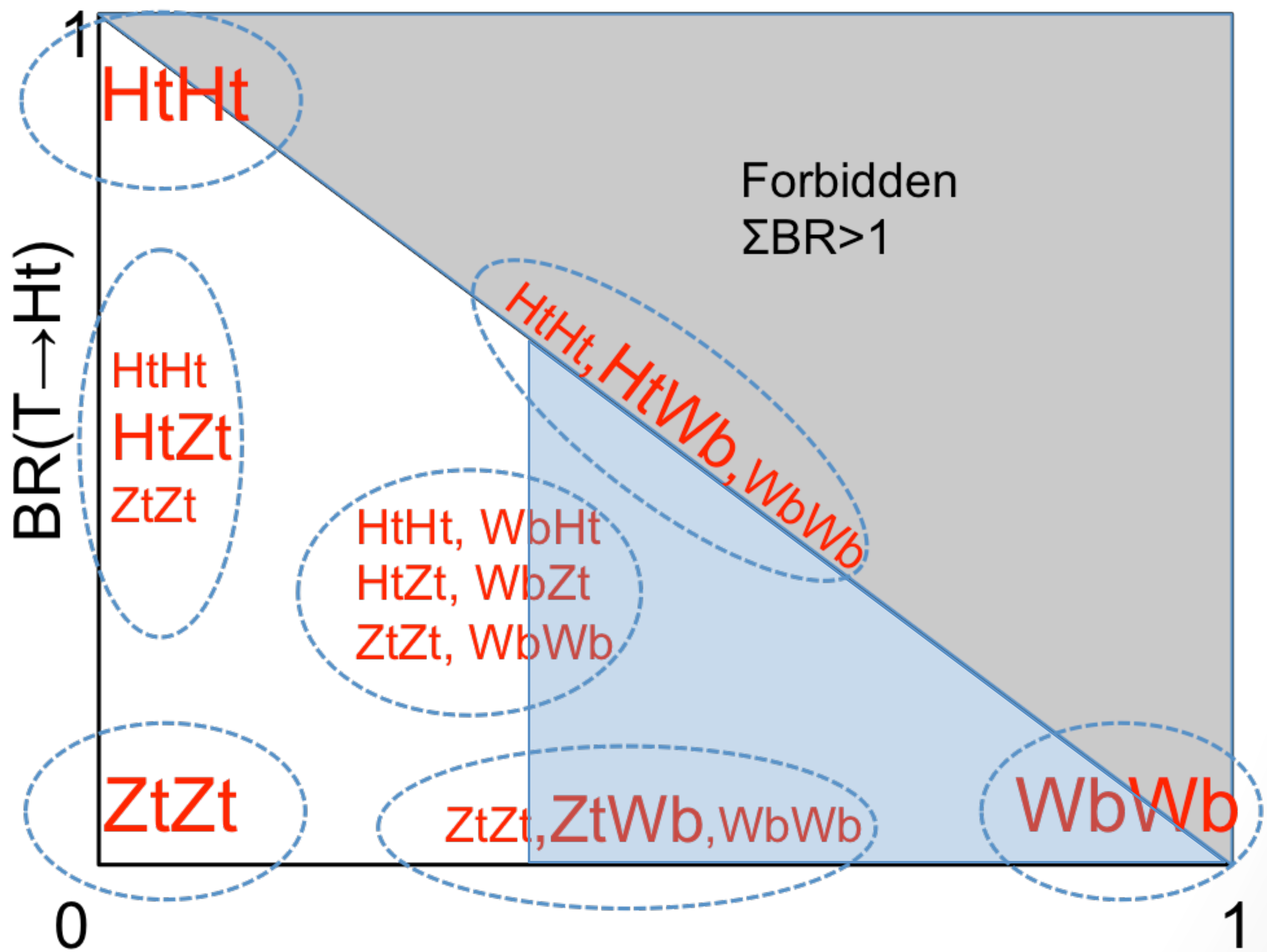
Results 2D

- We are probing a region of phase space that was never probed before!



- For example, a T quark with a mass of 600GeV and BR(T→Ht)>0.3 is excluded at 95% C.L. regardless of the values of BR(T →Wb)

Wb+X



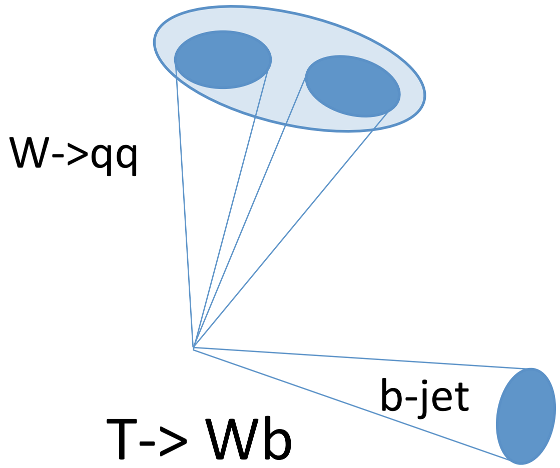
1
HtHt
Forbidden
ΣBR>1
BR(T→Ht)
HtHt, HtWb, WbWb
HtHt
HtZt
ZtZt
HtHt, WbHt
HtZt, WbZt
ZtZt, WbWb
ZtZt
ZtZt, ZtWb, WbWb
WbWb
0
1

Strategy

- This analysis focuses on events with boosted hadronic and leptonic Ws in the final state:
  - Developed a strategy to identify boosted hadronic Ws
  - Apply tight cuts
- Heavy quarks T decaying to Wb
- The reconstructed mass will be used as discriminant
  - Hadronic mass $m(W_{had},b)$
  - Optimized for WbWb final states

Strategy

- Optimize the analysis for masses > 500GeV
- Important fraction of boosted W bosons
  - Small angular separation between the decay products
- Boosted hadronic W reconstruction:
  - Combining 2 close-by jets



Strategy

- Optimize the analysis for masses > 500GeV
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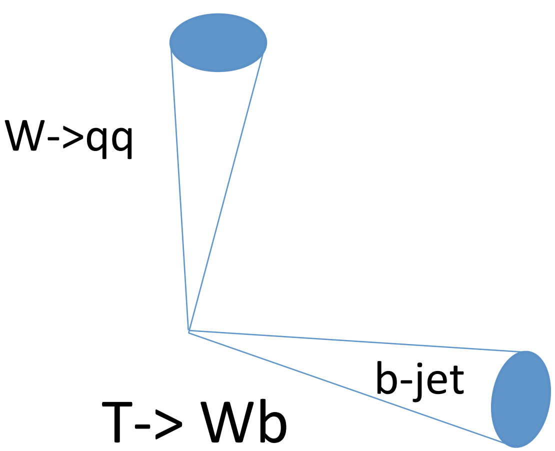
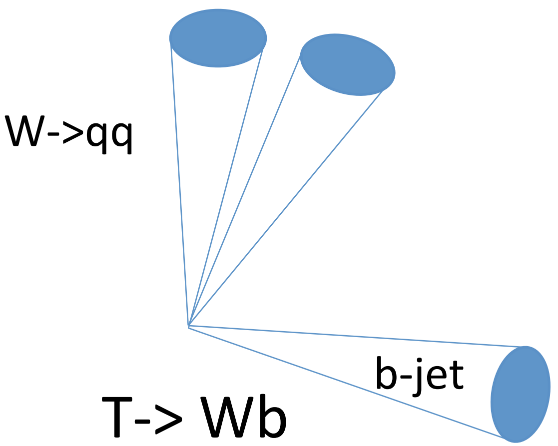
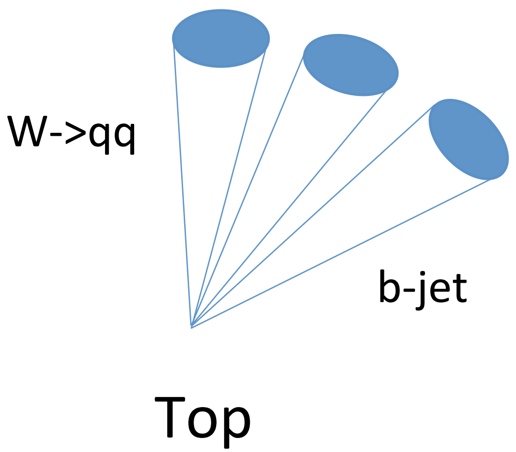
- Boosted hadronic W reconstruction:
  - Combining 2 close-by jets
  - In a single jet



Strategy

- Optimize the analysis for masses > 500GeV
- Important fraction of boosted W bosons
  - small angular separation between the decay products
- Boosted hadronic W reconstruction:
  - Combining 2 close-by jets
  - In a single jet
  - ΔR(W,b) very discriminant between top and heavy quark





Analysis details

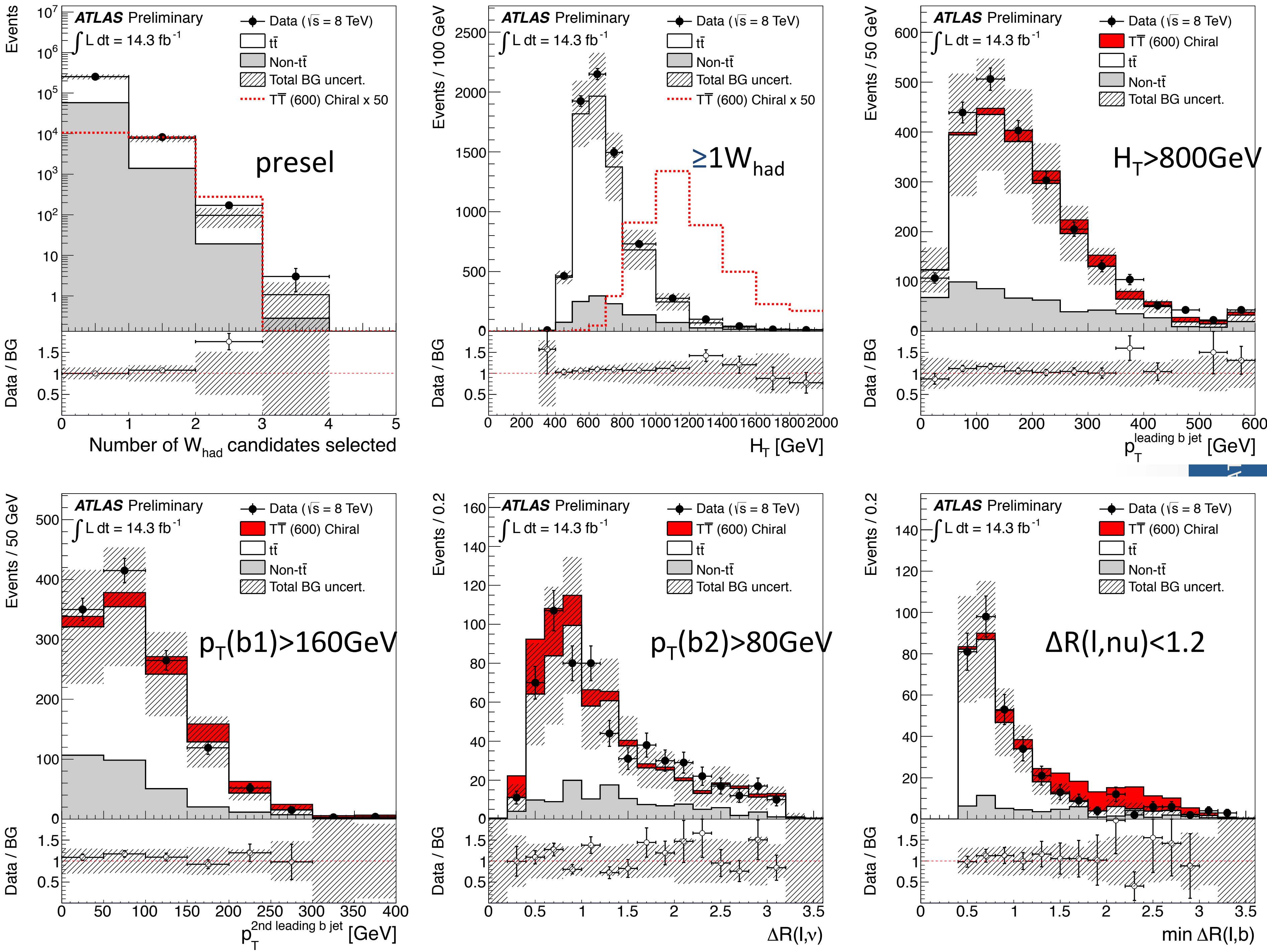
- This analysis selects as b-jets the two highest MV1 weight jets in the event, one of them being tagged
  - Leading MV1 weight jet -> tagged
  - Sub-leading MV1 weight jet -> not necessarily tagged
- When talking about b-jet p_T cuts, or minΔR(W,b) and minΔR(l,b) those are the jets to be considered
- Reconstructed heavy quark mass:
  - Pair W-had and b-jet
  - Pair W-lep and b-jet
  - Take the combination that minimize $|M_{had}-M_{lep}|$ (4 solutions, 2 b-jets and 2 neutrino solution)

W_{had}, mass reconstruction

- Select at least 1 hadronic W:
  - <u>Type-I:</u>
    - Jet p_T > 250GeV; 60<m(j) <120GeV
  - <u>Type-II:</u>
    - 60 < m(jj) < 120GeV, p_T(jj)>250GeV, ΔR(jj)<0.8 rejecting the two highest MV1 weight jets
  - If more than 1 select the highest p_T one to reconstruct the mass
- Mass reconstruction:
  - Solve neutrino equation: 0 or 2 p_Z solutions. If 0 set the neutrino η to the lepton η
  - Pair W_{had} and W_{lep} with b-jets
  - Chose the solution that minimizes $|M_{lep} - M_{had}|$
  - M_{had} used as final discriminant

Event selection

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
	$\min\Delta R(\ell, b) > 1.4$, $\min\Delta R(W_{\mathrm{had}}, b) > 1.4$

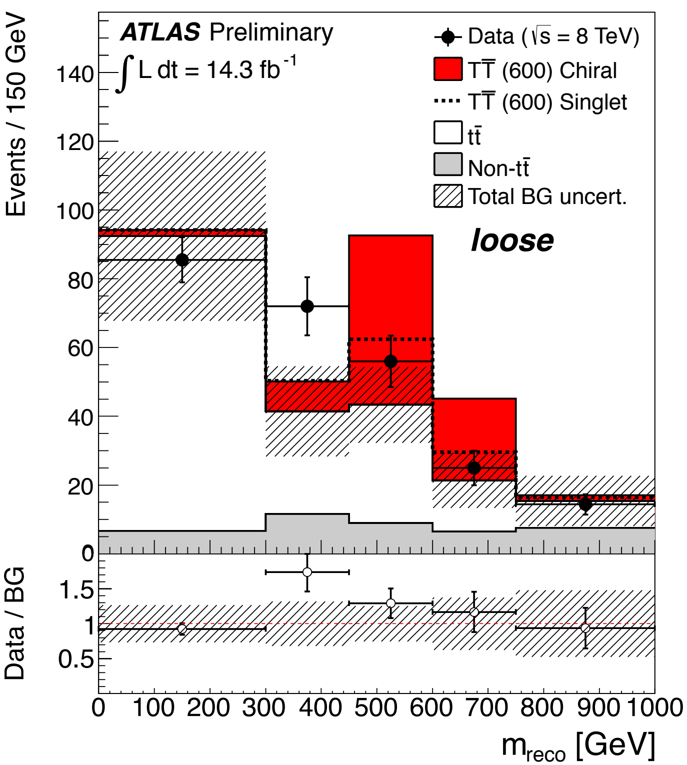


ATLAS Preliminary
∫L dt = 14.3 fb⁻¹
Data (√s = 8 TeV)
tt̄
Non-tt̄
Total BG uncert.
TT̄ (600) Chiral x 50
presel
Events
Data / BG
Number of W_had candidates selected
ATLAS Preliminary
∫L dt = 14.3 fb⁻¹
Data (√s = 8 TeV)
tt̄
Non-tt̄
Total BG uncert.
TT̄ (600) Chiral x 50
≥1W_had
Events / 100 GeV
Data / BG
H_T [GeV]
ATLAS Preliminary
∫L dt = 14.3 fb⁻¹
Data (√s = 8 TeV)
TT̄ (600) Chiral
tt̄
Non-tt̄
Total BG uncert.
H_T>800GeV
Events / 50 GeV
Data / BG
p_T^leading b jet [GeV]
ATLAS Preliminary
∫L dt = 14.3 fb⁻¹
Data (√s = 8 TeV)
TT̄ (600) Chiral
tt̄
Non-tt̄
Total BG uncert.
p_T(b1)>160GeV
Events / 50 GeV
Data / BG
p_T^2nd leading b jet [GeV]
ATLAS Preliminary
∫L dt = 14.3 fb⁻¹
Data (√s = 8 TeV)
TT̄ (600) Chiral
tt̄
Non-tt̄
Total BG uncert.
p_T(b2)>80GeV
Events / 0.2
Data / BG
ΔR(l,ν)
ATLAS Preliminary
∫L dt = 14.3 fb⁻¹
Data (√s = 8 TeV)
TT̄ (600) Chiral
tt̄
Non-tt̄
Total BG uncert.
ΔR(l,nu)<1.2
Events / 0.2
Data / BG
min ΔR(l,b)

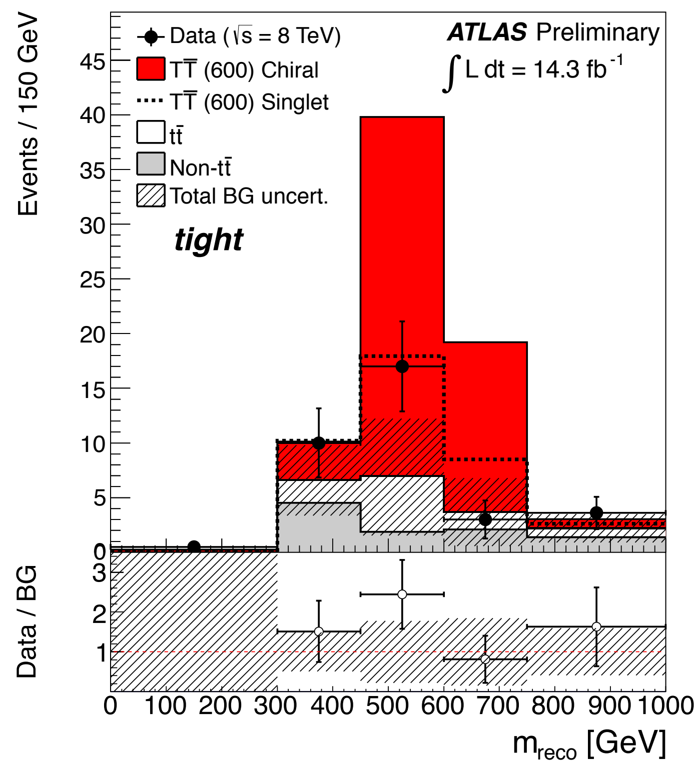
Signal region

	loose selection	*tight* selection
$t\bar{t}$	264 ± 80	10 ± 6
$t\bar{t}V$	5.1 ± 1.8	0.5 ± 0.2
W+jets	16 ± 11	6 ± 5
Z+jets	1.1 ± 1.4	0.2 ± 0.5
Single top	30 ± 7	4.4 ± 1.6
Dibosons	0.21 ± 0.15	0.06 ± 0.05
Total background	317 ± 90	21 ± 9
Data	348	37
$T\bar{T}$(600 GeV)		
Chiral fourth-generation	88 ± 10	54 ± 7
Vector-like singlet	41 ± 4	20.3 ± 2.2

minΔR(l,b-jets)>1.4
minΔR(W,b-jets)>1.4



Reconstructed mass used to set limits

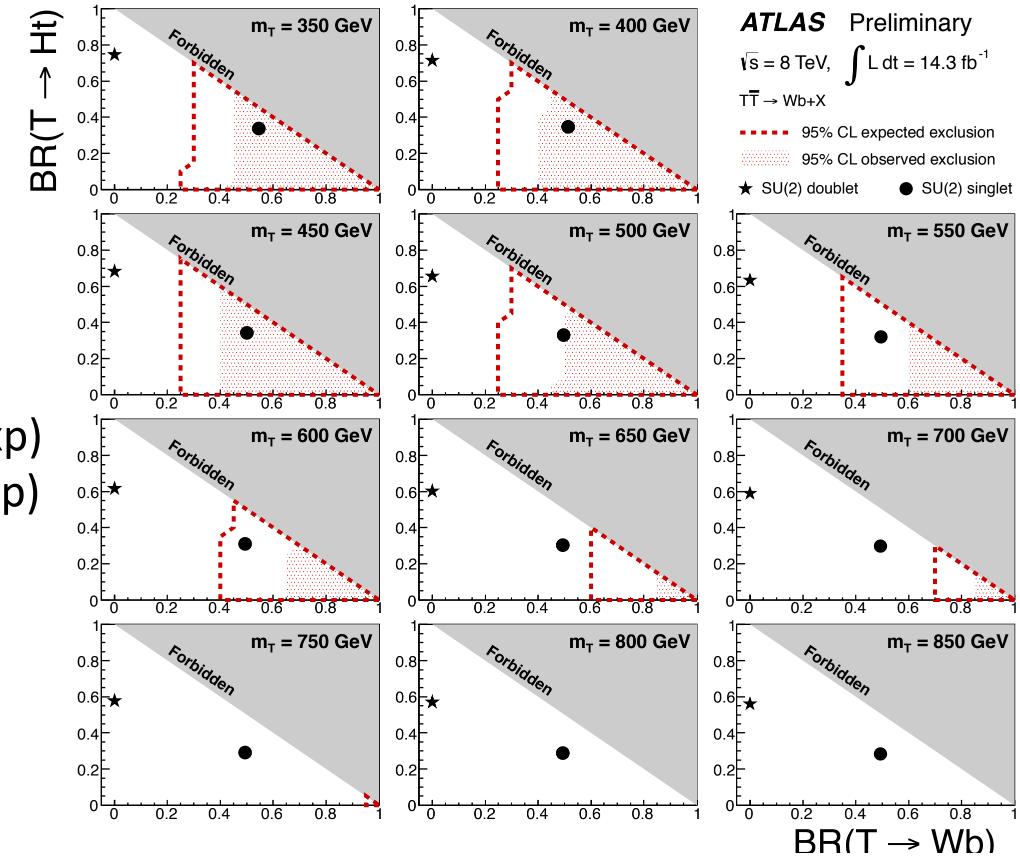


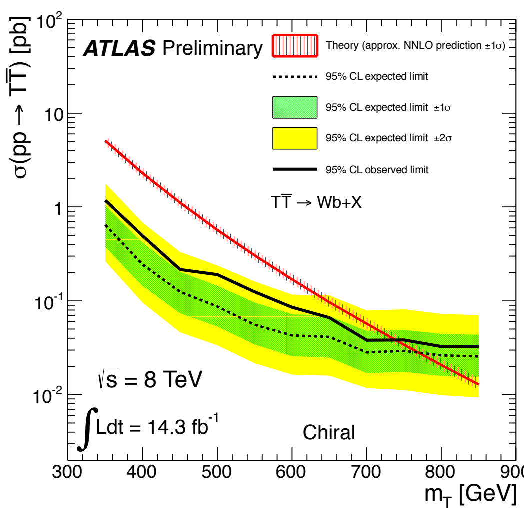
Systematics

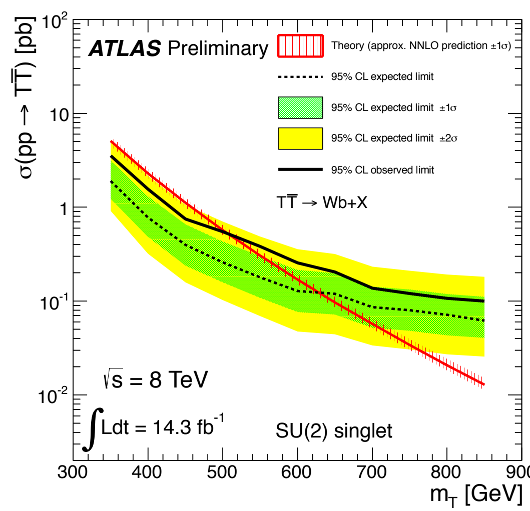
	$T\bar{T}$ (600 GeV)	$t\bar{t}$	Non-$t\bar{t}$
Uncertainties [%] affecting only the normalisation of the m_{reco} distribution:			
Luminosity	+3.6/-3.6	+3.6/-3.6	+3.6/-3.6
Lepton trigger, reconstruction and ID efficiency	+2.0/-2.0	+2.0/-2.0	+2.0/-2.0
$t\bar{t}$ cross section	–	+10/-11	–
Uncertainties [%] affecting both normalisation and shape of the m_{reco} distribution:			
Jet energy scale	+6.6/-8.4	+15/-15	+33/-22
Jet energy resolution	+8.4/-8.4	+3.6/-3.6	+9.3/-9.3
Jet identification efficiency	+2.3/-2.7	+2.3/-2.5	+1.9/-2.6
b-quark tagging efficiency	+6.7/-7.3	+6.7/-8.9	+1.8/-2.2
c-quark tagging efficiency	+1.6/-1.6	+4.1/-4.1	+5.6/-5.6
Light-jet tagging efficiency	+0.3/-0.3	+0.7/-0.7	+2.7/-2.7
$t\bar{t}$ modelling: NLO MC generator	–	+48/-48	–
$t\bar{t}$ modelling: parton shower and fragmentation	–	+25/-25	–
$t\bar{t}$ modelling: initial and final state QCD radiation	–	+8.8/-8.8	–
W+jets normalisation	–	–	+8.9/-7.8
W+heavy-flavor fractions	–	–	+18/-19
W+jets modelling: scale variation	–	–	+11/-11
Z+jets cross section	–	–	+1.1/-1.1
Single top cross section	–	–	+1.9/-1.5
Diboson cross section	–	–	$< 0.1\%$
$t\bar{t}V$ cross section	–	–	+1.5/-1.5
Total	+14/-15	+59/-59	+42/-35

Results

Chiral -> 740(770)GeV Obs (Exp)
Singlet ->505(630) GeV Obs(Exp)

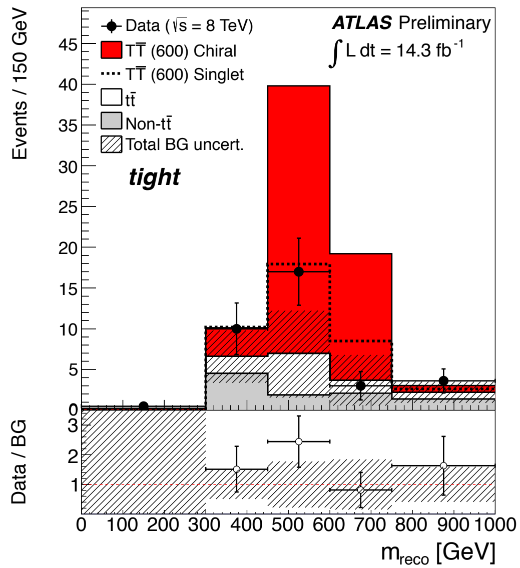


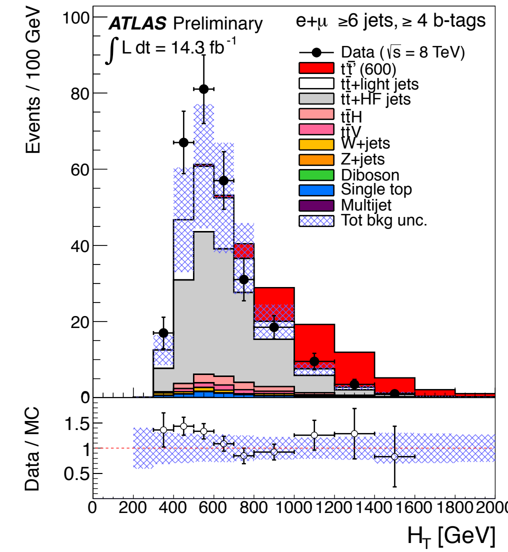


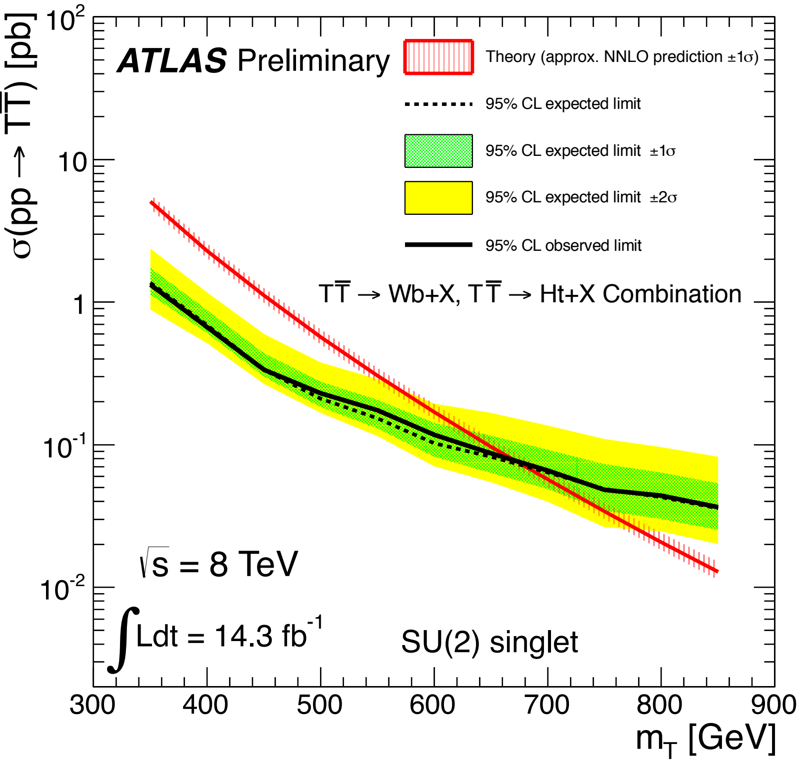


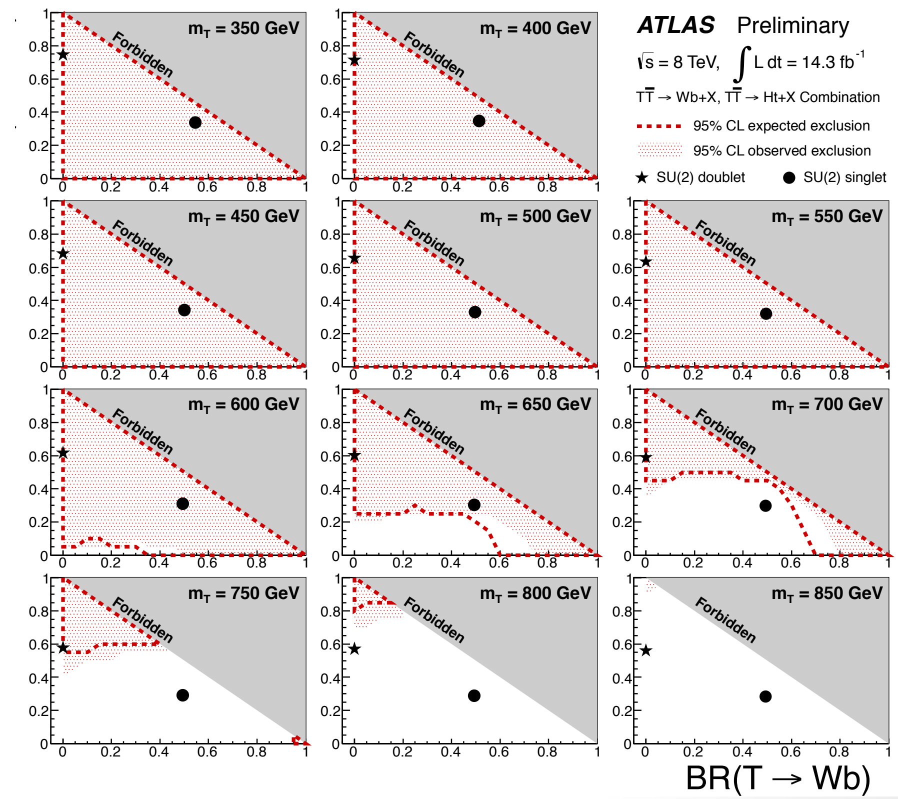
Combined results

Only ATLAS combination
limits versus mass in the singlet scenario 670(675) GeV Obs(Exp)







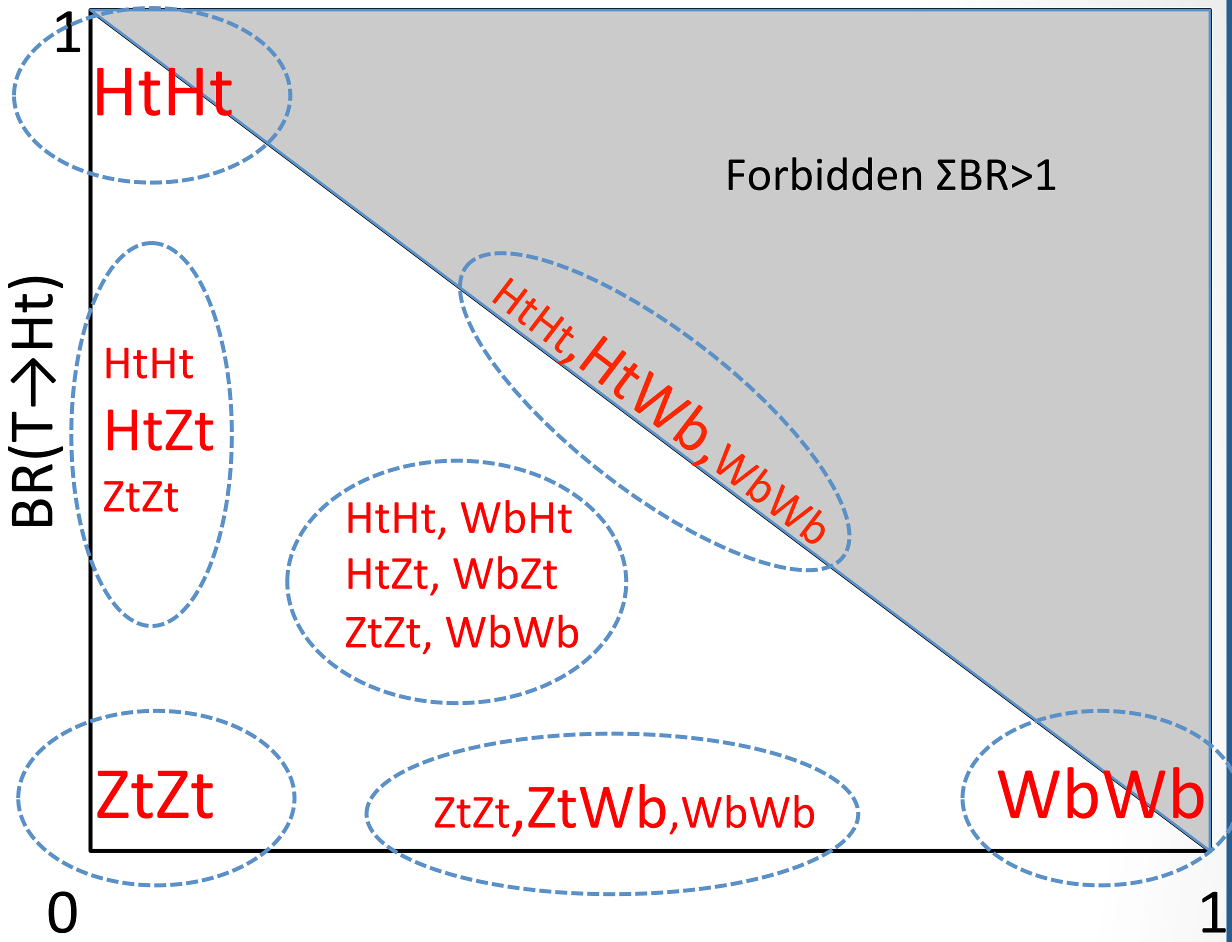


Conclusion and Outlook

- ATLAS performed the search for new heavy quarks in several decay channels
- Unfortunately no sign of new physic yet :(
- Our program of heavy quark searches is barely covering the tip of the iceberg....
  - Haven't done much in terms of combination
  - And in term of signal overlap
- Very exciting prospects ahead!
  - Higher energy in the center of mass!
  - Single production becomes very interesting
  - Lots of fun coming soon :)

Bonus

Ht+X



- This analysis focuses on high jet (≥6) and b-jet (==2, ==3 and ≥4) multiplicities