Search for New Physics with TOP quarks in ATLAS at 8 TeV – $t\bar{b}$, $t\bar{t}$, VLQ –

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Motivation

- Standard Model well confirmed by LHC, but...
- Many possible **extensions of the SM*** (GUT, extra-dimension(s), Little Higgs...)
- Predict new particles, usually **coupled preferentially to top quark** (heaviest particle so far):
  - new bosons:
    - $W' \to t\bar{b}$
    - $g_{KK}/Z' \to t\bar{t}$
  - new coloured fermions: Vector-Like Quarks (VLQ)

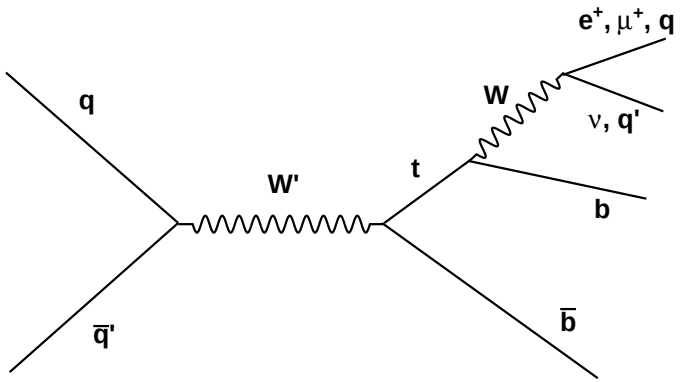
*Here, only non-SUSY BSM physics is considered

Next slides are about...

Why searching for W' ?

- W boson of Standard Model couples only to left-handed fermions
  $\Rightarrow$ search for new W boson coupling to **right-handed** fermions (W'_R)
- Other models predict a **heavier partner** of the SM W
  $\Rightarrow$ search for W'_L

$W' \to t\bar{b}$ production and decay



- Couplings not known, but $g_{uW'd}/g_{tW'b}$ assumed like SM
- Only two different final states

$W \to$	Analysis	$\mathcal{L}$ [fb^{-1}]
$\ell\nu$	ATLAS-CONF-2013-050	14
qq'	**arXiv:1408.0886 [hep-ex]** (EPJC)	20

Analysis overview

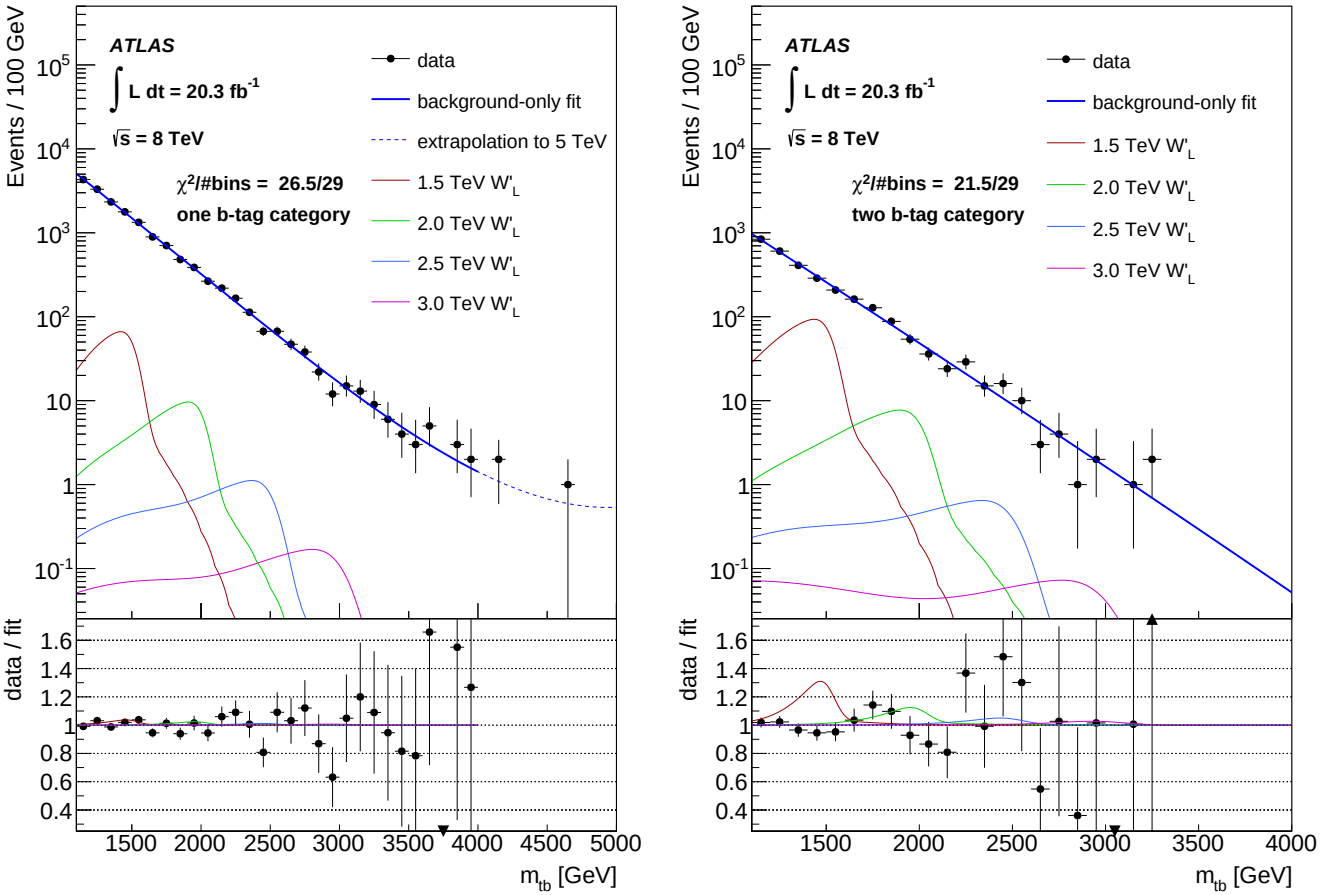
- Target: $W' \to t(\to q\bar{q}'b)\bar{b}$ in the range [1.5,3] TeV
- Decay of **boosted** top $\Rightarrow$ use of **large-R jets**
- Main backgrounds: multijets (from data), $t\bar{t}$ (from MC)
- Unbinned fit of m_{tb} **spectrum**

Event selection

- Calorimeter trigger ($\sum E_T > 700$ GeV)
- Veto on high quality e or μ
- Jets ($p_T > 350$ GeV):
  - exactly one small-R (0.4) b-tagged $\Rightarrow$ b
  - exactly one large-R (1.0) **top-tagged** $\Rightarrow$ t
  - $\Delta R_{tb} > 2.0^{\dagger}$
- Two channels:
  - **one** b-**tag** (no additional b-tagged jet)
    - background: 99% multijet
  - **two** b-**tag** (one additional small-R b-tagged jet inside top-tagged jet)
    - background: 88% multijet, 11% $t\bar{t}$

$^{\dagger}\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

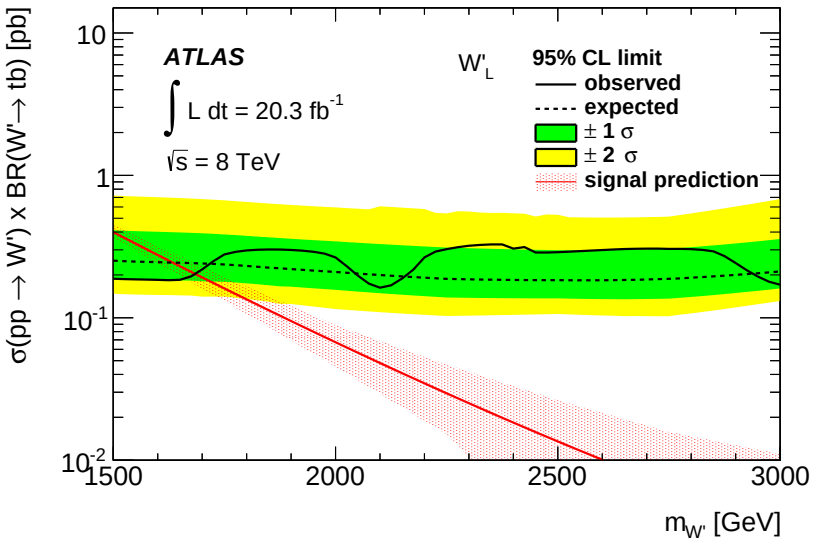
m_{tb} spectra



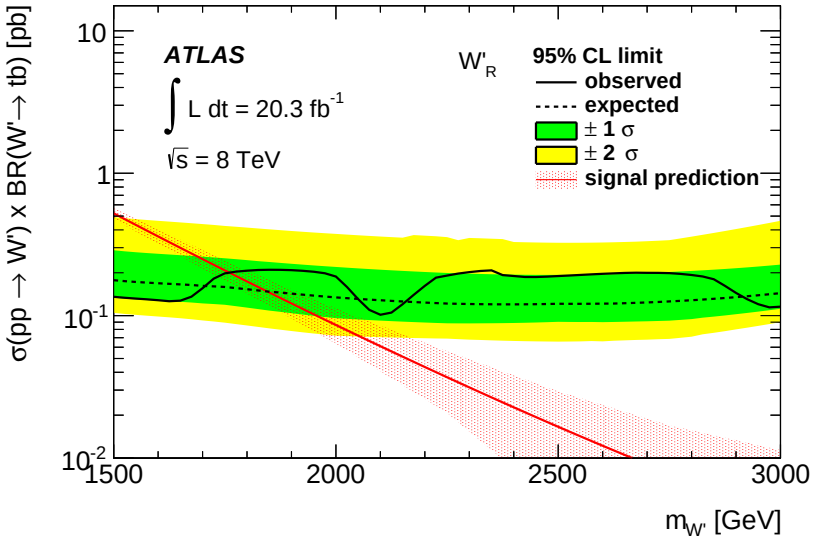
Events above 4 TeV not considered in statistical interpretation

Limits (95% C.L.) on cross sections

Left-handed



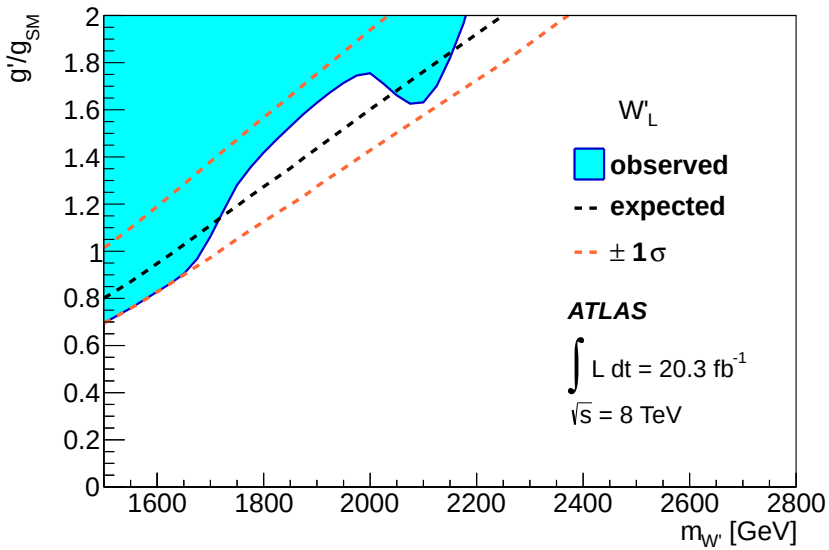
Right-handed



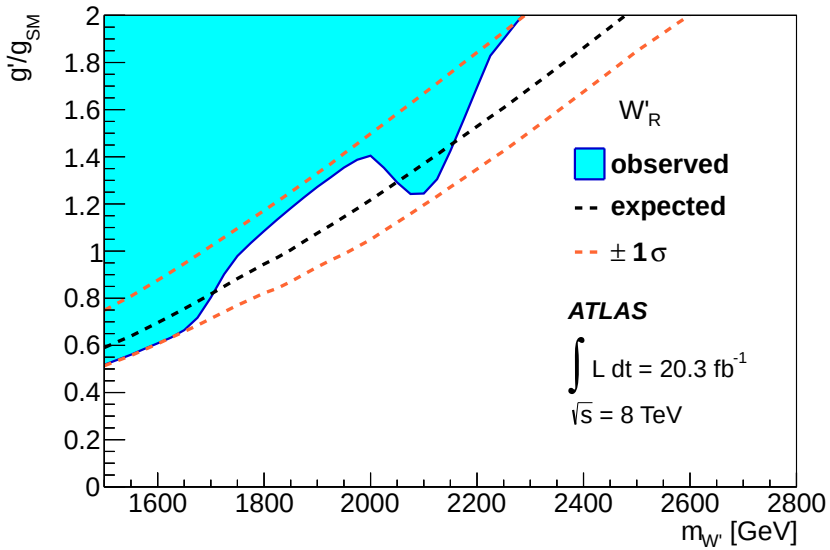
- Assuming $g'_{L/R} = g_{SM}$: $m_{W'_L} > 1.68$ TeV, $m_{W'_R} > 1.76$ TeV

Generic limits

Left-handed



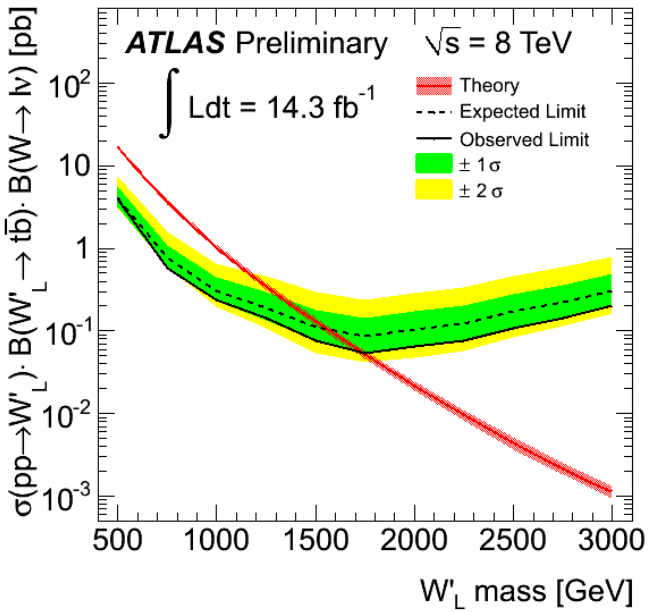
Right-handed



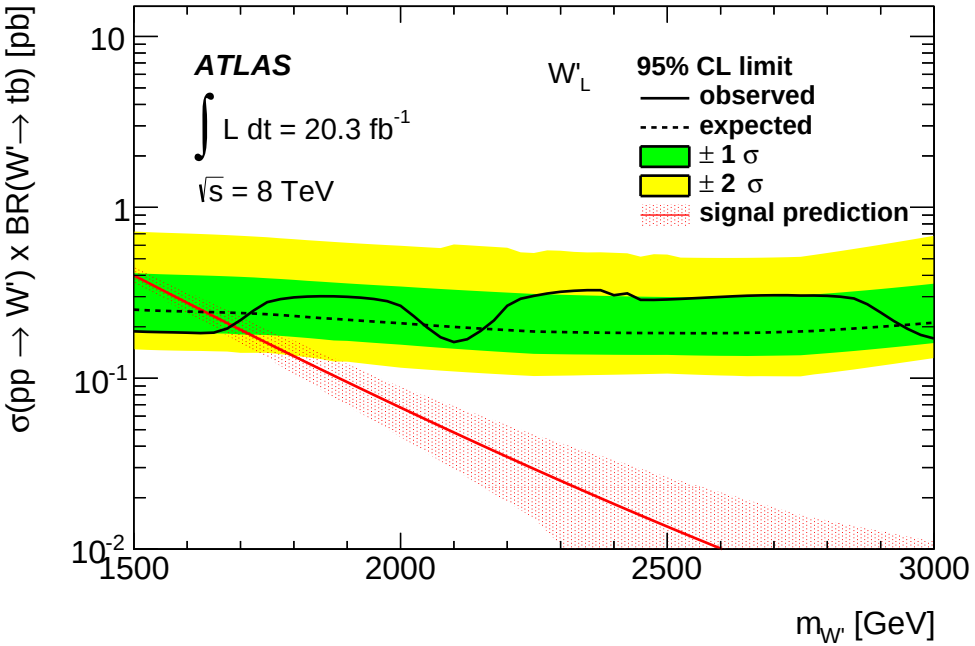
- For $g'_{L/R} > 2g_{SM}$, the width of the $W'_{L/R}$ becomes too large with respect to the experimental resolution

Left-handed W'

Leptonic



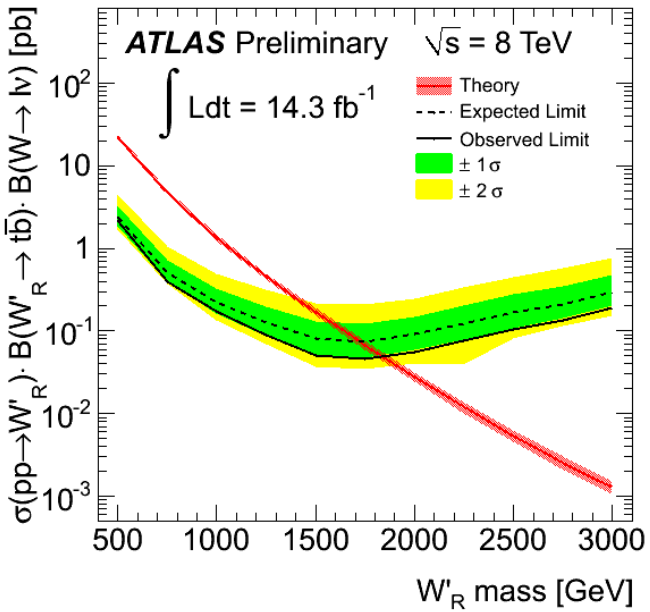
Hadronic



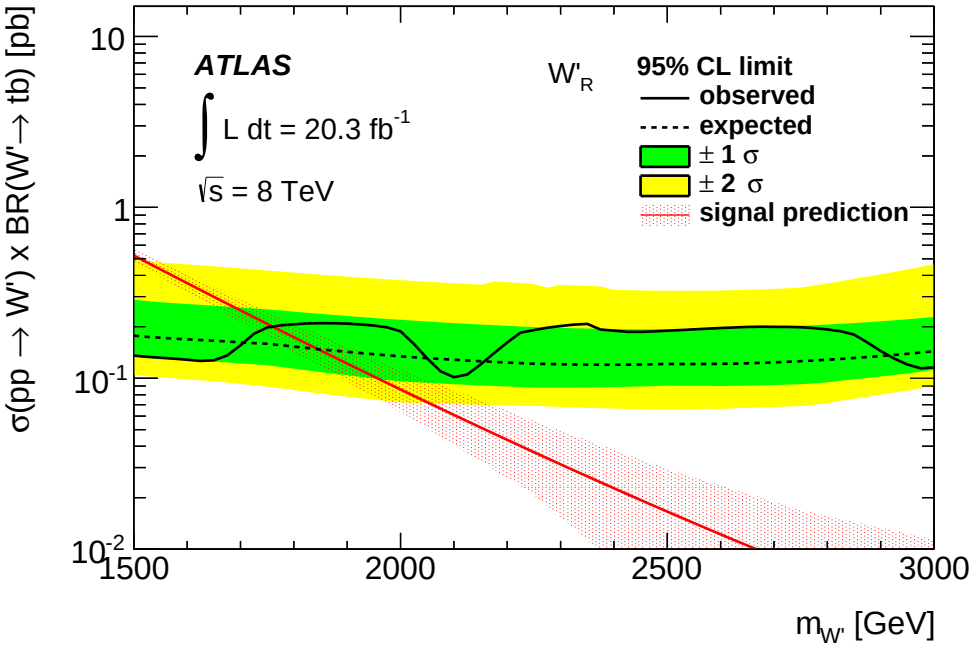
- Assuming $g'_L = g_{SM}$: $m_{W'_L} > 1.74$ TeV (leptonic, to be updated)

Right-handed W'

Leptonic



Hadronic



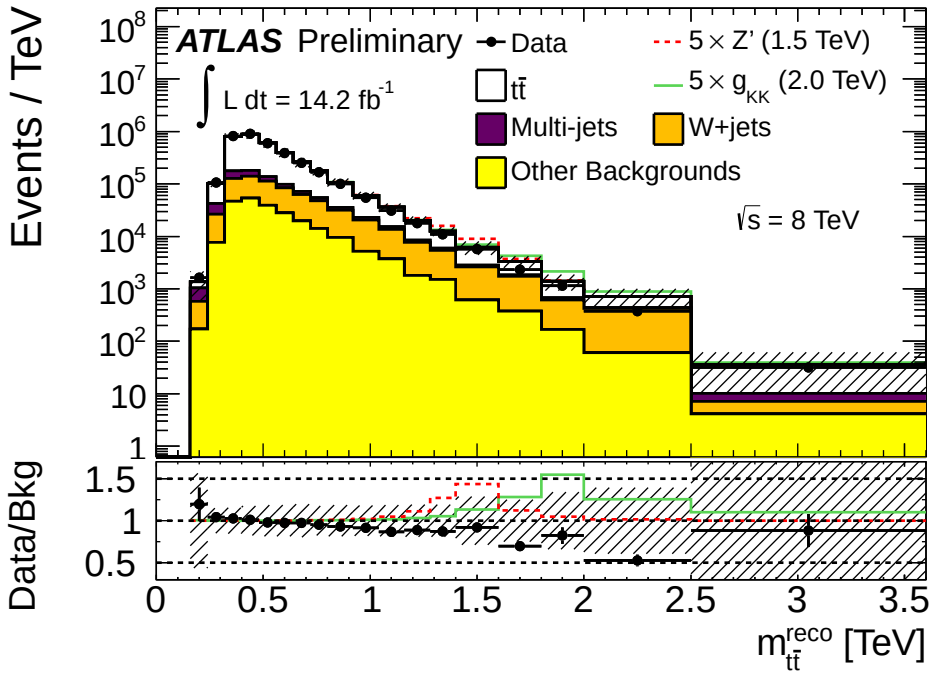
- Assuming $g'_R = g_{SM}$: $m_{W'_R} > 1.84$ TeV (leptonic, to be updated)

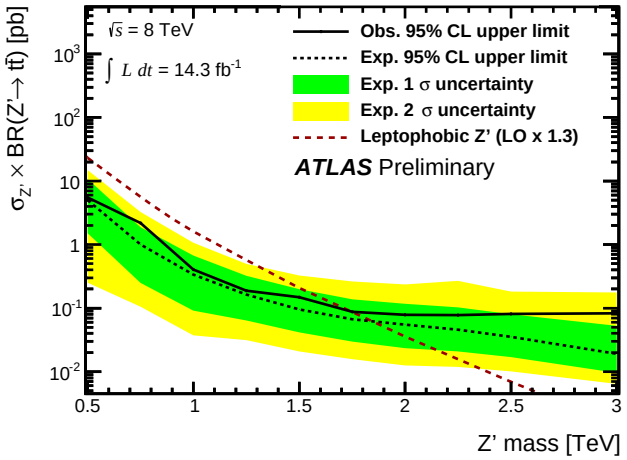
Next slides are about...

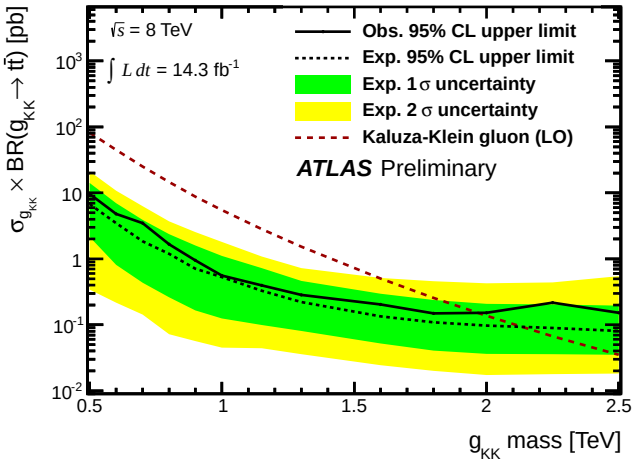
Analysis overview

- ATLAS-CONF-2013-052
- 14 fb^{-1} of 8 TeV data
- Single lepton (e/μ) trigger (24 GeV)
- At least one b-tagged jet
- Two channels:
  - **resolved**: $\ell + \nu + 4$ small-R jets (χ^2 method for combinatorics reduction)
  - **boosted**: $\ell + \nu + 1$ small-R jet (leptonic top) + 1 high mass large-R jet (hadronic top)
- $t\bar{t}$ invariant mass spectrum compared to SM prediction

Results







- $m_{Z'} > 1.8$ TeV (narrow leptophobic)
- $m_{g_{KK}} > 2.0$ TeV (Randall-Sundrum model)

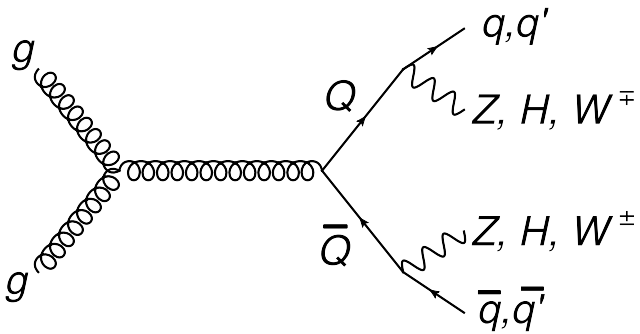
Next slides are about...

Why searching for vector-like quarks ?

- Simple implementation of a fourth generation of quarks is now excluded
- VLQ still **allowed by present data**:
  - color-triplet spin-1/2 fermions ("quarks")
  - whose left- and right-handed components have same weak isospin ("vector-like")
- Predicted in various BSM models, including composite Higgs, can solve naturalness problem without SUSY

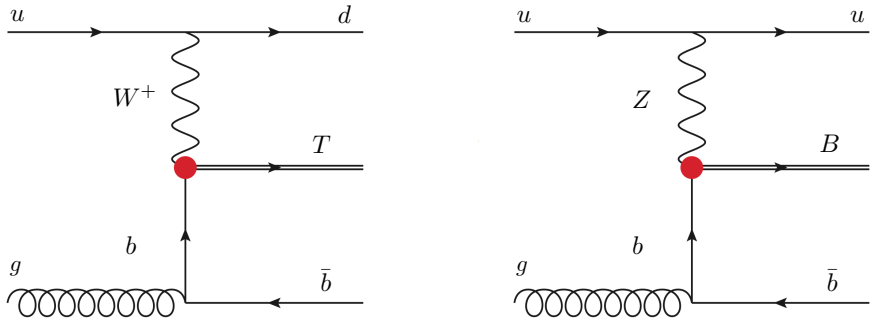
Vector-like quarks production

Pair production



Cross-section independent on flavour of Q

Single production



Cross-sections depend on electroweak coupling of B/T

Vector-like quarks decays

- Assuming coupling with third generation quarks only
- Several analyses to cover all possible decays

$T \to$	$B \to$	Analysis	$\mathcal{L}$ [fb^{-1}]
Wb		ATLAS-CONF-2013-060	14
	Wt	ATLAS-CONF-2013-051	14
Ht		ATLAS-CONF-2013-018	14
	Hb		
Zt	Zb	**ATLAS-CONF-2014-036**	20

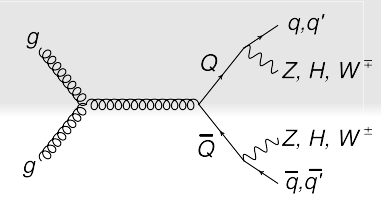
Analysis overview

- Target: $T \to Zt$ and $B \to Zb$ decays
- No assumption on T/B branching ratios
- Pair and **single** production
- Main backgrounds: $Z + b$, WZ, $t\bar{t} + Z$ (from MC)
- Comparison of distributions of **discriminating variables** between data and expected background

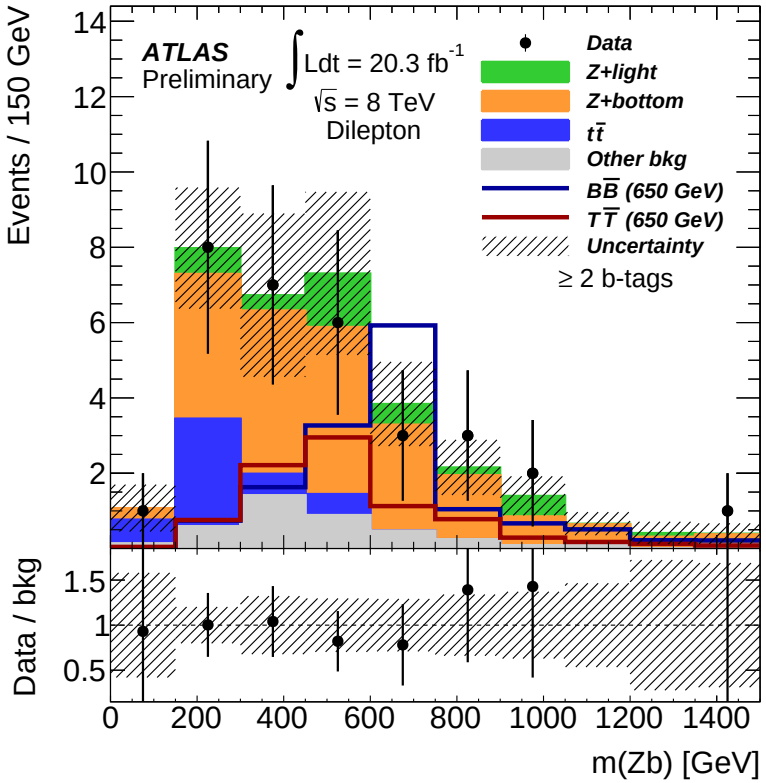
Event selection

- Single e or μ trigger (24 GeV)
- At least e^+e^- or $\mu^+\mu^-$ with $|m_{\ell^+\ell^-} - m_Z| < 10$ GeV, $p_T(\ell^+\ell^-) \geq 150$ GeV
- At least 2 central jets
- Two channels:
  - **dilepton** (exactly 2 leptons), at least 2 b-tagged jets
  - **trilepton** (at least 3 leptons), at least 1 b-tagged jet

Pair production: discriminating variables

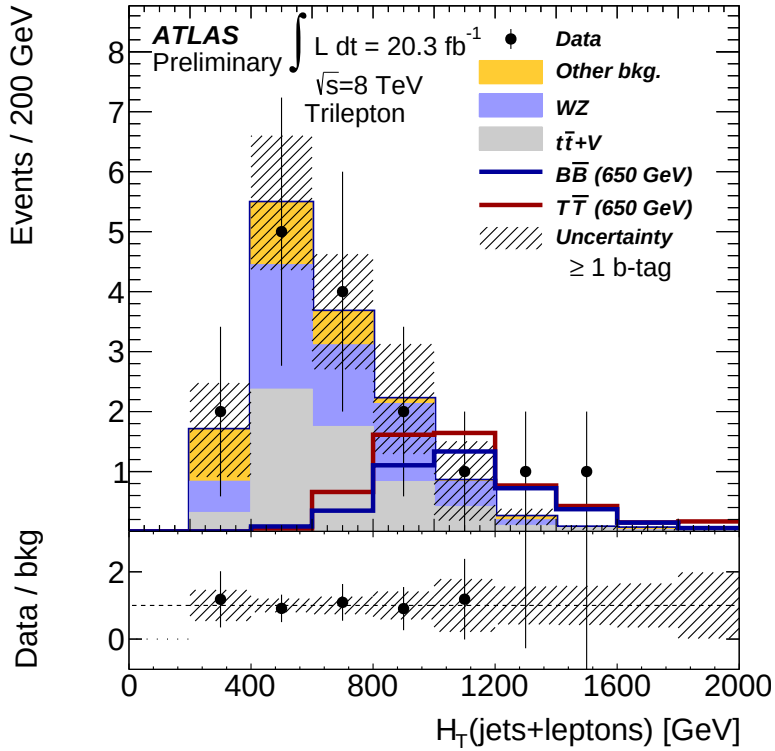


Dilepton



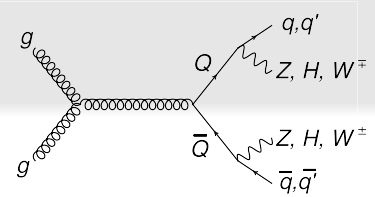
$$H_T(jets) = \sum_{jets} p_T \geq 600 \text{ GeV}$$

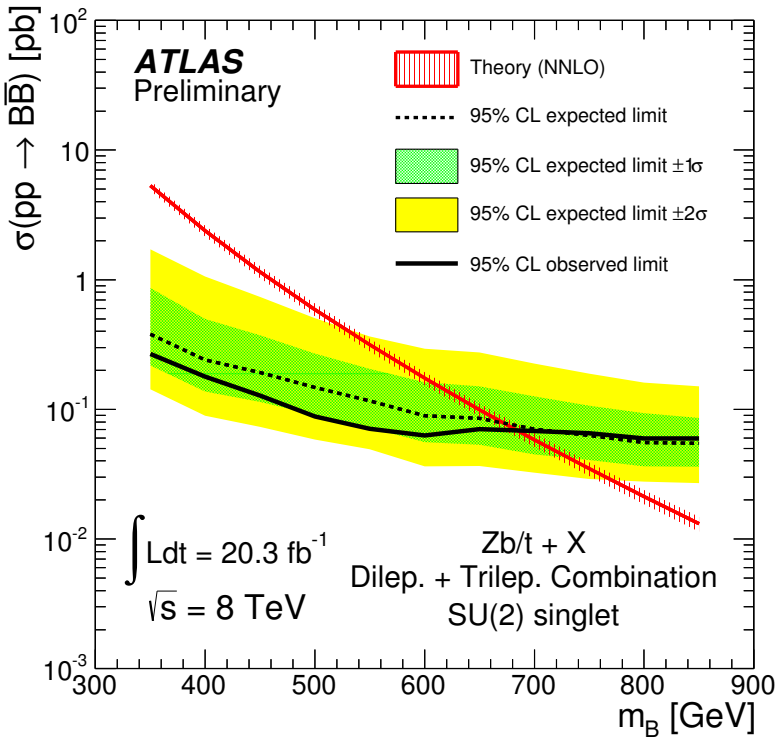
Trilepton

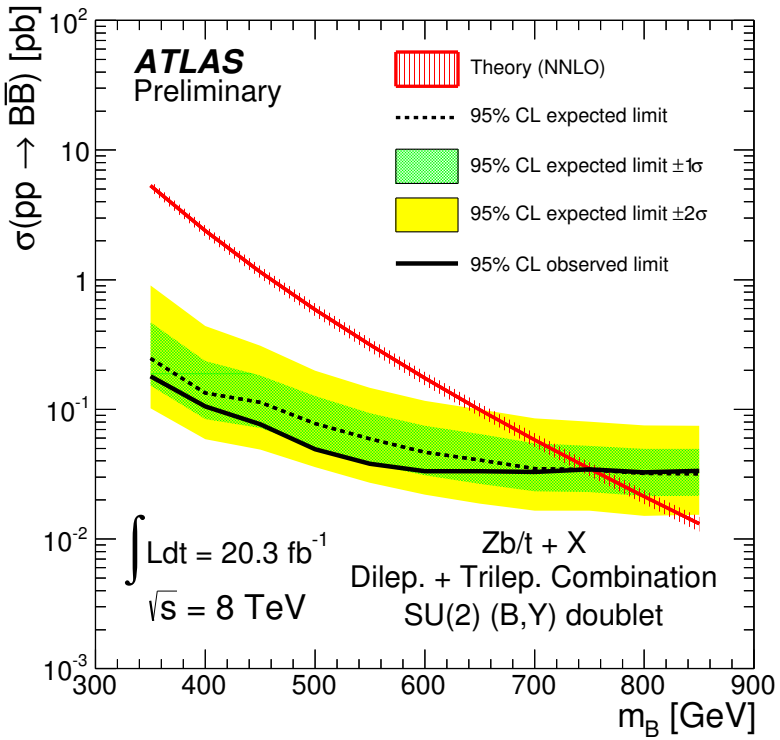


$$H_T(jets + leptons) = \sum_{jets+leptons} p_T$$

Pair production: limits for B

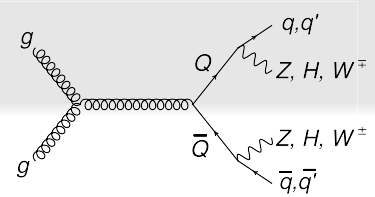


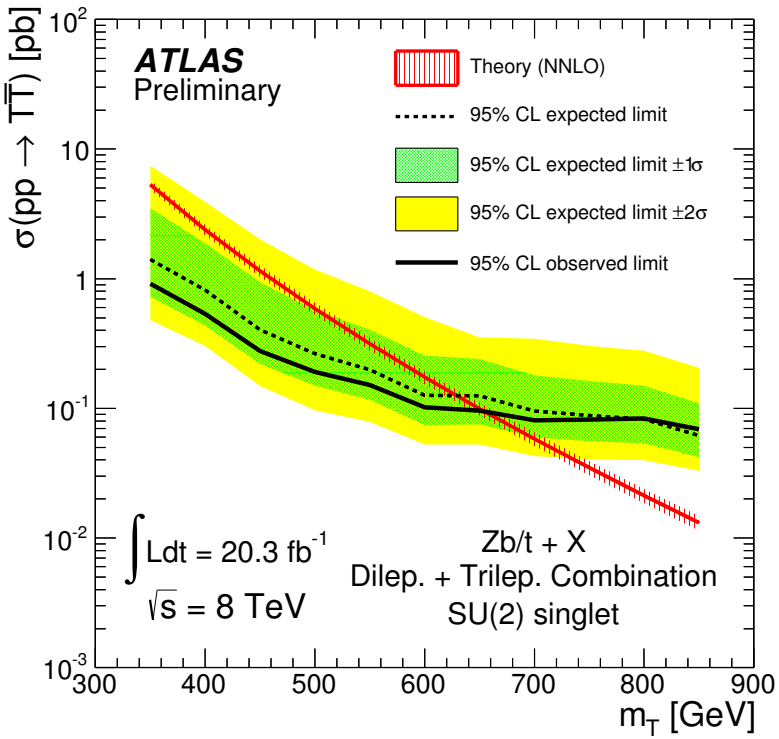


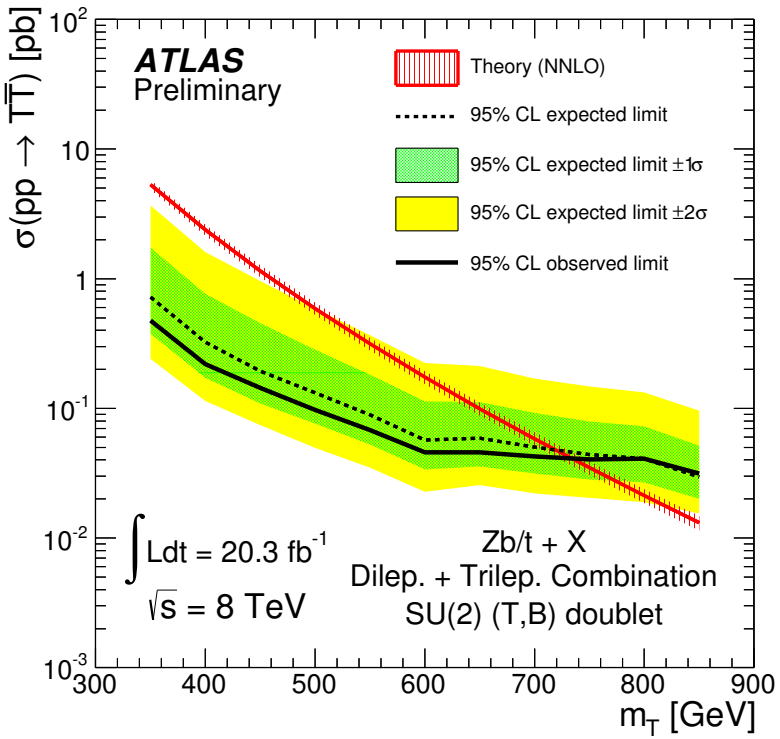


- $SU(2)$ singlet case $\Rightarrow$ $m_B > 685$ GeV
- $SU(2)$ doublet case $\Rightarrow$ $m_B > 755$ GeV

Pair production: limits for T

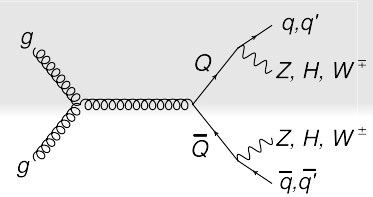


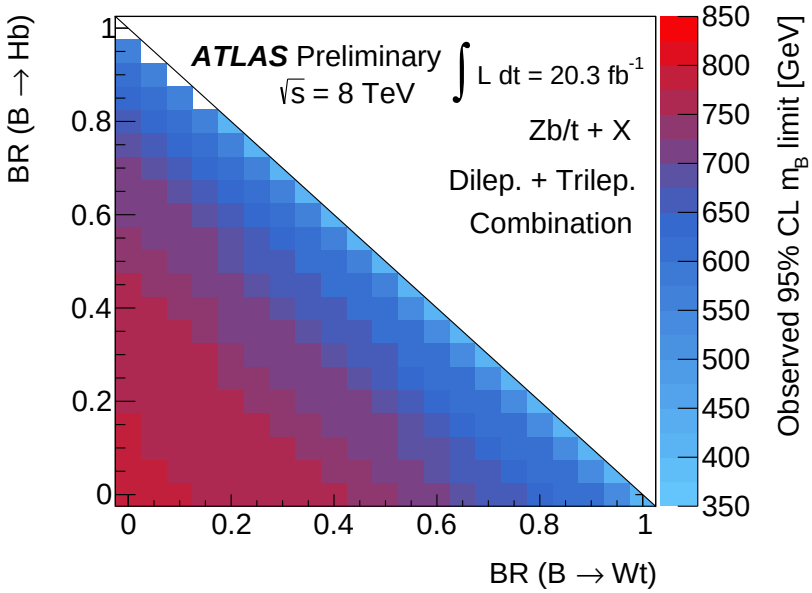


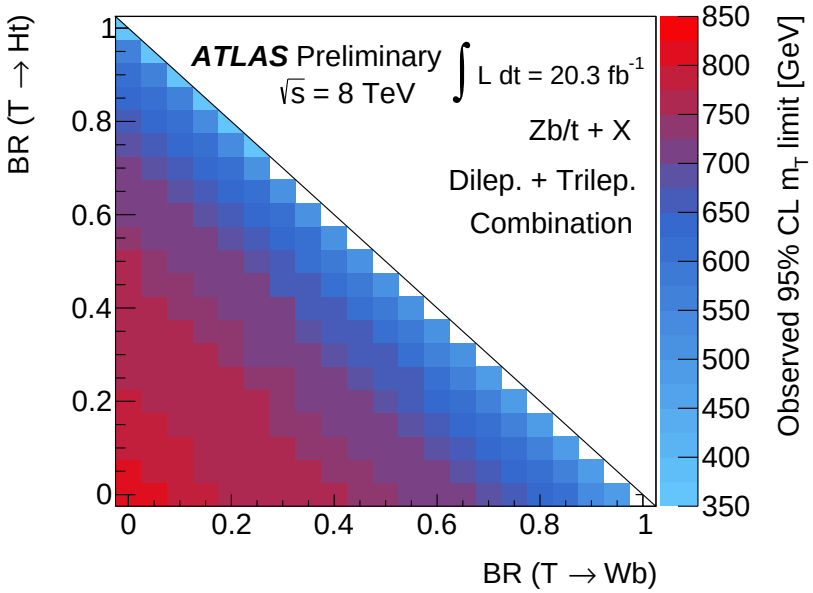


- $SU(2)$ singlet case $\Rightarrow$ $m_B > 655$ GeV
- $SU(2)$ doublet case $\Rightarrow$ $m_B > 735$ GeV

Pair production: generic limits

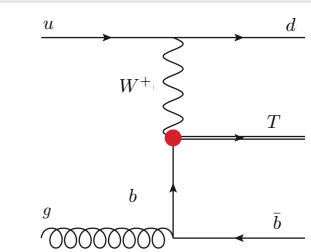




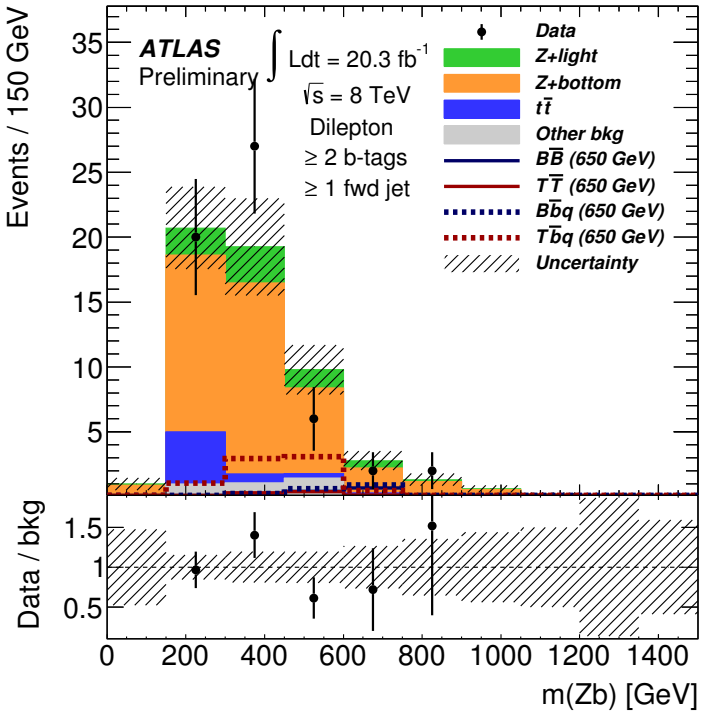


- Lower mass limits for any branching ratio combination
- Best sensitivity in lower-left corners where BR($B \to Zb$)=100% and BR($T \to Zt$)=100%

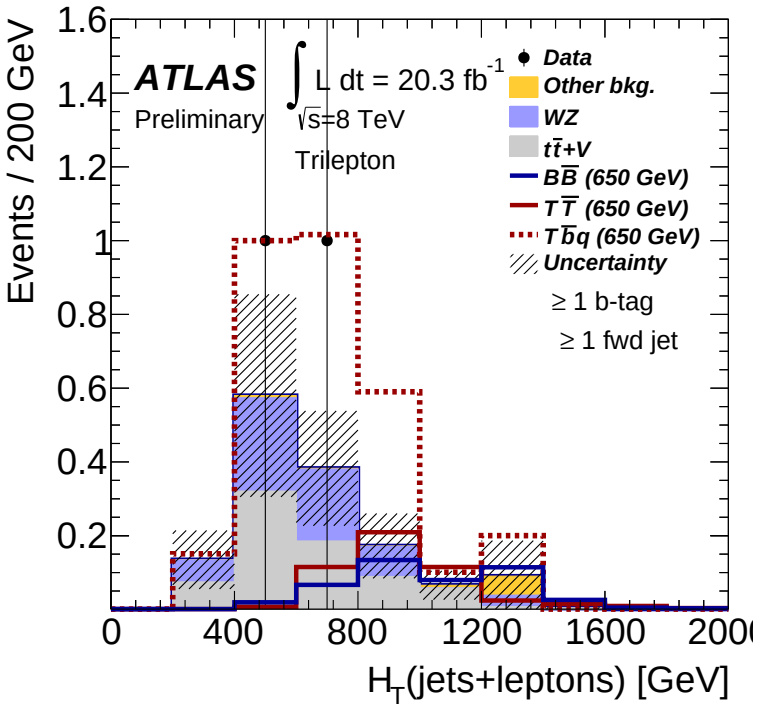
Single production: discriminating variables



Dilepton



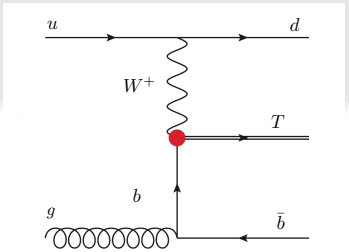
Trilepton

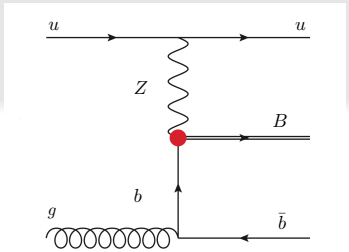


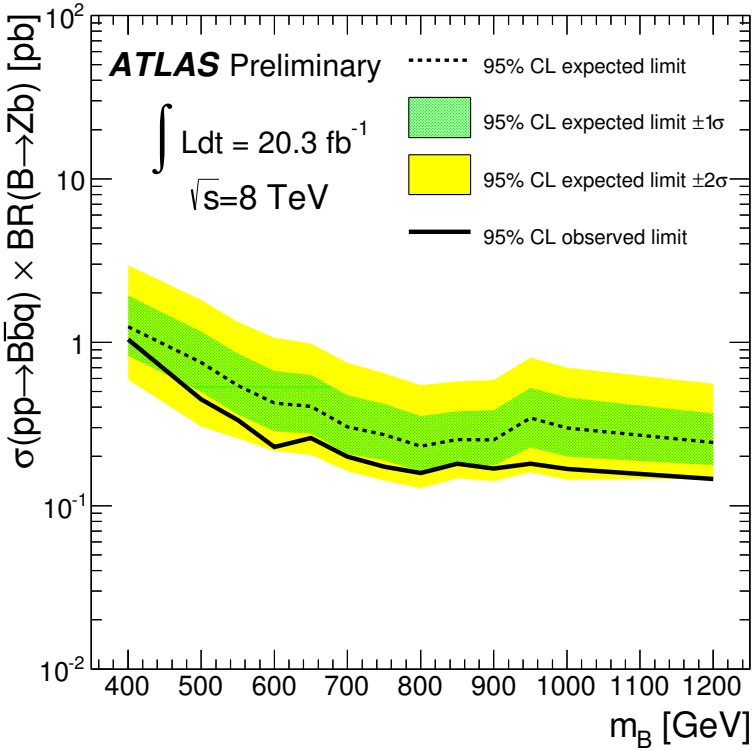
Not sensitive to $B\bar{b}q$

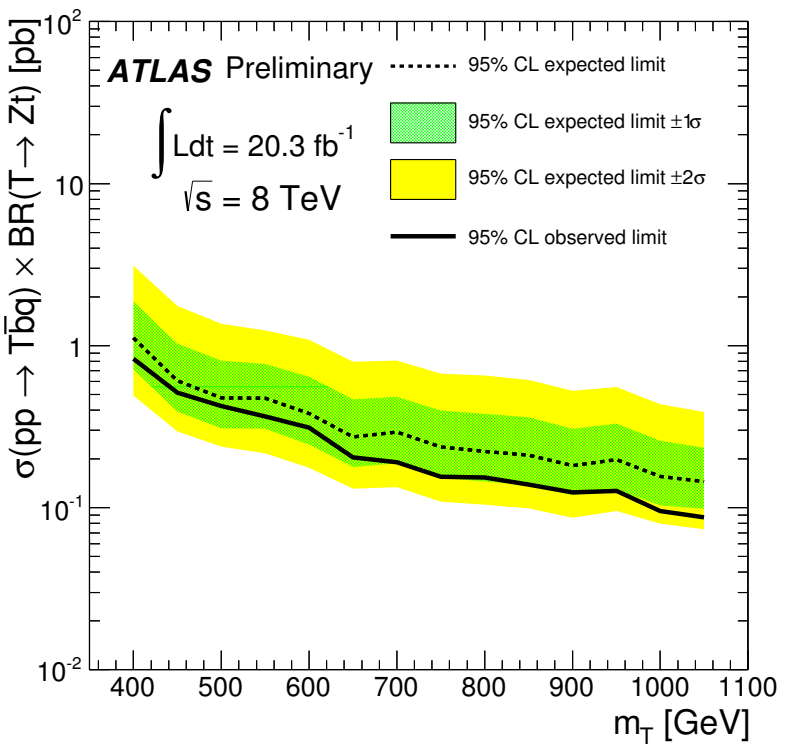
At least 1 forward jet

Single production: limits



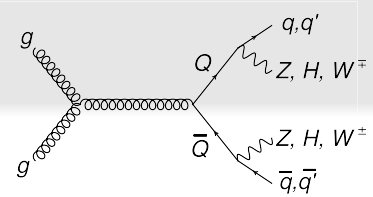


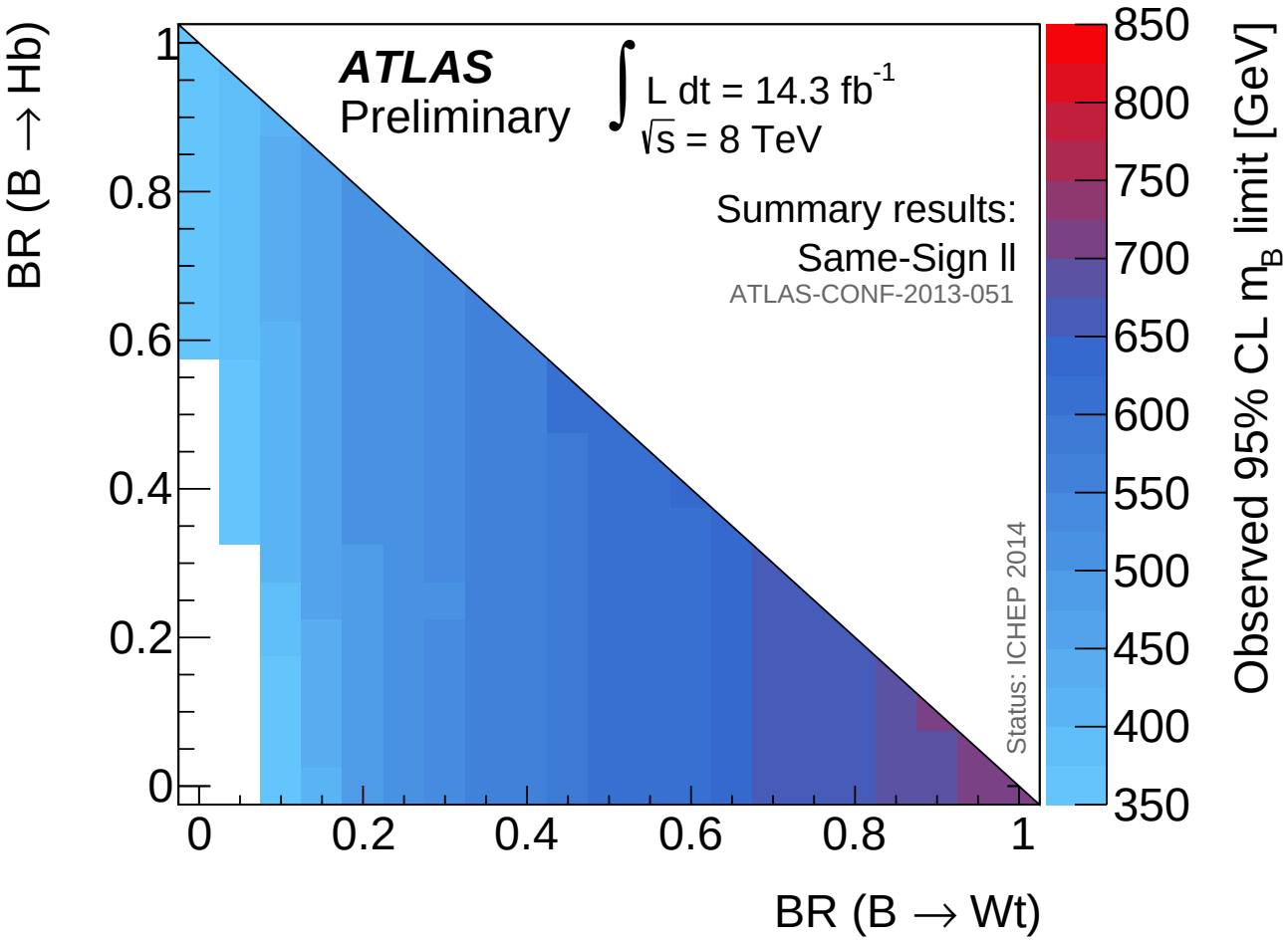




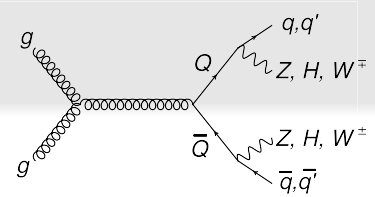
- Sensitivity not sufficient to constrain electroweak couplings *TWb* and *BZb*

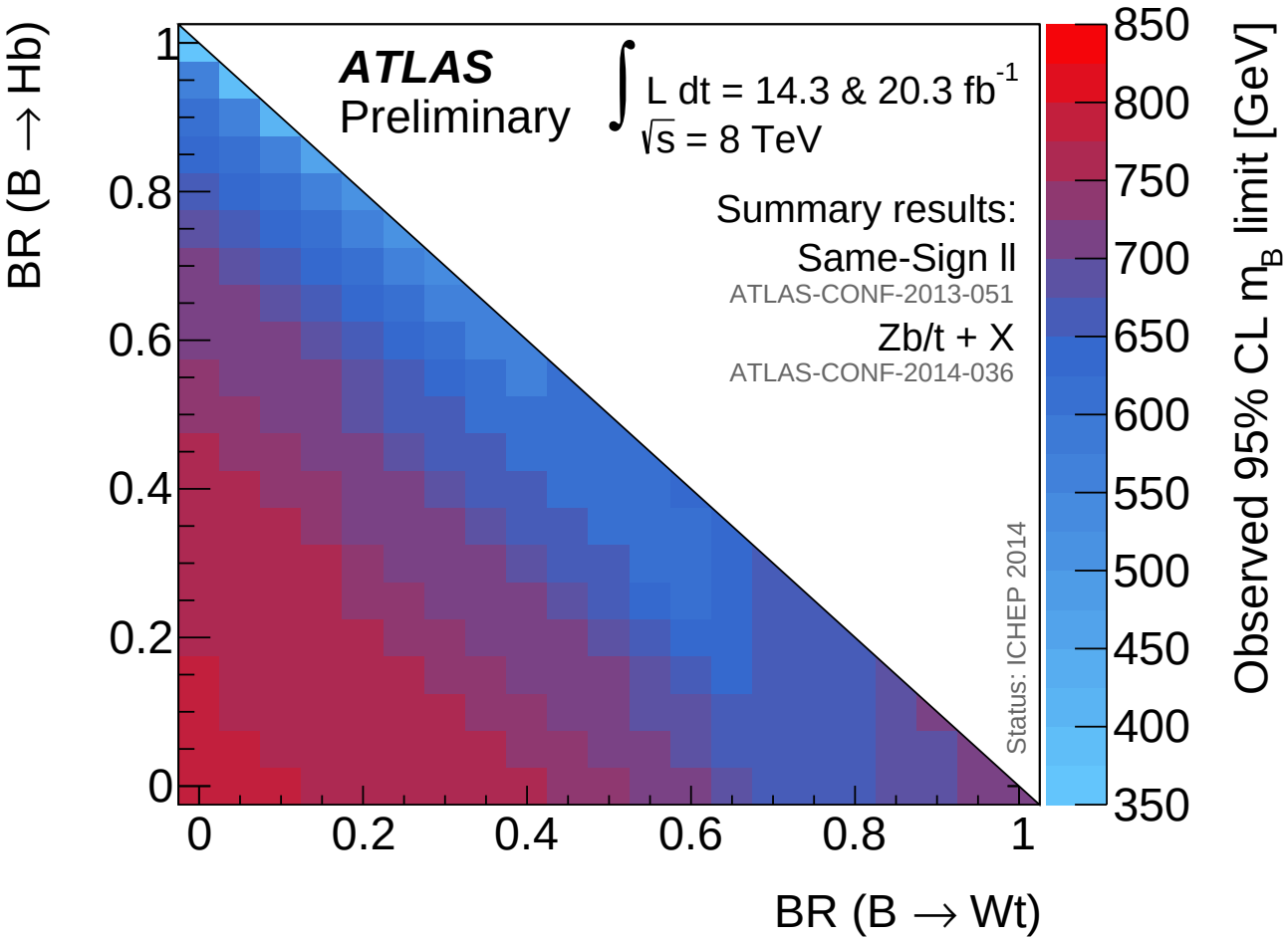
Pair production: generic limit on m_B



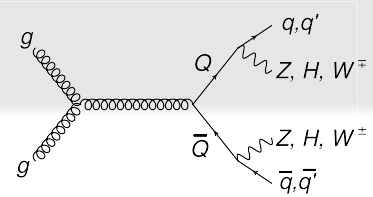


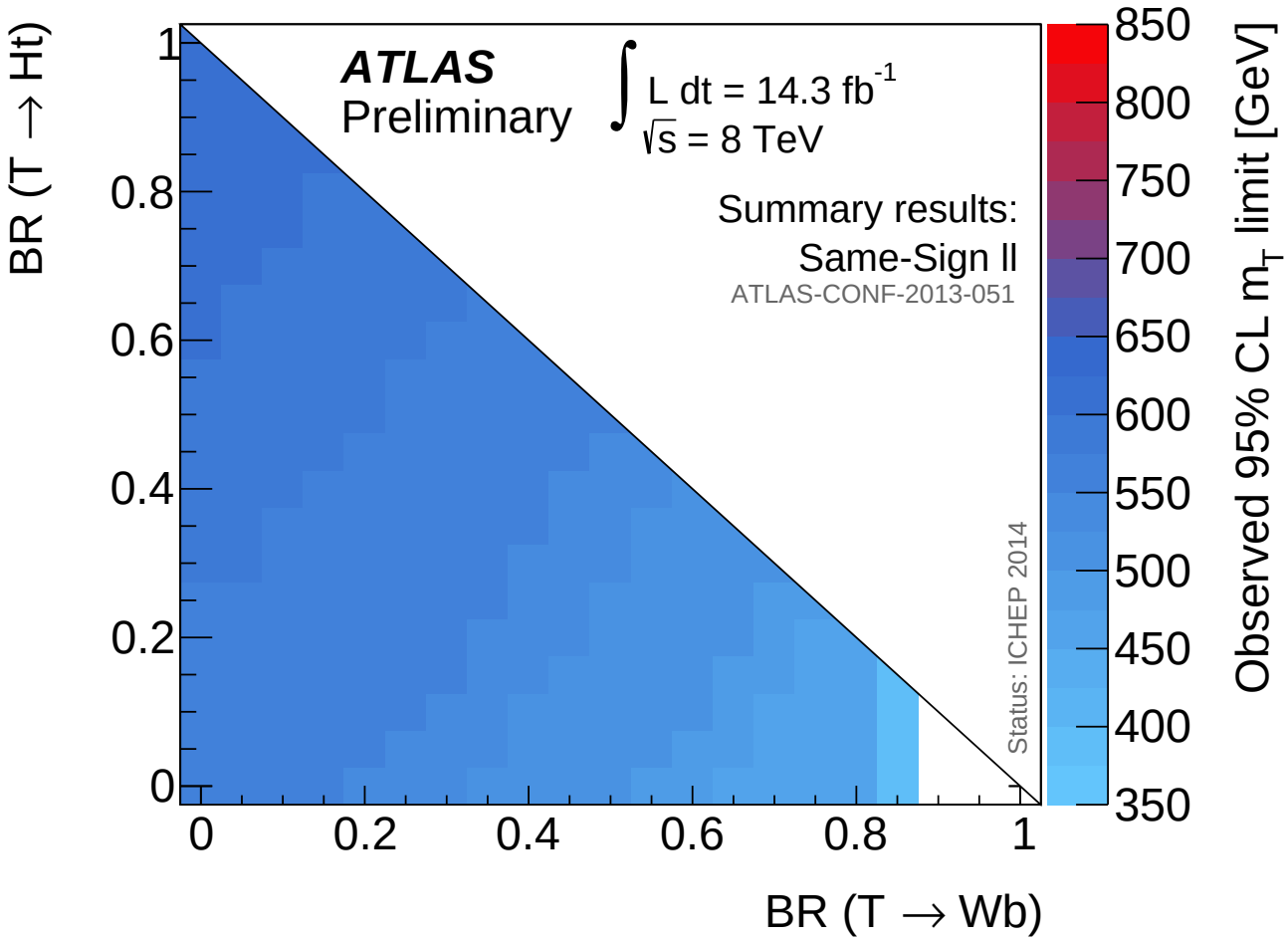
Pair production: generic limit on m_B



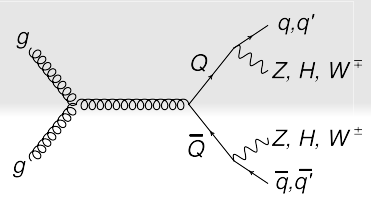


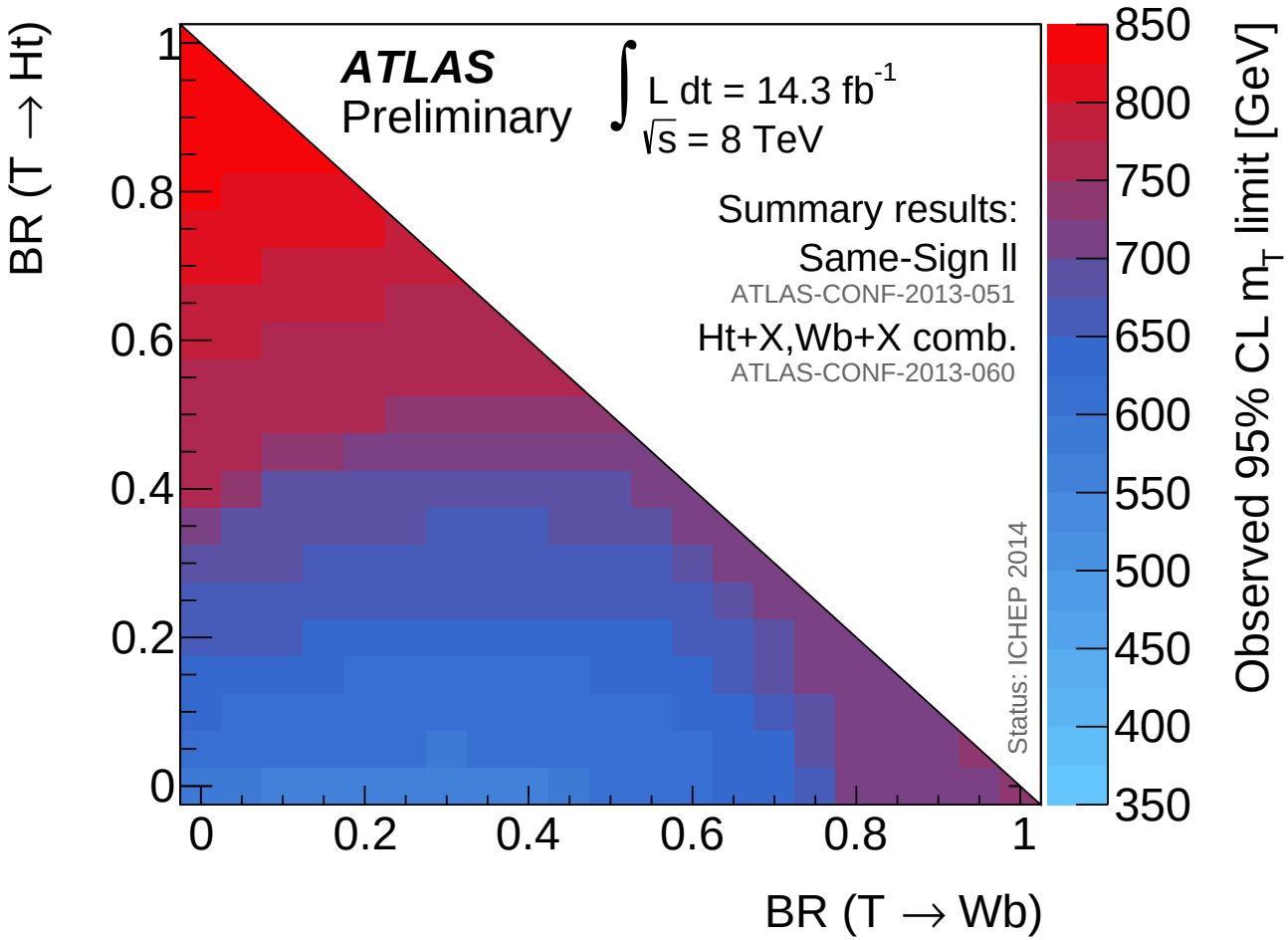
Pair production: generic limit on m_T



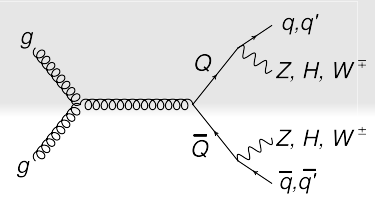


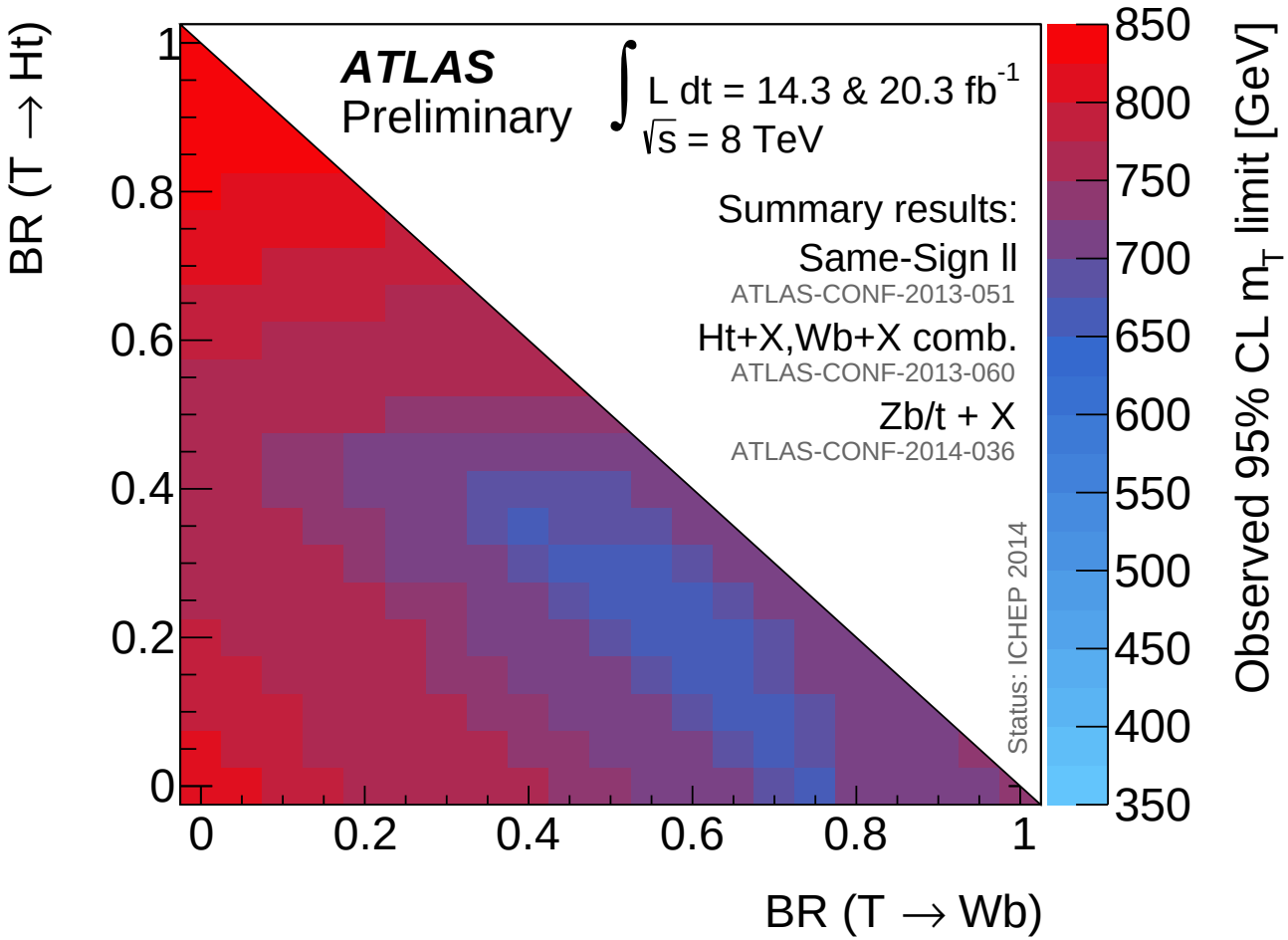
Pair production: generic limit on m_T





Pair production: generic limit on m_T

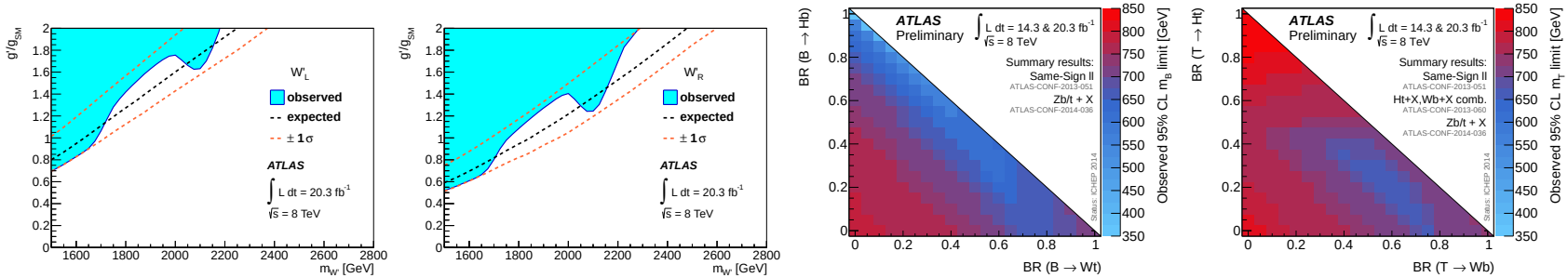




Next slides are about...

Summary

- Many ATLAS analyses searching for non-SUSY new bosons or new fermions with top quarks
- All results consistent with Standard Model so far
- Most recent on $W' \to t\bar{b} \to jets$ and $T/B \to Zt/b + X$:



- More results (leptonic $W' \to t\bar{b}$, $g_{KK}/Z' \to t\bar{t}$, other VLQ decay channels) to be released in the near future

Thank you for your attention

Additional slides

Full hadronic analysis: signal MC samples

- Models in MADGRAPH 5
- PYTHIA 8.165
- CTEQ6L1

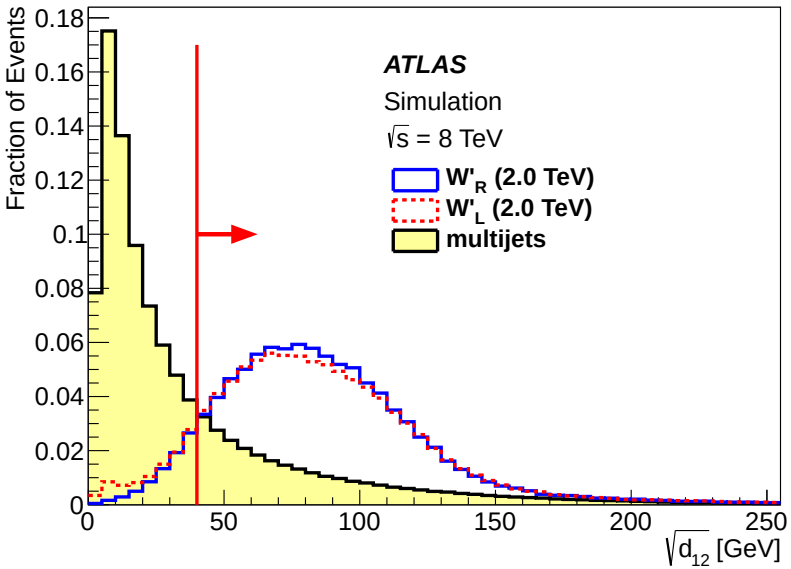
Full hadronic analysis: event selection details

- All 8 TeV data (20.3 fb^{-1}), trigger: $\sum_{calo} E_T \geq 700$ GeV
- No high quality e or μ
- Jets (anti-k_t):
  - small-R (0.4):
    - $p_T > 25$ GeV, $|\eta| < 2.5$
    - $\sum_{jets} p_T > 850$ GeV (for trigger efficiency)
    - exactly one b-tagged with $p_T > 350$ GeV $\Rightarrow$ b
  - large-R (1.0):
    - $p_T > 350$ GeV, $|\eta| < 2.0$
    - exactly one **top-tagged** $\Rightarrow$ t
  - $\Delta R_{tb} > 2.0$, $m_{tb} > 1.1$ TeV
- Two channels:
  - **one** b-**tag** (no additional b-tagged jet)
  - **two** b-**tag** (one additional small-R b-tagged jet with $\Delta R_{b_2 t} < 1.0$)

Top-tagger

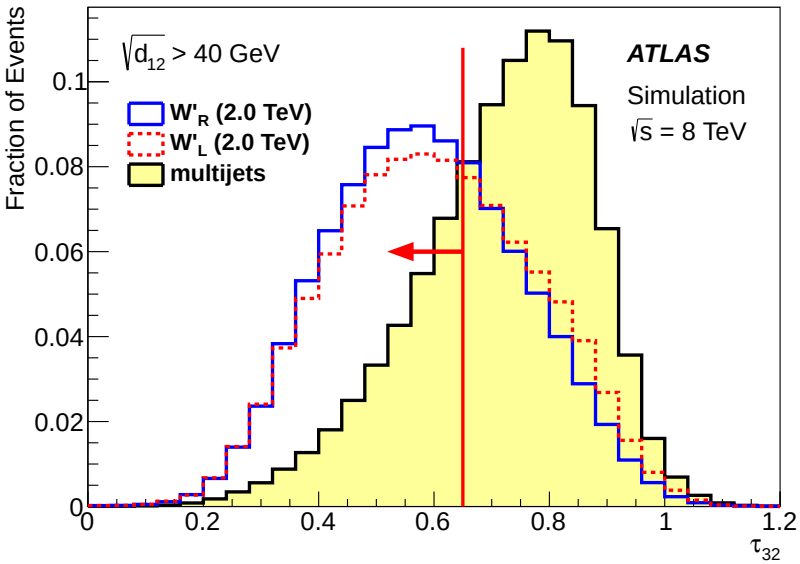
- Specifically optimised top-tagger for this analysis
- Cut optimisation done on 2 TeV signal samples and a high-p_T QCD multijet MC sample

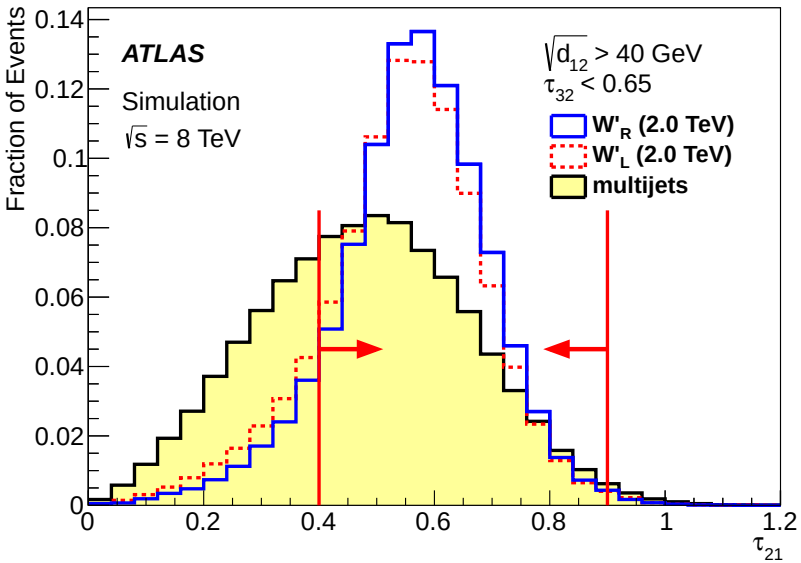
- Splitting scale $\sqrt{d_{12}} = \min(p_{T1}, p_{T2})\Delta R_{12}$ splitting in two subjets
- Close to $m_{top}/2$ for top jets, close to 0 for light, b or gluon jets



Top-tagger: N-subjettiness

- τ_{ij}: close to 1 for j-subjet-like jets, close to 0 for i-subjet-like jets





N-subjettiness

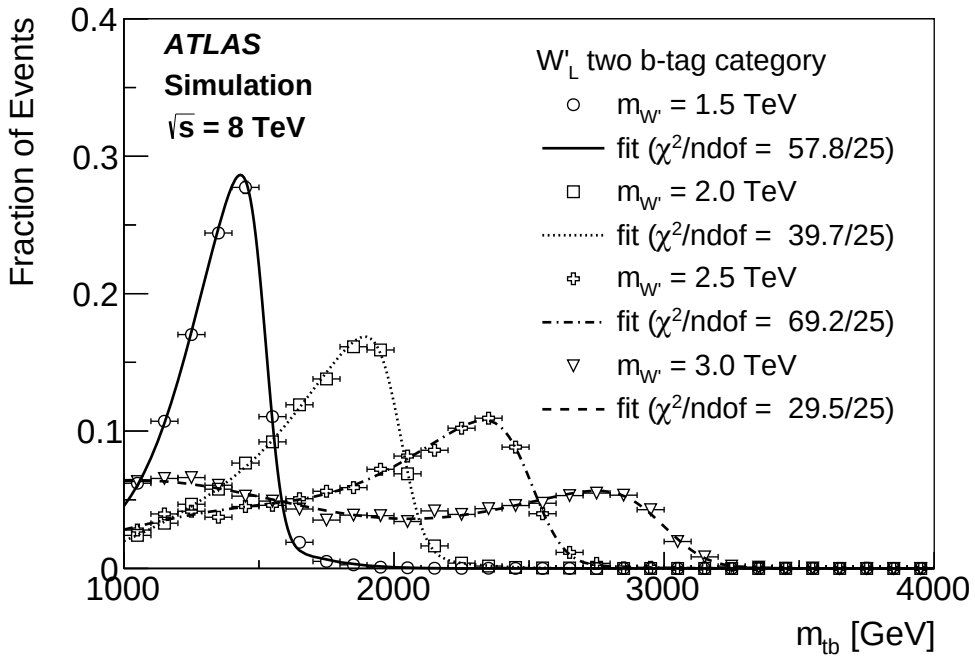
- Reclustering (with k_t) of the large-R jet with exactly N subjets

$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \min(\delta R_{1k}, ..., \delta R_{Nk})$$

$$d_0 = \sum_k p_{Tk} R$$

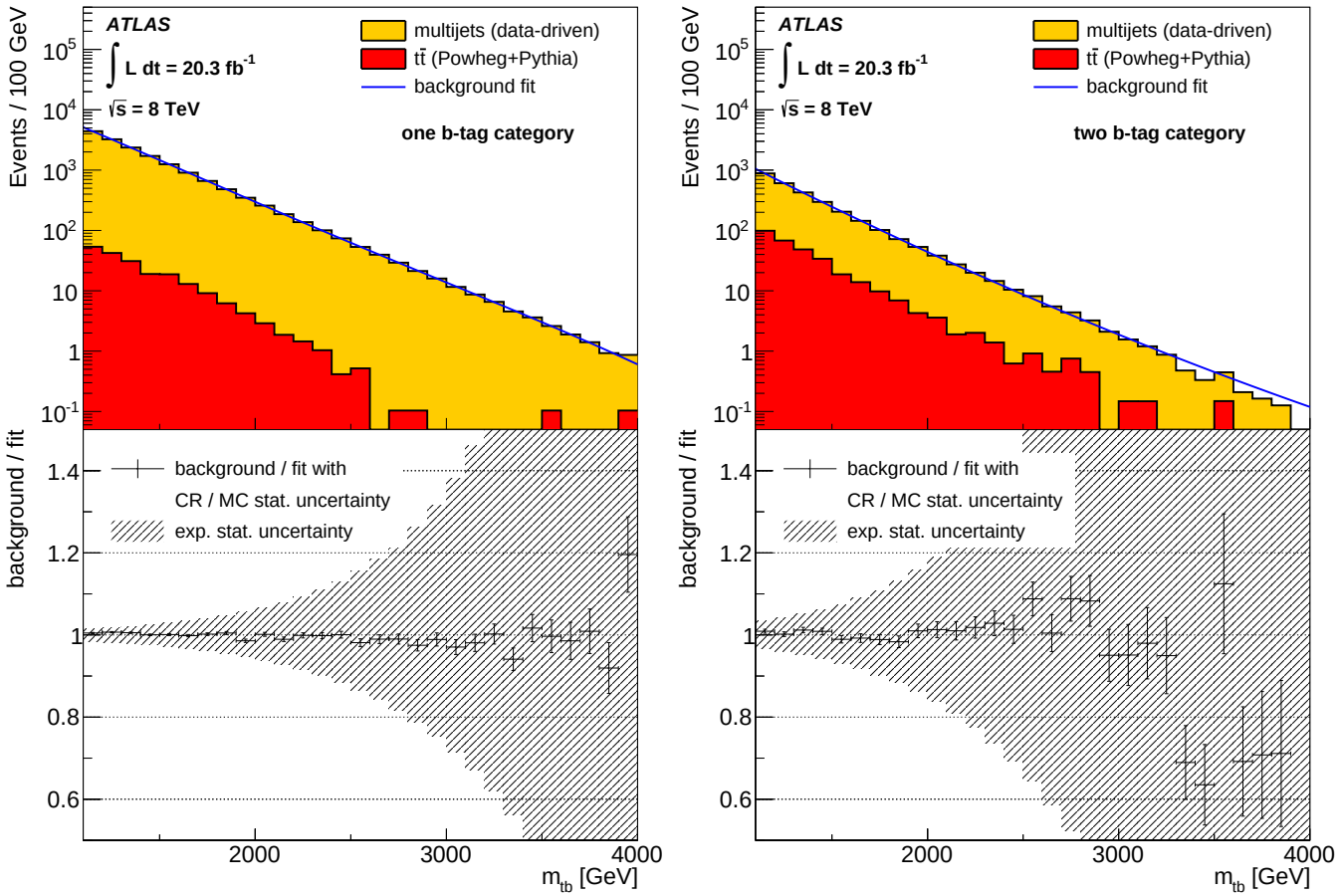
- k: constituent of the jet, R: radius of original jet, δ_{ik}: distance between i^{th} and k^{th} constituents
- $\tau_{ij} = \tau_i/\tau_j$: close to 1 for j-subjet-like jets, close to 0 for i-subjet-like jets

Full hadronic analysis: function for signal



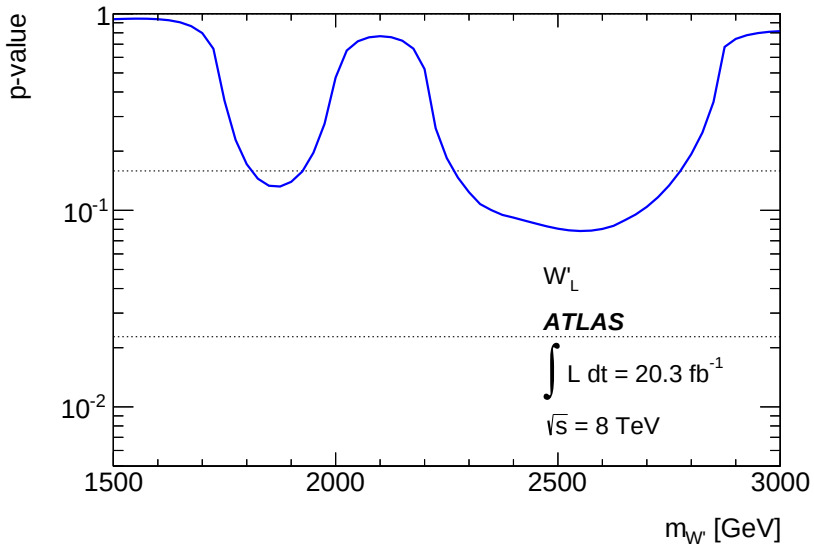
- (Gaussian×Gaussian error function)+Gaussian
- Interpolation of parameters between the generated mass points

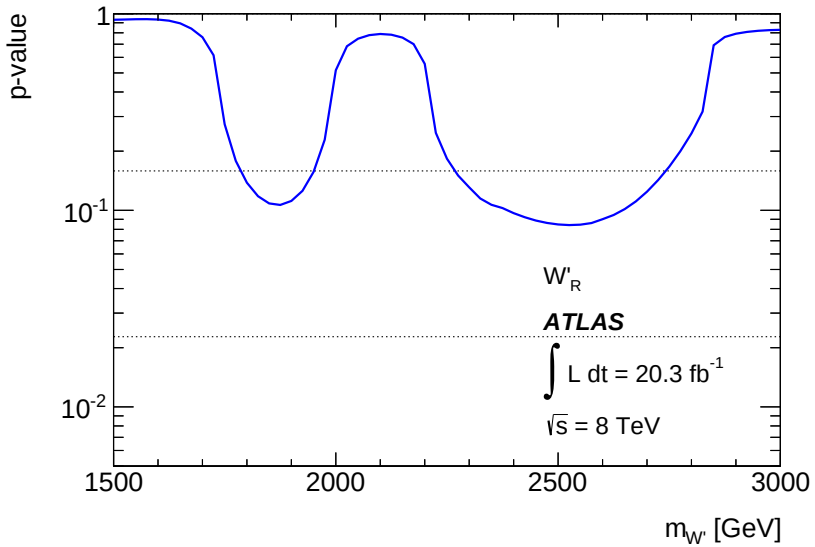
Full hadronic analysis: function for background



- $\exp(\sum_{k=1}^{n} c_k m_{tb}^k)$, n=4 (one b-tag), 2 (two b-tag)

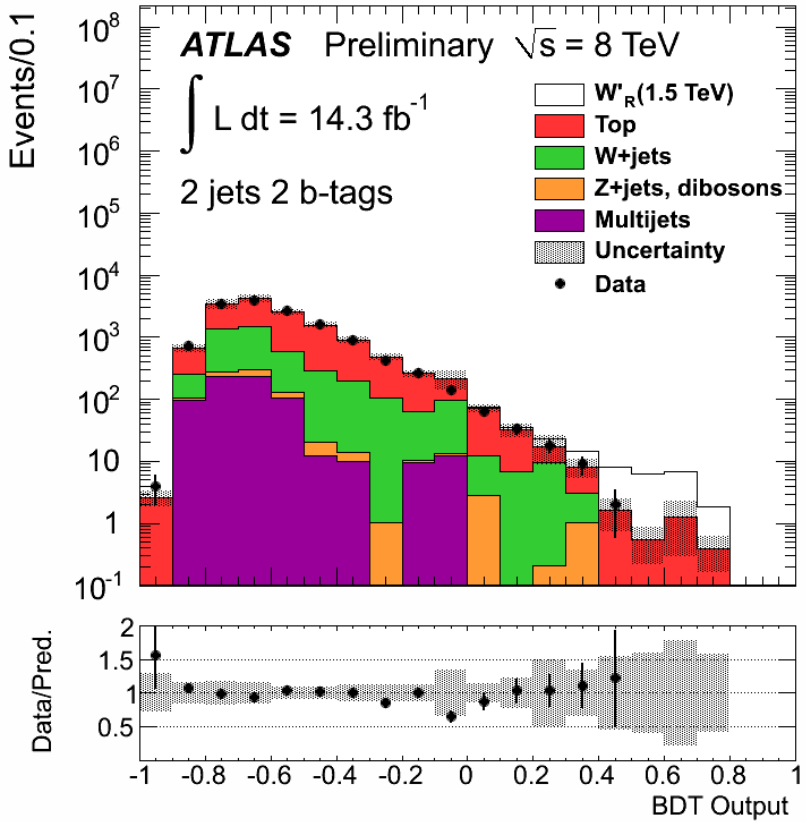
Full hadronic analysis: p-values

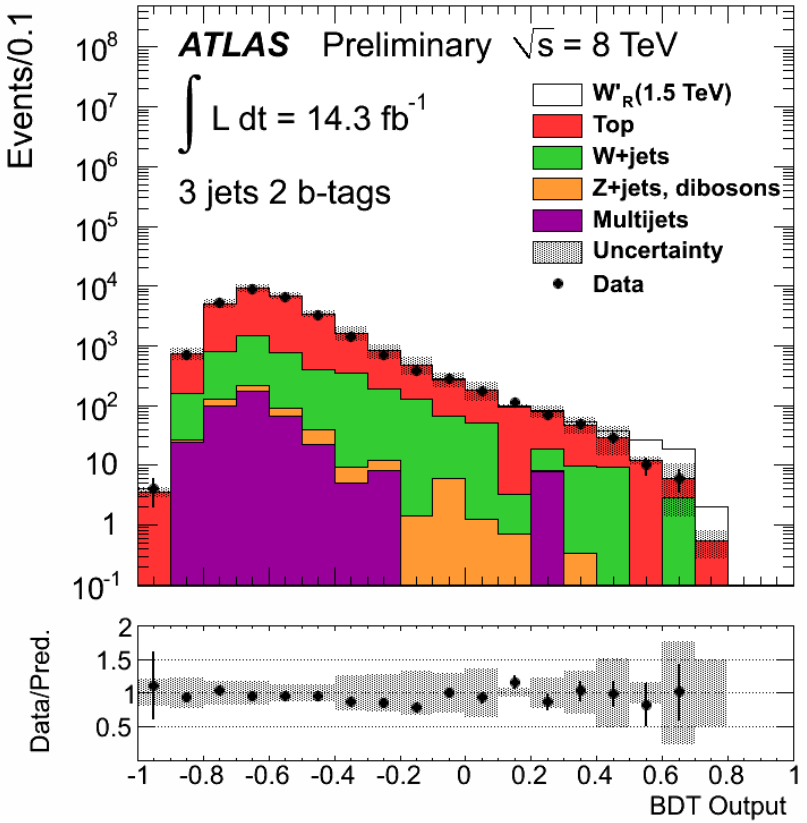




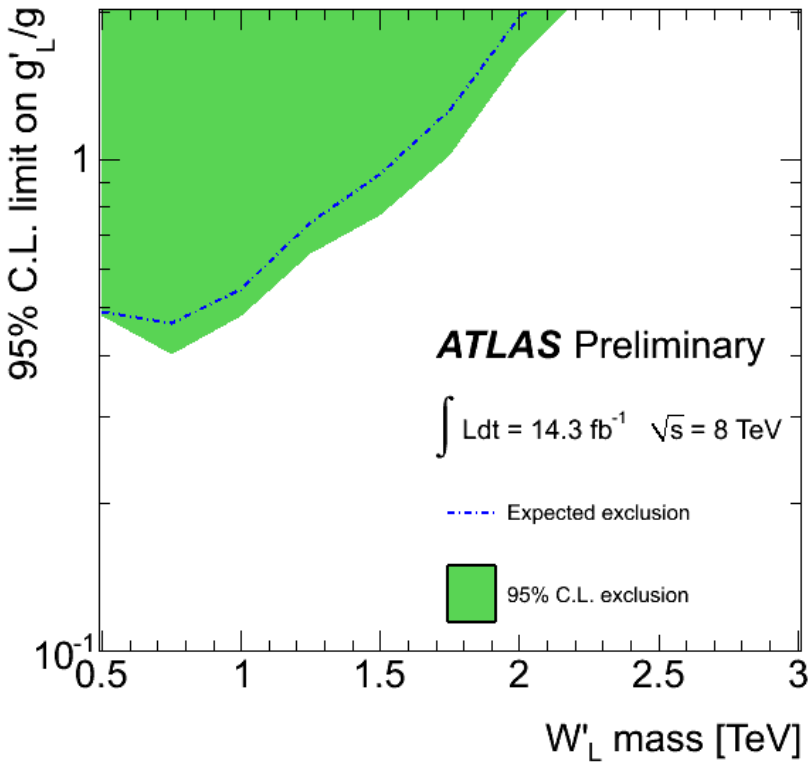
Maximal local significance: 1.4σ

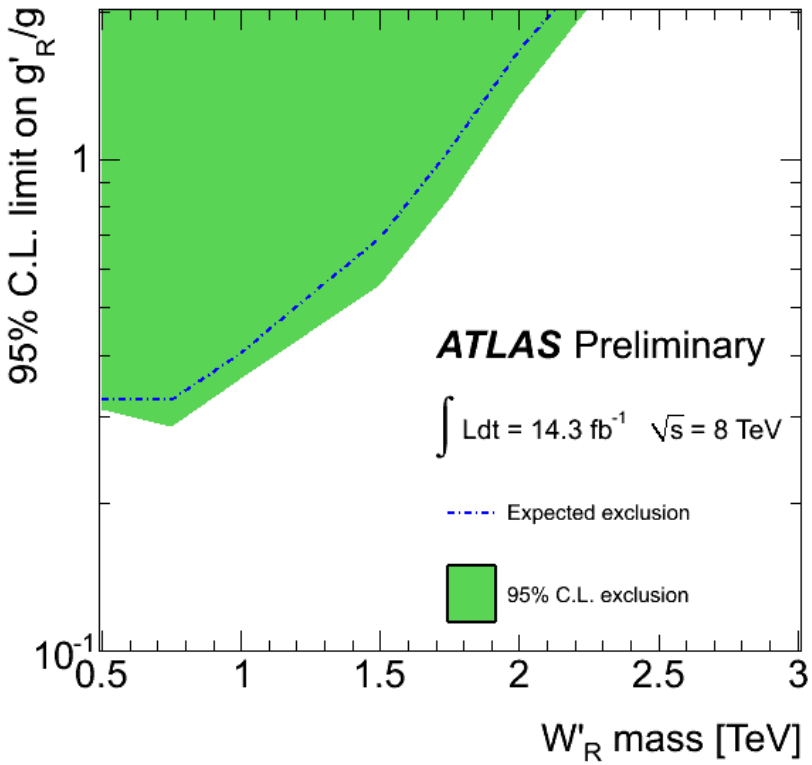
Leptonic analysis: BDT outputs



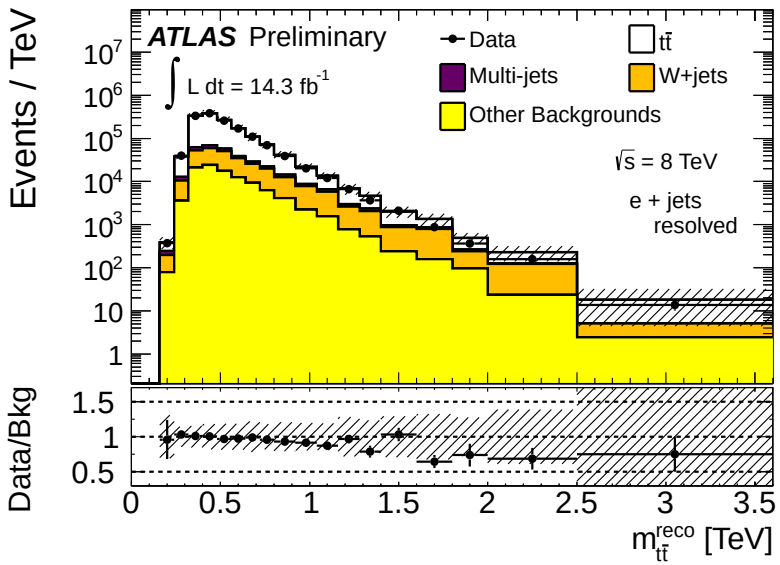


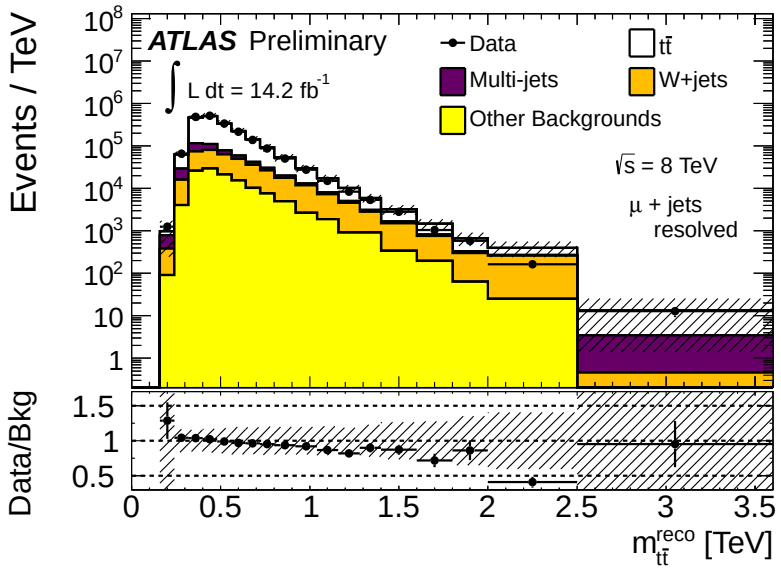
Leptonic analysis: generic limits



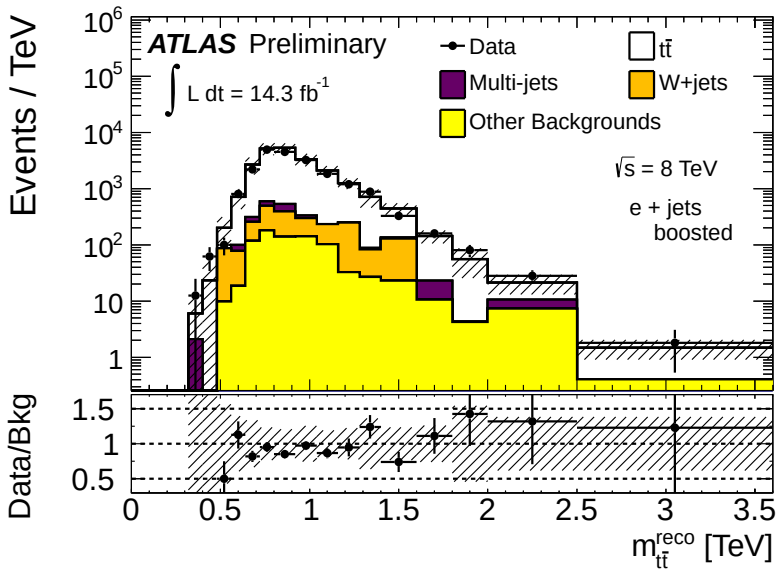


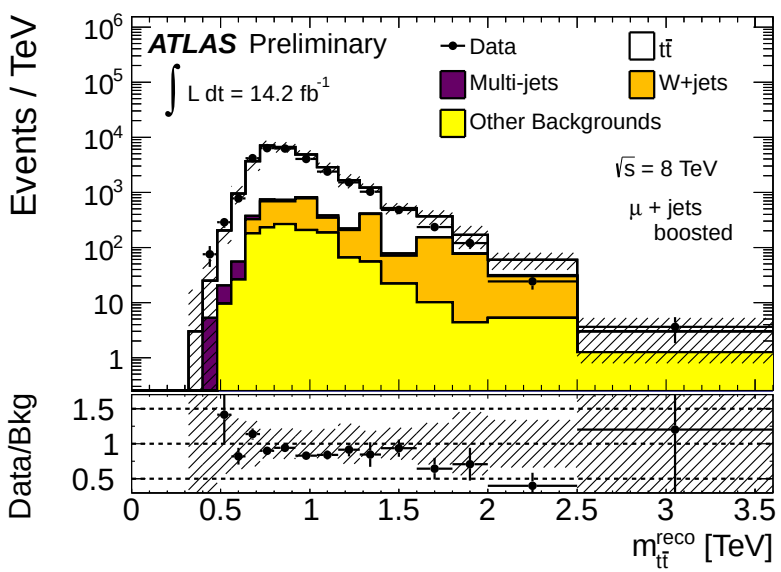
Resolved analysis



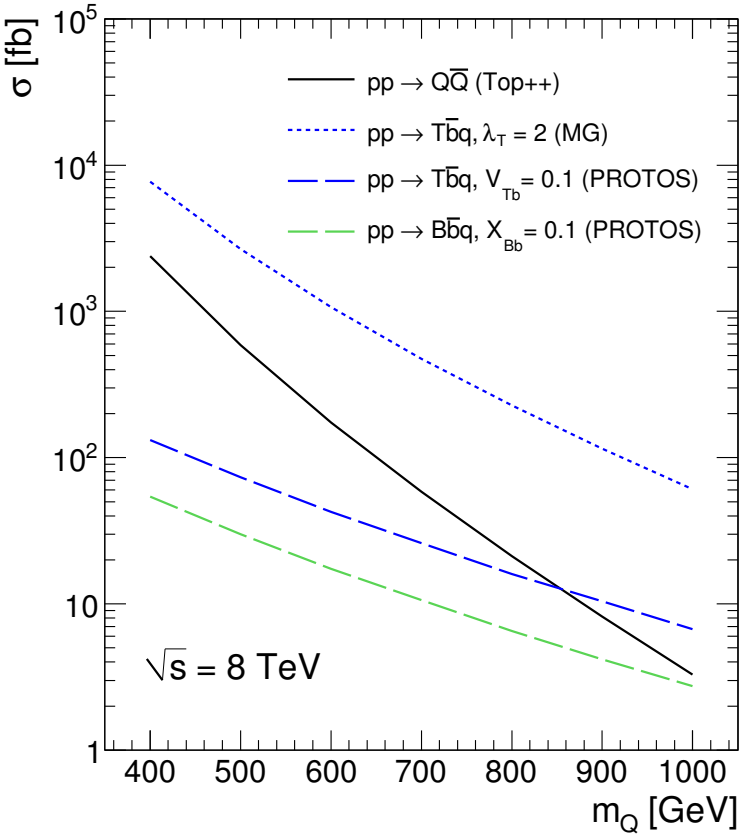


Boosted analysis



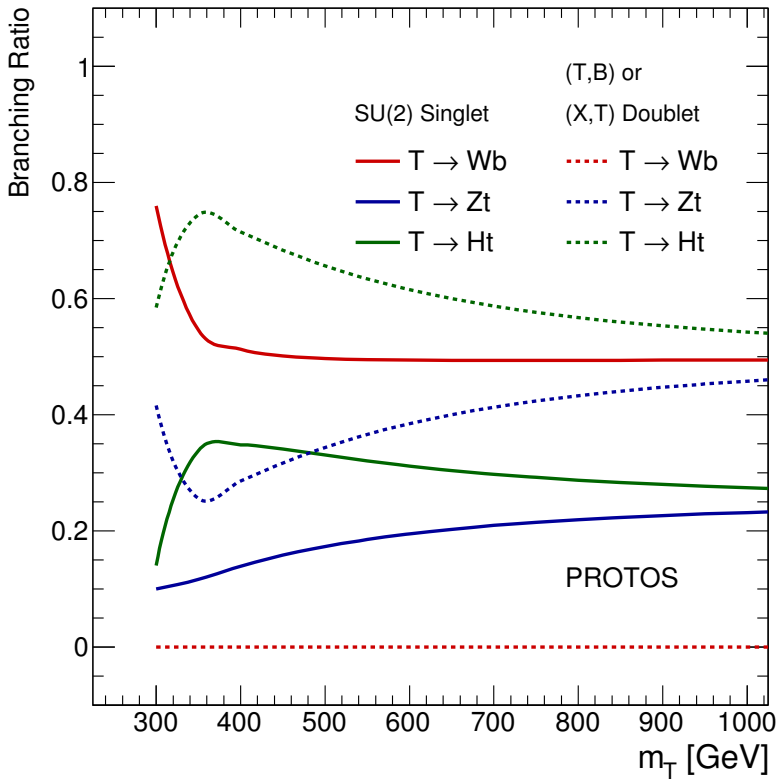


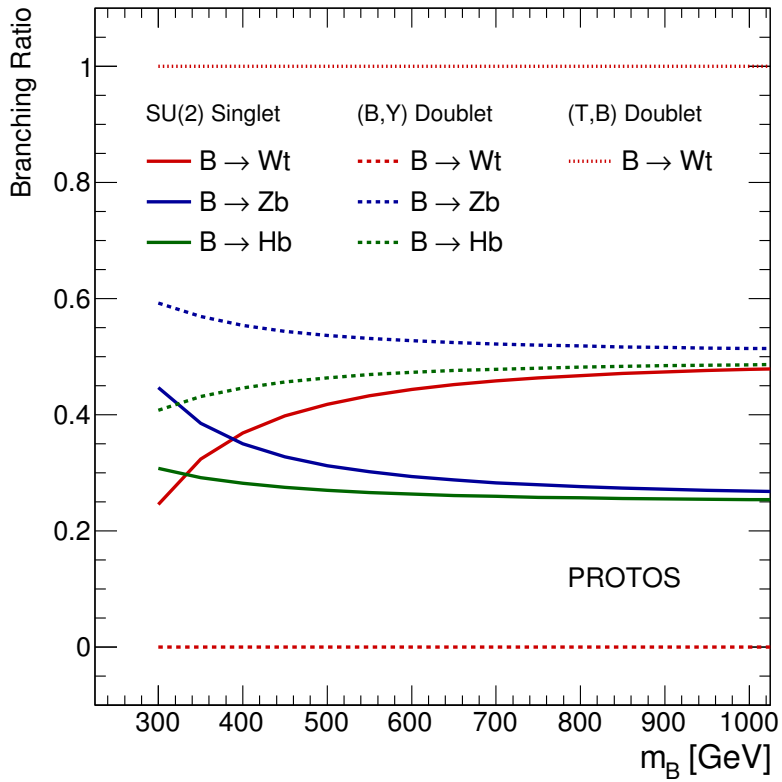
Production cross-section



- λ_T: related to coupling of TWb vertex ($V_{Tb} \approx \frac{\lambda_T v}{\sqrt{2} m_T}$)
- V_{Tb}: generalised CKM matrix element (TWb vertex)
- X_{Bb}: mixing between B and b (BZb vertex)

Branching ratios





X: charge +5/3, Y: charge -4/3

$Zb/t + X$: signal MC samples

- Pair production:
  - cross-sections from TOP++ v2.0 (NNLO)
  - generated with PROTOS v2.2 + PYTHIA v6.421
  - MSTW 2008 LO 68% CL
  - decays to equal (1/3) branching ratios (reweighting)
  - $SU(2)$ singlet and doublet couplings compared: negligible effect
  - $[350, 850]$ GeV (step of 50 GeV), fast simulation, 400, 600 and 800 GeV with full simulation

$Zb/t + X$: signal MC samples

- Single production:
  - cross-sections from
    - PROTOS: single vector-like multiplet at low energy
    - MADGRAPH v5: composite Higgs model from arXiv:1207.0830 for $T\bar{b}q$
  - generated with PROTOS ($B\bar{b}q$) and MADGRAPH ($T\bar{b}q$)
  - $T\bar{b}q$ compared to parton-level PROTOS samples
  - $[400, 1050]$ GeV for $T\bar{b}q$, $[400, 1200]$ GeV for $B\bar{b}q$ (step of 50 GeV)
  - fast simulation for $T\bar{b}q$, full simulation for $B\bar{b}q$

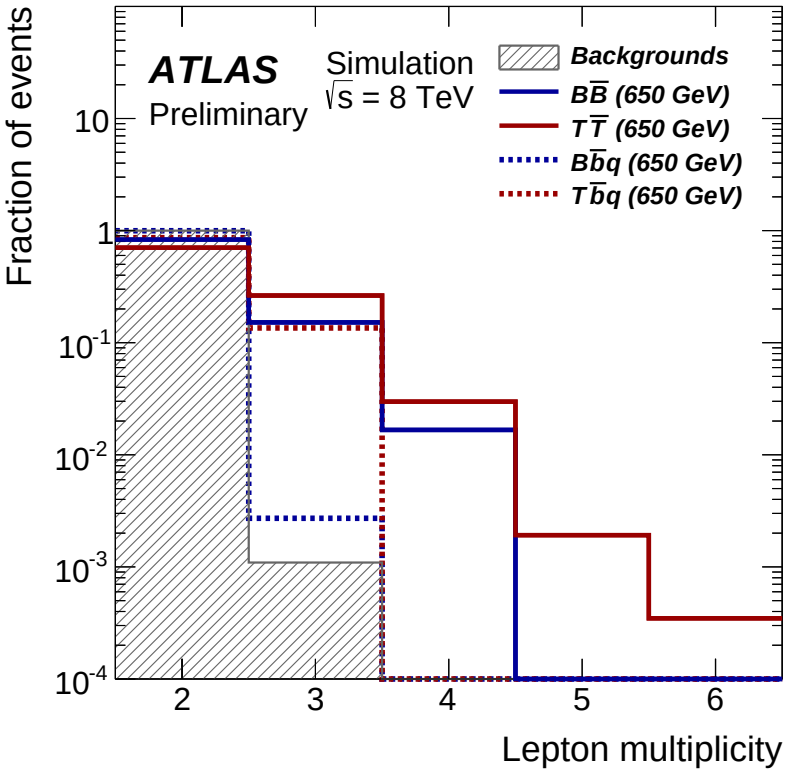
$Zb/t + X$: background MC samples

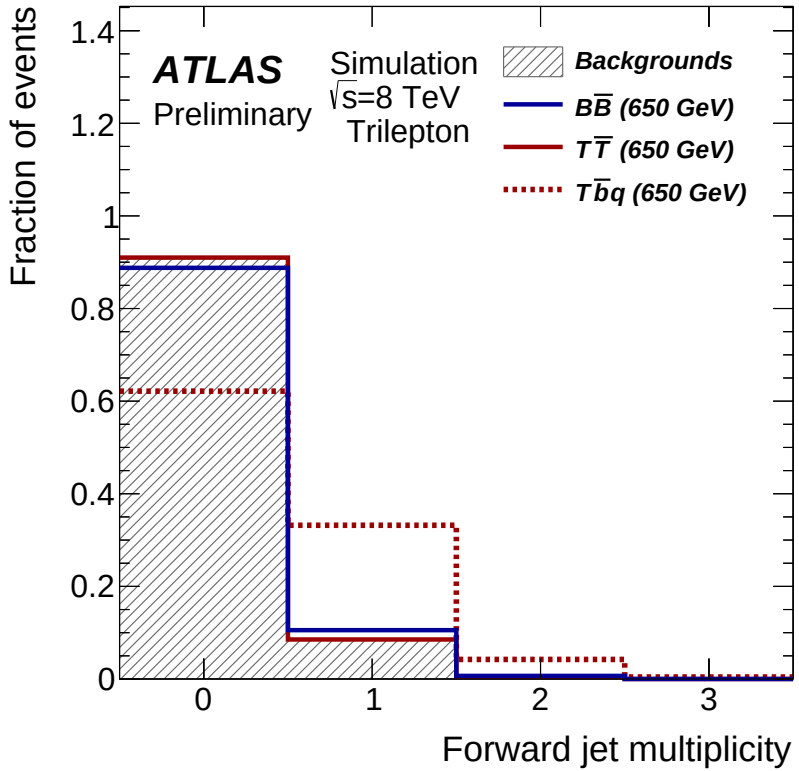
- Z+jets: SHERPA (CT10), cross-checks with ALPGEN+PYTHIA (CTEQ6L1); NNLO
- VV: SHERPA; NLO
- $t\bar{t} + V$: MADGRAPH+PYTHIA; NLO
- $t\bar{t}$: POWHEG+PYTHIA (CT10); TOP++
- Wt, t (s-channel): MC@NLO+HERWIG; NLO
- t (t-channel): ACERMC+PYTHIA; NLO

Reconstruction of physics objects

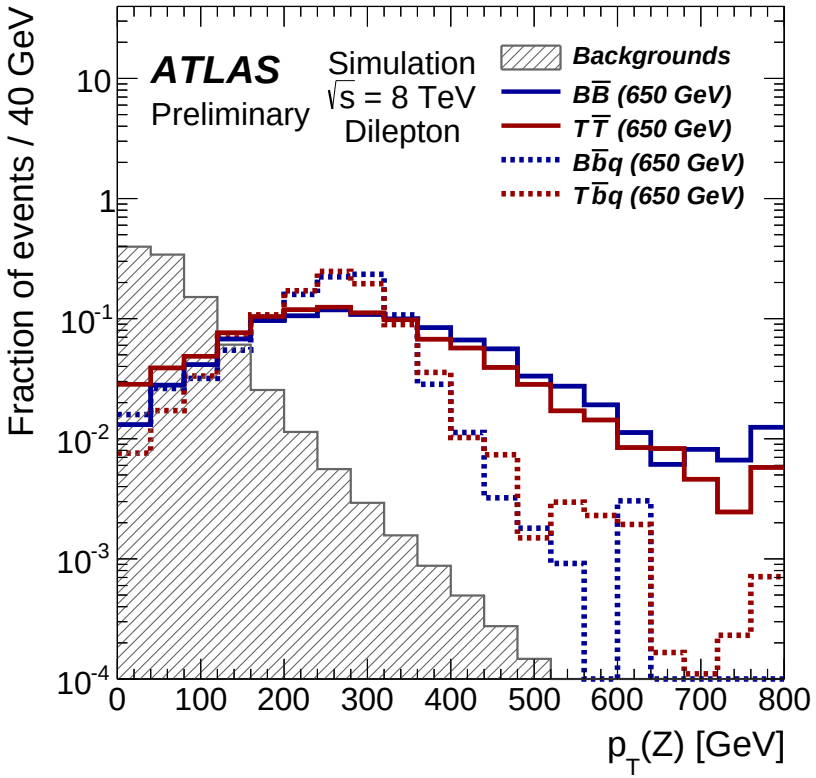
- Electrons:
  - $E_T > 25$ GeV, $|\eta_{cluster}| < 2.47$
  - Medium requirement for electrons in Z-peak
  - Tight requirement for extra electron(s)
  - Calorimeter isolation in cone with $\Delta R = 0.2$, track isolation with $\Delta R = 0.3$
- Muons:
  - $p_T > 25$ GeV, $|\eta| < 2.5$
  - Track isolation in cone with $\Delta R = 10$ GeV$/p_T^{\mu}$
- Jets:
  - Anti-k_t with $R = 0.4$
  - Central jets with $p_T > 25$ GeV, $|\eta| < 2.5$
  - Forward jets with $p_T > 35$ GeV, $2.5 < |\eta| < 4.5$

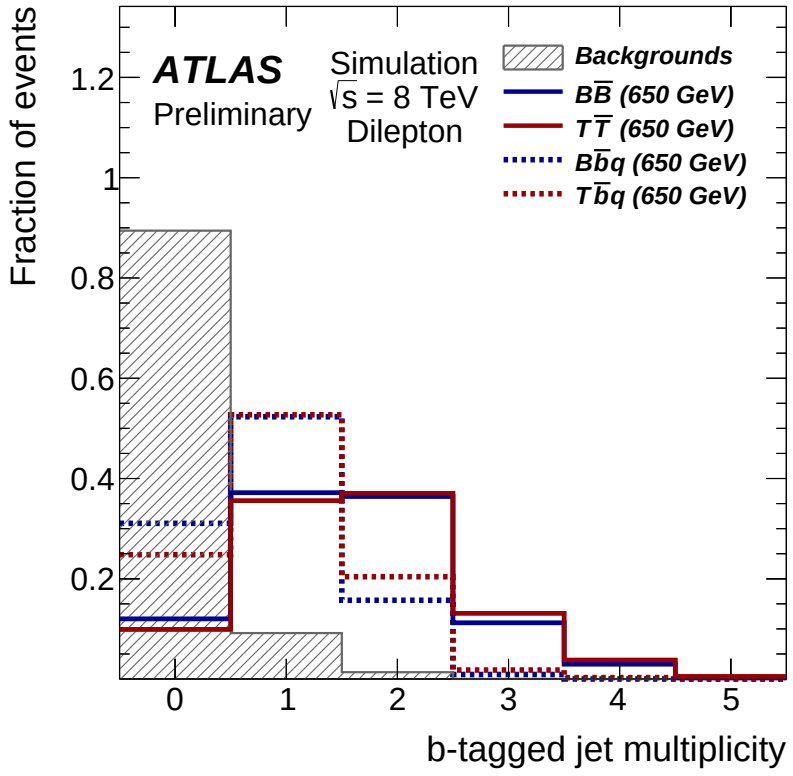
$Zb/t + X$: distributions for Z+2 central jets events





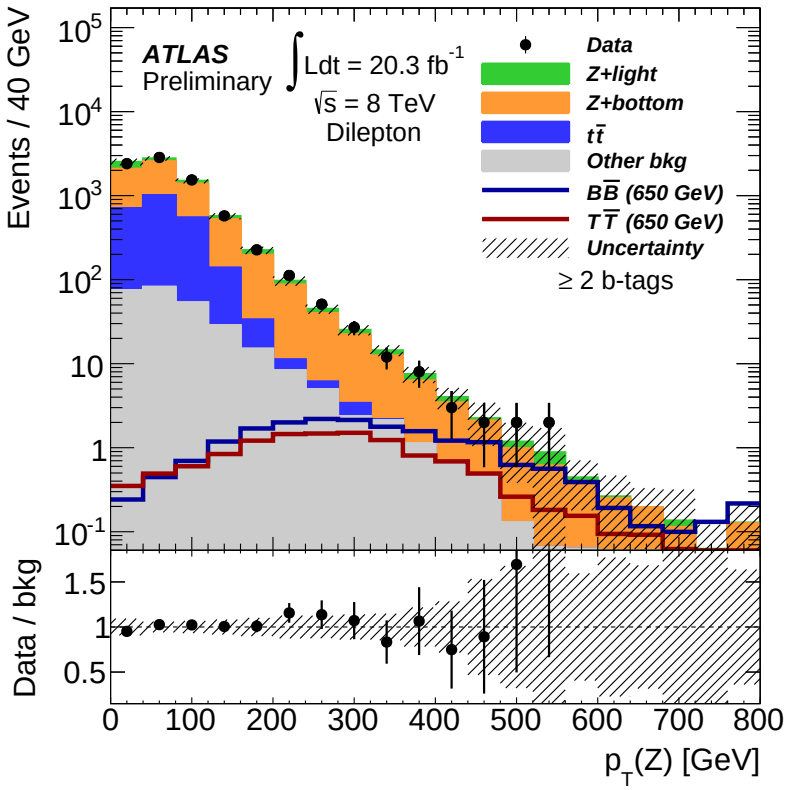
$Zb/t + X$: distributions for dilepton events

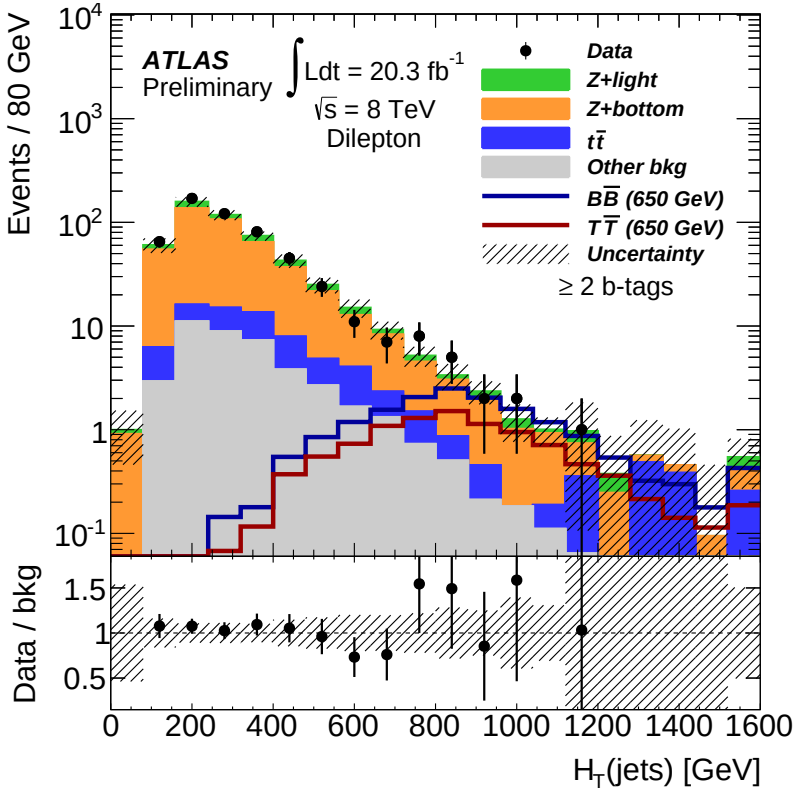




$Zb/t + X$: distributions for dilepton events

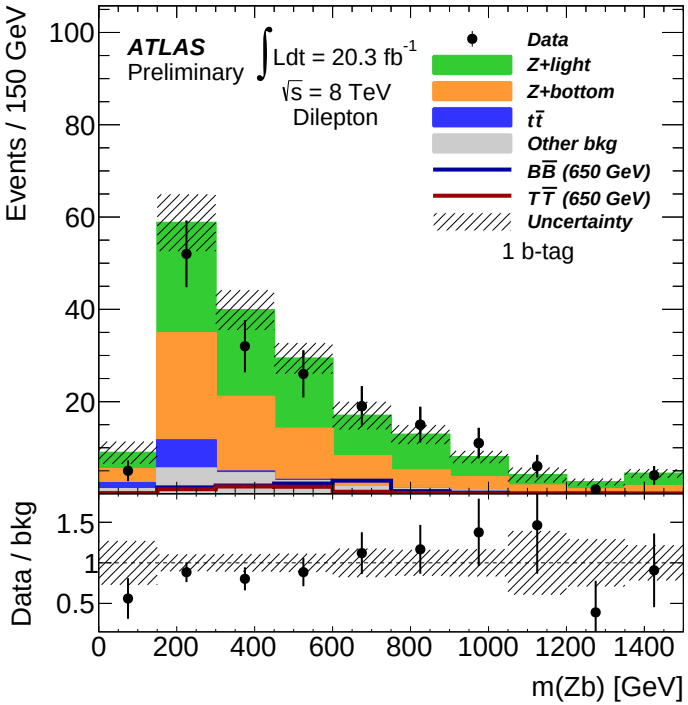
With at least 2 b-tagged jets

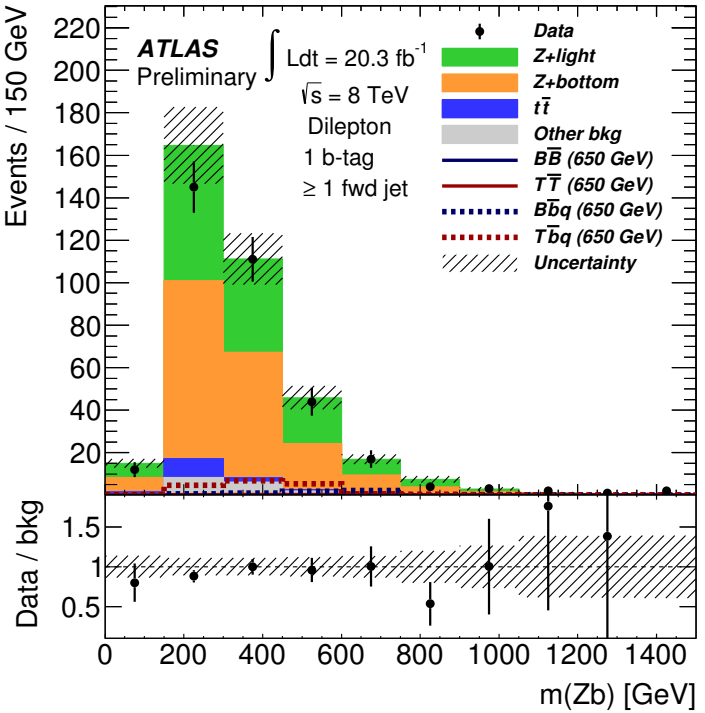




$Zb/t + X$: distributions for dilepton events

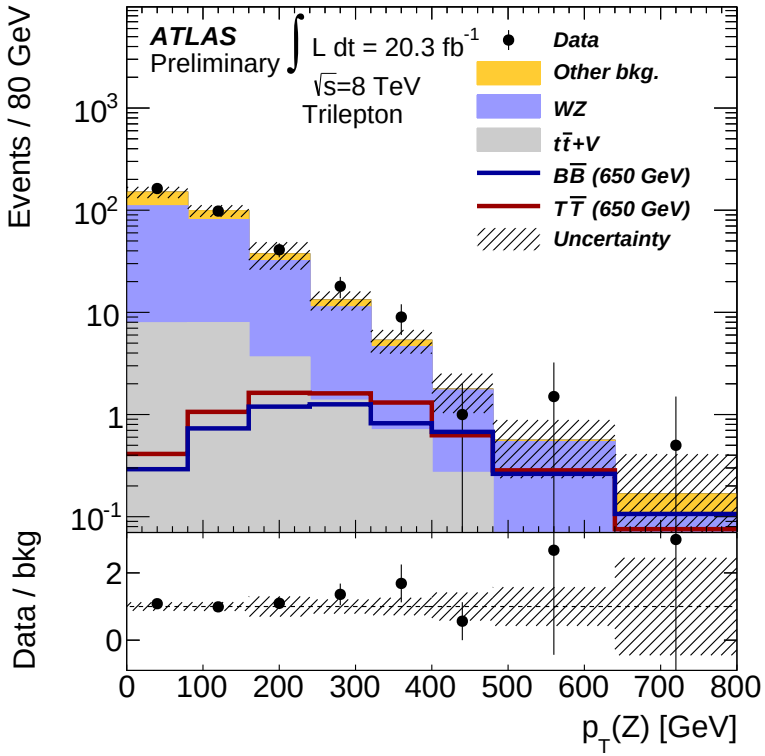
With only 1 b-tagged jet (control regions)

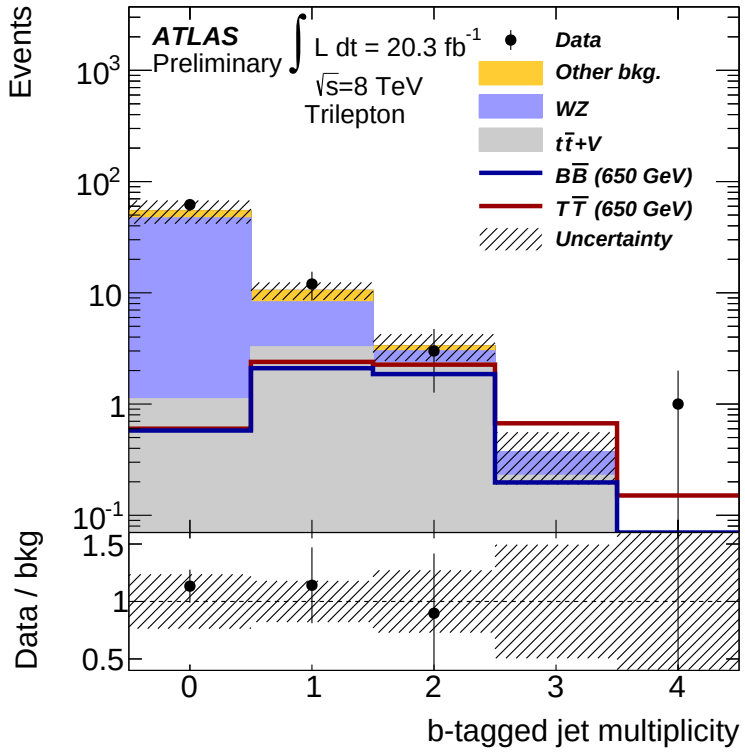




$H_T(jets) > 600$ GeV

$Zb/t + X$: distributions for trilepton events

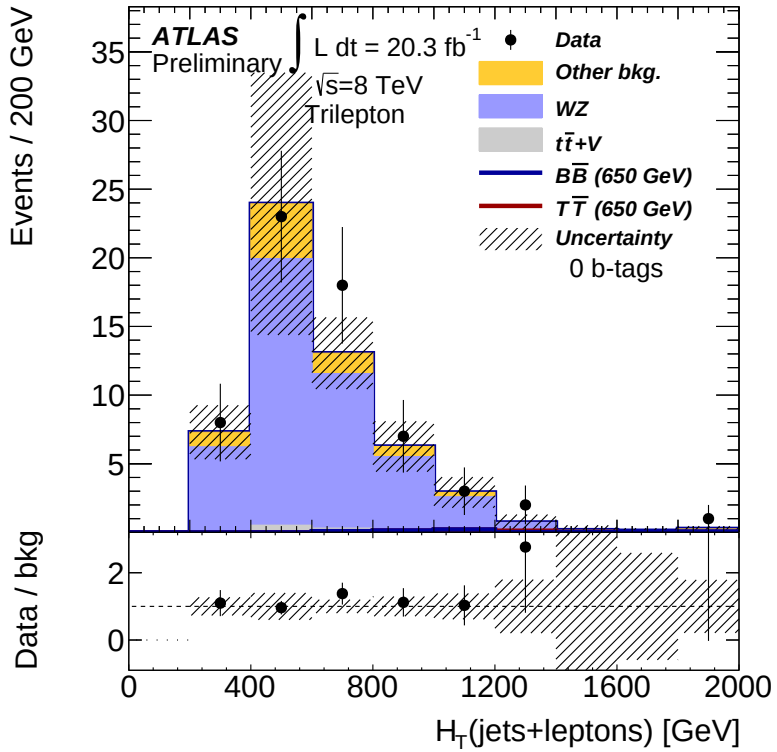




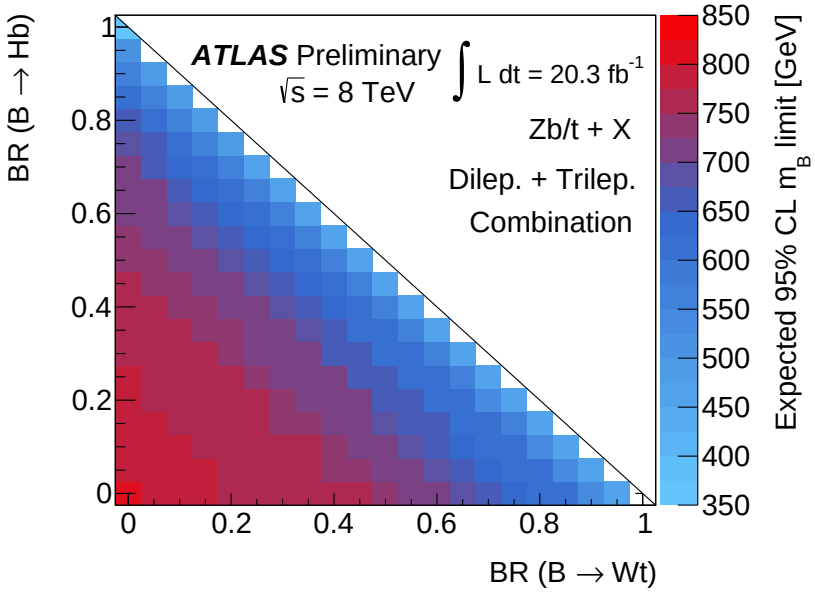
$p_T(Z) > 150$ GeV

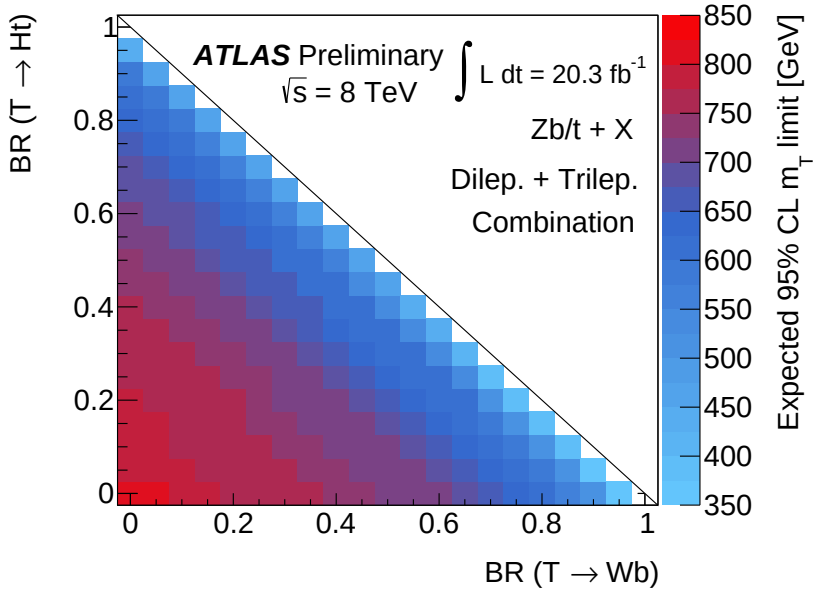
$Zb/t + X$: distributions for trilepton events

With no b-tagged jet (control region)



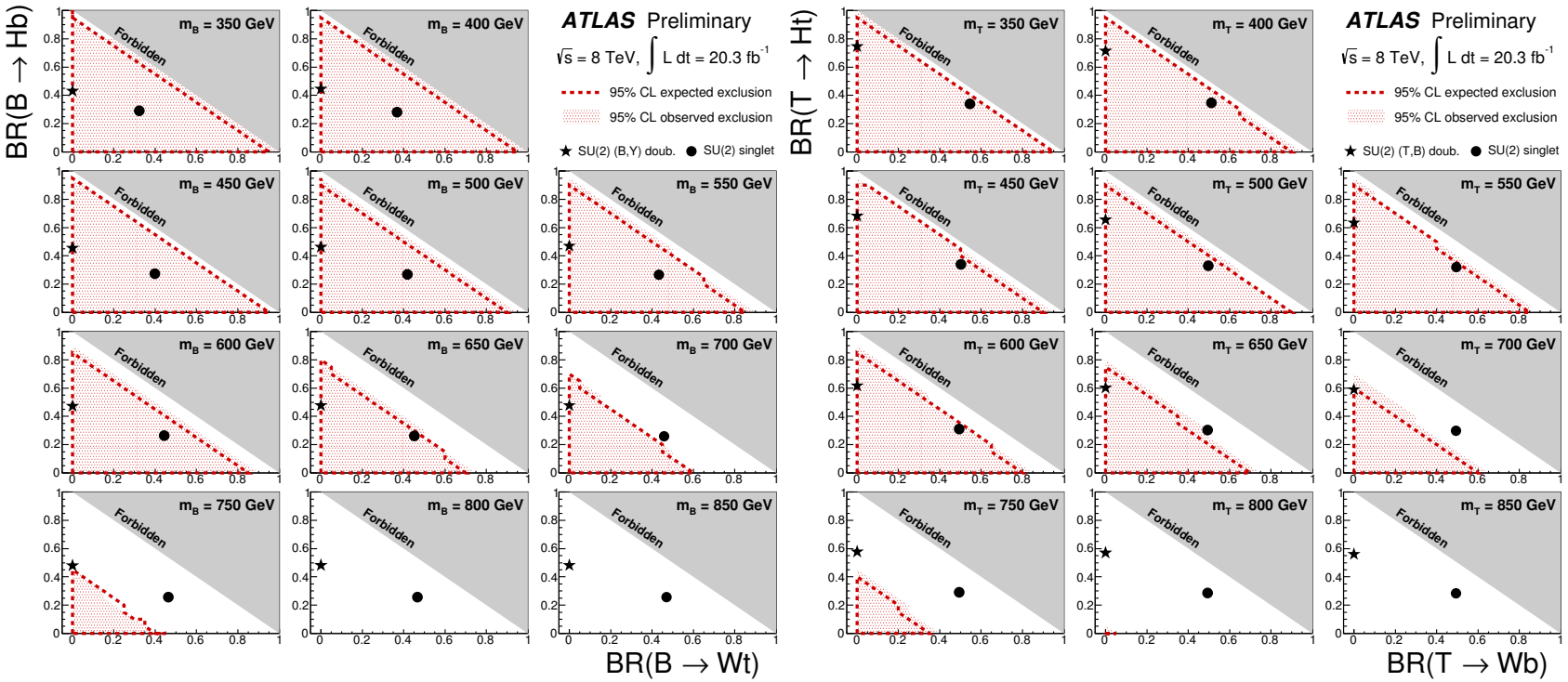
$Zb/t + X$, pair production: expected generic limits





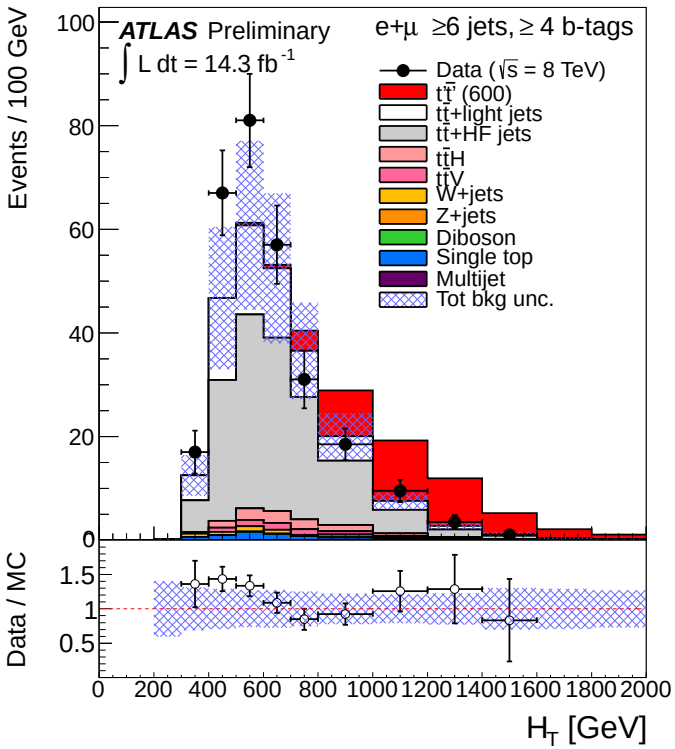
- $\mathrm{BR}(B \to Wt)+\mathrm{BR}(B \to Hb)+\mathrm{BR}(B \to Zb)=1$
- $\mathrm{BR}(T \to Wb)+\mathrm{BR}(T \to Ht)+\mathrm{BR}(T \to Zt)=1$

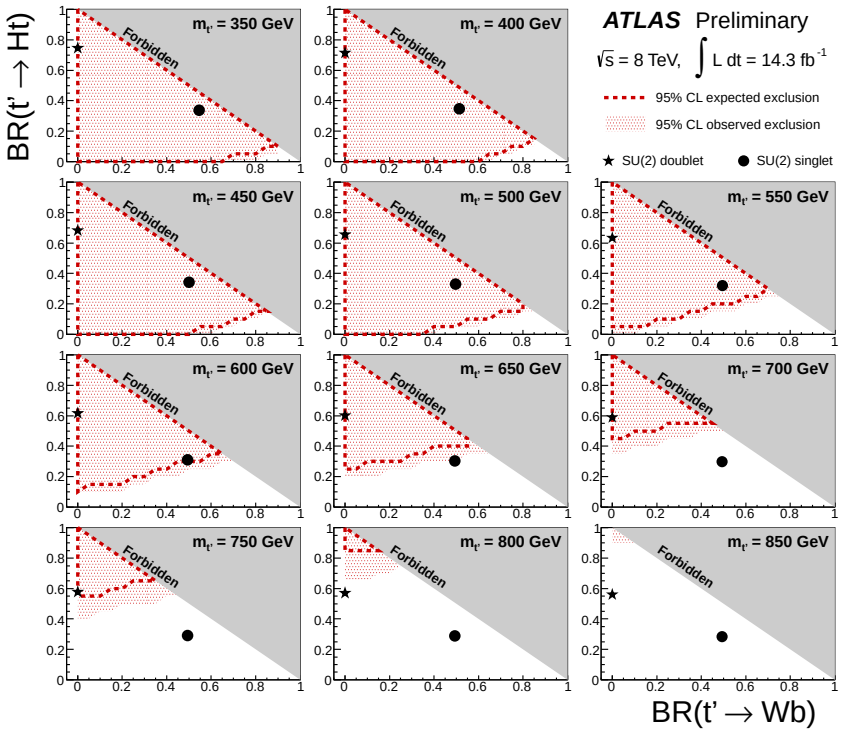
$Zb/t + X$, pair production: generic limits



$T \to Ht$ analysis (ATLAS-CONF-2013-018)

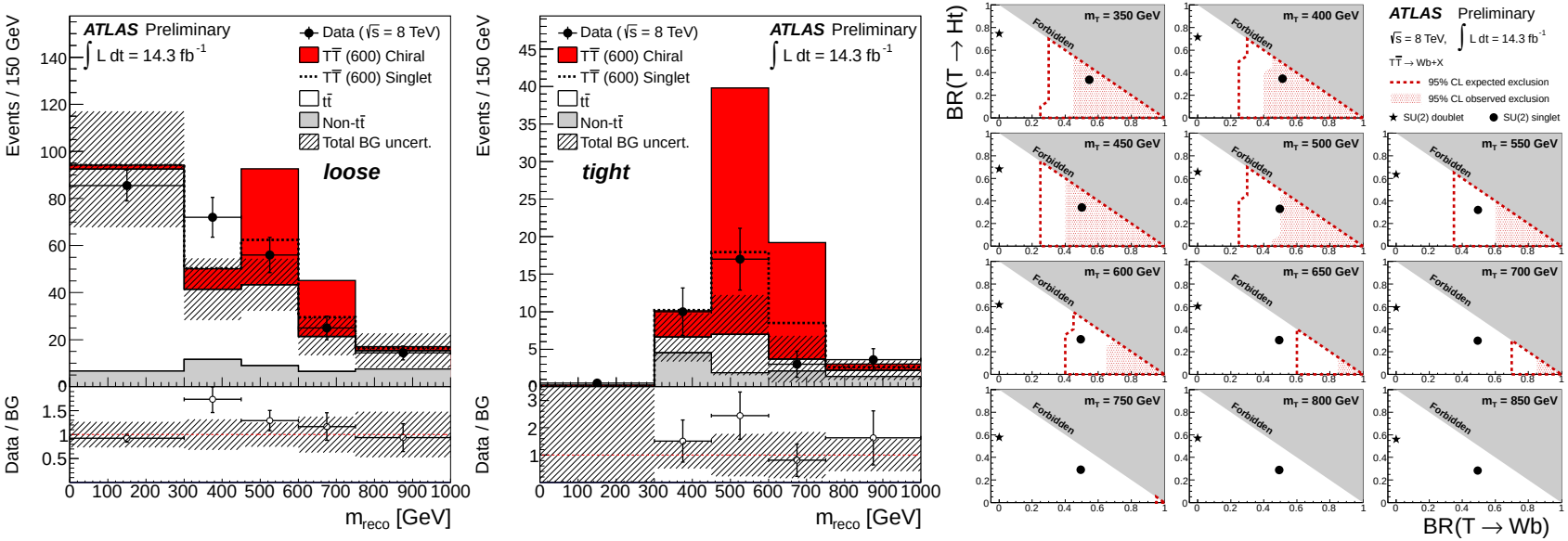
- Lepton+jets, targets $T \to H(\to b\bar{b})t$ in $T\bar{T}$ production





$T \to Wb$ analysis (ATLAS-CONF-2013-060)

- Lepton+jets, targets $T \to Wb$ in $T\bar{T}$ production



Same-sign dilepton analysis (ATLAS-CONF-2013-051)

- Same-sign dilepton, targets $B \longrightarrow Wt$ in $B\bar{B}$ production
- Also sensitive to $T \longrightarrow Zt, Ht$ in $T\bar{T}$ production