

# BSM top related searches in ATLAS

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**Top Quark Physics Day**

MIAPP summer institute "Challenges, Innovations and Developments in Precision  
Calculations for the LHC" @ TU Munich 2014



# Overview



- **Vector-like quark searches**

- searches in different decay modes, pair production and single production
- summary and combination of limits

- **ttbar, top+jets, tb, Wt resonance searches**

- ttbar resonances using resolved and boosted topologies

- $W' \rightarrow tb$  using boosted and resolved topologies

- $b^* \rightarrow Wt$  using resolved topologies

- ttbar+jets via  $W'$  or  $\phi$  resonance

- **FCNC in top decay and production**

- FCNC in decay  $t \rightarrow Zq$

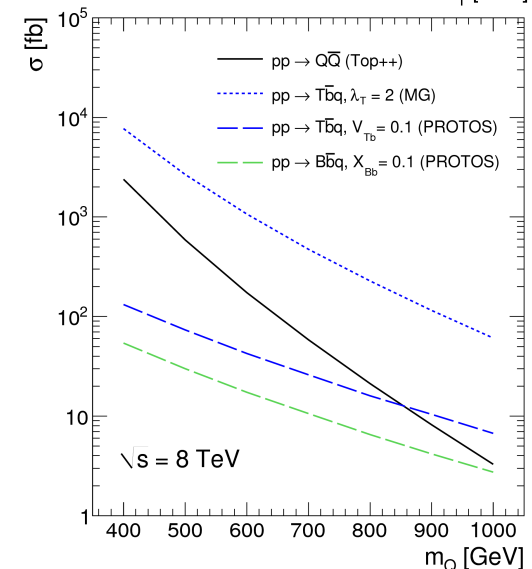
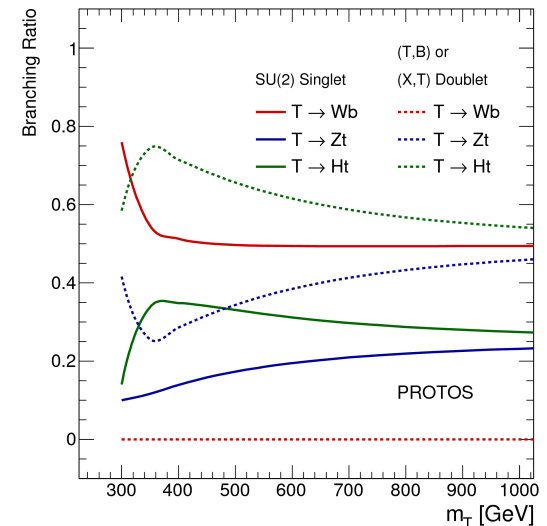
- FCNC in single top production  $gq \rightarrow t$

# Vector-like quark searches



- **Vector-like quarks**

- colour-triplet, spin 1/2 fermions, left- and right-handed chiral components have same transformations under the weak isospin group
- can appear in many models to cancel Higgs divergence: GUTs, little Higgs, composite Higgs
- T with charge +2/3, B with charge -1/3, either as **singlet**, **doublet (T,B)** or **doublet (X,T)** with X with charge +5/3, **doublet (Y,B)** with Y with charge -4/3
- mixing predominantly with third generation quarks
- cross section for pair production using Top++/Hathor calculation@NNLO+NNLL, decay to H,Z,W using BR from Protos
- Single production 2->3 process in single production, with MadGraph using  $\lambda_T$  as coupling parameter, or Protos using  $V_{Tb}/V_{Bb}$  set to upper limit from EW precision measurements
- Limits on mass using BR from Protos calculations and setting limits in BR plane



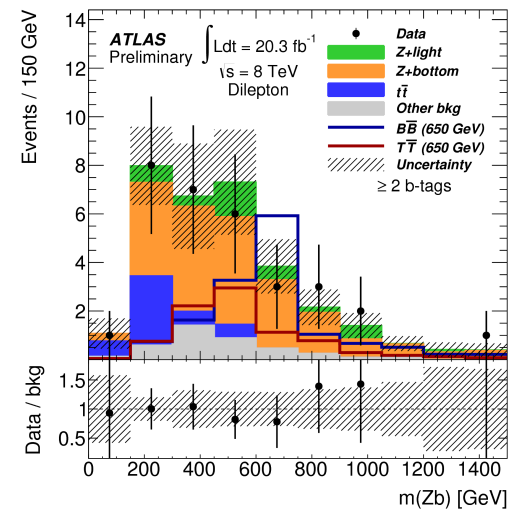
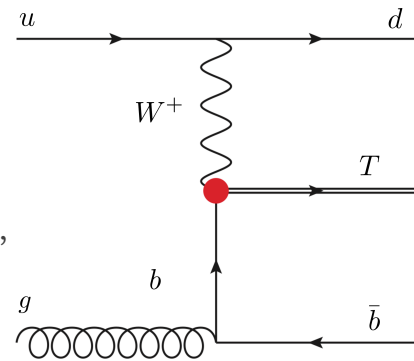
# T->Zt, B->Zb pair and single T production



ATLAS-CONF-2014-030

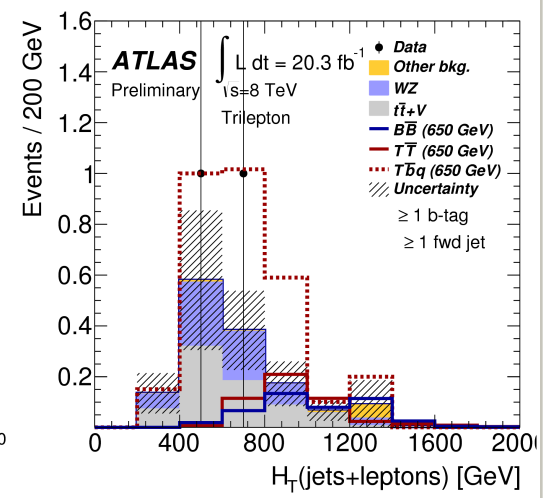
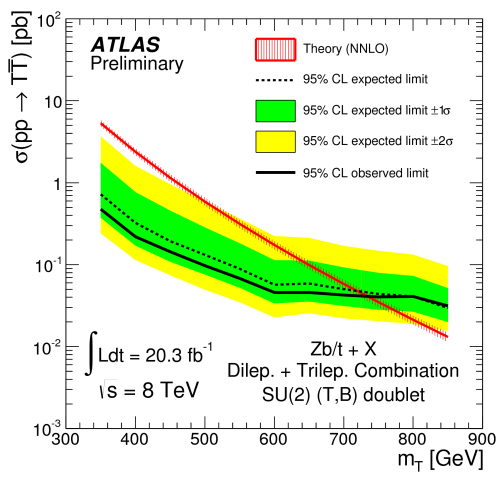
- **search in dilepton or trilepton final states using full 8TeV dataset**

- **two or three lepton final state**, at least 2jets, invariant mass of **OS pair around Z mass**,  $p_T(Z) > 150 \text{ GeV}$ , one or two b-tagged jet
- looser selection for electrons from Z
- **dilepton** using  **$m(Zb)$  distribution**, 2 b-tagged jets - pair production :  $H_T > 600 \text{ GeV}$ , single production: at least one forward jet
- **trilepton** using  **$H_T$  distribution**, at least 1 b-tag jet, single production: at least one forward jet



- **Combined mass limits @95%CL**

- $m(\text{B singlet}) > 685 \text{ GeV}$  (670 GeV)
- $m(\text{B doublet}) > 755 \text{ GeV}$  (755 GeV) (B, Y)
- $m(\text{T singlet}) > 655 \text{ GeV}$  (625 GeV)
- $m(\text{T doublet}) > 735 \text{ GeV}$  (720 GeV) (T, B)
- for single production  $\lambda_T < 1.5$





# T → Wb pair production



ATLAS-CONF-2013-000

- **search in lepton+jets final state using  $14.3 \text{ fb}^{-1}$  of 8 TeV data**

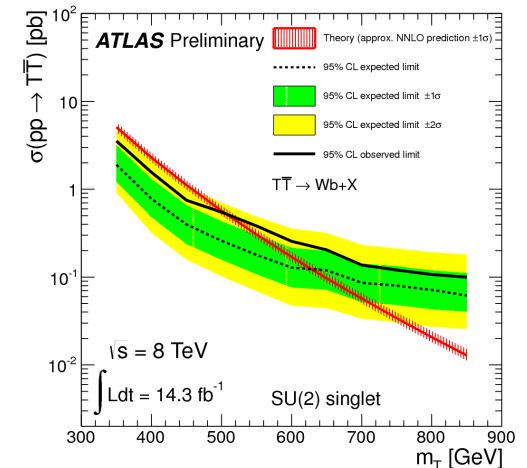
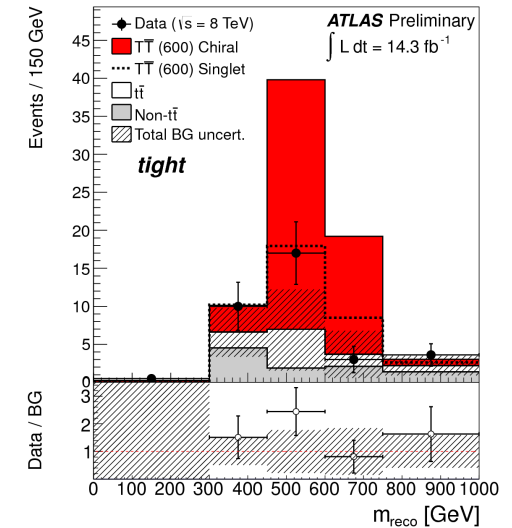
- single lepton selection, at least 4 jets, at least 1-btag (70% WP), large  $E_T^{\text{Miss}}$
- reject events with six or more jets, three or more tagged jets, remove overlap with  $TT \rightarrow Ht+X$ ,  $H \rightarrow bb$

- **Reconstruction of the T candidate mass**

- identify b-quarks by highest b-tagging weight,  $p_T > 160, 80 \text{ GeV}$
- hadronic W: **one jet**,  $p_T > 250 \text{ GeV}$ , mass  $60-120 \text{ GeV}$  or **two jets**, dijet  $p_T > 200 \text{ GeV}$  and  $\Delta R < 0.8$ , mass  $60-120 \text{ GeV}$
- $H_T > 800 \text{ GeV}$ ,  $\Delta R(l, \nu) < 1.2$ ,  $\min \Delta R(l, b) > 1.4$ ,  $\min \Delta R(W, b) > 1.4$
- $m_{\text{reco}}$  from combination with smallest difference between hadronic T and leptonic T

- **Limits on chiral and VLQ**

- $m(\text{chiral } T, Y \rightarrow Wb) > 740(770) \text{ GeV}$ ,  
 $m(\text{VLQ } T \text{ singlet}) > 505(630) \text{ GeV}$



# T → Ht pair production



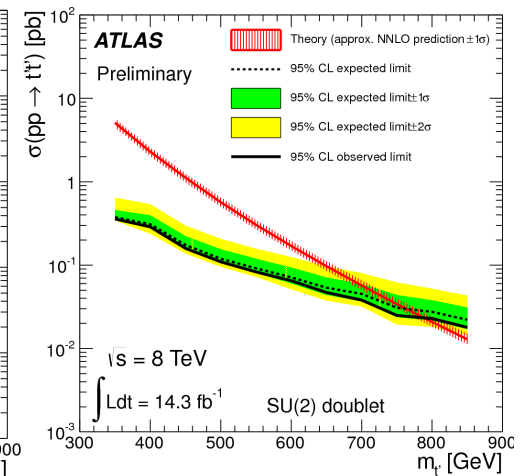
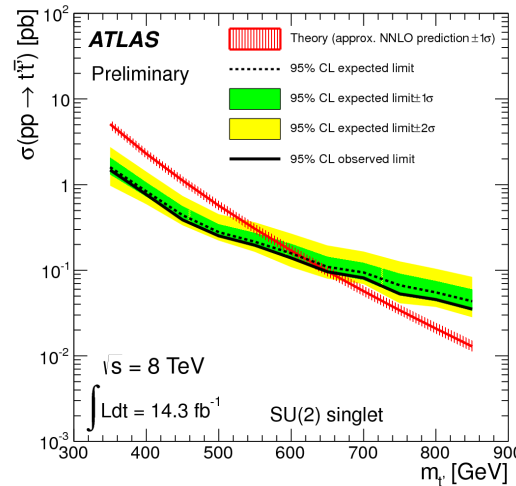
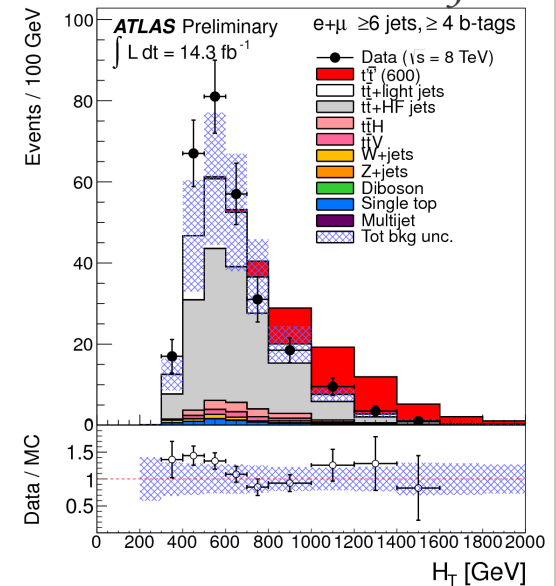
ATLAS-CONF-2013-016

- search at high jet and high b-tag multiplicity (H → bb) using 14.3 fb<sup>-1</sup> of 8 TeV data

- at least 6 jets, at least 2 b-tags
- split analysis in 2,3,4 b-tags, for 2-tag events: H<sub>T</sub> < 700 GeV

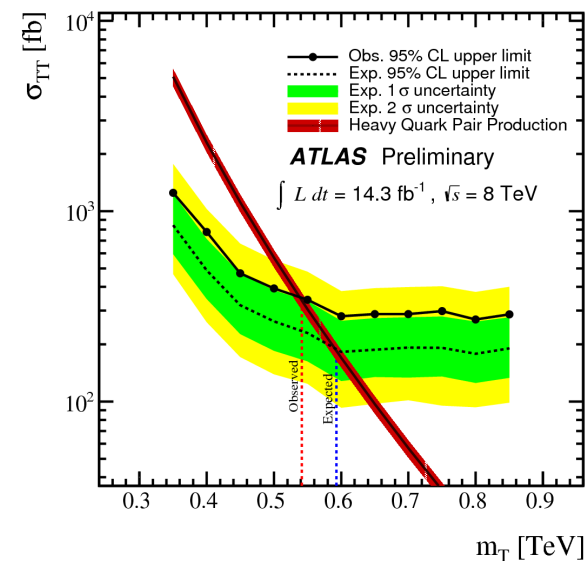
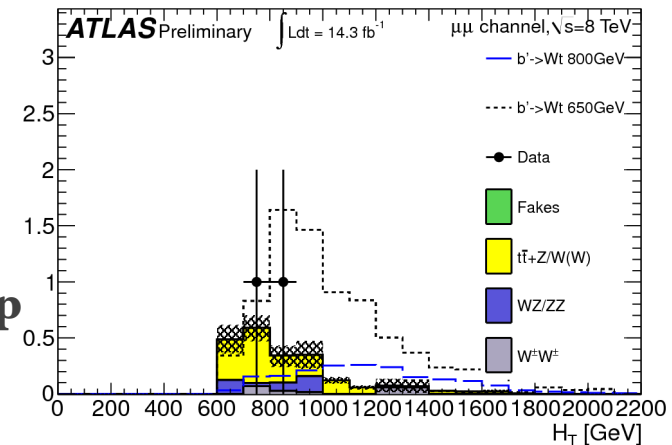
- Limit setting on H<sub>T</sub> simultaneously in all channels

- m(T<sub>singlet</sub>) > 640 (615) GeV
- m(T<sub>doublet</sub>) > 790 (745) GeV

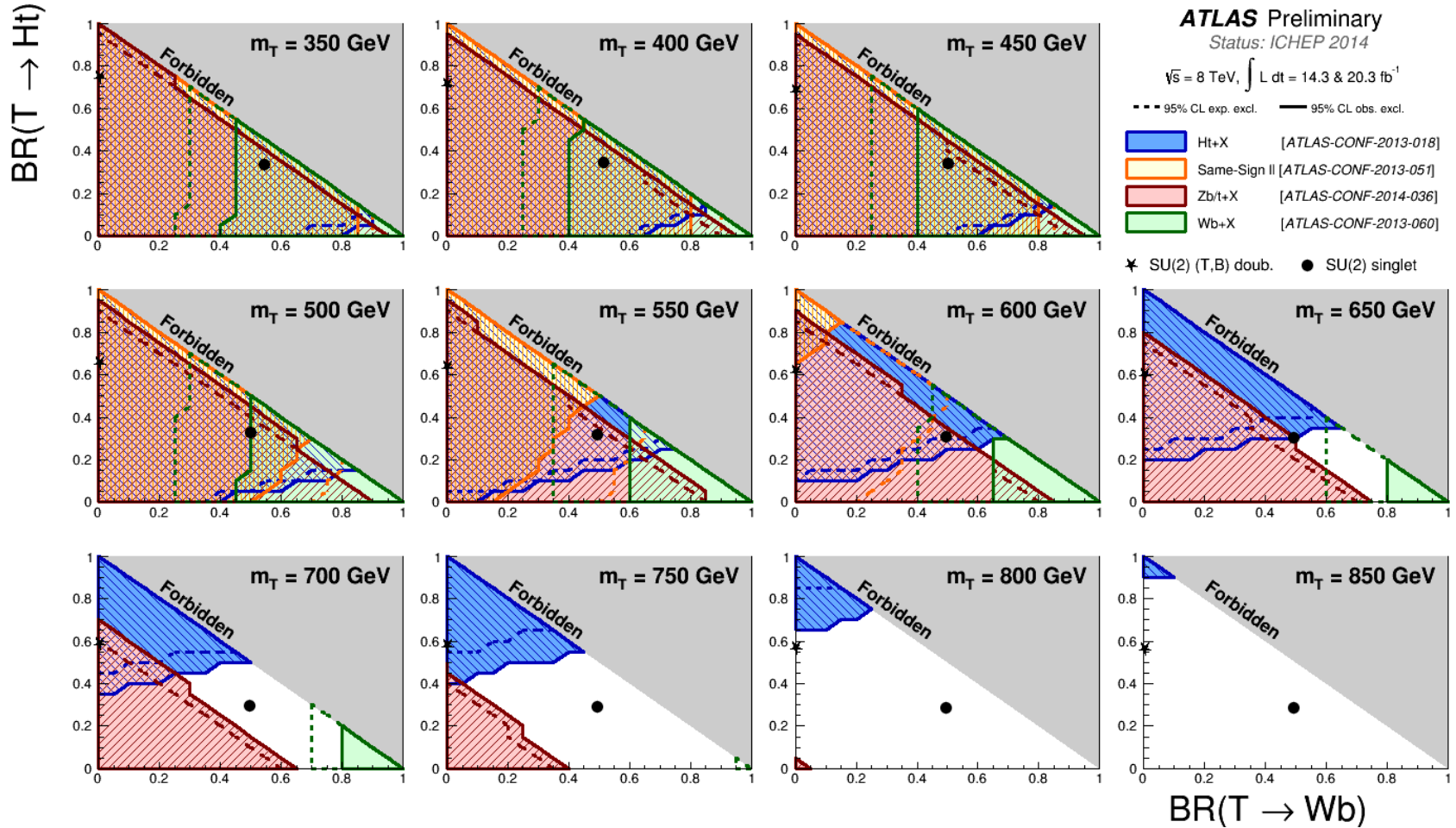


# same-sign dilepton with b-jets

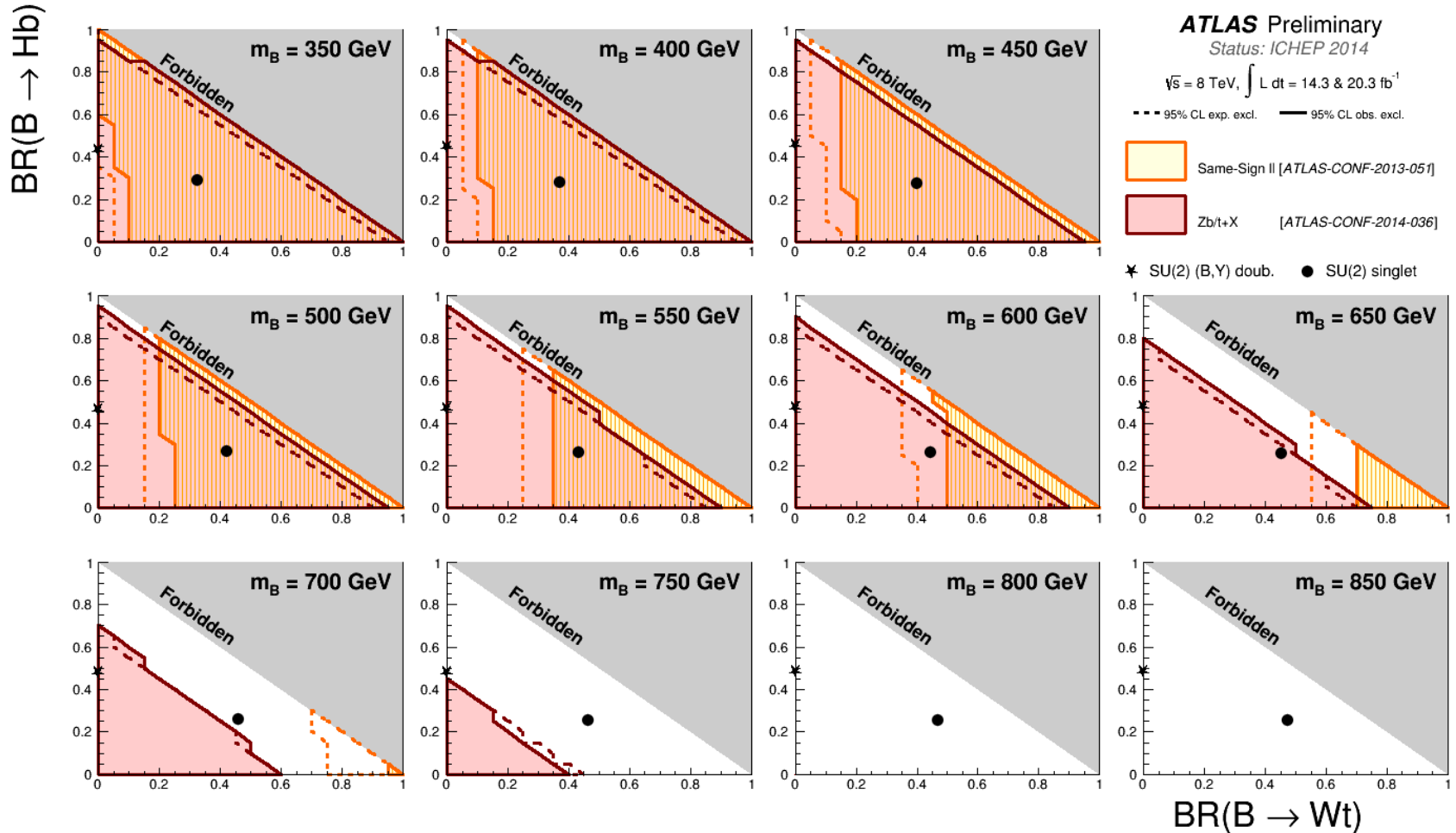
- **selection in  $14.3\text{fb}^{-1}$  8 TeV data has small SM contribution**
  - one SS lepton pair, at least one b-tag
- **cut-and-count analysis**, interpretation for **chiral  $b' \rightarrow Wt$ , VLQ T/B, non-resonant four-top** (sgluon pair, KK excitation in 2UED/RPP model), **SS top** ( $uu \rightarrow tt$  via heavy particle)
  - $m_{ll} > 15\text{GeV}$ , outside of Z,  $HT > 550$
  - $HT > 650$  for  $b'$ , VLQ (singlet) —  $m(b') > 720\text{GeV}$ ,  $m(B) > 590\text{GeV}$ ,  $m(T) > 540\text{GeV}$
  - $HT > 650$ , more than two b-jets, 4 tops —  $\sigma(4\text{tops}) < 85\text{fb}$ ,  $m(\text{sgluon}) > 800\text{GeV}$ ,  $m(\text{KK}) > 900\text{GeV}$ , limits on contact interaction coupling strength versus scale
  - lepton positive charge, SS top —  $\sigma(\text{SS top}) < 0.2\text{fb}$



# Combination VLQ T



# Combination VLQ B

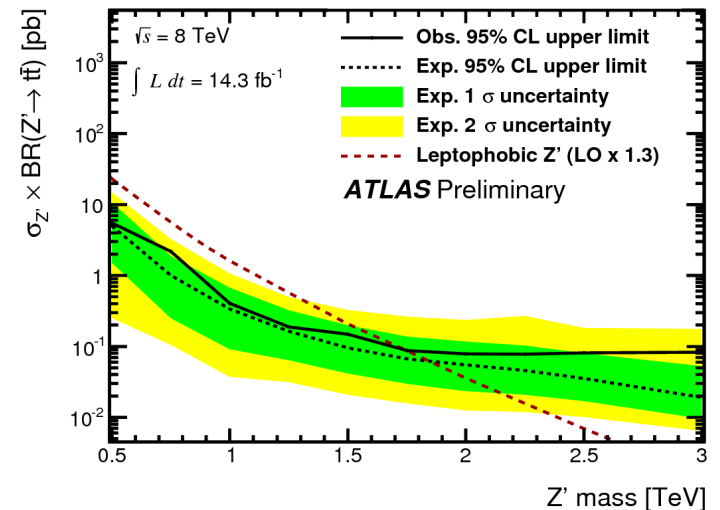
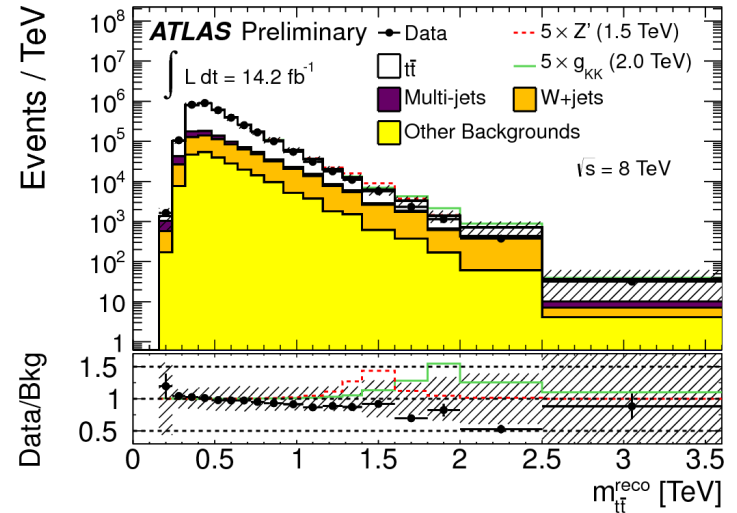


# ttbar resonances



ATLAS-CONF-2013-05

- search in  $14.3\text{fb}^{-1}$  of 8 TeV data with resolved and boosted channels using single lepton selection
  - **boosted:** large  $R(=1.0)$  anti- $k_t$  jets include trimming (small subjets  $R=0.3$  (inclusive  $k_t$  jets) with small  $p_T$  fraction 0.05 removed)
  - $p_T > 300$ ,  $|\eta| < 2.0$ ,  $m_{\text{jet}} > 100\text{GeV}$ , splitting scale  $\sqrt{\langle dR \rangle} > 40\text{GeV}$
  - at least one *small R* jet,  $\Delta R(j,l) < 1.5$ , one b-tag
  - $\Delta R(\text{large R jet, small R jet}) > 1.5$ ,  
 $\Delta R(\text{large R jet, lepton}) > 2.3$
  - **resolved:** at least four jets *small R* jets or three *small R* with at least one  $m_{\text{jet}} > 60\text{GeV}$
- kinematic reconstruction with  $\chi^2$  minimisation
- setting limits using invariant mass distribution for different models
  - topcolor, leptophobic  $Z'$ ,  $m(Z') > 1.8\text{TeV}$
  - Kaluza-Klein (KK) gluons in Randall-Sundrum models with an extra dimension with a warped geometry  $m(g_{\text{KK}}) > 2.1\text{TeV}$



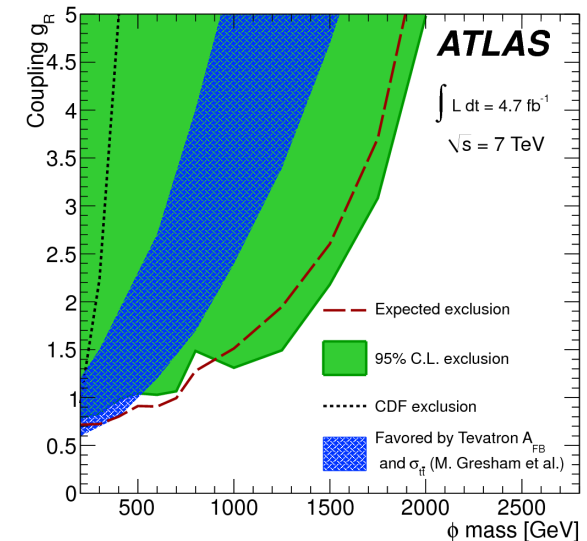
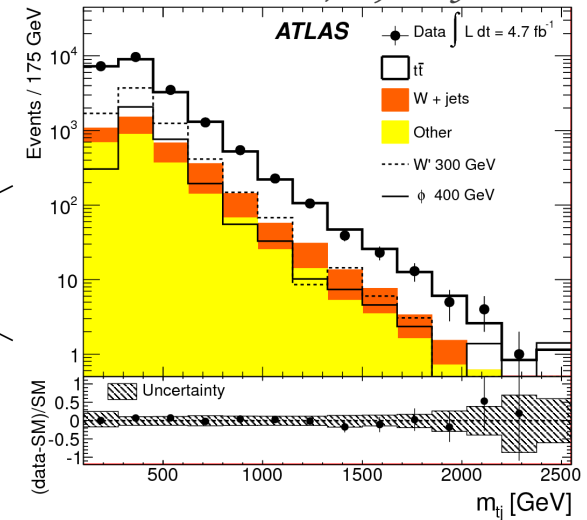
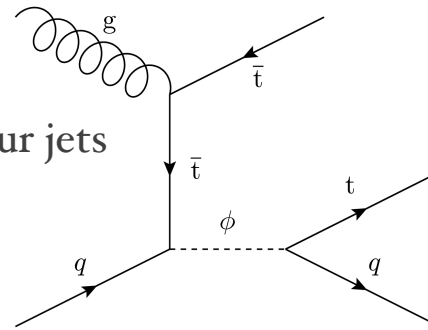




# resonant top plus jets production

PRD 86, 091103 (2012)

- **search using full 7 TeV dataset**
  - single lepton selection, at least four jets
- **top flavour violating process, new particle  $W'$  or  $\phi$  produced in association**
  - proposed as origin from  $A_{FB}$  of top production at Tevatron
  - colour singlet  $W' \rightarrow t\bar{t} + q$ , colour triplet  $\phi \rightarrow t + q$
  - not self conjugate, only right handed coupling  $g_R$
- **kinematic fit to assign reconstructed objects**
  - largest  $m(t+j)$  and  $m(t\bar{t}+j)$  are used
- **Limits @95%CL on  $W'$ ,  $\phi$  mass and coupling  $g_R$** 
  - $m(W') > 430$  (500) GeV,  $m(\phi) > 430$  (700) GeV, region for masses and couplings favoured by Tevatron excluded

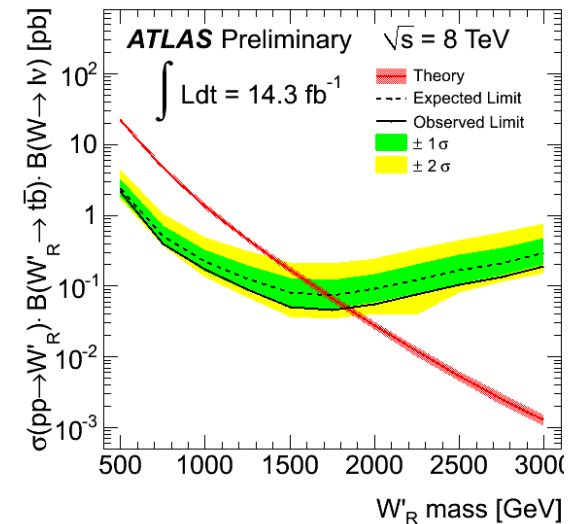
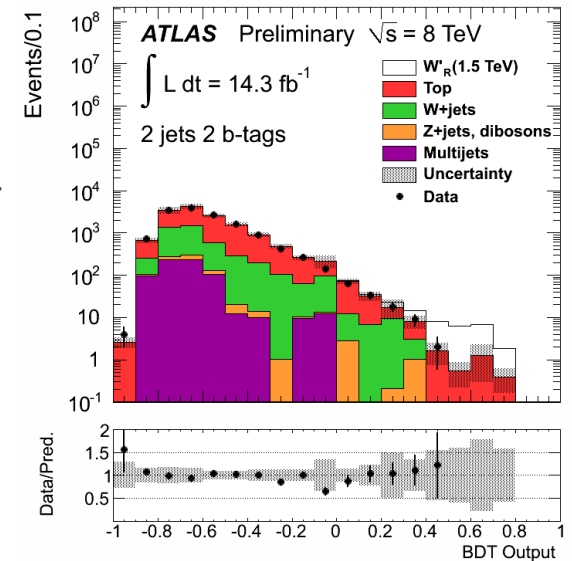


# W' → tb + lepton search



ATLAS-CONF-2013-050

- **search for W' using effective model for W' coupling to fermions using 14.3 fb<sup>-1</sup> of 8 TeV data**
  - motivated by leptophobic models, e.g. leptonic decay of right-handed W' kinematically forbidden, if  $m(\nu_{RH}) > W'$
  - leptonic decay mode: lepton+2 or 3 jets, exactly two b-tagged jets
- **BDT from 14 (13) kinematic variables in 2 (3) jet events**
  - kinematic reconstruction of the system, with other kinematic variables input to BDT
  - invariant mass cut  $m(tb) > 270 \text{ GeV}$
- **Limit setting for W'<sub>L</sub> and W'<sub>R</sub> @95% CL, also set limits on left/right handed coupling**
  - $m(W'_L) > 1.74(1.56) \text{ TeV}$  and  $m(W'_R) > 1.84(1.72) \text{ TeV}$



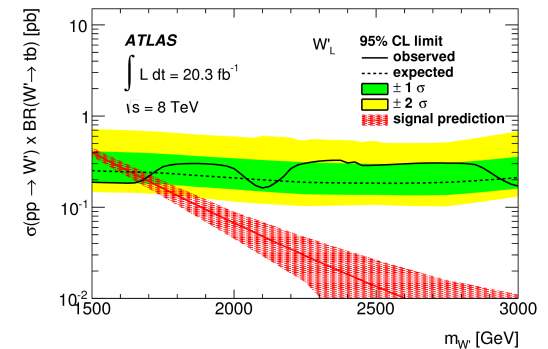
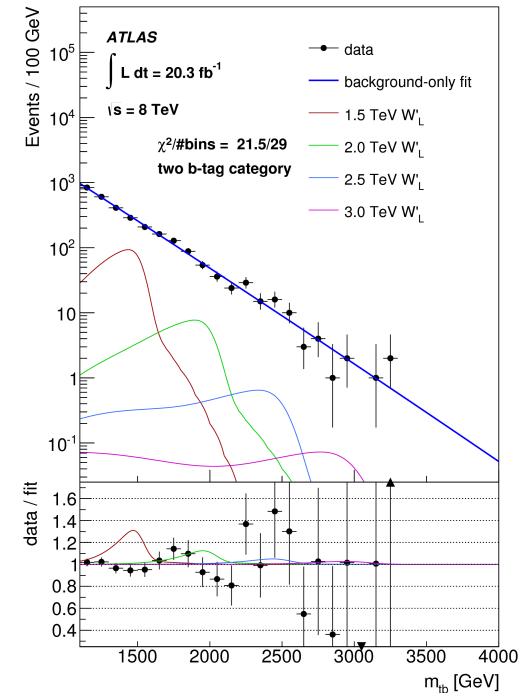


# W' → tb + had search



arxiv:1408.0886

- **search for W' using effective model for W' coupling to fermions using full 8 TeV dataset**
  - hadronic decay mode using boosted algorithms
  - *large R* jet with  $p_T > 350$ , one-to-two splitting scale  $\sqrt{d_{12}} > 40 \text{ GeV}$ , ratio of n-subjettiness  $\tau_{32} < 0.65$  and  $0.4 < \tau_{21} < 0.9$
  - one *large R* jet, at least one b-jet,  $p_T > 350 \text{ GeV}$ ,  $\Delta R > 2.0$ ,  $M_{\text{inv}} > 1.1 \text{ TeV}$
  - $H_T > 850 \text{ GeV}$ , 1+2-tagged ( $\Delta R(b, \text{top}) < 1.0$ )
  - reject events with leptons
- **Limits @95% CL set on  $m(W)$  and coupling from  $m_{tb}$  distribution after background fit**
  - Comparable limits  $m(W'_L) > 1.70 (1.64) \text{ TeV}$  and  $m(W'_R) > 1.76 (1.84) \text{ TeV}$

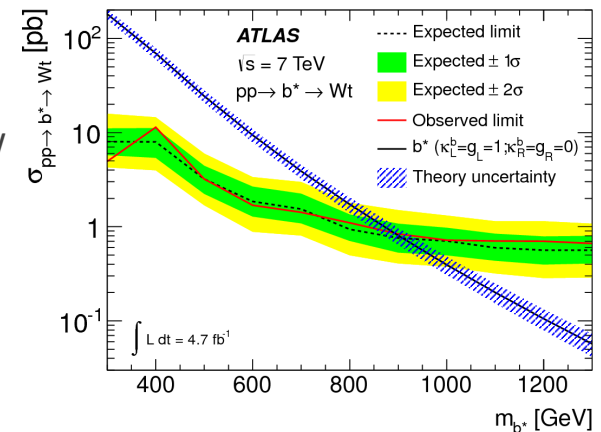
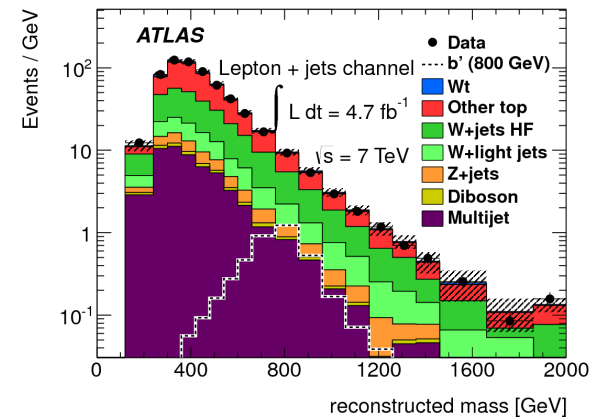
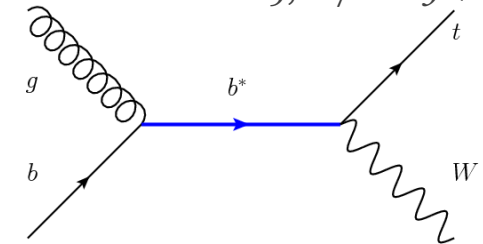


# Excited $b^* \rightarrow Wt$ search

PRD 85, 072003 (2012)



- **search for excited  $b^*$  using full 7 TeV dataset**
  - strong production of excited  $b^*$ , coupling to third generation quarks, decay weakly to  $Wt$
- **dilepton and single lepton selection**
  - dilepton selection, exactly one jet, no b-tag requirement
  - single lepton selection, exactly three jets, exactly one b-tag
  - sensitive distribution dilepton:  $H_T$ , single lepton: *reconstructed mass* of three jets, lepton and neutrino
- **Limits @95%CL on mass for maximally left- or/ and right-handed coupling and coupling itself**
  - $m(b^*_{LH}) > 870(910)\text{GeV}$ ,  $m(b^*_{LH}) > 920(950)\text{GeV}$ ,  
 $m(b^*_{LH/RH}) > 1030(1030)\text{GeV}$



# FCNC in top decay $t \rightarrow Zq$

JHEP 1209 (2012) 159



- **measurement of FCNC rate using  $2.1 \text{ fb}^{-1}$  of  $7 \text{ TeV}$  data**

- FCNC suppressed by GIM, but enhanced in BSM models

- **trilepton selection**

- *three leptons* (leptons or track-lepton (TL)), at least two jets, high  $E_T^{\text{Miss}}$

- lepton  $p_T > 25, 20, 20 \text{ GeV}$ , TL  $p_T > 25 \text{ GeV}$ , any OS lepton/TL pair with Z-mass

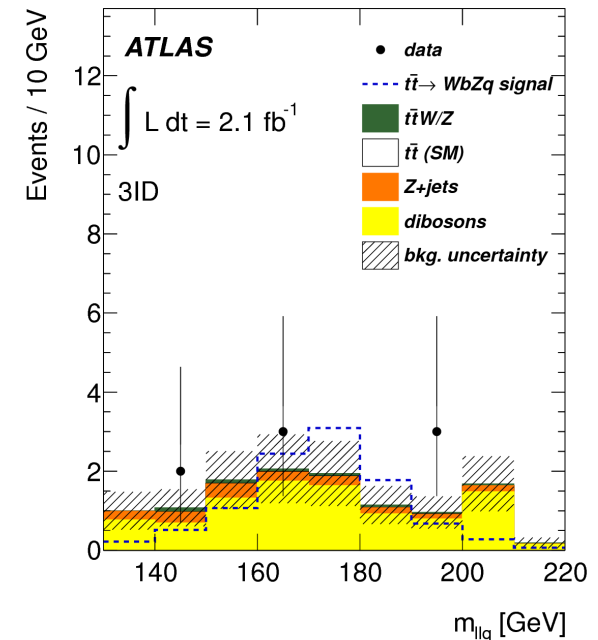
- *selection with TL*: one b-tag @ 80% WP

- **kinematic reconstruction with  $\chi^2$  fit and  $t\bar{t} \rightarrow WbZb$  hypothesis**

- constraints on  $t, W/Z$  mass during fit (40, 30, 15 GeV) and cut on fitted masses and fit quality

- **limit from the number of selected events on FCNC rate @ 95% CL**

- $\text{BR}(t \rightarrow Zq) < 0.73\%$

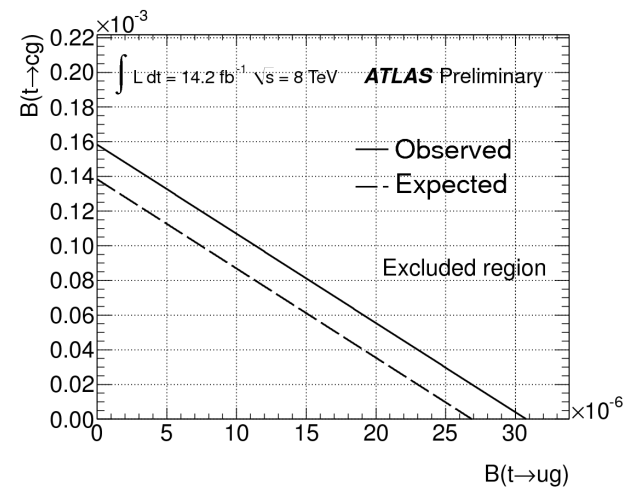
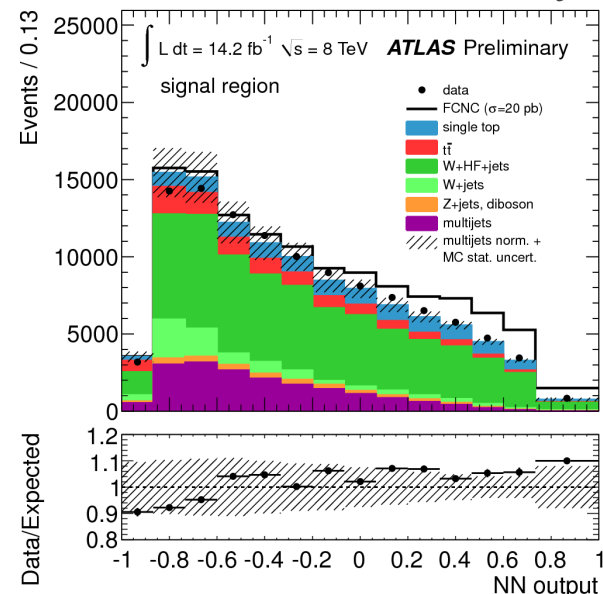




# FCNC in single top production

ATLAS-CONF-2013-065

- **search for FCNC in single top production using  $14.2\text{fb}^{-1}$  of  $7\text{TeV}$  data**
  - single top topology easier to distinguish from QCD in production than decay
- **single lepton selection**
  - exactly one lepton,  $E_T^{\text{Miss}}$  selection, exactly one b-tagged jet
- **fit to NN output using 13 kinematic variables**
  - FCNC signal softer top  $p_T$ , almost back-to-back of decay products, top vs anti-top production enhanced
- **Limits on coupling and  $\text{BR}(t \rightarrow cg)$ ,  $\text{BR}(t \rightarrow ug)$  set @95%CL**
  - $\text{BR}(t \rightarrow ug) < 3.1 \cdot 10^{-5}$  and  $\text{BR}(t \rightarrow cg) < 1.6 \cdot 10^{-4}$  (assuming the other  $\text{BR}=0$ )
  - $\kappa_{ugt}/\lambda < 5.1 \cdot 10^{-3} \text{TeV}^{-1}$ ,  $\kappa_{cgt}/\lambda < 1.1 \cdot 10^{-2} \text{TeV}^{-1}$



# Summary



- **BSM related top searches in ATLAS**

- Vector-like bottom and top quark searches, in singlet and doublet models
  - searches in different decay modes (H, W, Z), pair production and single production (single T), as a function of mass and BR, combination
- $t\bar{t}$  (resolved and boosted), top+jets,  $W' \rightarrow tb$ ,  $b^* \rightarrow Wt$  resonance searches
- FCNC in top decay  $t \rightarrow Zq$  and production  $qg \rightarrow t$

- **Many other analysis setting indirect limits on new physics**

- Measurements of SM properties of top quark or  $Wtb$  vertex, e.g.  $W$ -helicity measurements, anomalous coupling in single top production, top polarisation
- **So far no significant deviation from SM observed**

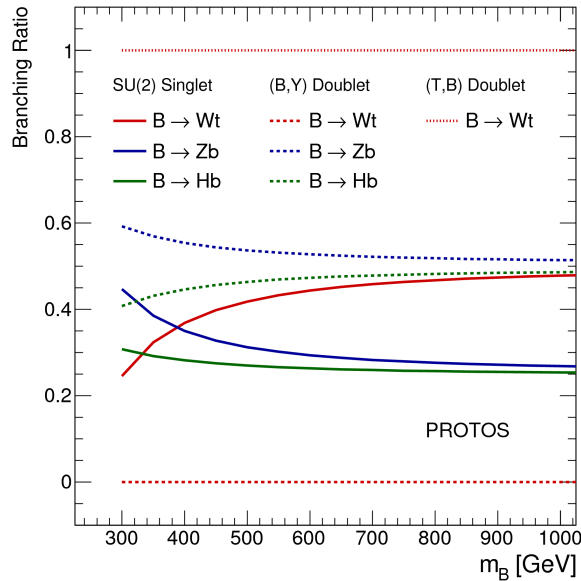
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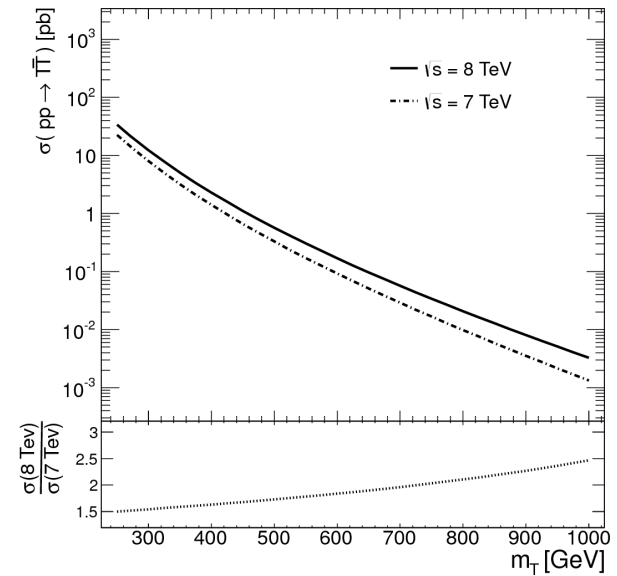
# Vector-like quarks



- BR B from Protos**

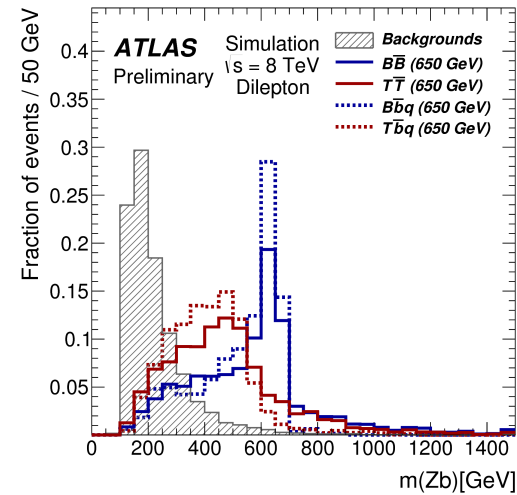
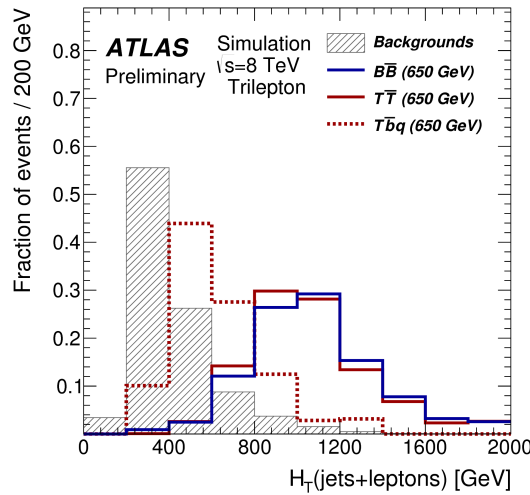
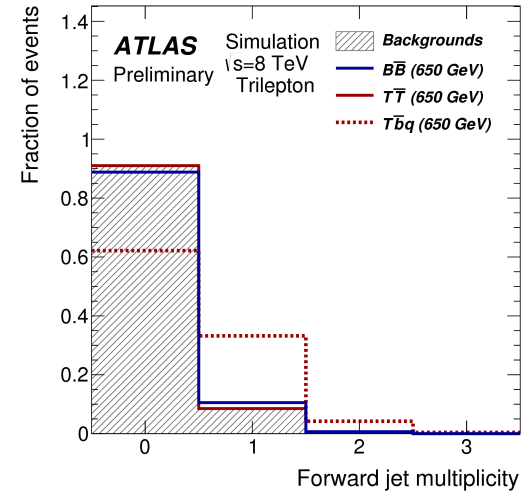
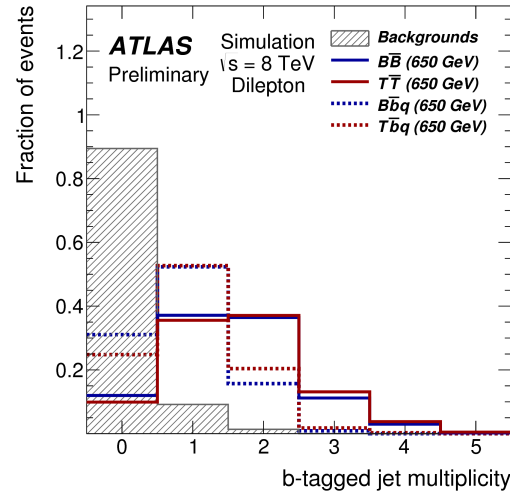
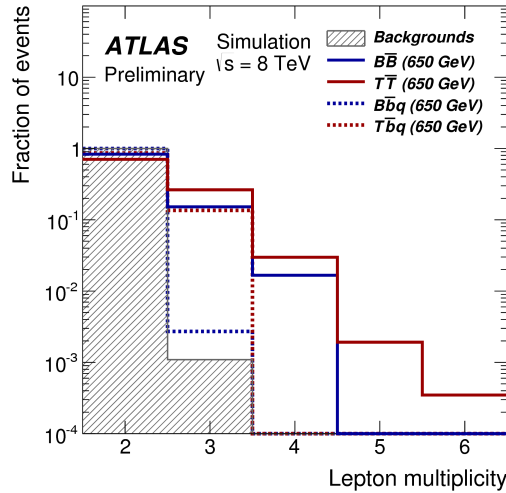


- Total cross section  $T\bar{T}$  from Hathor**





# T- $\rightarrow$ Zt, B- $\rightarrow$ Zb pair and single T production





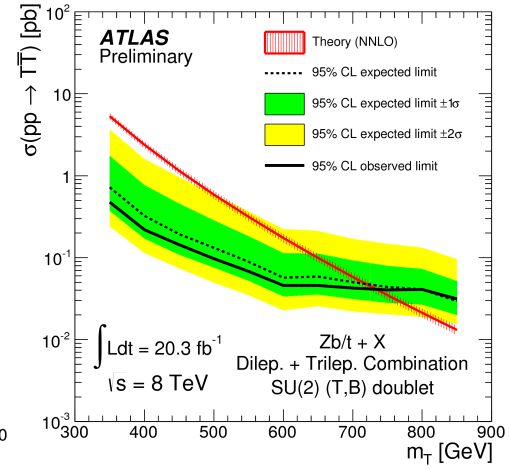
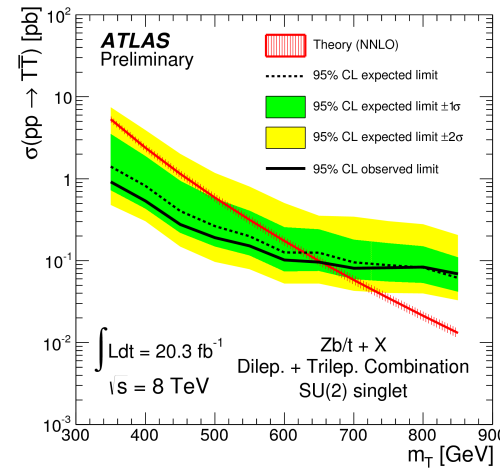
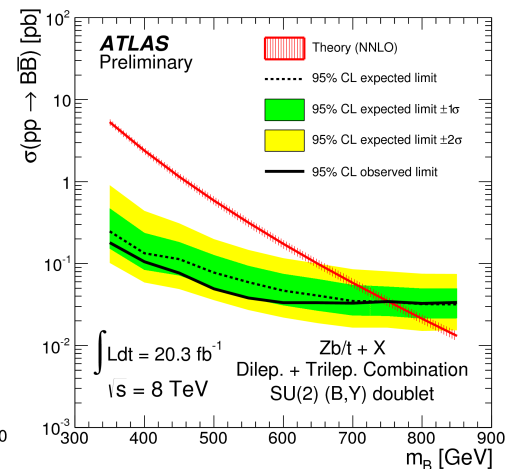
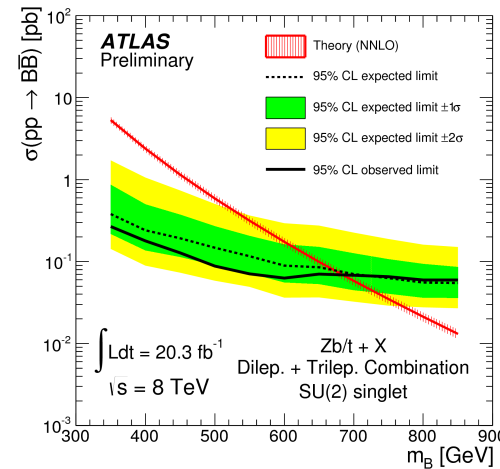


# T->Zt, B->Zb pair and single T production

ATLAS-CONF-2014-030

## • Combined mass limits @95%CL

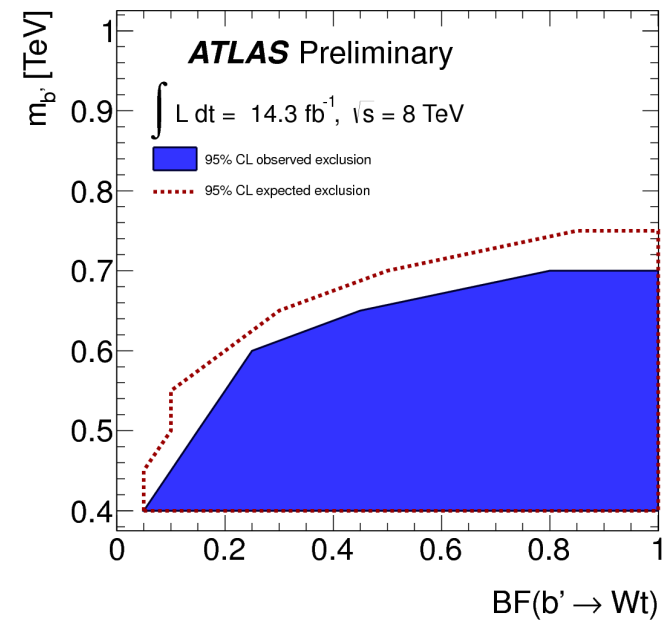
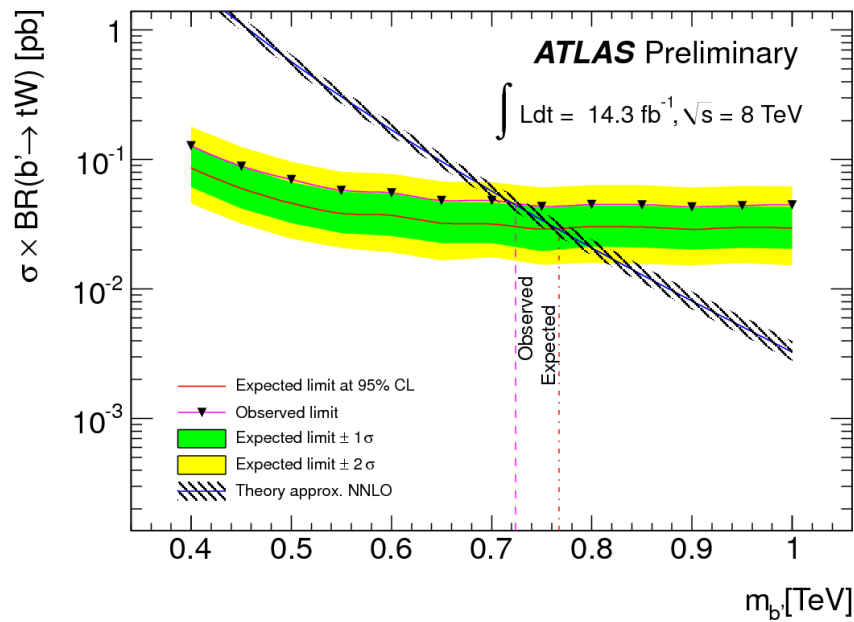
- $m(\text{B singlet}) > 685 \text{ GeV}$  (670 GeV)
- $m(\text{B doublet}) > 755 \text{ GeV}$  (755 GeV), (B, Y)
- $m(\text{T singlet}) > 655 \text{ GeV}$  (625 GeV)
- $m(\text{T doublet}) > 735 \text{ GeV}$  (720 GeV) (T, B)
- for single production  $\lambda_T < 1.5$



# Same-sign dilepton



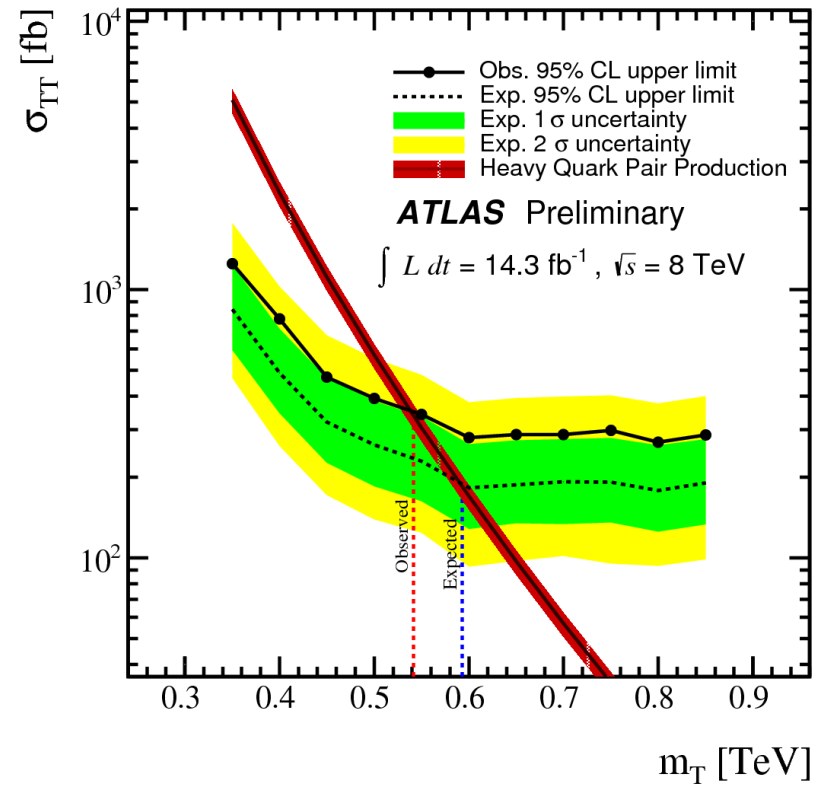
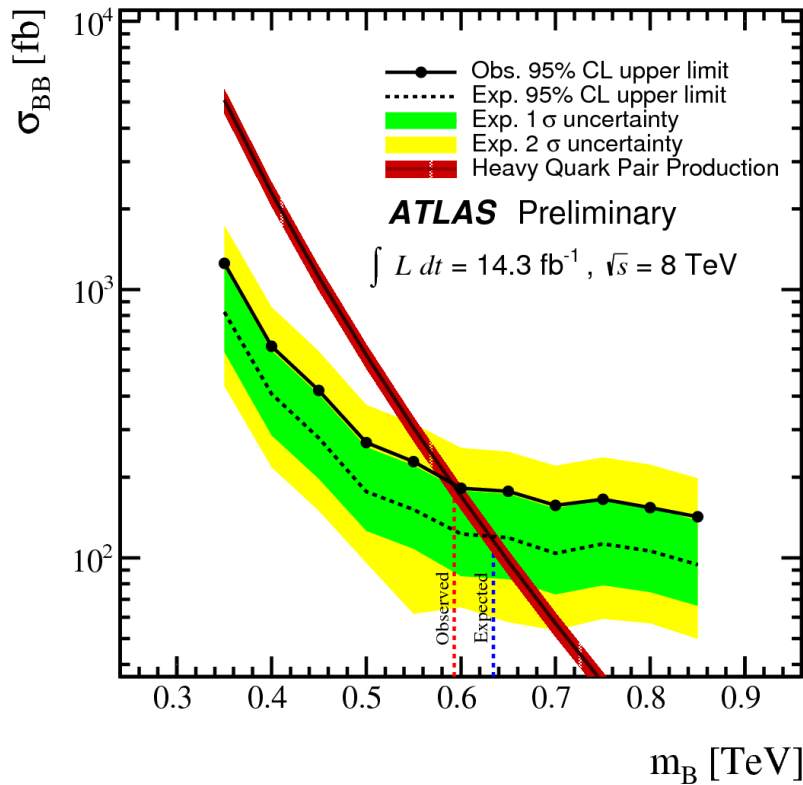
- chiral B limit



# Same-sign dilepton



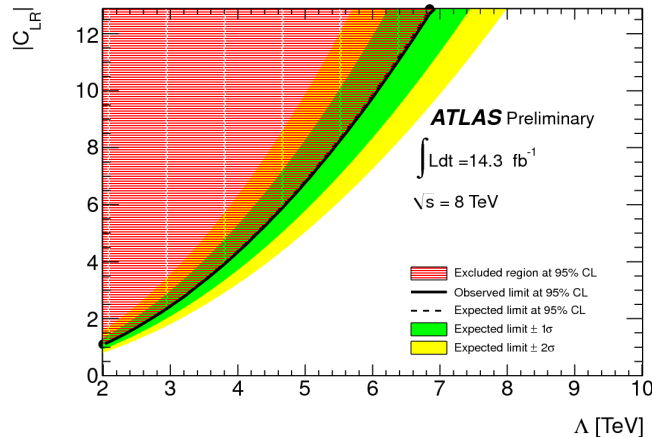
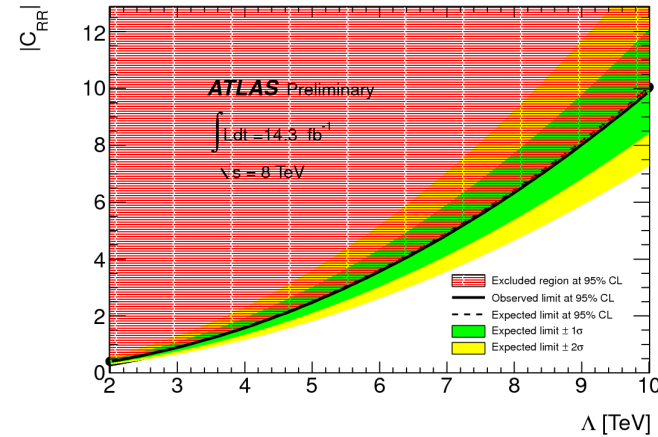
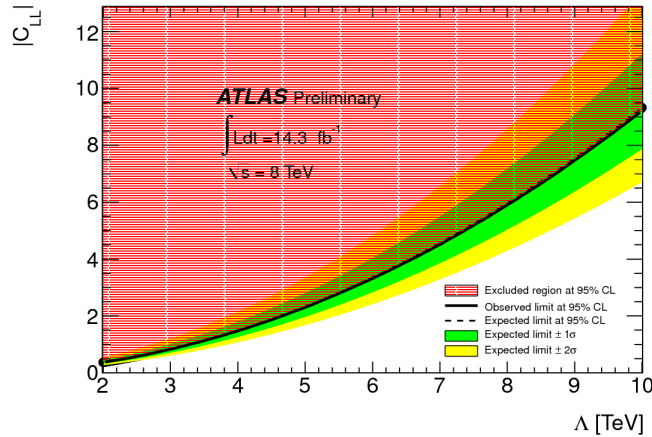
- VLQ limits



# Same-sign dilepton



- Limits on SS top-pair production



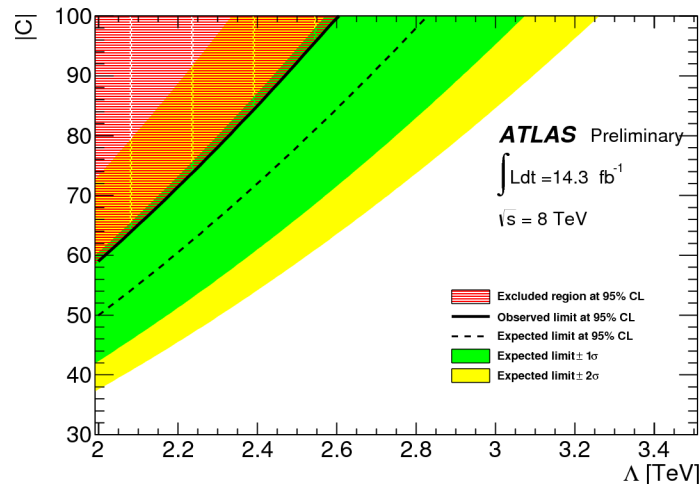
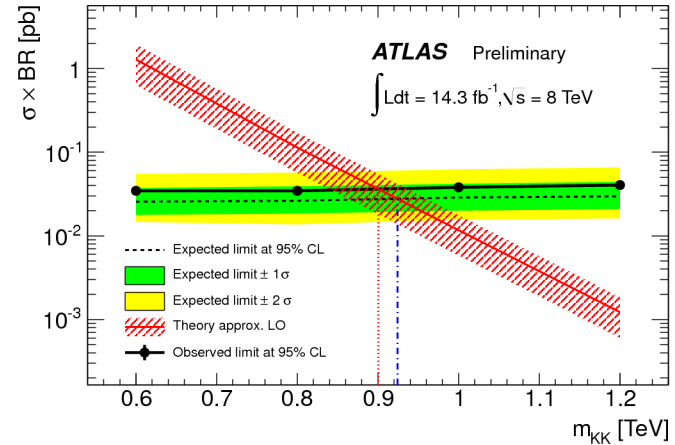
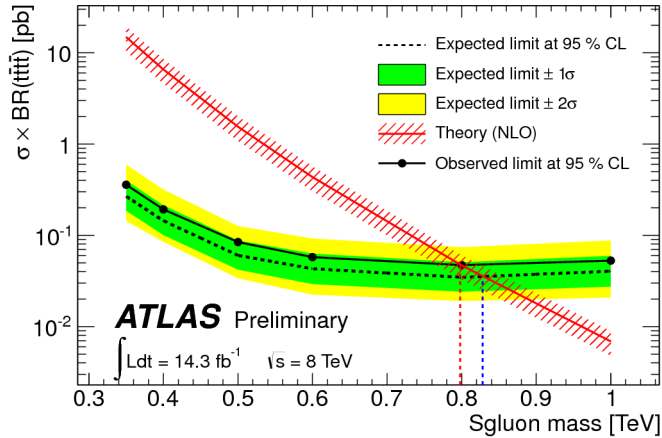
$$\mathcal{L}_{4F} = \frac{1}{2} \frac{C_{LL}}{\Lambda^2} (\bar{u}_L \gamma^\mu t_L)(\bar{u}_L \gamma_\mu t_L) + \frac{1}{2} \frac{C_{RR}}{\Lambda^2} (\bar{u}_R \gamma^\mu t_R)(\bar{u}_R \gamma_\mu t_R) - \frac{1}{2} \frac{C_{LR}}{\Lambda^2} (\bar{u}_L \gamma^\mu t_L)(\bar{u}_R \gamma_\mu t_R) - \frac{1}{2} \frac{C'_{LR}}{\Lambda^2} (\bar{u}_{La} \gamma^\mu t_{Lb})(\bar{u}_{Rb} \gamma_\mu t_{Ra}) + \text{h.c.}$$

# Same-sign dilepton



- Effective four-top coupling

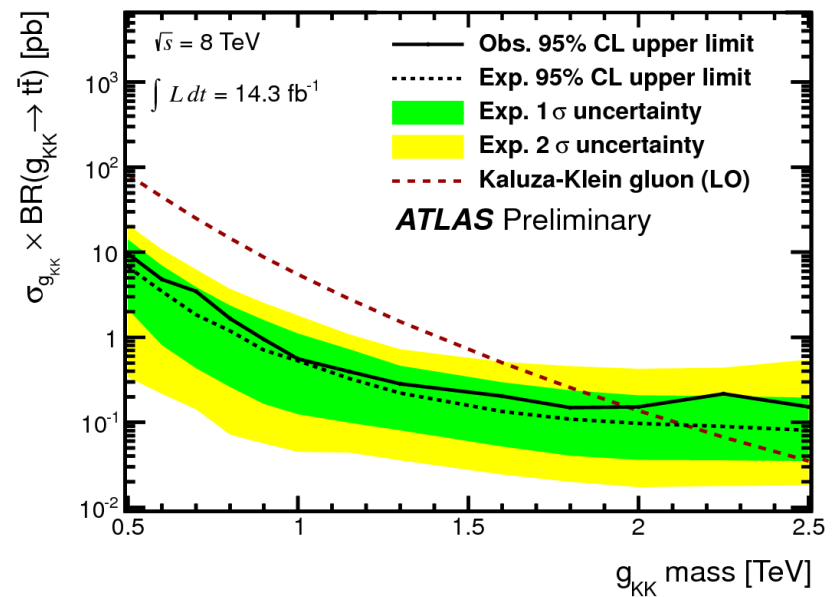
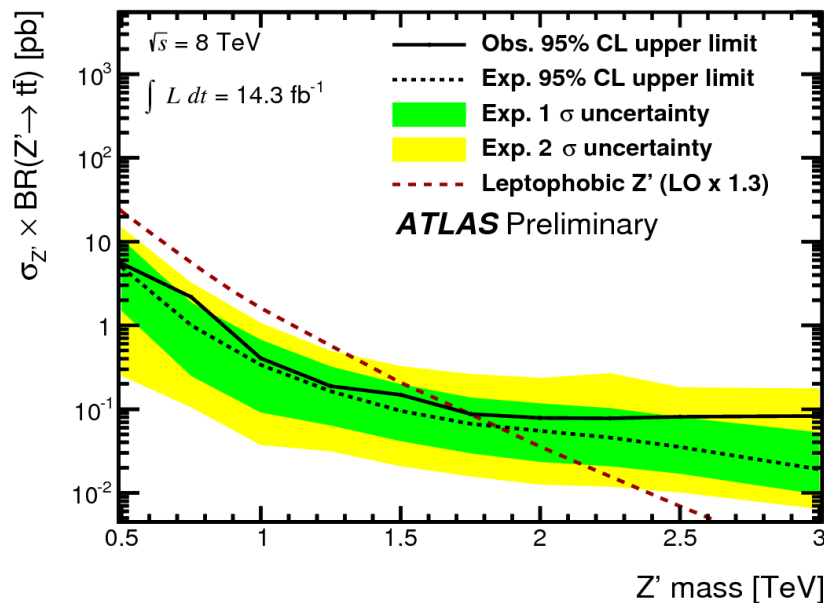
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C}{\Lambda^2} (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma_\mu t_R)$$



# ttbar resonances

- **setting limits on models**

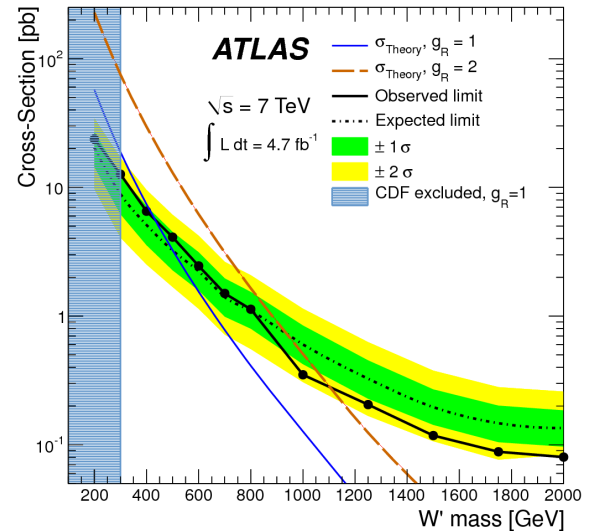
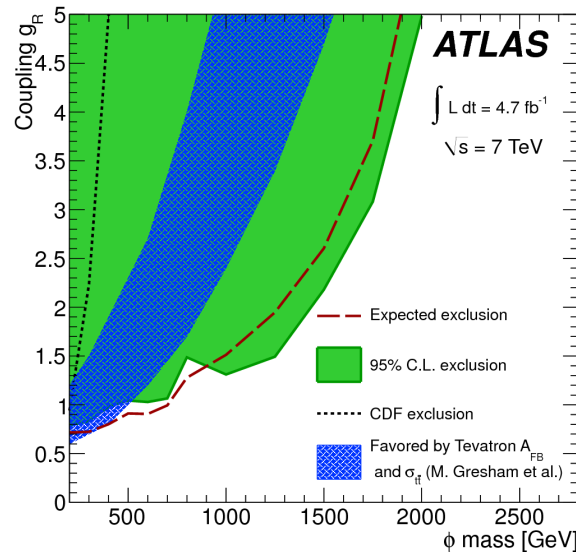
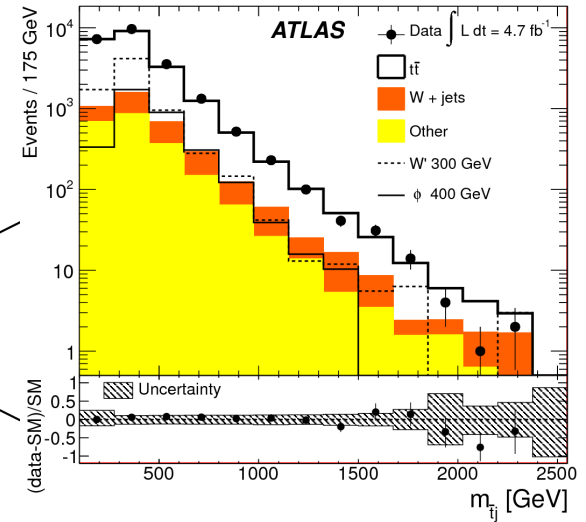
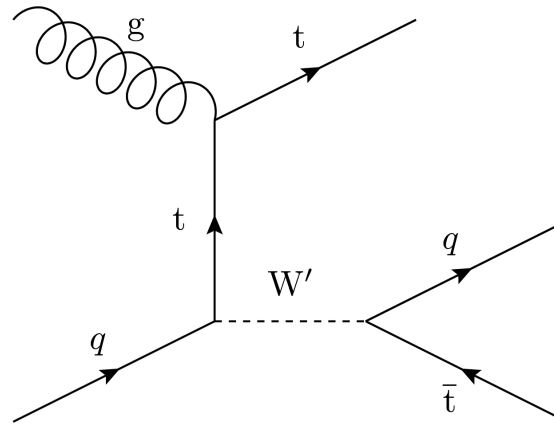
- topcolor, leptophobic  $Z'$
- Kaluza-Klein (KK) gluons in Randall-Sundrum models with an extra dimension with a warped geometry



# resonant $t\bar{t} + \text{jets}$



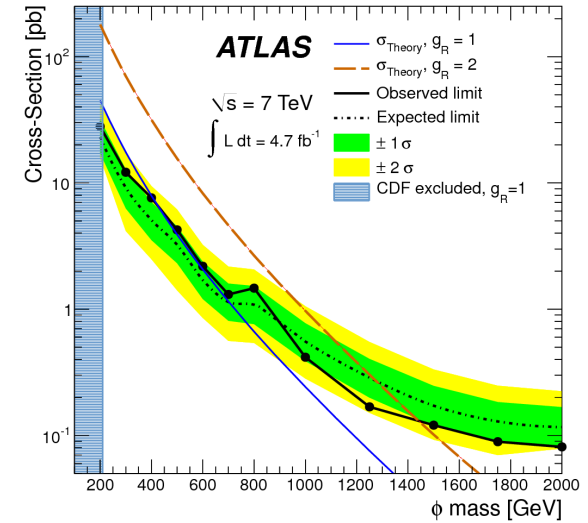
- $W' \rightarrow t\bar{t} + \text{jets}$



# resonant $t\bar{t} + \text{jets}$

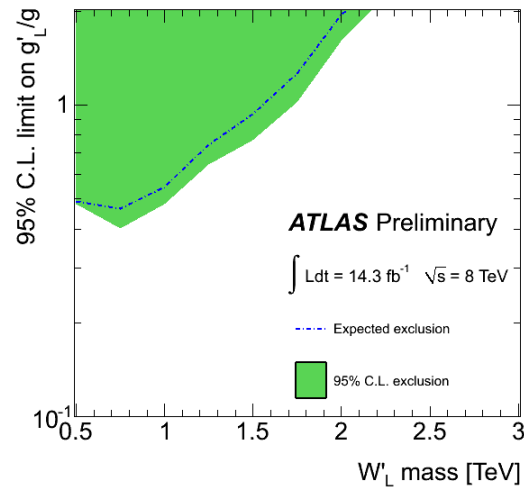
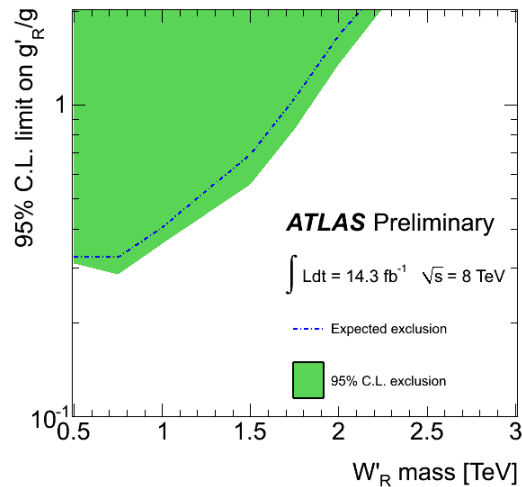
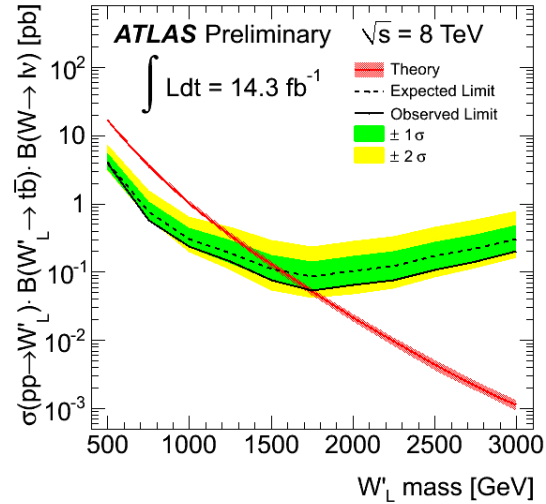
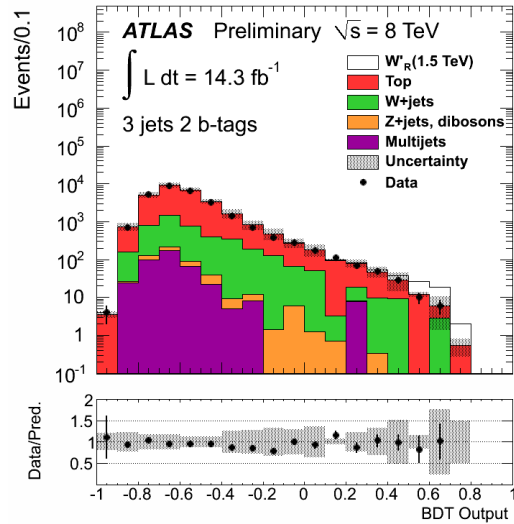


- mass limits on  $\phi$

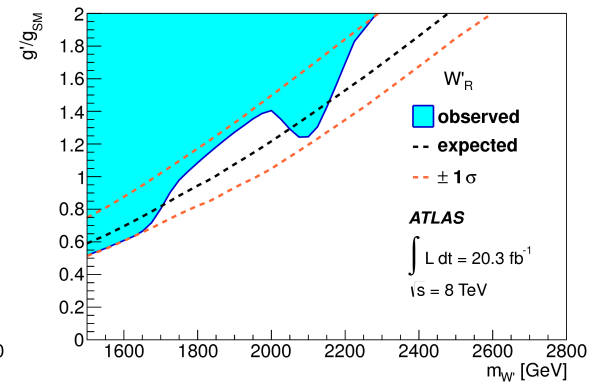
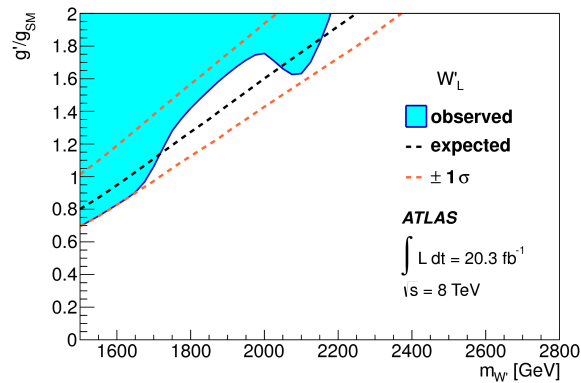
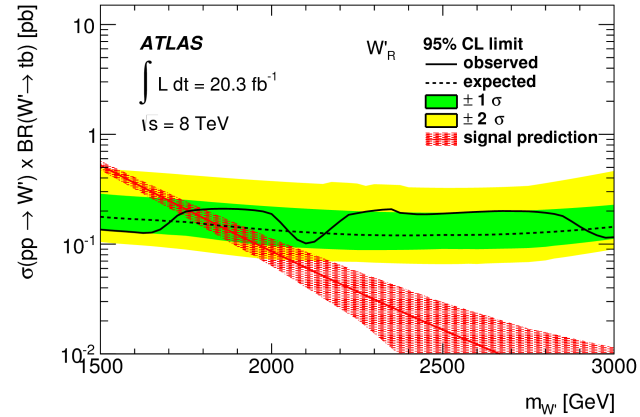
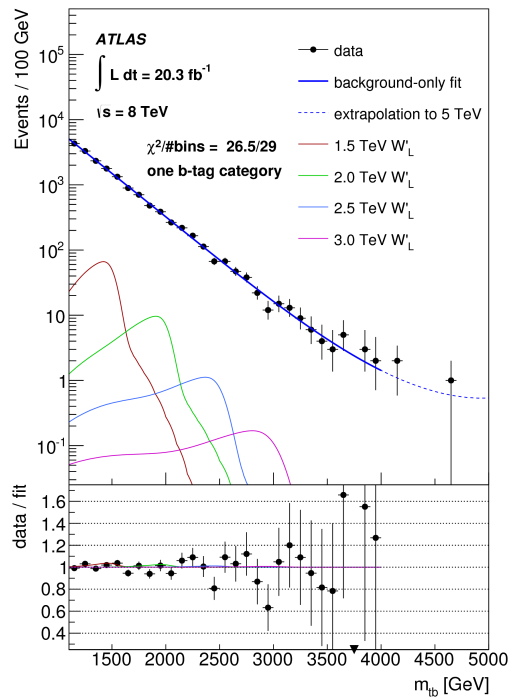




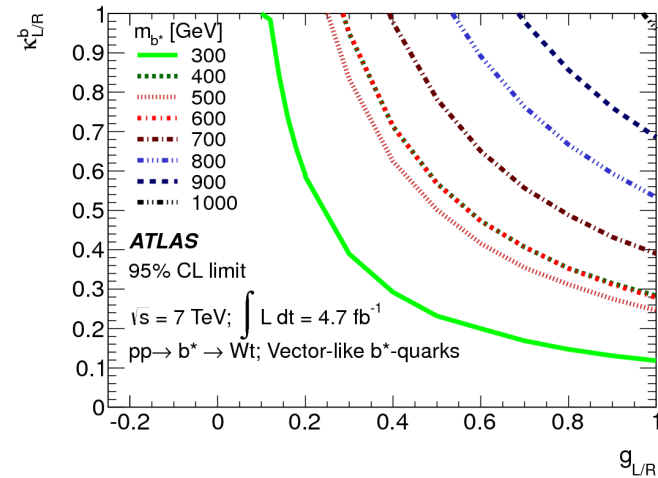
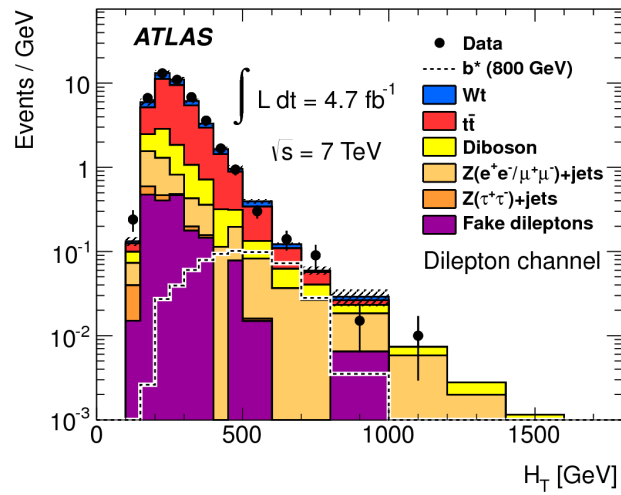
# W' -> tb leptonic search



# W' → tb hadronic search



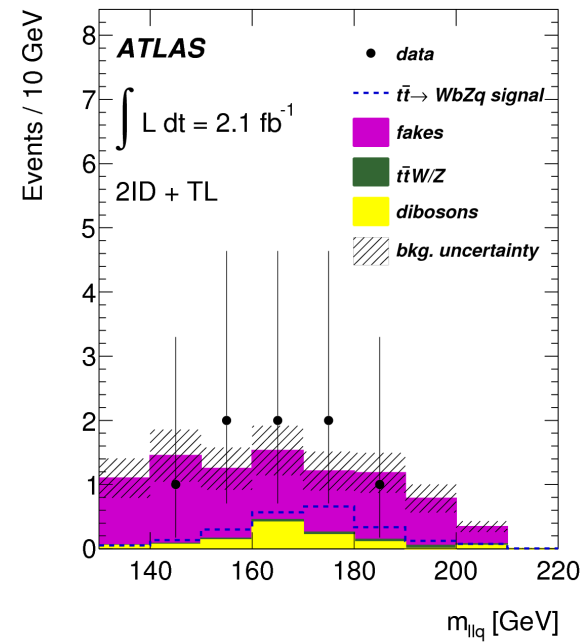
# Excited $b^*$ search



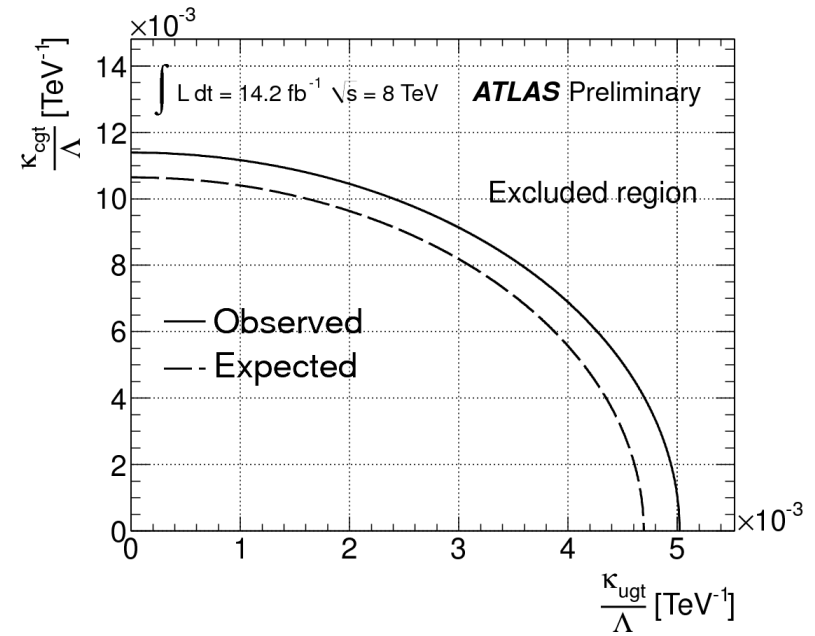
# FCNC $t \rightarrow Zq$



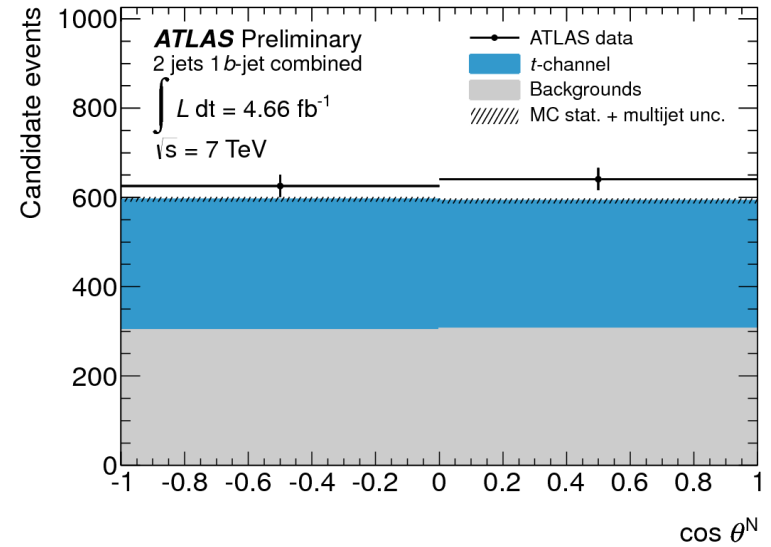
- **Track-lepton selection**



# FCNC in single top production



# Anomalous coupling in $Wtb$ vertex



# Anomalous coupling in $Wtb$ vertex



ATLAS-CONF-2013-032

- search for CP violation in  $Wtb$  vertex using effective Lagrangian with possibly CP violating phase  $\text{Im}(g_R)$

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}$$

- Measuring the FB asymmetry  $A_{\text{FB}}^N$  in  $\cos\theta_N$  in q-N-T coordinate system (q=W direction in helicity basis, N orthogonal to q/polarisation plane)
- single top t-channel selection, leptonic decay mode
  - jet  $p_T > 25$  GeV, forward jet  $p_T > 35$ , one b-tag, kinematic reconstruction of top from lepton/MET/b-jet,  $150 \text{ GeV} < m(\text{top}) < 190 \text{ GeV}$
  - jet  $|\eta| > 2$ ,  $H_T > 210$
- Unfold  $\cos\theta_N$  to parton level
  - $A_{\text{FB}}^N \sim 0.64 \text{P Im}(g_R)$ , agreement with SM within uncertainty

