Study of FCNC in top quark production and decay with the ATLAS detector

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on behalf of the ATLAS collaboration

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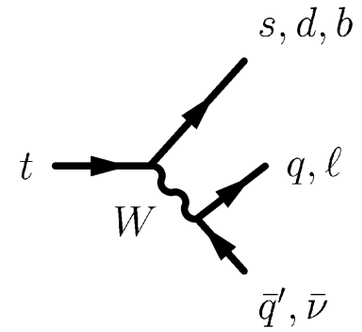
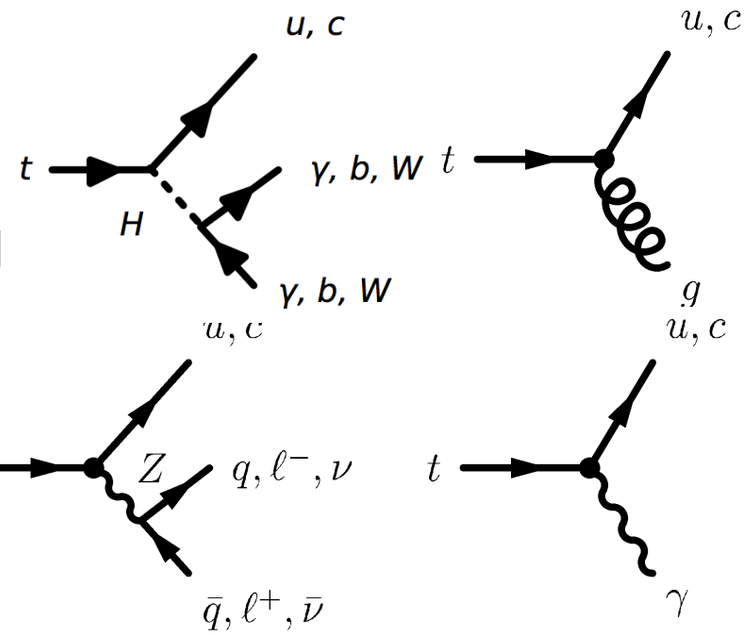
Introduction

- Top decays
  - Charged current decays:
    BR(t→bW) ~ 100%
    BR(t→sW) ~ 0.2%
    BR(t→dW) ~ 0.01%



  - FCNC decays:
    - Forbidden at tree level in the SM
    - Heavily suppressed at higher corrections.
    - BSM can enhance FCNC production.



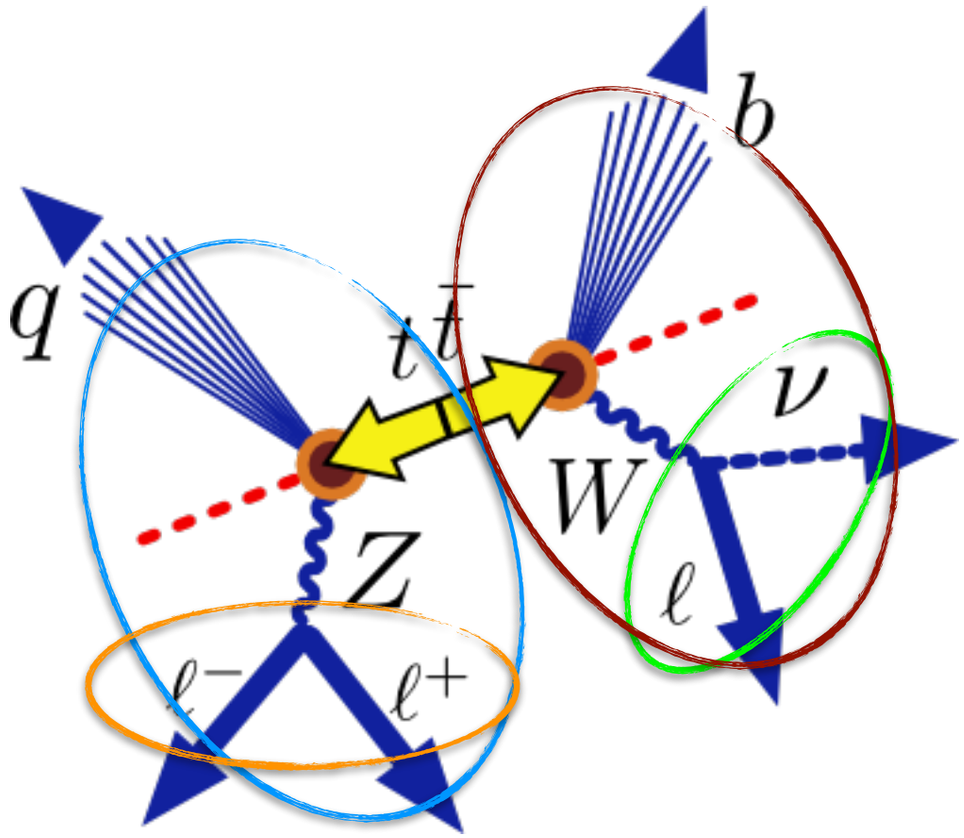
Process	SM	QS	2HDM	FC-2HDM	MSSM	*RPV* SUSY	TC2	RS
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	—	$\sim 10^{-11}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$	$3 \cdot 10^{-5}$	—	$\sim 10^{-9}$
$t \to ug$	$3.7 \cdot 10^{-14}$	$1.5 \cdot 10^{-7}$	—	—	$8 \cdot 10^{-5}$	$2 \cdot 10^{-4}$	—	$\sim 10^{-11}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}	$\sim 10^{-6}$	—	—
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$\sim 10^{-6}$	$\sim 10^{-9}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$	$3 \cdot 10^{-5}$	$\sim 10^{-4}$	$\sim 10^{-5}$
$t \to cg$	$4.6 \cdot 10^{-12}$	$1.5 \cdot 10^{-7}$	$\sim 10^{-4}$	$\sim 10^{-8}$	$8 \cdot 10^{-5}$	$2 \cdot 10^{-4}$	$\sim 10^{-4}$	$\sim 10^{-9}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$	—	—

Acta Phys. Polon. B35 (2004) 2695–2710; Phys. Rev. D68 (2003) 015002; Phys. Rev. D 75 (2007) 015002

Search for FCNC decays in t→Zq [JHEP09 (2012) 139]

- Search for top quark pair production with an FCNC (Zq) and a SM decay.
  $\sqrt{s} = 7\ \mathrm{TeV}, \mathcal{L} = 2.1\ \mathrm{fb}^{-1}$

- Event selection:
  - 3 ID or 2 ID + 1 track lepton (TL).
    ID → track and calorimeter information used in reconstruction.
    TL → only track information used.
  - ≥ 2 jets (≥1 b-jet in 2ID+1TL events).
  - MET > 20 GeV
  - $|m_{\ell\ell} - m_Z| < 15$ GeV



$$\chi^2 = \frac{\left(m^{reco}_{j_a l_a l_b} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{j_b l_c \nu} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{l_c \nu} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m^{reco}_{l_a l_b} - m_Z\right)^2}{\sigma_Z^2}$$

$$m_t = 172.5\ \mathrm{GeV}, m_W = 80.4\ \mathrm{GeV}, m_Z = 91.2\ \mathrm{GeV}$$
$$\sigma_t = 15\ \mathrm{GeV}, \sigma_W = 10\ \mathrm{GeV}, \sigma_Z = 3\ \mathrm{GeV}$$

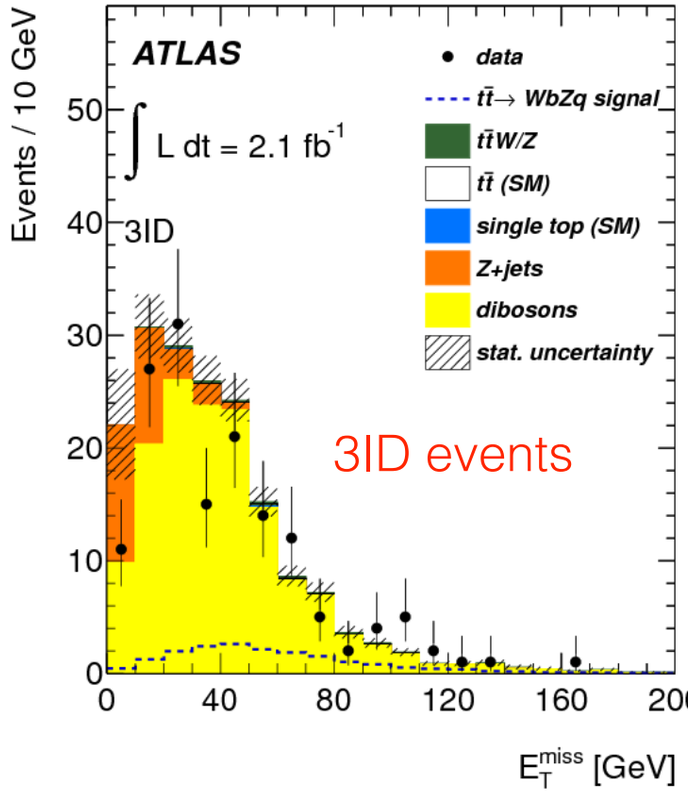
- Reconstruction of top anti-top system through a χ^2 minimisation.

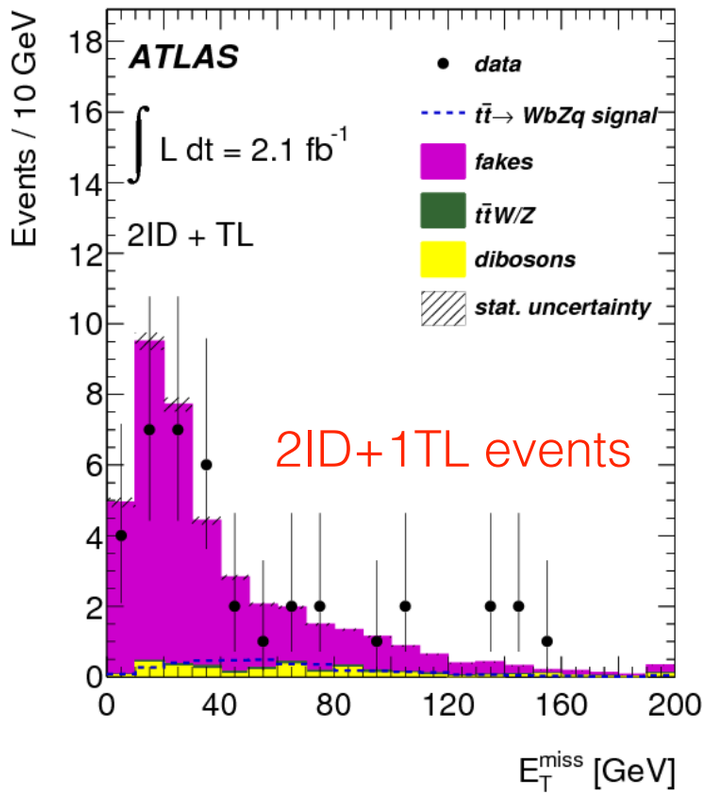
Search for FCNC decays in t→Zq [JHEP09 (2012) 139]

- Backgrounds:
  - **3 real leptons:**
    Diboson (ZZ, WZ) MC samples.
  - **2 real + 1 fake (3ID events):**
    Evaluated with data-driven method.
    Control region: Z mass peak in MET bins.
  - **Bad jet reconstruction:**
    DD method predicted no contribution.
  - **Fake track lepton (2ID+1TL events):**
    Derived using γ+jets sample.

- Systematics:
  - **3ID events:**
    ZZ and WZ modelling, JES, electron reconstruction, $\sigma(t\bar{t})$.
  - **2ID+1TL events:**
    ZZ and WZ modelling,$\sigma(t\bar{t})$, ISR/FSR.

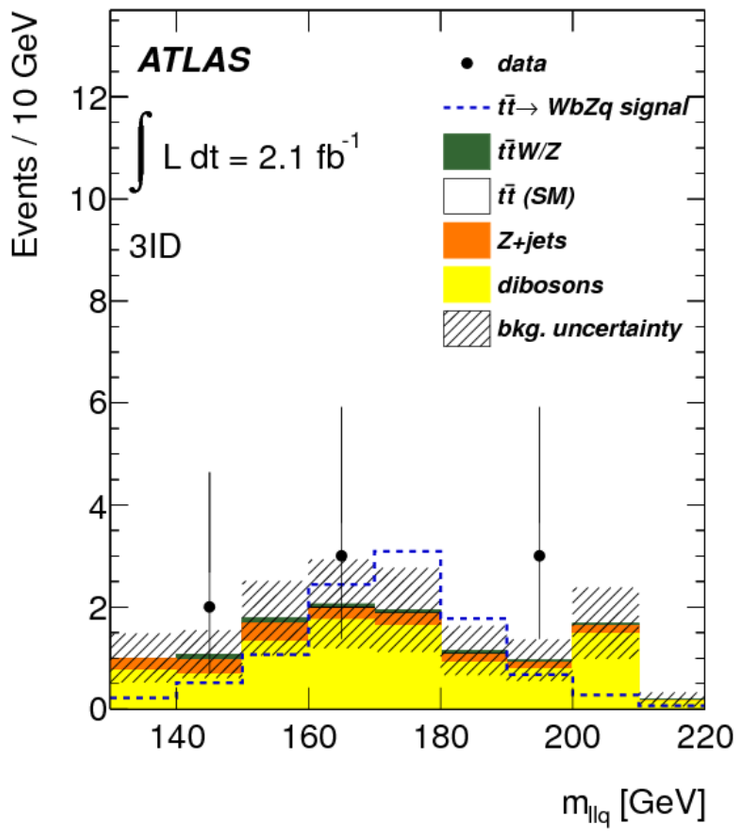
	3ID	2ID+TL
ZZ and WZ	9.5 ± 4.4	$1.0 \pm {}^{0.5}_{0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}$, WW	0.07 ± 0.02	
Z+jets	1.7 ± 0.7	7.6 ± 2.2
Single top	0.01 ± 0.01	
2+3 fake leptons	$0.0 \pm {}^{0.2}_{0.0}$	
Expected background	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency	$(0.205 \pm 0.024)\%$	$(0.045 \pm 0.007)\%$

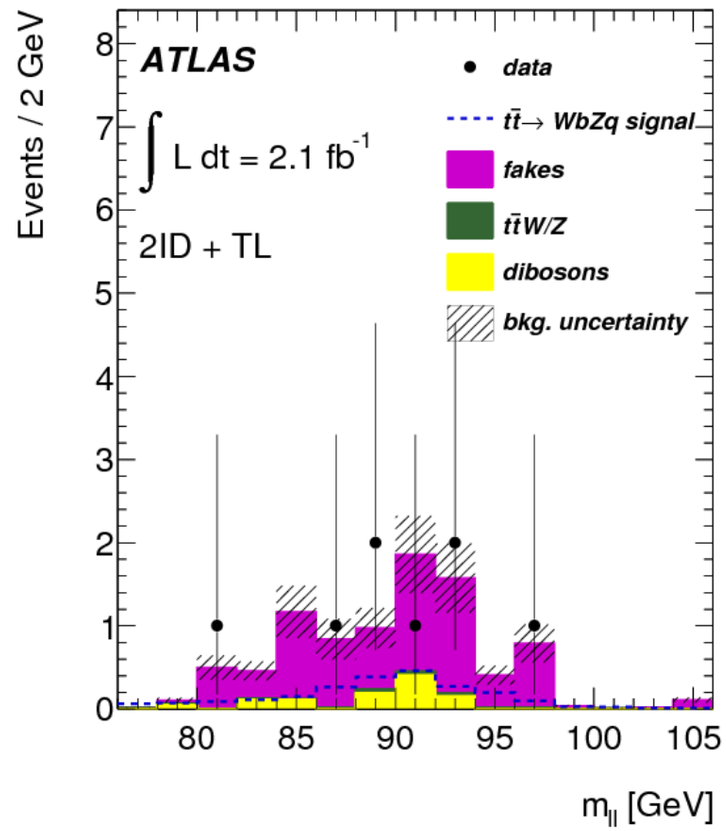




Search for FCNC decays in t→Zq [JHEP09 (2012) 139]

- No evidence of FCNC decays is found.
- CL_S method used to set upper limit on FCNC branching ratios with a cut and count experiment.



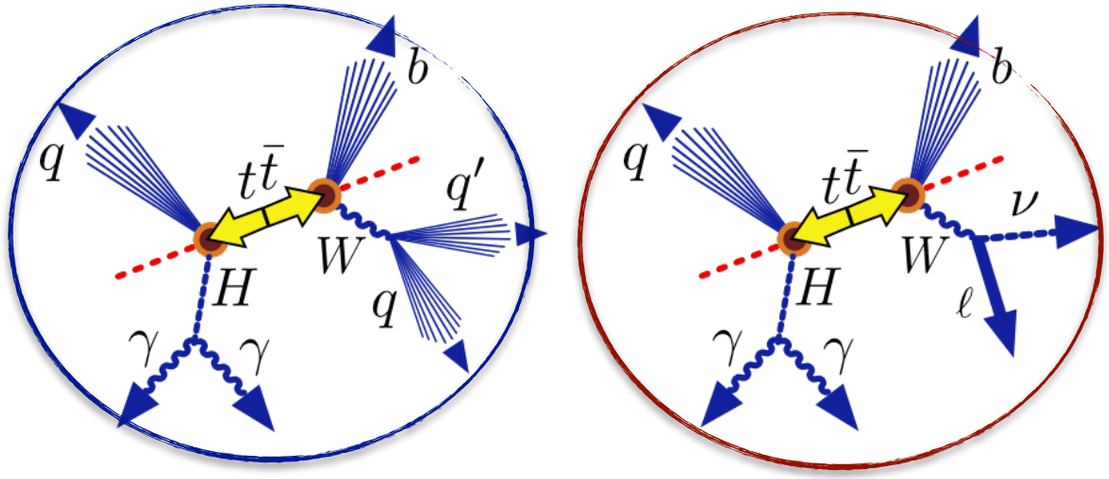


95% C.L. upper limits on branching ratios

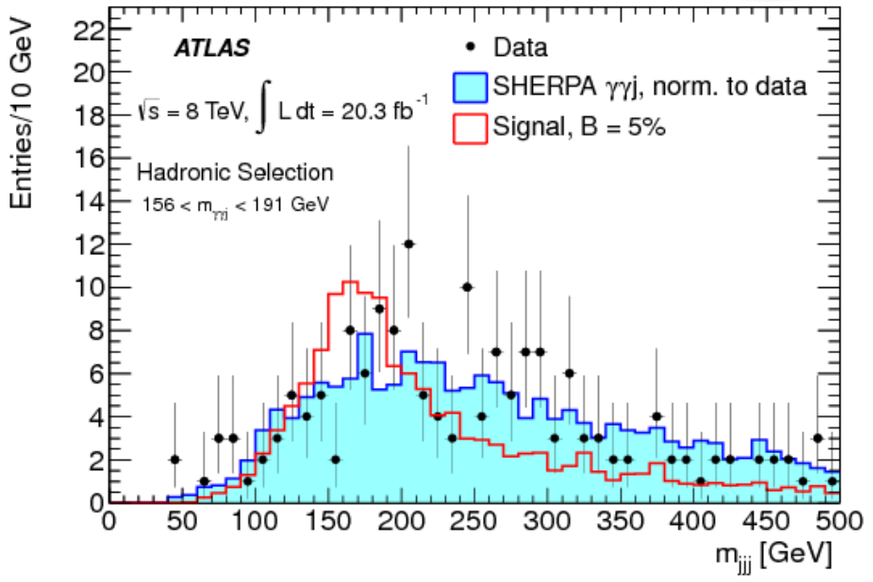
channel	observed	(-1σ)	expected	$(+1\sigma)$
3ID	0.81%	0.63%	0.95%	1.4%
2ID+TL	3.2%	2.15%	3.31%	4.9%
Combination	0.73%	0.61%	0.93%	1.4%

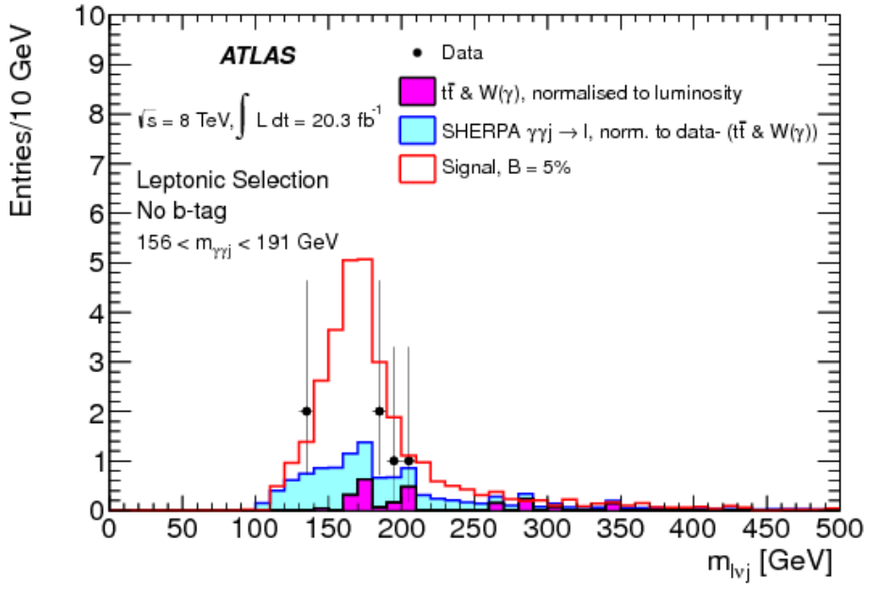
Search for FCNC decays in t→H($\gamma\gamma$)q [JHEP06 (2014) 008]

- Search for top quark pair production with an FCNC (qH) and a SM decay.
- $\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7$ fb^{-1}
  $\sqrt{s} = 8$ TeV, $\mathcal{L} = 20.3$ fb^{-1}



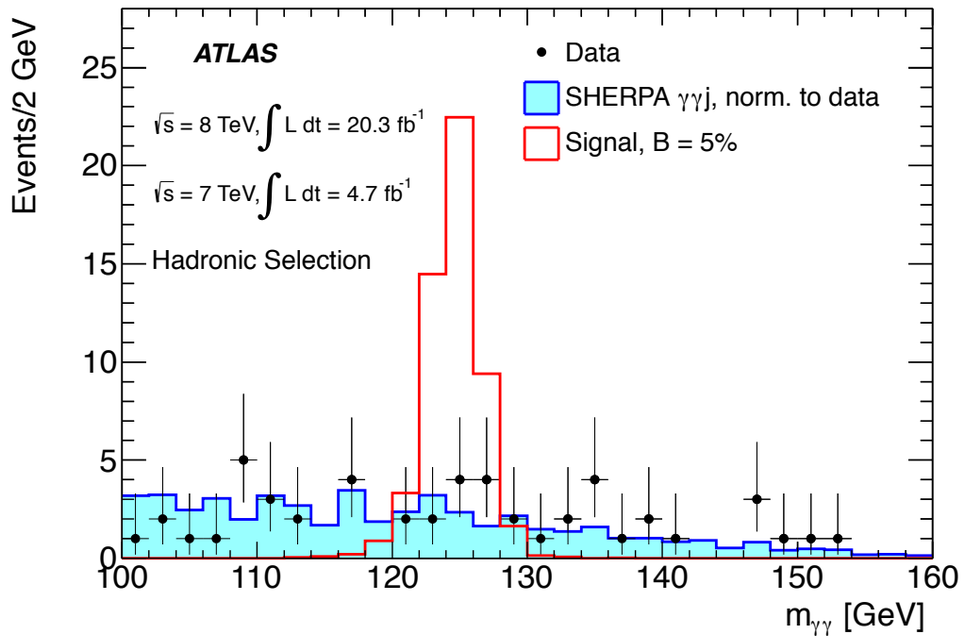
- Event selection:
  - ≥ 2 photons; $p_T(\gamma_1) > 40$ GeV, $p_T(\gamma_2) > 30$ GeV.
  - Hadronic selection:
    = 0 leptons.
    = 4 jets (≥1 b-tagged).
    $156\ \text{GeV} \leq m_t^{FCNC} \leq 191\ \text{GeV}$
    $130\ \text{GeV} \leq m_t^{SM} \leq 210\ \text{GeV}$
  - Leptonic selection (8 TeV only):
    = 1 lepton.
    ≥ 2 jets (= 1 b-tagged).
    $m_{\mathrm{T}}^{W} > 30\ \text{GeV}$
    $156\ \text{GeV} \leq m_t^{FCNC} \leq 191\ \text{GeV}$
    $135\ \text{GeV} \leq m_t^{SM} \leq 205\ \text{GeV}$



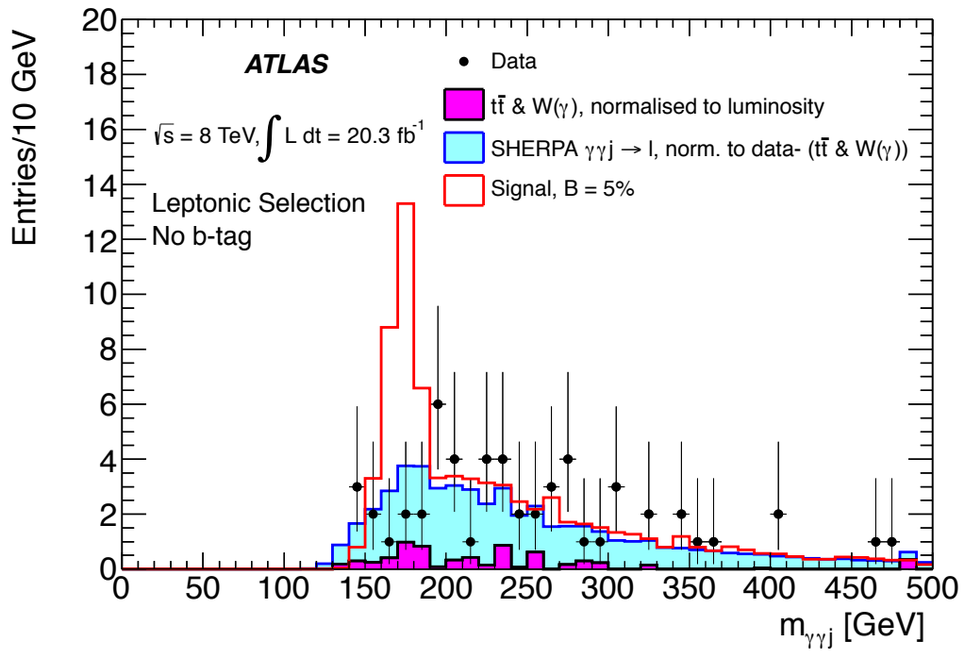


Search for FCNC decays in t→H($\gamma\gamma$)q [JHEP06 (2014) 008]

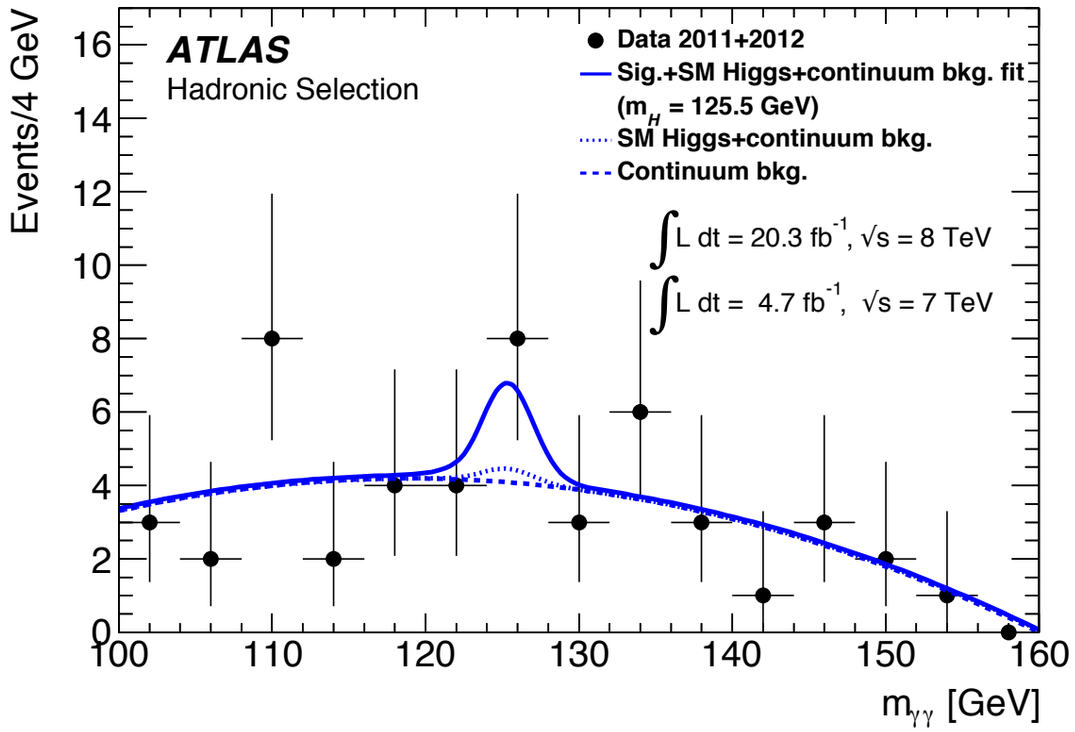
- Backgrounds:
  - $t\bar{t}$ and W(γ) from MC samples normalised to luminosity.
  - Sherpa $\gamma\gamma$j:
    Normalised to data.
  - SM Higgs production:
    Small contribution dominated by $t\bar{t}H$ (~60%).
    ggF, VBF, WH, ZH also considered.



- Main systematic uncertainties:
  Photon identification, JES, b-tagging and ISR/FSR.



Search for FCNC decays in t→H($\gamma\gamma$)q [JHEP06 (2014) 008]

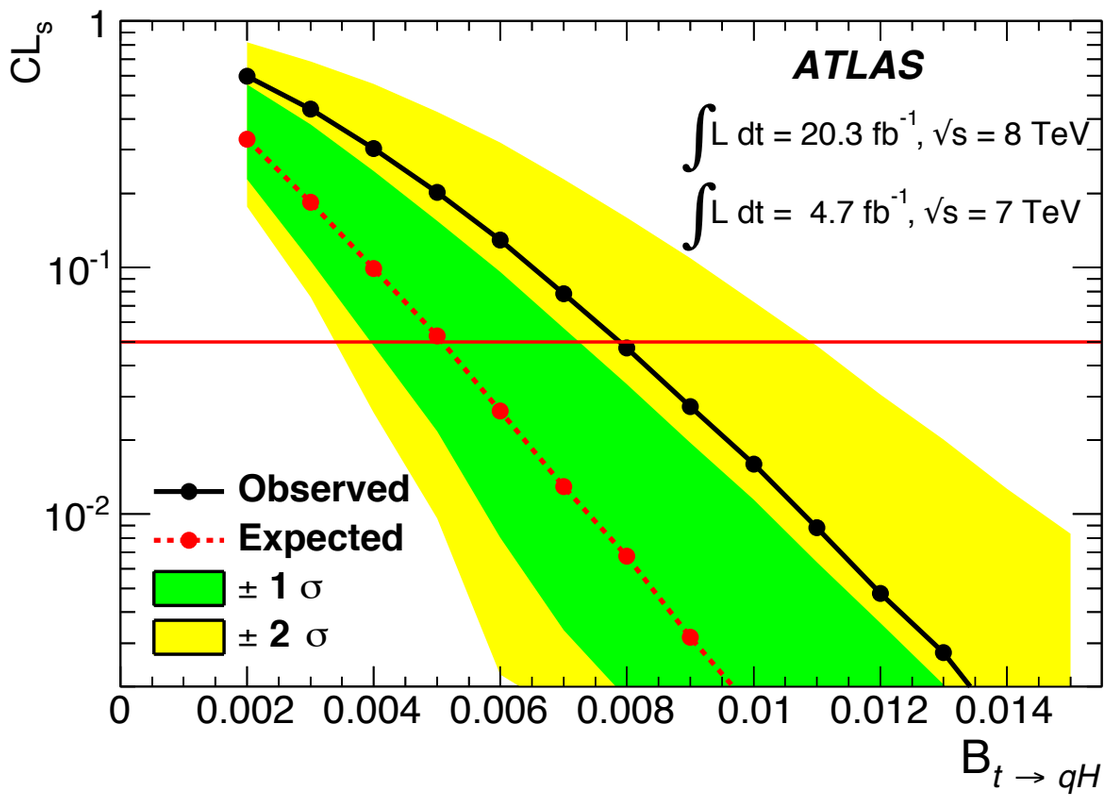


- Fit to data is performed for signal and background estimation.
  Control region:
  100 GeV ≤ m$\gamma\gamma$ ≤ 122 GeV and
  129 GeV≤ m$\gamma\gamma$ ≤ 160 GeV
  Signal region:
  122 GeV ≤ m$\gamma\gamma$ ≤ 129 GeV
- $m_{\gamma\gamma}$ is used in the hadronic channel.
- Counting experiment is done for the leptonic channel.

- Since no significant deviation from SM is found, CL_S method is used to set limits on BR(t→Hq).

95% C.L. upper limit on BR

Observed	**Expected**
0.79%	0.51%

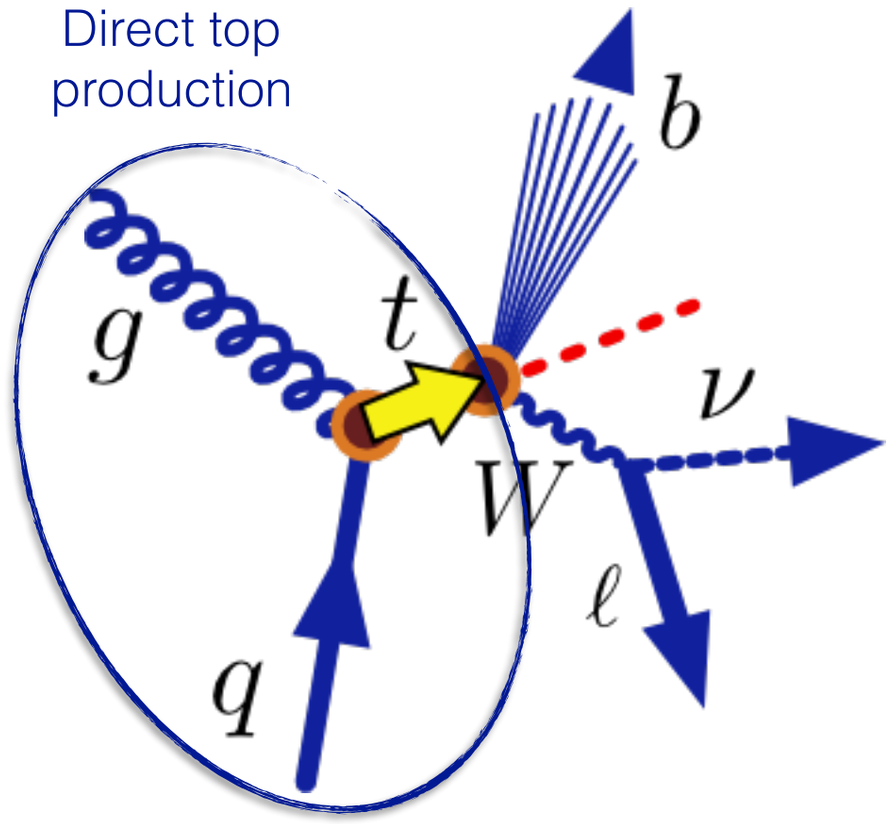


Search for FCNC in direct top production (gq→t) [ATLAS-CONF-2013-063]

- This analysis targets direct top quark production via FCNC.

$$\sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 14.2 \text{ fb}^{-1}$$

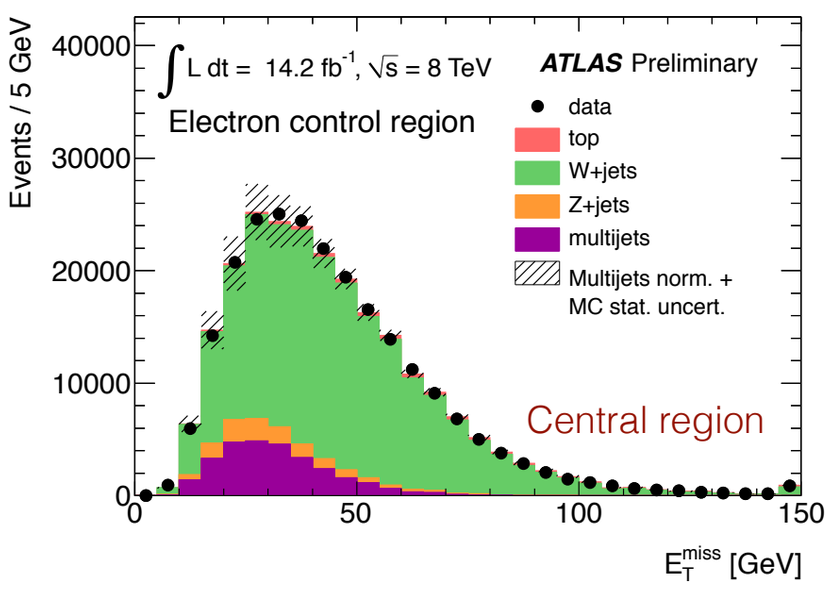
- Differences with respect to SM single-top production:
  - W and b back-to-back.
- Compared to W/Z+jets, the W boson is more boosted.
- Ratio between top/anti-top production is closer to 3 (in SM is closer to 2).

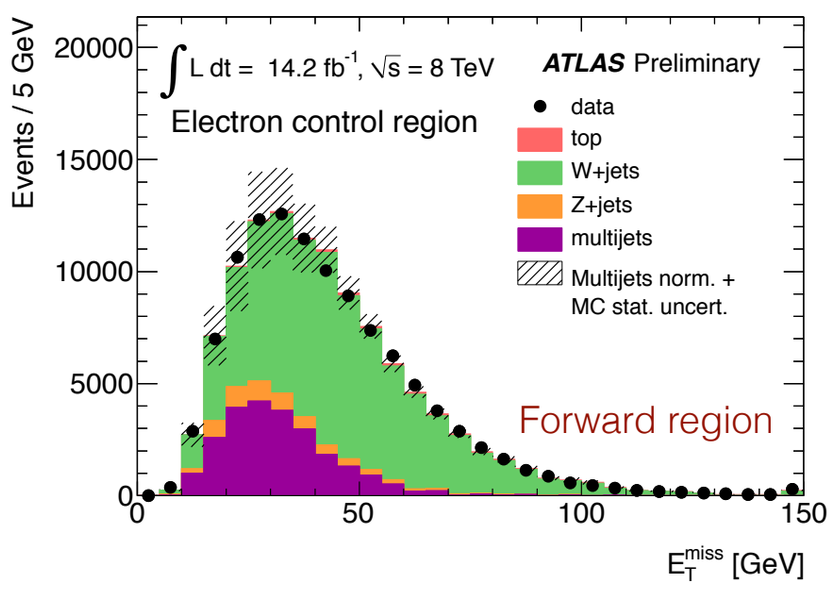


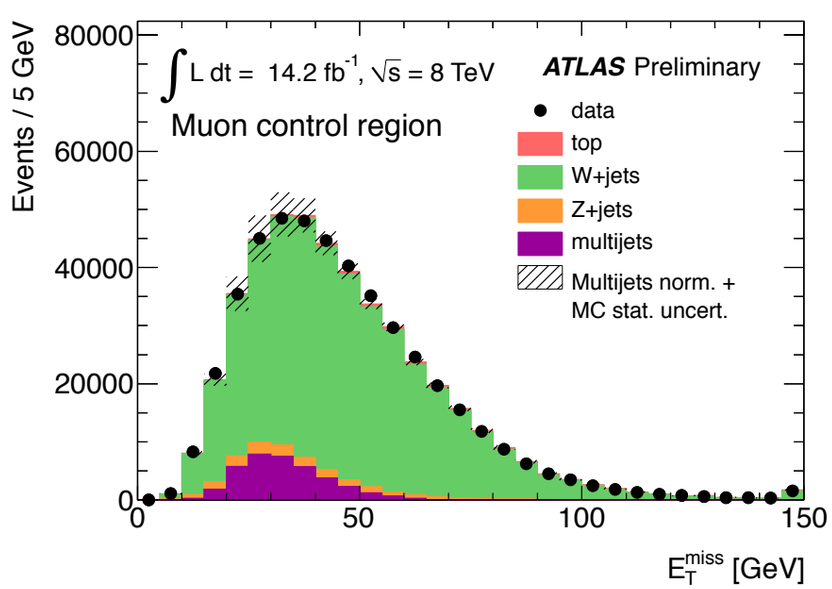
- Event selection
  - Top quark decays through SM Wb decay.
  - = 1 lepton ($p_T \geq 25$ GeV).
  - MET > 30 GeV.
  - = 1 b-tagged jet.

Search for FCNC in direct top production (gq→t) [ATLAS-CONF-2013-063]

- Backgrounds:
  - Single-top production, top pair production and W/Z+jet are evaluated with MC simulation.
  - Multijet background:
    - Electron channel:
      Shape → Sherpa dijet samples.
      Normalisation → fit to data in MET distribution separated in central and forward region.
    - Muon channel:
      Matrix method used to obtain shape and normalisation.





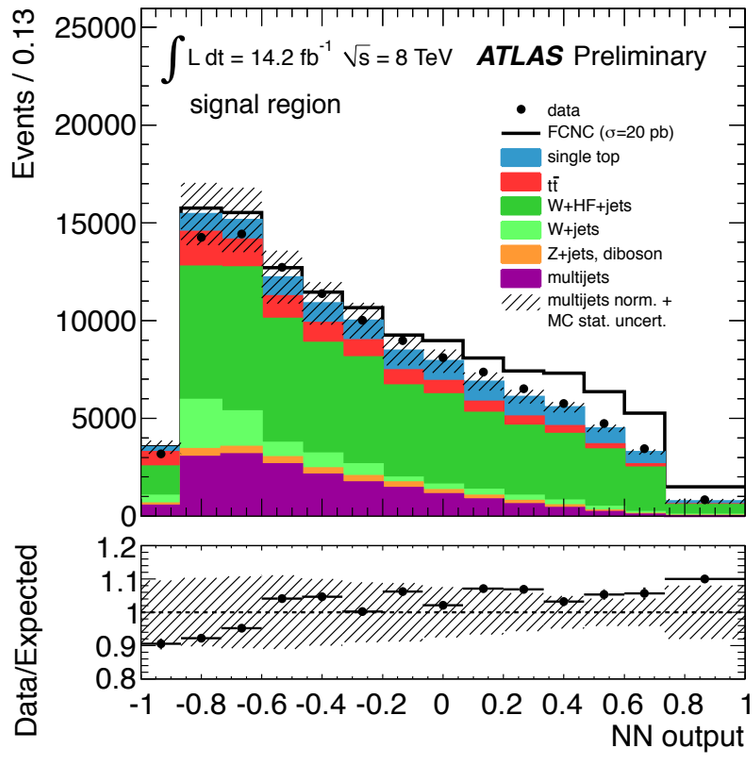


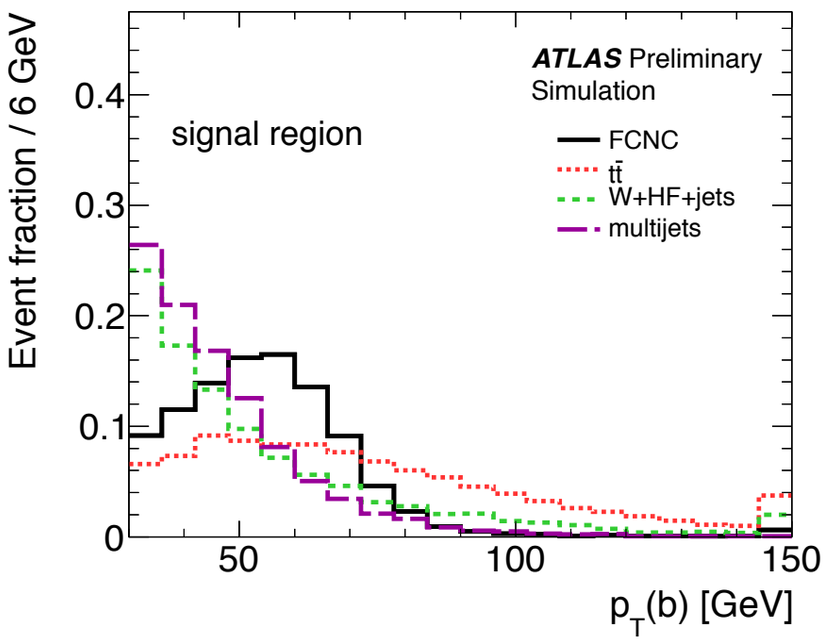
- Main systematic uncertainties:
  b-tagging, MET and background modelling.

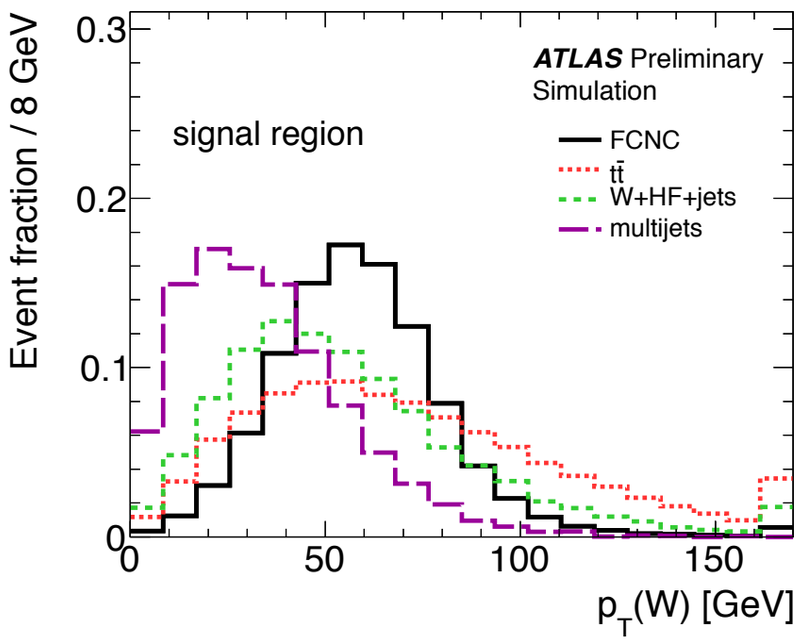
Search for FCNC in direct top production (gq→t) [ATLAS-CONF-2013-063]

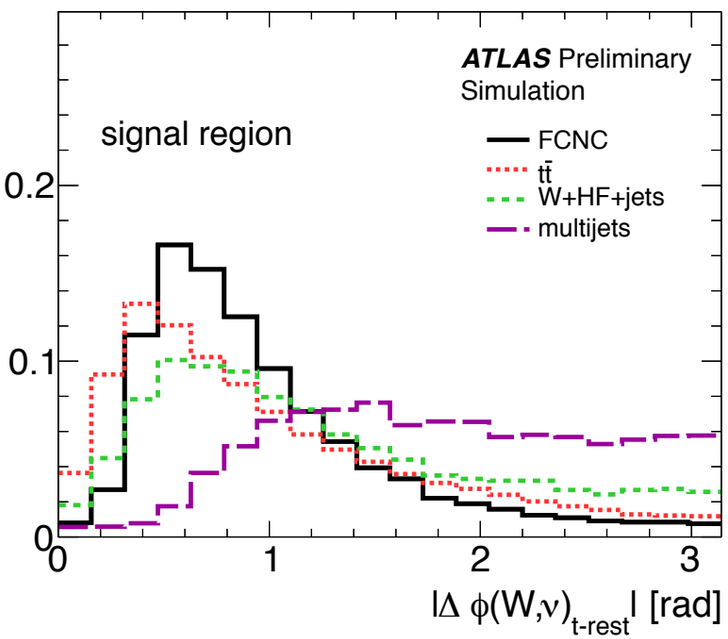
- A multi-variate analysis is done to improve the analysis (neural-network using 13 variables).

Variable	loss of total correlation (%)	Variable	loss of total correlation (%)
$p_{\mathrm{T}}(b)$	34	$\Delta\phi(\ell, W)$	6
$p_{\mathrm{T}}(W)$	19	$\Delta\phi(b, \ell\nu b)$	5
$\Delta\phi(W, \nu)$ in the top quark rest frame	13	$\Delta R(\ell, \ell\nu b)$	5
Charge of the lepton $q(\ell)$	12	$\Delta\phi(W, \ell\nu b)$	4
$\eta(\ell)$	11	$\eta(\nu)$	4
$\Delta\phi(\ell, b)$	9	$E_{\mathrm{T}}^{\mathrm{miss}}$	4
$\eta(\ell\nu b)$	9		





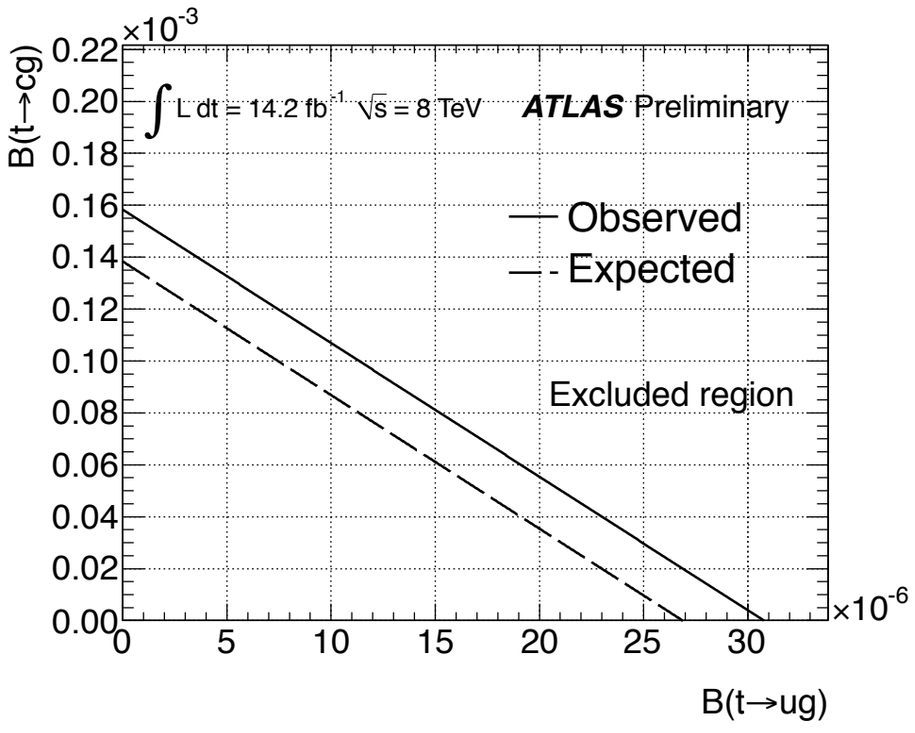


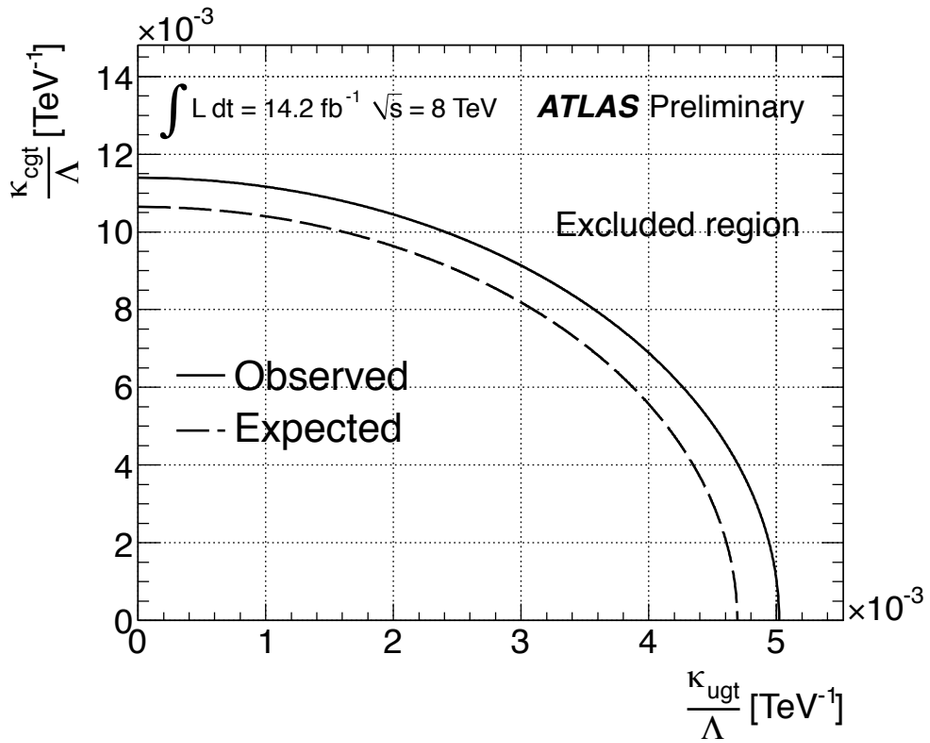


Search for FCNC in direct top production (gq→t) [ATLAS-CONF-2013-063]

Process	electron channel central	electron channel forward	electron channel total	muon channel total
single-top	4190 ± 210	1091 ± 57	5280 ± 270	6870 ± 350
$t\bar{t}$	3300 ± 330	870 ± 88	4200 ± 400	5300 ± 500
W+jets	2400 ± 700	1130 ± 350	4000 ± 1000	5100 ± 1300
W+HF+jets	16000 ± 9000	7000 ± 4000	23000 ± 13000	31000 ± 17000
Z+jets	720 ± 170	279 ± 74	990 ± 240	2000 ± 500
multijets	2800 ± 1400	2500 ± 1300	5400 ± 2700	13000 ± 6000
Total Expected	30000 ± 9000	12000 ± 4000	42000 ± 13000	63000 ± 18000
data	31271	12680	43951	68574

- Since no deviation from SM is found upper limits on BR(t→qg) are set at 95% C.L.
- Assuming BR(t→Wb)=1 and using NLO prediction for theoretical cross-sections limits on the couplings can be obtained

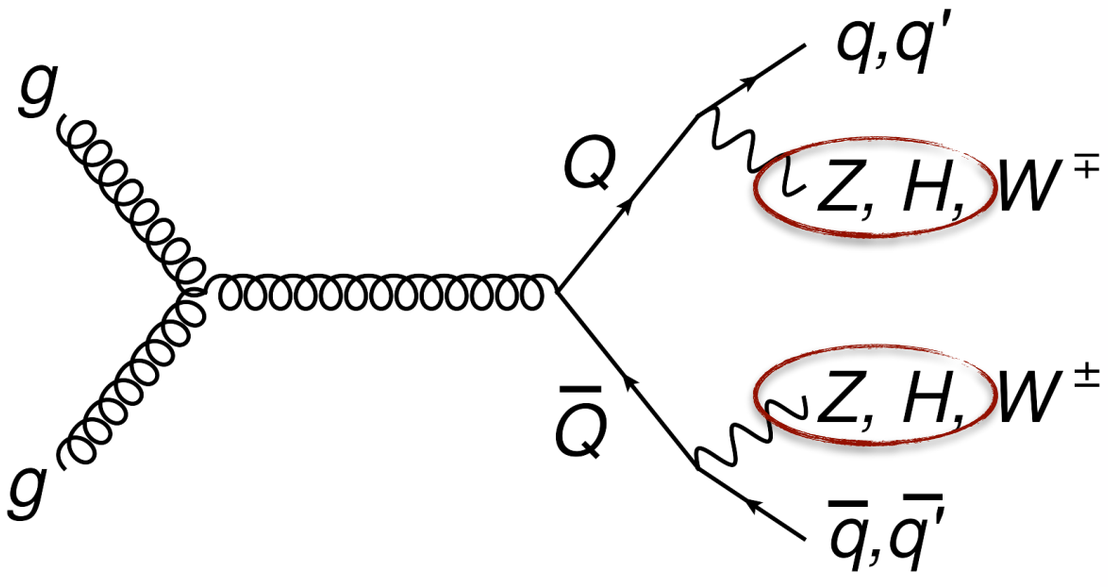




FCNC in vector-like quarks

- FCNC plays an important role in several BSM models.

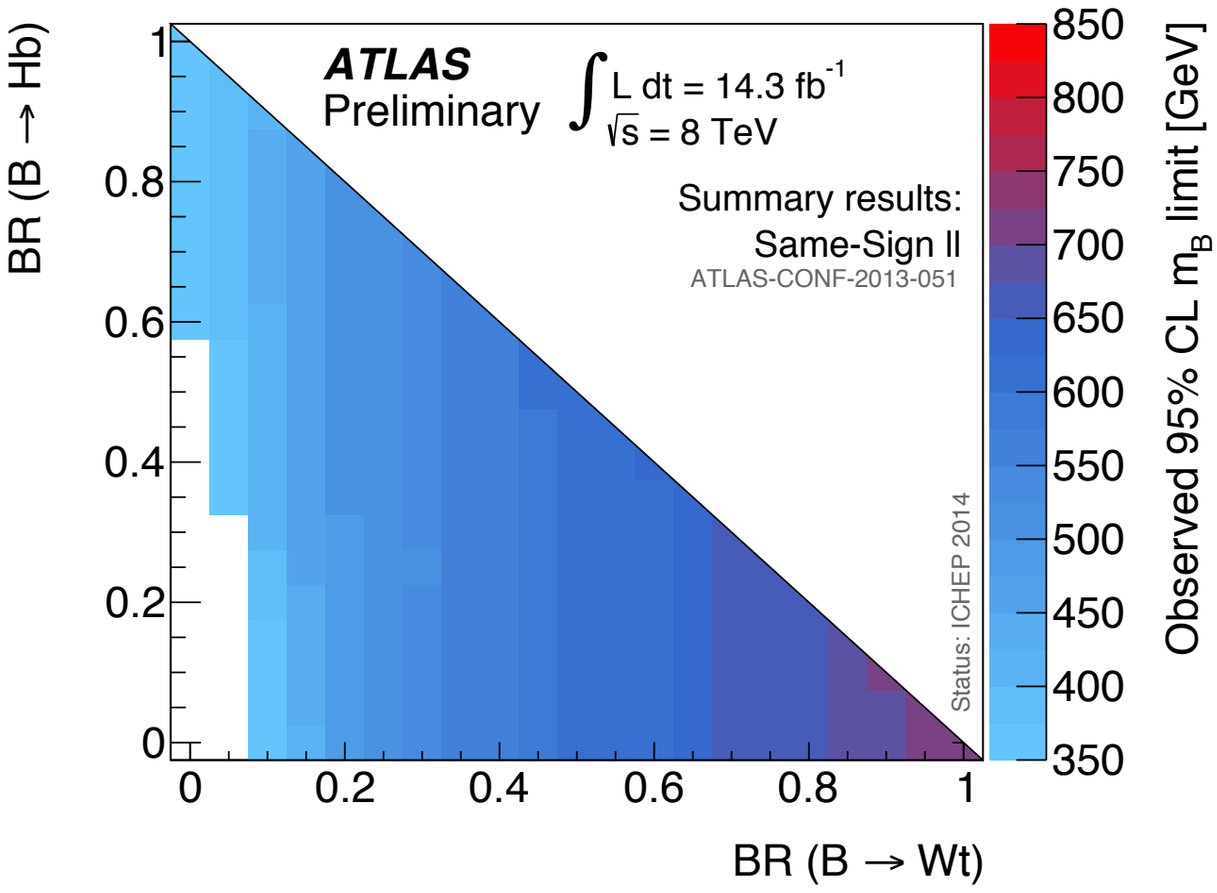
- Example:
  Vector-like quarks models have important FCNC decays.
  Left and right chiralities have same transformation rules under SU(2).
  Allows decays from heavy vector-like quark top partner to a SM top quark.



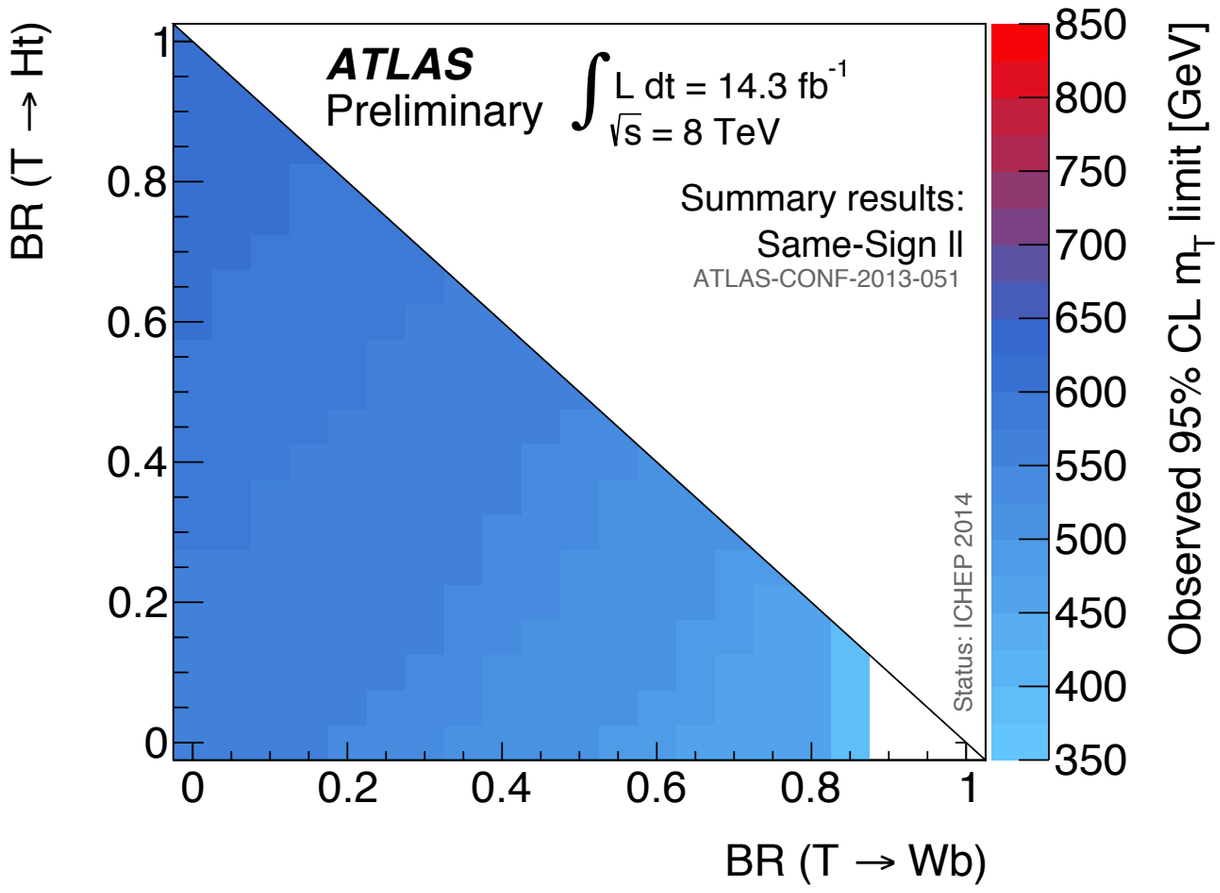
- Different searches target different decay modes.
  - Zb/t+X
    ATLAS-CONF-2014-036
  - Ht+X
    ATLAS-CONF-2013-018
  - Same-Sign dilepton
    ATLAS-CONF-2013-051
  - Wb+X
    ATLAS-CONF-2013-060

FCNC in vector-like quarks

Vector-like B

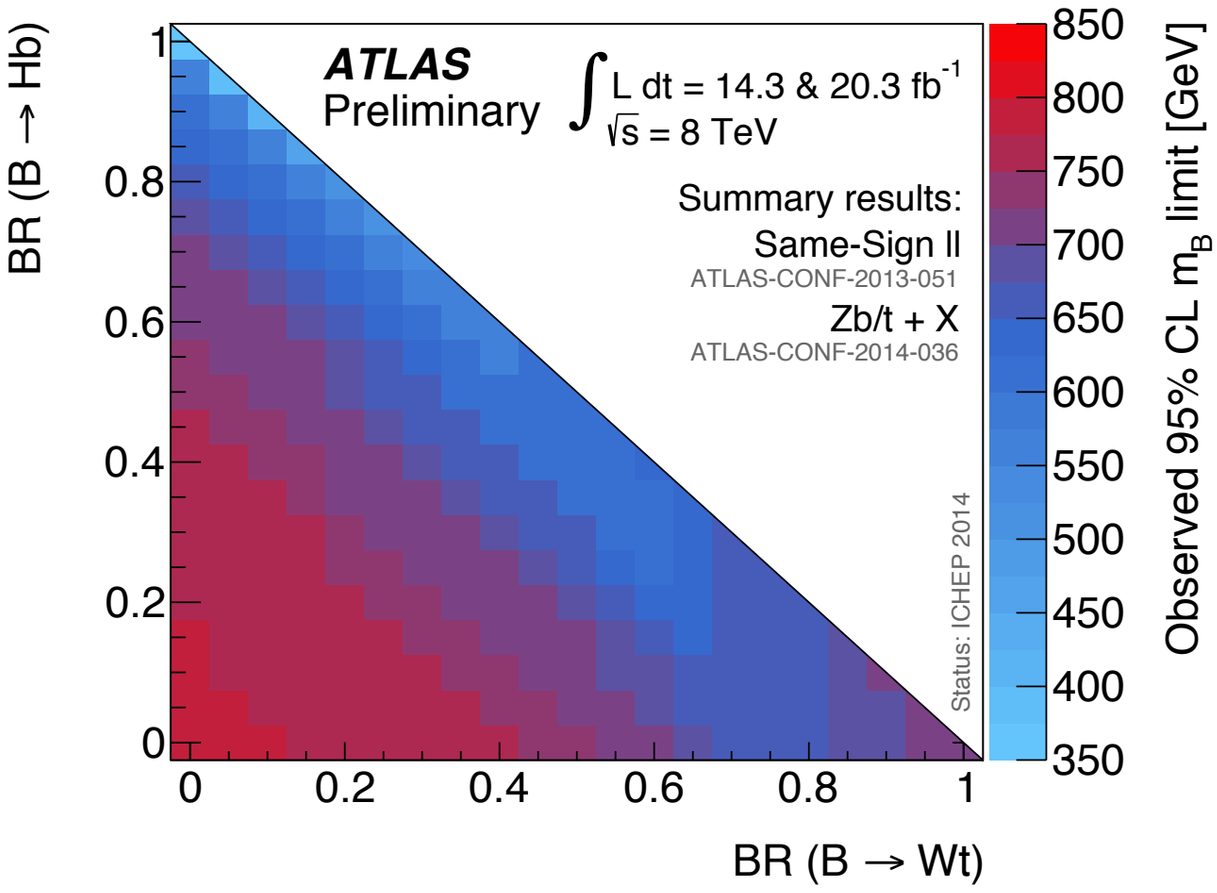


Vector-like T

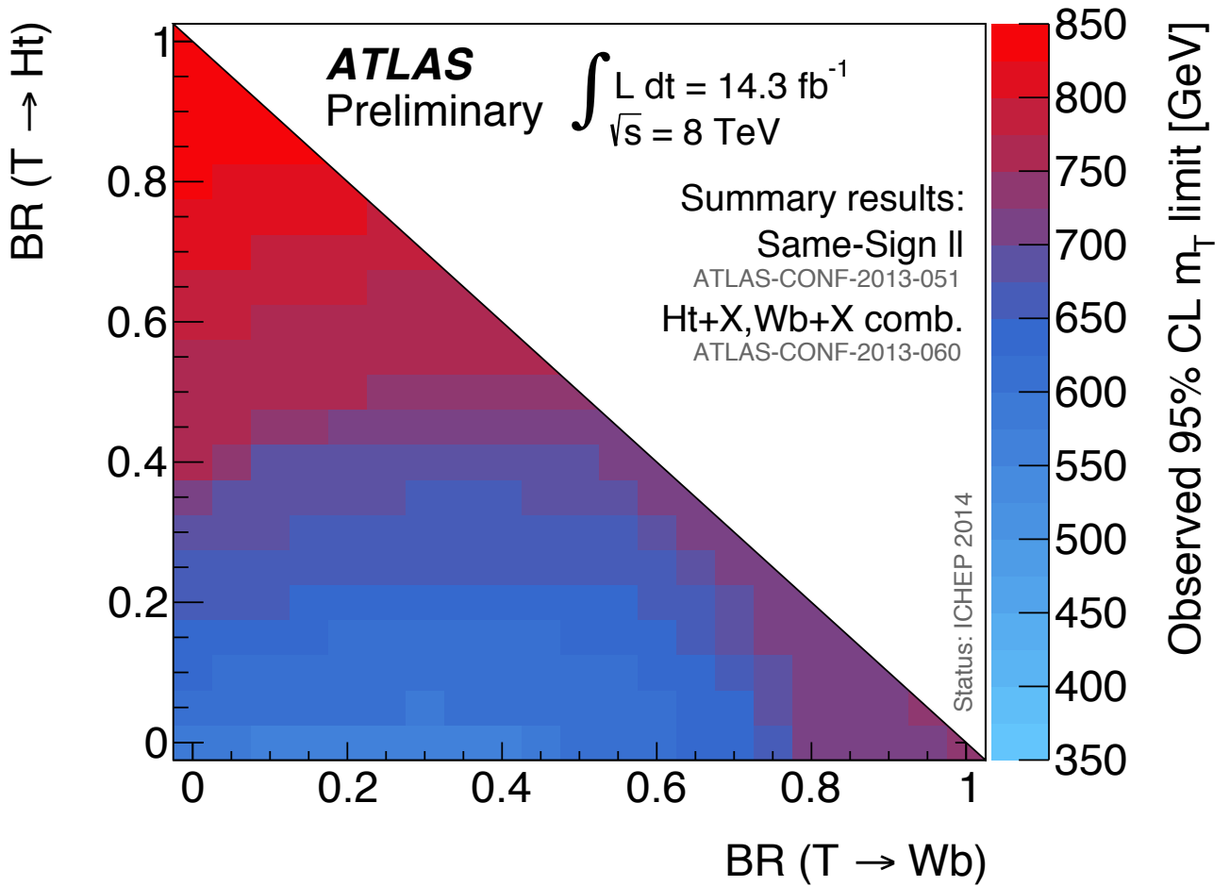


FCNC in vector-like quarks

Vector-like B

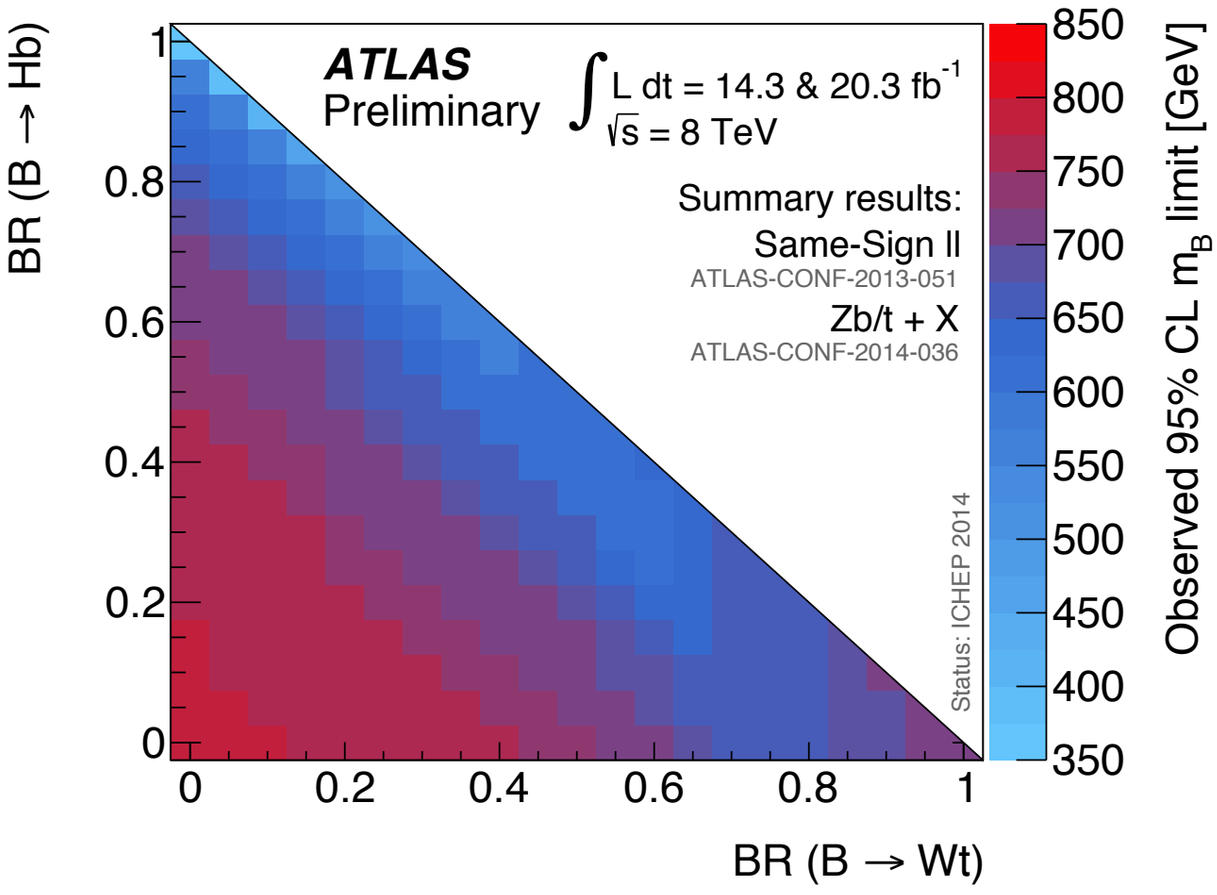


Vector-like T

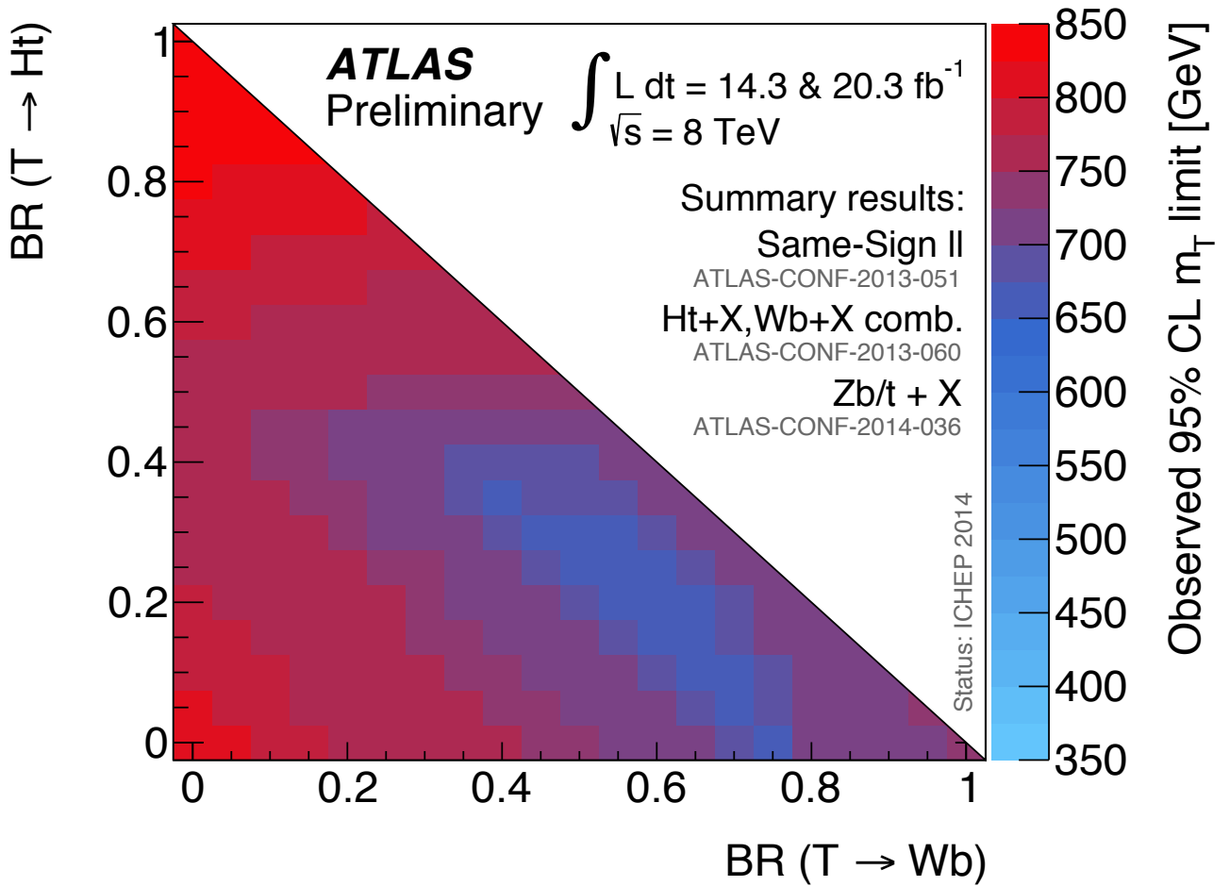


FCNC in vector-like quarks

Vector-like B

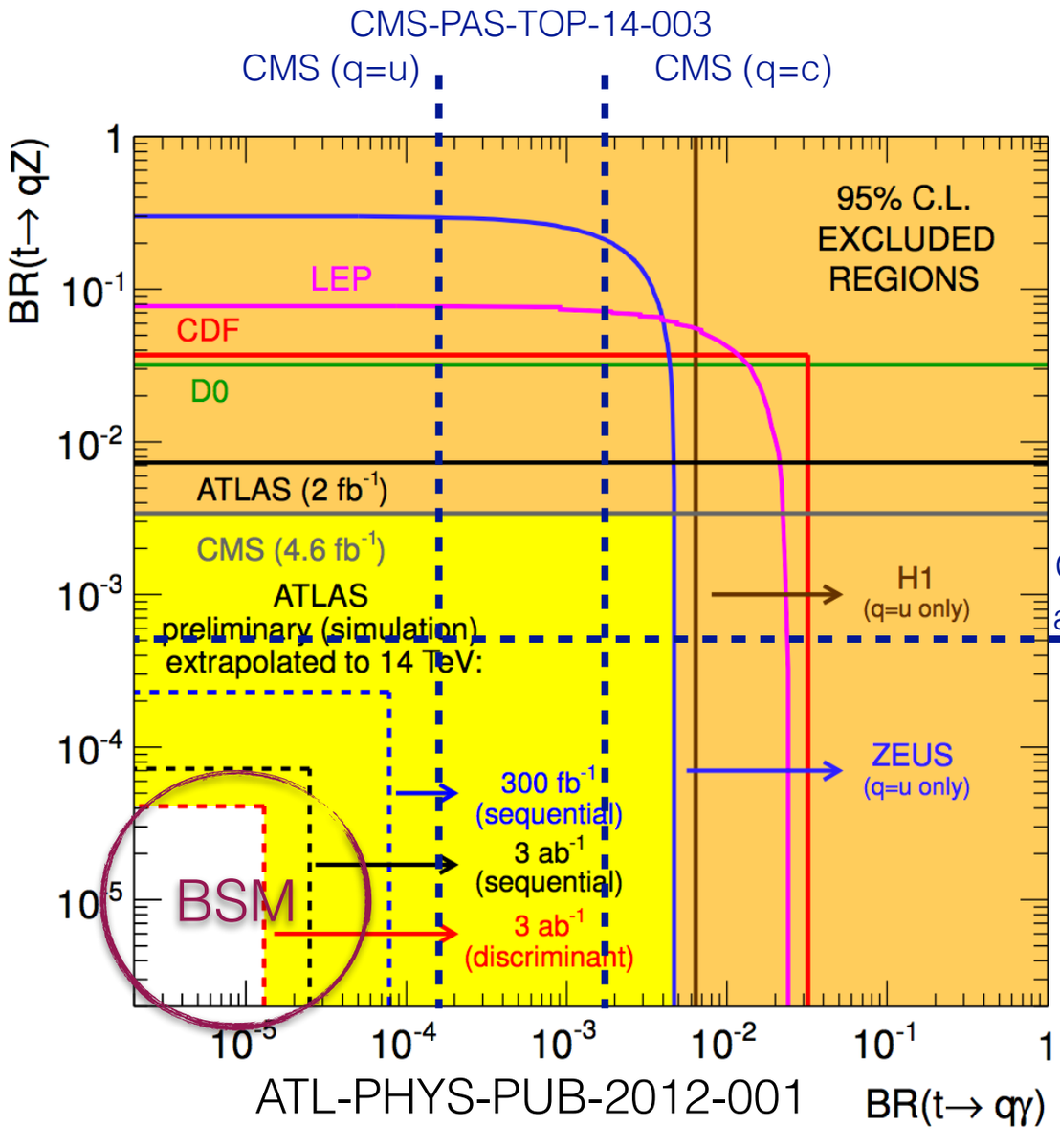


Vector-like T

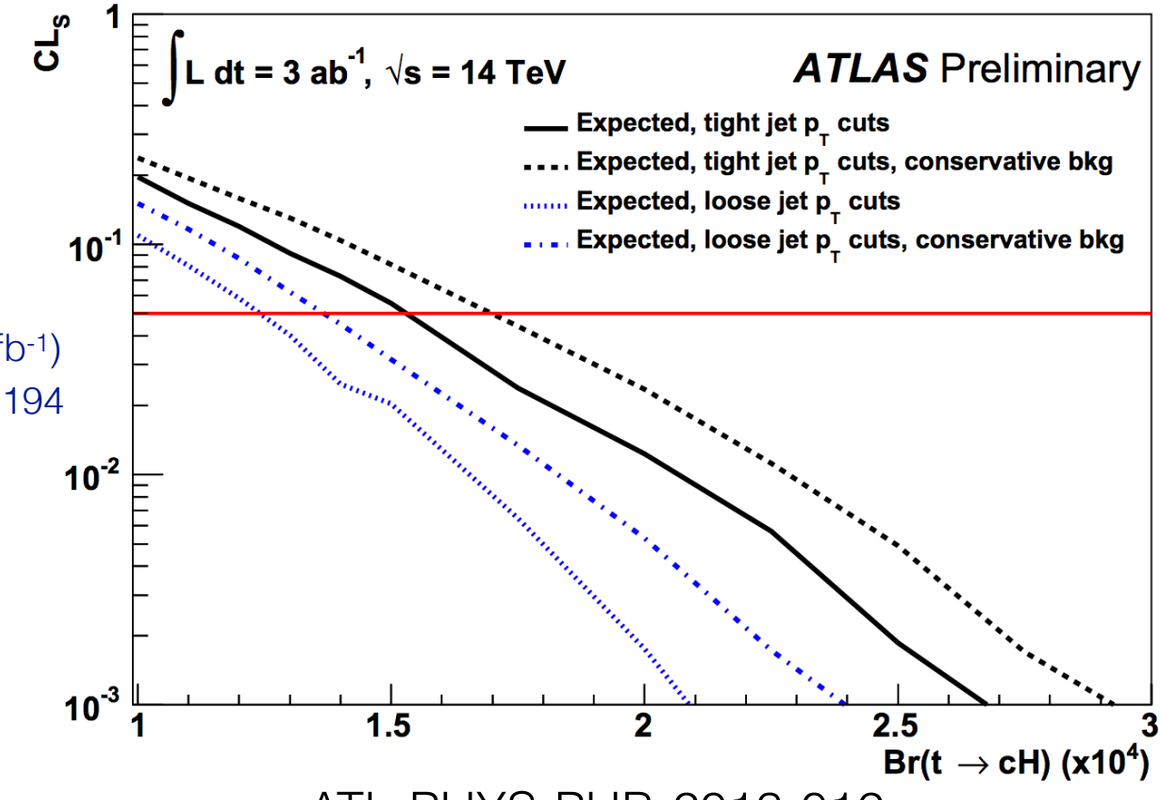


Future prospects

- The update to the high-luminosity LHC with a center of energy of 14 TeV and an integrated luminosity up to 3 ab^{-1} will allow to test top FCNC with an unprecedented precision.



CMS (19.7 fb^{-1})
arXiv:1312.4194



ATL-PHYS-PUB-2013-012

Conclusions

- FCNC processes play an important role as a test for the SM as well as for different BSM models.
- Several ATLAS analyses addressing different channels.
- No evidence for new physics found.
- Full run 1 data-set still being analysed.
- The higher center of mass energy and luminosity of run 2 will allow us to study FCNC processes with an unprecedented precision.

Stay tuned for updates.

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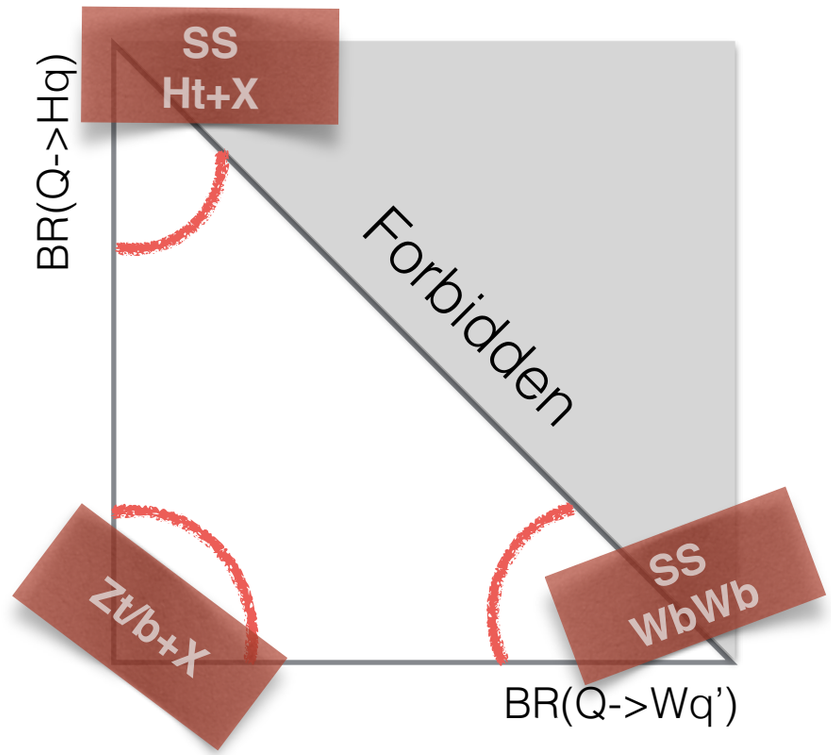
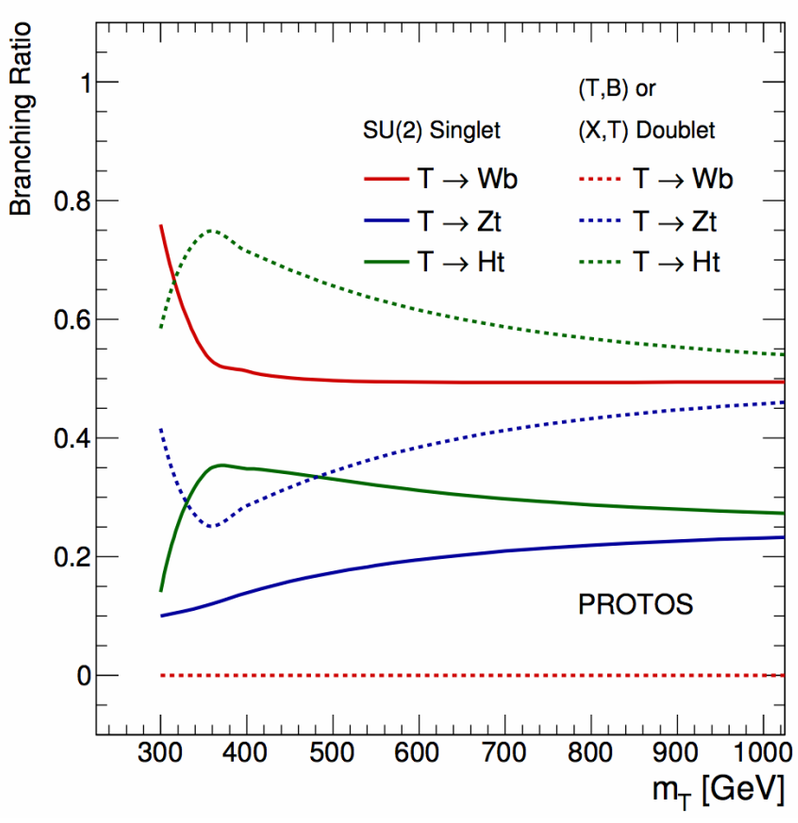
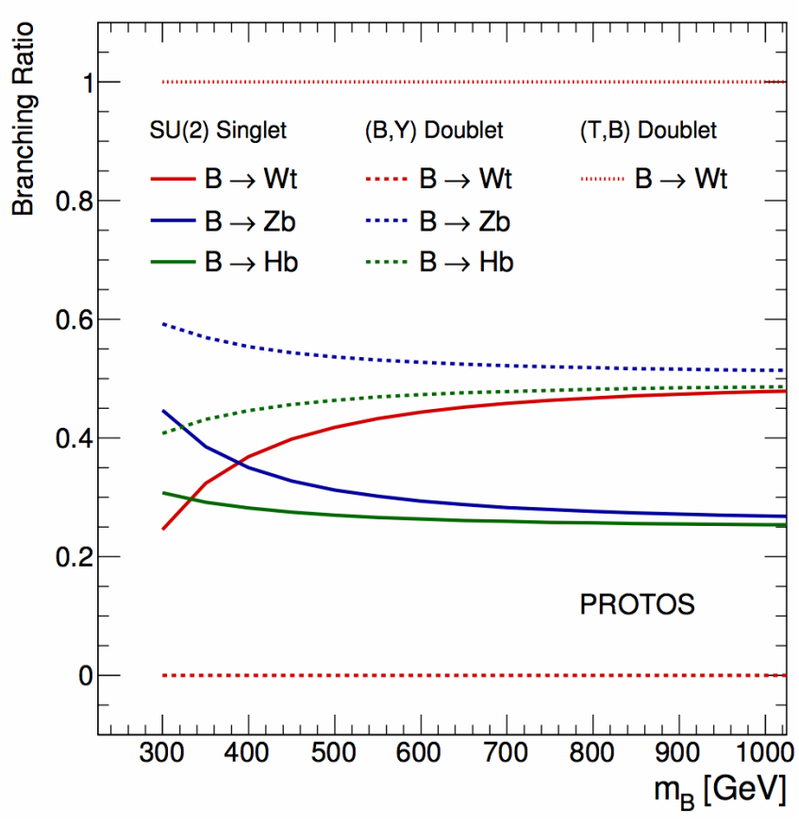
Backup

VLQ analyses

- Try to cover all the phase space possible.
- Different analyses are sensible to different regions.
- FCNC branching ratios are at least 25% in singlet model (for high masses) and up to 50% for doublet models.

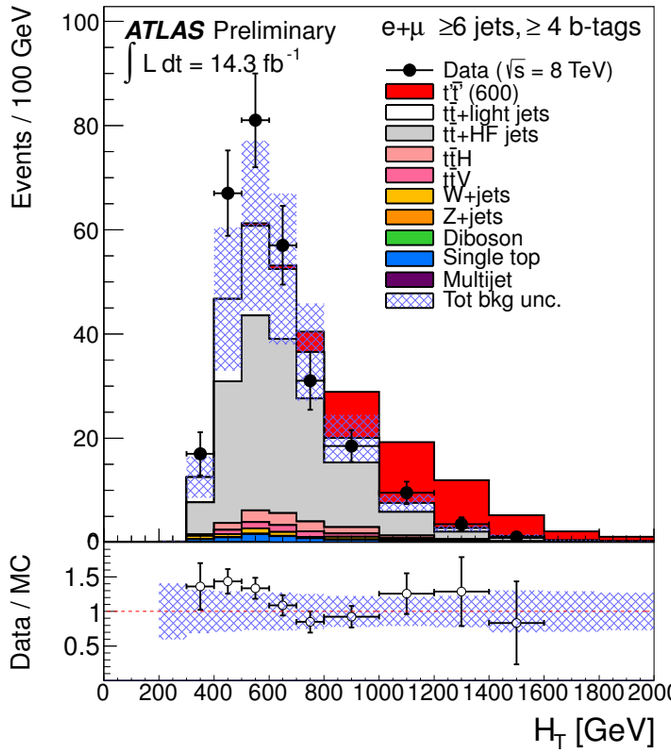


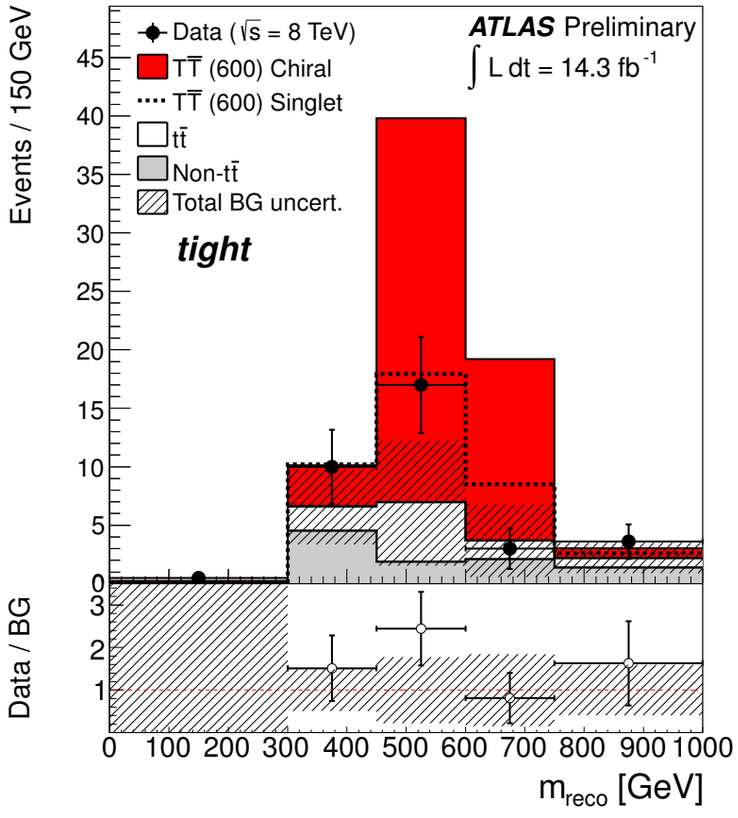




VLQ analyses

- $Ht + X$:
  - At least 6 jets (≥ 4 b-jets), 1 lepton, $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}(W) > 60$ GeV. $2, 3$ b-jets regions used to constrain systematics uncertainties.
  - Discriminant variable: $H_{\mathrm{T}} = \sum_j p_{\mathrm{T}}(j) + p_{\mathrm{T}}(\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$

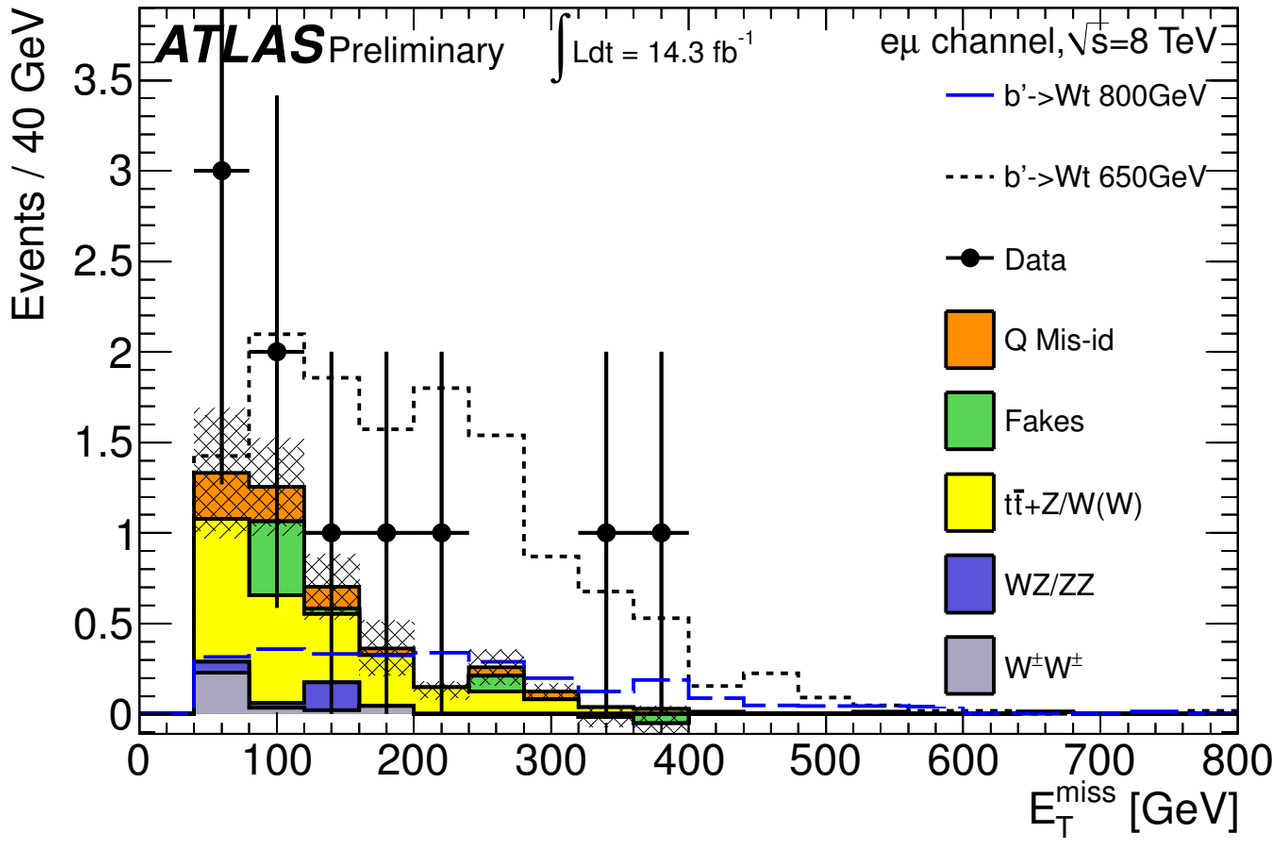




- $Wb + X$
  - Exploit boosted W from T quark: $\Delta R(\ell, \nu) < 1.2$, $\min\left[\Delta R(\ell, b_{1,2})\right] > 1.4$, $\min\left[\Delta R(W_{had}, b_{1,2})\right] > 1.4$.
  - Discriminant variable: m_T, reconstructed with W boson and b quark which gives lowest mass difference between leptonic and hadronic decay.

VLQ analyses

- Same-sign:
  - At least 2 jets (≥ 1 b-jet),
    2 SS leptons,
    Z veto $(ee, \mu\mu)$,
    high $E_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T}.
  - Cut and count experiment.



- $Zb/t + X$:

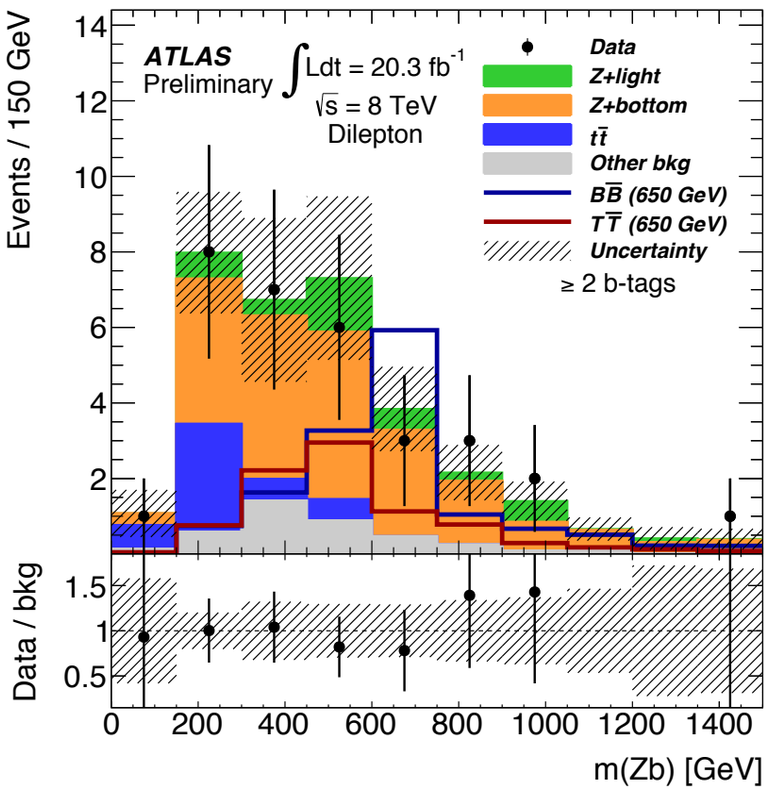
Event selection			
Z boson candidate preselection ≥ 2 central jets $p_{\mathrm{T}}(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	**Single production**	**Pair production**	**Single production**
$H_{\mathrm{T}}(\mathrm{jets}) \geq 600$ GeV	≥ 1 fwd. jet	–	≥ 1 fwd. jet
Final discriminant			
$m(Zb)$		H_{T}(jets+leptons)	

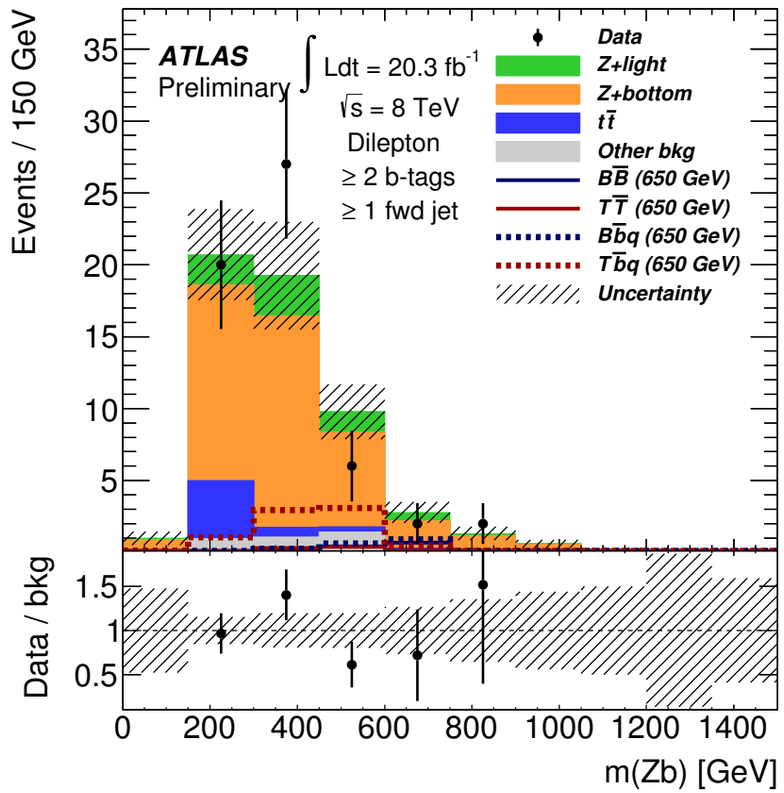
VLQ analyses

Pair production

Single production

Dilepton





Trilepton