

Searching for anomalous top quark couplings and decays with the ATLAS detector



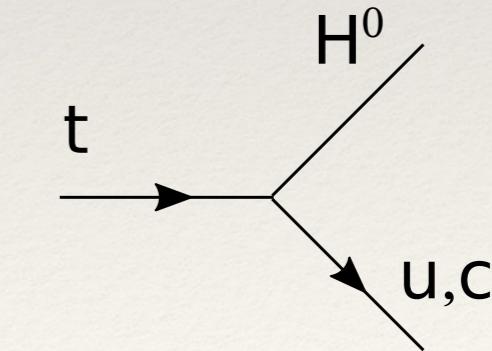
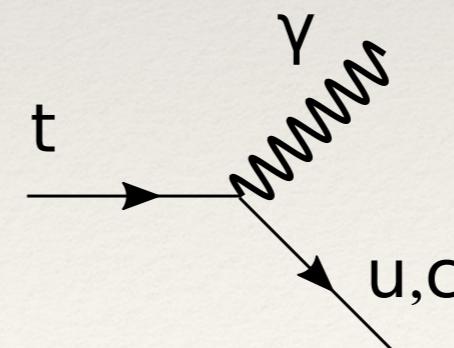
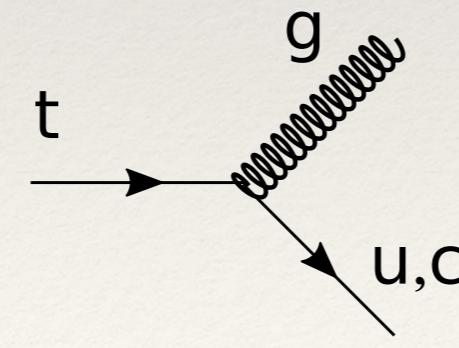
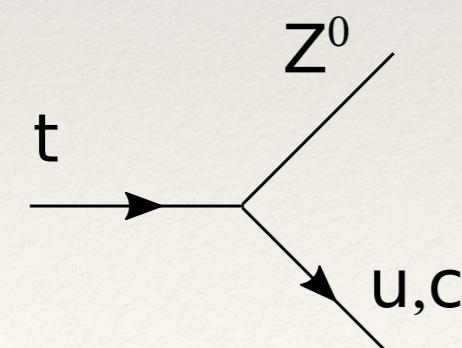
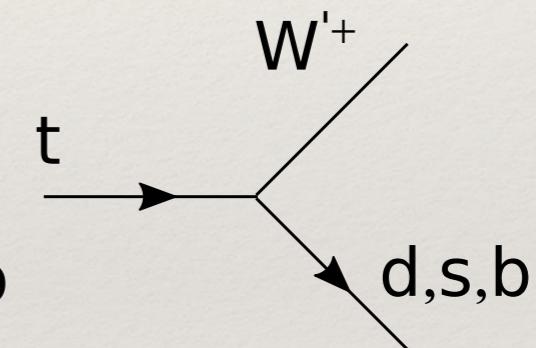
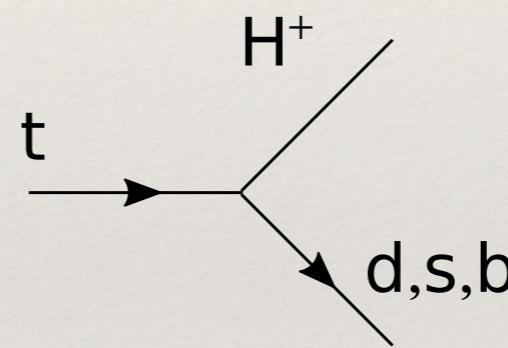
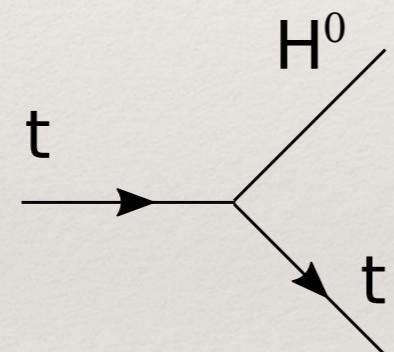
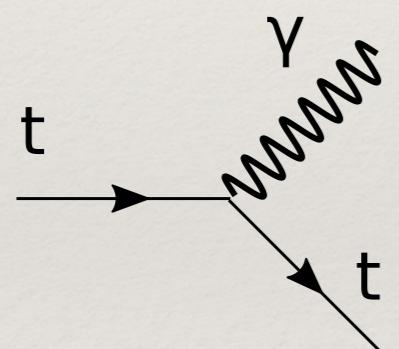
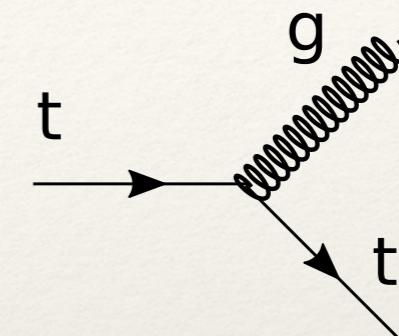
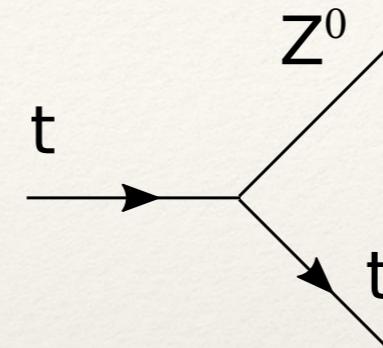
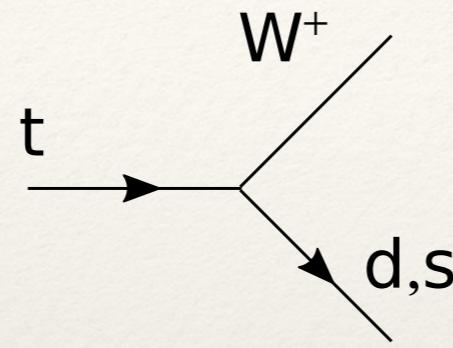
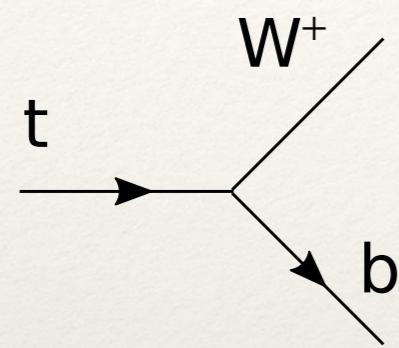
European Physical Society Conference on High Energy Physics
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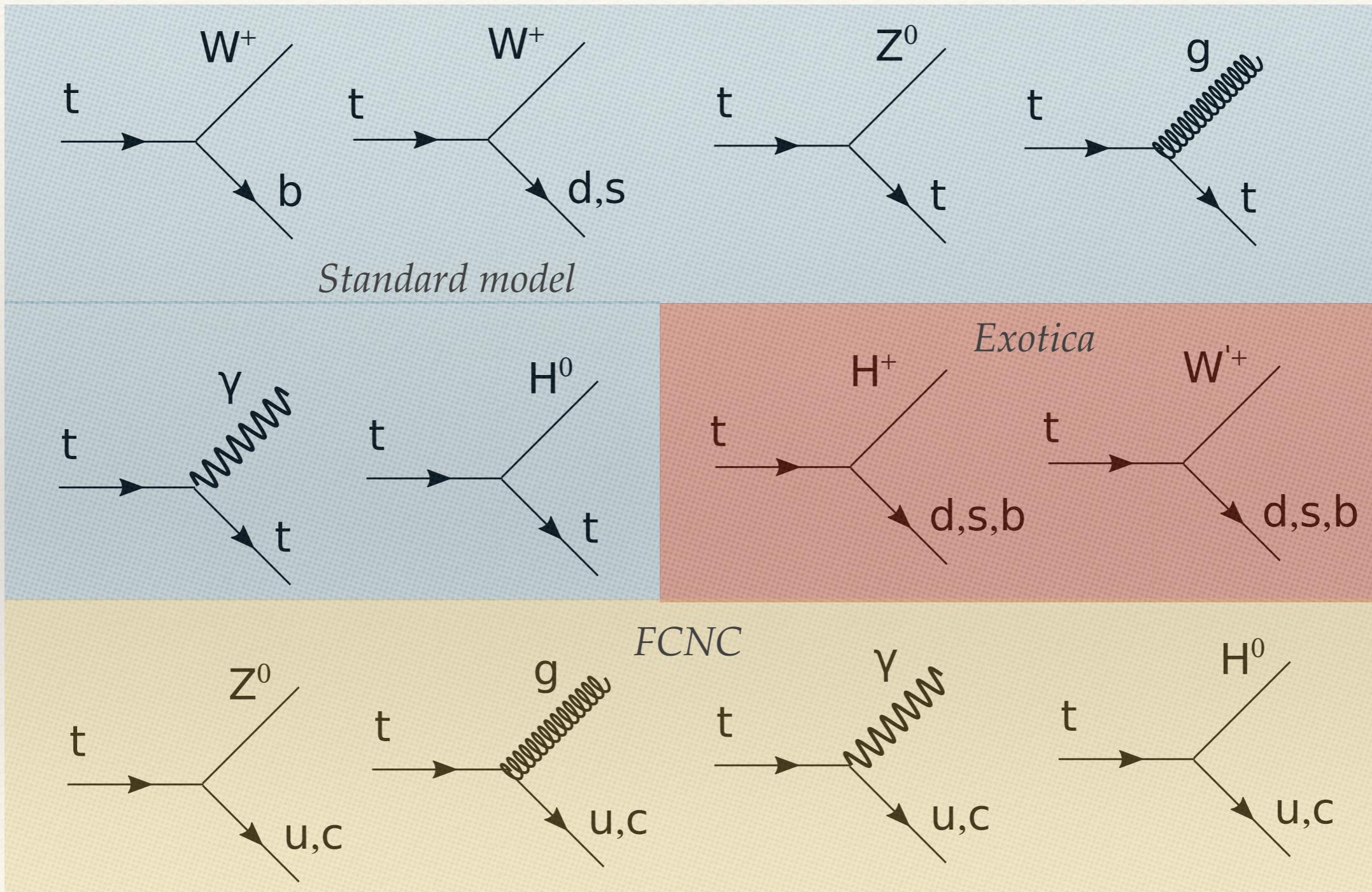
Joe Boudreau
University of Pittsburgh for
the ATLAS Collaboration



Catalogue of standard & exotic processes involving the top quark. The ATLAS top physics program is concerned with all of these.

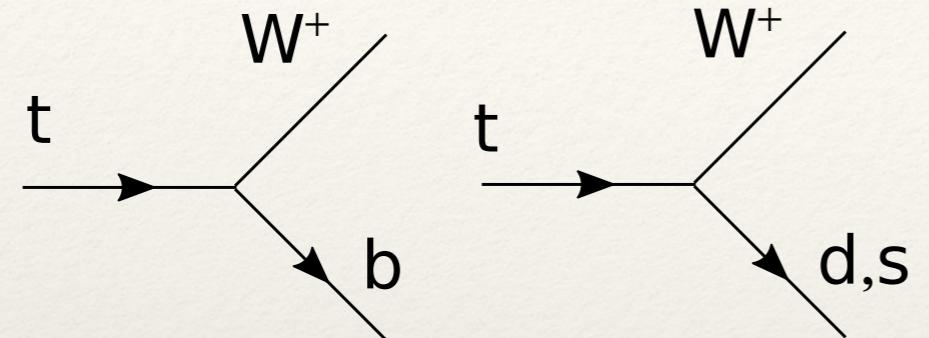


These can be categorized as *standard*, *exotic*, and *FCNC* processes.

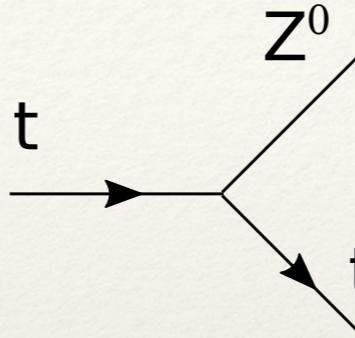


Effective Field Theory: physics at a higher mass scale Λ alters the coupling constants. A minimal set parameterizes its effect.

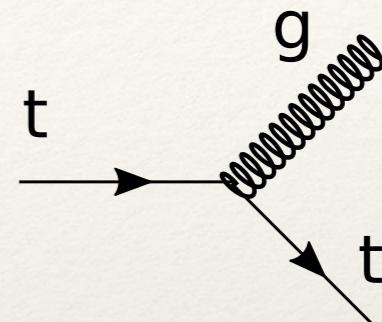
Nucl.Phys.B812:181–204,2009 & Nucl.Phys.B821:215–227,2009



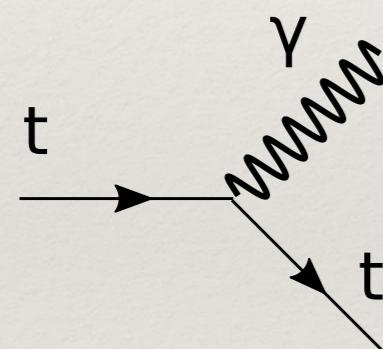
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + H.c.$$



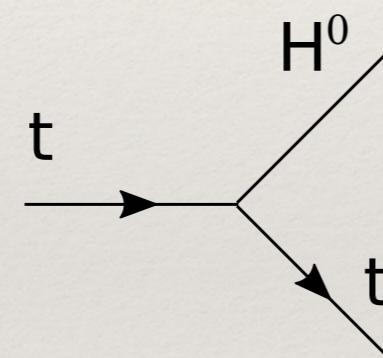
$$\begin{aligned} \mathcal{L}_{Ztt} = & -\frac{g}{2c_W} \bar{t} \gamma^\mu (X_{tt}^L P_L + X_{tt}^R P_R - 2s_W^2 Q_t) t Z_\mu \\ & - \frac{g}{2c_W} \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (d_V^Z + i d_A^Z \gamma_5) t Z_\mu \end{aligned}$$



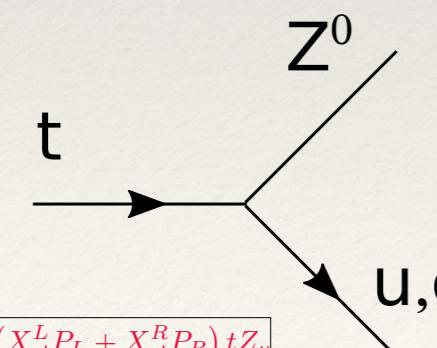
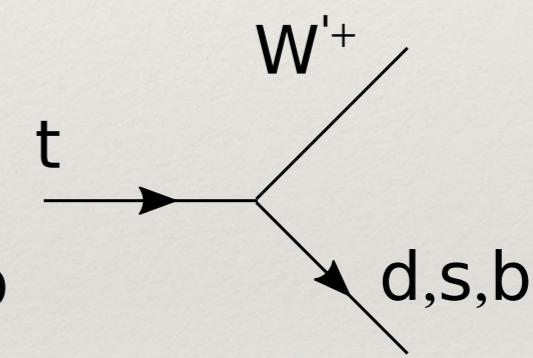
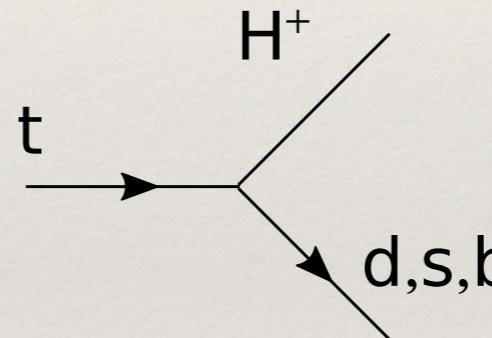
$$\mathcal{L}_{gtt} = -g_s \bar{t} \frac{\lambda^a}{2} \gamma^\mu t G_\mu^a - g_s \bar{t} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^g + i d_A^g \gamma_5) t G_\mu^a$$



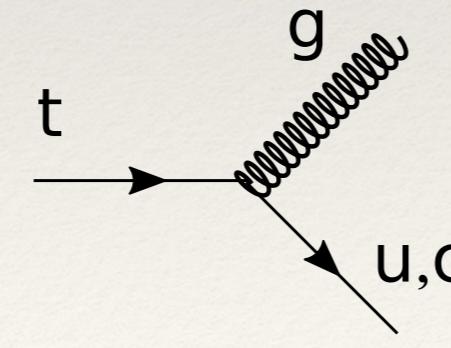
$$\mathcal{L}_{\gamma tt} = -e Q_t \bar{t} \gamma^\mu t A_\mu - e \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^\gamma + i d_A^\gamma \gamma_5) t A_\mu$$



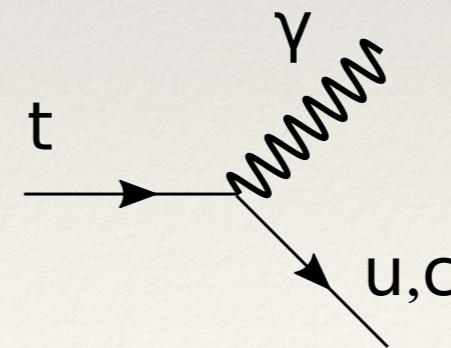
$$\mathcal{L}_{Htt} = -\frac{1}{\sqrt{2}} \bar{t} (Y_t^V + i Y_t^A \gamma_5) t H$$



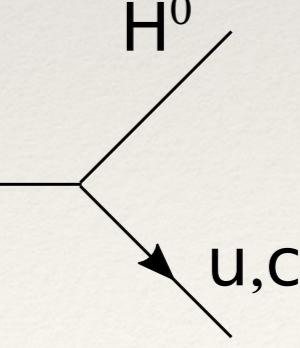
$$\begin{aligned} \mathcal{L}_{Ztc} = & -\frac{g}{2c_W} \bar{c} \gamma^\mu (X_{ct}^L P_L + X_{ct}^R P_R) t Z_\mu \\ & - \frac{g}{2c_W} \bar{c} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (\kappa_{ct}^L P_L + \kappa_{ct}^R P_R) t Z_\mu + H.c. \end{aligned}$$



$$\mathcal{L}_{gtc} = -g_s \bar{c} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (\zeta_{ct}^L P_L + \zeta_{ct}^R P_R) t G_\mu^a$$

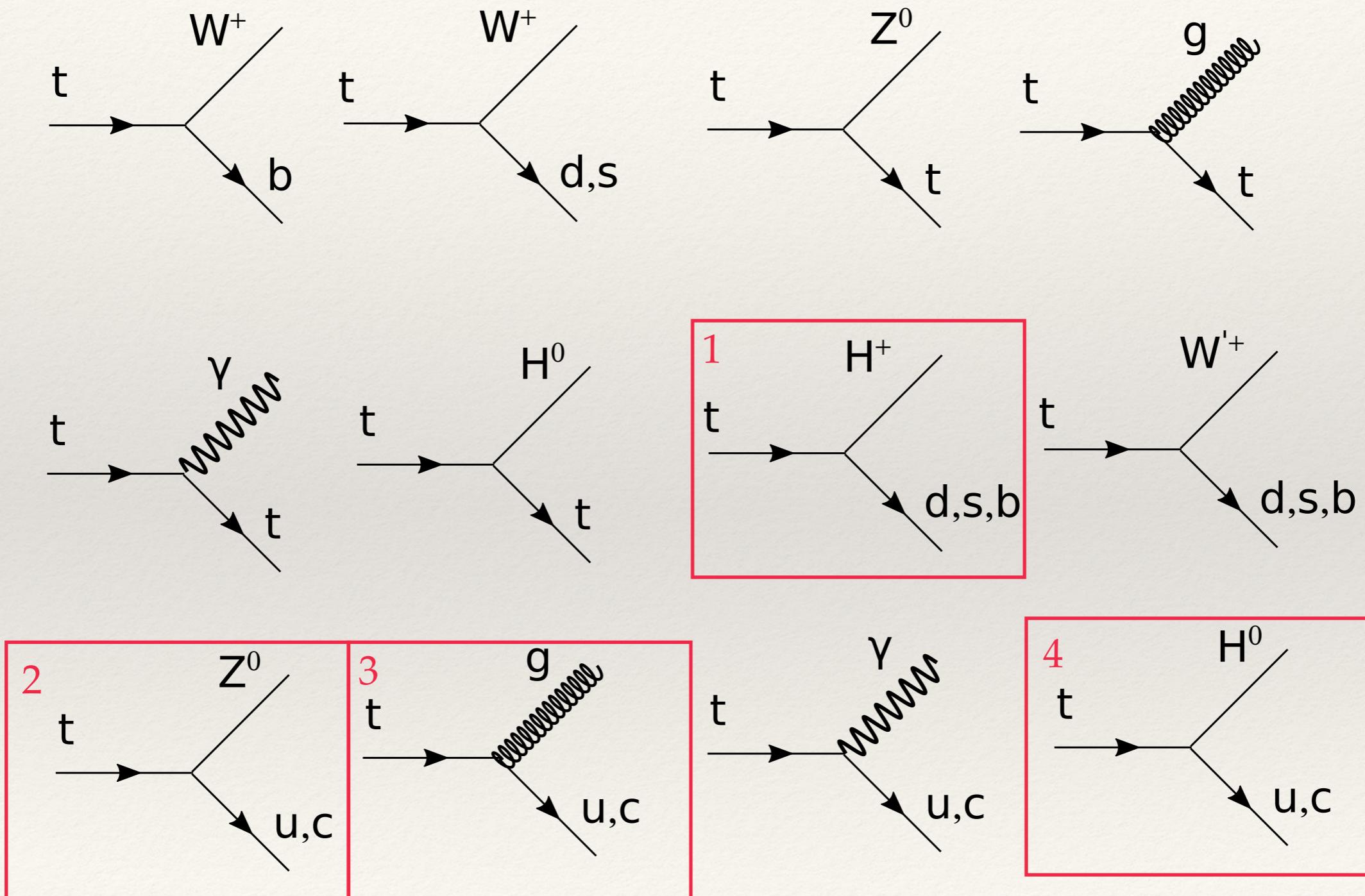


$$\mathcal{L}_{\gamma tc} = -e \bar{c} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (\lambda_{ct}^L P_L + \lambda_{ct}^R P_R) t A_\mu + H.c.$$

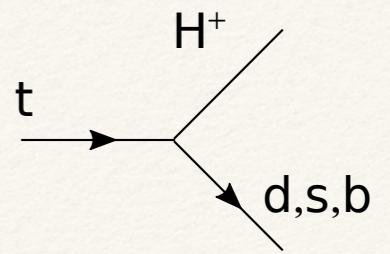


$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}} \bar{c} (\eta_{ct}^L P_L + \eta_{ct}^R P_R) t H + H.c.$$

Scope of this talk:



I. Top quark branching ratios

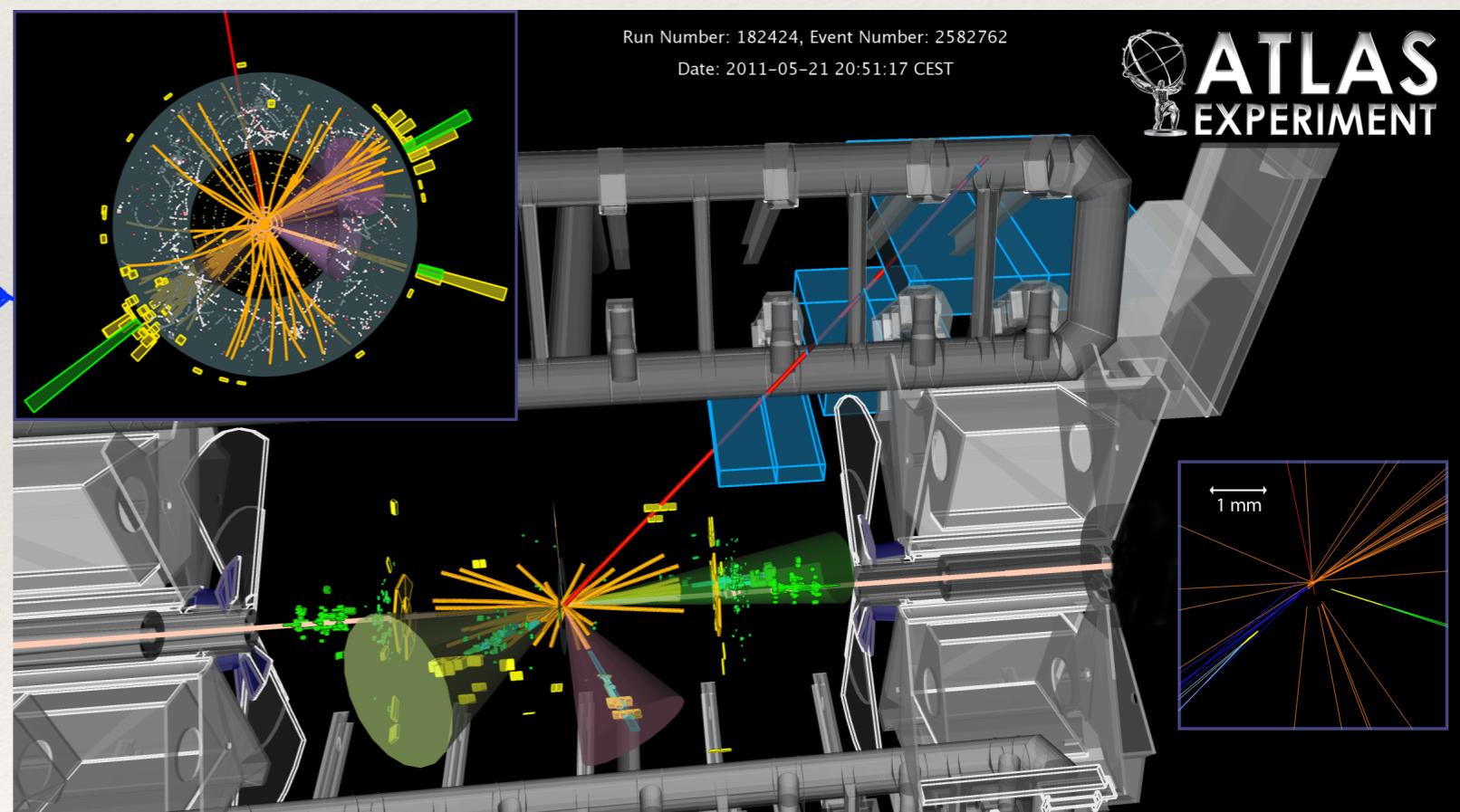


- The standard top quark decay via a W boson respects universality.
- But a decay to a charged Higgs boson has mass-dependent couplings.
- The strategy of the analysis: measure separately the rates of

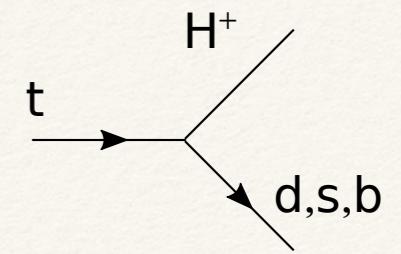
- e + jets
 - μ + jets
 - ee + jets
 - $\mu\mu$ + jets
 - $e\mu$ + jets
 - $e\tau$ + jets
 - $\mu\tau$ + jets
- }
- } Lepton + jets
- }
- } Dilepton+jets
- }
- } Lepton + τ^+ jets

*in a sample enriched in $t\bar{t}$ events in
4.6 fb^{-1} of pp collisions at 7 TeV*

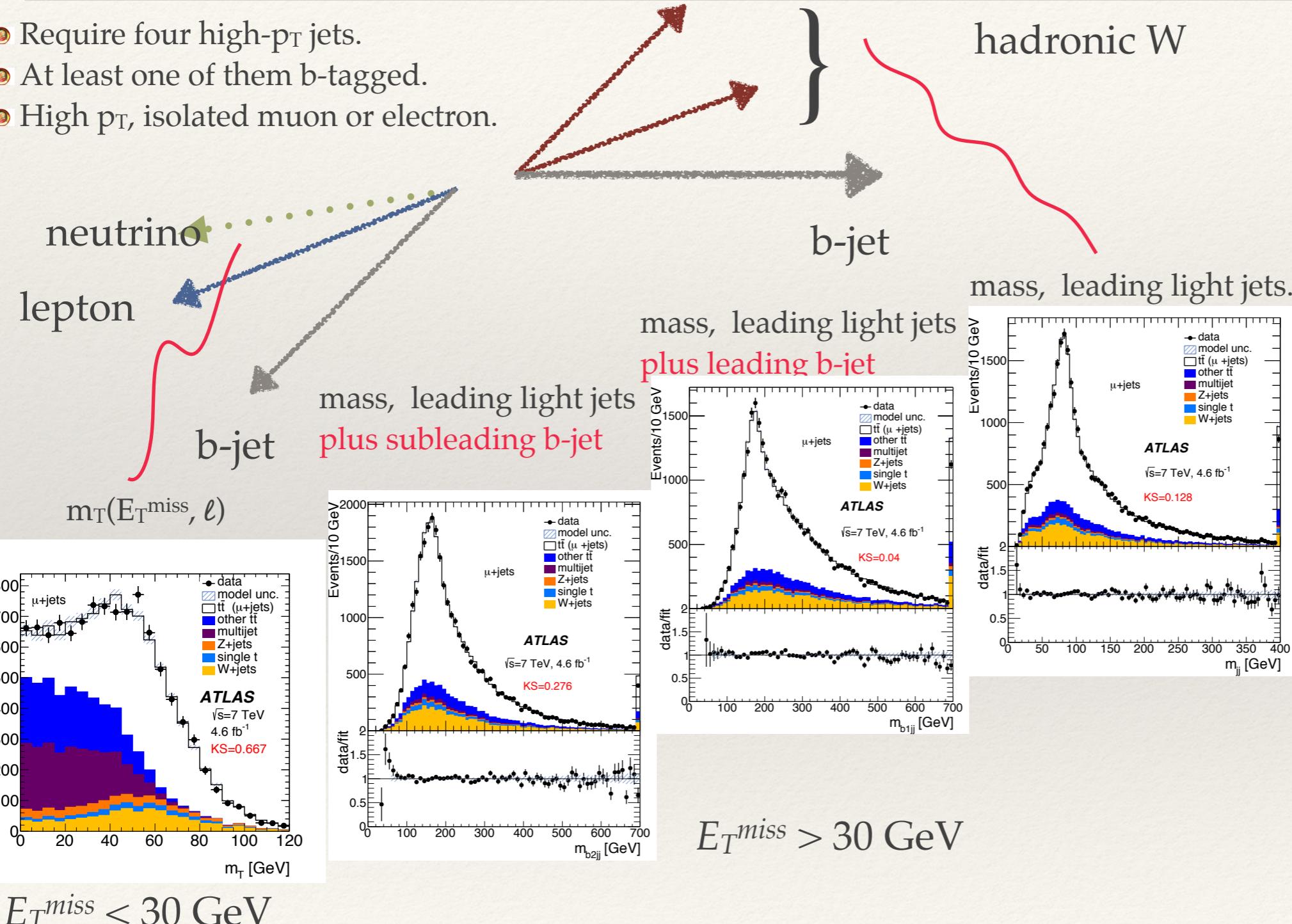
- Yield in these 7 categories can be compared with SM prediction that $BR(t \rightarrow Wq) = 100\%$.



I. Top quark branching ratios: lepton + jets channels



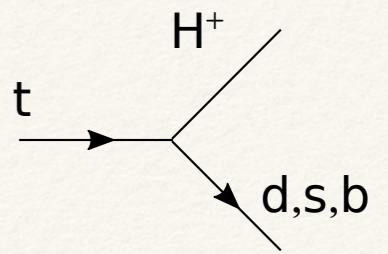
- Require four high- p_T jets.
- At least one of them b-tagged.
- High p_T , isolated muon or electron.



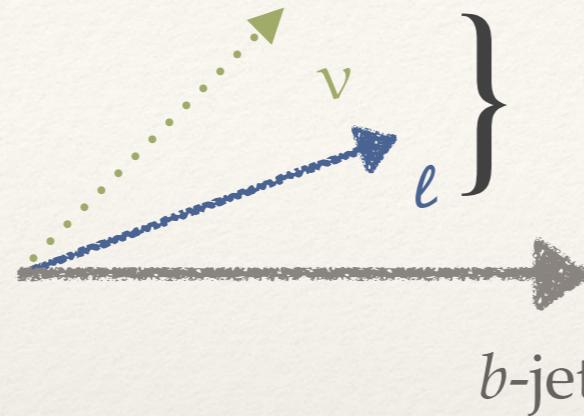
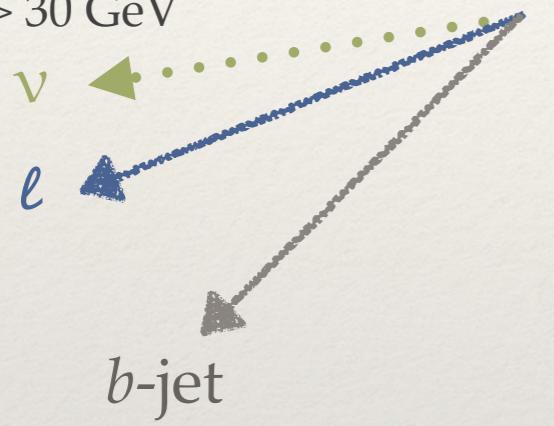
These four mass variables are fit to the total number of multijet, $t\bar{t}$, and $W+jets$ events..

Channel	$e+jets$	$\mu+jets$
$t\bar{t} \rightarrow \ell+jets$ (MC)	19710 ± 280	25090 ± 310
$t\bar{t}$ (other) (MC)	2674 ± 30	3393 ± 30
$W+jets$ (MC)	4800 ± 500	5600 ± 500
Z+jets (MC)	1900 ± 500	790 ± 200
Single top (MC)	910 ± 70	1170 ± 80
Diboson (MC)	5.0 ± 0.2	6.1 ± 0.2
Multijet	1000 ± 120	2800 ± 140
Total Background	11333 ± 700	13700 ± 600
Signal+Background	31000 ± 800	38800 ± 700
Data	30733	40414
χ^2/ndf	188/207	218/207

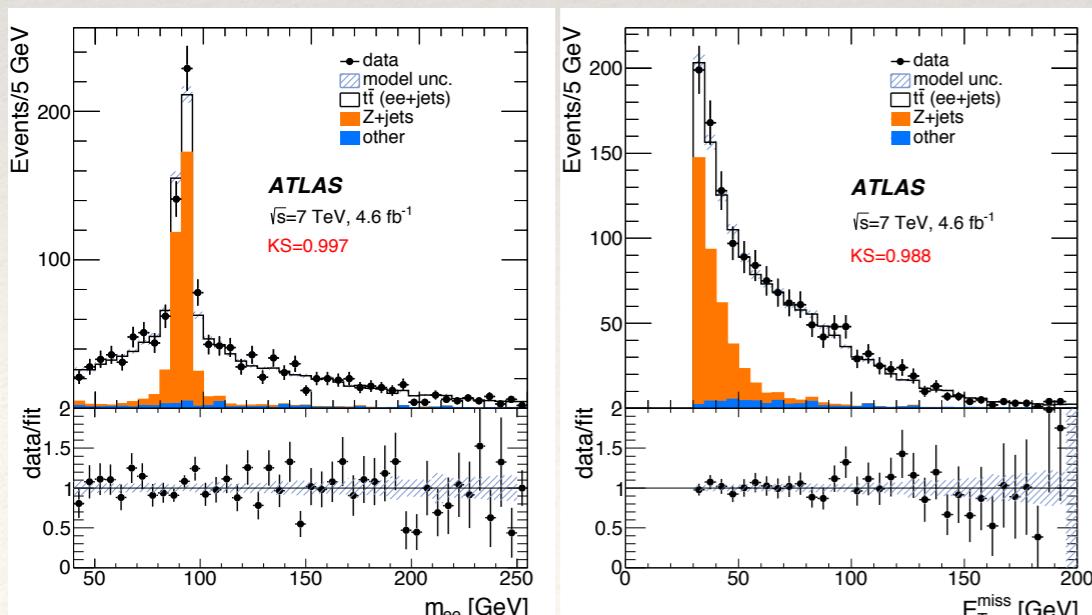
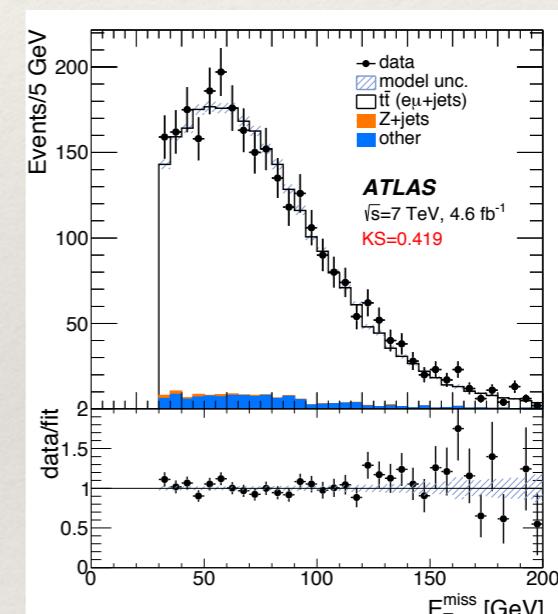
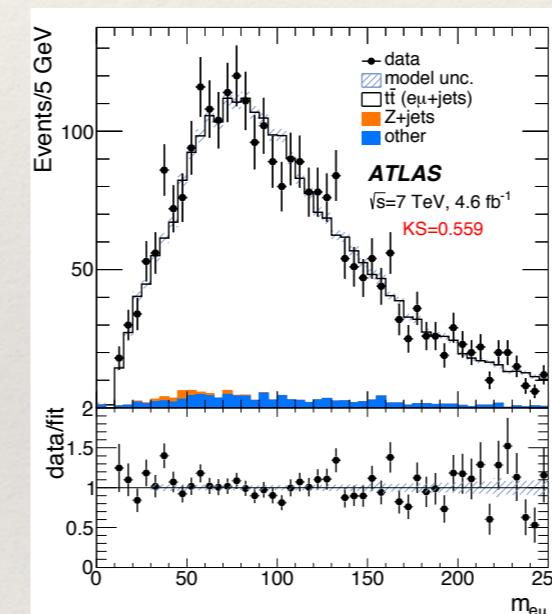
I. Top quark branching ratios: dilepton+jets channels



- Require two high- p_T jets.
- At least one of them b-tagged.
- High p_T isolated μ or e
- opposite sign high- p_T μ or e
- $E_T^{\text{miss}} > 30 \text{ GeV}$



Observables: E_T^{miss} and $m(\ell\ell')$

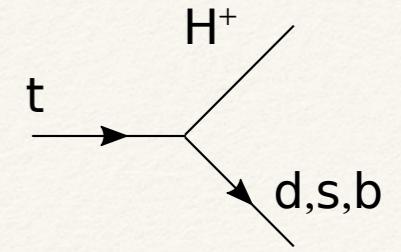


E_T^{miss} and $m(\ell\ell')$ are fit to the total number of $t\bar{t}$, and $Z + \text{jets}$ events.

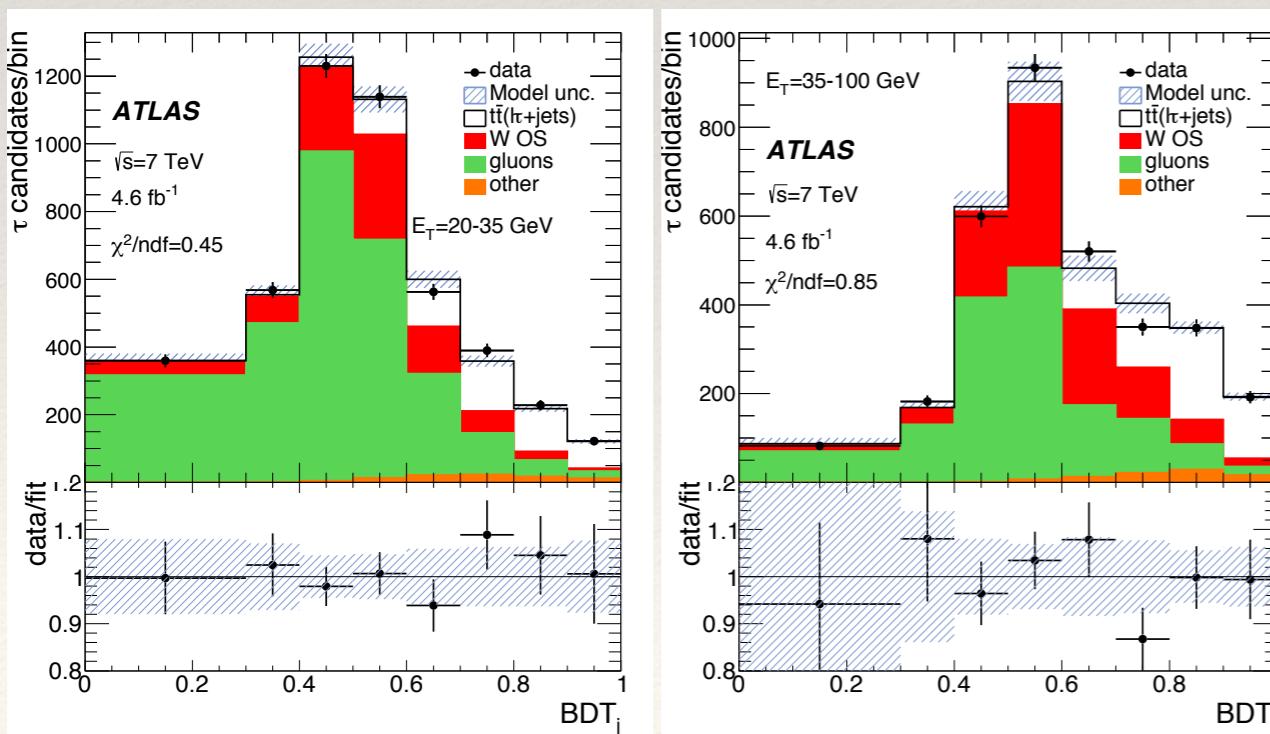
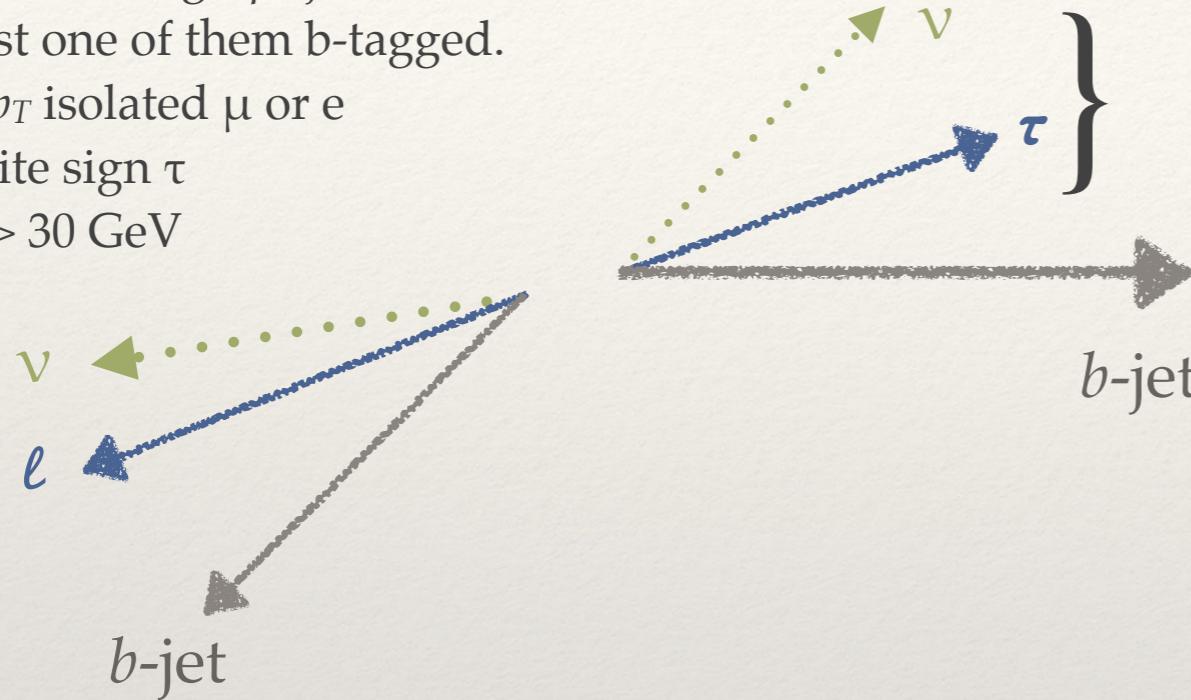
i.e. the joint pdf is fit.

Channel	$\mu\mu + \text{jets}$	$ee + \text{jets}$	$e\mu + \text{jets}$
$t\bar{t}$ (MC)	2890 ± 80	1000 ± 40	2640 ± 50
(2536 ± 11)	(903 ± 6)	(2420 ± 11)	
$Z + \text{jets}$ (MC)	1380 ± 50	379 ± 11	13 ± 4
(1267 ± 8)	(385 ± 11)	(13 ± 4)	
Single top (MC)	86 ± 8	36 ± 7	98 ± 9
Diboson (MC)	22 ± 1	8.1 ± 0.5	3.3 ± 0.3
Fake leptons	17 ± 10	17 ± 8	19 ± 10
Total Background	1430 ± 50	442 ± 15	136 ± 12
Signal+Background	4400 ± 100	1440 ± 40	2770 ± 80
Data	4102	1447	2848
χ^2/ndf	35/34	31/34	58/49

I. Top quark branching ratios: lepton+ τ +jets channels



- Require two high- p_T jets.
- At least one of them b-tagged.
- High p_T isolated μ or e
- opposite sign τ
- $E_T^{miss} > 30$ GeV



Strategy: separate the sample into events with real τ s and fake τ s based upon BDT response.

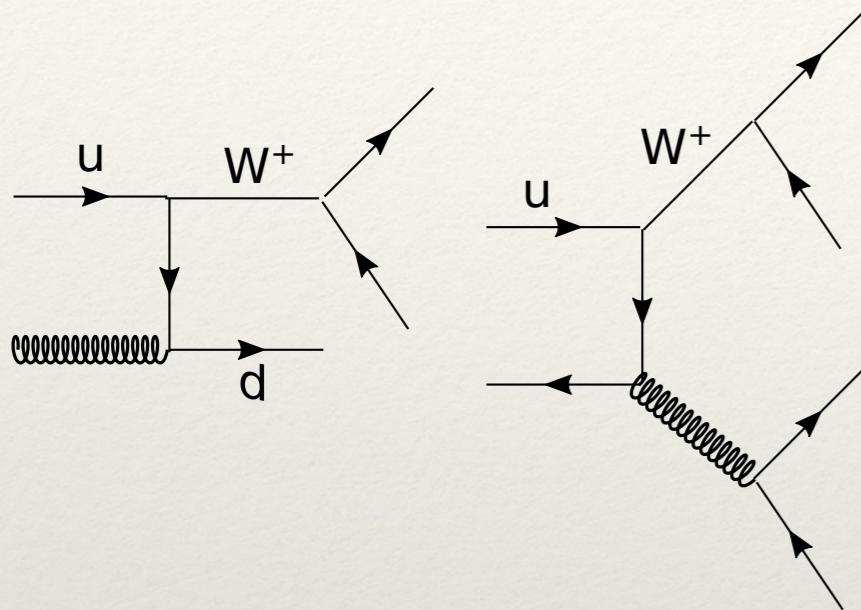
Then subtract sources of real τ + lepton.

Much more difficult to untangle the number of signal events because

- Large contributions from fake τ s
- Different BDT shape for light quark jets and for gluon jets.
 - A charged parton fakes easily a charged lepton more easily than a neutral parton.
 - So two templates are used for fakes. They are derived from data.

	$N_{t\bar{t}}^{\text{MC}}$	$B_{\text{non } t\bar{t} \tau}$	B_{lepton}	N_S^{Fitted}	$N_{t\bar{t}}^{\text{Fitted}}$
$20 < E_T^\tau < 35$ GeV	611 ± 5	76.2 ± 3.5	17.1 ± 1.1	N/A	N/A
$35 < E_T^\tau < 100$ GeV	621 ± 5	69.5 ± 3.3	17.6 ± 1.1	N/A	N/A
Combined E_T^τ bins	1232 ± 8	146 ± 5	34.8 ± 1.5	1460 ± 60 ($\chi^2/\text{ndf} = 0.69$)	1280 ± 60

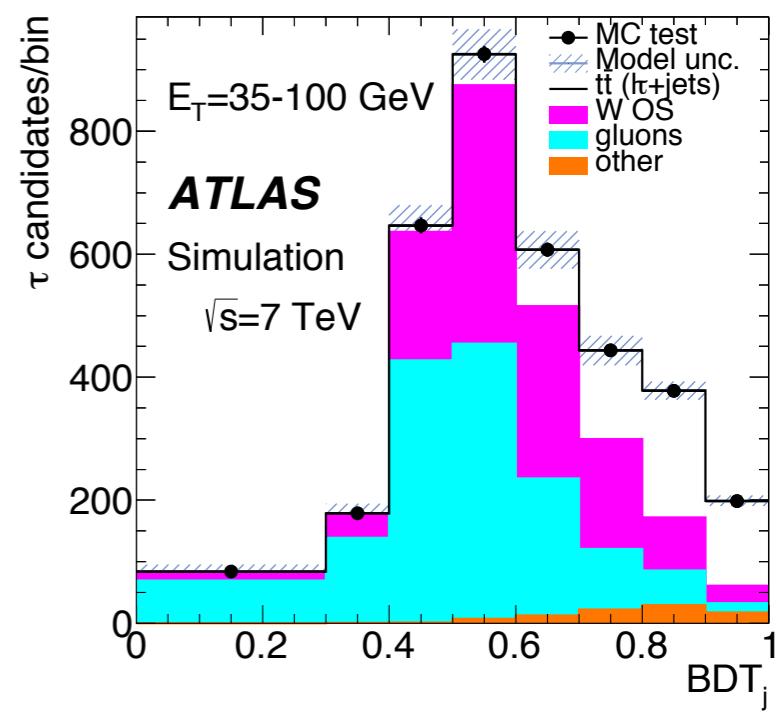
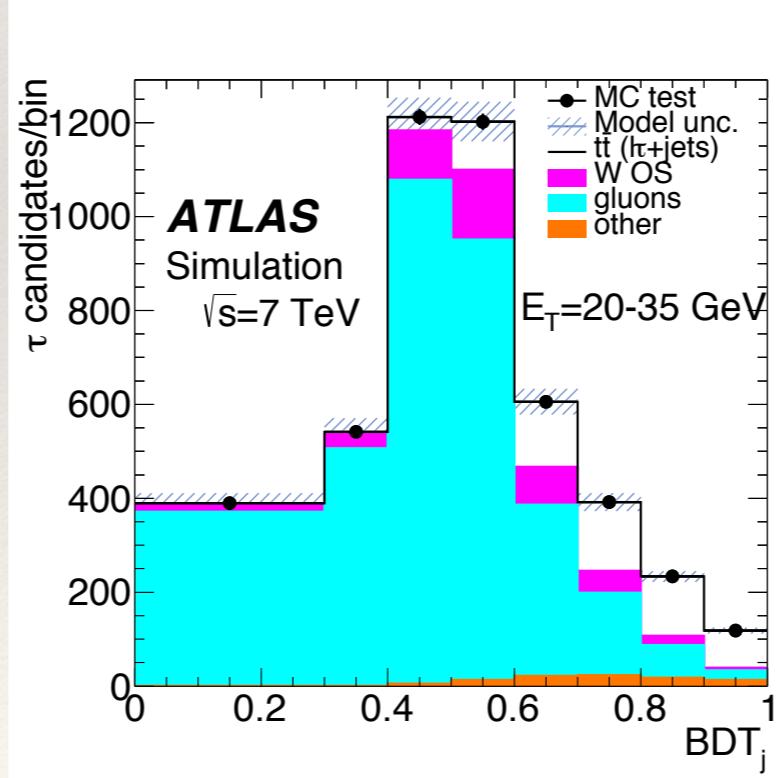
The derivation of the fake τ templates is quite involved.



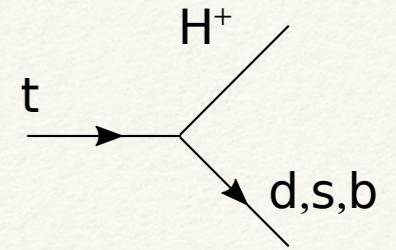
W^+ quark jet: sign correlation when q fakes τ

W^+ gluon jet: no sign correlation when q fakes τ

- ➊ A control region is constructed (releases b-tagging requirement)
- ➋ Two samples:
 - ➌ $W+1\text{-jet}$ (SS and OS)
 - ➍ $W+2\text{ jets}$ (SS and OS)
- ➎ Templates are determined for +quark jet backgrounds & W +gluon jet backgrounds.
- ➏ Then these templates are fit to the data in the signal region.
- ➐ The entire procedure is validated on Monte Carlo



I. Top quark branching ratios: results



	$e + \text{jets}$	$\mu + \text{jets}$	$ee + \text{jets}$	$\mu\mu + \text{jets}$	$e\mu + \text{jets}$	$\ell\tau + \text{jets}$
$\mathcal{A}_{ch} \cdot \epsilon_{ch} (\%)$	14.02 ± 0.02	17.88 ± 0.02	7.09 ± 0.04	19.74 ± 0.08	9.50 ± 0.04	4.36 ± 0.02

Compute the acceptance & efficiency from Monte Carlo

Correct the measured event yields for acceptance & efficiency

Numbers are $\sigma \cdot \mathcal{BR}$ [events / pb]

	N_{ej} $N_{\ell j}$	$N_{\mu j}$	N_{ee}	$N_{\mu\mu}$ $N_{\ell\ell}$	$N_{e\mu}$	$N_{\ell\tau}$
Measured	30.62 ± 0.26 61.19 ± 0.40	30.57 ± 0.29	3.06 ± 0.12	3.19 ± 0.10 12.31 ± 0.20	6.06 ± 0.12	6.39 ± 0.30
SM	30.40 ± 1.2 60.64 ± 2.4	30.40 ± 1.2	2.86 ± 0.11	2.86 ± 0.11 10.95 ± 0.44	5.72 ± 0.20	6.39 ± 0.25

Extract from these the total cross section $\sigma(t\bar{t}) = 183 \pm 9(\text{stat}) \pm 23(\text{syst}) \pm 3(\text{lumi})$ as well as branching ratios;

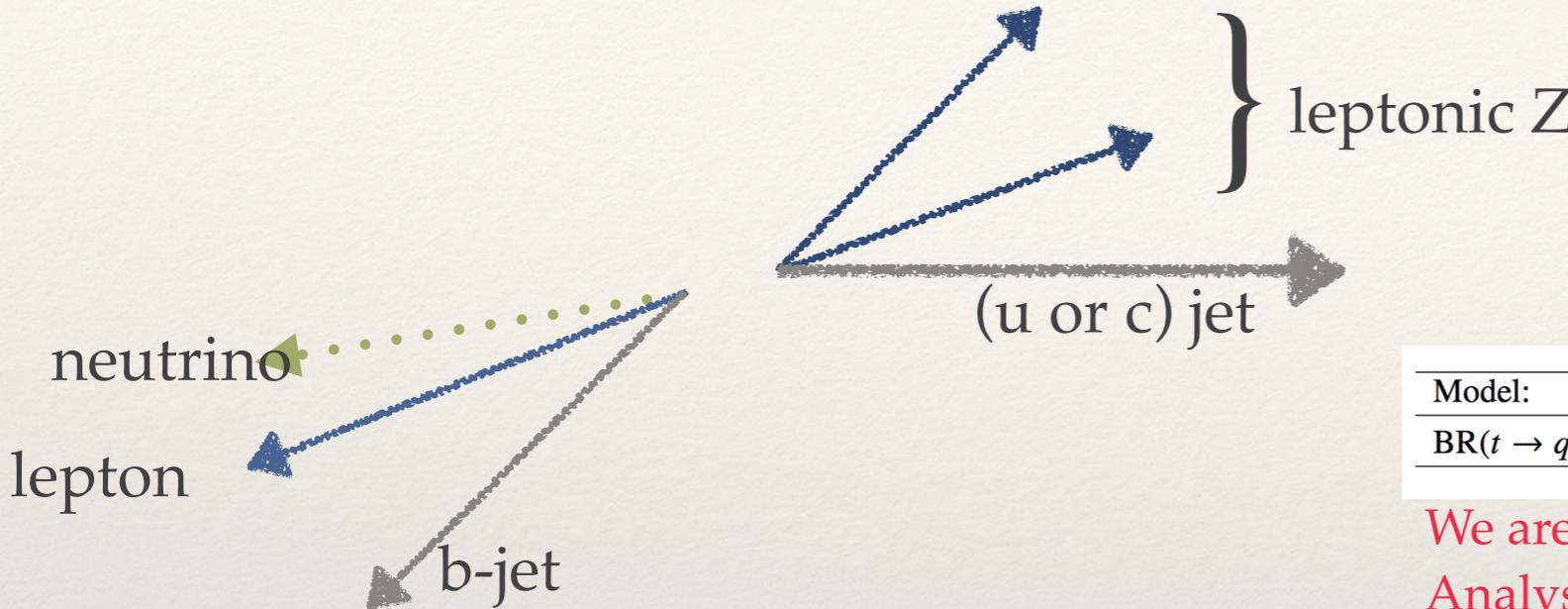
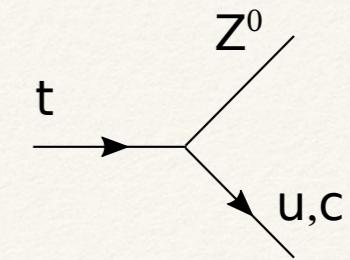
	Measured (top quark)	SM	LEP (W)
$\sigma_{t\bar{t}}$	$178 \pm 3 \text{ (stat.)} \pm 16 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$	$177.3 \pm 9.0^{+4.6}_{-6.0} \text{ pb}$	
B_j	$66.5 \pm 0.4 \text{ (stat.)} \pm 1.3 \text{ (syst.)}$	67.51 ± 0.07	67.48 ± 0.28
B_e	$13.3 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$	12.72 ± 0.01	12.70 ± 0.20
B_μ	$13.4 \pm 0.3 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$	12.72 ± 0.01	12.60 ± 0.18
B_τ	$7.0 \pm 0.3 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$	7.05 ± 0.01	7.20 ± 0.13

Systematic errors are dominated by jet energy scale.

Bottom line: no evidence for BSM top quark decays.

II. Search for $t \rightarrow qZ$ decays

*note: $q=[u \text{ or } c]$ <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-08>



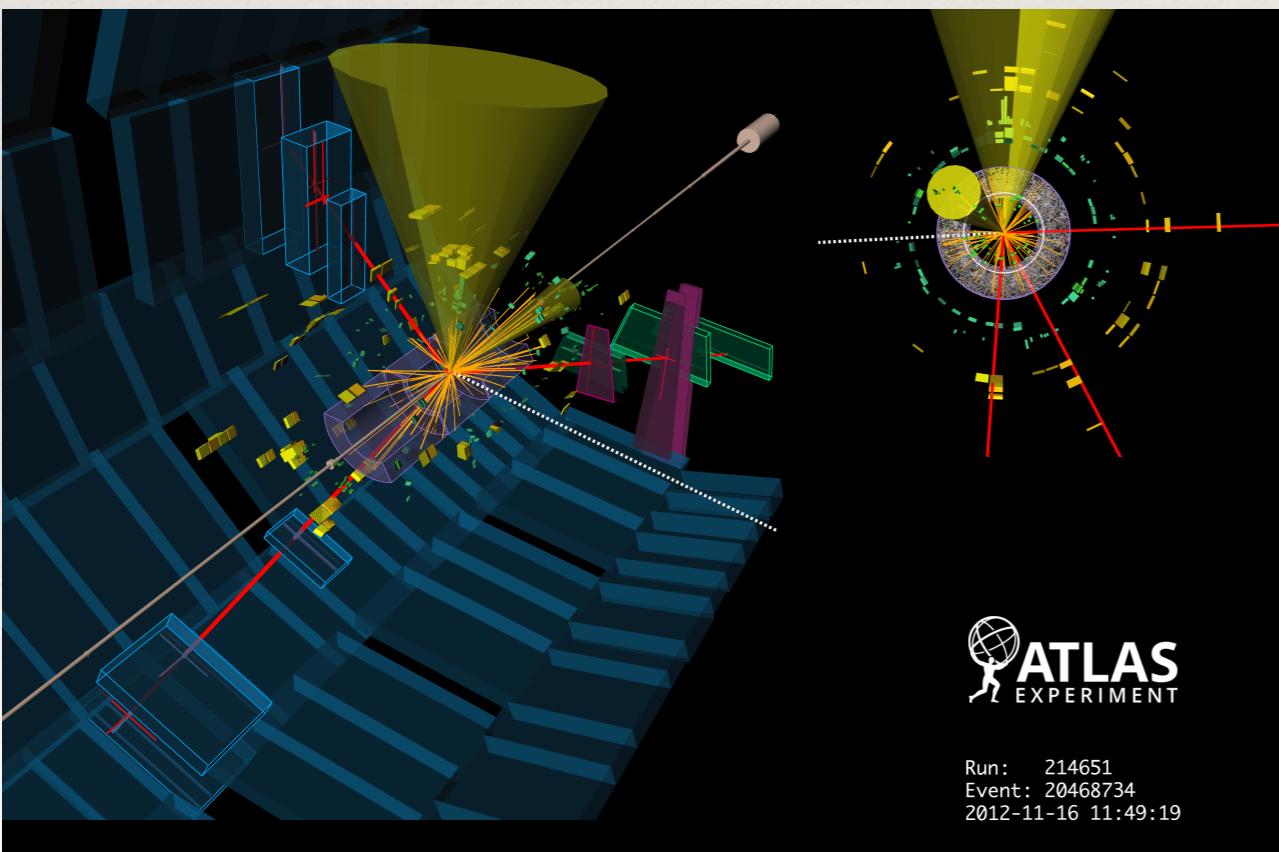
$$\begin{aligned} \mathcal{L}_{Ztc} = & -\frac{g}{2c_W} \bar{c} \gamma^\mu (X_{ct}^L P_L + X_{ct}^R P_R) t Z_\mu \\ & -\frac{g}{2c_W} \bar{c} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (\kappa_{ct}^L P_L + \kappa_{ct}^R P_R) t Z_\mu + H.c. \end{aligned}$$

Model:	SM	QS	2HDM	FC 2HDM	MSSM	R	SUSY	RS
$\text{BR}(t \rightarrow qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	

We are looking for the dramatic *trilepton* signature.
Analysis based upon 20.3 fb-1 pp collisions at 8 TeV

Cuts:

- ➊ Three isolated leptons
- ➋ Z-boson + lepton
- ➌ E_T^{miss}
- ➍ Two jets, at least one with b tag
- ➎ Consistency with
 - ➏ W mass
 - ➏ Z mass
 - ➏ (anti)top masses

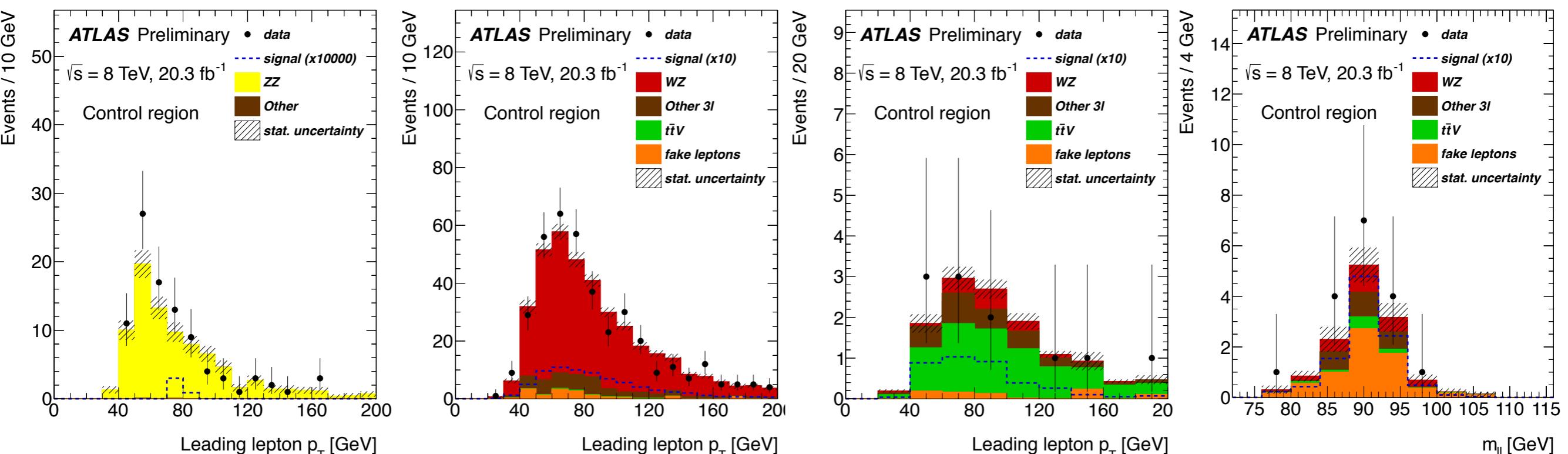
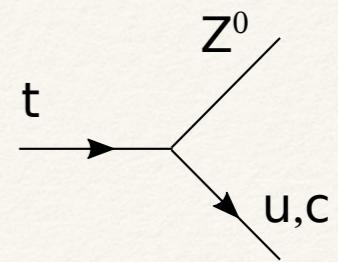


Background from diboson (WW, WZ), triboson (WWZ, WZZ, ZZZ), t̄tZ, Z+jets w/ fake leptons.

ZZ, WZ, and t̄tZ, Z+jets control regions defined & used to control background modeling

II. $t \rightarrow qZ$ decays: control plots

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPO-2014-08>



ZZ control region.

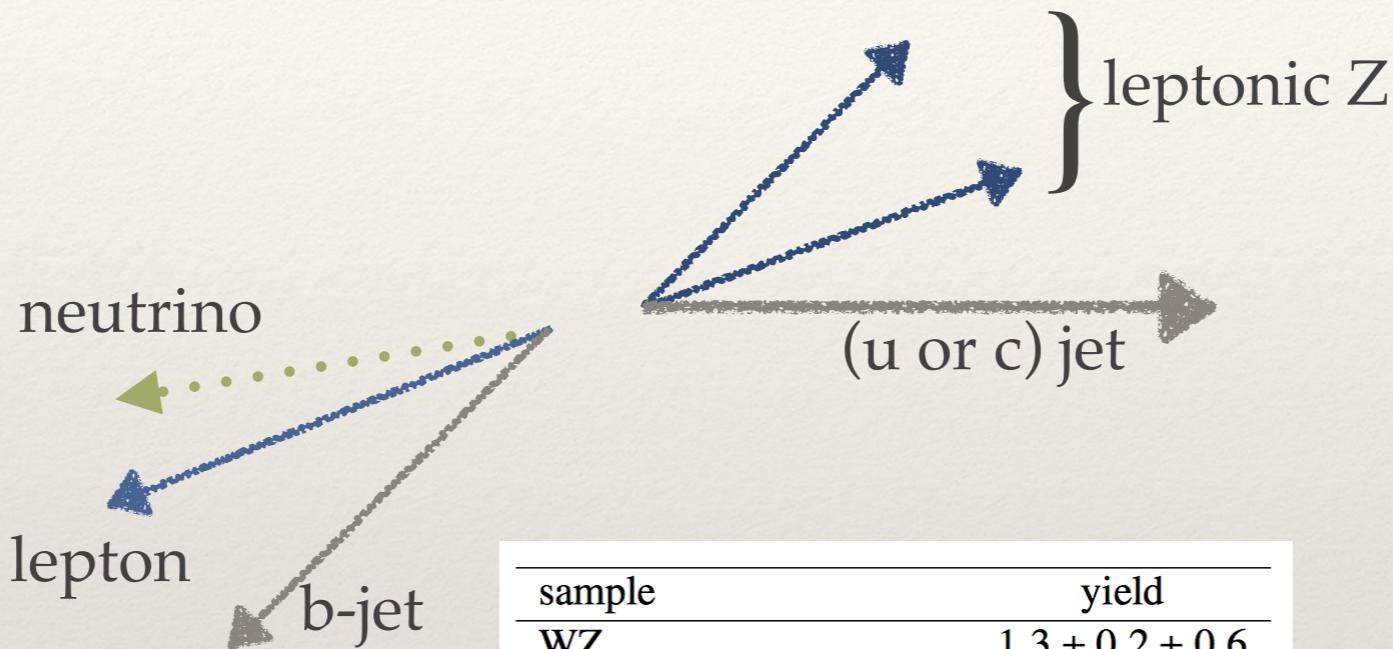
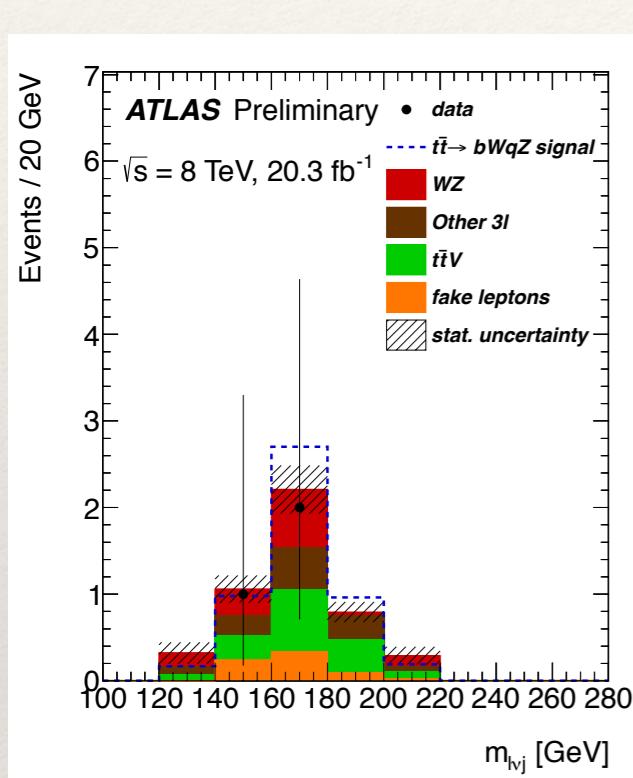
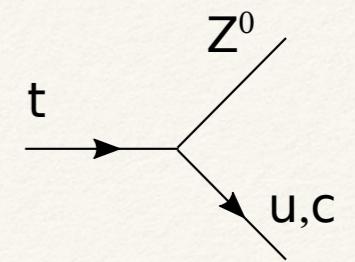
WZ control region.

$t\bar{t}V$ control region.

fake lepton control region. Fake lepton background estimated using “matrix method”

II. $t \rightarrow qZ$ decays: results

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPO-2014-08>

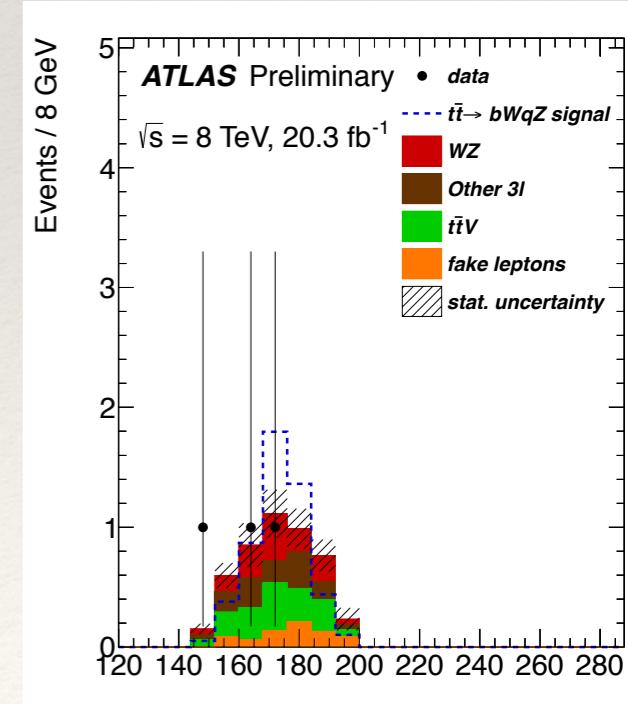
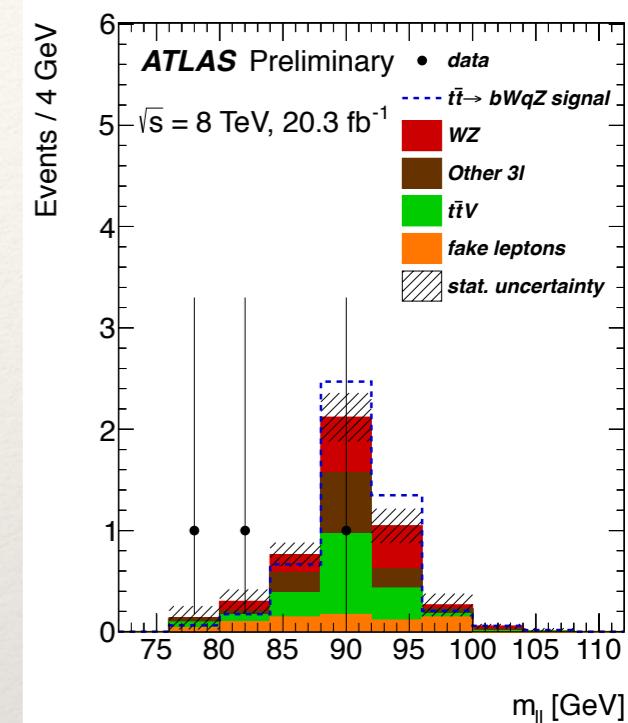


3 events are found, $4.7 \pm 0.4 \pm 1.0$
expected from background ==> no
evidence for FCNC $t \rightarrow Zq$ decays.

$\text{BR}(t \rightarrow Zq) < 0.07\% \text{ (95\% CL)}$

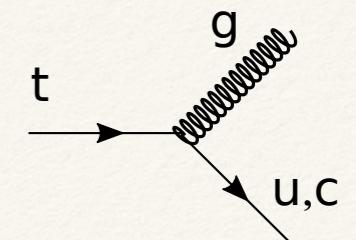
sample	yield
WZ	$1.3 \pm 0.2 \pm 0.6$
$t\bar{t}V$	$1.5 \pm 0.1 \pm 0.5$
tZ	$1.0 \pm 0.1 \pm 0.5$
fake leptons	$0.7 \pm 0.3 \pm 0.4$
other backgrounds	$0.2 \pm 0.1 \pm 0.1$
Total background	$4.7 \pm 0.4 \pm 1.0$
data	3
signal efficiency [$\times 10^{-4}$]	$7.8 \pm 0.1 \pm 0.8$

Main systematics are signal modelling
modeling, background modeling, and
jet energy scale



III. FCNC production of single top quarks

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-13/>



- Studied through the production processes like

- Interaction Lagrangian:

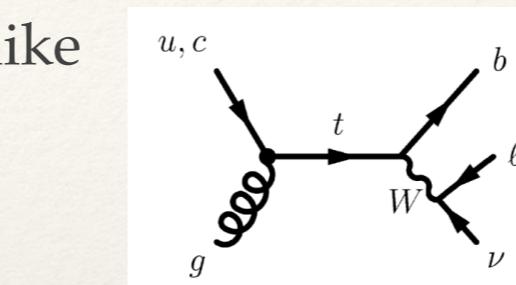
$$\mathcal{L}_{gtc} = -g_s \bar{c} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (\zeta_{ct}^L P_L + \zeta_{ct}^R P_R) t G_\mu^a$$

Aguilar-Saavedra Nucl.Phys.B812:181-204,2009

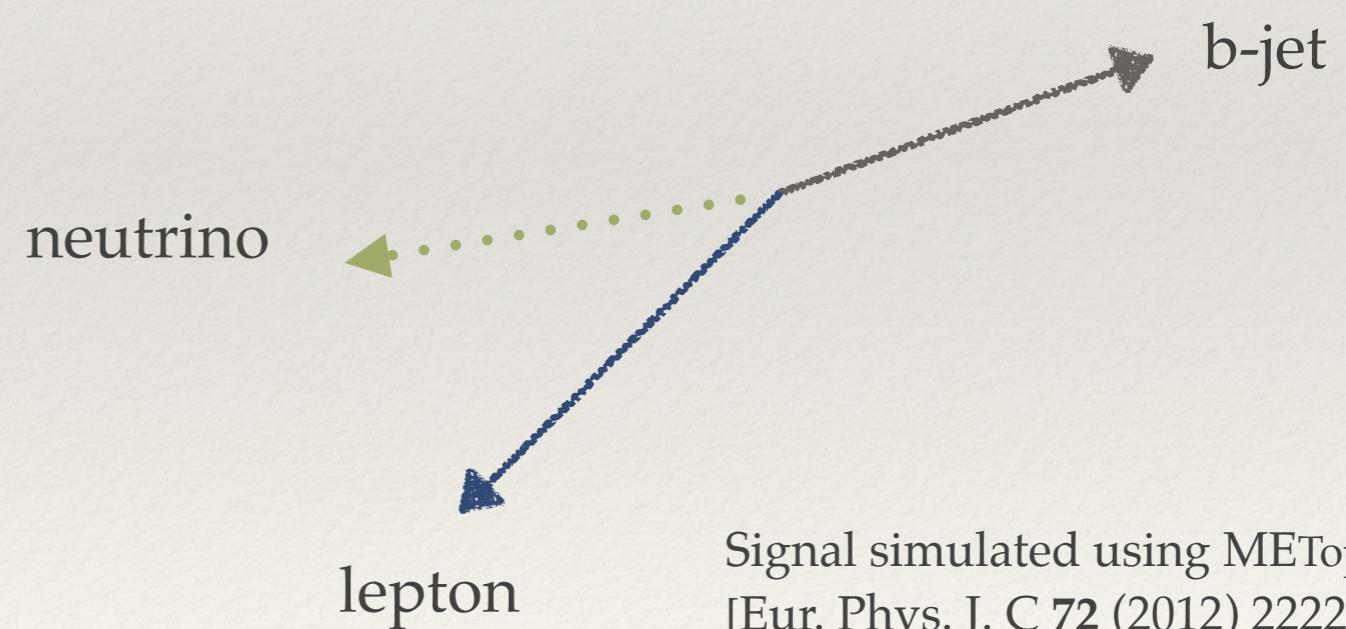
$$\mathcal{L}_S = -g_s \sum_{q=u,c} \frac{\kappa_{qgt}}{\Lambda} \bar{q} \lambda^a \sigma^{\mu\nu} (f_q + h_q \gamma_5) t G_{\mu\nu}^a + H.c.$$

Coimbra et al. Eur. Phys. J. C 72 (2012) 2222

Signature: leptonic decay of a top quark (lepton, E_T^{miss} , b-jet and nothing else in the event).

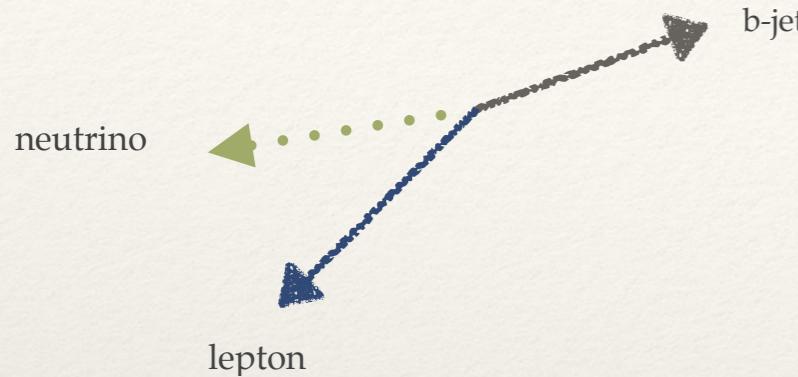
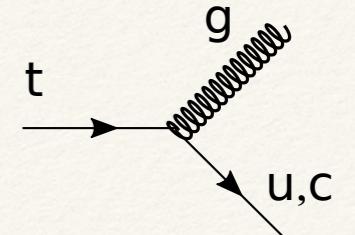


rather than the decay process.



III. FCNC single top production: selection cuts and backgrounds

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-13/>



Selection cuts:

- Isolated **muon** or **electron** $pT > 25 \text{ GeV}$
- **Jet**, $p_T > 25 \text{ GeV}$ with a **b-tag**
 - efficiency 50%
 - light quark mistag rate 0.07%
 - charm quark mistag rate 3.9%
- $E_T^{\text{miss}} > 30 \text{ GeV}$
- $m_T(W) > 50 \text{ GeV}$ suppresses multijet bkg.

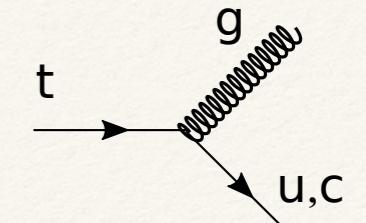
and

a $\Delta\phi(\text{b-jet}, \text{l})$ -dependent p_T cut
to further reduce multijet
background.

A control region enhanced in $W+jets$ is constituted by relaxing the b-tagging requirement.

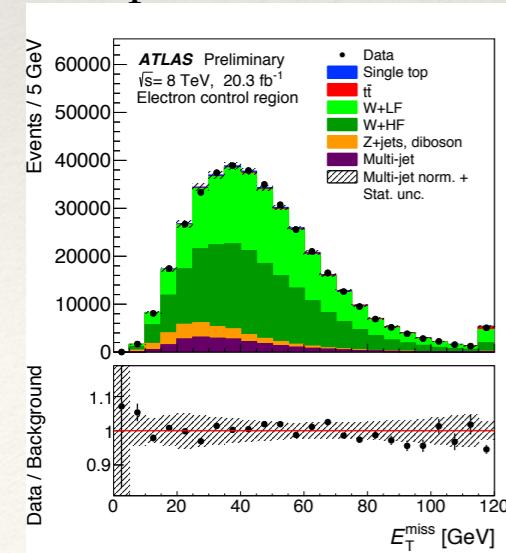
III. FCNC single top production:background estimation

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-13/>

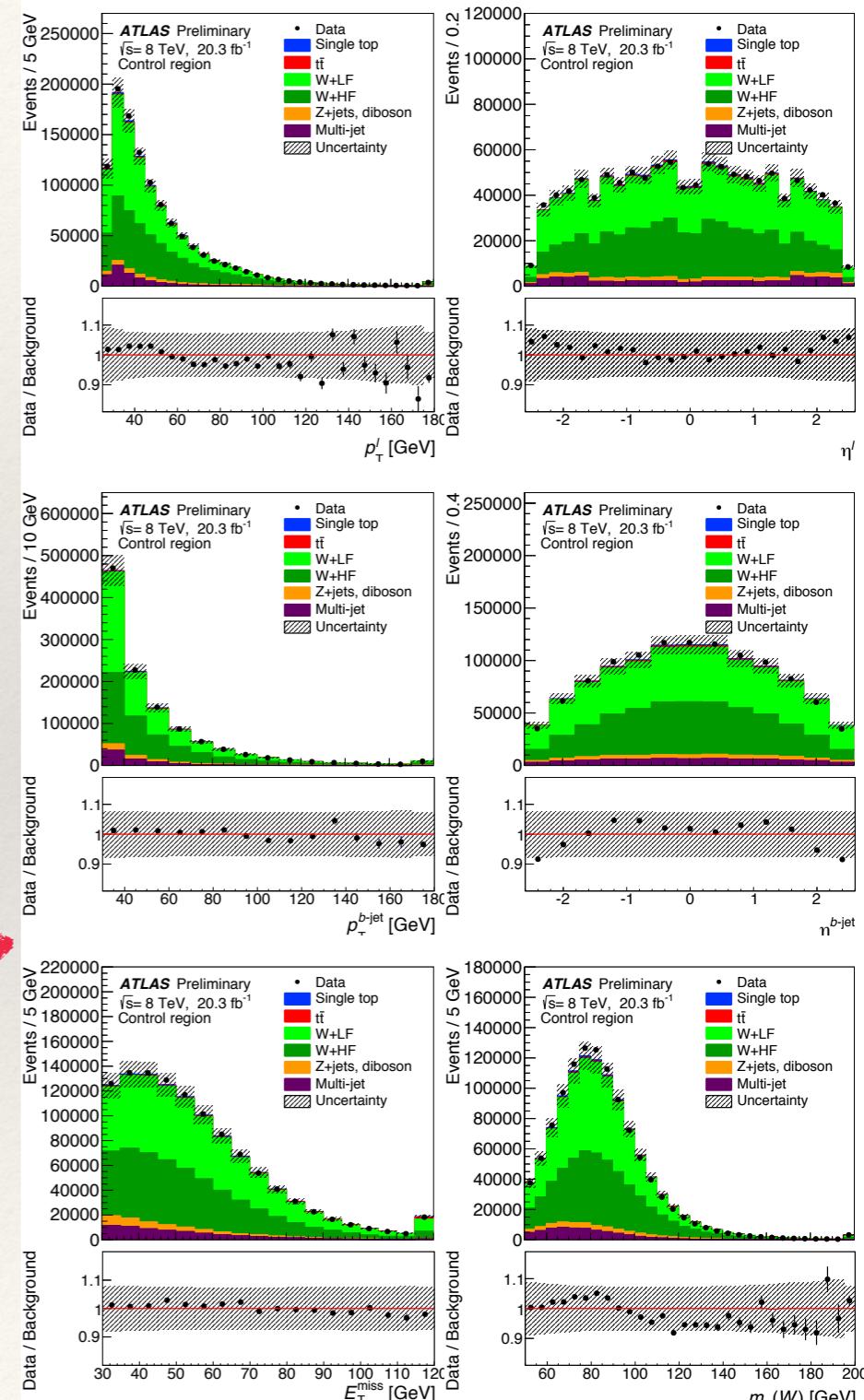


Backgrounds:

- $t\bar{t}$, W+Light Flavor, W+Heavy Flavor, Z+jets, diboson: estimate from MC
- QCD Multijet with fake lepton
- muons: *anti-muon model* a data driven model in which the shape of the muon multijet background is obtained by inverting several of the muon ID cuts.
- electrons: *jet-lepton model* in which the shape of the QCD multijet background is taken from pythia dijet events in which an electron-like jet is found (p_T , η requirements and 80-95% of the energy is deposited in the EM calorimeter).
- Systematic errors are then evaluated re-evaluating the background using the *matrix method* in which the distribution of real and fake leptons in a control region is obtained from the size of samples constituted with loose and tight lepton selections.
- Templates are normalized by fitting to the E_T^{miss} distribution.



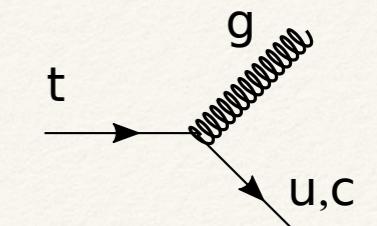
Control plots show good agreement in other kinematic distributions



III. FCNC single top production: results

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2014-13/>

Final results are obtained by fitting the data to the output of a neural net trained to separate signal from background.



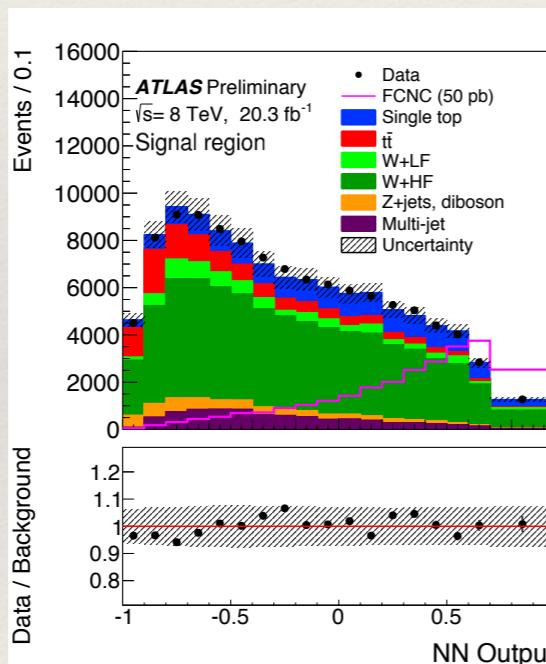
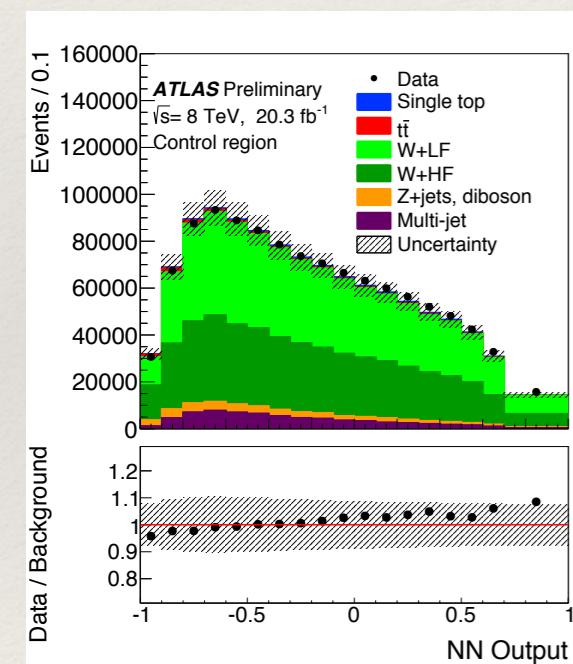
Limit:

$$\sigma_{qg \rightarrow t} \times \mathcal{B}(t \rightarrow Wb) < 3.4 \text{ pb} \quad 95\% \text{ CL}$$

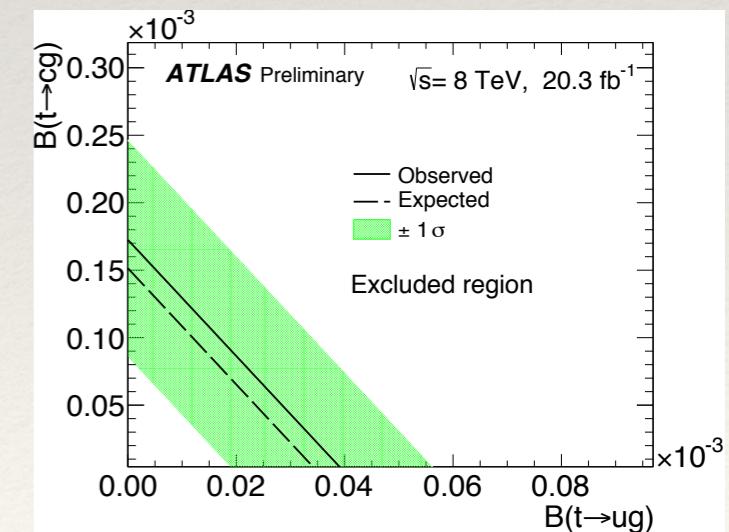
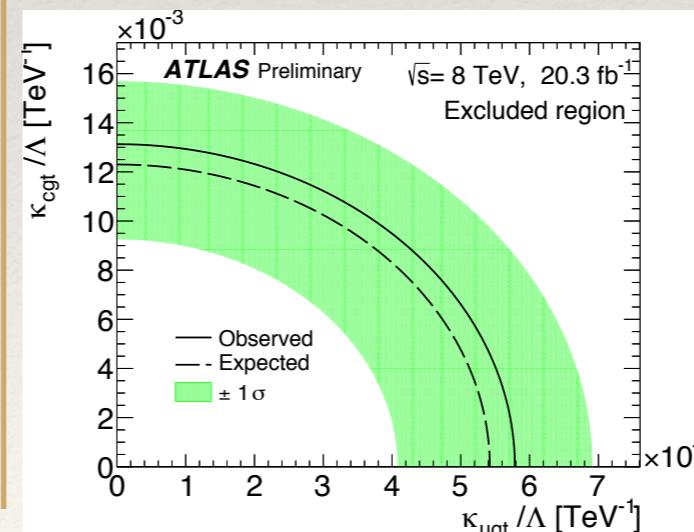
Further interpretations:

$$\mathcal{B}(t \rightarrow ug) < 4.0 \times 10^{-5} \quad \mathcal{B}(t \rightarrow cg) < 17 \times 10^{-5} \quad 95\% \text{ CL}$$

$$\kappa_{ugt}/\Lambda < 5.8 \times 10^{-3} \text{ TeV}^{-1} \quad \kappa_{cgt}/\Lambda < 13 \times 10^{-3} \text{ TeV}^{-1} \quad 95\% \text{ CL}$$



No evidence for FCNC production of single top quarks.

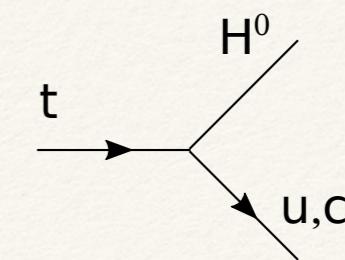


Can be used to infer limits on FCNC decays, too.

IV. Search for $t \rightarrow Hc$ decays

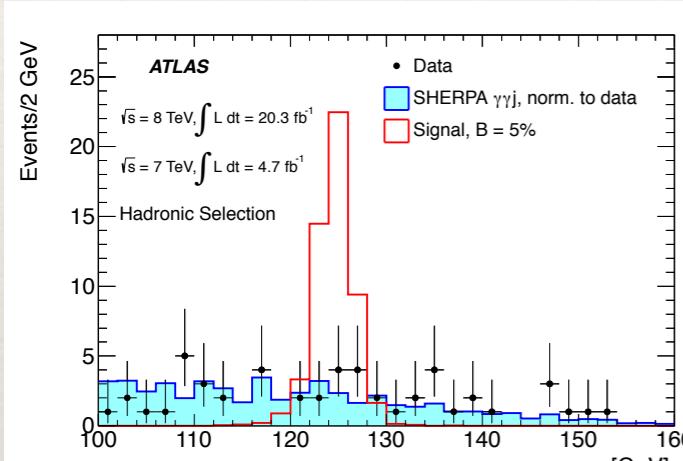
arXiv:1403.6293

look for hadronic or leptonic top decay using opposite a FCNC $t \rightarrow Hc$ decay
cut-based analysis using all of the 7 TeV (4.7 fb^{-1}) and 8 TeV data (20.3 fb^{-1})



The hadronic channel:

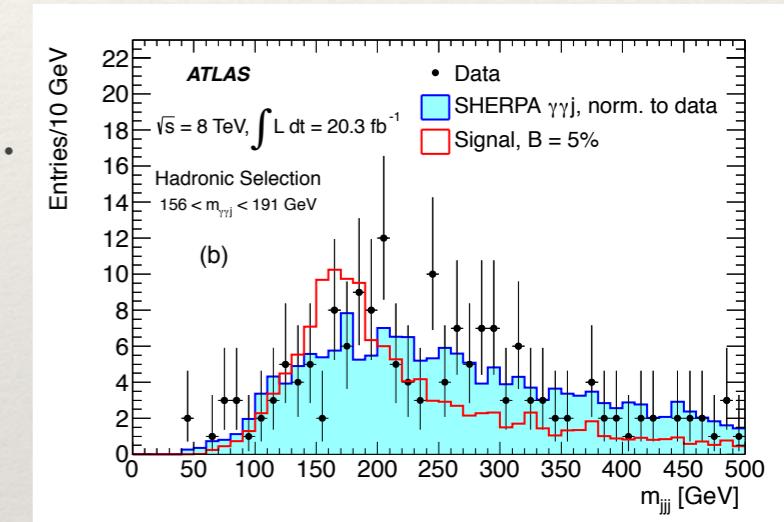
$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}}\bar{c}(\eta_{ct}^L P_L + \eta_{ct}^R P_R) t H + H.c.$$



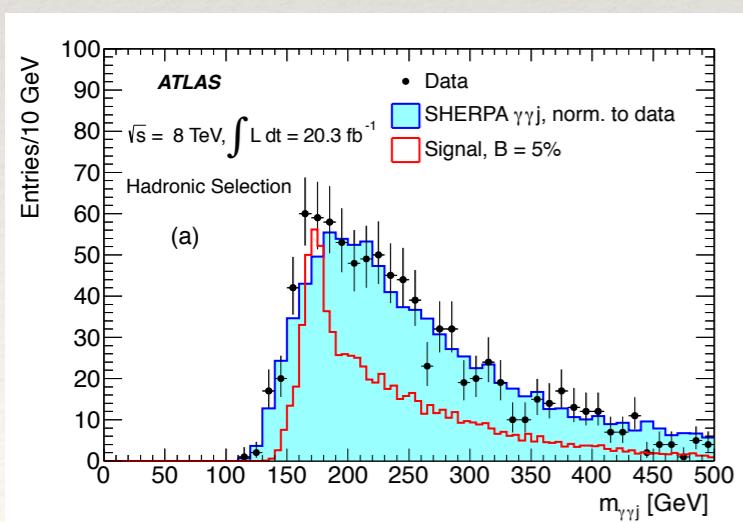
3.

Require ≥ 4 jets of which ≥ 1 b-tagged.

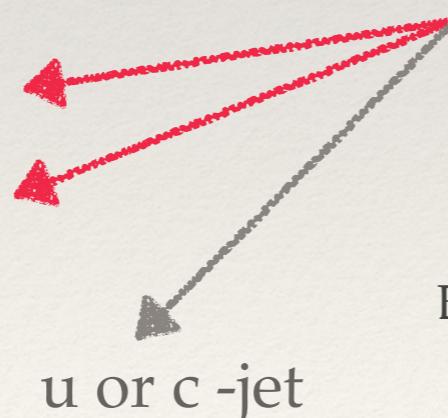
hadronic top decay



2. Window: [130,210] GeV



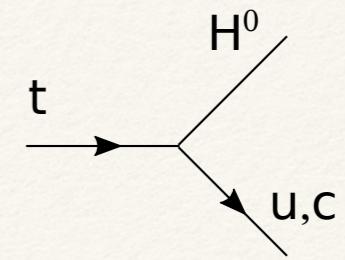
1. Window: [156,191] GeV
(four entries per event)



Backgrounds: nonresonant $\gamma\gamma$ production with additional jets
QCD multijets with fake γ
Resonant background (real Higgs decays)

IV. Search for $t \rightarrow H c$ decays

arXiv:1403.6293



The leptonic channel:

Backgrounds: nonresonant $\gamma\gamma$ production with additional jets

QCD multijets with fake γ

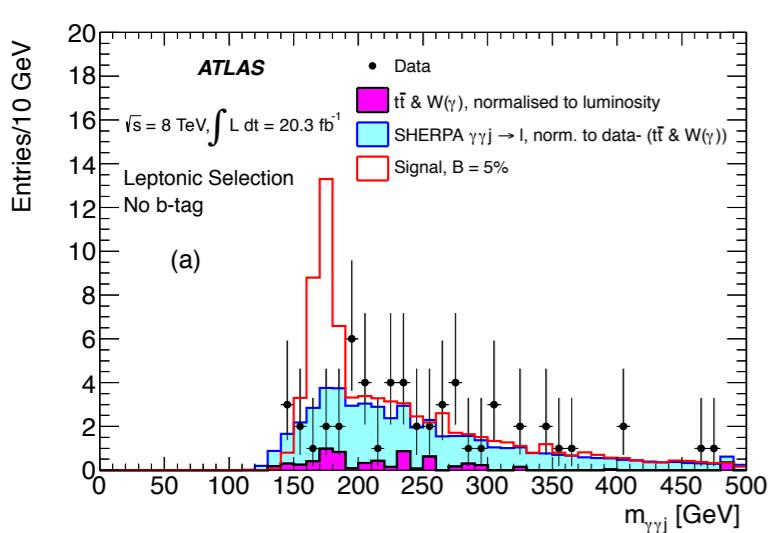
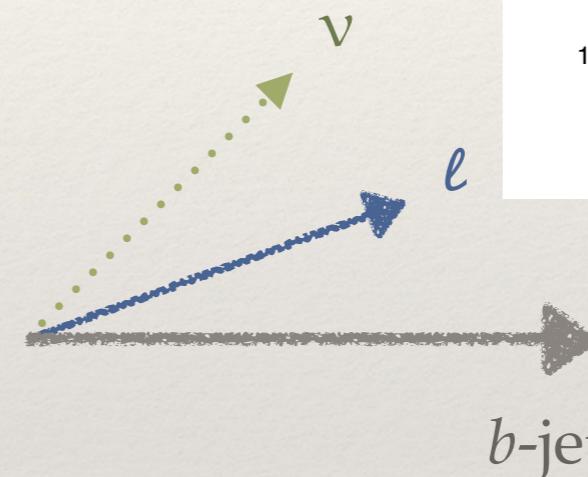
$t\bar{t}$ production

$W\gamma$ production

Resonant background (real Higgs decays)

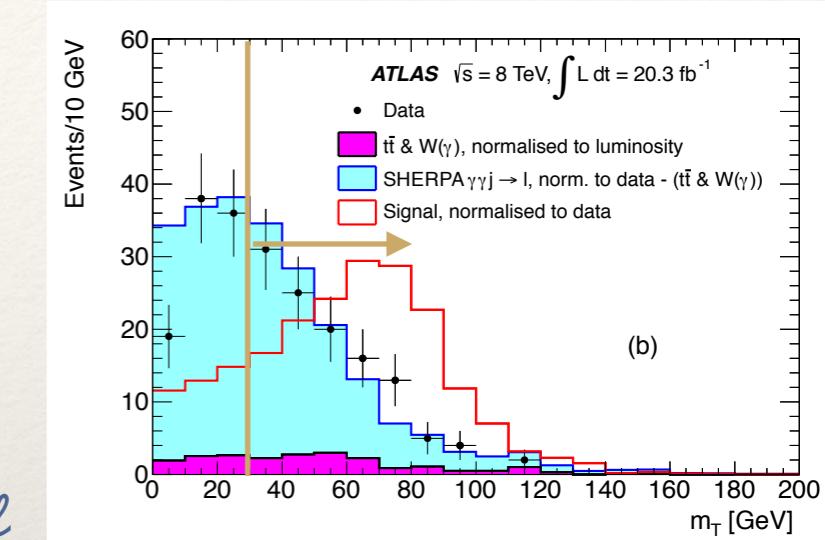
Require $>= 2$ jets

“Leading” jet selection based on p_T & bag

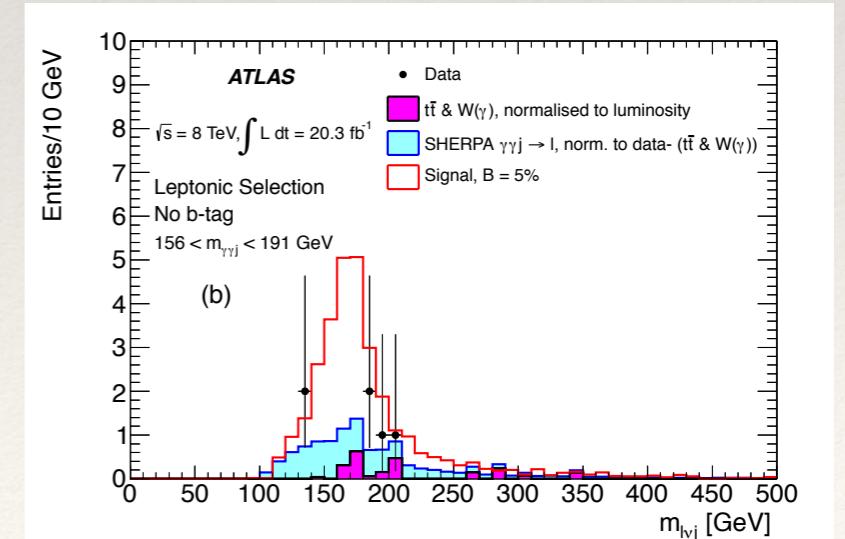


1. Window: [156,191] GeV

(two entries per event)



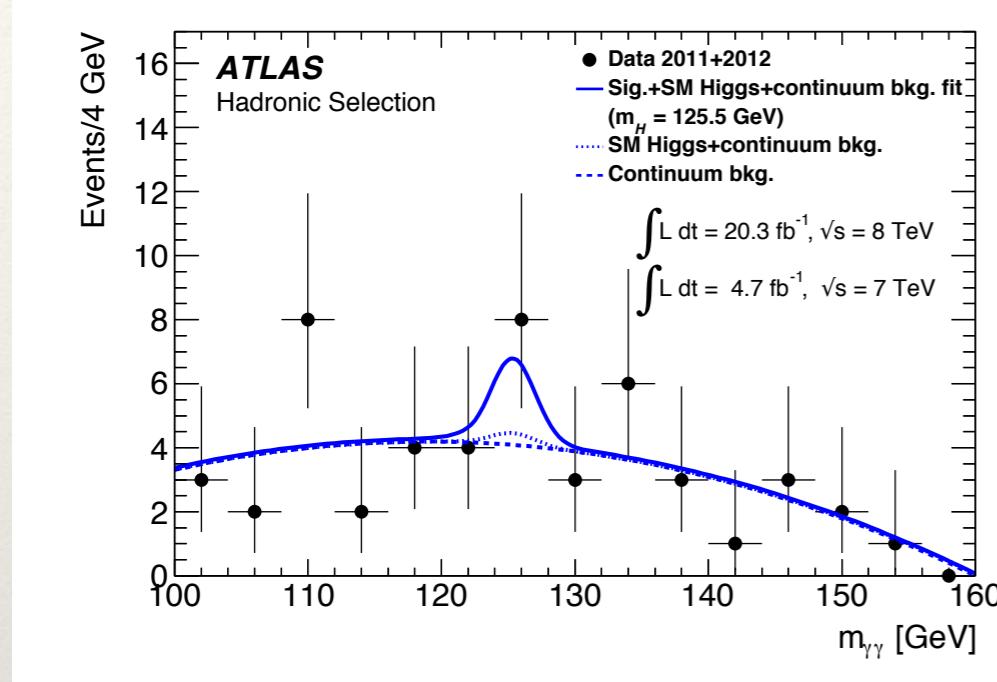
b-jet



2. Window: [135,205] GeV

IV. Search for $t \rightarrow H c$ decays: results

arXiv:1403.6293



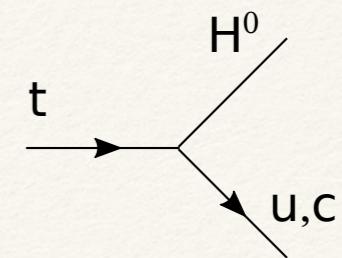
The fit is consistent with the background-only hypothesis at the 18% level.

A limit is set:

$$B(H \rightarrow t\bar{q}) < 0.79\% \quad 95\% \text{ CL}$$

$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17 \quad 95\% \text{ CL}$$

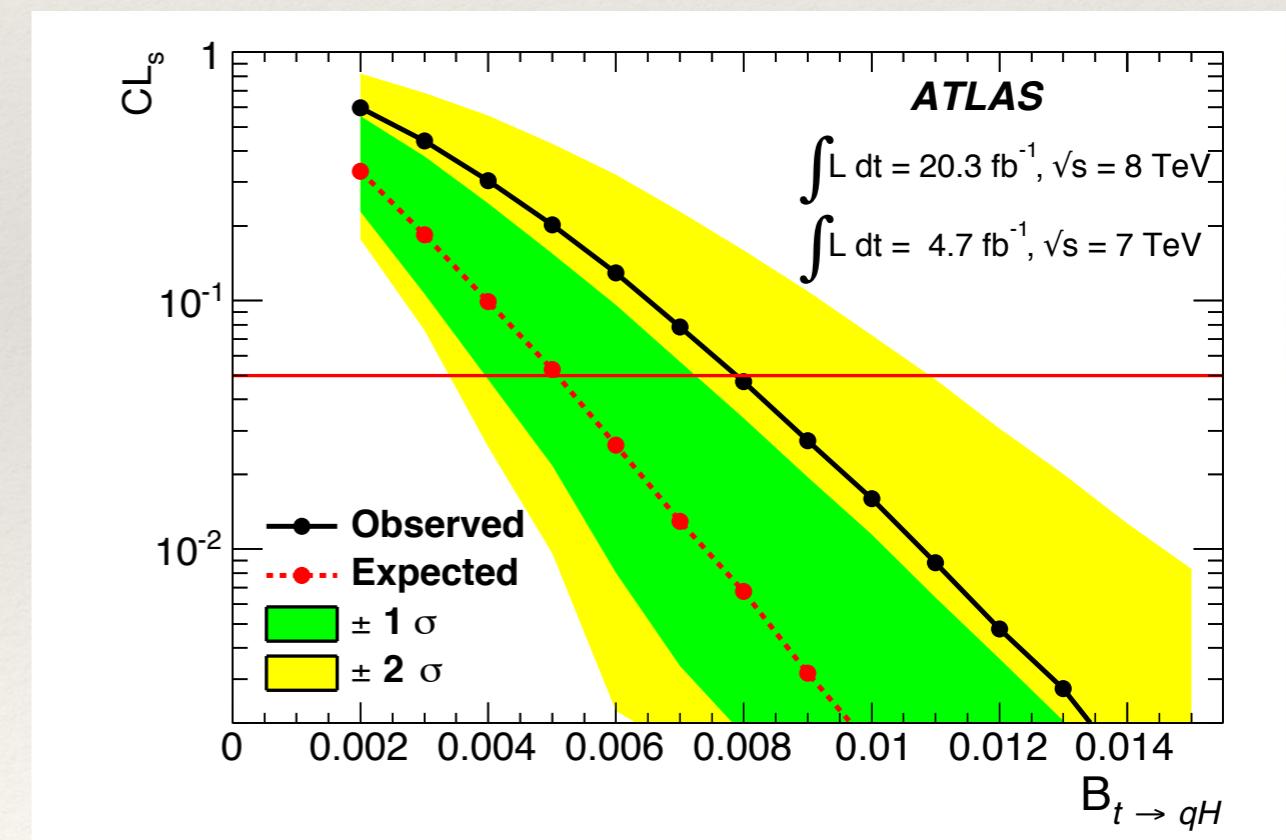
Jet Energy scale, ISF/FSR, and b-tagging dominate the systematic uncertainties.



For final results, only the shape of the background is taken from simulation.

The signal strength and branching fraction are taken from a fit to the mass spectrum.

Small contribution to background from real Higgs, fake hadronic top.





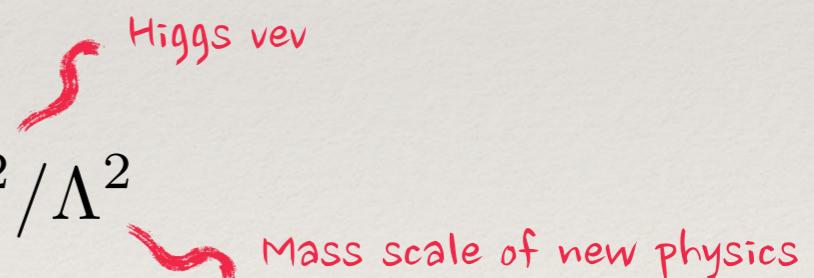
Conclusions

- >We presented four analyses sensitive to standard exotic, and FCNC decay modes of the top quark
- No sign of anomalies in the branching ratios of top to SM decay modes.
- No sign of anomalous FCNC decay modes $t \rightarrow Zq$, $t \rightarrow Hq$, $t \rightarrow gq$
- Results can be shown (or interpreted) in terms of branching ratios, summarised to the right in the table.

Channel	Branching Ratio	
$t \rightarrow \text{jets}$	$66.5 \pm 0.4 \pm 1.3\%$	
$t \rightarrow e\nu + X$	$13.3 \pm 0.4 \pm 0.5\%$	
$t \rightarrow \mu\nu + X$	$13.4 \pm 0.3 \pm 0.5\%$	
$t \rightarrow \tau\nu + X$	$7.0 \pm 0.3 \pm 0.5\%$	
$t \rightarrow Zq$	$< 7.0 \times 10^{-4}$	95% CL
$t \rightarrow Hq$	$< 7.9 \times 10^{-3}$	95% CL
$t \rightarrow ug$	$< 4.0 \times 10^{-5}$	95% CL
$t \rightarrow cg$	$< 4.0 \times 10^{-5}$	95% CL

But we keep working all of these channels since:

New physics enters into anomalous couplings as v^2/Λ^2



And higher precision is equivalent to higher reach in the mass scale Λ for new physics in top quark production & decay.

As the LHC reaches for higher energies, the top group reaches for higher precision and higher mass scales.

