FCNC searches at ATLAS and CMS

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Rencontres de Moriond 2019

March 17th 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

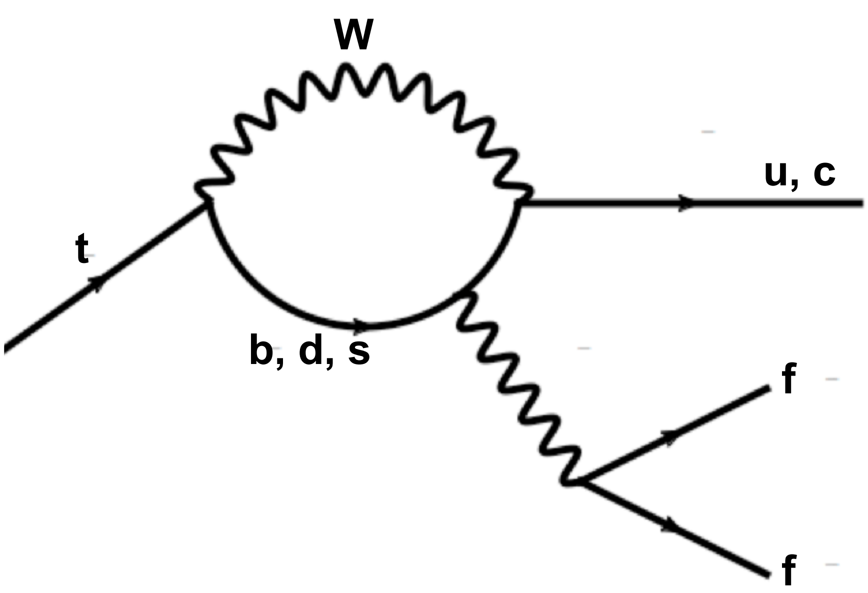
ATLAS EXPERIMENT

DESY.

FCNC

Introduction

- **F**lavour **C**hanging **N**eutral **C**urrents
  - Forbidden at tree-level in SM: need **more complex diagrams** to achieve
    - Very low branching ratio in SM
      - BR($t \rightarrow qH$) ~ 10^{-15}
      - BR($t \rightarrow qZ$) ~ 10^{-14}

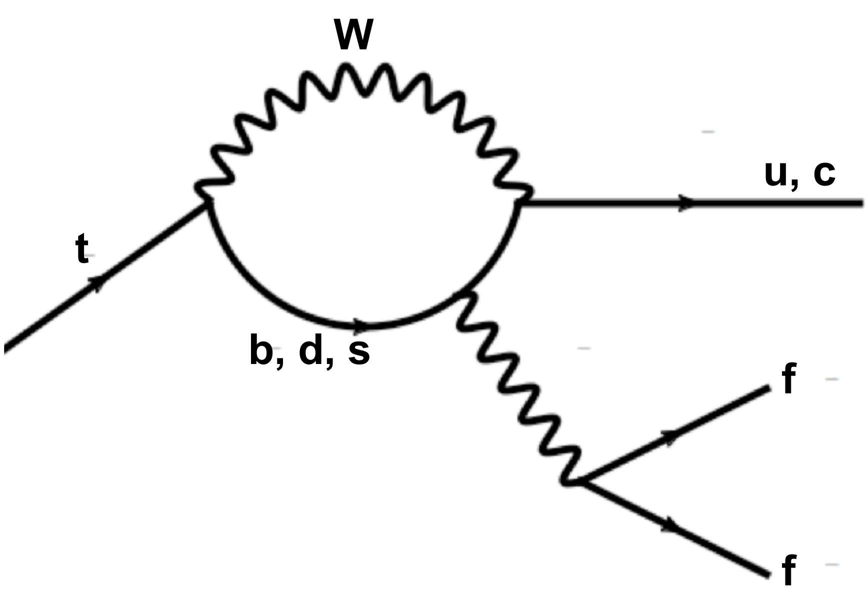


FCNC

Introduction

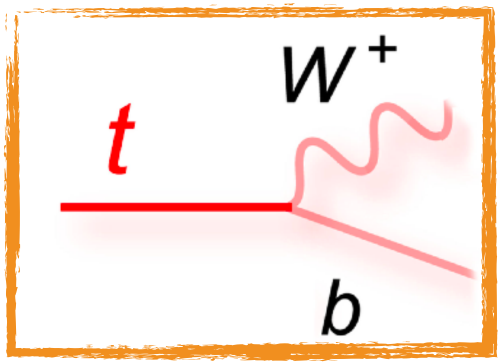
- **F**lavour **C**hanging **N**eutral **C**urrents
  - Forbidden at tree-level in SM: need **more complex diagrams** to achieve
    - Very low branching ratio in SM
      - BR($t \rightarrow qH$) ~ 10^{-15}
      - BR($t \rightarrow qZ$) ~ 10^{-14}

- **Enhanced in many BSM theories**
  - 2HDM models (~10^{-6})
    - Including RPV SUSY scenarios
  - MSSM (~10^{-7})
  - Extra-dimensions (~10^{-5})
  - …



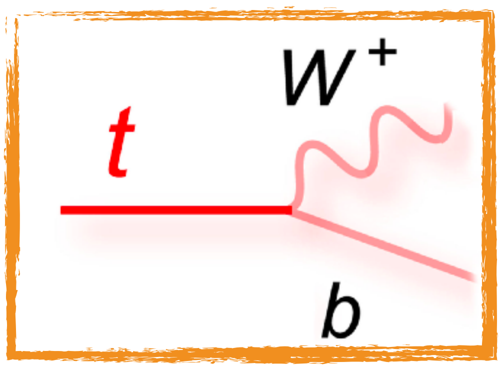
Constraints on FCNC ⟺ Constraints on new phenomena

In this talk



Standard Model

In this talk



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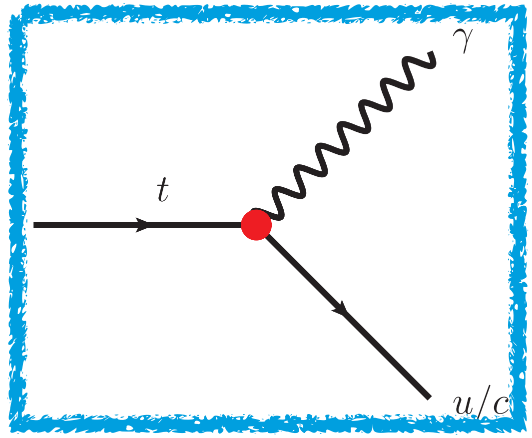
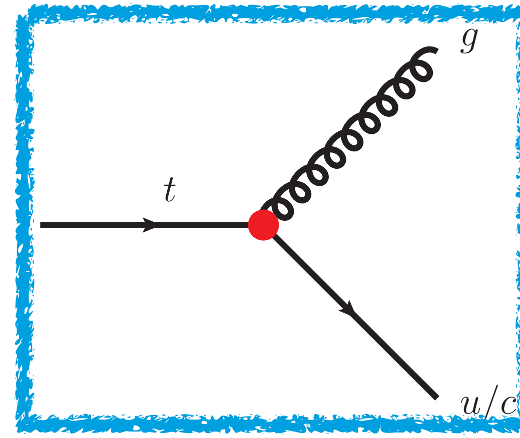
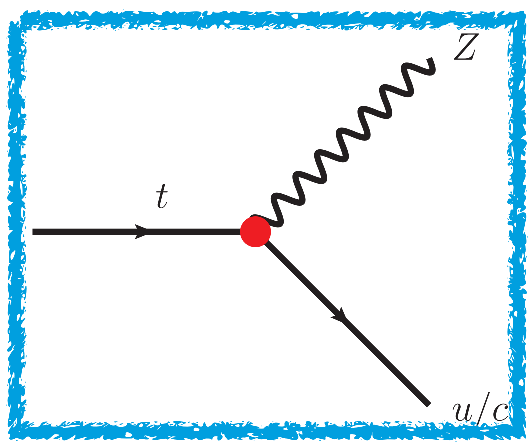


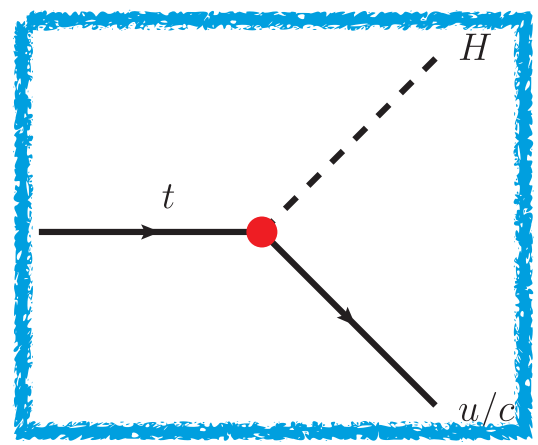
$t \to \gamma q$



$t \to gq$

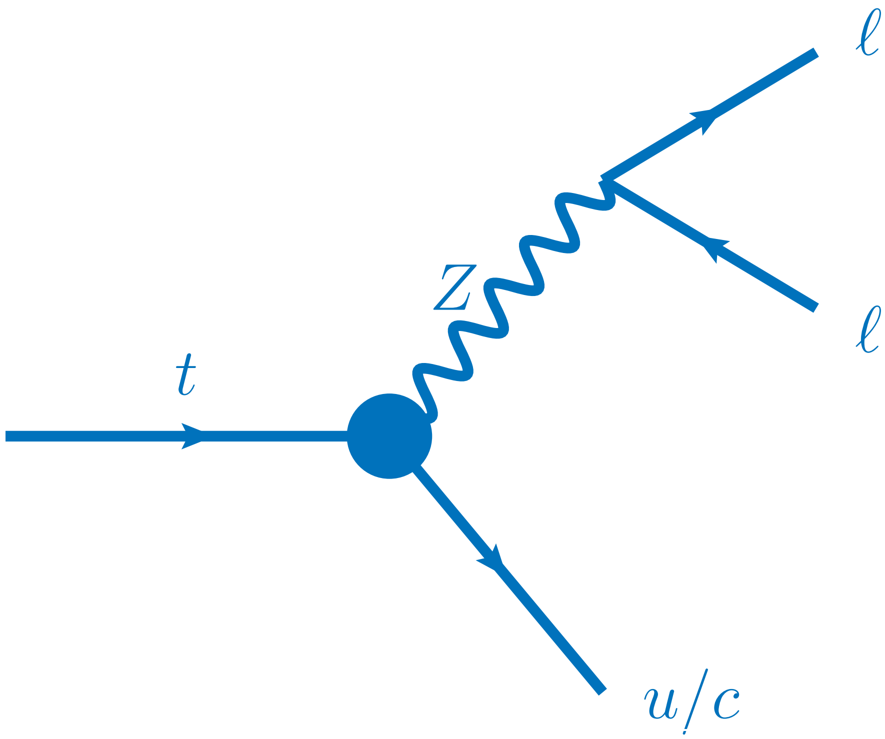


$t \to Zq$



$t \to Hq$

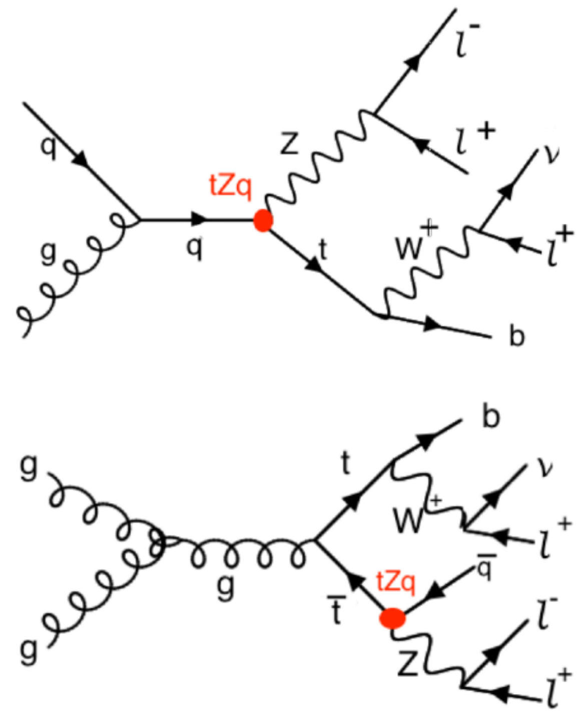
FCNC couplings



$$t \rightarrow Zq$$

tZq: common aspects

- **Clear experimental signature**
  - 3 leptons (2 with m_{ll} close to Z-mass)
- **Top single- and pair-production (SP & PP)**
  - CMS considers both (SP & PP)
  - ATLAS focuses on PP



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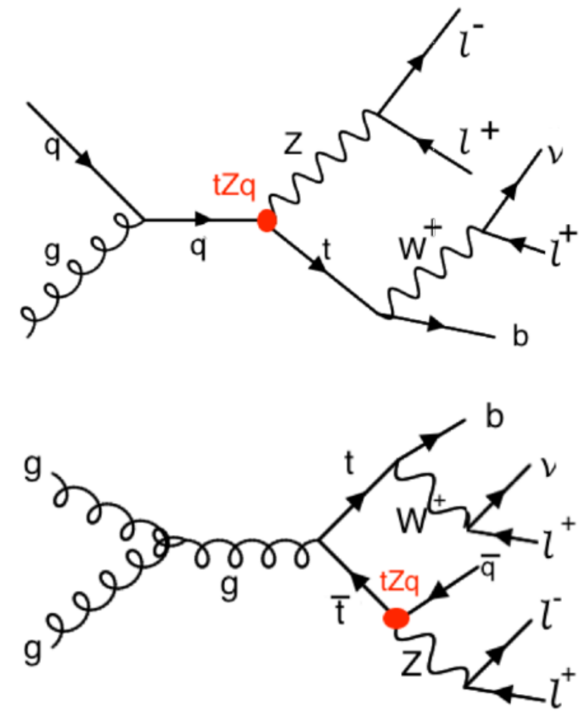

- **Clear experimental signature**
  - 3 leptons (2 with m_{ll} close to Z-mass)
- **Top single- and pair-production (SP & PP)**
  - CMS considers both (SP & PP)
  - ATLAS focuses on PP
- **Typical analysis strategy**
  - **Selection** of (b)-jets from top quark decays or FCNC vertex
  - Event **reconstruction** in signal region (SR)
  - Background **calibration** in control regions (CR)
  - Simultaneous **fit** across all regions

ATLAS search

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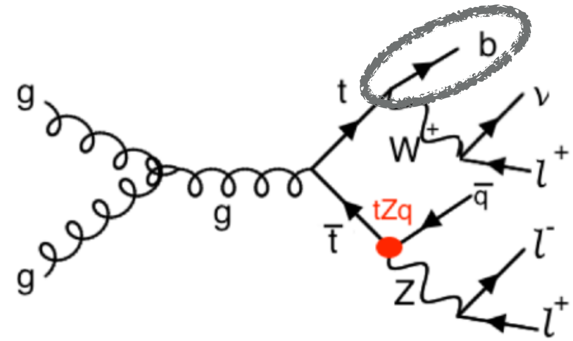
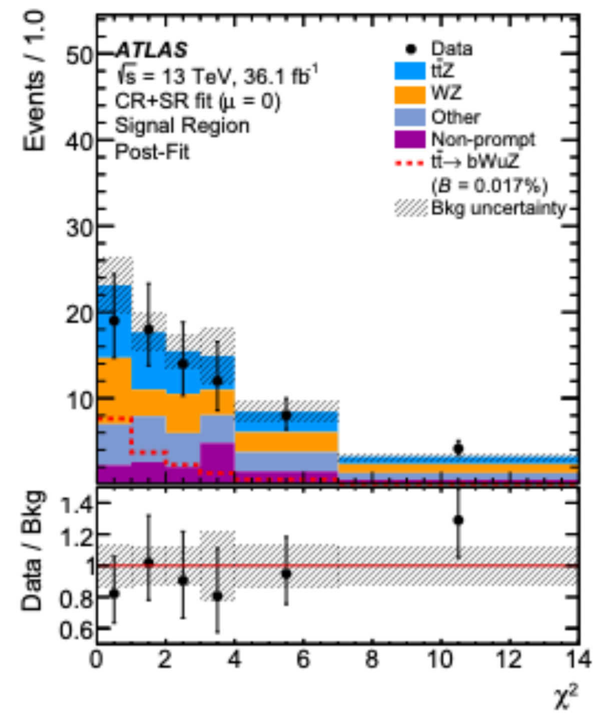
- **= 1 b-jet** required in SR
- **Reconstruction** using a **minimised χ^2 variable**

$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b\ell_c\nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W},$$

  - Used to discriminate signal/background





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JHEP 07 (2018) 176

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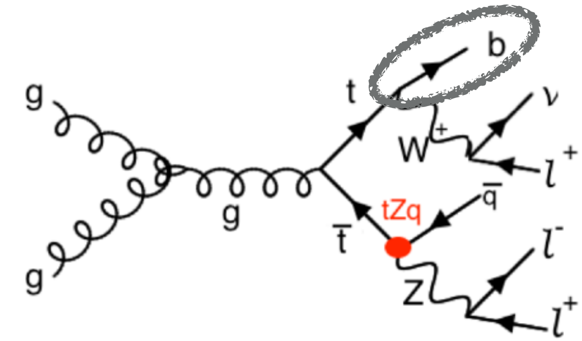
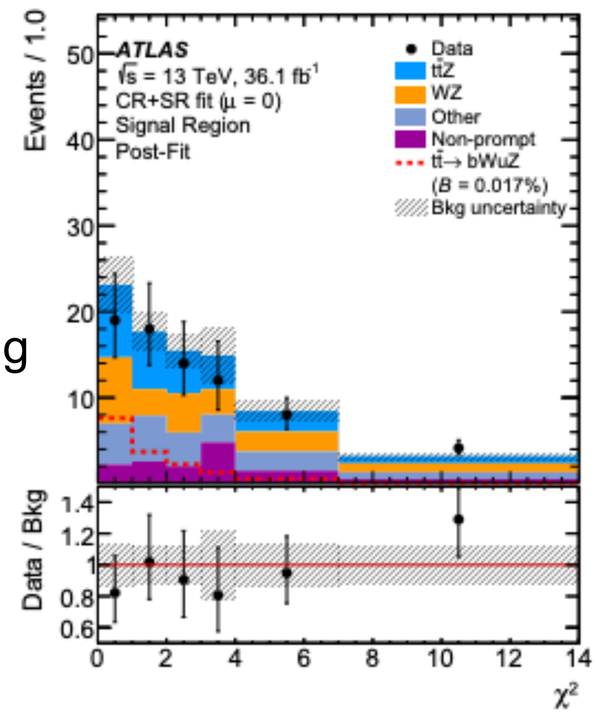
  - Used to discriminate signal/background

- Main **backgrounds** from **ttZ and WZ events**
- Main **systematic** uncertainties: background modelling

$$\mathcal{B}(t \to Zu) < 1.7\ (2.4) \times 10^{-4}$$

$$\mathcal{B}(t \to Zc) < 2.4\ (3.2) \times 10^{-4}$$

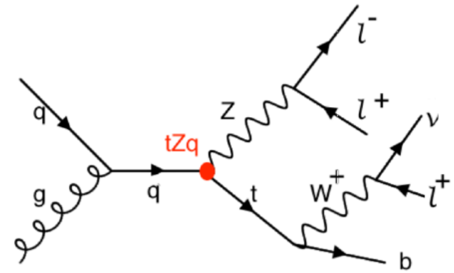


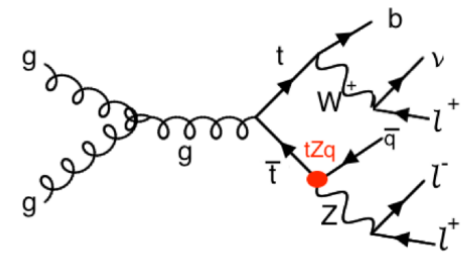


CMS search

CMS-PAS-TOP-17-017

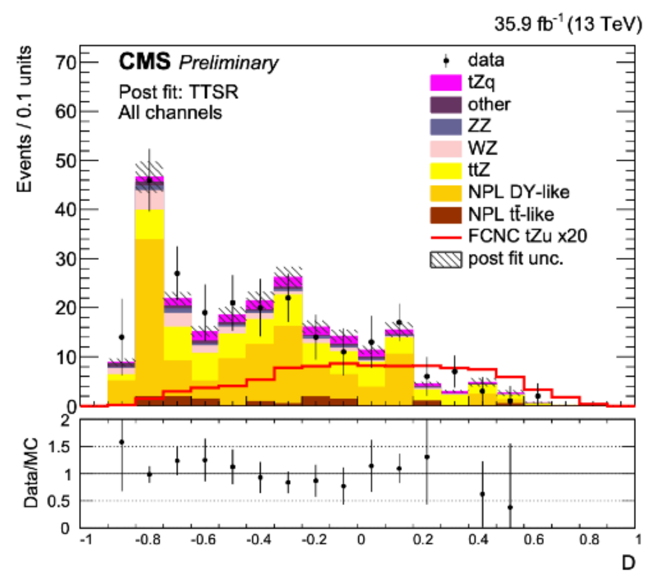
- Dedicated **selection** for SP- and PP-enriched regions
  - = 1 b-jet for SP
  - 2 or 3 jet including ≥ 1 b-jet for PP
- **Reconstruction** with BDT
  - Especially using jet quantities (kinematics, angular, …)
  - Used to discriminate signal/background in each SR (trained specifically for PP/SP)
- Main **backgrounds** from **ttZ and non-prompt leptons (NPL)**
- Main **systematic** uncertainties: NPL uncertainties

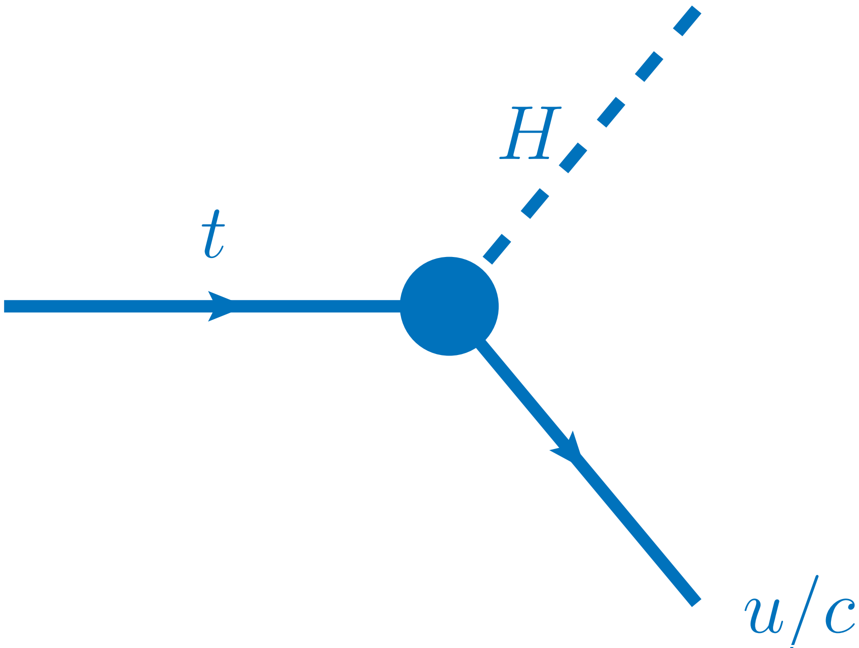




$$\mathscr{B}(t \to Zu) < 2.4\ (1.5) \times 10^{-4}$$

$$\mathscr{B}(t \to Zc) < 4.5\ (3.7) \times 10^{-4}$$

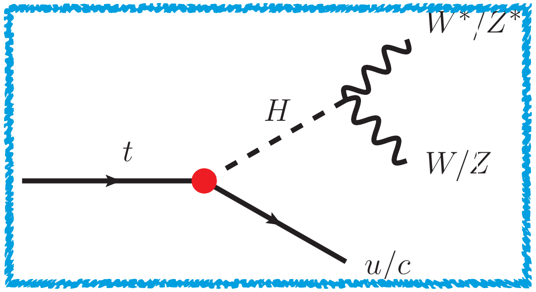




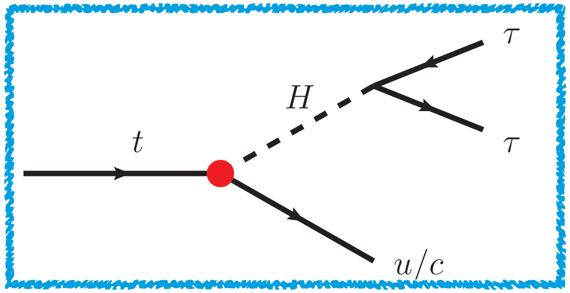
$$t \rightarrow Hq$$

Signatures

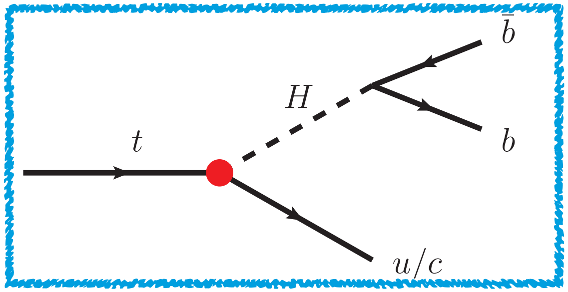
- Many accessible signatures depending on **Higgs boson decay**



$H \rightarrow WW^*/ZZ^*$

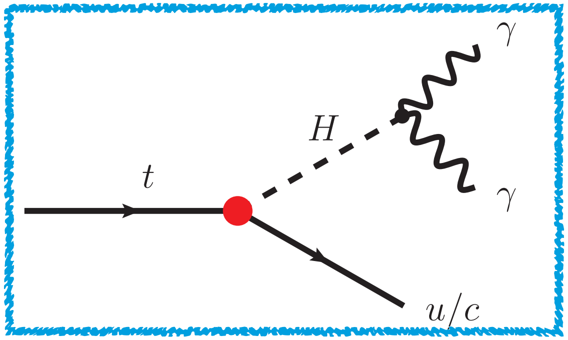


$H \rightarrow \tau\tau$



$H \rightarrow b\bar{b}$

- **Dedicated analyses** for each signature
- **Combined interpretation** performed by ATLAS



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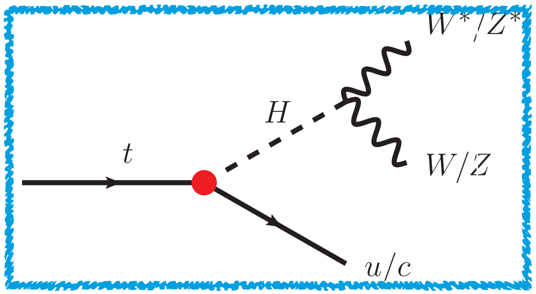

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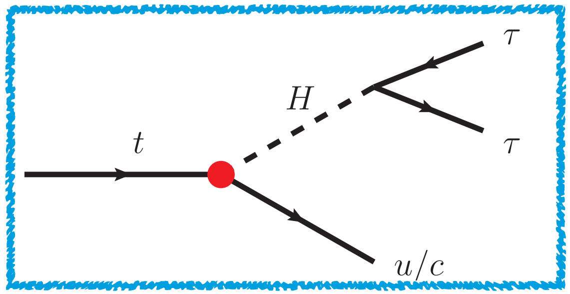

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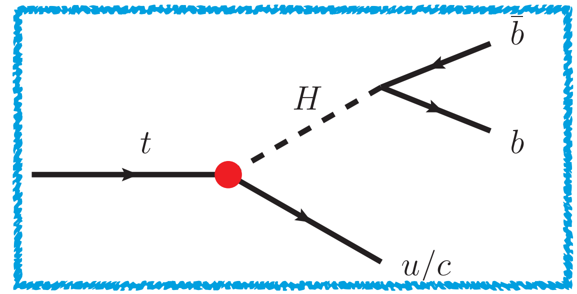

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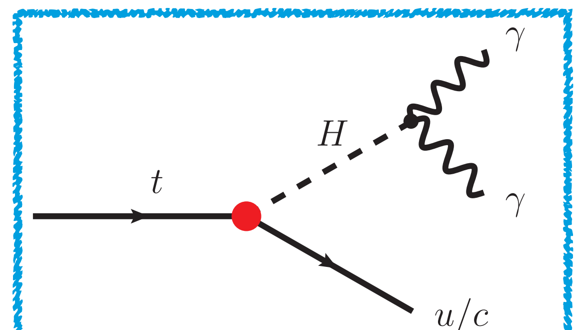
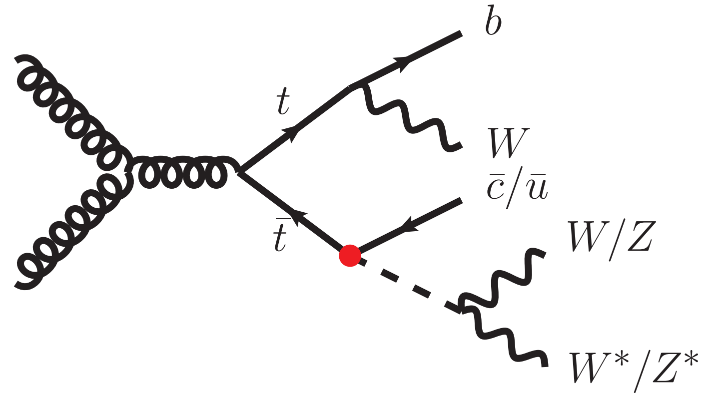


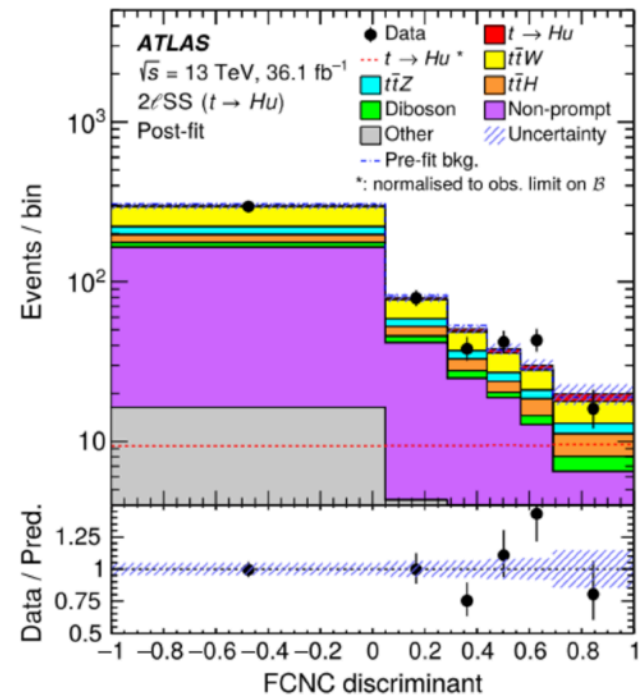
$H \rightarrow \gamma\gamma$

$t \to H(WW^*/ZZ^*)q$

Phys. Rev. D 98 (2018) 032002

- **Multilepton**: 2 same-sign leptons / 3 leptons
  - Very pure final state !
- Main **backgrounds** from **ttW and non-prompt leptons**: estimated from MC and data, resp.
- Event **reconstruction**: BDTs
  - 2 combined BDTs
    - Signal *vs* non-prompt leptons or ttW





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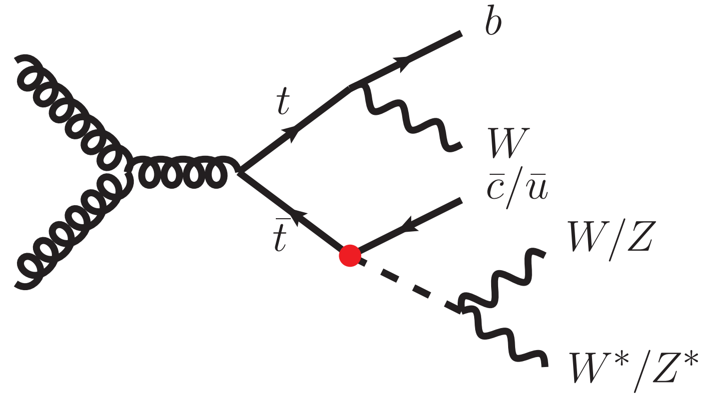

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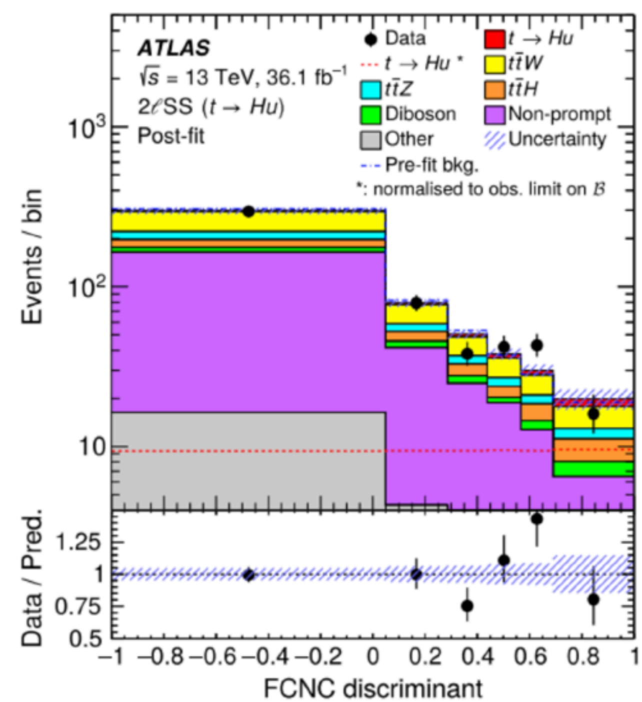
- Main **backgrounds** from **ttW and non-prompt leptons**: estimated from MC and data, resp.
- Event **reconstruction**: BDTs
  - 2 combined BDTs
    - Signal *vs* non-prompt leptons or ttW
- Main **systematic** uncertainties: background modelling (statistics for DD backgrounds)

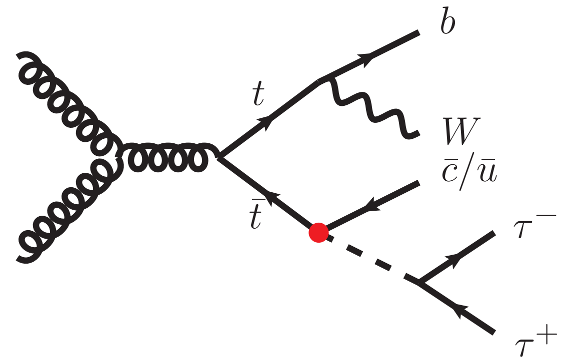
$$\mathcal{B}(t \to Hu) < 1.9(1.5) \times 10^{-3}$$
$$\mathcal{B}(t \to Hc) < 1.6(1.5) \times 10^{-3}$$

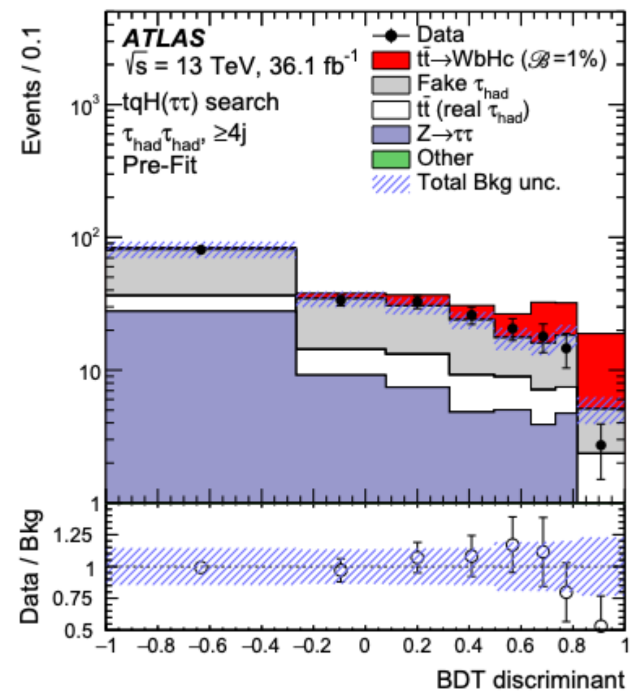


$t \to H(\tau\tau)q$

arXiv:1812.11568
(Submitted to JHEP)

- Select events with **lepton and/or hadronic taus**
  - Classify events depending on $N_{had-\tau}$
- Main **background** from **fake taus**: data-based estimate in CR
- **Event reconstruction** using kinematic fit
  - Using all input objects to reconstruct system
  - Kinematics used for signal vs back. BDT





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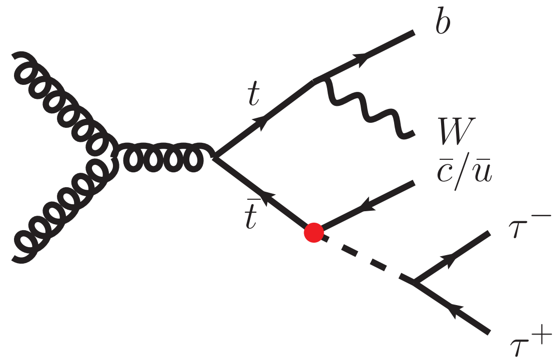
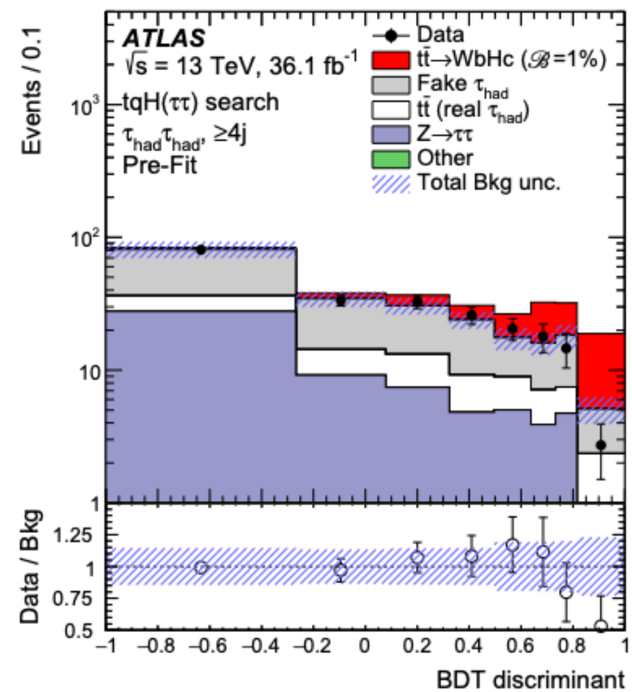
- Main background from **fake taus**: data-based estimate in CR
- Event reconstruction using kinematic fit
  - Using all input objects to reconstruct system
  - Kinematics used for signal vs back. BDT
- Main systematic uncertainties: fake tau modelling uncertainties

$$\mathcal{B}(t \to Hu) < 1.7\ (2.0) \times 10^{-3}$$
$$\mathcal{B}(t \to Hc) < 1.9\ (2.1) \times 10^{-3}$$





$t \to H(b\bar{b})q$

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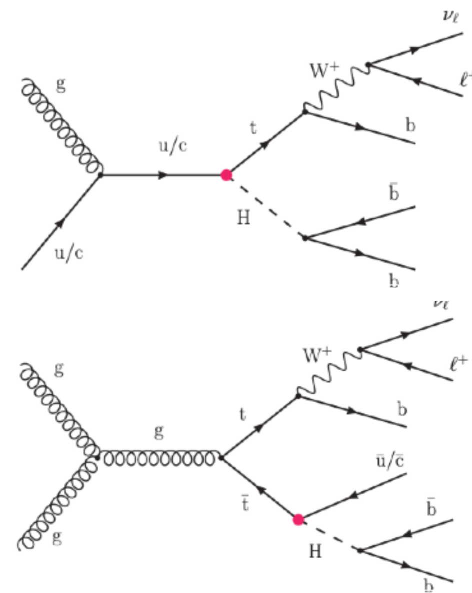
- Final state with **1-lepton** and several **jets** / **b-jets**
  - Different selections for SP and PP
- Leading **background**: $t\bar{t}$ + jets (sometimes from HF)
  - Estimated from simultaneous fit across all regions
- Event **reconstruction**
  - BDT to **reconstruct system** (assign objects)
  - New BDT to **separate** signal vs background
- **Systematics**: dominated by b-tagging uncertainties



$$\mathscr{B}(t \to Hu) < 4.7\ (3.4) \times 10^{-3}$$

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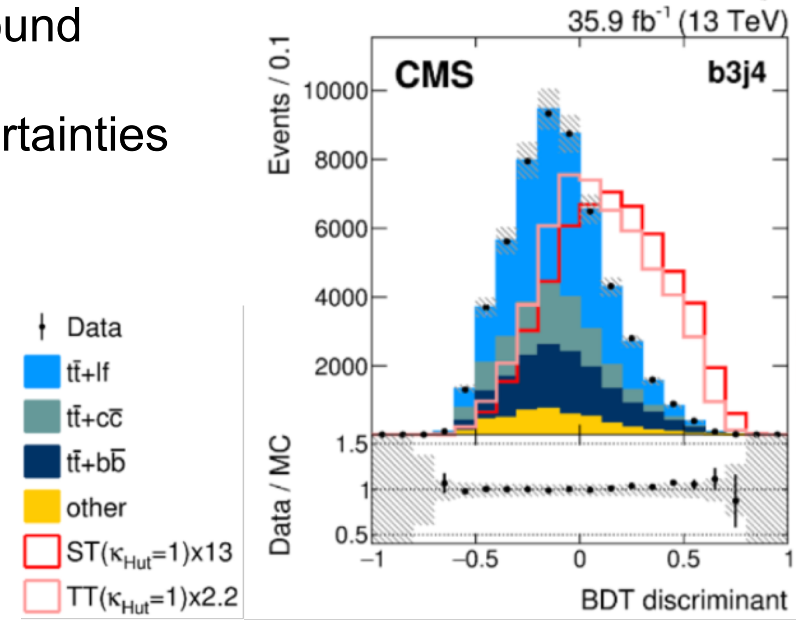

$t \to H(b\bar{b})q$

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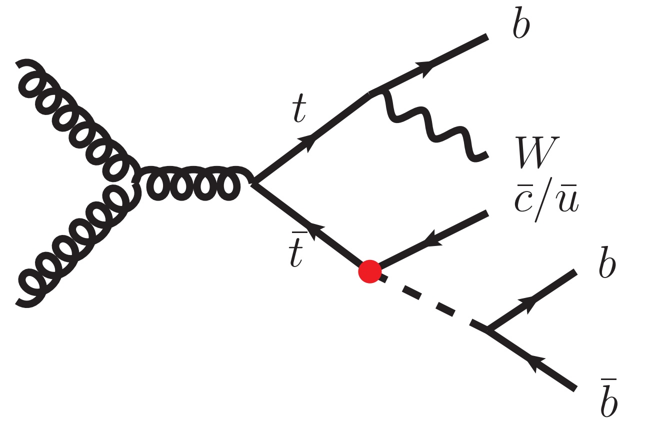
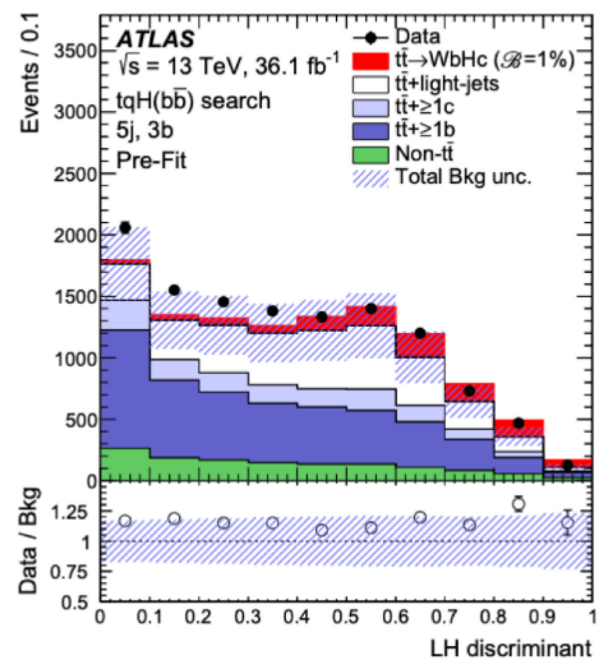


- Final state with **1-lepton** and several **jets** / **b-jets**
- Main background: ttbar + HF jets
- Event reconstruction: using likelihood ratio discriminant based **on object kinematics**

compatibility with signal

$$D(\mathbf{x}) = \frac{P^{\mathrm{sig}}(\mathbf{x})}{P^{\mathrm{sig}}(\mathbf{x}) + P^{\mathrm{bkg}}(\mathbf{x})}$$

compatibility with background



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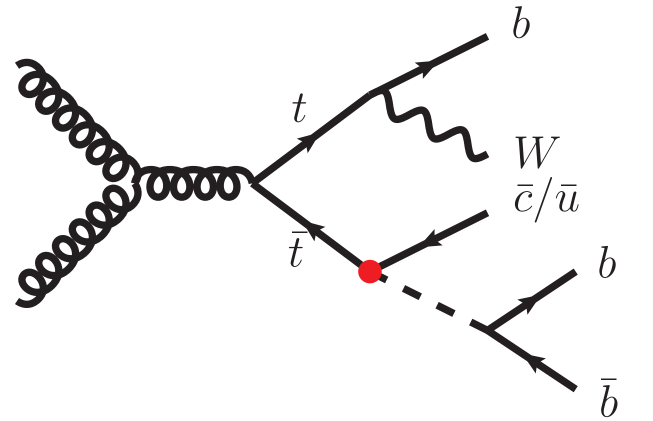

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- Main **background**: ttbar + HF jets
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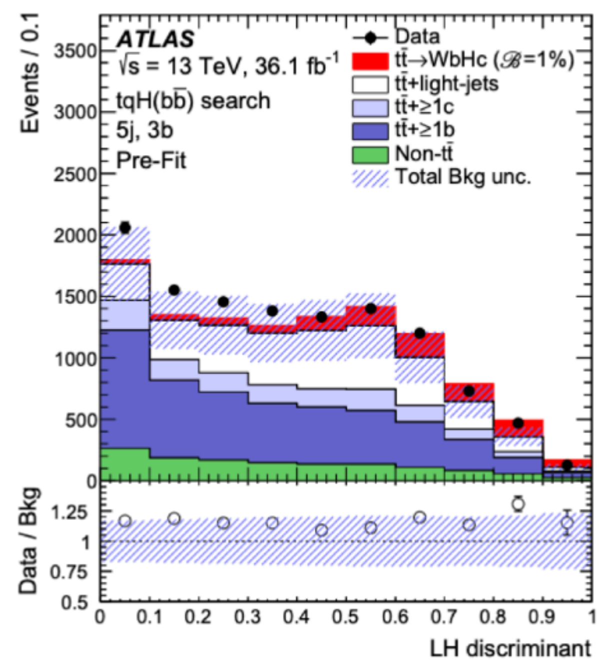
$$D(\mathbf{x}) = \frac{P^{\text{sig}}(\mathbf{x})}{P^{\text{sig}}(\mathbf{x}) + P^{\text{bkg}}(\mathbf{x})}$$

compatibility with background

- Main systematic **uncertainties**: ttbar + HF modelling and c-jet mistagging

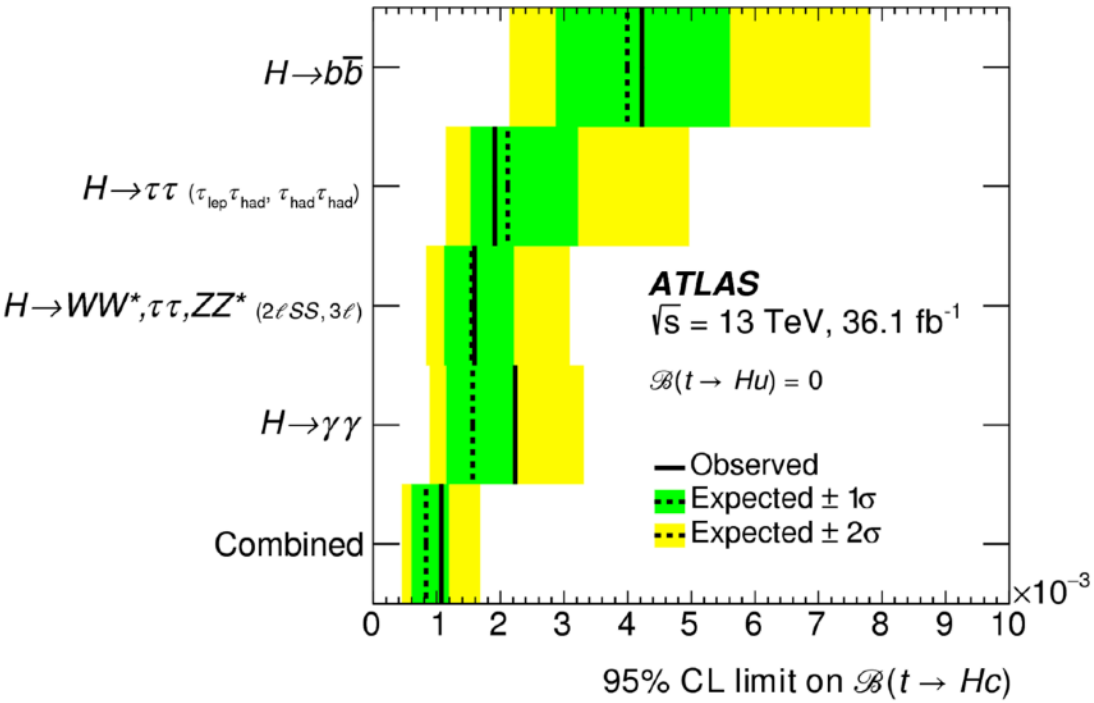


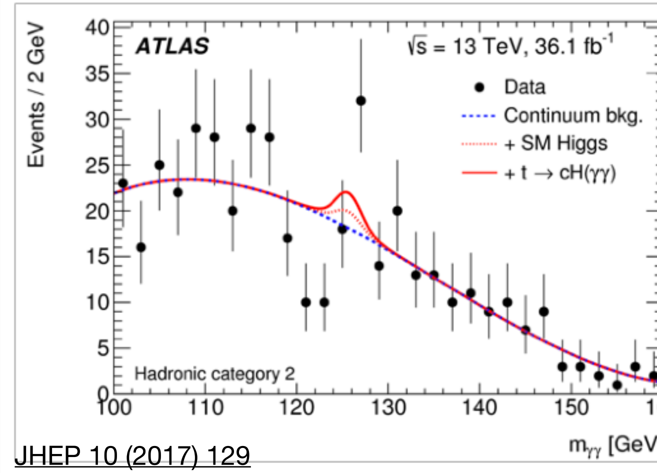
$$\mathscr{B}(t \to Hu) < 5.2\ (4.9) \times 10^{-3}$$

$$\mathscr{B}(t \to Hc) < 4.2\ (4.0) \times 10^{-3}$$

ATLAS Combination

arXiv:1812.11568
(Submitted to JHEP)



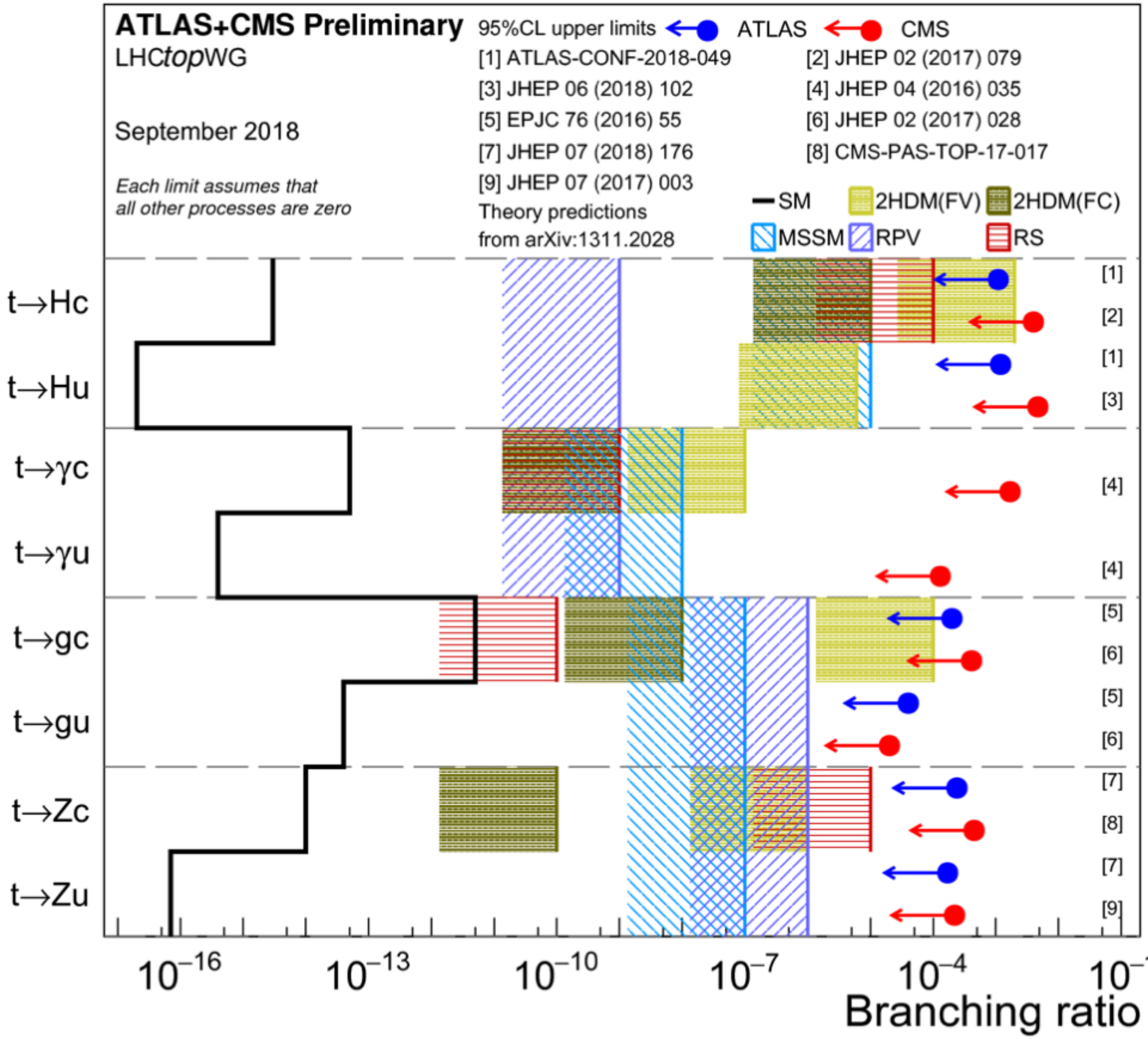


JHEP 10 (2017) 129

$$\mathscr{B}(t\to Hu) < 1.2\ (0.83)\times10^{-3}$$

$$\mathscr{B}(t\to Hc) < 1.1\ (0.83)\times10^{-3}$$

Summary plot



Conclusion

- Strong programme searching for **FCNC processes in top sector**
  - Investigated for several FCNC couplings and final states
- Sensitivity **far from SM expectations** … but …
- … **reaching sensitivity to some BSM** extensions !

- Next round of analyses, with **full 13 TeV dataset** will benefit from:
  - More data (~4 times more)
  - Improved analysis techniques and precision

Stay tuned for the next results !

Thank you

Contact

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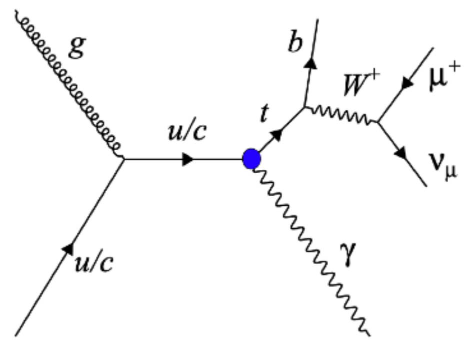
More references

ATLAS		
t —> qZ (ttbar @ 13 TeV)	March 2018	JHEP 07 (2018) 176
t —> Hc/u multilepton (ttbar @ 13 TeV)	May 2018	Phys. Rev. D 98 (2018) 032002
t —> H(yy)q (ttbar @ 13 TeV)	May 2017	JHEP 10 (2017) 129
t —> Hq (bb + combo) (ttbar @ 13 TeV)	December 2018	arXiv:1812.11568 (Submitted to JHEP)
t —> gq (single-top @ 8 TeV)	August 2015	EPJC 76 (2016) 55
HL-LHC — t —> qZ	January 2019	ATL-PHYS-PUB-2019-001
CMS		
t —> Hc (ttbar @ 8 TeV)	October 2016	JHEP 02 (2017) 079
t —> H(bb)u (single top and ttbar @ 13 TeV)	December 2017	JHEP 06 (2018) 102
t —> Zc (single-top and ttbar @ 13 TeV)	November 2017	CMS-PAS-TOP-17-017
t —> Zu (single-top @ 8 TeV)	February 2017	JHEP 07 (2017) 003
t —> qg (single top @ 8 TeV)	October 2016	JHEP 02 (2017) 028
t —> yq (single top @ 8 TeV)	November 2015	JHEP 04 (2016) 035

$t \to \gamma q / g q$

- Probe anomalous couplings in **single-top quark production** (LHC Run 1)
- $t \to \gamma q$
  - Using muon+photon events at 8 TeV
  - BDT used to separate FCNC from SM

$$\mathscr{B}(t \to \gamma u(c)) < 0.17(2.2) \times 10^{-4}$$



JHEP 04 (2016) 035

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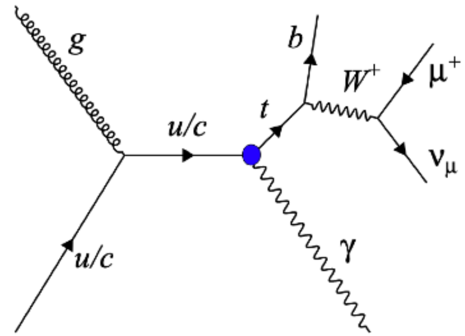
  - BDT used to separate FCNC from SM

$$\mathscr{B}(t \to \gamma u(c)) < 0.17(2.2) \times 10^{-4}$$



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- $t \to gq$
  - NN used to disentangle SM and FCNC processes

CMS	$\mathscr{B}(t \to gu) < 0.20\ (0.28) \times 10^{-4}$	$\mathscr{B}(t \to gc) < 4.1\ (2.8) \times 10^{-4}$
ATLAS	$\mathscr{B}(t \to gu) < 0.40\ (0.35) \times 10^{-4}$	$\mathscr{B}(t \to gc) < 2.1\ (1.8) \times 10^{-4}$

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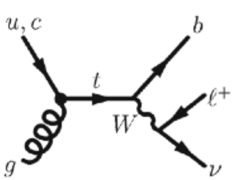

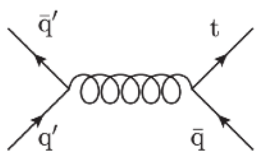

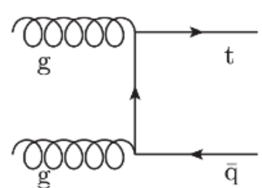

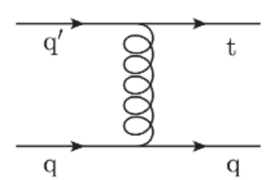

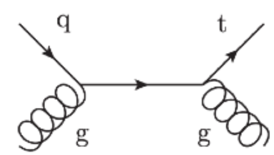

t —> Zu/c (I)

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- **Process probed:** $t\bar{t} \to WbZ(\ell\ell)q$
- **Analysis basic selection:** 2 SFOS leptons, MET > 20 GeV, ≥2 jets, =1 b-jet
- **Analysis strategy:** Event reconstruction with chi2 + cuts on masses of chosen combination

$$\chi^2 = \frac{\left(m^{\mathrm{reco}}_{j_a\ell_a\ell_b} - m_{t_{\mathrm{FCNC}}}\right)^2}{\sigma^2_{t_{\mathrm{FCNC}}}} + \frac{\left(m^{\mathrm{reco}}_{j_b\ell_c\nu} - m_{t_{\mathrm{SM}}}\right)^2}{\sigma^2_{t_{\mathrm{SM}}}} + \frac{\left(m^{\mathrm{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W},$$

- **Main backgrounds + estimation strategy**: diboson + ttZ/tZ constrained in CRs

Selection	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0 (CR1)	SR
No. leptons	3	3	4	3	3
OSSF	Yes	Yes	Yes	Yes	Yes
$\lvert m^{\mathrm{reco}}_{\ell\ell} - 91.2\ \mathrm{GeV}\rvert$	< 15 GeV	< 15 GeV	< 15 GeV	> 15 GeV	< 15 GeV
No. jets	≥ 4	≥ 2	≥ 1	≥ 2	≥ 2
No. b-tagged jets	2	0	0	0 (1)	1
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 20 GeV	> 40 GeV	> 20 GeV	> 20 GeV	> 20 GeV
$m_{\mathrm{T}}^{\ell\nu}$	-	> 50 GeV	-	-	-
$\lvert m^{\mathrm{reco}}_{\ell\nu} - 80.4\ \mathrm{GeV}\rvert$	-	-	-	-	< 30 GeV
$\lvert m^{\mathrm{reco}}_{j\ell\nu} - 172.5\ \mathrm{GeV}\rvert$	-	-	-	-	< 40 GeV
$\lvert m^{\mathrm{reco}}_{j\ell\ell} - 172.5\ \mathrm{GeV}\rvert$	-	-	-	-	< 40 GeV

t —> Zu/c (II)

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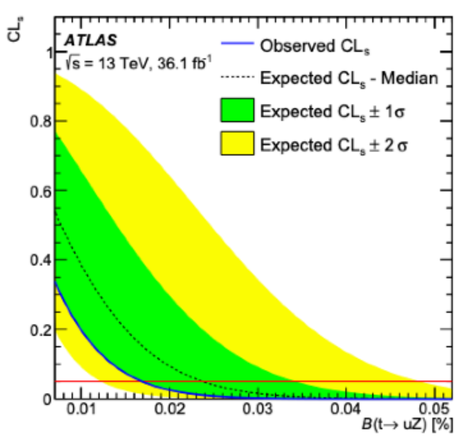
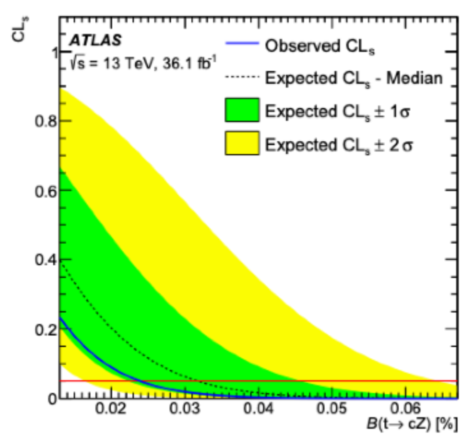
- **Main systematic uncertainties:** background theory uncertainties (modelling + normalisation)
- **Results**:

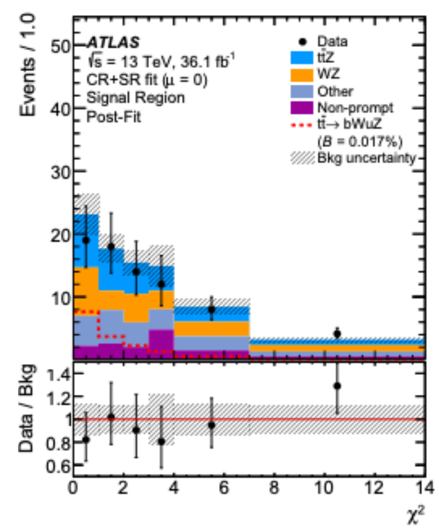
Sample	Yields	
	Pre-fit	Post-fit
$t\bar{t}Z$	37 ± 5	37 ± 4
WZ	32 ± 19	32 ± 8
ZZ	6.2 ± 3.2	6.4 ± 3.0
Non-prompt leptons	26 ± 11	20 ± 7
Other backgrounds	23 ± 4	23 ± 4
Total background	124 ± 26	119 ± 10
Data	116	116
Data / Bkg	0.94 ± 0.21	0.97 ± 0.12
Signal $t \to uZ$ ($\mathcal{B} = 0.1\%$)	101 ± 8	103 ± 8
Signal $t \to cZ$ ($\mathcal{B} = 0.1\%$)	85 ± 7	87 ± 7

	Expected	Observed
t —> uZ	2.4×10^{-4}	1.7×10^{-4}
t —> cZ	3.2×10^{-4}	2.4×10^{-4}

- **Key plots**







t —> Zu/c (I)

- **Process probed:** $t\bar{t} \rightarrow WbZ(\ell\ell)q$ and $qg \rightarrow Z(\ell\ell)t$
- **Analysis basic selection:** =3 leptons (2 from Z), 1 ≤ Njets ≤ 3, m_T(W) < 300 GeV
- **Analysis strategy:** simultaneous fit across lepton channels (4) X region types (5)
  - In CRs —> kinematic variable
  - In SRs —> **BDT discriminant** (uses especially jet-related variables)
- **Main backgrounds + estimation strategy:** Fake leptons from DY/ttbar. MC background + contraints in CRs

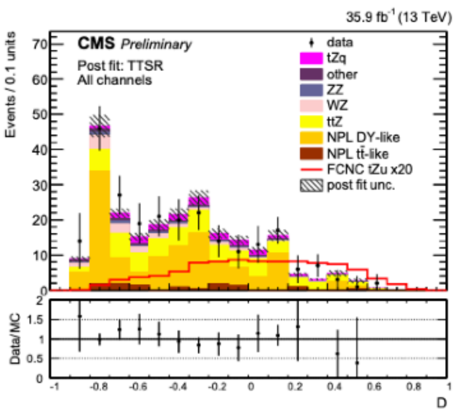
	WZ control region (WZCR)	single top quark signal region (STSR)	top quark pair signal region (TTSR)	single top quark control region (STCR)	top quark pair control region (TTCR)
Number of jets	$\geq 1, \leq 3$	1	$\geq 2, \leq 3$	1	$\geq 2, \leq 3$
Number of b jets	0	1	≥ 1	1	≥ 1
$\lvert M(Z_{\text{reco}}) - M_Z \rvert < 7.5$ GeV	Yes	Yes	Yes	No	No

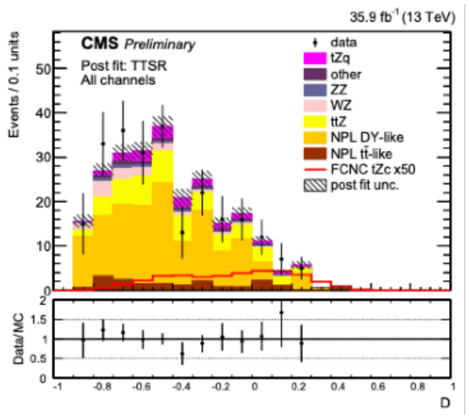
t —> Zu/c (II)

- **Main systematic uncertainties:** background normalisation
- **Results:**

	Expected	Observed
t —> uZ	1.5 x 10^{-4}	2.4 x 10^{-4}
t —> cZ	3.7 x 10^{-4}	4.5 x 10^{-4}

- **Key plots:**





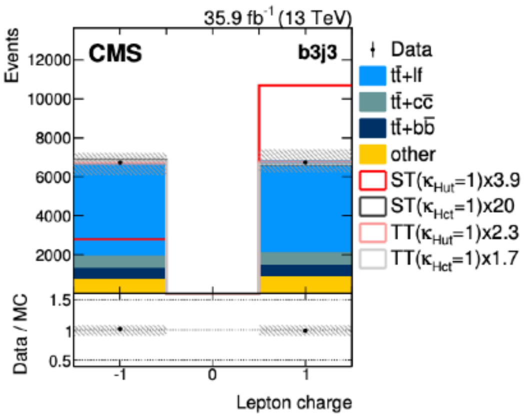
t —> H(bb)q

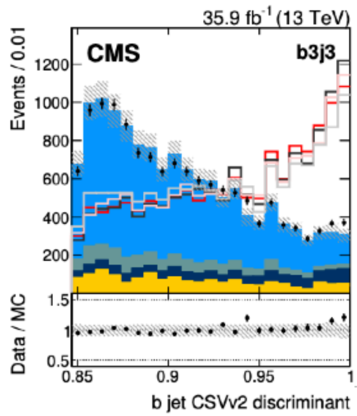
- **Process probed:** t —> Hq with single and pair-production
- **Analysis basic selection:** =1-lepton, =3j or ≥4j (2,3,4 b-jets in each)
- **Analysis strategy:** event reconstruction based on BDT + signal/back. discrimination
- **Main backgrounds + estimation strategy:** main background from ttbar. High b-jet multiplicity regions: dominated by ttbar+HF
- **Main systematic uncertainties:** b-tagging uncertainties
- **Results:**

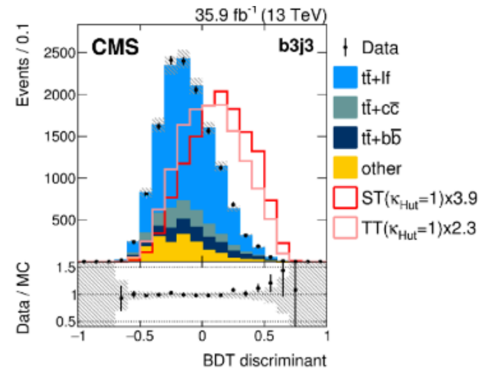
	Expected	Observed
t —> uH	3.4×10^{-3}	4.7×10^{-3}
t —> cH	4.4×10^{-3}	4.7×10^{-3}

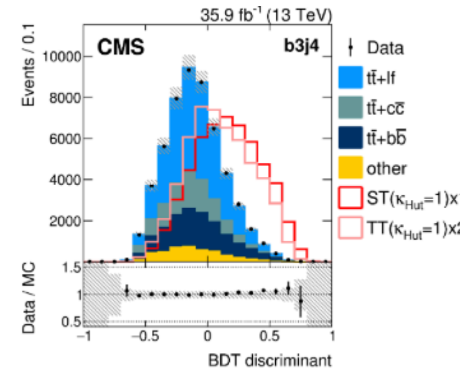
t —> H(bb)q

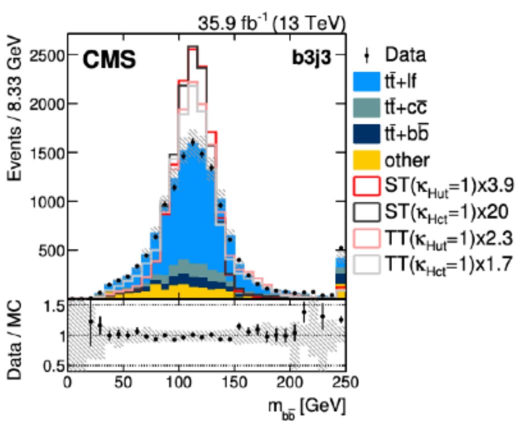
- **Key plots:**

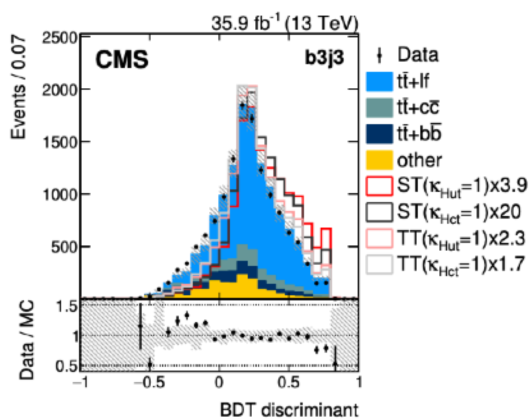


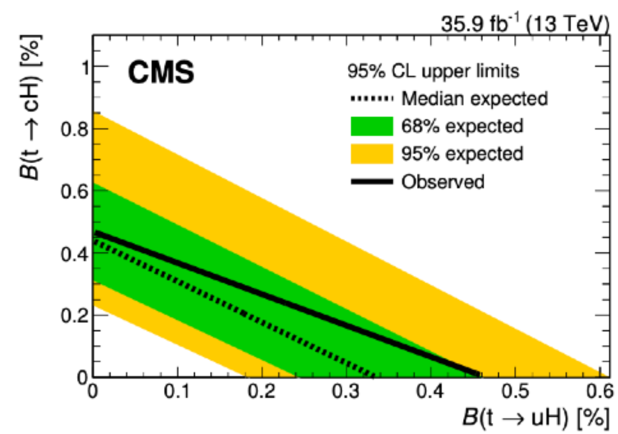












tHq - Multilepton

Phys. Rev. D 98 (2018) 032002

- **Process probed:** ttbar with FCNC coupling in decay (dominated by H—> WW*)
- **Analysis basic selection**: 2 same-sign (3l) with ≥4j (≥2j) with 1-2 (≥1) b-jet
- **Analysis strategy**: BDT background/signal separation
  - BDT signal vs ttbar (i.e. against non-prompt leptons)
  - BDT signal vs ttV (i.e. against prompt leptons)
  - Both BDTs combined linearly
- **Main backgrounds + estimation strategy:** NPL and ttV backgrounds.
  - Prompt lepton backgrounds from MC
  - NPL and charge Q-MisID backgrounds from data (matrix method and likelihood)

tHq - Multilepton

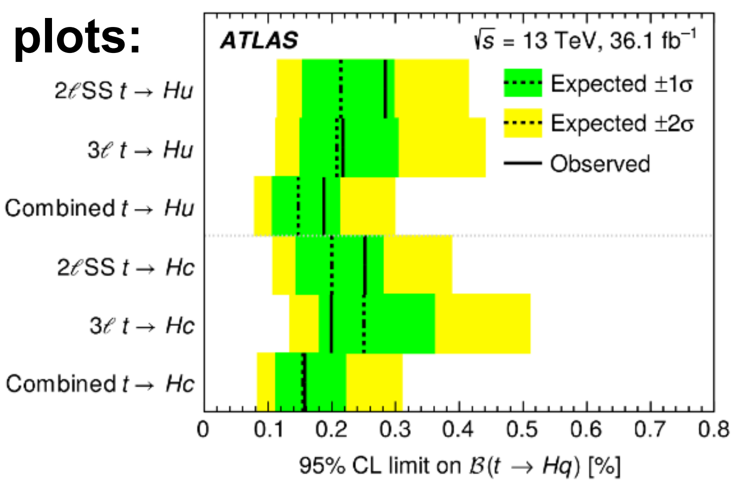
Phys. Rev. D 98 (2018) 032002

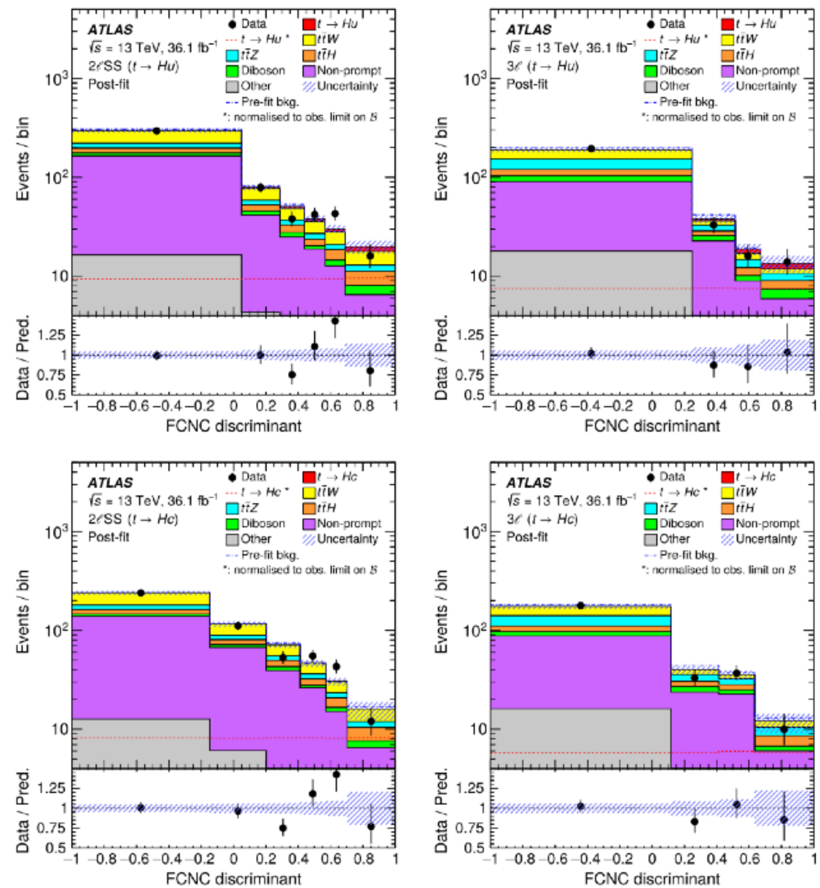
- **Main systematic uncertainties:** data driven statistical uncertainties and diboson+HF modelling uncertainties

- Results:

	Expected	Observed
t —> uH	1.5 x 10^{-3}	1.9 x 10^{-3}
t —> cH	1.5 x 10^{-3}	1.6 x 10^{-3}

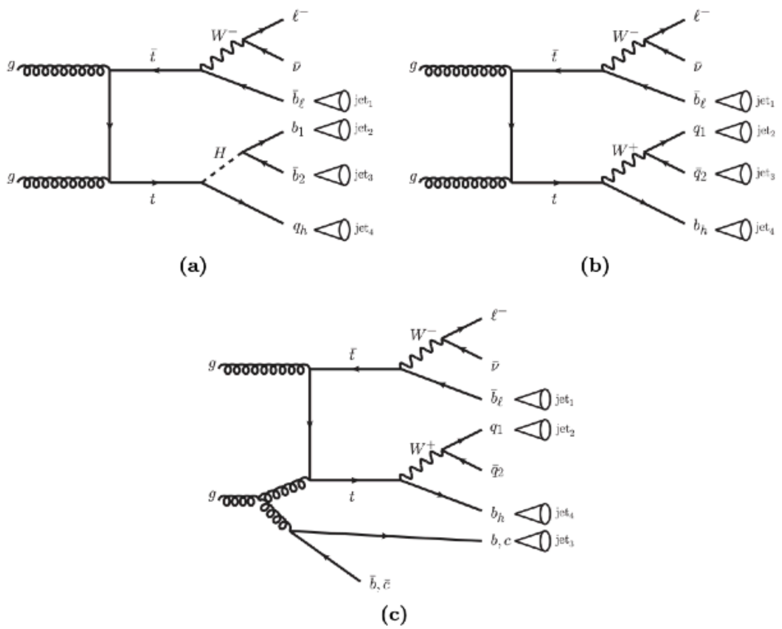
- **Key plots:**





tHq - Hbb

- **Process probed:** ttbar pair with decay to H(bb)q
- **Analysis basic selection:** 1-lepton, ≥4j, ≥2b-jets
- **Analysis strategy:**
  - Event classification for each jet/b-jet combination
  - In each category: FCNC discriminant built from LLH



$$D(\mathbf{x}) = \frac{P^{\rm sig}(\mathbf{x})}{P^{\rm sig}(\mathbf{x}) + P^{\rm bkg}(\mathbf{x})},$$

$$P^{\rm sig}_{\rm kin}(\mathbf{x}) = P^{\rm sig}(M_{\ell\nu b_\ell}) P^{\rm sig}(X_{b_1 b_2 q_h}) P^{\rm sig}(M_{b_1 b_2}).$$

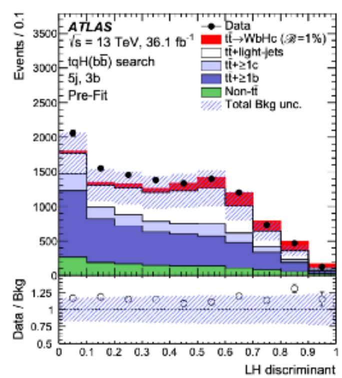
$$P^{\rm sig}(\mathbf{x}) = \frac{\sum_{k=1}^{N_p} P^{\rm sig}_{\rm btag}(\mathbf{x}^k) P^{\rm sig}_{\rm kin}(\mathbf{x}^k)}{\sum_{k=1}^{N_p} P^{\rm sig}_{\rm btag}(\mathbf{x}^k)},$$

tHq - Hbb

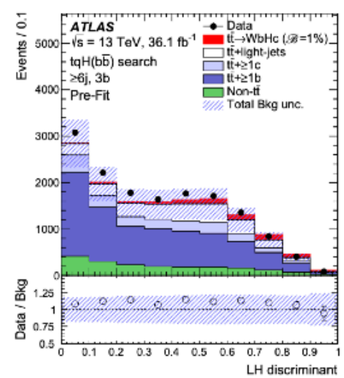
- **Main backgrounds + estimation strategy:** ttbar background (often + HF jets)
  - Simultaneous PLL fit across all regions with detail NP set for ttbar
- **Main systematic uncertainties:** ttbar modeling + c-jet mis-tagging
- **Results:**

	Expected	Observed
t —> uH	4.9 x 10^{-3}	5.2 x 10^{-3}
t —> cH	4.0 x 10^{-3}	4.2 x 10^{-3}

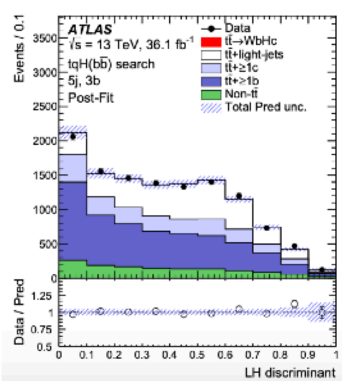
- **Key plots:**

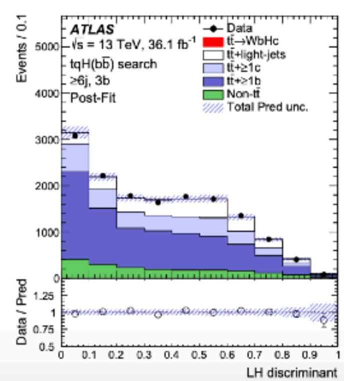


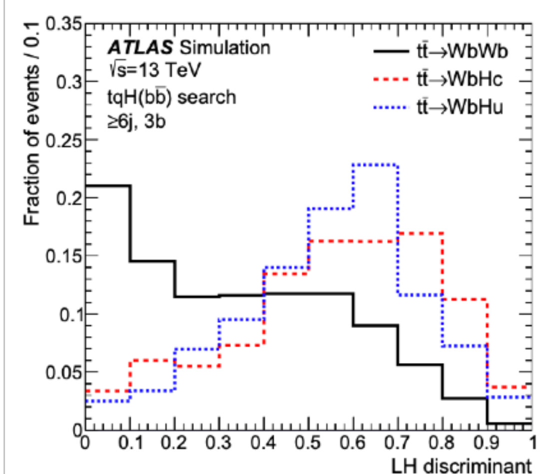
(b)



(c)

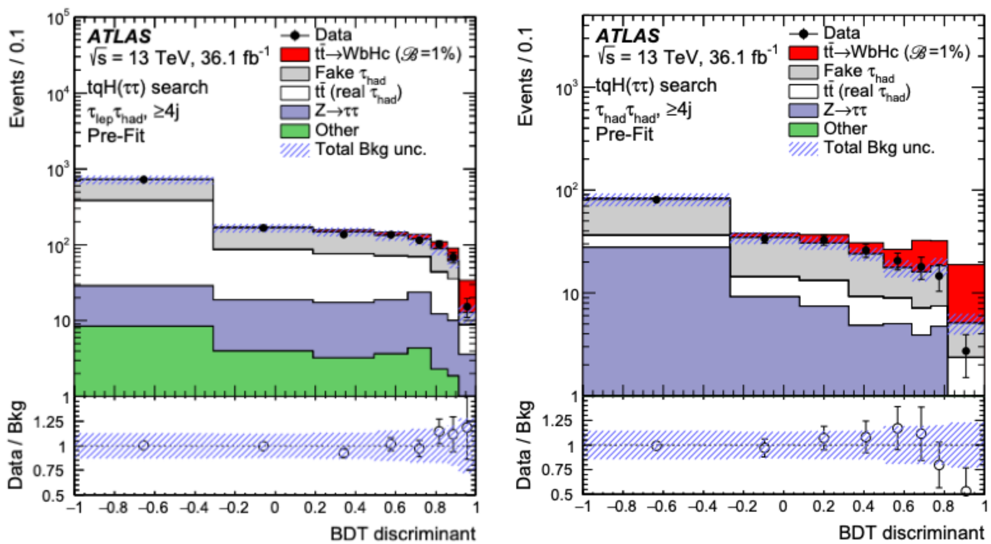






tHq - Htautau

- **Process probed:** ttbar with FCNC H(tautau) dacay
- **Analysis basic selection:** ≥2 taus (lep/had decay of a tau)
    - *had-had:* tau trigger, 0 leps, q1xq2<0, ≥3 jets, ≥1 bjet
    - *lep-had:* lep trigger, 1 lep, ≥1 had tau, q_lep x qtau <0, ≥3 jets, ≥1 bjet
- **Analysis strategy:** events classified in =3j and ≥4j categories
    - Event reconstruction using a chi2 algorithm
    - Reconstructed observables used to build BDT back./sig. discriminant

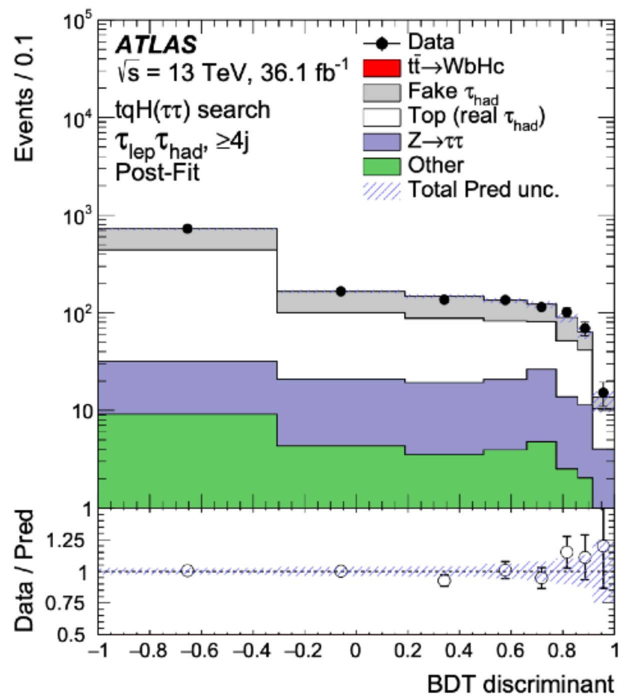


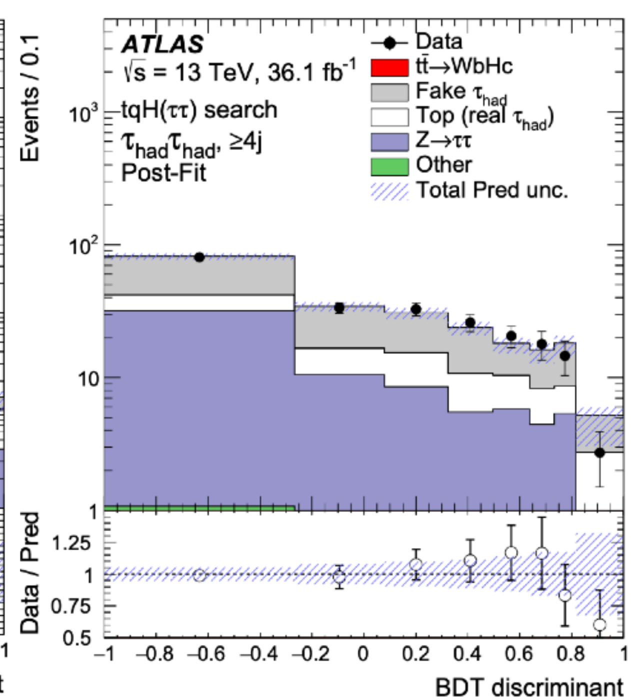
tHq - Htautau

- **Main backgrounds + estimation strategy**: fake taus + ttbar + Z(tautau)
  - ttbar/Z —> MC with constraints through PLL
  - Fake taus: “data driven” template estimated from control region
- **Main systematic uncertainties:** fake taus modeling uncertainties
- **Results**:

	Expected	Observed
t —> uH	2.0×10^{-3}	1.7×10^{-3}
t —> cH	2.1×10^{-3}	1.9×10^{-3}

- **Key plots:**





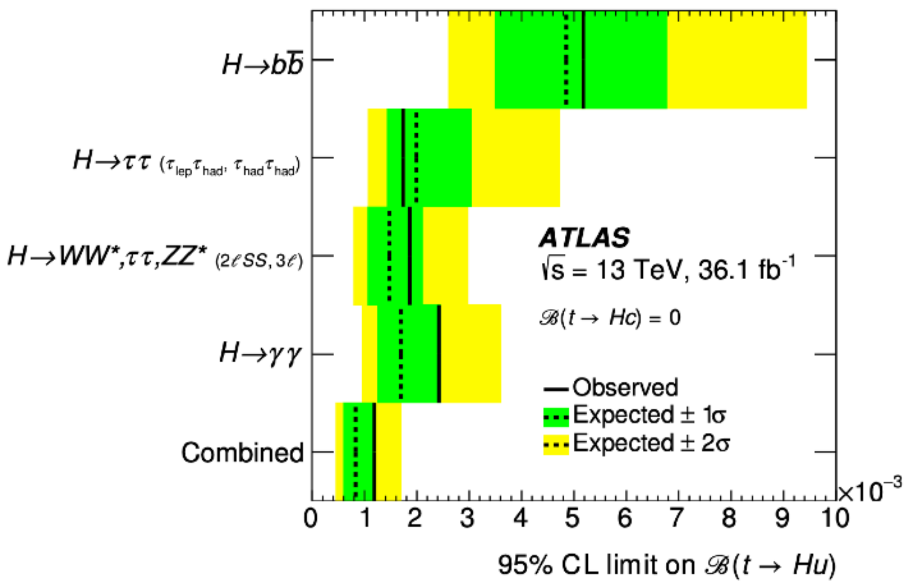
tHq - Hgam-gam

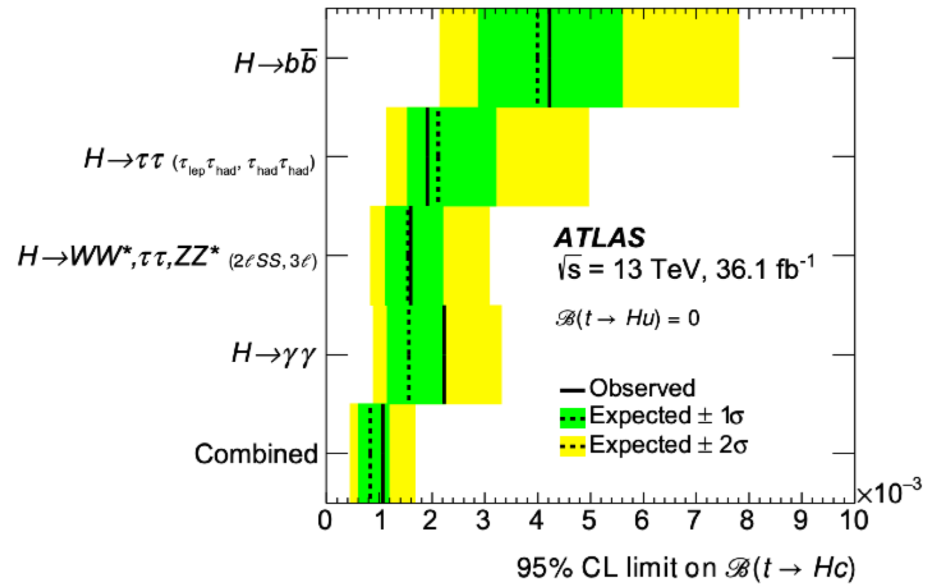
- **Process probed:** ttbar pair with FCNC tqH(gam-gam)
- Analysis basic selection: two tight photons
  - *Hadronic*: ≥4j, ≥1 b-jet. 3-body reconstruction and mass conditions on reconstructed tops.
  - Leptonic: 1-lepton, ≥2 jets, mT(lep,MET) > 30 GeV, 3 body reco and condition on masses
- **Analysis strategy:** inspect m(gam-gam) spectrum after selection (had) / event count (lep)
- **Main backgrounds + estimation strategy**:
  - Hadronic: gam-gam+jets —> estimation with fit to data
  - Leptonic: ttgam, Wgam-gam, gam-gam+jets —> background calibration to data
- **Main systematic uncertainties:** analysis stat-limited
- Results:

	Expected	Observed
t —> uH	2.4×10^{-3}	1.7×10^{-3}
t —> cH	1.6×10^{-3}	2.2×10^{-3}

tHq - ATLAS Combination

- **Combination of all channels**





	Expected	Observed
t —> uH	0.83×10^{-3}	1.2×10^{-3}
t —> cH	0.83×10^{-3}	1.1×10^{-3}