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Search for FCNC processes in the top-quark sector

With the ATLAS experiment

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Outlines

[1] Towards a physics Beyond the Standard Model

[2] The ATLAS experiment

[3] Searching for “top FCNC processes”

[4] Some of the latest ATLAS results

[5] Conclusions

[1] Towards a physics Beyond the Standard Model

Towards a physics beyond the Standard Model

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- The Standard Model: A success up to now
  - Describes the links between
    - 12 fundamental particles
    - 3 interactions (EM, weak, strong)
  - Mass origin with the B.E.H. mechanism
    - Higgs boson discovery in 2012 by ATLAS & CMS
- However some limitations …
  - Gravitation, interaction hierarchy, naturalness, Matter/Antimatter asymmetry, dark matter, neutrino mass, etc.

"Low energy approximation of a more fundamental theory?"

Beyond the Standard Model theories

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- Two main approaches
  - Enhancing fundamental symmetries
  - Playing with space-time dimensionality

Questions / Ideas	Dark Matter	EWSB Origin	Naturalness	Unification	New forces	New particles
SuSy	✓	✓	✓	✓	✓	Neutralino $\tilde{\chi}_i^0$ Super-partners $\tilde{t}$, $\tilde{b}$, etc.
Extra dimensions	✓	✓	✓	✓	✓	Kaluza Klein gluons g_{kk} , gravitons G_{KK}, etc.
Higgs sector extensions		✓	✓		✓	New scalar bosons H^+, H, A
SU(2) gauge sym. extension				✓	✓	New heavy gauge Bosons W', Z'
…	…	…	…	…	…	…

"Gazillion of new particles expected"

Indirect vs. direct search for New Physics

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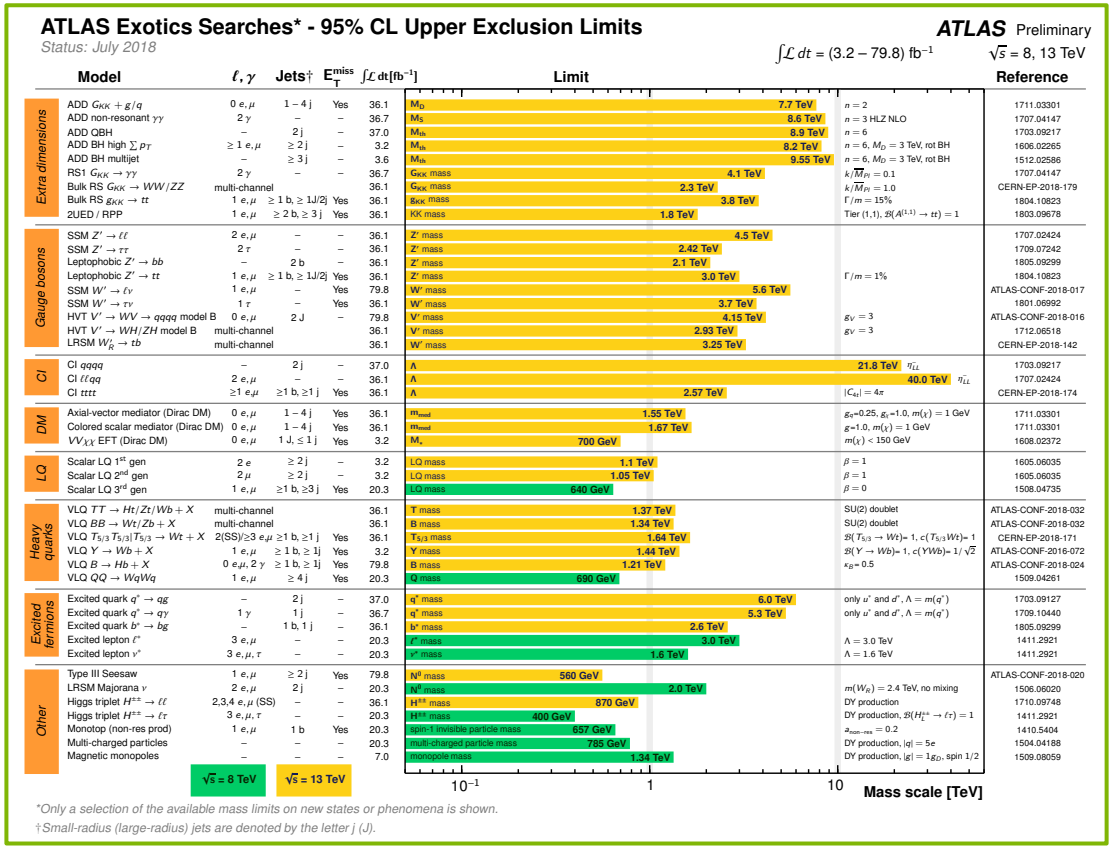
- No evidence (yet) for on-shell production of new particles
- Lower limits are growing

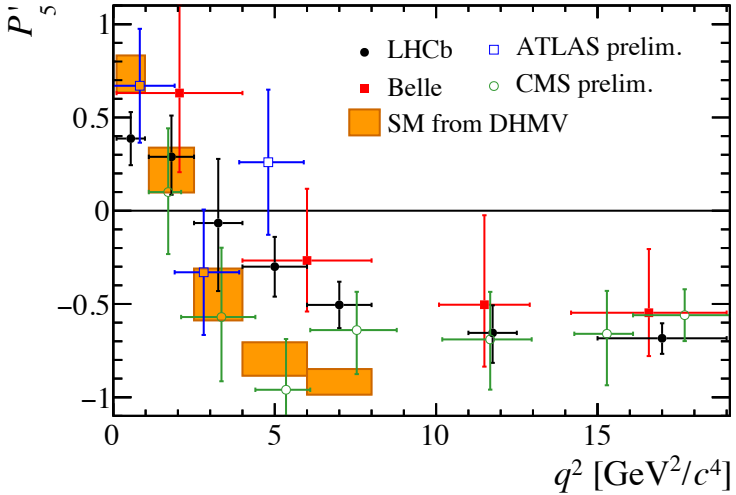
"Access higher mass scales by deviations in coupling measurements and search for rare processes"



Searching for Flavour Changing Neutral Currents

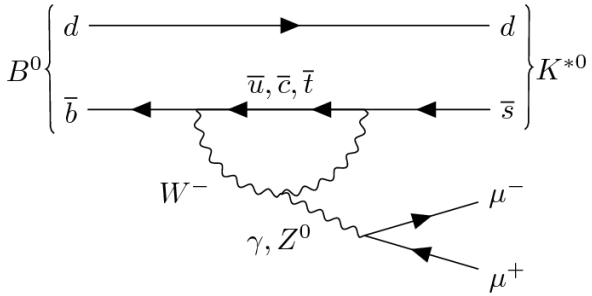
- Interaction process where a fermion undergoes a change of flavour without alternating its charge
  - Forbidden at tree level by the Glashow-Iliopoulos-Maiani (GIM) mechanism in the SM
  - Heavily suppressed at higher corrections

"BSM can enhance FCNC contributions by introducing new particles or interactions"



e.g. Recent tension in $B \to K^* \mu^+ \mu^-$

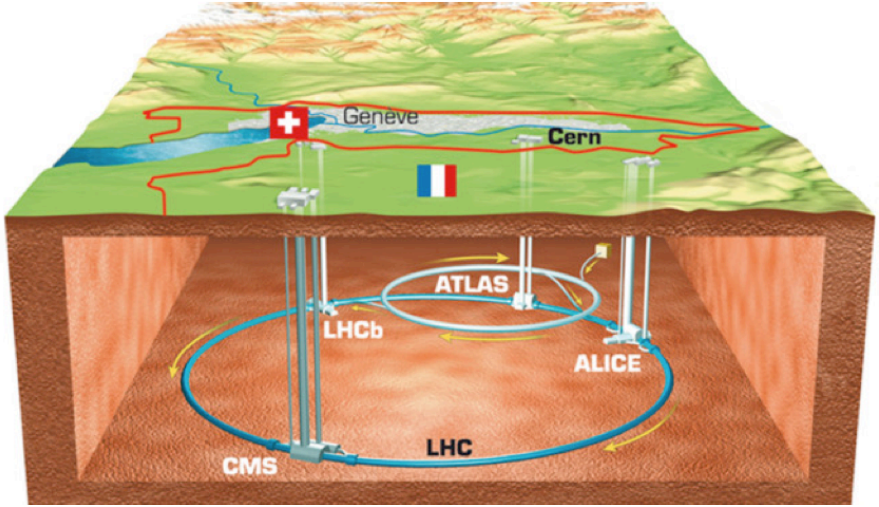
$b \to s$ transition only mediated by loop diagrams in SM



[2] The ATLAS experiment

The Large Hadron Collider

- Most power full particle accelerator/collider in the world



Higher energy collisions

Proton-proton (heavy ions)

$\sqrt{s}$ = 7, 8, 13 TeV

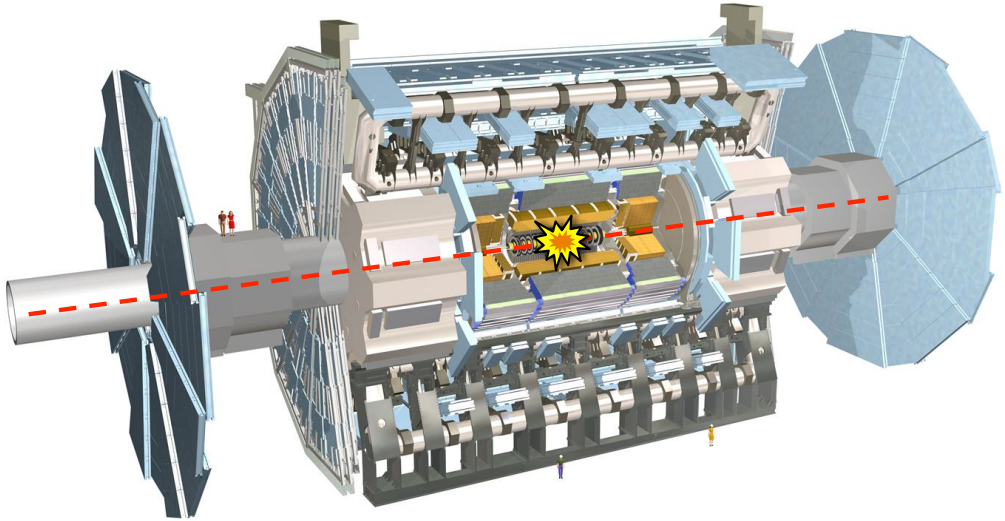
Access to massive particles

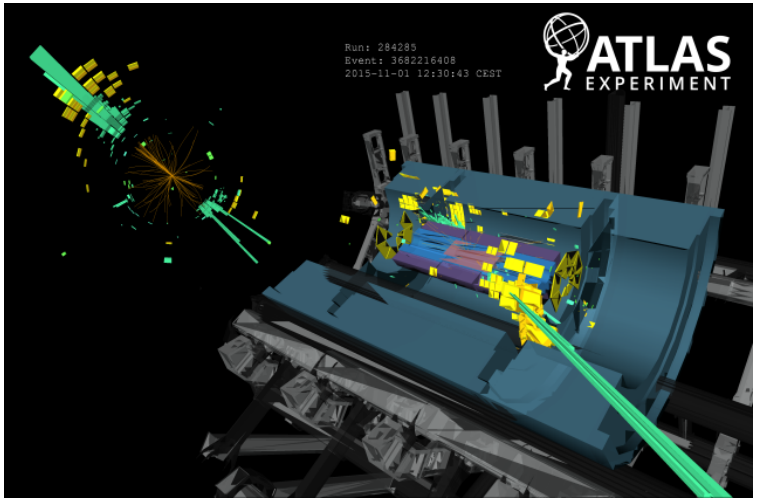
Very high collision frequency

~ MHz

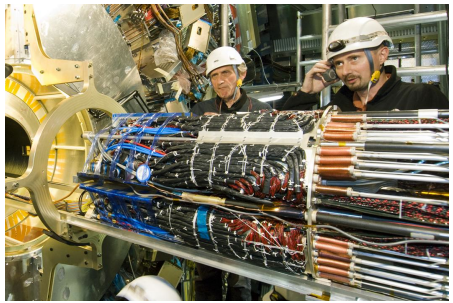
Study rare phenomena

A Toroïdal Lhc ApparatuS

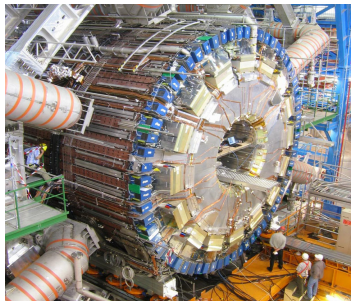




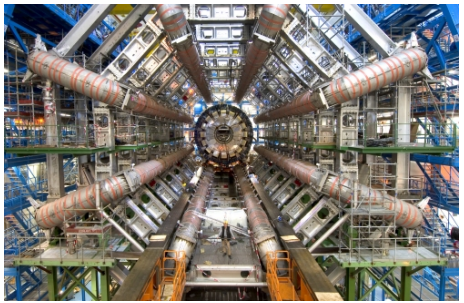
Inner Detector



Calorimeter



Toroidal magnet



Muon chambers

LHC and luminosity in Run II

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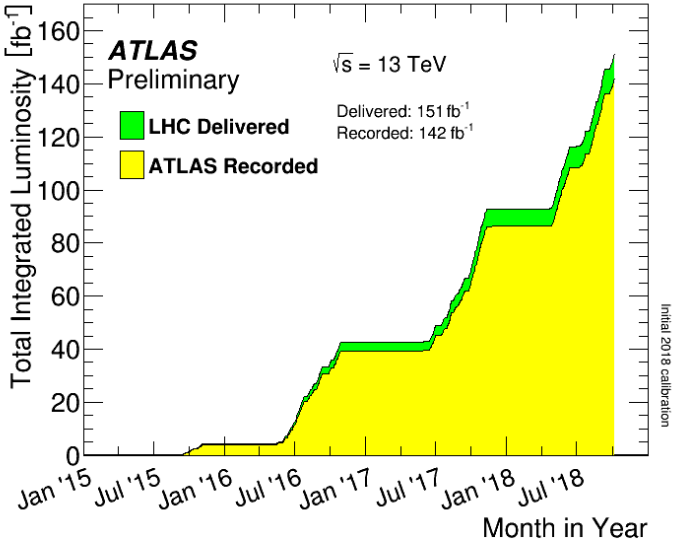
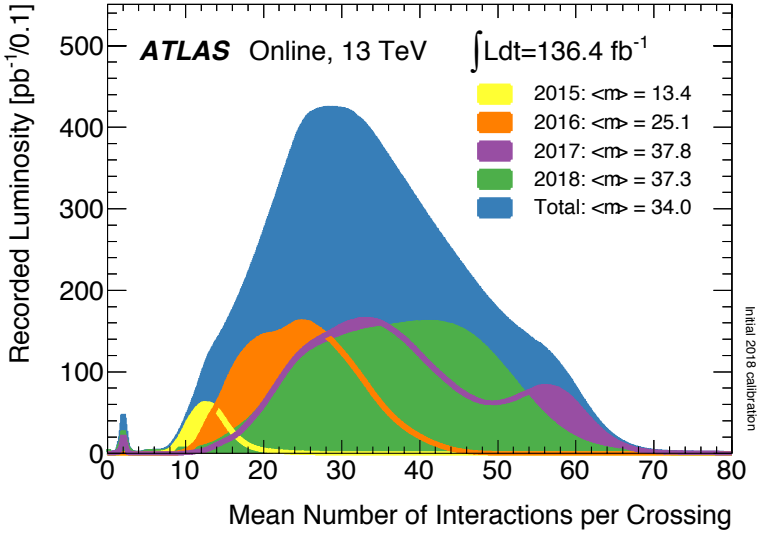
Higher energy and luminosity

More than 140 fb^{-1} accumulated for pp collisions



Large pile-up in Run II

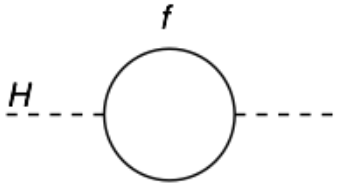
Up to 70 collisions per bunch-crossing in 2017



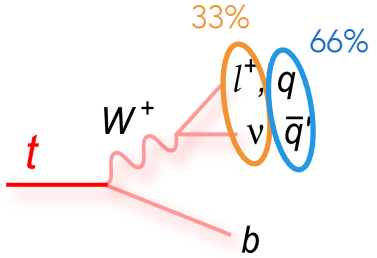
[3] Searching for “top FCNC processes”

The top quark

- A unique particle
  - Most massive elementary particle: $m_t \approx 175$ GeV
  - Decays before hadronising, allowing study of bare quarks
  - Large coupling to Higgs boson & special role in EWSB



Leads radiative corrections to the Higgs mass



$\tau_{top} \approx 10^{-25}$ s

$\tau_{had} \approx h/\Lambda_{QCD} \approx 10^{-23}$ s

$V_{tb} \approx 1$

- An important probe for testing SM & BSM Physics
  - Test pQCD at NNLO precision (fixed-order) and constrain Parton Distribution Functions (PDFs)
  - Determine SM parameters (m_t, $|V_{tb}|$) and measure rare processes ($t\bar{t}+V$, tZ, tH etc.)
  - Constrain New Physics: Direct searches ($t\bar{t}$ resonances, $W' \rightarrow t\bar{b}$), Anomalous couplings

A particle abundantly produced at the LHC

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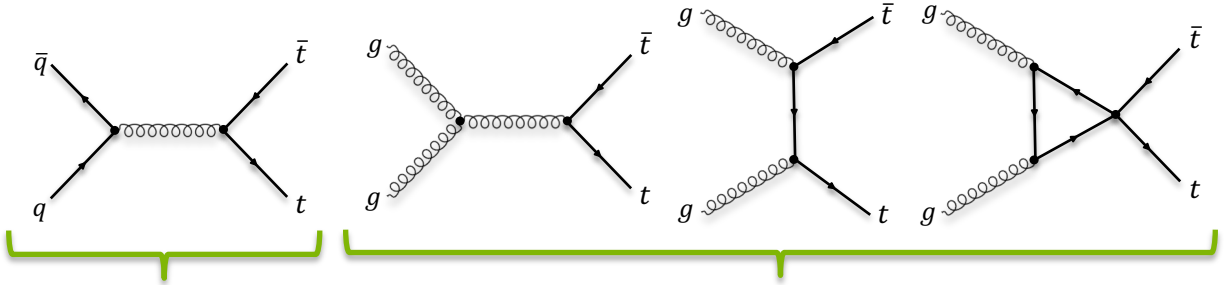
Dominated by $t\bar{t}$ pairs productions (~832 pb at $\sqrt{s} = 13$ TeV)

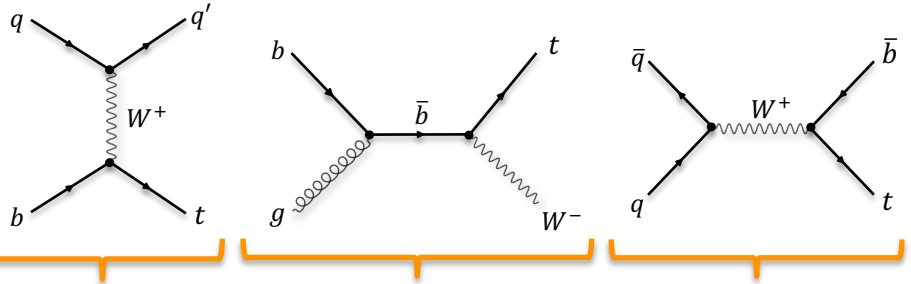


quark-antiquark annihilation (~10%)

gluon-gluon fusions (~ 90%)

Up to now, an impressive agreement between predictions and measurements

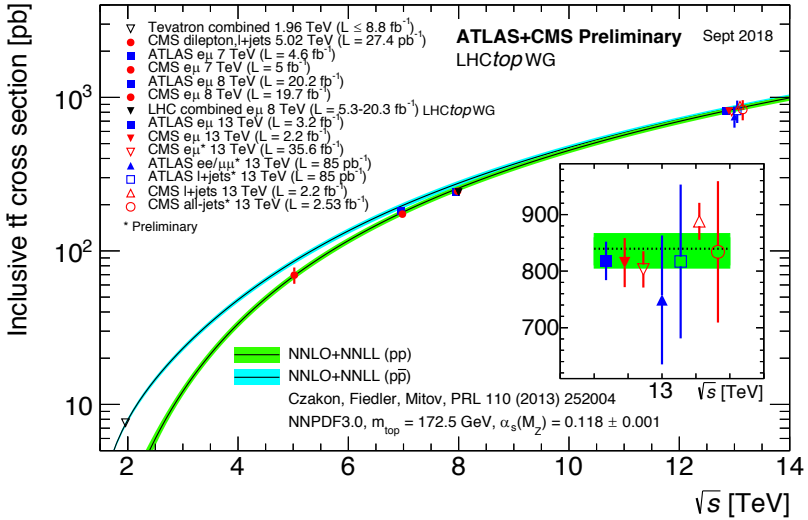
Single top-quark productions



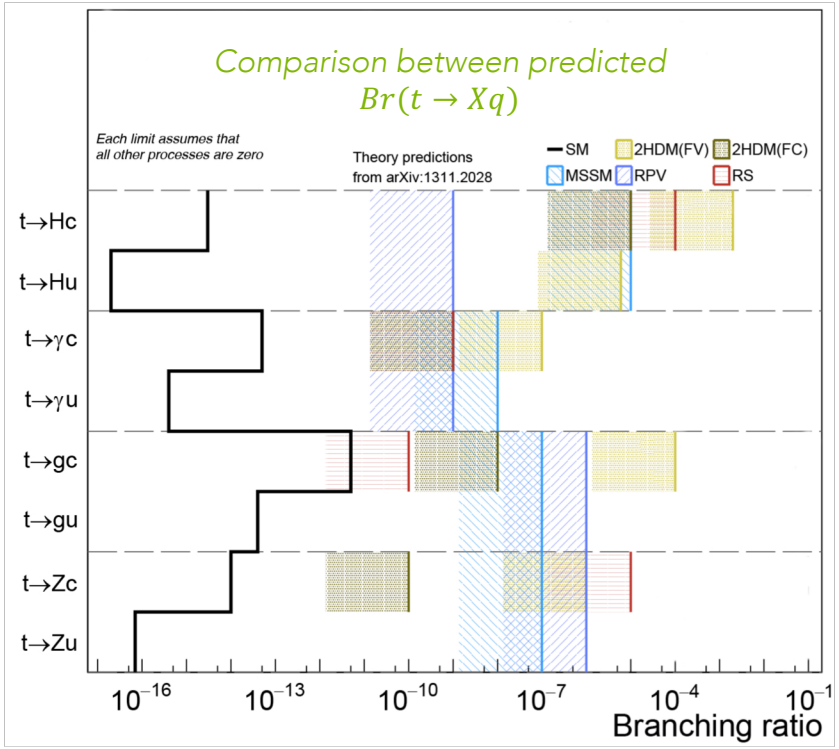
t-channel (~220 pb) 73%

tW associated production (~71.7 pb) 24%

s-channel (10.3 pb) ~3%



BSM contributions to top FCNC processes



Two-Higgs doublet models
e.g. In tree-level FVC between SM fermions and heavy (pseudo)-scalar H or A. In flavour-conserving model via loops with H^+

Super Symmetry
e.g. Flavour violation with light-squarks (NB: advancing squark mass limits suppress loop-induced branching ratios)

Warped extra dimensions
e.g. FVC between SM fermions and Kaluza-Klein (KK) excitations of SM gauge bosons or between top and Higgs boson from processes involving loops of fermion KK modes

Orders of magnitude in excess of SM expectations

**FVC = Flavour Violated Coupling*

Relying on a model independent approach

- Building an Effective Field Theory (EFT)
  - Add all "possible" operators to SM Lagrangian
  - Respect SM symmetries (resulting in $d > 4$)
  - Lowest order for top-quark physics is $d = 6$

SM Lagrangian

Wilson coefficient

Dimension

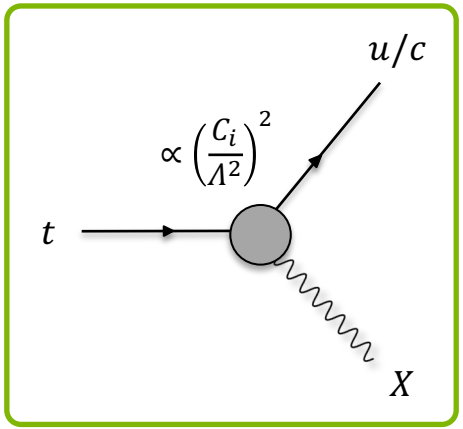
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} + h.c.$$

Effective Lagrangian

New-physics scale

Operator

e.g. top FCNC interaction



Top effective theory for FCNC

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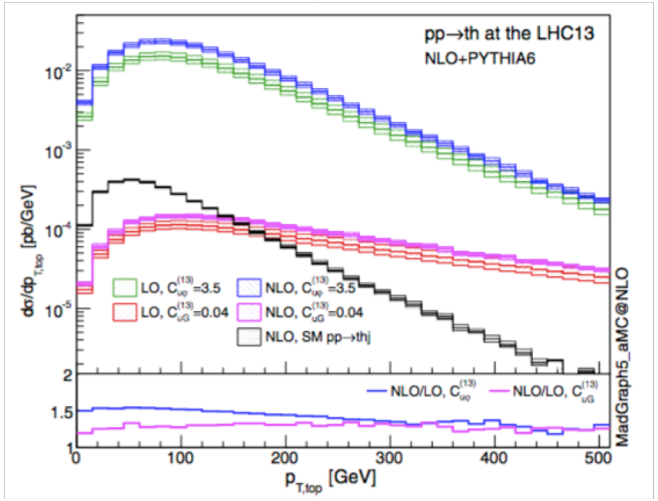
- Provide model independent approach for such BSM interactions
  - NLO computations in QCD for this class of processes started recently
    → Large corrections ~ 30% - 80% and considerable reduction of residual theoretical uncertainties
- A technology within reach for physics analyses
  - e.g. TopFCNC model currently used by ATLAS (C. Degrande, F. Maltoni, J. Wang, C. Zhang) [link]
    → UFO model containing 6D operators affecting top flavour-changing processes

Total cross sections

	LO		NLO		NLO vs. LO relative dif.
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty	
$C_{u\varphi}^{(13)} = 3.5$	2603	$+13.0\% - 11.0\%$	3858	$+7.4\% - 6.7\%$	+48%
$C_{uG}^{(13)} = 0.04$	40.1	$+16.5\% - 13.2\%$	50.7	$+4.0\% - 5.2\%$	+26%
$C_{u\varphi}^{(23)} = 3.5$	171	$+9.7\% - 8.7\%$	310	$+7.3\% - 6.3\%$	+81%
$C_{uG}^{(23)} = 0.09$	9.53	$+11.0\% - 9.7\%$	16.6	$+5.5\% - 5.1\%$	+73%

Differential cross sections



Main top FCNC research focuses

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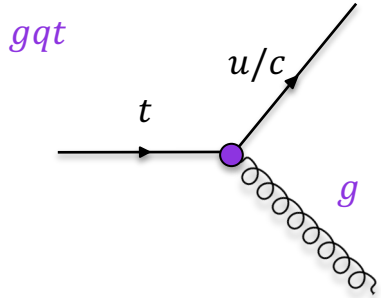
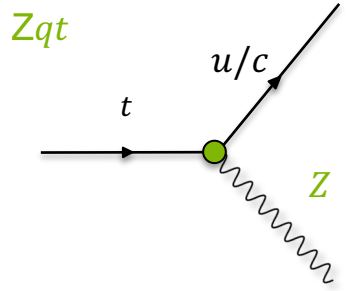
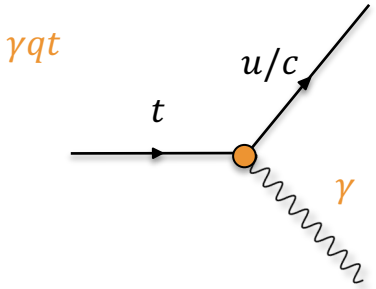
FCNC in strong interaction

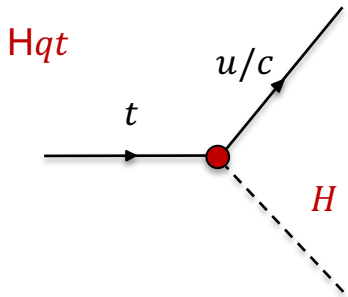




Probe EW sector

Probe EW sector

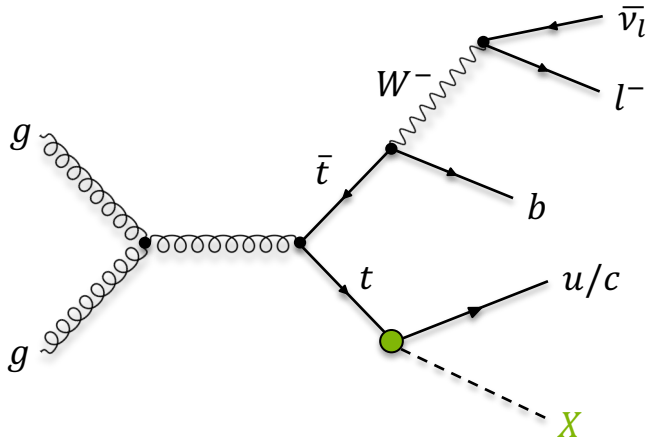




Probe EW sector

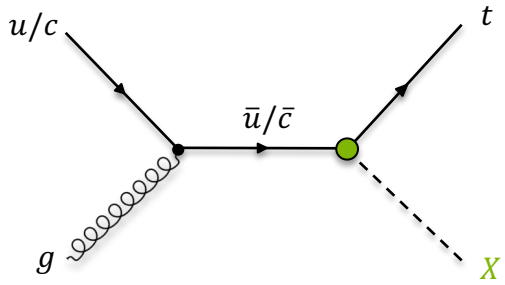
Most important top FCNC processes at LHC

Decay processes $t \to qX$ with $X = \gamma, Z, H$



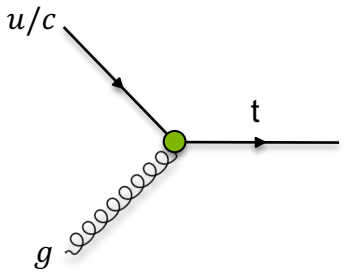
Benefits from the large $t\bar{t}$ production cross section
The first approach …

Production modes $qg \to tX$



Wider kinematic range accessible, probes interactions at higher scales where new physics effects could be enhanced

Or simply $qg \to t$



[4] Some of the latest ATLAS results

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Search FCNC in single top-quark production

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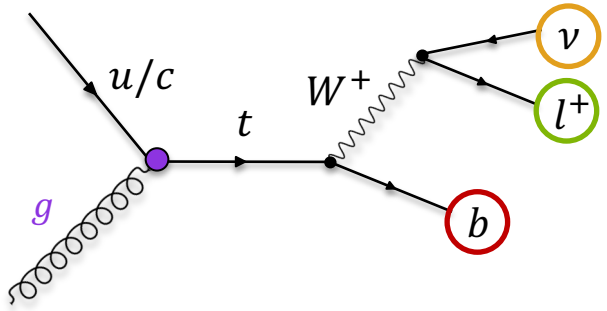
Eur. Phys. J C76 (2016 87)



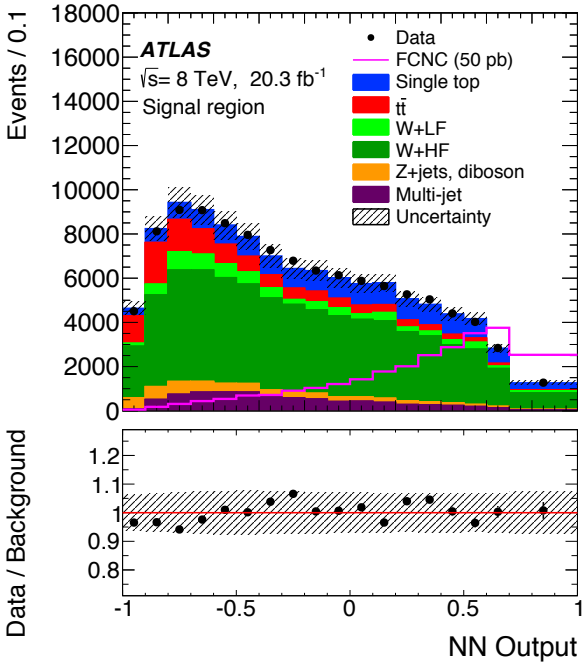
- Definition of the signal region
  - 1 charged lepton (e, μ) with p_T >25 GeV and $|\eta| < 2.5$
  - E_T^{miss} > 30 GeV, $m_T(W)$ > 50 GeV
  - 1 b-tagged jets (50% b-jet efficiency) with p_T >50 GeV and $|\eta| < 2.5$

Process	Control region	Signal region
Single top	11 500 ± 620	14 400 ± 770
$t\bar{t}$	10 700 ± 650	12 000 ± 740
W+LF	526 900 ± 130 000	6 700 ± 1 900
W+HF	445 200 ± 240 000	62 100 ± 34 000
Z+jets	40 000 ± 9 700	4 990 ± 1 200
Multi-jet	68 300 ± 12 000	7 430 ± 1 300
Total expected	1 100 000 ± 280 000	107 000 ± 34 000
Data	1 112 225	108 152

- Backgrounds
  - W+jets ← *Validated with looser b-tagging requirement*
  - $t\bar{t}$
  - single top
  - Multi-jets ← *Estimated with data-driven technics*
  - Z+jets

Search FCNC in single top-quark production

Eur. Phys. J C76 (2016 87)



- MVA approach (NN) used to discriminate signal and background

Variable	Definition
$m_{\mathrm{T}}(\mathrm{top})$	Transverse mass of the reconstructed top quark
p_{T}^{ℓ}	Transverse momentum of the charged lepton
$\Delta R(\mathrm{top}, \ell)$	Distance in the η–ϕ plane between the reconstructed top quark and the charged lepton
$p_{\mathrm{T}}^{b\text{-jet}}$	Transverse momentum of the b-tagged jet
$\Delta\phi(\mathrm{top}, b\text{-jet})$	Difference in azimuth between the reconstructed top quark and the b-tagged jet
$\cos\theta(\ell, b\text{-jet})$	Opening angle of the three-vectors between the charged lepton and the b-tagged jet
q^{ℓ}	Charge of the lepton
$m_{\mathrm{T}}(W)$	W-boson transverse mass
η^{ℓ}	Pseudorapidity of the charged lepton
$\Delta\phi(\mathrm{top}, W)$	Difference in azimuth between the reconstructed top quark and the W boson
$\Delta R(\mathrm{top}, b\text{-jet})$	Distance in the η–ϕ plane between the reconstructed top quark and the b-tagged jet
η^{top}	Pseudorapidity of the reconstructed top quark
p_{T}^{W}	Transverse momentum of the W boson

Exclusion limits on extracted on $\sigma_{qg\to t} \cdot Br(t \to Wb)$ using binned likelihood fit to NN output

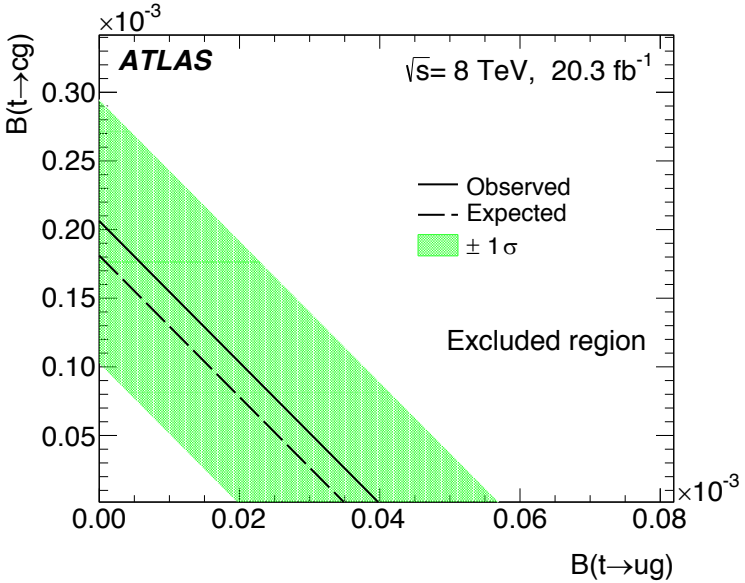
Obs. limit : $\sigma_{qg\to t} \cdot Br(t \to Wb) < 3.4$ pb

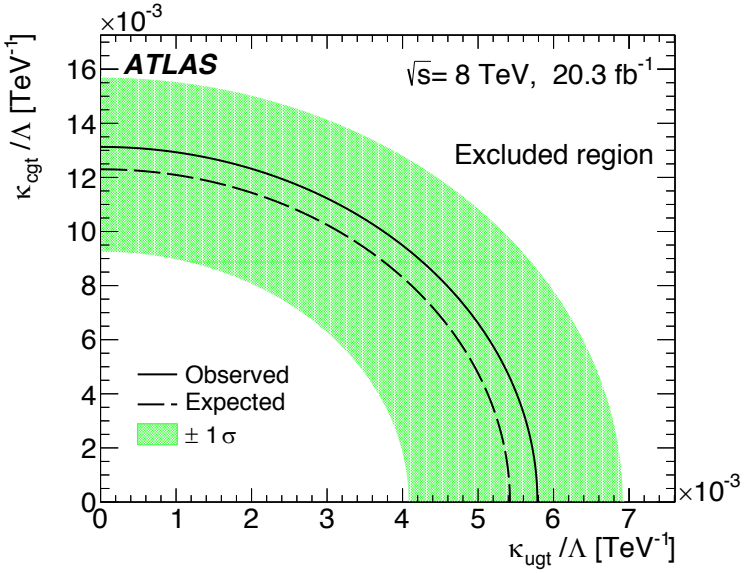
Exp. limit : $\sigma_{qg\to t} \cdot Br(t \to Wb) < 2.9$ pb

Search FCNC in single top-quark production

Eur. Phys. J C76 (2016 87)

- Exclusion limits on branching ratios and EFT interpretation





Limits on branching ratios

$Br(t \to ug) < 4.10^{-5}$

$Br(t \to cg) < 17.10^{-5}$

Interpretation in terms of limits on FCNC couplings

$\kappa_{ugt}/\Lambda < 5.8.10^{-3}$ TeV^{-1}

$\kappa_{cgt}/\Lambda < 13.10^{-3}$ TeV^{-1}

[4] Some of the latest ATLAS results

Search for FCNC decay $t \to u(c) + Z$ *in* $t\bar{t}$ *events*

Search for FCNC decay $t \to u(c) + Z$ in $t\bar{t}$ events

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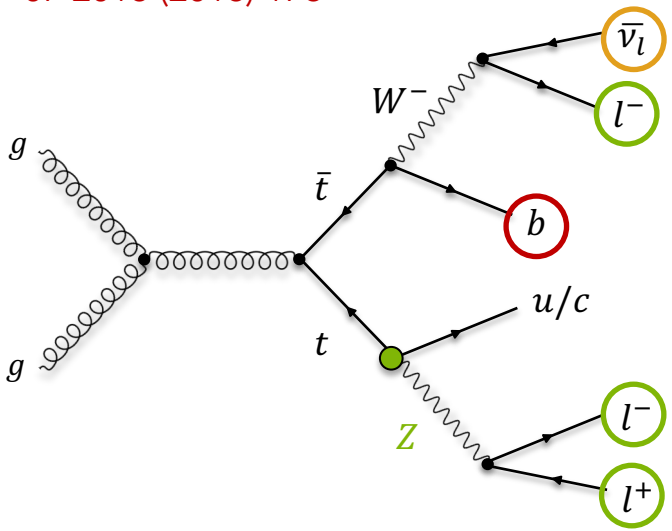

- Definition of the signal region
  - 3 leptons with p_T >15 GeV and $|\eta|$ < 2.5
  - E_T^{miss} > 40 GeV
  - ≥ 2 jets with p_T >15 GeV and $|\eta|$ < 2.5
  - Exactly 1 b-tagged jets (77% b-jet efficiency)
  - Mass requirements
    - $|\, m_{ll} - 91.2\ \text{GeV}\,| < 15\ \text{GeV}$
    - $|\, m_{lv} - 80.4\ \text{GeV}\,| < 30\ \text{GeV}$
    - $|\, m_{lvb} - 172.5\ \text{GeV}\,| < 40\ \text{GeV}$
    - $|\, m_{jll} - 172.5\ \text{GeV}\,| < 40\ \text{GeV}$

- Background processes
  - $t\bar{t}H$
  - WZ and ZZ
  - $t\bar{t}$ and Z+jets with one non-prompt lepton
  - tZ and tWZ

- Kinematic fit to signal hypothesis

$$\chi^2 = \frac{\left(m^{reco}_{jalala} - m_{t_{FCNC}}\right)^2}{\sigma^2_{t_{FCNC}}} + \frac{\left(m^{reco}_{jblcv} - m_{t_{SM}}\right)^2}{\sigma^2_{t_{SM}}} + \frac{\left(m^{reco}_{lcv} - m_W\right)^2}{\sigma^2_W}$$

* Determined from simulation

Search for FCNC decay $t \to u(c) + Z$ in $t\bar{t}$ events

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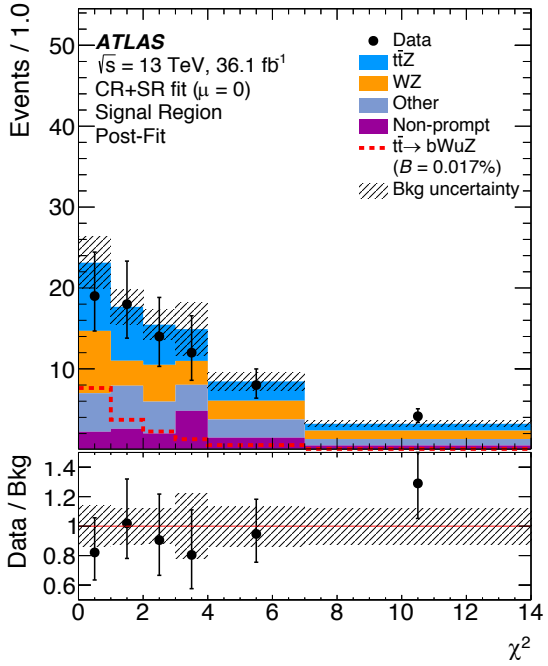
- χ^2 used as final discriminant in the signal region
  - Simultaneous fit in 5 CRs and SR under the background-only hypothesis



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

Search for FCNC decay $t \to u(c) + Z$ in $t\bar{t}$ events

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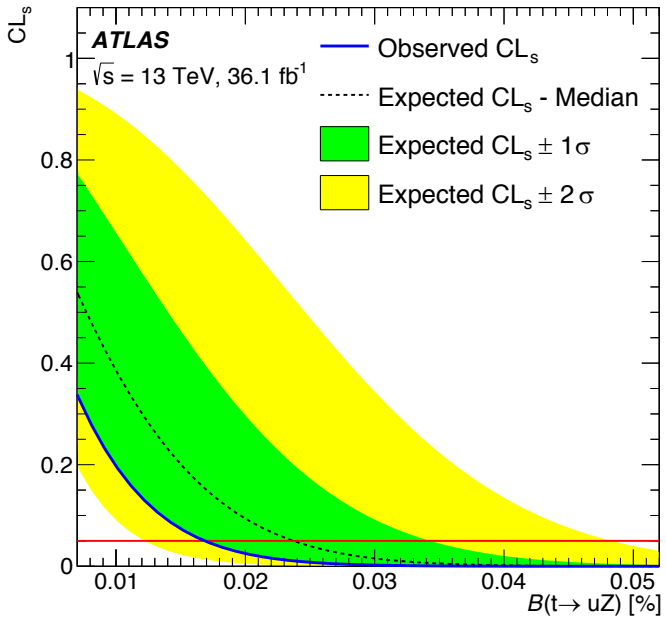
- Expected and observed exclusion limits on branching ratios and EFT interpretation



	$\mathcal{B}(t \to uZ)$	$\mathcal{B}(t \to cZ)$
Observed	1.7×10^{-4}	2.4×10^{-4}
Expected -1σ	1.7×10^{-4}	2.2×10^{-4}
Expected	2.4×10^{-4}	3.2×10^{-4}
Expected $+1\sigma$	3.4×10^{-4}	4.6×10^{-4}

Limits on $\mathrm{Br}(t \to qZ)$

Operator	Observed	Expected
$\lvert C_{uB}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uW}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uB}^{(32)} \rvert$	0.30	0.34
$\lvert C_{uW}^{(32)} \rvert$	0.30	0.34

Limits on 6D-operator coefficients

[4] Some of the latest ATLAS results

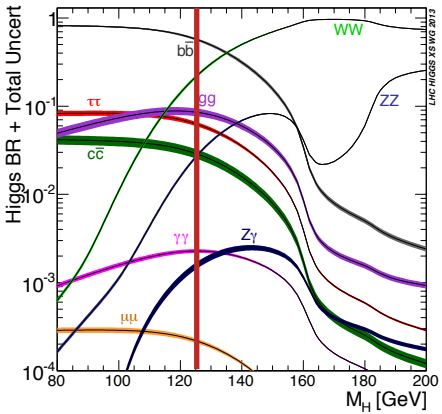
Search for FCNC decay $t \to u(c) + H$ in $t\bar{t}$ events

Higgs decay channel & design of the analysis

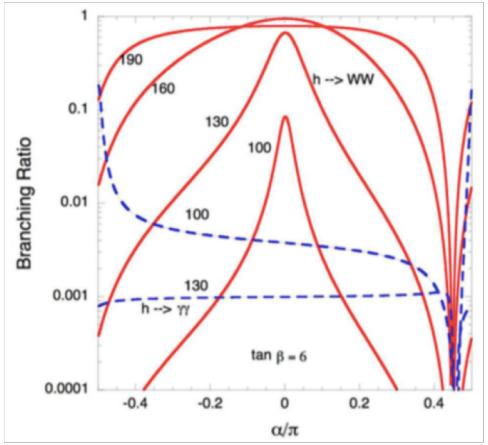
- $H \to b\bar{b}$
  - Challenging channel
  - Large background
  - *l*+jets final states
  - Needs optimised *b*-tagging and MVA technics
- $H \to \tau\tau,\ WW^*, ZZ^*$
  - Cleaner experimental signature probing mutli-lepton final states
  - Reduced background
  - Suffer from low statistics
- $H \to \gamma\gamma$
  - Small branching ratio
  - Very pure signature, reaching competitive sensitivity in FCNC $t\bar{t}(t \to qH)$ analyses

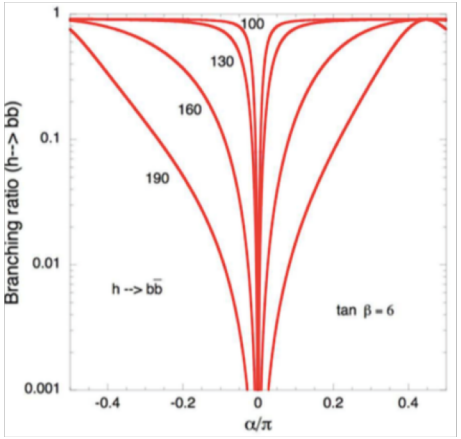
Dominant decay channels in SM and usually in BSM

In the Standard Model



In 2HDM

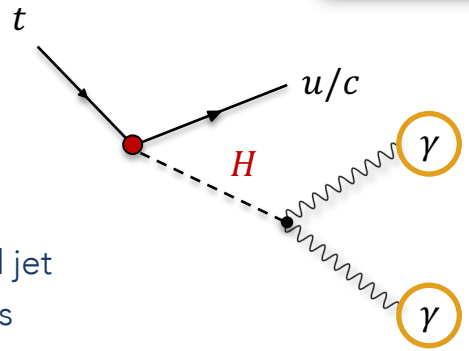




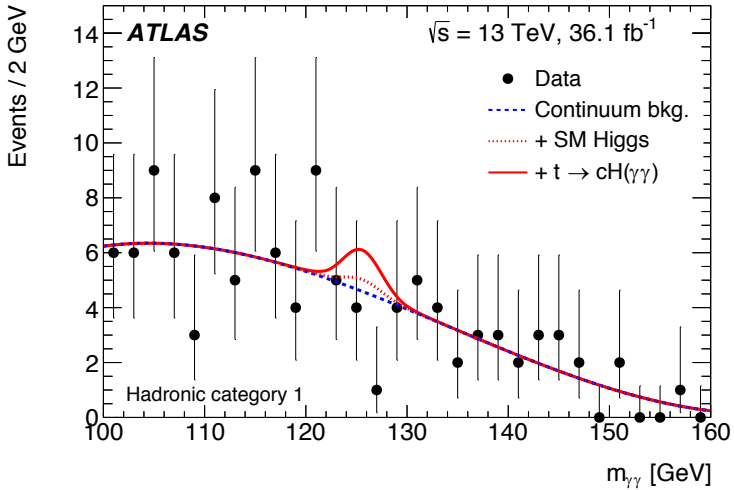
Search for FCNC decay $t \to qH$ with $H \to \gamma\gamma$

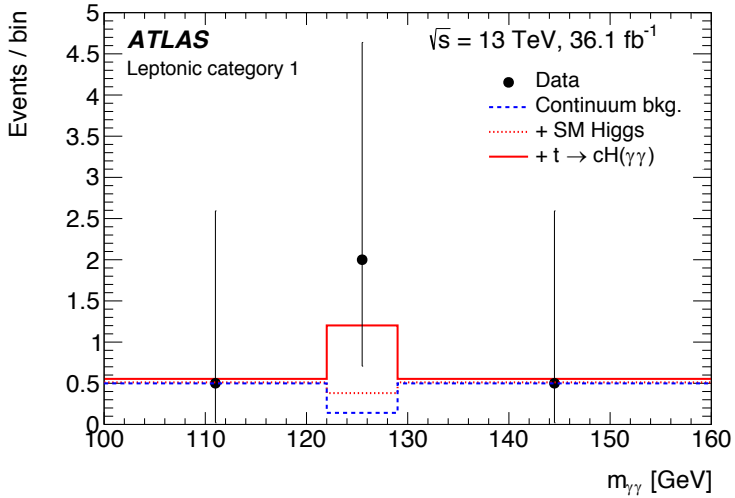
JHEP 10 (2017) 129

- Select event with 2 photons
  - p_T >40, 30 GeV and 100 < $m_{\gamma\gamma}$ < 160 GeV
- Data divided in 4 categories
  - 2 hadronic categories: no identified lepton, 4 jets, ≥ 1 b-tagged jet
  - 2 leptonic categories: 1 lepton (e, μ) with p_T > 10,15 GeV, ≥ 1 jets



e.g. Category 1 events passing full selection

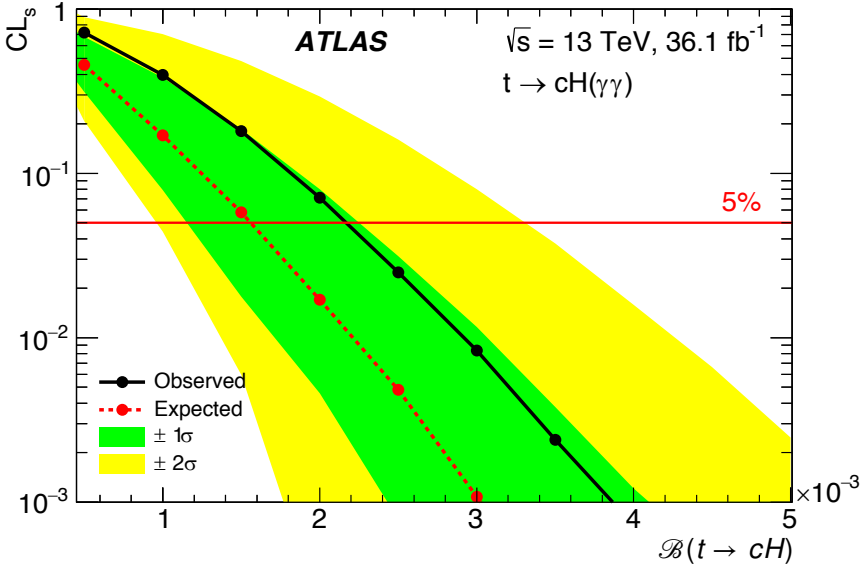


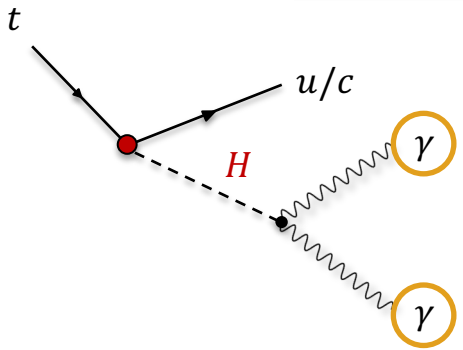


Search for FCNC decay $t \to qH$ with $H \to \gamma\gamma$

JHEP 10 (2017) 129

- Fit performed to di-photon mass with signal function at m_H
  - Backgrounds (primarily $\gamma\gamma j$ and $t\bar{t}\gamma$) from sideband fit





Observed (expected) exclusion limits from $H \to \gamma\gamma$ channel

$Br(t \to qH) < 0.22\%$ (0.16%)
$Br(t \to qH) < 0.24\%$ (0.17%)

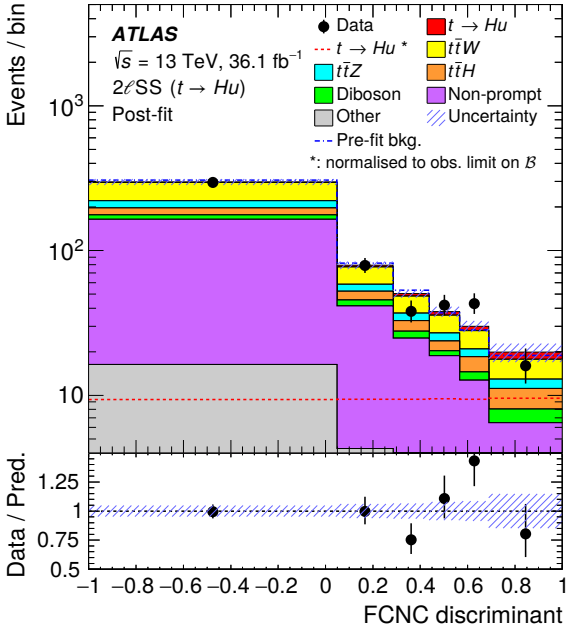
Search for FCNC decay $t \to qH$ with multileptons

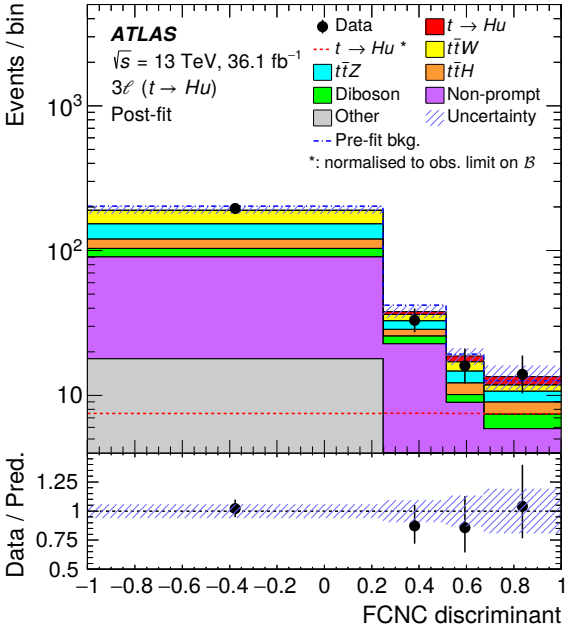
PRD 98 (2018) 032002

- Search $H \to \tau\tau,\ WW^*,\ ZZ^*$ in two channels
  - $2l$ same-sign, ≥ 4 jets, 1 or 2 b-jet
  - $3l$, ≥ 2 jets, 1 b-jets

Making use of $t\bar{t}H$ data (PRD 97 (2018) 072003)
Optimising analysis for FCNC signal

Boosted Decision Trees (BDT) employed to discriminate signal from background

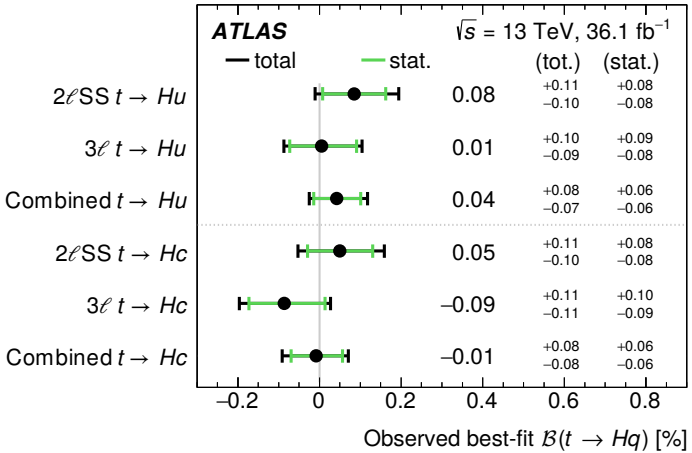


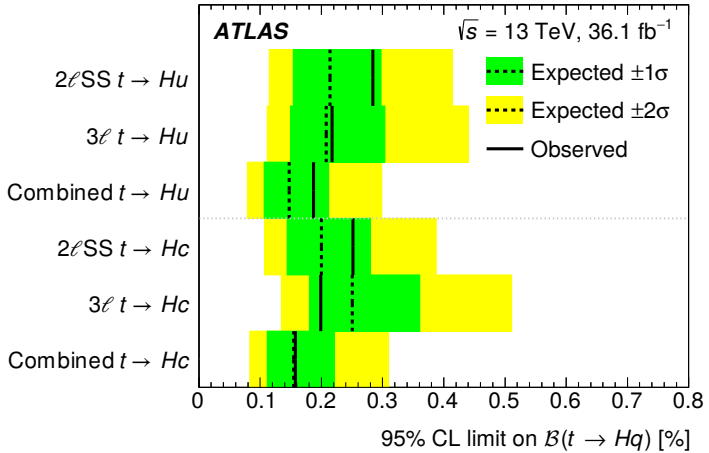


Search for FCNC decay $t \to qH$ with multi-leptons

PRD 98 (2018) 032002

- $Br(t \to qH)$ extracted from binned likelihood fit to BDT discriminant combining $2lSS$ and $3l$ ch.
  - Best-fit and upper limits obtained





Observed (expected) exclusion limits from multi-leptons channels

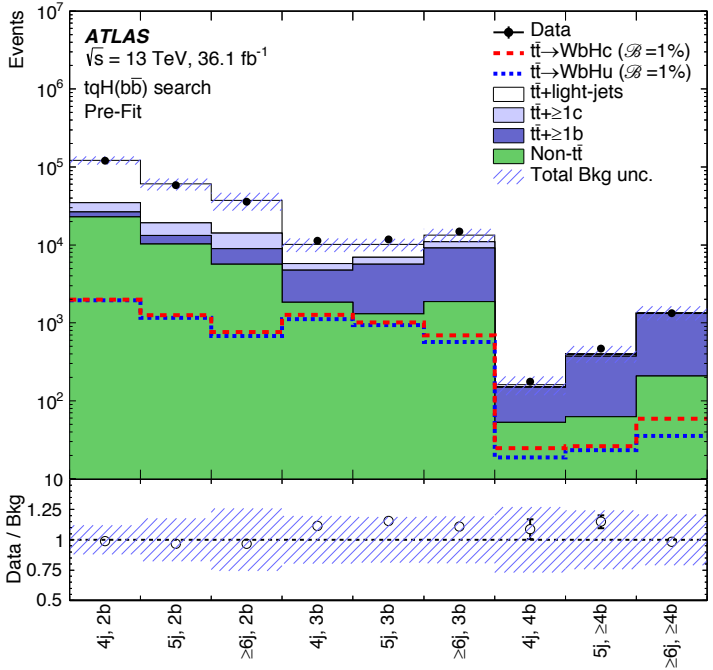
$Br(t \to uH) < 0.19\%$ (0.15%)
$Br(t \to cH) < 0.16\%$ (0.15%)

Search for FCNC decay $t \to qH$ with $H \to b\bar{b}$

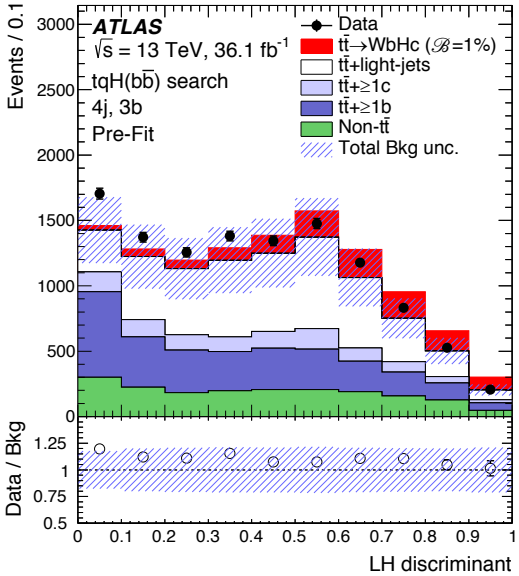
BERGISCHE UNIVERSITÄT WUPPERTAL

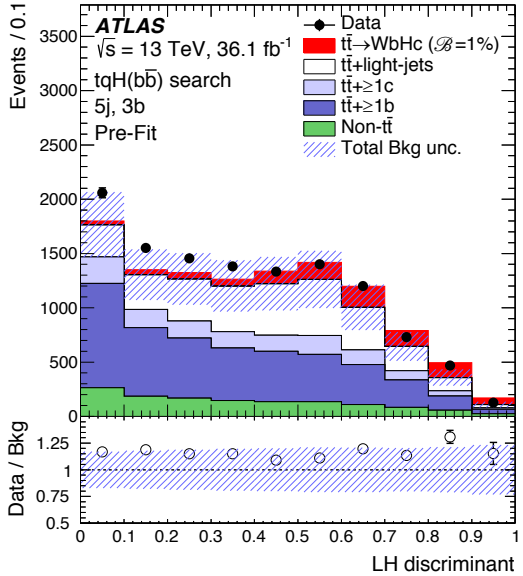
arXiv:1812.11568 – Submitted to JHEP

- Lepton+jets channels split into 9 analysis regions – *n* jets *m* *b*-jets



- Likelihood (LH) discriminant constructed to separate signals and backgrounds





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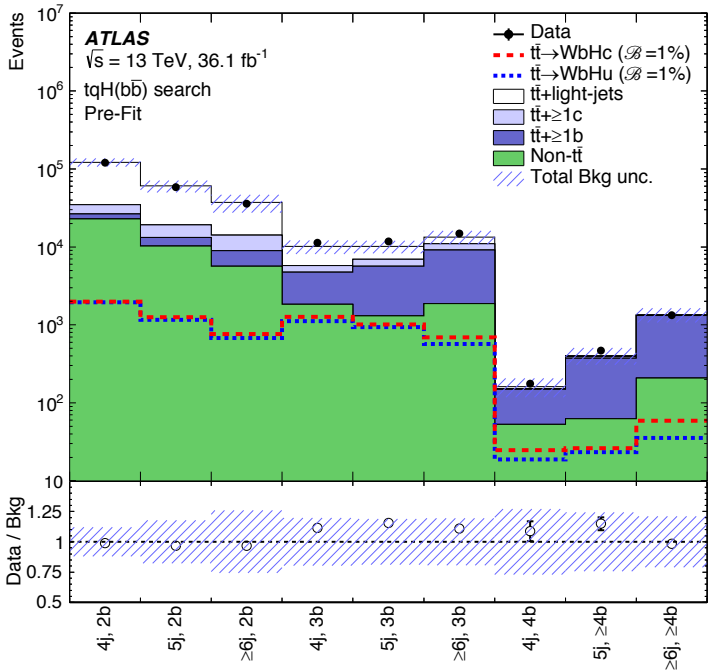


- Similarly $Br(t \to qH)$ extracted from binned likelihood fit to LC discriminant combining all channels

Observed (expected) exclusion limits from $H \to b\bar{b}$ *channels*

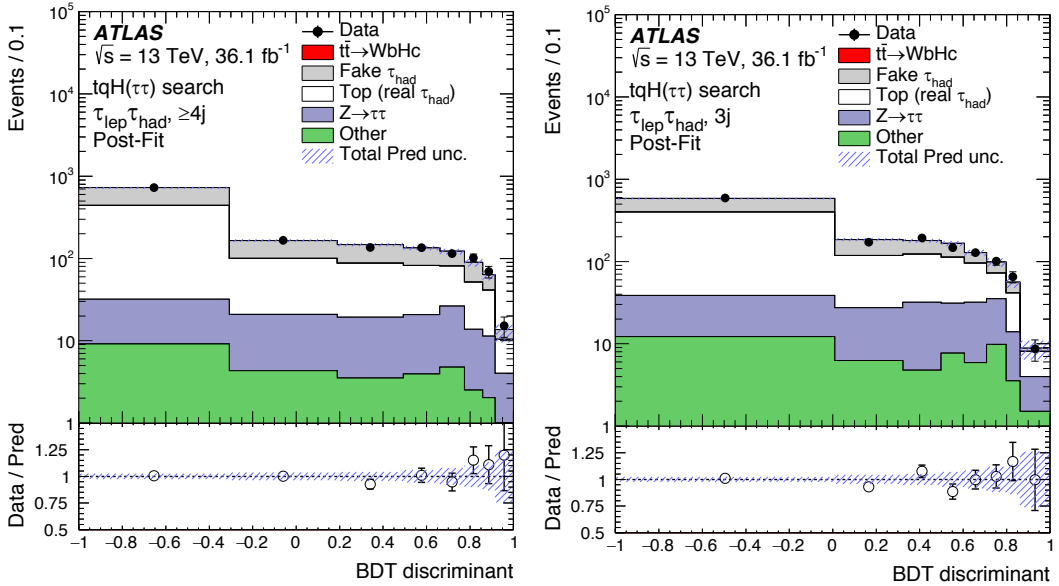
$Br(t \to uH) < 0.52\%$ (0.49%)
$Br(t \to cH) < 0.42\%$ (0.30%)

Search for FCNC decay $t \to qH$ with $H \to \tau^+\tau^-$

BERGISCHE UNIVERSITÄT WUPPERTAL

arXiv:1812.11568 – Submitted to JHEP

- Further exploiting the $H \to \tau^+\tau^-$ decay channel
  - Four SRs designated: (τ_{lep}, τ_{had}, 3 jets), (τ_{lep}, τ_{had}, $\geq$ 4 jets), (τ_{had}, τ_{had}, 3 jets), (τ_{had}, τ_{had}, $\geq$ 4 jets)
  - χ^2 kinematic reconstruction of $H \to \tau^+\tau^-$ decay



Boosted Decision Trees (BDT) employed to discriminate signal from background

Search for FCNC decay $t \to qH$ with $H \to \tau^+\tau^-$

BERGISCHE UNIVERSITÄT WUPPERTAL

arXiv:1812.11568 – Submitted to JHEP

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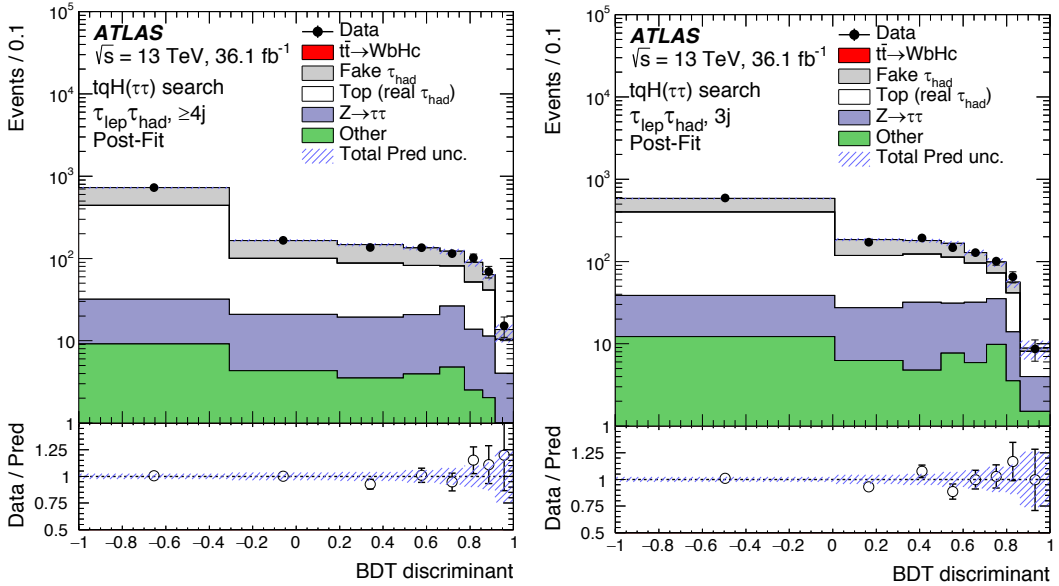

- Similarly $Br(t \to qH)$ extracted from binned likelihood fit to BDT disc.

Observed (expected) exclusion limits from $H \to \tau^+\tau^-$ channels

$Br(t \to uH) < 0.17\%$ (0.20%)
$Br(t \to cH) < 0.19\%$ (0.21%)

Combining FCNC decay $t \to qH$ results

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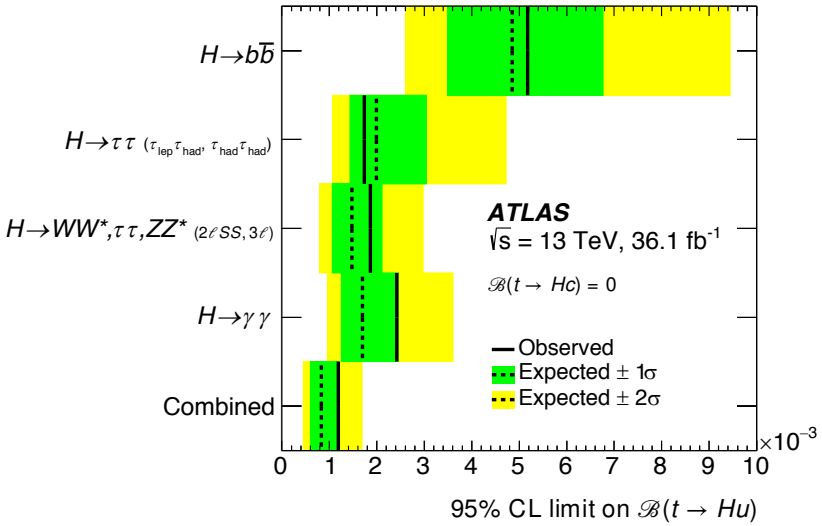
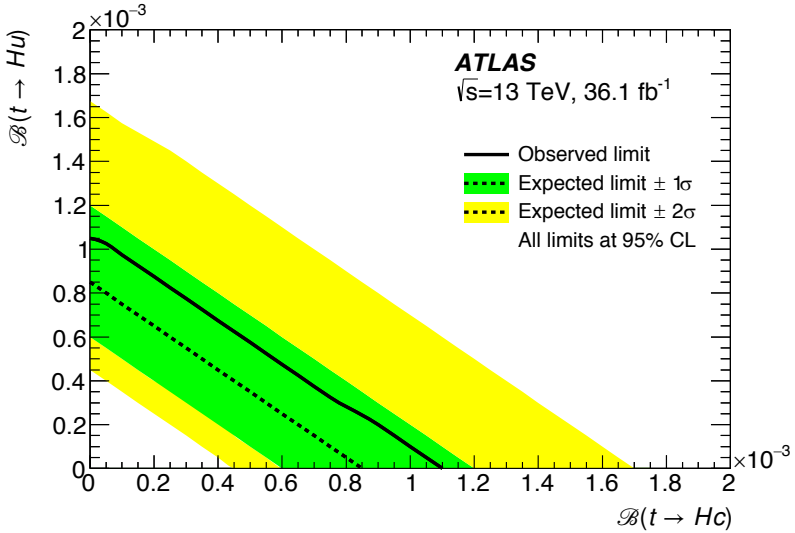
arXiv:1812.11568 – Submitted to JHEP

- Full likelihood combination of $H \to b\bar{b}$, $\tau^+\tau^-$, multilepton, $\gamma\gamma$ channel searches





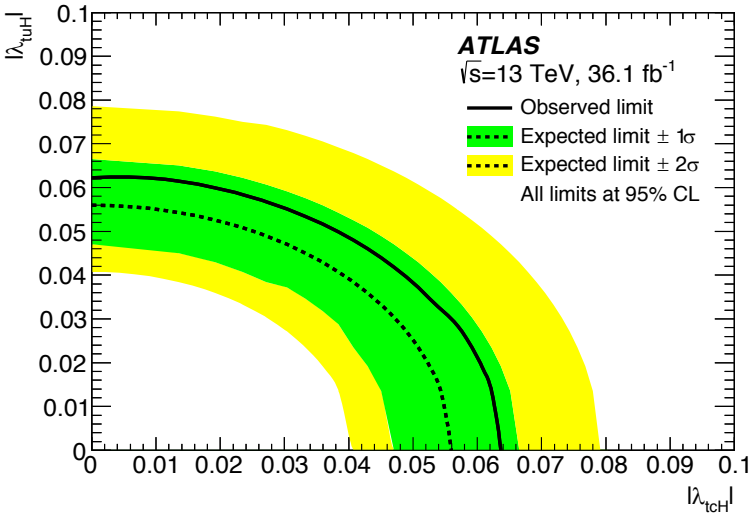
Combined limits on branching ratios

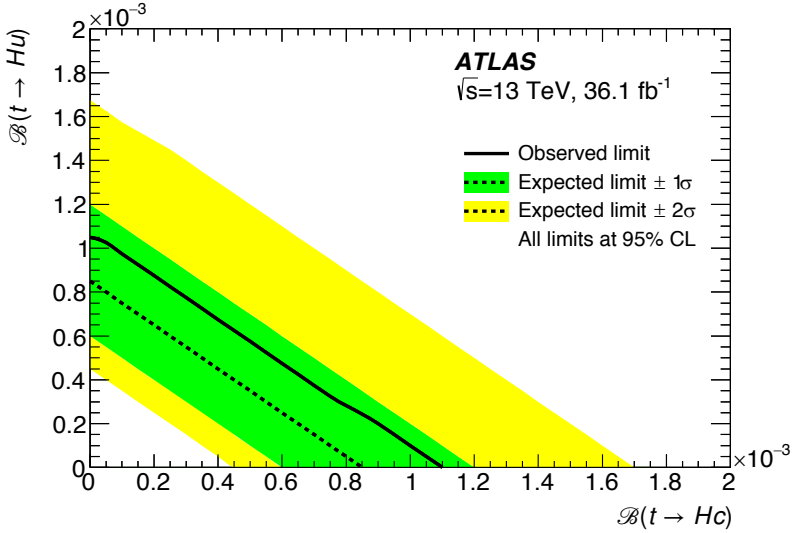
Combining FCNC decay $t \to qH$ results

BERGISCHE UNIVERSITÄT WUPPERTAL

arXiv:1812.11568 – Submitted to JHEP

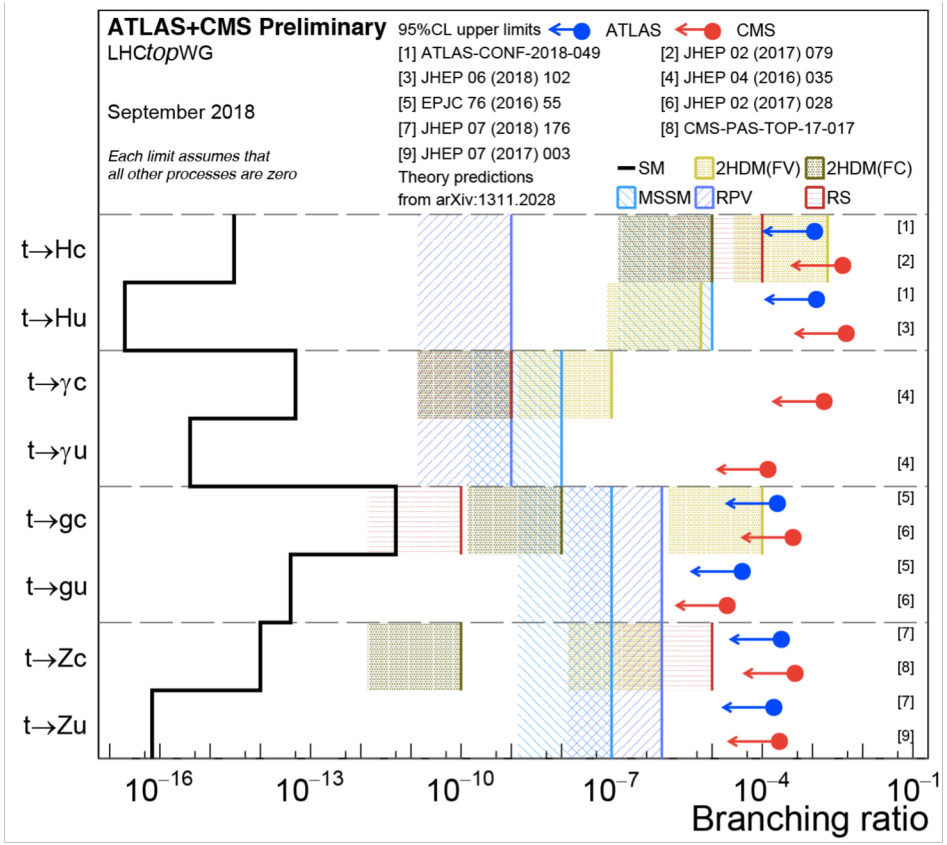
- Full likelihood combination of $H \to b\bar{b}$, $\tau^+\tau^-$, multilepton, $\gamma\gamma$ channel searches





Interpretation in terms of limits on FCNC couplings

Summary



- Summary of the current 95% CL level observed limits on $Br(t \to Xq)$ (with $X = g, Z, \gamma$ or H, and $q = u$ or c) obtained by ATLAS … and CMS

"Best LHC limits starting to probe phase space of particular BSM models"

[5] Conclusions

Conclusions

- Search for New Physics more than ever at the heart of LHC experiment research programs
  - No evidence (yet) for on-shell production of new particles
  - Access higher mass scales by deviations in coupling measurements and search for rare processes
- A comprehensive high-precision search for FCNC processes pursued with the ATLAS experiment
  - In both top-quark production and decay
  - Developing more ambitious analysis strategies (using MVA, multi-channel combinations, etc.)
  - Best LHC limits starting to probe space of particular BSM models
- The next steps
  - Further exploit toq-quark production mode in combination with top-quark decay analyses
  - Making use the full Run II statistics

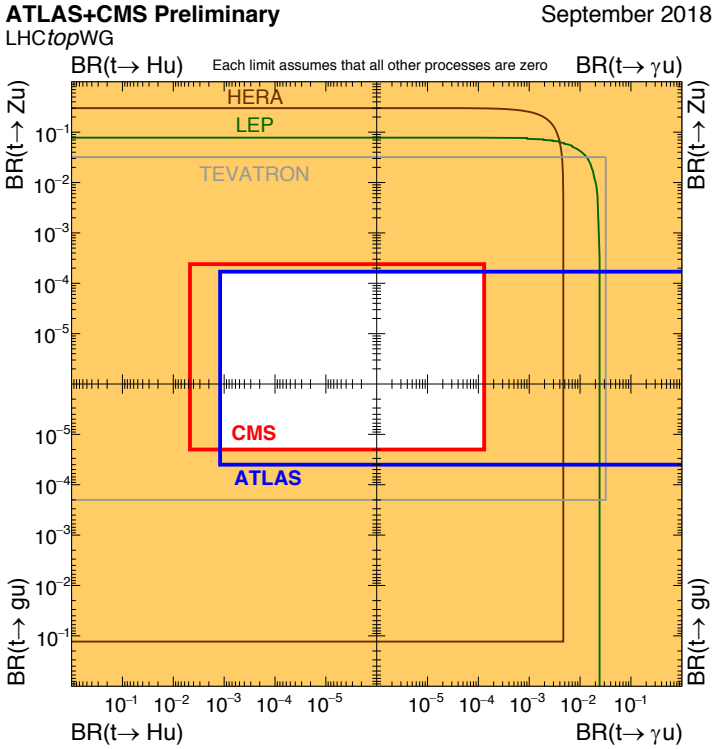
"Promising research area for run-3 and HL-LHC"

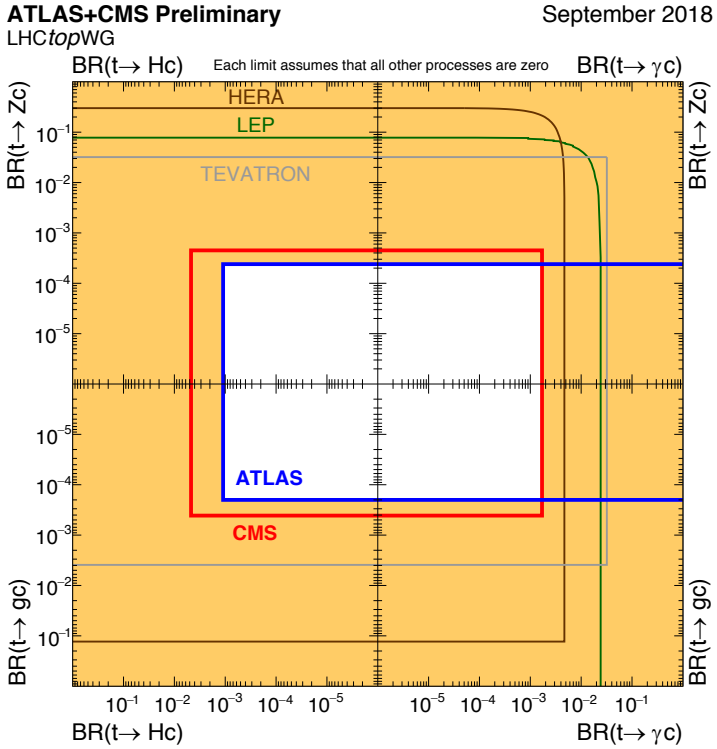
Thank you

Abstract

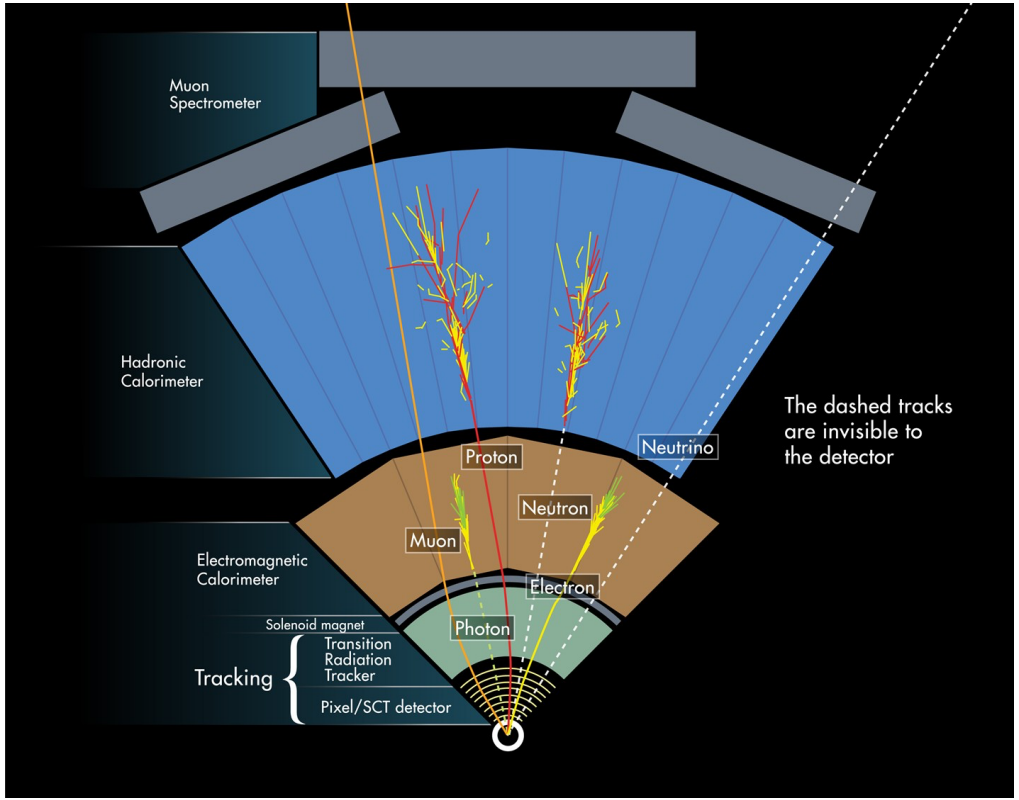
The search for Flavour Changing Neutral Current (FCNC) processes constitutes an important research topic at the LHC. Forbidden at tree level and highly suppressed at higher orders in the Standard Model, FCNC processes can present enhanced contributions in many extensions of the Standard Model. Therefore, such processes become particularly attractive for probing New Physics in the top-quark sector, where searches for top-quark anomalous couplings offer complementarity to the searches for new heavy resonances which have not yet been successful. In this context, a comprehensive high-precision search for FCNC processes in both top-quark production and decay is pursued with the ATLAS experiment. This seminar presents the status of this research activity

Summary


ATLAS+CMS Preliminary
September 2018
LHCtopWG
BR(t→ Hu)
Each limit assumes that all other processes are zero
BR(t→ γu)
HERA
LEP
TEVATRON
CMS
ATLAS
BR(t→ Zu)
BR(t→ gu)


ATLAS+CMS Preliminary
September 2018
LHCtopWG
BR(t→ Hc)
Each limit assumes that all other processes are zero
BR(t→ γc)
HERA
LEP
TEVATRON
ATLAS
CMS
BR(t→ Zc)
BR(t→ gc)

Objects for top physics



Nearly all object signatures are important

Electrons, muons (and taus)

Jets and flavour-tagging

Missing energy from neutrinos

… and photons e.g. $t\bar{t}\gamma$