February 15th , 2019

Search for FCNC processes in the top-quark sector

With the ATLAS experiment

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Outline

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[1] Towards a physics Beyond the Standard Model

Towards a physics beyond the Standard Model

- 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

"Enhancing fundamental symmetries or playing with spacetime dimensionality"

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

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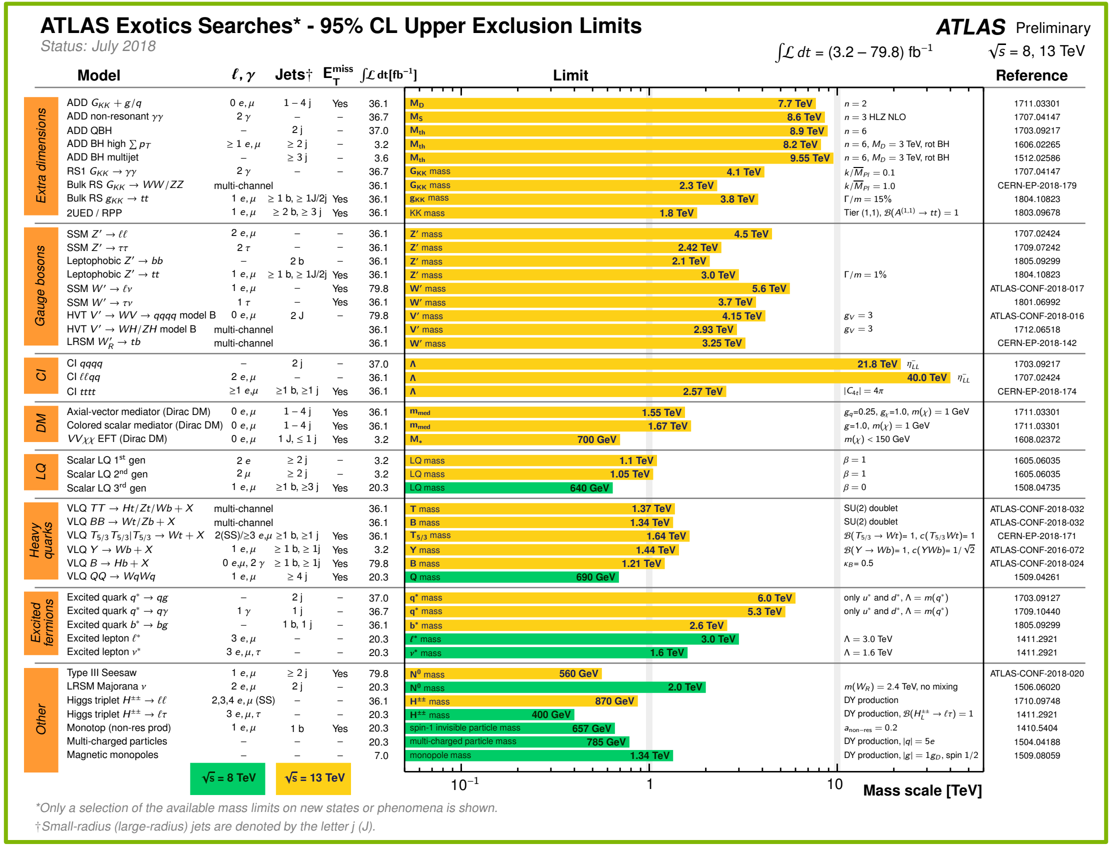
…	…	…	…	…	…	…

Gazillion of new particles expected

Direct vs. indirect search for New Physics

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



Direct vs. indirect search for New Physics

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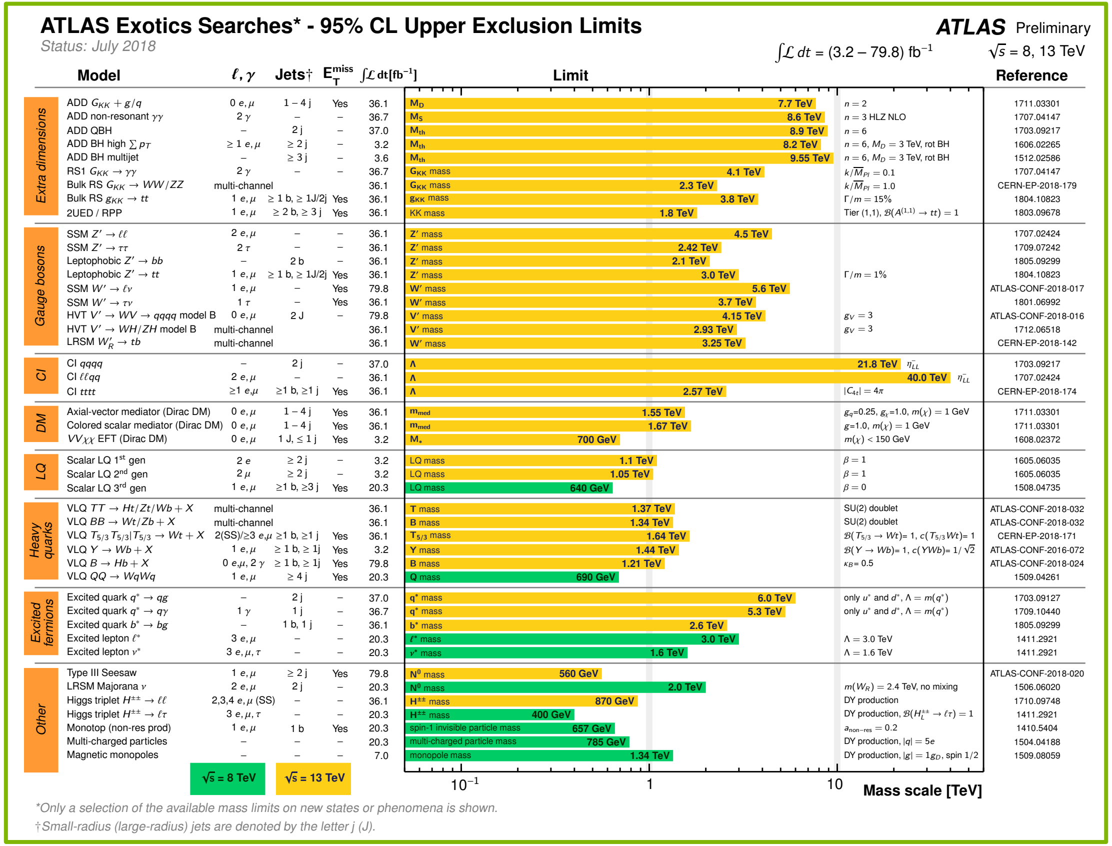
- Lower limits are growing

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



Searching for Flavour Changing Neutral Currents

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- 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"

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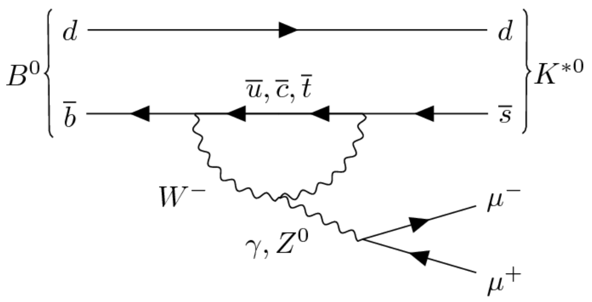
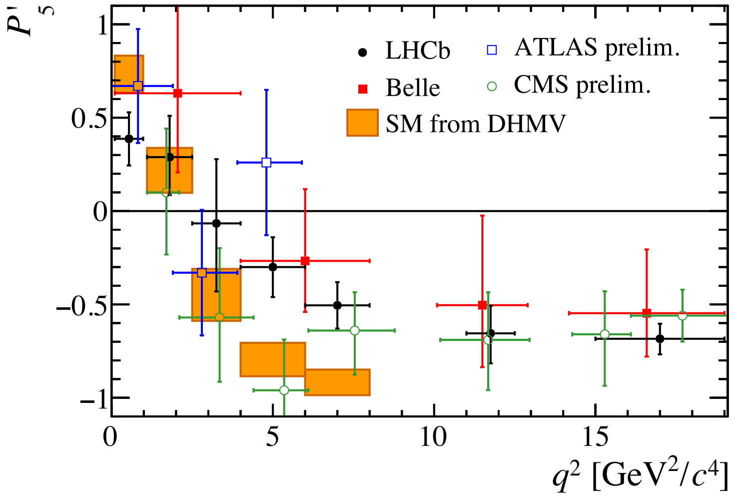
"BSM can enhance FCNC contributions by introducing new particles or interactions"

e.g. Recent tension in $B_d^0 \to K^* \mu^+ \mu^-$

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





[2] The ATLAS experiment

The Large Hadron Collider

World most powerful particle accelerator/collider

High energy collisions
Proton-proton (heavy ions)
$\sqrt{s}$ = 7, 8, 13 TeV
→ Access to massive particles

Very high collision frequency
~ 40 MHz
→ Study rare phenomena

The Large Hadron Collider

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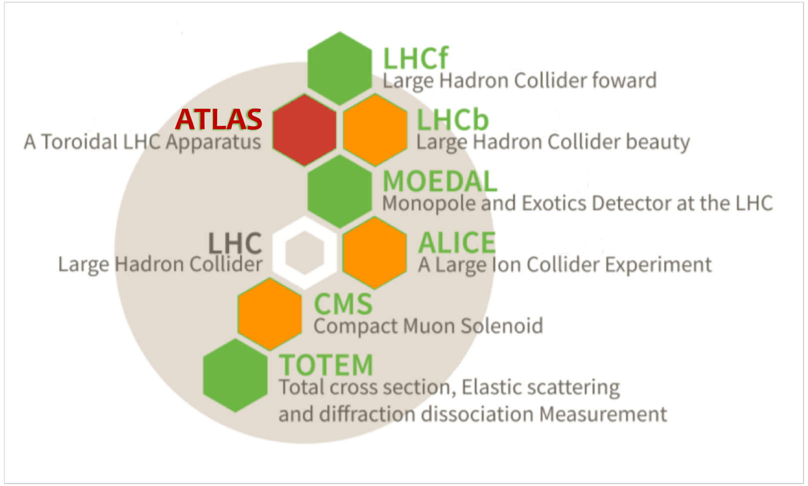
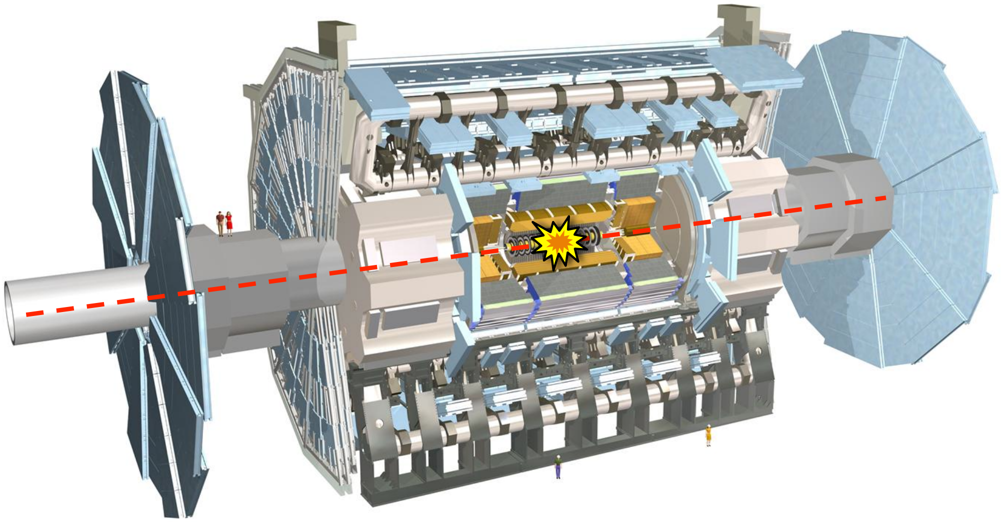
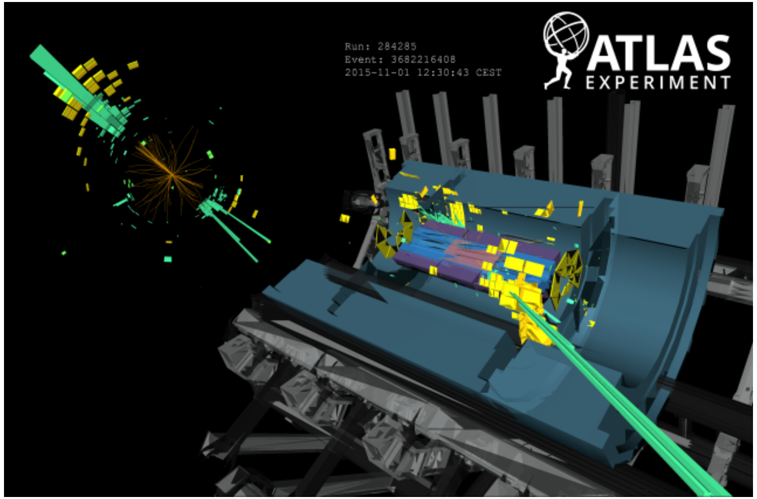
World most powerful particle accelerator/collider

Experiments at the LHC

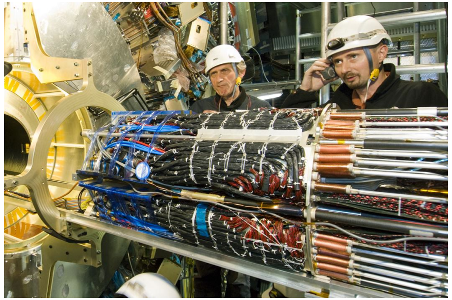


A Toroïdal Lhc ApparatuS

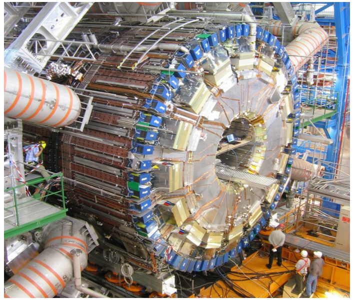




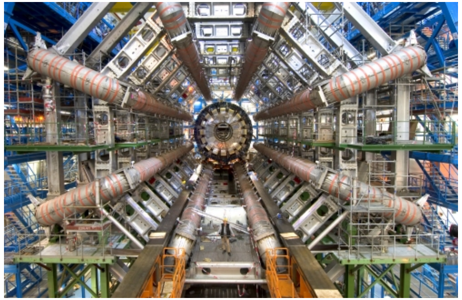
Inner Detector



Calorimeter



Toroidal magnet

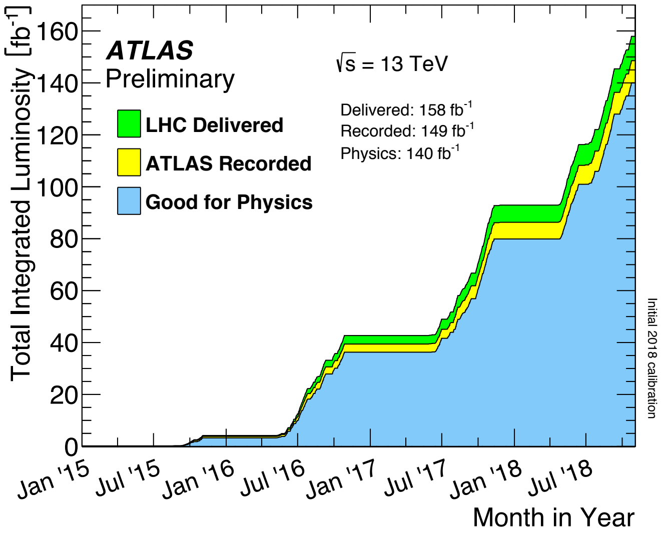


Muon chambers

Luminosity in LHC Run II

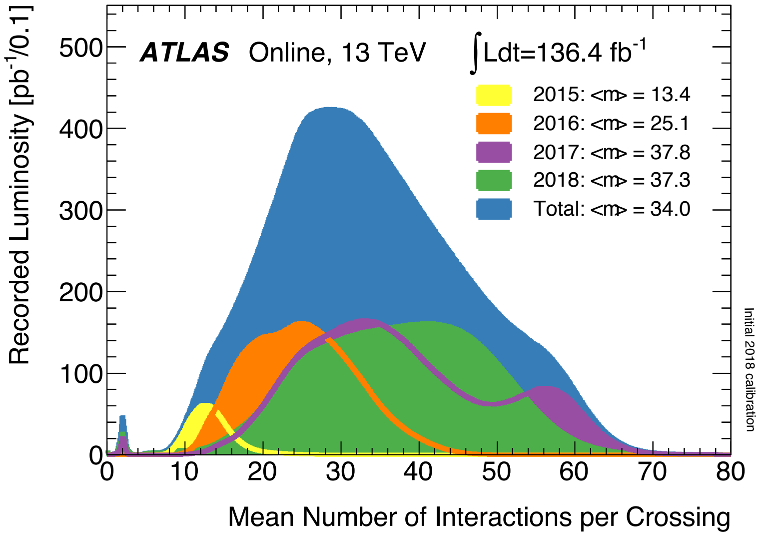
Higher energy and luminosity

~150 fb^{-1} accumulated for pp collisions



Large pile-up in Run II

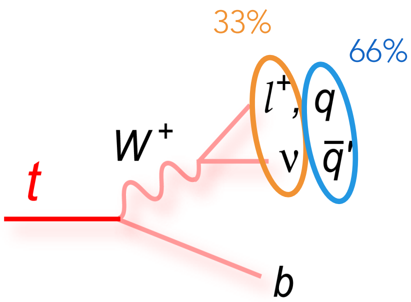
Up to 70 collisions per bunch-crossing in 2017



[3] Searching for “top FCNC processes”

The top quark

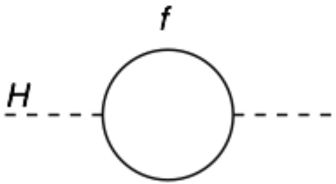
- A unique particle
  - Most massive elementary particle: $m_t \approx 175$ GeV
  - Decays before hadronising, allowing study of bare quarks
  - Large coupling to Higgs boson & special role in EWSB



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

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

$V_{tb} \approx 1$



Leads radiative corrections to the Higgs mass

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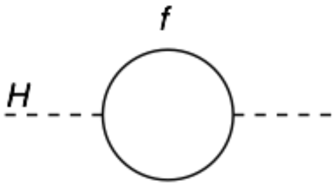

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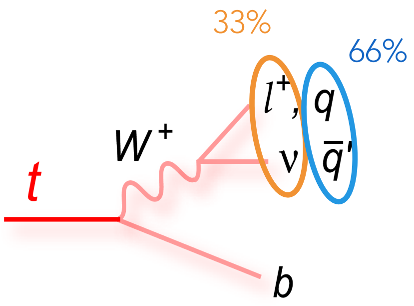

$\tau_{\text{top}} \approx 10^{-25}$ s
$\tau_{\text{had}} \approx h/\Lambda_{\text{QCD}} \approx 10^{-23}$ s

$V_{tb} \approx 1$

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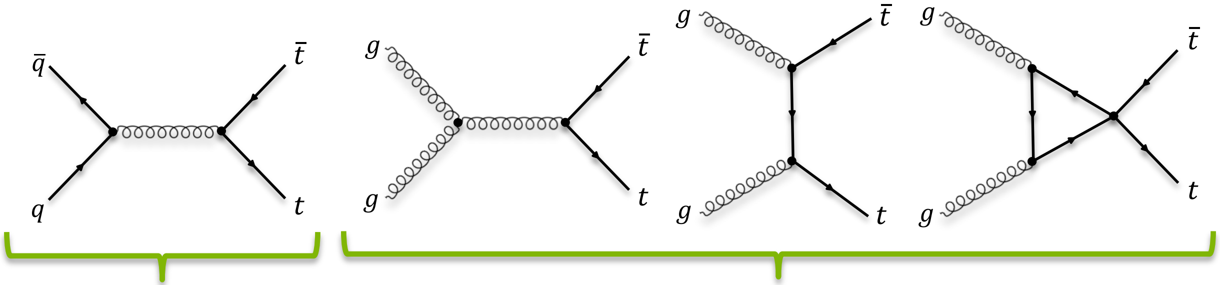
Dominated by $t\bar{t}$ pairs productions (~832 pb at $\sqrt{s}$ = 13 TeV)

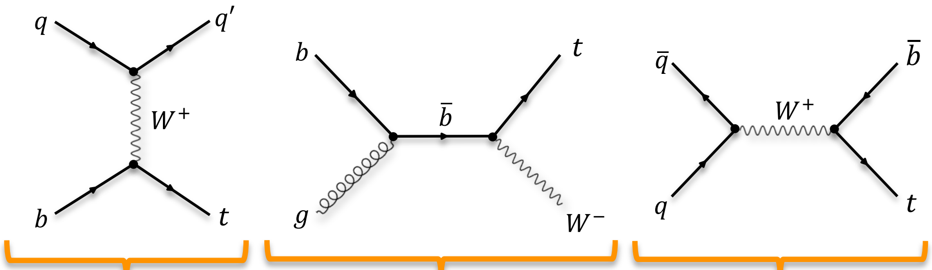


quark-antiquark annihilation (~10%)

gluon-gluon fusions (~ 90%)

Up to now, an impressive agreement between predictions and measurements

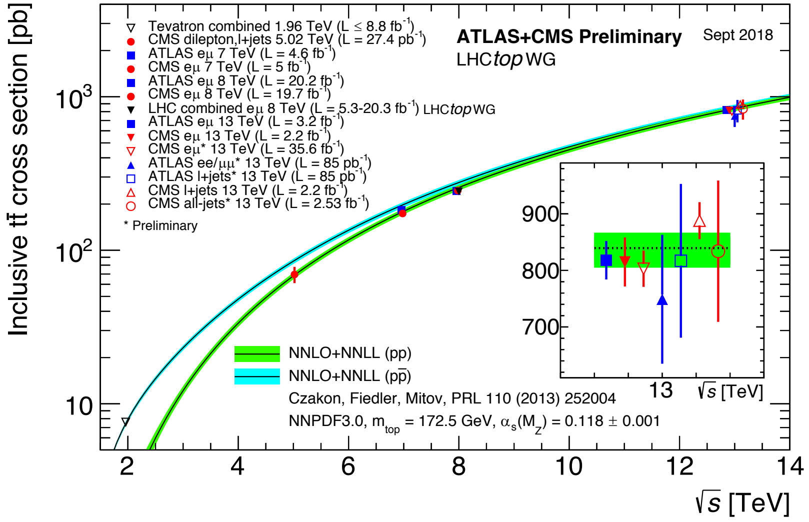
Single top-quark productions



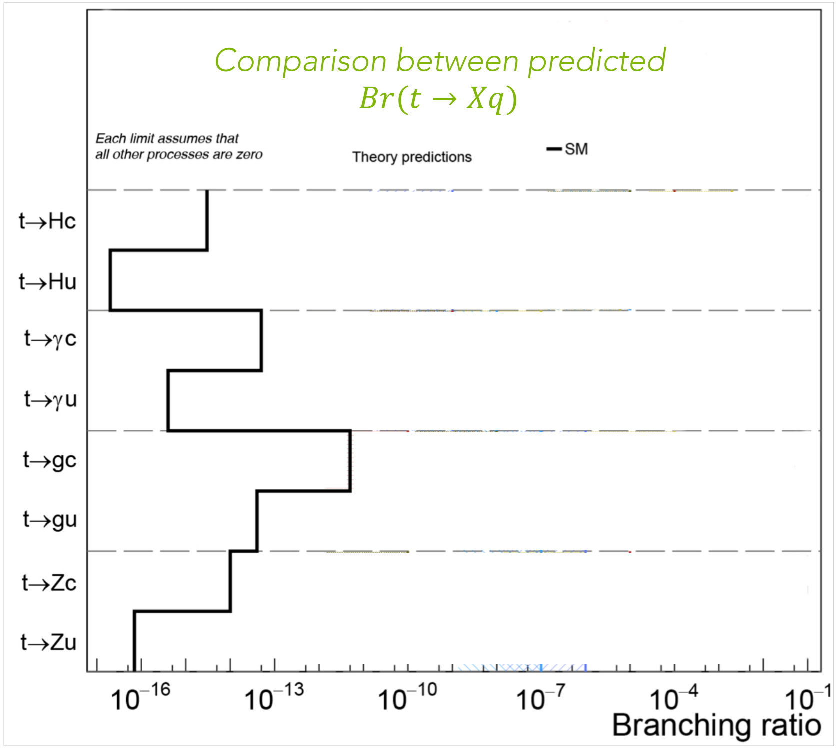
t-channel (~220 pb) 73%

tW associated production (~71.7 pb) 24%

s-channel (10.3 pb) ~3%



BSM contributions to top FCNC processes



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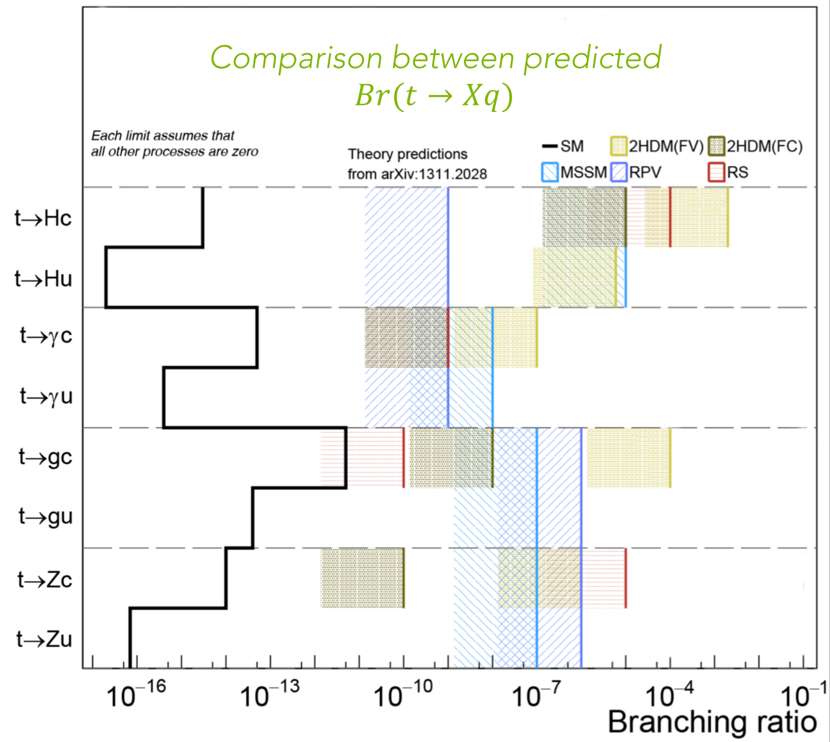


Two-Higgs doublet models

e.g. • *In tree-level FVC between SM fermions and H or A*

• *In flavour-conserving model via loops with* H^+

Super Symmetry

e.g. • *FVC with light-squarks* $\tilde{q}$

(NB: advancing $\tilde{q}$ *mass limits suppress loop-induced Br)*

Warped extra dimensions

e.g. • *FVC between SM fermions and KK excitations*

• *From loop processes involving of fermion KK modes*

"Orders of magnitude in excess of SM expectations"

**FVC = Flavour Violated Coupling*

Relying on a model independent approach

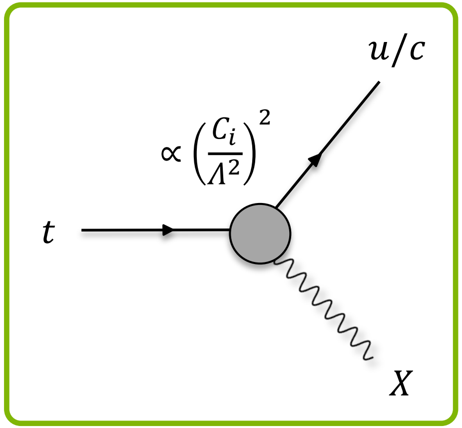
- Building an Effective Field Theory (EFT)
  - Parameterize physics at scale $\Lambda \gg \sqrt{s}$ in terms higher order operators
  - Respect SM symmetries (resulting in $d > 4$)
  - Lowest order for top-quark physics is $d = 6$

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



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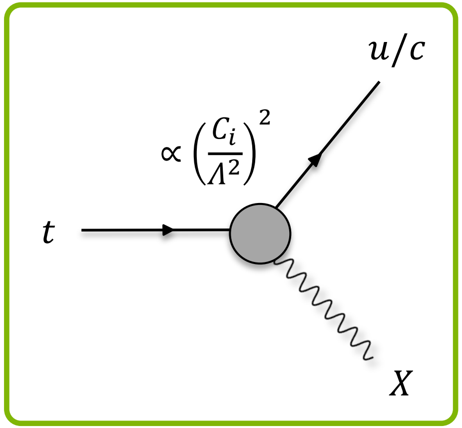


$$\Longrightarrow |\mathcal{M}|^2 = |\mathcal{M}^{SM}|^2 + \mathcal{M}^{SM}\,\mathcal{M}^{EFT*} + |\mathcal{M}^{EFT}|^2$$

- If process highly suppressed in SM (such as FCNC)
  → Leading contribution: quardratic terms

Top effective theory for FCNC

- 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

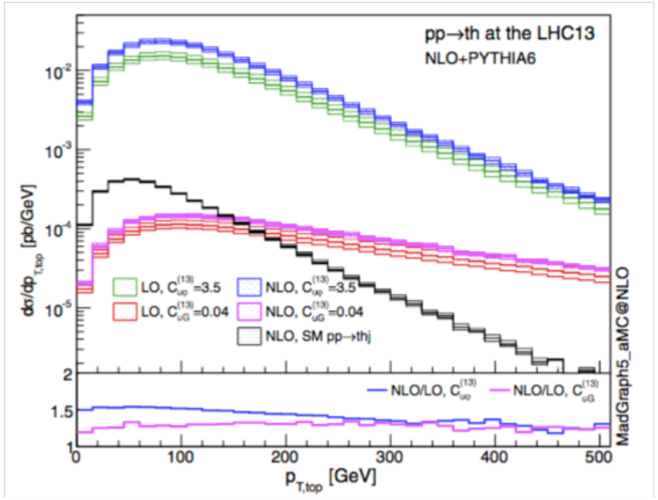
Total cross sections

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

NLO vs. LO relative dif.

+48%
+26%
+81%
+73%

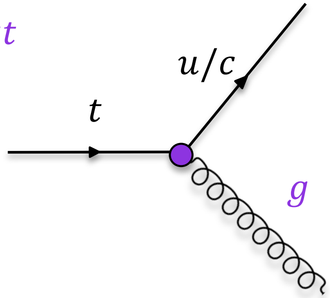
Differential cross sections



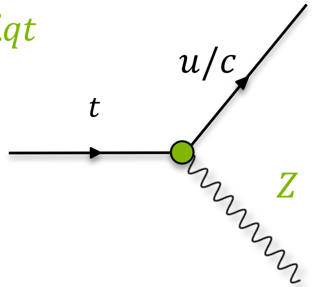
Main top FCNC research focuses

FCNC in
Strong interaction

gqt



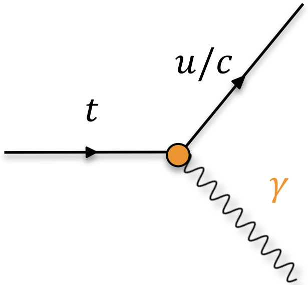
Zqt



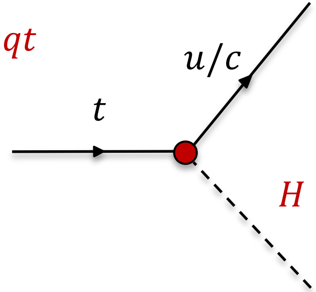
Probe EW sector
Gauge coupling

Probe EW sector
Gauge coupling

γqt



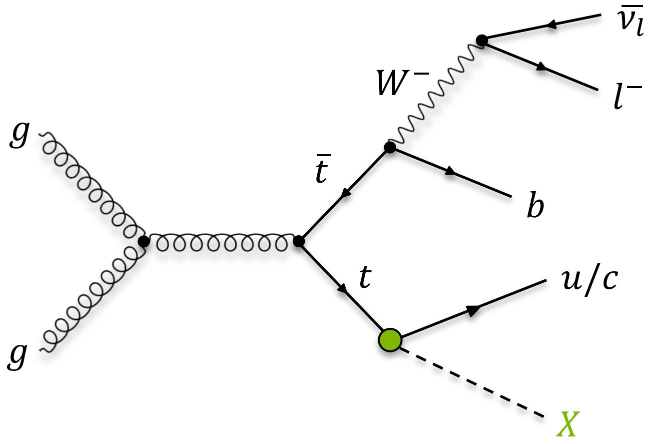
Hqt



Probe EW sector
Scalar coupling

Most important top FCNC processes at LHC

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



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

Most important top FCNC processes at LHC

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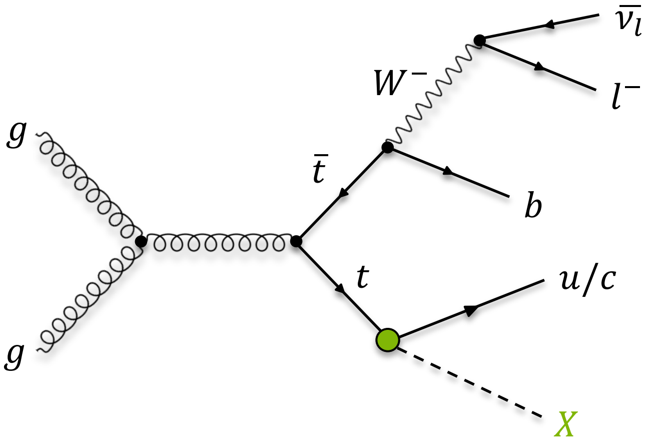
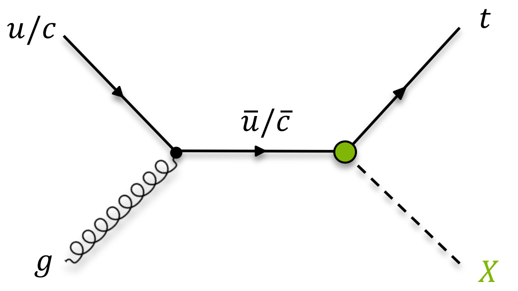
Decay processes $t \rightarrow qX$ with $X = \gamma, Z, H$



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

Production modes $qg \rightarrow tX$



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

Most important top FCNC processes at LHC

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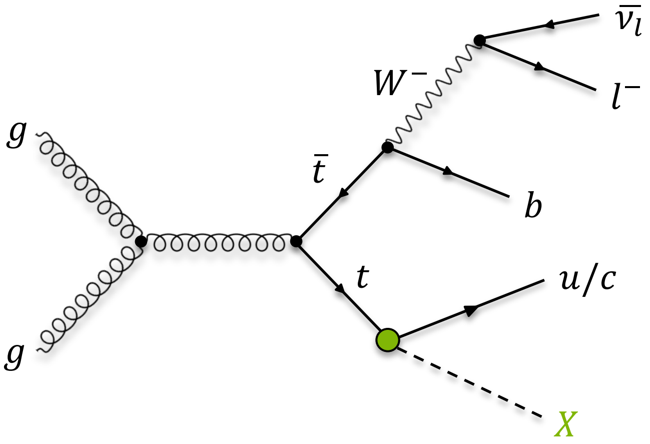

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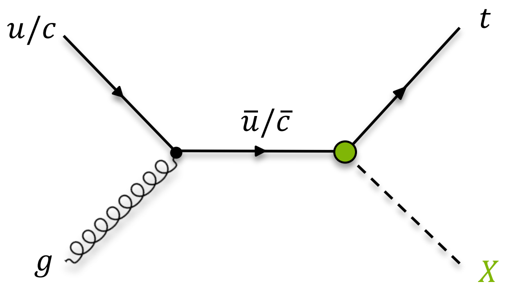
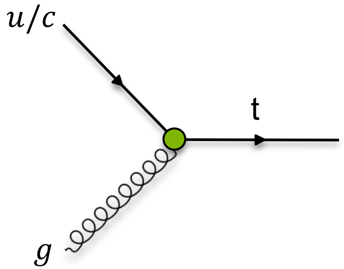


Wider kinematic range accessible, probes interactions at higher scales where new physics effects could be enhanced

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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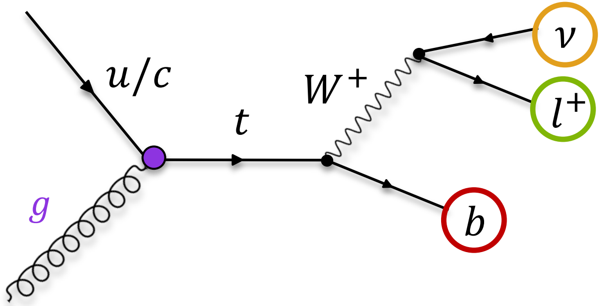
Eur. Phys. J C76 (2016 87)



- 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

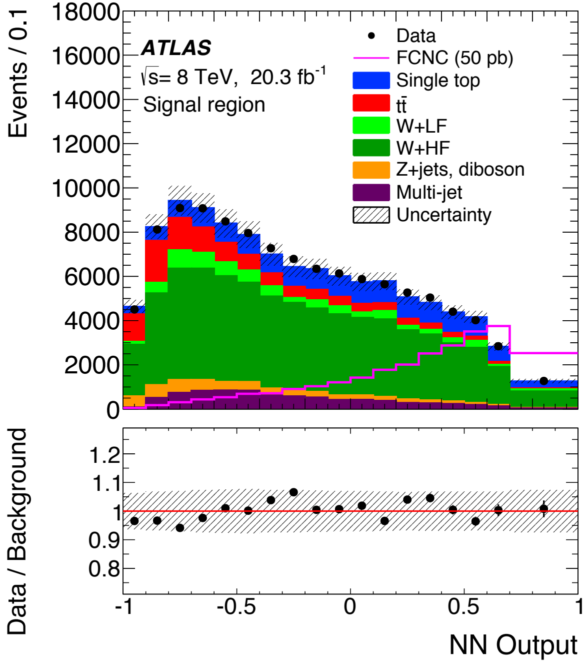
- Backgrounds
  - W+jets
  - $t\bar{t}$
  - Single top
  - Multi-jets
  - Z+jets

Validated with looser b-tagging requirement (W+jets)

Estimated with data-driven technics (Multi-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

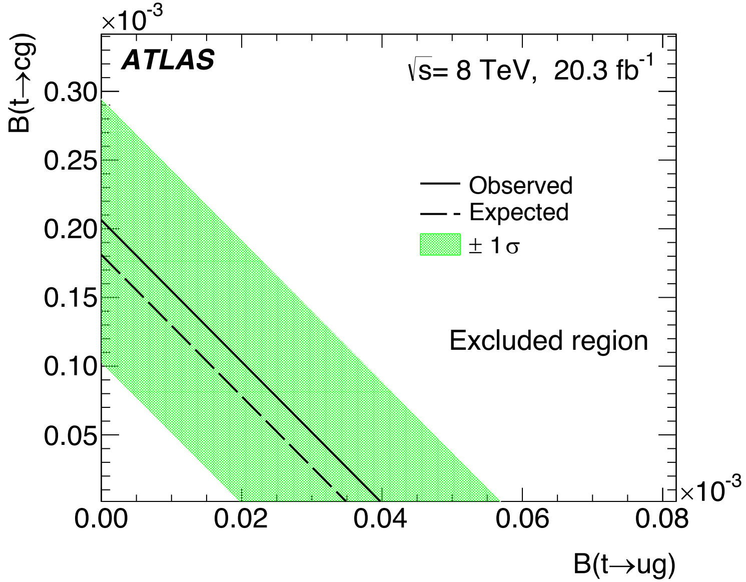
Obs. limit : $\sigma_{qg\to t} \cdot Br(t \to Wb) < 3.4$ pb

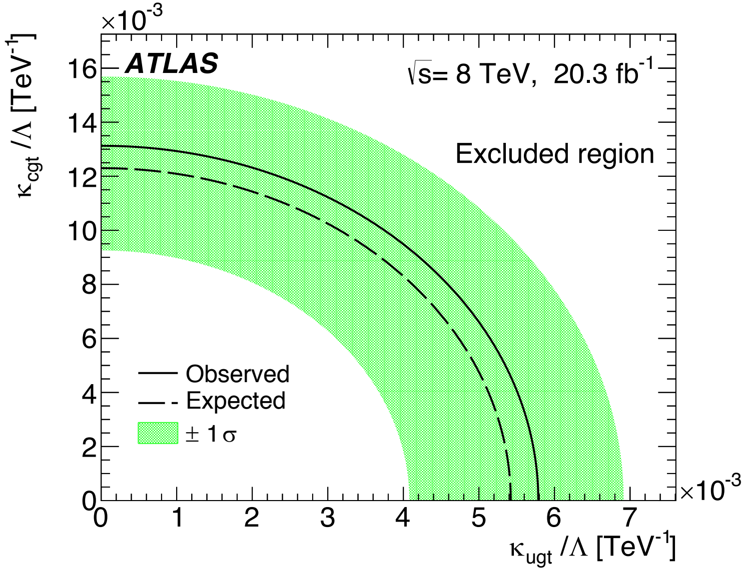
Exp. limit : $\sigma_{qg\to t} \cdot Br(t \to Wb) < 2.9$ pb

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}

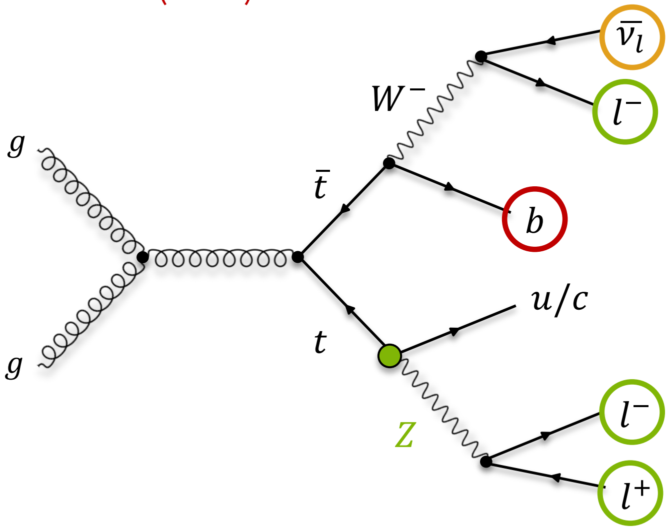
$\kappa_{cgt}/\Lambda < 13.10^{-3}$ TeV^{-1}

[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

JHEP 07 2018 (2018) 176



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

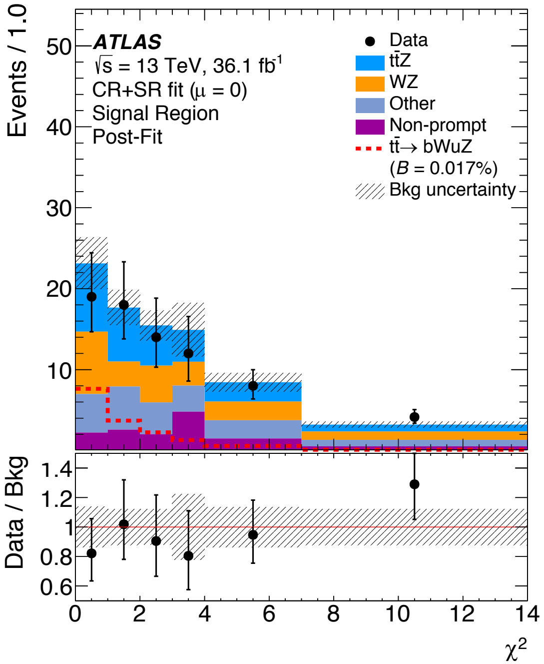
$$\chi^2 = \frac{\left(m_{j_a l_a l_a}^{reco} - m_{t_{FCNC}}\right)^2}{\sigma_{t_{FCNC}}^2} + \frac{\left(m_{j_b l_c \nu}^{reco} - m_{t_{SM}}\right)^2}{\sigma_{t_{SM}}^2} + \frac{\left(m_{l_c \nu}^{reco} - m_W\right)^2}{\sigma_W^2}$$

* Determined from simulation

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

JHEP 07 2018 (2018) 176

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

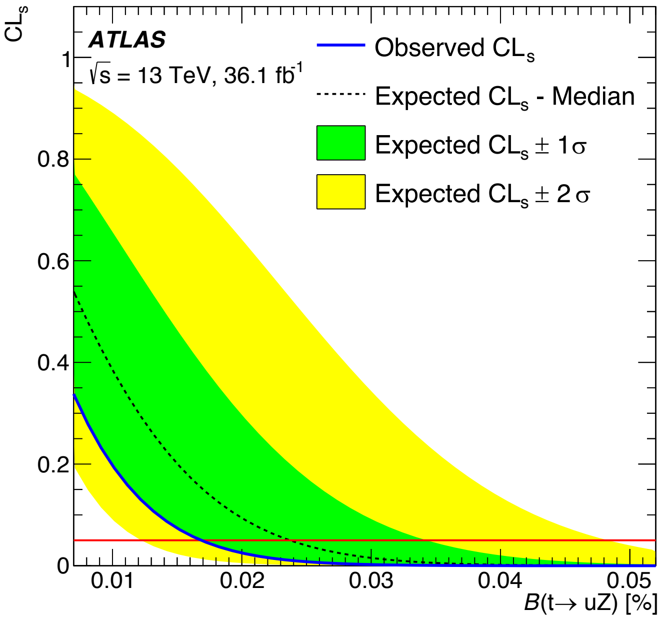


Sample	Yields	
	Pre-fit	Post-fit
$t\bar{t}Z$	37 ± 5	37 ± 4
WZ	32 ± 19	32 ± 8
ZZ	6.2 ± 3.2	6.4 ± 3.0
Non-prompt leptons	26 ± 11	20 ± 7
Other backgrounds	23 ± 4	23 ± 4
Total background	124 ± 26	119 ± 10
Data	116	116
Data / Bkg	0.94 ± 0.21	0.97 ± 0.12
Signal $t \to uZ$ ($\mathcal{B} = 0.1\%$)	101 ± 8	103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

JHEP 07 2018 (2018) 176

- 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

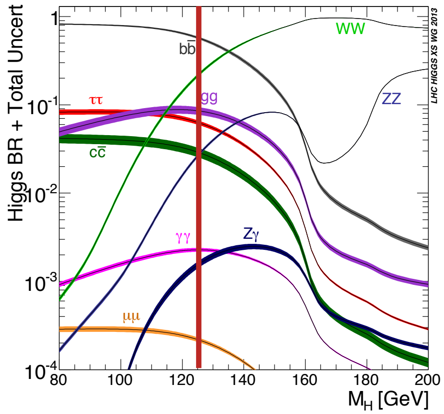
Search for FCNC decay $t \rightarrow u(c) + H$ *in* $t\bar{t}$ *events*

Higgs decay channel & design of the analysis

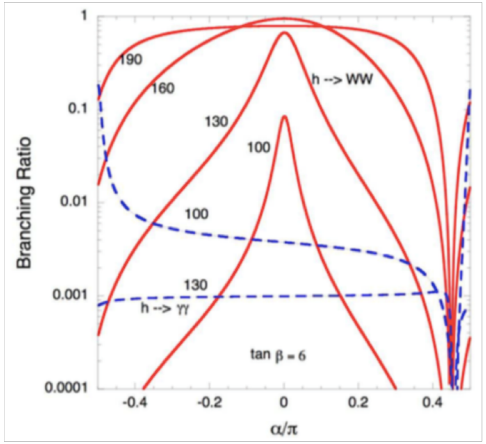
- $H \to b\bar{b}$
  - Challenging channel
  - Large background
  - *l*+jets final states
  - Needs optimised *b*-tagging and MVA technics
- $H \to \tau\tau,\ WW^{*}, ZZ^{*}$
  - Cleaner experimental signature probing mutli-lepton final states
  - Reduced background
  - Suffer from low statistics
- $H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

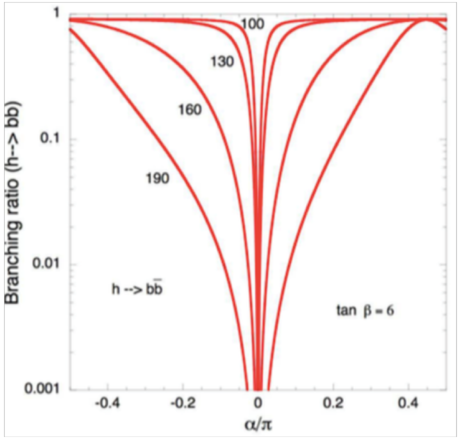
Dominant decay channels in SM and usually in BSM

In the Standard Model



In 2HDM

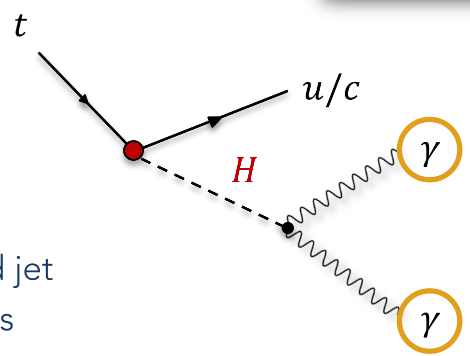




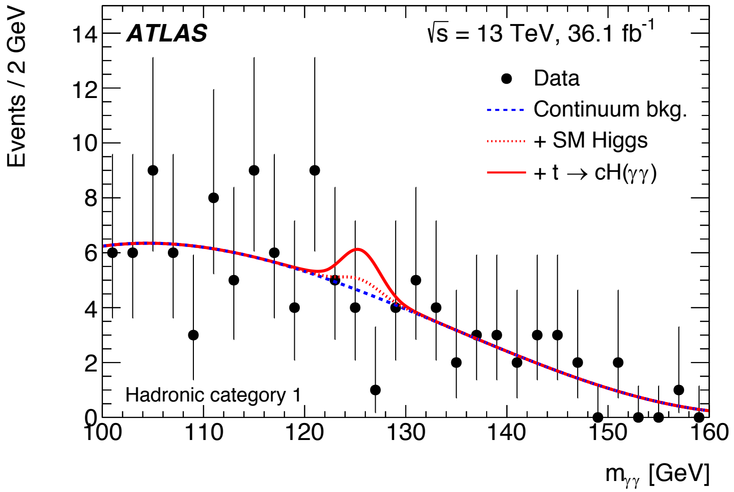
Search for FCNC decay $t \rightarrow qH$ with $H \rightarrow \gamma\gamma$

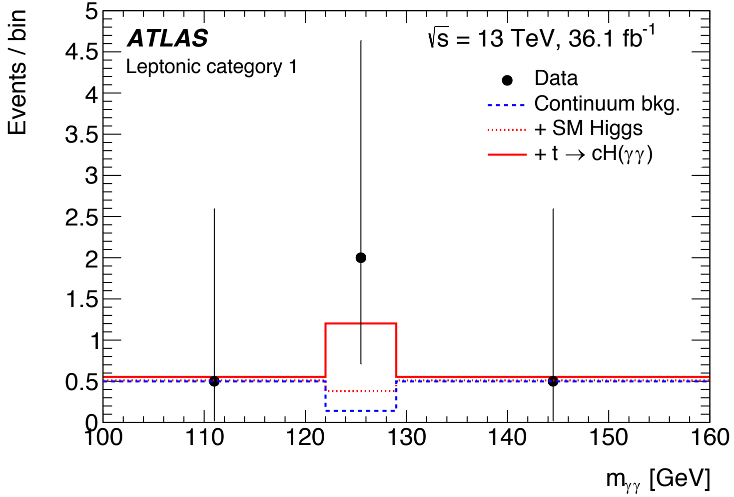
JHEP 10 (2017) 129

- 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



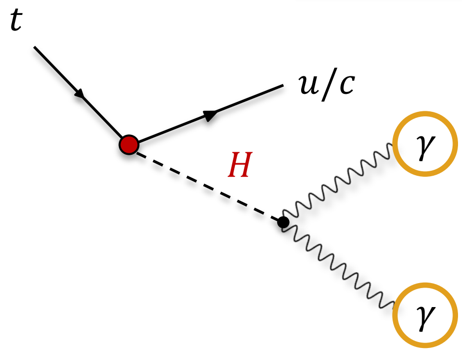
e.g. Category 1 events passing full selection



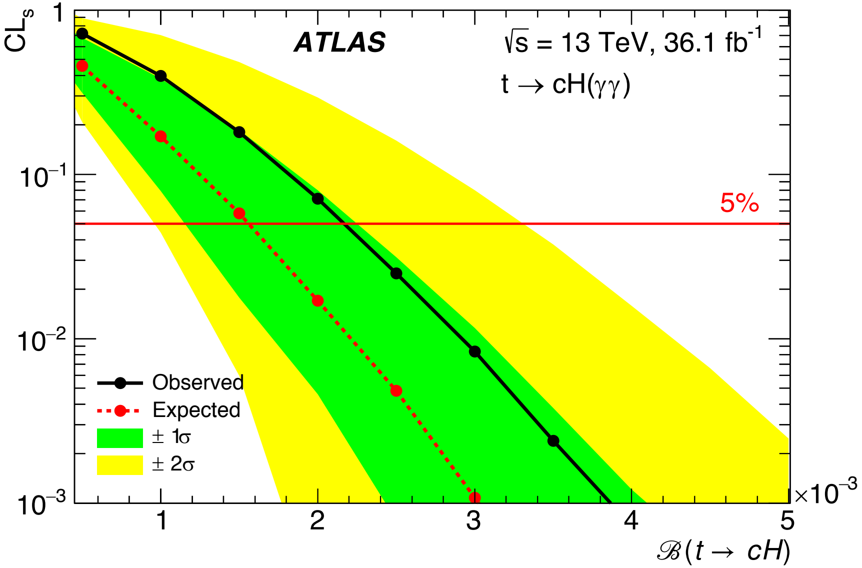


Search for FCNC decay $t \to qH$ with $H \to \gamma\gamma$

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

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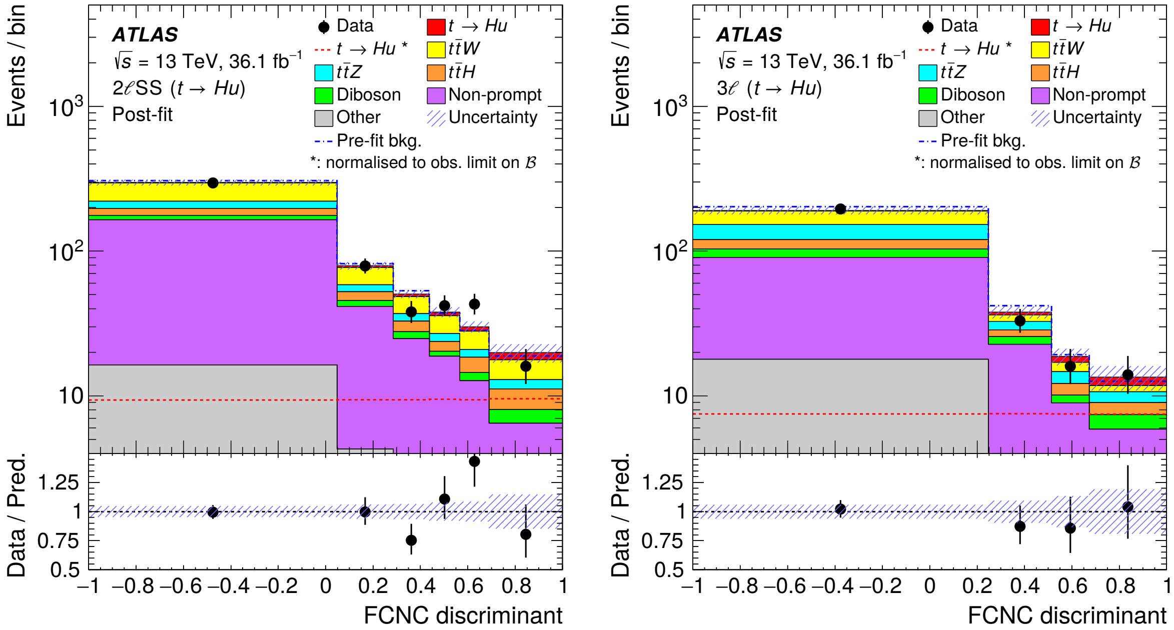
PRD 98 (2018) 032002

- 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

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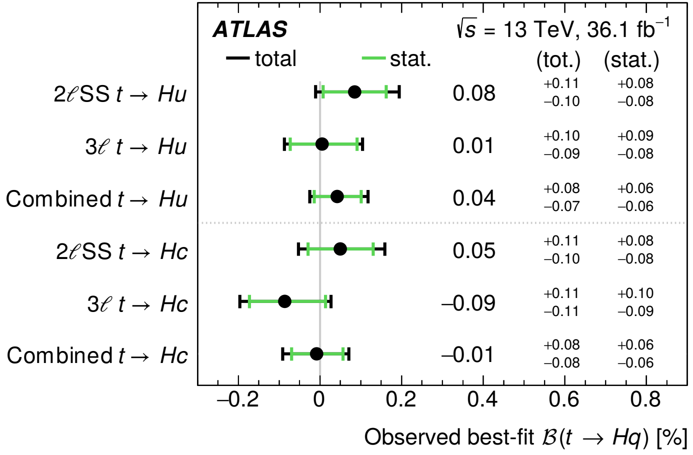
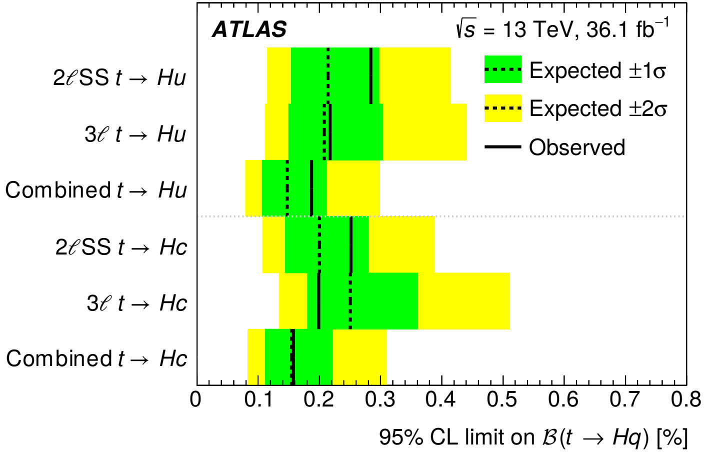
PRD 98 (2018) 032002

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



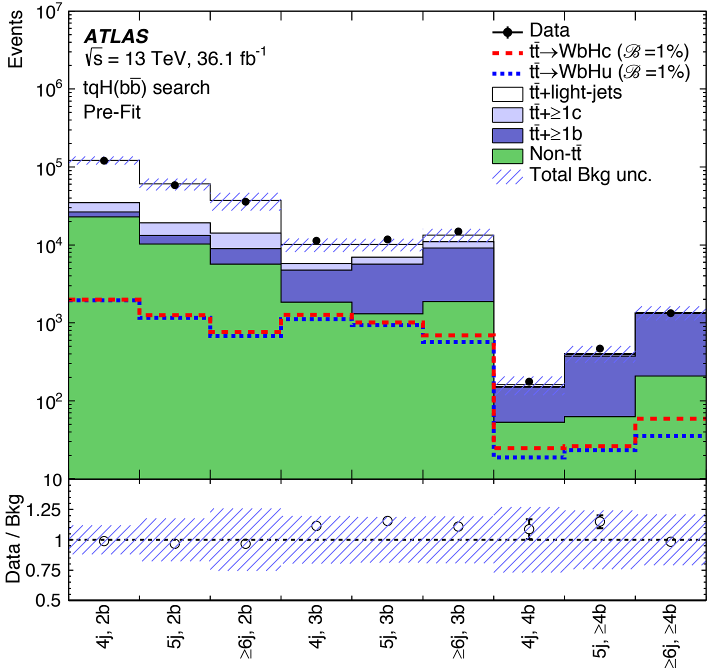


Observed (expected) exclusion limits from multi-leptons channels → $Br(t \to uH) <$ 0.19% (0.15%)
$Br(t \to cH) <$ 0.16% (0.15%)

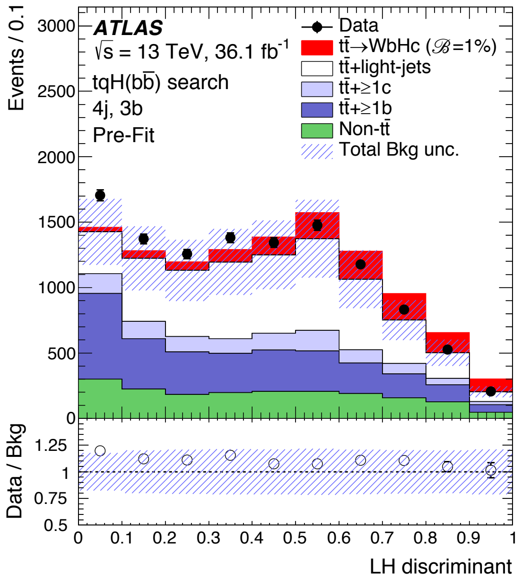
Search for FCNC decay $t \to qH$ with $H \to b\bar{b}$

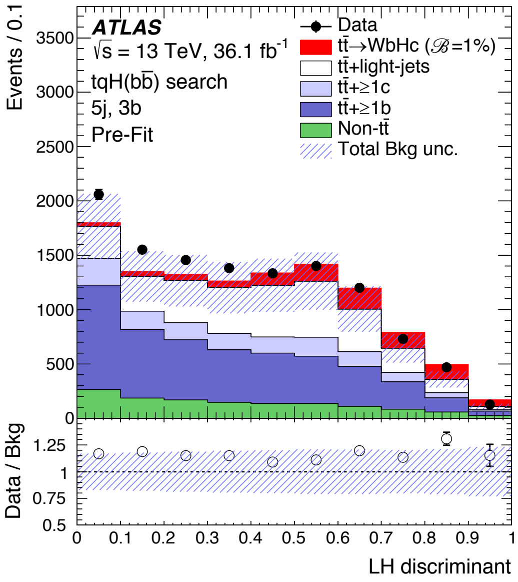
arXiv:1812.11568 – Submitted to JHEP

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



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



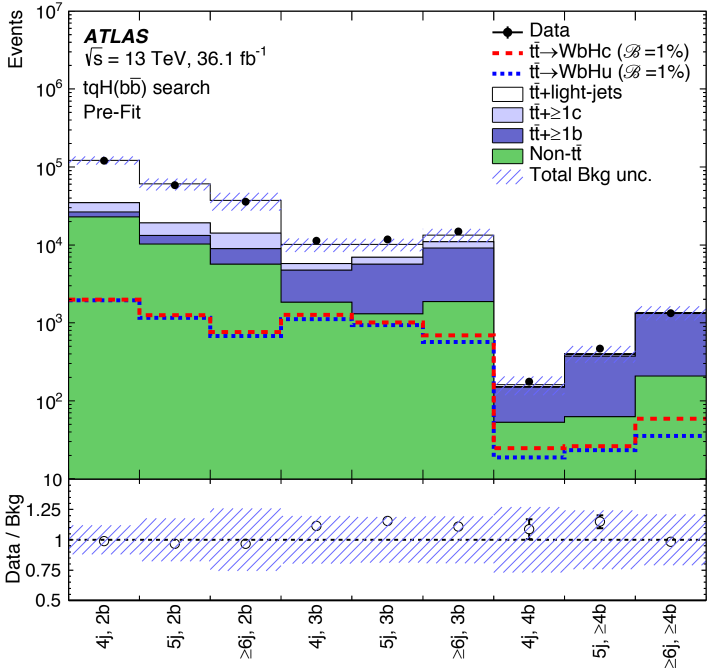


Search for FCNC decay $t \rightarrow qH$ with $H \rightarrow b\bar{b}$

BERGISCHE UNIVERSITÄT WUPPERTAL

arXiv:1812.11568 – Submitted to JHEP

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



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

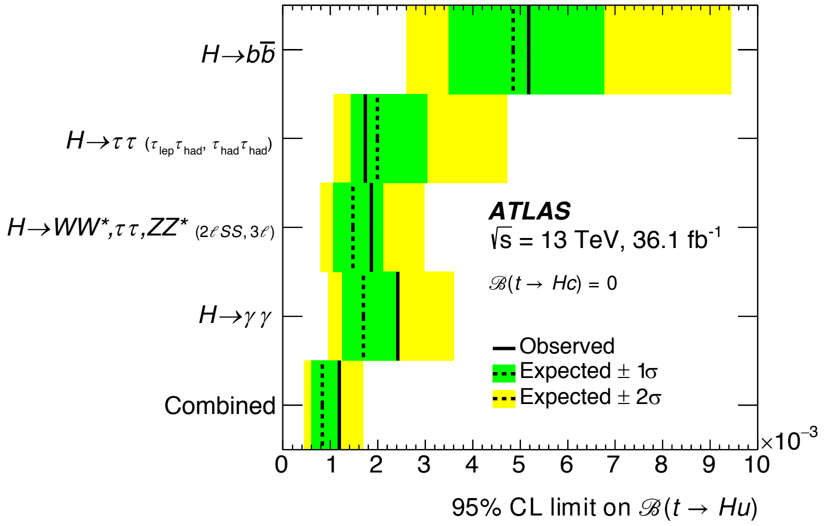
Observed (expected) exclusion limits from $H \rightarrow b\bar{b}$ channels

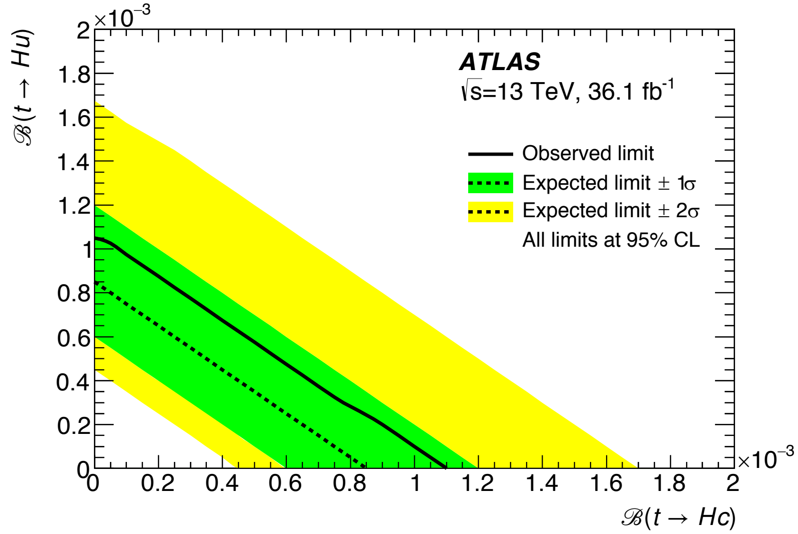
$Br(t \rightarrow uH)$< 0.52% (0.49%)
$Br(t \rightarrow cH)$< 0.42% (0.30%)

Combining FCNC decay $t \to qH$ results

arXiv:1812.11568 – Submitted to JHEP

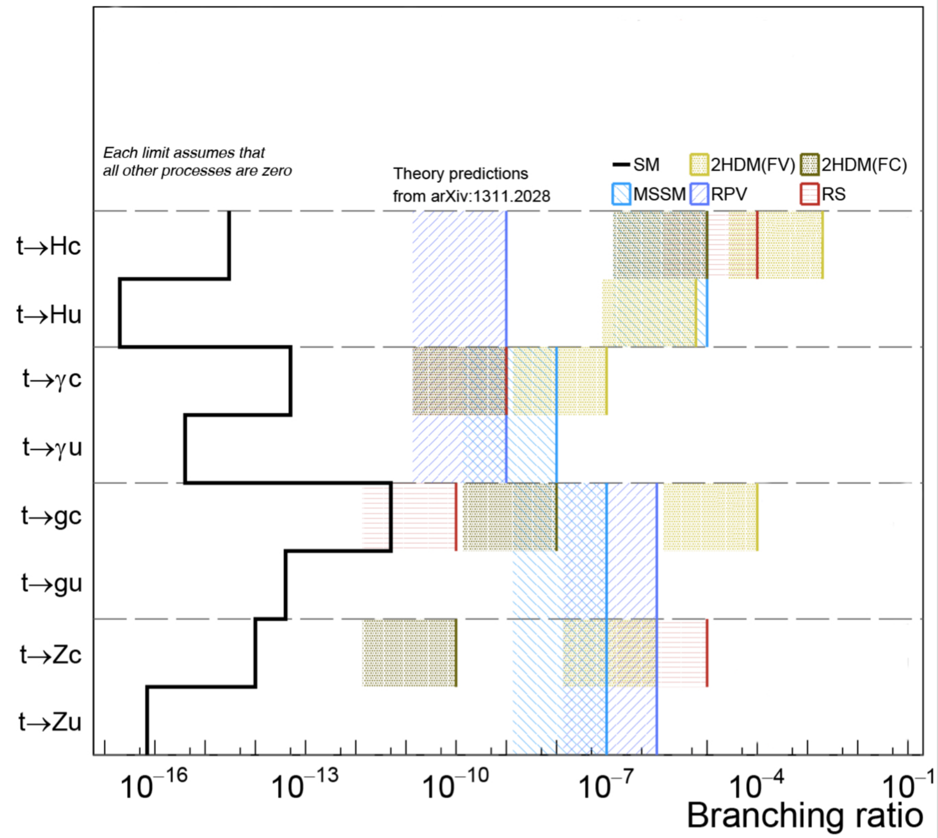
- Full likelihood combination of $H \to b\bar{b}$, $\tau^+\tau^-$, multilepton, $\gamma\gamma$ channel searches





Combined limits on branching ratios

Summary


Each limit assumes that
all other processes are zero
Theory predictions
from arXiv:1311.2028
SM
2HDM(FV)
2HDM(FC)
MSSM
RPV
RS
t→Hc
t→Hu
t→γc
t→γu
t→gc
t→gu
t→Zc
t→Zu
10^{-16}
10^{-13}
10^{-10}
10^{-7}
10^{-4}
10^{-1}
Branching ratio

Summary

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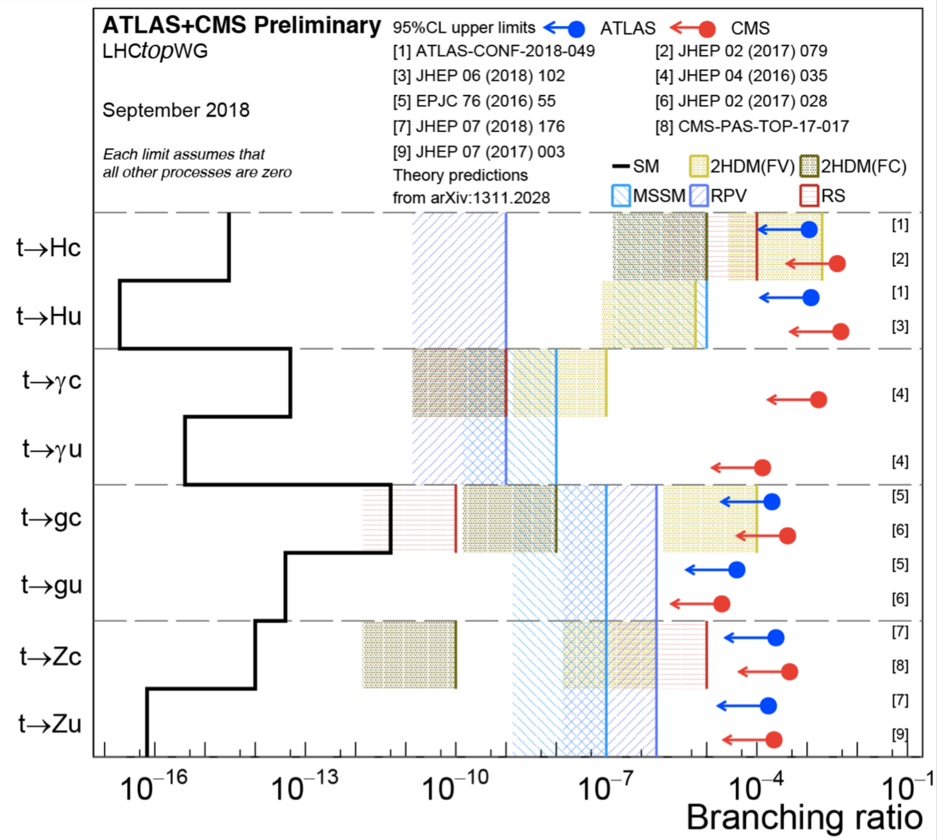
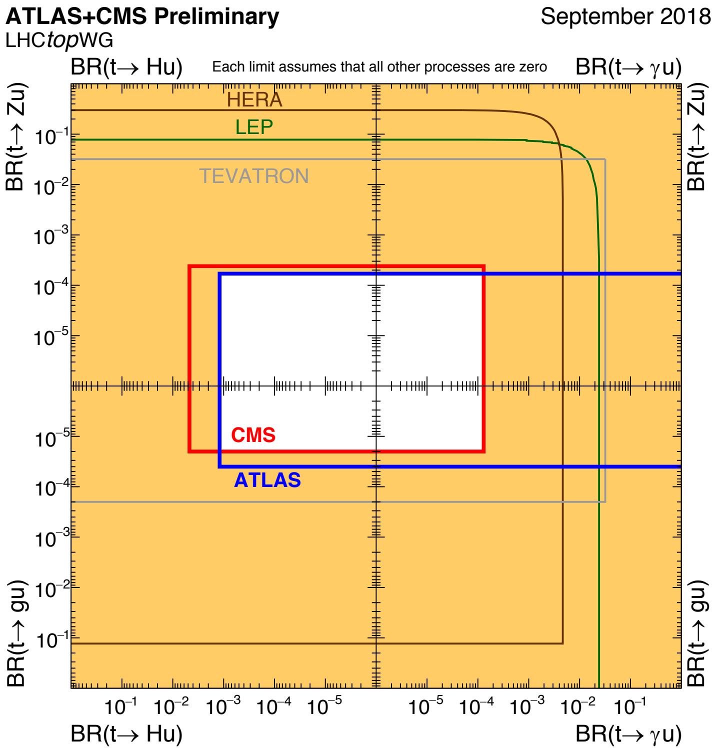
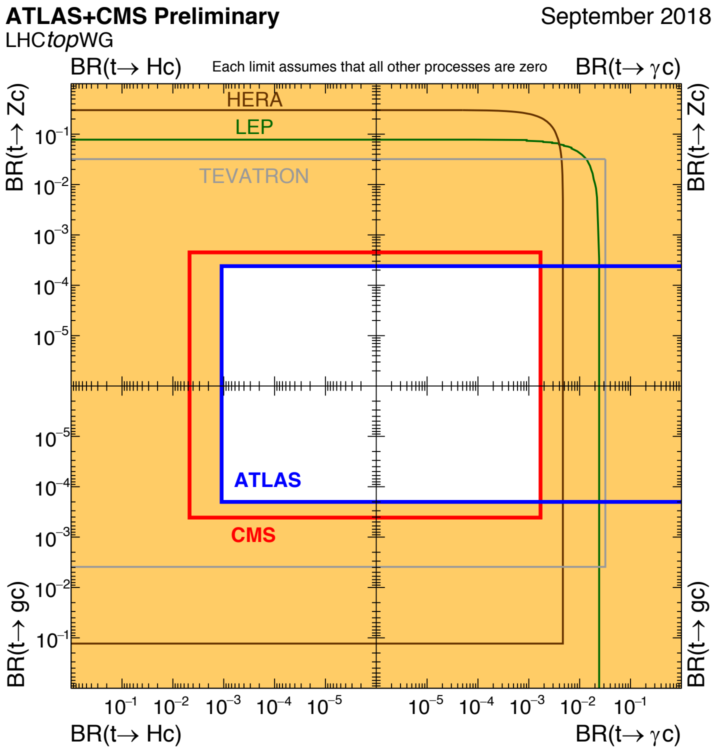


- Summary of the current 95% CL level observed limits on $Br(t \to Xq)$ (with $X = g, Z, \gamma$ or H, and $q = u$ or c) obtained by ATLAS … and CMS

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

Summary


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


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

[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 top-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