Searches for rare and BSM top quark processes at the ATLAS experiment

Birmingham HEP Seminar

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Will George

University of Birmingham

Top Quark Physics at the LHC

- Top phenomenology driven by its mass
  - Heaviest known elementary particle
  - Y_t~1 → large coupling to Higgs
  - Potentially large couplings to hypothetical new particles

- ATLAS Run 2 dataset: huge sample of top events
  - ~115 mn top pairs, ~40 mn single top
  - Clear decay signature ~100% to *Wb* ($|V_{tb}|$~1)
  - Unprecedented sensitivity to rare SM top processes
  - Possibility to probe possible new physics interactions

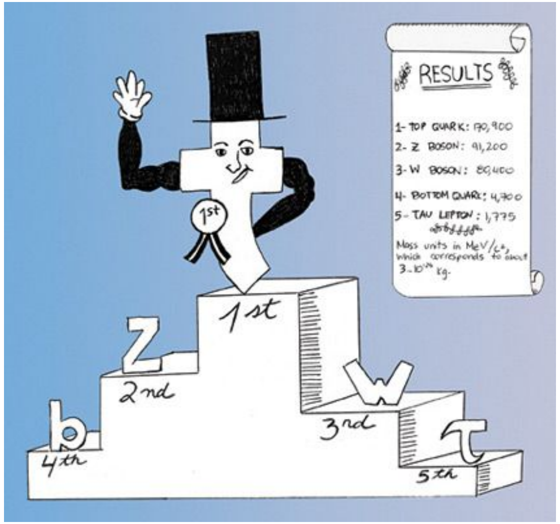

Image credit: Symmetry

Today: rare & BSM top interactions

ATLAS EXPERIMENT

- No new physics searches at the LHC have yet been fruitful
- Raises possibility that $\Lambda_{NP} >> \Lambda_{EW}$ → motivates indirect searches for non-SM couplings
  - Observation of 4 top quark production
  - Searches for flavour-changing neutral current (FCNC) interactions of the top quark
  - Search for charged lepton flavour-violating (CLFV) interactions of the top quark
- All measurements discussed are from Run 2 (2015-2018) using the full 13 TeV dataset of 140 fb^{-1}

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Sensitive to BSM corrections/MC modelling (4 top quark production)

Unobservable in SM → evidence would point to BSM (FCNC and CLFV searches)

Effective field theory (EFT)

ATLAS EXPERIMENT

- For Λ_{NP} significantly greater than experimental sensitivity, we can employ an EFT approach
  - E.g. Fermi theory of β-decay - point-like four fermion interaction
  - Perform calculations without knowledge of short-distance theory
- Construct effective Lagrangian in terms of SM fields:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i,n} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

Operators introducing new interactions

Familiar SM ("renormalisable")

Encodes strength of coupling

SMEFT

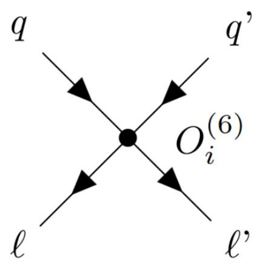
- SMEFT: 59 independent dim-6 operators (assuming B-conservation)

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

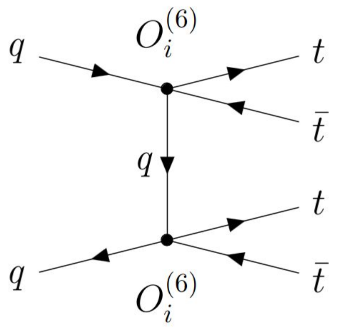
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		(arXiv:1008.4884)

Table 3: Four-fermion operators.

CLFV-inducing



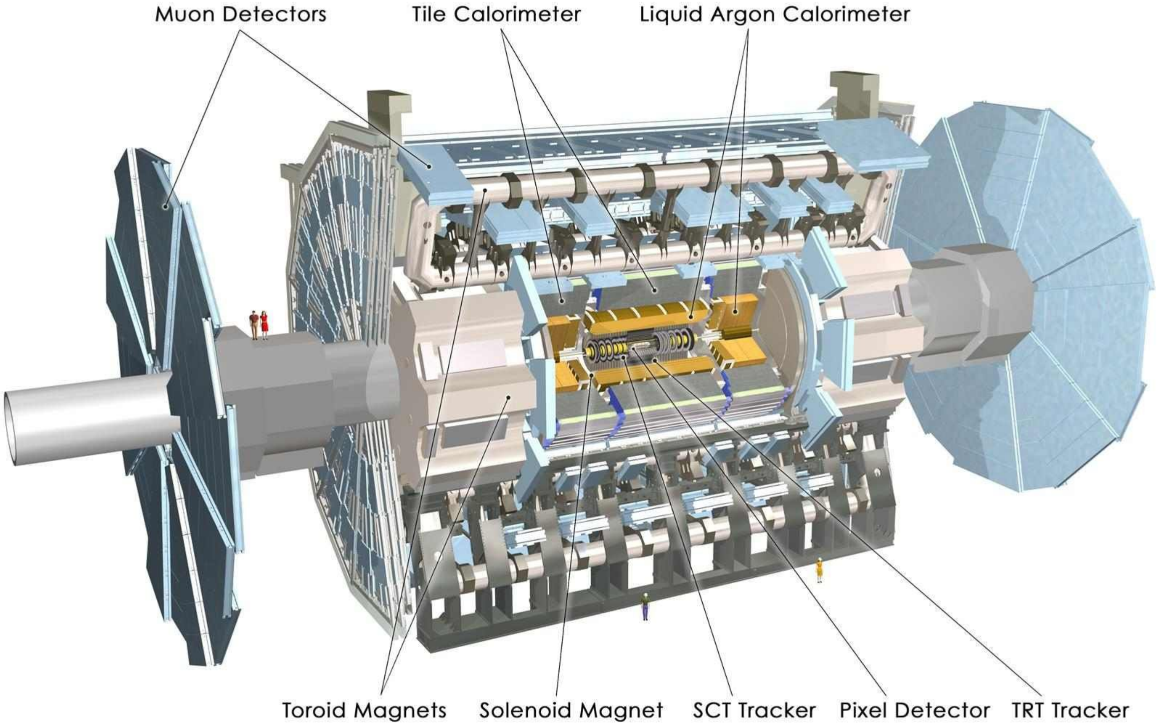
Enhanced four top cross-section



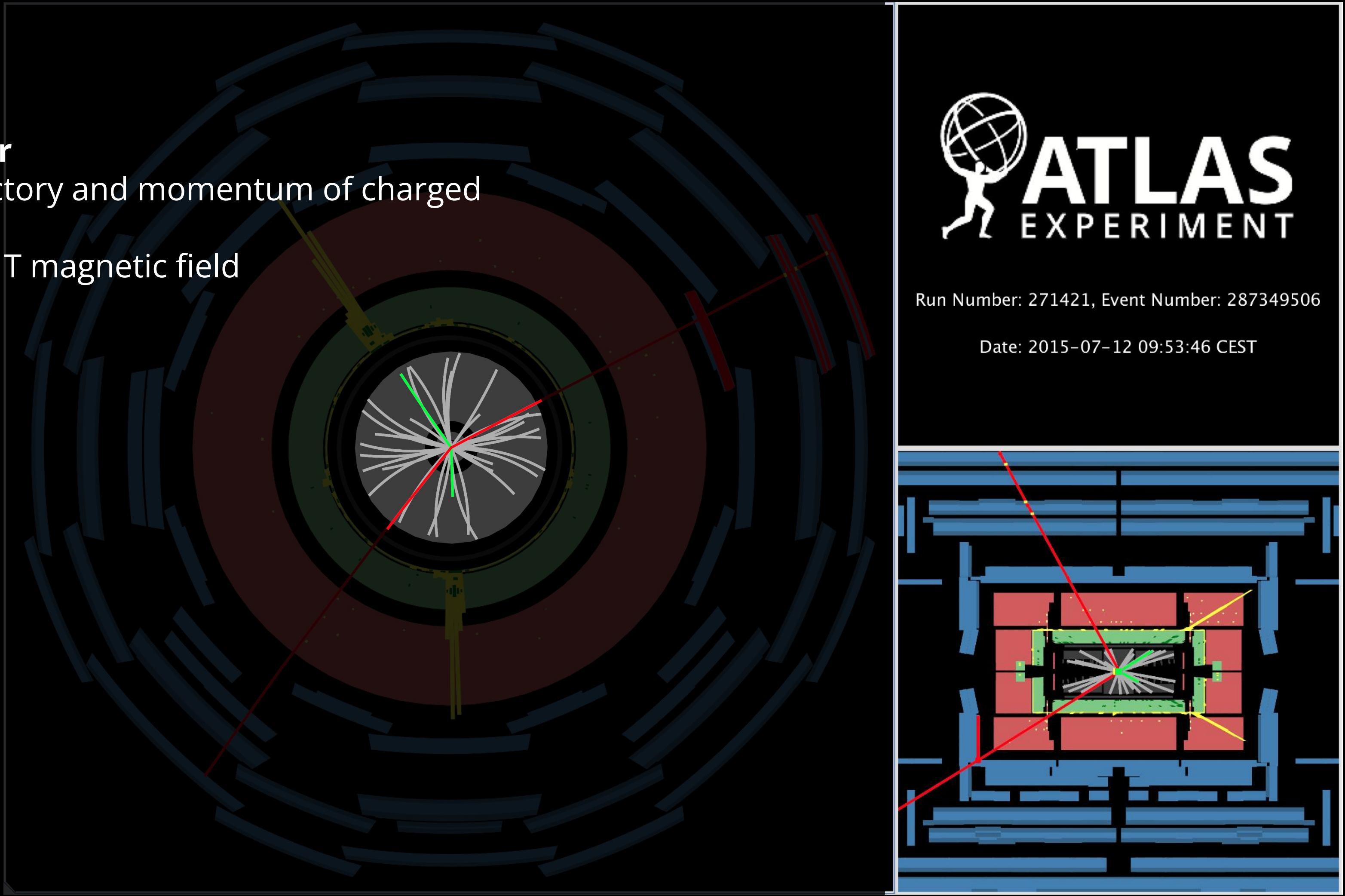
p,r,s,t = flavour/family indices

The ATLAS experiment

- Multipurpose particle detector
  - Forward–backward symmetric
  - Almost full 4π coverage around interaction point
- LHC bunch crossing rate ~40 MHz
  - Most crossings result only in soft QCD interactions
- Two-level trigger system to select potentially interesting physics events at rate of ~1 kHz

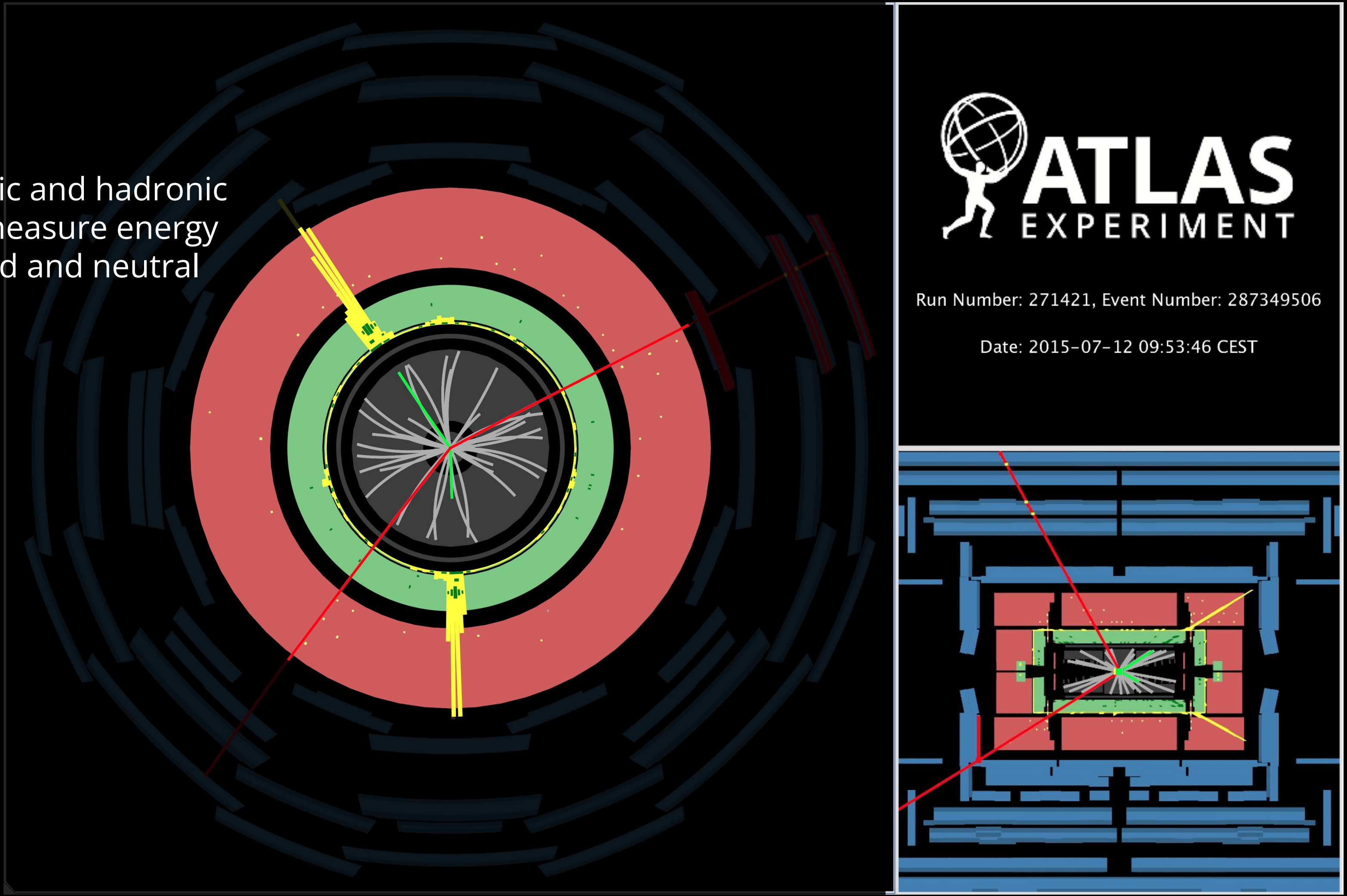


Inner detector
Measure trajectory and momentum of charged particles
Immersed in 2 T magnetic field

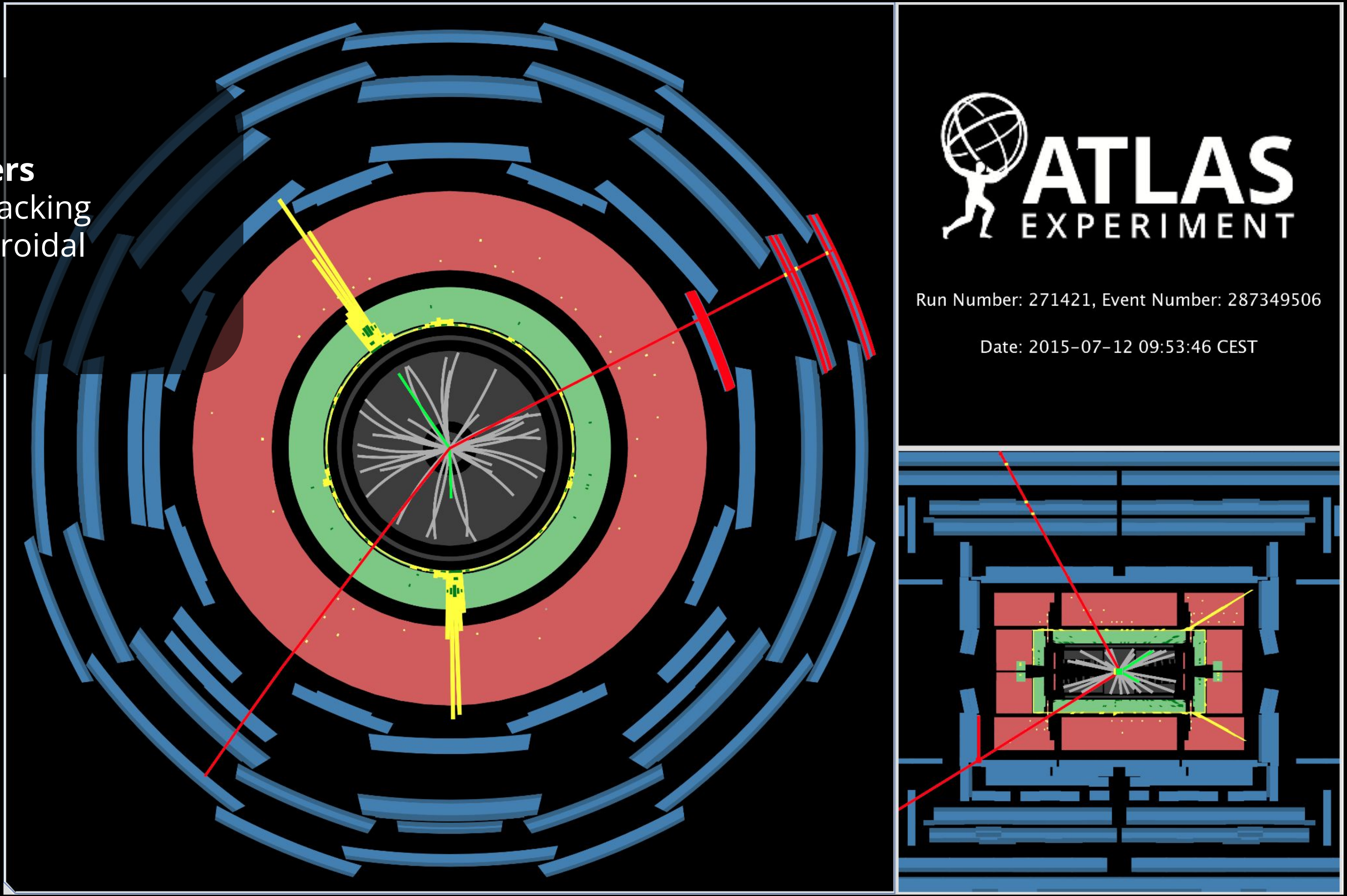


Calorimeters

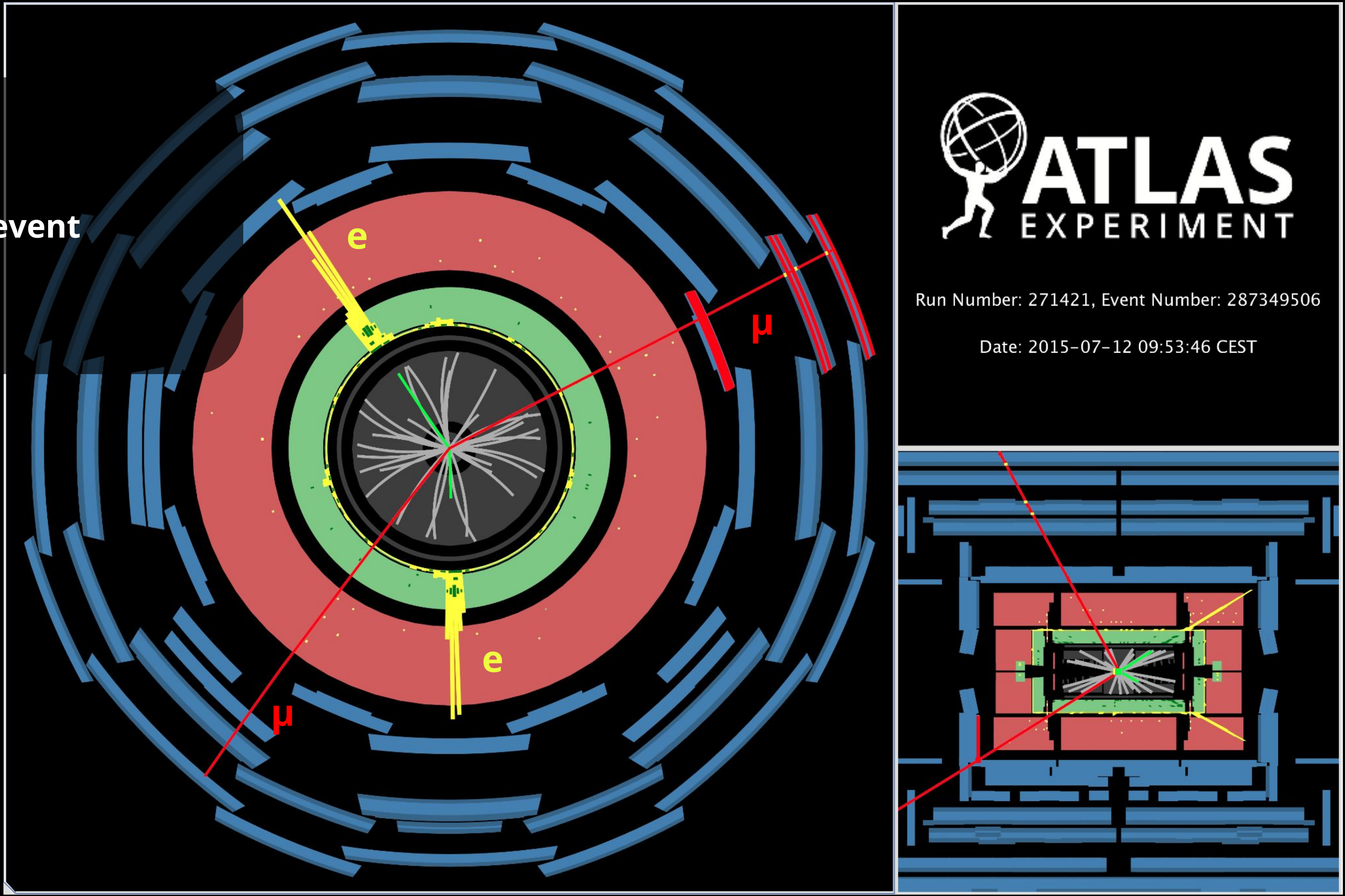
Electromagnetic and hadronic calorimeters measure energy of both charged and neutral particles



Muon chambers
Large-radius tracking chambers in toroidal magnetic field



ZZ candidate event



(Top) analyses at ATLAS

- Select events of interest based on triggers
  - Analyses discussed today use single-lepton or dilepton triggers
- Apply reconstructed object selections to events passing trigger(s)
  - Electrons, photons, muons
  - Jets (collimated shower of hadrons from quarks/gluons)
  - Hadronically-decaying tau leptons
  - Missing transverse energy (MET) → neutrinos, mis-calibration, BSM?

(Top) analyses at ATLAS

ATLAS EXPERIMENT

- B-tagging:
  - Determine likelihood that a jet originated from a B-hadron decay (as opposed to C- or light hadron decay)
- Events categorised into regions by event kinematics/further object selection
  - SRs - signal-dominated regions → sensitivity to process of interest
  - CRs - signal-depleted regions → correct/modelling background processes
- Profile likelihood fit across all regions
  - Systematic uncertainties profiled as nuisance parameters

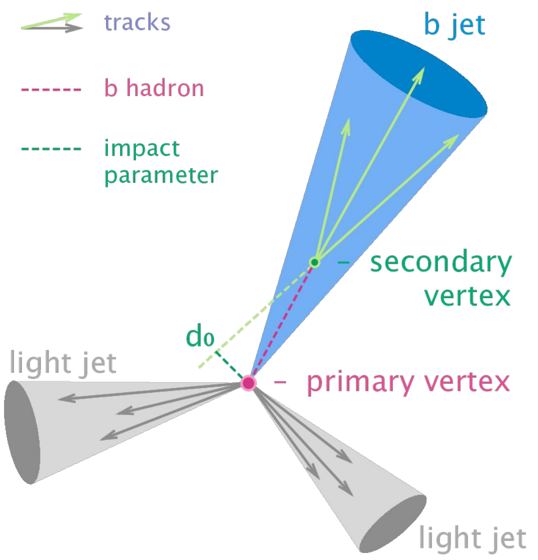
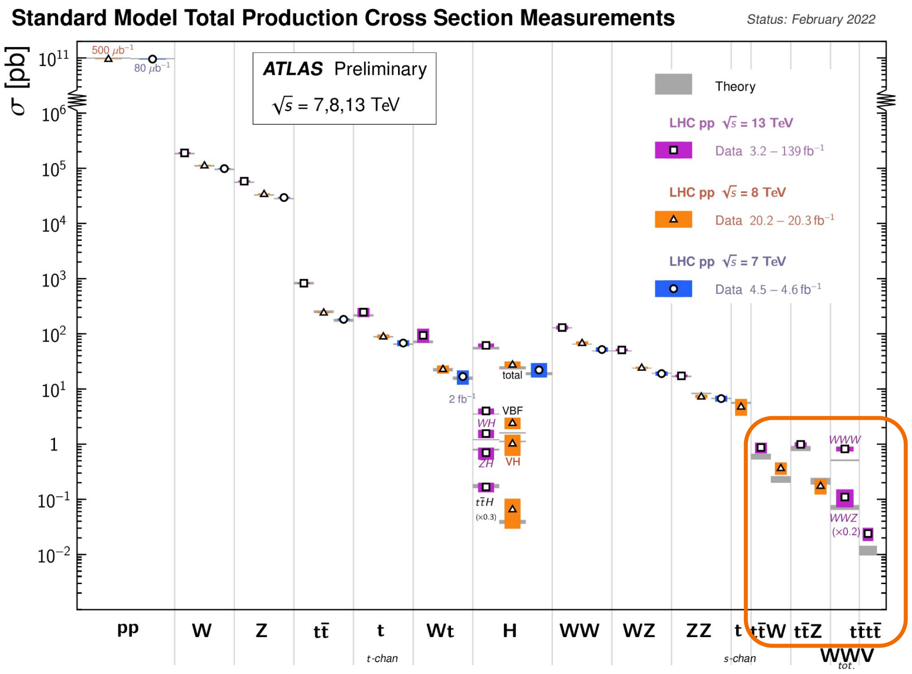


Image credit: Nazar Bartosik

Rare SM top processes

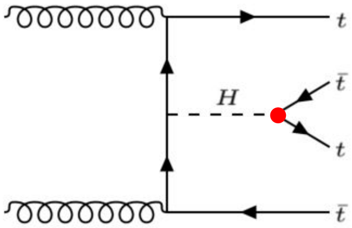


Four top quark production

Motivation

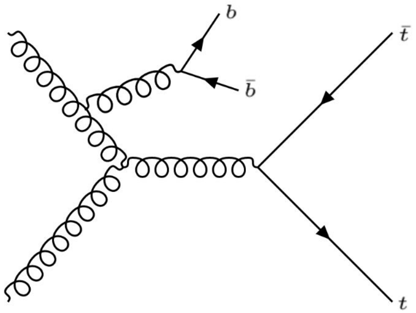
- Very rare SM process (σ^{SM}_{4t} = 12.0 ± 2.4 fb)
- Many BSM models predict enhancements to σ_{4t}
  - E.g. gluino pair production, 2HDM
  - Sensitivity to four-fermion EFT couplings
- Also sensitive to CP properties of y_t

EW 4t production - sensitivity to y_t



Measurement channels

- 1ℓ/2ℓOS (57% BR)
  - Large irreducible $t\bar{t}$+HF→ significant theoretical uncertainties
- 2ℓSS/3ℓ (13% BR) ⟶ arXiv:2303.15061
  - Low background (dominated by $t\bar{t}H/Z/W$ + jets)



$t\bar{t}$+$b\bar{b}$ production

Four top production - background estimation

- Low background 2ℓSS/3ℓ channel
- Signature: high jet multiplicity, high b-jet multiplicity, high overall energy
- Data-driven background estimations to correct MC modelling
  - Dedicated CRs for non-prompt/fake leptons
  - **Dedicated correction to $t\bar{t}W$**

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_0 or ℓ_1 is from virtual photon (γ^*) decay ℓ_0 and ℓ_1 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_0 or ℓ_1 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge is ± 1	$p_T^{\ell_2}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge is ± 1	$p_T^{\ell_2}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_0 and ℓ_1 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_0 and ℓ_1 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$	GNN score

$$H_T = \sum_{j}^{N_{jets}} p_T^j + \sum_{\ell}^{N_\ell} p_T^\ell$$

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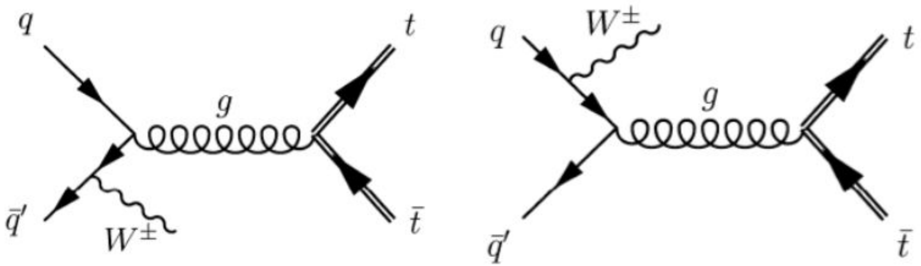
$$H_T = \sum_{j}^{N_{jets}} p_T^j + \sum_{\ell}^{N_\ell} p_T^\ell$$

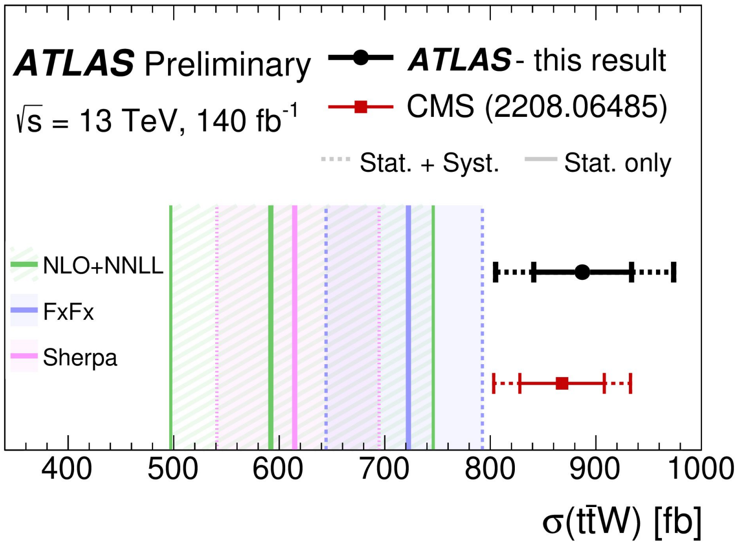
Aside: ttW

LO ttW production



- Observed in Run 1, differential measurements now available
- Irreducible background to many multi-lepton analyses (incl. ttH)
- **Theory seen to consistently underestimate cross-section**
- Currently nothing to explain discrepancy → ideally use data-driven treatments

ATLAS-CONF-2023-019



Four top production - ttW background estimation

ATLAS EXPERIMENT

- Jet multiplicity-dependent correction: derive four scaling factors using four CRs

$$a_0 \quad a_1 \quad \mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})} \quad \mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})}$$

- Rely on known scaling properties of QCD jets at hadron colliders *
  - For low N_{jets} expect Poisson scaling → N(j+1)/N(j) = const/(1+j)
  - At high N_{jets} expect fixed probability of additional emission → N(j+1)/N(j) = constant

$$\mathrm{NF}_{t\bar{t}W(j)} = \mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right] + \mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right]$$

Scaling factor for events with j > 4 jets

“Staircase” scaling

Poisson scaling

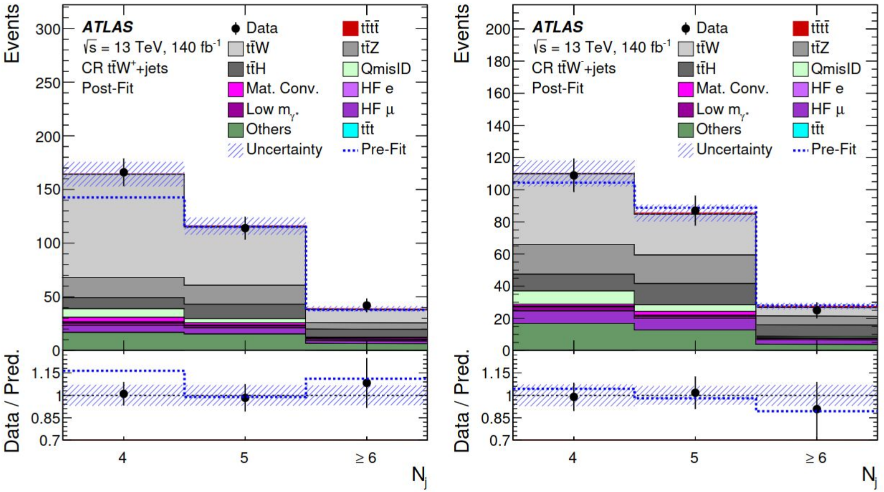
* arXiv:1208.3676

Four top production - ttW background estimation

ATLAS EXPERIMENT

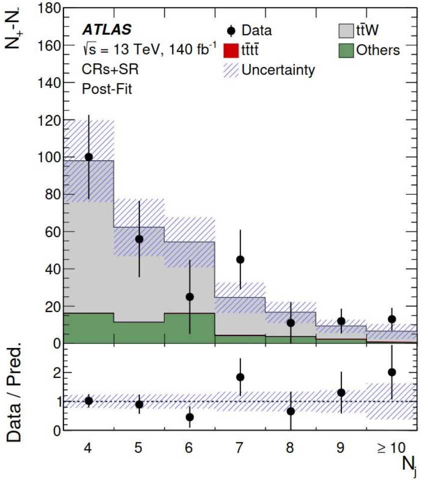
$$\mathrm{NF}_{t\bar{t}W(j)} = \mathrm{NF}_{t\bar{t}W^{+}(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right] + \mathrm{NF}_{t\bar{t}W^{-}(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right]$$

$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^{+}(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^{-}(4\mathrm{jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$



Left: ttW control regions

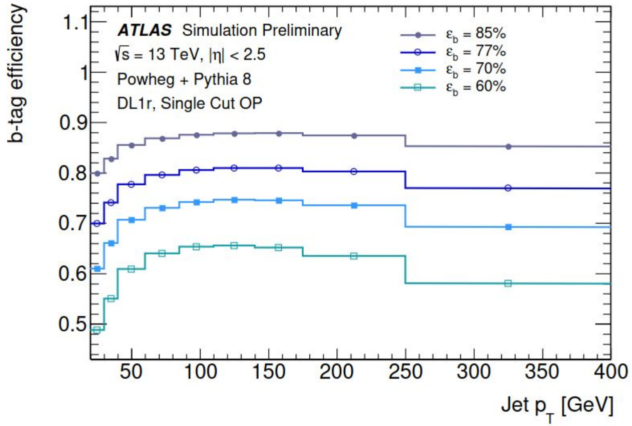
Right: difference of events with total +ve and -ve charge in all regions

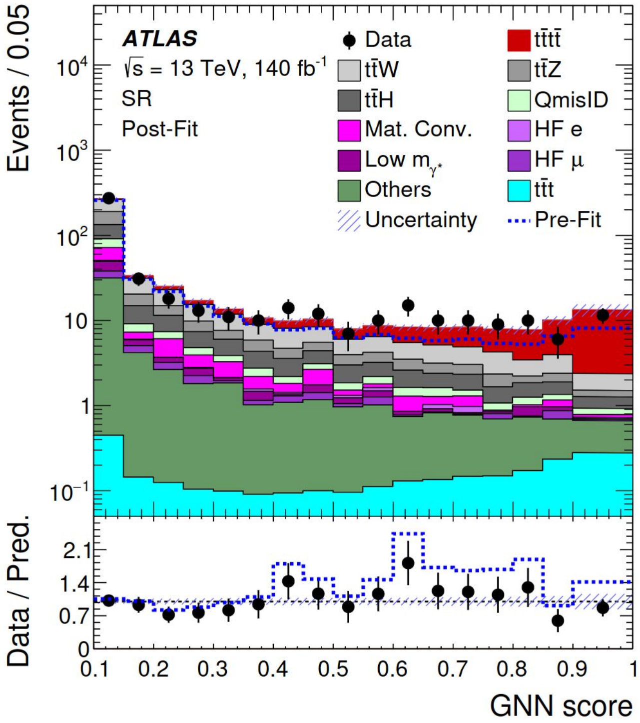


Four tops - signal extraction

arXiv:2303.15061

- Fully-connected graph neural network
  - Reconstructed j/ℓ/E_T^{miss} as nodes
  - Angular separations encoded in edges
- 6-way splitting for training/application using SR
- Key input: pseudo-continuous b-tagging scores - categorise how likely jets are to contain *b*-hadrons





Four tops - results

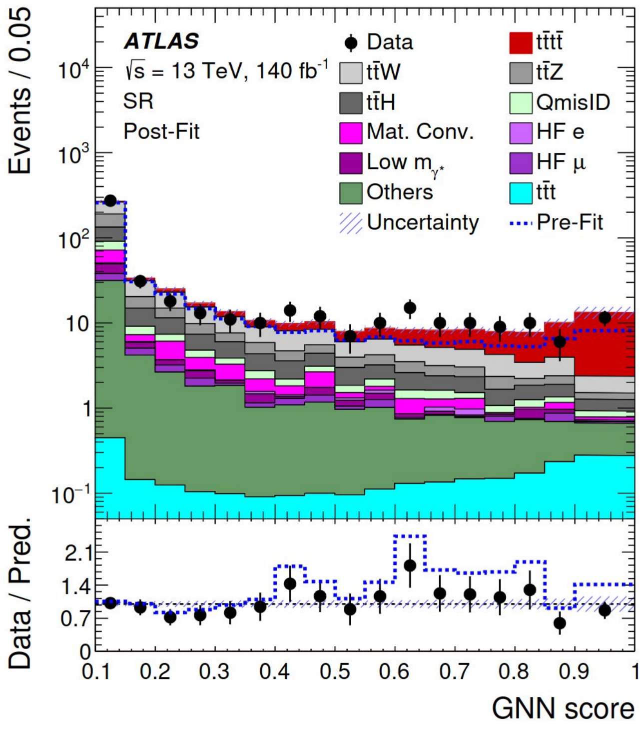
arXiv:2303.15061

$$\mu = 1.89^{+0.37}_{-0.35}(\text{stat})\,^{+0.62}_{-0.37}(\text{syst}) = 1.89\,^{+0.73}_{-0.51}.$$

$$\sigma_{t\bar{t}t\bar{t}} = 22.7^{+4.7}_{-4.4}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.7\,^{+6.6}_{-5.5}\text{ fb}.$$

- Profile likelihood fit across SR and all CRs
- Observed (exp.) significance: 6.1σ (4.3σ)
- Dominant systematics from modelling of signal and data-driven estimate of ttW background
- CMS also report observation with 5.5σ

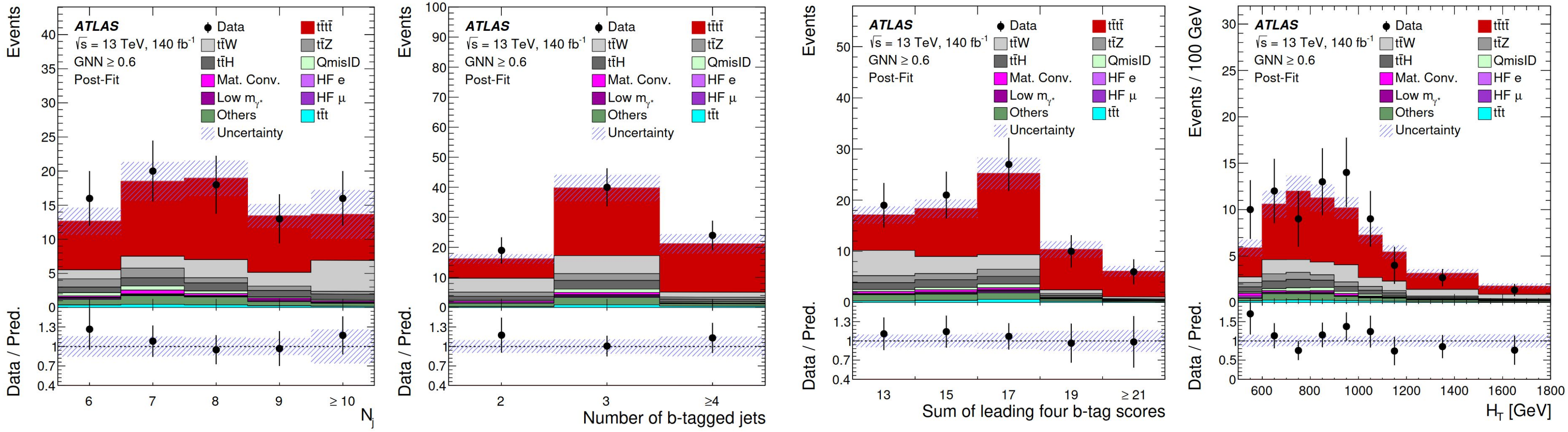
Observation of 4 tops production!



Observation of 4t production

arXiv:2303.15061

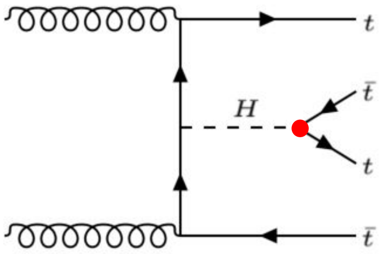
S+B model shows good agreement with observed data in high GNN score region

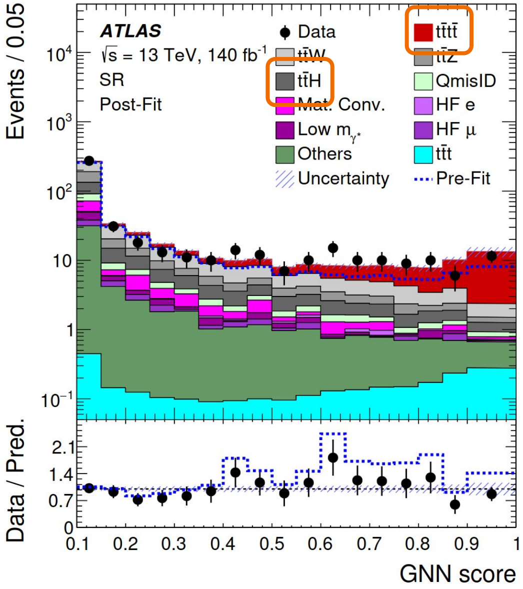


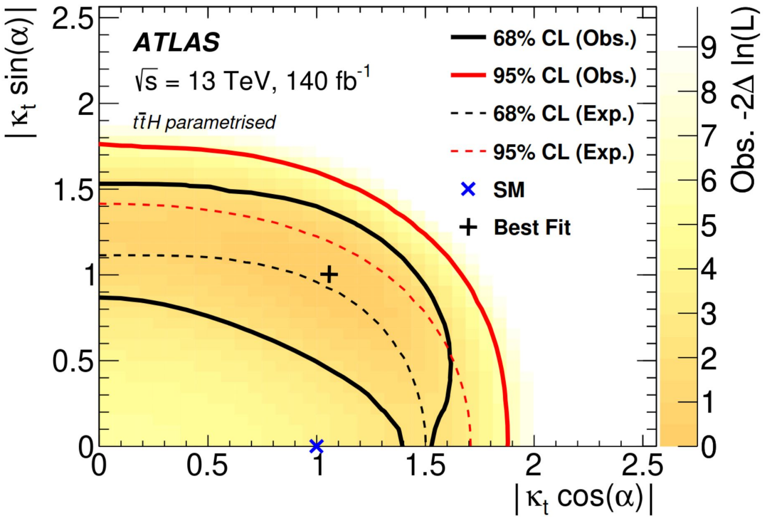
Four tops ⟶ top Yukawa coupling

arXiv:2303.15061

- Sensitive to Yukawa coupling strength (κ_t) and CP mixing angle (α)
- Parametrise four top signal and ttH GNN distributions in κ_t and α





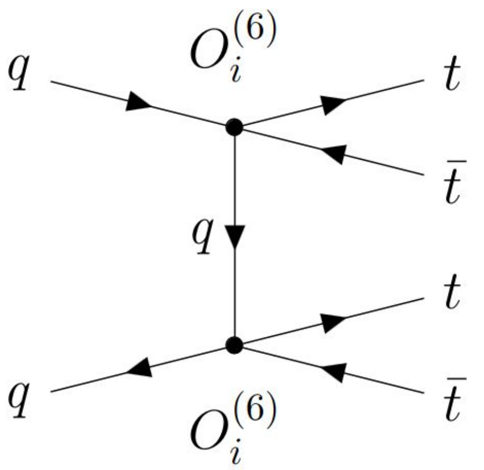


Four tops ⟶ EFT

arXiv:2303.15061

ATLAS EXPERIMENT

- BSM physics could enhance four top cross-section
- New physics with strong couplings to tops should show up in four top production



$$\sigma_{t\bar{t}t\bar{t}} = \sigma_{t\bar{t}t\bar{t}}^{SM} + \frac{1}{\Lambda^2}\sum_i C_i \sigma_i^{(1)} + \frac{1}{\Lambda^4}\sum_{i\le j} C_i C_j \sigma_{i,j}^{(2)}$$

Operators	Expected C_i/Λ^2 [TeV^{-2}]	Observed C_i/Λ^2 [TeV^{-2}]
O_{QQ}^1	[-2.4,3.0]	[-3.5,4.1]
O_{Qt}^1	[-2.5,2.0]	[-3.5,3.0]
O_{tt}^1	[-1.1,1.3]	[-1.7,1.9]
O_{Qt}^8	[-4.2,4.8]	[-6.2,6.9]

Limits comparable with those found by CMS - JHEP11 (2019) 082

Four tops ⟶ three tops?

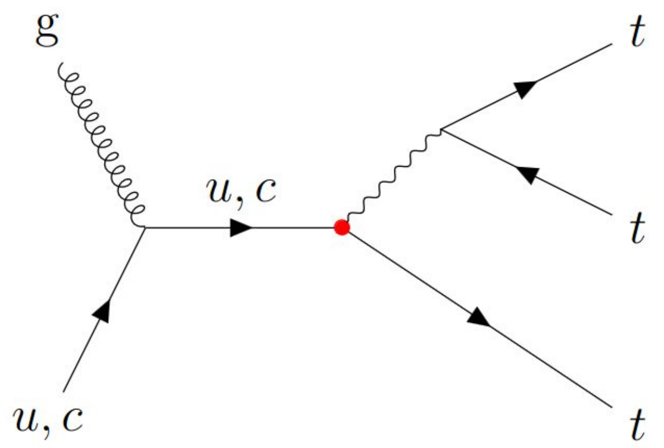
arXiv:2303.15061

- Set limits on cross-section of very rare 3 tops process (σ^{SM}_{3t} = 1.67 fb)
- Three top cross-section expected to be significantly enhanced by top FCNC couplings

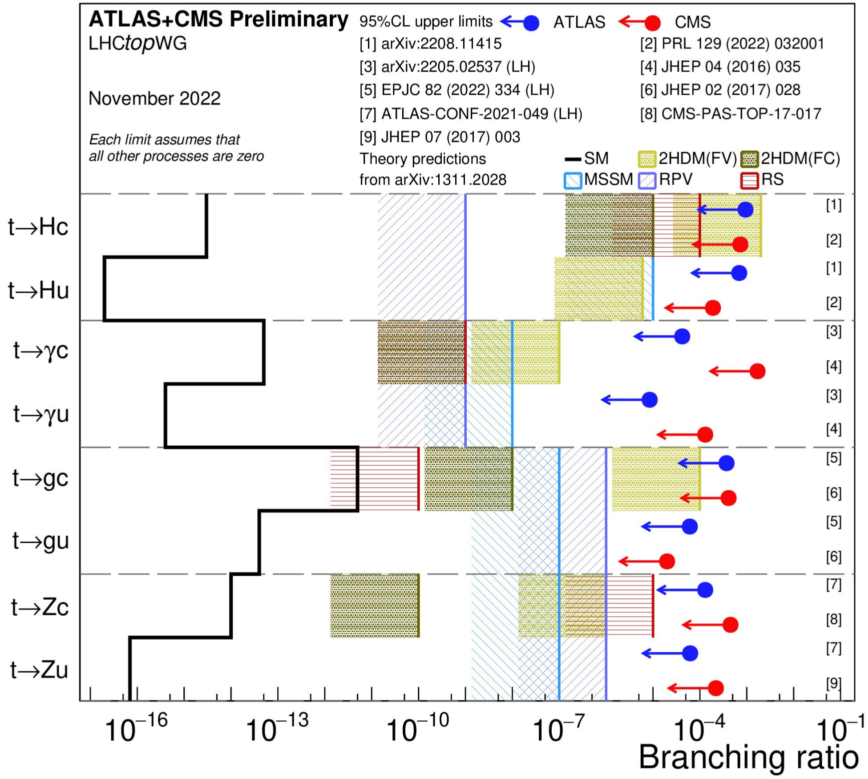
Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$tt\bar{t}$	[4.7, 60]	[0, 41]
$tt\bar{t}W$	[3.1, 43]	[0, 30]
$tt\bar{t}q$	[0, 144]	[0, 100]

$$\sigma_{tt\bar{t}} = \sigma_{tt\bar{t}W} + \sigma_{tt\bar{t}q}$$

Possible top FCNC interaction with SM boson



Search for FCNC interactions of the top quark



Flavour in the SM

ATLAS EXPERIMENT

Flavour universality broken by Yukawa couplings of Higgs to fermion fields

Fermion mass terms generated through EWSB:

$$m_f = \frac{\nu}{\sqrt{2}} y_f$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i\bar{\psi} D\psi$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Flavour in the SM

ATLAS EXPERIMENT

Complex Yukawa matrices can be diagonalised by rotations in flavour space to obtain physical fermion masses

This however introduces a flavour-violating term in CC interactions with W:

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\overline{u}_L \gamma^\mu \underbrace{(V_u^\dagger V_d)}_{V_{CKM}} d_L + \overline{\nu}_L \gamma^\mu \underbrace{(V_\nu^\dagger V_e)} e_L \right) W_\mu^+ + h.c.$$

arXiv:1709.00294

V_{CKM}

Absence of ν_R in SM allows $V_e = V_\nu \rightarrow$ no LFV in lepton sector

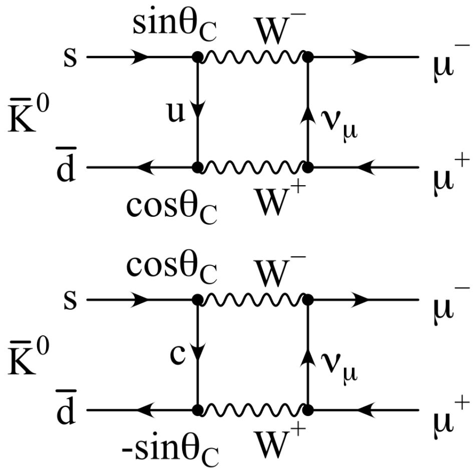
➔ No LFV in lepton sector

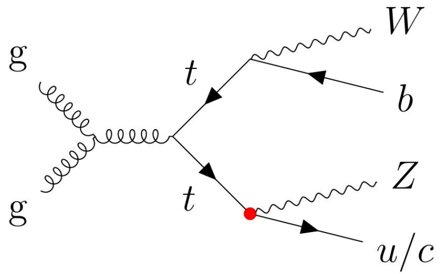
➔ In quark sector, LFV restricted to charged-current interactions

Why search for FCNCs in top interactions?

ATLAS EXPERIMENT

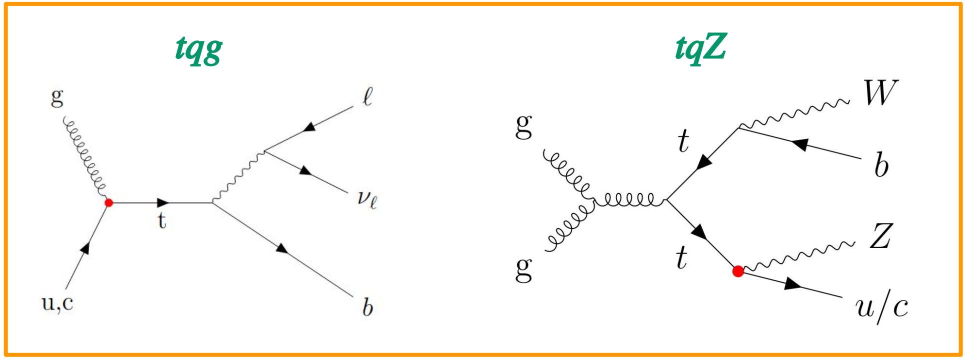
- Forbidden at tree level in the Standard Model
- Heavily suppressed at loop level through GIM mechanism
- Top FCNC searches performed at LEP, HERA Tevatron
- Large top mass → many channels
    - Search in both single top production and top pair decay

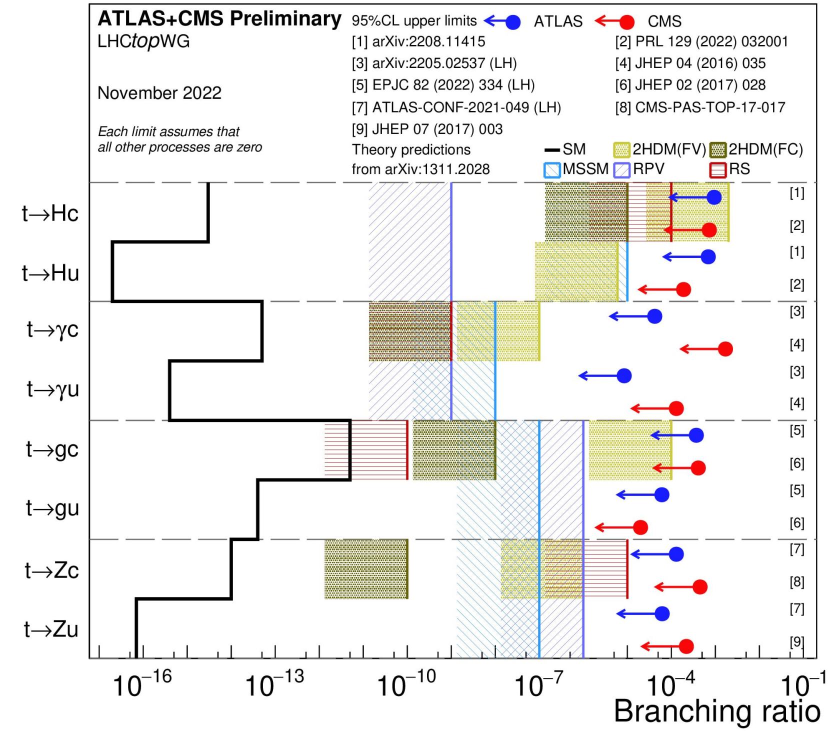




Why search for FCNCs in top interactions?

- SM predictions: BR ~ 10^{-12} to 10^{-17}
- Wide variety of BSM models predict FCNCs with rates observable at LHC
- Describe FCNC couplings in terms of EFT framework





Why search for FCNCs in top interactions?

- SM predictions: BR ~ 10^{-12} to 10^{-17}
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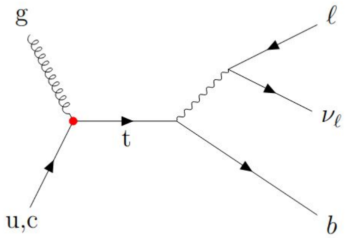
- Describe FCNC couplings in terms of EFT framework

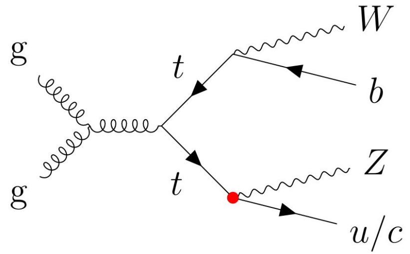
Dimension-6 EFT operators sensitive to top FCNCs

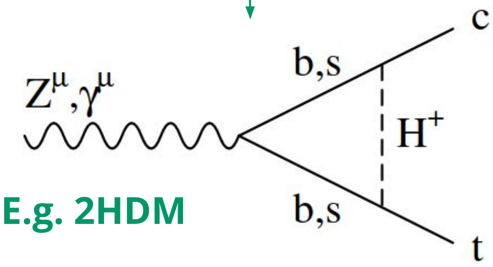
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$

tqg



tqZ

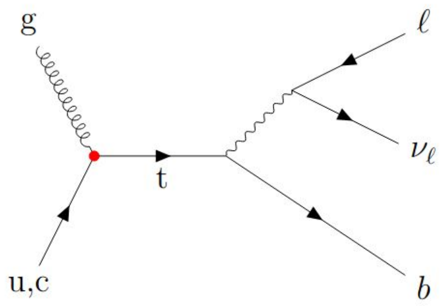


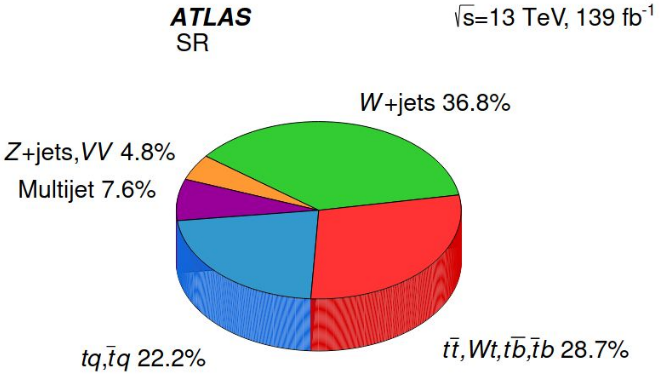


E.g. 2HDM

FCNC *tqg* (Eur. Phys. J. C 82 (2022) 334)

- Search for **single top production** via FCNC *tqg* vertex (q = u/c)
  - Single lepton, 1 *b*-tagged jet and MET
- Dedicated high-purity b-tagging calibration to suppress W + $b\bar{b}$
- Data-driven estimate for events with fake leptons from multi-jet background
- Neural networks (NNs) used to discriminate between u+$g \rightarrow t$, c+$g \rightarrow t$ and background
  - Kinematic input variables including reconstructed top kinematics



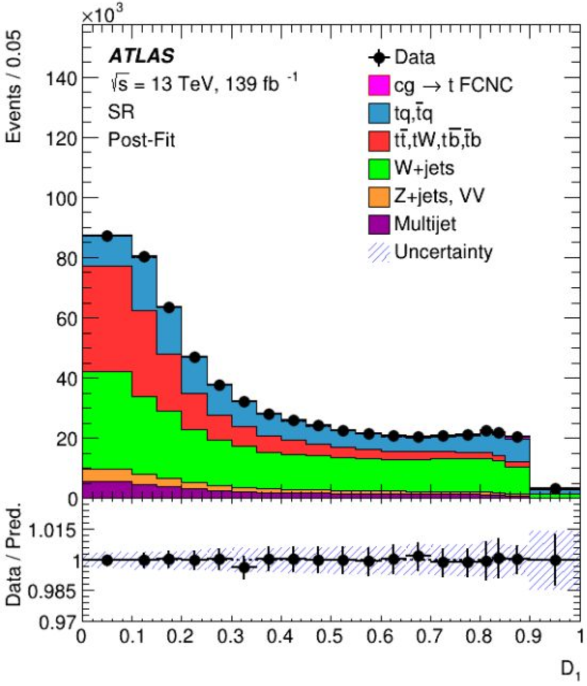


FCNC *tqg* (Eur. Phys. J. C 82 (2022) 334)

- Profile likelihood fit to NN discriminants in SR
- Dominant uncertainties:
  - ugt: MC stat uncertainty and modelling of W+jets
  - cgt: parton shower modelling of FCNC cgt and SM tq processes

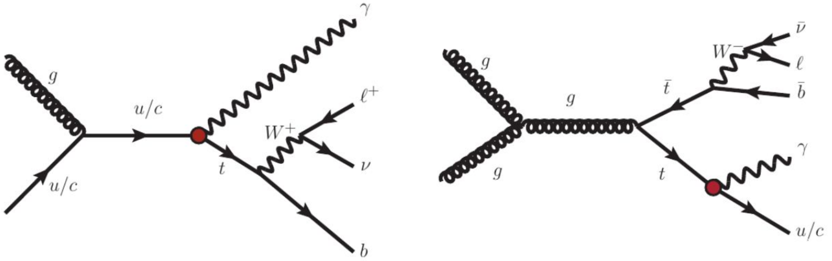
$$\mathcal{B}(t \to u + g) < 0.61 \times 10^{-4}$$
$$\mathcal{B}(t \to c + g) < 3.7 \times 10^{-4}$$
$$\frac{|C_{uG}^{ut}|}{\Lambda^2} < 0.057\ \text{TeV}^{-2} \qquad \frac{|C_{uG}^{ct}|}{\Lambda^2} < 0.14\ \text{TeV}^{-2}$$

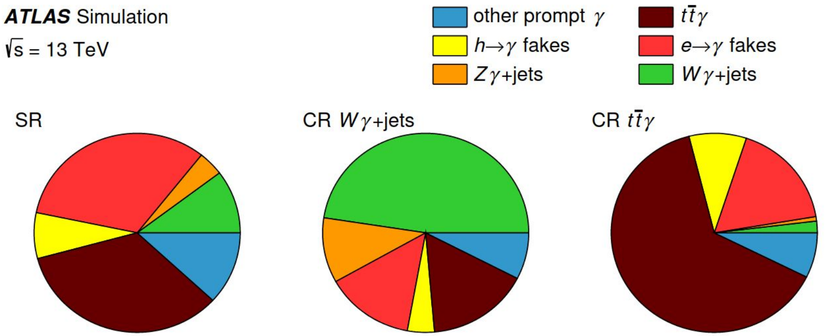
(95% CL)



FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)

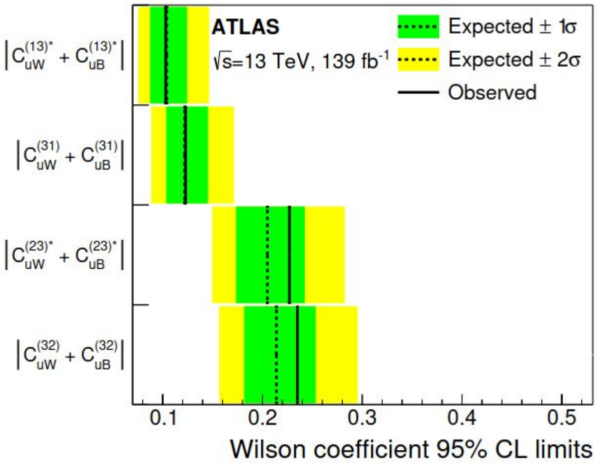
- Search for FCNC $tq\gamma$ in **top production and decay**
  - Single lepton, high p_T γ, MET
- CRs for main backgrounds with prompt photons ($t\bar{t}\gamma$, Wγ+jets)
- Data-driven corrections to rate of electron/hadron→γ fakes

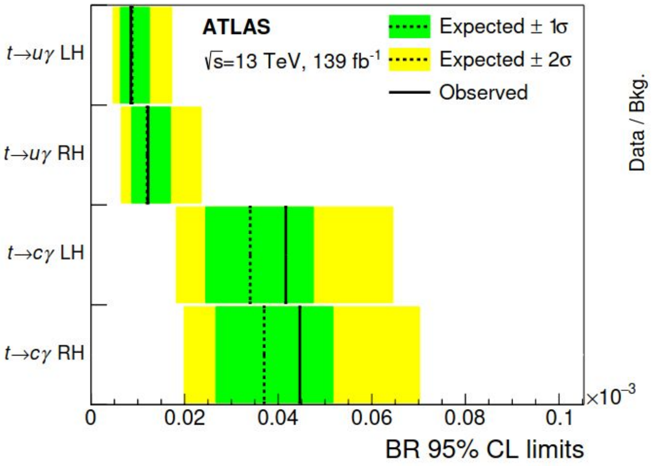


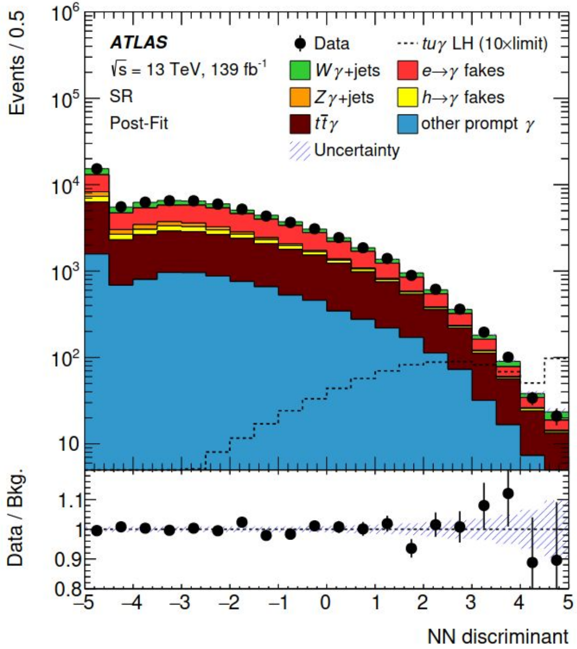


FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)

- Multiclass deep neural networks to split events into two signal modes and background
- Dominant uncertainties:
  - Limited statistics ($tu\gamma$), $tq\gamma$ theory cross-section, h $\rightarrow \gamma$ estimate ($tc\gamma$)



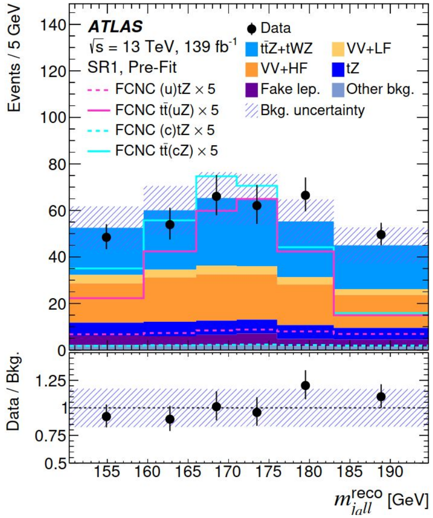




$$\mathcal{D} = \ln \frac{a \cdot y_{\text{prod}} + (1-a) \cdot y_{\text{dec}}}{y_{\text{bkg}}}$$

FCNC tqZ (arXiv:2301.11605)

- Search for FCNC tqZ in **top production and decay**
  - Trilepton event selection (*low background channel*)
- Two SRs targeting production and decay processes
  - Split by mass of reconstructed top(s)
- Additional CRs for dominant (diboson, $t\bar{t}Z$) and fake lepton ($t\bar{t}$) backgrounds



Reconstructed top mass assuming $t\rightarrow qZ$ decay

Common selections		
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV ≥ 1 OSSF pair, with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV		
SR1	SR2	
≥ 2 jets	1 jet	2 jets
1 b-jet	1 b-jet	1 b-jet
–	$m_T(\ell_W, \nu) > 40$ GeV	$m_T(\ell_W, \nu) > 40$ GeV
$\lvert m^{reco}_{j_a\ell\ell} - m_t\rvert < 2\sigma_{t_{FCNC}}$	–	$\lvert m^{reco}_{j_a\ell\ell} - m_t\rvert > 2\sigma_{t_{FCNC}}$
–	$\lvert m^{reco}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{SM}}$	$\lvert m^{reco}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{SM}}$

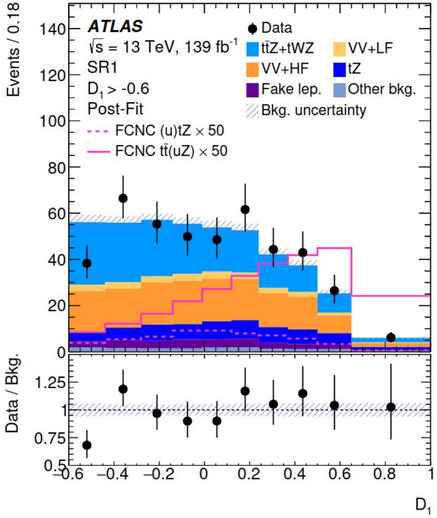
FCNC tqZ (arXiv:2301.11605)

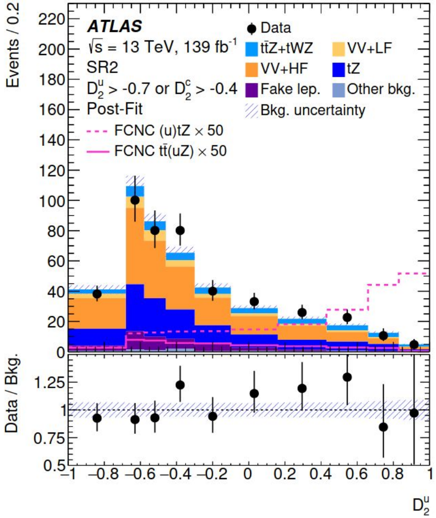
ATLAS EXPERIMENT

- GBDTs used for S/B discrimination
  - Reconstructed top kinematics provide key inputs
- Dominant uncertainty: limited statistics

Observable	Vertex	Coupling	Observed	Expected
SRs+CRs				
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3}\times10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20\,^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19\,^{+0.04}_{-0.03}$
SR1+CRs				
$\mathcal{B}(t \to Z$ [illegible]	[illegible]	[illegible]	[illegible]	[illegible] $\times10^{-5}$
$\mathcal{B}(t \to Z$ [illegible]	[illegible]	[illegible]	[illegible]	[illegible] $\times10^{-5}$
$\mathcal{B}(t \to Z$ [illegible]	[illegible]	[illegible]	[illegible]	[illegible] $\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.0×10^{-5}	$6.6\,^{+2.9}_{-1.8}\times10^{-5}$

Sensitive to same EFT operators as $tq\gamma$

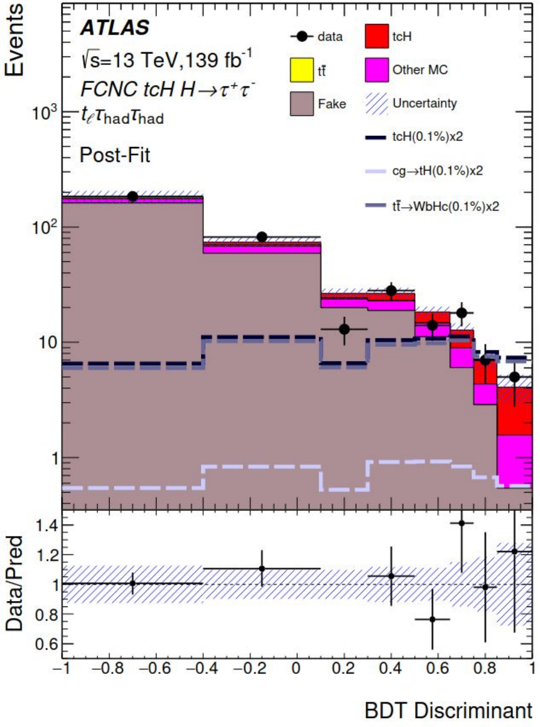




FCNC $tqH(\tau\tau)$ (arXiv:2208.11415)

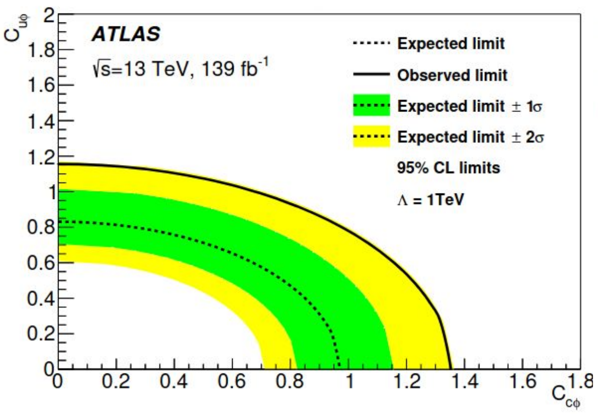
- Search for FCNC tqH in **top production and decay**
  - **Require $H \to \tau\tau$ decay**
- Many SRs targeting different top and τ-lepton decays channels
- Data-driven background estimates for fake τ_{had} and fake/non-prompt light leptons
- BDTs used for S/B discrimination
  - Rely on event kinematics for training (including kinematic reconstruction where possible)

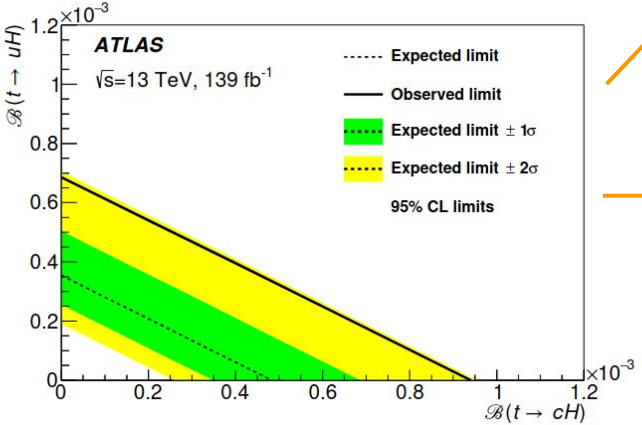
BDT discriminant in most sensitive SR

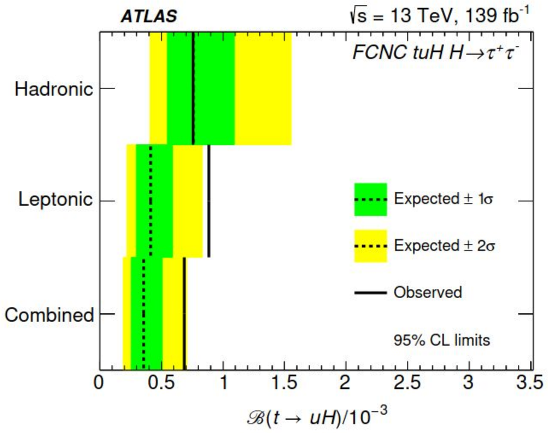


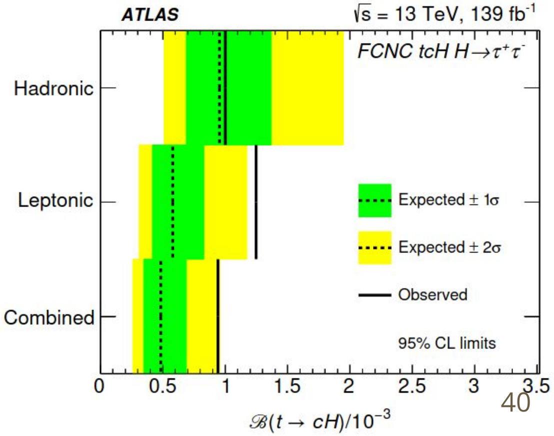
FCNC $tqH(\tau\tau)$ (arXiv:2208.11415)

- Profile likelihood fit to 7 SRs and 6 CRs
- Observe slight excess (2.3σ) above expected background
- Dominant uncertainties: statistics, MC statistics, fake estimation

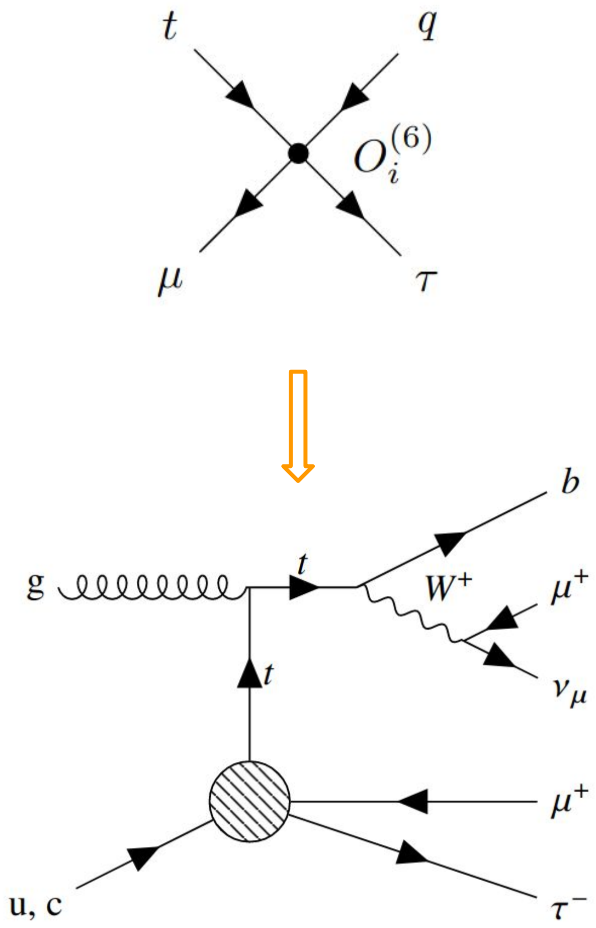






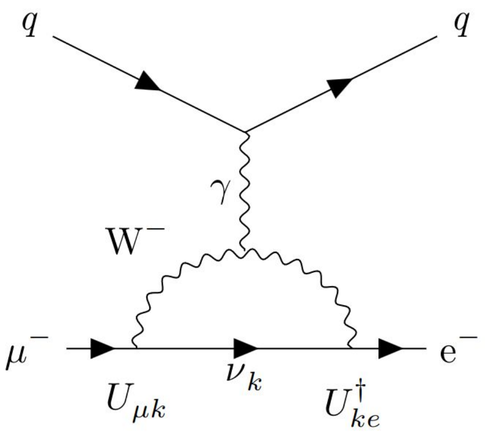


Search for CLFV interactions of the top quark



Neutrino oscillations & CLFV

- Neutrino oscillations → LFV in lepton sector but far beyond any experimental sensitivity



$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{k=1,3}\frac{U_{\mu k}U^*_{ek}m^2_{\nu_k}}{M^2_W}\right|^2$$

arXiv:1709.00294

- New physics which introduces additional terms involving lepton fields in Lagrangian will in general lead to LFV

SUSY

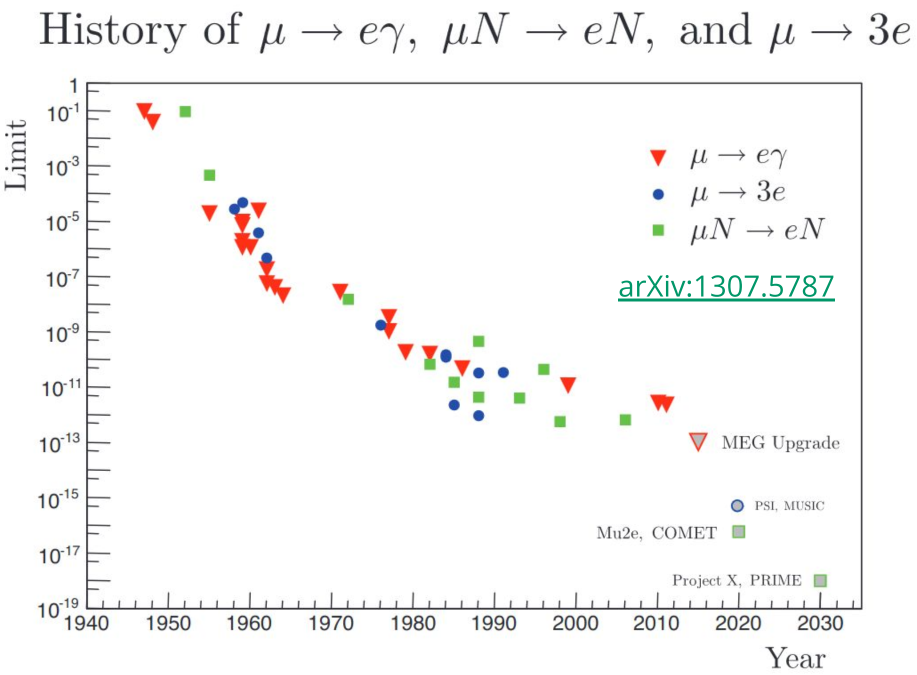
LQs

2HDMs

Why search for CLFV in top quark interactions?

ATLAS EXPERIMENT

- Best sensitivity typically in muon channels
  - Best CLFV limits from MEG: $B(\mu \to e\gamma) < 4.2 \times 10^{-13}$ (90% CL) *
- Models predicting CLFV in muons also apply to taus, often additionally enhanced due to larger mass (e.g. LQs)
- **Searches for LFV involving taus, tops, H, Z require colliders**

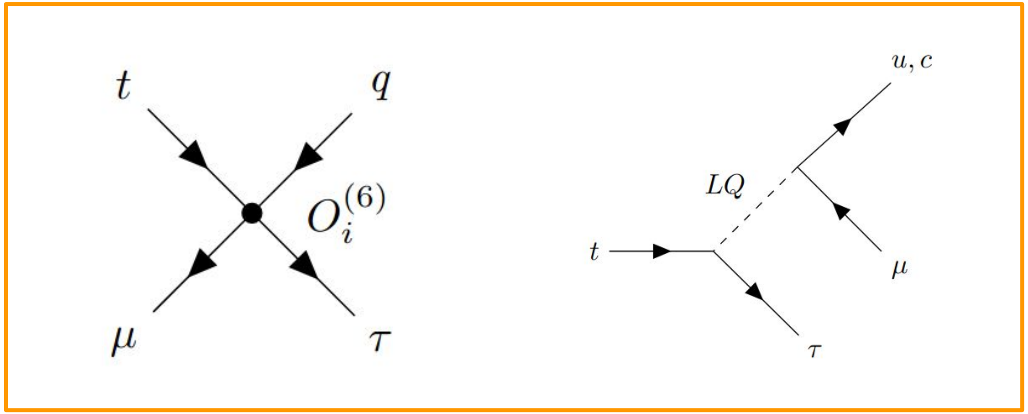


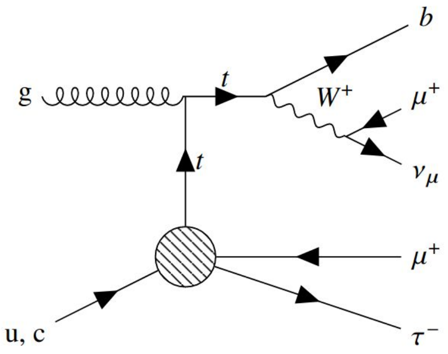
arXiv:1307.5787

* *Eur. Phys. J. C* **76**, 434 (2016)

CLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT



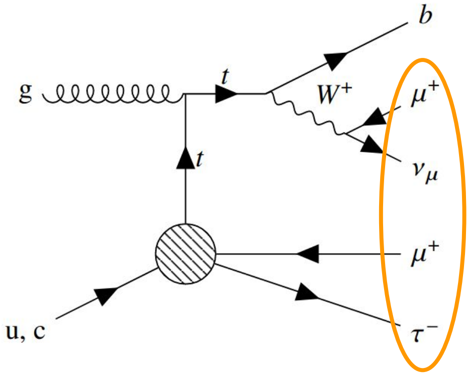


- First direct search for tμτq coupling
- Complements searches for *teμq* coupling by ATLAS (arXiv:1809.09048) and CMS (JHEP 06 (2022) 082, CMS PAS TOP-22-005)

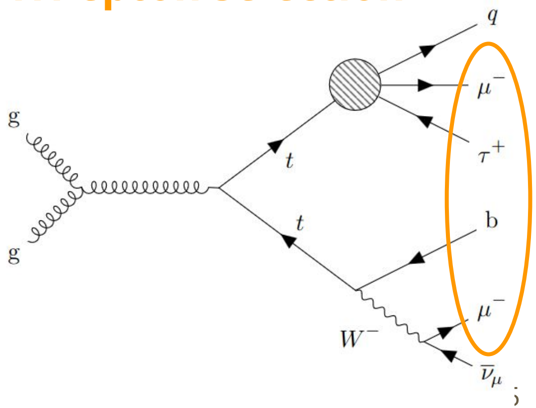
CLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

- Signal includes single top production and top quark pair decay
- Trilepton selection including *hadronic taus*
- Same-sign muons in SR → significant background reduction



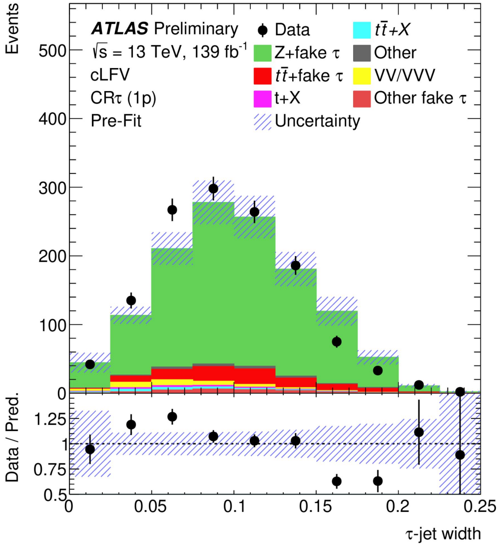
Trilepton selection



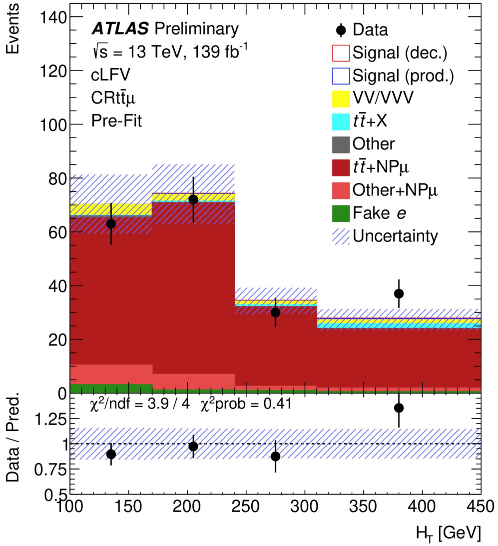
	SR1	SR2	CRτ	CRttμ
Lepton flavour	$2\mu 1\tau_{\text{had-vis}}$			$2\mu 1e\ (\ell_3 = \mu)$
N_{jets}	≥ 2	1	≥ 2	≥ 2
$N_{b-\text{tags}}$	1	1	1	≤ 2
Muon p_T cut	> 15 GeV	> 15 GeV	> 15 GeV	> 10 GeV
Lowest p_T muon selection	*Tight*	*Tight*	*Tight*	*Loose*
Muon charges	SS	SS	OS	-
$\lvert m_{\mu\mu}^{OS} - M_Z \rvert$	-	-	<10 GeV	>10 GeV

CLFV in top quark interactions (ATLAS-CONF-2023-001)

- Data-driven background estimations for fake background processes
- Scale factors to correct rate of fake τ_{had} background
- Correct normalisation of non-prompt background in fit



Fake τ_{had} control region



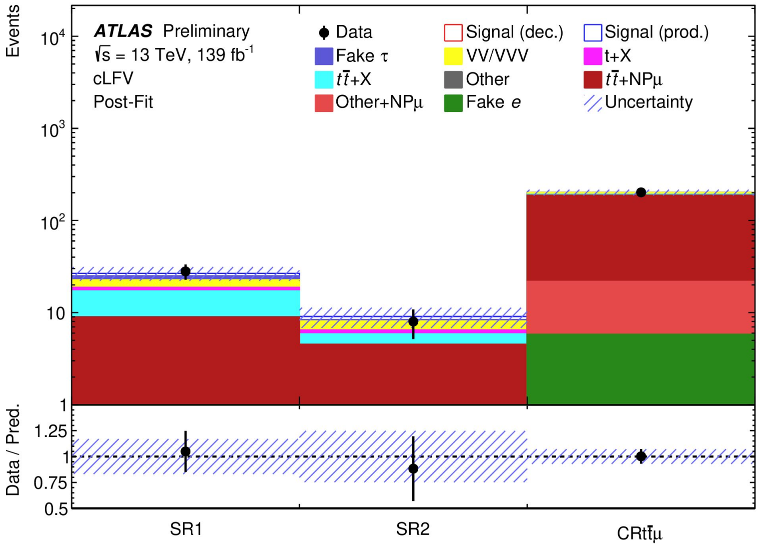
Non-prompt μ control region

CLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

- Profile likelihood fit across two SRs and non-prompt muon CR
- Good agreement between data and background-only model
- Statistically limited

	Exclusion limit $B(t \to \mu\tau q)$	
	Stat. only	All systematics
Expected	7.57×10^{-7}	9.82×10^{-7}
Observed	9.43×10^{-7}	10.8×10^{-7}



CLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

- Stringent limits on Wilson coefficients corresponding to 2Q2L operators
  - Improve upon the previous results by up to a factor of 51

$$\Gamma(t \to \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{lq}^{-(ijk3)}|^2 + 4|c_{eq}^{(ijk3)}|^2 + 4|c_{lu}^{(ijk3)}|^2 + 4|c_{eu}^{(ijk3)}|^2 + |c_{lequ}^{1(jik3)}|^2 + |c_{lequ}^{1(ij3k)}|^2 + 48|c_{lequ}^{3(jik3)}|^2 + 48|c_{lequ}^{3(ij3k)}|^2\Big\}$$

	95% CL upper limits on Wilson coefficients c/Λ^2 [TeV^{-2}]							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Previous (u)	12	12	12	12	26	26	3.4	3.4
ATLAS expected (u)	0.47	0.44	0.43	0.46	0.49	0.49	0.11	0.11
ATLAS observed (u)	0.49	0.47	0.46	0.48	0.51	0.51	0.11	0.11
Previous (c)	14	14	14	14	29	29	3.7	3.7
ATLAS expected (c)	1.6	1.6	1.5	1.6	1.8	1.8	0.35	0.35
ATLAS observed (c)	1.7	1.6	1.6	1.6	1.9	1.9	0.37	0.37

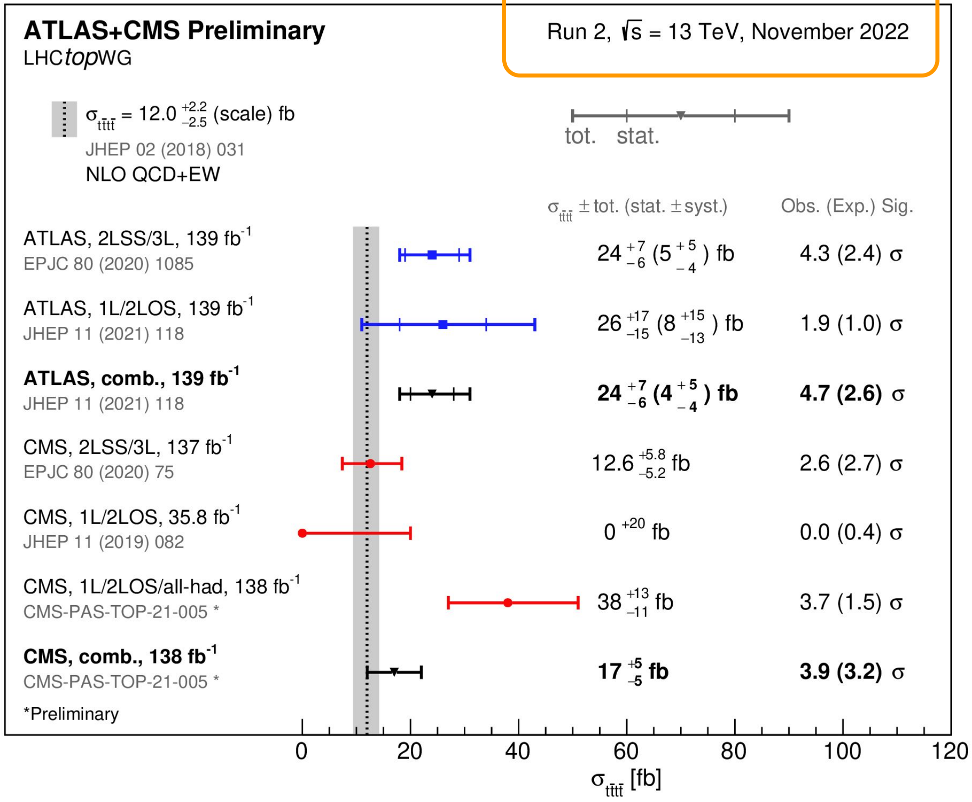
Previous limits and equation from JHEP04 (2019) 014 (reinterpretation of JHEP07 (2018) 176)

Concluding remarks

- Many exciting Run 2 rare top results!
  - Observation of four top production
  - Diverse BSM couplings programme
- No evidence for new physics as of yet...
  - In many cases setting most stringent limits on these branching ratios to date
- Many measurements statistically limited → significant improvements with Run 3 and beyond
- Modelling of signal and background is frequently a limiting systematic
  - Much work is going into improving modelling of generators and theoretical predictions

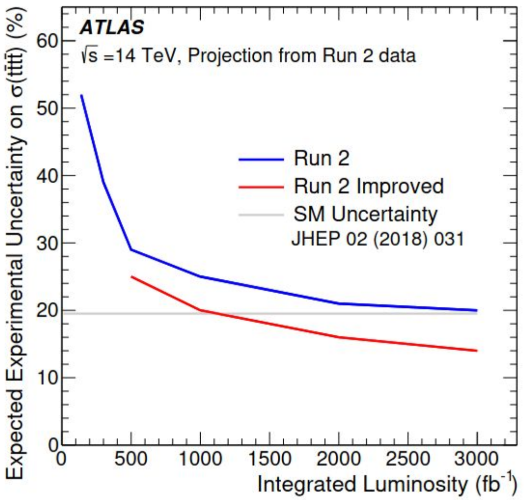
BACKUP

History of 4t production measurements at the LHC



Both ATLAS and CMS now report observation of this process

HL-LHC 4t prospects (ATL-PHYS-PUB-2022-004)



Study into HL-LHC sensitivity - ATL-PHYS-PUB-2022-004

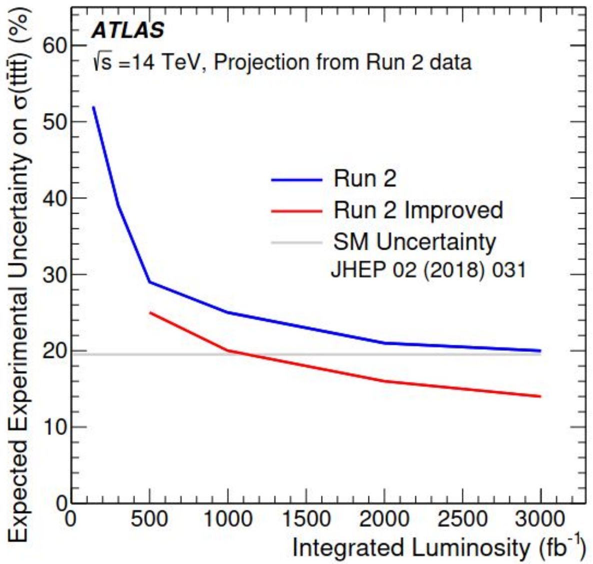
Consider conservative/optimistic systematic reductions with 3000 ifb at 14 TeV in 2ℓSS/3ℓ channel

Expected significance (wrt B-only hypothesis): 4.2-6.4σ

Expected uncertainty on cross section: 14%-20%

HL-LHC $4t$ prospects

(ATL-PHYS-PUB-2022-004)



Integrated luminosity (fb^{-1})	"Run 2"	"Run 2 Improved"
500	3.5	4.1
1000	3.9	4.9
2000	4.0	5.9
3000	4.2	6.4

Uncertainty source	Treatment in the "Run 2 Improved" model
Signal modelling	
$t\bar{t}t\bar{t}$ cross section	Half of Run 2
$t\bar{t}t\bar{t}$ modelling	Half of Run 2
Background modelling	
$t\bar{t}W$+jets modelling	
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
Jets multiplicity modelling	Scaled by Run 2 pulls
Additional heavy flavour jets	Scaled by luminosity
$t\bar{t}$ modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Non-prompt leptons modelling	Scaled by luminosity
$t\bar{t}H$+jets and $t\bar{t}Z$+jets modelling	
Cross section	Half of Run 2
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
PDF	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Other background modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Charge misassignment	Same as Run 2
Template fit shape uncertainties	
Mat. Conv., γ^*, and HF non-prompt leptons	Scaled by luminosity
Other fake leptons	Half of Run 2
Additional heavy flavour jets	Half of Run 2
Instrumental	
Jet uncertainties	Same as Run 2
Jet flavour tagging (light-flavour jets)	Half of Run 2
Luminosity	Same as Run 2
Jet flavour tagging (b-jets)	Half of Run 2
Jet flavour tagging (c-jets)	Half of Run 2
Other experimental uncertainties	Same as Run 2

Four top production - background estimation

Fake/non-prompt background	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m_{\gamma^*}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$	$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$

$$NF_{t\bar{t}W(j)} = NF_{t\bar{t}W^+(\text{4jet})} \times \Pi_{j'=4}^{j'=j-1} \left[a_0 + \frac{a_1}{1+(j'-4)} \right] + NF_{t\bar{t}W^-(\text{4jet})} \times \Pi_{j'=4}^{j'=j-1} \left[a_0 + \frac{a_1}{1+(j'-4)} \right]$$

$t\bar{t}W$ background	a_0	a_1	$NF_{t\bar{t}W^+(\text{4jet})}$	$NF_{t\bar{t}W^-(\text{4jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$

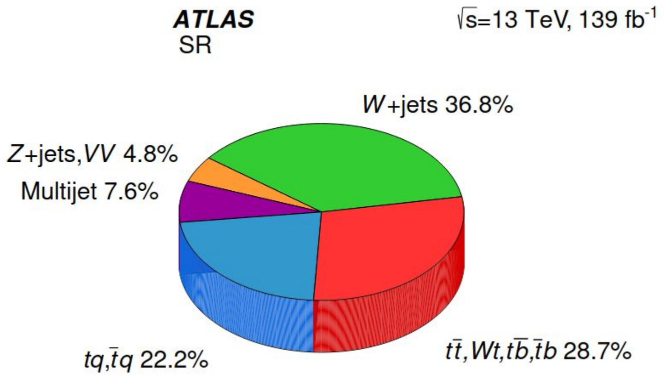
FCNC *tqg* (Eur. Phys. J. C 82 (2022) 334)

Observable	Common requirements
$n_{\text{Tight}}(e) + n_{\text{Medium}}(\mu)$	$= 1$
$n_{\text{Loose}}(e) + n_{\text{Loose}}(\mu)$	$= 1$
$E_{\text{T}}^{\text{miss}}$	> 30 GeV
$m_{\text{T}}(W)$	> 50 GeV
$n(j)$	≥ 1
$p_{\text{T}}(\ell)$	$> 50\,\text{GeV} \cdot \left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$

	Analysis regions			
	SR	W+jets VR	$t\bar{t}$ VR	tq VR
$n(\lvert\eta(j)\rvert < 2.5)$	$= 1$	$= 1$	$= 2$	$= 1$
$n(b)$	$= 1$	$= 1$	$= 2$	$= 1$
ϵ_b	30%	60% (veto 30%)	30%	30%
$n(\lvert\eta(j)\rvert > 2.5)$	≥ 0	≥ 0	≥ 0	$= 1$
$D_{1(2)}$	–	$0.3 < D_{1(2)} < 0.6$	–	$0.2 < D_{1(2)} < 0.4$

Fake estimation for events with fake leptons from multi-jet background

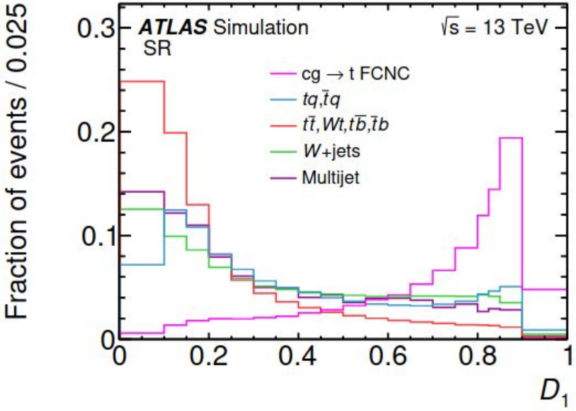
- e: shape from dijet MC (jet electron method)
- μ: shape from data enriched in non-prompt muons
- Maximum likelihood fit to E^{T}_{miss} (m_T) distribution in e (μ) channel to correct normalisation

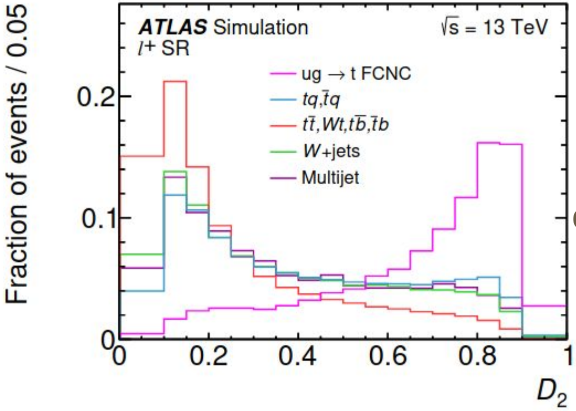


FCNC tqg (Eur. Phys. J. C 82 (2022) 334)

- Two NNs to discriminate S/B
  - D_1 trained only on $c+g\to t$ (incl. $\bar{c}+g\to\bar{t}$) - optimised for sea quark production
  - D_2 trained only on $u+g\to t$ (excl. $\bar{u}+g\to\bar{t}$) - optimised for valence quark production
  - Multijet background excluded from NN training
- Use D_1 in cgt analysis and ℓ^- channel of ugt analysis
- Use D_2 in ℓ^+ channel of ugt analysis

NN output discriminant distribution for cgt analysis

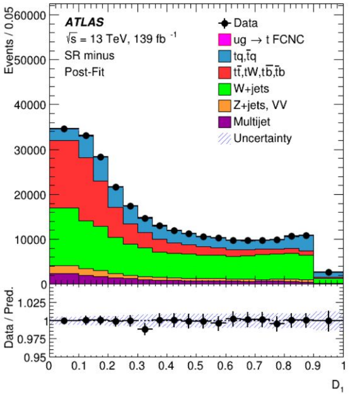


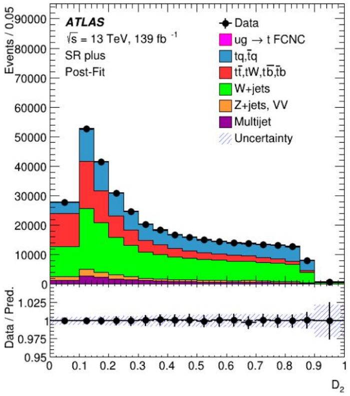


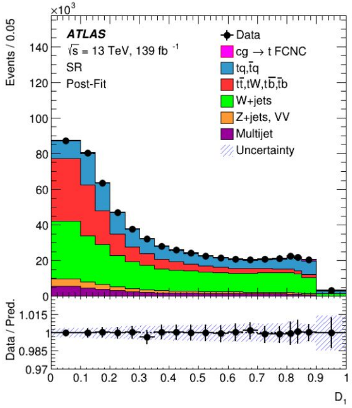
NN output discriminant distribution for ugt analysis

FCNC *tqg* ([Eur. Phys. J. C 82 (2022) 334](#))

NN discriminant distributions in SRs







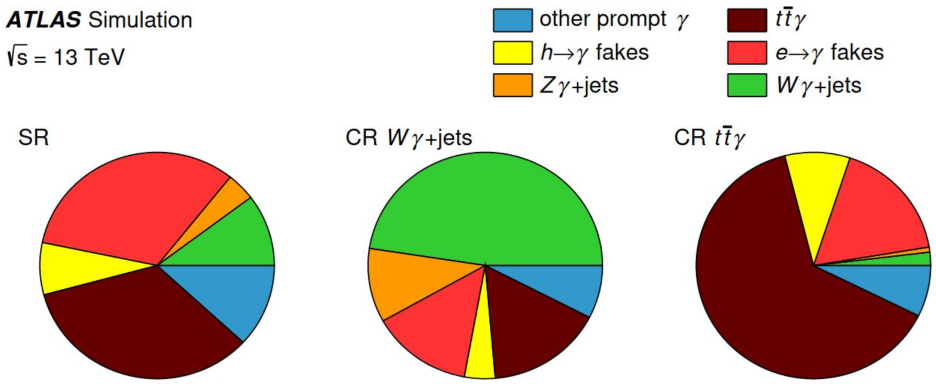
Scenario	Description	$\mathcal{B}_{95}^{\text{exp}}(t \to u + g)$	$\mathcal{B}_{95}^{\text{exp}}(t \to c + g)$
(1)	Data statistical only	1.1×10^{-5}	2.4×10^{-5}
(2)	Experimental uncertainties also	3.1×10^{-5}	12×10^{-5}
(3)	All uncertainties except MC statistical	3.9×10^{-5}	18×10^{-5}
(4)	All uncertainties	4.9×10^{-5}	20×10^{-5}

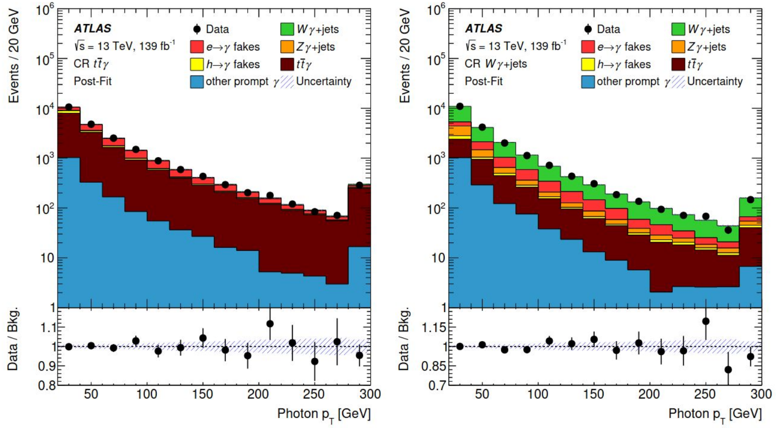
FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)

Object	SR	CR $t\bar{t}\gamma$	CR $W\gamma$+jets
Photon (p_T > 20 GeV)	= 1		
Lepton (p_T > 27 GeV)	= 1		
E_T^{miss}	> 30 GeV		
Jets (p_T > 25 GeV)	≥ 1	≥ 4	≥ 1
b-tagged jets (60% WP)	= 1	–	= 0
b-tagged jets (70% WP)	= 1	≥ 1	= 0
b-tagged jets (77% WP)	= 1	≥ 2	= 1
$m(e,\gamma)$	–	–	$\notin$ [80, 100] GeV

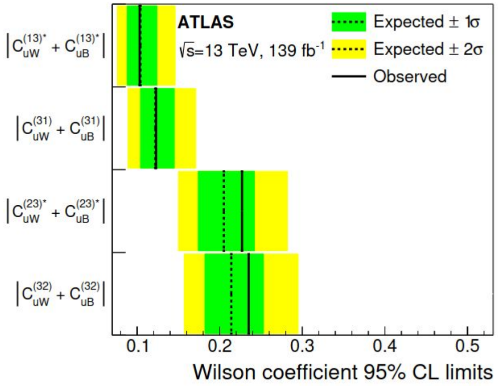
Data-driven corrections to rate of e/h→γ fakes

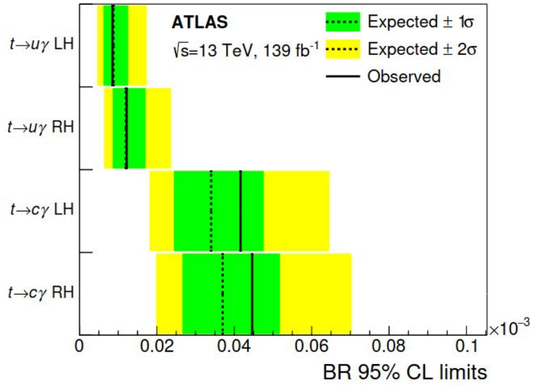
- e→γ: correct rate of Z→eγ to Z→ee in bins of photon η and reconstruction type
- h→γ: ABCD method using modified photon ID & isolation; binning in photon p_T, η and reconstruction type



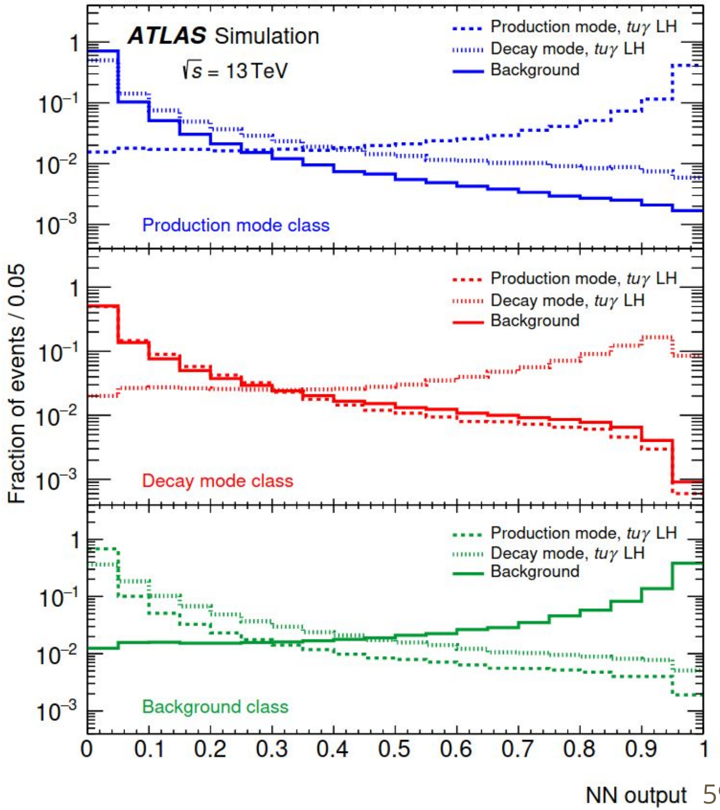


FCNC $tq\gamma$ (Phys. Lett B (2022) 137379)





Effective coupling	Coefficient limits		Coupling	BR limits $[10^{-5}]$	
	Expected	Observed		Expected	Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$0.122^{+0.023}_{-0.018}$	0.123	$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*}\rvert$	$0.205^{+0.037}_{-0.031}$	0.227	$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)}\rvert$	$0.214^{+0.039}_{-0.032}$	0.235	$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46



FCNC tqZ (arXiv:2301.11605)

Common selections		
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV ≥ 1 OSSF pair, with $\|m_{\ell\ell} - m_Z\| < 15$ GeV		
SR1	SR2	
≥ 2 jets	1 jet	2 jets
1 b-jet	1 b-jet	1 b-jet
–	$m_T(\ell_W, \nu) > 40$ GeV	$m_T(\ell_W, \nu) > 40$ GeV
$\|m^{reco}_{j_a\ell\ell} - m_t\| < 2\sigma_{t_{FCNC}}$	–	$\|m^{reco}_{j_a\ell\ell} - m_t\| > 2\sigma_{t_{FCNC}}$
–	$\|m^{reco}_{j_b\ell_W\nu} - m_t\| < 2\sigma_{t_{SM}}$	$\|m^{reco}_{j_b\ell_W\nu} - m_t\| < 2\sigma_{t_{SM}}$

Common selections			
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV			
$t\bar{t}$ CR	$t\bar{t}Z$ CR	Side-band CR1	Side-band CR2
≥ 1 OS pair, no OSSF	≥ 1 OSSF pair with $\|m_{\ell\ell} - m_Z\| < 15$ GeV	≥ 1 OSSF pair with $\|m_{\ell\ell} - m_Z\| < 15$ GeV	≥ 1 OSSF pair with $\|m_{\ell\ell} - m_Z\| < 15$ GeV
–	–	–	$m_T(\ell_W, \nu) > 40$ GeV
≥ 1 jet	≥ 4 jets	≥ 2 jets	1 jet
1 b-jet	2 b-jets	1 b-jet	1 b-jet
–	–	$\|m^{reco}_{j_a\ell\ell} - m_t\| > 2\sigma_{t_{FCNC}}$	–
–	–	$\|m^{reco}_{j_b\ell_W\nu} - m_t\| > 2\sigma_{t_{SM}}$	$\|m^{reco}_{j_b\ell_W\nu} - m_t\| > 2\sigma_{t_{SM}}$

- GBDTs used for S/B discrimination
  - Reconstructed top kinematics provide key inputs
  - Separate training for each SR based on dominant FCNC process

FCNC $tqH(\tau\tau)$ (arXiv:2208.11415)

ATLAS EXPERIMENT

Requirement	Leptonic channels $t_h\tau_{\text{lep}}\tau_{\text{had}}$	Leptonic channels $t_\ell\tau_{\text{had}}\tau_{\text{had}}$	Leptonic channels $t_\ell\tau_{\text{had}}$	Hadronic channel $t_h\tau_{\text{had}}\tau_{\text{had}}$
Trigger	single-lepton trigger			di-τ trigger
Leptons	=1 isolated e or μ			=0 isolated e or μ
τ_{had}	=1 τ_{had}	=2 τ_{had}	=1 τ_{had}	=2 τ_{had}
Electric charge (Q)	$Q_\ell \times Q_{\tau_{\text{had1}}} = -1$	$Q_{\tau_{\text{had1}}} \times Q_{\tau_{\text{had2}}} = -1$	$Q_\ell \times Q_{\tau_{\text{had1}}} = 1$	$Q_{\tau_{\text{had1}}} \times Q_{\tau_{\text{had2}}} = -1$
Jets	≥3 jets	≥1 jets	≥2 jets	≥3 jets
b-tagging	=1 b-jets			=1 b-jets

Regions		b-jets	Light-flavour jets	Leptons	Hadronic τ decays	Charge
SR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_\ell\tau_{\text{had}}$-1j	1	1	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell\tau_{\text{had}}$-2j	1	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	1	2	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{lep}}\tau_{\text{had}}$-3j	1	≥ 3	1	1	$\tau_{\text{lep}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-2j	1	2	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j	1	≥ 3	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ OS
VR	$t_\ell\tau_{\text{had}}\tau_{\text{had}}$-SS	1	≥ 0	1	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
	$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j SS	1	≥ 3	0	2	$\tau_{\text{had}}\tau_{\text{had}}$ SS
CRtt	$t_\ell t_\ell 1b\tau_{\text{had}}$	1	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_\ell 2b\tau_{\text{had}}$	2	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jSS	2	2	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-2jOS	2	2	1	1	$t_\ell\tau_{\text{had}}$ OS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jSS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ SS
	$t_\ell t_h 2b\tau_{\text{had}}$-3jOS	2	≥ 3	1	1	$t_\ell\tau_{\text{had}}$ OS

FCNC $tqH(\tau\tau)$ (arXiv:2208.11415)

Signal Region	$t \to cH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to cH$ Significance	$t \to cH$ $\mathcal{B}$ [10^{-3}]	$t \to uH$ 95% CL upper limit [10^{-3}] Observed (Expected)	$t \to uH$ Significance	$t \to uH$ $\mathcal{B}$ [10^{-3}]
$t_h\tau_{\text{had}}\tau_{\text{had}}$-2j	$1.80\,(2.72^{+1.18}_{-0.76})$	−0.96 (0.78)	$-1.03^{+1.03}_{-1.03}$	$1.07\,(1.60^{+0.71}_{-0.45})$	−0.90 (1.31)	$-0.55^{+0.58}_{-0.58}$
$t_h\tau_{\text{had}}\tau_{\text{had}}$-3j	$1.14\,(1.02^{+0.45}_{-0.29})$	0.34 (1.87)	$0.16^{+0.47}_{-0.47}$	$0.97\,(0.86^{+0.38}_{-0.24})$	0.36 (2.25)	$0.14^{+0.40}_{-0.40}$
Hadronic combination	$1.00\,(0.95^{+0.42}_{-0.27})$	0.26 (1.99)	$0.11^{+0.43}_{-0.43}$	$0.76\,(0.76^{+0.33}_{-0.21})$	0.12 (2.52)	$0.04^{+0.34}_{-0.34}$
$t_\ell\tau_{\text{had}}$-2j	$4.77\,(4.23^{+1.72}_{-1.18})$	0.41 (0.47)	$0.85^{+2.06}_{-2.06}$	$3.84\,(3.48^{+1.42}_{-0.97})$	0.36 (0.58)	$0.61^{+1.68}_{-1.68}$
$t_\ell\tau_{\text{had}}$-1j	$3.80\,(3.56^{+1.51}_{-0.99})$	0.22 (0.58)	$0.36^{+1.70}_{-1.70}$	$2.98\,(2.78^{+1.17}_{-0.78})$	0.22 (0.73)	$0.29^{+1.33}_{-1.33}$
$t_h\tau_{\text{lep}}\tau_{\text{had}}$-2j	$4.71\,(5.71^{+2.68}_{-1.60})$	−0.52 (0.38)	$-1.36^{+2.56}_{-2.56}$	$2.50\,(2.97^{+1.25}_{-0.83})$	−0.47 (0.70)	$-0.66^{+1.38}_{-1.38}$
$t_h\tau_{\text{lep}}\tau_{\text{had}}$-3j	$2.71\,(2.71^{+1.25}_{-0.76})$	−0.03 (0.77)	$-0.03^{+1.26}_{-1.26}$	$2.02\,(2.03^{+0.86}_{-0.57})$	−0.05 (0.99)	$-0.03^{+0.98}_{-0.98}$
$t_\ell\tau_{\text{had}}\tau_{\text{had}}$	$1.35\,(0.61^{+0.27}_{-0.17})$	2.64 (3.31)	$0.74^{+0.33}_{-0.33}$	$0.97\,(0.44^{+0.19}_{-0.12})$	2.64 (4.38)	$0.53^{+0.24}_{-0.24}$
Leptonic combination	$1.25\,(0.58^{+0.25}_{-0.16})$	2.61 (3.46)	$0.69^{+0.31}_{-0.31}$	$0.88\,(0.41^{+0.18}_{-0.11})$	2.60 (4.62)	$0.49^{+0.22}_{-0.22}$
Combination	$0.94\,(0.48^{+0.20}_{-0.14})$	2.34 (4.02)	$0.51^{+0.24}_{-0.24}$	$0.69\,(0.35^{+0.15}_{-0.10})$	2.31 (5.18)	$0.37^{+0.18}_{-0.18}$

CLFV in top quark interactions (ATLAS-CONF-2023-001)

ATLAS EXPERIMENT

Preselection:	
Number of leptons	$N_\ell = 3,\ p_\mathrm{T} > 10$ GeV, $\lvert\eta\rvert < 2.5$
Leading muon / electron p_T	$p_\mathrm{T} > 27$ GeV
Trigger matching	≥ 1 trigger-matched muon / electron
Sum of lepton charges	$\sum q_i = \pm 1$

	SR1	**SR2**	**CRτ**	**CR$tt\mu$**
Lepton flavour	$2\mu 1\tau_\text{had-vis}$			$2\mu 1e$ ($\ell_3 = \mu$)
N_jets	≥ 2	1	≥ 2	≥ 2
$N_{b-\text{tags}}$	1	1	1	≤ 2
Muon p_T cut	> 15 GeV	> 15 GeV	> 15 GeV	> 10 GeV
Lowest p_T muon selection	*Tight*	*Tight*	*Tight*	*Loose*
Muon charges	SS	SS	OS	-
$\lvert m_{\mu\mu}^{OS} - M_Z \rvert$	-	-	<10 GeV	>10 GeV

CLFV in top quark interactions (ATLAS-CONF-2023-001)

Operator	Lorentz Structure	
$O_{lq}^{1(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$O_{lq}^{3(ijkl)}$	$(\bar{l}_i\gamma^\mu\sigma^I l_j)(\bar{q}_k\gamma_\mu\sigma^I q_l)$	Vector
$O_{eq}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$O_{lu}^{(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$O_{eu}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$^\ddagger O_{lequ}^{1(ijkl)}$	$(\bar{l}_i e_j)\varepsilon(\bar{q}_k u_l)$	Scalar
$^\ddagger O_{lequ}^{3(ijkl)}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\varepsilon(\bar{q}_k\sigma_{\mu\nu} u_l)$	Tensor

$$\Gamma(t \to \ell_i^+\ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{lq}^{-(ijk3)}|^2 + 4|c_{eq}^{(ijk3)}|^2 + 4|c_{lu}^{(ijk3)}|^2 + 4|c_{eu}^{(ijk3)}|^2$$
$$+|c_{lequ}^{1(jik3)}|^2 + |c_{lequ}^{1(ij3k)}|^2 + 48|c_{lequ}^{3(jik3)}|^2 + 48|c_{lequ}^{3(ij3k)}|^2\Big\}$$