Seeing a single top quark: Search for $tq\gamma$ production and The combination of ATLAS searches for FCNC in $t \to Hq$ decays

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ATLAS EXPERIMENT

Outline

The Standard Model of Particle Physics

The Large Hadron Collider and the ATLAS Detector

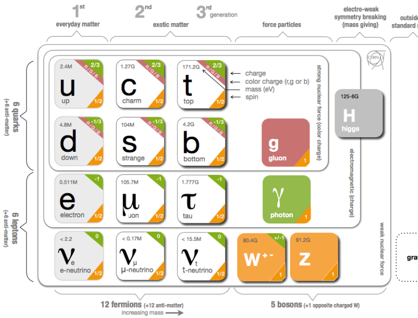
Seeing a single top quark: Search for $pp \to tq\gamma$ production

The combination of ATLAS searches for FCNC in $t \to Hq$ decays

THE STANDARD MODEL OF PARTICLE PHYSICS

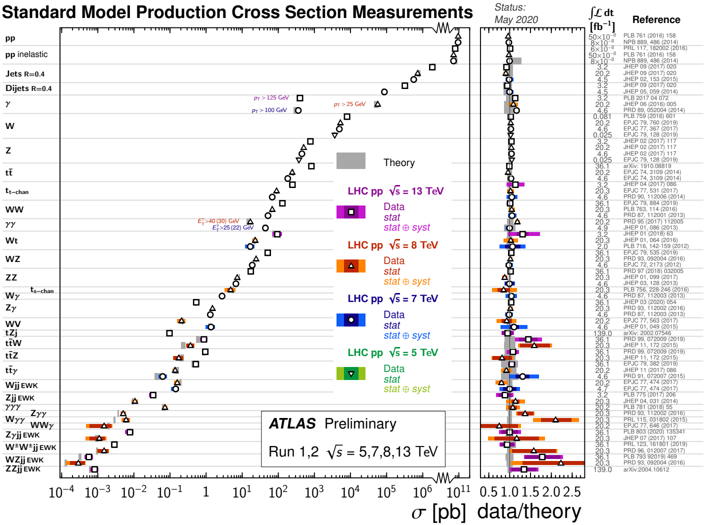
The Standard Model (SM) is a quantum field theory that describes the fundamental constituents of the universe and their interactions

- Interactions are defined by the $SU(3) \times SU(2) \times U(1)$ local gauge symmetry
- Strong interactions are mediated by gluons
- Electromagnetic and Weak interactions are mediated by γ, $W^{\pm}$ and Z bosons
- Gauge bosons and fermions acquire mass through Higgs mechanism by coupling with the Higgs field



SUCCESSFUL PREDICTIONS OF THE SM

The agreement between the observed values and their theoretical expectations, spanning over 15 orders of magnitude at 3 different energy scales, shows the remarkable success of the SM.



Open questions in the Particle Physics

Shortcomings of the SM

- Matter - antimatter asymmetry
- What is Dark Matter?
- What is Dark Energy?
- Massive neutrinos
- Gravitational interaction?

Clearly, there must be some source of physics beyond the Standard Model (BSM). Two main strategies for searching new physics include:

- Look for deviations with precise measurements of SM predictions: Search for $pp \rightarrow tq\gamma$ process
- Direct search for new particles/interactions predicted in BSM theories: Search for flavour changing neutral currents in $t \rightarrow Hq$ decays

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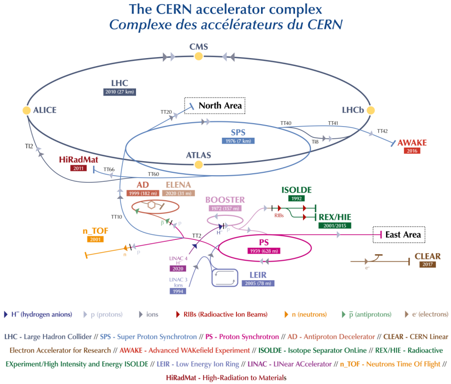
The Large Hadron Collider

The Large Hadron Collider (LHC) is a circular particle accelerator designed to collide proton beams at $\sqrt{s} = 14$ TeV

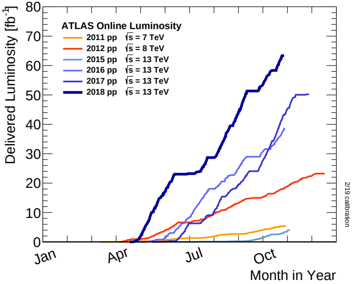


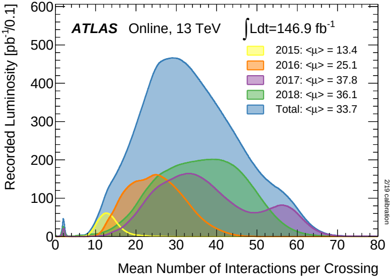
- 27 km in circumference and located 100 m beneath the surface
- Two general purpose detectors: ATLAS and CMS
- Two specialized detectors: LHC*b* and ALICE
- Super conducting coils are used to provide a magnetic field of up to 8.3 T

Run-2 performance

In Run-2 data taking period, LHC delivered *pp* collisions at $\sqrt{s}$=13 TeV (2015-2018).

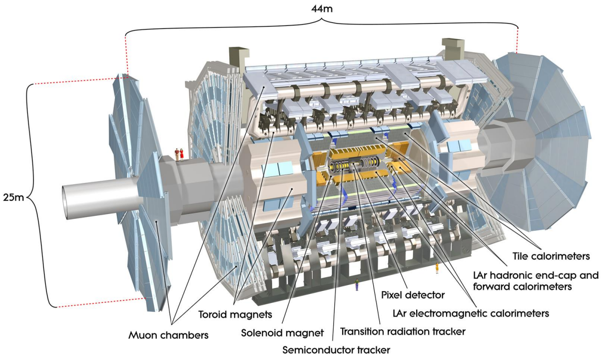
- 2544 bunches per beam
- 1.15×10^{11} protons/bunch
- Bunch crossing every 25 ns $\Rightarrow$ collision rate = 40 MHz
- Total event rate $\sim$ 1.4×10^9 Hz; Higgs production $<$ 1 Hz





THE ATLAS DETECTOR

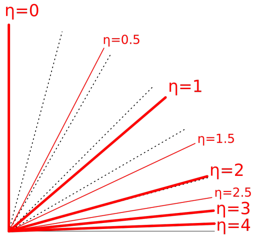
ATLAS is a 7000 ton general purpose detector. It is hermetic and provides near 4π coverage in solid-angle

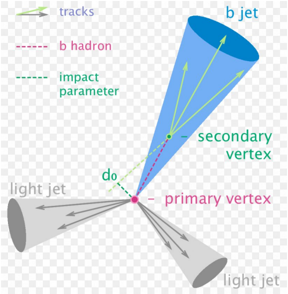


Three major groups of subdetectors: Inner Detector, Calorimeters and Muon Spectrometer

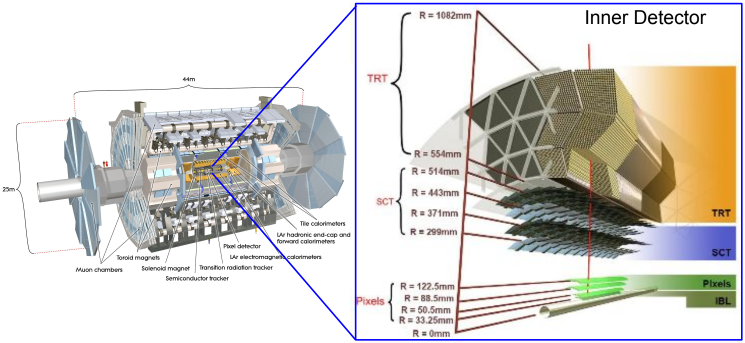
GENERAL TERMS

- Pseudorapidity = η = - ln $tan(\theta/2)$
- Jet = A narrow cone of hadrons and other particles produced in the hadronization of a quark or gluon
- b-jets = jets coming from b-quarks
- Forward object = Any object with $|\eta| > 2.5$
- Central object = Any object with $|\eta| < 2.5$
- Missing Energy = Imbalance in the momentum in transverse direction





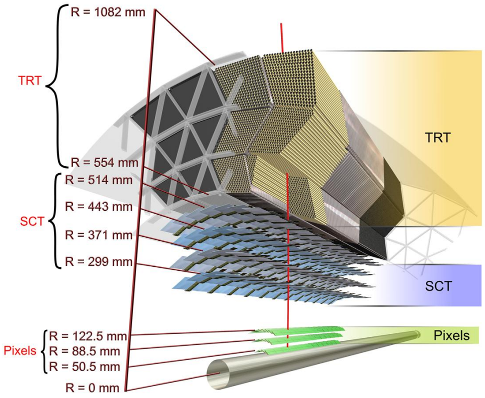
INNER DETECTOR



[ATLAS Collaboration.Eur. Phys. J. C 77 (2017) 332] 1

Inner Detector

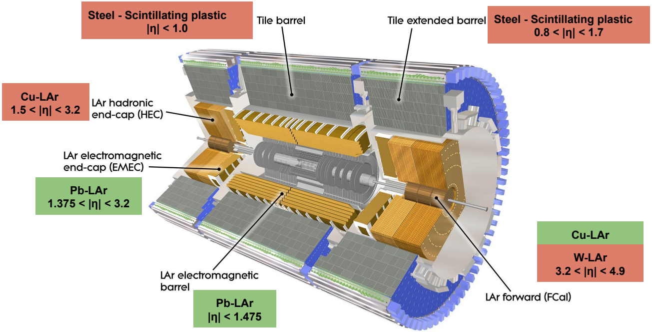
Inner Detector (ID) consist of three subsystems: Pixel detector, Semiconductor tracker (SCT), Transition Radiation Tracker (TRT)



- Provides coverage for $|\eta| < 2.5$
- Immersed in 2 T magnetic field generated by a solenoid
- Measures the momentum of charged particles from the radius of curvature
- Used for Electron Identification and Vertex Reconstruction

CALORIMETERS

- Two types of sampling calorimeters: Electromagnetic calorimeter & Hadronic Calorimeter

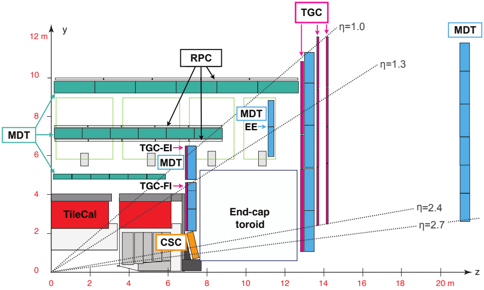


- Alternating layers of absorbers to produce showers and active material to measure the energy

Muon Spectrometer (MS)

MS is composed of four subsystems: Monitored Drift Tubes (MDT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC), Thin-Gap Chambers (TGC)

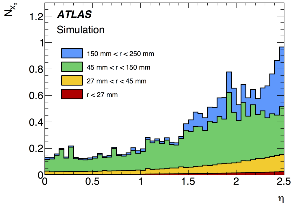
- Provides coverage for $|\eta| < 2.7$
- Large torodial magnets are used for generating 4 T magnetic field
- Used for precision measurements of muons



RECONSTRUCTION OF PHOTONS

Reconstruction of photon candidates:

- Clusters are reconstructed in the ECAL
- Tracks are reconstructed in the ID



Conversion Type	# tracks matched to cluster
Unconverted	Zero
SingleSi	One track only, with Si hits
SingleTRT	One track only, no Si hits (TRT only)
DoubleSi	Two tracks, both with Si hits
DoubleTRT	Two tracks, none with Si hits (TRT only)
DoubleSiTRT	Two tracks, only one with Si hits

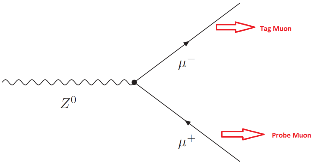
Promt Photons: Photons from the hard scattering process
Fake photons: Radiation from hadrons, mis-identified electrons
Discriminating prompt photons from fake photons:

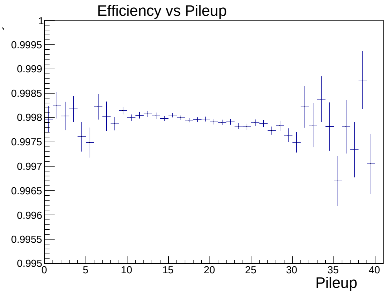
- `Identification`: rectangular cuts on the variables related to the shower shape in the EM calorimeter
- `Isolation`: Amount of energy around the photon must be below a threshold

Inner Detector Efficiency (ϵ_{ID}) Monitoring

- Goal: Investigated the pileup dependence of ID efficiency for measuring luminosity with Z counting
- Used `Tag and Probe` method
- Tag: Muon reconstructed by both the ID and MS
- Probe: MS track $\ni$ M(Tag Muon + MS track) $\in$ (86,96) GeV

$$\text{ID efficiency} = \frac{\text{\# probes with a matching track in the ID}}{\text{Total number of probes}}$$



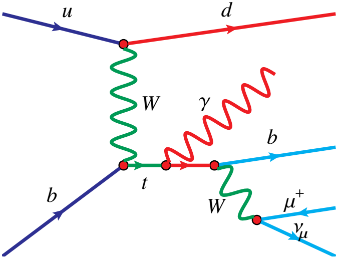


Outline

Associated production of a single top quark and a photon ($tq\gamma$)

$pp \to tq\gamma$ is one of the rare processes predicted by the SM (Happens once in 50 billion pp collisions at the LHC.)

- Observation and precise measurement of $\sigma(tq\gamma)$ provides an important test for the SM
- $\sigma(tq\gamma)$ is sensitive to
  - top quark's interaction with photon and $W^{\pm}$ bosons
  - electric and magnetic dipole moments of the top quark



- This process not been observed at 5σ by any experiment yet
- Final state at leading order has exactly 1ℓ, 1γ, 1 forward jet, 1 b-jet, a neutrino which is manifest as a transverse momentum imbalance (MET)

Interaction between the top quark and photon

The most-general $t\gamma$-vertex function:

$$\Gamma_\mu(q^2) = -ie\{\gamma_\mu[F_{1V}(q^2) + F_{1A}(q^2)\gamma_5] + \frac{\sigma_{\mu\nu}}{2m_t}q^\nu[iF_{2V}(q^2) + F_{2A}(q^2)\gamma_5]\},$$

In the limit $q^2 \to 0$,

$$F_{1V}(0) = Q_t; \quad F_{2V}(0) = a_t Q_t; \quad F_{2A} = \frac{2m_t d_t}{e},$$

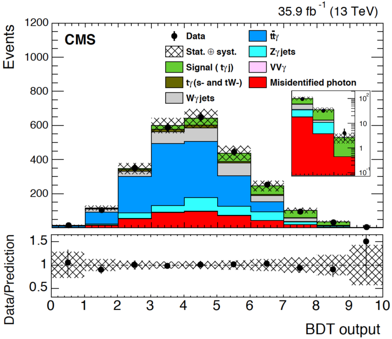
Where, a_t and d_t are the anomalous magnetic and electric dipole moments of the top quark.
In the SM,

- At tree level, all form factors except F_{1V} are equal to zero.
- When higher-order loop corrections are considered, $a_t \sim 0.02$ and $d_t < 10^{-30}\, e$ cm.

Any observation of deviations would indicate the physics beyond the SM.

Results from the CMS Collaboration

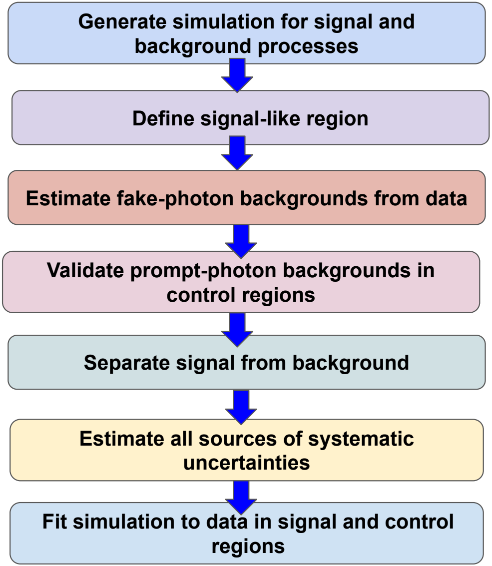
- The CMS collaboration presented evidence for this process with 36 fb^{-1} of data (2015-16) Phys. Rev. Lett. 121, 221802 (2018)
- Only considered single μ events
- Observed (expected) significance 4.4σ (3.0σ)
- Measured $\sigma(pp \to t\gamma j)\mathcal{B}(t \to \mu\nu b)$ = 115 $\pm$17(stat)$\pm$30(syst) fb, in the phase space $p_{T,\gamma} > 27$ GeV, $|\eta_\gamma| < 1.44$ and $\Delta R(X, \gamma) > 0.5$ for $X \in (\mu, j, b)$



ATLAS SEARCH FOR $tq\gamma$ PRODUCTION

- Peter and I started the first-ever ATLAS search for this process in collaboration with two other people from Technische Universität Dortmund (Björn Wendland and Johannes Erdmann)
- Uses 139 fb^{-1} of data collected during the Run-2 data taking period
- Goal of the current analysis is the observation and the measurement of inclusive cross-section of $tq\gamma$ production
- This analysis is still in progress and very close to unblinding. Today, I will present only expected results
- After establishing this process, a subsequent analysis will be performed featuring differential cross-section measurements and EFT interpretation

Analysis Strategy



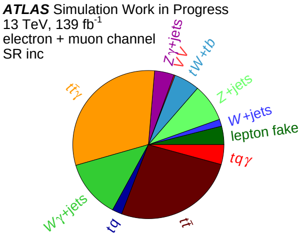
Composition of pre-selection region

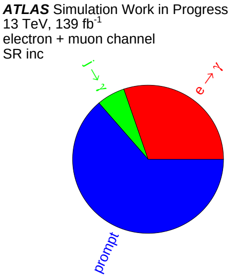
Selection:

- Exactly 1 lepton
- At least 1 photon
- Exactly 1 b-jet
- Missing $p_T > 30$ GeV
- $M(e\gamma) \notin (70, 110)$ GeV

Major backgrounds:

- Prompt photon backgrounds: $tt\gamma$, $W\gamma$, $Z\gamma$
- Events with fake photons ($t\bar{t}$, Z+jets etc.)





What are $e \to \gamma$ fakes?

- Electrons and photons are reconstructed using very similar algorithms $\Rightarrow$ electrons may sometimes mis-reconstructed as photons
- Happens mainly due to tracking inefficiency or failure to find a match between the ID track and the EM cluster
- Simulation does not model these fakes well.
- Rate of an electron faking as photon is $\sim 9\%$ (from data)

Estimation of $e \to \gamma$ fake rate scale factor

$$e \to \gamma \text{ fake rate} = F_{e\to\gamma} = \frac{N(Z \to e\gamma)}{2 \times N(Z \to e^+e^-)} \tag{1}$$

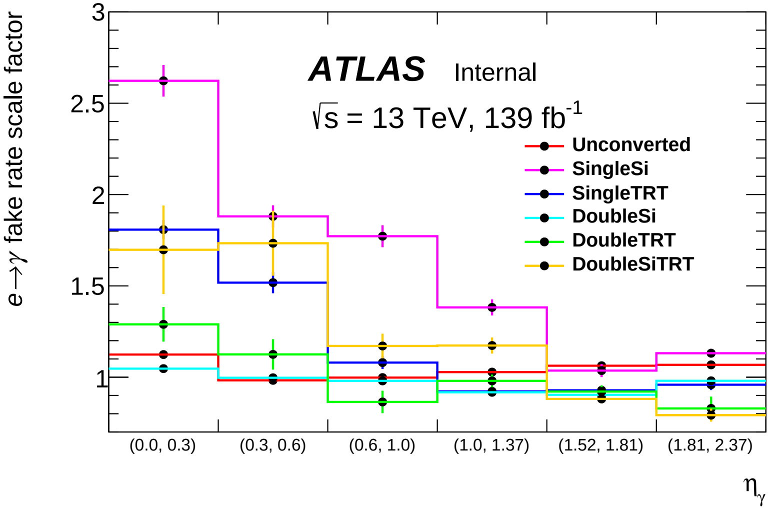
$$\text{Scale factor (SF)} = \frac{F^{\text{Data}}_{e\to\gamma}}{F^{\text{MC}}_{e\to\gamma}} \tag{2}$$

Scale factors are derived in bins of following variables:

- η_γ: Amount of the detector material traversed by the photon depends on η_γ
- Conversion type: Fake rates depend on different classes of photon identification

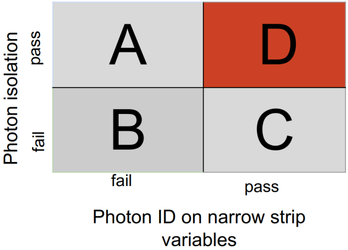
SFs in bins of photon η and CT

- Scale factor has been calculated in bins of η_γ and photon conversion type



Estimation of $j \to \gamma$ fakes

- $j \to \gamma$ fakes arise mainly from $\pi^0 \to \gamma\gamma$ decays and radiation from hadronic decays
- ABCD method is used to derive scale factors to correct the mis-modelling in simulation
- Exploits weak correlation between the photon isolation and identification criteria



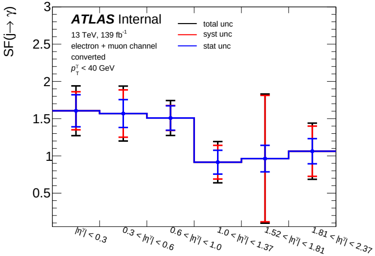
$$\frac{N^{\text{h-fake}}(A)}{N^{\text{h-fake}}(B)} \approx \frac{N^{\text{h-fake}}(D)}{N^{\text{h-fake}}(C)}$$

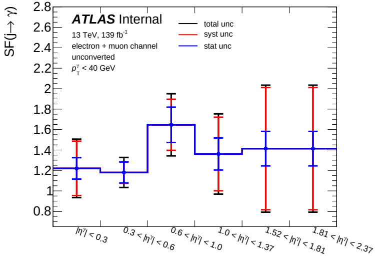
$$N^{\text{h-fake}}_{\text{data}}(i) = N^{\text{total}}_{\text{data}}(i) - N^{\text{prompt}}_{\text{MC}}(i) - SF(e \to \gamma) \times N^{\text{h-fake}}_{\text{MC}}(i)$$

$$\boxed{\text{SF}(j \to \gamma) = \frac{N^{\text{h-fake}}_{\text{data}}(D)}{N^{\text{h-fake}}_{\text{MC}}(D)}}$$

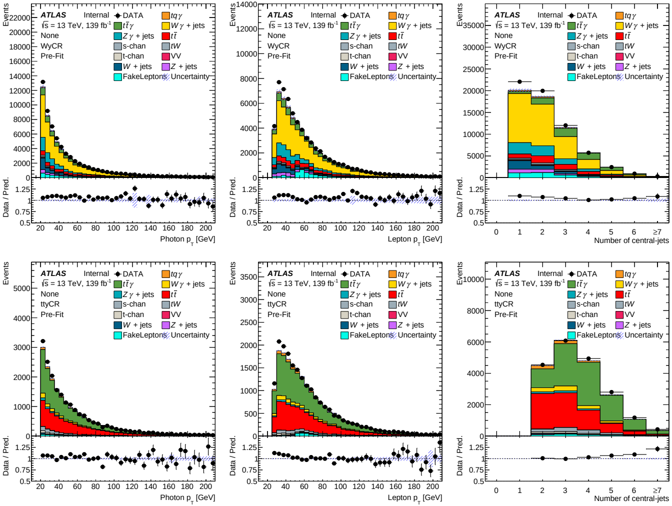
$j \to \gamma$ FAKE RATE SCALE FACTORS

$j \to \gamma$ fake rate scale factors are derived in bins of p_T^γ, η^γ for converted and unconverted photons.





VALIDATION OF MAJOR BACKGROUNDS



Separation of Signal & Background

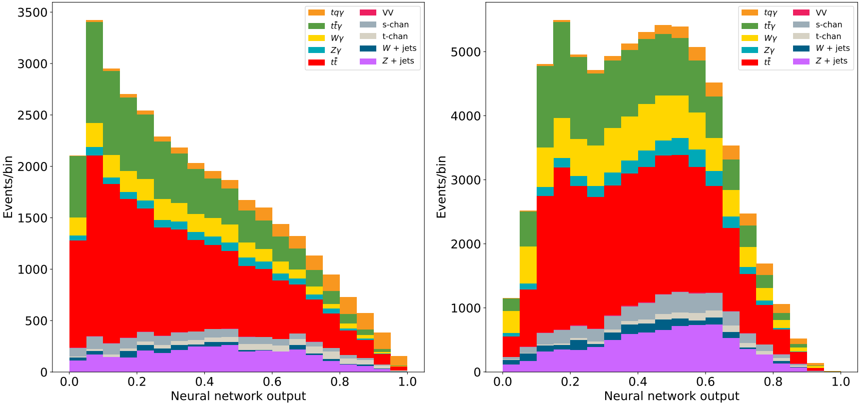
Pre-selection region is divided into two categories based number of forward jets: 0 fj and ≥ 1 fj.
A neural network is used in each category to separate signal & background.
Input feature selection:

- A total of 135 (94) features are considered in $\geq$1 fj (0 fj) category.
- Through optimization, 19 (15) variables are selected for $\geq$1 fj (0 fj) category.

Variable	0-fj	$\geq$ 1-fj
b-jet η	X	
Number of jets	X	X
$\Delta\eta(b,\ \gamma)$	X	X
Transverse mass	X	X
Top quark mass	X	X
p_T of $(b+\gamma)$	X	
Invariant mass of $(b+\ell)$	X	X
b-jet pseudo-continuous tag weight bin	X	X
Invariant mass of $(b+\gamma)$	X	X
b-jet p_T	X	
p_T of (top-quark + γ)	X	
Lepton ID	X	X
$\Delta\eta(b,\ \ell)$	X	X
Missing transverse momentum	X	
$\Delta R(b,\ \ell)$	X	
Invariant mass of (b+forward-jet)		X
Invariant mass of $(\ell+\gamma)$		X
$cos(\theta)$ (γ, leading forward-jet)		X
HT		X
p_T of leading forward-jet		X
$\Delta\eta$(leading forward-jet, γ)		X
Energy of (γ, leading forward-jet)		X
Is leading non b-tagged jet η >2.5 ?		X
Number of forward-jets		X
Energy of W-boson		X
Total variables	15	19

NN OUTPUT

NN output for ≥ 1-fj category (left) and 0-fj category (right)



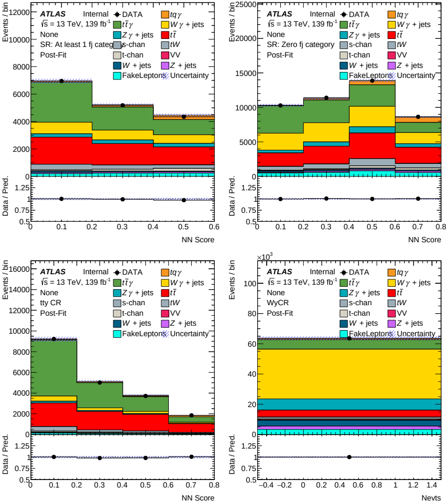
Systematic uncertainties

Systematic uncertainty	Type	Components
Luminosity	N	1
Pile-up reweighting	SN	1
Physics Objects		
Photon	SN	2
Electron	SN	4
EGamma	SN	2
Muon	SN	15
Jet energy scale (JES)	SN	29
Jet energy resolution (JER)	SN	8
Jet vertex tagger (JVT)	SN	1
b-tagging efficiency	SN	45
c-tagging efficiency	SN	20
light-tagging efficiency	SN	20
$E_{\mathrm{T}}^{\mathrm{miss}}$	SN	3
Total (Experimental)		152
Data-driven background estimates		
$e \to \gamma$ fakes	N	1
$h \to \gamma$ fakes	N	1
Non-prompt leptons	N	1
Total (Data-driven reducible background)		3

$tq\gamma$ modelling		
μ_R	SN	1
μ_F	SN	1
Parton shower and hadronisation model	SN	1
PDF uncertainty	SN	1
$t\bar{t}\gamma$ modelling		
μ_R	SN	1
μ_F	SN	1
Parton shower and hadronisation model	SN	1
PDF uncertainty	SN	1
PYTHIA8 var3c	SN	1
$W\gamma$ modelling		
μ_R	SN	1
μ_F	SN	1
PDF uncertainty	SN	1
$Z\gamma$ modelling		
μ_R	SN	1
μ_F	SN	1
PDF uncertainty	SN	1
$t\bar{t}$ modelling		
μ_R	SN	1
μ_F	SN	1
PDF uncertainty	SN	1
PYTHIA8 var3c	SN	1
Other background modelling		
Single-top Cross section	N	1
Z+jets Cross section	N	1
W+jets Cross section	N	1
Diboson Cross section	N	1
Total (Signal and background modelling)		23
Total (Exp.+Theory+Data-driven)		178

Fit to data in background enriched regions

- Bins with S/B < 10% are fitted to data
- Signal strength parameter, $\mu_{tq\gamma} = \frac{\sigma_{tq\gamma}}{\sigma^{\text{SM}}_{tq\gamma}}$, is fixed at 1.0
- $\mu_{t\bar{t}\gamma}$ and $\mu_{W\gamma}$ are freely floated



Fit Results:

$$\mu_{t\bar{t}\gamma} = 0.98\ ^{+0.07}_{-0.07}$$

$$\mu_{W\gamma} = 1.23\ ^{+0.13}_{-0.13}$$

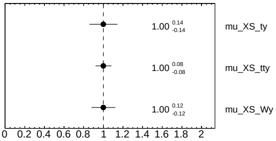
Expected results

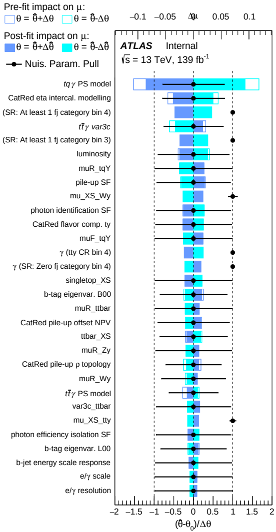
Signal and background regions are fitted to Asimov dataset (MC expectation)

- NN score is used as discriminant in 0 fj, $\geq$ 1-fj, $t\bar{t}\gamma$ CR regions.
- In $W\gamma$ CR, a single bin fit is performed.
- $\mu_{tq\gamma}$, $\mu_{t\bar{t}\gamma}$ and $\mu_{W\gamma}$ are freely floated.

Expected $\boxed{\mu_{tq\gamma} = 1.0\ ^{+0.14}_{-0.14}} = 1.0\ ^{+0.05}_{-0.05}$ (stat.) $^{+0.13}_{-0.13}$ (syst.)

Expected significance w.r.t no-signal hypothesis: $6.5\ \sigma$ (stat. + syst.)





SUMMARY

- A brief summary of the first ATLAS search for $pp \to tq\gamma$ process is presented.
- This analysis is currently entering the ATLAS review process.
- A few optimizations related to NN hyperparameters and the signal region binning are currently in progress.
- Aim is to publish an observation letter with this analysis
- A subsequent analysis will feature differential cross-section measurements to probe anomalous top-photon form factors

Outline

The Standard Model of Particle Physics

The Large Hadron Collider and the ATLAS Detector

Seeing a single top quark: Search for $pp \rightarrow tq\gamma$ production

The combination of ATLAS searches for FCNC in $t \rightarrow Hq$ decays

Flavour Changing Neutral Currents: Introduction

- Flavour changing neutral current decays like $t \rightarrow qH (q = u, c)$ are forbidden at tree level and highly suppressed at higher orders in the SM
- $\mathscr{B}(t \rightarrow qH)_{SM} \sim 3\times 10^{-15} \Rightarrow$ Any observation will be a clear sign of physics beyond the SM
- Many BSM models feature larger tHq couplings compared to the SM

$$\mathcal{L}_{\mathrm{FCNC}} = -\lambda_{t_\mathrm{L} q_\mathrm{R}} \bar{t}_\mathrm{L} q_\mathrm{R} H - \lambda_{q_\mathrm{L} t_\mathrm{R}} \bar{q}_\mathrm{L} t_\mathrm{R} H + \mathrm{h.c.}$$

  - e.g. models where SM quarks mix with extra singlets, non-flavor-violating 2HDM
  - Largest branching ratio $\mathscr{B} \sim 1.5\times 10^{-3}$ appears in the ansatz of Cheng and Sher in which the tree level coupling scales with top quark masses as $\lambda_{tqH} = \sqrt{2 m_q m_t}/v$

ATLAS SEARCHES FOR tqH FCNC

- In Run-2, ATLAS collaboration has performed 4 independent searches with 36.1 fb^{-1} of data collected in 2015-16
  - All analyses look for FCNC decays in $t\bar{t}$ events exploiting the large x-section of this process
  - Probed decay mode: $t\bar{t} \rightarrow Wb + qH$
  - Each analysis targets different decay mode of the Higgs boson
  - The Higgs boson produced in the FCNC decay is assumed to decay like the SM Higgs boson

tqH analysis	Results
$H \rightarrow \gamma\gamma$	JHEP 10 (2017) 129
$H \rightarrow WW^*, \tau\tau, ZZ^*$ $(2\ell SS, 3\ell)$	Phys.Rev.D98,032002
$H \rightarrow b\bar{b}$	JHEP05(2019)123
$H \rightarrow \tau\tau$ $(\tau_{\text{had}}\tau_{\text{lep}},\ \tau_{\text{had}}\tau_{\text{had}})$	
Combination	

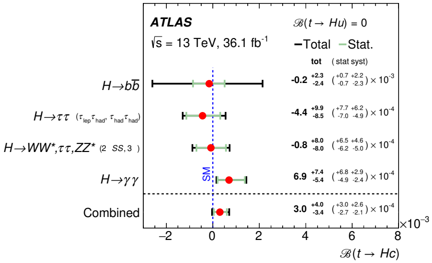
Combination of ATLAS tqH searches

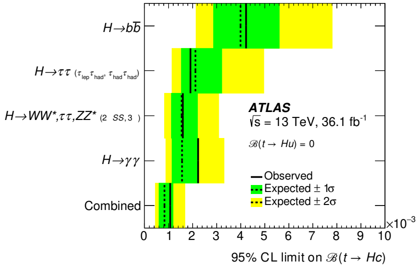
- A binned likelihood function $\mathcal{L}(\mathscr{B}_{comb}, \vec{\theta})$ is constructed by combining the distributions of discriminants from each individual analysis
- Correlations of systematic uncertainties across individual analyses found to have no significant impact. This is because,
  - All searches expect $tqH(b\bar{b})$ are dominated by statistics
  - Dominant systematic uncertainties in each search are different
- Systematic uncertainties related to luminosity, $t\bar{t}$ x-section, signal modelling and jet-related uncertainties are correlated

$t \to cH$ RESULTS

- Assumed $\mathscr{B}(t \to uH) = 0$
- Best fit $\mathscr{B}(t \to cH) = 3.0^{+4.0}_{-3.4} \times 10^{-4}$

95% CL Limits	Observed Limit	Expected Limit
$\mathscr{B}(t \to cH)$	1.1×10^{-3}	8.3×10^{-4}

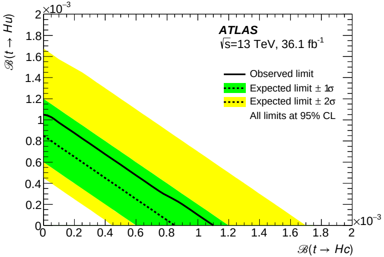


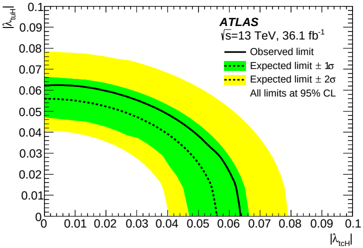


Simultaneous search for $t \to cH$ and $t \to uH$ signals

- 95% CL upper limits obtained while simultaneously searching for $t \to cH$ and $t \to uH$ decays are shown here
- Translating upper limits on $\mathscr{B}$ into upper limits on the Yukawa coupling λ_{tqH}

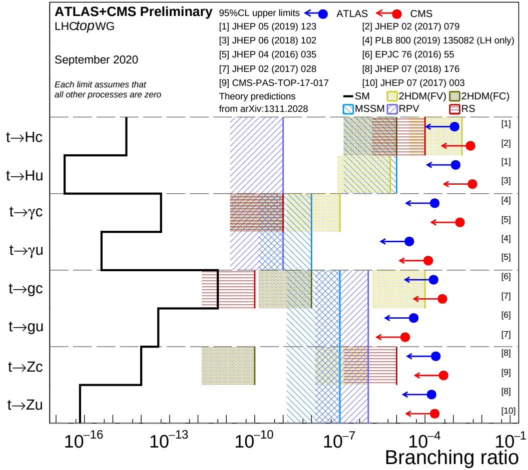
$$\mathscr{B} = (0.27 \pm 0.010) \times \lambda_{tqH}^2$$





FCNC Summary

- We obtained the most restrictive direct bounds on the tqH interactions so far



Thank You

FCNC Summary

- 95% CL upper limits on $\mathscr{B}(t \to qH)$ obtained from combination of ATLAS tqH searches:

95% CL Limits	Observed Limit	Expected Limit
$\mathscr{B}(t \to cH)$	1.1×10^{-3}	8.3×10^{-4}
$\mathscr{B}(t \to uH)$	1.2×10^{-3}	8.3×10^{-4}

- Corresponding limits on the $|\lambda_{tqH}|$ are:

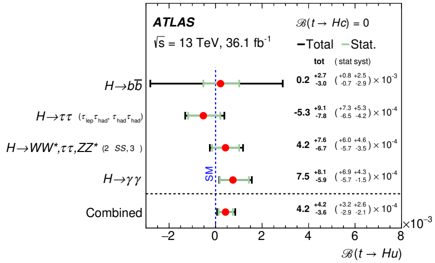
95% CL Limits	Observed Limit	Expected Limit
$|\lambda_{tcH}|$	0.064	0.055
$|\lambda_{tuH}|$	0.066	0.055

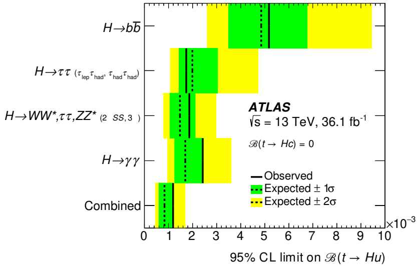
- These are the most restrictive direct bounds on tqH interactions so far

$t \to uH$ RESULTS

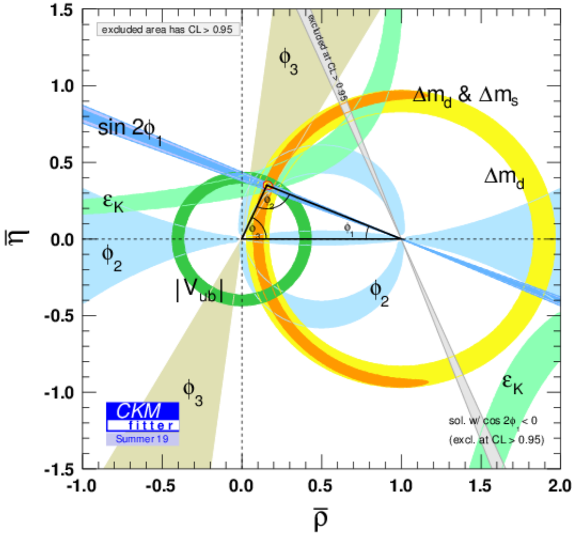
- Assumed $\mathscr{B}(t \to cH) = 0$
- Best fit $\mathscr{B}(t \to uH) = 4.2^{+4.1}_{-3.6} \times 10^{-4}$

95% CL Limits	Observed Limit	Expected Limit
$\mathscr{B}(t \to uH)$	1.2×10^{-3}	8.3×10^{-4}





CKM MEASUREMENTS



$tq\gamma$ MC PRODUCTION

- $tq\gamma$ MC sample has been produced with MADGRAPH5+PYTHIA8 at NLO
- 4-flavour scheme is used (i.e., parton distribution functions for b-quarks is set to zero)
- $\mu_R = \mu_F = H_T/2$

$$H_T = \sum_i \sqrt{m_i^2 + p_{T,i}^2}$$

- Generator level selection cuts:
  - $\Delta R(\gamma, X) > 0.2 \; \forall \; X \in (\ell, b, j)$
  - Photon $p_T > 10$ GeV
  - $|\eta_{(\ell,\ \gamma)}| < 5.0$
- Cross-section obtained from the generator = 1.14 pb

CONTROL AND VALIDATION REGIONS $e \to \gamma$ FAKES

Two control regions and one validation region enriched with Z+jets events are used for estimating $e \to \gamma$ scale factors

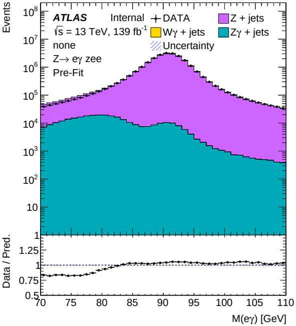
Object	$Z \to e^+e^-$ CR	$Z \to e\gamma$ CR	$Z \to e\gamma$ VR
Photons	=0 w/ $p_T > 15$ GeV	=1 w/ $p_T > 15$ GeV	=1 w/ $p_T > 15$ GeV
Electrons	=2 (OS) w/ $p_T >$27 GeV	=1 w/ $p_T > 27$ GeV	=1 w/ $p_T > 27$ GeV
b-jets	-	=0 w/ $p_T > 25$ GeV	$\geq$1 w/ $p_T > 25$ GeV
Missing p_T	< 30 GeV	< 30 GeV	< 30 GeV
$M(e^+e^-)$	[70, 110] GeV	-	-
$M(e\gamma)$	-	[70, 110] GeV	[70, 110] GeV
Purpose	Measure $\frac{N^{\text{Data}}(Z \to e^+e^-)}{N^{\text{MC}}(Z \to e^+e^-)}$	Measure $\frac{N^{\text{Data}}(Z \to e\gamma)}{N^{\text{MC}}(Z \to e\gamma)}$	Validate SFs

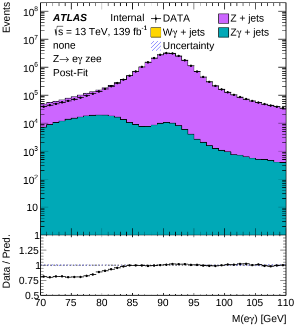
All regions are orthogonal to SR (inverted MET cut) and to each other

$N^{\text{DATA}}(Z \to e^+e^-)$ / $N^{\text{MC}}(Z \to e^+e^-)$ CALCULATION

- Fit MC templates of $M(e^+e^-)$ distribution, to data in $Z \to e^+e^-$ CR
- Normalization for the template of $Z \to e^+e^-$ process is determined from the fit
- Normalization for all other backgrounds are fixed to their MC expectations

Observed value of
$N^{\text{Data}}(Z \to e^+e^-)$ / $N^{\text{MC}}(Z \to e^+e^-)$ $= 1.03 \pm 0.00026$





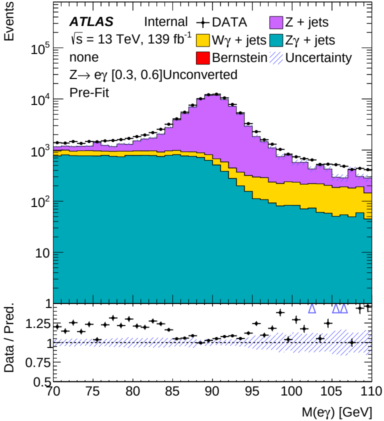
CALCULATION OF $N^{\text{DATA}}(Z \rightarrow e\gamma)$ / $N^{\text{MC}}(Z \rightarrow e\gamma)$

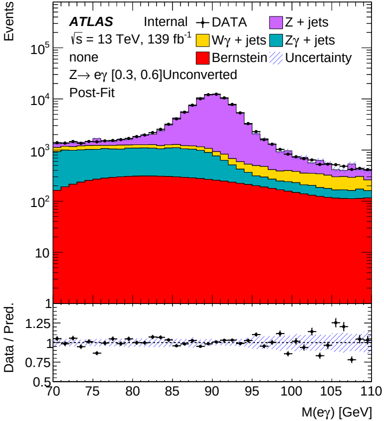
$N^{\text{Data}}(Z \rightarrow e\gamma)$ / $N^{\text{MC}}(Z \rightarrow e\gamma)$ is measured by fitting templates of $M(e\gamma)$ distribution to data in the $Z \rightarrow e\gamma$ CR.

- Template shape of $M(e\gamma)$ distribution for $Z \rightarrow e\gamma$ process is obtained from MC. Normalization is determined from the fit.
- For major bkgs, $W\gamma$ and $Z\gamma$, both normalization and shape are obtained from MC.
- Third order Bernstein polynomials are used as $M(e\gamma)$ templates for missing rare backgrounds like VV, W+jets and γ+jets, etc.

Calculation of $N^{\text{Data}}(Z \to e\gamma)$ / $N^{\text{MC}}(Z \to e\gamma)$

- M($e\gamma$) distribution for $Z \to e\gamma$ region is shown here before (left) and after(right) fitting to data
- Bin: Unconverted Photon and $\eta_\gamma \in (0.3, 0.6)$
- $N^{\text{Data}}(Z \to e\gamma)$ / $N^{\text{MC}}(Z \to e\gamma)$ = 1.02 $\pm$ 0.018 (stat.)





ESTIMATION OF $e \to \gamma$ FAKE RATE

- $e \to \gamma$ fake rate ($F_{e\to\gamma}$): Ratio of probability that an electron is mis-reconstructed as an photon to the probability that an electron is correctly reconstructed.
- $F_{e\to\gamma}$ can be estimated from Z+jets events that are reconstructed as e^+e^- and $e\gamma$ pairs,

$$F_{e\to\gamma} = \frac{N(Z \to e\gamma)}{2 \times N(Z \to e^+e^-)} \quad (3)$$

  (A factor of 2 is included in the denominator as either of the two electrons can be mis-reconstructed as photon.)
- $e \to \gamma$ fake rates are calculated both in MC ($F^{\mathrm{MC}}_{e\to\gamma}$) and data ($F^{\mathrm{Data}}_{e\to\gamma}$)

$(e \to \gamma$ FAKE RATE$)$ SCALE FACTOR

Scale factor to be applied to MC is given by

$$\text{Scale factor (SF)} = \frac{F_{e\to\gamma}^{\text{Data}}}{F_{e\to\gamma}^{\text{MC}}} \tag{4}$$

Simplifying,

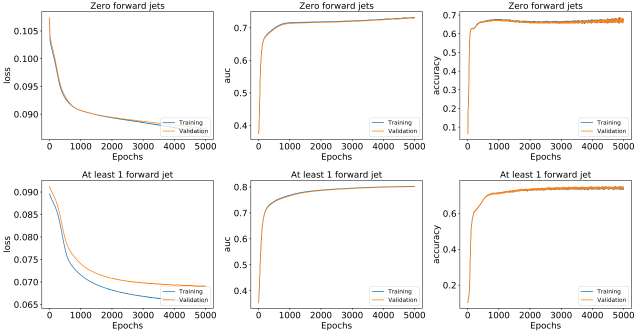
$$\text{SF} = \frac{N^{\text{Data}}(Z \to e\gamma)\ /\ N^{\text{MC}}(Z \to e\gamma)}{N^{\text{Data}}(Z \to e^+e^-)\ /\ N^{\text{MC}}(Z \to e^+e^-)} \tag{5}$$

NN SETUP

NN Architecture:

- 2 hidden layers with 24 and 15 nodes
- Activation = LeakyReLU
- Loss = Binary cross-entropy
- Metrics: Binary accuracy and AUC

Neural Network Summary

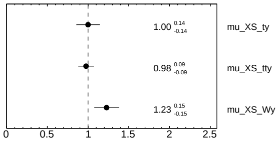


Asimov with bkg-fit parameters

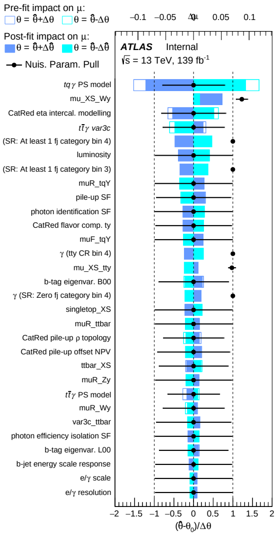
Fit setup:

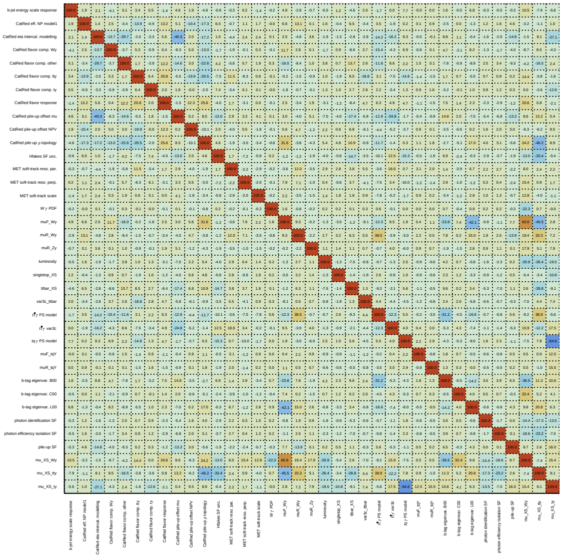
- 4 regions: 0 fj, $\geq$ 1-fj, $t\bar{t}\gamma$ CR, $W\gamma$ CR.
- NN score is used as discriminant in 0 fj, $\geq$ 1-fj, $t\bar{t}\gamma$ CR regions.
- In $W\gamma$ CR, a single bin fit is performed.
- $\mu_{tq\gamma}$, $\mu_{t\bar{t}\gamma}$ and $\mu_{W\gamma}$ are freely floated.
- Pruning threshold: 1% for shape & normalization uncertainties.
- **Asimov data is generated with NPs obtained from fit to data in background enriched regions**

Expected significance: 6.41 σ



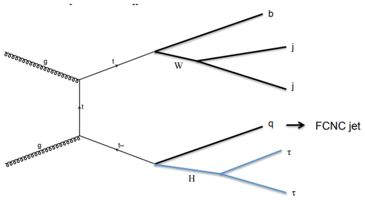
ASIMOV WITH BKG-FIT PARAMETERS - 3





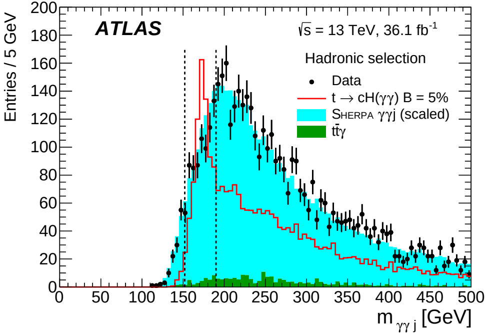
FCNC Signal Monte Carlo generation

- Signal events $pp \to t\bar{t}, t \to Hq$ are generated at NLO using MadGraph5_aMC@NLO
- MadSpin is used for top quark decay
- To make the search model independent, Higgs boson produced in the decay is assumed to decay like the SM Higgs boson
- Pythia8 is used for Higgs boson decay, parton showering, hadronization and underlying-event generation



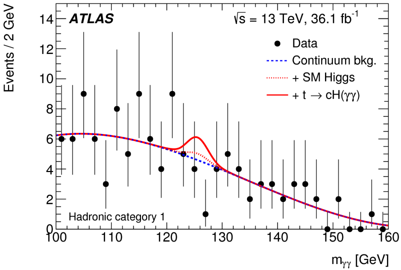
(1) $tqH,\ H \to \gamma\gamma$ ANALYSIS

- Small branching ratio (0.23%), but clean diphoton signature
- Major backgrounds: $\gamma\gamma j,\ t\bar{t}\gamma,\ W\gamma\gamma$ and $Z\gamma\gamma$
- Based on the decay mode of W boson, events are classified into two categories (hadronic/leptonic)



Signal region optimization

- Two top quarks in the $t\bar{t}$ event are reconstructed with corresponding masses (M_1, M_2) by forming three-body objects from photons, leptons, jets and MET
- By applying selection cuts on M_1 and M_2, signal is separated from the background
- An unbinned maximum likelihood fit is performed as a function of $m_{\gamma\gamma}$ to determine the best-fit value of $\mathscr{B}(t \to qH)$



$tqH(\gamma\gamma)$ RESULTS

Observed yields:

Selection	Hadronic		Leptonic	
Category	1	2	1	2
Signal $t \to cH$	2.4	3.7	0.82	0.23
SM Higgs boson resonant background	1.1	3.1	0.24	0.22
Other background	16	63	0.14	0.29
Total background	17	66	0.38	0.51
Data	14	69	2	1

- Leading systematic uncertainties: $t\bar{t}$ production x-section, $\mathscr{B}(H \to \gamma\gamma)$, integrated luminosity and photon energy scale & resolution

- $\mathscr{B}_{observed}(t \to cH) = 6.9^{+7.4}_{-5.4} \times 10^{-4}$
- $\mathscr{B}_{observed}(t \to uH) = 7.5^{+8.1}_{-5.9} \times 10^{-4}$

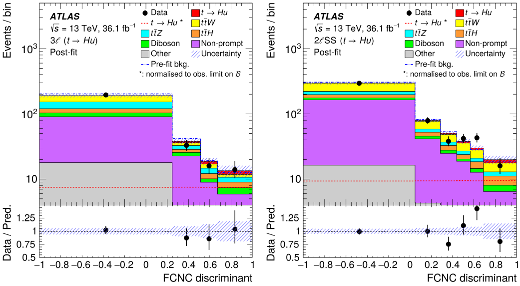
95% CL Limits	Observed Limit	Expected Limit
$\mathscr{B}(t \to cH)$	2.2×10^{-3}	1.6×10^{-3}
$\mathscr{B}(t \to uH)$	2.4×10^{-3}	1.7×10^{-3}

(2) tqH(ML) ANALYSIS

- This analysis targets multilepton signatures resulting from Higgs decay to $WW^*, \tau\tau, ZZ^*$
  - Final states considered: same-sign $2l$ and $3l$
  - Events with τ_{had} are vetoed to avoid overlap with $tqH(\tau\tau)$ analysis
- Major backgrounds: ttV and Fake leptons from $t\bar{t}$ decays
  - Two special lepton BDTs are trained to reject backgrounds
  - A BDT to remove charge mis-assigned leptons using track and calorimeter cluster information
  - Another, to remove non-prompt leptons using properties of low-p_T jets formed around lepton tracks and other information
  - Fake lepton backgrounds are estimated using *Matrix Method*

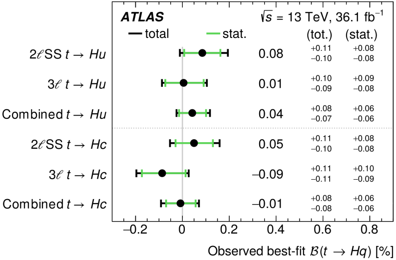
SIGNAL REGION OPTIMIZATION

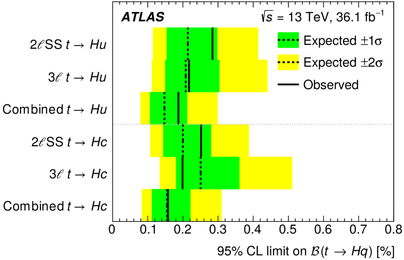
- Two different BDT discriminants are used in each channel for each signal
  - one for optimizing against $t\bar{t}$ and another for $t\bar{t}V$
  - Both are combined in the end into a single discriminant via a linear combination
- Inputs to the BDT: flavor and kinematic properties of leptons, jets & angular separations between them etc.



tqH(ML) RESULTS

95% CL Limits	Observed Limit	Expected Limit
$\mathscr{B}(t \to cH)$	1.6×10^{-3}	1.5×10^{-3}
$\mathscr{B}(t \to uH)$	1.9×10^{-3}	1.5×10^{-3}

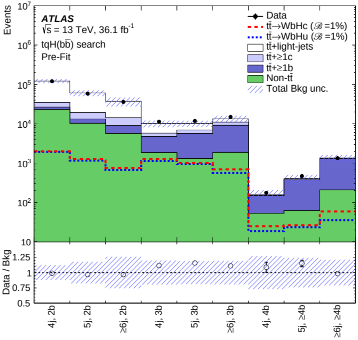




(3) $tqH(b\bar{b})$ ANALYSIS

- Targets $t\bar{t} \to Wb + Hq$ events, with $H \to b\bar{b}$ and $W \to l\nu$
- At truth level, signal events have at least 4 jets, with 3 of them originating from b-quarks
- Signal events are required to have exactly one lepton
- Major backgrounds: $t\bar{t}$+jets, multi-jet events
- *Matrix Method* is used to estimate the fake lepton background from multi-jet events
- Based on the # jets (4, 5, $\geq$6) and # b-tagged jets (2, 3, $\geq$4), phase space is split into 9 different regions

TREATMENT OF $t\bar{t}$+JETS BACKGROUND

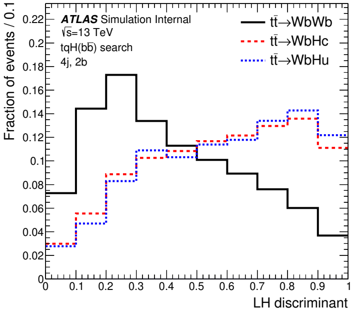


- Major bkg in (nj, 2b): $t\bar{t}$+light jets
- Major bkg in (nj, 4b): $t\bar{t}+\geq 1b$
- Major bkg in (nj, 3b): both $t\bar{t}$ light+jets and $t\bar{t}+\geq 1b$ contribute significantly

- Most sensitive regions of this analysis: (4j, 3b) and (5j, 3b).
- S/B of other regions is very low. They are used to improve $t\bar{t}$+jets prediction and its systematic uncertainties

Background rejection

- Likelihood discriminant is used to separate signal from the background
- Inputs: invariant masses of leptons, jets and MET, and those corresponding to W, t, and H resonances and etc.



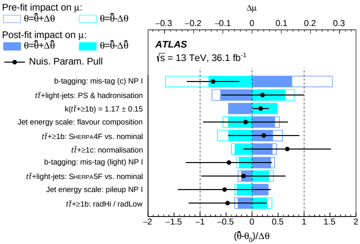
$tqH(b\bar{b})$ RESULTS

- Maximum likelihood fit is performed to get the best fit value of $\mathscr{B}(t \to qH)$
  - $t\bar{t} + 1b$ normalization is floated during the fit
  - $t\bar{t} + 1c$ normalization is fixed with 50% uncertainty

- $\mathscr{B}_{observed}(t \to cH) = -0.2^{+2.3}_{-2.4} \times 10^{-3}$
- $\mathscr{B}_{observed}(t \to uH) = 0.2^{+2.7}_{-3.0} \times 10^{-3}$

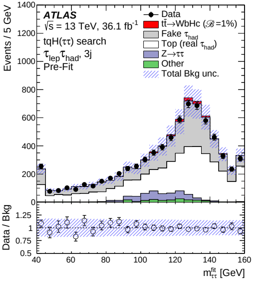
95% CL Limits	Observed Limit	Expected Limit
$\mathscr{B}(t \to cH)$	4.2×10^{-3}	4.0×10^{-3}
$\mathscr{B}(t \to uH)$	5.2×10^{-3}	4.9×10^{-3}

Leading systematic uncertainties:



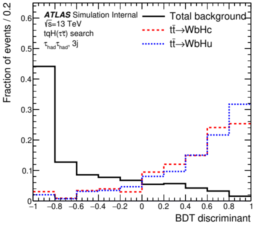
(4) $tqH, H \to \tau\tau$ ANALYSIS

- Sensitive to $t\bar{t} \longrightarrow Wb + Hq$ events with $H \to \tau\tau$ & $W \to jj$
- Based on # jets (3j or $\geq$ 4j) and decay modes of τ leptons ($\tau_{\text{had}}\tau_{\text{had}}$ or $\tau_{\text{lep}}\tau_{\text{had}}$), events are classified into four categories
- Major backgrounds: Fake τ-lepton bkgs from $t\bar{t}$ & multijet production
- Fake τ-lepton backgrounds in SR are modelled using templates derived from CRs orthogonal to SR



SIGNAL REGION OPTIMIZATION

- BDT discriminant is used for separating signal from the background.
- Kinematic variables like $m_{\tau\tau}$, m_{Hq}, etc are used for the training.



Results:

- $\mathscr{B}_{observed}(t \to cH) = -4.4^{+9.9}_{-8.5} \times 10^{-4}$
- $\mathscr{B}_{observed}(t \to uH) = -5.3^{+9.1}_{-7.8} \times 10^{-4}$
- Leading systematic uncertainties: Fake τ-lepton estimation, Jet energy resolution

95% CL Limits	Observed Limit	Expected Limit
$\mathscr{B}(t \to cH)$	1.9×10^{-3}	2.1×10^{-3}
$\mathscr{B}(t \to uH)$	1.7×10^{-3}	2.0×10^{-3}