Searches for new physics in FCNC top decays in multilepton final states

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Introduction

- Flavor-changing neutral currents (FCNC) are forbidden at tree level and strongly suppressed at higher order in SM, ex.

$$\boxed{t \to Hq, (q = u, c)}$$

- Large enhancements in branching ratio are possible in some beyond Standard Model (SM) scenarios, $\mathcal{B}(t \to Hc) \sim 0.1\%$ ($\sim 10^{-15}$ in SM)

- Search for FCNC in $t\bar{t}$ decays, $\sigma_{FCNC} = \sigma_{t\bar{t}} \cdot \mathcal{B}_{FCNC} \cdot (1 - \mathcal{B}_{FCNC}) \cdot 2$

- ATLAS Run 1 results: 95% CL observed (expected) upper limit on $\mathcal{B}$
  - $\mathcal{B}(t \to Hu) < 0.45(0.29)\%$
  - $\mathcal{B}(t \to Hc) < 0.46(0.25)\%$

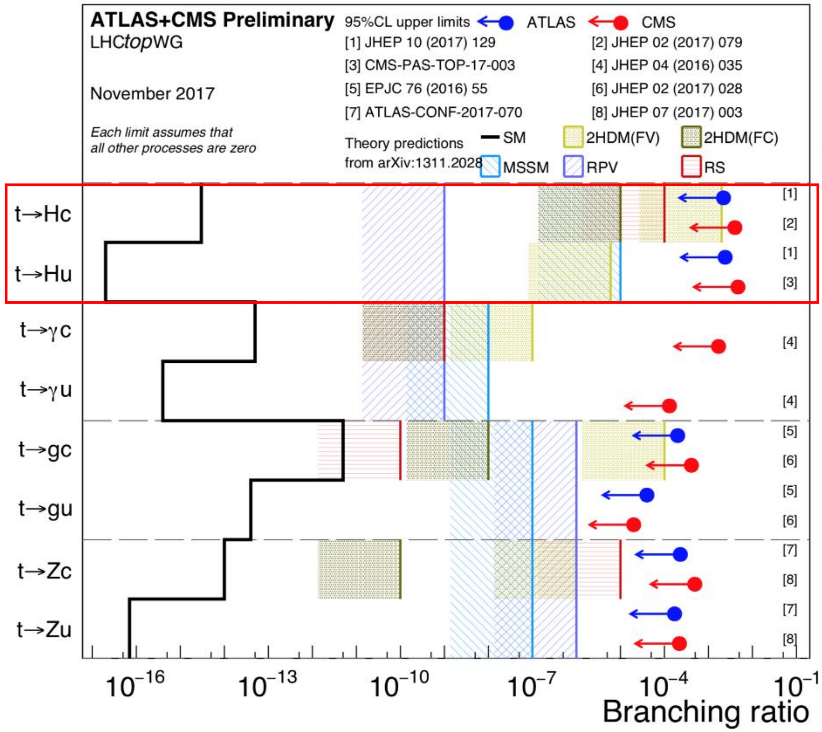
- ATLAS Run 2 analyses (by Higgs boson decay):
  - $H \to \gamma\gamma$: $\mathcal{B}(t \to Hc) \leq 0.22(0.16)\%$*
  - $\boxed{H \to \mathrm{WW}^*,\ \mathrm{ZZ}^*, \tau_{lep}\tau_{lep}\text{: } \textbf{this presentation}}$

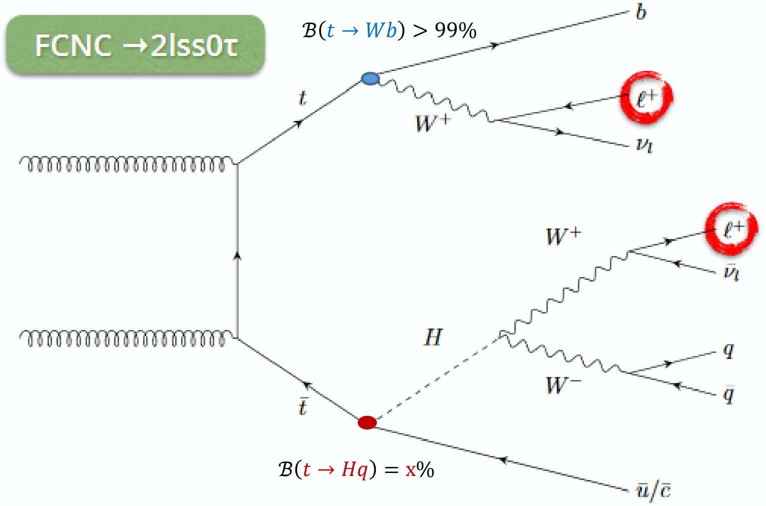
- Decay chain example (assuming $H \to \mathrm{WW}^*$):

$$t\bar{t} \to Wb + Hq \to 3W + b + q$$

$$4\ jets\ (incl.\ 1b) + \boldsymbol{2\ell SS}^{**} + E_T^{miss}$$

$$2\ jets\ (incl.\ 1b) + \boldsymbol{3\ell} + E_T^{miss}$$

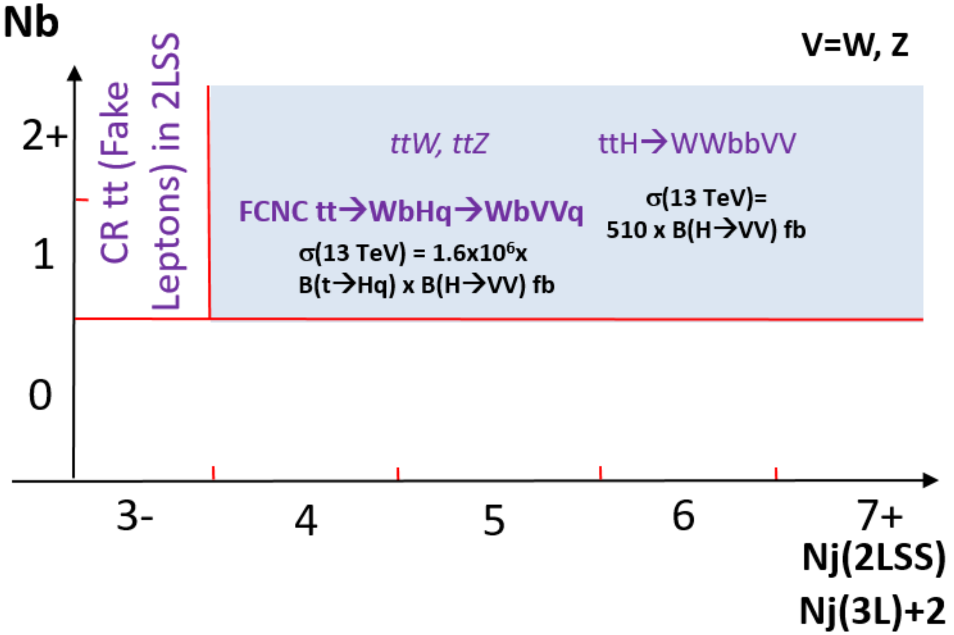




*[JHEP **10**(2017) 129](#) **Same sign

Analysis strategy

- The analysis is based on 36.1 fb^{-1} of data at $\sqrt{s} = 13$ TeV
- Two relaxed (pre-MVA*) regions with no τ_{had}:
  1. $\boldsymbol{2\ell SS}$: N_{jet}>=4 + N_{b-jet}>=1
  2. $\boldsymbol{3\ell}$: N_{jet}>=2 + N_{b-jet}>=1
  - Constrain on N_{jet} comes from fake lepton estimate (need a Control Region with N_{jet}=2,3 to measure fake lepton rate)



- In the pre-MVA region the background is dominated by **ttV** and **fake leptons** (coming from b decays in $t\bar{t}$ events)

$$t\bar{t}V \rightarrow 2W + V + 2b \rightarrow \text{4j (inc. 2b)} + 2\ell\text{SS} + E_T^{miss} \text{ or 2-4j (inc. 2b)} + 3\ell + E_T^{miss}$$

$$t\bar{t} \rightarrow 2W + 2b \rightarrow \text{3j (inc. 1b)} + 2\ell\text{SS} + E_T^{miss} \text{ or 1j (inc. 1b)} + 3\ell + E_T^{miss}$$

- Main backgrounds treatment
  1. dedicated algorithm to reduce leptons from b decays (at the level of pre-MVA region)
  2. dedicated MVA to separate FCNC from **ttV** and **fake leptons** (on top of the pre-MVA region)

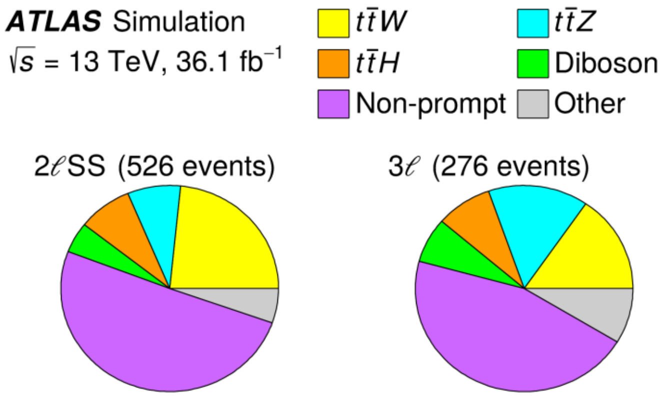
- Fit data distribution of the MVA discriminant

**Multivariate Analysis*

I. Event yields in pre-MVA region

- Pre-MVA basic selections
  - $\boldsymbol{2\ell SS}$
    - p_T leptons($l_0^{\pm} l_1^{\pm}$) >(20,20) GeV
    - N_{jet}>=4, N_{b-jet}=1,2
    - 0 τ_{had}
  - $\boldsymbol{3\ell}$
    - p_T leptons($l_0^{\mp} l_1^{\pm} l_2^{\pm}$) >(10,15,15) GeV
    - N_{jet}>=2, N_{b-jet}>=1
    - 0 τ_{had}
- Pre-fit event yields

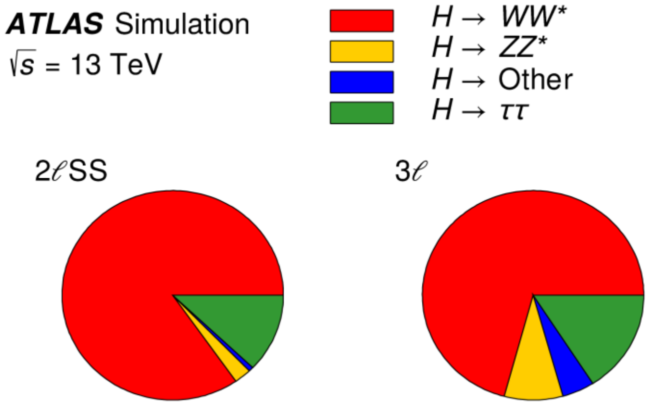
Background composition (pre-fit)



Category	Non-prompt	ttV	ttH	Diboson	Other prompt SM	Total SM	FCNC** $t \to Hu$	FCNC** $t \to Hc$	Data
$\boldsymbol{2\ell SS}$	266±40	165±19	43±4	25±15	28±6	**526±39**	61±13	62±13	**514**
$\boldsymbol{3\ell}$	126±31	84±8	23±3	20±11	24±5	**276±33**	32±6	30±6	**258**

$**assuming\ \mathcal{B}(t \to Hq) = 0.2\%$

$t \to Hq$ signal composition

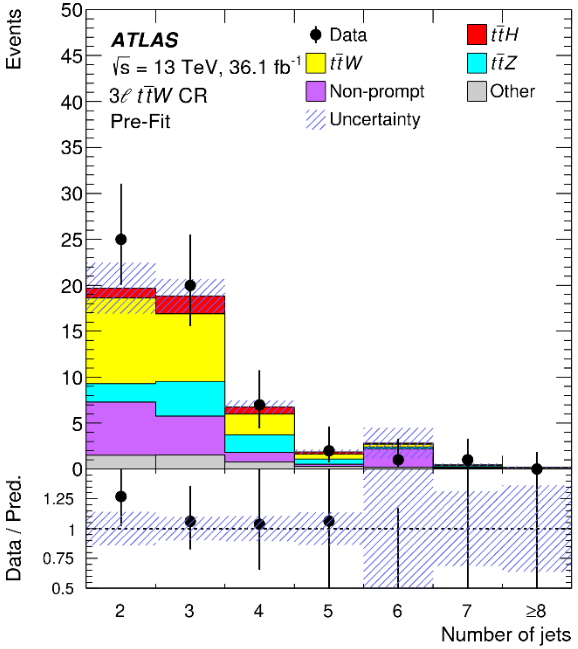


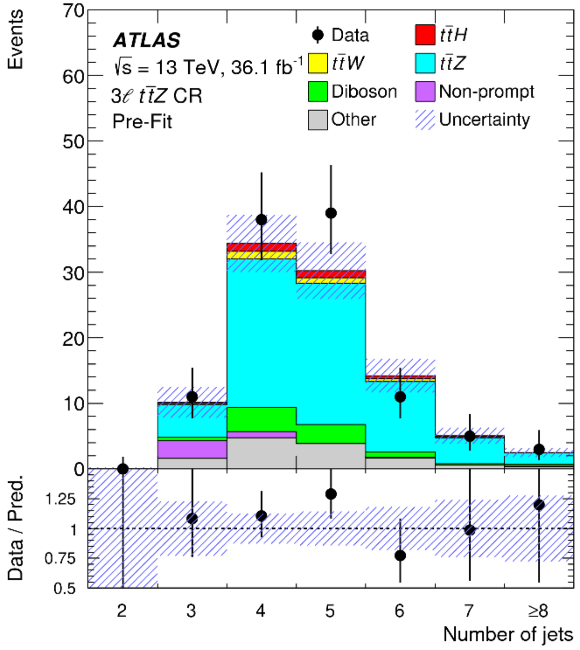
- Around half of the background is non-prompt
- $H \to WW^*$ is dominant

II. Background estimates (1)

- **Irreducible backgrounds**

- Dominated by ttW ($\boldsymbol{2\ell SS}$), ttZ($\boldsymbol{3\ell}$) and Diboson
- MC models well the data in the dedicated ttV (V=W,Z) validation regions

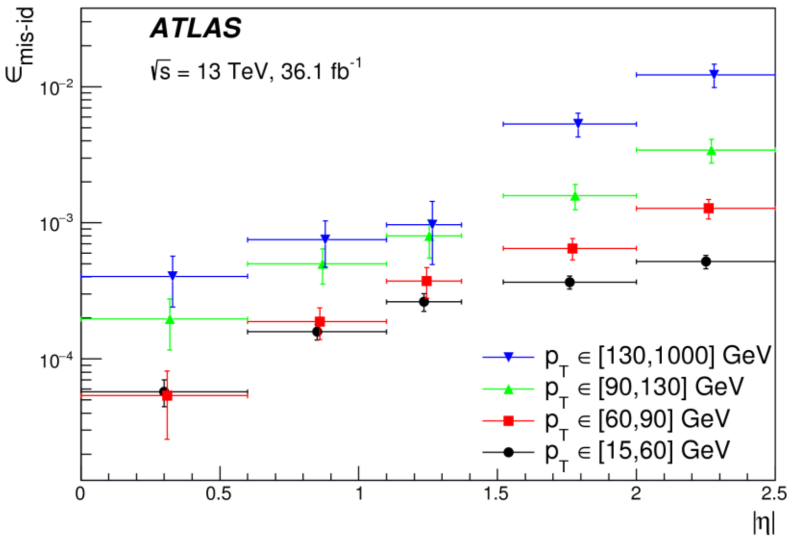




- **Reducible backgrounds (a):** QmisID (mainly from $t\bar{t}$) (electrons with mis-identified electric charge)

- Use a data-driven method
  - Based on $Z \rightarrow e^{+}e^{-}$ events
  - Charge flip rate extracted in p_T, η bins
  - apply weight on the opposite sign events in the pre-MVA region

$$\boxed{w_{QmisID} = \epsilon_{\text{mis id},1}(1 - \epsilon_{\text{mis id},2}) + \epsilon_{\text{mis id},2}(1 - \epsilon_{\text{mis id},1})}$$

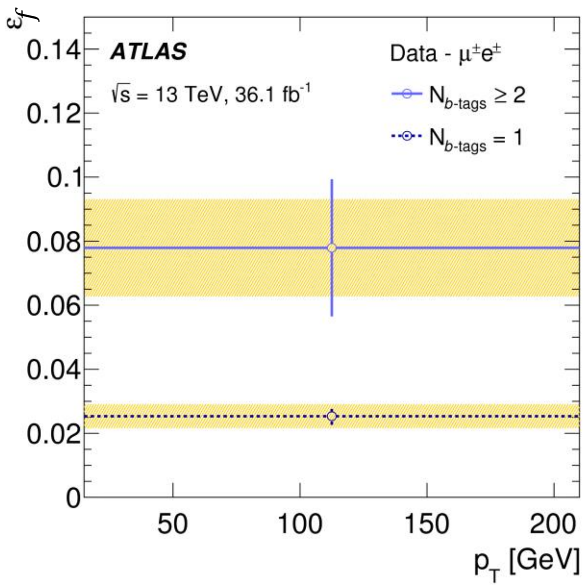


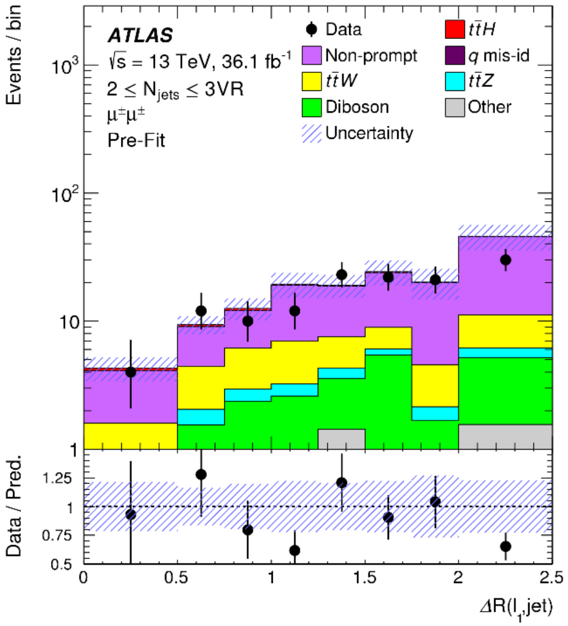
II. Background estimates (2)

➢ **Reducible background (b):** Fake Leptons (mainly from $t\bar{t}$)

- Use Matrix Method
  - Real lepton efficiency ε_r in $t\bar{t}$ events CR (**opposite sign**)
  - Fake lepton efficiency ε_f in **same sign** $t\bar{t}$ events (**2 – 3 jets**)

$$\begin{pmatrix} N^{rr} \\ N^{rf} \\ N^{fr} \\ N^{ff} \end{pmatrix} = \begin{pmatrix} \varepsilon_{r,1}\varepsilon_{r,2} & \varepsilon_{r,1}\varepsilon_{f,2} & \varepsilon_{f,1}\varepsilon_{r,2} & \varepsilon_{f,1}\varepsilon_{f,2} \\ \varepsilon_{r,1}\not\varepsilon_{r,2} & \varepsilon_{r,1}\not\varepsilon_{f,2} & \varepsilon_{f,1}\not\varepsilon_{r,2} & \varepsilon_{f,1}\not\varepsilon_{f,2} \\ \not\varepsilon_{r,1}\varepsilon_{r,2} & \not\varepsilon_{r,1}\varepsilon_{f,2} & \not\varepsilon_{f,1}\varepsilon_{r,2} & \not\varepsilon_{f,1}\varepsilon_{f,2} \\ \not\varepsilon_{r,1}\not\varepsilon_{r,2} & \not\varepsilon_{r,1}\not\varepsilon_{f,2} & \not\varepsilon_{f,1}\not\varepsilon_{r,2} & \not\varepsilon_{f,1}\not\varepsilon_{f,2} \end{pmatrix}^{-1} \begin{pmatrix} N^{TT} \\ N^{T\not T} \\ N^{\not TT} \\ N^{\not T\not T} \end{pmatrix}$$





- Good closure test with $t\bar{t}$ MC

- Validation in dedicated region:
  - Good agreement with data

$$\varepsilon_f = \frac{N^{tight}_{data} - N^{tight}_{qmis-ID(data)} - N^{tight}_{promptlepton(MC)} - \boxed{N^{tight}_{t\to Hu}}}{N^{loose}_{data} - N^{loose}_{qmis-ID(data)} - N^{loose}_{promptlepton(MC)}}$$

- Special treatment needed because of signal contamination in the fake lepton CR

$$N^{\text{new}}_{\text{fake}} = N^{\text{orig}}_{\text{fake}} - \frac{\mathfrak{B}}{0.2\%} \times N^{\text{sub}}_{\text{fake}}$$

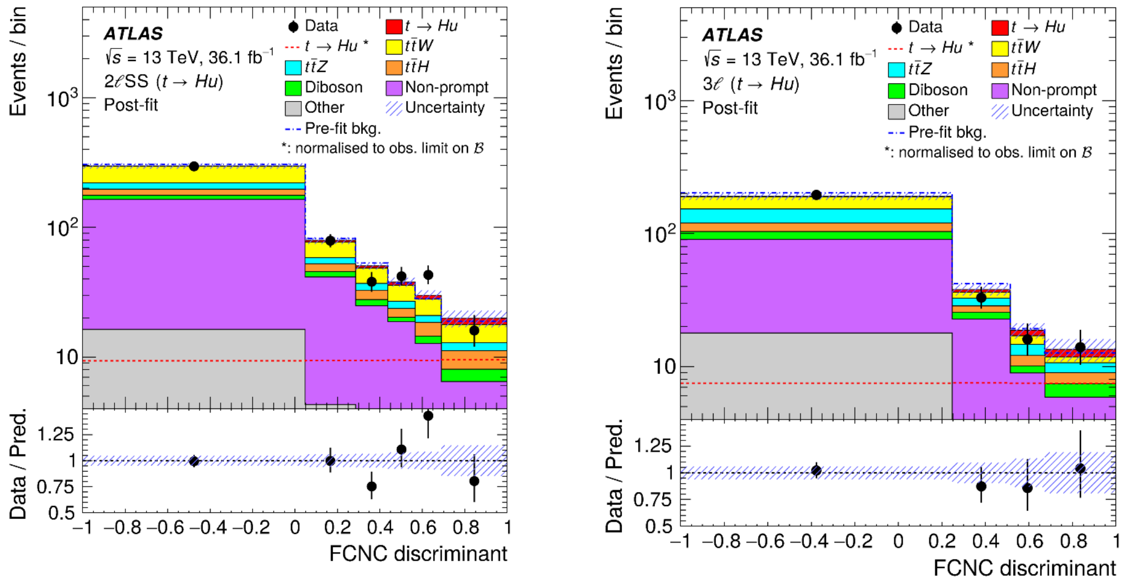
- Subtract signal in CR

III. Event MVA

- To further reject background 2 BDTs scores are computed (per channel) against the 2 main backgrounds
  - BDT_{ttbar}: FCNC signal *vs* non-prompt (Data Driven)
  - BDT_{ttV}: FCNC signal *vs* (ttZ+ttW)

	tHu measurement	tHc measurement
$2\ell SS$	(tHu+tHc) *vs* non-prompt (tHu+tHc) *vs* ttV	(tHu+tHc) *vs* non-prompt (tHu+tHc) *vs* ttV
3ℓ	tHu *vs* non-prompt tHu *vs* ttV	tHc *vs* non-prompt tHc *vs* ttV

$t \to Hu$ final discriminant (post-fit)



- A combined BDT score is obtained with a linear combination

$$FCNC\ discriminant = \frac{a \cdot BDT_{ttbar} + BDT_{ttV}}{a+1}$$

- Optimization procedure is performed in terms of best expected limit on $\mathcal{B}(t \to Hq)$ for:
  - Linear combination weight: a
  - Number of bins in each category : 6 bins for $\boldsymbol{2\ell SS}$, 4 bins for $\boldsymbol{3\ell}$
  - Bin widths: equal amount of signal events in each bin (flat signal)

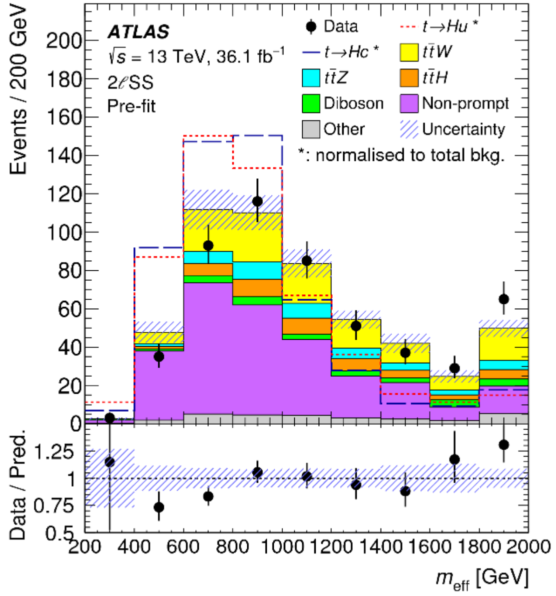
**Boosted Decision Tree*

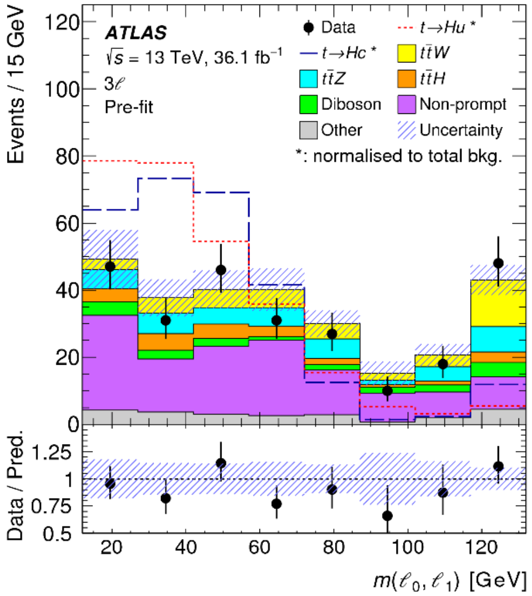
III. Event MVA input variables

- List of input variables used in BDTs training in the two categories

	Variable	$2\ell SS$	3ℓ
Lepton properties	p_T of higher-p_T lepton	×	
	p_T of lower-p_T lepton	×	
	p_T of lepton ℓ_0		×
	p_T of lepton ℓ_1		×
	p_T of lepton ℓ_2		×
	Dilepton invariant masses (all combinations)*	×	×
	Trilepton invariant mass		×
	Best Z candidate invariant mass		×
	$\lvert\eta\rvert$ between leptons	×	
	Lepton flavor	×	
Jet properties	Number of jets	×	×
	Number of b-tagged jets	×	×
	p_T of highest-p_T jet		×
	p_T of second highest-p_T jet		×
	p_T of highest-p_T b-tagged jet		×
Angular distances	$\Delta R(\ell_0, \ell_1)$		×
	$\Delta R(\ell_0, \ell_2)$		×
	ΔR(higher-p_T lepton, closest jet)	×	
	ΔR(lower-p_T lepton, closest jet)	×	
	$\Delta R(\ell_1$, closest jet)		×
	Smallest $\Delta R(\ell_0$, b-tagged jet)		×
Global	E_T^{miss}	×	
	m_{eff}	×	×
	Number of variables:	11	18

3 combinations for 3l





- Signal particularities (compared to main backgrounds) :
  - Relatively soft events (lower m_{eff})
  - Lower $m(l_0, l_1)$ and $\Delta R(l_0, l_1)$ for 3l
  - Only one true b-jet

$$m_{eff} = E_T^{miss} + \sum p_T^{lep} + \sum p_T^{jet}$$

IV. Fit results summary

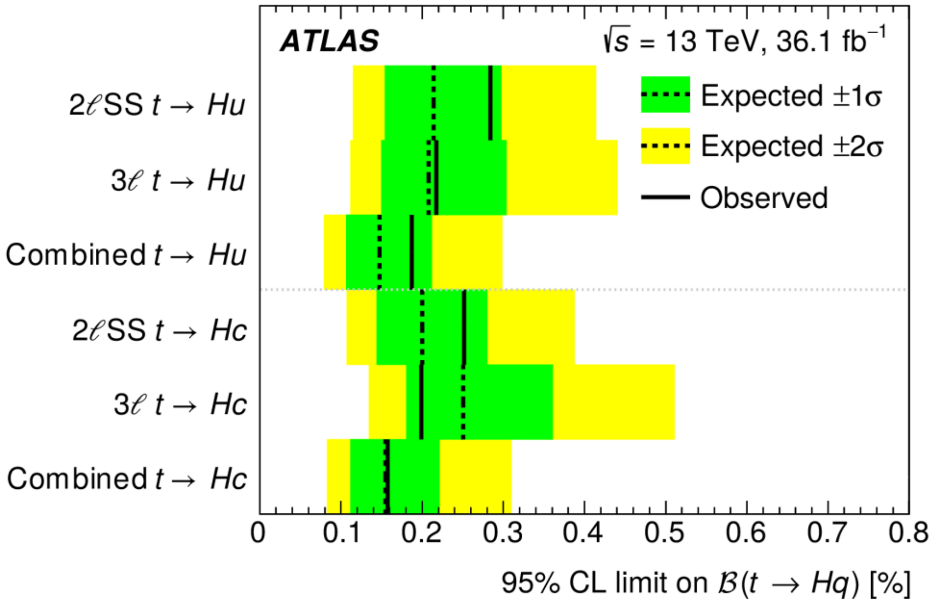
- Upper limit @95% CL under background only hypothesis on top FCNC branching ratio in %:

$t \to Hu$

	Best-fit $\mathcal{B}(t \to Hu)$ [%]		Observed (Expected) Upper Limit on $\mathcal{B}(t \to Hu)$ [%]	
	stat.	stat. + syst.	stat.	stat. + syst.
2ℓSS	$0.08\,^{+0.08}_{-0.08}$	$0.08\,^{+0.11}_{-0.10}$	0.23 (0.15)	0.28 (0.21)
3ℓ	$0.01\,^{+0.09}_{-0.08}$	$0.01\,^{+0.10}_{-0.09}$	0.20 (0.18)	0.22 (0.21)
Combined	$0.04\,^{+0.06}_{-0.06}$	$0.04\,^{+0.08}_{-0.07}$	0.17 (0.12)	0.19 (0.15)

$t \to Hc$

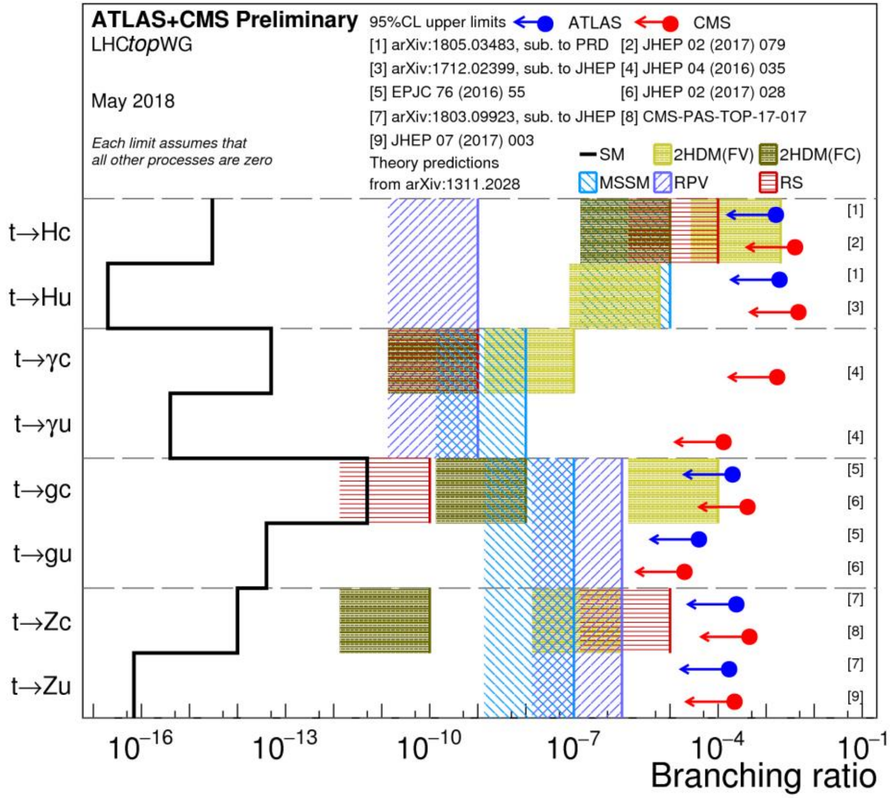
	Best-fit $\mathcal{B}(t \to Hc)$ [%]		Observed (Expected) Upper Limit on $\mathcal{B}(t \to Hc)$ [%]	
	stat.	stat. + syst.	stat.	stat. + syst.
2ℓSS	$0.05\,^{+0.08}_{-0.08}$	$0.05\,^{+0.11}_{-0.10}$	0.22 (0.15)	0.25 (0.20)
3ℓ	$-0.09\,^{+0.10}_{-0.09}$	$-0.09\,^{+0.11}_{-0.11}$	0.19 (0.23)	0.20 (0.25)
Combined	$-0.01\,^{+0.06}_{-0.06}$	$-0.01\,^{+0.08}_{-0.08}$	0.15 (0.13)	0.16 (0.15)



- Results still dominated by statistical uncertainty
- Results comparable with latest ATLAS FCNC result on $t \to Hc$ $(H \to \gamma\gamma)$ with 36.1 fb^{-1} of pp collisions at 13 TeV
  - observed (expected) limit is 0.22% (0.16%) (*JHEP* ***10***(2017) 129)

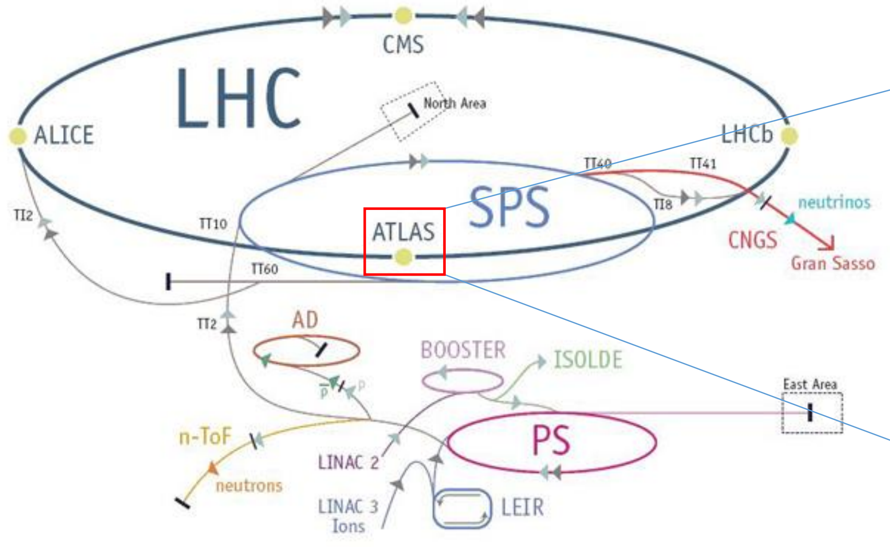
Summary & Conclusions

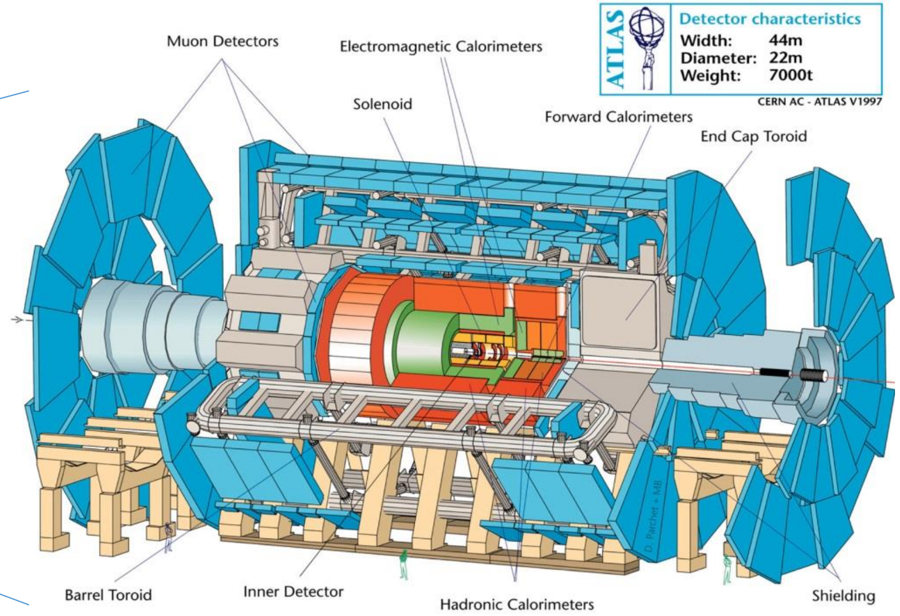
- A search for flavor-changing neutral currents (FCNC), $t \to Hq$ $(q = u, c)$, with $H \to WW, ZZ, \tau_{lep}\tau_{lep}$ based on 36.1 fb^{-1} (13TeV) was presented
  1. Consider $\boldsymbol{2\ell SS}$ and $\boldsymbol{3\ell}$ channels (no hadronic τ decay)
  2. Optimize an MVA against fake lepton and ttV, combined into a final discriminant
- Combined $\boldsymbol{2\ell SS}$ + $\boldsymbol{3\ell}$ **fit for $\boldsymbol{\mathcal{B}}$** compatible with 0:
  - $\mathcal{B}(t \to Hu)$: $\boldsymbol{0.04^{+0.08}_{-0.07}\%}$
  - $\mathcal{B}(t \to Hc)$: $\boldsymbol{-0.01^{+0.08}_{-0.08}\%}$
- Combined $\boldsymbol{2\ell SS}$ + $\boldsymbol{3\ell}$ **observed (expected) upper limit** at 95% CL :
  - $\mathcal{B}(t \to Hu)$: $\boldsymbol{0.19\ \% \ (0.15\ \%)}$
  - $\mathcal{B}(t \to Hc)$: $\boldsymbol{0.16\ \% \ (0.15\ \%)}$
- Statistics limited results
- Best limits to date on $\mathcal{B}(t \to Hu)$ and $\mathcal{B}(t \to Hc)$
- Results already published: [Phys. Rev. D 98 (2018) 032002]



BACKUP

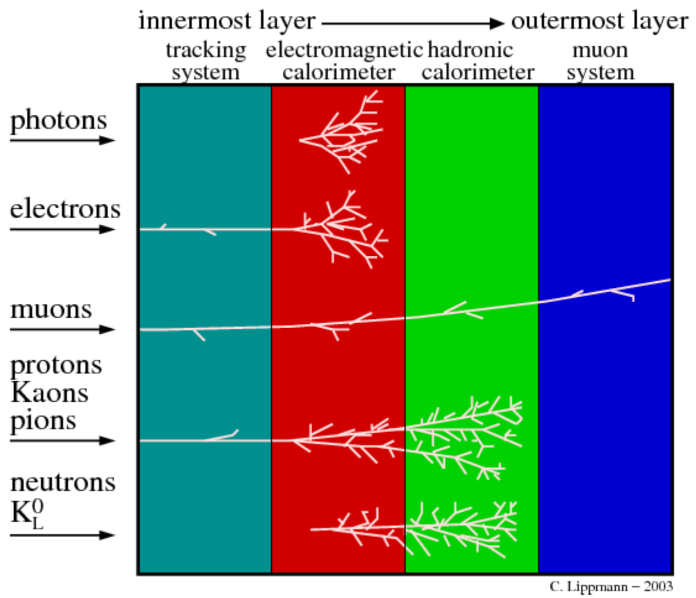
LHC and ATLAS





- The Large Hadron Collider (LHC):
  - proton-proton accelerator, $\sqrt{s} = 14^{*}$ TeV
- *Linac2→Booster→PS→SPS→LHC*

Run #	Period	$\sqrt{s}$ [TeV]	integrated luminosity $[fb^{-1}]$
Run 1	2010-2011	7	5.5
	2012	8	22.8
Run 2	2015-2016	13	43.1
	2017	13	50.4
	2018**	13	40.1



*design **as of 21st of August 2018

Object Reconstruction

- Trigger: Lowest unprescaled single-lepton and di-lepton trigger chain

L* - less loose (Loose+isolated + non-prompt BDT)

	e			μ		
	L	L*	T	L	L*	T
Isolation	No	Yes		No	Yes	
Non-prompt lepton MVA	No	Yes		No	Yes	
Identification	Loose		Tight	Loose		
Charge mis-assignment veto	No		Yes	N/A		
Tranverse impact parameter significance $\lvert d_0 \rvert / \sigma_{d_0}$	$< 5\sigma$			$< 3\sigma$		
Longitudinal impact parameter $\lvert z_0 \sin\theta \rvert$	< 0.5 mm					

ttHML:[*Phys. Rev. D 97 (2018) 072003*]

- Use standard objects:
  - Jets : anti-k_t algorithm with R=0.4
  - B-tagging working point (70% efficiency): *MV2c10*
  - Loose and tight leptons (table)

- Use dedicated algorithms for reducible background:
  - *Non-prompt lepton MVA:*
    - Used to reduce leptons from b decays (non-prompt leptons) at the level of the pre-MVA regions
  - *Charge flip MVA* :
    - Used to reduce events with **electrons** that have wrongly reconstructed charge at the level of the pre-MVA regions

Lepton MVAs: *Non-prompt lepton MVA*

Variable	Description
N_{track} in track jet	Number of tracks collected by the track jet
IP2 $\log(P_b/P_{\text{light}})$	Log-likelihood ratio between the b and light jet hypotheses with the IP2D algorithm
IP3 $\log(P_b/P_{\text{light}})$	Log-likelihood ratio between the b and light jet hypotheses with the IP3D algorithm
N_{TrkAtVtx} SV + JF	Number of tracks used in the secondary vertex found by the SV1 algorithm in addition to the number of tracks from secondary vertices found by the JetFitter algorithm with at least two tracks
$p_T^{\text{lepton}}/p_T^{\text{track jet}}$	The ratio of the lepton p_T and the track jet p_T
ΔR(lepton, track jet)	ΔR between the lepton and the track jet axis
p_TVarCone30$/p_T$	Lepton track isolation, with track collecting radius of $\Delta R < 0.3$
E_TTopoCone30$/p_T$	Lepton calorimeter isolation, with topological cluster collecting radius of $\Delta R < 0.3$

Lepton MVAs: *charge flip MVA*

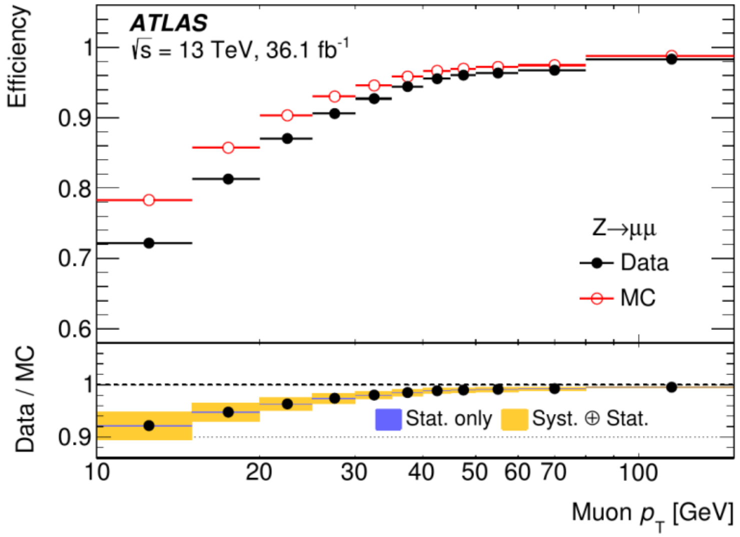
Variable	Description
p_{T}	Transverse momentum
η	Pseudo-rapidity
charge$\times d_0$	Electric charge times the transverse impact parameter
E/p	Ratio of the cluster energy to the track momentum
R_ϕ	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centred at the electron cluster position
$\Delta\phi_1$	$\Delta\phi$ between the cluster position in the strip layer and the extrapolated track
$\Delta\phi_{rescaled}$	$\Delta\phi$ between the cluster position in the middle layer and the extrapolated track, where the track momentum is rescaled to the cluster energy before extrapolating the track to the middle layer
$\frac{q/p}{\sigma_{q/p}}$	Significance of the curvature of the track defined as the ratio of the reconstructed charge to the track momentum

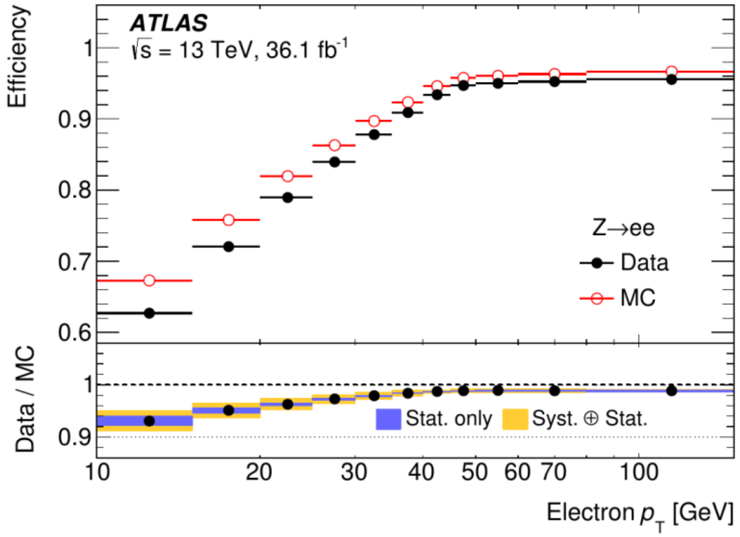
Lepton MVAs

- *Non-prompt lepton MVA*:
  - uses lifetime information to veto non-prompt leptons that otherwise pass standard isolation selections

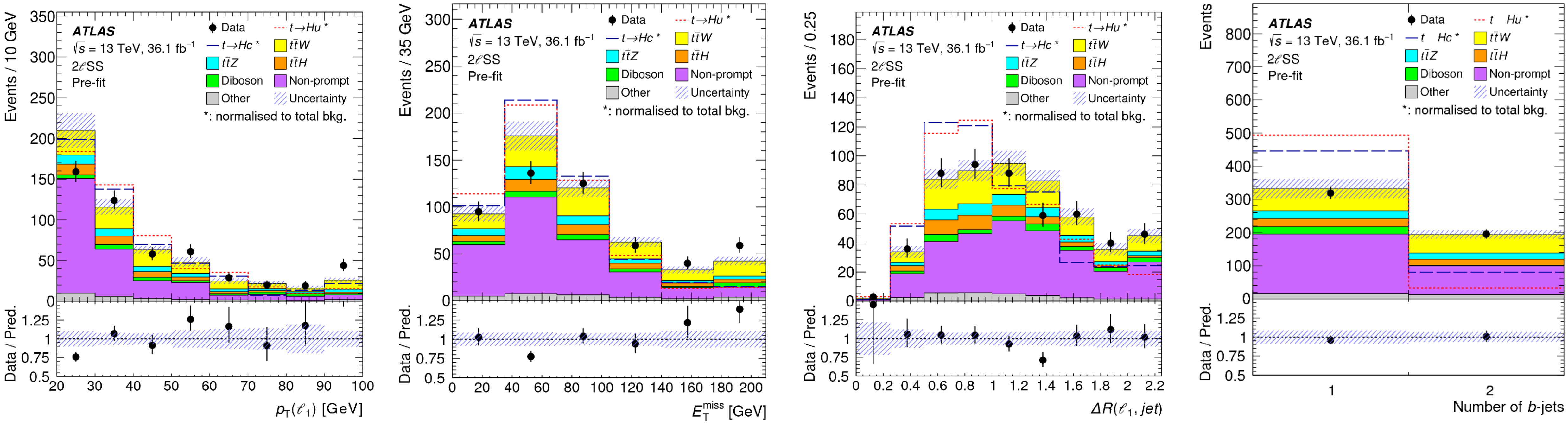
    Find a track jet within $\Delta R < 0.4$ from selected e (μ) (99% of cases) → Use track jet information to train BDT (ttbar MC) → Check if track jet + lepton compatible with a *b* or *c* jet
  - Input variables:
    - Use lepton and overlapping track jets properties variables
    - lepton track/calorimeter isolation variables
  - Improves over combination of *impact parameters cuts* + *isolation* + *lepton identification*
- *Charge flip MVA*:
  - Use electron track and calorimeter information
  - Factor 17x background rejection for a 95% signal efficiency
- Calibration performed with dedicated method in $Z \to \mu\mu$ and $Z \to ee$ events

ttHML:[Phys. Rev. D 97 (2018) 072003]

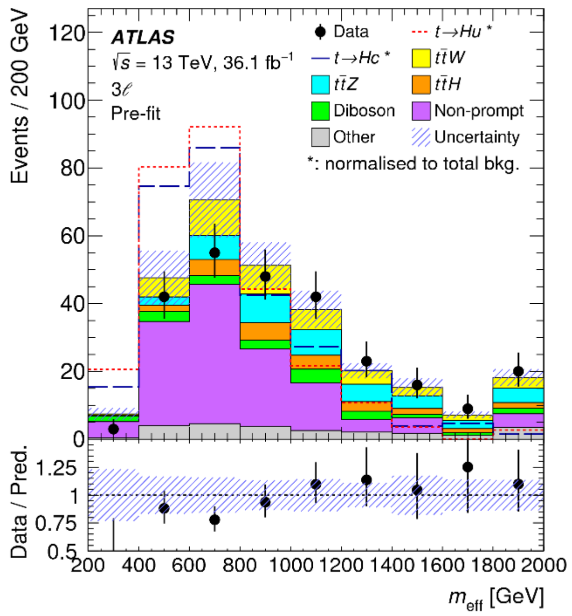


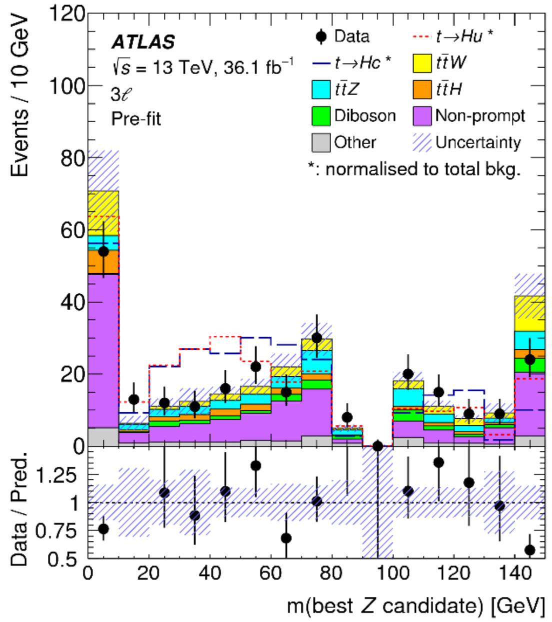


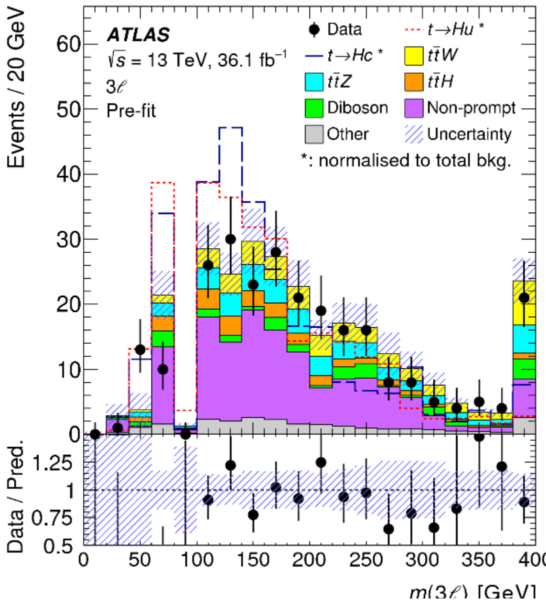
Event MVA input variables: 2lss

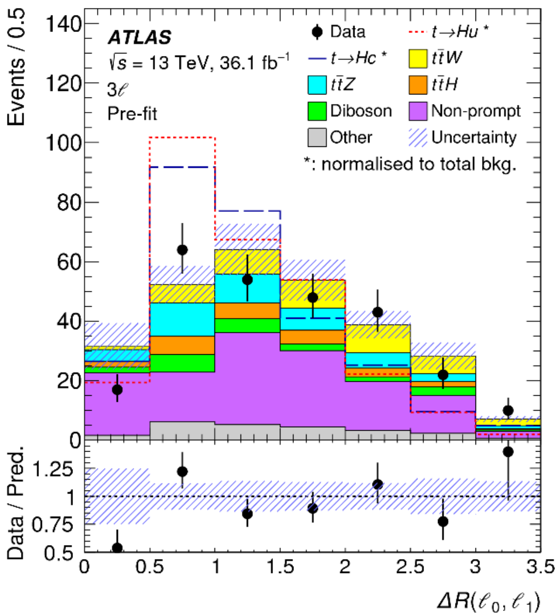


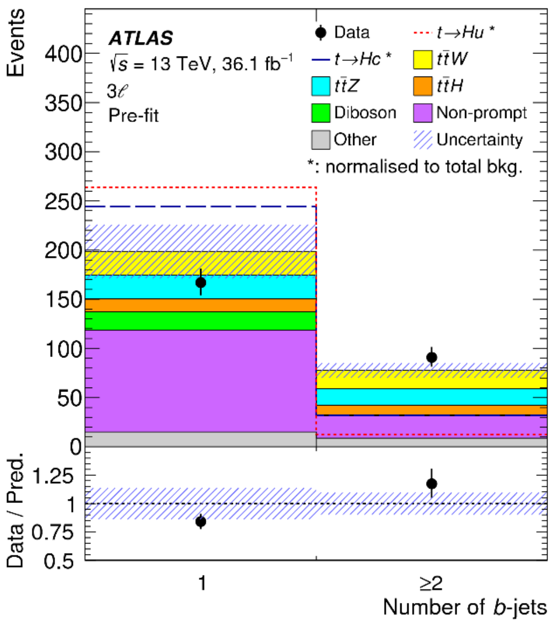
Event MVA input variables: 3l

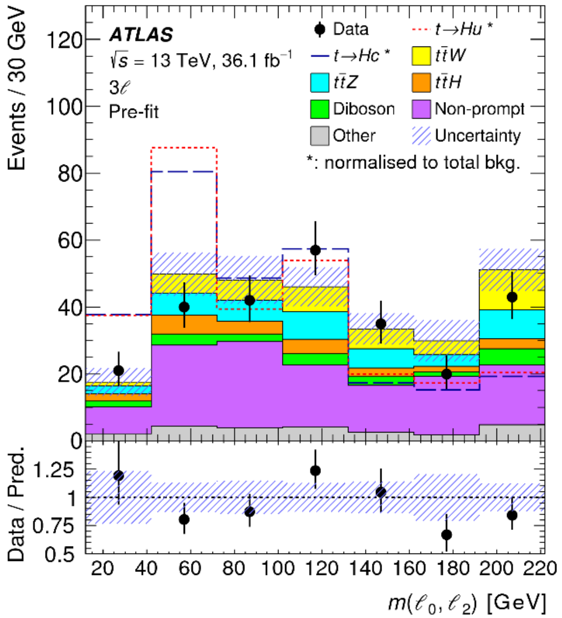


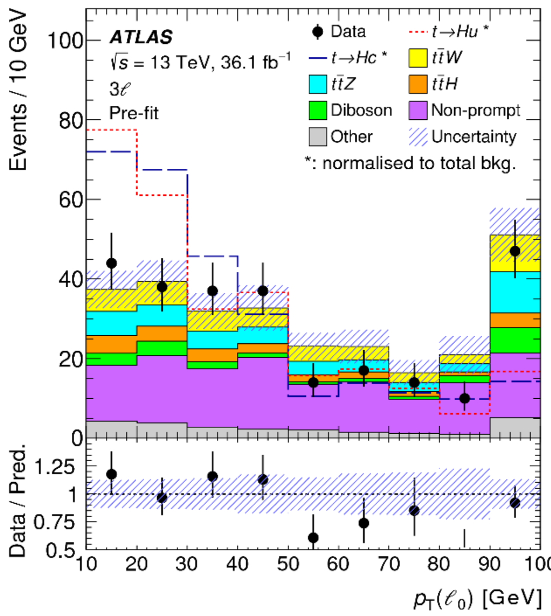












IV. Fit model

- Maximum-likelihood fit is performed on $\mathbf{2\ell ss}$ and $\mathbf{3\ell}$ channels simultaneously to extract the branching ratio $\mathcal{B}$ and its 95% CL upper limit under background-only hypothesis.

- The test statistic, $q_{\mathcal{B}}$, is constructed from the profile log-likelihood ratio:

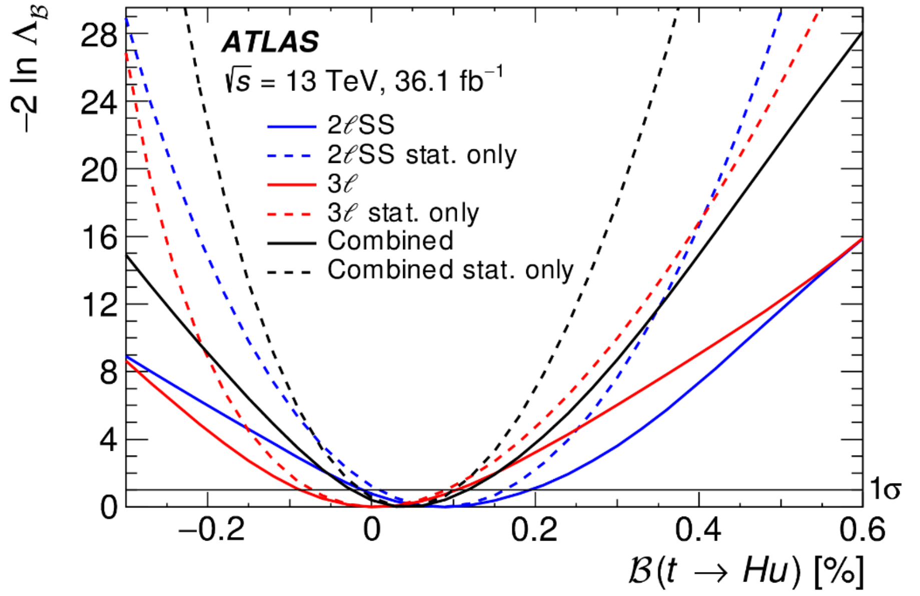
$$q_{\mathcal{B}} = -2\ln\Lambda_{\mathcal{B}} = -2\ln\frac{\mathcal{L}\left(\mathcal{B},\hat{\hat{\vec{\theta}}}\right)}{\mathcal{L}\left(\hat{\mathcal{B}},\hat{\vec{\theta}}\right)}$$

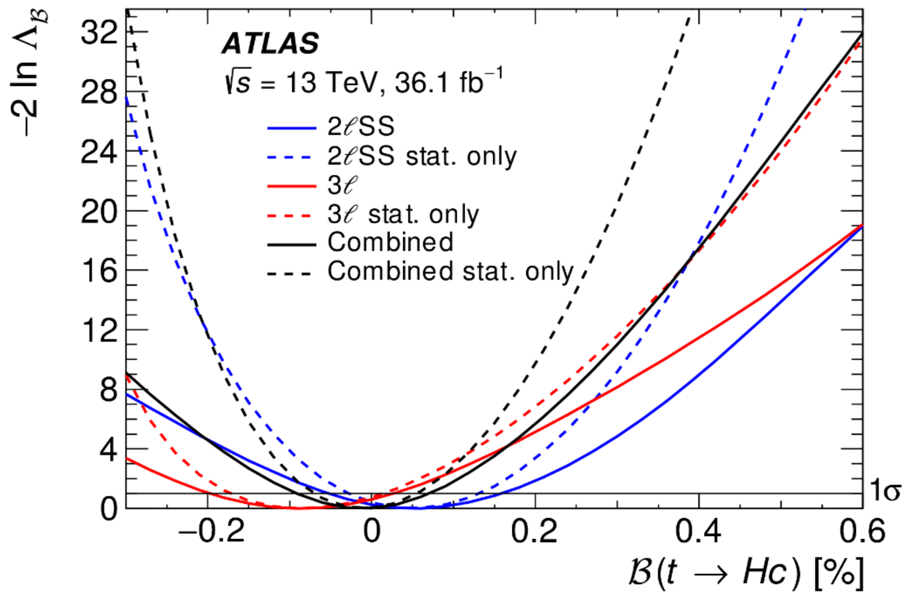
  where $\hat{\mathcal{B}}$ and $\hat{\vec{\theta}}$ are the parameters that maximize the likelihood and $\hat{\hat{\vec{\theta}}}$ are the nuisance parameters (NPs) that maximize the likelihood for a given $\mathcal{B}$

- The same likelihood is also used to obtain 95% CL upper limit on $\mathcal{B}$ using the CLs method.

- One parameter of interest (POI): $\mathcal{B}(t \to Hu)$ with $\mathcal{B}(t \to Hc) = 0$ and vice-versa

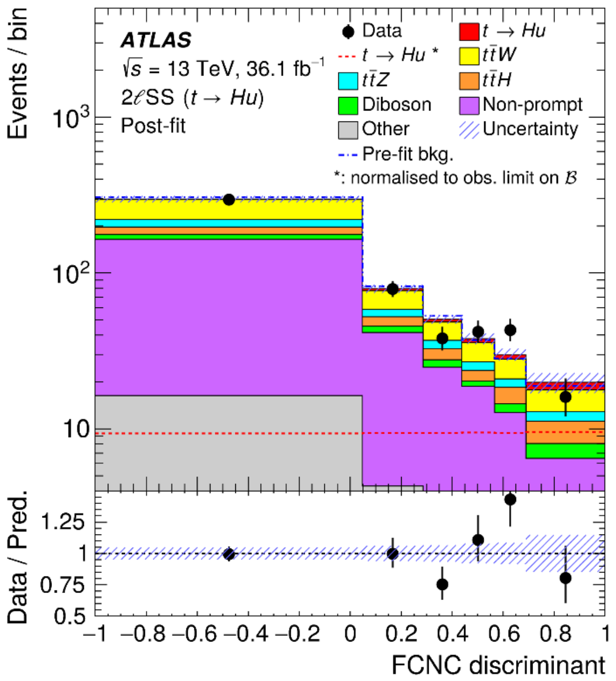
- Smooth distributions for the logarithmic likelihood (plots)



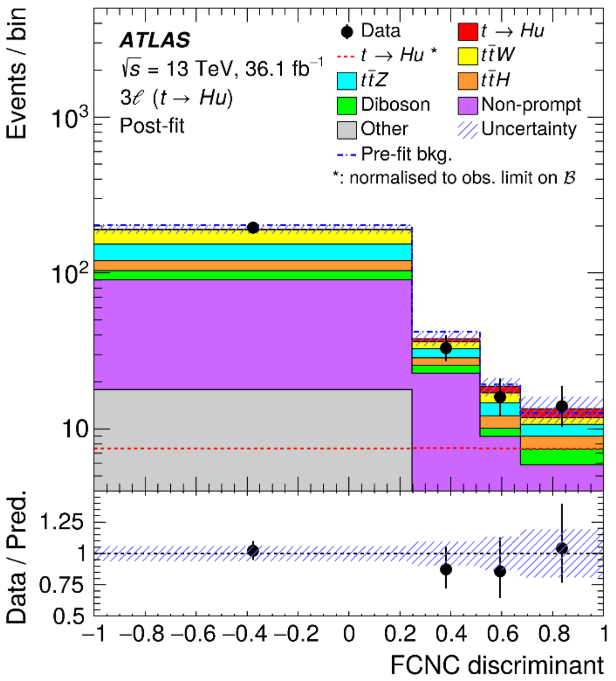


IV. Fit: Results $t \rightarrow Hu$

$2\ell SS$



3ℓ



- Fit performed on optimized combined BDTs
- Combined fit 2lss & 3l
- $\mathcal{B}(t \rightarrow Hc)$ assumed to be 0
- Fitted $\mathcal{B}(t \rightarrow Hu)$ compatible with 0

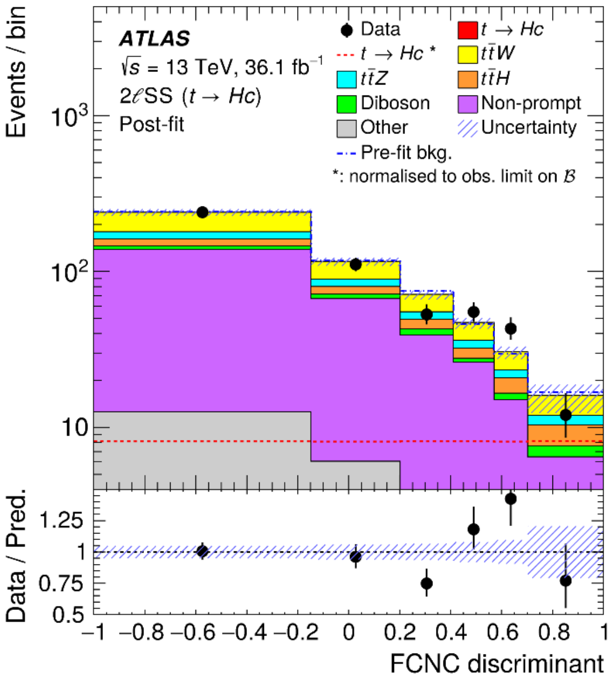
	Best-fit $\mathcal{B}(t \rightarrow Hu)$ [%] stat.	Best-fit $\mathcal{B}(t \rightarrow Hu)$ [%] stat. + syst.
2ℓSS	$0.08\ ^{+0.08}_{-0.08}$	$0.08\ ^{+0.11}_{-0.10}$
3ℓ	$0.01\ ^{+0.09}_{-0.08}$	$0.01\ ^{+0.10}_{-0.09}$
Combined	$0.04\ ^{+0.06}_{-0.06}$	$0.04\ ^{+0.08}_{-0.07}$

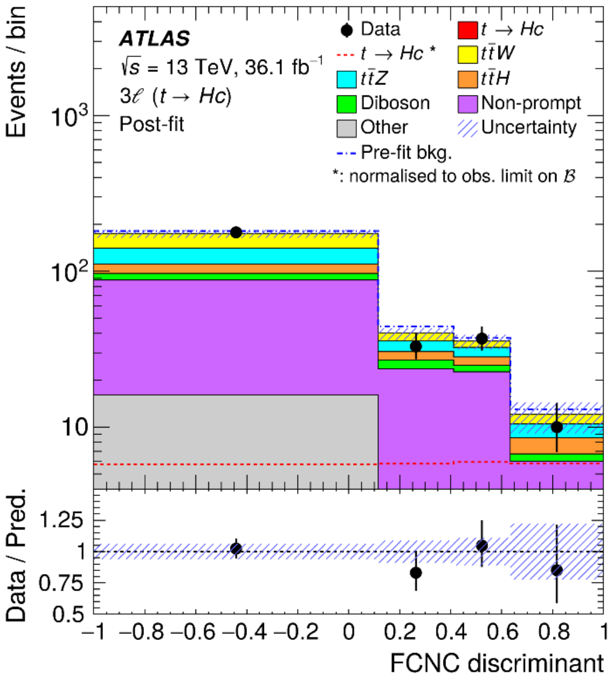
Stat limited

Category		Non-prompt leptons	$t\bar{t}V$	$t\bar{t}H$	Diboson	Other prompt SM	Total SM	FCNC	Data
$t \rightarrow Hu$									
2ℓSS	Pre-fit	266 ± 40	165 ± 19	43 ± 4	25 ± 15	28 ± 6	526 ± 39	61 ± 13	514
	Post-fit	240 ± 37	167 ± 18	43 ± 4	24 ± 14	28 ± 6	502 ± 33	13 ± 21	
3ℓ	Pre-fit	126 ± 31	84 ± 8	23 ± 3	20 ± 11	24 ± 5	276 ± 33	32 ± 6	258
	Post-fit	104 ± 20	84 ± 8	23 ± 3	19 ± 10	24 ± 5	254 ± 18	7 ± 11	

IV. Fit: Results $t \to Hc$

$2\ell SS$ | **3ℓ**





- Fit performed on optimized combined BDTs
- Combined fit 2lss & 3l
- $\mathcal{B}(t \to Hu)$ assumed to be 0
- Fitted $\mathcal{B}(t \to Hc)$ compatible with 0

	Best-fit $\mathcal{B}(t \to Hc)$ [%] stat.	Best-fit $\mathcal{B}(t \to Hc)$ [%] stat. + syst.
2ℓSS	$0.05\ ^{+0.08}_{-0.08}$	$0.05\ ^{+0.11}_{-0.10}$
3ℓ	$-0.09\ ^{+0.10}_{-0.09}$	$-0.09\ ^{+0.11}_{-0.11}$
Combined	$-0.01\ ^{+0.06}_{-0.06}$	$\boxed{-0.01\ ^{+0.08}_{-0.08}}$

Stat limited

Category		Non-prompt leptons	$t\bar{t}V$	$t\bar{t}H$	Diboson	Other prompt SM	Total SM	FCNC	Data
$t \to Hc$									
2ℓSS	Pre-fit	266 ± 40	165 ± 19	43 ± 4	25 ± 15	28 ± 6	526 ± 39	62 ± 13	514
	Post-fit	264 ± 41	165 ± 18	42 ± 4	20 ± 11	28 ± 6	520 ± 36	$\boxed{-3 \pm 25}$	
3ℓ	Pre-fit	126 ± 31	84 ± 8	23 ± 3	20 ± 11	24 ± 5	276 ± 33	30 ± 6	258
	Post-fit	116 ± 21	84 ± 8	23 ± 3	15 ± 8	23 ± 5	262 ± 19	$\boxed{-1 \pm 12}$	

- No $t \to Hc$ visible in post-fit because of negative fitted value

Fit results: expected best fit