FCNC Top $\rightarrow$Higgs
in ATLAS and CMS
in particular using $H\rightarrow\gamma\gamma$

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Starting point (in ATLAS)

After the Higgs boson discovery in July 2012…

- Either go for precision measurements (mass, branching ratios, differential cross-sections,…)
- Or use Higgs bosons in the final state as a tag for « BSM » physics

➢ Higgs +MET,….

➢ Look for « forbidden » Higgs couplings
In Orsay, where the group was setup for $\gamma\gamma$ analysis , we asked ourselves if

ttbar, with $t \rightarrow cH$, followed by $H \rightarrow \gamma\gamma$ would be competitive for a FCNC search in top decays

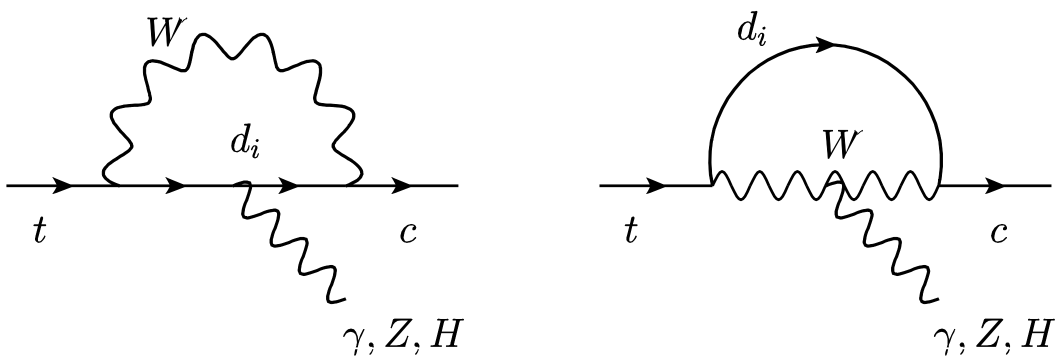
-pro : $\gamma\gamma$ was among the most important « Higgs discovery channels » (with ZZ* 4-leptons , and WW*)
in case of an observation, the mass peak would be a more credible « proof » than a bdt excess
-con: branching ratio of 2.27 E-03 is not a very good starting point
-however, to 100 inv fb at 13 TeV (ttbar Xsection of 832pb) correspond 160 millions top decays
ie S/sqrt(B) and systematics may be more important than S itself….

In the Standard Model…

- In the SM , Higgs FCNC are forbidden at tree level

- More generally, in 1977 Glashow and Weiberg showed that « Natural flavor conservation » is insured in Higgs couplings provided there is only ONE Higgs boson coupling to all up quarks (or to down ones, or to both as in SM) .

- However at one loop, top-Higgs FCNCs are perfectly allowed (and Z, γ as well, and also gluon)



- Due to the GIM mechanism and the large width of the top , the calculated BR is minute (E-12 to E-15…)
- Observation of t→cH at any level would be a clear signal of BSM physics

Phenomenological Lagrangien

$L = L_{SM} - g_W/(2\sqrt{2})\,(\lambda_{tc}\, t_L\, c_R\, H + \lambda_{ct}\, c_L\, t_R\, H)$ (Aguilar-Saavedra…)

-left quark doublet contracted with Higgs doublet

-2 coefficients λ_{ct} and λ_{tc} taken equal; use $\lambda_{tcH} = \sqrt{(\lambda^2_{tc}+\lambda^2_{ct})}$

idem with u quark

From L, one can calculate:

-the top to Higgs branching ratio

$Br = 0.27\,\lambda^2_{tcH}$

$\Gamma_{t\to cH} = G_F M^2_W/(16\pi\sqrt{2})\,\lambda^2_{tcH}\, m_t\,(1 - m^2_H/m^2_t)^2$

$\Gamma_{t\to bW} = \sqrt{2}\, G_F/(16\pi)\, m^3_t\,(1 - 3x^4 + 2x^6)$

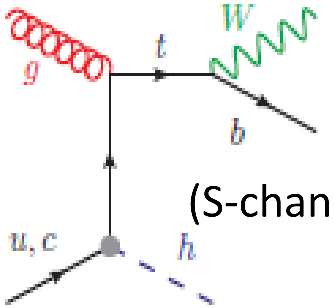
(x=mW/mt)

-the tH FCNC production cross-section (Kamenik et al 2014)

$\sigma(pp \to tH) = 74\ (180)\ \lambda^2_{tcH}$ (pb) at 8 (13) TeV

[σ = 0.67 pb at 13 TeV for Br = 1×10^{-3}]

Similar result by Degrande,Durieux,Maltoni & Zhang at NLO, using EFT formalism (arXiv 1305.7386 and 1412.7166)



(S-channel as well)

Much larger for u quarks due to PDF. Production on c is only ~20% of u , for a fixed Br.

λtcg can also contribute, but is neglected given $B(t\to ug) < 4\ 10^{-5}$

Summary of 95%CL limits for Br ($t \rightarrow cH$) at 7/8 TeV

ATLAS

	Expected (%)	Observed	Remark
diphoton	0.51	0.79	Had and leptonic W
MLL(WW*,ZZ*, $\tau\tau$)	0.54	0.79	2l-SS (1 τ_{had}) and 3 lep
bb	0.42	0.56	Lept-W
Combined	0.25	0.46	1509.06047

CMS

	Expected	Observed	Remark
diphoton	0.67	0.47	Had and leptonic W
MLL(WW*,ZZ*.τlτl)	0.89	0.93	2l-SS and 3lep
bb	0.89	1.16	>=3 b-jets, lept-W
Combined	0.43	0.40	1610.04857

Limits on tcZ are typically 10 times smaller

CMS FCNC H$\rightarrow$ bb 13 TeV (36 fb^{-1})

arXiv 1712.02399v2
CMS-TOP-17-003

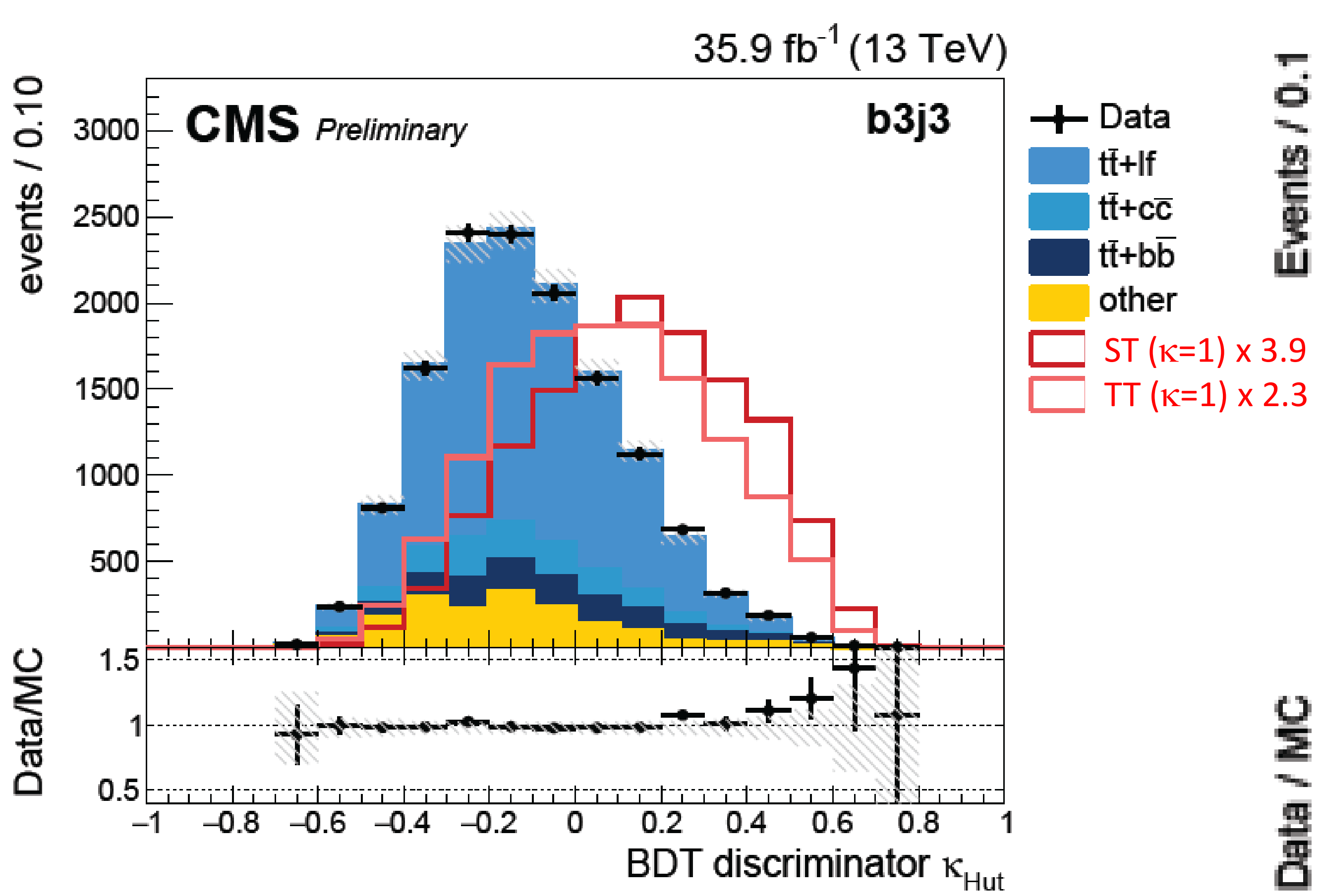
Analysis selection:

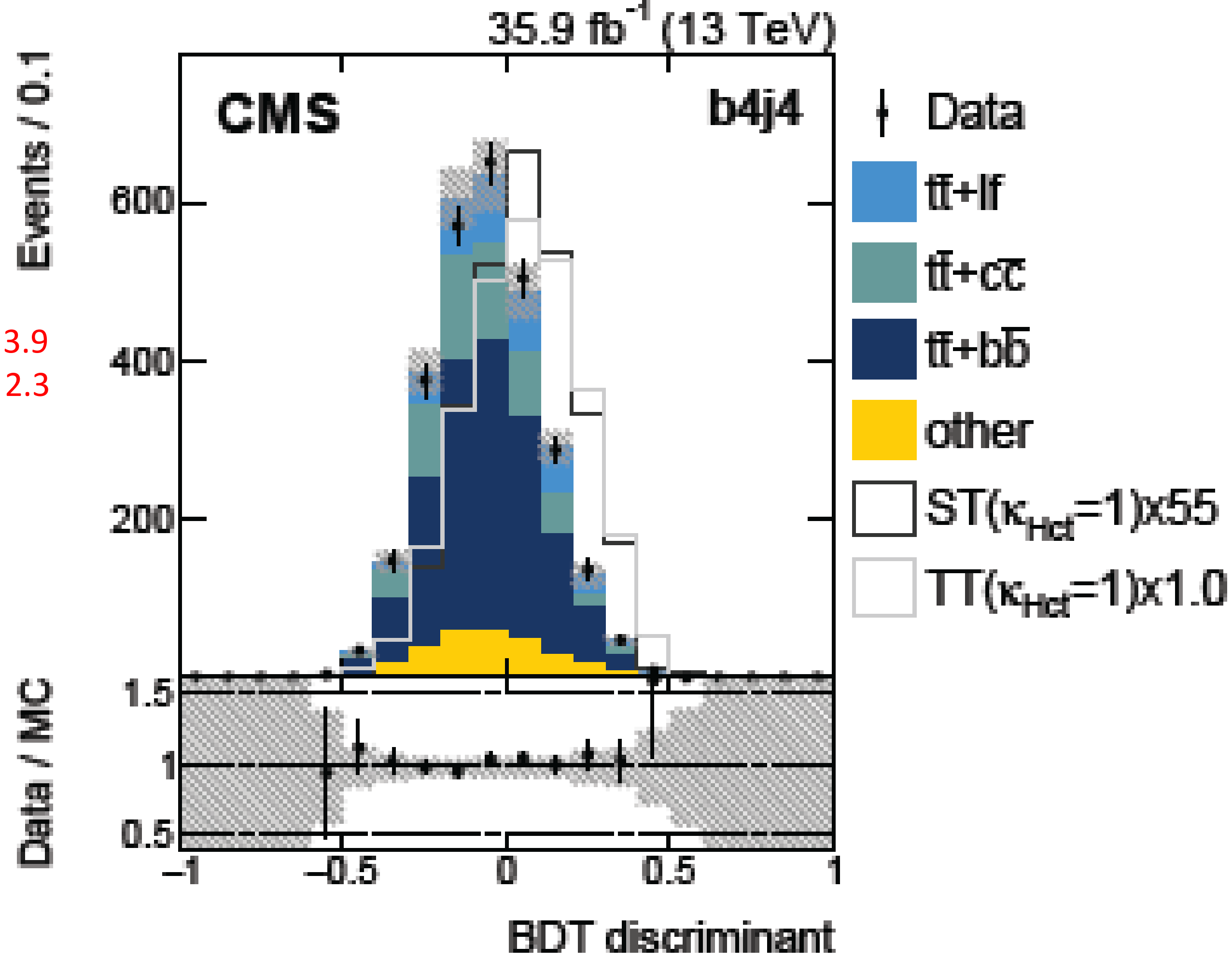
- Exactly one isolated lepton. Trigger threshold 24 (32) GeV for muons (electrons)
- At least 3 jets (pT>30 GeV),
  among which at least 2 are b-tag (ε = 70%)
- Jets and leptons up to $|\eta|$ =2.4 (except crack 1.44-1.57 for electrons)
- Particle Flow reconstruction and pile-up correction
- neutrino ET from PT_miss, EL from mass constraints

Signal simulation: MG5 for both tt production with t$\rightarrow$qH decay,
and tH production (LO)

Background simulation: ttbar (dominant)and single top
use Powheg +Pythia8

Bdt discriminant
within each of several categories
b2j3, b2j4, b3j3,b3j4





Exemple of b3j3, sensitive to tH,
BDT trained for tuH.
Signals normalised independently
to data

Exemple of b4j4, not sensitive to tH,
BDT trained for tcH

Separate bdt training for tH prodution on u and c quarks, and for tt production⊕c(u)H decay
Sensitivity to charm quark in tt final state from larger b-tag probability than for light quarks

B-tagging , generator differences, and JES dominate the systematic effects

Limits obtained using asymptotics (large number of events in all categories)

	Expected (%)	Observed	Remark
bb- 8TeV (tcH)	0.89	1.16	20 ifb , no tH
13 TeV (tuH)	0.34	0.47	36 ifb
13 TeV (tcH)	0.44	0.47	36 ifb

Compared to the 8 TeV analysis, the expected tcH limit is improved by a factor 2 for an increase in the number of top decays (σ , L) by a factor 6.
Inclusion of tH in simulation results in a ~20% improvement of the tuH limit wrt tcH

arXiv 1707.01404 JHEP 10 (2017) 129

ATLAS 13 TeV ttbar, with $t\rightarrow cH$, $H\rightarrow\gamma\gamma$

The two decay modes of the W of the « other top » exploited: full hadronic and leptonic selections:
36.1 ifb from 13 TeV data of 2015 and 2016

Basic selection: 2 tight isolated photons (40,30) ($|\eta|<2.37$ except $|\eta| \in [1.37\text{-}1.52]$) plus either:
-at least 4 jets (pT>30 GeV), no leptons [one b-tag]
-exactly one lepton (electron or muon), at least 2-jets (pT>30) [one b-tag]

trigger: diphoton (35, 25)

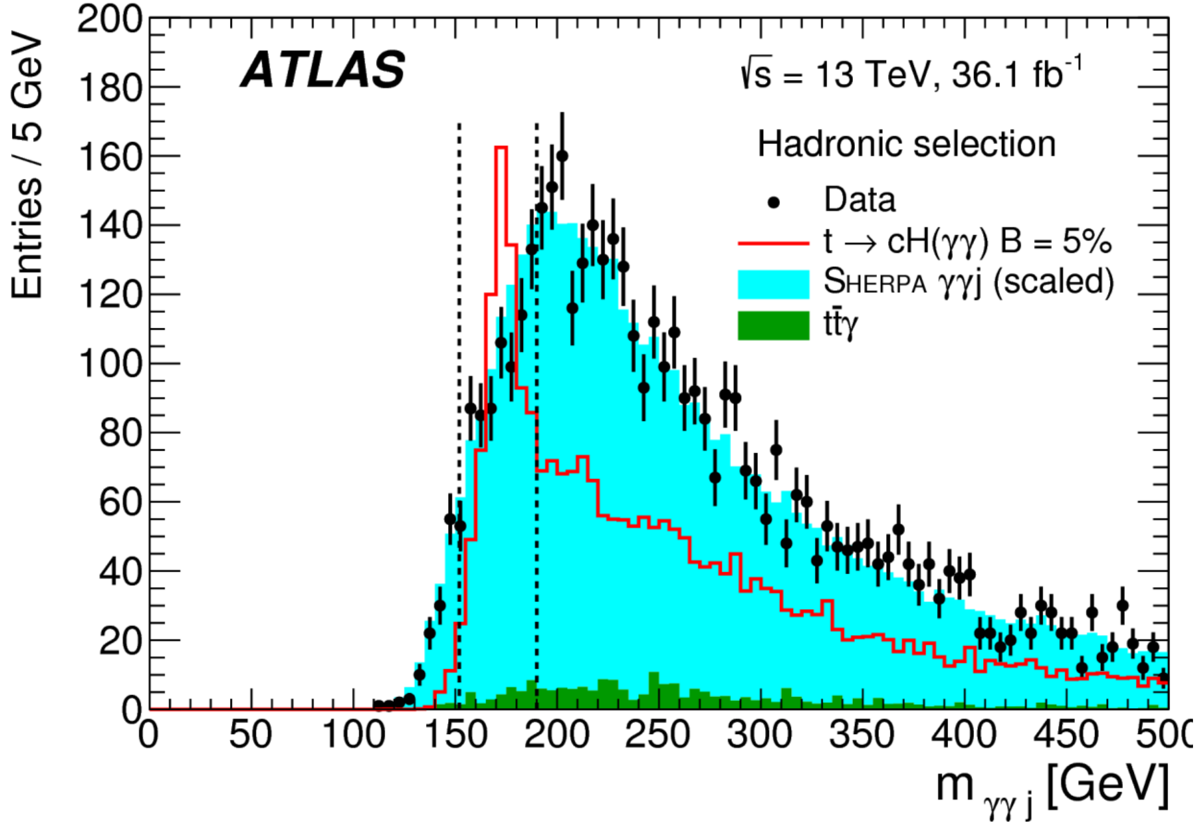
jets: anti-kT (R=0.4) up to $|\eta|=4.4$ « JVT » up to 2.4, PT<60 to remove pile-up
b-tagging at 77% efficiency ($|\eta|<2.4$)
Only the 4 (2) leading jets are considered as such

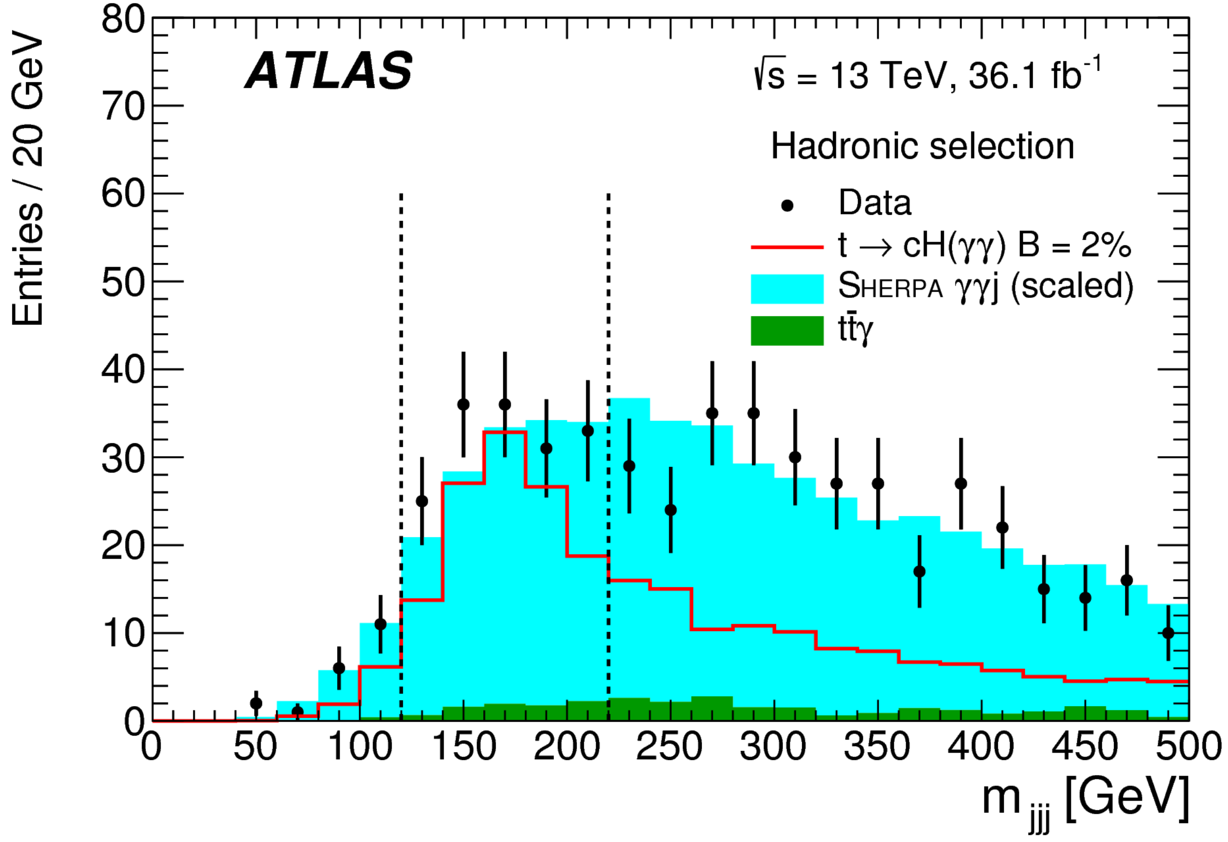
vertex from NN(photon pointing, tracks) ε >97 %

Signal Simulation: MG5_a MC@NLO with TopFCNC-UFO $\oplus$ Pythia8 ; t->cH and t->uH
Non-resonant background: Sherpa diphoton , $tt\gamma$ and (W,Z) $\gamma\gamma$
Resonant background: SM Higgs production; dominated by ttH (MG5_aMC@NLO)

S+B fit of the $\gamma\gamma$ inv. mass distribution, ie bkg estimate is purely « data driven »

Hadronic selection



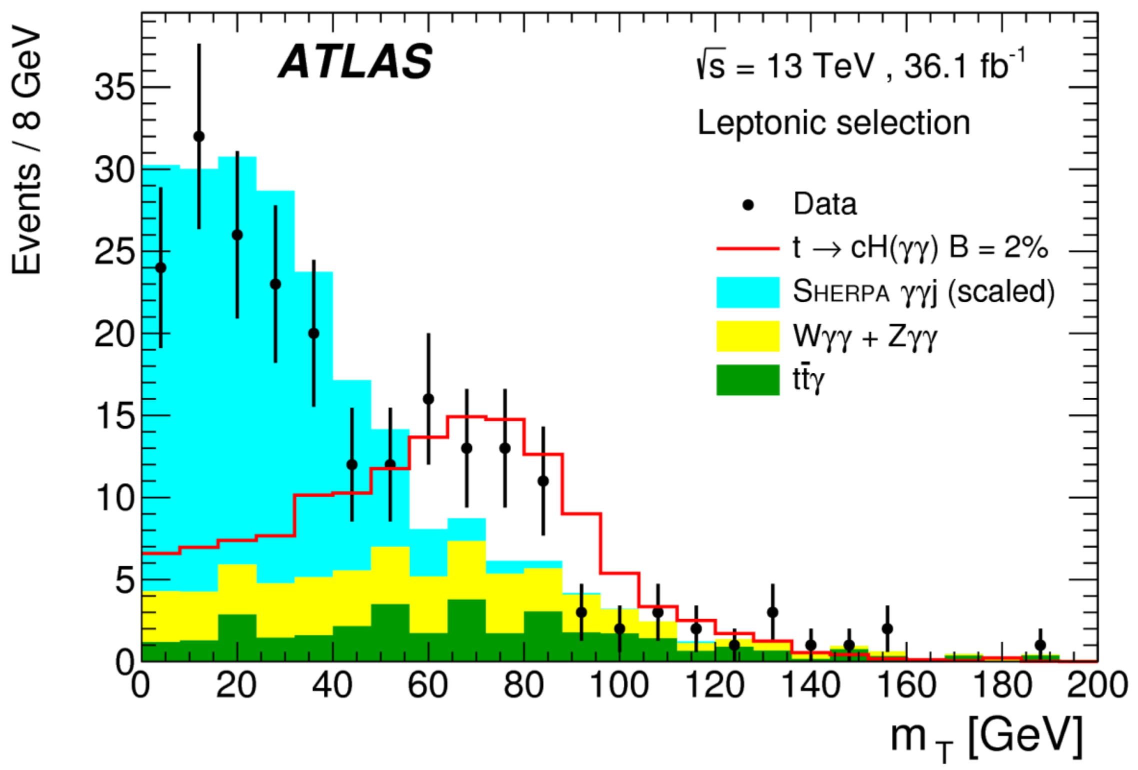


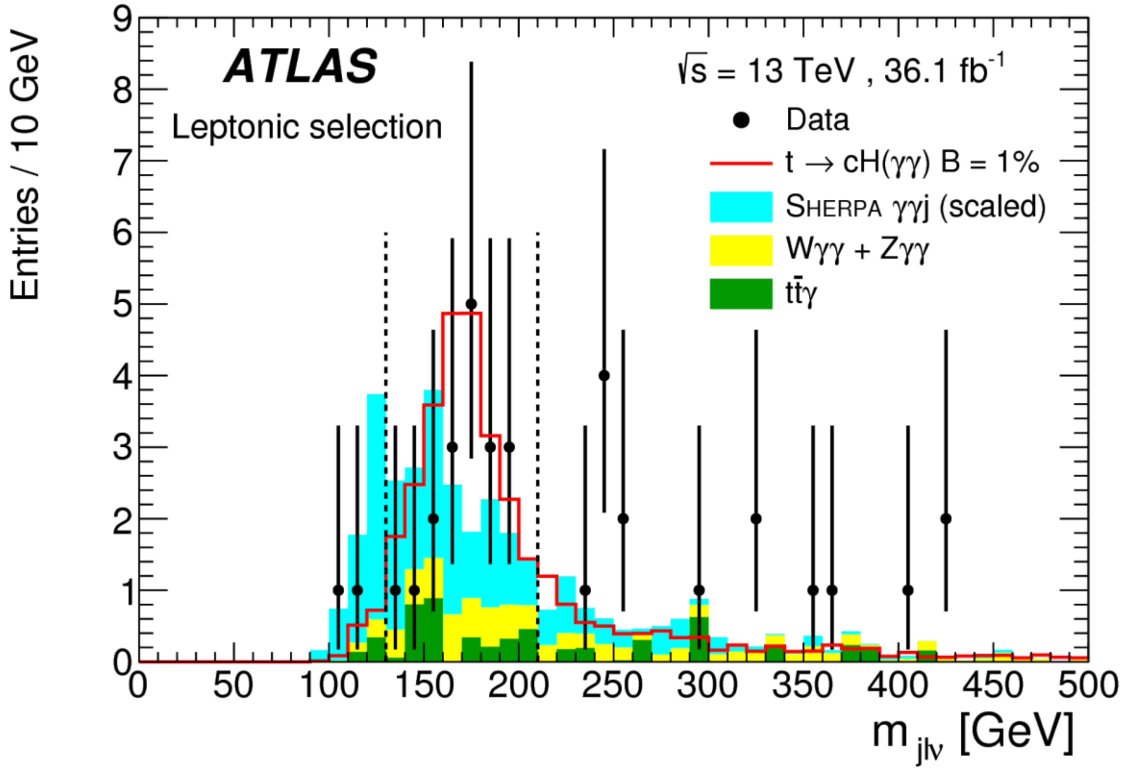
4 combinations/event

Excellent γγj mass resolution
« MTop1 » acceptance bin =[152-190] GeV

Only combinations fulfilling Mtop1 enter
Categorie-1=« MTop2 » in [120-220] GeV

Leptonic Selection

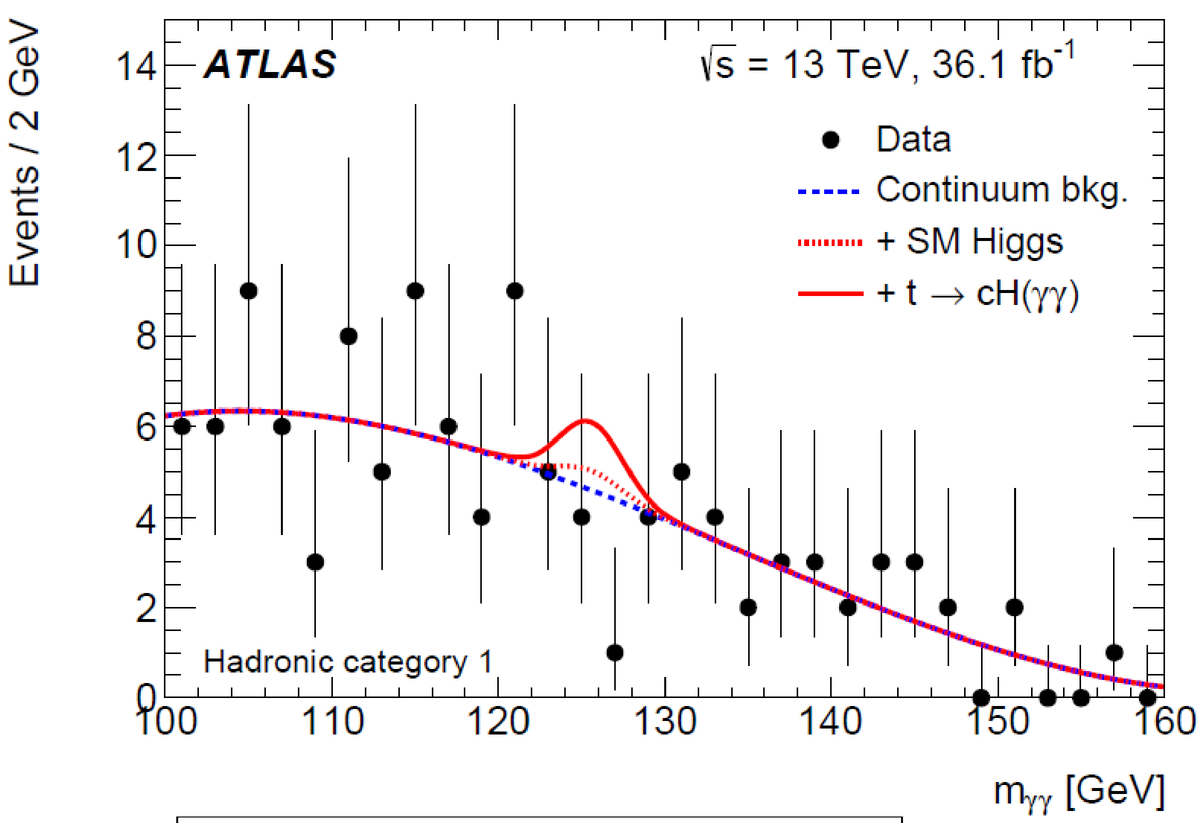


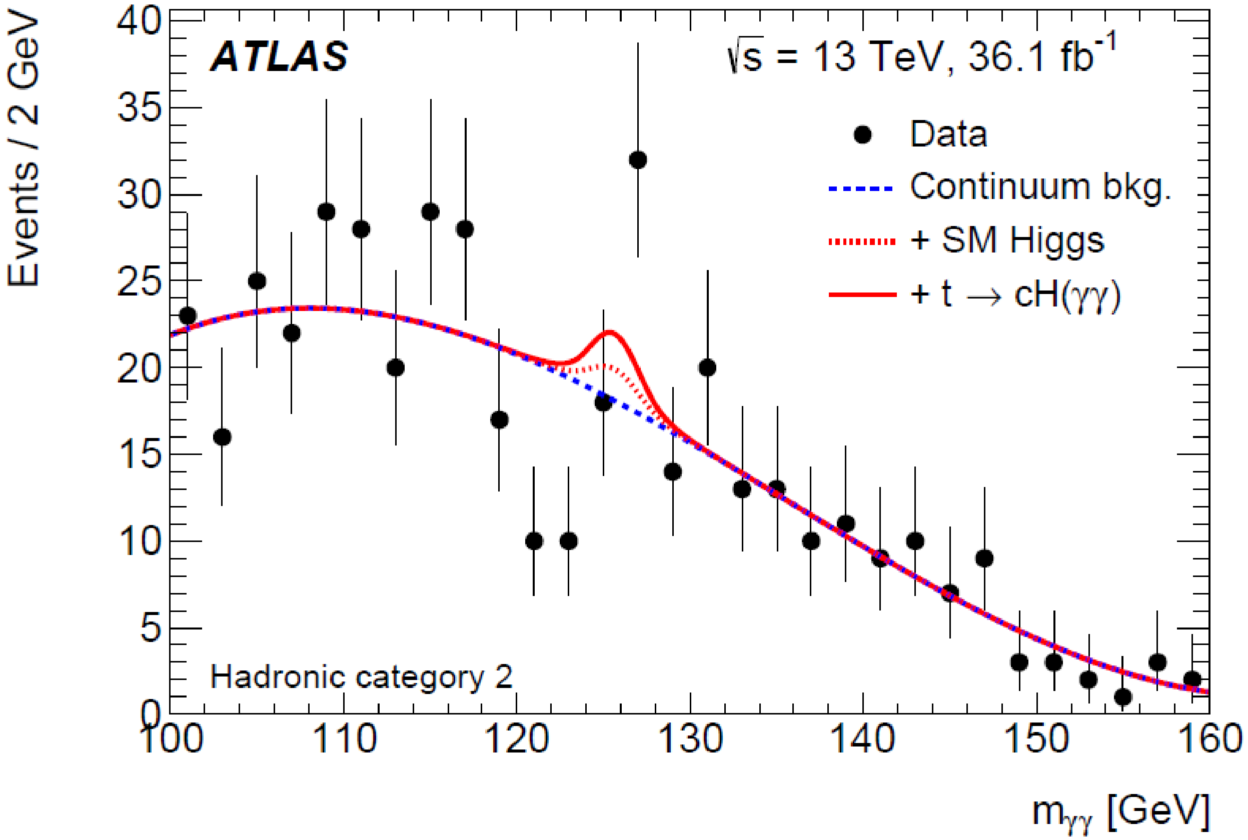


ttγ and (W,Z)γγ somewhat on the low side.
MC stat is low. Stat now improved…

Only MT>30 GeV, and Mtop1 [152,190] enter
Categorie 1: Mtop2 in [130-210]

Hadronic selection : 2 categories



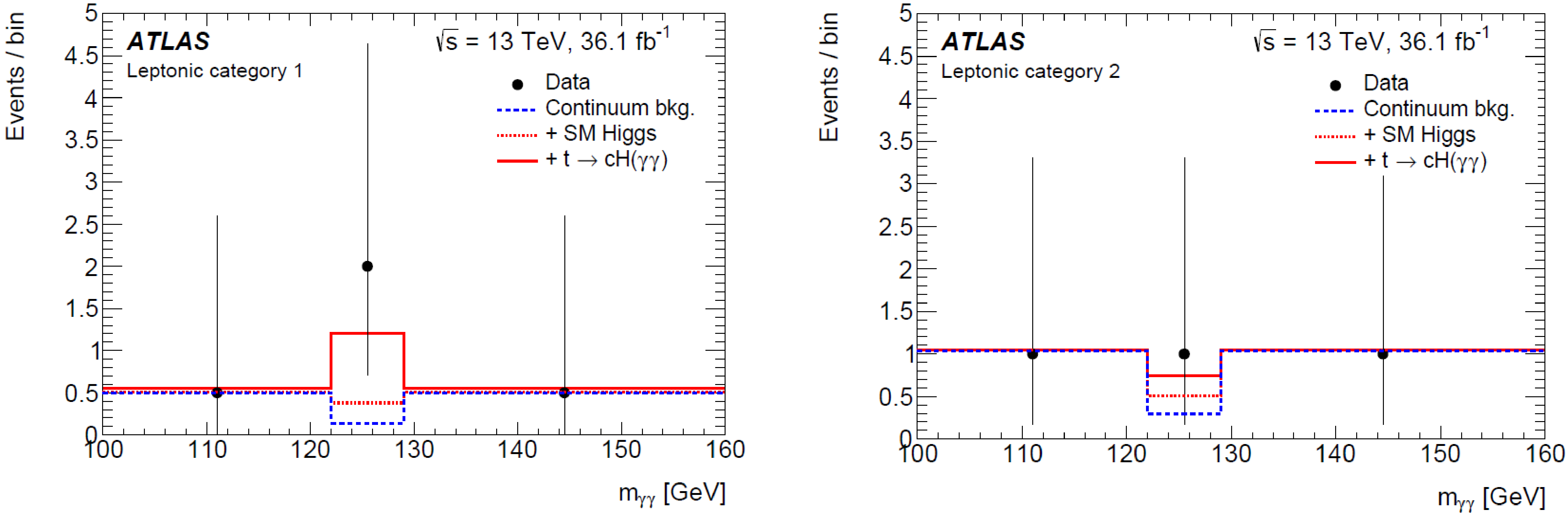


Categorie 1: at least 1 combination
Passing Mtop1 & Mtop2
(b-tag jet is « any of the 4 jets »)
115 data events selected

Categorie 2: same as cat-1 except that the
Mtop2 condition is not fulfilled.
437 data evts selected

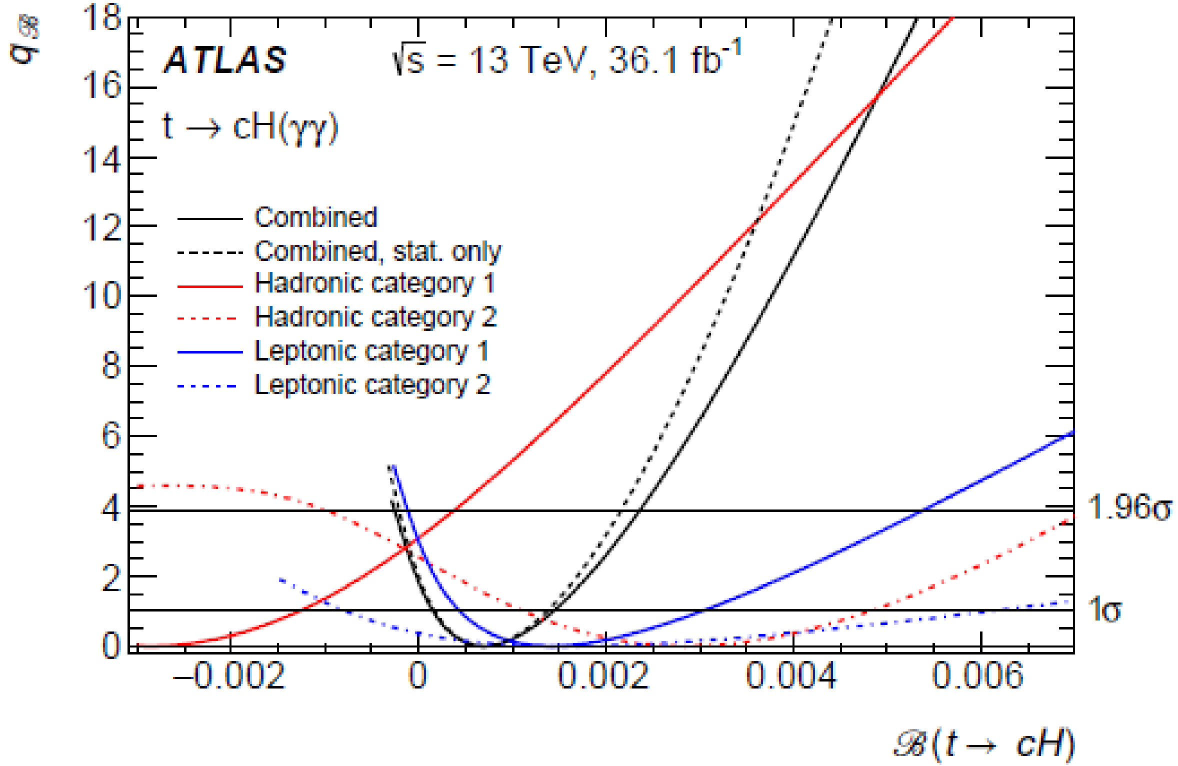
The fit is combined with the 2 leptonic categories;
The degree of the polynomial (3) is determined from Sherpa

Leptonic selection: 2 categories



Fit combined with the 2 hadronic categories.
Only 2 bins: [122-129] and the rest
The background ratio between [122-129] and the rest is weakly constrained by ttγ and (WZ)γγ and Sherpa, while the bkg level is fixed by the content of [100-160]-[122-129]

γγ final result



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
Acceptance & efficiency (%)	2.89	4.15	0.96	0.27

- Leptonic and hadronic have about the same sensitivity
- The uncertainty is statistics dominated
- Main Systematics: JES, b-tagging, generator
- Best Fit: $\hat{\mathcal{B}} = 6.9^{+6.8}_{-5.2}(\text{stat.})^{+3.1}_{-1.5}(\text{syst.}) \times 10^{-4}$
- 95% CL upper limit
  tcH Br < 2.2 x 10^{-3} (1.6 x 10^{-3} expected)
  tuH Br < 2.4 x 10^{-3} (1.7 x 10^{-3} expected)
- Coupling limit $\sqrt{\lambda_{tcH}^2 + 0.92\lambda_{tuH}^2} < 0.090$
- Cheng and Sher λ_{tcH} ~ √ (2 mc mt)/v ~ 0.06

ATLAS 13 TeV , multileptons (WW*,ZZ*,$\tau\tau$(ll))

Exploits the tt final state where the W of the SM top has a leptonic decay (e,μ), and
the Higgs of t$\rightarrow$cH decays in either WW*, ZZ* or $\tau\tau$ with at least one additional leptonic (e,μ)decay.

Basic selection: trigger: single lepton(20 to 26) or dilepton(12 to 22)

either -2 « tight »leptons SS (20,20) (electron:$|\eta|$<2.47 except $|\eta| \in$ [1.37-1.52]), muon $|\eta|$ <2.5)
plus at least 4 jets (pT>25 GeV), [one or two b-tag]

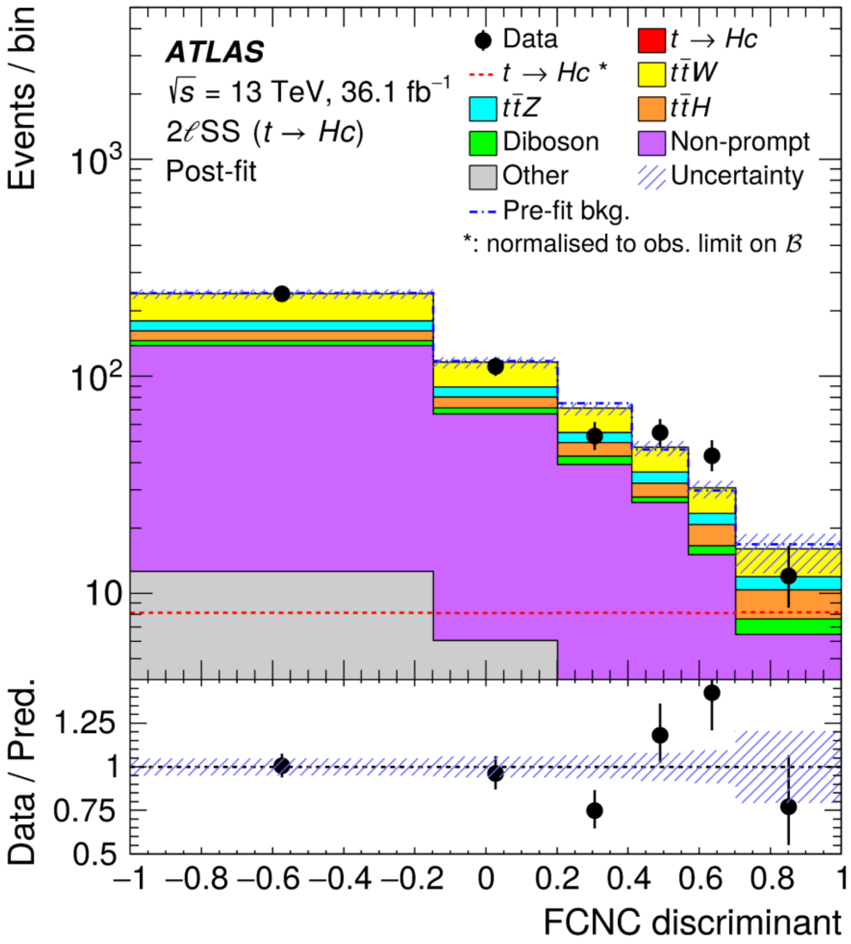
or -3 leptons (15,15,10:TTL) (looser is the one with opposite charge to the other 2)
plus at least 2 jets (pT>25 GeV), [at least one b-tag]

jets: anti-kT (R=0.4) up to $|\eta|$=2.5 « JVT » up to 2.4, PT<60 to remove pile-up
b-tagging at 70% efficiency ($|\eta|$<2.4)

Signal Simulation: MG5_a MC@NLO with MadSpin $\oplus$ Pythia8 ; t->cH and t->uH
SM backgrounds: ttW, ttZ, ttH : MG5_aMC@NLO ; di and triboson, single-top,..

Signal selection by BDTs, one trained against SM background (ttV,..),
the other against fake leptons (like b-decays in tt events) , then combined.
Separate BDTs for tcH and tuH and for 2 leptons SS and 3 leptons.

Exemple of BDT output; tcH for 2leptons SS and 3 leptons, data compared to best fit

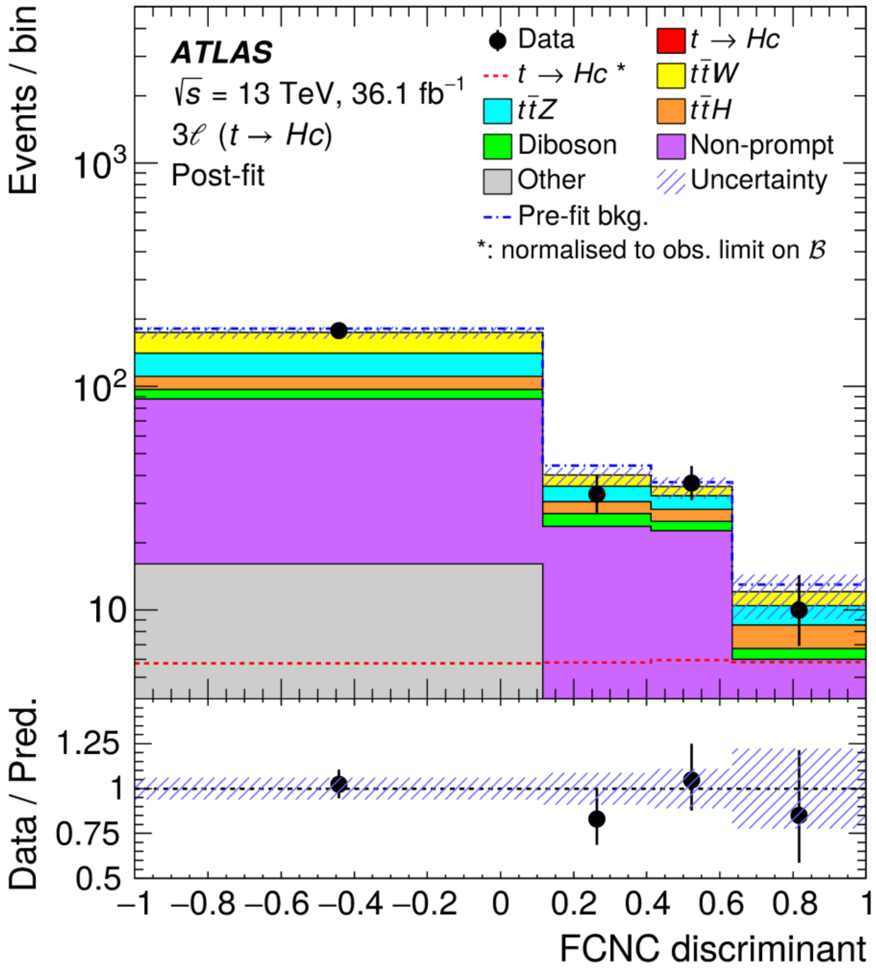


Binned Likelihood fit on 2lSS and 3l together, for tcH and tuH separetly

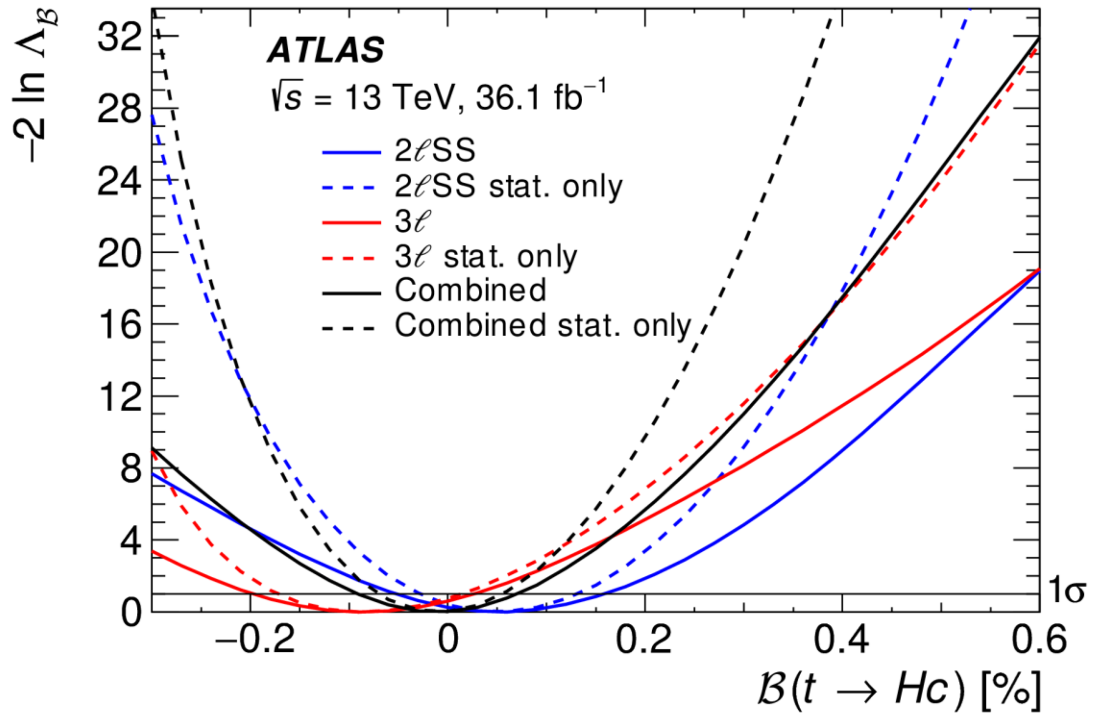
t→cH histo normalised to best fit is invisible

t→cH dotted red line: normalised to the 95%CL limit of 0.16%

Largest contribution in high-BDT bin from ttW, ttZ and ttH



Fit Results



- Acceptance (incl Br): 5.6 (2.1) x 10^{-4} for 2lSS(3l) dominated by H→WW*
- ttH ~ 30% of FCNC at the observed limit

	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)

Limit for t-Hu is 0.19 (0.15)

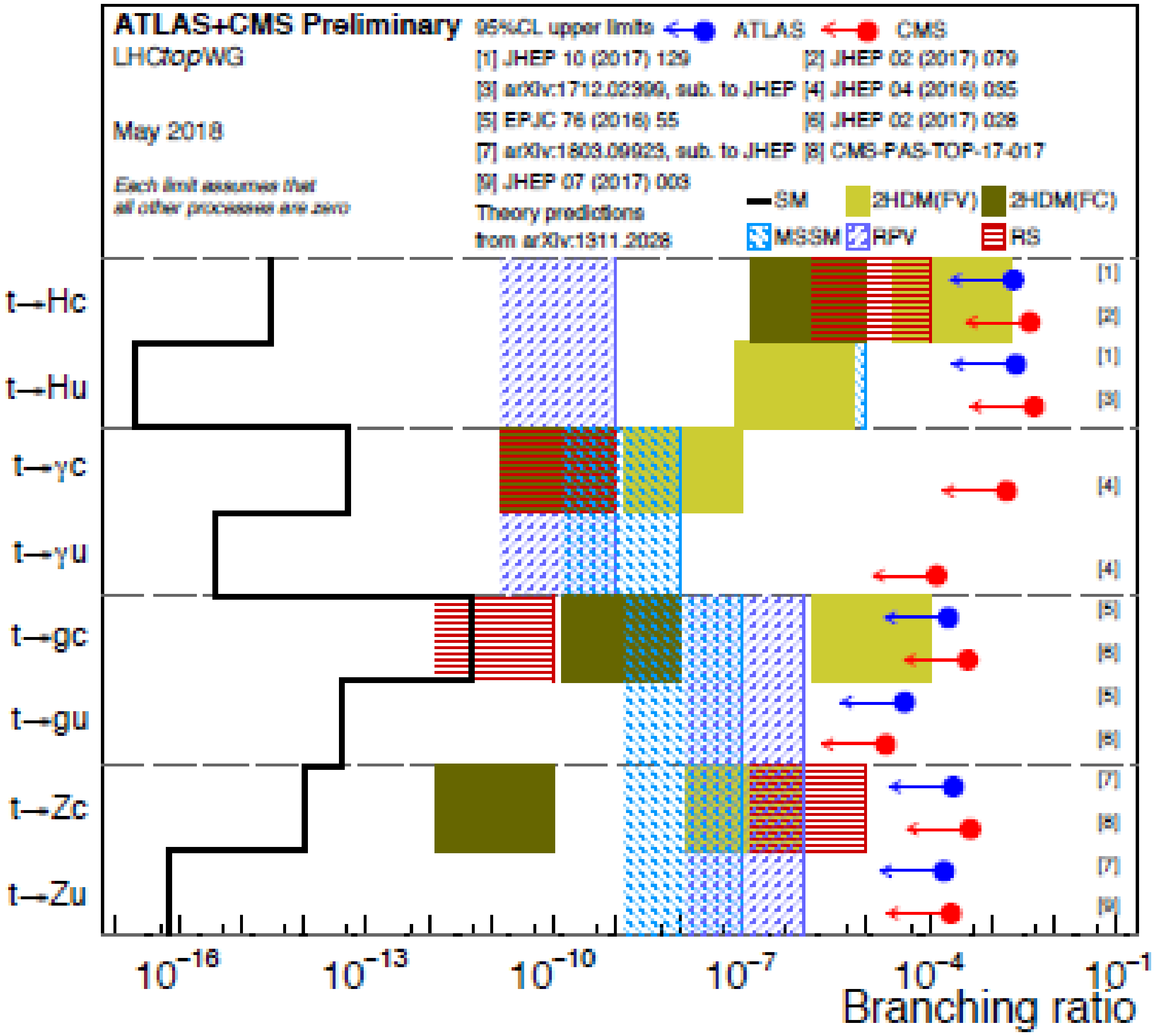
Sensitivity comparable to the diphoton mode
Uncertainties dominated by statistics, but systematics start to contribute

Summary

- Several channels contribute to the limits obtained for tcH and tuH couplings
- « Higgs discovery channels » $\gamma\gamma$ and multileptons play a leading role and are not yet limited by systematic uncertainties.
- Taking account of the tH final state brings some additionnal sensitivity for tuH
- Resonant background from ttH soon sizeable
- Optimistic models a la Cheng-Sher in the range now accessible (for tcH).

Back-up

FCNC



May-2018
Atlas-ML not included

Lagrangian from EFT (Degrande, Durieux,Maltoni, Zhang)

arXiv 1305.7386v2 and 1412.7166v2

- t->qH by FCNC actually from a dimension 6 Operator $O_{u\varphi}^{(1,3)} = -y_t^3(\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}$ with $y_t = \frac{\sqrt{2}m_t}{v}$
- Width of t->cH $\Gamma^{(0)} = \frac{|C_{u\varphi}|^2}{\Lambda^4}\frac{\sqrt{2}G_F m_t^7}{8\pi}\left(1-\frac{m_h^2}{m_t^2}\right)^2$ $\Gamma^{(0)} = 7.11|C_{u\varphi}(\mu)|^2 \times 10^{-4}\,\mathrm{GeV}$
- For a Br limit of 1x 10^-3 this gives $C_{u\varphi}$ = 1.4 corresponding to λ_{tcH} ~ 0.06
- In turn, using this formalism in madgraph5 for NLO simulations of tH production at 13 TeV, gives a cross section - for C=1.4 - of 0.8 pb fom u quarks and 0.12 pb from c-quarks (to be compared to SM ttH cross-section of 0.51 pb, and SM tHJb cross-section of 0.07pb).
- tH production has not been considered so far in ATLAS FCNC analyses; now prepared for next round
- CMS used tH (calculated at LO) (and ttbar) for their analysis at 13 TeV, based on the bb final state

Acceptance and expected signal for B=0.2 %
(acceptance does not include $H\to\gamma\gamma$ Br of 2.27 10^{-3})

Selection	Hadronic		Leptonic	
Category	1	2	1	2
	Signal $t \to cH$			
Acceptance with stat. unc. [%]	2.89 ± 0.10	4.15 ± 0.12	0.96 ± 0.03	0.27 ± 0.02
Expected events for $\mathcal{B} = 0.2\%$	$7.85^{+0.64}_{-0.67}$	$11.30^{+0.91}_{-0.96}$	$2.60^{+0.21}_{-0.23}$	$0.71^{+0.07}_{-0.07}$
	SM Higgs boson resonant background			
Expected events	$1.17^{+0.09}_{-0.11}$	$3.27^{+0.25}_{-0.27}$	$0.26^{+0.02}_{-0.03}$	$0.23^{+0.02}_{-0.02}$
$t\bar{t}H$ fraction	90%	68%	92%	77%