ATLAS EXPERIMENT
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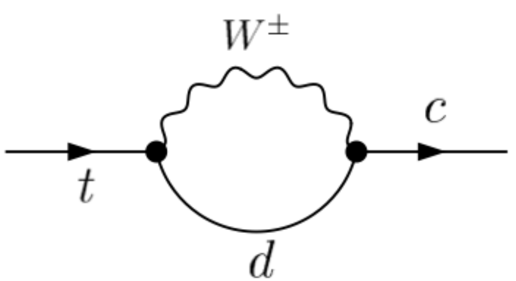
Search for FCNC in $t \rightarrow cH$

- Motivation
- Analyses
  - Di-photon analysis
  - Inclusive multi-lepton final states
- Conclusion

Motivation

Why search for top decays to light up type quark + X, $t \to cX$?

✓ Flavour changing neutral current (FCNC) involving light u, c quarks are highly suppressed in the standard model : GIM mechanism



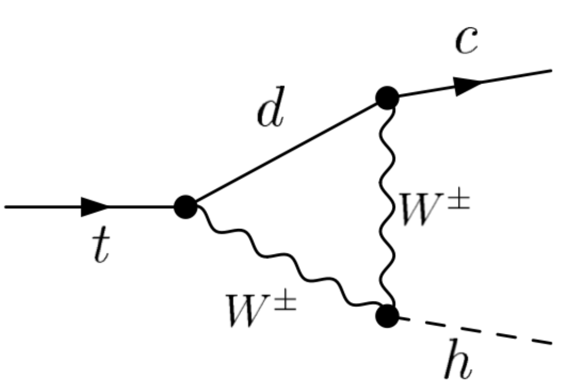
+ Z,γ, (g) line attached to any (quark) line

$$\Gamma(t \to cV) \propto |V_{cb}|^2 \alpha_{QED}^2 \alpha m_t \left(\frac{m_b}{m_W}\right)^4$$

Loop controlled by down quark ~ m_b
⇒ much more suppressed than FCNC in the down sector (e.g. $b \to s\gamma$)

- $V = g$: $\alpha = \alpha_s$, Br ~ 10^{-12}
- $V = Z/\gamma$: $\alpha = \alpha_{QED}$, Br ~ 10^{-14}-10^{-13}

Even worth for the decay to Higgs boson
Br ~ 10^{-15}



Is this generic in most of popular BSM models ?

- Additional heavy quarks, e.g. vector like quarks :

  3x3 CKM matrix no longer unitary
  $\Rightarrow$ GIM mechanism to suppress SM amplitudes relaxed

  tree level flavour changing gauge and scalar interactions

  E.g. for Q = 2/3 up type singlet :

  $B(t \to cZ) \sim < 10^{-4}$
  $B(t \to cH) \sim < 4.\ 10^{-5}$
  ($B(t \to c(\gamma/g))$ less enhanced)

  (down type Q = -1/3 singlet gives much less enhancements because of more constrains in the down quark sector)

Two Higgs Doublet Models : prejudice from ***Natural Flavor Conservation***

Avoid fine tuning (small couplings) to get rid of FCNC by :

⇒ coupling a single doublet to fermions

2HDM-I

⇒ coupling up-type fermion to a doublet and down type to another one

2HDM-II (SUSY)

⇒ No tree level FCNC, but large enhancements still possible ($B \sim 10^{-5}$)

especially in SUSY-QCD from tree level FC gluino couplings

(more and more constrained by direct SUSY searches…)

or in general 2HDM-II, at high tanβ (purely EW contribution)

However small couplings can be *natural* : NFC not really needed

e.g. Cheng-Sher scenario (inspired from Fritzsch ansatz) : mass matrix given by

$$M_{ij} = \Delta_{ij}\sqrt{m_i m_j} \qquad \Delta_{ij} \sim O(1)$$

Leading to Yukawa couplings $\lambda_{ij} \sim \frac{\sqrt{m_i m_j}}{v} \sim \frac{\sqrt{m_i m_j}}{2m_W} g$

⇒ 2HDM-III

less well defined than the two others, tree level FCN scalar interactions

but still no gauge FCNC (GIM intact)

For $(i,j) = (t,c)$, $\lambda \sim 10\%\ g$, not a small coupling !

For light quarks, light masses involved ⇒ small couplings and constrains from flavour OK

So, why search for top decays to light up type quark + X, $t \to cX$?

- ✓ LHC Run I : observation of a new (scalar) boson H with mass $m_H \sim 125.5$ GeV/c^2

  $m_t > m_H + m_c \Rightarrow$ why not ? 

- ✓ FCNC are experimentally less constrained (single top production at LEP, Hera, Tevatron D-D mixing, $t \to q\, Z/\gamma$ at Tevatron) than the ones in the down type sector
- ✓ LHC is a top factory, that can be used to search for such processes, e.g. in top decays

  $t \to q\ g/\gamma/Z/H$

$(c/u\ (SM) \sim |V_{cb}/V_{ub}|^2)$

	SM expectation	Max expect. in some exotics (*)	Limits on Br, % (95% CL)
$t \to c(u)\ g$	$\sim 5.\ 10^{-12}$ $(4.\ 10^{-14})$	$\sim 2.\ 10^{-4}$ $(2.\ 10^{-4})$	Direct : very hard at LHC Search for single top strong production instead : 7.6 10^{-5} (1.5 10^{-5}), ATLAS 8TeV, 14.2 fb^{-1}
$t \to c(u)\ \gamma$	$\sim 5.\ 10^{-14}$ $(4.\ 10^{-16})$	$\sim 2.\ 10^{-6}$ $(2.\ 10^{-6})$	hard
$t \to c(u)\ Z$	$\sim 10^{-14}$ (10^{-16})	$\sim 10^{-4}$ (10^{-4})	0.07 / 0.73 (8 TeV CMS 19.5 fb^{-1}/ 7 TeV ATLAS 2.1 fb^{-1})
$t \to c(u)\ H$	$\sim 3.\ 10^{-15}$ $(2.\ 10^{-17})$	$\sim 10^{-3}$ (10^{-5})	-

$\Rightarrow$ Any observation of such processes is a non ambiguous sign of new physics
Some models predict enhancement by several order of magnitude
(not to the % level though...), largest enhancement from 2HDM models (especially type III)

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Analyses

ATLAS-CONF-2013-81
ATLAS-PHYS-PUB-2013-012

Playing with di-photon events (ATLAS) :

Search for FCNC in top decays $t \to cH$, followed by $H \to \gamma\gamma$
Pair production of top quarks are considered :
one of the top decays to cH, the other decays to Wb

$$pp \to t\bar{t} \to W^{+}b\ Hc \to f\bar{f}'\ b\ \gamma\gamma\ c + c.c.$$

For $H = H_{SM}$ and $B(t \to cH) = 1\%$,
expect N ~ 260 produced events in the LHC RunI data set

A rather straightforward analysis : start from the standard $H \to \gamma\gamma$ inclusive selection
→ two high p_T (30/40 GeV/c) isolated photons (tight identification criteria)
→ add cuts on jets and invariant masses to fully reconstruct the final state
(one W (lept. or hadr.), one Higgs boson, two tops)

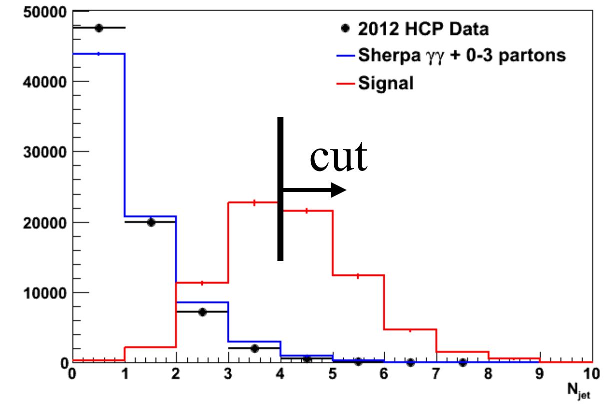
Initial $\gamma\gamma$ sample :
~ 24K (7 TeV) + ~ 119 K (8 TeV) events
with $m_H \in [100,160]$ GeV/c^2
$\oplus$

- three jets : the hadronic channel (at 7 and 8 TeV)
- a lepton (e/μ), a neutrino and a b-jet : the leptonic channel (only at 8 TeV)

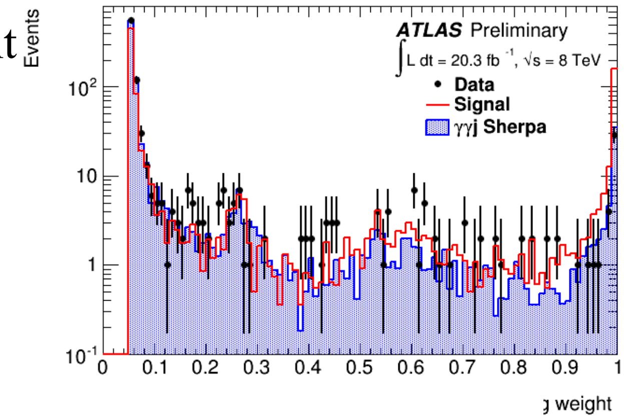
Hadronic channel

At least 4 jets
At least one b-tag (70% b-efficiency)
No lepton
From the 4 leading jets :
$m_{\gamma\gamma j} \in [156,191]$ GeV/c^2
$m_{\varphi\varphi j} \in [130,210]$ GeV/c^2
(if 5th or 6th b-tagged, and 4th or 5th not, use it instead)

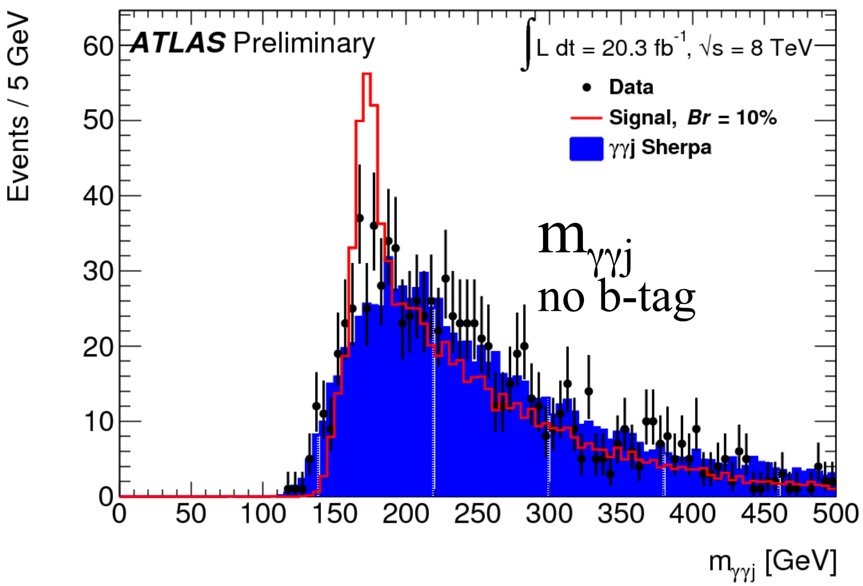
Jet multiplicity

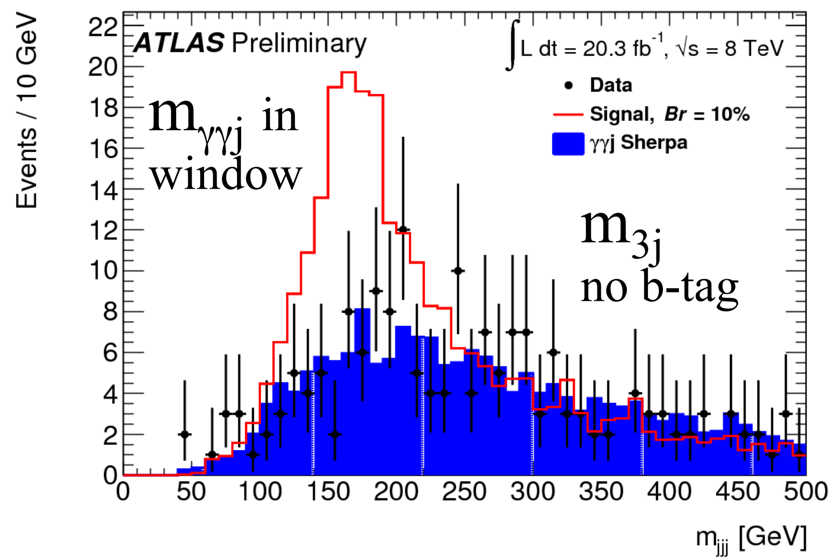


b-tag discriminant
($N_{jet} > 3$)



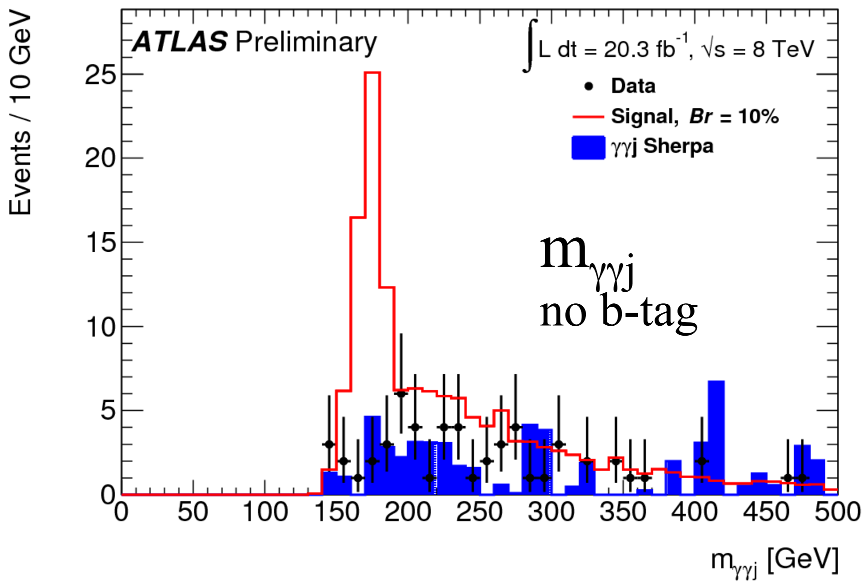
Do not intend to predict the background from MC
but decent agreement between data and Sherpa MC shapes

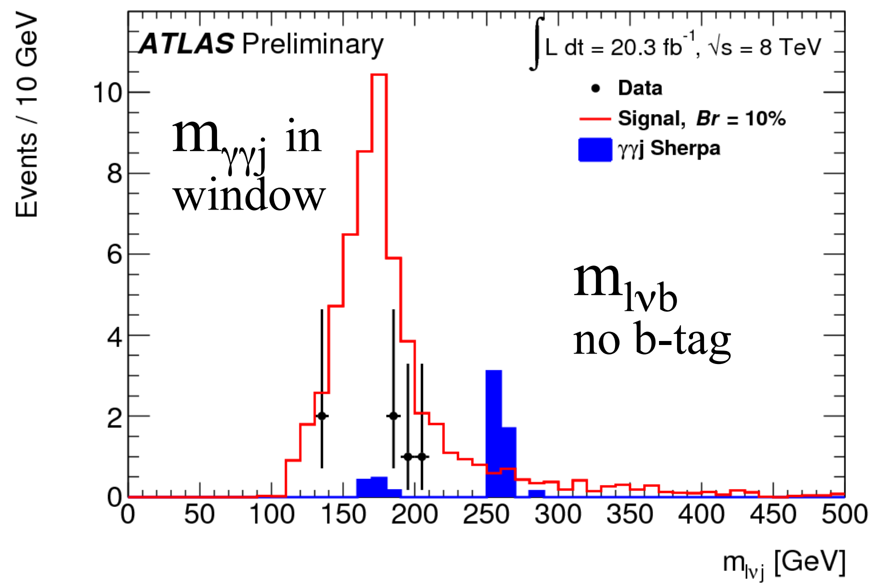




Leptonic channel

One lepton, at least 2 jets
At least one b-tag (70% b-efficiency)
No other lepton
$m_T(l,E_T^{miss}) > 30$ GeV/c^2
From the 2 leading jets :
$m_{\gamma\gamma j} \in [156,191]$ GeV/c^2
$m_{l\nu j} \in [135,205]$ GeV/c^2
(p_z^{ν} from W mass constrain)
(if 3rd or 4th b-tagged, and 2nd or 3rd not, use it instead)



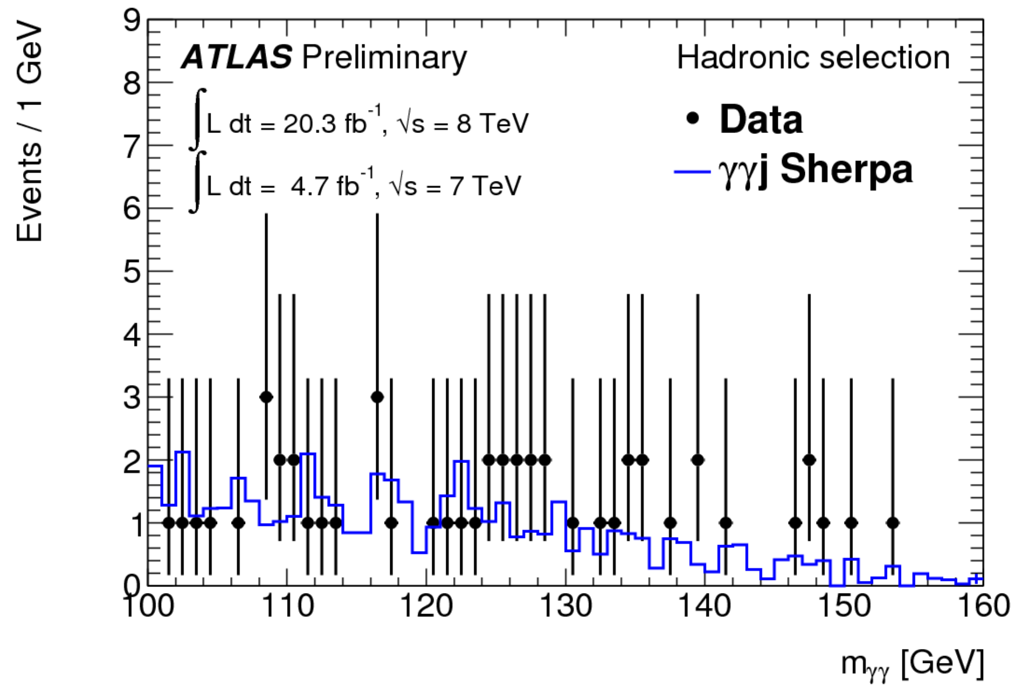


Results :

- **Hadronic channel** (7+8 TeV combined) :

$N_{FCNC}(B(t \rightarrow cH) = 1\%) = 10.9 \pm 0.8_{theory}$
$N^{SM}{}_{H} = 0.28 \pm 0.10_{theory+lumi}$

$N_{obs} = 50$



- **Leptonic channel** (8 TeV) :

$N_{FCNC}(B(t \rightarrow cH) = 1\%) = 2.9 \pm 0.2_{theory}$
$N^{SM}{}_{H} = 0.05 \pm 0.01_{theory+lumi}$

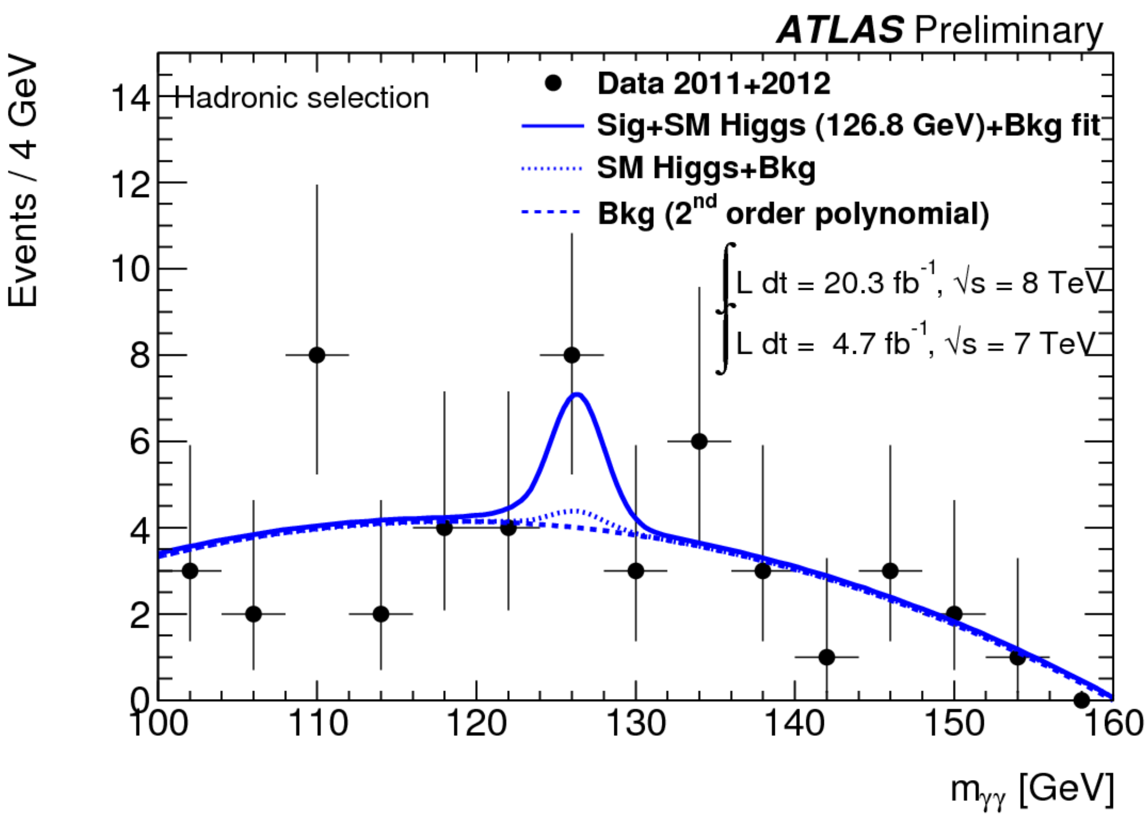
$N_{obs} = 1$, $m_{\gamma\gamma} = 147$ GeV/c^2

- **Systematic uncertainties** : dominated by photon ID and isolation,
(increased w.r.t. standard H analysis to account for busier environment)
+ jet energy scale, b-tagging and underlying event modelisation

Statistical interpretation :

- Hadronic channel : enough events to determine background under the peak from fit to the $m_{\gamma\gamma}$ distribution :
  bkg shape = 2nd order polynomial / signal shape : Crystal-Ball + wide Gaussian

- Leptonic channel, two bin shape analysis : constrain bkg expectation in signal region ([123,129] GeV/c^2) from control region [100,123[U]129,160] GeV/c^2



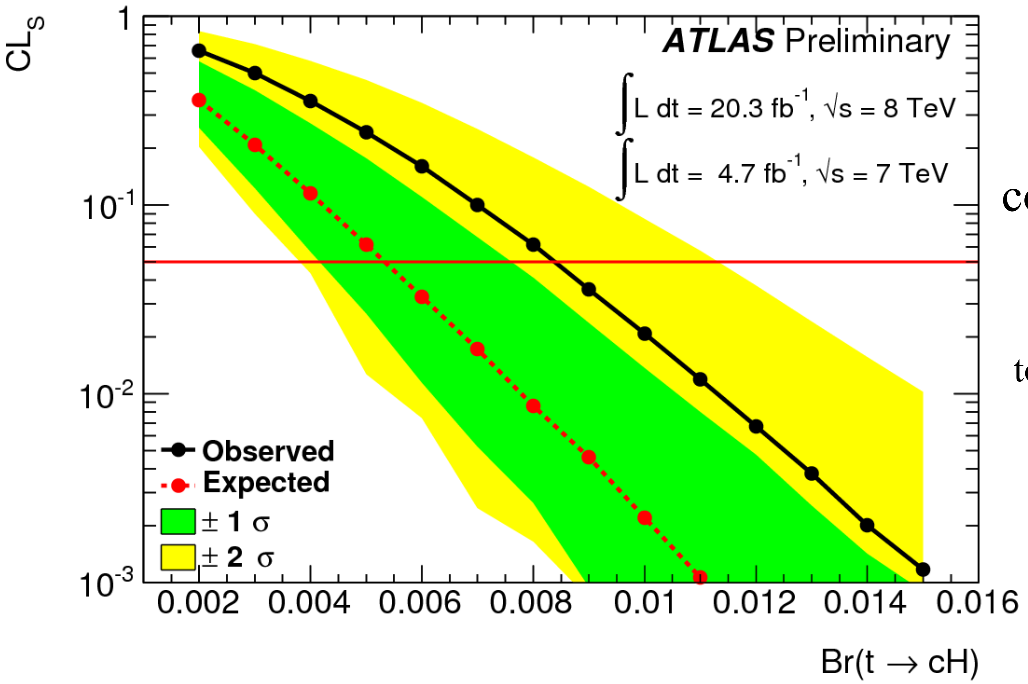
Fixing m_H = 126.8 GeV/c^2 fitted branching ratio :

$$Br = 0.26^{+0.31}_{-0.26}\%$$

corresponding to a signal yield of

$$N_S = 3.7^{+4.4}_{-3.7}$$

No signal observed ⇒ limit



$B(t \to cH) < 0.83\%$ @ 95% CL (0.53% expected)

corresponding to a limit on the *tcH* coupling

$\lambda_{tcH} < 1.91\ B^{0.5} \sim 0.17$ (0.14 expected)

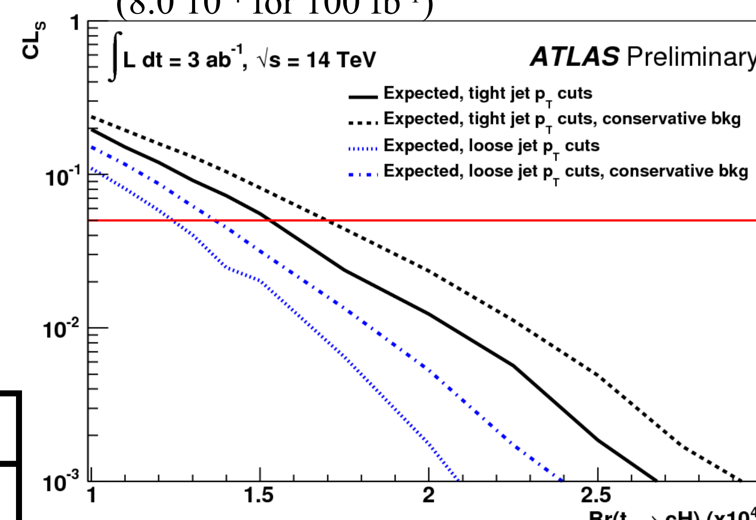
to be compared to top quark Yukawa coupling

$\lambda_{tcH} \sim 1$

Might expect

$B(t \to cH) < 1.5\ 10^{-4}$ % @ 95% CL

($8.0\ 10^{-4}$ for 100 fb^{-1})



Prospects at HL-LHC (14 TeV/3ab^{-1})

- ✓ signal cross-section (σ_{tt}) : x 3.9
- ✓ non resonant bkg σ : x 2.2
- ✓ resonant bkg (ttH) : x 4.7
- ✓ but needs tighter cuts (higher pile-up)

events in signal window

	FCNC	SM Higgs	Bkg
Hadronic	13	24	350
Leptonic	7	14	25

Sensitivity to "real" models with $H \to \gamma\gamma$ channel only !

Re-interpreting multi lepton searches (CMS) :

- Use the weak boson and tau decays of H, in multi-lepton final states
  - more events ($B(H \to WW^* \to e/\mu\ \nu\ e/\mu\ \nu) \sim 1\% + ZZ^* + \tau^+\tau^-$)
  - more difficult to interpret than the di-photon channel in case of an excess (no full reconstruction)

  $\Rightarrow$ better for limit setting…

3 leptons
+ a number of categories defined from

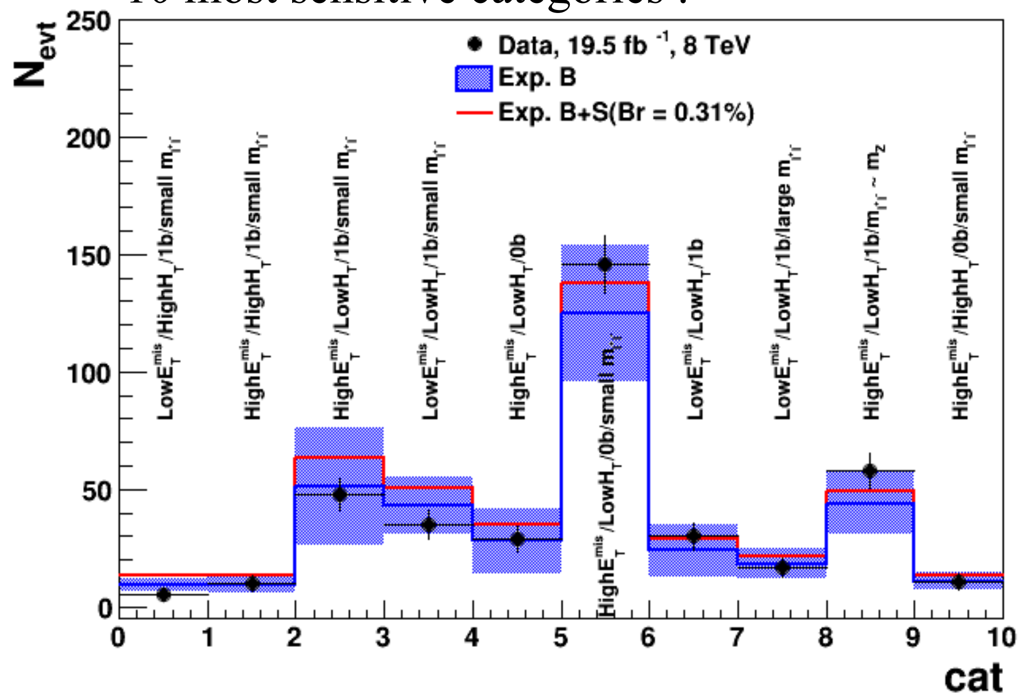
- ✓ number of b-tagged jets (0 / ≥1)
- ✓ H_T (sum of all good jet p_T)
- ✓ E_t^{mis}
- ✓ the consistency of an Opposite Sign Same Flavour lepton pair with a Z

No excess seen ⇒ limit

$B(t \to cH) < 0.31\%$ @ 95% CL (0.31% expected)

(essentially from $H \to WW^*$: if no $ZZ^*/\ \tau^+\tau^-$: B < 0.37%)

Comparison Data / Bkg prediction for the 10 most sensitive categories :



corresponding to a limit on *tcH* coupling

$\lambda_{tcH} < 0.1$

Conclusion

- SM yields for FCNC $t \rightarrow cX$ process are extremely small (beyond reach of any experiment)

- Some not-so-unlikely models of BSM predict branching ratios within the reach of LHC : e.g. in 2HDM-III,

  $B(t \rightarrow cH)$* up to 10^{-3} can be obtained

  $\Rightarrow$ spectacular signatures : Higgs feed down from top pair production

The sensitivity at LHC runII will be greatly improved thanks to the ~ 4x enhancement of the top pair production cross-section

- Some of these models have also direct impact on the Higgs boson phenomenology

  (e.g. $H \rightarrow cc$ might be as large as $H \rightarrow bb$,

  $H \rightarrow gg$ / $\tau^+\tau^-$ might be modified significantely)

* $t \rightarrow uH$ is also possible
ATLAS search sensitive to this decay