Search for FCNC tqH interactions with ATLAS detector

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QINGDAO2021,15-20 Aug

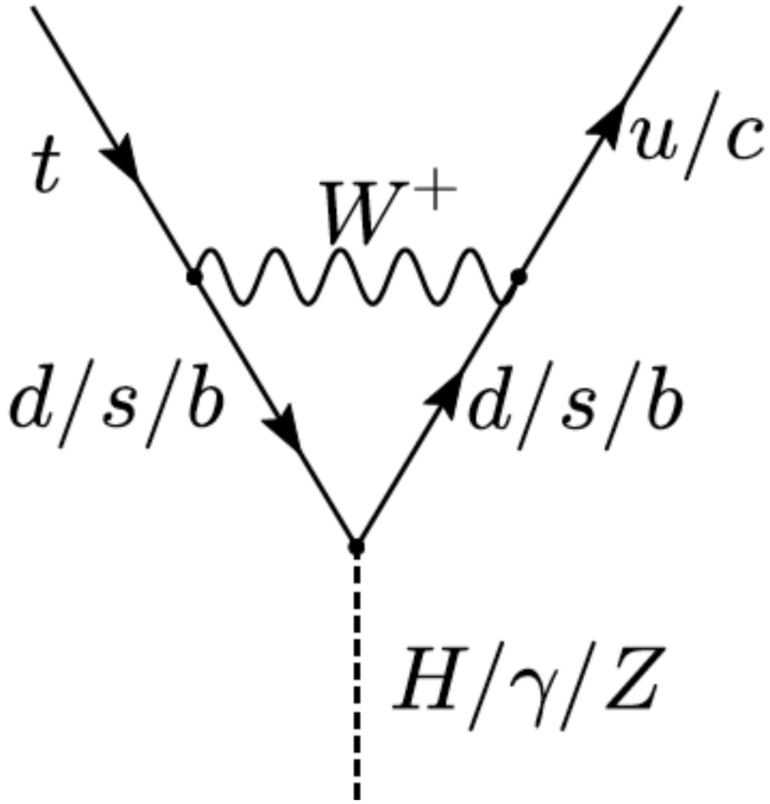
Outline

- Introduction of FCNC tqH interactions
- Overview of searches using 36fb^{-1} data (2015 + 2016)
  - $t \to qH$ decay searches using top-quark pair events

    $H \to \tau^+\tau^-$ $H \to VV$ $H \to b\bar{b}$ $H \to \gamma\gamma$
  - Details of $H \to \tau^+\tau^-$ analysis (led by Tsinghua University)
    - Event selection
    - Background Estimation
    - Kinematics signature
    - Limit setting
  - Summary

Top quark FCNC interactions

- FCNC process is highly suppressed in the Standard Model (SM) due to CKM unitarity:
  Phys. Rev. D 2 (1970) 1285 (GIM mechanism)



- SM top FCNC branching ratios arXiv:hep-ph/0409342

$$\mathrm{Br}(t \to cH) \simeq 3 \times 10^{-15}$$
$$\mathrm{Br}(t \to cZ) \simeq 3 \times 10^{-14}$$
$$\mathrm{Br}(t \to cg) = \left(4.6^{+1.1}_{-0.9} \pm 0.2 \pm 0.4^{+2.1}_{-0.7}\right) \times 10^{-12}$$
$$\mathrm{Br}(t \to c\gamma) = \left(4.6^{+1.2}_{-1.0} \pm 0.2 \pm 0.4^{+1.6}_{-0.5}\right) \times 10^{-14}$$

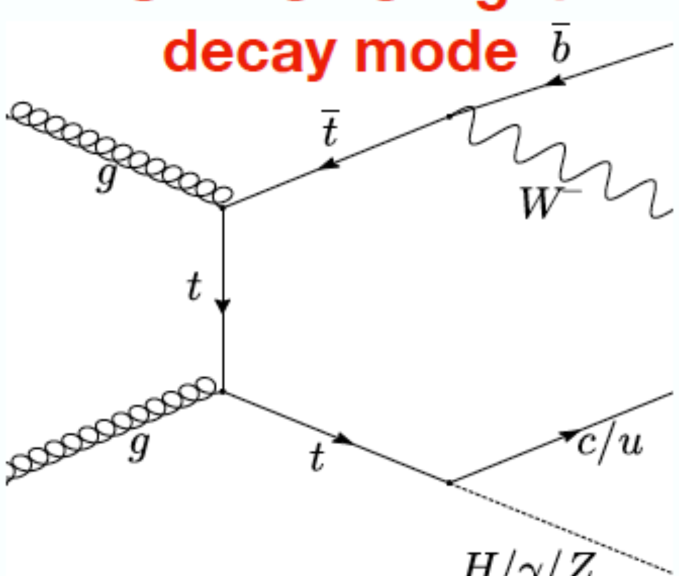
- Why top:
  - Top quark is the only quark that decays before hadronisation. The calculation of the decay width is straight forward.
  - Top is the only quark which is heavier than Higgs. The decay width is much larger than other heavy quark mesons.
  - LHC is a top factory.

Top quark FCNC interactions

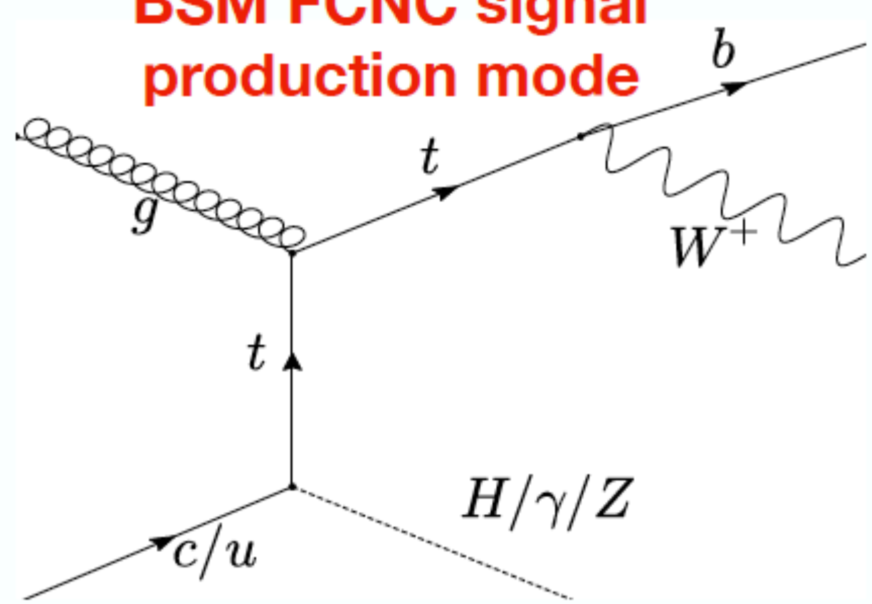
In contrast, large enhancements in these branching ratios are possible in some beyond-SM scenarios: arXiv:hep-ph/0409342

	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	$\boxed{1.5 \times 10^{-3}}$	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

BSM FCNC signal decay mode



BSM FCNC signal production mode



Overview of $t\bar{t}$ FCNC analysis

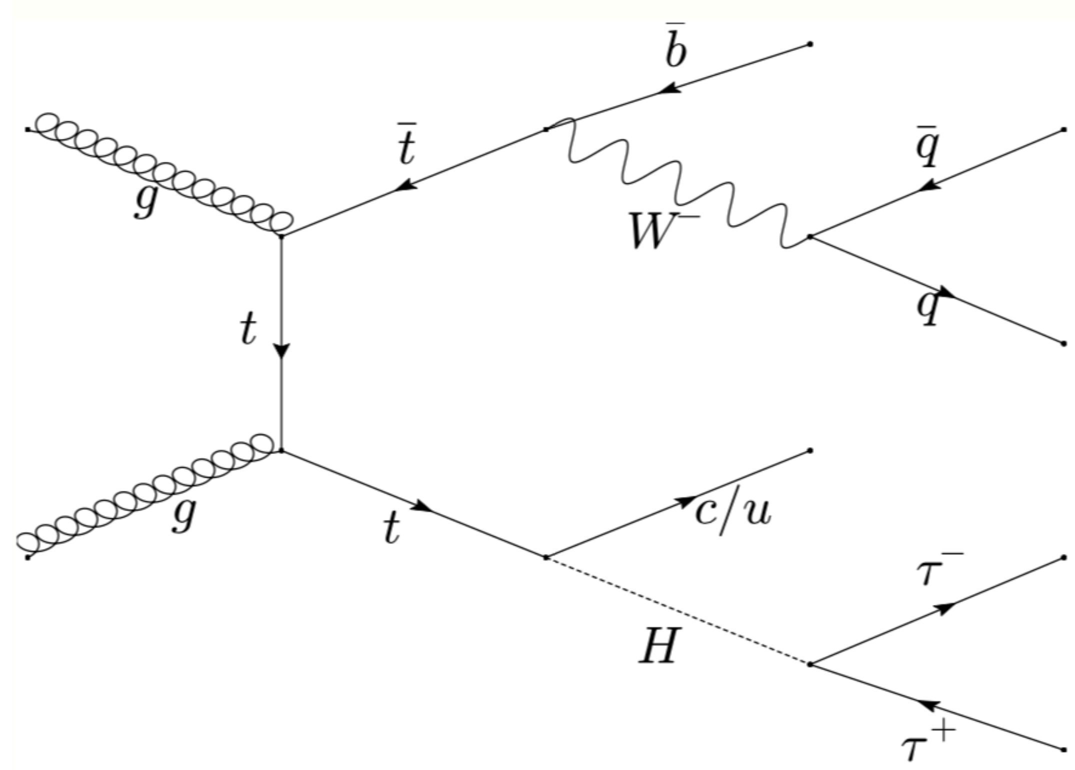
Channels	b-jet	jet	photon	lepton	tau	Major background	limit setting	limitation
$H\to\gamma\gamma$ hadronic	1	>= 4	2	0	/	$\bar{t}t\gamma$, $\gamma\gamma$+jet	fit to mγγ spectrum	stat. domi
$H\to\gamma\gamma$ leptonic	1	>=2	2	1	/	$\bar{t}t\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$	event counting	stat. domi
$H\to VV$ 2lSS	1,2	>=4	/	2	0	Non-prompt $\bar{t}tV$, $\bar{t}tH$	fit to BDT	stat. domi
$H\to VV$ 3l	>=1	>=2	/	3	0		fit to BDT	stat. domi
$H\to\tau\tau$ lephad	1	>=3	/	1	>=1	$\bar{t}t$	fit to BDT	stat. & syst.
$H\to\tau\tau$ hadhad	1	>=3	/	0	>=2	Multi-jet, $\bar{t}t$	fit to BDT	stat. & syst.
$H\to bb$	3	4/5	/	1	/	$\bar{t}t$+jets	fit to Likelihood	syst. domi

Observed(expected) 95% CL upper limit

BR in ‰	$t \to uH$		$t \to cH$	
	leptonic	hadronic	leptonic	hadronic
$H \to \gamma\gamma$	Combined result: 2.4 (1.7)		Combined result: 2.2 (1.6)	
$H \to VV$(ML)	2lSS: 2.8 (2.1) 3l: 2.2 (2.1)	/	2lSS: 2.5 (2.0) 3l: 2.0 (2.5)	/
$H \to \tau\tau$	/	1.7 (2.0)	/	1.9 (2.1)
$H \to bb$	5.2 (4.9)	/	4.2 (4.0)	/
combined	1.2 (0.83)		1.1 (0.83)	

$t\bar{t}$ FCNC $H \to \tau^+\tau^-$

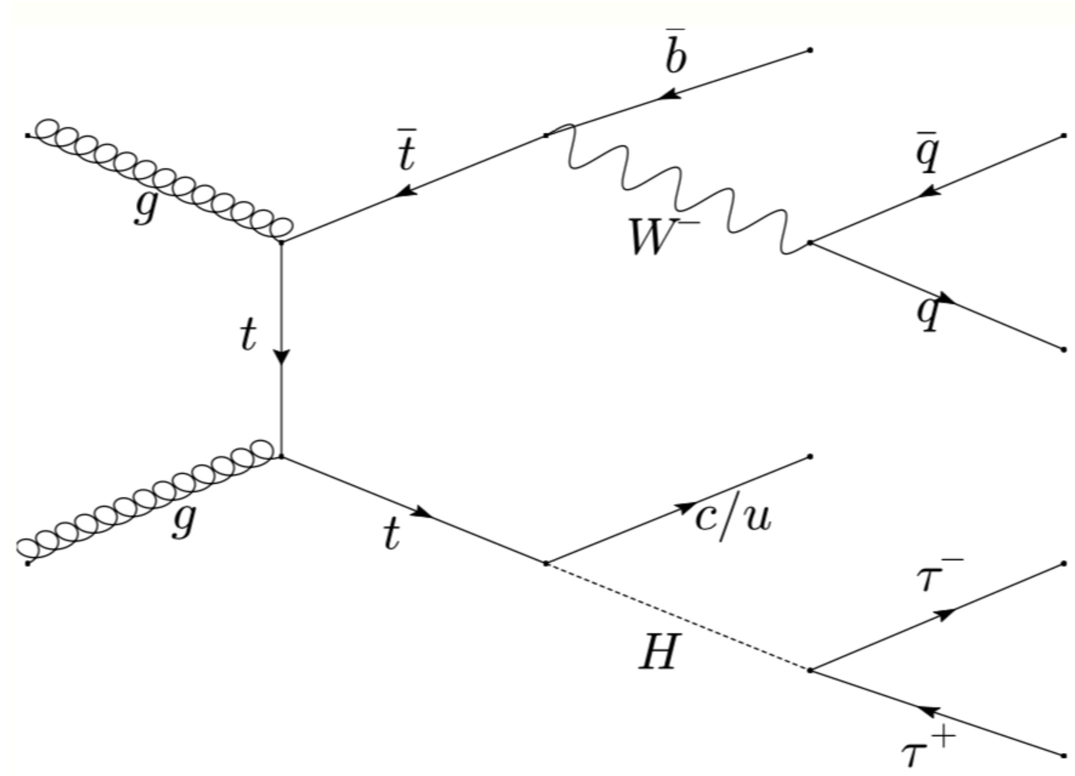
- Signal signature
  - 1 b jet
  - 3 light-flavored/c jets
  - 2 taus(lephad/hadhad)
- Major backgrounds:
  - Lephad:
    - $t\bar{t}$
    - Z+jets with Z to tautau
  - Hadhad
    - $t\bar{t}$
    - QCD
    - Z+jets with Z to tautau



- Signal strength：
  - Rank 2 among all the FCNC analysis. Rank 1 is bb which has huge systematics uncertainty.
- Challenges:
  - H resonance is not straightforward.
  - Fake tau background.

Event selection

- Trigger:
  - Lephad: Single lepton trigger
  - Hadhad:di-tau trigger
- Basic selection:
  - >= 3 jets with exactly 1 b-tagged.



Categories	Exactly one e/μ at least one Loose τ	Veto e/μ, at least two Loose τ's the leading tau is medium
At least 4 jets	$\tau_{\rm lep}\tau_{\rm had}$, $\geq$4jet	$\tau_{\rm had}\tau_{\rm had}$, $\geq$4jet
Exactly 3 jets	$\tau_{\rm lep}\tau_{\rm had}$, 3jet	$\tau_{\rm had}\tau_{\rm had}$, 3jet

Kinematics signature

- **To find the jet from top FCNC decay:** **Jet ambiguity problem**

  Minimize $\Delta R_x, x = 3j, 4j$ among all of the possible combinatorics for 3jet, ≥4jet events respectively.

$$t \to qH \qquad\qquad t \to bq\bar{q}$$

$$\Delta R_{4j} \equiv \boxed{\Delta R(j_{\mathrm{FCNC}}, H)} + \boxed{\Delta R(j_1, b) + \Delta R(j_2, b) + \Delta R(j_1, j_2)}$$
$$\Delta R_{3j} \equiv \Delta R(j_{\mathrm{FCNC}}, H) + \Delta R(j_W, b)$$

  Where j_{FCNC} denotes the FCNC jet candidate, j_i denotes the i-th jet from W decay. b denotes the b-jet.

- **To find the 4-momenta of neutrinos:** **Missing energy problem**

  Scan the 4-momanta of the neutrinos to mimimize χ^2. (Assuming they are massless)

$$\chi^2 = -2\ln\mathcal{P}_1 - 2\ln\mathcal{P}_2 + \left(\frac{m_{\tau_1}^{\mathrm{fit}} - 1.78}{\sigma_\tau}\right)^2 + \left(\frac{m_{\tau_2}^{\mathrm{fit}} - 1.78}{\sigma_\tau}\right)^2 + \left(\frac{m_H^{\mathrm{fit}} - 125}{\sigma_{\mathrm{Higgs}}}\right)^2 + \left(\frac{E_{x,\mathrm{miss}}^{\mathrm{fit}} - E_{x,\mathrm{miss}}}{\sigma_{\mathrm{miss}}}\right)^2 + \left(\frac{E_{y,\mathrm{miss}}^{\mathrm{fit}} - E_{y,\mathrm{miss}}}{\sigma_{\mathrm{miss}}}\right)^2$$

  Where $\mathcal{P}$ is the probability of tau decay kinematics obtained from $Z \to \tau\tau$ control region. The footnote "fit" means the value is derived from the reconstructed neutrinos.

Fake background estimation

Irreducible background:

- $\bar{t}t$ process with real τ leptons.
- Di-boson background.
- $Z \to l^+l^-$.

Reducible background:

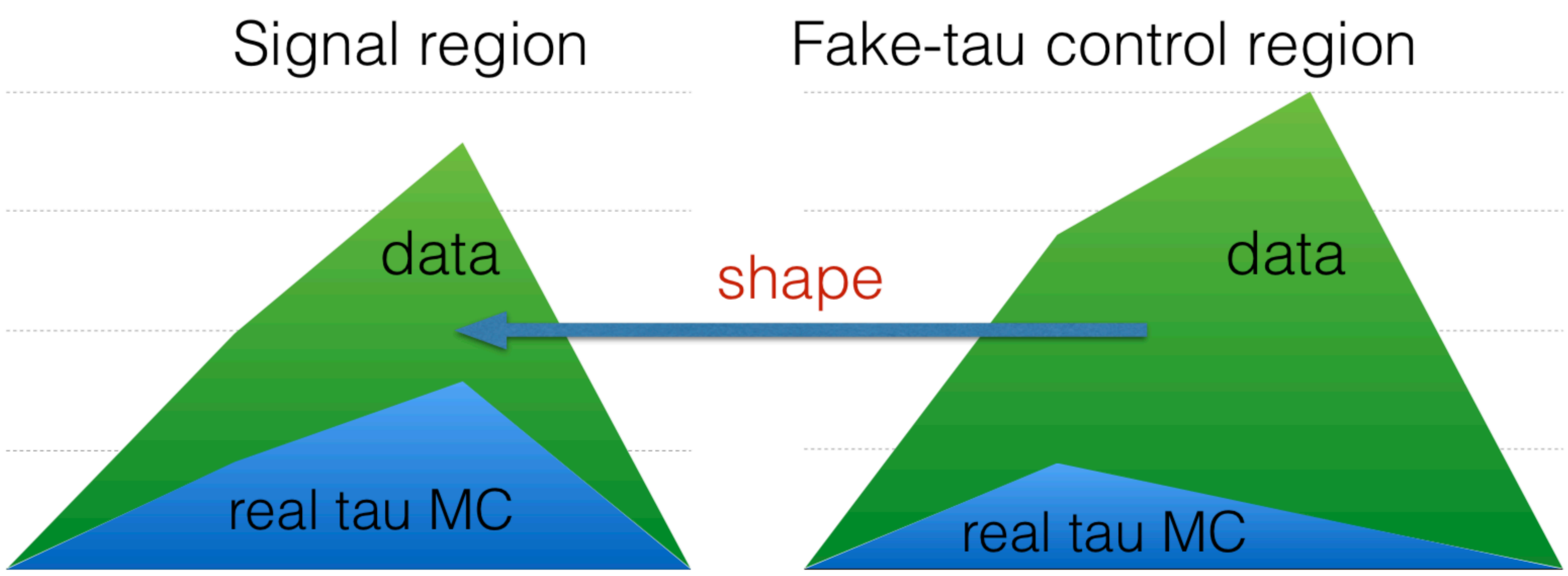
- multi-jet process.
- $\bar{t}t$ process with fake τ leptons.
- W+jets.

- The irreducible backgrounds (with real taus and small fraction of lepton faking taus) are modeled by MC
- Data driven method is used to model reducible (jets faking taus) backgrounds

Fake background estimation

The leading (sub-leading) tauID in $\tau_{\text{lep}}\tau_{\text{had}}$ ($\tau_{\text{had}}\tau_{\text{had}}$) categories	Opposite charged	Same charged
Medium	Signal region	
Anti-Medium	Fake-tau control region	

$$|\text{Reducible}^{\text{SR}}> = \mu(|\text{Data}^{\text{Fake-tau CR}}> - |\text{MC}^{\text{Fake-tau CR}}_{\text{Irreducible}}>)$$



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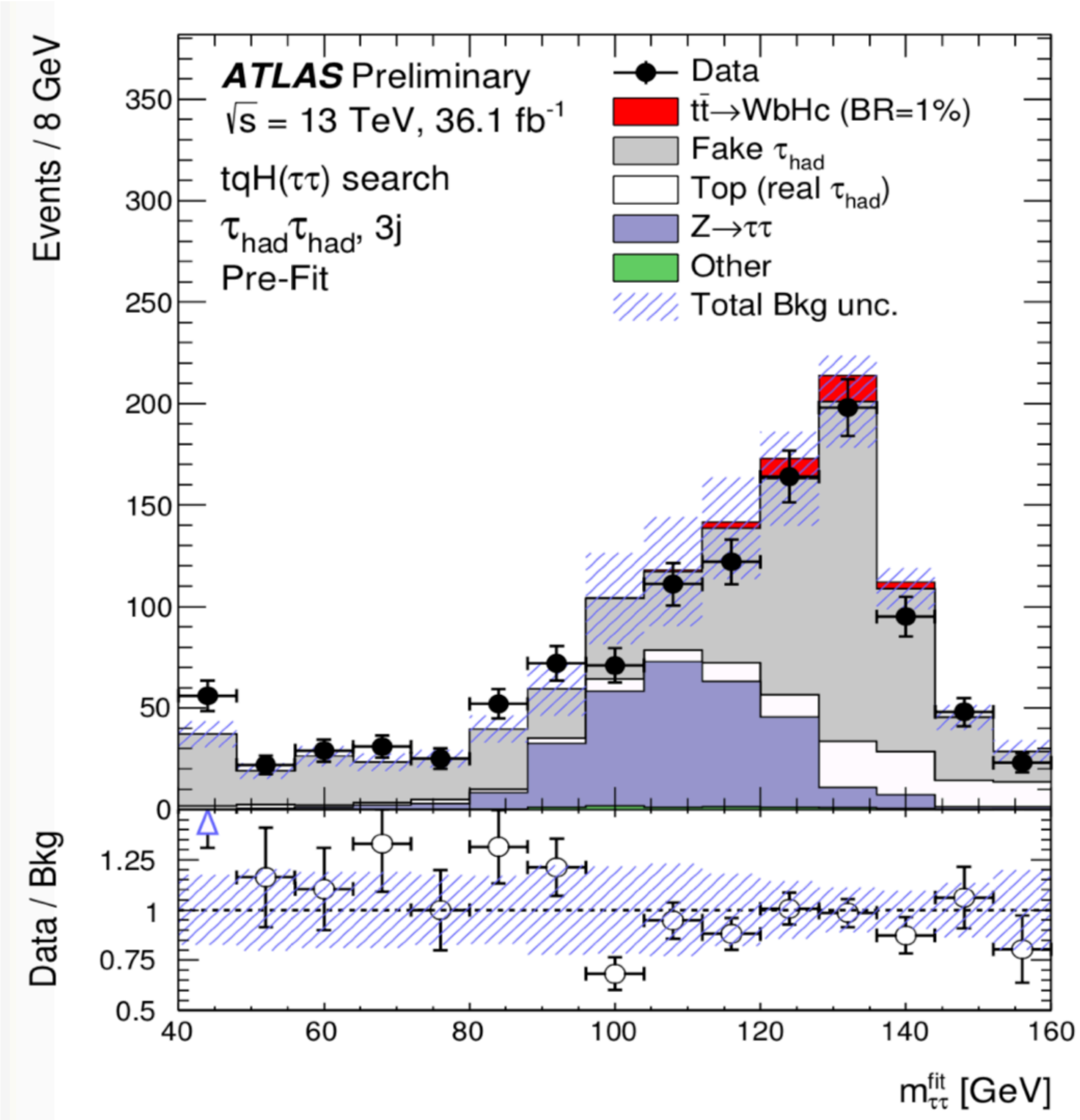
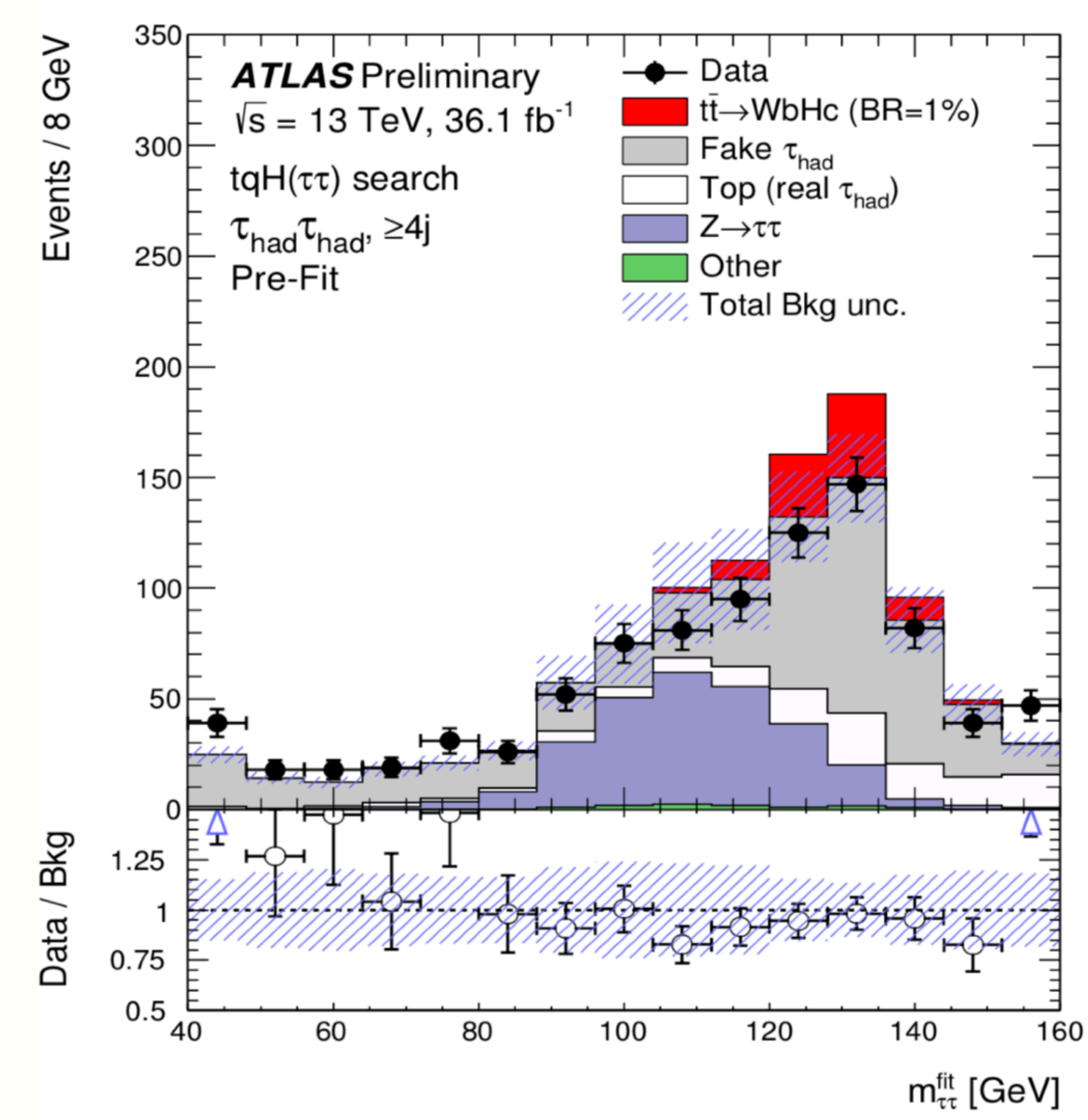
Pre-fit Plots

The reconstructed Higgs mass clearly peaks at 125GeV

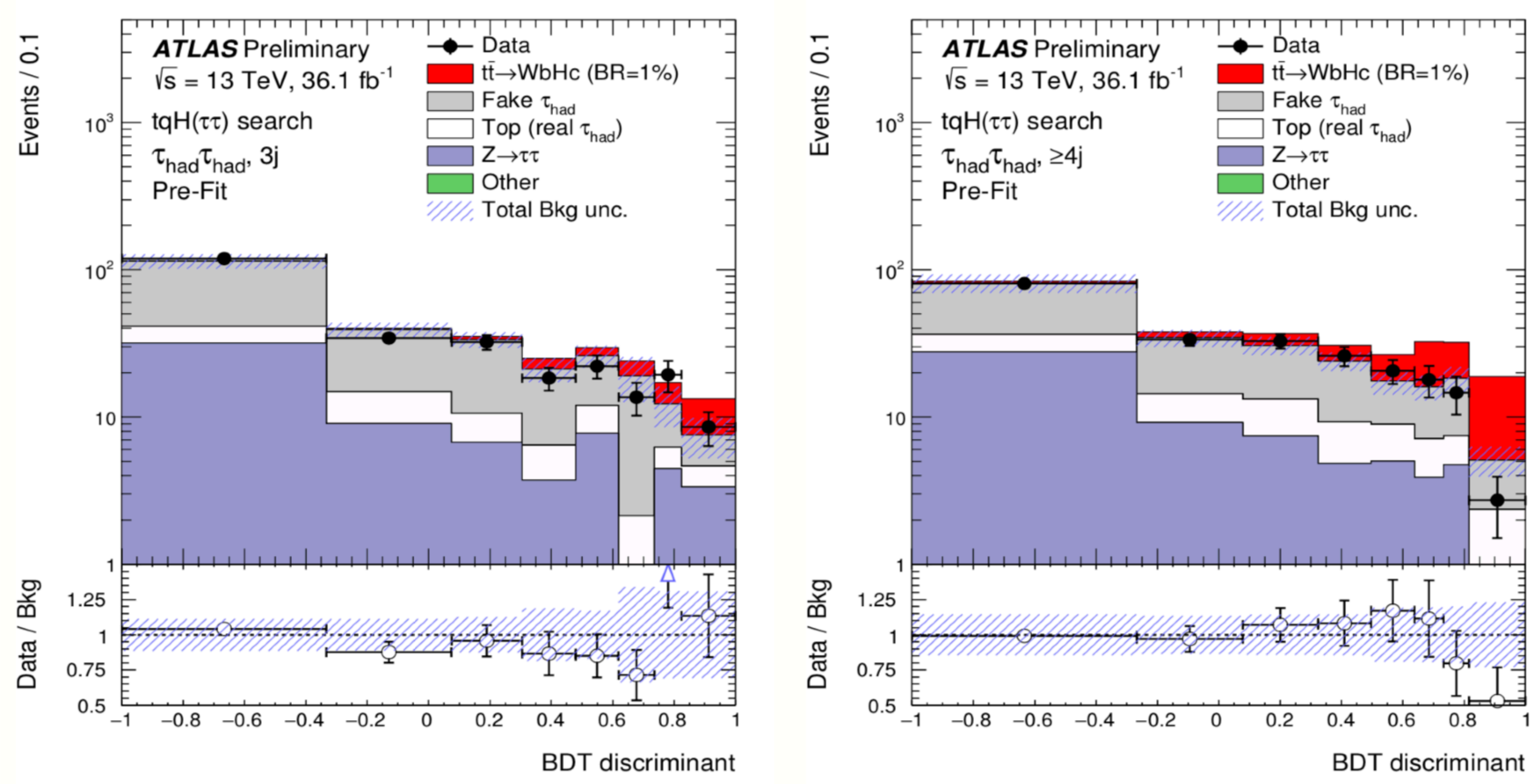




Multivariate Analysis

Takes advantage of the information derived from the topology reconstruction:

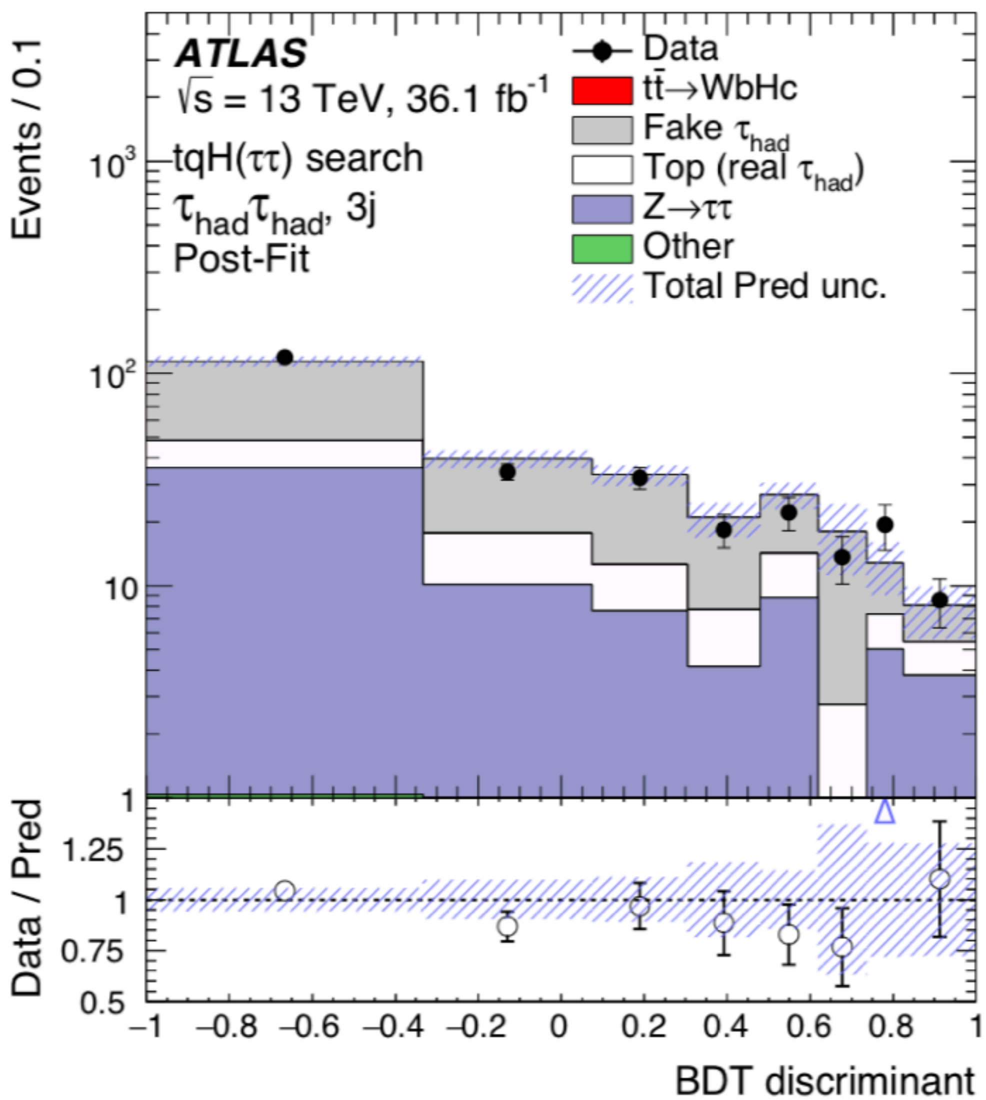
- Invariant mass of Higgs
- Invariant mass of top quarks
- Invariant mass of W boson
- The missing transverse energy
- The energy fraction of visible decay product of tau leptons
- ….

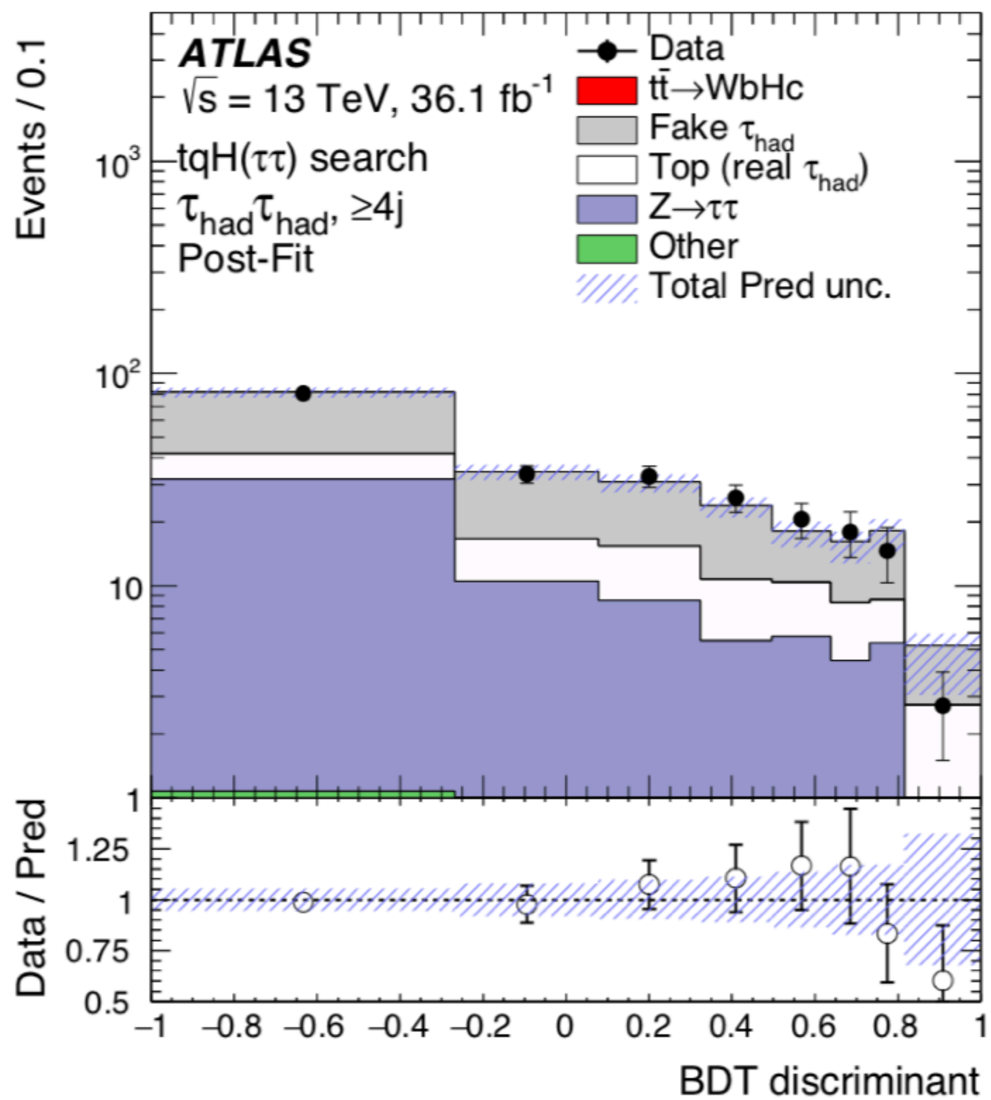


Limit setting

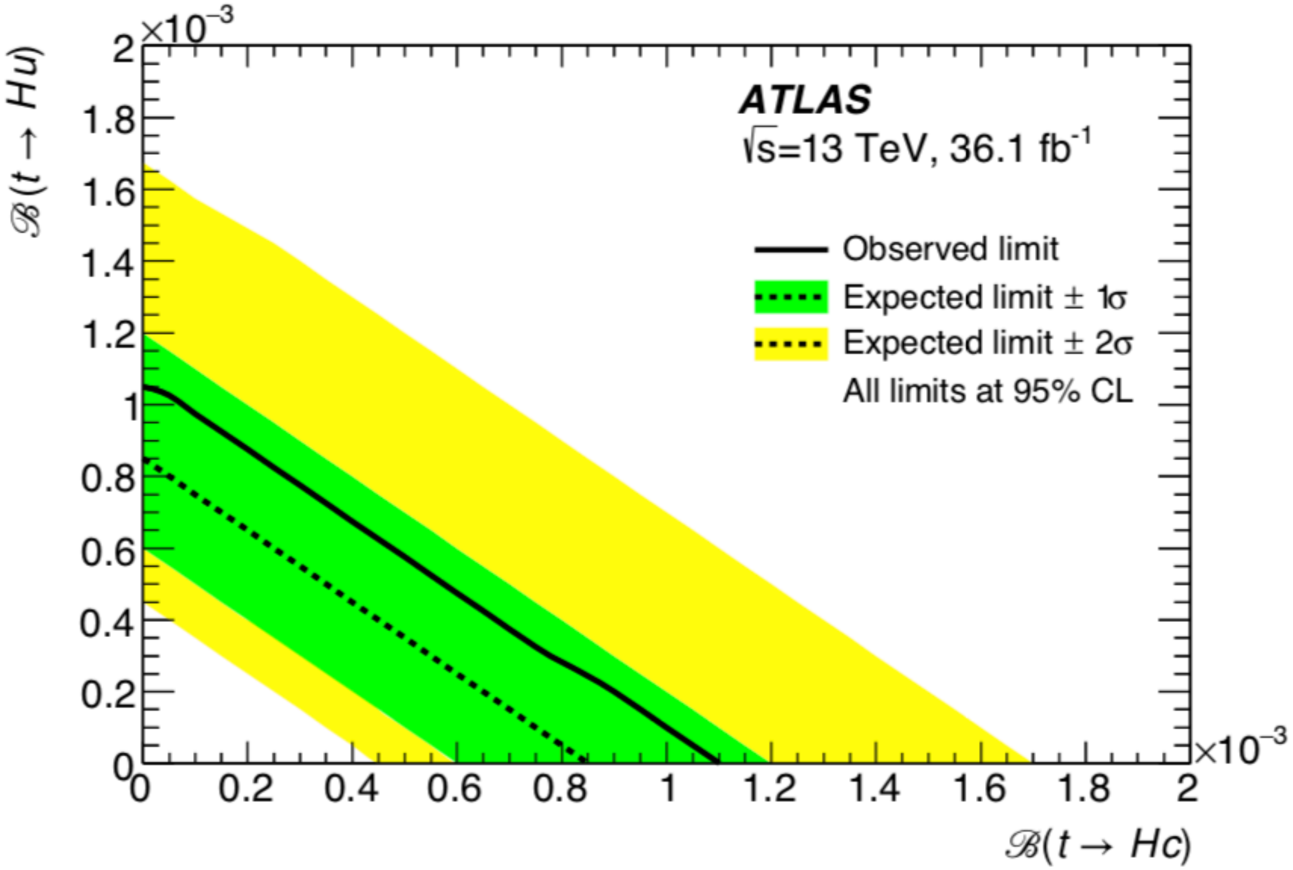
A combined fit is conducted based on the MVA discriminant to study the statistics. No deviation from the SM expectation is observed. Upper limits are derived for the FCNC decaying branching ratio.

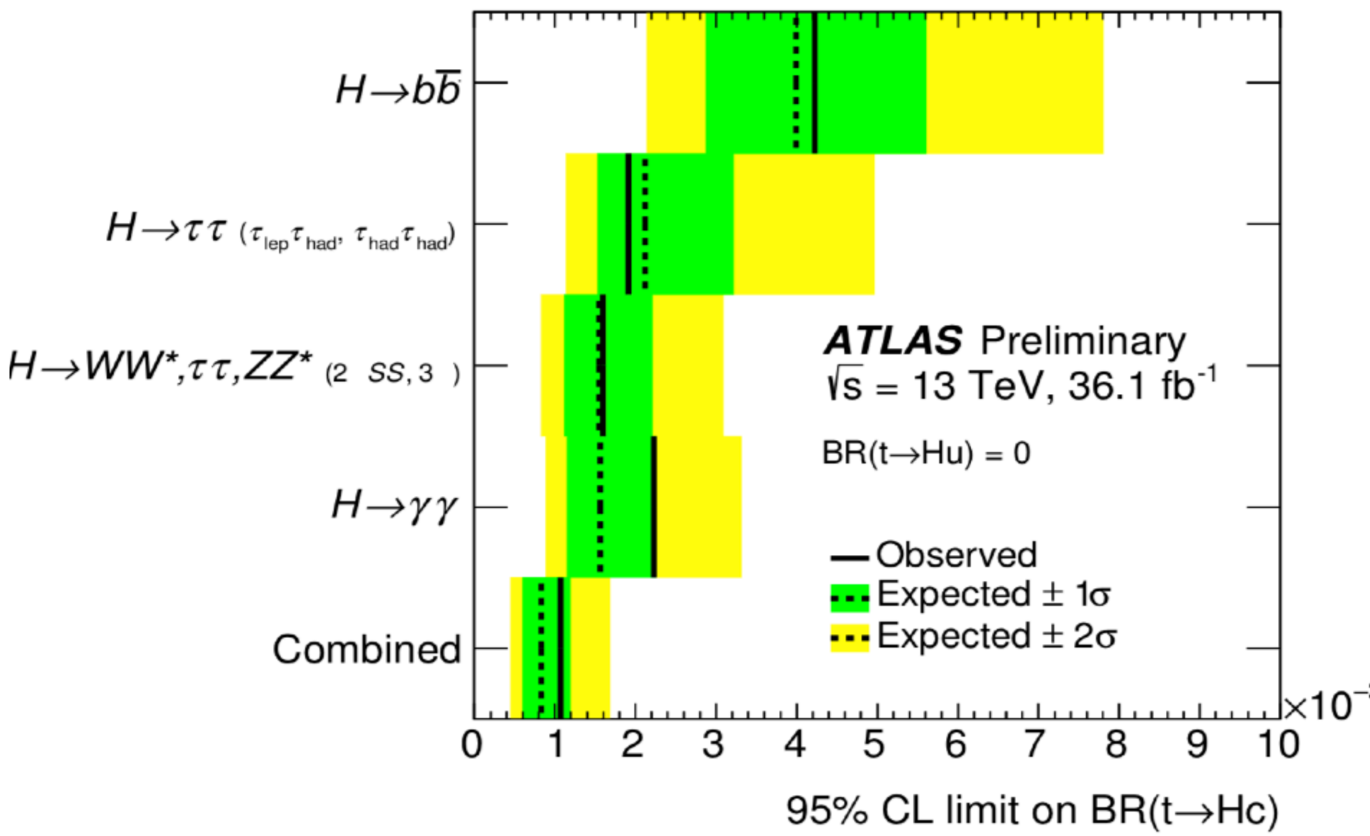
limits in %	$t \to Hc$	$t \to Hu$
Expected	$0.21^{+0.11}_{-0.06}$	$0.20^{+0.10}_{-0.06}$
Observed	0.19	0.17





Combination (JHEP 05 (2019) 123)





	95% CL upper limits on $\mathcal{B}(t \to Hc)$ Observed (Expected)	95% CL upper limits on $\mathcal{B}(t \to Hu)$ Observed (Expected)
$H \to b\bar{b}$	4.2×10^{-3} (4.0×10^{-3})	5.2×10^{-3} (4.9×10^{-3})
$H \to \tau\tau$ $(\tau_{\rm lep}\tau_{\rm had},\ \tau_{\rm had}\tau_{\rm had})$	1.9×10^{-3} (2.1×10^{-3})	1.7×10^{-3} (2.0×10^{-3})
$H \to WW^*, \tau\tau, ZZ^*$ $(2\ell{\rm SS},\ 3\ell)$	1.6×10^{-3} (1.5×10^{-3})	1.9×10^{-3} (1.5×10^{-3})
$H \to \gamma\gamma$	2.2×10^{-3} (1.6×10^{-3})	2.4×10^{-3} (1.7×10^{-3})
Combination	1.1×10^{-3} (8.3×10^{-4})	1.2×10^{-3} (8.3×10^{-4})

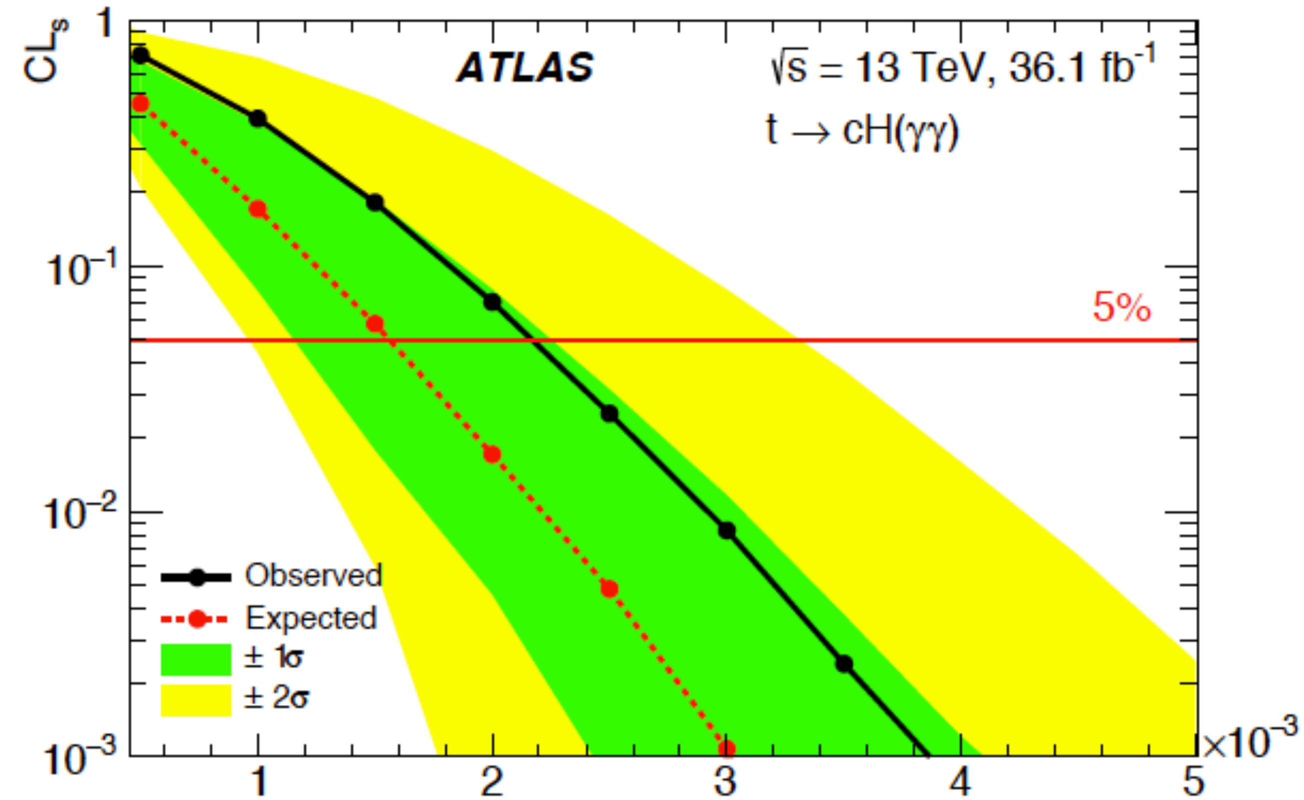
Summary

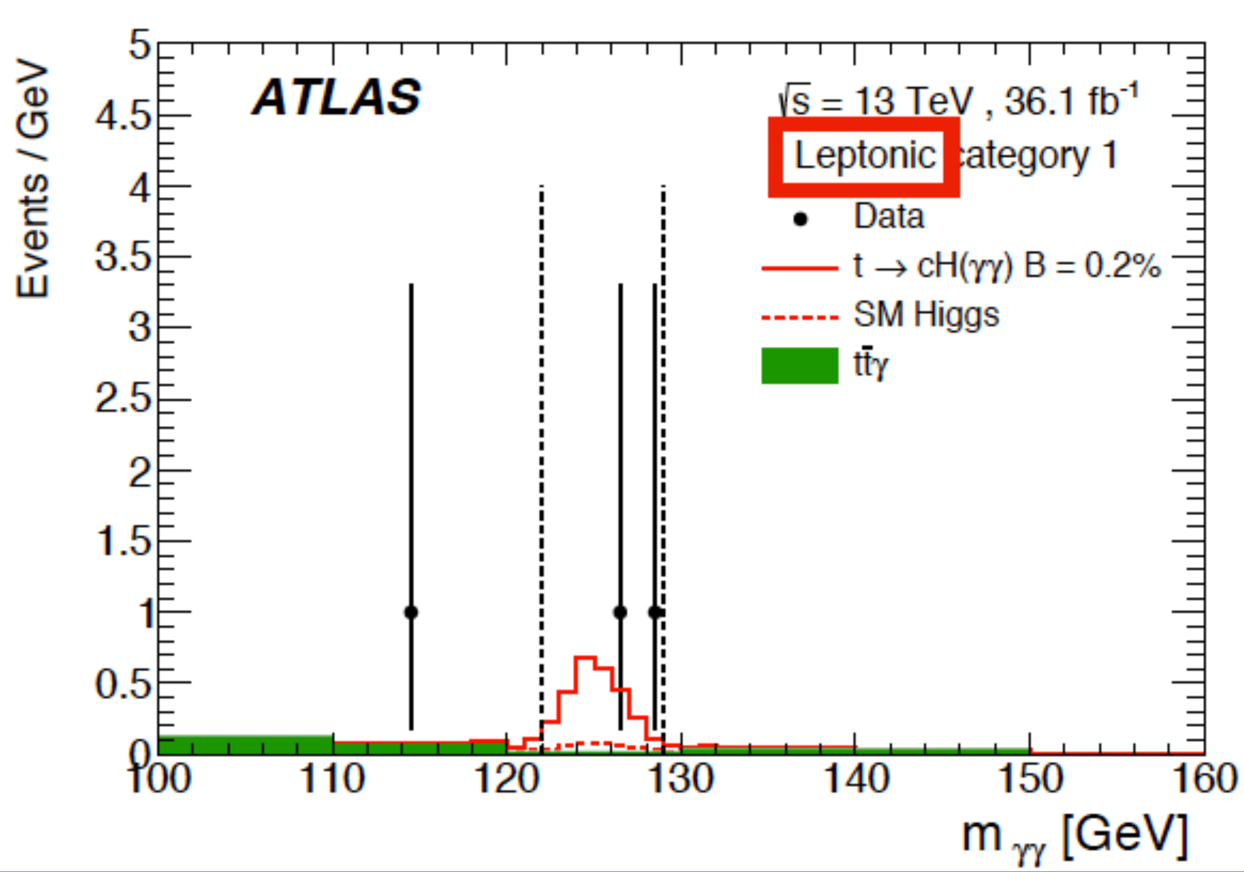
- The tqH interaction is an interesting physics approach to new physics and various searches using data from 2015 and 2016 using ATLAS detector are presented
- The combined limit reached ~0.1% for top to qH decay. which is good enough to reject flavor violating 2HDM
- The channel $H \to \tau^+\tau^-$ led by Tsinghua University ATLAS group shows great potential and provides a competitive limit.
- The full Run-2 analysis is in EB phase and will have a ATLAS circulation in October.

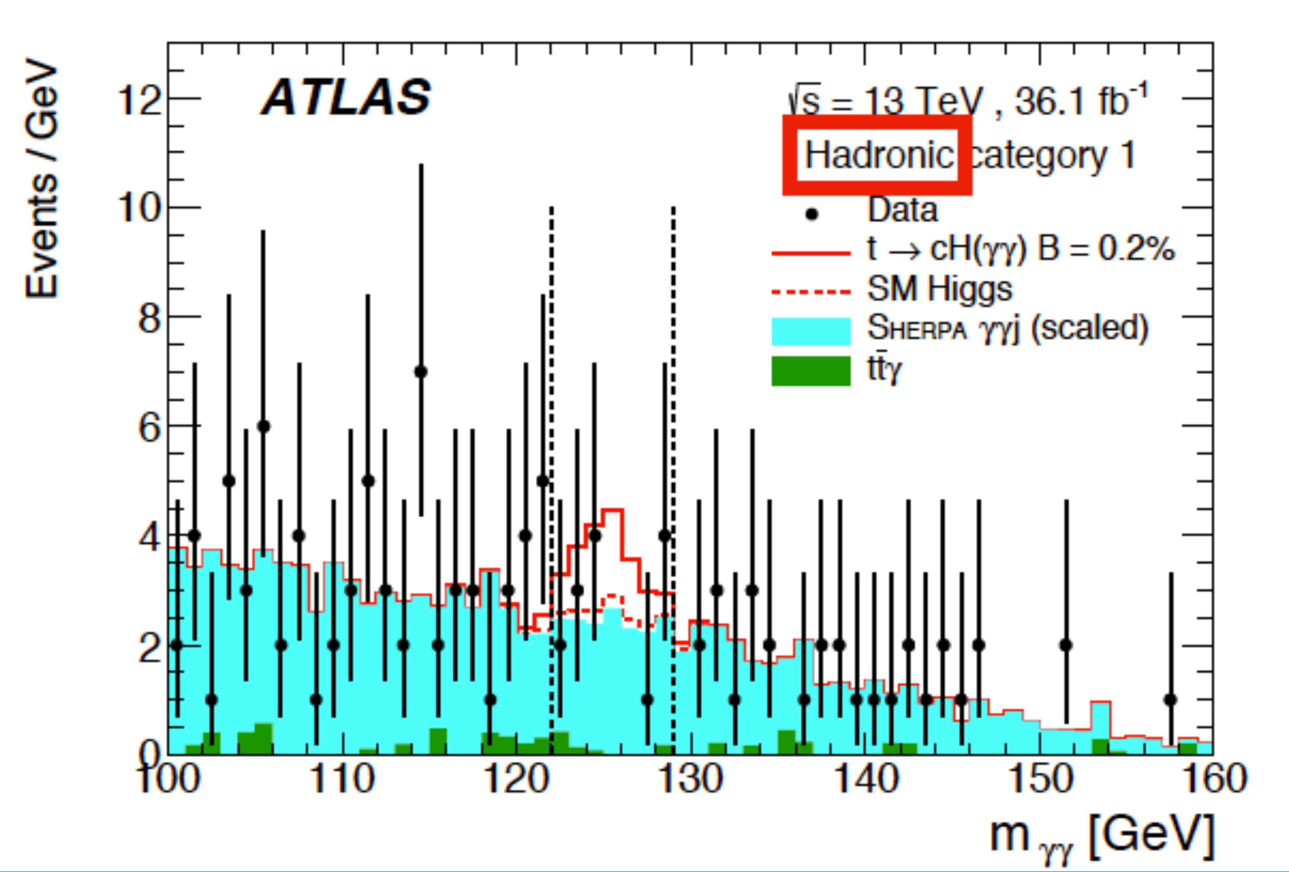
Backup

$t \to qH \to q\gamma\gamma$(10.1007/JHEP10(2017)129)

- Search both in hadronic and leptonic channel
- Signal regions:
  - Hadronic: 2γ, >=4 jets with 1 b-tagged
  - leptonic: 2γ, >=2 jets with 1 b-tagged, 1 lepton
- Strategy:
  - Hadronic: Fit mγγ spectrum
  - Leptonic: Event counting





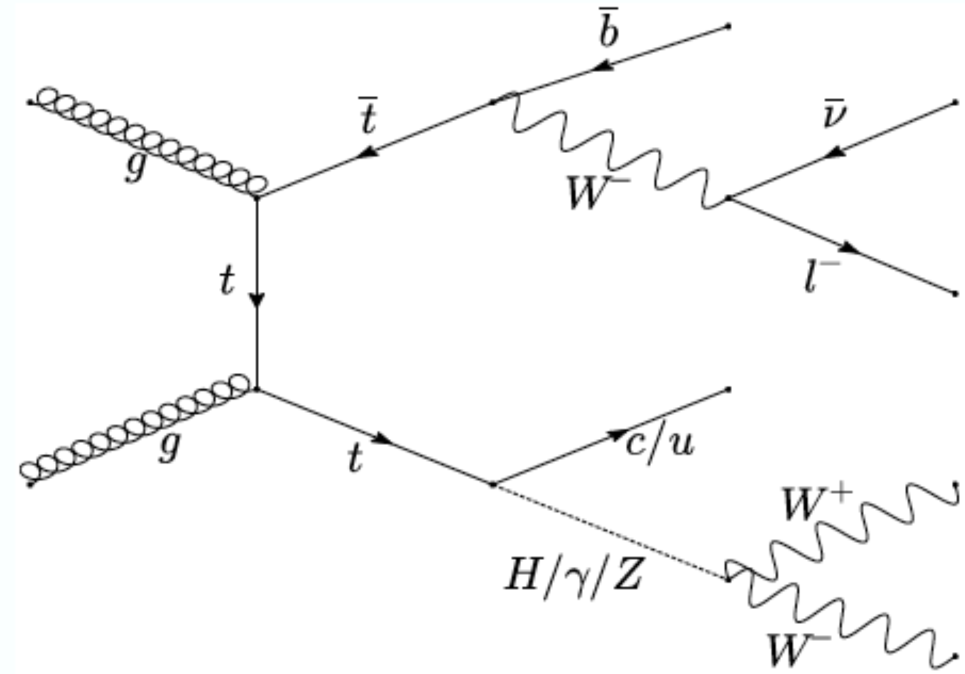


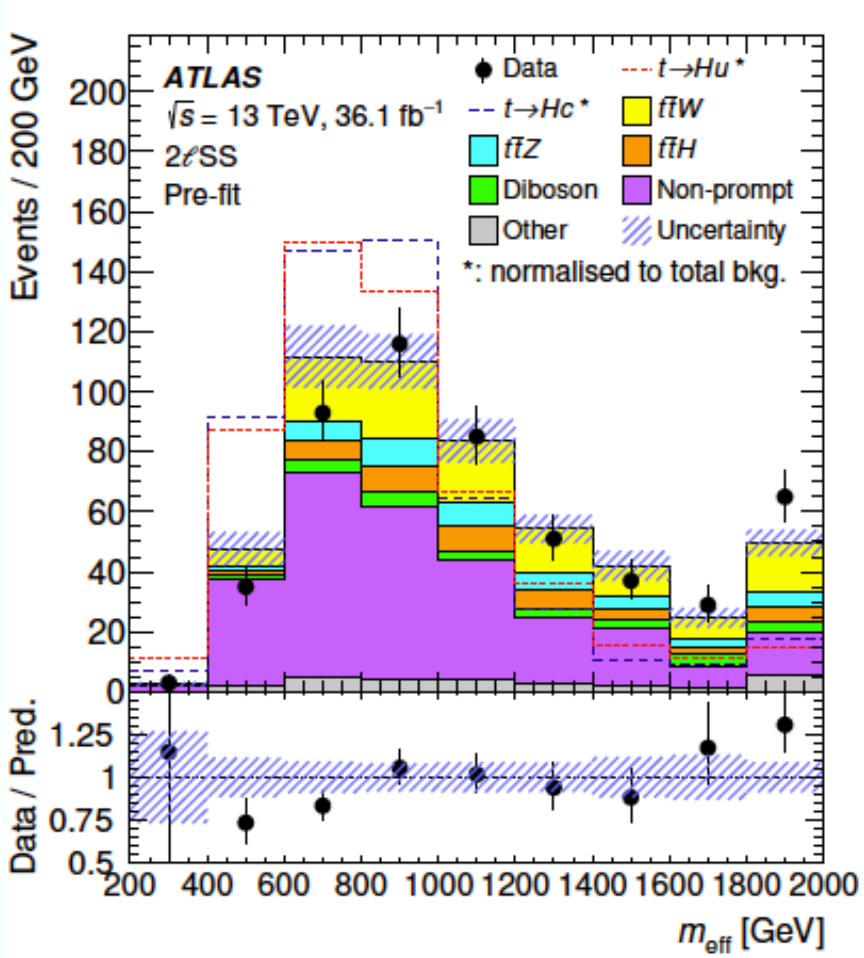
$t \to qH \to qVV$ (Phys. Rev. D 98, 032002)

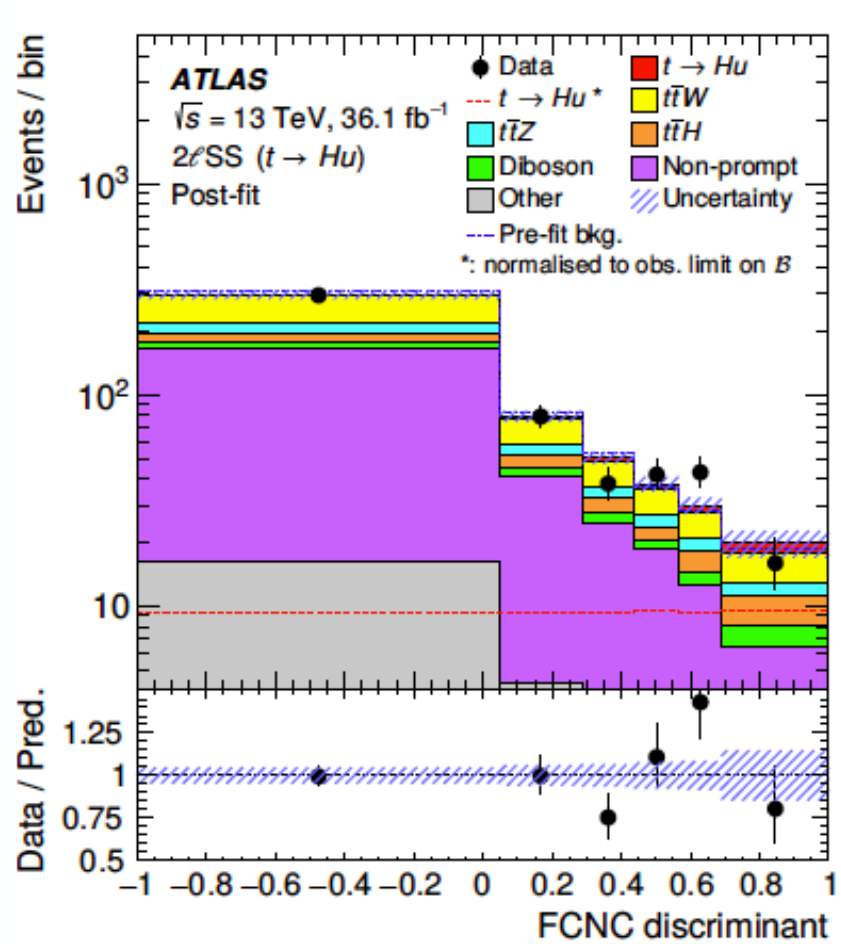
- Signal regions:

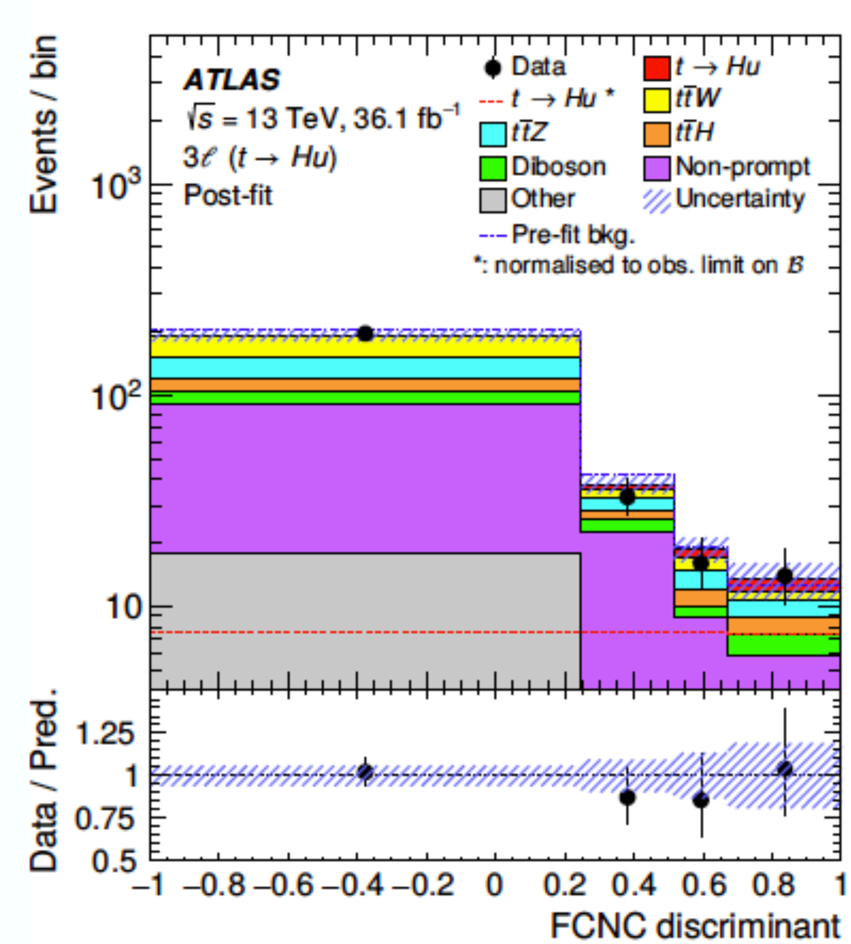
  2lSS: 2 same charged lepton, >= 4 jets with 1 or 2 b-tagged

  3l: 3 leptons, abs(Σcharge) = 1, >= 2 jets with >=1 b-tagged
- Searches only in leptonic channel
- Strategy:
  - Estimate non-prompt leptons using matrix method
  - BDT discriminant fitting









$t \to qH \to qb\bar{b}$ (JHEP 05 (2019) 123)

- combined paper with $H \to \tau^+\tau^-$
- Searches only in leptonic channel
- Signal region:

  1 lepton, 4/5 jets, 3 b-jets

- Strategy:
  - MC based, constraining systematics using control region
  - Likelihood discriminant fitting

$$LH(\mathbf{x}) = \frac{P^{\mathrm{sig}}(\mathbf{x})}{P^{\mathrm{sig}}(\mathbf{x}) + P^{\mathrm{bkg}}(\mathbf{x})}$$