Top-Higgs Interactions

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(Refugee from the Texas Session)

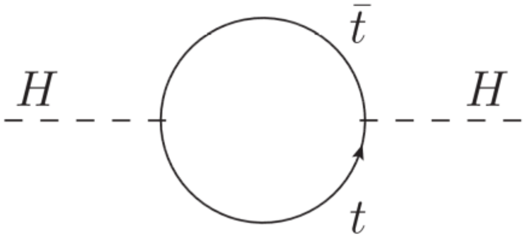
TEXAS
The University of Texas at Austin

The Higgs and Fermions

- The Higgs field solves two *related* but *distinct* problems
  - how to give the W & Z nonzero masses with gauge-invariant interactions
  - how to give fermions nonzero masses with gauge-invariant interactions
  - not obvious both should be solved in "minimal" SM fashion of single Higgs doublet, e.g. can introduce second doublet with complicated structure of fermion interactions
- Fermion interactions illuminate nature of Higgs sector independently from gauge bosons

The top-Higgs (Hierarchy) problem

- Top quark very heavy ⟶ top-Higgs interaction very strong
  - cannot ignore quantum corrections from the top quark to bare Higgs parameters

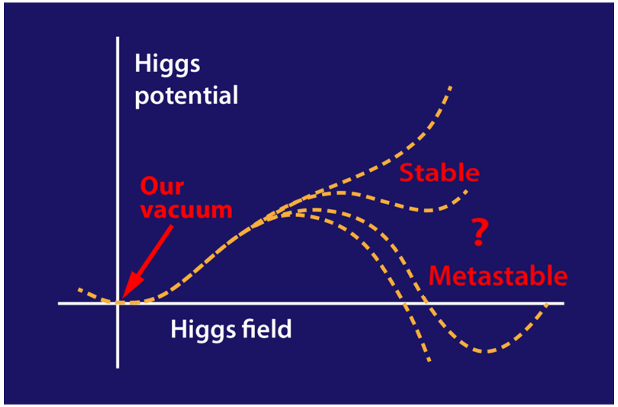


$$\Delta(\mu^2)_{top} = \mathcal{O}(1) \times y_t^2 \Lambda_{cutoff}^2$$

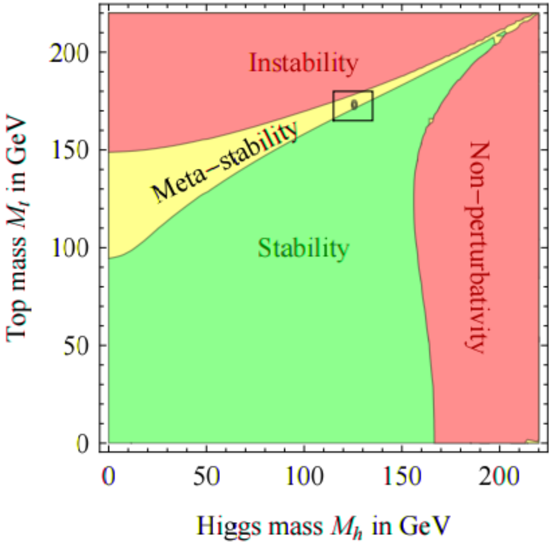
  - if Λ_{cutoff} ~ quantum gravity scale ⟶ correction is 10^{32} times observed value!
  - Need extreme cancellation of "bare" parameter and correction
  - motivates new physics models which cancel correction, lower Λ_{cutoff}, or both (supersymmetry, extra dimensions, composite Higgs …)
- Higgs properties enormously affected by top quark interactions

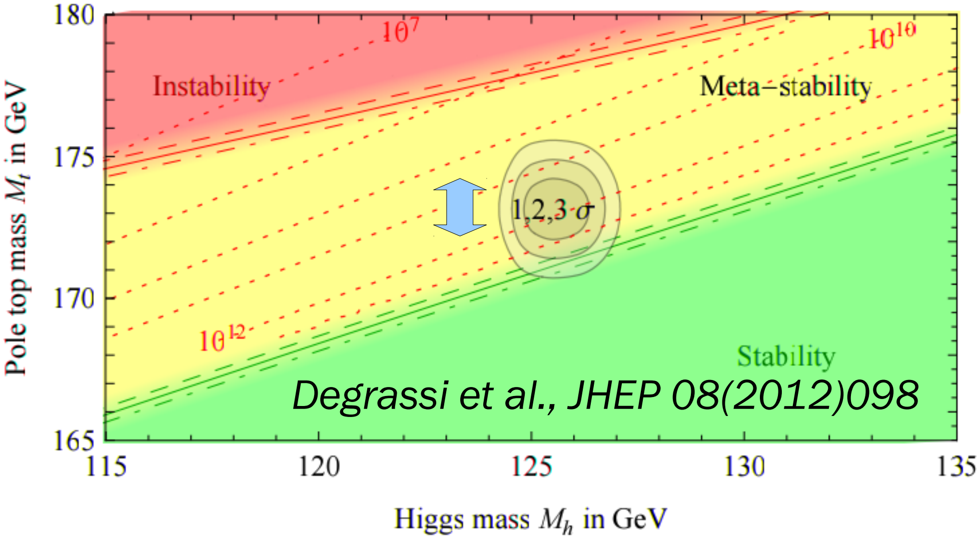
Is our vacuum stable?

- If no BSM before GUT scale: we are on a knife edge between a stable and unstable vacuum
  - Higgs-top quark interactions change effective potential
- LHC can help tell us if the vacuum is metastable
  - top-Higgs Yukawa coupling → top mass & Higgs coupling measurements



APS/Alan Stonebraker

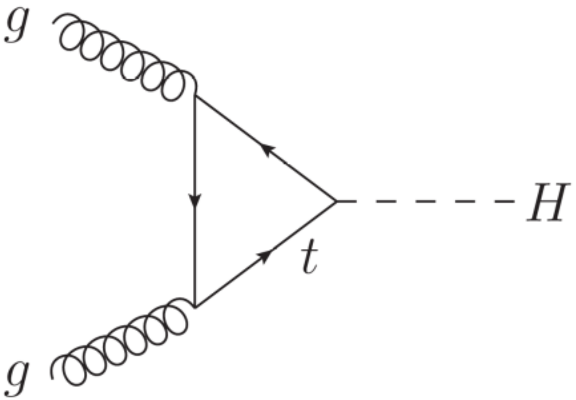


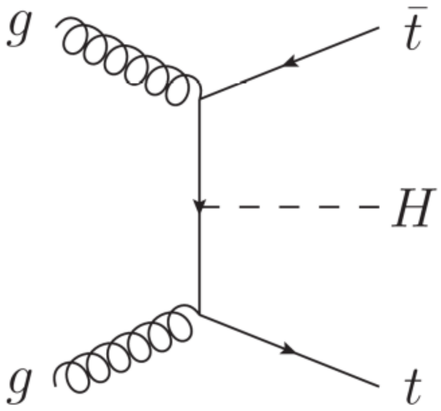


Degrassi et al., JHEP 08(2012)098

How to measure the Top-Higgs Yukawa Coupling

- Highest rate way: gg ⟶ H through top loop
- Effects of top are not distinguishable from new physics in gg ⟶ H
- A tree-level measurement is possible: pp ⟶ $t\bar{t}H$
  - multiple search channels based on top, Higgs decay

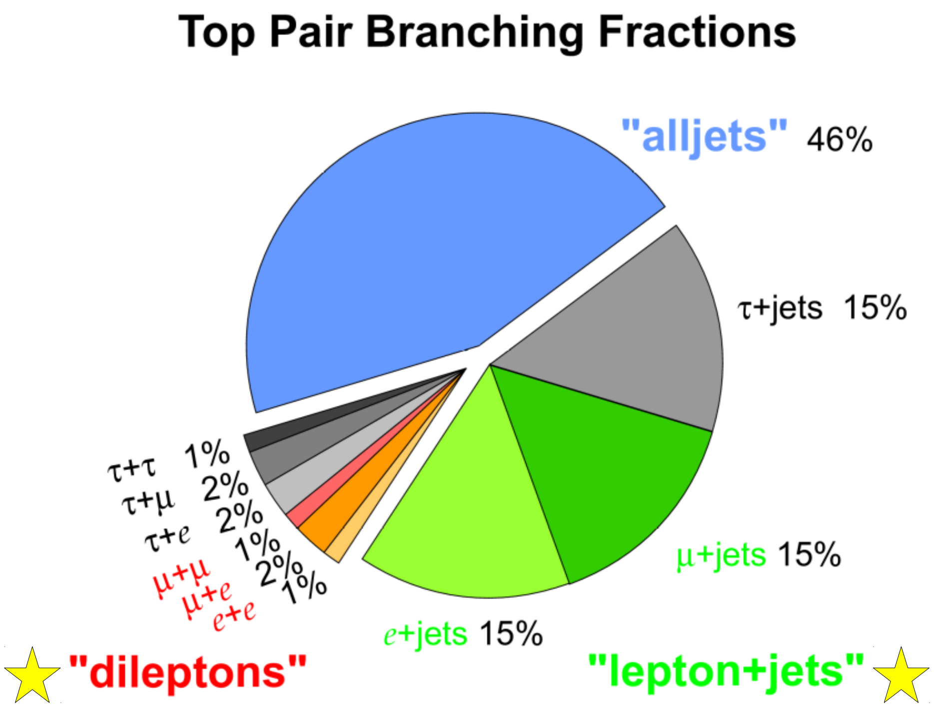


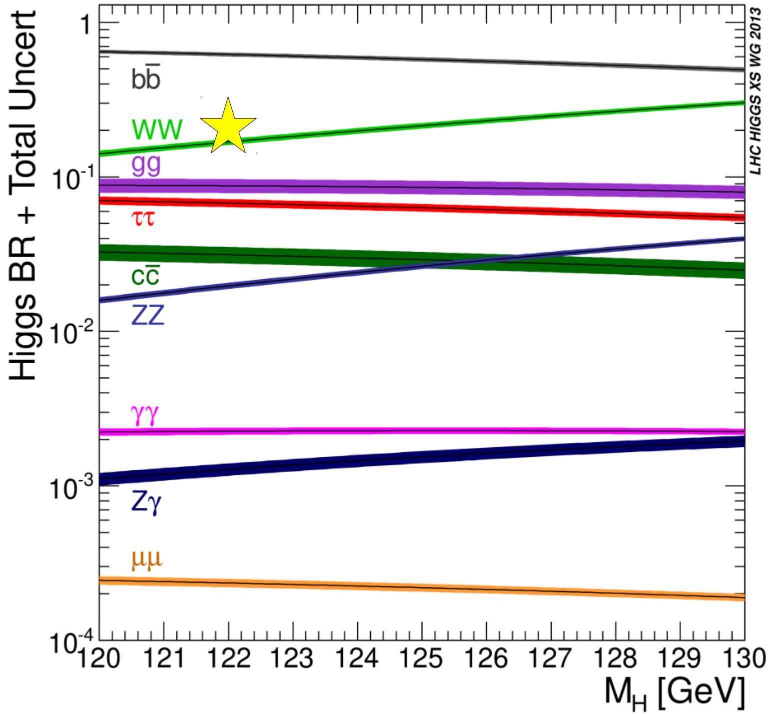


@ 13 TeV:	44 pb	NNLL+NNLO QCD + NLO EW	510 fb	NLO QCD

$t\bar{t}H$ Channels

- Look at channels based on top & Higgs boson decays
  - try to choose channels with well-controlled & *small* backgrounds…



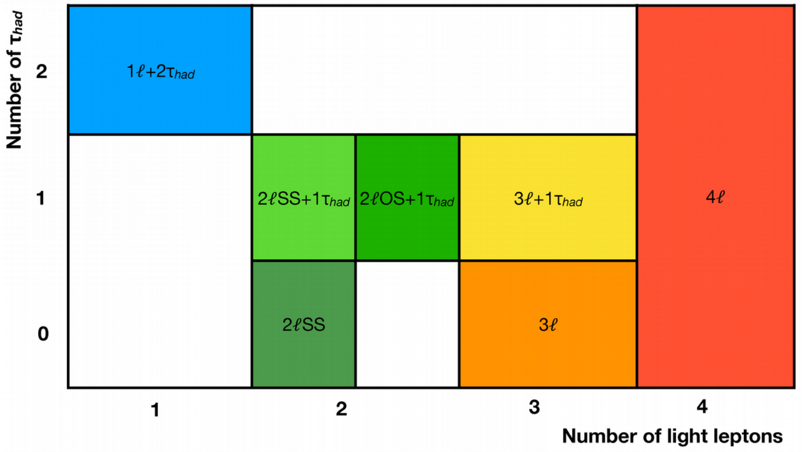


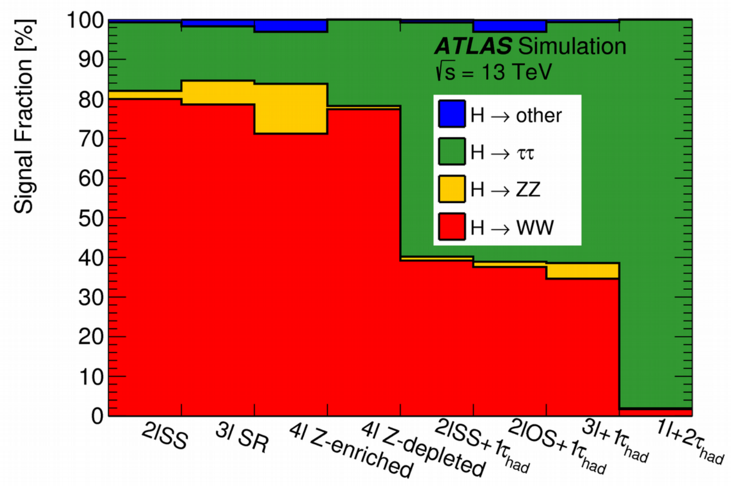
Multileptonic $t\bar{t}H$

- Target H → WW, ττ, ZZ decays
  - do not attempt to disentangle before fit

PRD 97 072003 (2018)

- Use signatures not reachable in $t\bar{t}$ decay: 2 same sign leptons, 3 leptons, 4 leptons [incl. τ]





acceptance × efficiency @ preselection

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\rm had}$	2ℓSS$+1\tau_{\rm had}$	2ℓOS$+1\tau_{\rm had}$	$3\ell+1\tau_{\rm had}$	Total
$A\times\epsilon\ (\times10^{-4})$	23	13	0.6+0.1	2.3	1.7	7.8	0.8	50

Cut-Based Cross Checks

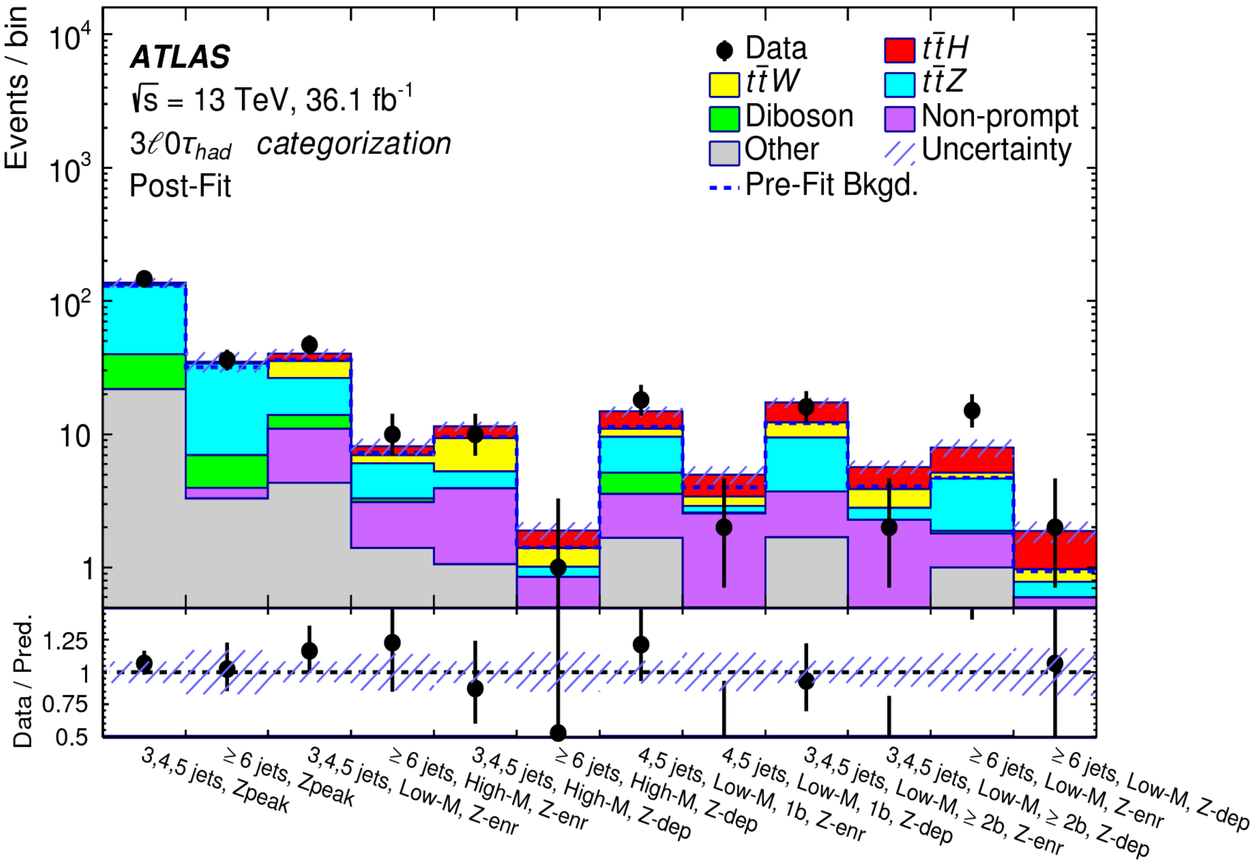
Three most powerful categories have cut-based cross checks for MVAs

Compatible with MVA results

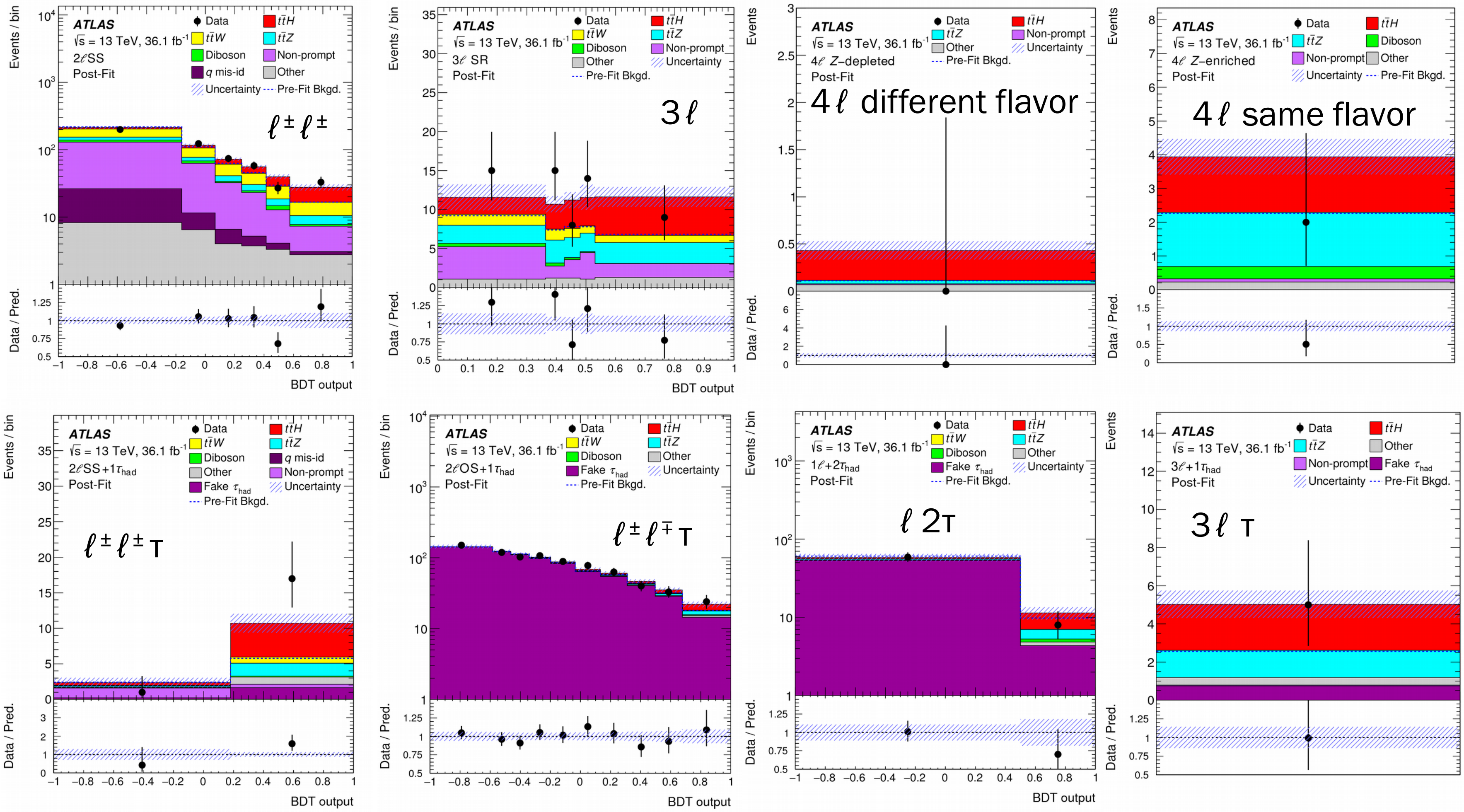
Shown: data vs MC using nominal μ and nuisance parameters for 3ℓ

Exploits:

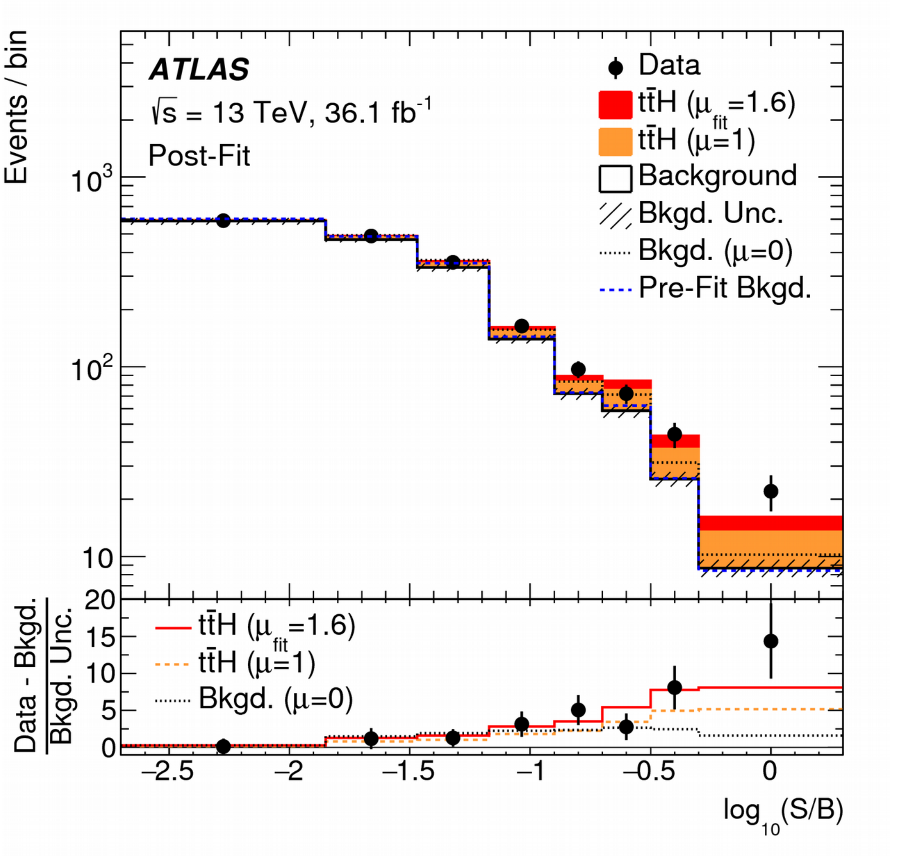
- higher #jet in signal
- H → $\ell\nu\ell\nu$ spin correlation (small $\ell\ell$ mass)
- no lepton flavor correlation in signal

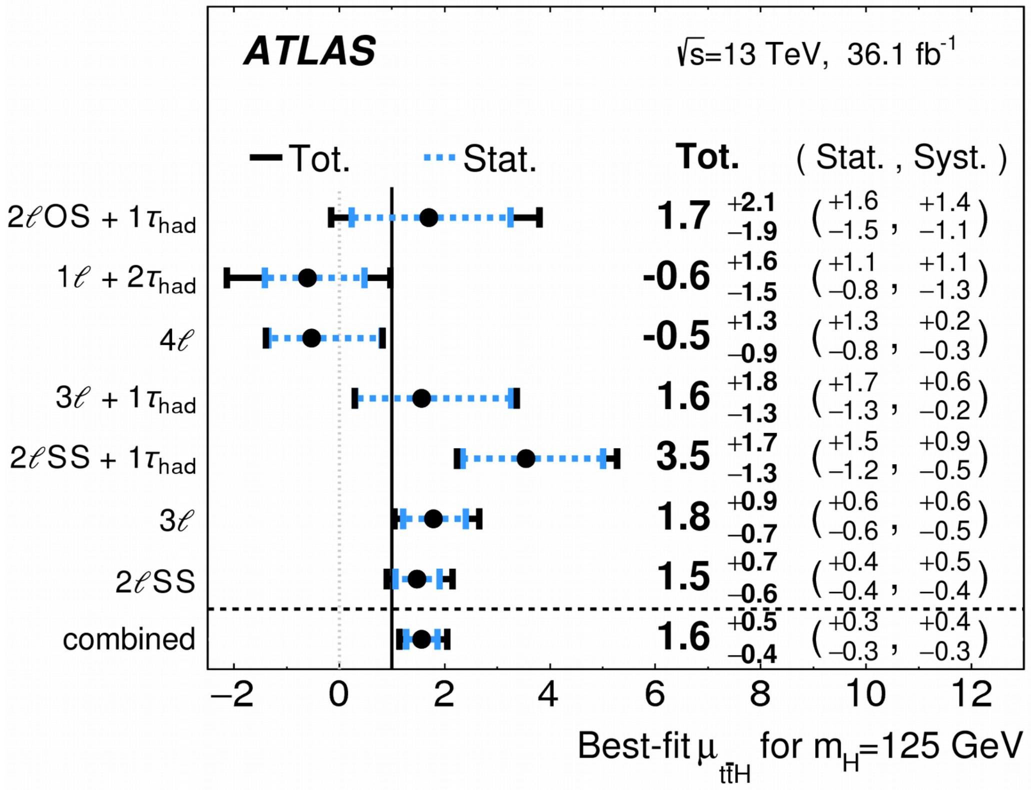


Multilepton Channels



$t\bar{t}H$ Multilepton Results





Multilepton Results

Channel	Best-fit μ Observed	Best-fit μ Expected	Significance Observed	Significance Expected
2ℓOS+$1\tau_{\text{had}}$	$1.7\,^{+1.6}_{-1.5}$ (stat.) $^{+1.4}_{-1.1}$ (syst.)	$1.0\,^{+1.5}_{-1.4}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	0.9σ	0.5σ
1ℓ+$2\tau_{\text{had}}$	$-0.6\,^{+1.1}_{-0.8}$ (stat.) $^{+1.1}_{-1.3}$ (syst.)	$1.0\,^{+1.1}_{-0.9}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	–	0.6σ
4ℓ	$-0.5\,^{+1.3}_{-0.8}$ (stat.) $^{+0.2}_{-0.3}$ (syst.)	$1.0\,^{+1.7}_{-1.2}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	–	0.8σ
3ℓ+$1\tau_{\text{had}}$	$1.6\,^{+1.7}_{-1.3}$ (stat.) $^{+0.6}_{-0.2}$ (syst.)	$1.0\,^{+1.5}_{-1.1}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	1.3σ	0.9σ
2ℓSS+$1\tau_{\text{had}}$	$3.5\,^{+1.5}_{-1.2}$ (stat.) $^{+0.9}_{-0.5}$ (syst.)	$1.0\,^{+1.1}_{-0.8}$ (stat.) $^{+0.5}_{-0.3}$ (syst.)	3.4σ	1.1σ
3ℓ	$1.8\,^{+0.6}_{-0.6}$ (stat.) $^{+0.6}_{-0.5}$ (syst.)	$1.0\,^{+0.6}_{-0.5}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	2.4σ	1.5σ
2ℓSS	$1.5\,^{+0.4}_{-0.4}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	$1.0\,^{+0.4}_{-0.4}$ (stat.) $^{+0.4}_{-0.4}$ (syst.)	2.7σ	1.9σ
Combined	$1.6\,^{+0.3}_{-0.3}$ (stat.) $^{+0.4}_{-0.3}$ (syst.)	$1.0\,^{+0.3}_{-0.3}$ (stat.) $^{+0.3}_{-0.3}$ (syst.)	4.1σ	2.8σ

>4σ observed significance for $t\bar{t}H$ from multileptons alone

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30

13 TeV, 36 fb^{-1}

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$t\bar{t}H$ combination: see Simone Monzani's talk

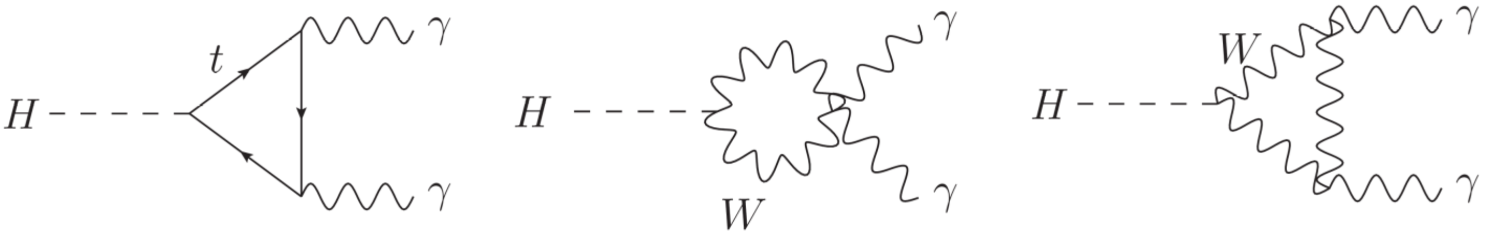
Formalism for Couplings

- Allow scale factors κ_i for the couplings of the SM $\Gamma(H \to X) = \kappa_X^2 \Gamma(H \to X)_{\mathrm{SM}}$
- Invisible or undetected decays have branching fraction $BR_{i,u}$
- Overall width scales as $\Gamma_H = \dfrac{\kappa_H^2}{1 - \mathrm{BR_{i,u}}} \Gamma_H^{SM}$

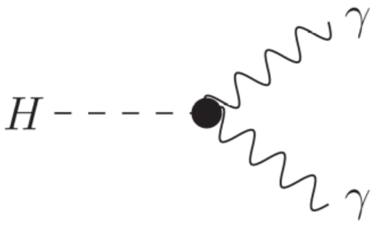
coherently scale all κ, increase $BR_{i,u}$:
no effect on observed ***on-shell*** *μ*

- Loop-induced couplings either *resolved* (expressed in terms of SM particle κ) or *unresolved* (have their own κ to capture possible new physics)

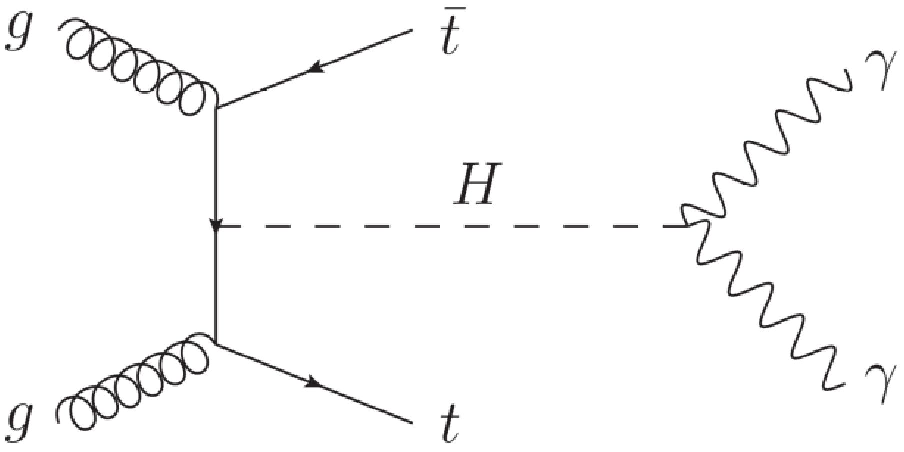
resolved



unresolved



Example of κ-formalism



On-shell!

$$\mu = \frac{\text{Rate}}{\text{SM Rate}} = \kappa_t^2 \times \frac{\mathcal{B}(H \to \gamma\gamma)}{\mathcal{B}(H \to \gamma\gamma)_{\text{SM}}}$$

$$\frac{\Gamma_{\gamma\gamma}/\Gamma_H}{\Gamma_{\gamma\gamma,SM}/\Gamma_{H,SM}}$$

unresolved $\kappa_t^2 \times \kappa_\gamma^2 \times \frac{\Gamma_{H,SM}}{\Gamma_H}$

resolved $\kappa_t^2 \times \left(1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\kappa_W\kappa_t\right) \times \frac{\Gamma_{H,SM}}{\Gamma_H}$

Can increase all κ coherently and keep same on-shell μ
if increase Γ_H to compensate (invisible/undetected decays)

$t\bar{t}H$ Couplings Interpretation

- $t\bar{t}H$ can access many couplings simultaneously
  - scan $\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau$ and $\kappa_V \equiv \kappa_W = \kappa_Z$
- Sign flip of top Yukawa coupling excluded at > 95% CL
  - needs to resolve $H \to \gamma\gamma$ loop for full power

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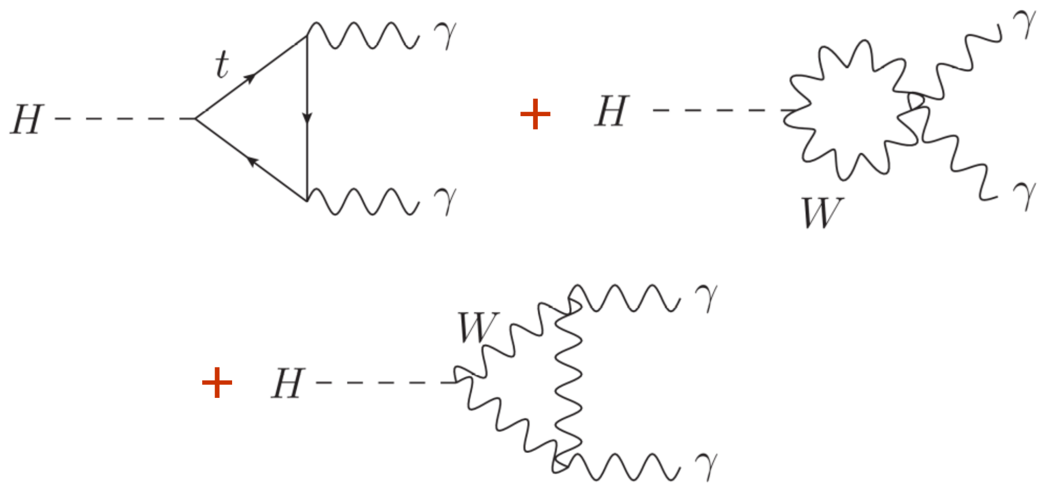
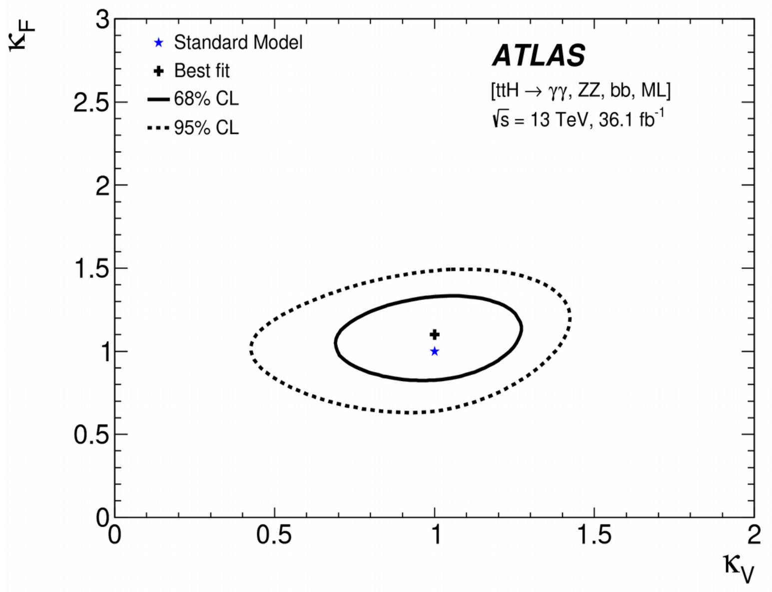
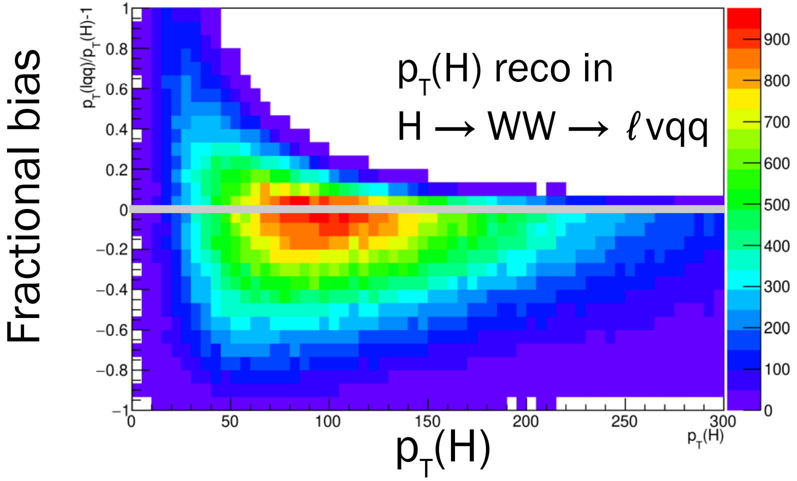


ttH channels only

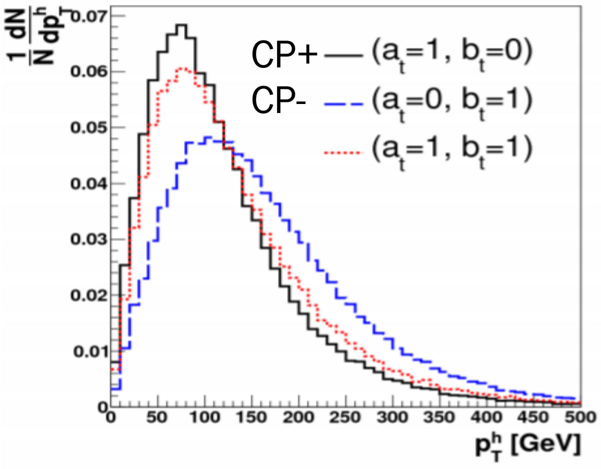


Future: Differential Measurements

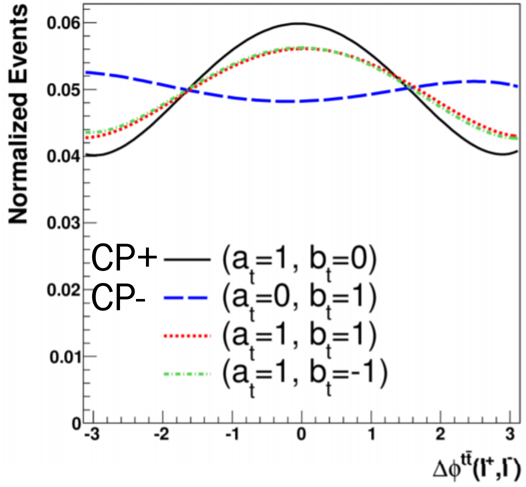
- Non-SM operator structures can result in modified Higgs p_T, top spin correlations, …
  - CP-odd couplings, higher-dim operators…



example: $$\mathcal{L} \ni -y_t \bar{t}(a + ib\gamma^5)th$$

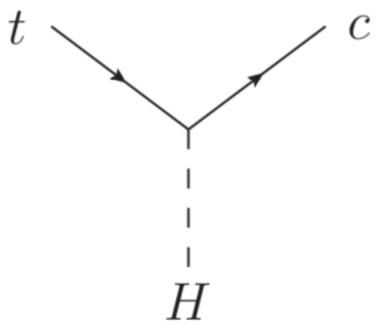


Boudjema et al., 1501.03157

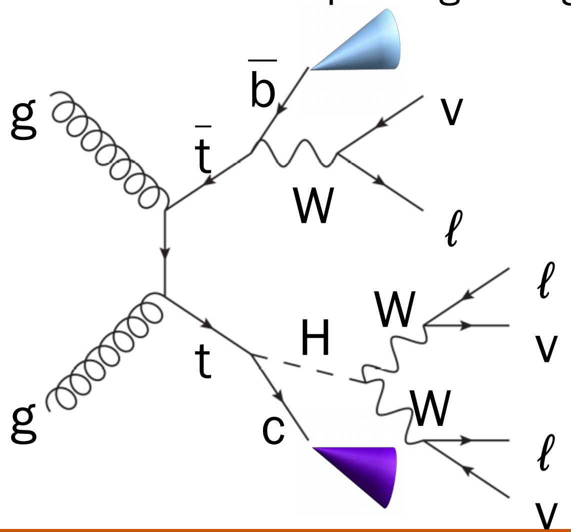


Top Flavor Changing Neutral Currents

- Top quark FCNC not observable in SM; more complex Higgs sectors may include e.g. top-charm-Higgs couplings
  - would cause the top quark decay t → Hc
  - any sign of this indicates new physics (more Higgs fields, …)
  - "Cheng-Sher ansatz": BR(t → Hc) ~ 0.15%



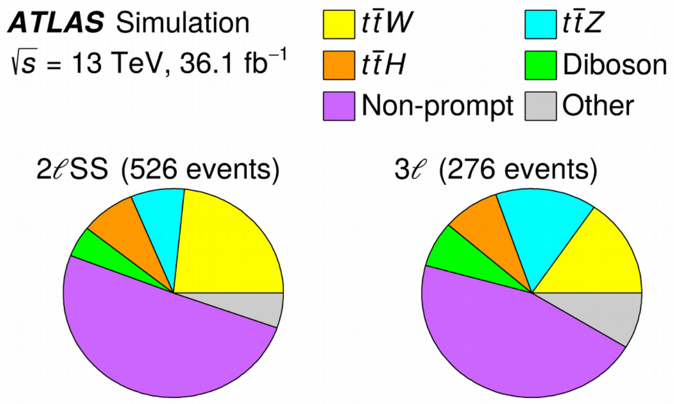
- Search for $t\bar{t}$ production with one top quark decaying by FCNC
  - reinterpret signal regions of multileptonic ttH search



Final states considered:
→ same sign dilepton
→ trilepton

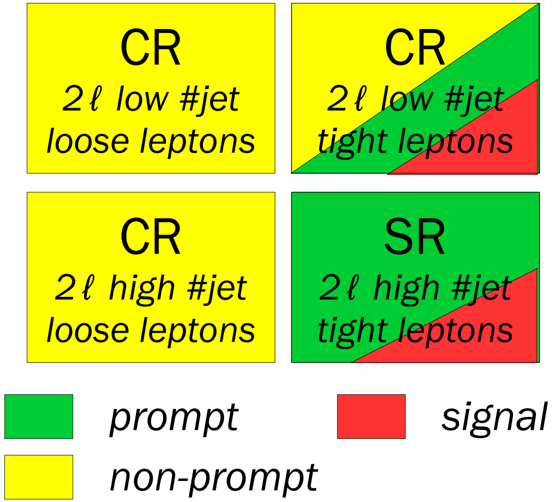
arxiv:1805.03483

backgrounds

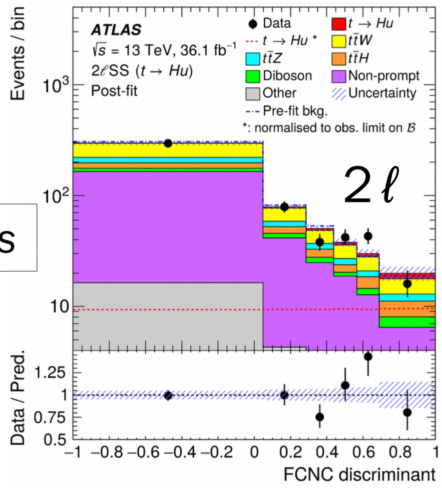


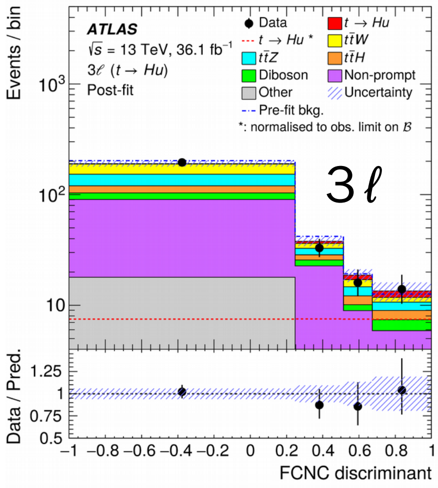
Multilepton FCNC Search

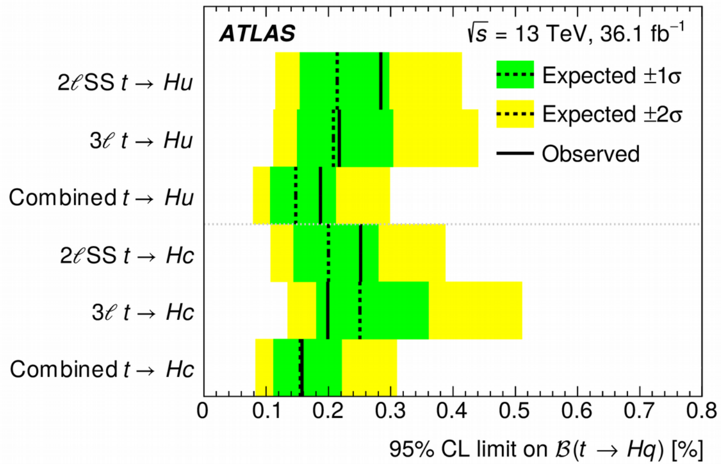
- Use BDTs to separate FCNC signal from backgrounds
  - important background of real leptons from b-hadron decays
- FCNC signal contaminates regions used for data-driven non-prompt lepton estimates!
  - tell fit how normalization, shape of non-prompt bkg change with nonzero signal
- Best fit: no FCNC signal, BR ≲ 0.16-0.19%



$t \longrightarrow Hu$ BDTs







Summary

- Direct searches for SM-like top-Higgs Yukawa coupling finally reaching high sensitivity
  - multilepton channels play a key role
- Search for off-flavor-diagonal top-Higgs couplings now excluding couplings in a phenomenologically interesting range
- More data → reduced statistical uncertainties, better systematic constraints, differential measurements
- Exciting future ahead!


Inks Lake SP