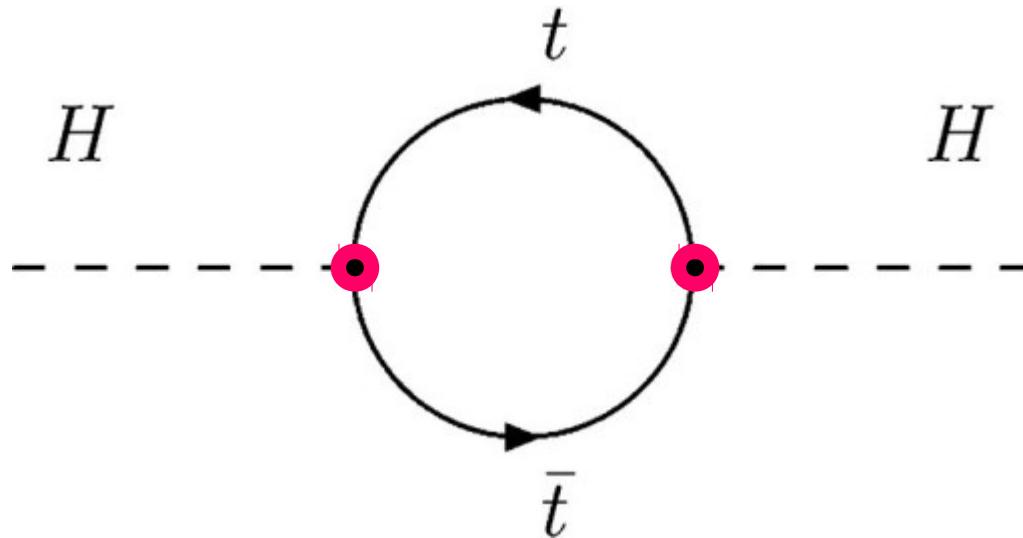


Associated Higgs production with top quarks

GK Krintiras on behalf of CMS Collaboration



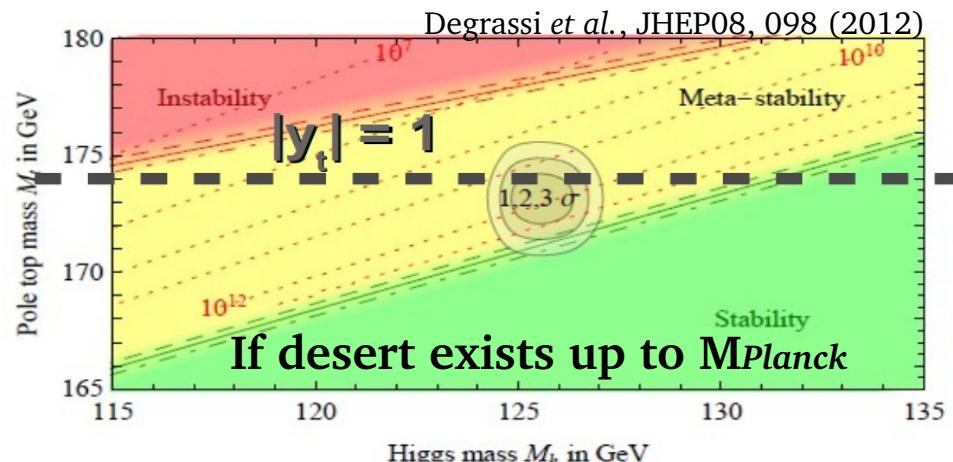
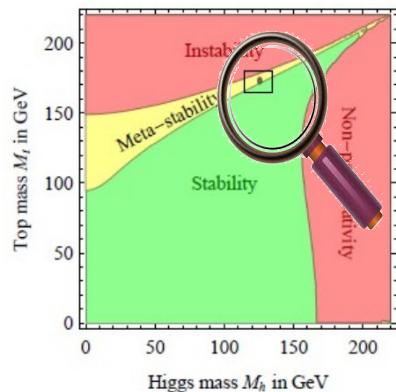
Living dangerously



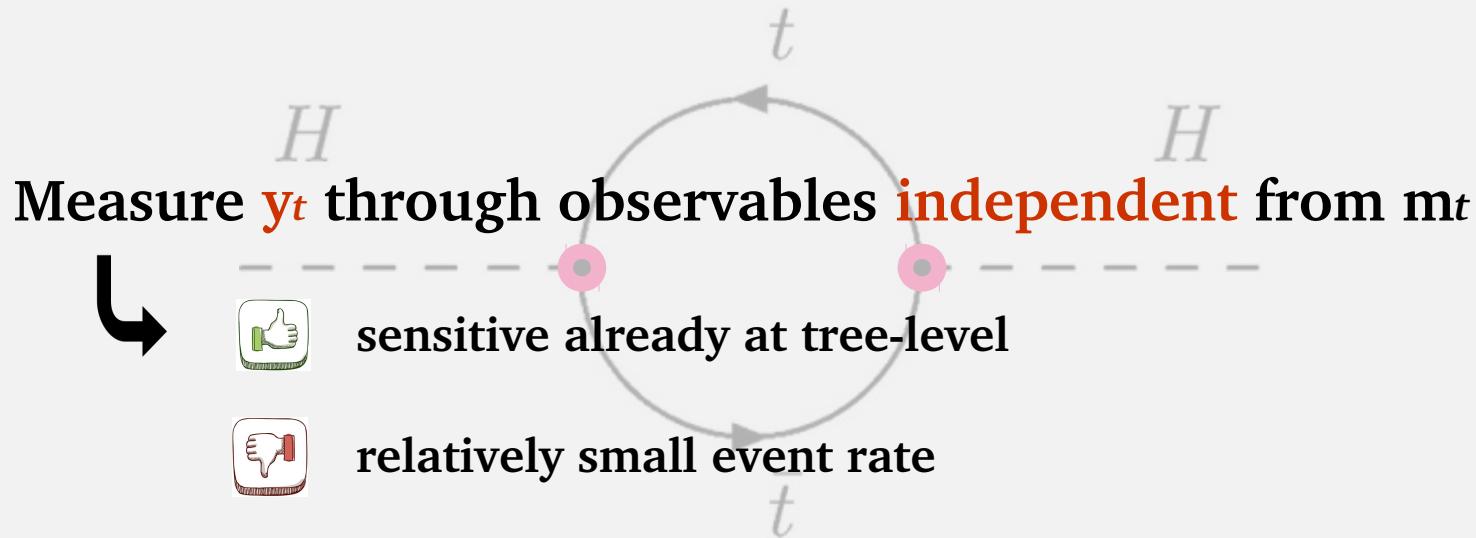
In SM, **Yukawa couplings** are determined uniquely by the particles' mass

↳ We measure $m_t = 172.44(0.4\%)^*$ \rightarrow ends up to $|y_t| = 0.990(0.3\%)$, i.e. **almost 1**

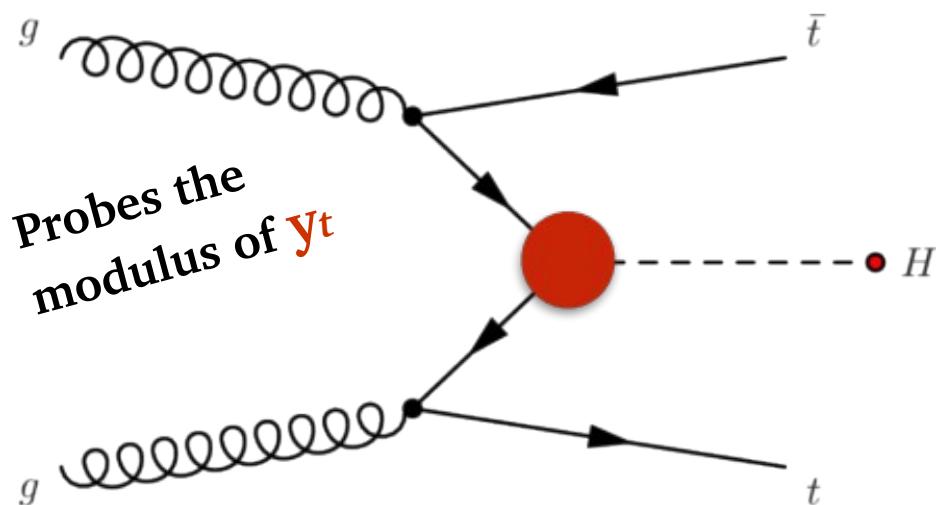
For a non dimensional parameter that's at least interesting



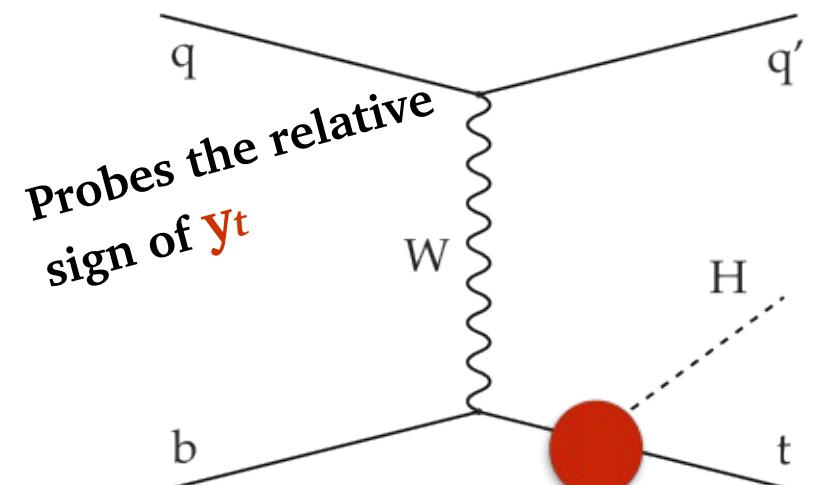
Associated Higgs (H) production with top (t) quarks



ttH production: $\sim 1/100$ of ggH



tH production: $\sim 1/30$ of ttH



Distinct experimental signatures of $t\bar{t}H$ and tH

- Searches are complementary, and could be grouped by the interplay of efficiency & purity over the studied :
- **Hadronic** event activity
- **Leptonic** event activity
- **Bosonic** event activity

- $H \rightarrow bb$, $H \rightarrow \tau_h\tau_h$

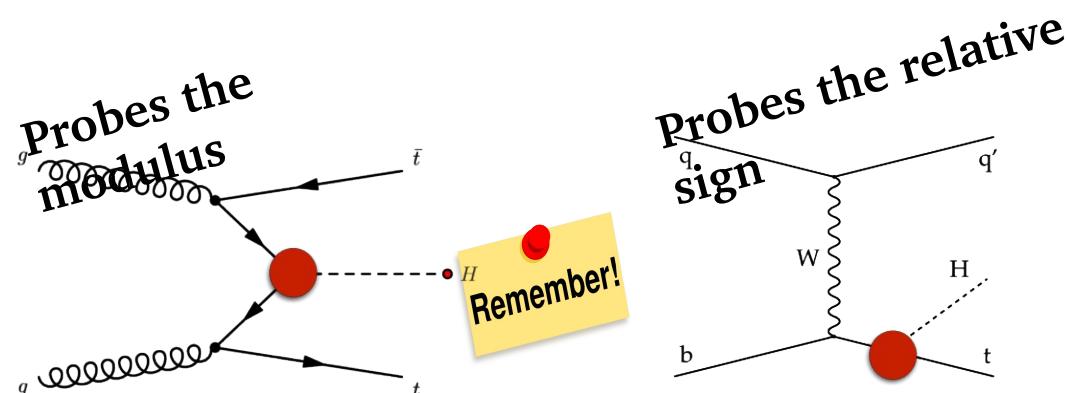
- **Leptonic** event activity

- $H \rightarrow WW$, $H \rightarrow \tau\tau_l$

- **Bosonic** event activity

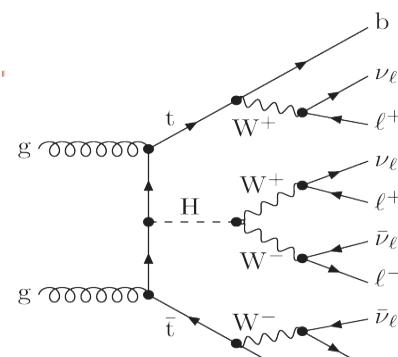
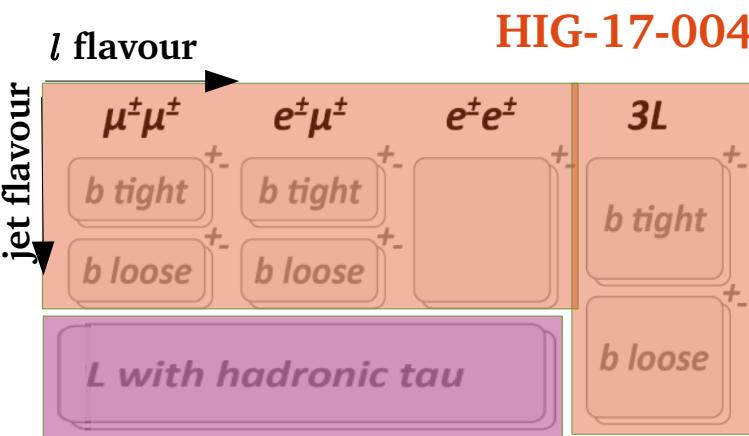
- $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$

“multileptons”

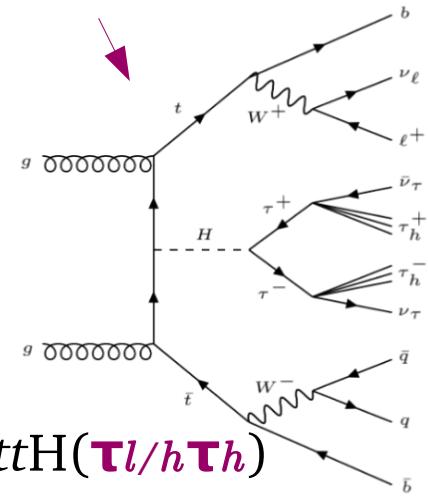


So, what's currently the status of analyses that study the modulus ?

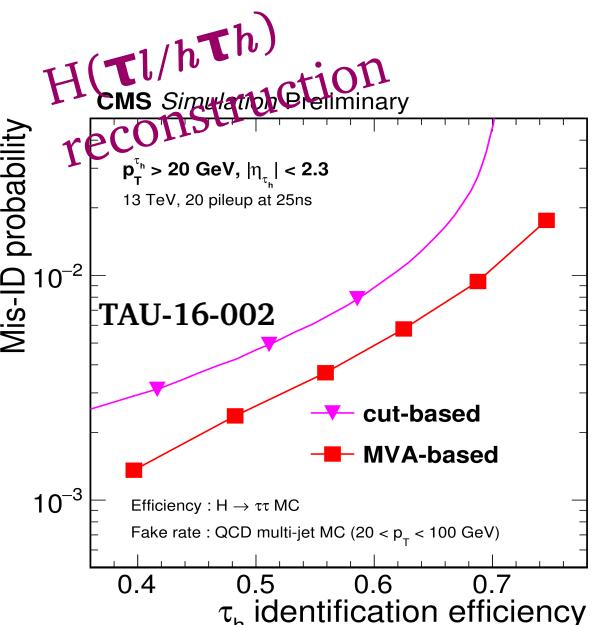
- Three pivotal updates with **36 fb⁻¹** of data
 - all in **multilepton** final state



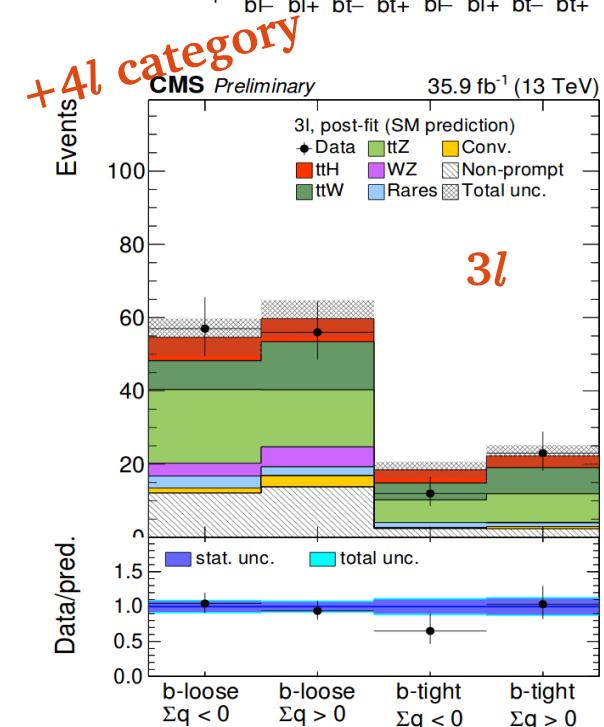
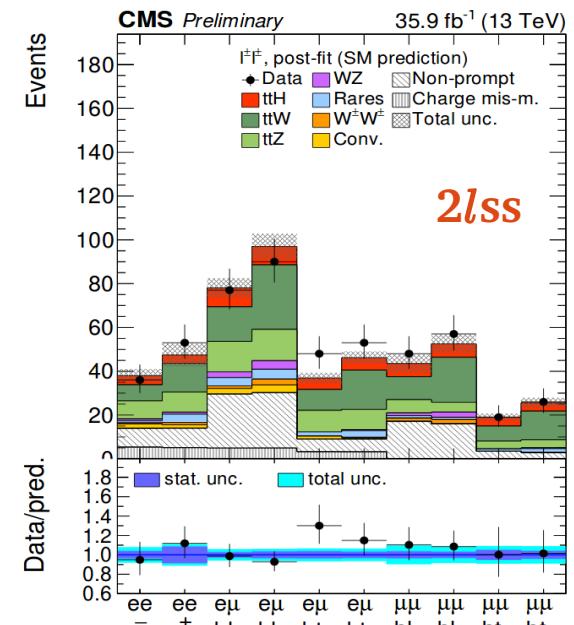
HIG-17-003



$ttH(\text{WW/ZZ}^*/\text{t}\bar{t}\text{t}\bar{t})$

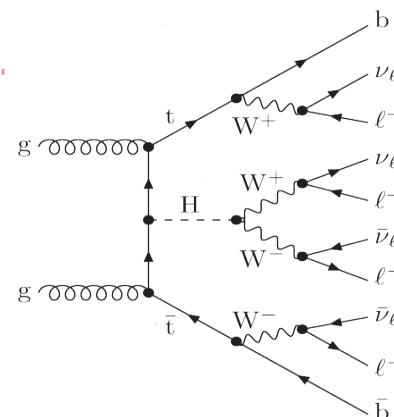
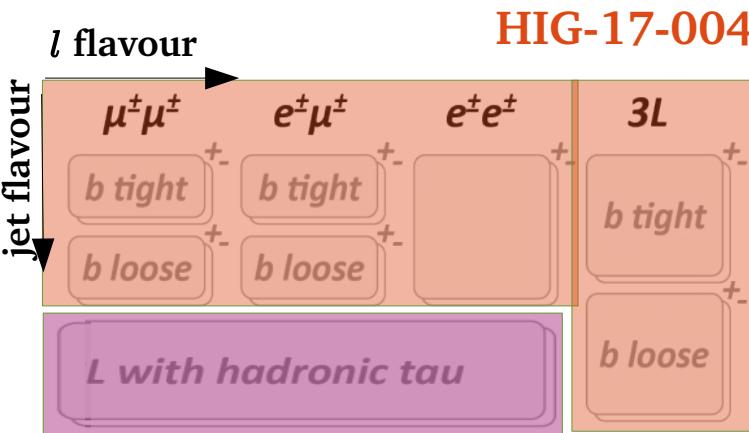


5

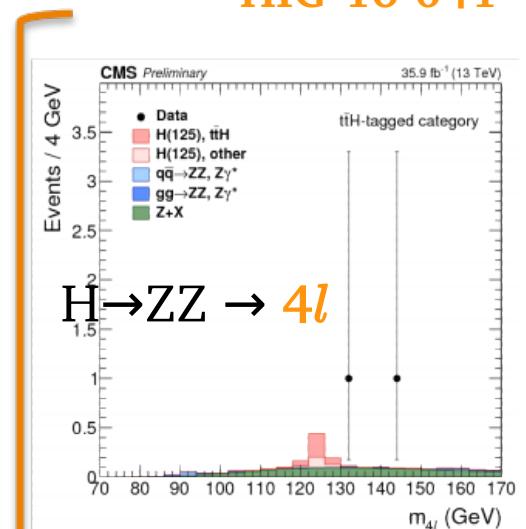


So, what's currently the status of analyses that study the modulus ?

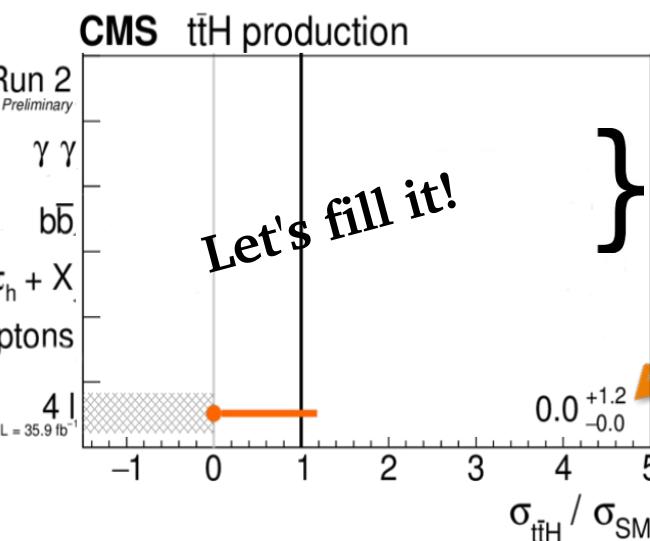
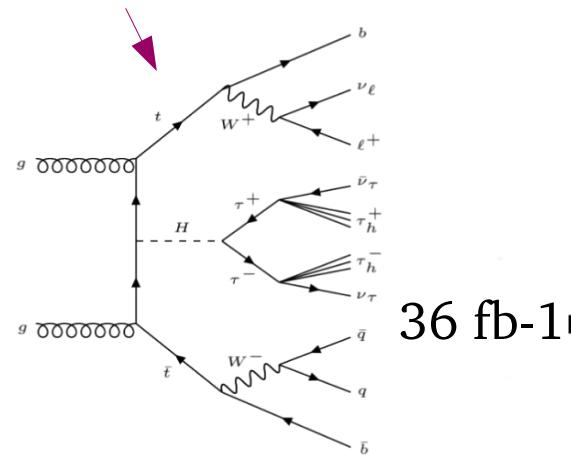
- Three pivotal updates with **36 fb⁻¹** of data
 - all in **multilepton** final state



HIG-16-041



HIG-17-003

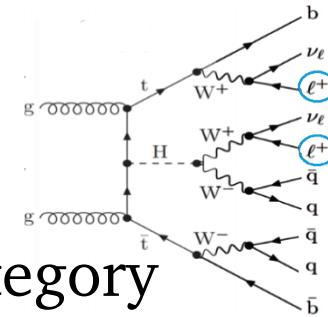


13 fb⁻¹

m_{4l} [118, 130]	
signal	0.5
bkg.	0.3
data	0

↗ No m_{4l} overlap between **HIG-17-004** and **HIG-16-041**

Treating the $t\bar{t}H(\text{WW}/\text{ZZ}^*/\tau\bar{\tau}\ell)$ signal with care



- Irreducible bkg. from $t\bar{t} + V$ bosons

- Two BDTs ($t\bar{t}H$ vs $t\bar{t}V$ and $t\bar{t}H$ vs $t\bar{t}$) built per lepton category

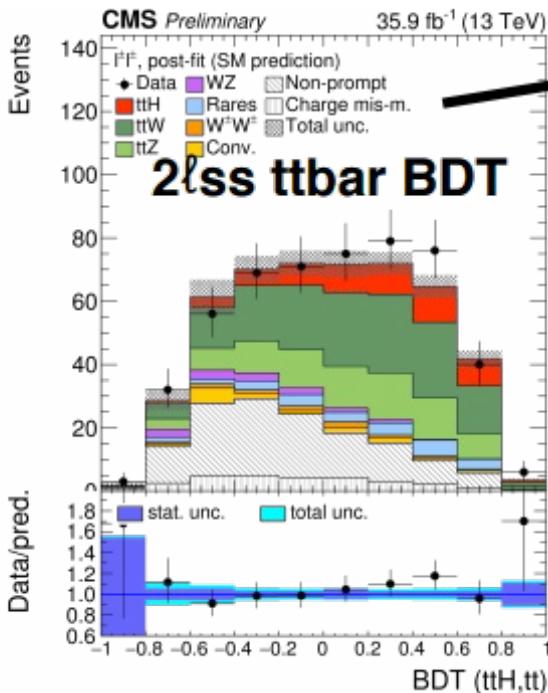
- 1D bins of 2D space spanned by the two BDTs

HIG-17-004

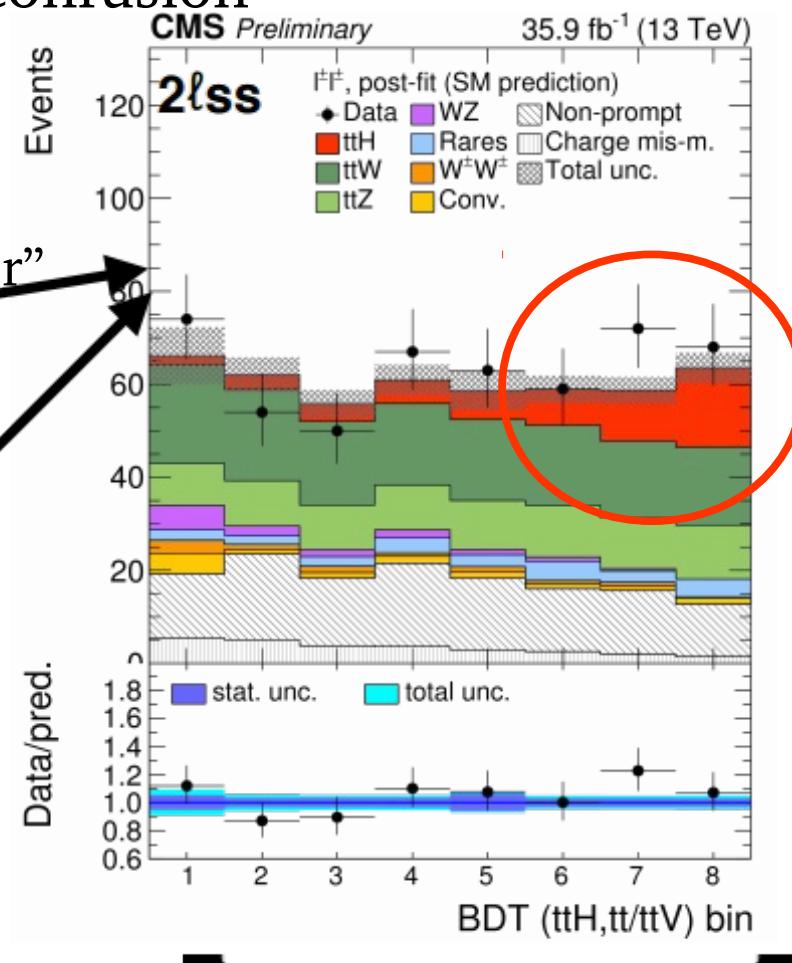
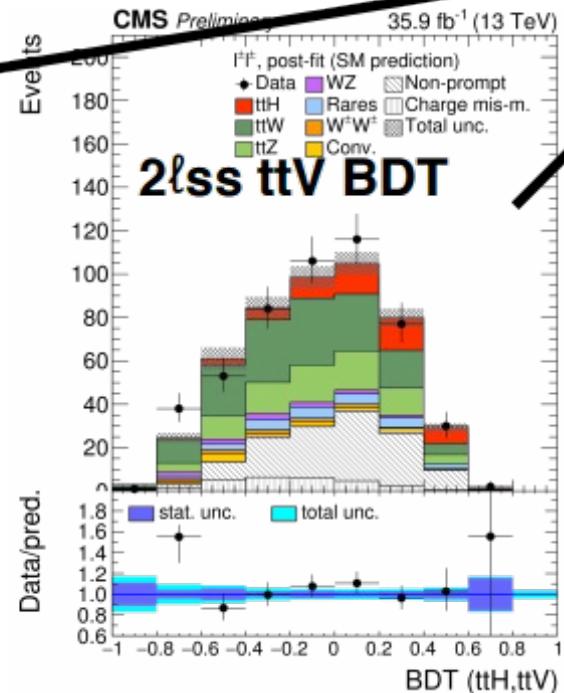
- Reducible bkg. from non-prompt l and l^{\pm} confusion

- from **control regions**

+ hadronic top “tagger”



+ $H \rightarrow WW(qq)$ “tagger”



Binning to ~ flatten bkg. 7

Treating the $t\bar{t}H(\text{WW}/\text{ZZ}^*/\tau\bar{\tau}\ell)$ signal with care

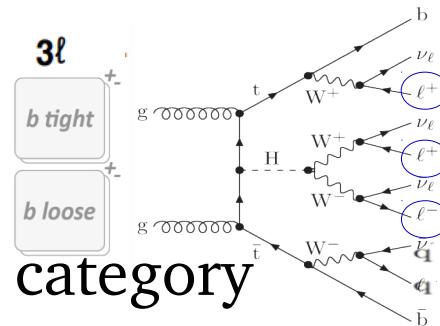
- Irreducible bkg. from $t\bar{t} + V$ bosons

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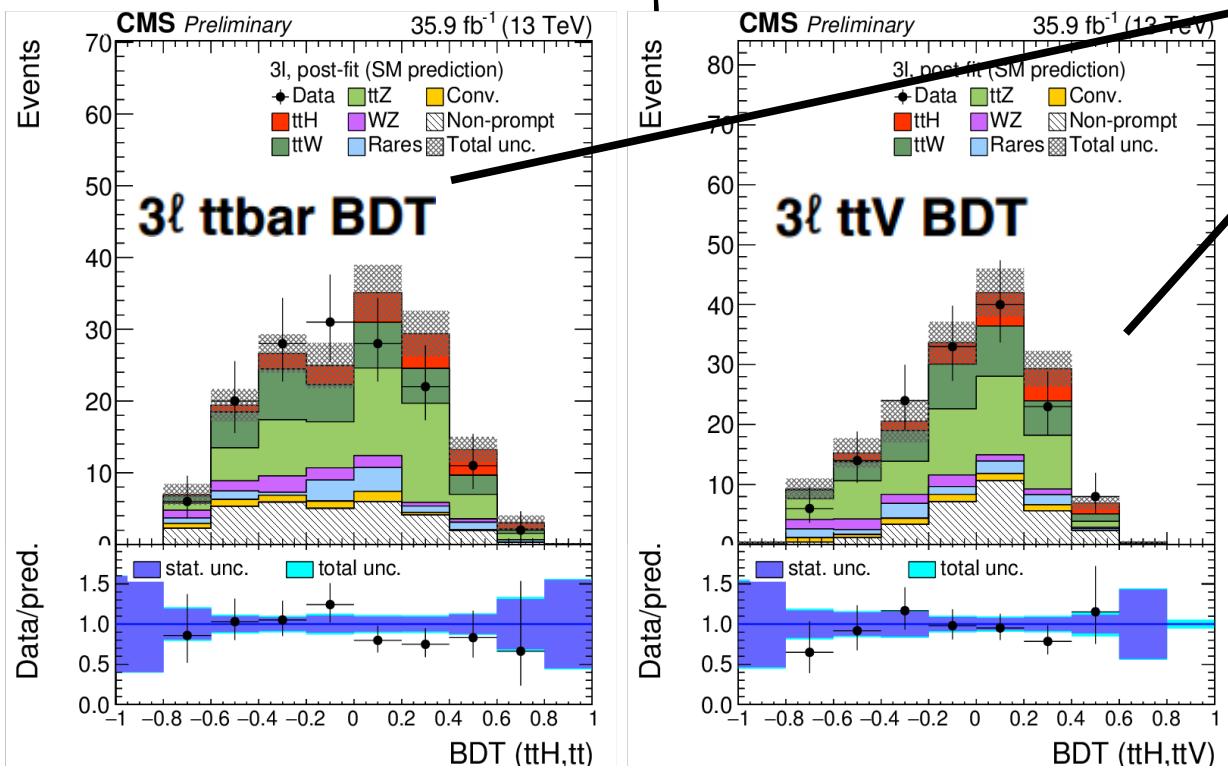
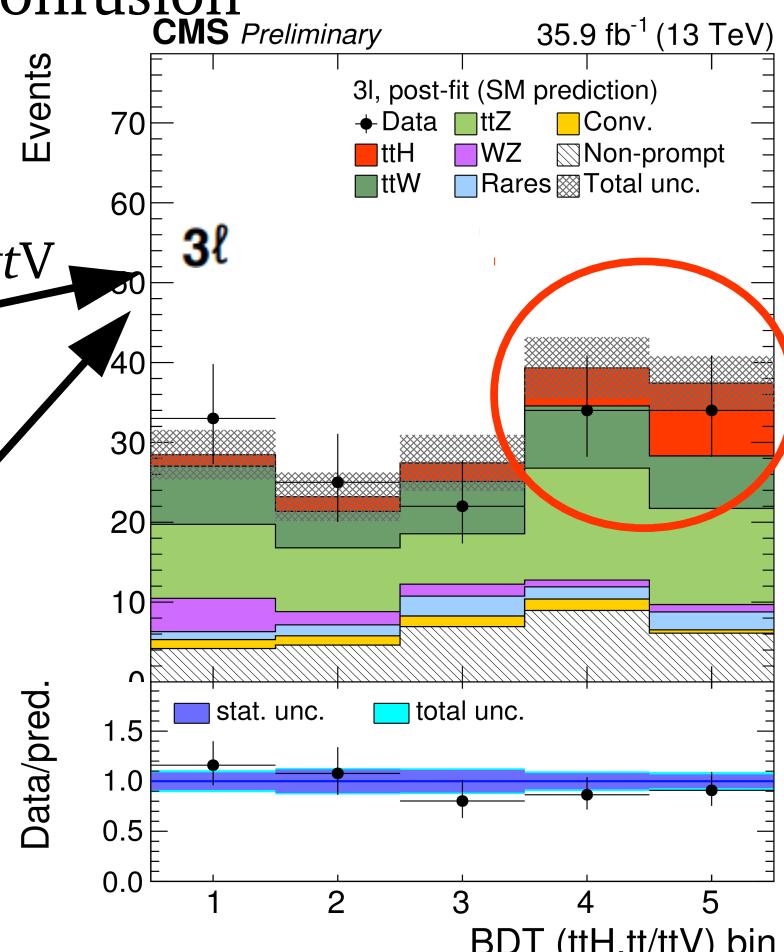
- 1D bins of 2D space spanned by the two BDTs

- Reducible bkg. from non-prompt l and l^\pm confusion

- from **control regions**



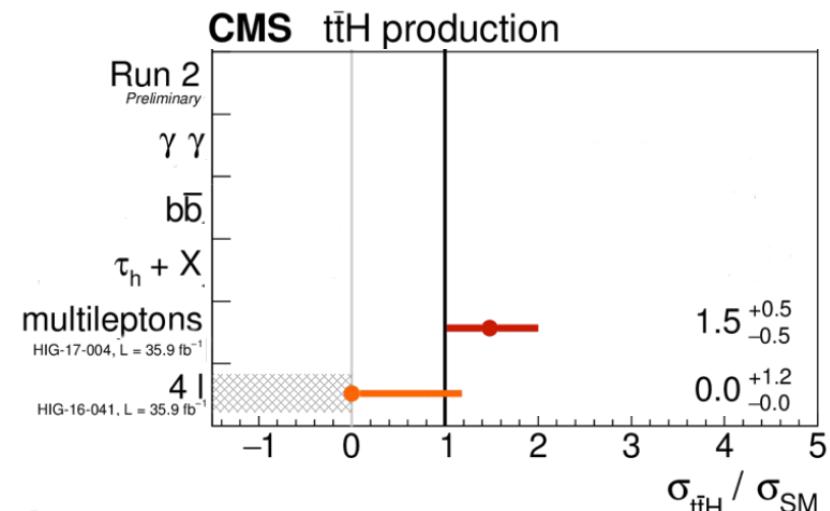
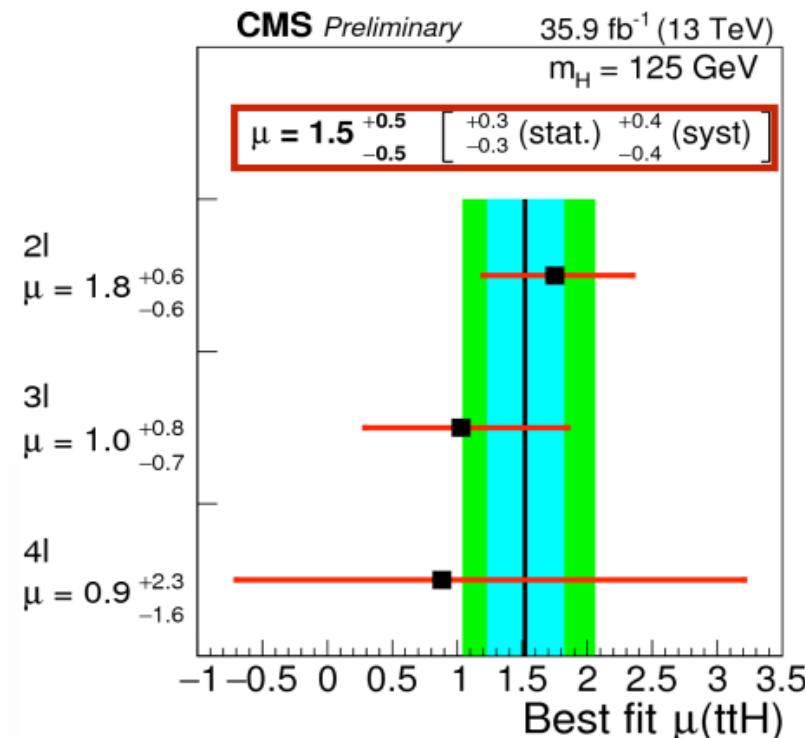
HIG-17-004



Treating the $t\bar{t}H(\text{WW/ZZ}^*/\tau\bar{\tau}\ell)$ signal with care

HIG-17-004

- ↗ Measurement limited by **statistics** and **systematics**
 - (almost) **equally dominated** by theo. and exp. uncertainties
- ↗ Best fit $t\bar{t}H$ yield $1.5 \pm 0.5 \times$ the SM prediction at **$3.3\sigma(2.5\sigma)$** level
 - no visible impact from the addition of the 2015 dataset (2.7 fb $^{-1}$)
 - **compatible with SM**; cross-checked with floating $t\bar{t}V$ in the fit

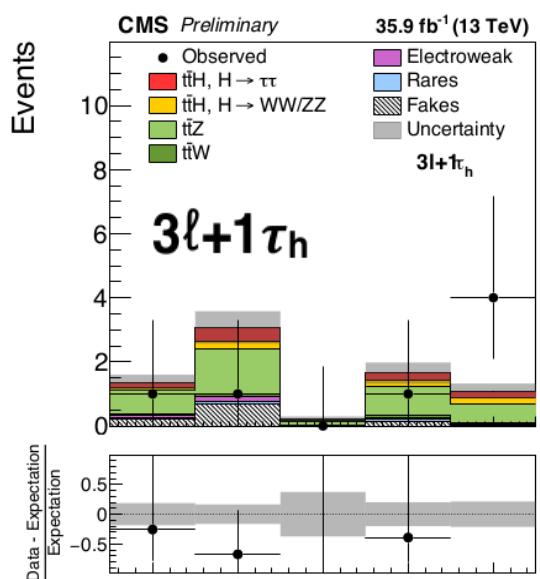
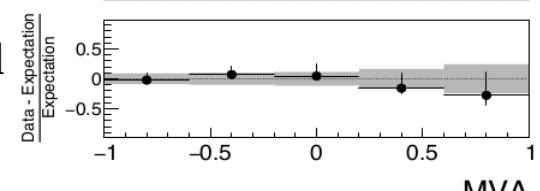
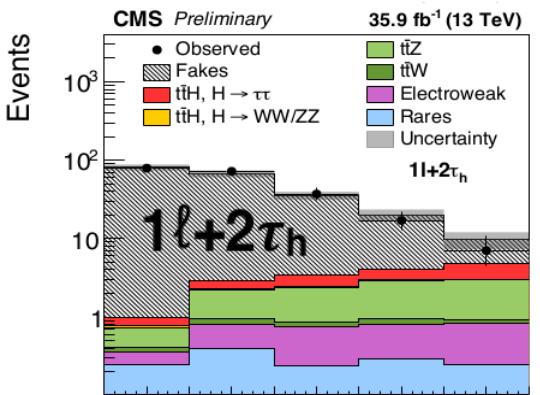
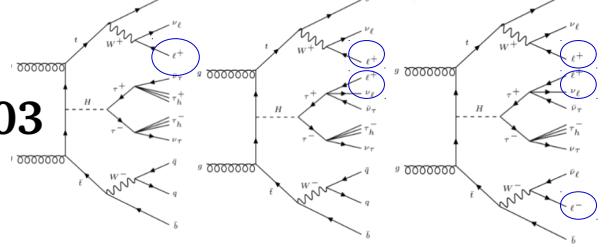
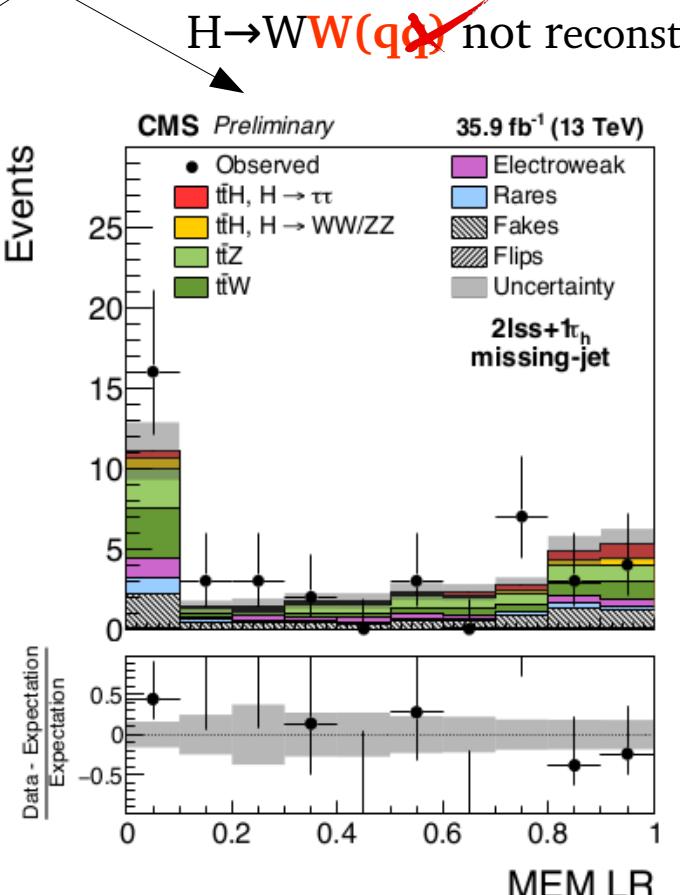
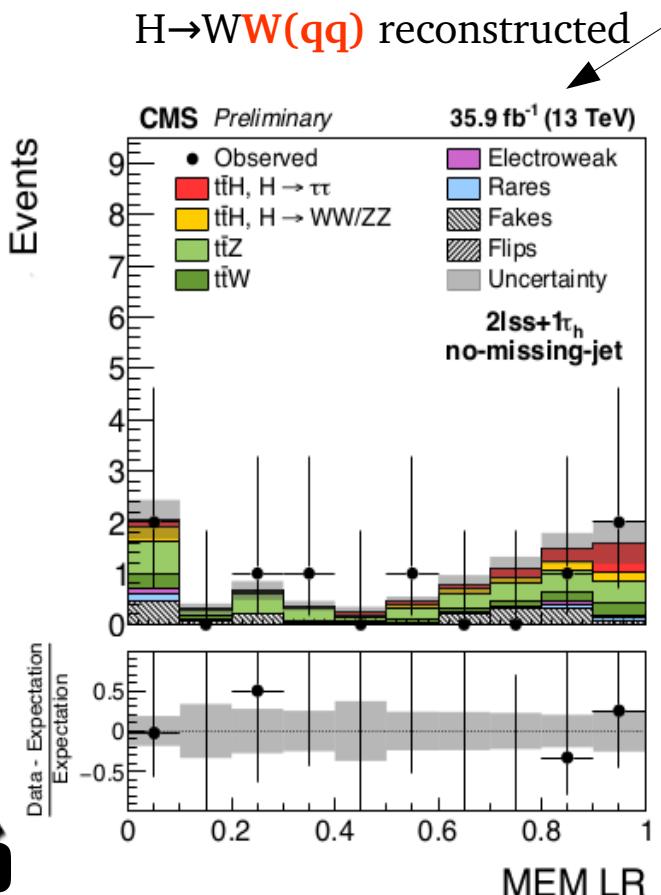


The first $t\bar{t}H(\tau_l/\tau_h)$ reconstruction in Run2

HIG-17-003

- ☒ $1l + \tau_h\tau_h$, $2lSS + \tau_h$ and $3l + \tau_h$ categories
- ☒ MVAs to increase the sensitivity per category
- ☒ bkg. similar to the “multileptons” case
- ☒ irreducible from MC; reducible from data

$2lSS+1\tau_h$



Mapped 2D BDT bin number ΔD_{MVA}

The first $t\bar{t}H(\tau_{l/h}\tau_h)$ reconstruction in Run2

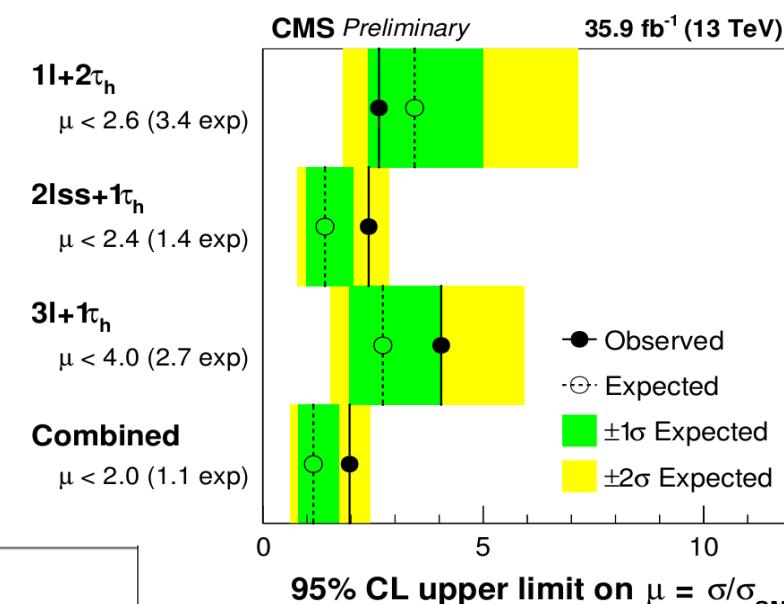
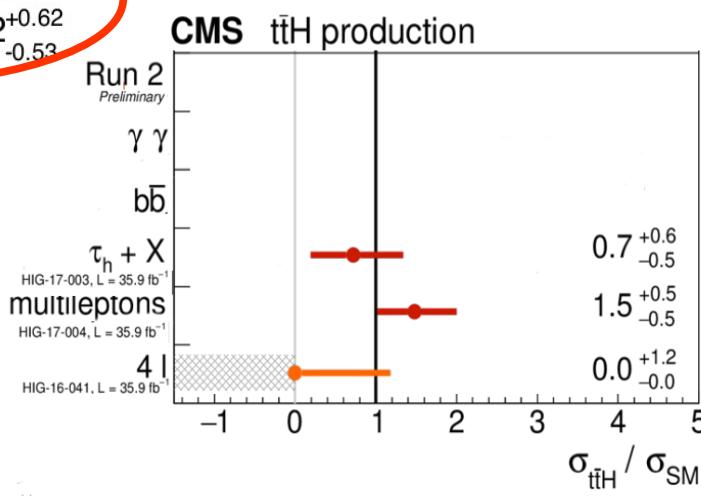
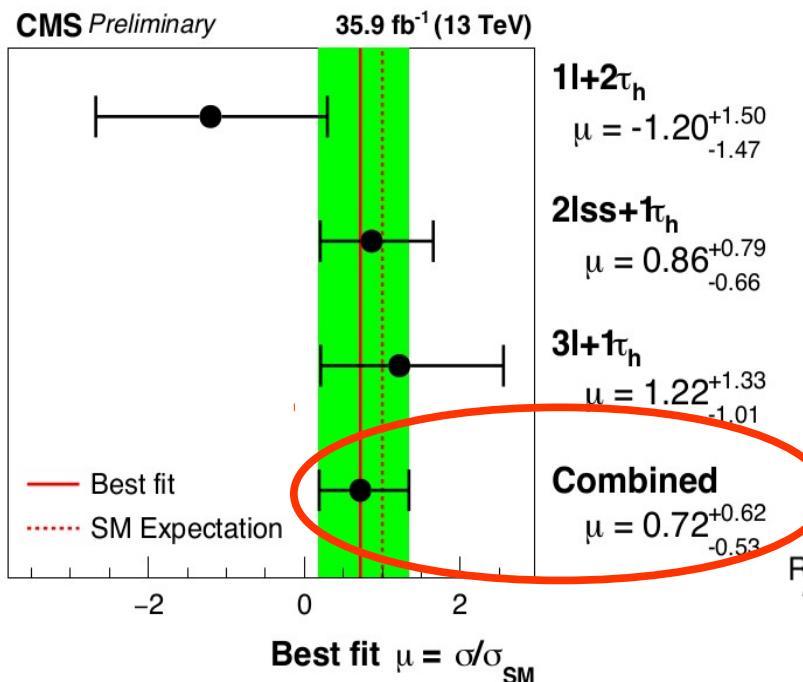
HIG-17-003

Measurement limited by **statistics** and **systematics**

- dominated both by irreducible and reducible bkg.

Significance of $t\bar{t}H$ production at **$1.4\sigma(1.8\sigma)$** level

- upper limit set at $2.0(2.2) \times$ the SM $t\bar{t}H$ production rate



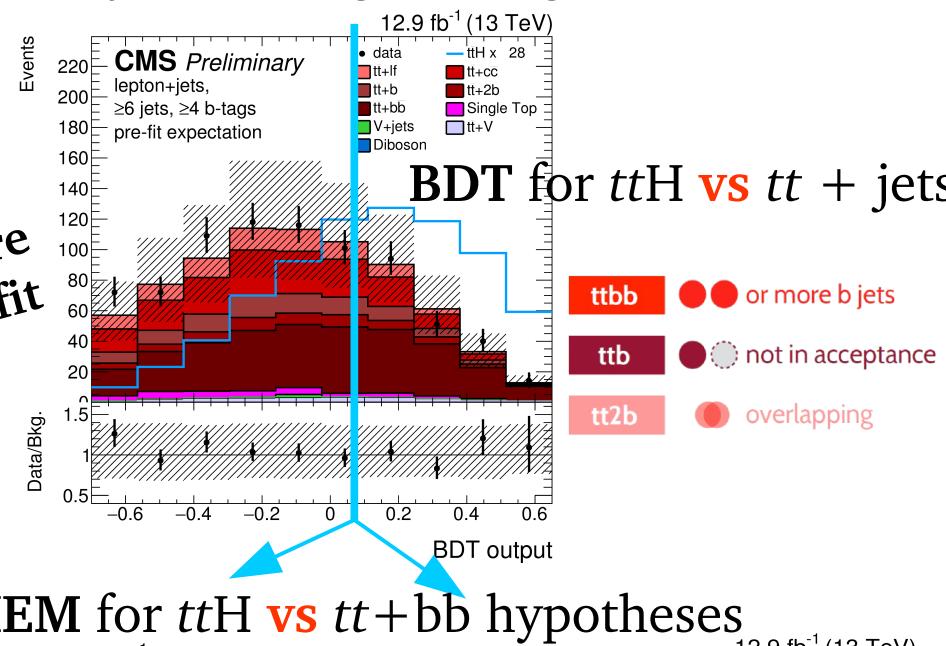
How to deal with the overwhelming bkg. in $t\bar{t}H(\text{bb})$

HIG-16-038

- Important to resolve jet combinatorics in jets/b-tags categories

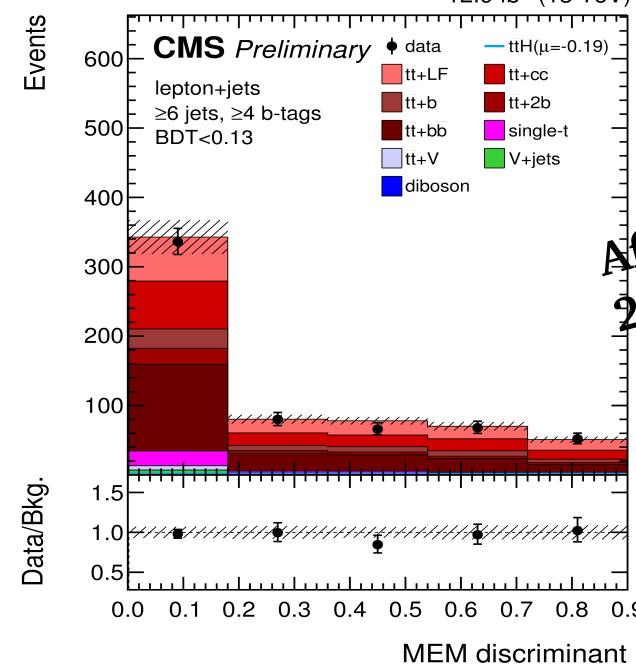
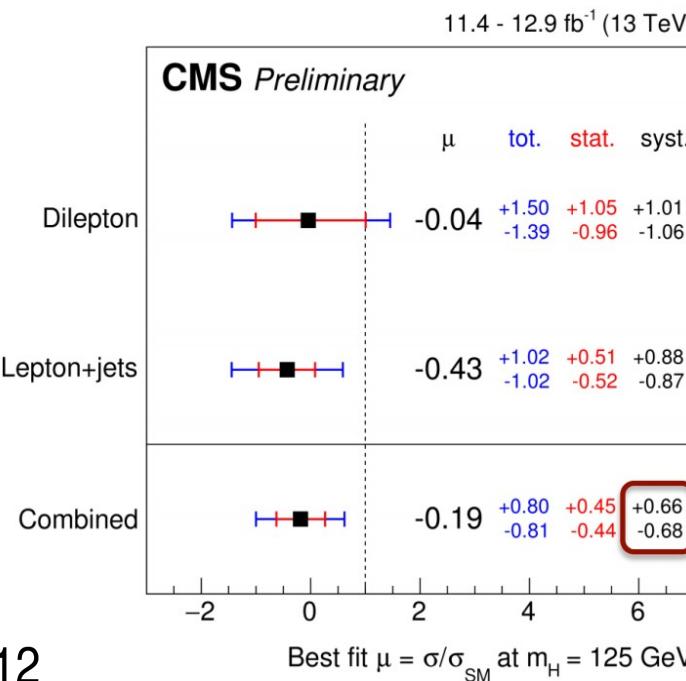
- MVAs in a 2D fit

- improves** MC prediction, and
- reduces** uncertainties
- correlations** well modeled

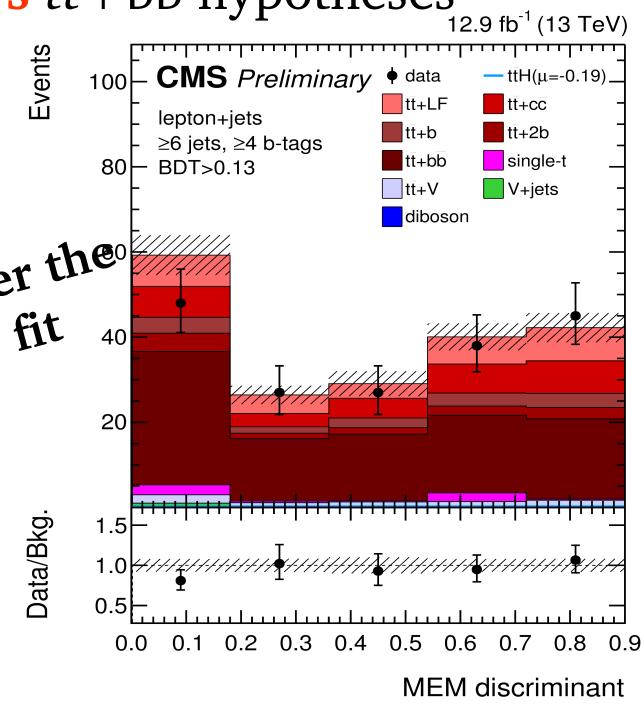


Before
any fit

MEM for $t\bar{t}H$ vs $t\bar{t}+bb$ hypotheses



After the
2D fit



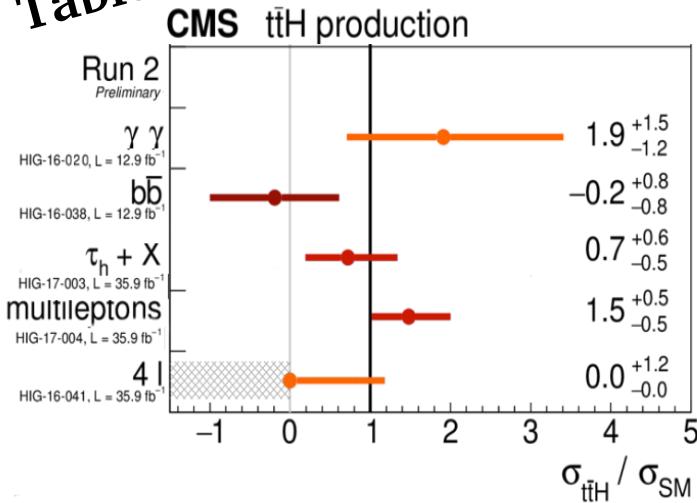
Where the sensitivity for the $t\bar{t}H(\gamma\gamma)$ stands ?

HIG-16-020

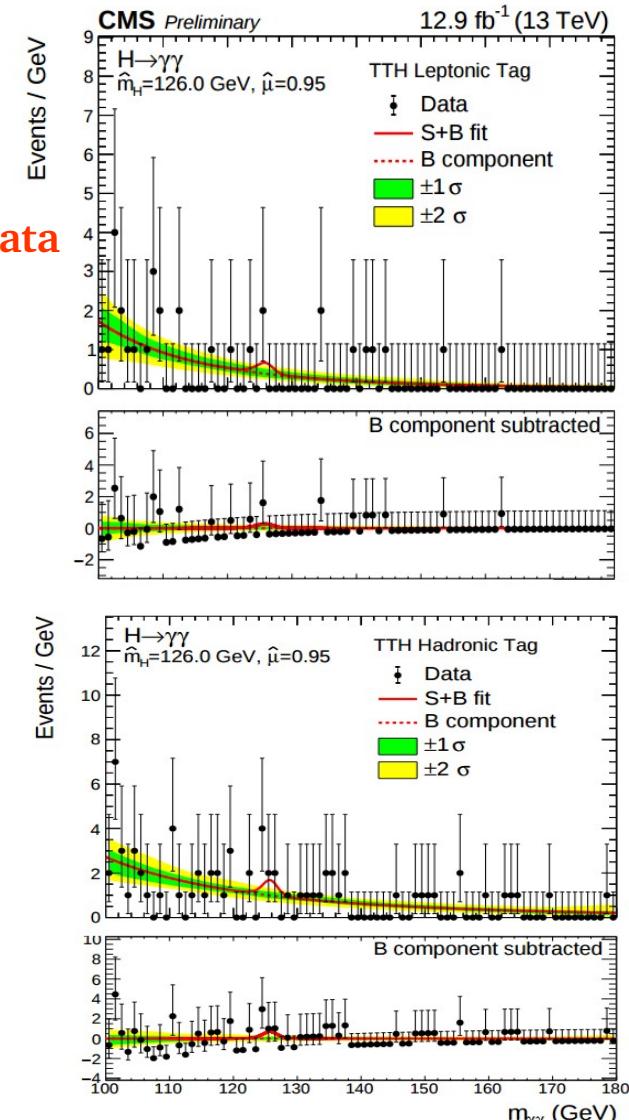
- Look for **small but clean** $m_{\gamma\gamma}$ peak with

- an expected photon energy resolution of $\sim 1\%$
- separately in **leptonic** (95% pure) & **hadronic** (80% pure) $t\bar{t}$ decays
- limited by **statistics**

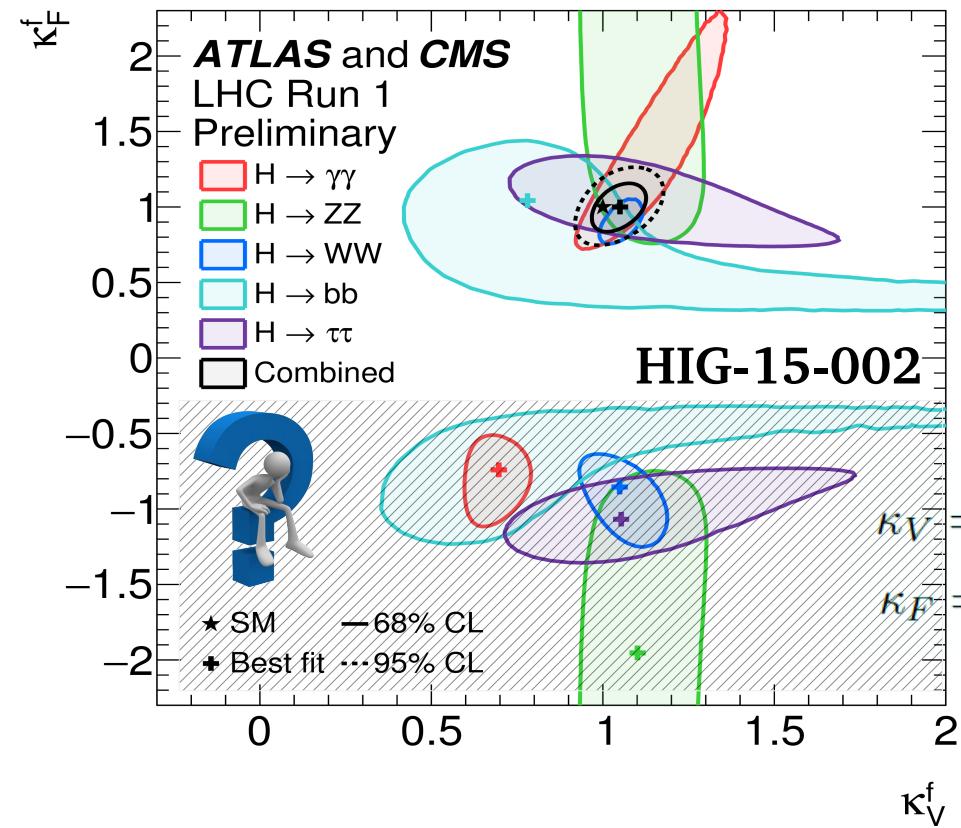
Table filled out!



- Background :** functional forms driven by **data**
- Signal :** n Gaussian model **fit to MC**

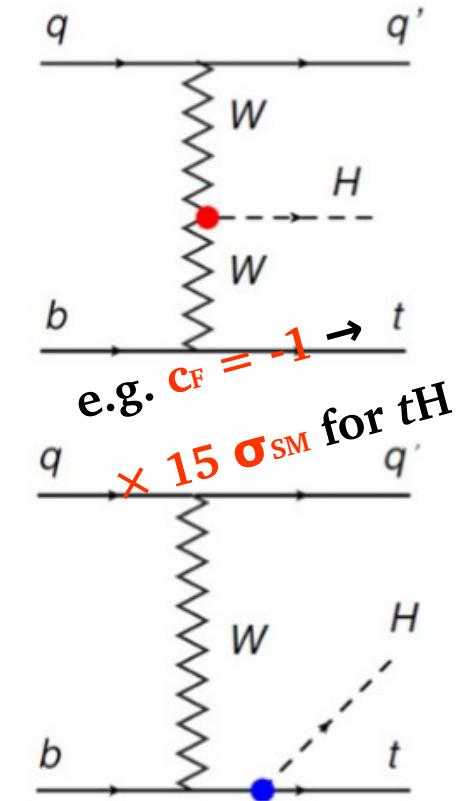


How to disentangle the **negative Yukawa** regions ?



$$\kappa_V = c_V \equiv g_{hWW} / g_{hWW}^{\text{SM}}$$

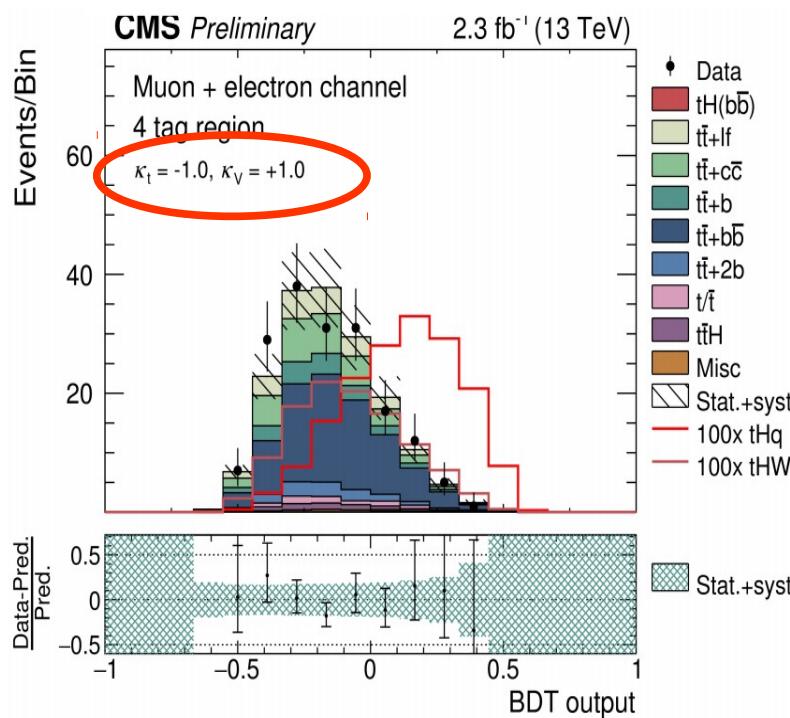
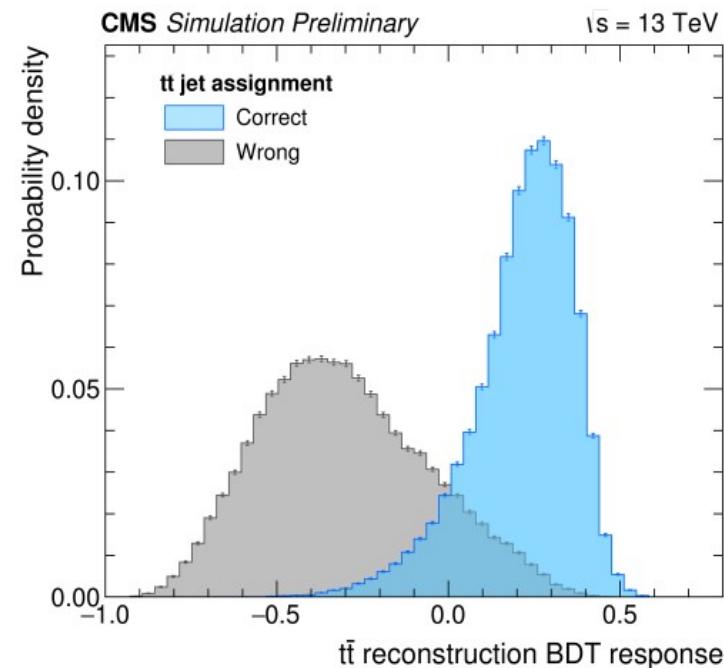
$$\kappa_F = c_F \equiv g_{hff\bar{f}} / g_{hff\bar{f}}^{\text{SM}}$$



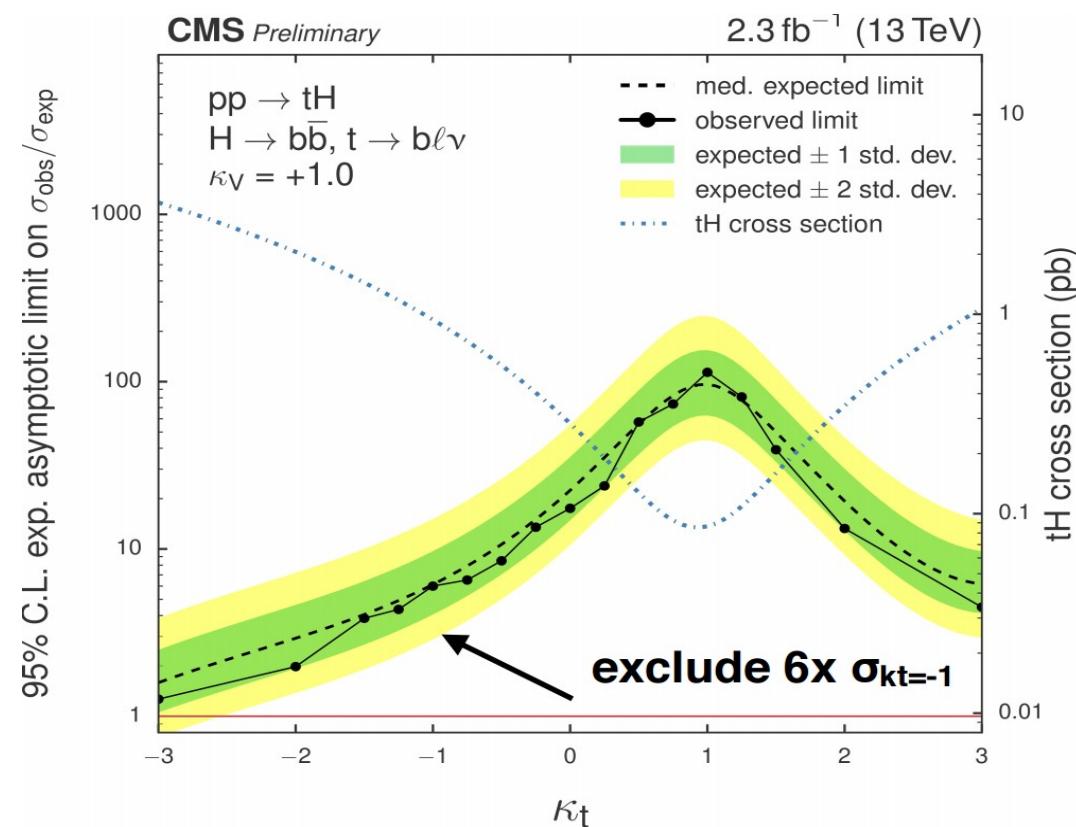
- Best fit at Run1 favors the SM solution (★) within **5σ** (!)
- But**, what if beyond SM Physics **is hidden** in loops (?)
- a direct way to **lift** the sign ambiguity is tH production
 - unitarity and renormalizability are spoiled in $c_V \neq c_F$ deviations
 - i.e. **enhancement** of amplitude \rightarrow **higher** production rate

First derived limits with Run2 data: $tH(\text{bb})$

HIG-16-019



- ▣ Jet assignment crucial
- ▣ MVA for tH vs tt hypotheses
- ▣ A second MVA for tH extraction
- ▣ first time done for multiple k_t/k_V scenarios



- Key improvements in $t\bar{t}H$; obviously **more data**

- Multileptons** && dedicated τ_h searches

- improved handling of reducible backgrounds
- better signal extraction and validation of $t\bar{t}V$

- bb** searches

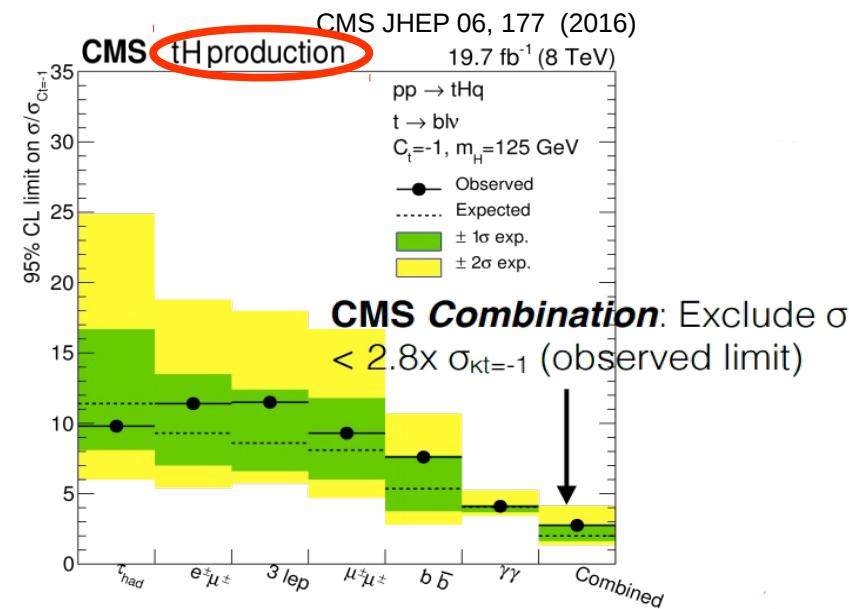
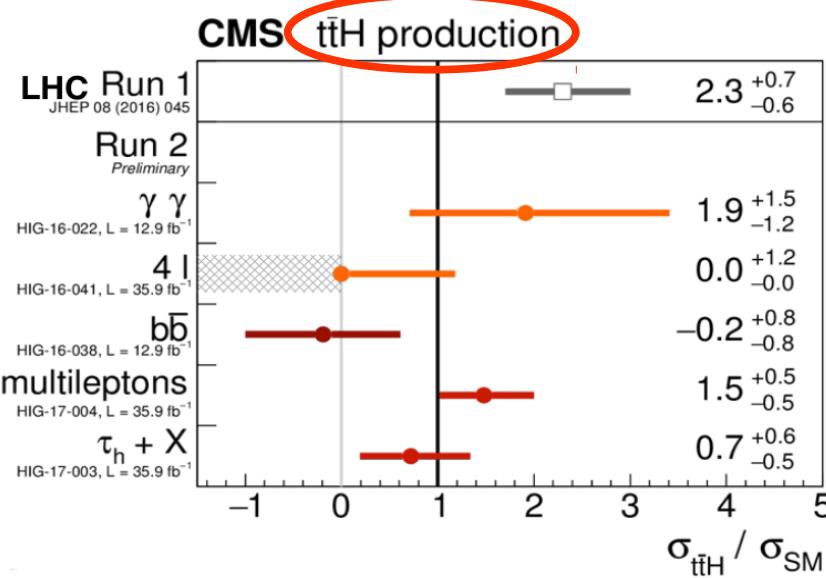
- improvement of the signal extraction
- modeling of $t\bar{t} + (b-) \text{ jets}$

■ **bb** sensitivity comparable with Run I dataset

- YY** searches

- statistics limited

■ rest of channels on the pipeline



Slides



- irreducible background from theory predictions
 - For the main $t\bar{t}V$ backgrounds, NLO QCD+EWK cross section (YR4), NLO QCD+PS MC (uncertainties $\sim 10\%$)
 - CMS also performed cross check with $t\bar{t}W$ & $t\bar{t}Z$ floating, including some CRs for $t\bar{t}W$ & $t\bar{t}Z$ in the fit
- reducible background from non-prompt leptons estimated from data:
 - Events in SR but with loose-but-not-tight leptons are weighted by lepton mis-identification probabilities
 - Mis-identification probabilities derived from multi-jet events
 - Sizeable relative systematic uncertainty, $O(30\%)$

- maximum $|\eta|$ of the two leading leptons
- jet multiplicity
- minimum ΔR separation between each of the two leading leptons and a jet
- transverse mass of the leading lepton and the E_T^{miss}
- maximum score among jet permutations of a BDT discriminator that aims at re-constructing hadronic top decays (for $t\bar{t}H$ vs $t\bar{t}$, $\ell^\pm\ell^\pm$ only);
- maximum score among jet permutations of a BDT discriminator that aims at tagging jets from Higgs decay products (for $t\bar{t}H$ vs $t\bar{t}V$, $\ell^\pm\ell^\pm$ only);
- highest and lowest p_T of the selected leptons (for $t\bar{t}H$ vs $t\bar{t}V$ only);
- matrix element weights for signal and irreducible backgrounds, combined in one likelihood ratio variable (3ℓ only).

1 $\ell+2\tau_h$
BDT trained against ttbar

- The invariant mass and angular separation of the two reconstructed τ_h .
- The transverse momenta of the two reconstructed τ_h .
- The observable H_T^{miss} , computed according to Eq. (3).
- The average angular separation between any pair of jets.
- The multiplicity of jets, with and without b-tagging criteria applied.

2 $\ell ss+1\tau_h$
MEM with $t\bar{t}H$ and
 $t\bar{t}V$ hypotheses

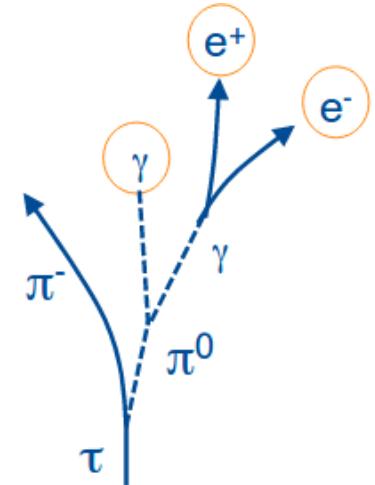
two sub-categories : with / without missing jet

3 $\ell+1\tau_h$
2BDTs: against
 $t\bar{t}V$ and ttbar

- The transverse momenta of the leading lepton and of the third lepton.
- The maximum $|\eta|$ of the two leading leptons.
- The multiplicity of jets.
- The angular separation of the leading and of the subleading lepton with respect to the nearest jet.
- The transverse mass of the leading lepton and the missing transverse energy vector.
- The observable H_T^{miss} .
- The average angular separation between any pair of jets.

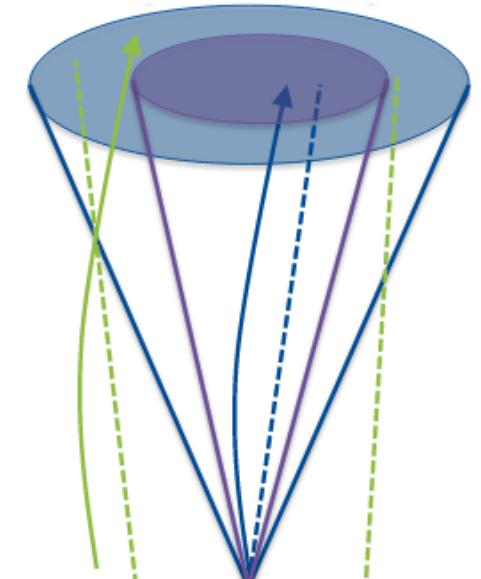
Hadron + strip (HPS) algorithm

- Seeded by reconstructed PF jets
- Neutral pions : strips 0.05×0.020 in $\eta\text{-}\Phi$
- Look into jet constituents, decay mode finding
 - a single charged particle without any strips: h^\pm ;
 - combination of one charged particle and one strip: $h^\pm\pi^0$;
 - combination of a single charged particle with two strips: $h^\pm\pi^0\pi^0$;
 - combination of three charged particles: $h^\pm h^\mp h^\pm$.



Dynamic strip reconstruction

- Widen strip size in the case of bremsstrahlung or τ_h nuclear interaction, depends on pT



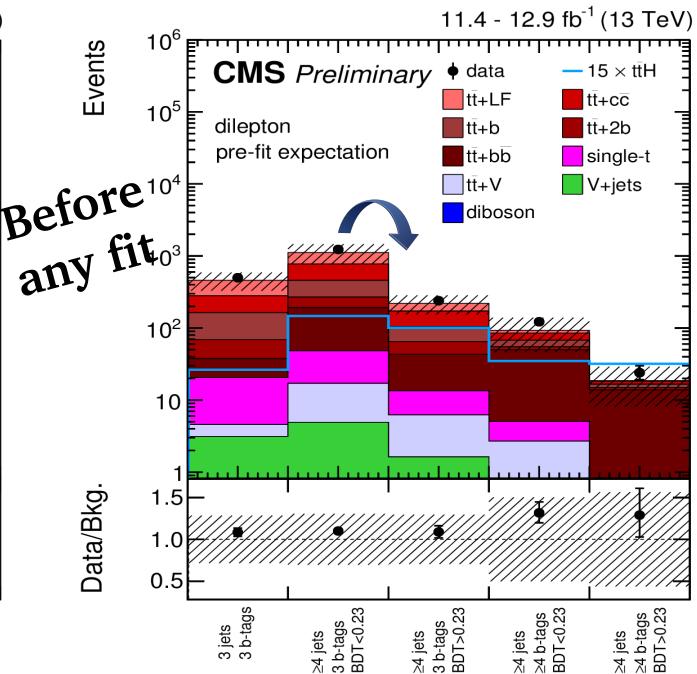
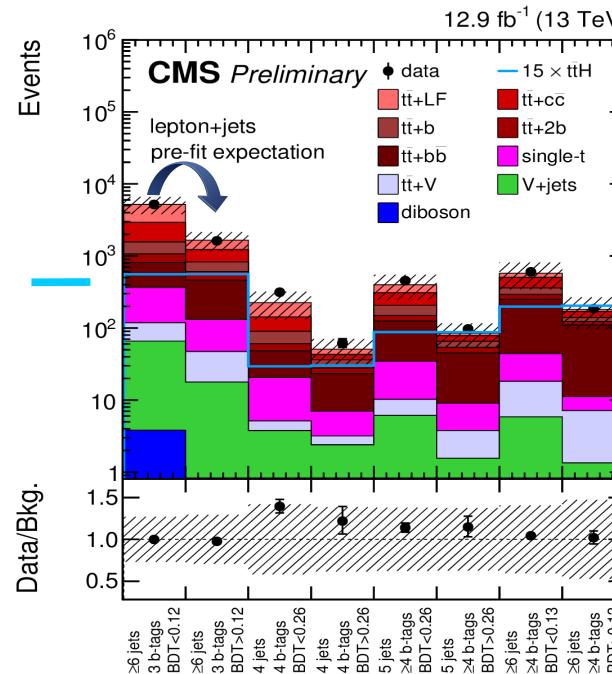
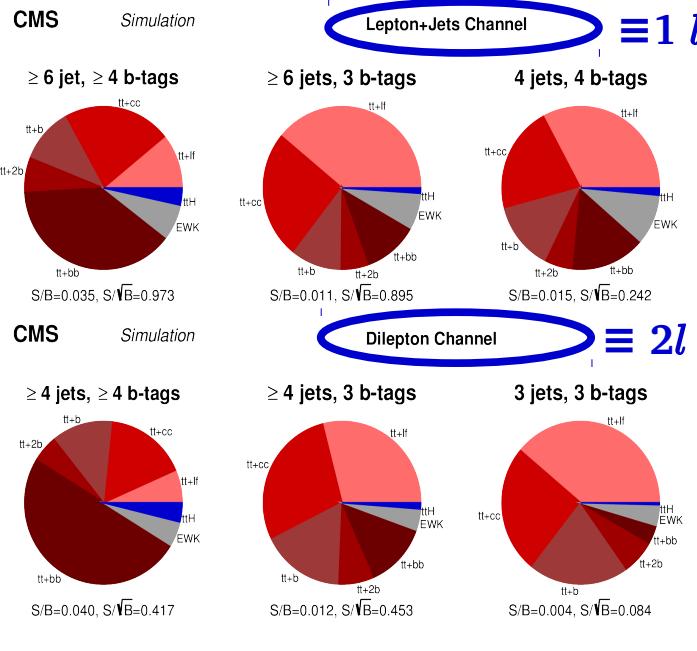
MVA based discriminator against jets

- Use isolation sums computed within a cone of 0.3, optimised for ttH busy hadronic environment

Important to resolve jet combinatorics in jets/b-tags categories

MVAs in a 2D fit

Signal enriched categories



First, a BDT that reduces bkg. (↘) and leaves signal almost intact (→) in each sub-category

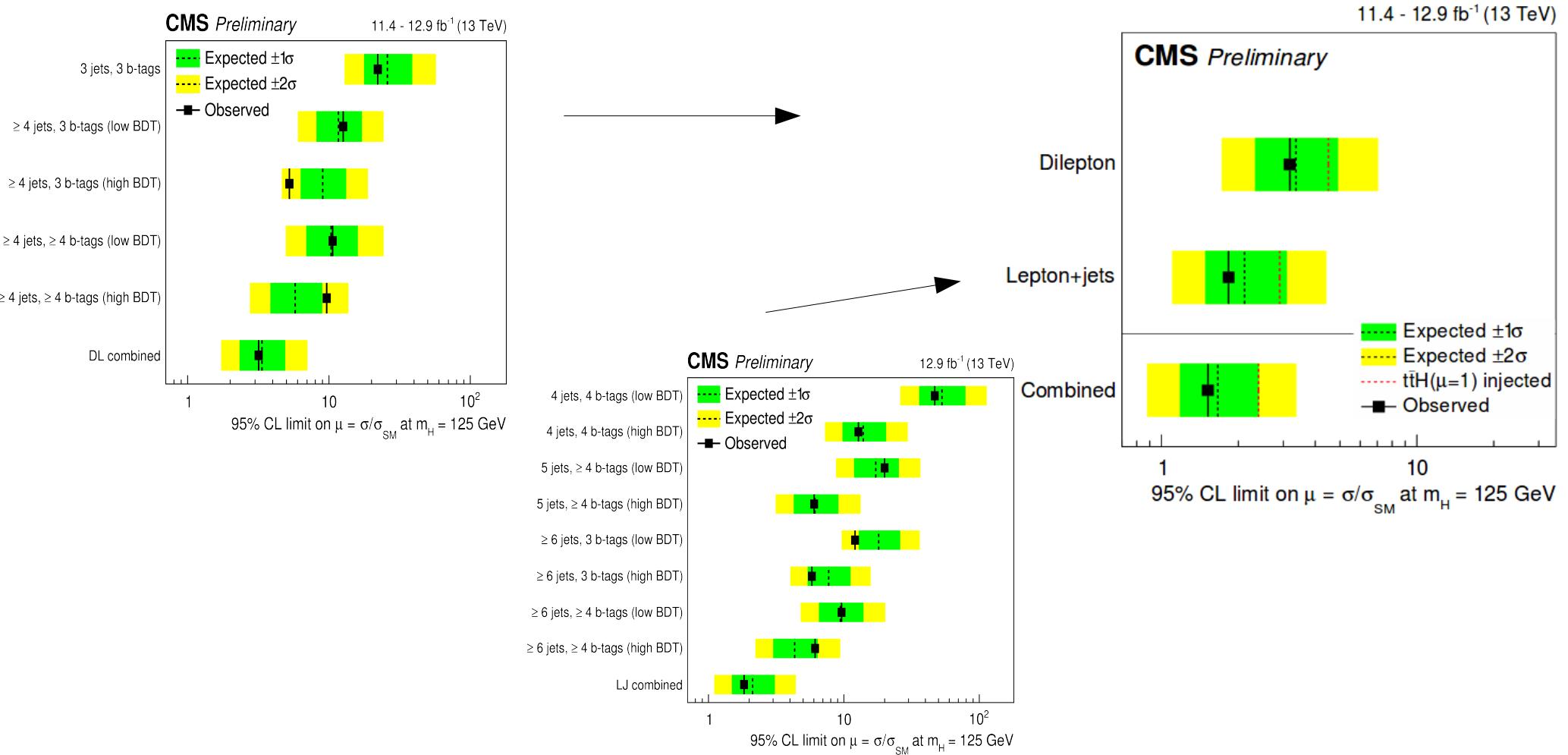
- (generic) discrimination of $t\bar{t}H$ **vs** $t\bar{t} + \text{jets}$
- BDT input variables **and** its structure **optimized**

How to deal with the overwhelming bkg. in $t\bar{t}H(\mathbf{bb})$

HIG-16-038

Measurement limited by **systematics**

- **dominated** by $t\bar{t} + (\text{b-})$ jets bkg.
- Upper limit set at $1.5(1.7) \times$ the SM $t\bar{t}H$ production rate
- improved Run1 limit **by a factor 2**

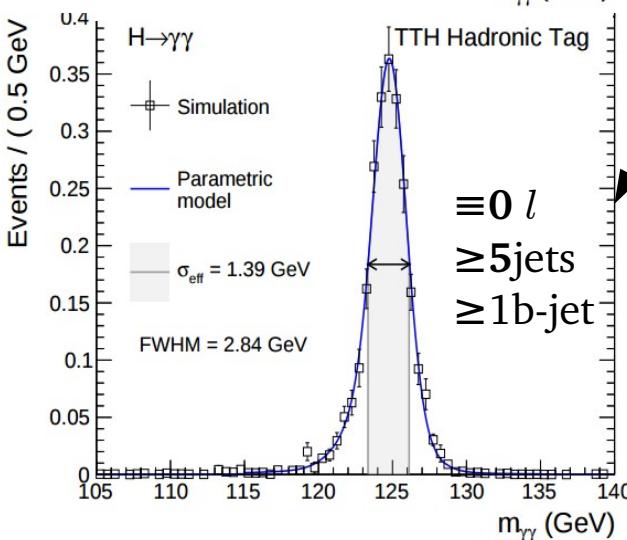
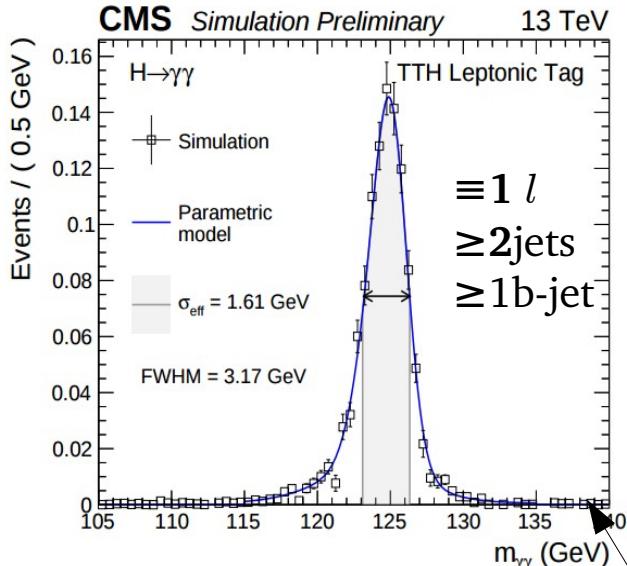


Where the sensitivity for the $t\bar{t}H(\gamma\gamma)$ stands ?

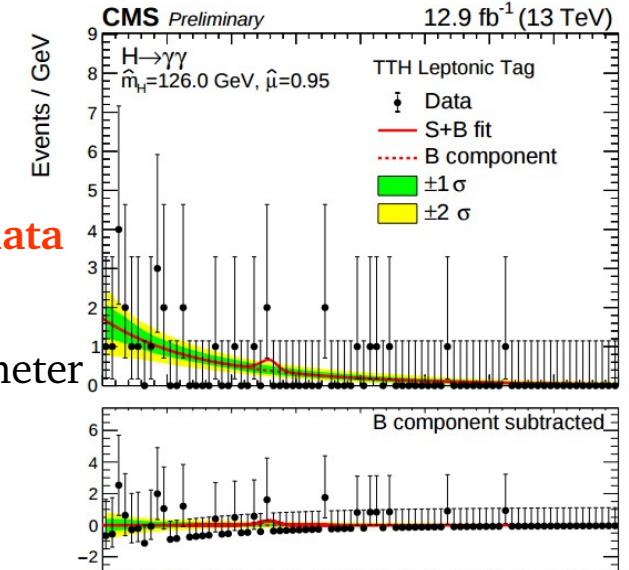
HIG-16-022

- Look for **small but clean** $m_{\gamma\gamma}$ peak with

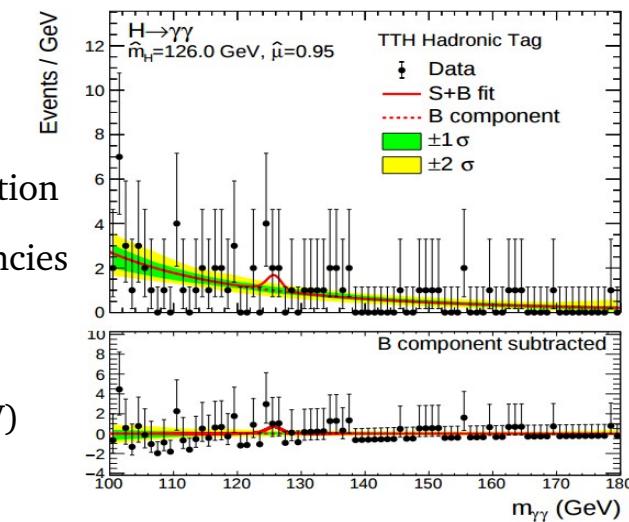
- an expected photon energy resolution of $\sim 1\%$
- separately in **leptonic** (95% pure) & **hadronic** (80% pure) $t\bar{t}$ decays



- Background :** functional forms driven by **data**
 - each form treated as a discrete nuisance parameter



- Signal :** n Gaussian model **fit to MC** that eases
 - the necessary tuning to the simulation
 - corrections for the relevant efficiencies to be applied
 - spline interpolation; for (7) mass hypotheses (within [120,130] GeV)

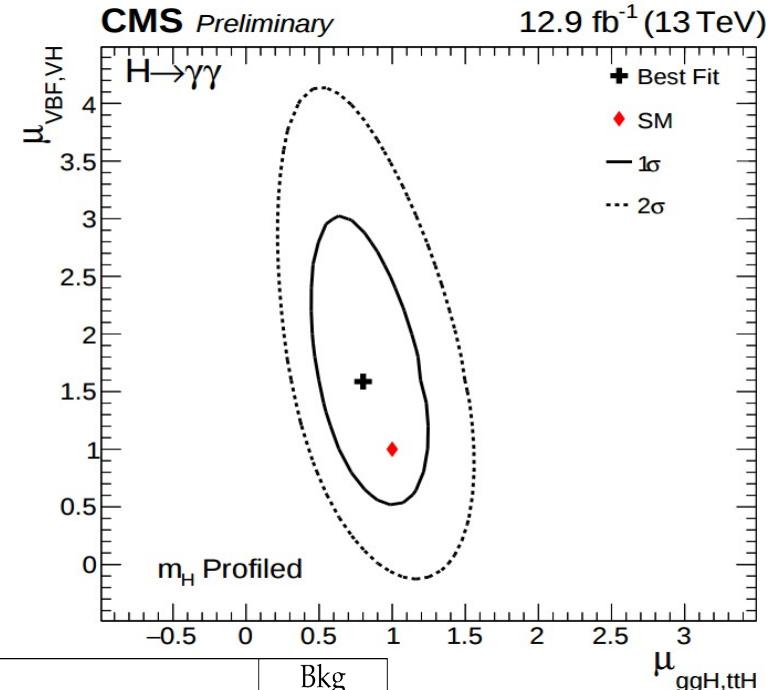
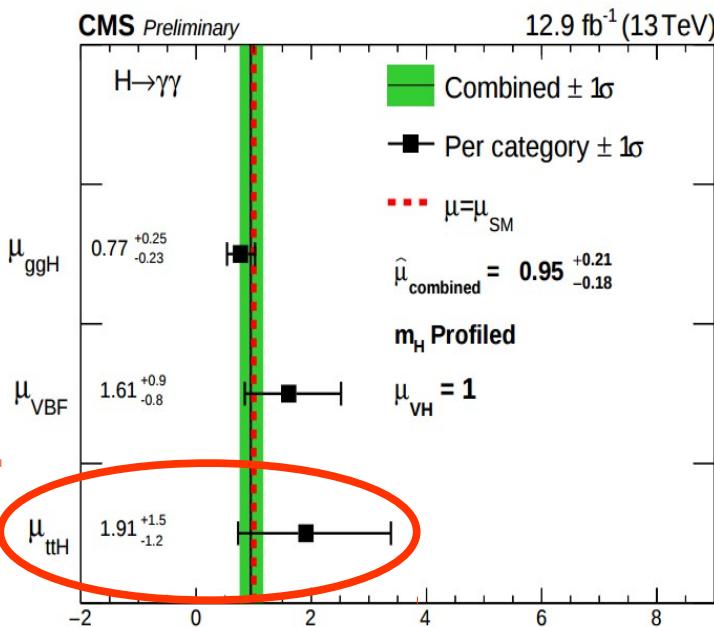


Where the sensitivity for the $t\bar{t}H(\gamma\gamma)$ stands ?

HIG-16-022

- Measurement currently dominated by **statistical power**

- **independently** from other production mechanisms
 - simultaneously (grouped) in **fermionic** and **bosonic** modes



Event Categories	$\hat{\mu} \bar{\mu}$ 125GeV Higgs boson expected signal								Bkg (GeV $^{-1}$)
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	1.47	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	2.17	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	1.33	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	1.40	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	1.52	2762.65

Difficulty to build models for negative Yukawa

- negative Yukawa coupling would point to new physics
- hard to explain, models are tightly constrained/have problems
- example: dim-6 operator

lower effective operator

$$\xrightarrow{\hspace{1cm}} \mathcal{L}_{\text{eff}}^{(1)} = \frac{Y^3}{\Lambda^2} \left(H^\dagger H - \frac{v^2}{2} \right) (H \bar{q}_3 u_3^c + h.c.)$$

- does not change top mass
- gives a contribution to the top Yukawa coupling

$$y_t^{\text{eff}} = \frac{\sqrt{2}m_t}{v} + \frac{Y^3}{\sqrt{2}\Lambda^2} \frac{v^2}{\Lambda^2}$$

[El Hedri, Fox, Wacker, arXiv:1311.6488]

- for $y_t^{\text{eff}} < 0$, the cutoff scale Λ must be close to electroweak scale
- need new sub-TeV particles to generate operator
- tightly constrained
- possibilities are vector-like ~~fermions~~ fermions, charged scalars