Search for the production of the Higgs boson in association with top quarks ($t\bar{t}H$) in $\gamma\gamma$ and multi-lepton channels at CMS

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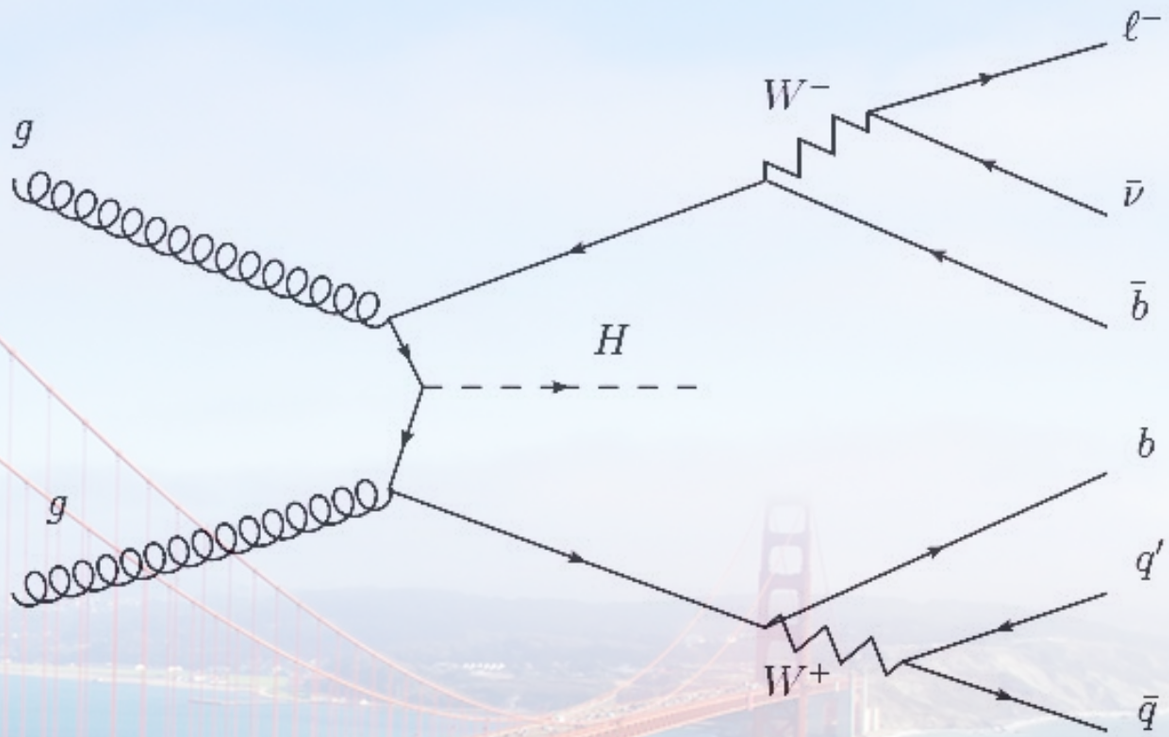


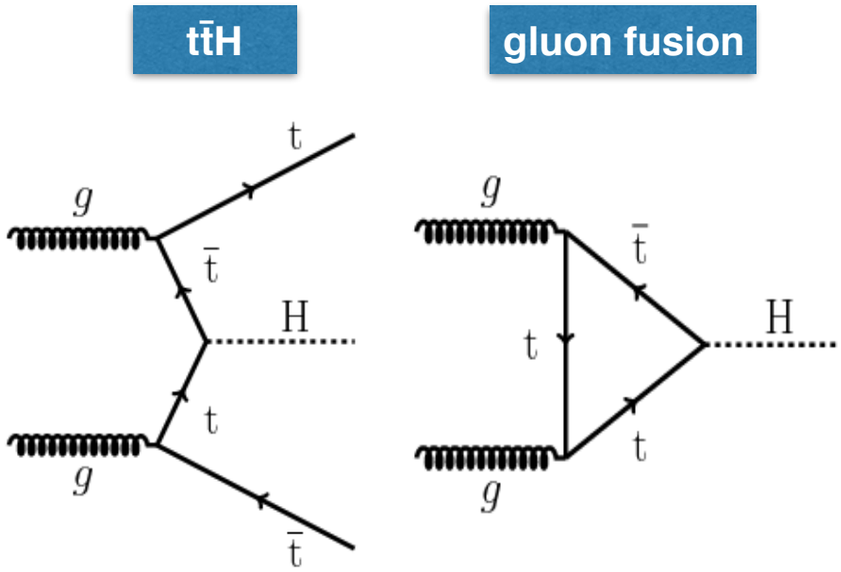
HIGGS COUPLINGS 2016, SLAC : 10TH NOVEMBER 2016

INTRODUCTION

- Production of the Higgs boson in association with a pair of top quarks ($t\bar{t}H$) probes the **$t\bar{t}H$ coupling**

  - ➡ Direct handle on the **$t\bar{t}H$ vertex at tree level** : gluon fusion involves a loop

  - ➡ Cross-section of $t\bar{t}H$ is **~508 fb at 13 TeV**, roughly **4 times** the value at 8 TeV, increased potential for discovery

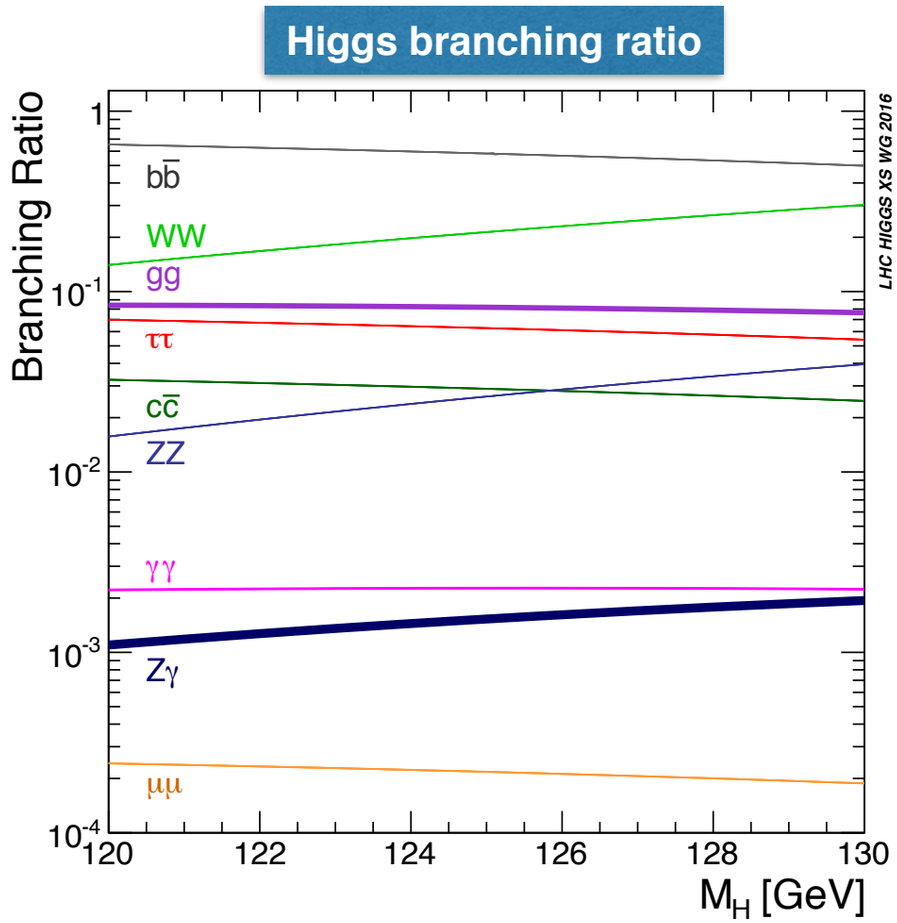


- Searches for **$t\bar{t}H$ at CMS** in Run 2 : based on decay channel of the Higgs

  - ➡ **$H\to\gamma\gamma$:** small branching ratio, but clean final state (low systematic uncertainties) **CMS PAS HIG-16-020**

  - ➡ **Multi-leptonic ($H\to ZZ^*$, $H\to WW^*$, $H\to\tau\tau$) :** higher rate, multi-lepton final state with low background **CMS PAS HIG-16-022**

  - ➡ **$H\to b\bar{b}$:** high branching ratio, but complex multi-jet final state **Talk by Gregor Kasieczka**



SUMMARY OF RUN-1 RESULTS

- Studies of the **$t\bar{t}H$ production** in LHC **Run-1** at **CMS** were based on the different Higgs decay channels : $\gamma\gamma$, $b\bar{b}$, $\tau\tau$ (hadronic) and multi-leptonic ($H\rightarrow ZZ^*$, $H\rightarrow WW^*$, $H\rightarrow\tau\tau$ with multi-lepton final states).

- **Combination** of different Higgs decay channels :

  - **$t\bar{t}H$** combination from **Run1 CMS** measurements **:**

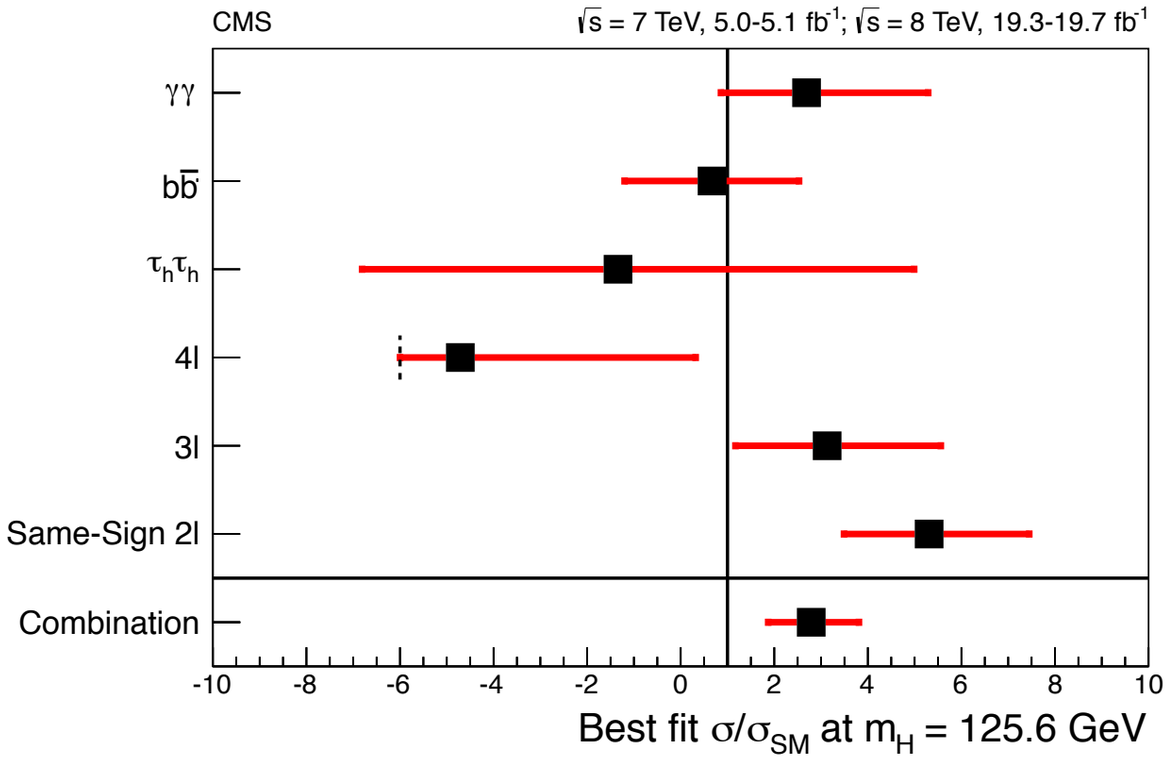
    - $\mu_{t\bar{t}H}$ = **2.8** ± 1.0

    - **95% CL limit = 4.5**

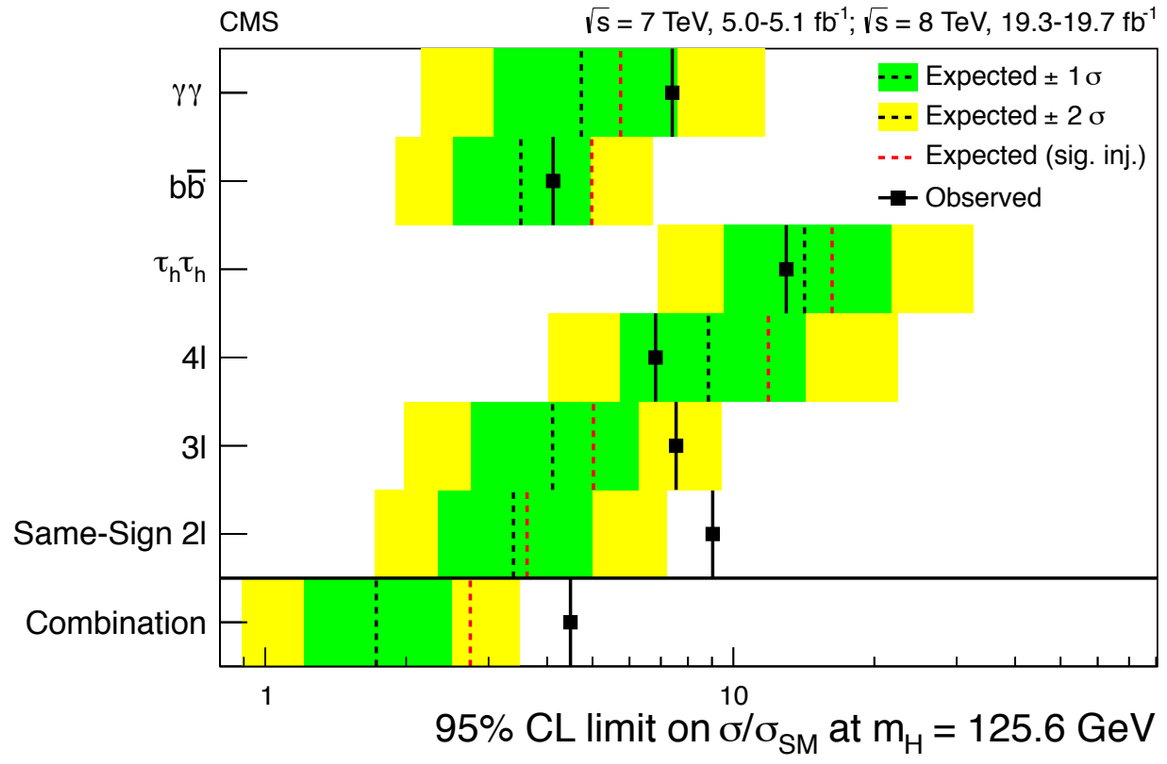
CMS PAS HIG-13-029

JHEP09(2014)087

Best fit signal strength : $\mu_{t\bar{t}H}$



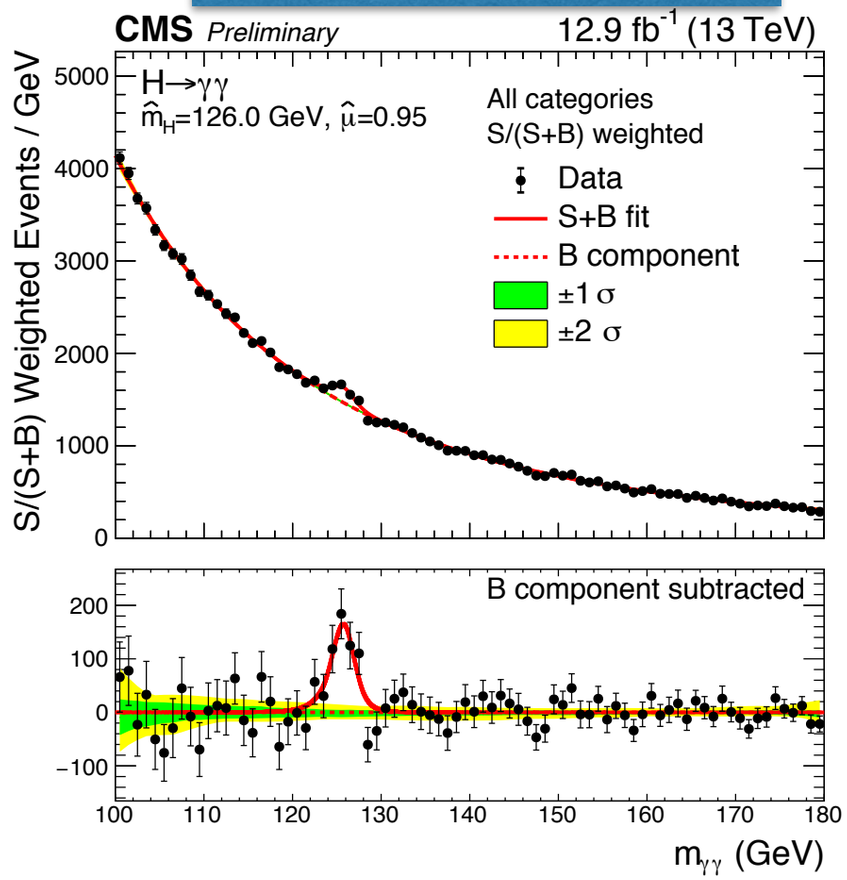
95% CL upper limit $\mu_{t\bar{t}H}$



ttH WITH H→γγ

- A part of the general H→γγ analysis **Talk by Louis Corpe**
  - ➡ Events with **two** high p_T isolated **photons** selected
  - ➡ Narrow **peak** around m_H on top of the falling **$m_{\gamma\gamma}$ distribution**
  - ➡ Different production modes (**ttH**, VBH, VH) identified based on **additional final state objects**
  - ➡ Signal, background extraction from **fit to $m_{\gamma\gamma}$ distribution**

$m_{\gamma\gamma}$ distribution (weighted)



- Overview of the H→γγ analysis :

Photon Reconstruction → Vertex Identification → Photon, Diphoton Selection → Event Categorisation → Signal, Bkg extraction; Stat analysis

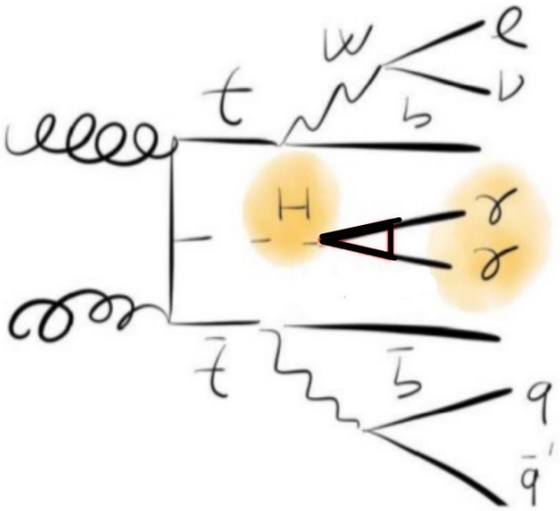
  - ➡ **Event categorisation** based on
    - **additional final state objects** to tag **production modes**
    - mass resolution and kinematics for the 'Untagged' categories

$t\bar{t}H$ WITH $H\rightarrow\gamma\gamma$: $t\bar{t}H$ CATEGORIES

- 2 categories corresponding to $t\bar{t}H$ based on the decay of the top quarks

- **TTH Leptonic Tag:**

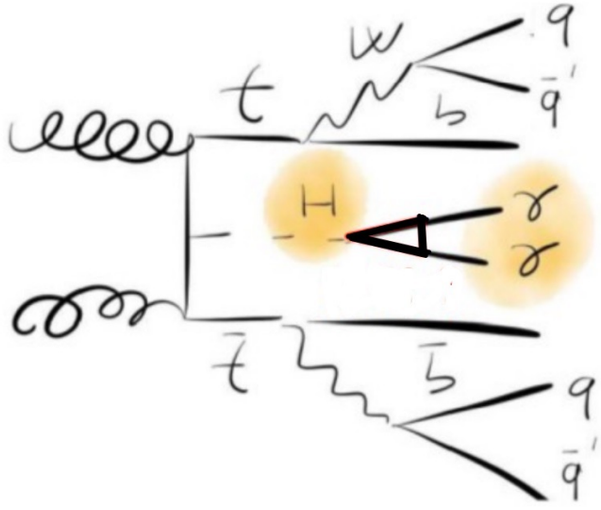
$$t\bar{t} \rightarrow bl\nu_l\bar{b}q\bar{q}' \quad \text{or} \quad t\bar{t} \rightarrow bl\nu_l\bar{b}l'\nu_{l'}$$



- ➡ At least **1 isolated lepton** (muon or electron)
- ➡ At least **2 jets**
- ➡ At least **1 B-tagged jet**
- ➡ Diphoton BDT cut

- **TTH Hadronic Tag**:

$$t\bar{t} \rightarrow bq\bar{q}'\bar{b}q\bar{q}'$$



- ➡ No leptons
- ➡ At least **5 jets**
- ➡ At least **1 B-tagged jet**
- ➡ Diphoton BDT cut

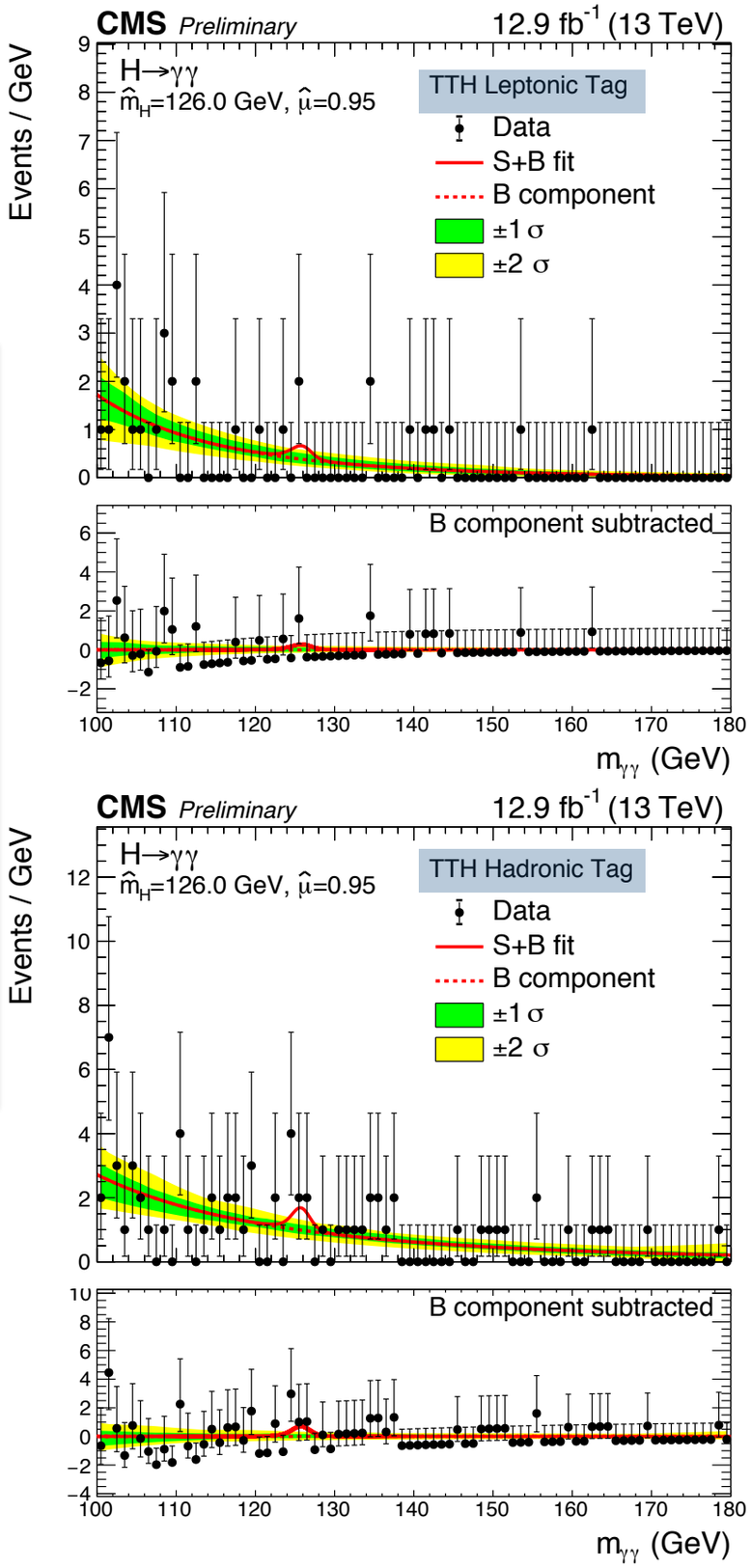
Expected signal for $t\bar{t}H$ categories : very pure in $t\bar{t}H$ contribution

Event Categories	SM 125GeV Higgs boson expected signal								Bkg (GeV^{-1})
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	
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

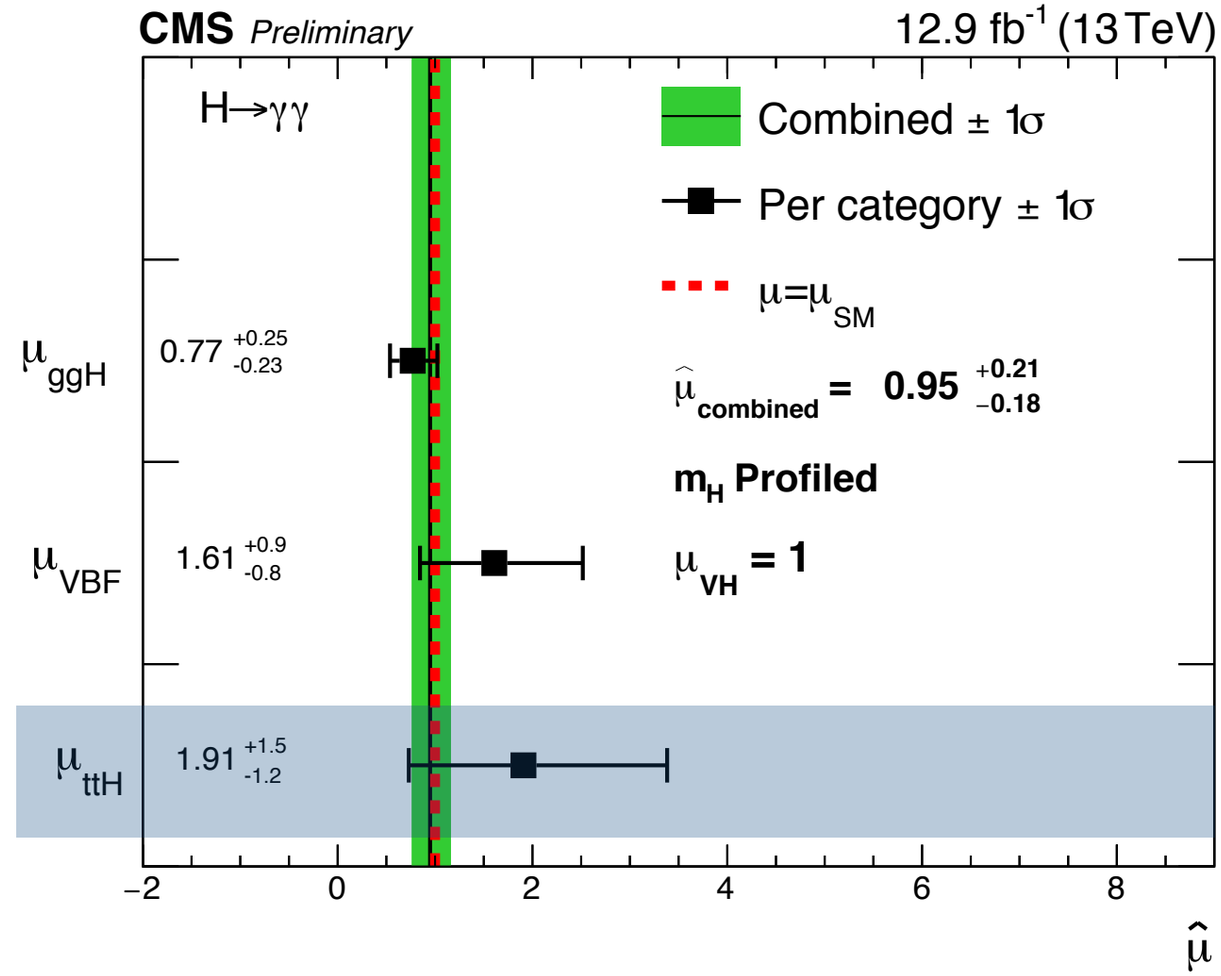
$t\bar{t}H$ WITH $H\rightarrow\gamma\gamma$: RESULTS

- Results based on **12.9 fb^{-1}** of data at **13 TeV** collected during **2016**

Signal plus background model fits to $m_{\gamma\gamma}$ distribution for $t\bar{t}H$ categories



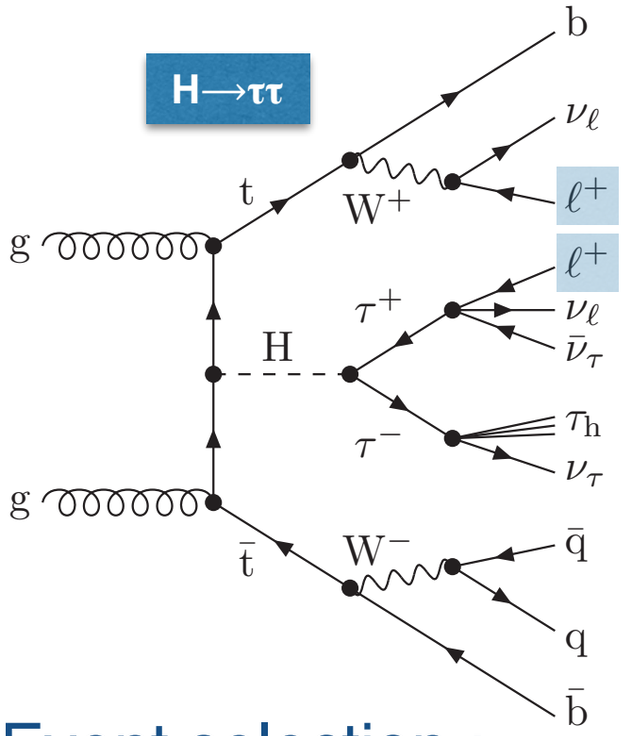
Signal strength for each process

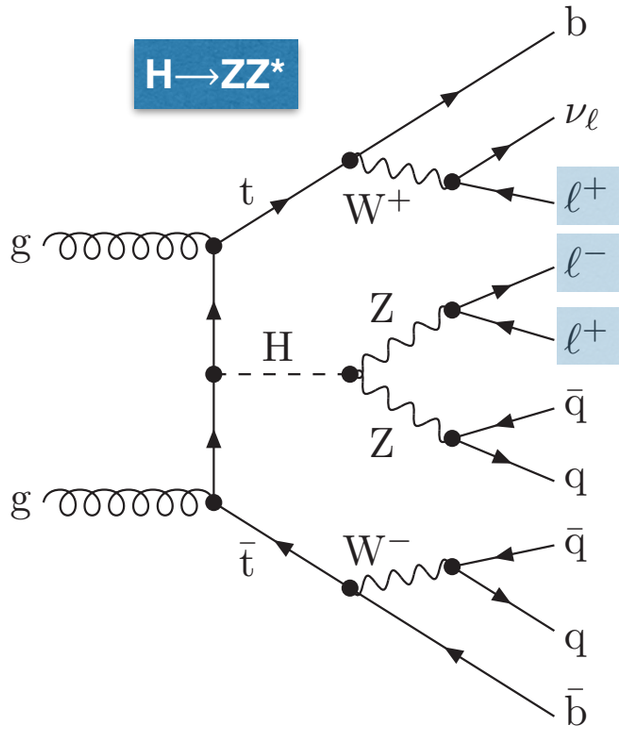


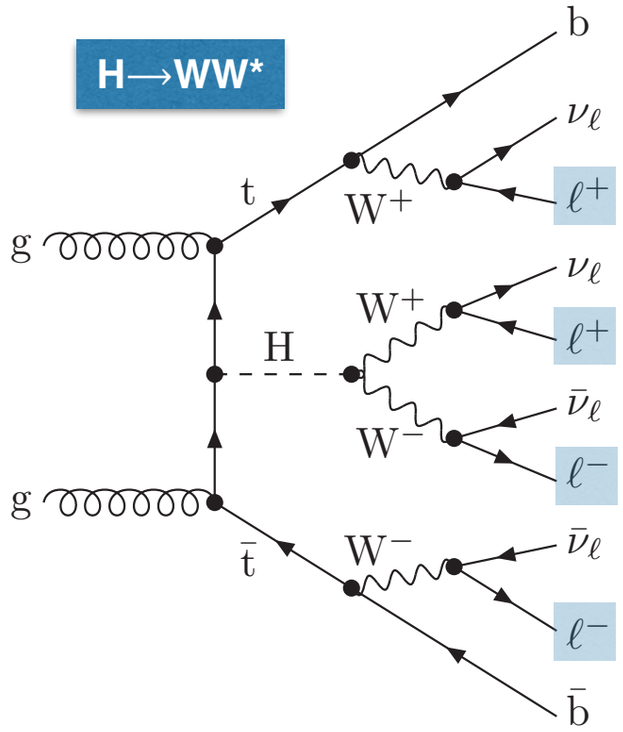
- Uncertainties are statistics dominated

ttH Multi-Leptonic

- Multi-lepton final states from **H⟶WW*, H⟶ZZ* , H⟶ττ**







- Event selection :

➡ **Same-sign dilepton** channel (**2LSS**):

- **2 leptons** with **same sign** : further categorisation into **ee, μμ, eμ channels**
- At least **4 jets**

➡ **Three lepton** channel (**3L**):

- **3 leptons** or **more**
- At least **2 jets**

➡ **B Tag jets**: at least **1 jet** passing **medium** WP or **2 jets** passing **loose** WP of B tag algorithm

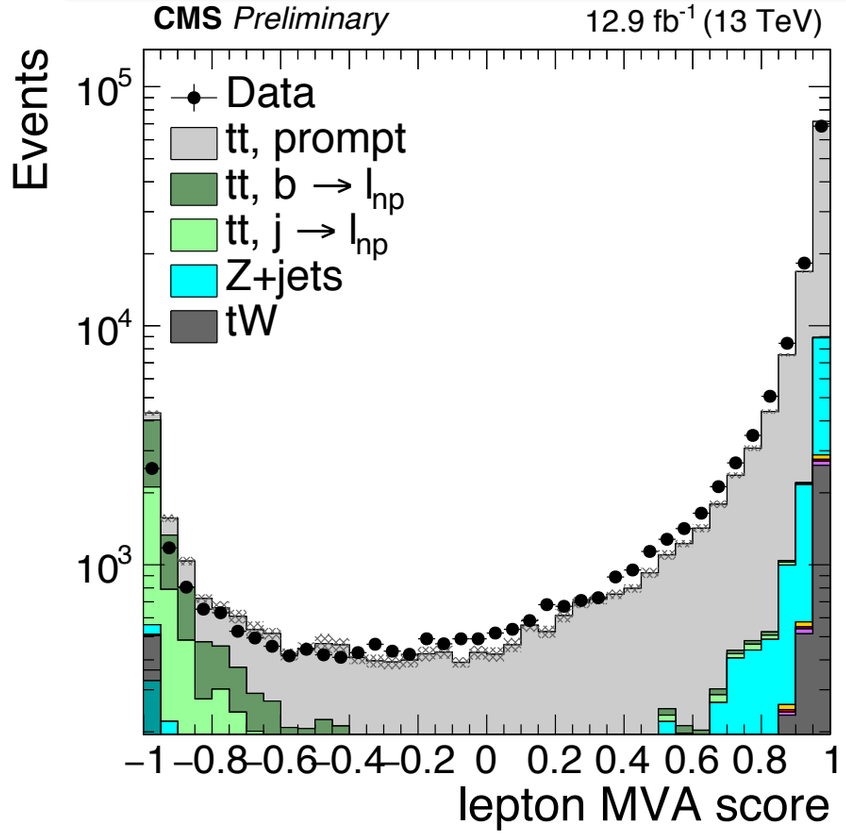
➡ **Z veto** : based on $m_{\ell\ell}$, E_T^{miss}, H_T^{miss}

ttH Multi-Leptonic : Lepton Selection

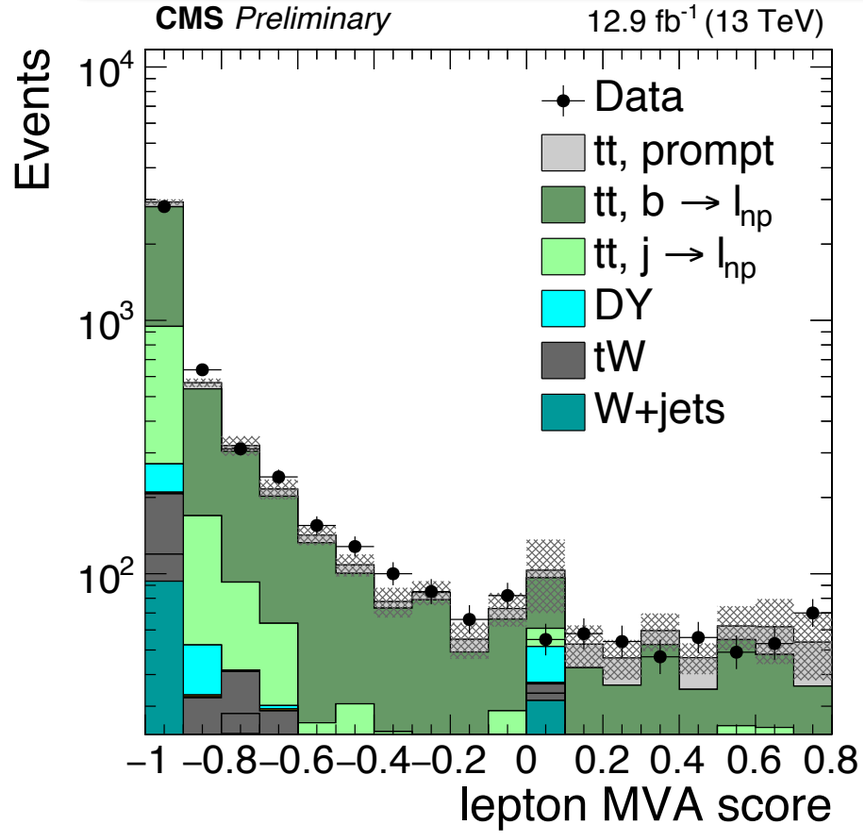
- Important source of to **background** coming from **non-prompt** leptons (from b jets in $t\bar{t}$, misidentified jets, decay-in-flight, photon conversions)

- Dedicated **multivariate discriminant** to **reject non-prompt** leptons. Inputs for the MVA:
  - ➡ Lepton **isolation** observables, **impact parameter** wrt vertex
  - ➡ **Ratio** of **lepton** and **jet p_T**, p_T wrt **direction of jet**

Opposite sign probe (prompt enriched)



Same sign probe (non-prompt enriched)



- Performance is **validated** in data control region. **Data control region** also used to **estimate** residual **non-prompt background** using loose-to-tight extrapolation.

$t\bar{t}H$ MULTI-LEPTONIC : EVENT YIELDS

Expected and observed yields after the selection in 2LSS and 3L final states

	$\mu\mu$	ee	eμ	3ℓ
$t\bar{t}W$	18.3 ± 0.9	6.8 ± 0.6	24.5 ± 1.1	12.2 ± 0.7
$t\bar{t}Z/\gamma^*$	5.8 ± 0.6	7.4 ± 0.6	15.3 ± 1.3	22.6 ± 1.0
Di-boson	1.4 ± 0.2	1.1 ± 0.2	2.6 ± 0.3	5.7 ± 0.4
tttt	0.8 ± 0.2	0.4 ± 0.1	1.5 ± 0.2	1.2 ± 0.1
tqZ	0.2 ± 0.3	0.4 ± 0.4	0.6 ± 0.6	2.7 ± 0.8
Rare SM bkg.	1.6 ± 0.3	0.5 ± 0.1	1.8 ± 0.1	0.3 ± 0.1
Charge mis-meas.		6.7 ± 0.1	10.0 ± 0.1	
Non-prompt leptons	33.4 ± 1.2	23.1 ± 1.1	61.9 ± 1.7	51.0 ± 1.8
All backgrounds	61.5 ± 1.7	46.4 ± 1.5	118.0 ± 2.5	95.7 ± 2.3
$t\bar{t}H$ ($H \to WW^*$)	6.3 ± 0.2	2.6 ± 0.1	8.5 ± 0.2	8.0 ± 0.2
$t\bar{t}H$ ($H \to \tau\tau$)	1.6 ± 0.1	0.7 ± 0.1	2.5 ± 0.1	2.1 ± 0.1
$t\bar{t}H$ ($H \to ZZ^*$)	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0
Data	74	45	154	105

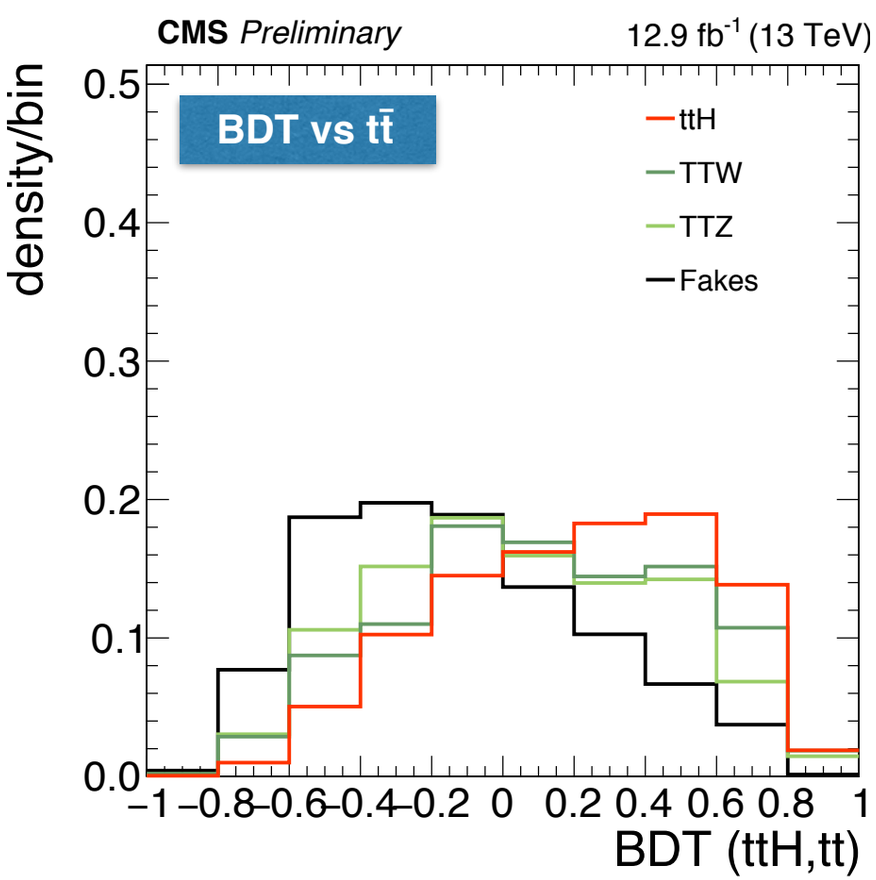
- Main sources of background :
  - ➡ **Signal like final states :** $t\bar{t}V$ (estimated from MC), Di-boson (validated in data)
  - ➡ **Others :** Non-prompt leptons (largely from $t\bar{t}$), charge mis-measured leptons : Data driven estimation
  - ➡ Multivariate BDT is used to separate the different types of backgrounds, use for signal extraction

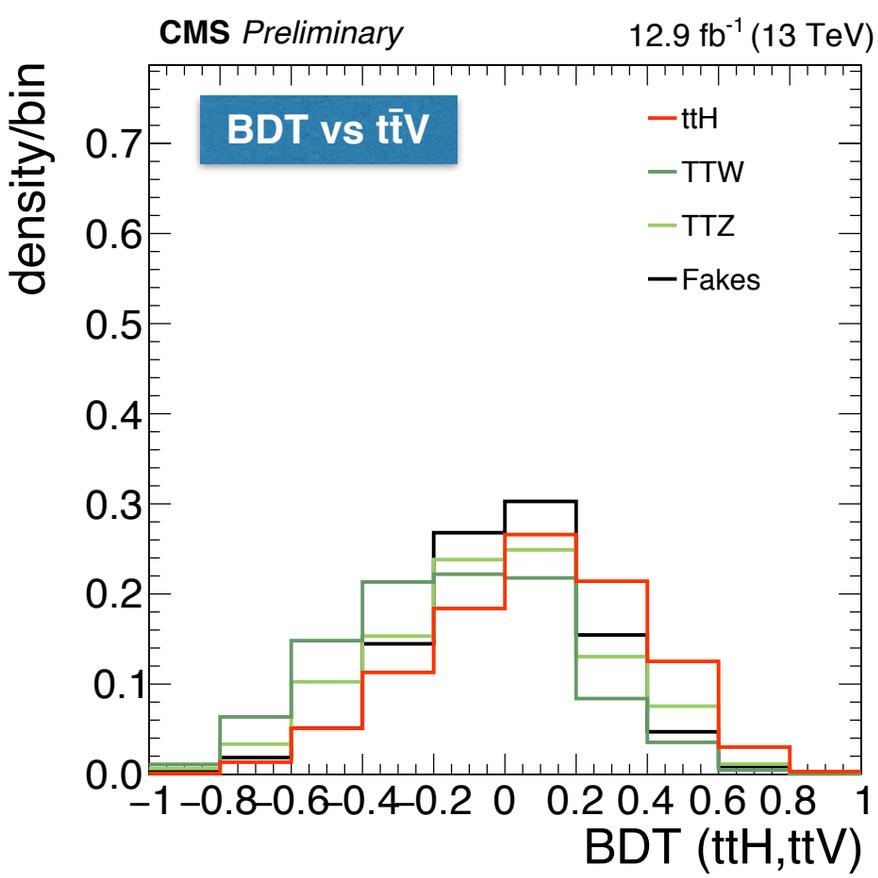
ttH Multi-Leptonic : Signal Extraction BDT

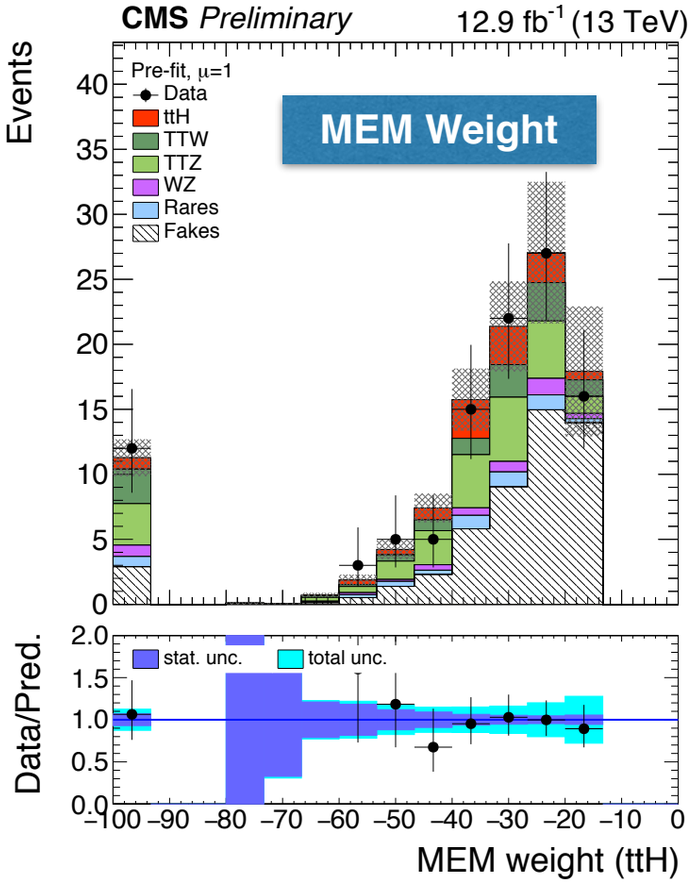
- Multivariate **BDT** discriminants trained in simulated events to separate the **signal** from **ttV** backgrounds and also **non-prompt (tt̄)** backgrounds.

- 2 separate BDTs trained using kinematical observables.
  - ➡ η of leptons, jet multiplicity, distance between lepton & jet, m_T
  - ➡ **For tt̄ :** E_T^{miss}, H_T^{miss}, distance between jets
  - ➡ **For ttV :** leading, trailing lepton p_T, for 3L category : matrix element weight (MEM weight) :

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k>2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$



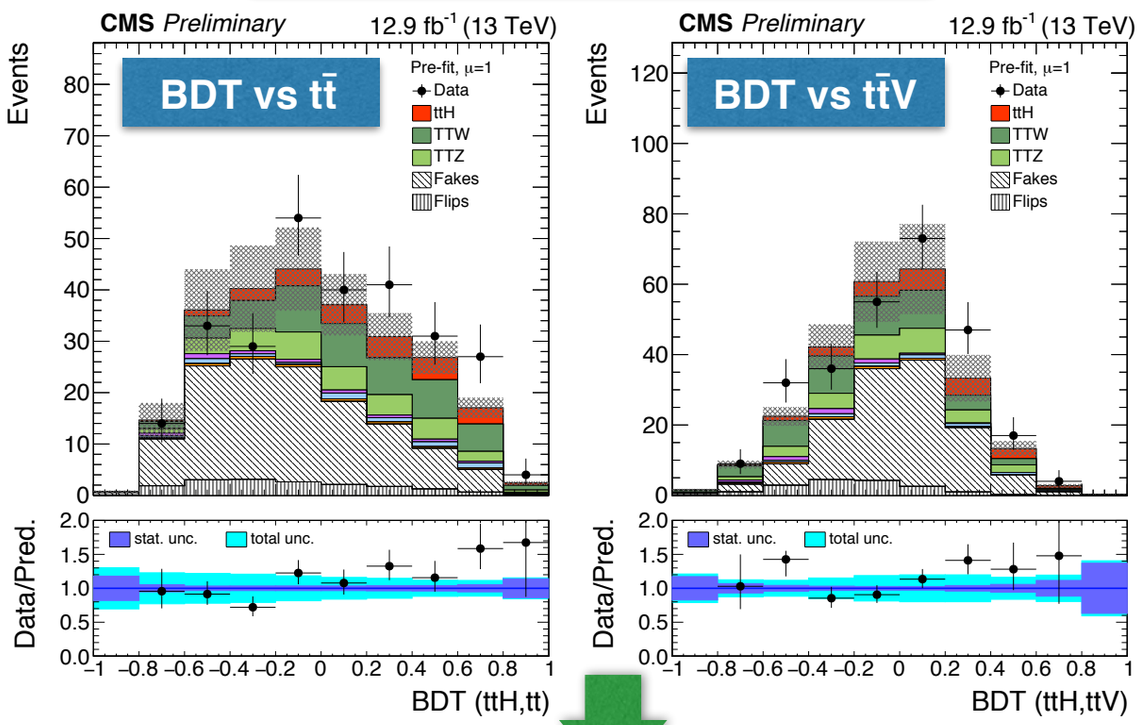




ttH Multi-Leptonic : Signal Extraction

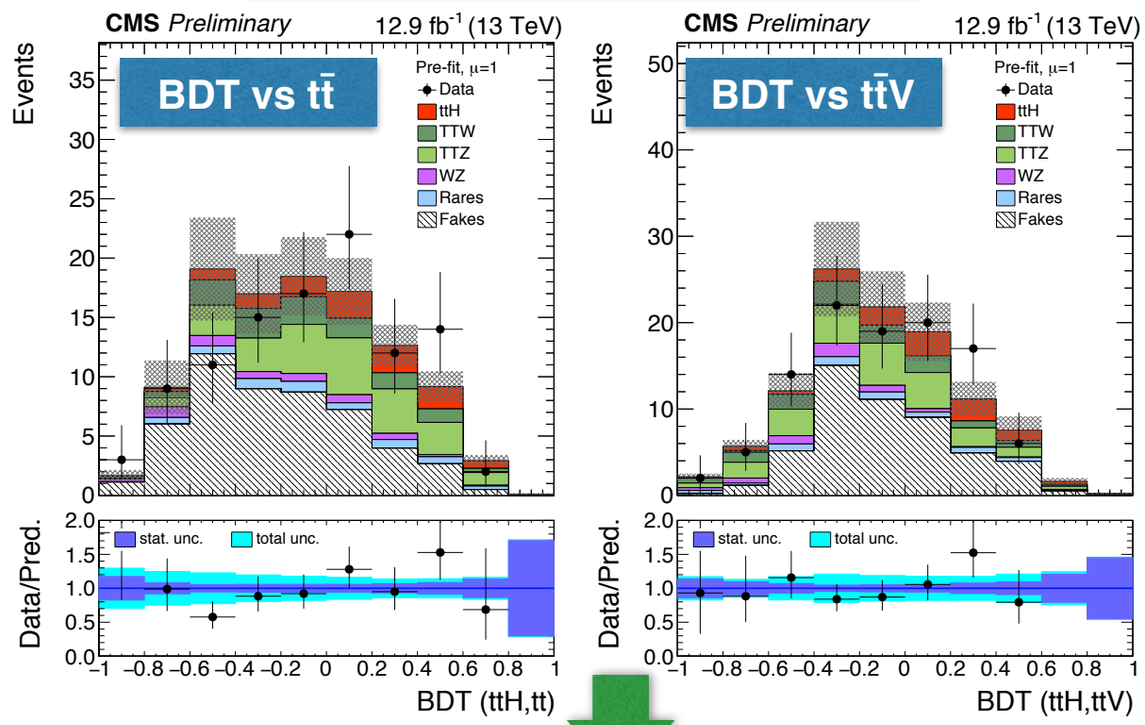
- 2 Dimensional fit to the two BDT discriminators is performed for signal extraction

2LSS



Combination of BDTs for 2LSS

3L



Combination of BDTs for 3L

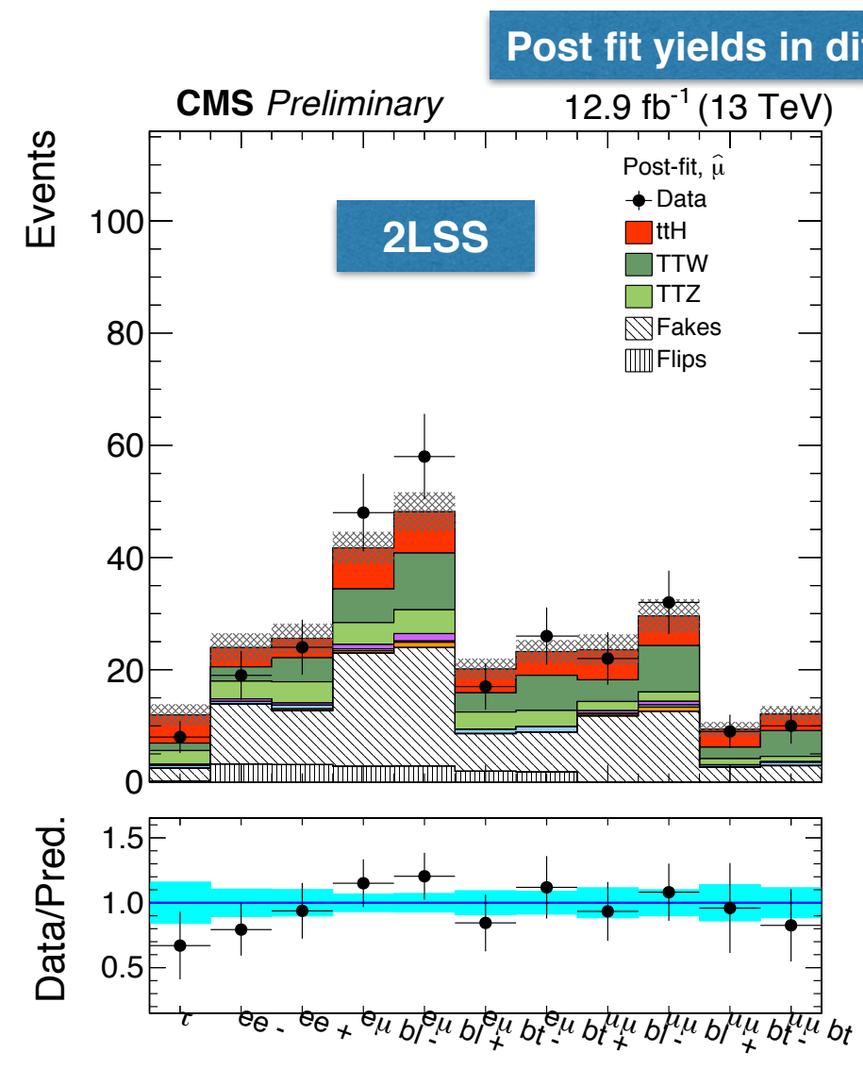
ttH Multi-Leptonic : Event Classification

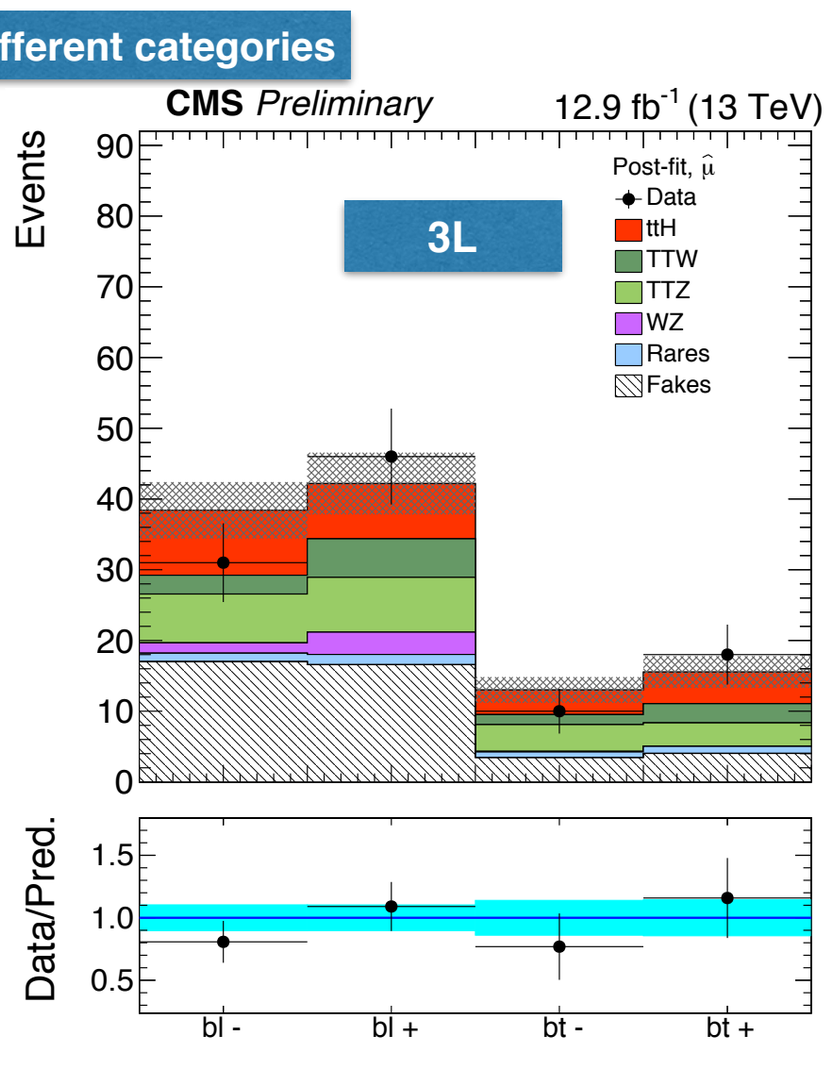
- Events in the 2LSS and 3L categories are further categorised before the final signal extraction
  - ➡ Whether the **b - tagged jets** pass a tighter WP
  - ➡ Sum of **leptonic charges** is **+** or **-**
  - ➡ Presence of **hadronic τ** for 2LSS

Event Categories

$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	3L
b tight $^{+}_{-}$	b tight $^{+}_{-}$	$^{+}_{-}$	b tight $^{+}_{-}$
b loose $^{+}_{-}$	b loose $^{+}_{-}$		b loose $^{+}_{-}$
SS2L with hadronic tau			

Post fit yields in different categories





- Main sources of systematic uncertainties:
  - ➡ Lepton selection efficiency
  - ➡ Fake rate measurement for background estimate

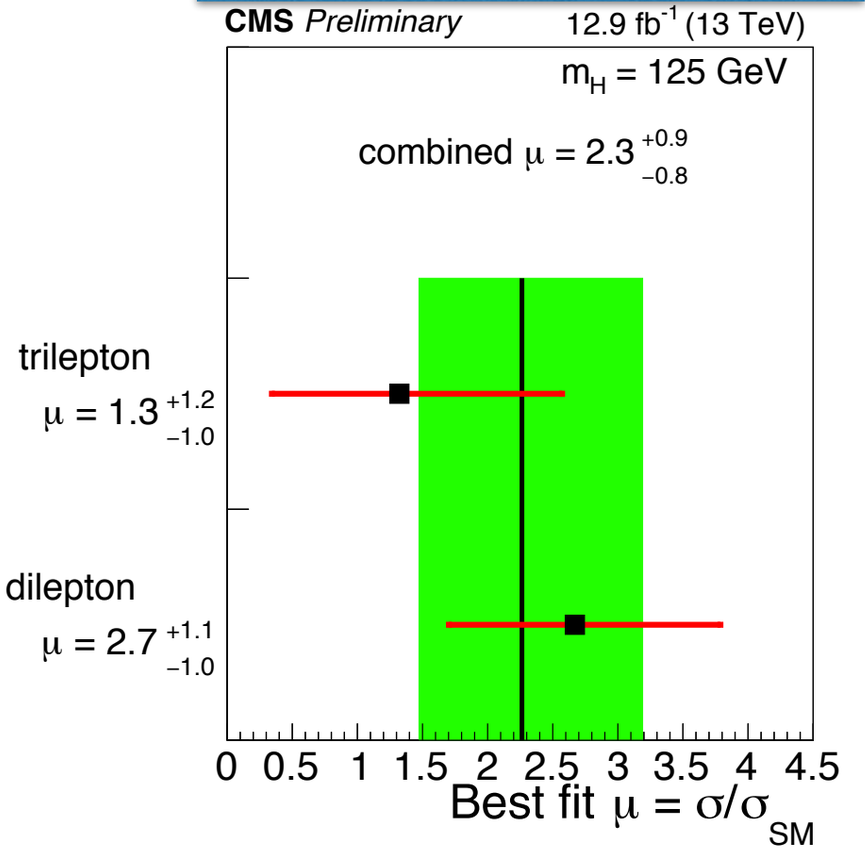
$t\bar{t}H$ MULTI-LEPTONIC : RESULTS

- Results based on **12.9 fb^{-1}** of data collected during **2016** and **combination** with **2.3 fb^{-1}** collected in **2015**

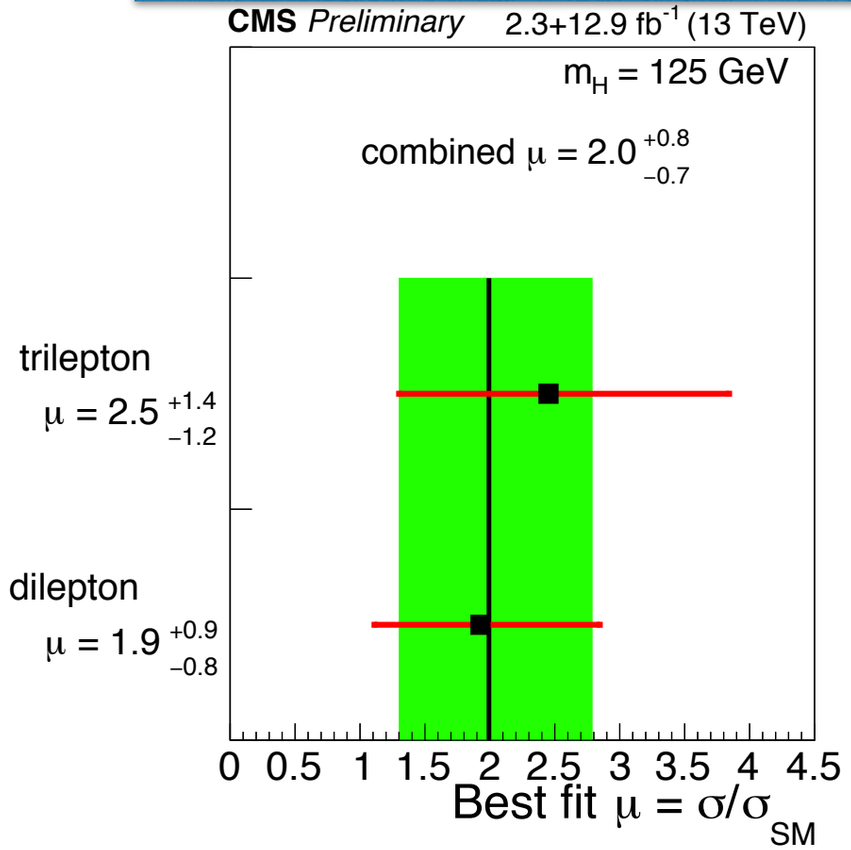
Limits and signal strength

Category	Obs. limit	Exp. limit $\pm1\sigma$	Best fit μ $\pm1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

Signal strength for 2016 analysis



Signal strength for 2016+2015 analysis



SUMMARY & OUTLOOK

- Studies of the **associated production of the Higgs boson and top quarks** with the **CMS** experiment with data collected in **early 2016** (2015) have been presented for the **H⟶γγ** and **multi-leptonic** channels.

- Probes of the **top-Higgs coupling** directly at the **tree level**

- Studies involve complex final states with leptons, jets etc. Special methods are used to improve signal purity and to reduce backgrounds.

- Current measurements are consistent with SM expectation:

  ➡ **$t\bar{t}H$ multi-leptonic :** $\mu = 2.0^{+0.8}_{-0.7}$ (2015 + 2016 combination : 2.3+12.9fb^{-1})

  ➡ **$t\bar{t}H$** with **H⟶γγ :** $\mu = 1.9^{+1.5}_{-1.2}$ (2016 : 12.9fb^{-1})

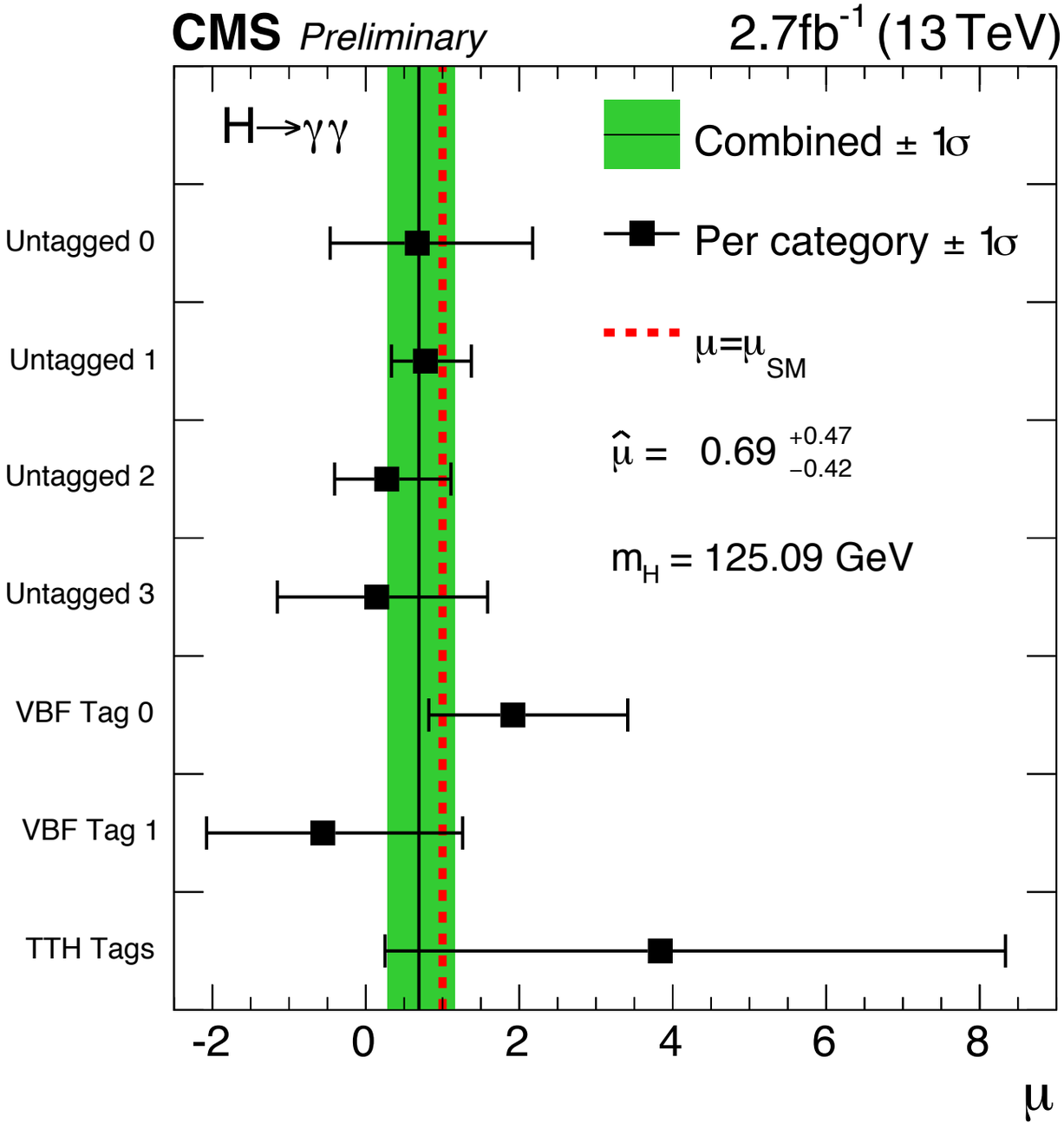
- Analyses to be **updated** with the **full dataset** collected during **2016** (**~3 times** the data presented here)

THANK YOU !

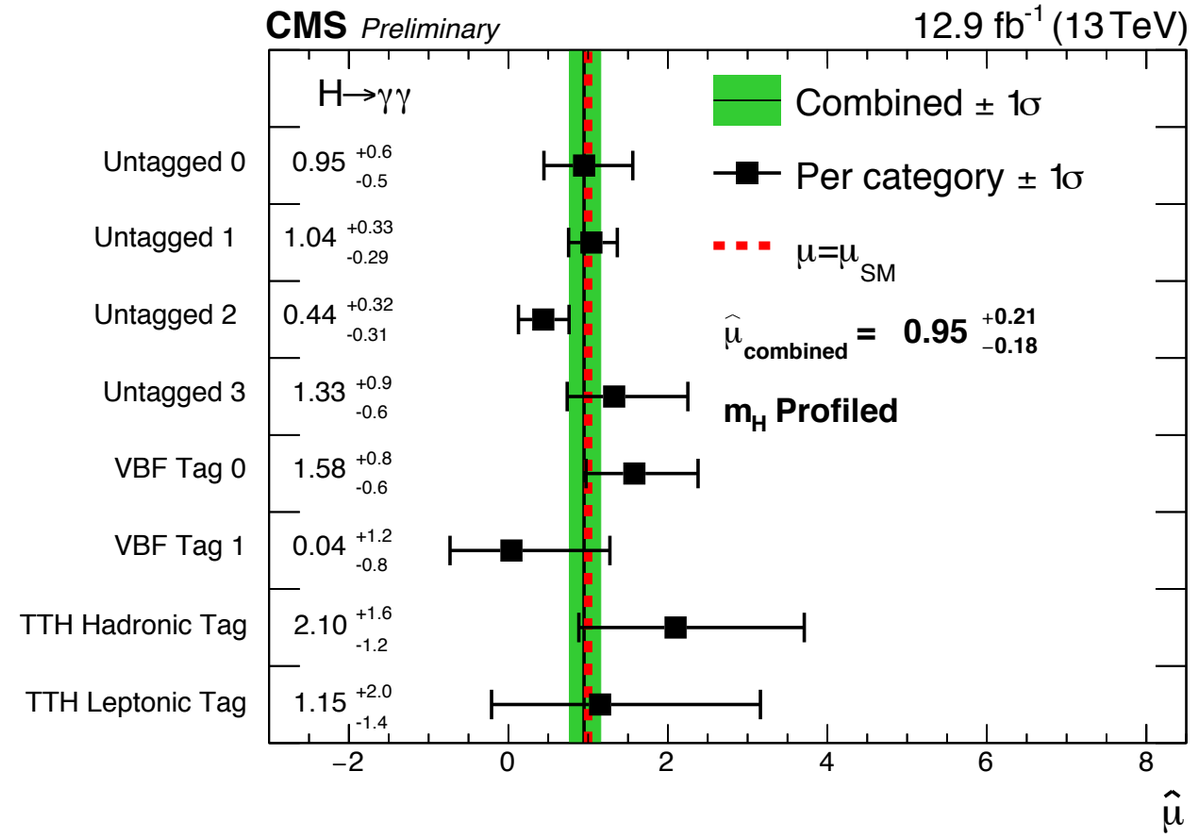
ADDITIONAL SLIDES

ttH WITH H→γγ : RESULTS (2015 DATA)

Signal strength for 2015 analysis



Signal strength for 2016 analysis



ttH Multi-Leptonic : Uncertainties

Sources of Uncertainty