Associated top-quark pair and Higgs boson production at CMS with 13 TeV data

LHCP 2016

Large Hadron Collider Physics

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for the CMS collaboration

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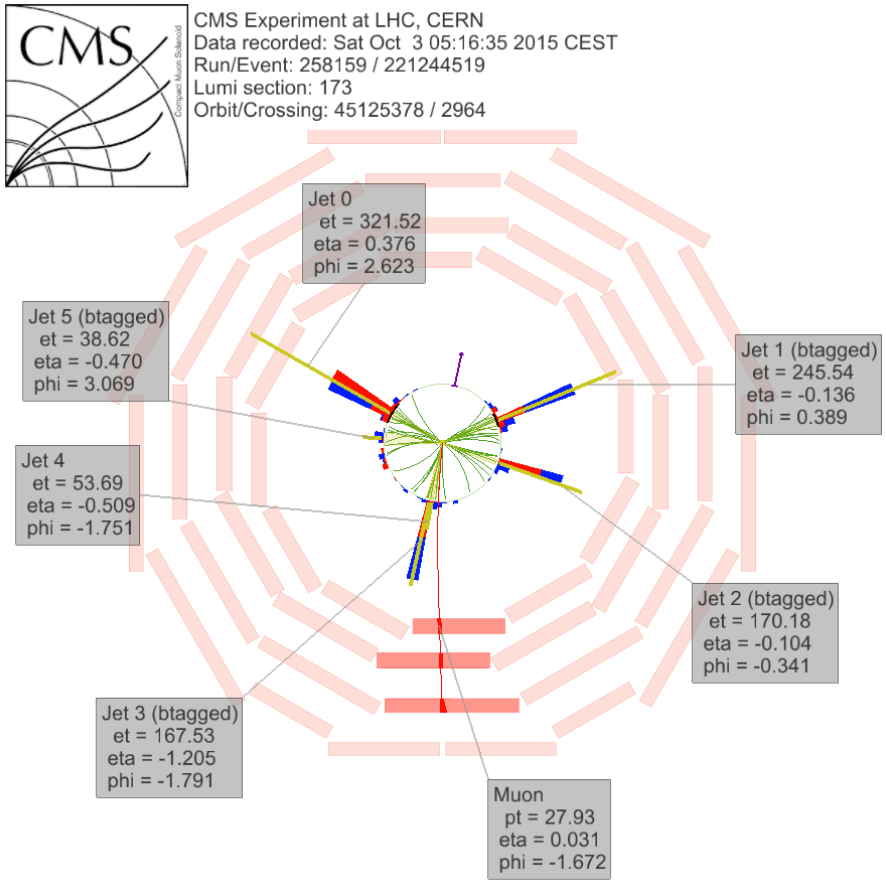
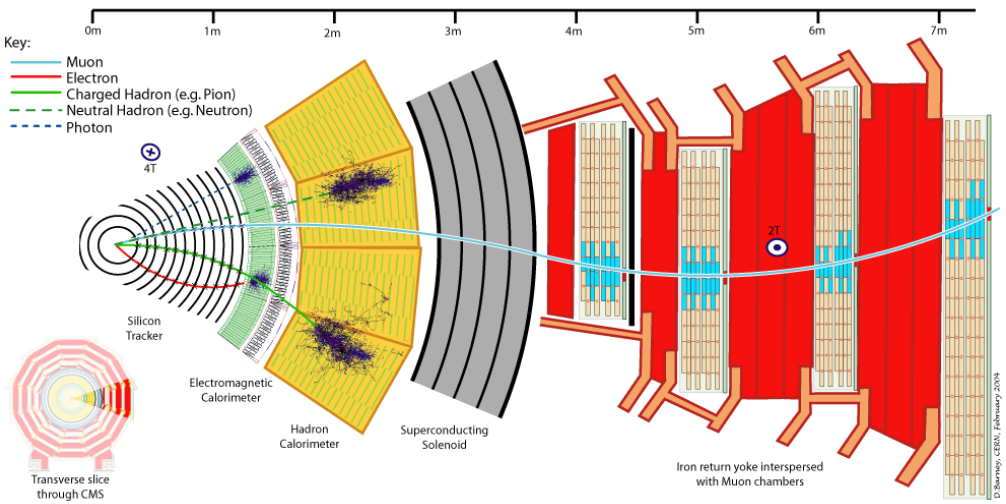
Outline

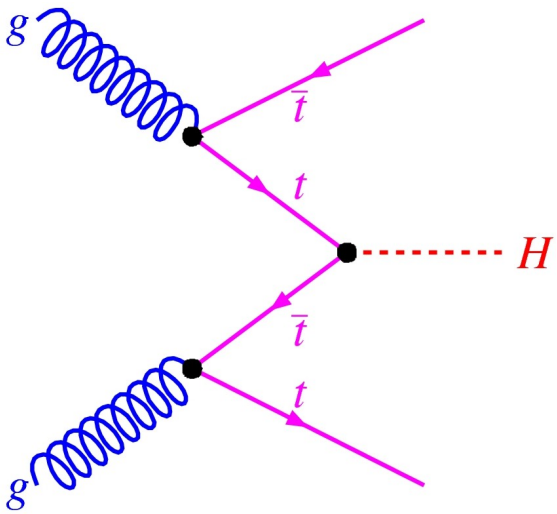
- $t\bar{t}H$ production and decays
- Results (13 TeV)
  - $t\bar{t}H(\gamma\gamma)$
  - $t\bar{t}H(multileptons)$
  - $t\bar{t}H(b\bar{b})$
- Combination





Introduction

- Focus of post-discovery Higgs physics is full characterization of new particle
  - In Standard Model (SM), top-Higgs Yukawa coupling strongest ($Y_T \approx 1$)
    $\rightarrow t\bar{t}H$ **only possibility of direct measurement**

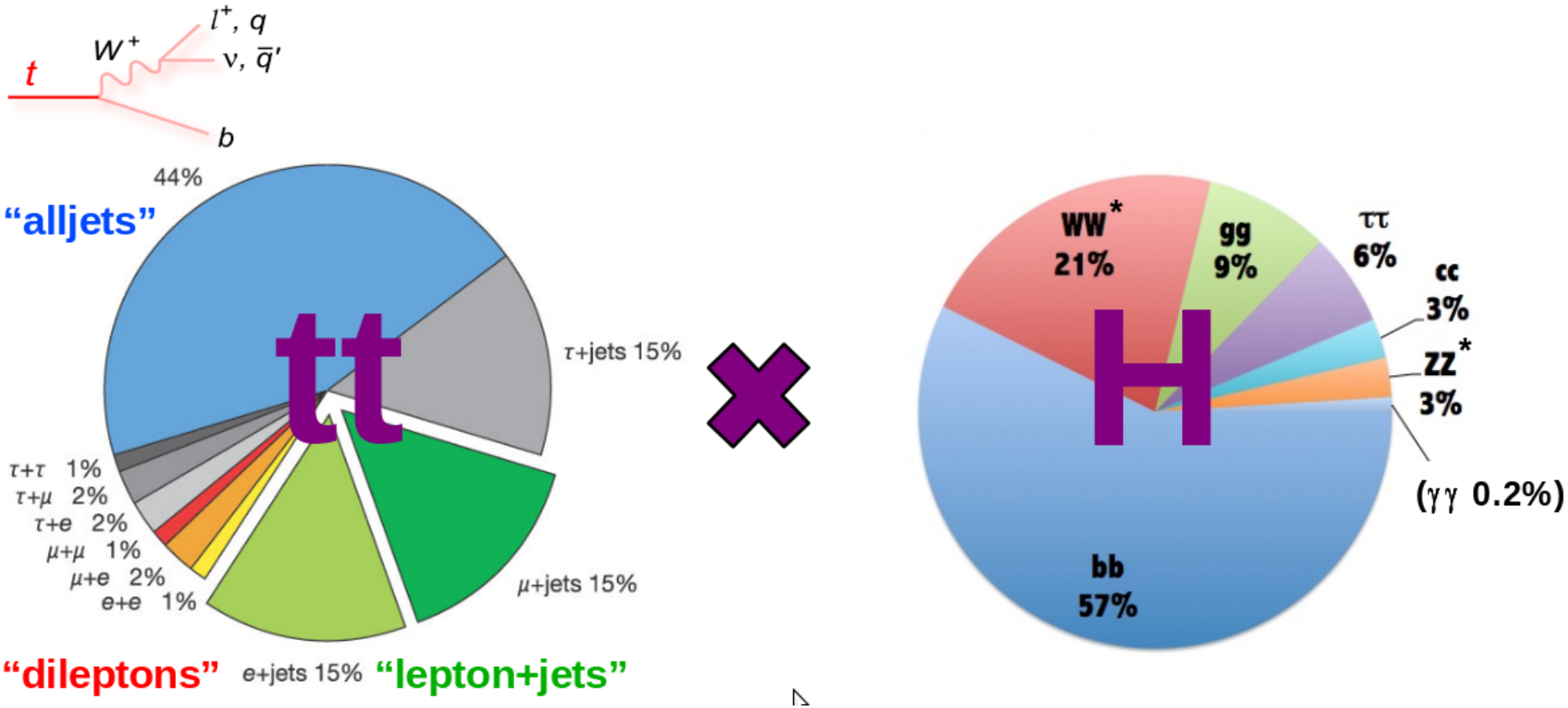


- Experimental challenges: Small signal cross section, overwhelming background
- Strong increase of cross section with center-of-mass energy
  – $\sim \times 3.8$ higher cross section at 13 TeV compared to 8 TeV

$t\bar{t}H$ (NLO) ($m_H = 125$ GeV)	Cross section
7 TeV	89 fb
8 TeV	133 fb
13 TeV	**507 fb**

- Dominant background $t\bar{t} + X$
  – Similar increase in cross sections
- Luminosity of 13 TeV analyzed data 2.3 - 2.7 fb^{-1}
  – Equivalent to $\approx$ 50% of 8 TeV statistics

$t\bar{t}H$ signature



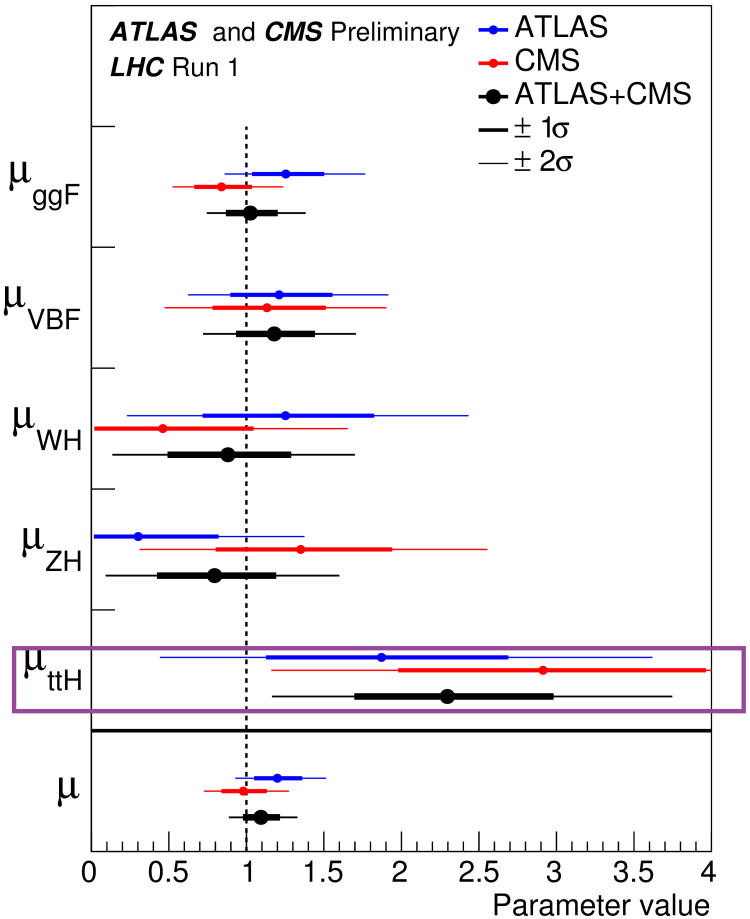
- $t\bar{t}H$ final states combine top pair and Higgs decay signatures
  - $t\bar{t}$ final state topology depends on W decay: "**dileptons**", "**lepton+jets**", "**alljets**"
  - $t\bar{t}H(bb)$: **dileptons**, **lepton+jets**
  - $t\bar{t}H(\gamma\gamma)$: **dileptons**, **lepton+jets**, **alljets**
  - $t\bar{t}H$(multileptons): **dileptons**, **lepton+jets**
    - leptonic decays of $H \rightarrow$WW*, ZZ*, $\tau\tau$

$t\bar{t}H$: knowledge from Run I (7 and 8 TeV)

HIG-15-002

- Combination of all Higgs analysis channels in ATLAS and CMS
- $\mu_{t\bar{t}H}$ dominated by $t\bar{t}H(\gamma\gamma)$, $t\bar{t}H$(multileptons), $t\bar{t}H(b\bar{b})$

Best-fit results
for the production signal strengths

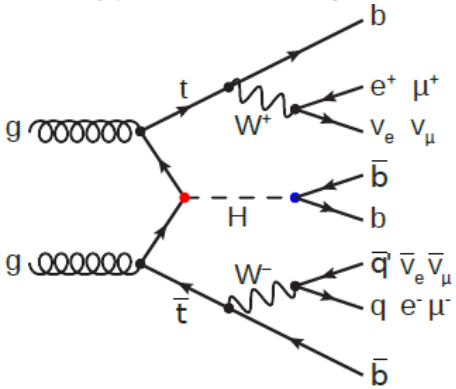


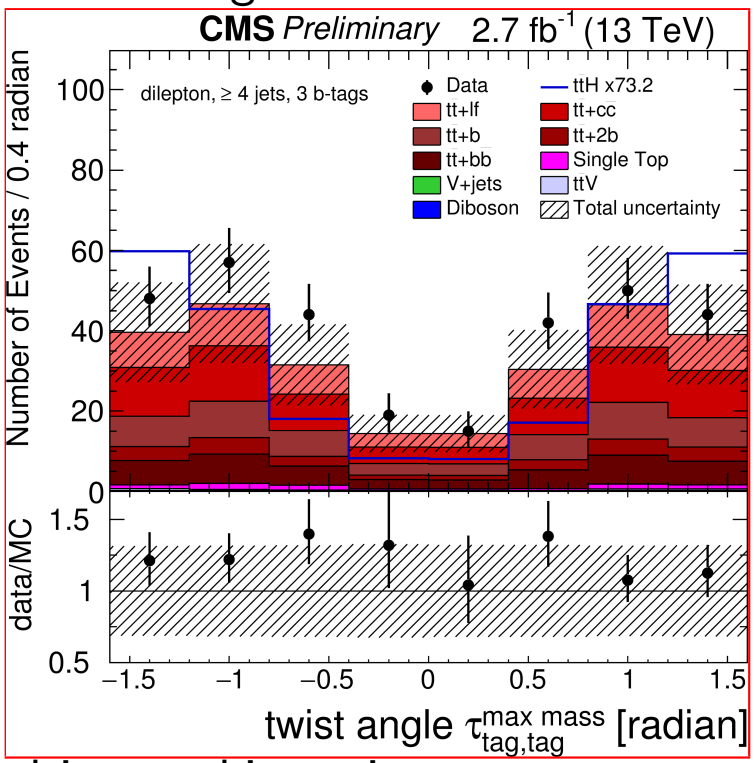
	$\mu_{t\bar{t}H}$
ATLAS	$1.9^{+0.8}_{-0.7}$
CMS	$2.9^{+1.0}_{-0.9}$
Combined	$\mathbf{2.3}^{+0.7}_{-0.6}$

$t\bar{t}H(b\bar{b})$

HIG-16-004

- Largest Higgs boson branching ratio
- Overwhelming background: $t\bar{t}$+jets
  - irreducible: $t\bar{t} + b\bar{b} \rightarrow$ theoretically challenging
- Many jets with similar kinematics, limited mass resolution for H$\rightarrow b\bar{b}$
- Main strategy: obtain good signal separation, constrain backgrounds





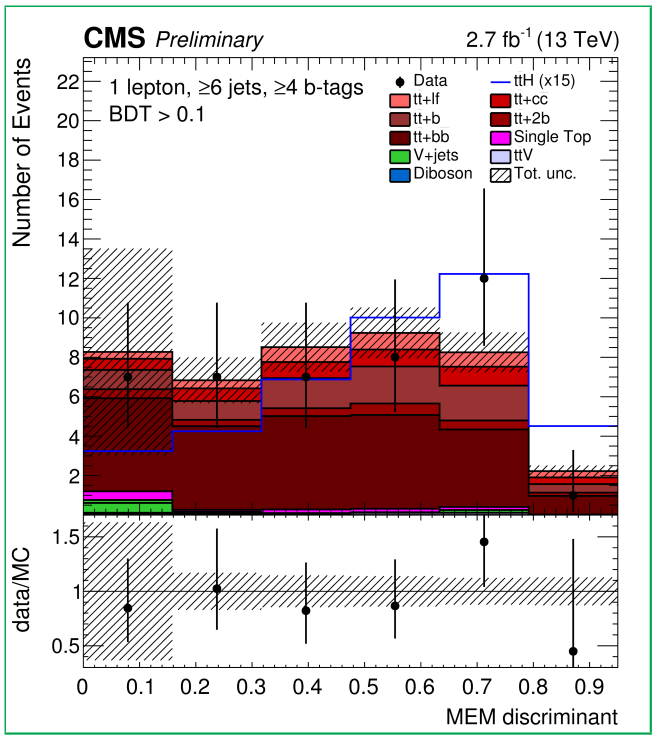
- Two categories: **lepton+jets** & **dileptons**
  - Lepton triggers and offline event selection
  - $=1$, $=2$ opposite sign leptons
  - ≥ 4, ≥ 3 jets
  - ≥ 2 b-tags

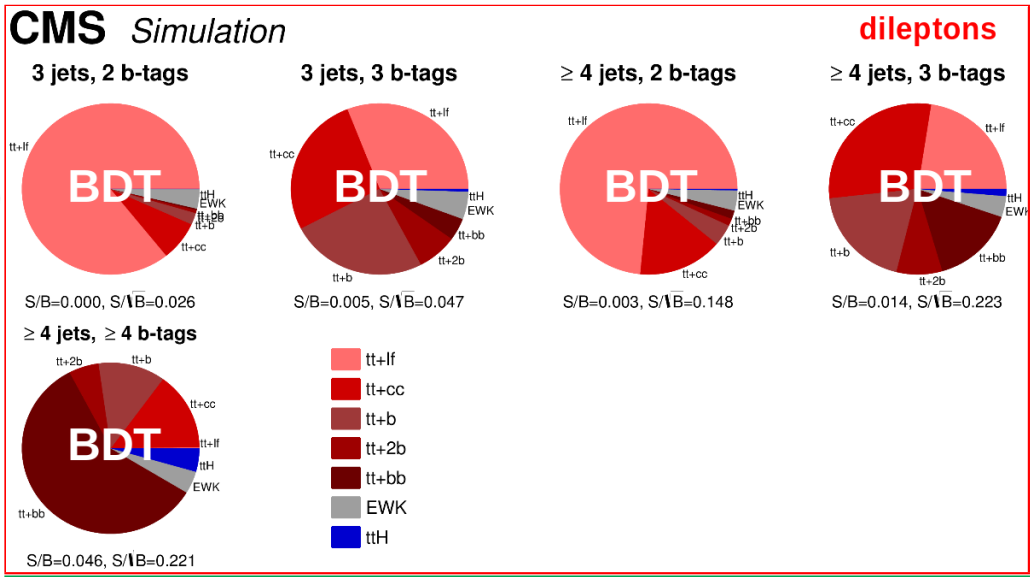
$\rightarrow$ lepton+jets: high statistics
$\rightarrow$ dileptons: minimal non $t\bar{t}$ backgrounds, minimal jet combinatorics

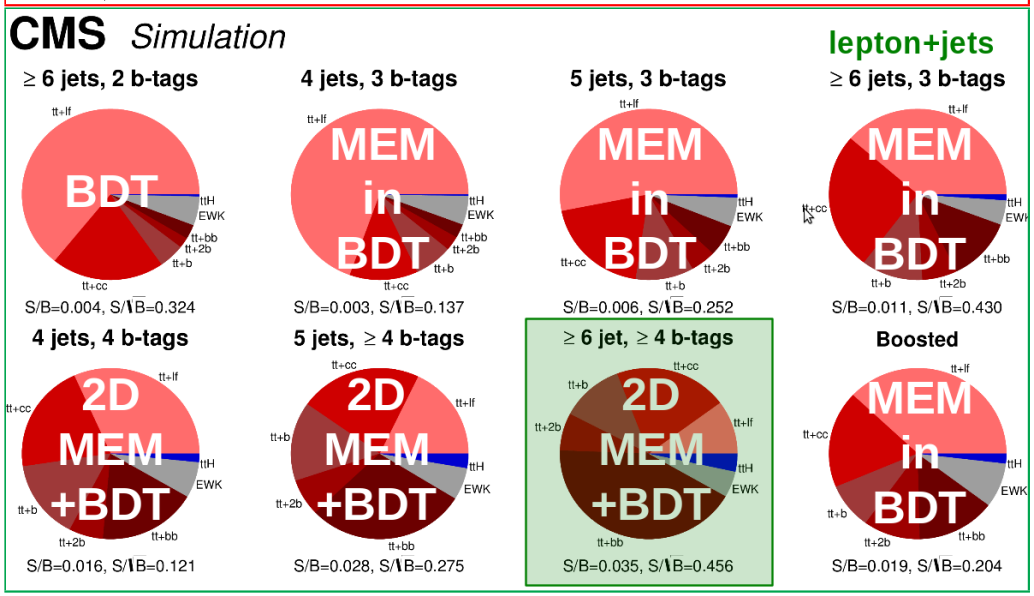
- Classify by **jets**, **b-tags** multiplicities and **boosted** jets (lepton+jets) $\rightarrow$ 13 subcategories

$t\bar{t}H(b\bar{b})$ - Signal Separation

- For each subcategory, optimise discriminator to improve sensitivity
  - ◇ dileptons, lepton+jets:
    Use **Boosted Decision Tree** (BDT)
  - ◇ lepton+jets:
    Use Matrix Element Method (MEM)
    – $t\bar{t}+b\bar{b}$ as background hypothesis,
    permute over all b-quark associations
    → **MEM as input in BDT**
    → **2D MEM+BDT analysis**



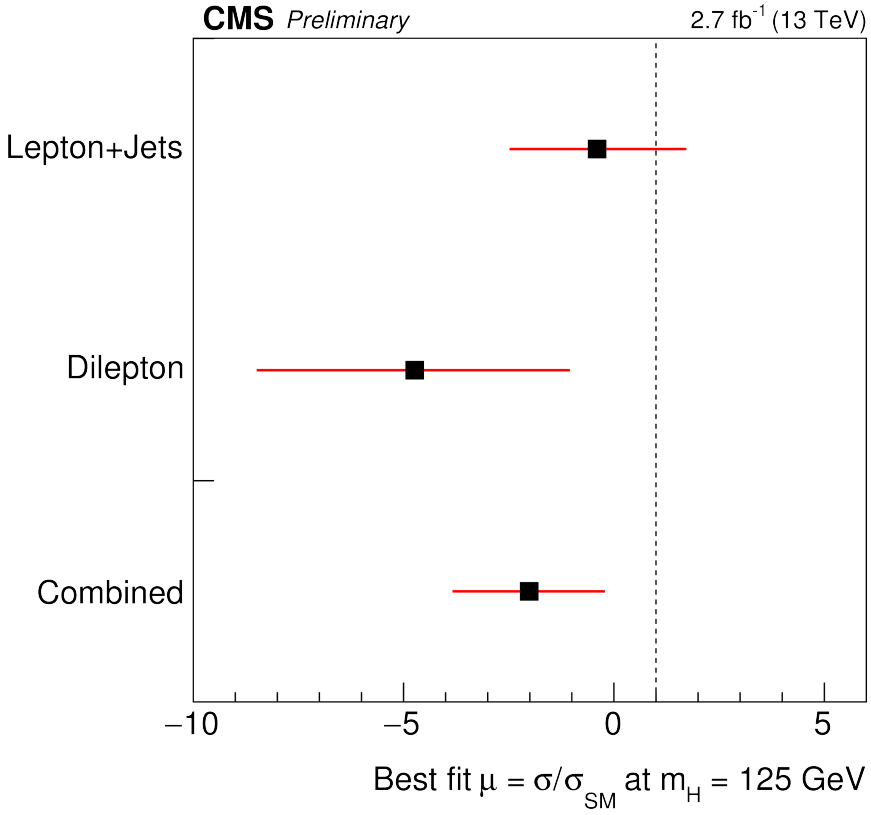




$t\bar{t}H(b\bar{b})$ - Results

- Simultaneous binned maximum likelihood fit across all categories
  → no significant excess, set upper limit on $\mu=\sigma/\sigma_{SM}$
  - ◇ Systematics dominated

combined best fit $\hat{\mu}_{obs} = -2.0^{+1.8}_{-1.8}$ → 1.7σ below SM expectation

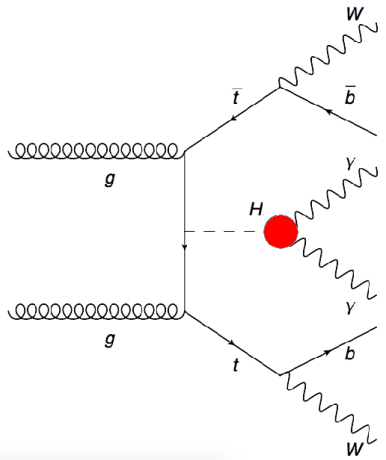


95% CL upper Limits (UL)

Category	Observed UL	Expected UL
Lepton+jets	4.0	$4.1^{+1.8}_{-1.2}$
Dilepton	5.2	$7.7^{+3.6}_{-2.3}$
Combined	2.6	$3.6^{+1.6}_{-1.1}$

$t\bar{t}H(\gamma\gamma)$

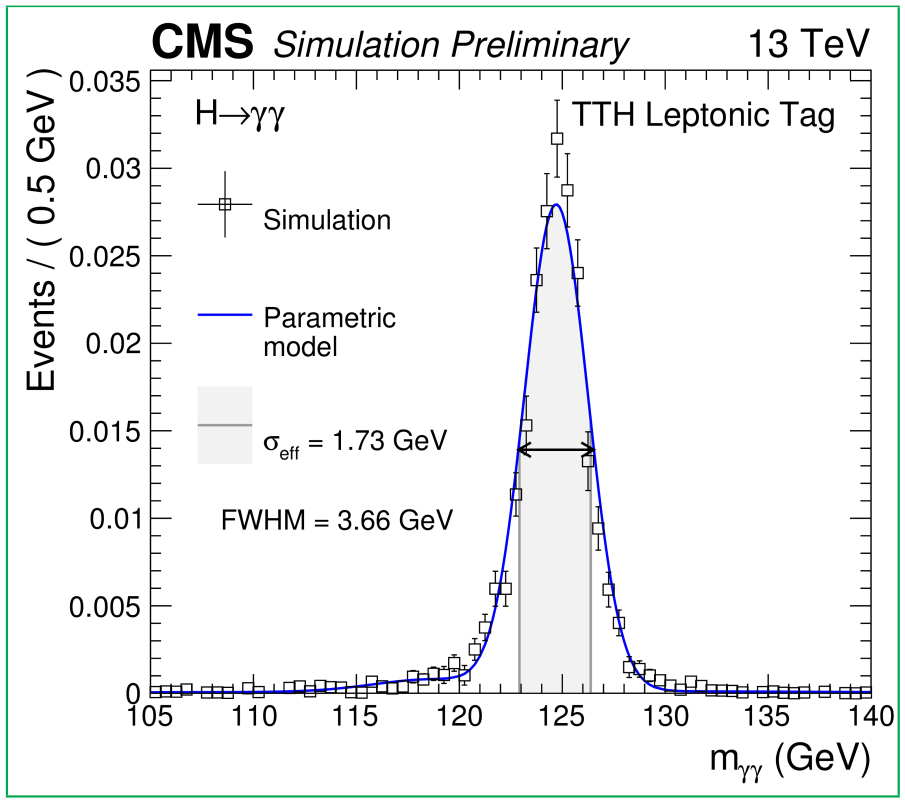
HIG-15-005



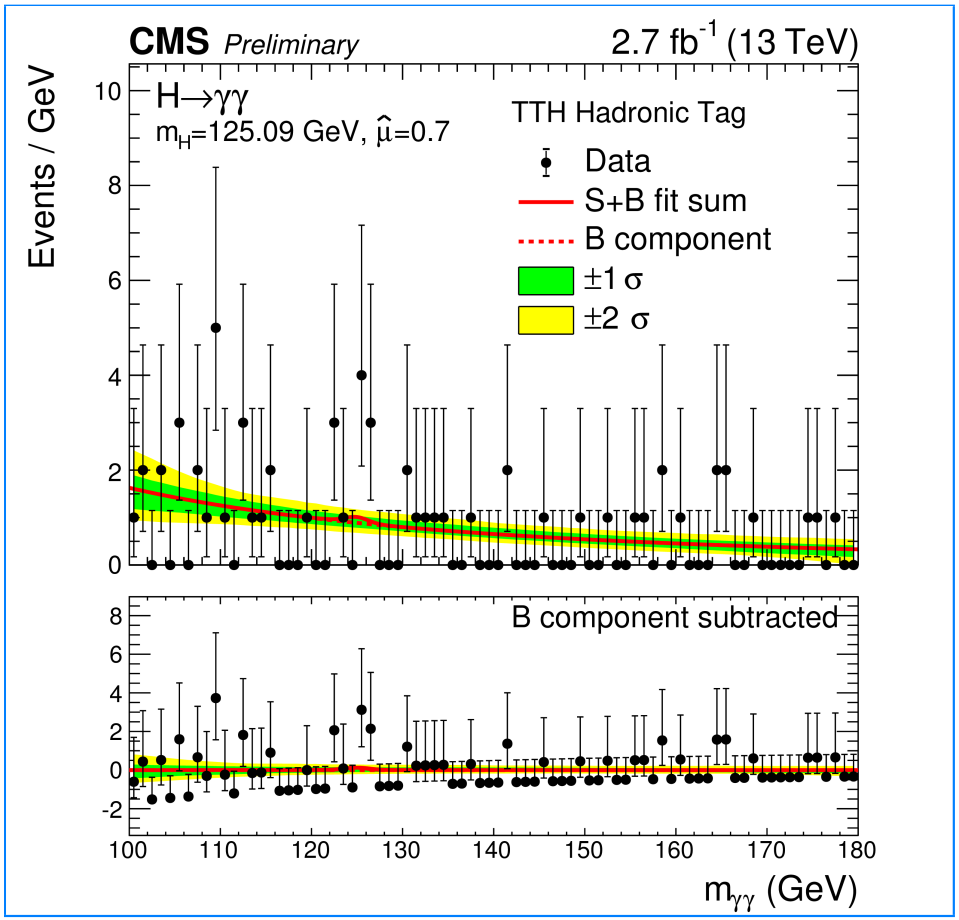
- Part of inclusive H→ $\gamma\gamma$ analysis
  - Diphoton selection to separate signal from background (BDT approach)
  - Event classification via **mass resolution**, signal/backg., production mechanism
  - Tagging of events produced by VBF, $t\bar{t}H$

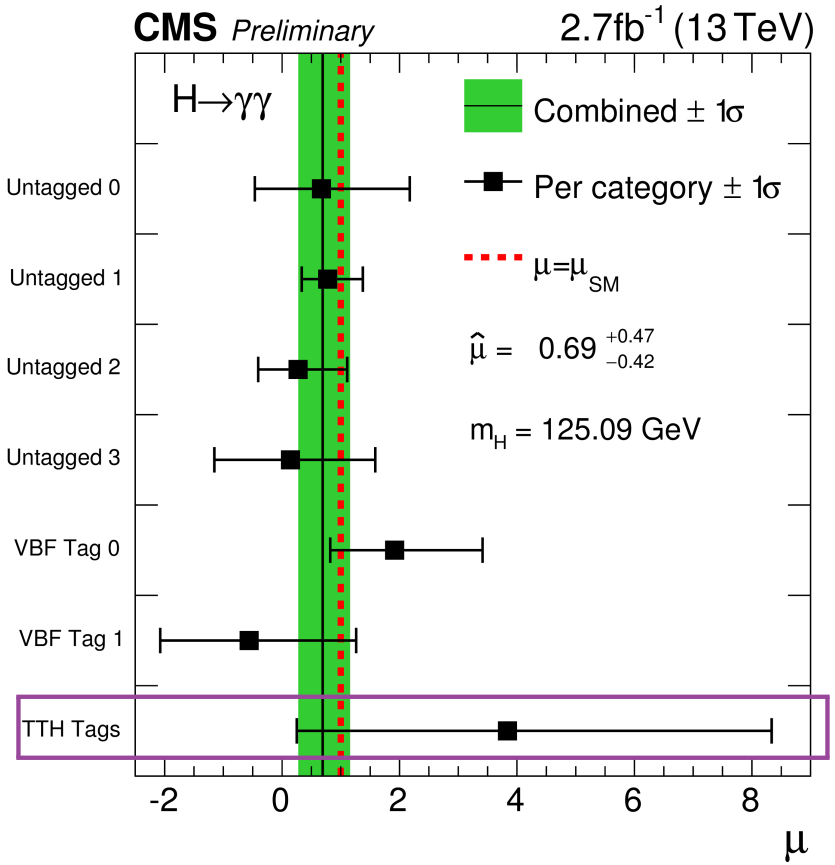
- Two $t\bar{t}H$ categories: **leptonic** & **hadronic** tag
  - Diphoton triggers and offline event selection
  - $\geq$1, 0 leptons
  - $\geq$2, $\geq$5 jets
  - $\geq$1 b-tag
  - diphoton BDT output cut

- Small branching ratio, but clean final state
- Main backgrounds:
  - irreducible: $t\bar{t}+\gamma\gamma$
  - reducible: $t\bar{t}+\gamma$+jet, $t\bar{t}$+jets
    → jets misidentified as isolated photons
- Challenges: suppress background, excellent $m_{\gamma\gamma}$ resolution



$t\bar{t}H(\gamma\gamma)$ - Results

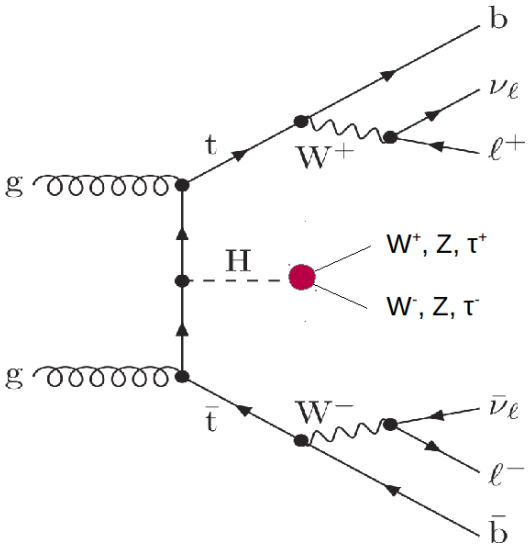




- Smooth fit functions, several functional forms
  - ◇ fit model validation in control regions by inverting photon ID + loosened event selection
- Event interpretation as for inclusive H→ $\gamma\gamma$: search for resonance in $m_{\gamma\gamma}$
- High-purity ttH selection → $\hat{\mu}_{obs} = 3.8^{+4.5}_{-3.6}$
  - ◇ statistically limited

$t\bar{t}H$(multileptons)

HIG-15-008



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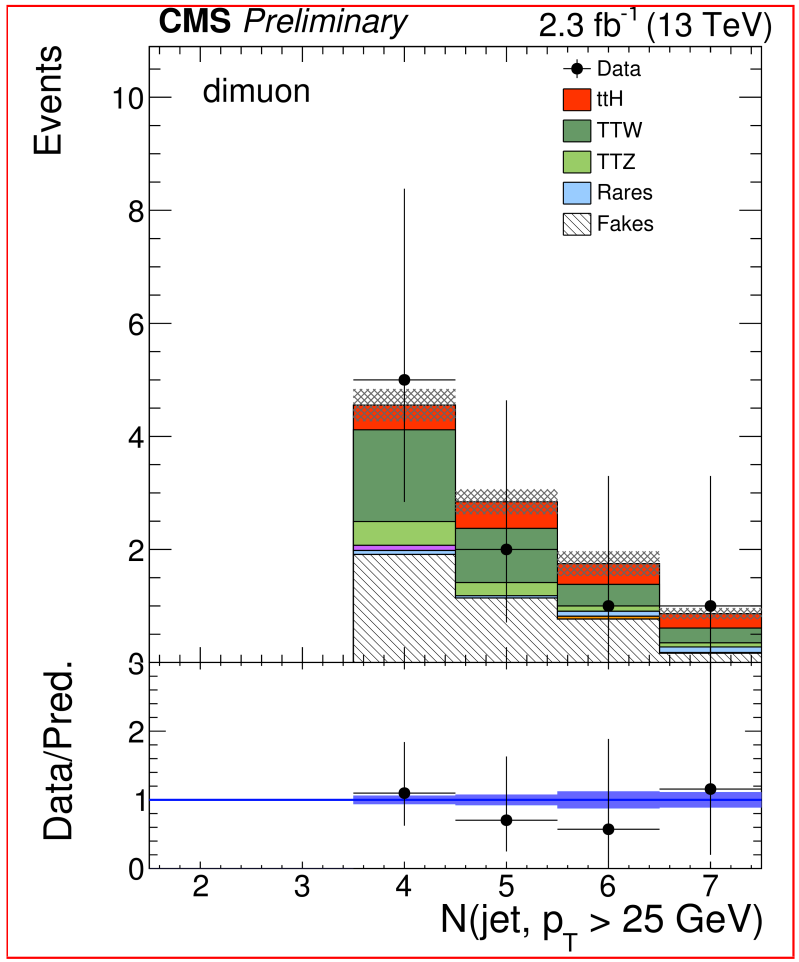


- Main backgrounds:
  - Irreducible (smallest): tt+V →from MC
  - Reducible: tt+jets →from data
- Two categories: **2 same sign leptons** & ≥3 leptons
  - Lepton triggers and offline event selection
  - ≥4, ≥2 jets
  - ≥1 b-tag

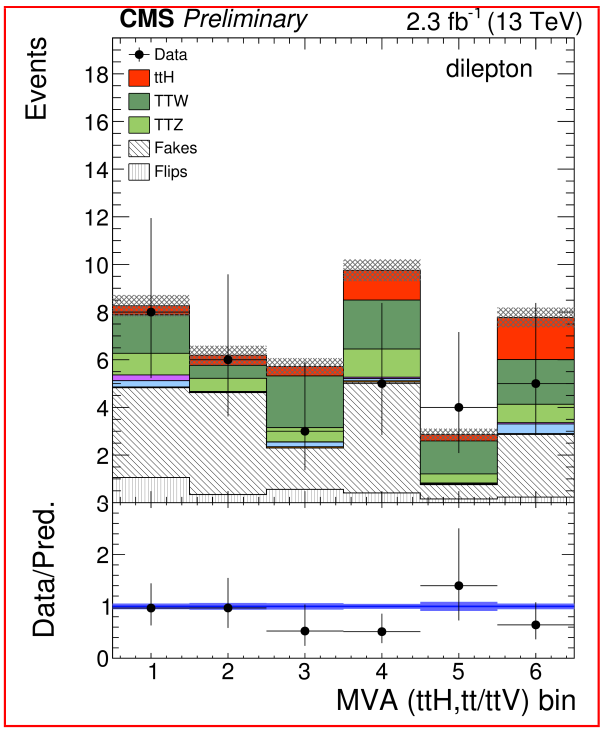
Sub-categories: lepton charge, presence of τ_h, lepton flavour, presence of ≥2 b-tags, signal/backg. bins

$t\bar{t}H(multileptons)$ - Results

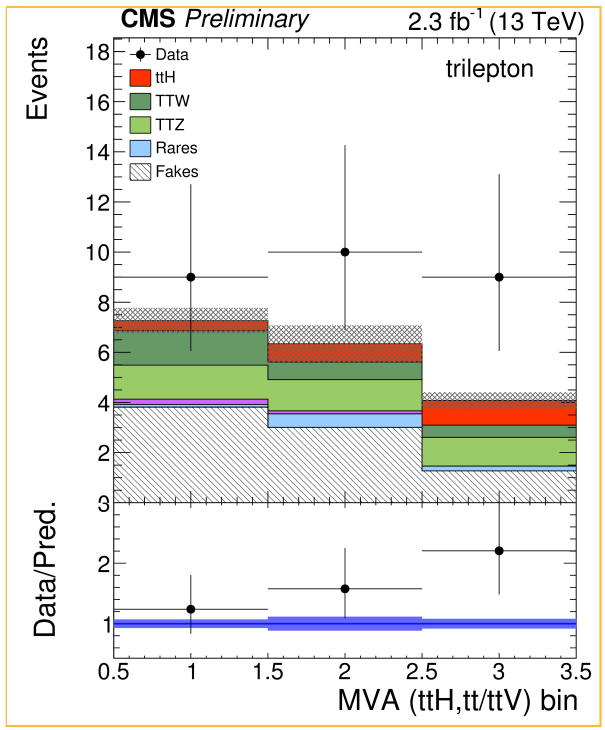
- Separation of signal from $t\bar{t}$, $t\bar{t}V$ via BDTs → categories division in signal/backg. bins
- Modelling of fake lepton backgrounds from control region relaxing lepton selection
  - ◇ Jet Mis-identification, B hadrons decay
  - ◇ Charge mis-assignment of electrons
- Combined best fit of all sub-categories $\hat{\mu}_{obs} = 0.6^{+1.4}_{-1.1}$

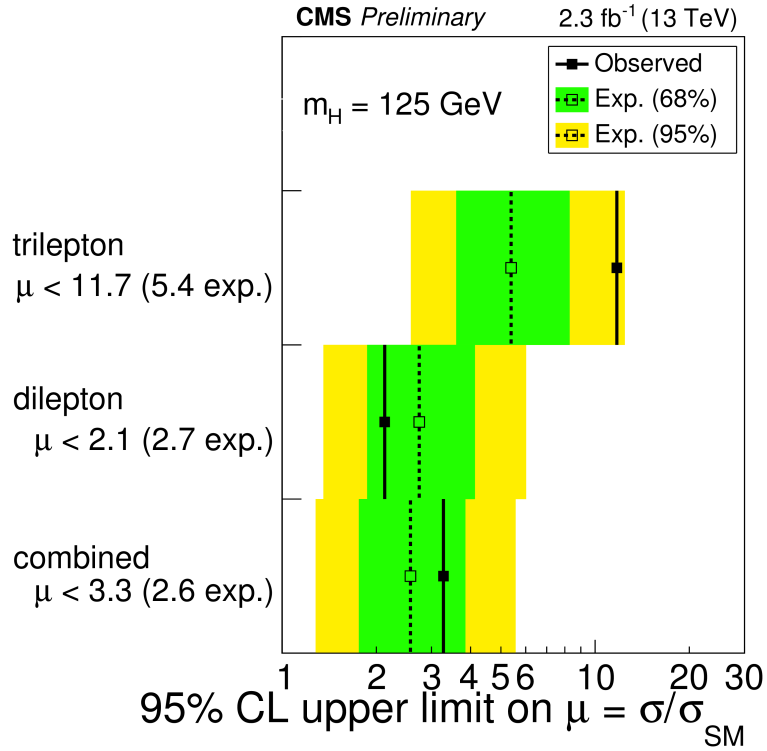
→ Slight deficit in dilepton, some excess in trilepton; no significant excess overall

dilepton



trilepton

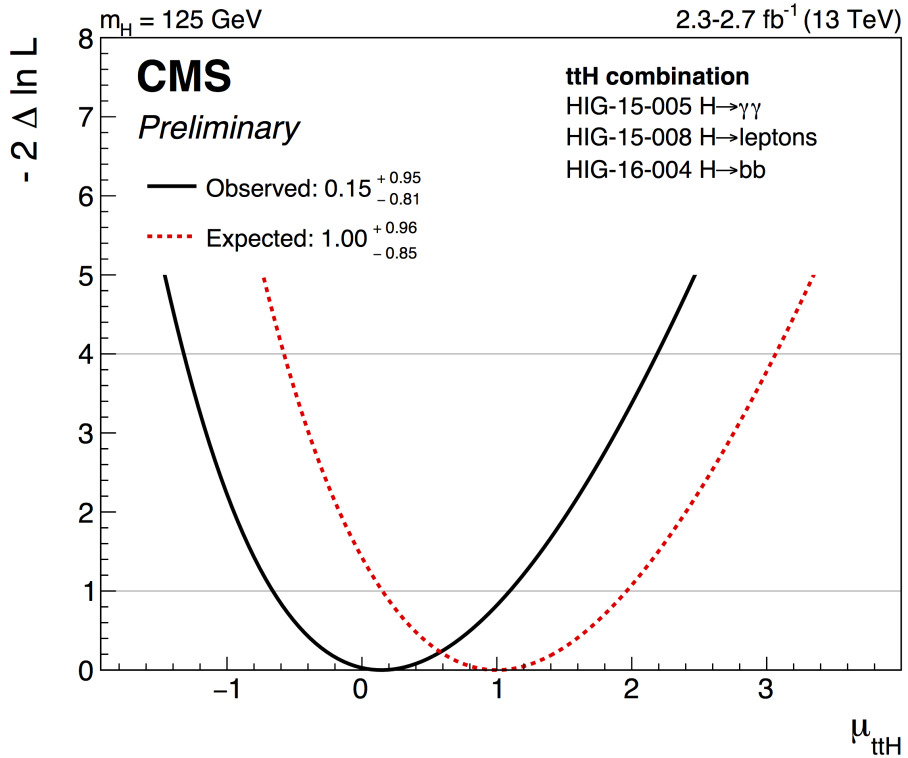




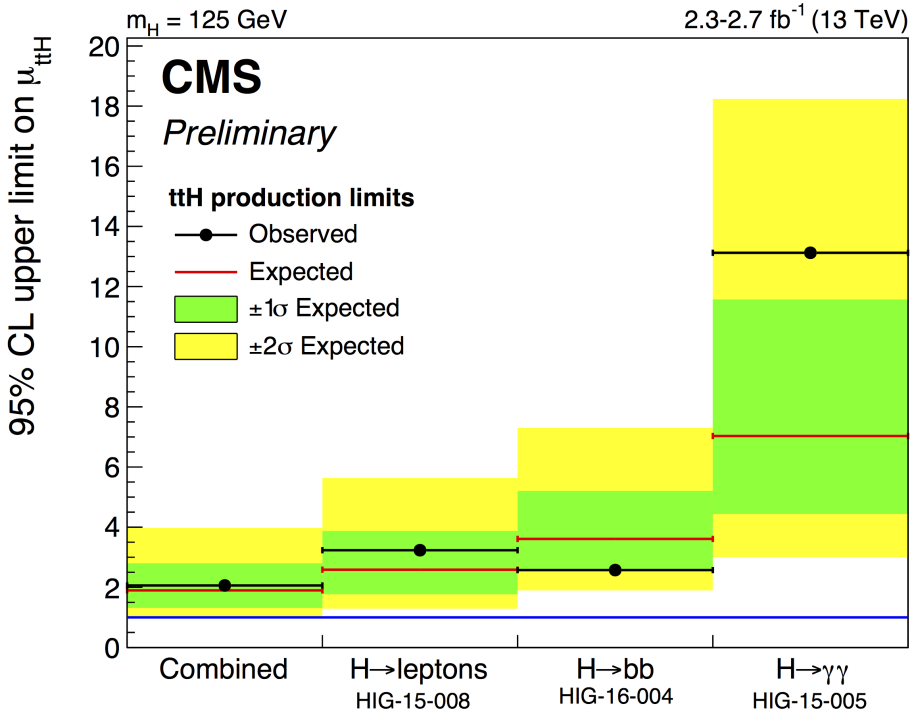
$t\bar{t}H$ - Combination

- Combined fit of 3 statistically independent analysis channels: $t\bar{t}H(b\bar{b})$, $t\bar{t}H(multilepton)$ and $t\bar{t}H(\gamma\gamma)$
  - ◇ Combined best fit: $\hat{\mu}^{t\bar{t}H}_{obs} = 0.15^{+0.95}_{-0.81}$
  - ◇ SM expectation best fit: $\hat{\mu}^{t\bar{t}H}_{SM} = 1.00^{+0.96}_{-0.85}$

$t\bar{t}H$ signal strength



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



Summary

- Top-Higgs coupling only accessible via associated $t\bar{t}H$ production
  – Important to understand loop contributions

→ Foundation with improved analysis techniques for 13 TeV

- Best fit for 3 statistically independent analysis channels with first 13 TeV data:

$t\bar{t}H(b\bar{b})$: $\hat{\mu}_{obs}^{t\bar{t}H(b\bar{b})} = -2.0^{+1.8}_{-1.8}$

$t\bar{t}H(\gamma\gamma)$: $\hat{\mu}_{obs}^{t\bar{t}H(\gamma\gamma)} = 3.8^{+4.5}_{-3.6}$

$t\bar{t}H(multilepton)$: $\hat{\mu}_{obs}^{t\bar{t}H(multilepton)} = 0.6^{+1.4}_{-1.1}$

combined best fit $\hat{\mu}_{obs}^{t\bar{t}H} = 0.15^{+0.95}_{-0.81}$

→ Overall in agreement with SM expectations
→ Similar sensitivity as 8 TeV analyses

- Expected luminosity with full 2016 run: ≈25 fb^{-1}
  – Many more exciting results are coming!!!
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG