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

LHC Day 2016
Large Hadron Collider Physics

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on behalf of the CMS collaboration

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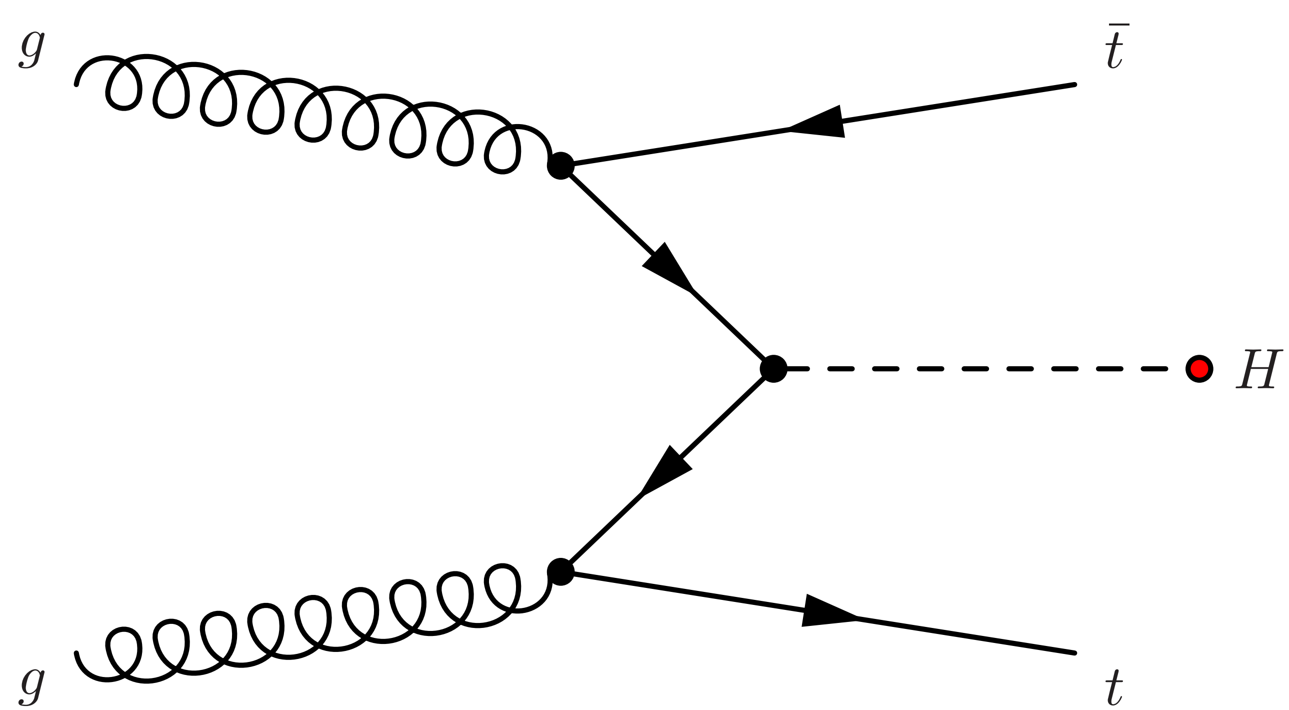
Outline

- Introduction & challenges
- ttH production & decay modes
- Recap Run I & Moriond combined results
- Analysis strategy & results at 13 TeV
  - ttH(bb)
  - ttH(γγ)
  - ttH(multileptons)
- Summary

Introduction

Post-discovery of Higgs boson the focus now on it's full characterization

- **Why associated ttH production?**
  - ttH offers direct measure of top Yukawa coupling & test SM consistency
  - Add sensitivity to other Higgs coupling measurements
  - Possibility to exploit several Higgs decay modes
  - Used in many Beyond Standard Model physics searches



Challenges

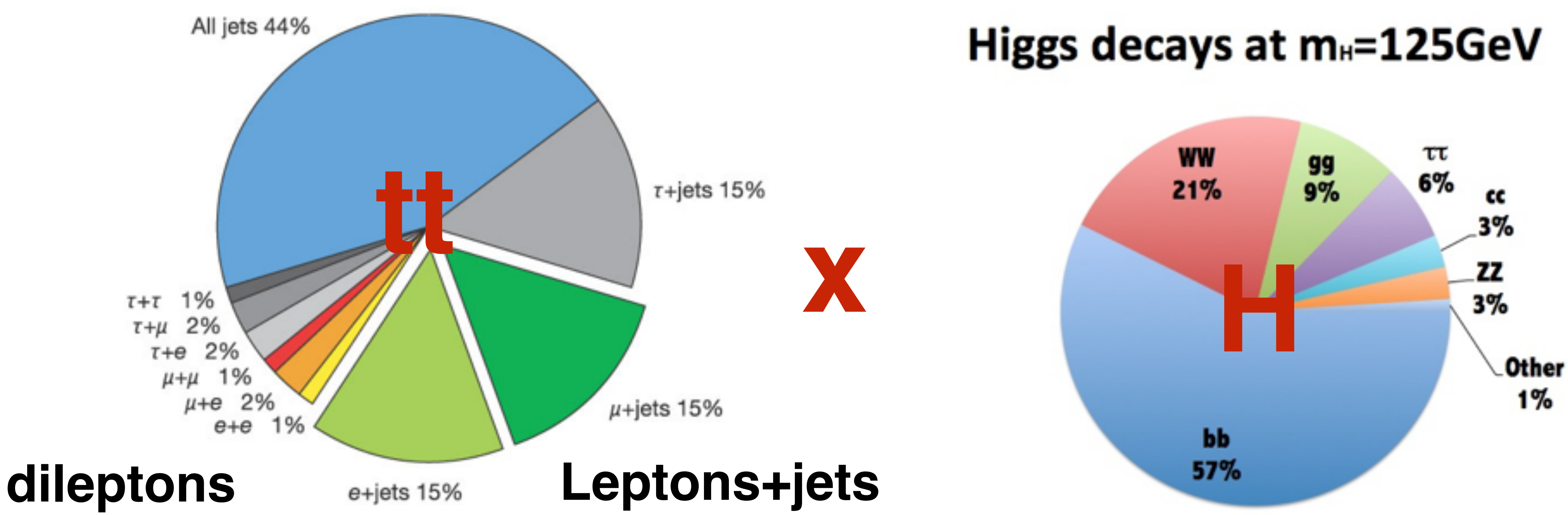
- **Experimental challenges**
  - Small signal cross section
  - Overwhelming background
- Cross section increased with center-of-mass energy
  - ~ 3.9 increase in cross section for 13 TeV (sensitivity approaching Run 1)

$\sqrt{s}$	$\sigma_{t\bar{t}H}$ at NLO ($m_H = 125$ GeV)
7 TeV	89 fb
8 TeV	133 fb
13 TeV	507 fb

    - Sensitive to potential new physics contributions
  - Dominant background from tt+XX
    - Similar increase in cross section
- Luminosity of 13 TeV data ~2.3-12.9 fb^{-1}
  - ≈ 2.5 more statistics than 8 TeV

ttH signature

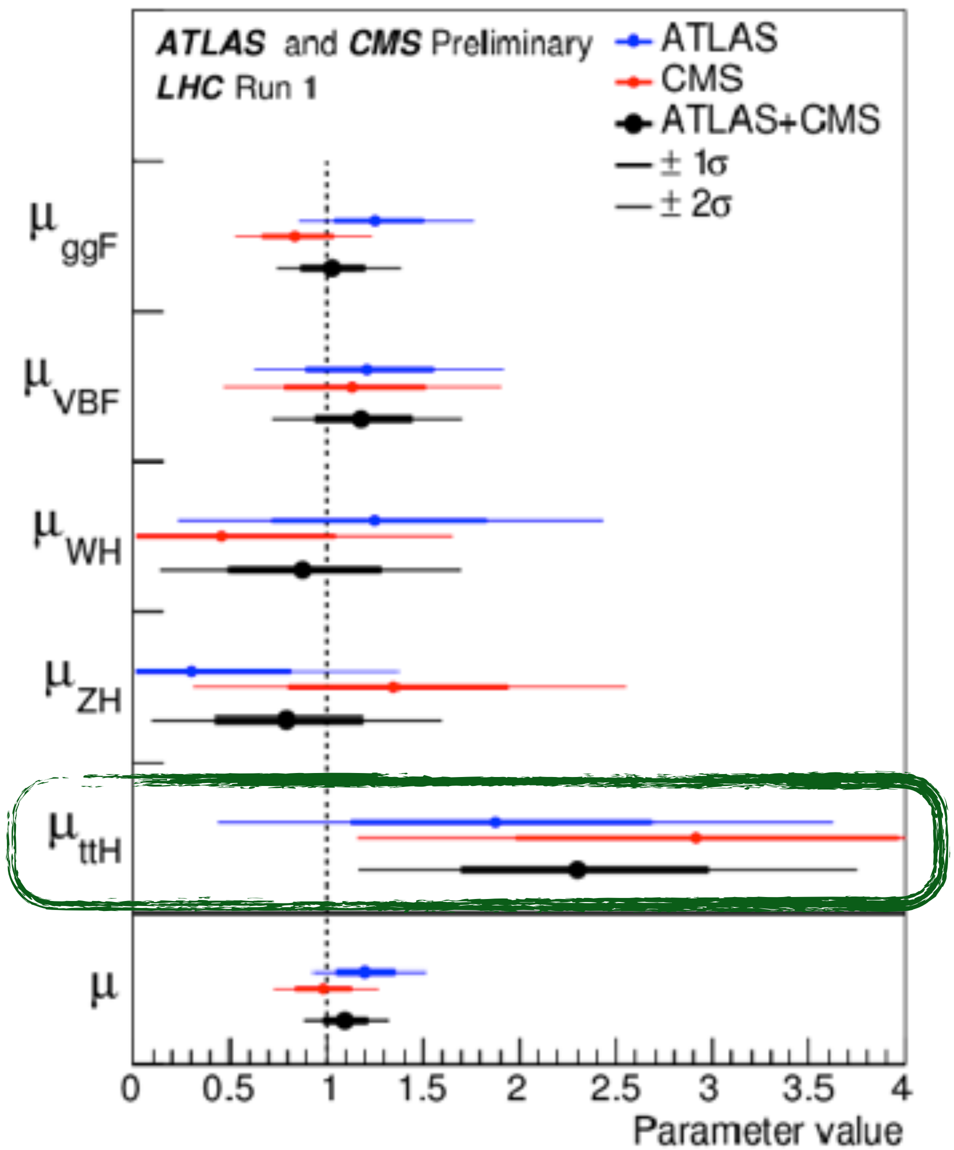
- **ttH final states** combine top & Higgs decay signatures
  - **tt final** state topology depends on W boson decay: lepton +jets, dilepton, all-jets
    - **ttH(bb):** lepton + jets, dileptons
    - **ttH(γγ):** lepton+jets, dileptons, all-jets
    - **ttH(multileptons):** lepton+jets, dileptons
      - Leptonic decays of Higgs boson → WW*, ZZ*, and ττ



Run I ttH results at 7 and 8 TeV (HIG-15-002)

- Recap knowledge from Run I results
  - combination of all Higgs analysis channels in ATLAS and CMS
- μ_{ttH} dominated by ttH(γγ), ttH(multileptons), and ttH(bb)

Best-fit results for the production signal strengths

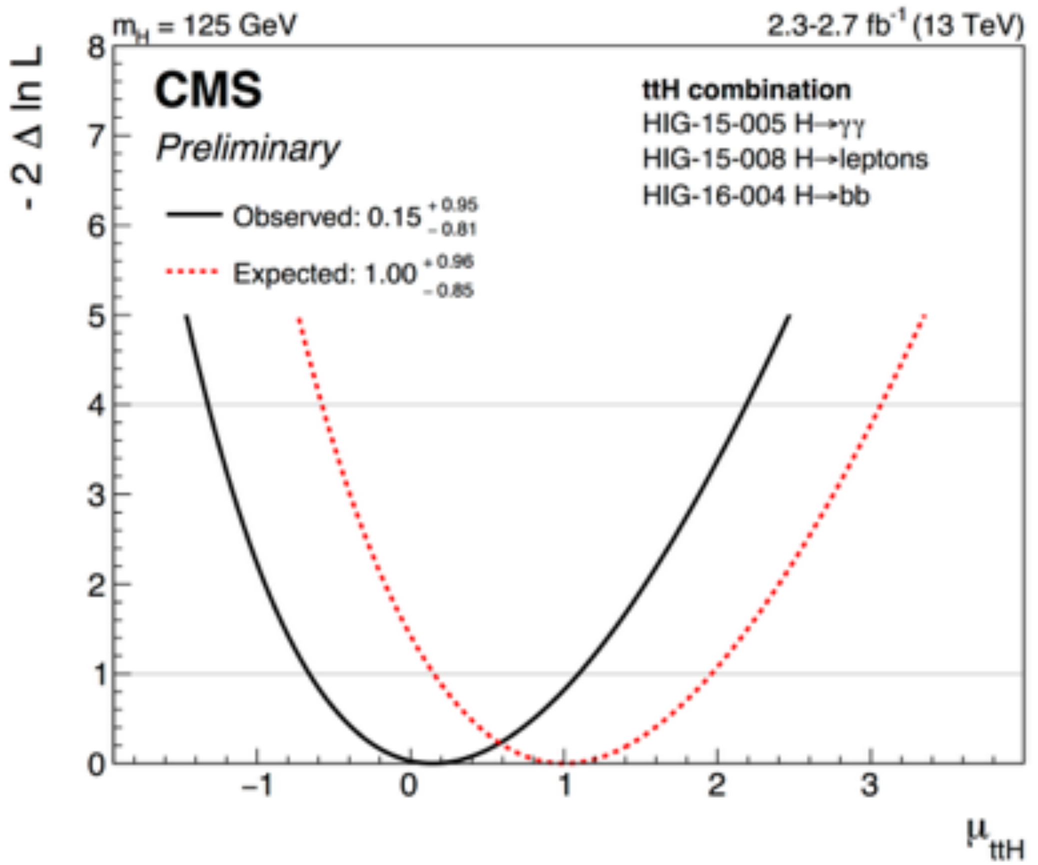


Collaboration	$\mu_{t\bar{t}H}$
ATLAS	$1.9^{+0.8}_{-0.7}$
CMS	$2.9^{+1.0}_{-0.9}$
Combined	$2.3^{+0.7}_{-0.6}$

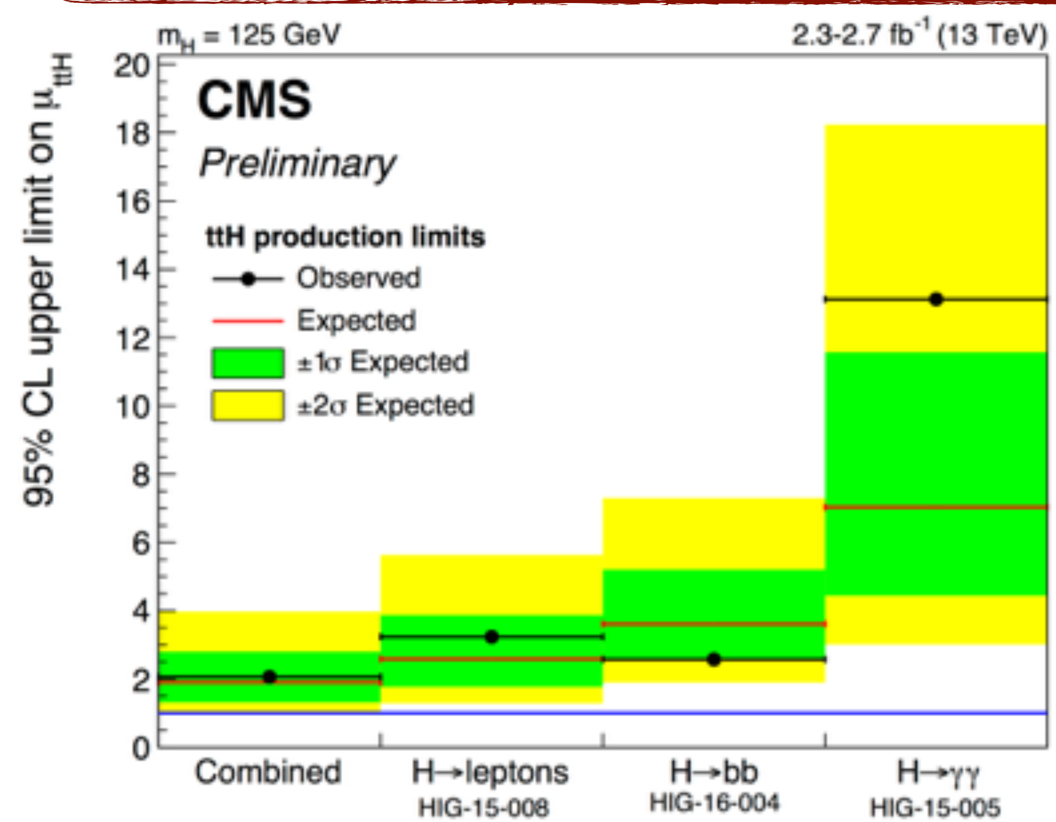
Moriond 2016 combined results

- Combined fit of 3 statistically independent analysis channels:
  - ttH(bb) (HIG-16-004), ttH(γγ) (HIG-15-005), and ttH(multileptons) (HIG-15-008)
- **Combined best-fit:** $\hat{\mu}^{t\bar{t}H}_{\text{observed}} = 0.15^{+0.95}_{-0.81}$
- **SM expected best fit:** $\hat{\mu}^{t\bar{t}H}_{\text{SM}} = 1.00^{+0.96}_{-0.85}$

ttH signal strength

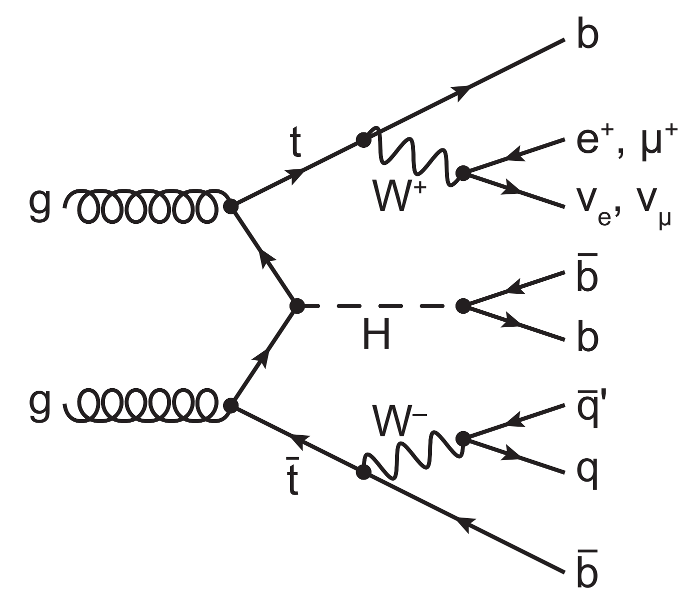


95% CL upper limit on μ_{ttH}



ttH(bb) (HIG-16-004)

- Large H → bb Branching fraction
- Dominant background: tt+jets
  - Irreducible contribution: tt+bb (theoretically challenging)
- Many jets with similar kinematics
  with limited mass resolution for H → bb
- **Analysis strategy:**
  obtain good signal separation & constrain background



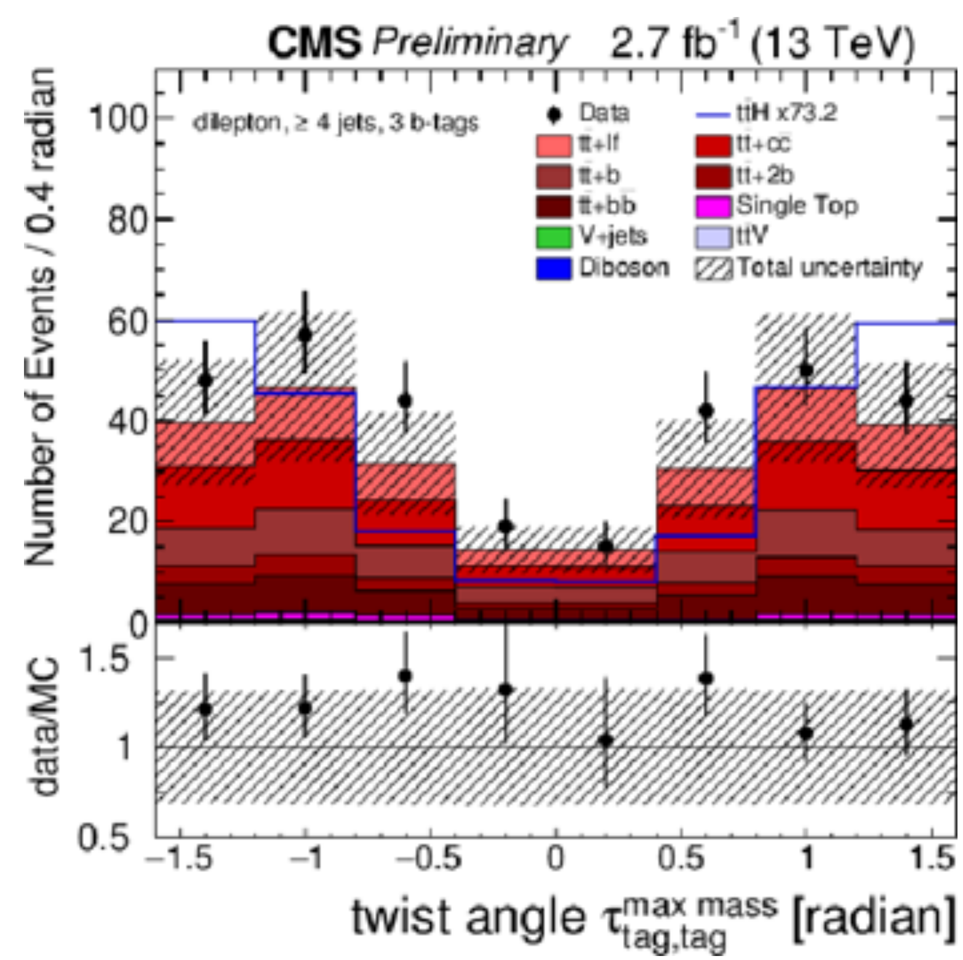
  - **Event categories:** 11 (5) lepton+jets (dilepton)
  - Lepton triggers and offline event selection

Lepton+jets

- exactly 1 lepton
- At least 4 jets
- At least 2 b-tagged jets

Dileptons

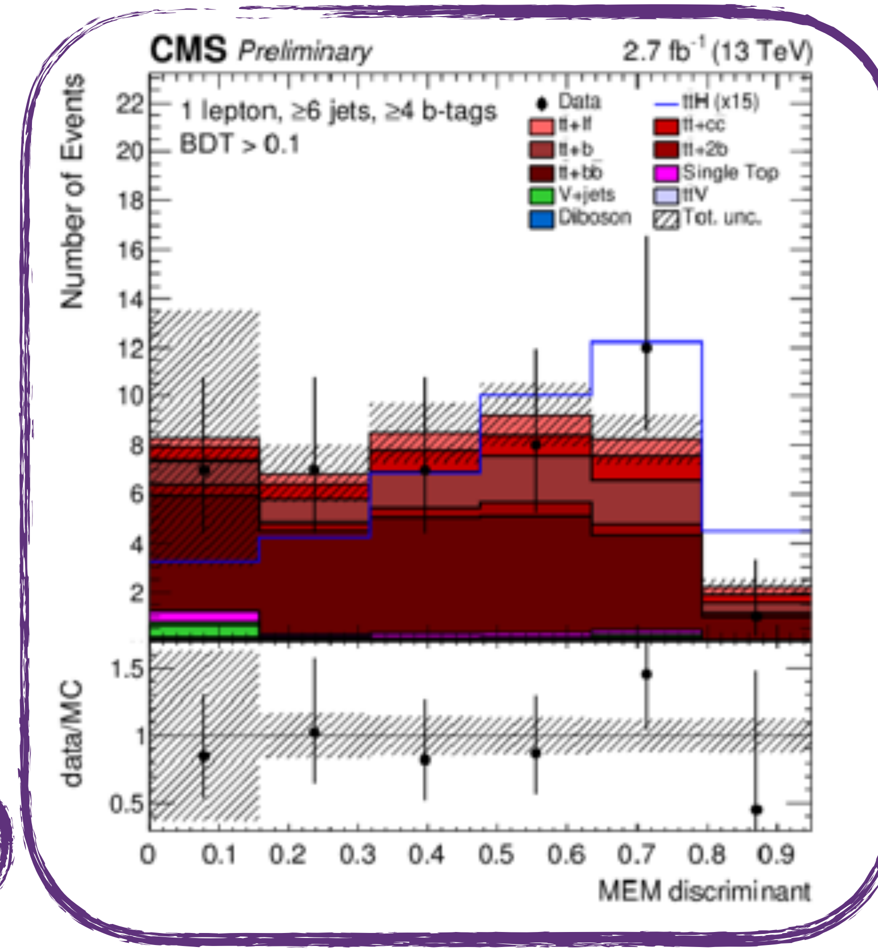
- 2 opposite sign leptons
- At least 3 jets
- At least 2 b-tagged jets



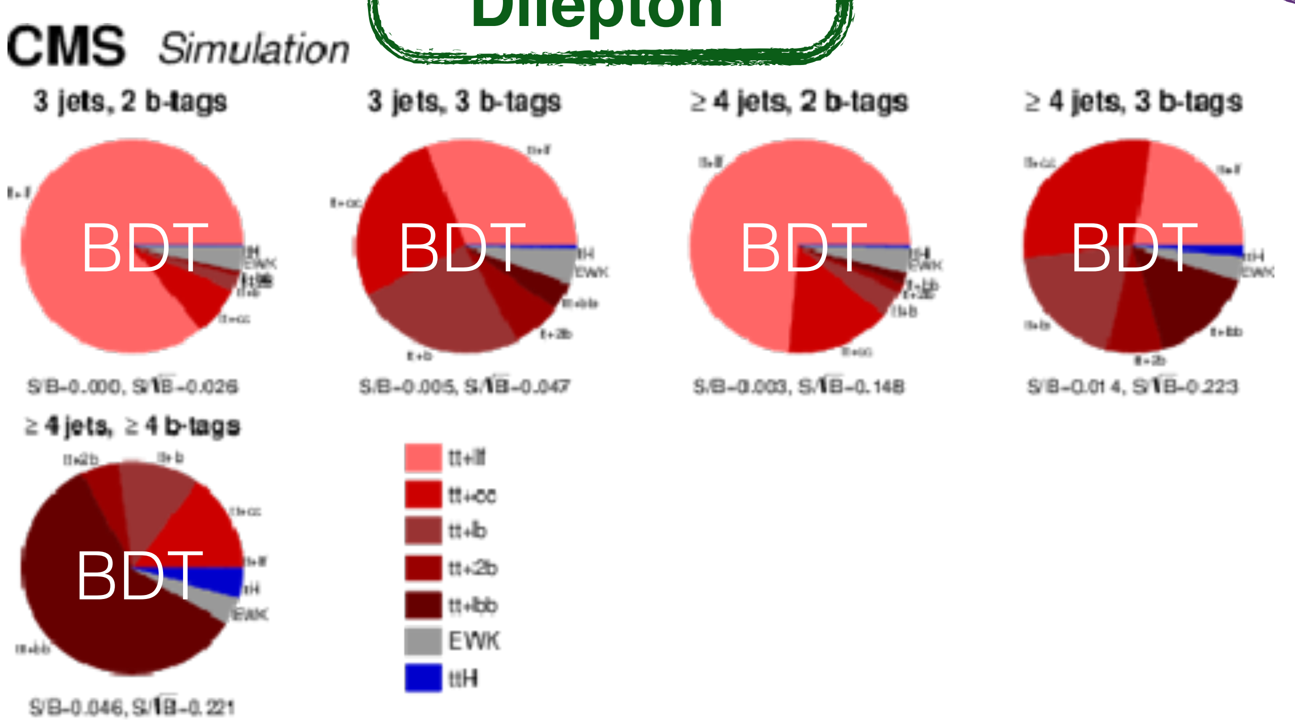
  - **Leptons + jets:** high statistics
  - **Dilepton:** minimal non-tt background,
    and minimal jet combinatorics
- Classify events based on jet, b-tag multiplicities and boosted jets (leptons+jets), a total of 13 sub-categories

ttH(bb) signal seperation

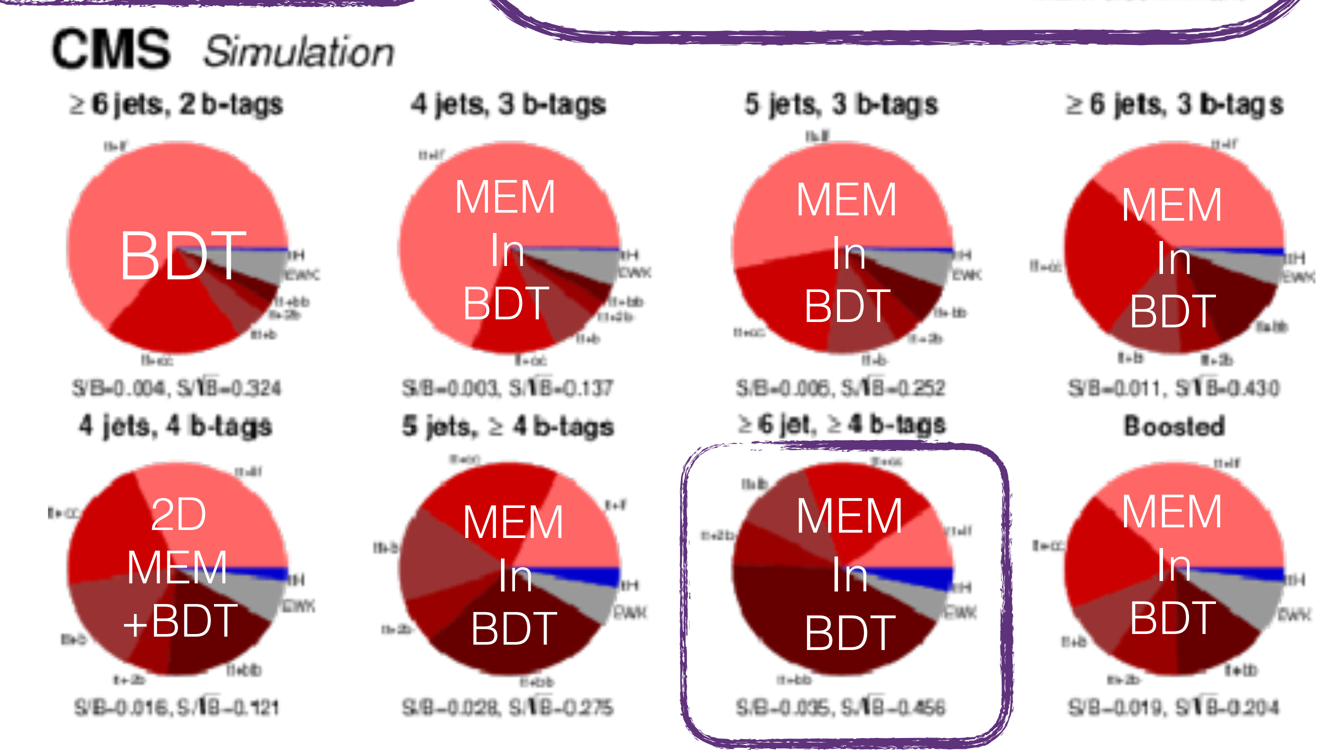
- Each sub-category discriminator is optimized to improve sensitivity
  - **Dilepton:** use Boosted Decision Tree (BDT)
  - **Lepton+jets:** use Matrix Element Method (MEM)
    - tt+bb as background hypothesis, permuting over all b-quark association
    - MEM as input to BDT modeling
    - 2Dim MEM+BDT analysis



Dilepton

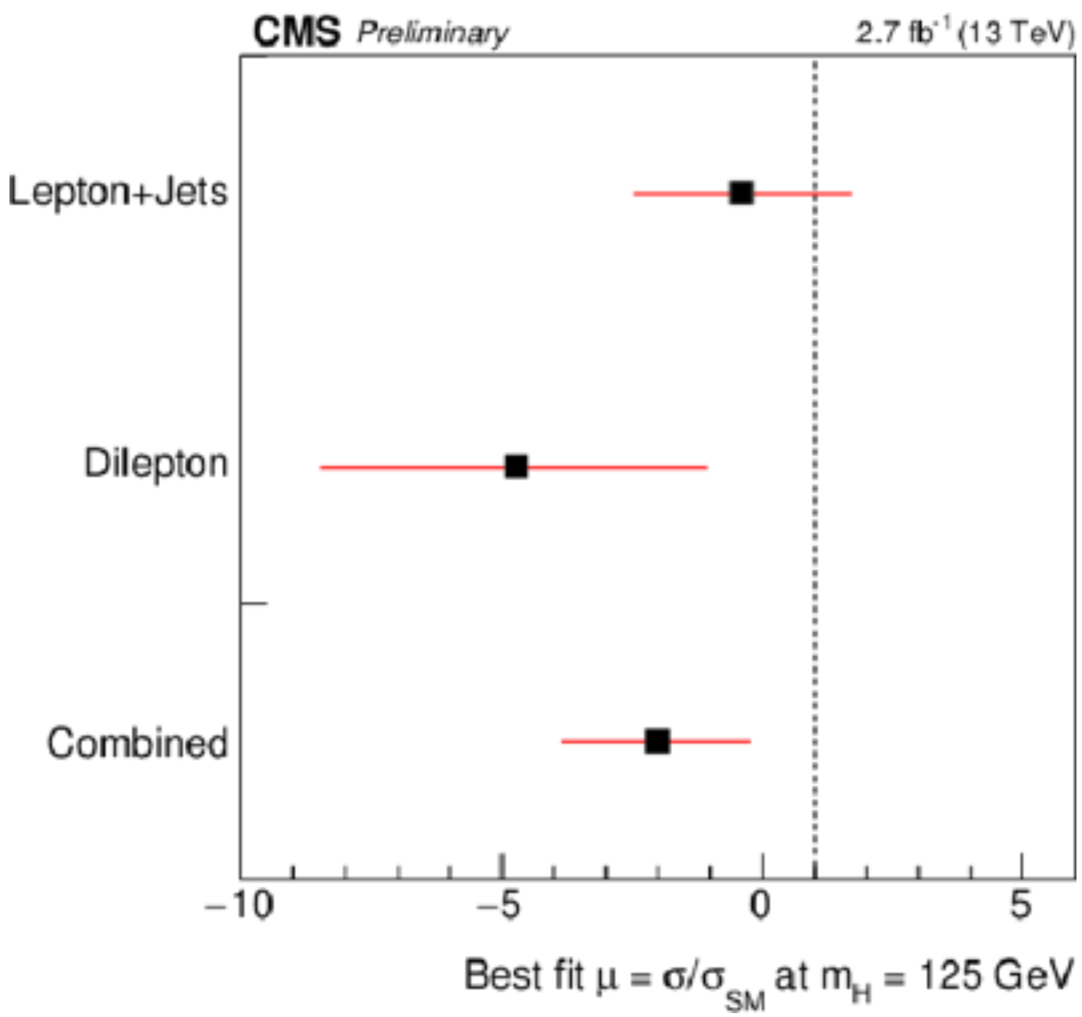


Lepton+jets



ttH(bb) results

- Simultaneous maximum likelihood fit of discriminant output across all event categories
- Observe no significant excess
  - set upper limit on $\mu = \sigma / \sigma_{SM}$
- Systematic dominated



Upper limit at 95% CL

Channel	Best-fit μ	Observed UL	Expected UL
Lepton+jets	$-0.4^{+2.1}_{-2.1}$	4.0	$4.1^{+1.8}_{-1.2}$
Dilepton	$-4.7^{+3.7}_{-3.8}$	5.2	$7.7^{+3.6}_{-2.3}$
Combined	$-2.0^{+1.8}_{-1.8}$	2.6	$3.6^{+1.6}_{-1.1}$

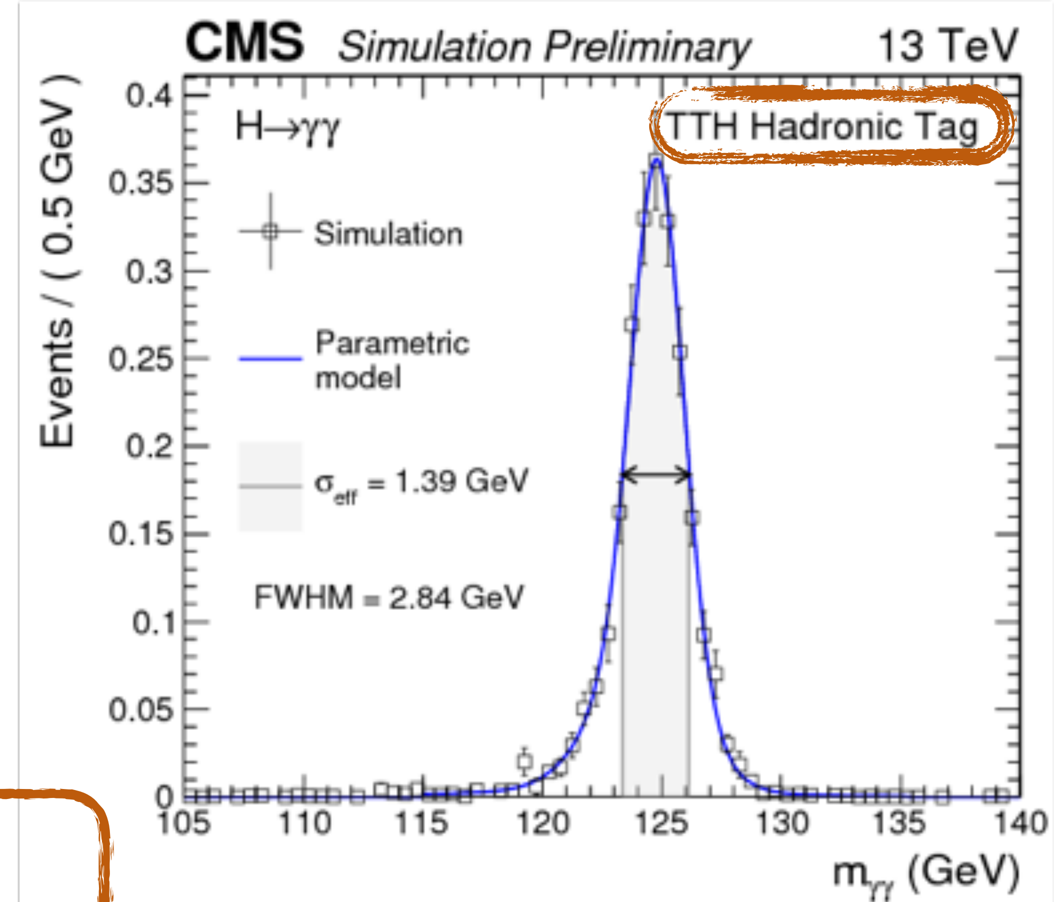
- Combined best-fit

$$\hat{\mu}_{\text{observed}} = -2.0^{+1.8}_{-1.8}$$

1.7 σ below SM expectation

ttH(γγ) (HIG-16-020)

- **ttH(γγ) part of the inclusive H→γγ analysis**
  - Dilepton selection to separate signal from background (BDT modeling)
  - Event categorization according to production mode and $m_{\gamma\gamma}$ resolution
  - Event tagging produced for VBF, and ttH processes



Leptonic

- Dilepton triggers & offline selection
- At least 1 lepton
- At least 2 jets
- At least 1 b-tagged
- Relies on diphoton BDT model cut

Hadronic

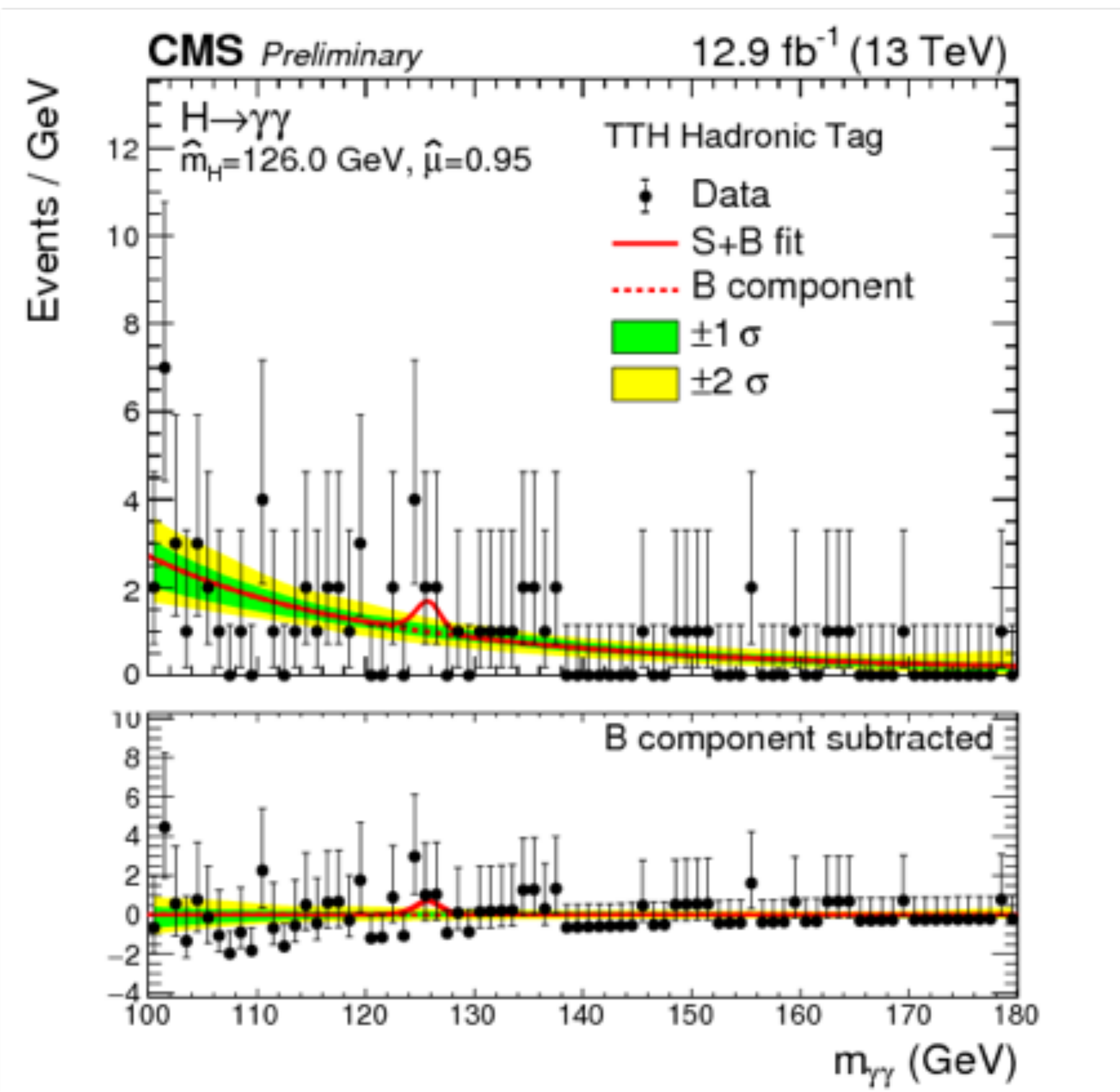
- Dilepton triggers & offline selection
- 0 leptons
- At least 5 jets
- At least 1 b-tagged
- Relies on diphoton BDT model cut

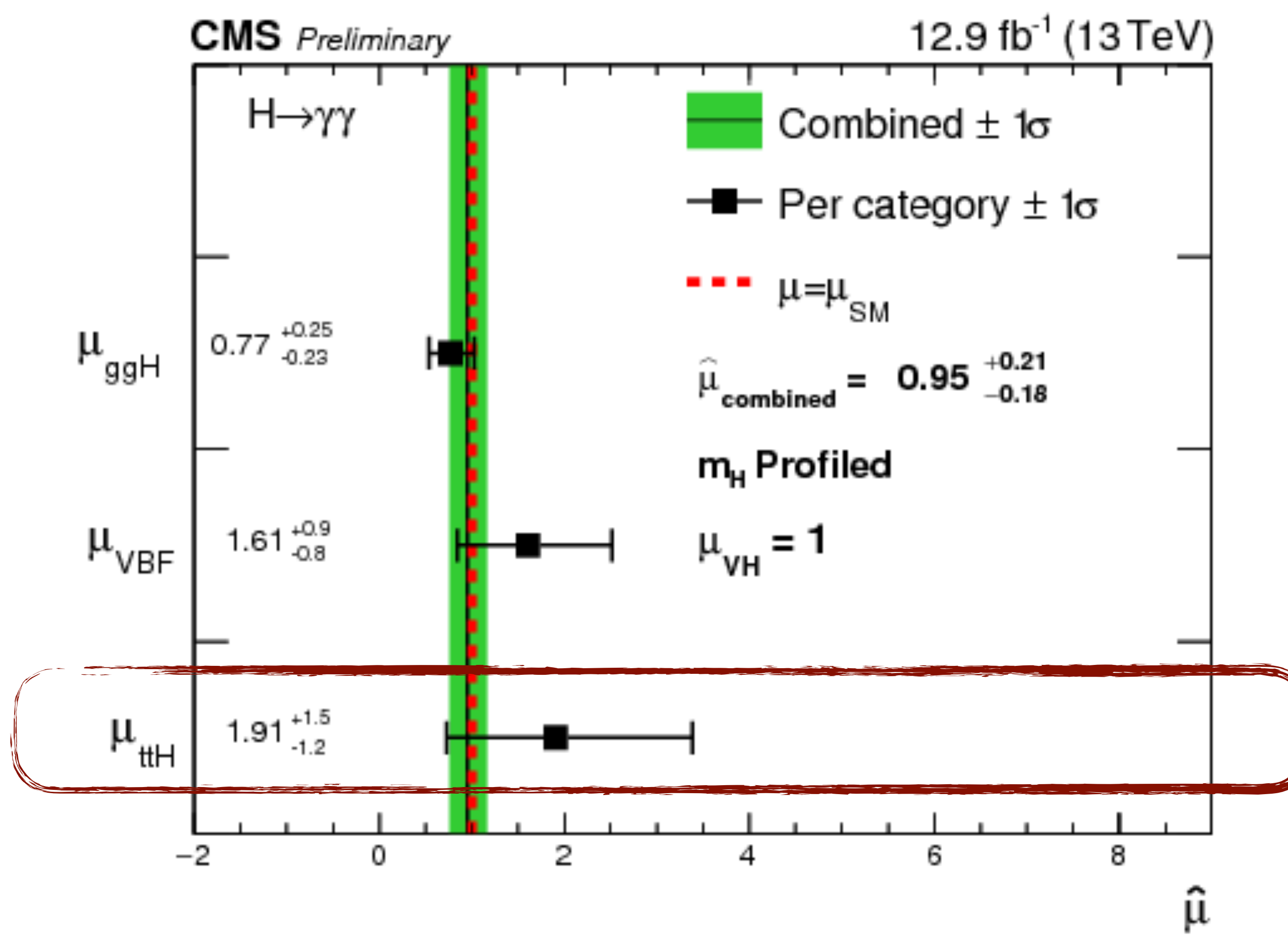
- Small branching fraction, but clean final states
- **Dominant backgrounds:**
  - Irreducible: tt+γγ
  - Reducible: tt+γ+jets, tt+jets (misidentified as isolated photons)
- **Challenge:**
  - suppression of fake photons and obtain excellent $m_{\gamma\gamma}$ resolution

ttH(γγ) results

- For background, smooth fit functions (treated in a likelihood fit)
  - Model fit validated in control regions by inverting photon ID + loosened event selection
- Event interpretation as for inclusive H → γγ (search for resonance $m_{\gamma\gamma}$)
- Selected ttH(γγ) process allows high-purity selection
  - Measurement statistically limited

$$\hat{\mu} = 1.9^{+1.5}_{-1.2}$$





ttH(multileptons) (HIG-16-022)

Targets at selecting events where H → WW*, ZZ*, and ττ

μμ-channel

Dominant backgrounds:

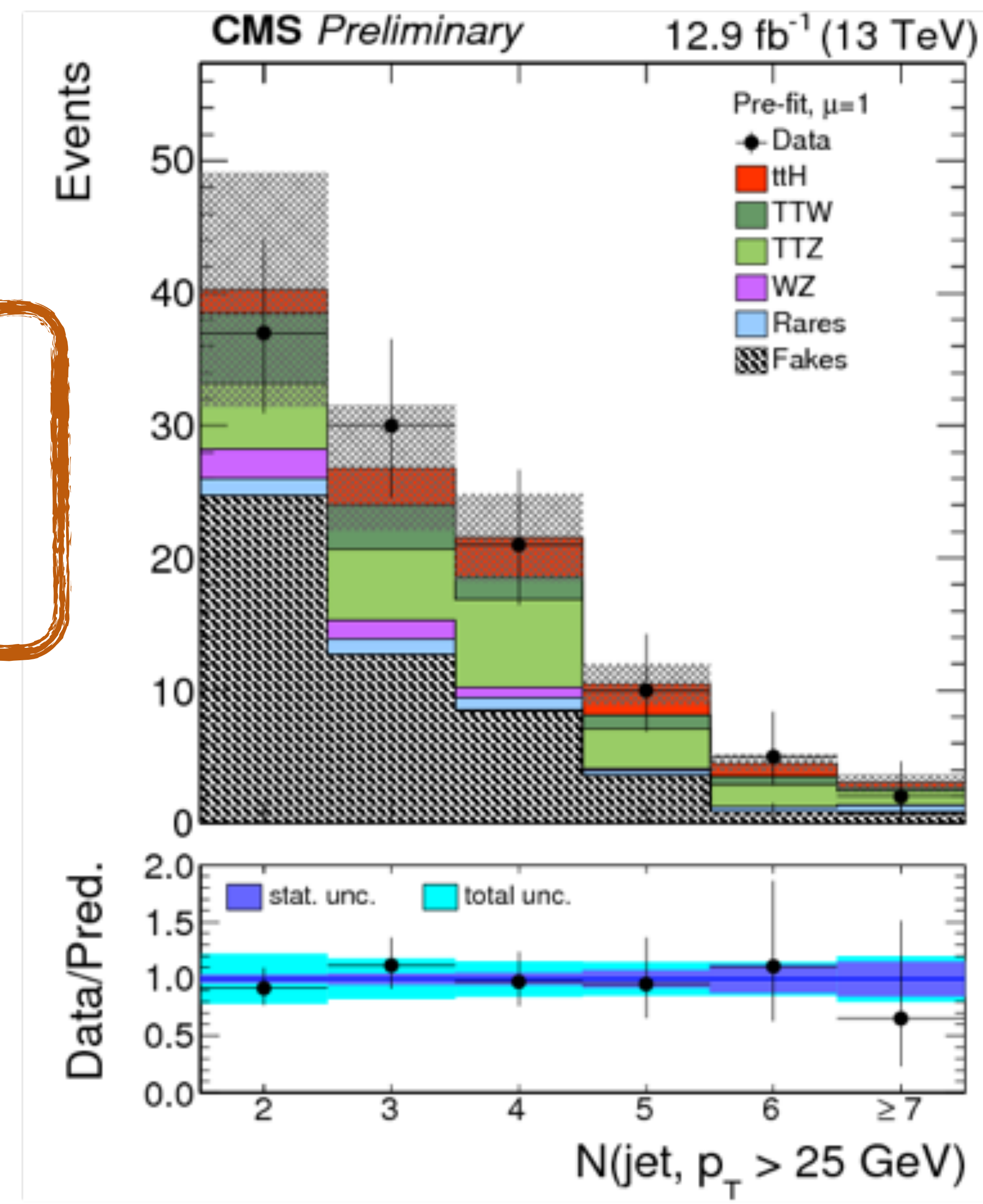
- Irreducible: tt+V (from MC)
- Reducible: tt+jets (from data)

2 same sign leptons

- At least 4 jets
- At least 1 b-tagged jets

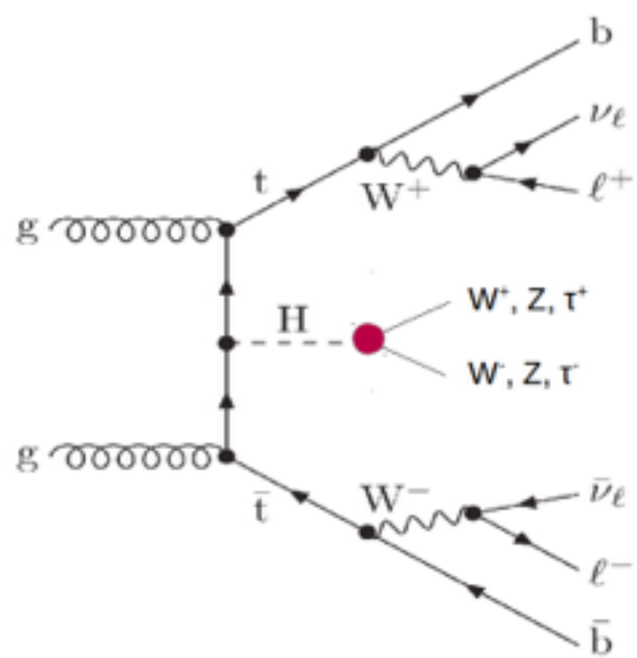
Tri-leptons

- At least 3 jets
- At least 1 b-tagged jets



Sub-classification:

- Lepton charge
- Presence of hadronic τ
- Lepton flavor
- Presence of at least 2 b-tags
- Signal/Background sensitivity



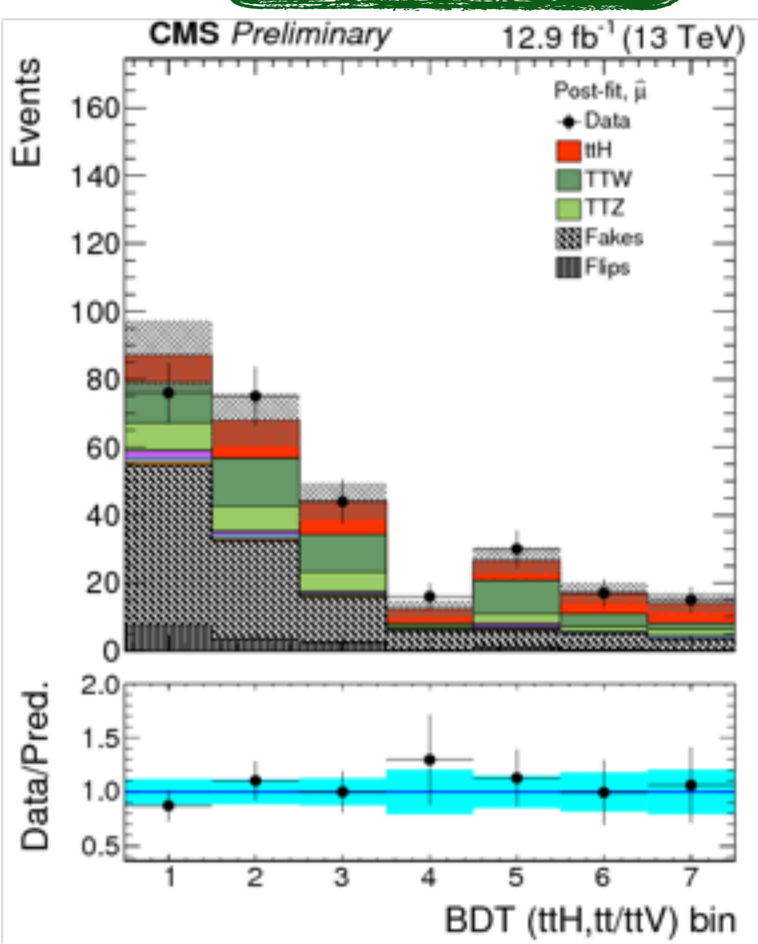
ttH(multileptons) results

- 2D fit separate BDTs against tt and ttV in each region (Categories based on signal/back sensitivity)
- Modeling of fake lepton backgrounds based on control regions by relaxing lepton selection
  - Charge mis-assignment of electrons
  - Jet mis-identification, B-hadron decay
- Combined best-fit over all sub-categories
  - No significant excess overall

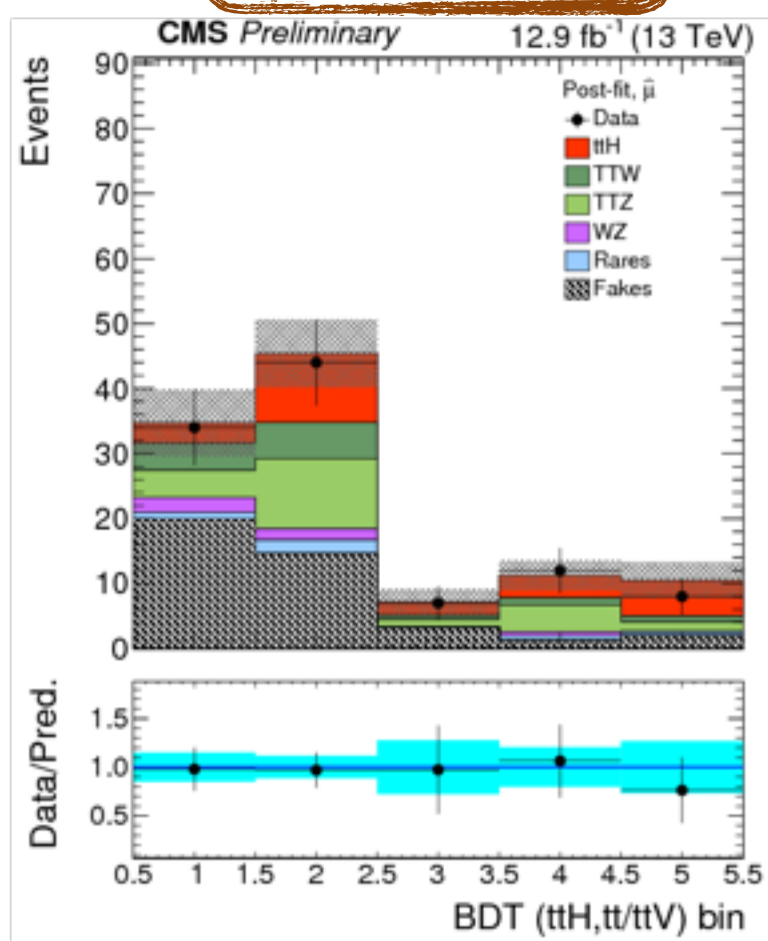
Combined categories
$\hat{\mu} = 2.3^{+0.9}_{-0.8}$

Combined with 2015 data
$\hat{\mu} = 2.0^{+0.8}_{-0.7}$

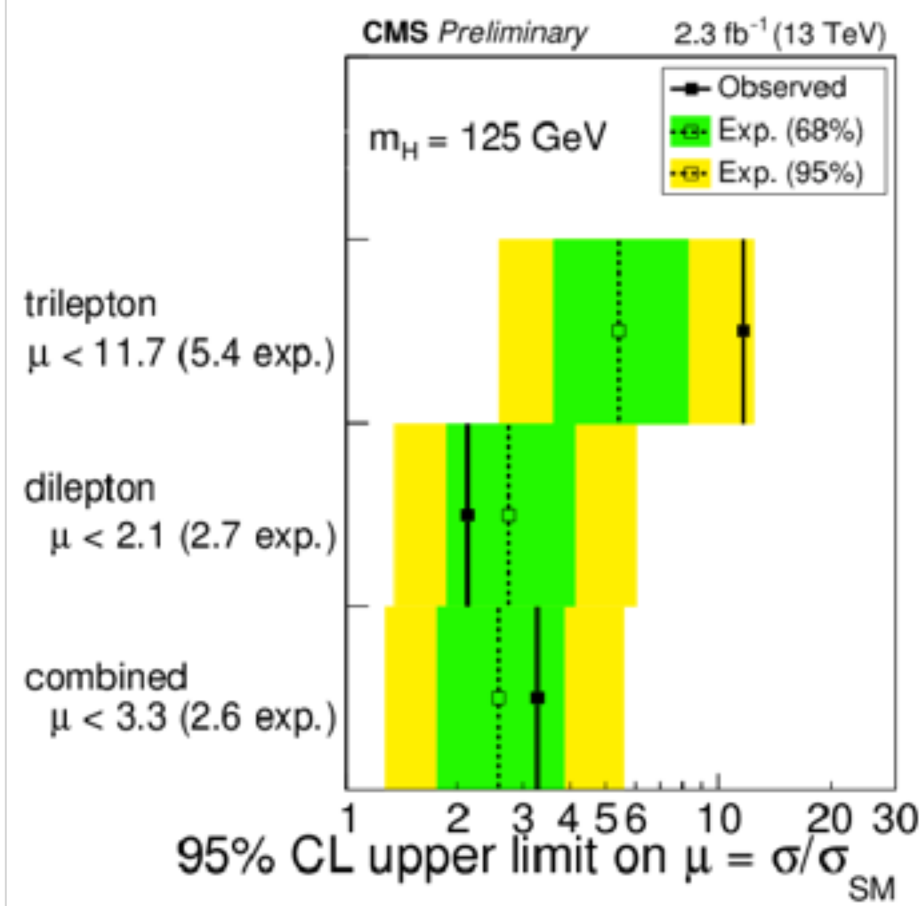
dilepton



trilepton



HIG-15-005



Summary

- Top-Higgs Yukawa coupling directly accessible through associated ttH production
  - Important for understanding loop contributions
  - Results based on improved analysis techniques for 13 TeV
- **Best-fit for 3** statistically independent analysis channels with 1st 13 TeV data

$\mathrm{t\bar{t}H(b\bar{b})}$	$\mathrm{t\bar{t}H(\gamma\gamma)}$	$\mathrm{t\bar{t}H(multilepton)}$
$\hat{\mu}^{\mathrm{t\bar{t}H(b\bar{b})}}_{\mathrm{observed}} = -2.0^{+1.8}_{-1.8}$	$\hat{\mu}^{\mathrm{t\bar{t}H(\gamma\gamma)}}_{\mathrm{observed}} = 3.8^{+4.5}_{-3.6}$	$\hat{\mu}^{\mathrm{t\bar{t}H(multilepton)}}_{\mathrm{observed}} = 2.0^{+0.8}_{-0.7}$
2.7 $\mathrm{fb^{-1}}$ 2015	12.8 $\mathrm{fb^{-1}}$ 2016	2.3/12.9 $\mathrm{fb^{-1}}$ 2015/16

  - Overall in agreement with SM expectations
  - The combined **μ of 2.3** corresponds to an observed (expected) significance of **4.4 (2.0) σ** over the null hypothesis (based on Moriond results)
  - Similar sensitivity as that of 8 TeV
- Expected luminosity of full 2016 data ≈ 30 $\mathrm{fb^{-1}}$
  - Many more results to come!
  - With every new analysis, our understanding of the Higgs boson and the SM continues to grow
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Reference

- https://cds.cern.ch/record/2053103/files/HIG-15-002-pas.pdf
- https://cds.cern.ch/record/2139578/files/HIG-16-004-pas.pdf
- https://cds.cern.ch/record/2205275/files/HIG-16-020-pas.pdf
- https://cds.cern.ch/record/2205282/files/HIG-16-022-pas.pdf
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- https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-15-005/index.html
- http://www.nature.com/nature/journal/v429/n6992/fig_tab/nature02589_F2.html
- http://www.quantumdiaries.org/tag/cms/page/4/

Introduction

Post-discovery of Higgs boson the focus now on it's full characterization

- **Why associated ttH production?**
  - ttH offers direct measure of top Yukawa coupling & test SM consistency
  - Possibility to exploit several Higgs decay modes
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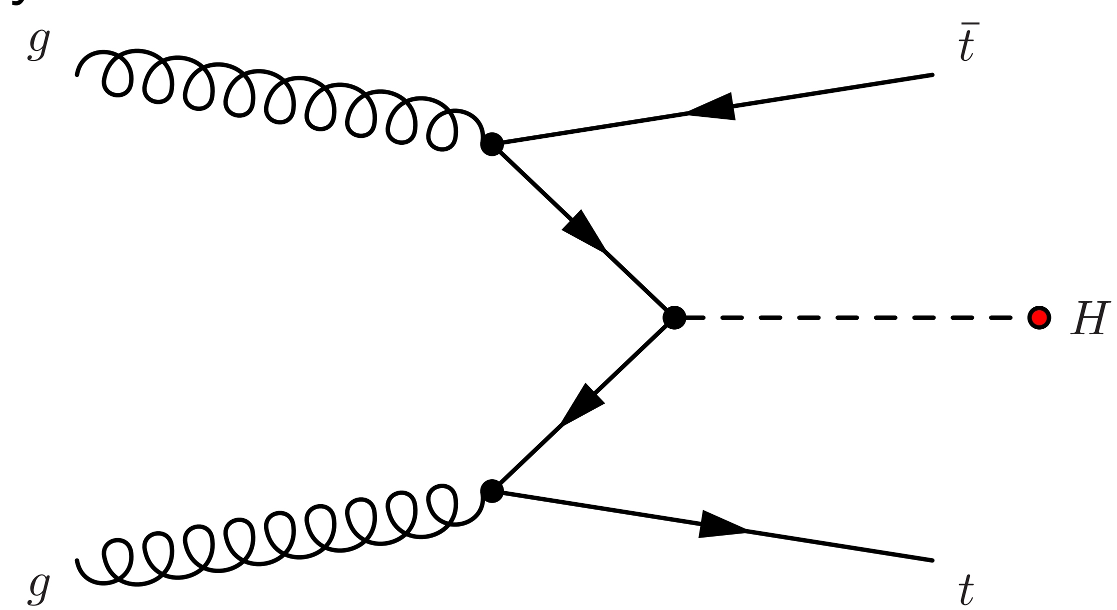

- **Experimental challenges**
  - Small signal cross section and overwhelming background
- Cross section increased with center-of-mass energy
  - ~ 3.9 increase in cross section for 13 TeV (sensitivity approaching Run 1)
    - Sensitive to potential new physics contributions
  - Dominant background from tt+XX
  - Similar increase in cross section
- Luminosity of 13 TeV data ~2.3-12.9 fb^{-1} (≈ 2.5 more statistics than 8 TeV)