Observation of $t\bar{t}H$ and measurement of CP structure of top Yukawa interaction with $H \rightarrow \gamma\gamma$

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LPC Physics Forum

$t\bar{t}H$ in the Standard Model

- Higgs production in association with a top quark-antiquark pair serves as probe to top Yukawa coupling, y_t:

$$\sigma_{t\bar{t}H} \propto y_t^2$$

- Cannot measure y_t through decay rates:
  - Higgs cannot directly decay into top quarks.
  - Indirect constraints come from $H \to \gamma\gamma$ decay and gluon fusion production (proceed through top quark triangle loops).
    - But, assumes that there are no BSM particles which also contribute to those loops.
- **$t\bar{t}H$ measurement is currently the best method to directly constrain y_t.**

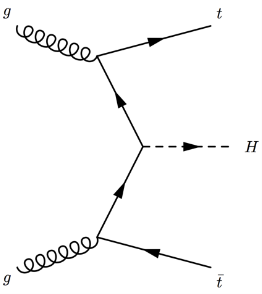


Figure 1: One of the tree-level diagrams for $t\bar{t}H$ production.

Why care about the top Yukawa coupling?

- y_t is an important SM measurement, but it is also compelling to study in context of BSM scenarios:
  - Precise measurements of y_t may give insights on presence of new physics.
  - From [1]:

    . . . at the present moment the only quantity which can help us to get an idea about the scale of new physics is the top Yukawa coupling y_t.

- Beyond y_t, we are also interested in the CP structure of the t-H coupling:
  - Interaction is CP-even in SM $\implies$ any non-zero CP-odd component would be an indication of new physics.
  - **CP structure of H couplings to fermions has never before been tested!**

[1] Bezrukov, F., and M. Shaposhnikov. "Why Should We Care About the Top Quark Yukawa Coupling?" Journal of Experimental and Theoretical Physics 120.3 (2015): 335?343. Crossref. Web.

Recent Results

- Observation of $t\bar{t}H$ production recently announced by CMS, using combination of multiple channels and Run 1 + Run 2 data [1].
- CMS [2] and ATLAS [3] recently announced measurements of signal strength and CP structure of $t\bar{t}H$ in the $H \to \gamma\gamma$ decay channel.

$$\text{signal strength} = \mu_{t\bar{t}H} = \frac{\sigma_{t\bar{t}H}^{obs}}{\sigma_{t\bar{t}H}^{SM}} \quad (1)$$

Summary of recent $t\bar{t}H$ results

Result	$\mathcal{L}$ (fb^{-1})	Obs. Signal Strength ($\mu_{t\bar{t}H}$)	Obs. (Exp.) Significance	Obs. (Exp.) CP-Odd Exclusion
CMS [2]	137	$1.38^{+0.36}_{-0.29}$	6.6 (4.7) σ	3.2 (2.6) σ
ATLAS [3]	139	1.4 ± 0.4	5.2 (4.4) σ	3.9 (2.5) σ

- In the following slides, I present the CMS result summarized in [2].

[1] CMS Collaboration, "Observation of $t\bar{t}H$ Production." Physical Review Letters 120.23 (2018)

[2] CMS Collaboration, "Measurements of $t\bar{t}H$ production and the CP structure of the Yukawa interaction between the Higgs boson and top quark in the diphoton decay channel", Submitted to *Phys. Rev. Lett.* arXiv:2003.10866 (March 2020).

[3] ATLAS Collaboration, "Study of the CP properties of the interaction of the Higgs boson with top quarks using top quark associated production of the Higgs boson and its decay into two photons with the ATLAS detector at the LHC", Submitted to *Phys. Rev. Lett.* arXiv:2004.04545 (April 2020).

H $\rightarrow \gamma\gamma$: The “Golden” Channel

The H $\rightarrow \gamma\gamma$ Channel

- Why study $t\bar{t}$H in the H $\rightarrow \gamma\gamma$ channel?
- Small branching fraction, $\mathcal{B}(\text{H} \rightarrow \gamma\gamma) \approx 0.2\%$
- But, many benefits:
  1. High signal-to-background ratio
  2. Excellent mass resolution
     - $\mathcal{O}(1\%)$ in most sensitive signal regions
  3. Small experimental systematic uncertainties
     - Thanks to clean signature and excellent performance of CMS ECAL

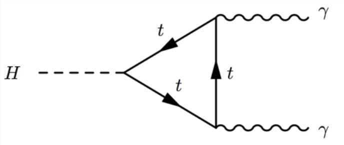


Figure 2: Feynman diagram of H $\rightarrow \gamma\gamma$ decay.

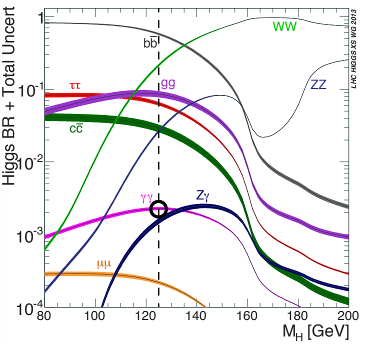


Figure 3: H branching fractions as a function of m_{H}. Taken from [1].

[1] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Derive Corrections with Z $\to ee$ Events

- Exploit similarities in electron/photon reconstruction to derive corrections & scale factors for simulation with tag-and-probe method in Z $\to ee$ events, including:
  1. **Selection efficiency SFs**
     - Measure difference in efficiencies between data and simulation for trigger efficiency and diphoton preselection (details) efficiency.
  2. **Photon scale & resolution**
     - Correct both the central value (scale) and width (resolution, implemented via smearing factor) of individual photon energies: details
  3. **Photon shower shape & isolation variable corrections**
     - Correct inputs to the photon identification BDT with a chained quantile regression method: details
     - Details of photon ID BDT: separate between prompt and fake photons (primarily $\pi_0 \to \gamma\gamma$).
- Some corrections derived in Z $\to \mu\mu\gamma$ events: details
- Differences between e/γ accounted for with systematic uncertainties.
  - Negligible impact on result ($< 1\%$).

Data-Driven Background Modeling

- Non-resonant backgrounds modeled with a fit to the $m_{\gamma\gamma}$ distribution in data.
  - **Fit in sidebands:** to avoid signal contamination in background model, perform fit with $m_{\gamma\gamma} \in [100, 115] \cup [135, 180]$ GeV, then extend pdf to region of interest.

- How to choose functional form?
  - Following discrete profiling method [1], fit a variety of functional forms & treat choice of function as a discrete nuisance parameter.
- Background MC only needed for developing analysis strategy, training MVAs, etc.

[1] Dauncey, P.D. et al. "Handling Uncertainties in Background Shapes: The Discrete Profiling Method." Journal of Instrumentation 10.04 (2015): P04015–P04015. Crossref. Web

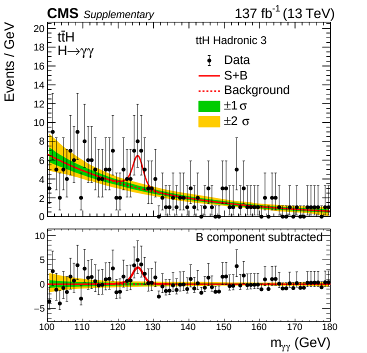


Figure 4: Background model with uncertainty.

Analysis Strategy

Overview of Analysis Strategy

- **Preselection:** Select for two high p_T, isolated photons and additional jets and leptons from top decays.
  - Split into two orthogonal channels: hadronic (0 leptons) and leptonic ($\geq$ 1 leptons).
- **MVAs:** for each channel, construct an MVA, "BDT-bkg", trained to separate $t\bar{t}H$ ($H \to \gamma\gamma$) from relevant SM backgrounds.
  - CP measurement utilizes an additional MVA, "$\mathcal{D}_{0-}$", trained to separate CP-even $t\bar{t}H$ from CP-odd $t\bar{t}H$.
- **Signal Region Definition:** use MVA score to define signal regions in each channel, with boundaries chosen to maximize expected sensitivity.
- **Signal Strength** ($\mu_{t\bar{t}H}$) **and CP Structure Extraction:** perform a simultaneous fit in all signal regions to the diphoton invariant mass spectrum ($m_{\gamma\gamma}$).

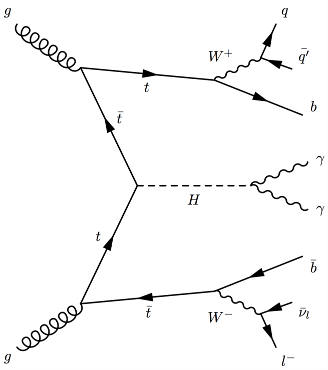


Figure 5: Semileptonic $t\bar{t}H$ event.

Preselection

- Events passing the diphoton preselection (details) may enter one of two orthogonal channels:

Hadronic Preselection

- $N_{\text{leptons}} == 0$
- $N_{\text{jets}} \geq 3,\ N_{\text{b-jets}} \geq 1$
- Loose cut on photon ID MVA (≥ -0.7)

Leptonic Preselection

- $N_{\text{leptons}} \geq 1$
- $N_{\text{jets}} \geq 1$
- Loose cut on photon ID MVA (≥ -0.7)

Big Picture

- Preselection is intentionally very loose, to ensure a high signal efficiency.
- Starting point for studying data/MC agreement and training MVAs to perform the "real" selection.

BDT-bkg

- For each channel train a binary classification BDT ("BDT-bkg") to distinguish between $t\bar{t}$H and other SM processes.
  - Signal: simulation of $t\bar{t}$H
  - Background: simulation of $\gamma\gamma$ + jets, $t\bar{t}$ + up to 2 photons, Z + γ, W + γ, etc and *data-driven description* of multi-jet and γ + jets.

- Features shown in red are inputs only to the Hadronic channel BDT-bkg, features shown in blue are inputs only to the Leptonic channel BDT-bkg.
- Limited description of photon/diphoton kinematics to prevent BDT from learning $m_{\gamma\gamma}$.

Input Features to BDTs

Category	Features		
Photon Kinematics	γ_1 $p_T/m_{\gamma\gamma}$	γ_1 η	γ_1 Pixel Seed Veto
	γ_2 $p_T/m_{\gamma\gamma}$	γ_2 η	γ_2 Pixel Seed Veto
	Max γ ID MVA	Min γ ID MVA	
Jet Kinematics	Jet 1 p_T	Jet 1 η	Jet 1 b-tag score
	Jet 2 p_T	Jet 2 η	Jet 2 b-tag score
	Jet 3 p_T	Jet 3 η	Jet 3 b-tag score
	Jet 4 p_T	Jet 4 η	Jet 4 b-tag score
	Max b-tag score	2nd max b-tag score	
	N_{jets}	H_T	
DiPhoton Kinematics	$p_T^{\gamma\gamma}/m_{\gamma\gamma}$	$Y_{\gamma\gamma}$	$\lvert\cos(\Delta\phi)_{\gamma\gamma}\rvert$
	$\Delta R_{\gamma\gamma}$	$\lvert\cos(\text{helicity angle}(\theta))\rvert$	
Lepton Kinematics	lepton p_T	lepton η	$N_{\text{leptons (tight ID)}}$
Event-level Kinematics	E_T^{miss}		

Data-Driven (γ) + jets Description

Need for MC Description of Background

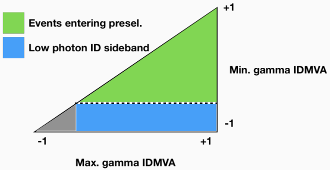
- MC description of background is used for:
  1. Training MVAs
  2. Optimization of signal regions
- Since **background model used for statistical analysis is derived from data**, it is not crucial to have good data/MC agreement!
- However, improving data/MC agreement will improve the MVA training and signal region optimization, leading to a more optimal result.

- **Challenge:** multi-jet and γ + jets events are main backgrounds ($> 50\%$) in the hadronic channel preselection, but poorly described by simulation.
  - Large underprediction of fake photons, very few raw simulated events.
  - Will lead to suboptimal MVA performance!

Data-Driven (γ) + jets Description

- **Challenge:** multi-jet and γ + jets events are main backgrounds ($> 50\%$) in the hadronic channel preselection, but poorly described by simulation.
- **Solution:** replace their simulation description with a data-driven description.

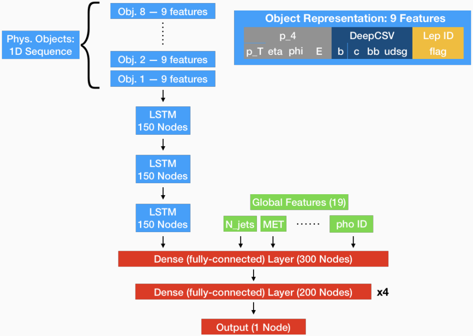
- Use events which fail the preselection cut on photon ID: "low photon ID sideband".
- Low photon ID sideband dominated ($> 95\%$) by multi-jet and γ + jets events.
- Replace minimum photon ID score for each event with a new value generated from a pdf for the photon ID of fake photons.
- Scale normalization appropriately and use in place of simulation samples.
  - Improves MVA performance $\implies$ ~5% improvement in expected significance for hadronic channel.



DNNs for Specific Backgrounds

- Each event is summarized into a set of (▸ high-level input features) – these form the basis for BDT training.
- Some information is lost in summarizing.
  - Can we exploit directly the low-level information in each event with a DNN?
  - Low-level information: four vectors of leading 8 jets and leptons.

- Consider jets and leptons as 1d sequence and use LSTM architecture.
- But, DNN only outperformed BDT when enough training events were available ($\gtrsim\approx 100$k).
- Train DNN on high-stats samples ($t\bar{t}H$ vs. $t\bar{t}+\gamma\gamma$, $t\bar{t}H$ vs. $\gamma\gamma$+jets) and use as additional input features to BDT.
- Improves MVA performance $\implies$ ~5% improvement in expected significance for hadronic channel.



Additional Improvements

Top Tagger BDT

- Binary classification BDT trained to distinguish jet triplets which come from a top quark (signal) from all other jet triplets (background).
  - Originally used in SUSY search for stop squarks [1].
- Addition to BDT-bkg results in $\sim$5% improvement in expected significance for hadronic channel.

Overlap Removal of $t\bar{t} + X$ Samples

- The $t\bar{t} + $jets and $t\bar{t} + \gamma +$ jets MadGraph samples can generate additional prompt photons when interfaced with pythia.
- Some, but not all, of this phase space is simulated by $t\bar{t} + \gamma\gamma \implies$ leads to double-counting some phase spaces unless carefully accounted for.

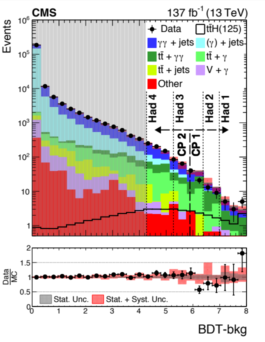
[1] CMS Collaboration, "Search for Direct Production of Supersymmetric Partners of the Top Quark in the All-Jets Final State in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV." Journal of High Energy Physics 2017.10 (2017). Crossref. Web.

Signal Region Definition with BDT-bkg

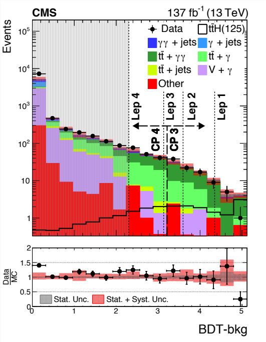
- Use the BDT-bkg distribution in each channel to define multiple signal regions.

- Boundaries for the 4 signal strength BDT-bkg categories per channel shown with *thinly* dashed lines.
- Boundaries for the 2 CP structure BDT-bkg categories per channel shown with **thickly** dashed lines.
- Each CP structure BDT-bkg category is split into an additional 3 categories sensitive to CP even vs. CP odd hypotheses.
- Boundaries chosen to maximize the expected sensitivity of each measurement.

Hadronic channel



Leptonic channel



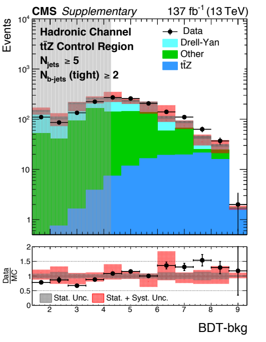
- Data and bkg MC in $m_{\gamma\gamma} \in [100, 115] \cup [135, 180]$ GeV

Validation of BDT-bkg in $t\bar{t}Z$

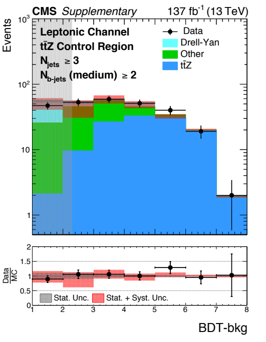
- Perform validation of BDT-bkg by studying data/MC agreement in dedicated control region targeting $t\bar{t}Z$ ($Z \to ee$).
  - $t\bar{t}H$ and $t\bar{t}Z$ have similar kinematics $\implies$ both should be isolated at high BDT-bkg scores.

- Control region definition:
  1. Diphoton preselection (details) with inverted CSEV requirement.
  2. Require m_{ee} within 10 GeV of m_Z.
  3. Additional jet/b-jet requirements for each channel.
- Data and simulation agree within uncertainties at high BDT-bkg (high $t\bar{t}Z$ purity).

Hadronic channel



Leptonic channel



Results

Systematic Uncertainties

- Dominant uncertainties and approximate impacts on $\mu_{\mathrm{t\bar{t}H}}$ shown below.
  - Impact of statistical uncertainty on signal strength measurement is $\sim$30%.

Theory Uncertainties

8% QCD renormalization & factorization scale uncertainty

4% Parton distribution function (PDF) uncertainties

2% $\mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)$, α_s uncertainties

Experimental Uncertainties

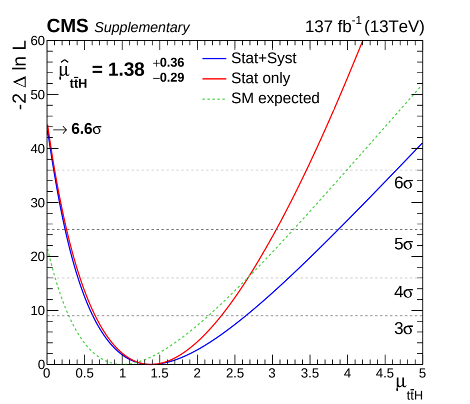
4% Shape of b-tagging discriminant

2% Integrated luminosity

1% Shape of photon ID MVA score, jet energy corrections & resolution uncertainties

Signal Strength

- Observed signal strength $\mu_{t\bar{t}H} = 1.38^{+0.36}_{-0.29}$ consistent with SM expectation.
  - Measured $\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = 1.56^{+0.34}_{-0.32}$ fb.
  - SM Prediction $\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = 1.13^{+0.08}_{-0.11}$ fb.
- Observed (expected) significance: 6.6σ (4.7σ).
- $m_{\gamma\gamma}$ distributions for each of the 8 signal regions available in ▸ backup.



CP Structure

Definition of $|f_{\text{CP}}^{\text{Htt}}|$

- The Htt amplitude can be expressed in terms of a CP-even and CP-odd component:

$$\mathcal{A}(\text{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t, \qquad (2)$$

- with κ_t and $\tilde{\kappa}_t$ the CP-even and CP-odd components, respectively.
    - In SM, $\kappa_t = 1$, $\tilde{\kappa}_t = 0$.
- The parameter we actually measure is the fractional magnitude of the CP odd component:

$$f_{\text{CP}}^{\text{Htt}} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\text{sgn}(\tilde{\kappa}_t/\kappa_t) \qquad (3)$$

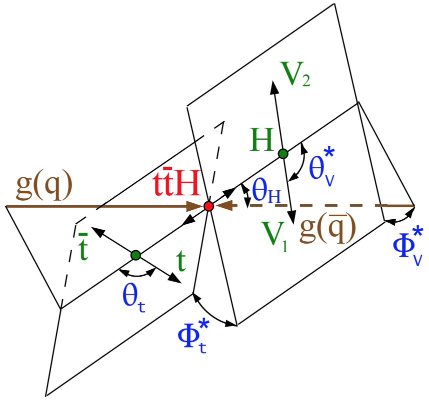
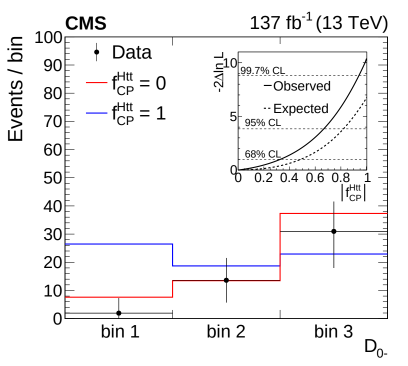


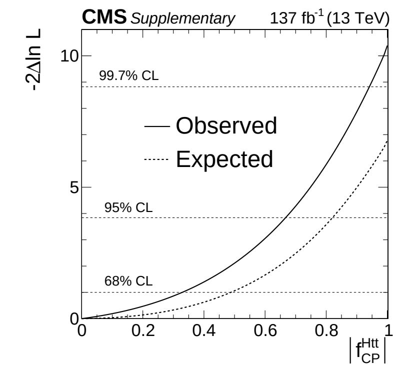
Figure 6: Taken from [1].

[1] Gritsan, Andrei V. et al. "Constraining Anomalous Higgs Boson Couplings to the Heavy-Flavor Fermions Using Matrix Element Techniques." Physical Review D 94.5 (2016): Crossref. Web.

CP Structure

- Observed $|f_{\text{CP}}^{\text{Htt}}| = 0.00^{+0.33}$ consistent with SM expectation.
- Observed (expected) significance for exclusion of pure CP-odd hypothesis ($f_{\text{CP}}^{\text{Htt}} = 1$): 3.2σ (2.6σ).
- $m_{\gamma\gamma}$ distributions for each of the 12 signal regions available in ▸ backup.





Conclusions & Future Prospects

Conclusions

- **First observation of $t\bar{t}H$ in a single decay channel.**
  - Background-only hypothesis excluded with a significance of 6.6σ.
  - Observed signal strength slightly higher than SM prediction (but still consistent): $\mu_{t\bar{t}H} = 1.38^{+0.36}_{-0.29}$.
- **First measurement of the CP structure of the top Yukawa interaction.**
  - Pure CP-odd hypothesis excluded with a significance of 3.2σ.
- Properties of the top Yukawa coupling consistent with SM expectation.

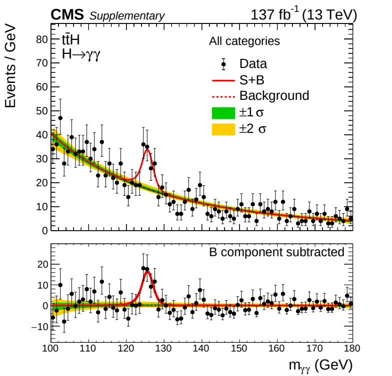
Future Prospects

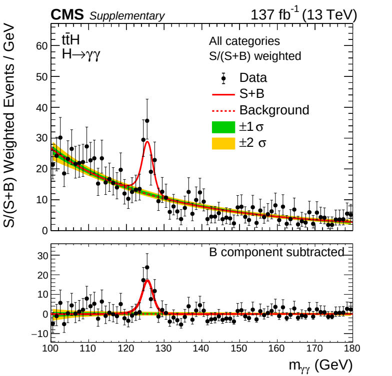
- **Run 3 measurements will benefit from increased luminosity.**
  - Measurements of $t\bar{t}$H signal strength and CP structure both statistically dominated.
  - Next set of measurements will shed more light on consistency of the top Yukawa coupling with the SM.
- **Components of analysis strategy applicable to other H $\rightarrow \gamma\gamma$ studies**.
  - Many developments improved the sensitivity of this analysis:
    1. Data-driven description of QCD/γ + jets backgrounds
    2. Deep neural networks for exploiting low-level information in each event
    3. BDT for top reconstruction
  - Core ideas can be reused in future H $\rightarrow \gamma\gamma$ studies!
    - Data-driven description of QCD/γ + jets likely to be used in BDT training for other production modes in upcoming CMS H $\rightarrow \gamma\gamma$ results.
    - Principles of DNN and dedicated MVAs for resolved heavy object reconstruction can also be reused.

Backup

Observed $m_{\gamma\gamma}$ Distributions

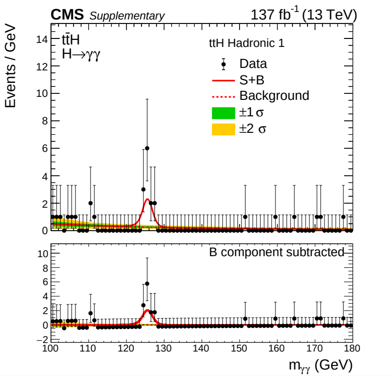
Signal Strength Categories: All

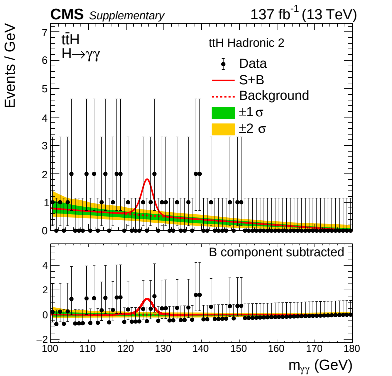




Observed $m_{\gamma\gamma}$ Distributions

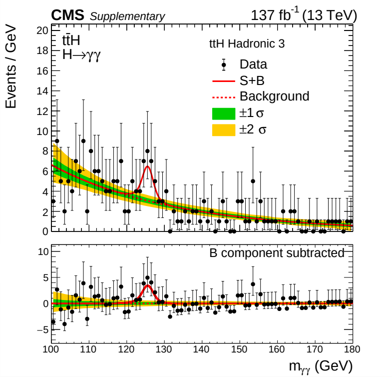
Signal Strength Categories: Hadronic

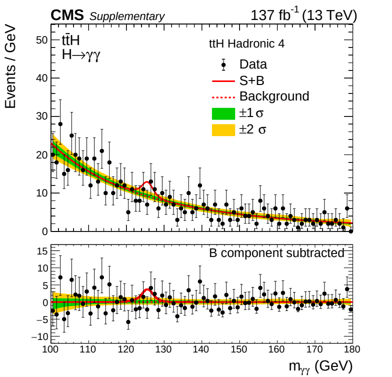




Observed $m_{\gamma\gamma}$ Distributions

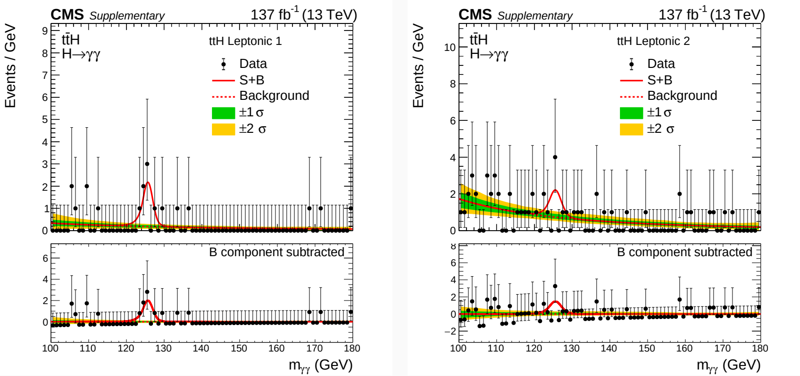
Signal Strength Categories: Hadronic





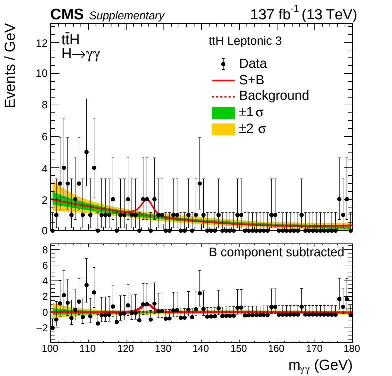
Observed $m_{\gamma\gamma}$ Distributions

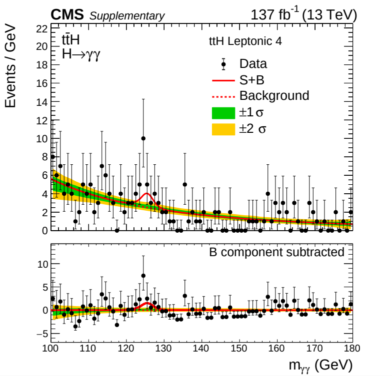
Signal Strength Categories: Leptonic



Observed $m_{\gamma\gamma}$ Distributions

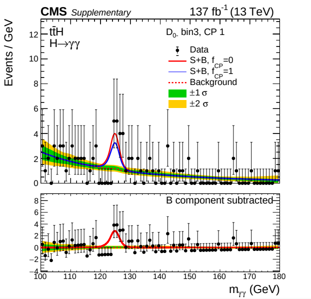
Signal Strength Categories: Leptonic

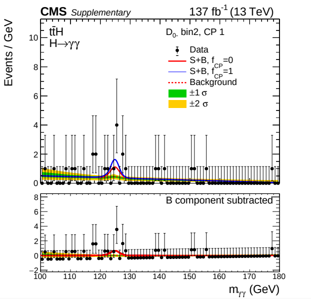


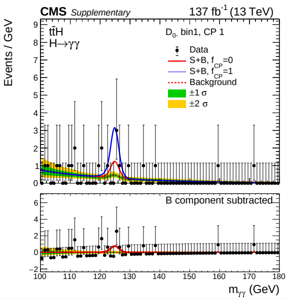


Observed $m_{\gamma\gamma}$ Distributions

CP Structure Categories

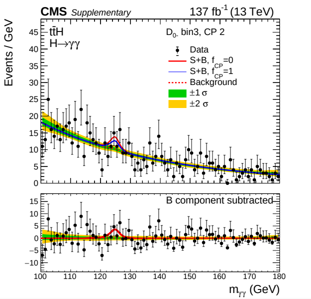


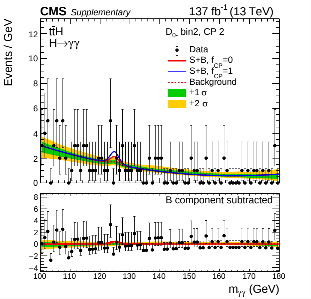


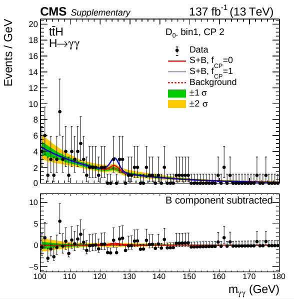


Observed $m_{\gamma\gamma}$ Distributions

CP Structure Categories

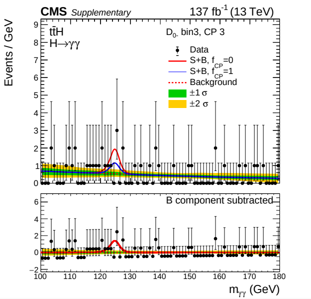


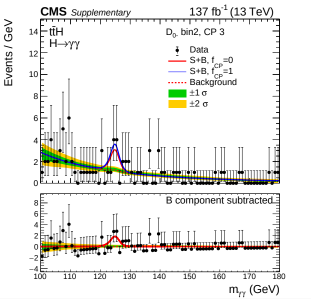


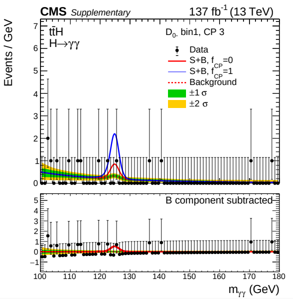


Observed $m_{\gamma\gamma}$ Distributions

CP Structure Categories







Observed $m_{\gamma\gamma}$ Distributions

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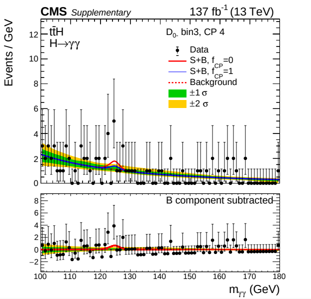

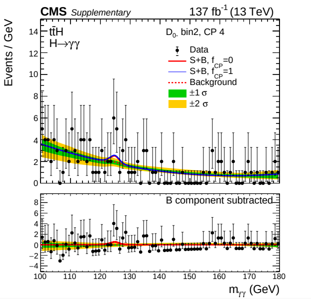

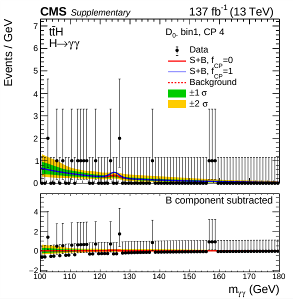

HLT Trigger

- HLT Triggers required in data:
  - 2016: `HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90*`
  - 2017/2018: `HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90*`
- Efficiency measured in bins of E_T, R_9, and η using tag and probe in Z $\rightarrow$ ee events.
  - Typical efficiencies are $> 95\%$.

Physics Objects

- **Vertex**: Use vertex selected by standard CMS vertex selection algorithm.
  - Found to be within 1cm of the true vertex for $> 99\%$ of t$\bar{\text{t}}$H events (see `HIG-18-018`).
- **Jets**
  - Reconstructed with anti-k_T algorithm with radius parameter 0.4.
  - Require $p_T > 25$ GeV, $|\eta| < 2.4$, apply loose jet ID following JetMET prescription, latest recommended JECs applied.
  - b-**Tagged Jets**: Use DeepCSV algorithm with reshaping correction applied to simulation.
  - Must not overlap with photons or leptons: $\Delta R > 0.4$
- **Leptons**
  - **Electrons**
    - Pass medium working point for EGamma POG MVA ID (with iso.).
    - $p_T > 10$ GeV, $|\eta| < 2.4$, must not have $|\eta| \in [1.4442, 1.566]$.
    - $m_{\gamma e}$ must not be within 5 GeV of m_Z.
  - **Muons**
    - Pass medium working point for Muon POG ID, rel-iso less than 0.25.
    - $p_T > 5$ GeV, $|\eta| < 2.4$
  - Both e and μ required to have $\Delta R(l, \gamma) > 0.2$.

DiPhoton Preselection

- Applied in analysis selection and also used for deriving corrections for photons:
  1. Leading (subleading) $p_T > 35(25)$ GeV, $|\eta| < 2.5$, not in EB-EE gap
  2. Pass conversion-safe electron veto
  3. Additional requirements shown in table (intended to mimic trigger):

	H/E	$\sigma_{i\eta i\eta}$ (5x5)	R_9 (5x5)	$\mathcal{I}_{\text{ph}}$ [GeV]	$\mathcal{I}_{\text{tk}}$ [GeV]
Barrel, $R_9 > 0.85$	< 0.08	–	> 0.5	–	–
Barrel, $R_9 \leq 0.85$	< 0.08	< 0.015	> 0.5	< 4.0	< 6.0
Endcap, $R_9 > 0.9$	< 0.08	–	> 0.8	–	–
Endcap, $R_9 \leq 0.9$	< 0.08	< 0.035	> 0.8	< 4.0	< 6.0

- Preselection efficiency measured with tag and probe in Z $\rightarrow$ ee events.
  - Ranges from $\sim$97% (EB, high R_9, SF $\approx$ 1.03) to $\sim$50% (EE, low R_9, SF $\approx$ 1.03) (reference)
- Electron veto efficiency measured in Z $\rightarrow \mu\mu\gamma$ events.
  - Ranges from $\sim$99% (EB, high R_9, SF $\approx$ 1.00) to $\sim$96% (EE, low R_9, SF $\approx$ 0.97)

Photon Scales & Smearings

- Challenges – even after applying photon energy regression trained on simulation (particle gun):
    1. Energy scale for e/γ is different between data and simulation.
    2. Energy resolution for e/γ is different between data and simulation.
- How to address? In Z $\rightarrow$ ee events, derive:
    - Photon energy scales: correct central value (bins of Run # $\times$ $R_9 \times \eta \times$ Gain)
    - Photon smearings: correct energy resolution (bins of η (2016, 2017), bins of $R_9 \times \eta$ (2018))

Photon Shower Shape & Isolation Corrections

- Variables describing the EM shower of photons in the ECAL show disagreement between data and simulation.
- Use a chained quantile regression method to correct the shower shape variables in simulation to match those of data.
  - Isolation variables corrected using stochastic correction method (details).
  - Important to correct as they are input features to the photon ID MVA.
- Systematic uncertainty covers remaining discrepancy between data and MC.

Photon ID MVA

- Dedicated BDT trained to distinguish between prompt photons and fake photons from jets (mainly $\pi_0 \rightarrow \gamma\gamma$).
    - Trained on γ + jets simulation.
    - Inputs include shower shape variables, isolation variables, etc. List (here).
- Loose cut on photon ID MVA applied on top of diphoton preselection, differences in efficiency between data and simulation accounted for with scale factor.

Photon ID MVA

- Inputs to the photon ID MVA include: (red = endcap only)
    1. Full 5x5 R_9
    2. Full 5x5 $\sigma_{i\eta i\eta}$
    3. η width
    4. ϕ width
    5. Covariance ($i\eta i\phi$)
    6. S4 ratio (E2x2 / E5x5)
    7. PF Photon Isolation
    8. Charged isolation wrt chosen vertex
    9. Charged isolation wrt worst vertex
    10. Photon supercluster η
    11. Photon supercluster E
    12. ρ
    13. ES effective sigma (preshower spread)
    14. ES energy / supercluster raw energy

Derive Corrections with Z $\rightarrow \mu\mu\gamma$ Events

- Similarity between e/γ useful, but also presents a challenge: electrons can be incorrectly reconstructed as photons.
- Two handles on e/γ discrimination:
  1. Conversion-safe electron veto (CSEV)
  2. Pixel seed veto (PSV)
- Both reject events in which there is evidence of a track compatible with the photon supercluster.
  - CSEV is much looser than PSV.
  - CSEV applied on all events, PSV used as an input to BDTs for signal-background discrimination.
- Differences in efficiency between data and simulation derived in Z $\rightarrow \mu\mu\gamma$ events.