Measurements of Higgs boson properties in the diphoton decay channel at √s =13 TeV

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on behalf of the CMS collaboration

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WUHAN
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Outline

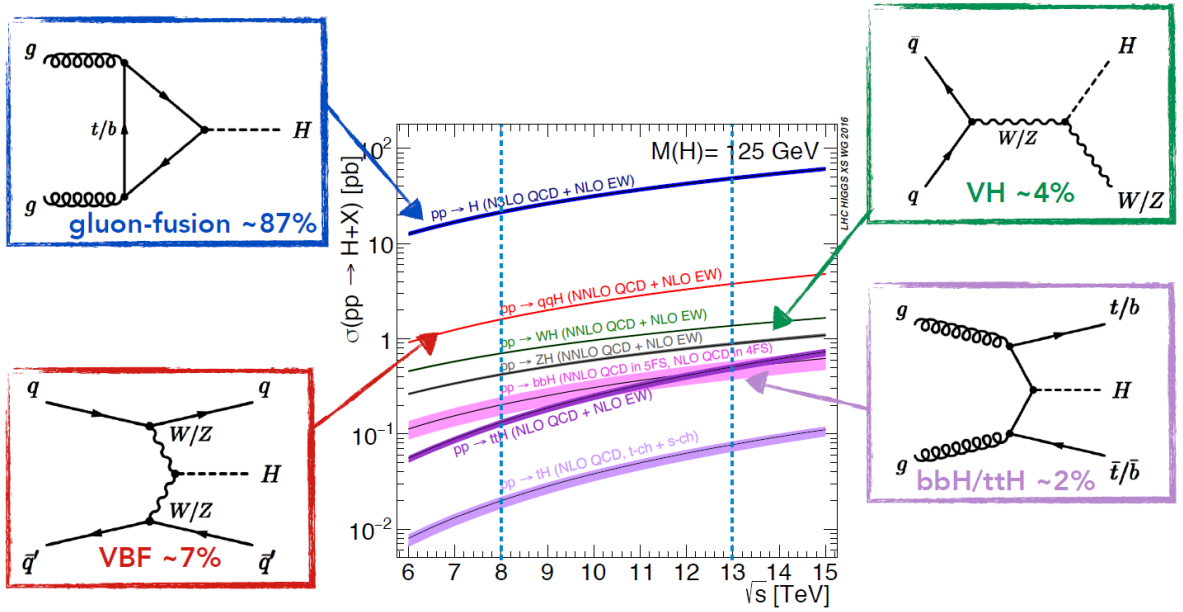
- **SM Higgs production and H→γγ decay**
- **Measurements with 2016 dataset**

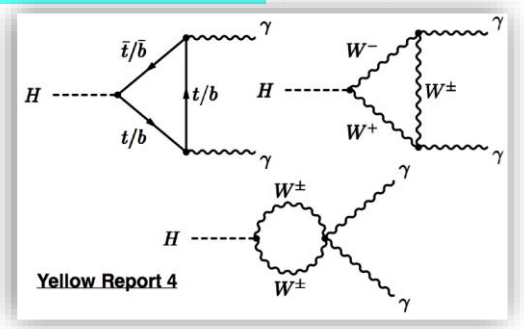
  Mass, signal strength and couplings : JHEP 11 (2018) 185 (Published on November 29, 2018)

  Fiducial cross section measurement : HIG-17-015 (PAS-PUB)
- **ttH→γγ measurement with 2017 dataset and combination with 2016 dataset:** HIG-18-018

- **Summary**

Higgs production and decay into γγ

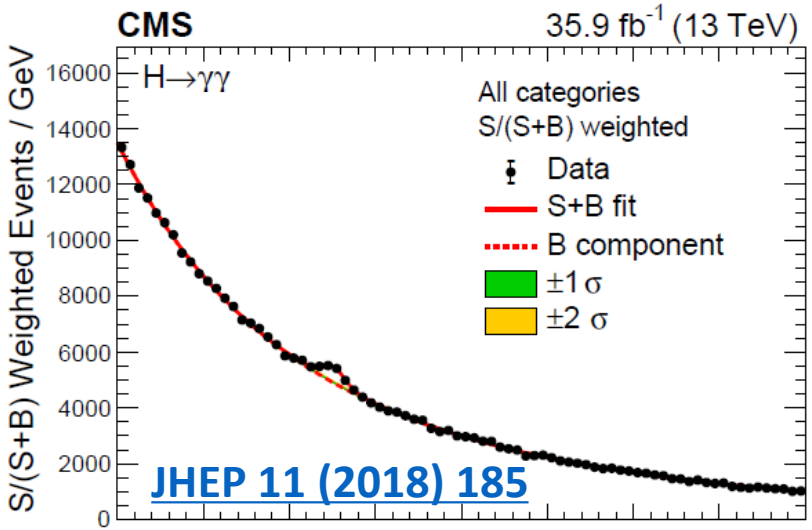




- **H→γγ : loop-induced decay, sensitive to BSM -** *new physics might contribute to the loop*
- **Small branching fraction (~0.2%)** but **excellent mass resolution (1-2%)**
  - ✓ Clean final state with two highly **energetic and isolated photons**
  - ✓ Final state can be **fully reconstructed** with **high resolution**

- **Significant increase in production cross section from 8 TeV (Run1 2012) to 13 TeV (Run2)**
  - ✓ $\sigma_{13TeV}/\sigma_{8TeV}$ of Higgs: ggH ~2.3, VBF ~2.4, VH ~2.0 and **ttH ~3.9**
  - ✓ *background increased by a factor of ~2*

- **H→γγ gives access to all the production modes**



- **Large backgrounds**
  - ✓ Continuum γγ (irreducible)
  - ✓ Fakes from γj and jj (reducible)

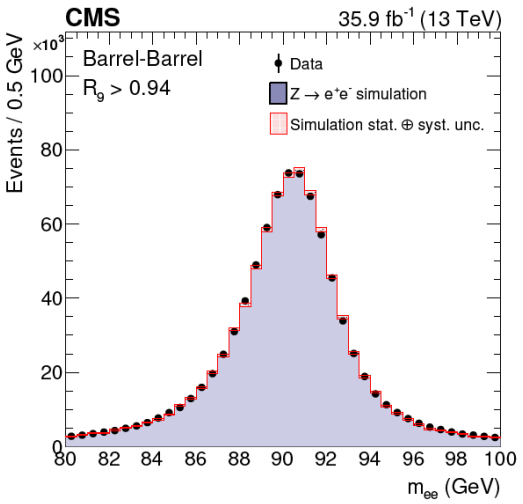
- **Search for a narrow peak on a falling background in mass distribution**

Analysis strategy

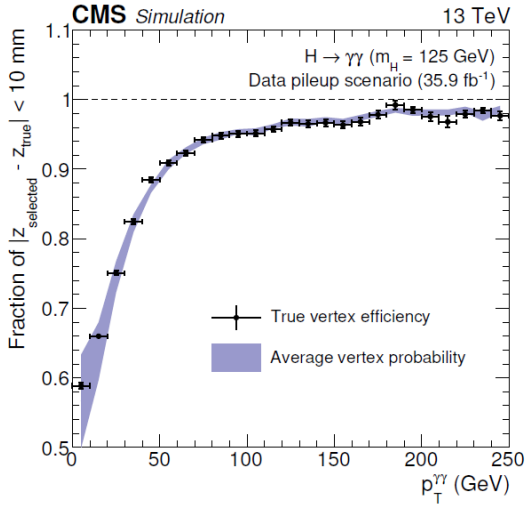
Analysis flow

- Data & MC
- Trigger
- Photon reconstruction and energy calibration
- Preselection
- Vertex identification and probability estimation
- Photon identification
- Diphoton BDT
- Selections of event categories : exclusive-/untagged
- Signal/bkg modeling
- Statistical analysis with “combine”
- **Results**

Photon Energy scale and resolution validated with Z→ee



BDT for vertex identification : validated on Z→μμ and γ+j



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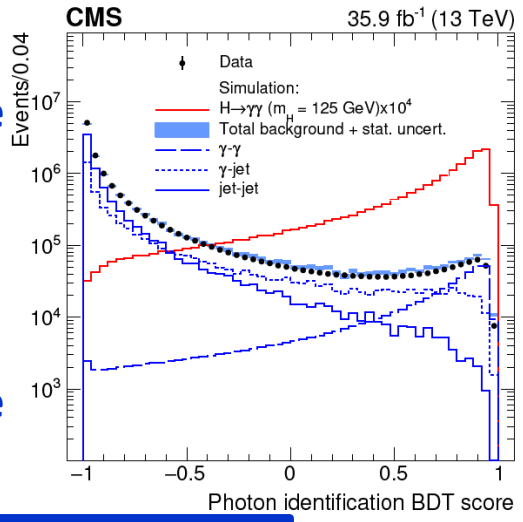
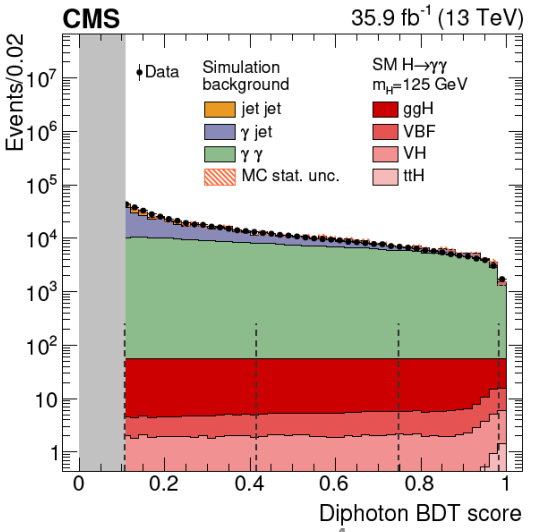
Photon ID BDT to discriminate prompt/fake photons



Diphoton BDT to discriminate signal and bkg

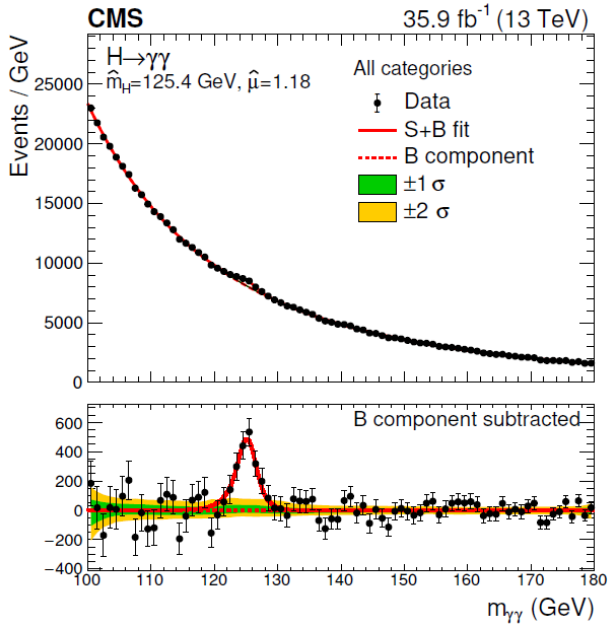


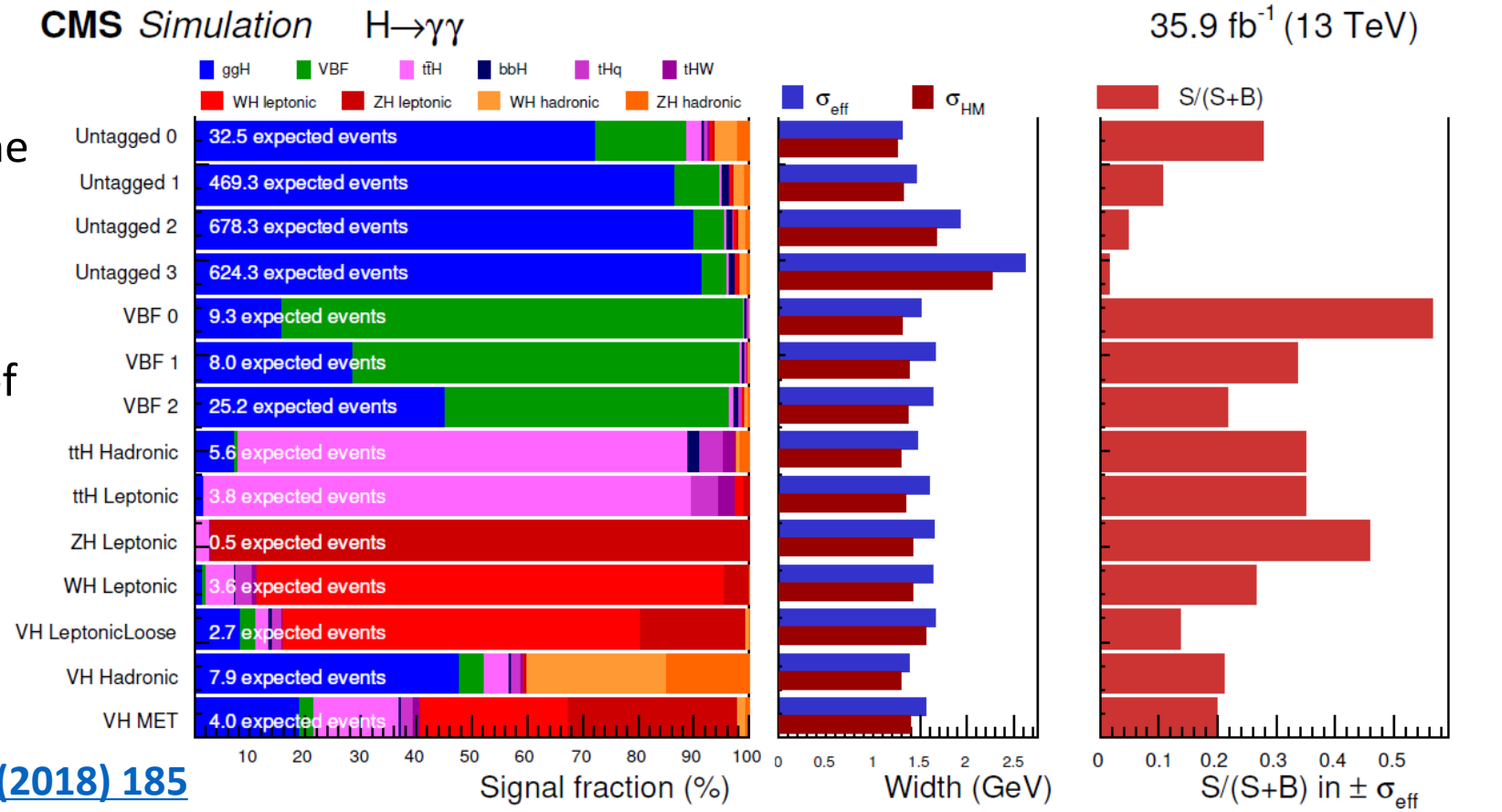
Common tools for different H→γγ measurements

Event categorization

- **Events categorized** into **14 classes according to production mechanism, mass resolution and S/B**, to improve the analysis sensitivity

- Extraction of signal through a **simultaneous maximum-likelihood** fit of **di-photon invariant mass** spectrum in ***each event class***





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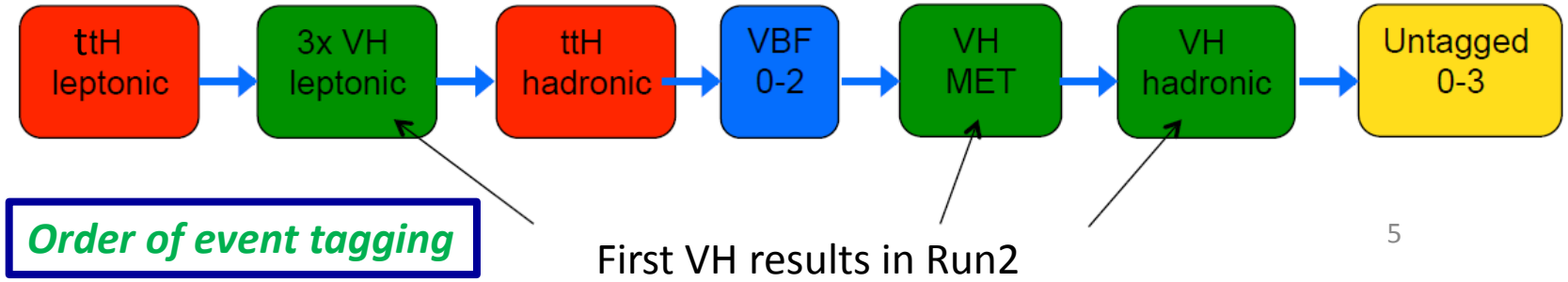
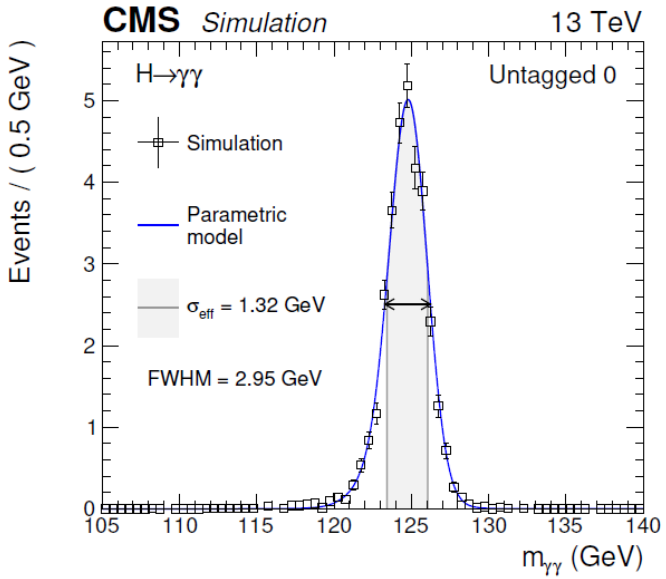
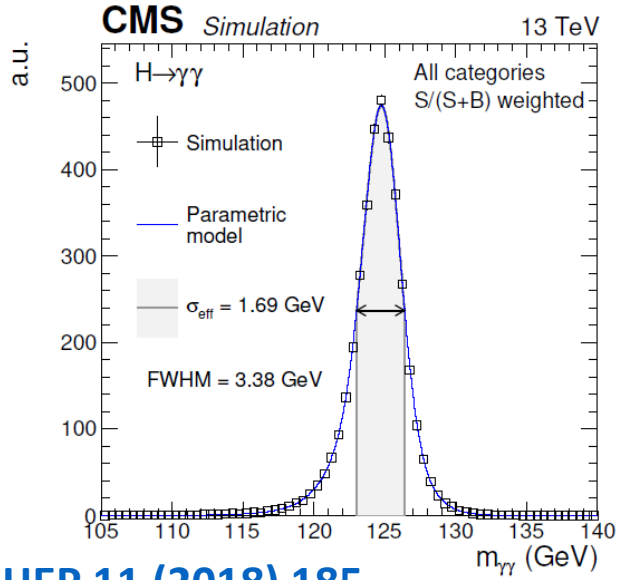


Signal and background parameterizations

- Fully parametric **signal** model from **MC** simulation
  - ✓ *sum of **n-Guassian** functions (n<=5)*
  - ✓ physical nuisances allowed to float
- Background model **data driven**
  - ✓ For each event category, use **different functional forms** (sums of ***exponentials***, sums of **power law** terms, ***Laurent*** series and ***polynomials***)
  - ✓ Background functional forms treated as **discrete nuisance parameter** in final minimization: “envelope” method or *discrete profiling method* [2015 JINST 10 P04015]





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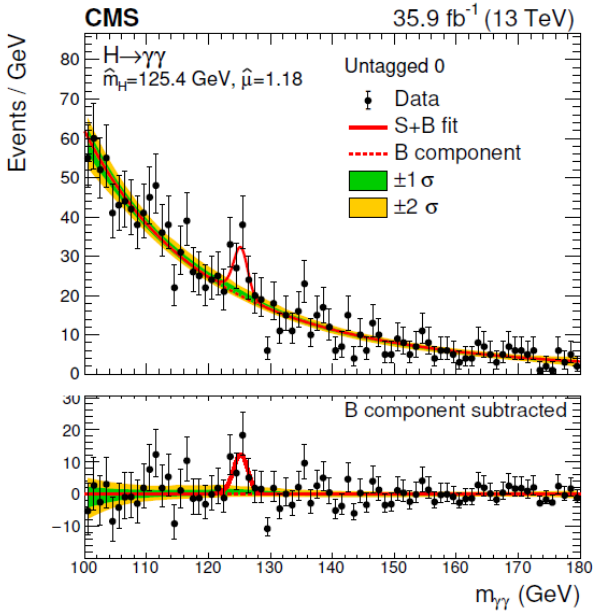
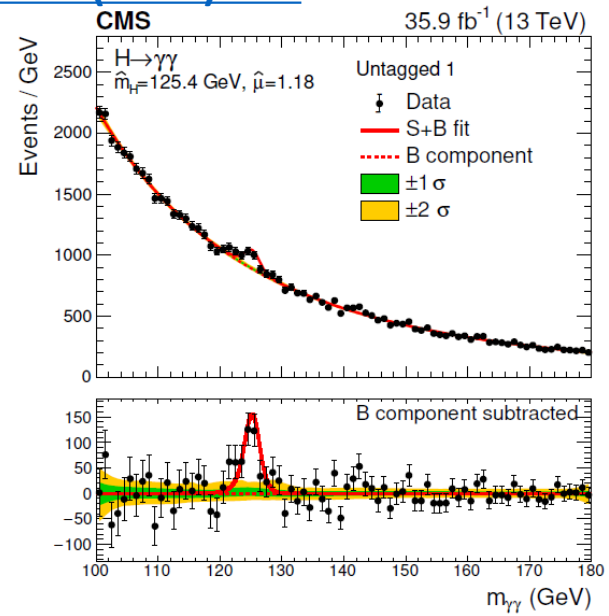
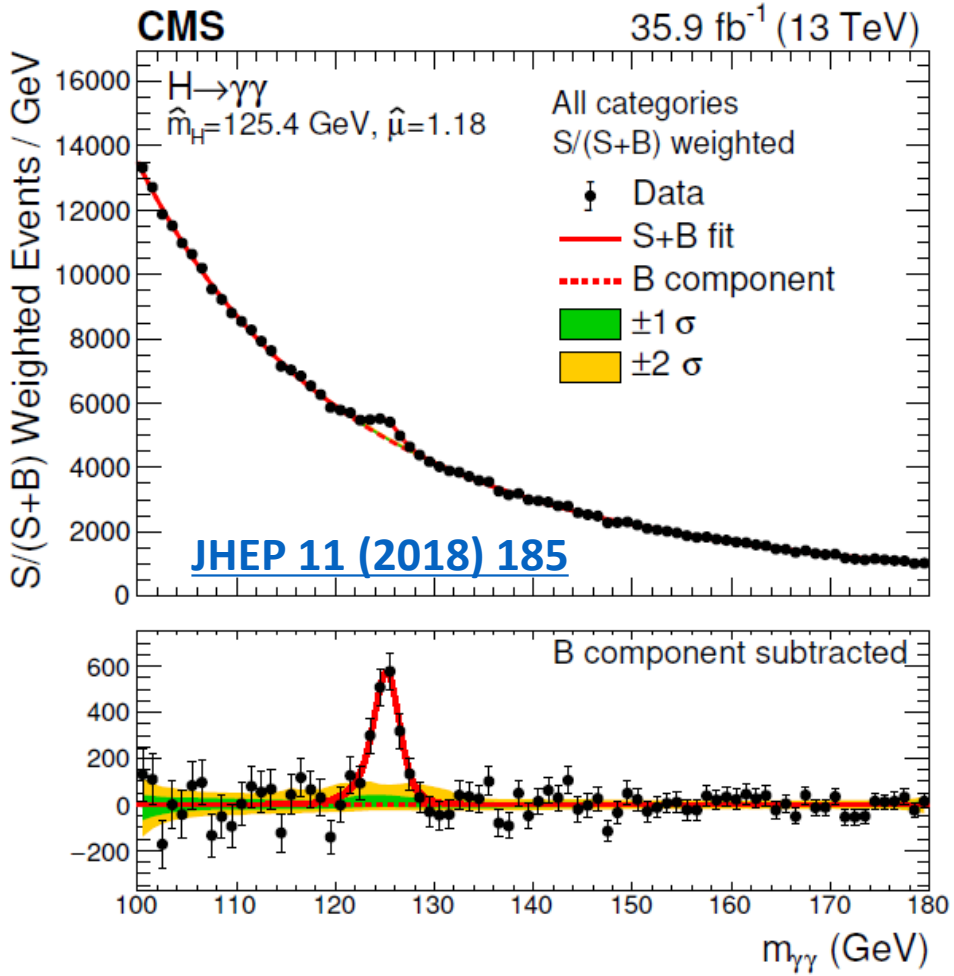
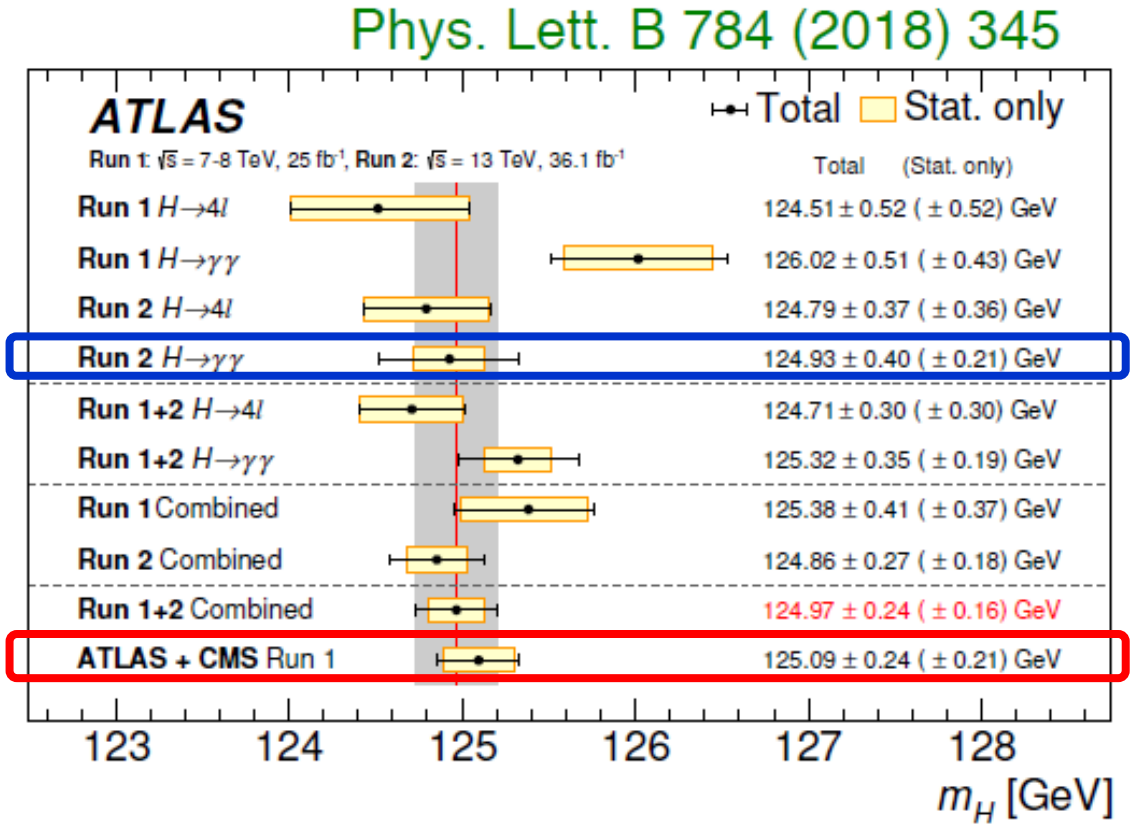




Mass

125.4 ± 0.3 GeV = 125.4 ± 0.2(stat.) ± 0.2(syst.) GeV





All categories (weighted by their sensitivity)

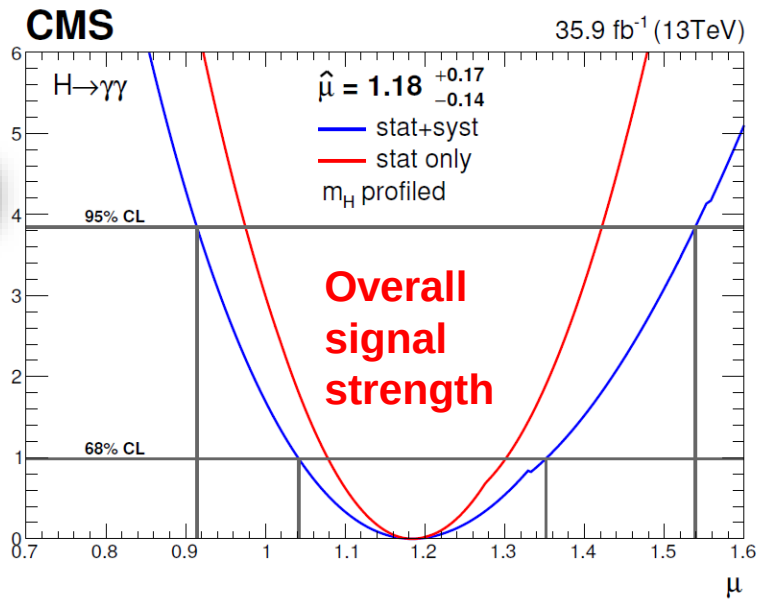
Signal strength

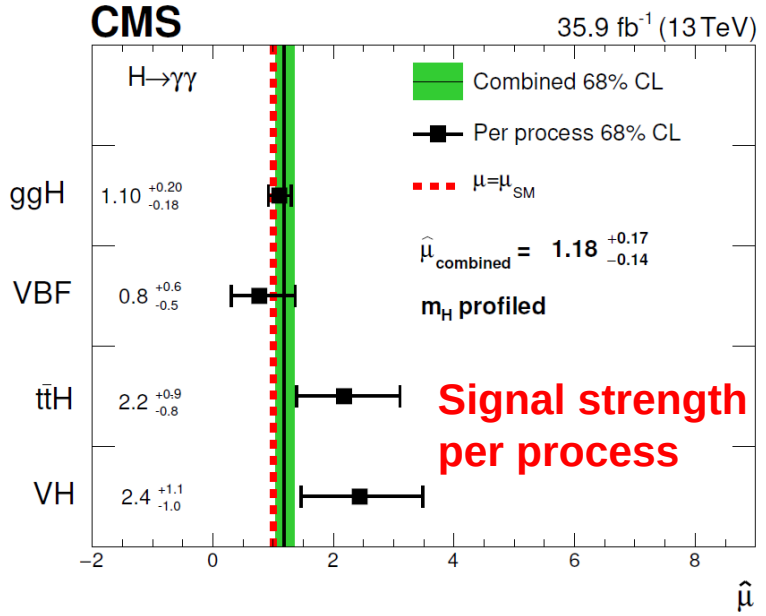
- **Overall signal strength**

$$\hat{\mu} = 1.18^{+0.17}_{-0.14} = 1.18\,^{+0.12}_{-0.11}\,(\text{stat})^{+0.09}_{-0.07}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{theo})$$

- Production mechanism **signal strengths** are SM-consistent

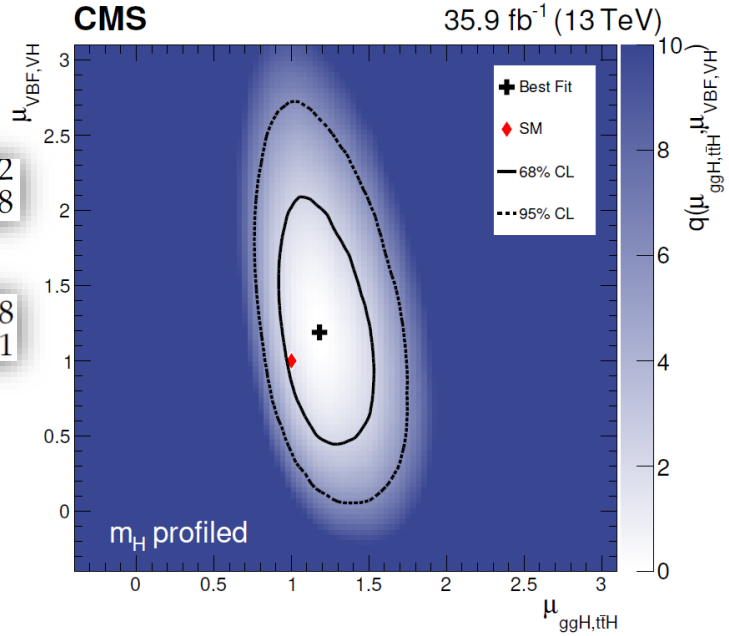
- **Signal strengths** measured in bosonic and fermionic parts are also SM-consistent

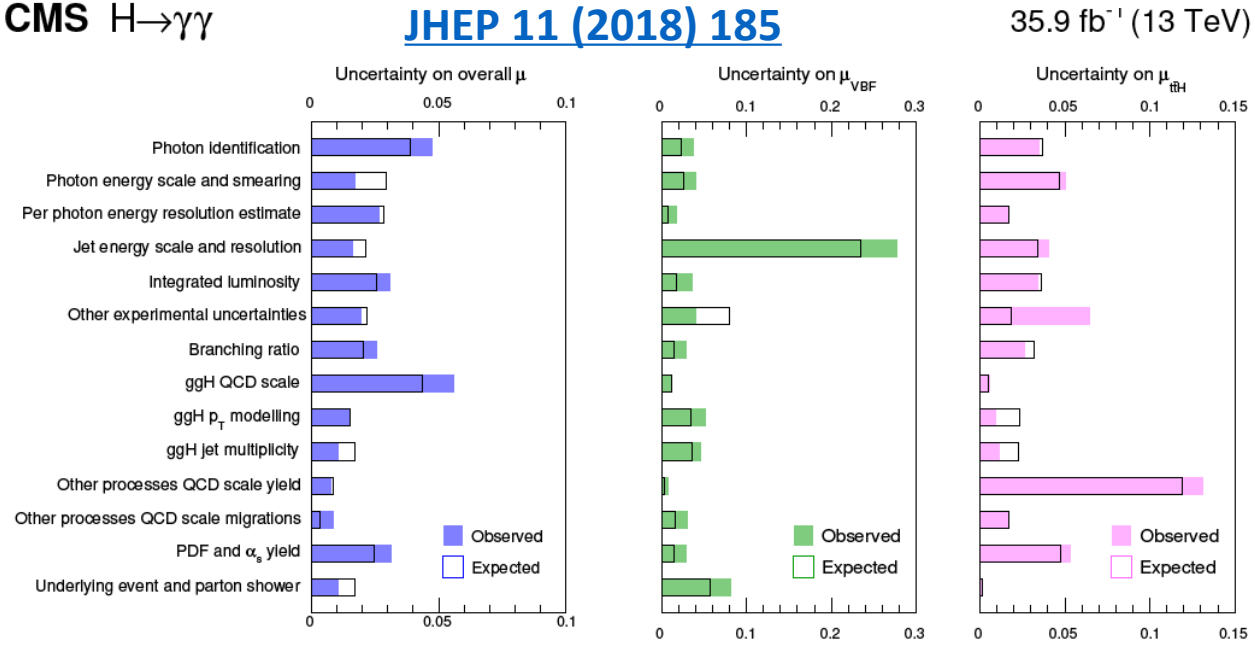




$$\hat{\mu}_{\mathrm{ggH,t\bar{t}H}} = 1.19^{+0.22}_{-0.18}$$

$$\hat{\mu}_{\mathrm{VBF,VH}} = 1.21^{+0.58}_{-0.51}$$



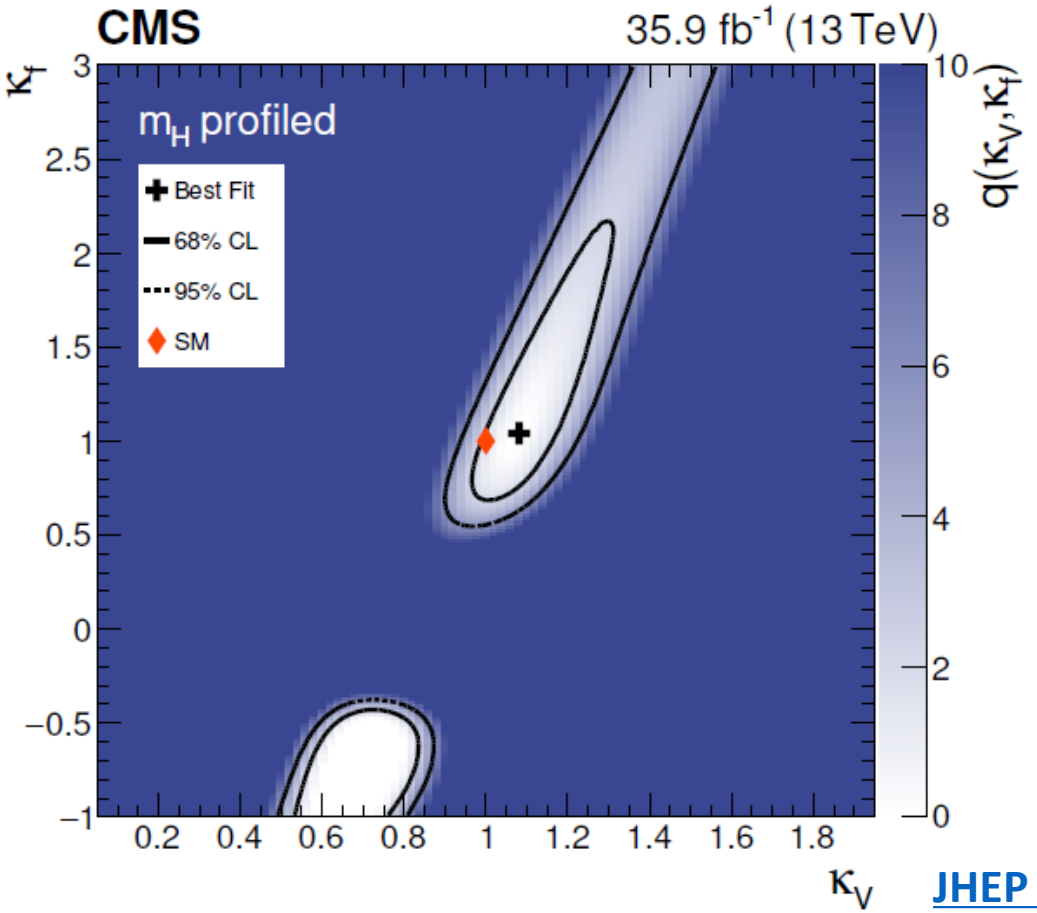


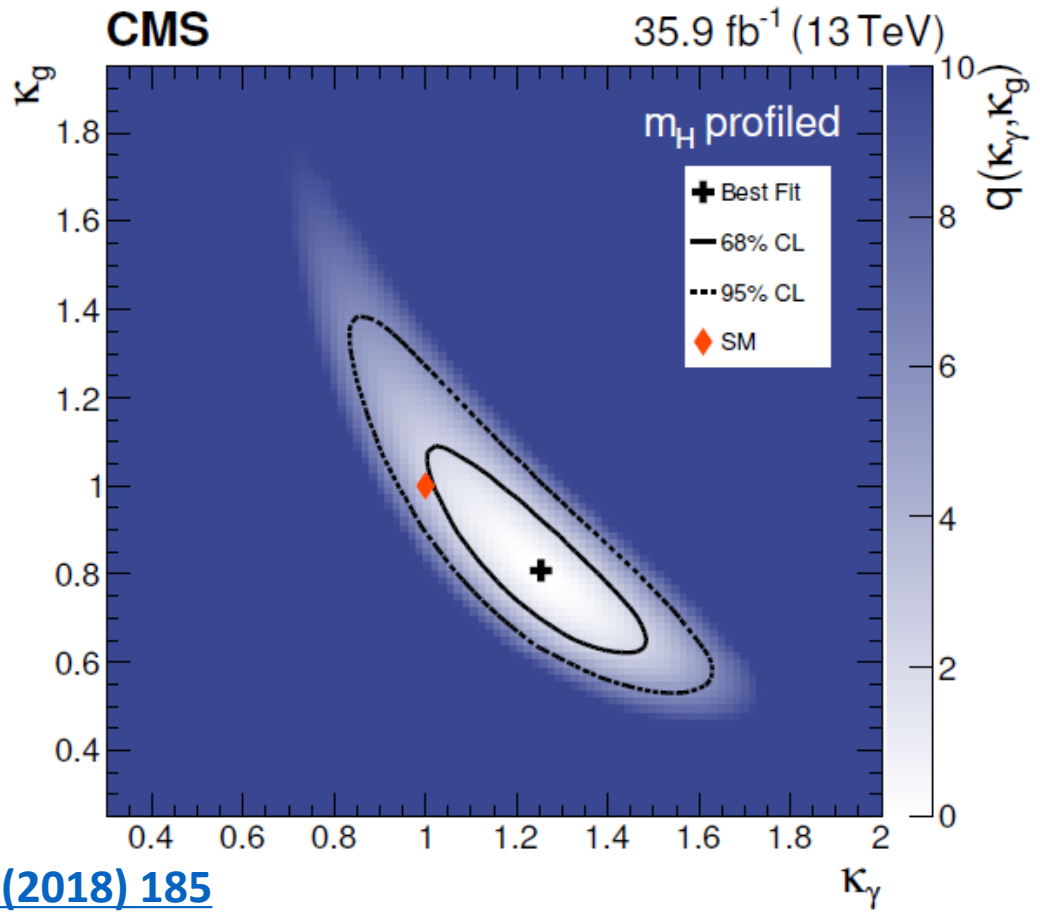
Coupling constants

Measurements of **coupling modifiers** to **vector bosons** and **fermions** (k_V, k_f) and to **photons** and **gluons** (k_γ, k_g)

$$\sigma(i \to H \to f) = \kappa_i^2 \sigma_i^{\mathrm{SM}} \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}}{\kappa_H^2 \Gamma_H^{\mathrm{SM}}}$$

Compatible with SM





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Cross section

Higgs Simplified Template Cross Section (STXS) :

Maximize the measurement precision and the sensitivity to BSM contributions

Cross section **split by production mode**

Cross section divided **in exclusive regions** of phase space (bins)

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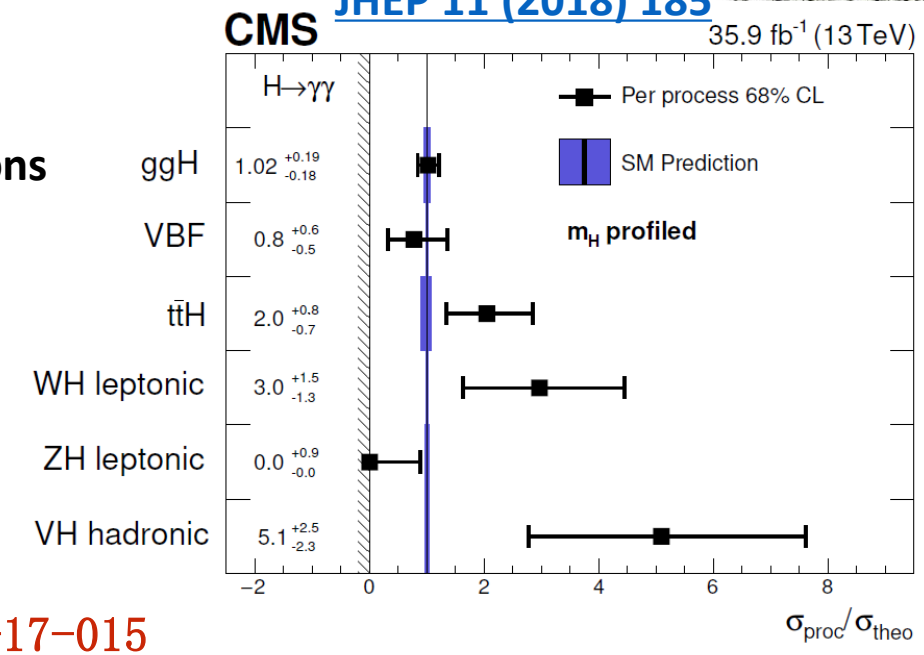


Fiducial cross section :

fiducial volume to **minimize model dependency**

3 untagged event categories based on expected **mass resolution**

Differential fiducial cross sections for **pT(γγ)** and **N(jets)**:

MADGRAPH aMC@NLO, **ggH powheg** + **other modes (VBF+VH+ttH, "HX") from MADGRAPH aMC@NLO**

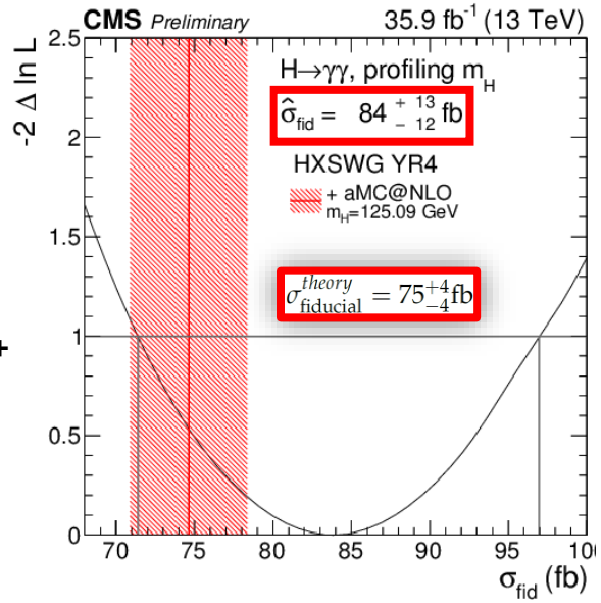
Fiducial volume:

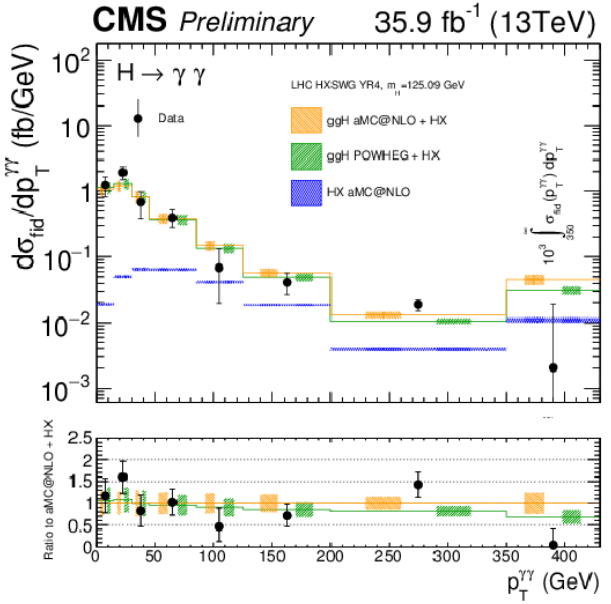
$p_{T1}/m_{\gamma\gamma} < 1/3$, $p_{T2}/m_{\gamma\gamma} < 1/4$

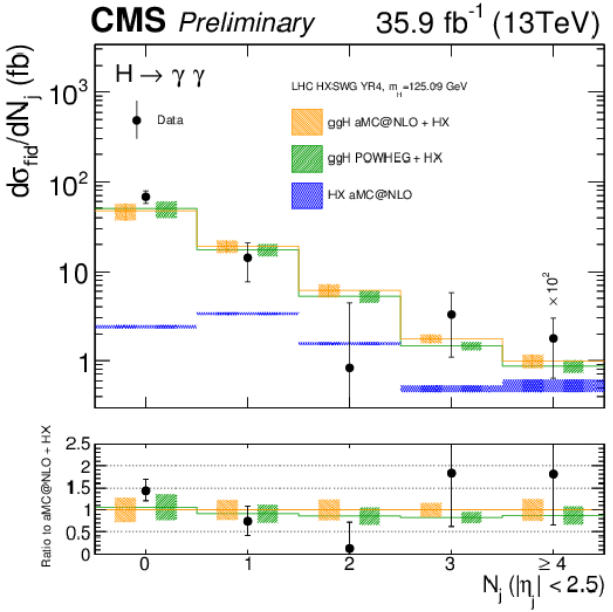
$|\eta_{1,2}| < 2.5$

$Iso_{gen1,2} < 10$ GeV ($\Delta R=0.3$)

CMS PAS HIG-17-015

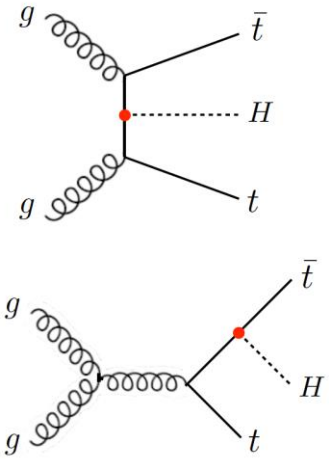


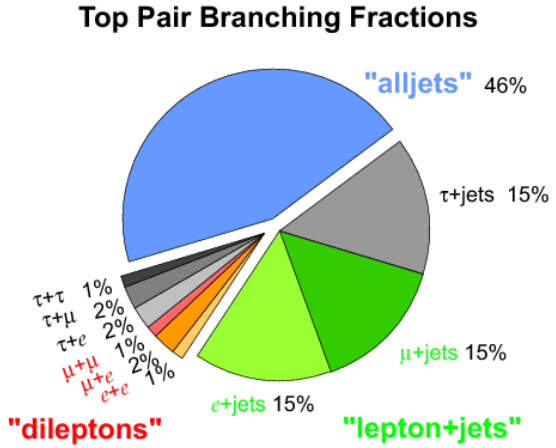




ttH observation

- **Largest coupling to the top quark**





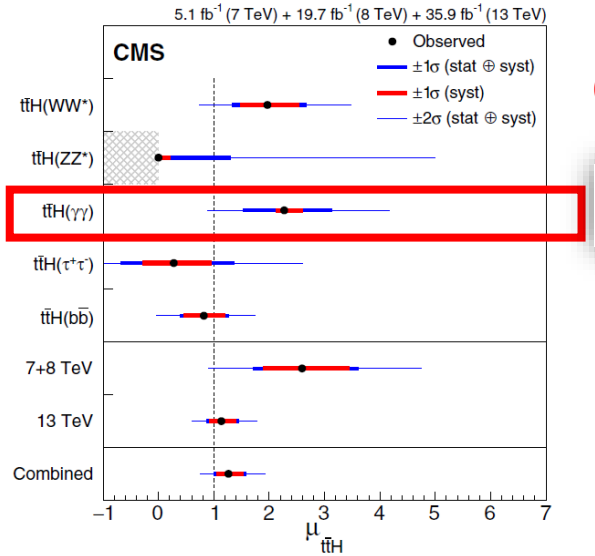
- **Very challenging**

  Complicated experimental signature

  Low cross section : σ_{ttH} = 507 fb (NLO QCD + NLO EW, 13TeV)

  Compare with SM cross section : σ_{tt} = 831,800 fb (NNLO QCD)

- First direct observation of the production mode with σ various decay channels combined:



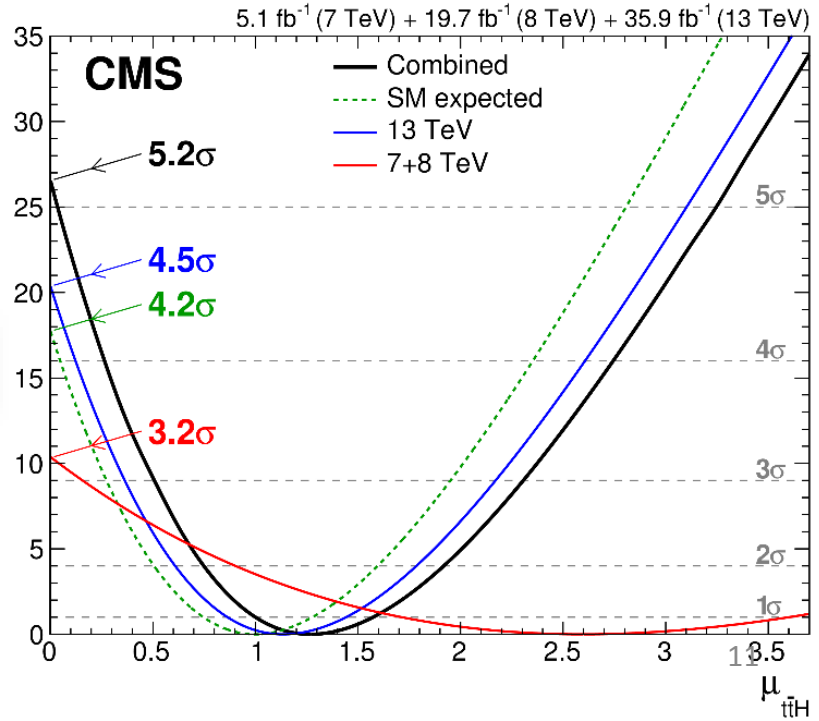
CMS Run1 + Run2 (2016 dataset)

Observed **5.2σ** (exp **4.2σ**)

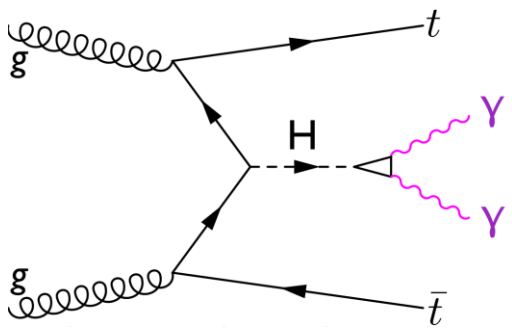
$$\mu = 1.26^{+0.31}_{-0.26}$$

$$= 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{exp})^{+0.14}_{-0.13}(\text{th, B})^{+0.15}_{-0.07}(\text{th, S})$$

Phys. Rev. Lett. 120, 231801 (2018)



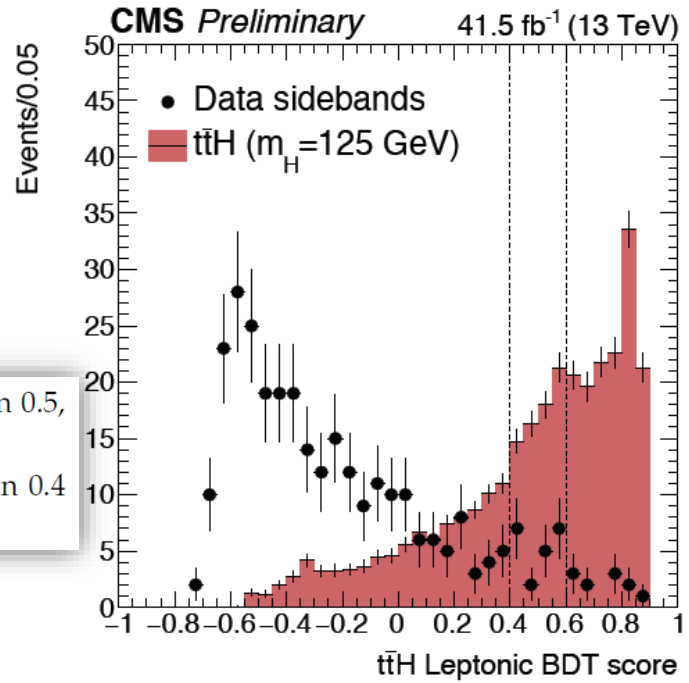
ttH→γγ measurement with 2017 data

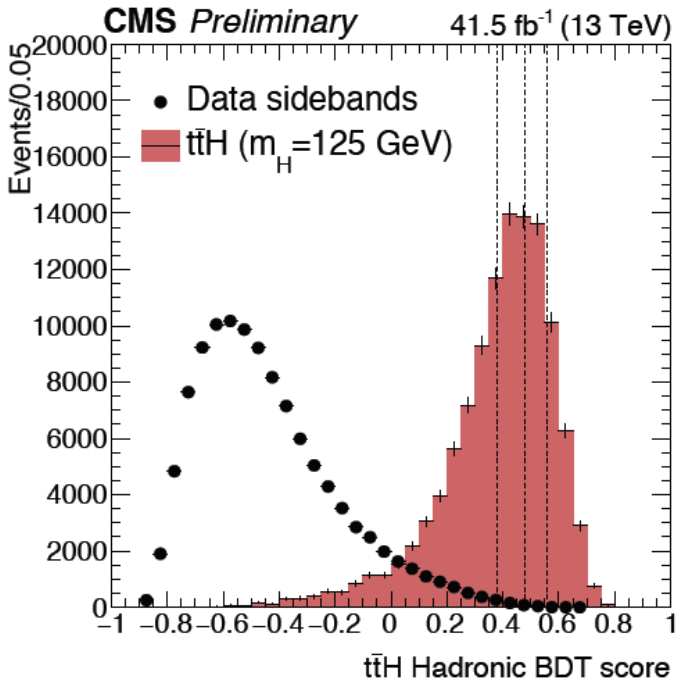


New!

- Very rare process but excellent mass resolution, very low background
- Use **BDT** to reject most non-ttH and non-resonant background

  - fully leptonic: $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}\ell\nu_\ell\ell'\nu_{\ell'}$;
  - semi-leptonic: $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}q\bar{q}\ell\nu_\ell$;
  - fully hadronic: $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}qq'\bar{q}\bar{q}'$.





2 leptonic event classes

- TTH Leptonic 0: events with at least two leptons and a BDT score greater than 0.5, or exactly one lepton and BDT score greater than 0.6;
- TTH Leptonic 1: events with exactly one lepton and a BDT score greater than 0.4 and smaller than 0.6.

3 hadronic event classes

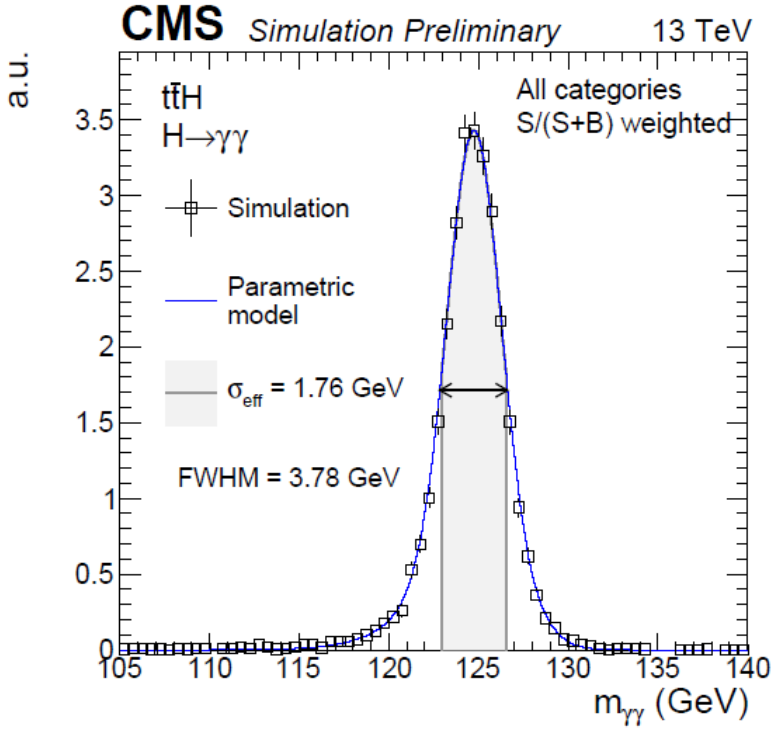
- TTH Hadronic 0: events with a BDT score greater than 0.56;
- TTH Hadronic 1: events with a BDT score between 0.48 and 0.56;
- TTH Hadronic 2: events with a BDT score between 0.38 and 0.48.

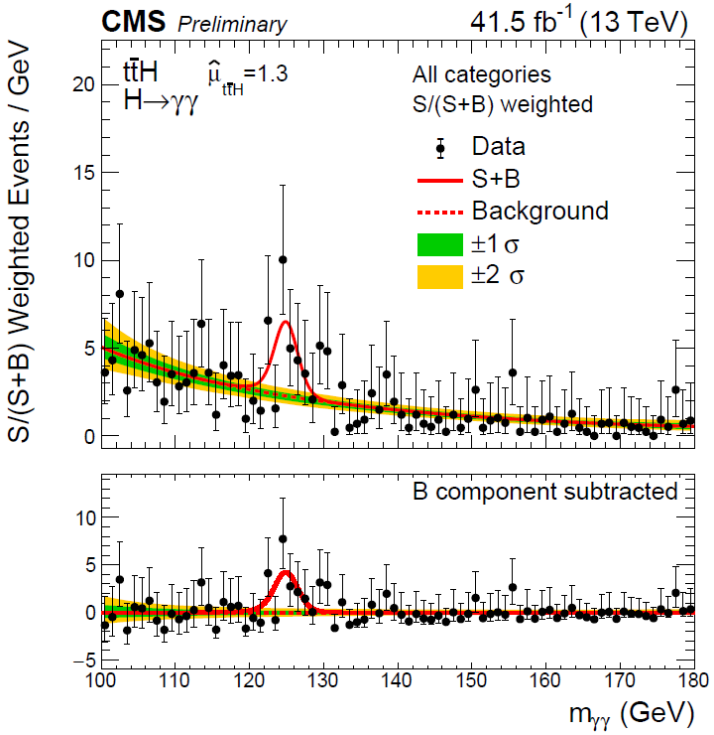
CMS PAS HIG-18-018

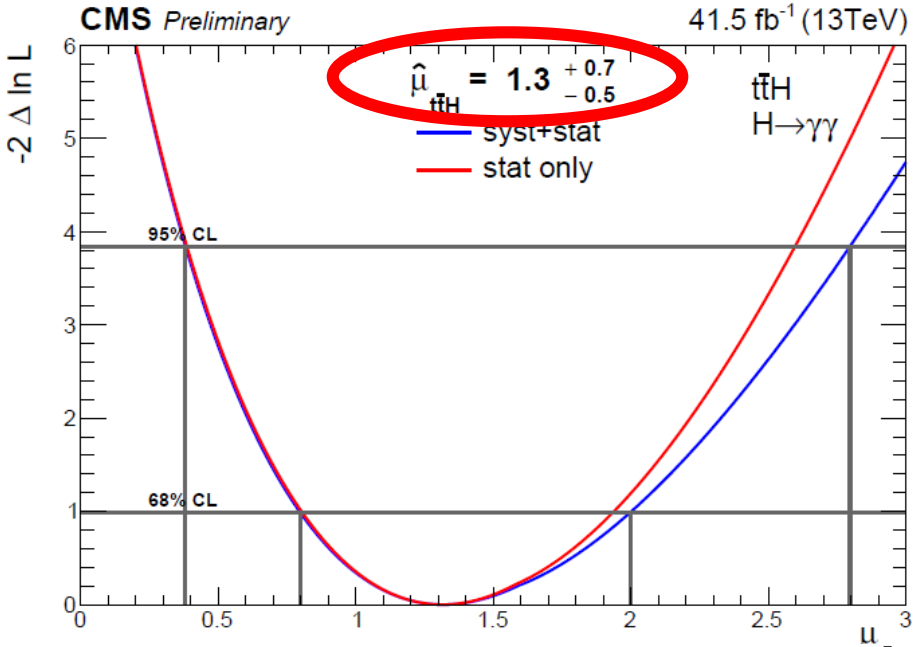
ttH→γγ measurement with 2017 data (cont.)

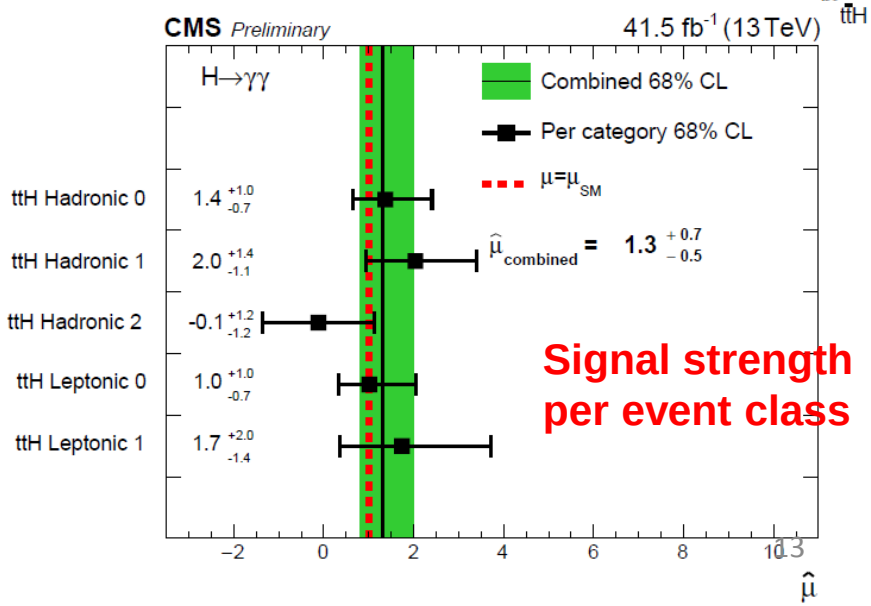
New!

- **Signal is extracted by a simultaneous maximum-likelihood fit to the diphoton mass in all event classes**





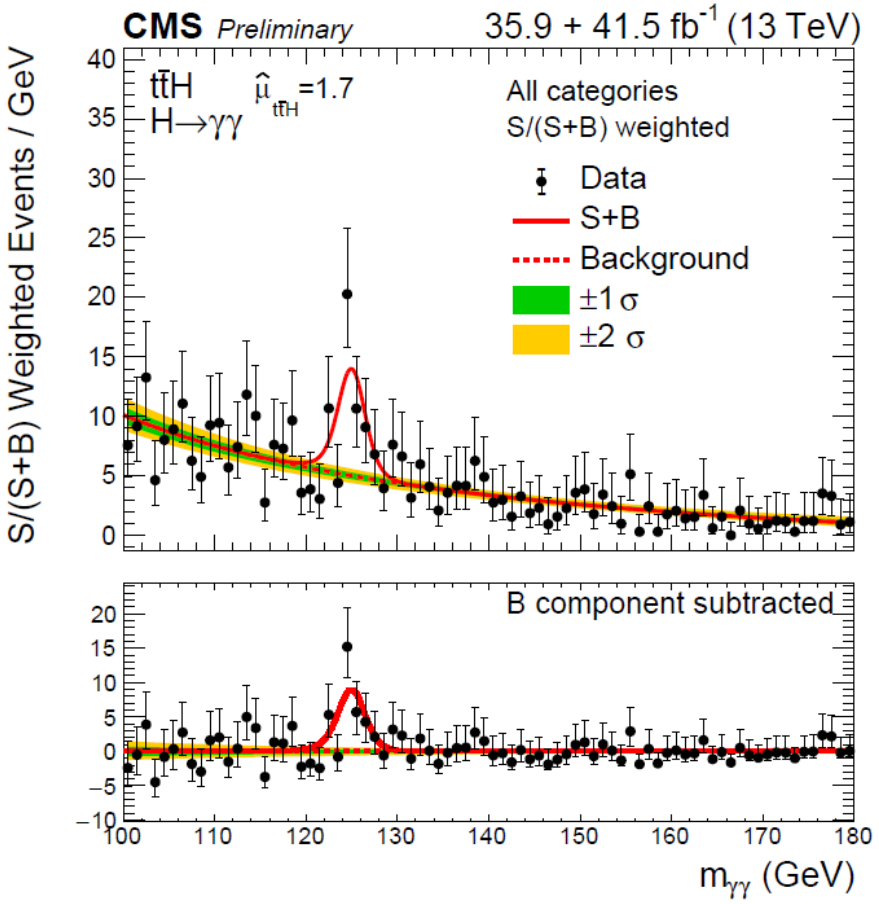




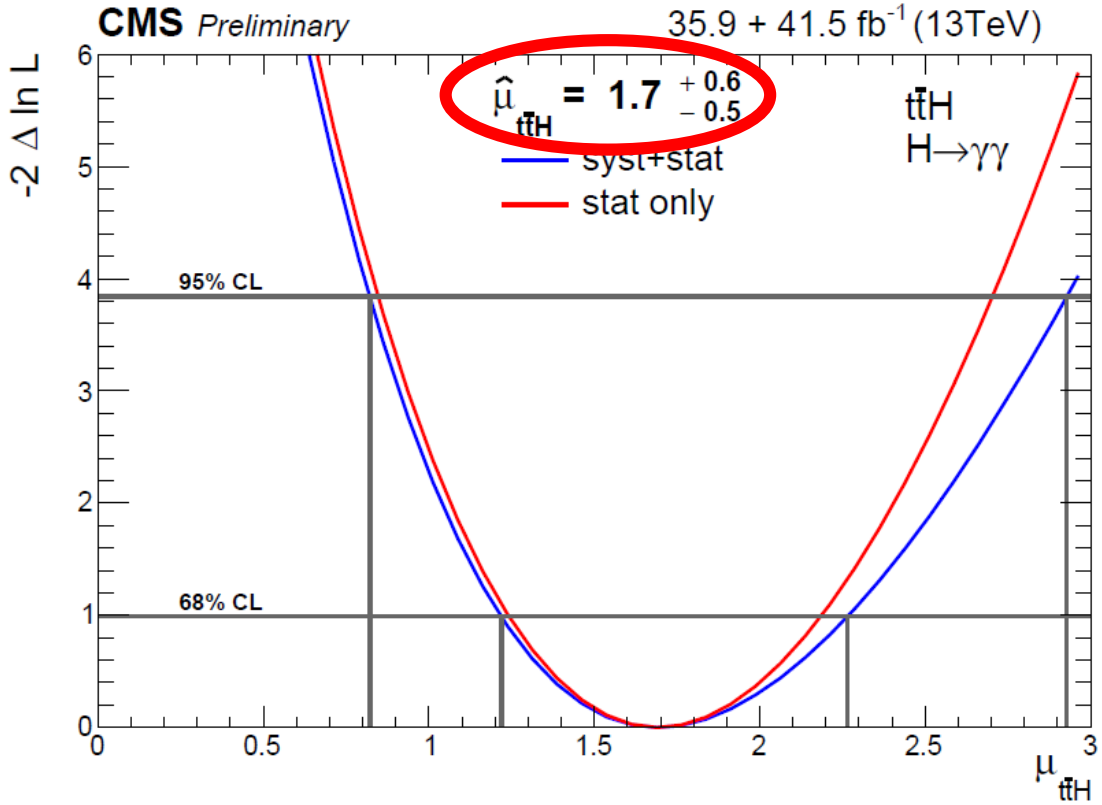
Signal strength per event class

CMS PAS HIG-18-018

ttH→γγ measurement : 2016 + 2017 data



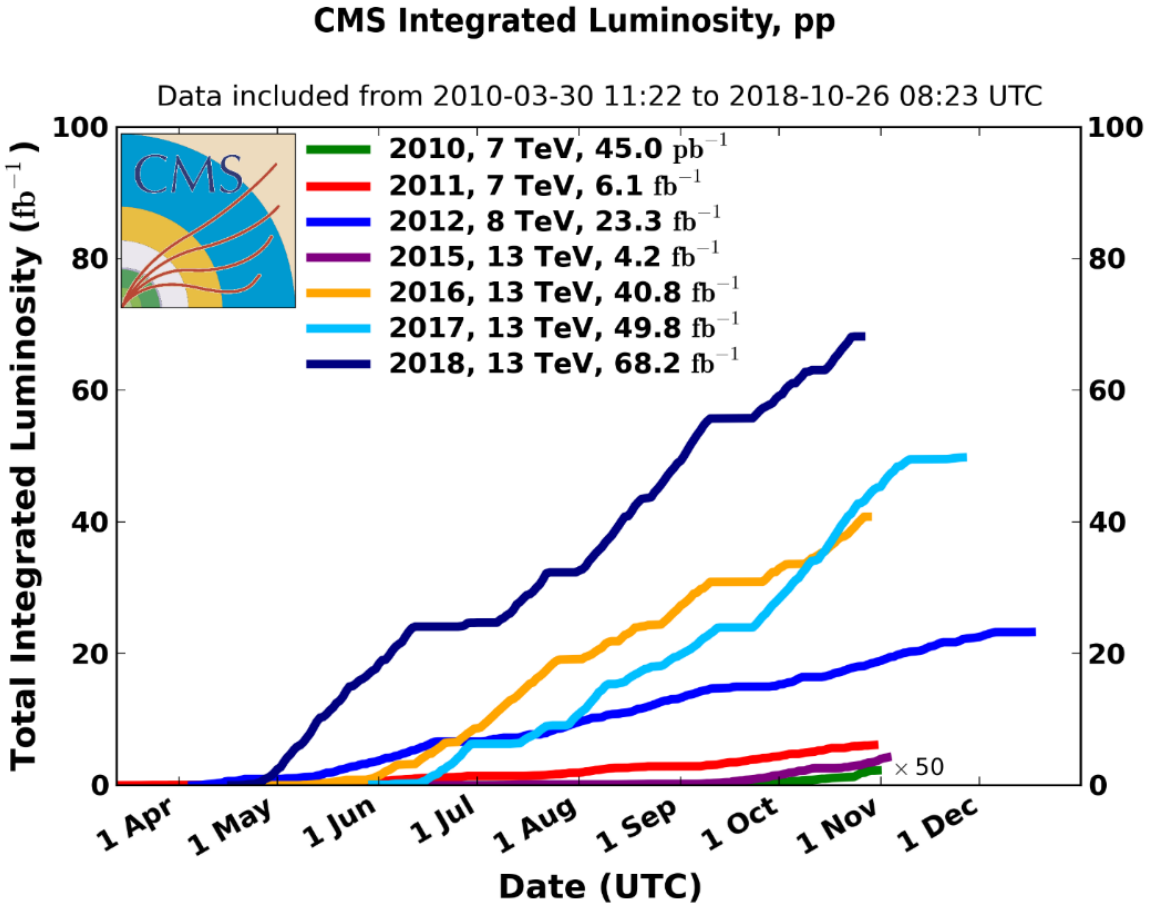
New!



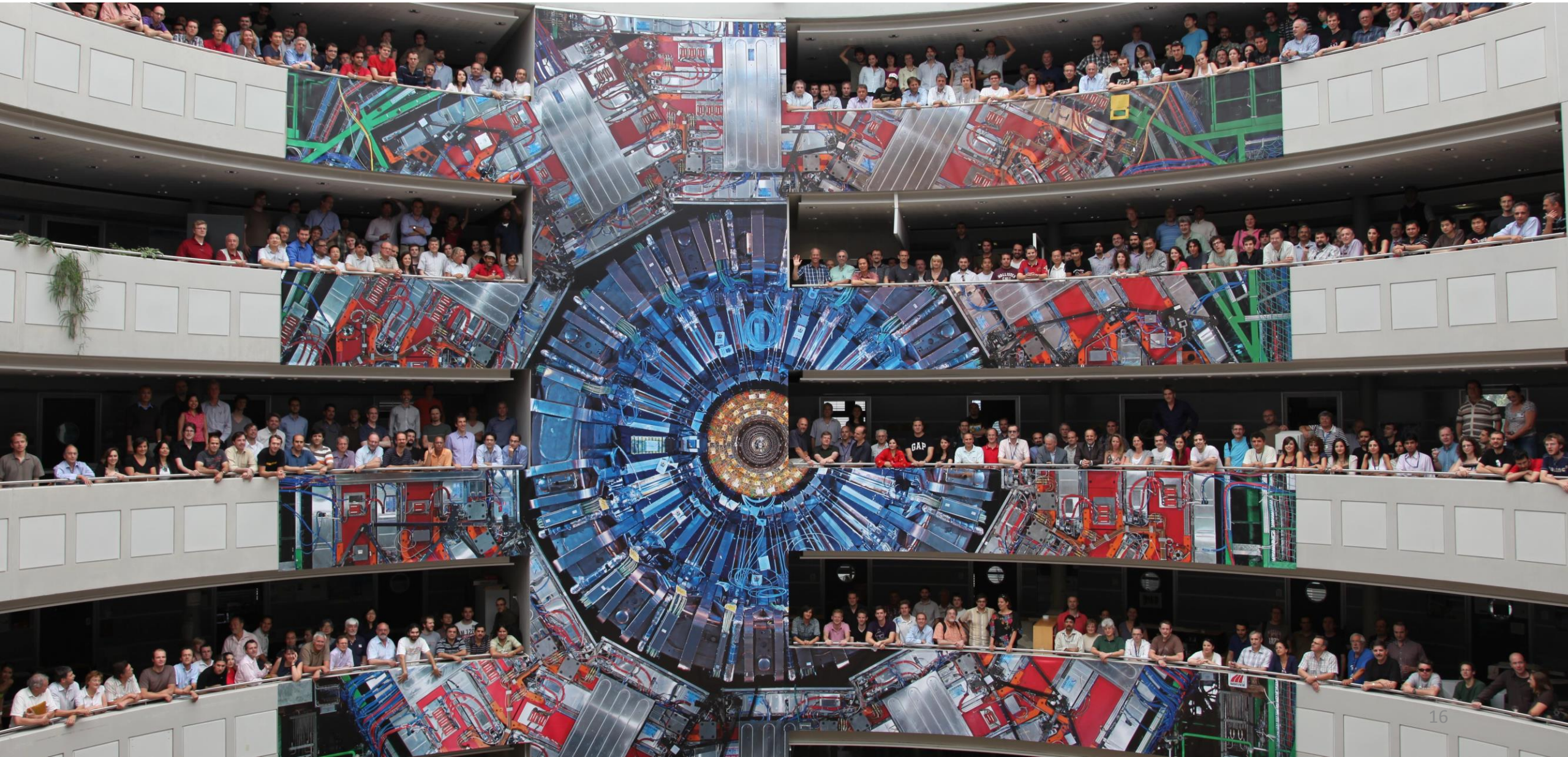
- **Combined (2016+2017) significance**: **4.1σ (2.7σ)**
- Dominant uncertainties
  - ✓ Theoretical: QCD scale uncertainties, PDF, α_S, Br(H→γγ)
  - ✓ Experimental: photon ID, JES/JER, b-discriminant

Summary

- **Latest results of H→$\gamma\gamma$ measurements with CMS Run2 data are presented**
- **All results are compatible with the Standard Model**
- More results to come with full Run-2 dataset!



Thanks for your attention!

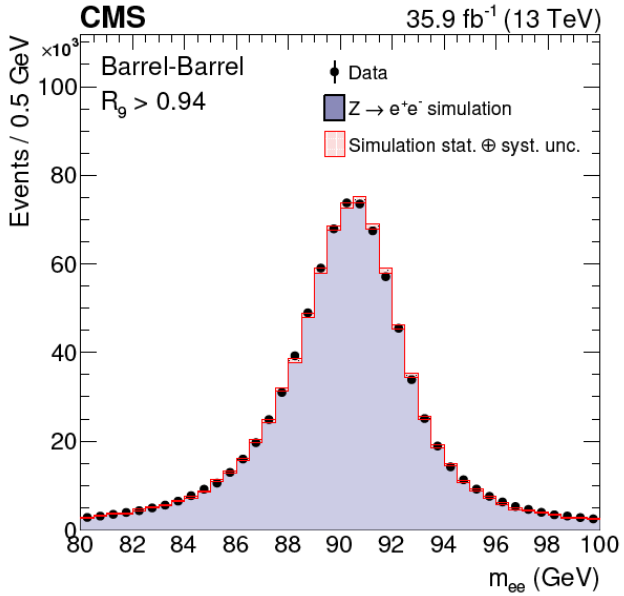


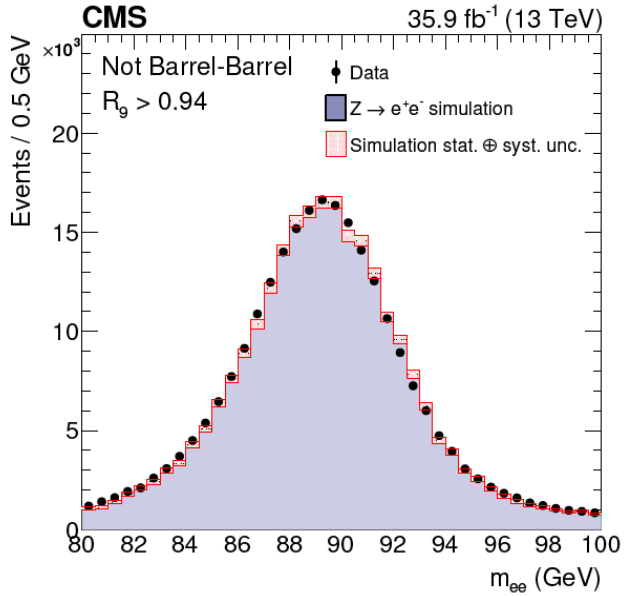
Backup slides

$m_{\gamma\gamma}$: Photon energy

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$

- Photons energy is computed from the sum of the energy of the **ECAL reconstructed hits, calibrated and corrected for several detector effects**
  - correction for **response changes** in time, $S_i(t)$
  - single-channel intercalibration (C_i)
  - **absolute scale** adjustment [2013 JINST 8 P09009]





- **Energy and its uncertainty** corrected for local and global shower containment with **a multivariate regression technique** **targeting E_{true}/E_{reco}**

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R_9 and η dependent scaling and MC smearing

- For energy scale vs time and resolution calibration, **Z→ee peak** used as reference

- **Corrected energies and resolutions used in analysis**

$m_{\gamma\gamma}$: primary vertex identification

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$

➢ Vertex assignment correct within **1 cm** → **has negligible** impact on mass resolution

➢ **Multivariate approach (BDT) for vertex identification**

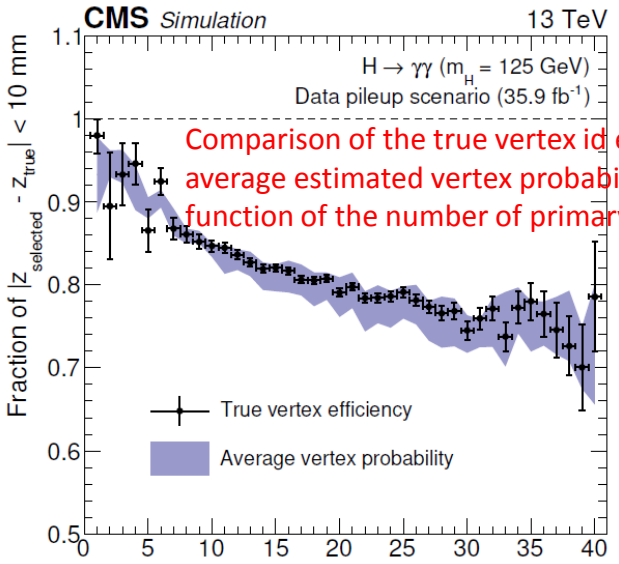
- Vertex ID BDT: **kinematic correlations and track distribution imbalance**

$$\sum_i |\vec{p}_T^{\,i}|^2 \,,\; -\sum_i (\vec{p}_T^{\,i} \cdot \frac{\vec{p}_T^{\,\gamma\gamma}}{|\vec{p}_T^{\,\gamma\gamma}|}) \text{ and } (|\sum_i \vec{p}_T^{\,i}| - p_T^{\gamma\gamma})/(|\sum_i \vec{p}_T^{\,i}| + p_T^{\gamma\gamma})$$

- if conversions are present **conversion information**
  - the number of conversions,
  - the pull $|z_{vtx} - z_e|/\sigma_z$ between the longitudinal position of the reconstructed vertex, z_{vtx}, and the longitudinal position of the vertex estimated using conversion track(s), z_e, where the variable σ_z denotes the uncertainty on z_e.

➢ A second MVA estimates **probability of correct vertex** choice, used for di-photon classification using BDT

➢ **Method validated** on Z→μμ events where vertex found after removing muon tracks and γ+j for converted γ



Comparison of the true vertex id eff and the average estimated vertex probability as a function of the number of primary vertices

Averaged efficiency is about 81%

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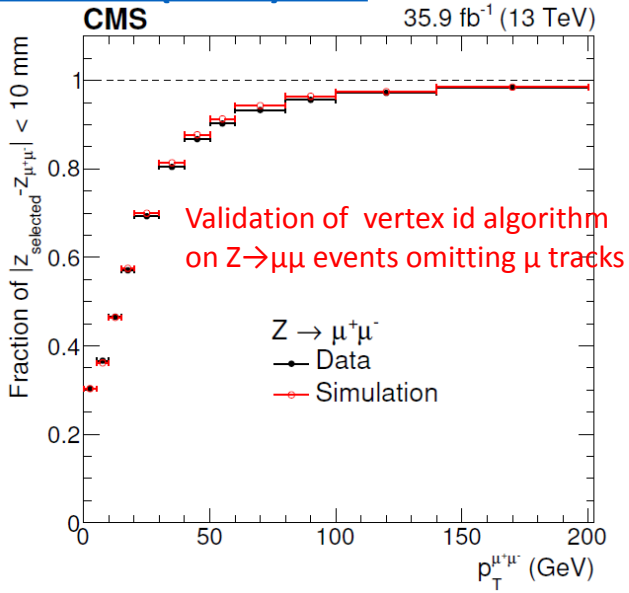

Validation of vertex id algorithm on Z→μμ events omitting μ tracks

Photon identification

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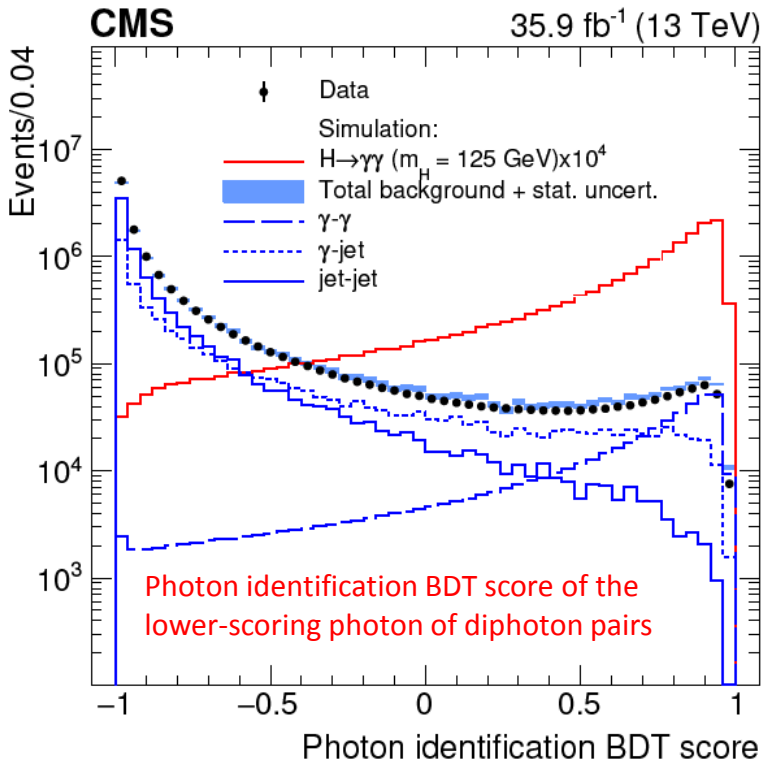
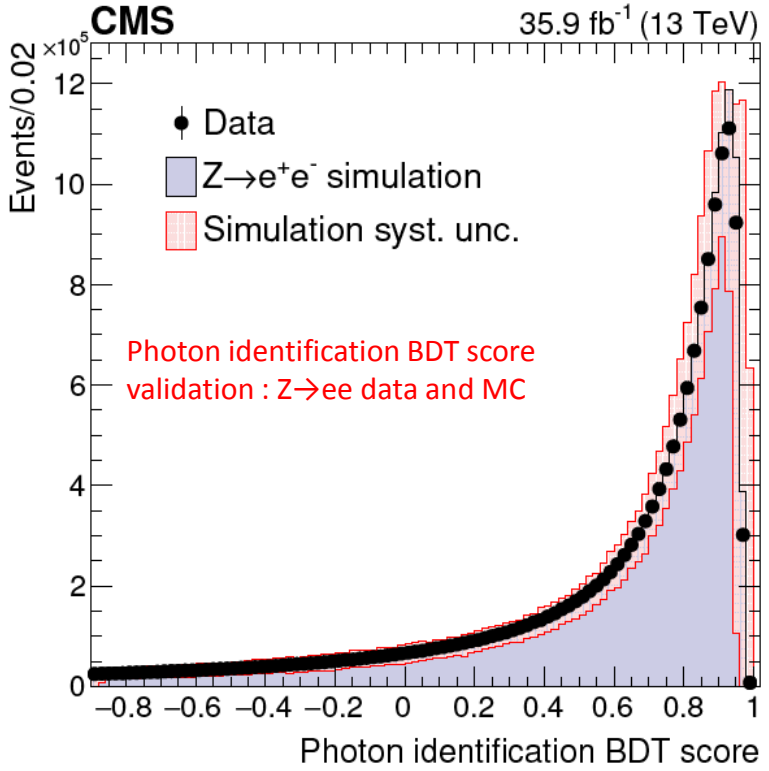
➢ **MVA based photon ID classifier (BDT)** to discriminate between prompt and fake photons

- Shower shape variables: σiηiη ,coviηiϕ, E2x2/E5x5, R9, η-width, ϕ-width, Preshower σRR
- Isolation variables: PF Photon ISO, PF Charged ISO - wrt selected vertex and to the worst (largest isolation sum) vertex
- ρ, ηSC, ERAW





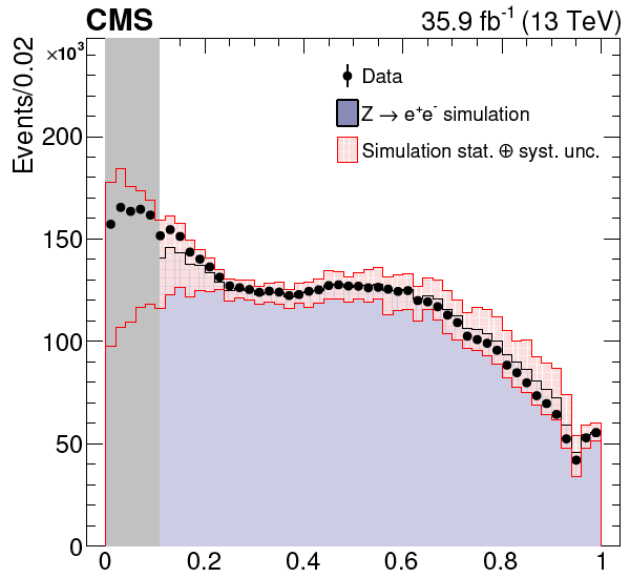
➢ Inputs and output of the MVA are **validated** on data and MC in **Z→ee** and **Z→μμγ** events

➢ Two photon BDT scores are used as **inputs of diphoton BDT** after **a looser direct cut at > -0.9**

Diphoton BDT

➢ **Multivariate discriminator (BDT)** used to separate diphoton pairs with signal-like kinematics, high photon ID scores and good mass resolution from background

- pT/Mγγ, η, cos(Δϕ), Photon ID MVA score of the two photons
- Per event relative mass resolutions (under correct and incorrect vertex hypothesis), vertex probability estimate



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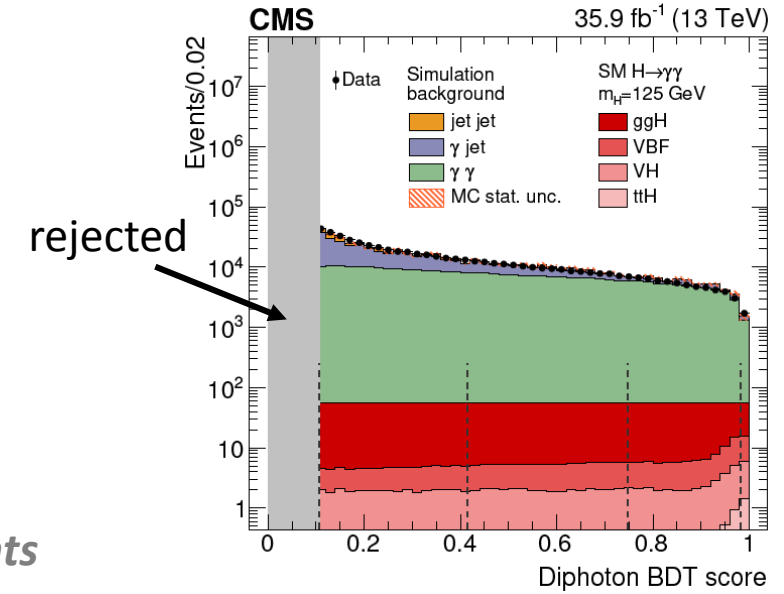
➢ **Validation** of Diphoton MVA is done on **Z→ee** events, with the electrons taken as photons

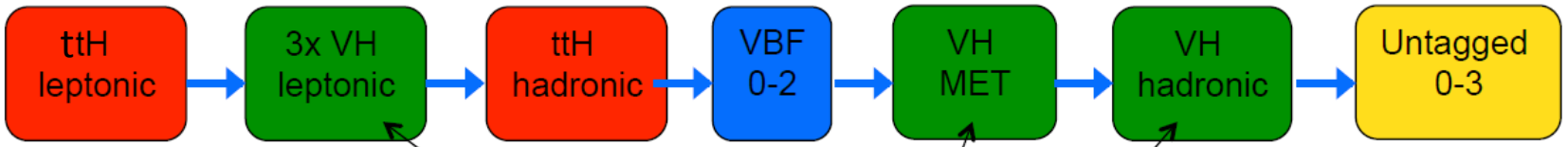


➢ Diphoton BDT used for the **untagged event** (ggH dominant) **categorization**, one of the **inputs of VBF combined BDT**, and **direct cut on diphoton BDT score for ttH/VH** tagged events

Higher BDT score gives better mass-resolution diphoton events

Event categorization

- Selected events are split into **14 categories** depending on **Higgs production modes** and kinematics, to improve the analysis sensitivity
- Top fusion (**ttH**): cut-based ***leptonic*** and mva-based ***hadronic*** (2cats)
- **VH**: cut-based method and split into ***leptonic, hadronic, MET*** (5cats)
- **VBF**: combined dijet + diphoton BDT with categories based on significance (3cats)
- **Untagged** (ggH): split by ***diphoton BDT score***, correspond to different S/B and invariant mass resolutions (4cats)



Order of event tagging

First VH results in Run2

2016 H→γγ : ttH

Objects

- **Jets**:
  - ak4PFCHS; pT>25 GeV; |η| <2.4
- **Bjets**:
  - PF CSV v2 (medium WP)
- **Muons**:
  - p_T>20 GeV; |η|<2.4; "tight muon"; miniIso<0.06
- **Electrons**:
  - p_T>20 GeV; |η|<2.5; 1.442<|η| <1.566; loose EGM ID

leptonic

$t\bar{t} \to bl\nu_l\bar{b}q\bar{q}'$ $t\bar{t} \to bl\nu_l\bar{b}l'\nu_{l'}$

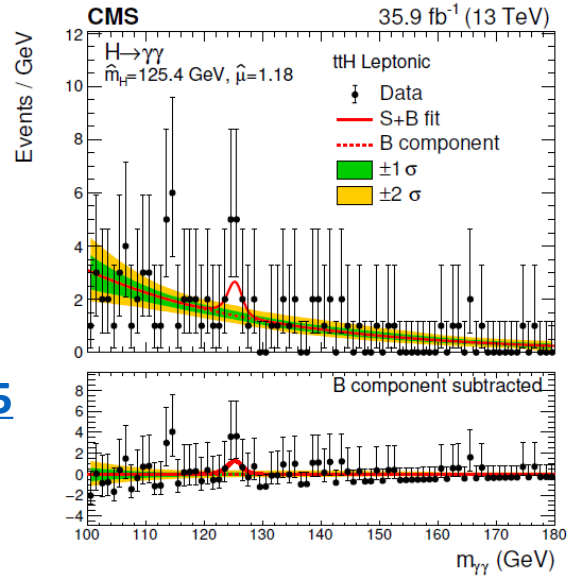
- **Selection**
  - (sub)leading photon $p_T/M_{\gamma\gamma}$>0.5(.25)
  - At least 2 jets with ΔR(j, γ or l) >0.4
  - At least one b-tagged jet
  - At least 1 lepton ΔR(l,γ)>0.35
  - For electron: $|M_{e\gamma}-M_Z|$>5 GeV
  - diphoton mva > 0.107

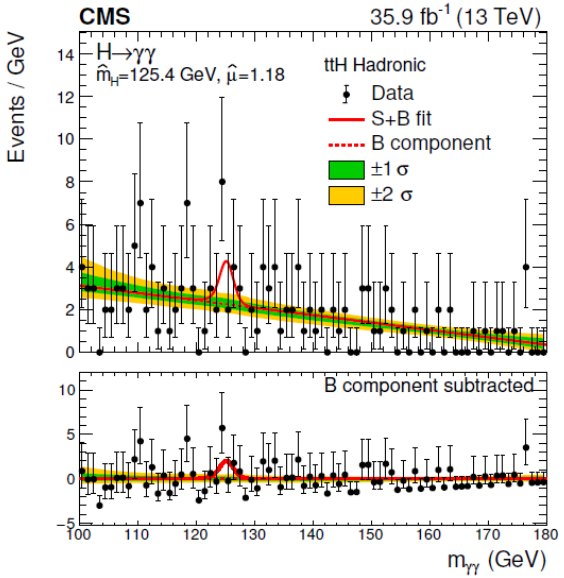
hadronic

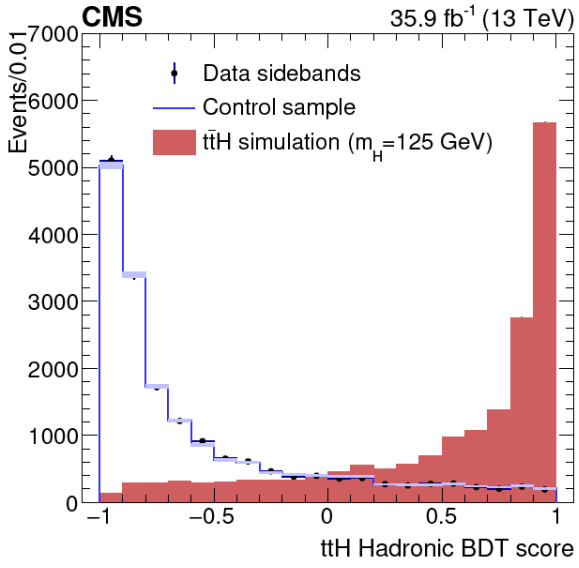
$t\bar{t} \to bq\bar{q}'\bar{b}q\bar{q}'$

- **Preselection:**
  - at least 3 jets
  - at least 1 loose b-jet
- 2-d optimization of diphoton MVA and ttH MVA
  - diphoton MVA > 0.577
  - ttH MVA > 0.75

Cut-based strategy replaced with mva to improve μ_{ttH} sensitivity







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2016 H→γγ : VH

3 VH leptonic categories $W \to l\nu$ or $Z \to l\bar{l}$

- **Muons**
  - p_T>20 GeV; |η|<2.4; "tight muon"; pf isolation < 0.25 (loose WP)
- **Electrons**
  - p_T>20 GeV; |η|<2.5; 1.442<|η|<1.566; loose EGM ID
- **Photons**
  - (sub)leading $p_T/m_{\gamma\gamma}$>0.375(0.25)

- **WH leptonic:**
  - one lepton:
  - p_T^{miss} > 45 GeV
  - ΔR(γ, l) >1.0
  - diphoton mva>0.28
  - <=2 jets

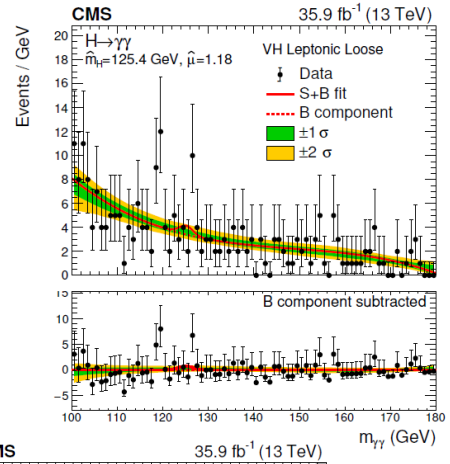
- **ZH leptonic:**
  - two leptons:
  - 70<m_{ll}<110 GeV
  - ΔR(γ, μ(e)) >0.5(1.0)
  - diphoton mva>0.107

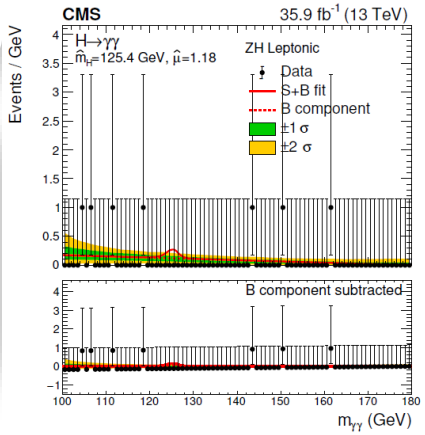
- **VH leptonic loose:**
  - one lepton:
  - p_T^{miss} < 45 GeV
  - ΔR(γ, l) >1.0
  - diphoton mva>0.28
  - <=2 jets

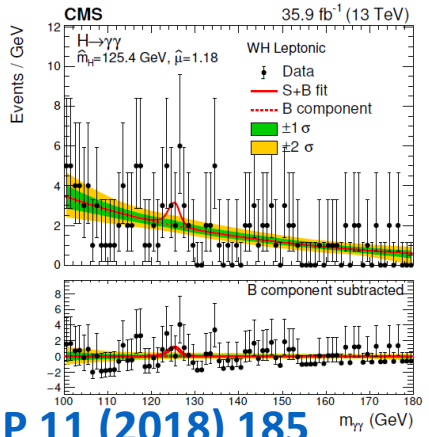
Diphoton MVA cuts were tuned

MET category

- $W \to l\nu$ (lepton out of acceptance) or $Z \to \nu\nu$
  - p_T^{miss} > 85 GeV
  - Δφ(γγ, p_T^{miss}) >2.4
  - diphoton MVA > 0.790 (0.6 before flattening)







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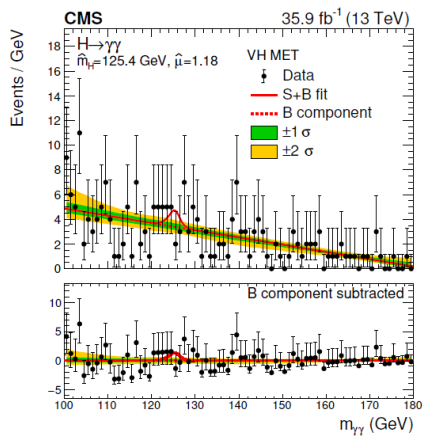
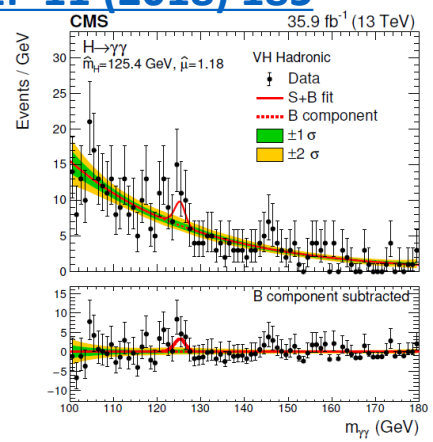




W->jj or Z->jj

hadronic category

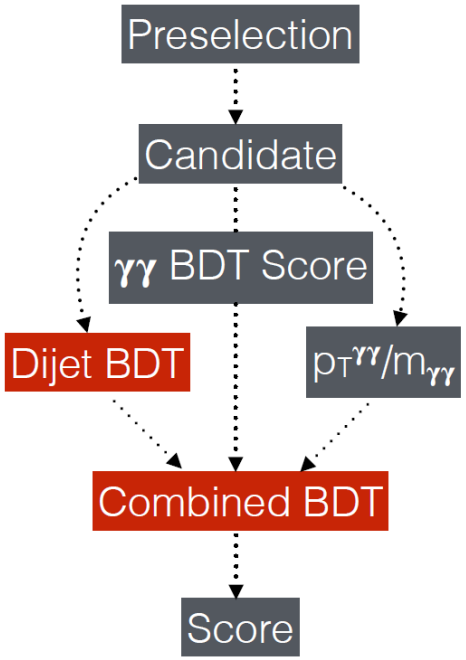
- **Photons**
  - (sub)leading $p_T/m_{\gamma\gamma}$>0.5(0.25)
  - $p_T^{\gamma\gamma}/m_{\gamma\gamma}$>1.0
- **Jets**
  - At least two jets
  - p_T > 40 GeV
  - |η| < 2.4
  - 60<m_{jj}< 120 GeV
  - |cosθ*| < 0.5

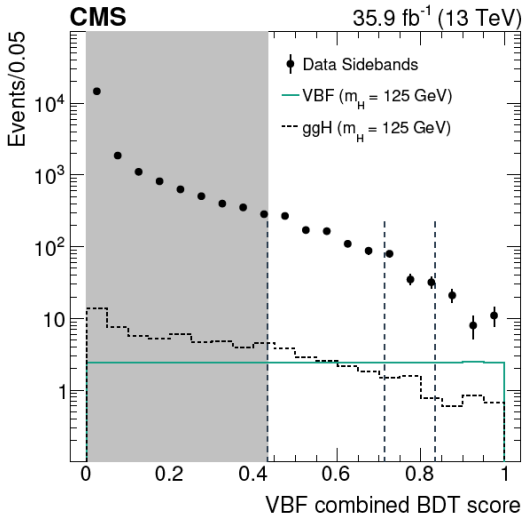
Diphoton MVA > 0.906

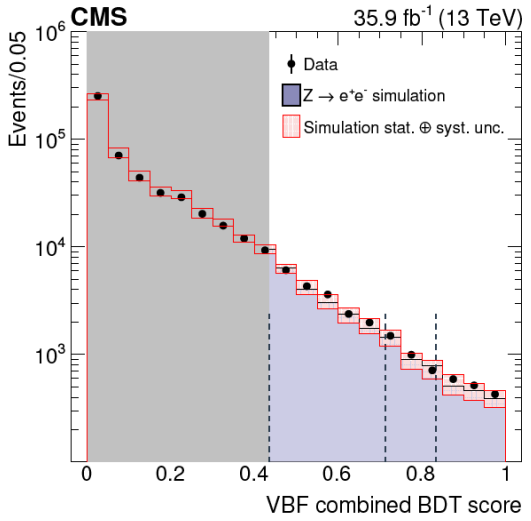
- before flattening (0.7)

2016 H→γγ : VBF Tag

- Preselection: Two jets with pT_{j1}>40GeV, pT_{j2} >30GeV, |η|<4.7, m_{jj}>250GeV
- Main Structure: two parts, the Dijet BDT & Combined BDT
- Dijet BDT: separates VBF dijet from BG (incl. gluon fusion) using dijet kinematics
- Combined BDT: separates signal/BG diphotons using diphoton BDT, dijet BDT and scaled diphoton pT
- 3 VBF-tagged categories using the combined MVA with boundary optimisation: cuts on combined score are simultaneously optimized for max significance across all categories







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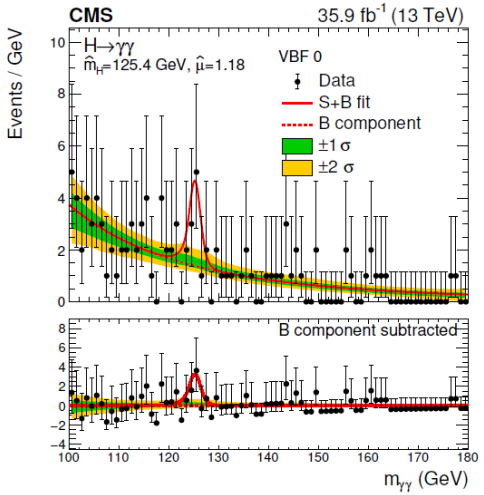
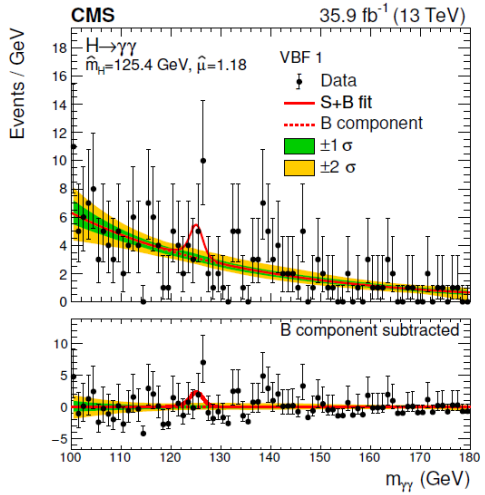
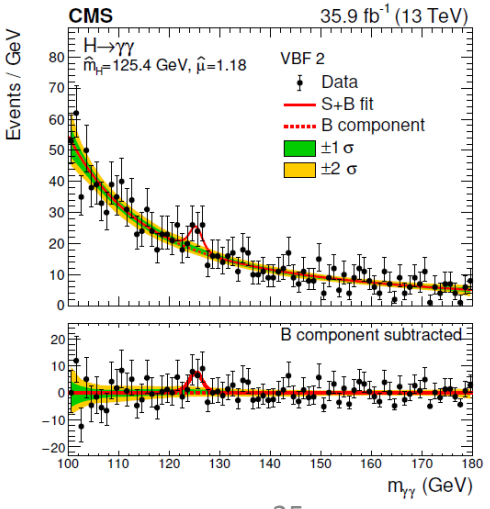
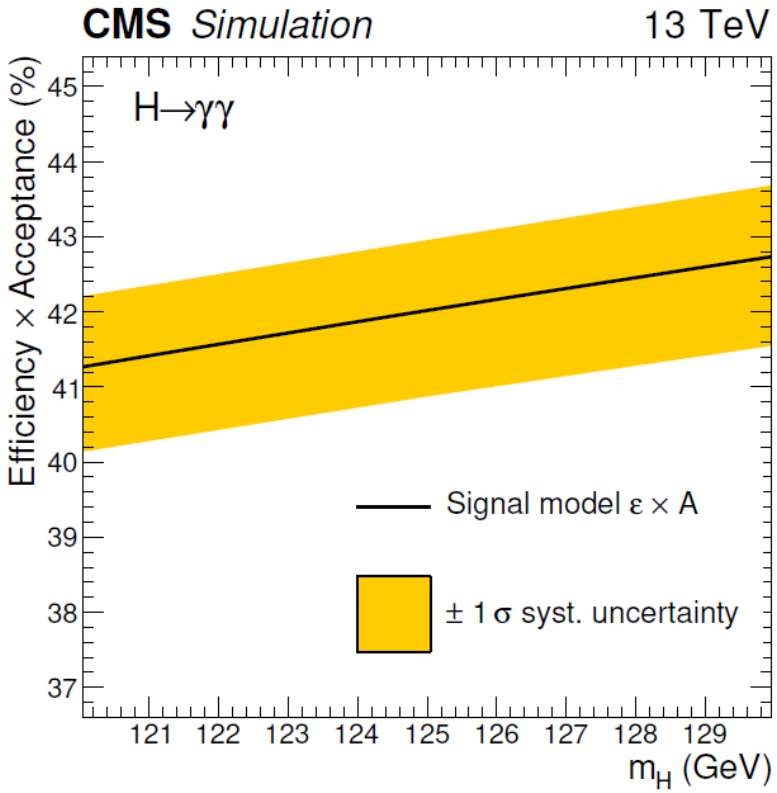
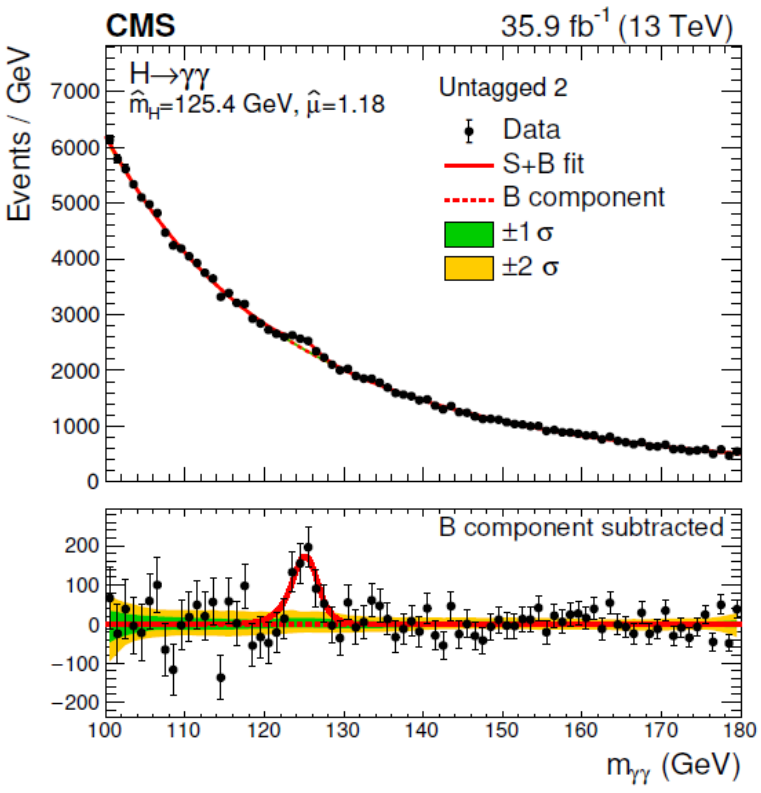


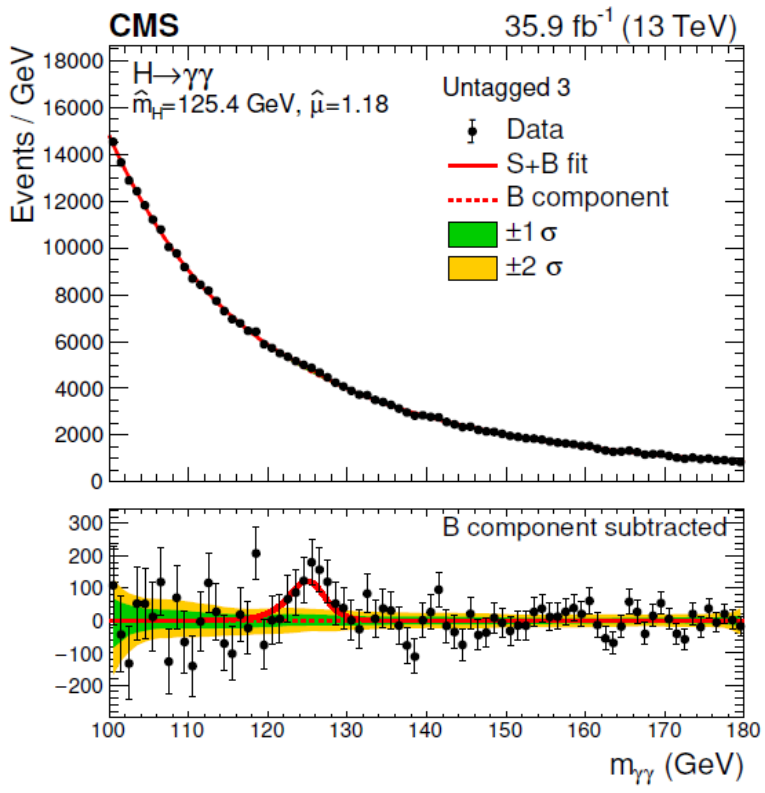




2016 backup plots







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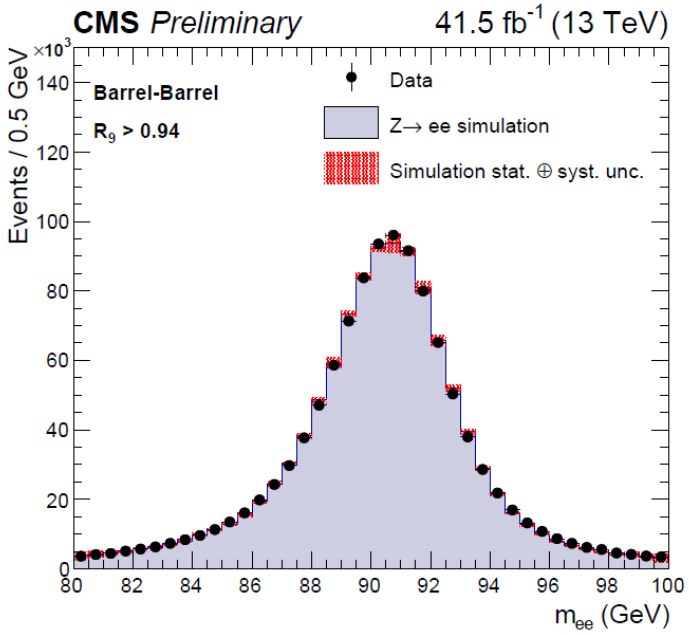
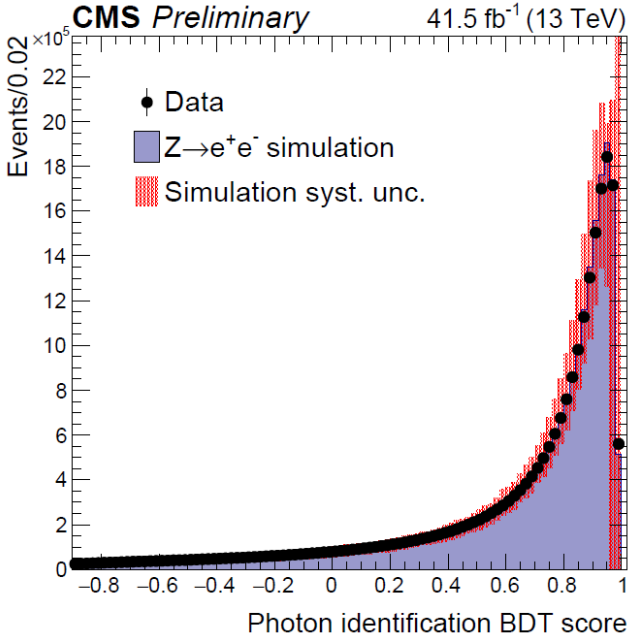
ttH→γγ with 2017 data





CMS PAS HIG-18-018

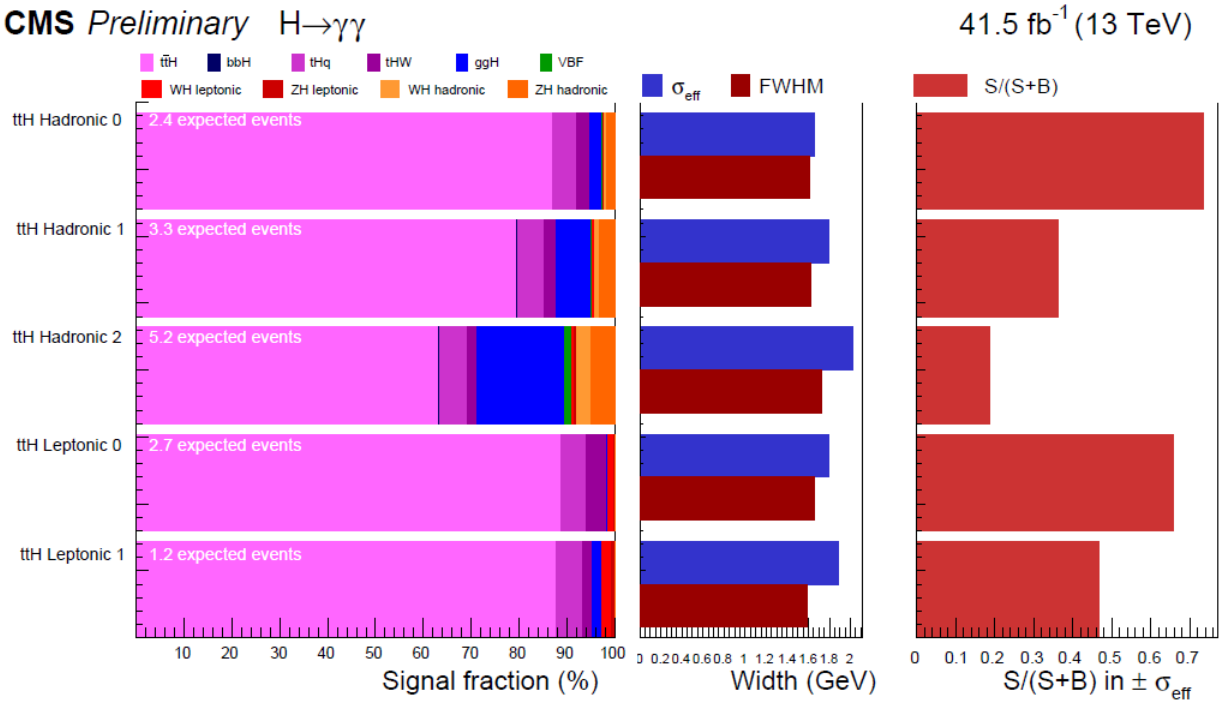
Input variables of hadronic BDT

- Photon variables:
  - the $p_T/m_{\gamma\gamma}$ of the two photons;
  - the η of the photons;
  - the azimuthal angle φ of the photons;
  - the photon identification BDT score of the photons;
  - the outcome of the pixel seed veto for the two photons
  - the $p_T/m_{\gamma\gamma}$ of the diphoton;
  - the rapidity of the diphoton;
- jet variables:
  - the number of jets;
  - the transverse momentum of the four highest p_T jets;
  - the η of the four highest p_T jets;
  - the sum p_T of all the reconstructed jets;
- b-tagged jet variables:
  - the value of the b-discriminant of the three jets with the highest score of the b-discriminant;
  - the value of the b-discriminant of the four highest p_T jets;
- the missing transverse momentum p_T^{miss}.

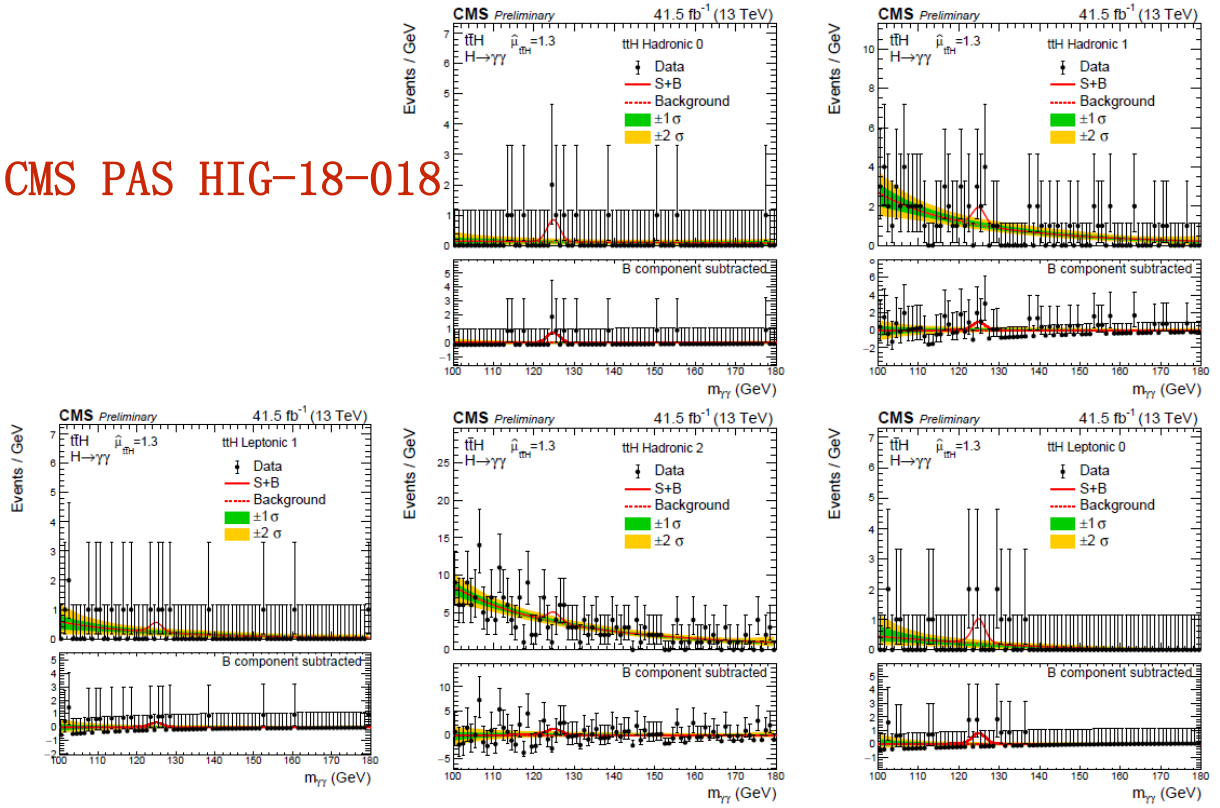
Input variables of leptonic BDT

- photon variables:
  - the $p_T/m_{\gamma\gamma}$ of the two photons; the p_T is scaled to the diphoton mass to keep the BDT blind to the diphoton invariant mass;
  - the η of the two photons;
  - the photon identification BDT scores of the two photons;
  - the azimuthal angle difference between the two photons $\Delta\phi(\gamma\gamma)$;
  - the outcome of the pixel seed veto for the two photons. The veto requires the absence of a track seed in the pixel detector matching the photon direction, reducing the background due to events where an electron is misidentified as a photon;
- jet variables:
  - the number of jets;
  - the transverse momentum of the three highest p_T jets;
  - the η of the three highest p_T jets;
- b-tagged jet variables:
  - the number of b-tagged jets;
  - the value of the b-discriminant of the two jets with the highest score of the b-discriminant;
- leptonic variables:
  - the transverse momentum of the highest p_T lepton;
  - the η of the lepton of the highest p_T lepton;
- the missing transverse momentum p_T^{miss}.

ttH→γγ with 2017 data (cont.)



CMS PAS HIG-18-018



Event categories	SM 125 GeV Higgs boson expected signal													Bkg
	Total	ttH	bbH	tHq	tHW	ggH	VBF	WH lep	ZH lep	WH had	ZH had	σ_{eff}	FWHM	(GeV^{-1})
ttH Hadronic 0	2.4	86.7 %	<0.05 %	5.0 %	2.8 %	2.6 %	0.1 %	0.1 %	0.1 %	0.7 %	1.8 %	1.66	1.61	0.2
ttH Hadronic 1	3.3	79.2 %	0.2 %	5.6 %	2.4 %	7.5 %	0.2 %	0.4 %	0.1 %	1.0 %	3.3 %	1.79	1.62	1.1
ttH Hadronic 2	5.2	62.9 %	0.2 %	5.9 %	1.9 %	18.4 %	1.3 %	0.6 %	0.4 %	3.2 %	5.1 %	2.02	1.72	3.8
ttH Leptonic 0	2.7	88.5 %	<0.05 %	5.2 %	4.4 %	0.2 %	<0.05 %	1.2 %	0.2 %	<0.05 %	0.1 %	1.79	1.66	0.3
ttH Leptonic 1	1.2	87.6 %	<0.05 %	5.5 %	1.8 %	2.0 %	0.2 %	1.9 %	0.8 %	<0.05 %	0.2 %	1.88	1.59	0.3
Total	14.8	77.2 %	0.1 %	5.5 %	2.6 %	8.7 %	0.5 %	0.7 %	0.3 %	1.5 %	2.8 %	1.84	1.65	5.6