Measurements of Higgs boson properties with $H\rightarrow\gamma\gamma$ at CMS

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on behalf of the CMS collaboration

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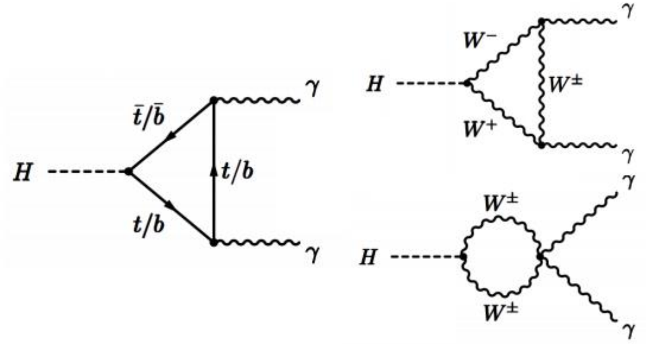
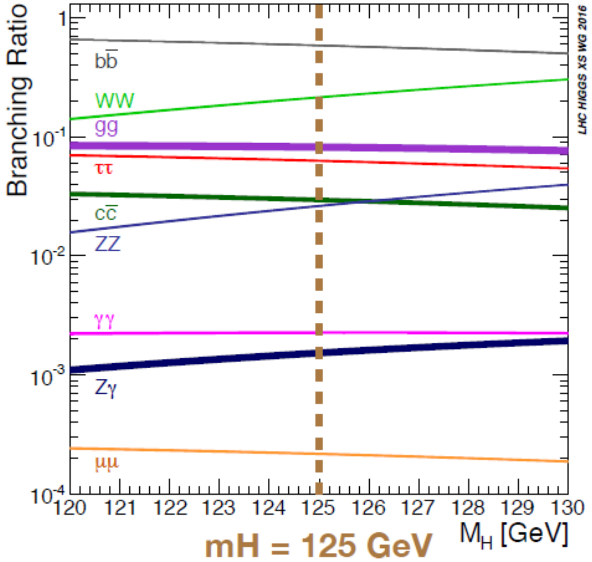
Overview of Higgs decaying into $\gamma\gamma$

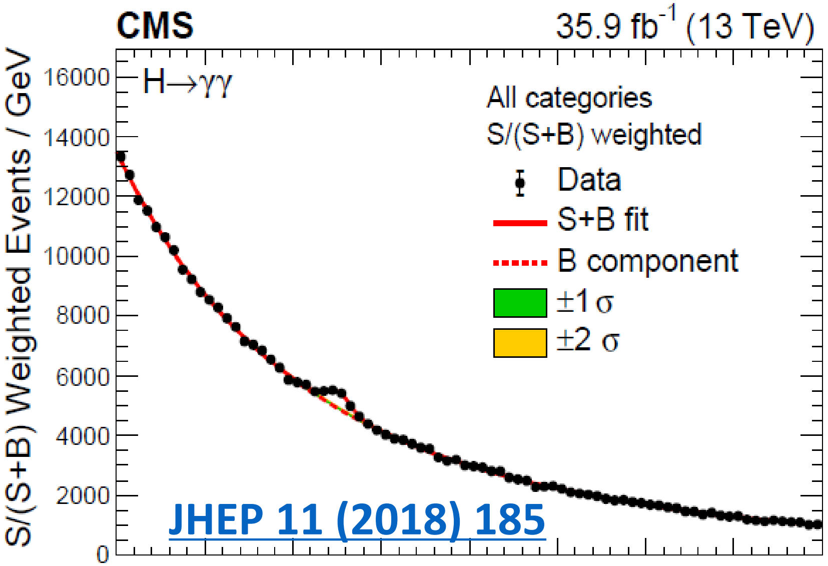
- At the LHC, $H \to \gamma\gamma$ channel plays a key role first in the **discovery of the Higgs boson**, and then in the **measurements of Higgs boson properties** and also in **searches for new physics**



- **Loop-induced decay**
  - ✓ **Interference** helps probe sign of couplings to SM particles
  - ✓ **New physics** could contribute to the loop

- **Small branching fraction** (0.2%)
  - ✓ Clean final state with two highly **energetic and isolated photons**
  - ✓ Final state can be **fully reconstructed** with **excellent mass resolution** (1-2%)





- **Large backgrounds**
  - ✓ Continuum $\gamma\gamma$ (irreducible)
  - ✓ Fakes from γj and jj (reducible)

Search for a narrow peak on a larger falling background in mass distribution

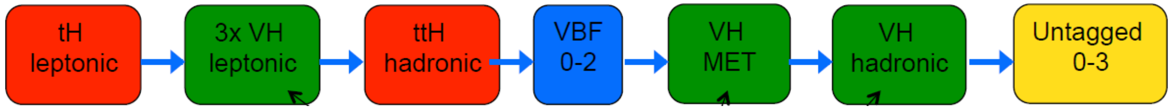
Analysis strategy

- **Signal mass reconstruction** $m_{\gamma\gamma}^2 = E_{\gamma_1}E_{\gamma_2}(1-\cos\alpha)$
  - ✓ select/reconstruct two **photons** with precise **photon energy** (**MVA *regression***)
  - ✓ Find the **primary vertex** of the Higgs decay (***MVA BDT***)

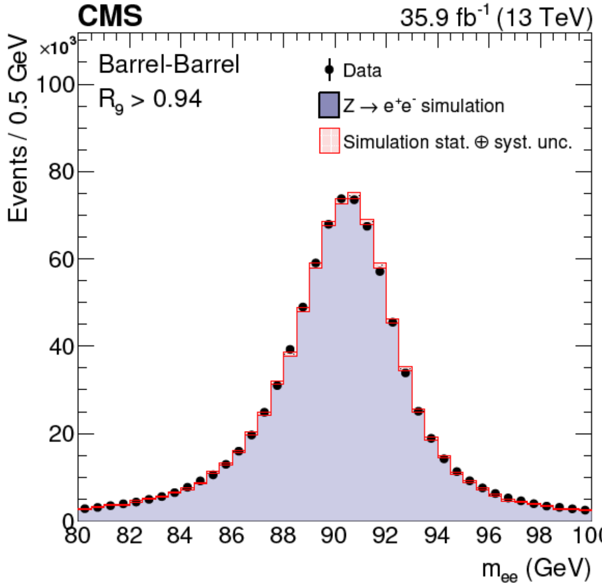
- **Background suppression**: photon identification *BDT*, inputs of diphoton BDT after looser cut (>-0.9)

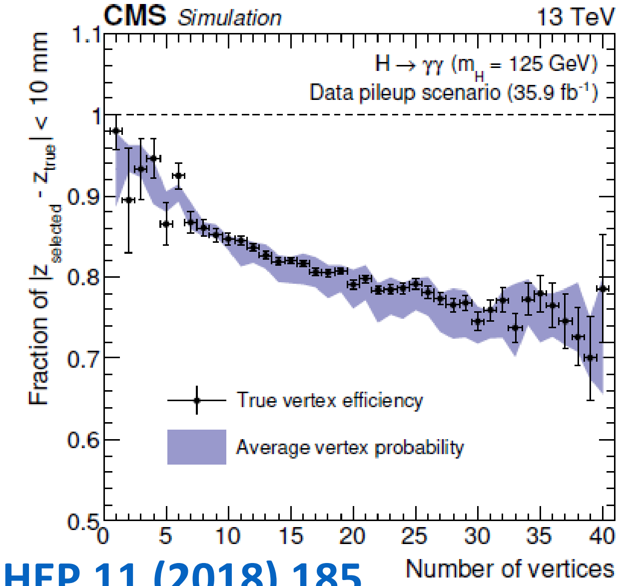
- **Diphoton BDT** based on kinematics including mass resolution, **to separate signal from background**

- **Event categorization according to production models, diphoton BDT** or **mass resolution** and **different S/B**, to **improve the analysis sensitivity**



2016 dataset in HIG-16-040: 14 non-overlapping categories in total





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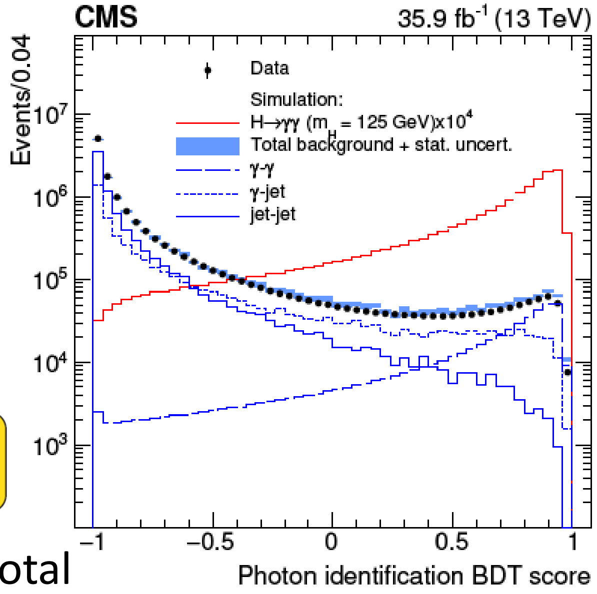
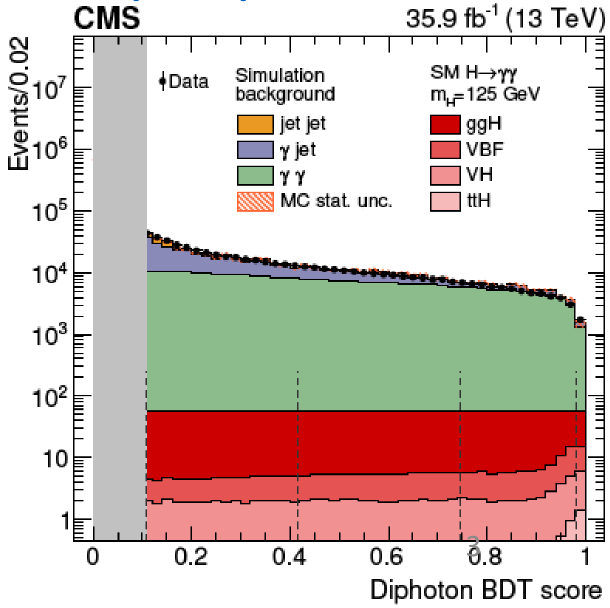
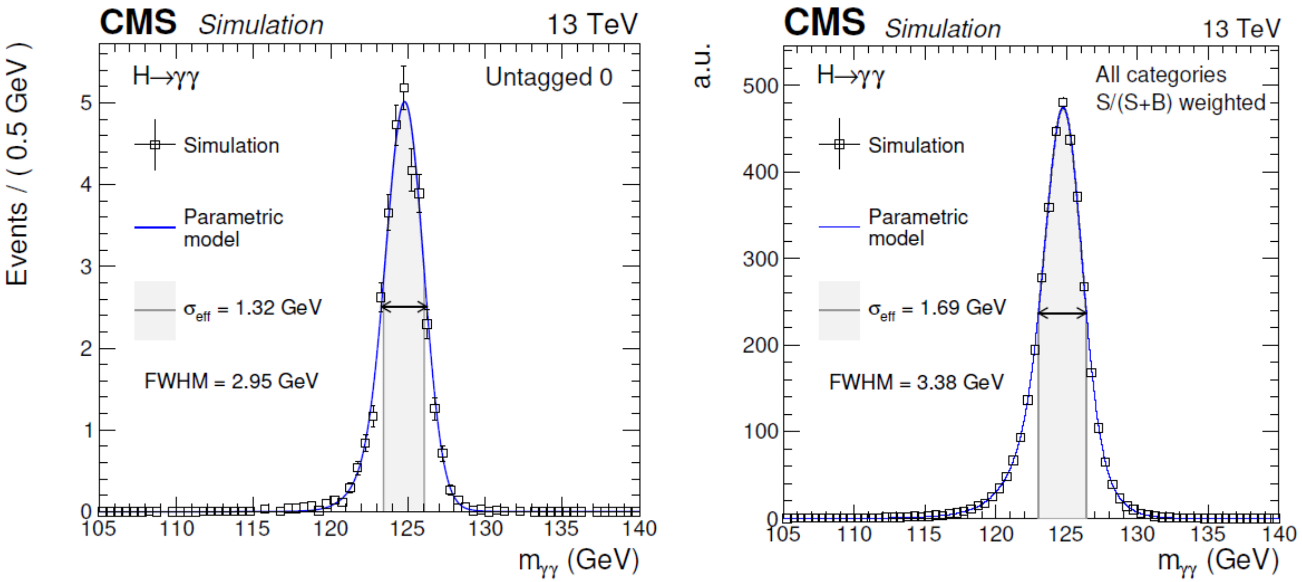




Analysis strategy (cont.)

- **Signal modeling :** full parametric **signal** model from **MC** simulation
  - ✓ All the corrections (reweighting, data/MC SFs, …) applied
  - ✓ *Sum of **n-Guassian** functions (n<=5)*
  - ✓ Physical nuisances allowed to float
- **Bkg modeling**
  - ✓ For each event category, use **different functional forms** (sums of ***exponentials***, sums of **power law** terms, ***Laurent*** series and Bernstein ***polynomials***)
  - ✓ Background functional forms treated as **discrete nuisance parameter** in final minimization: “envelope” method or ***discrete profiling method*** [2015 JINST 10 P04015]
- **Signal are extracted** by a simultaneous maximum-likelihood fit to the **diphoton mass** in all event classes



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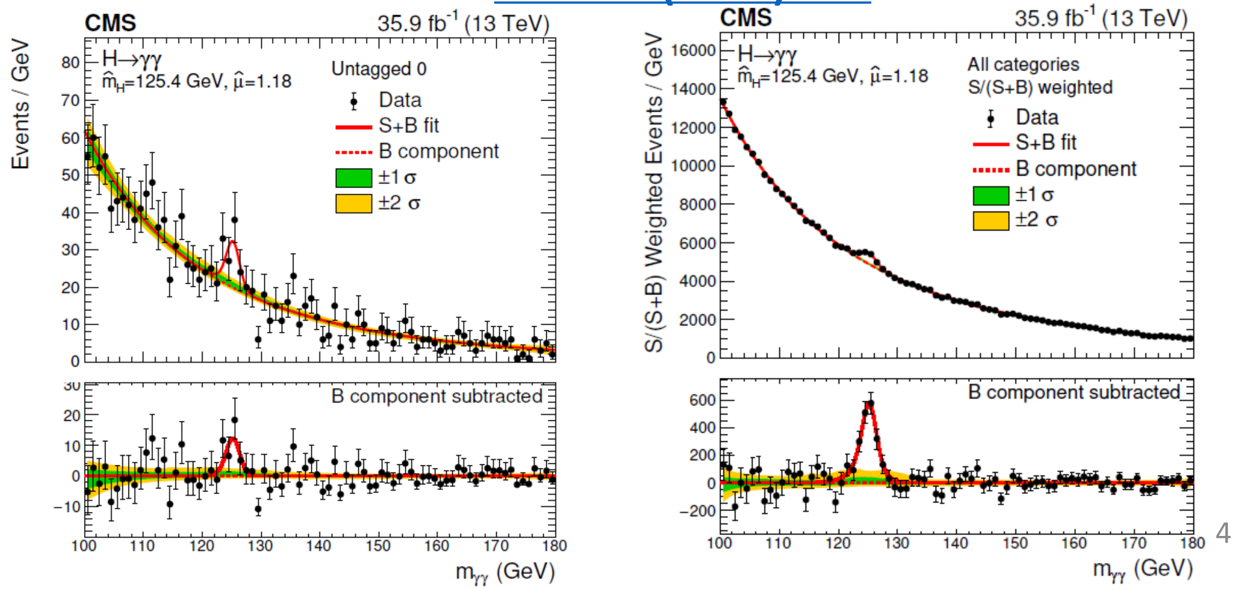
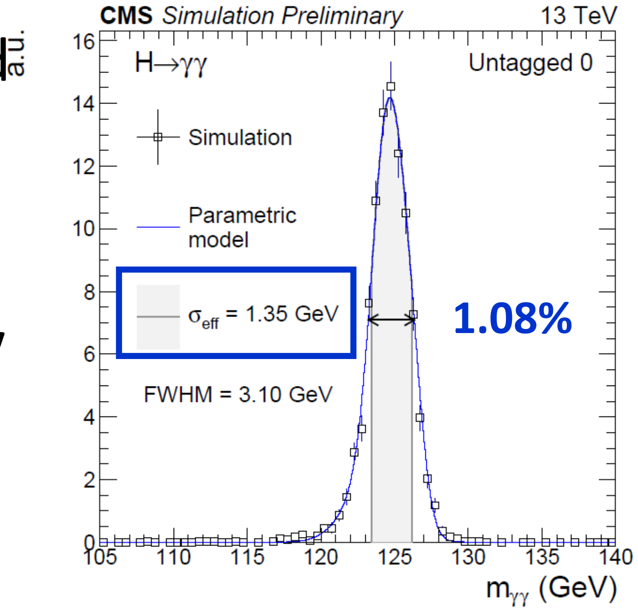
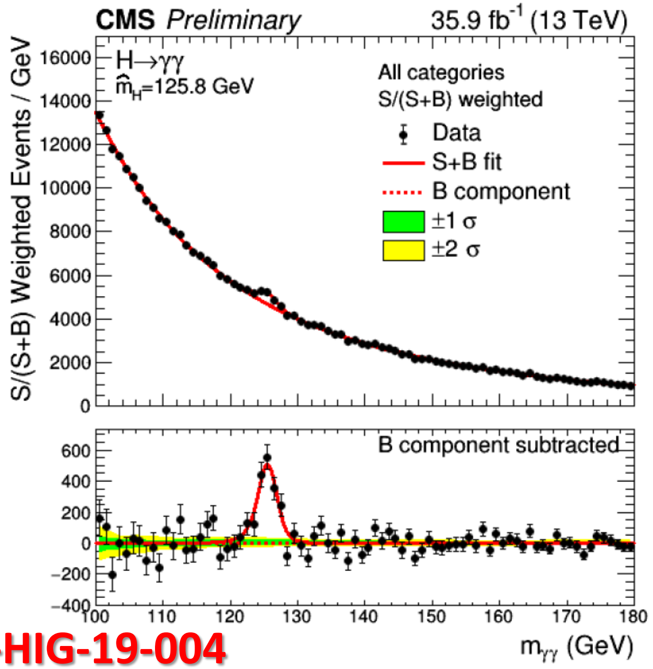


1. Higgs mass

- With **2016 legacy data**, events categorized into **3 VBF and 4 Untagged** (mainly ggH and all other events) categories
- Special efforts made to correct the **energy scale more precisely** than before
  - ✓ **Improved detector calibration** -> good agreement of the input variables to the energy regression correction
  - ✓ **More precise (granular Run-η-R9-pT dependent) scale correction**
- Photon energy scale systematics
- Additional uncertainties assigned to deal with e-γ differences : radiation damage induced non-uniformity of light collection





CMS-PAS-HIG-19-004

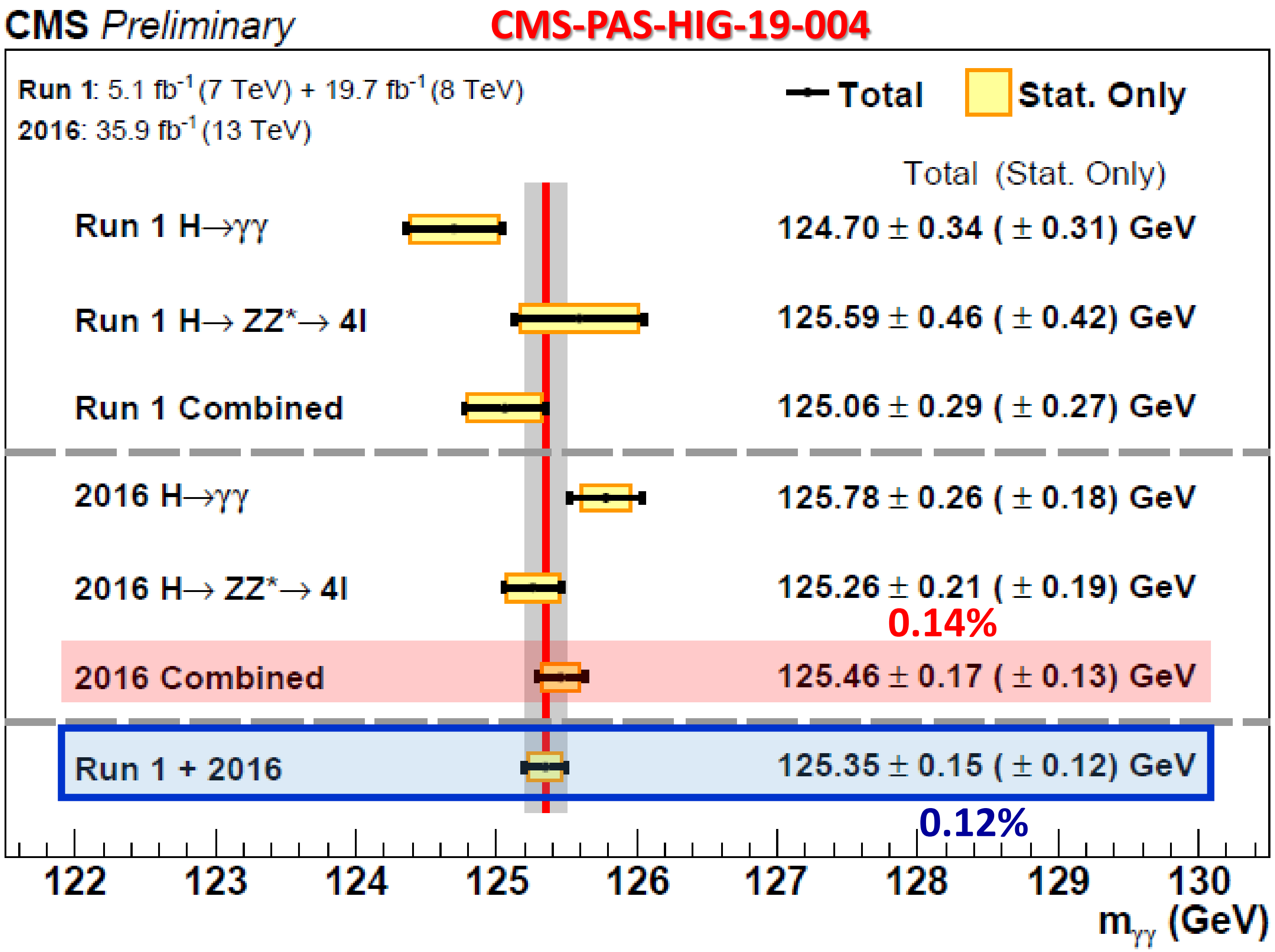
$$m_H = 125.78 \pm 0.26\ (0.18\ (\text{stat}) \pm 0.18\ (\text{syst}))\ \text{GeV}$$

0.21% precision

Source	Contribution [GeV]
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Non-uniformity of the light collection	0.11
Statistical uncertainty	0.18
Total uncertainty	0.26

1. Higgs mass (cont.)

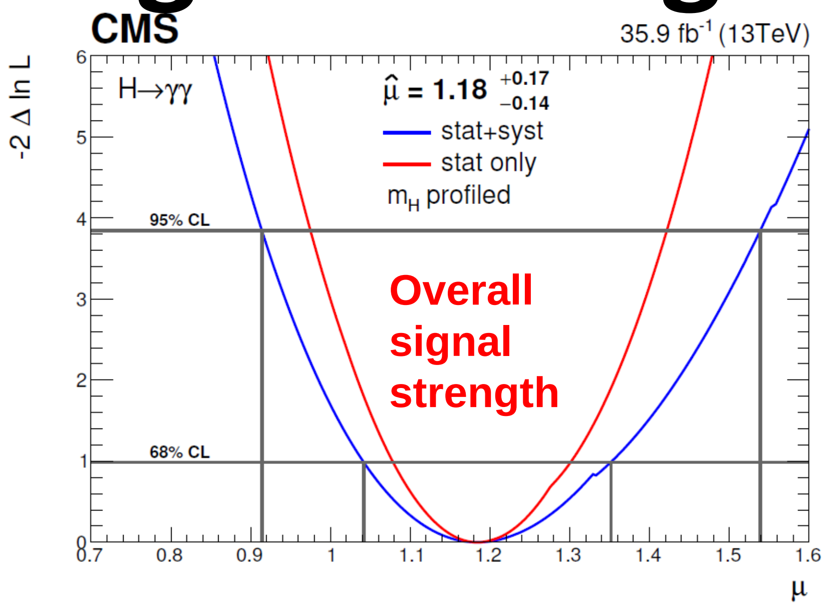
- Combination with the **H→ZZ* → 4l** mass measurement with the 2016 data set, then with the **Run 1** data set
- Between both channels, **luminosity** uncertainty is fully correlated
- Uncertainties in the **e/γ energy scale** between both channels are treated as uncorrelated
  - ✓ Pseudo-experiments show that, treating them as uncorrelated would **not bias the best-fit m_H value**, but would lead to an **underestimation of the total uncertainty** on m_H by at most 5%.
  - ✓ To be conservative, **increase the total uncertainty by 5%** for 2016 combination and Run 1 + 2016 combination.

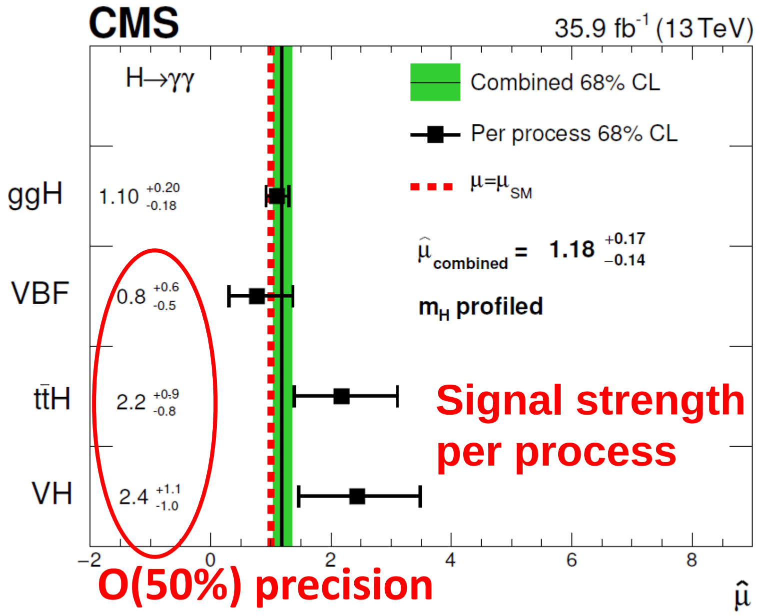


Best result up to now

2. Signal strength

- Signal strength modifier (μ) is defined as the ratio between the **measured signal cross section** and the **SM expectation**





O(50%) precision

- **Overall signal strength** ~14% precision

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

theoretical uncertainties and photon identification BDT score

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

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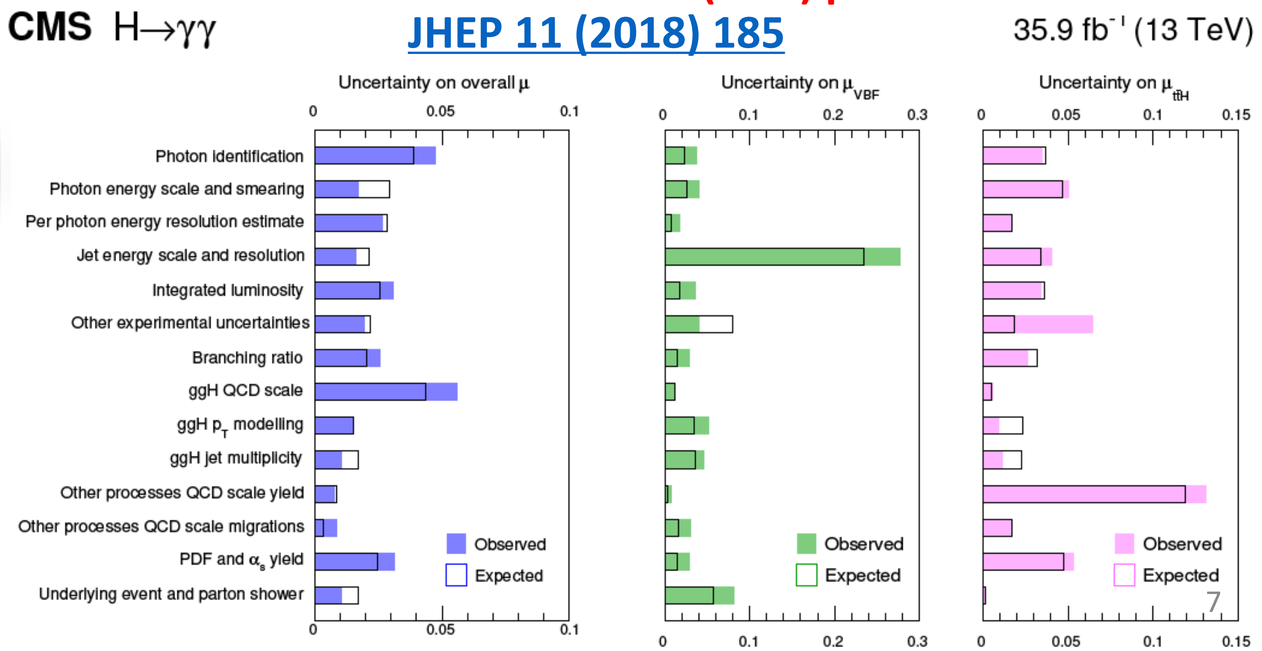
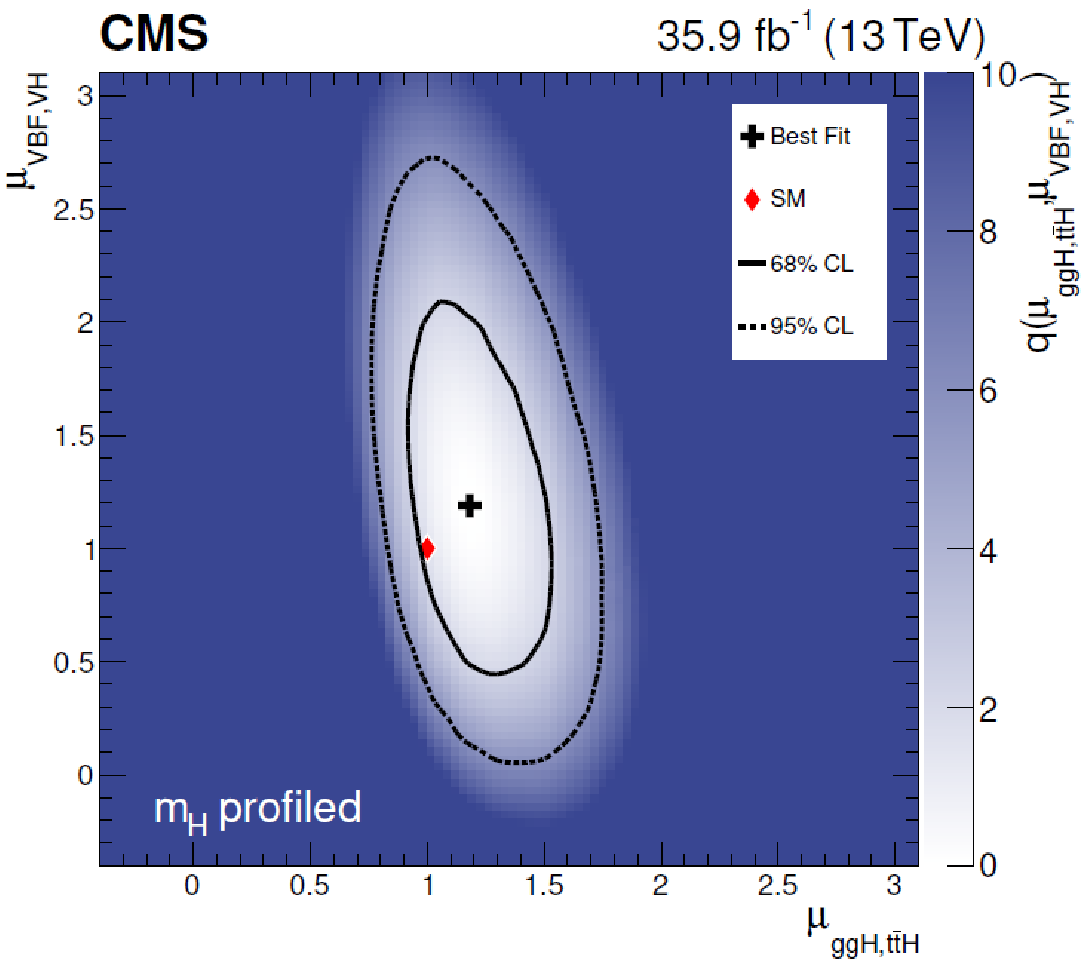


2. Signal strength (cont.)

- Signal strength modifier **$\mu_{ggH,ttH}$ vs $\mu_{VBF,VH}$** : to separates fermionic production modes (ggH+ttH) from vector boson production modes (VBF+VH)
- A **two-dimensional** likelihood scan
- **Result consistent with the SM expectation**



$$\widehat{\mu}_{\mathrm{ggH,t\bar{t}H}} = 1.19^{+0.22}_{-0.18} \qquad \widehat{\mu}_{\mathrm{VBF,VH}} = 1.21^{+0.58}_{-0.51}$$

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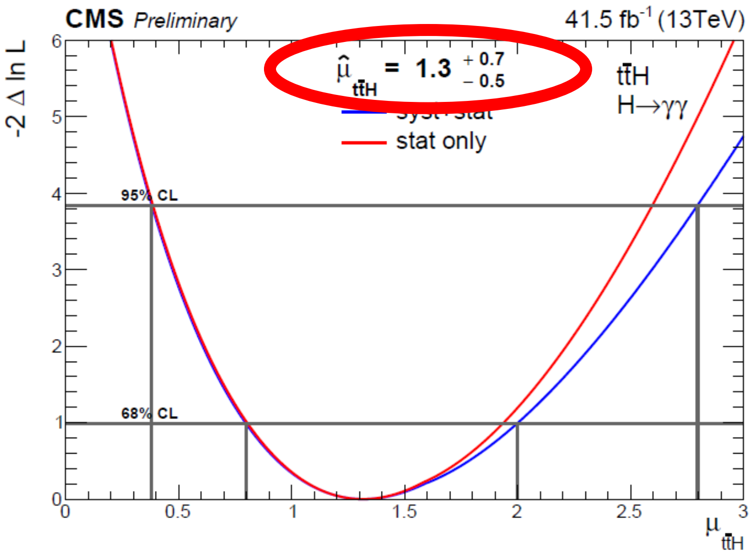
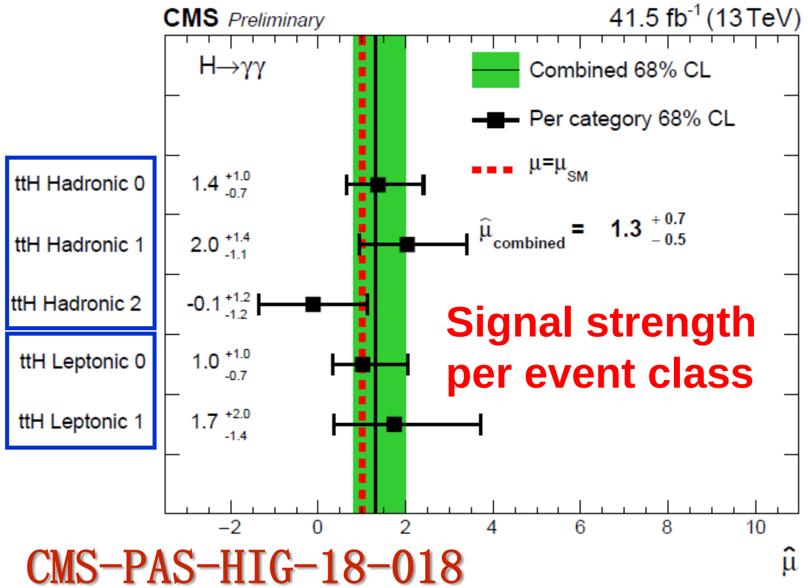
2. Signal strength of ttH

- **ttH measurements**
  - ✓ **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 ttH observation** with various decay channels combined (2016 + Run1 data sets)

- Measured **ttH→γγ with 2017 datasets and combined with 2016 datasets**

- **2017 analysis** use **BDT** to reject most non-ttH and non-resonant background
  - ✓ 2 leptonic event classes : lepton multiplicity and leptonic BDT score
  - ✓ 3 hadronic event classes : hadronic BDT score





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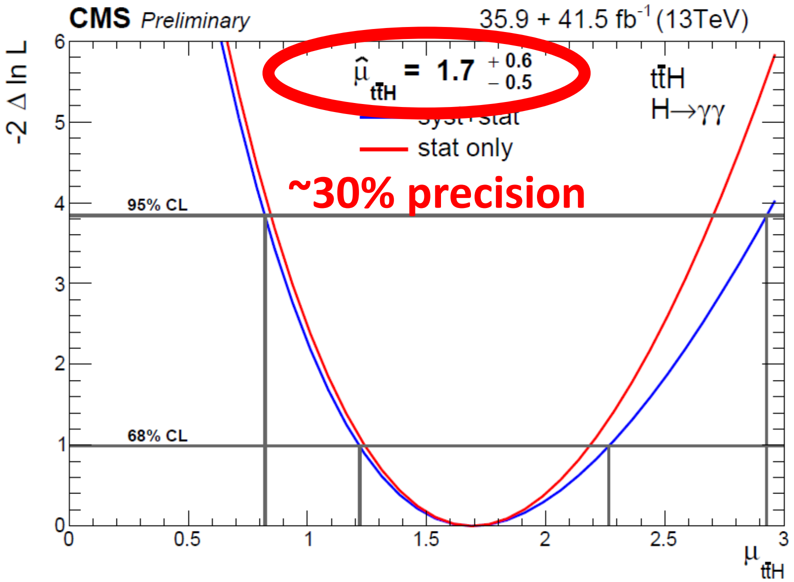


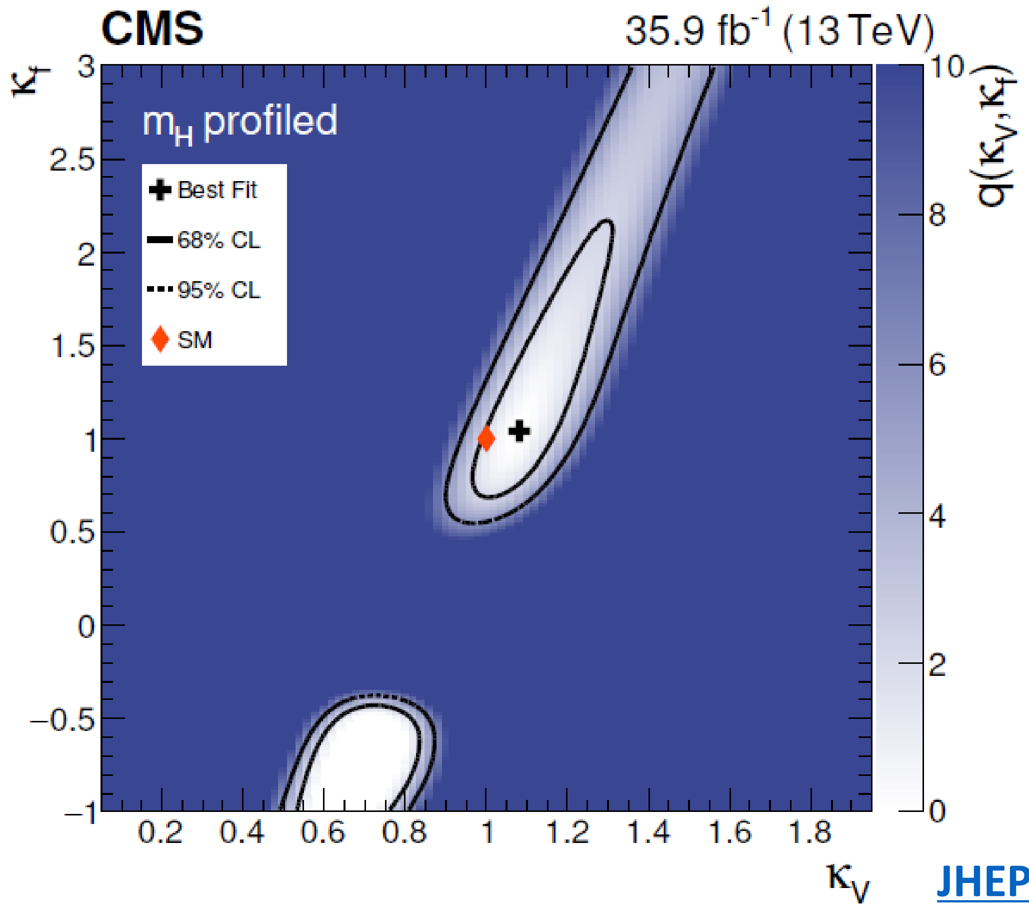
- **Combined (2016+2017) significance**: **4.1σ obs. (2.7σ exp.)**
- Dominant uncertainties
  - ✓ Theoretical: QCD scale uncertainties, PDF, α_S, Br(H→γγ)
  - ✓ Experimental: photon ID, JES/JER, b-discriminant

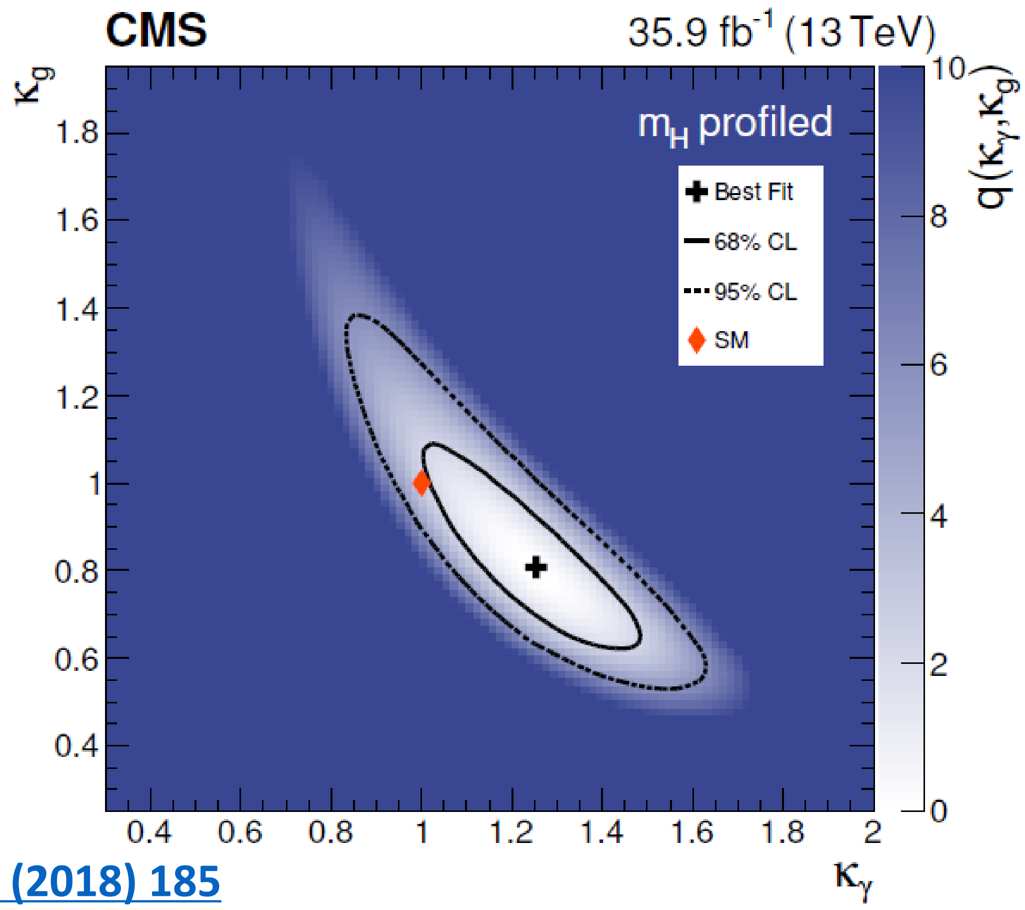
3. Couplings

"κ framework" : measurements of **coupling modifiers** to **vector bosons** and **fermions** **(κ_V, κ_f)** and to **photons** and **gluons** **(κ_γ, κ_g)**

Compatible with SM

$$\sigma(i \to H \to f) = \kappa_i^2 \sigma_i^{\rm SM} \frac{\kappa_f^2 \Gamma_f^{\rm SM}}{\kappa_H^2 \Gamma_H^{\rm SM}} \qquad \sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$





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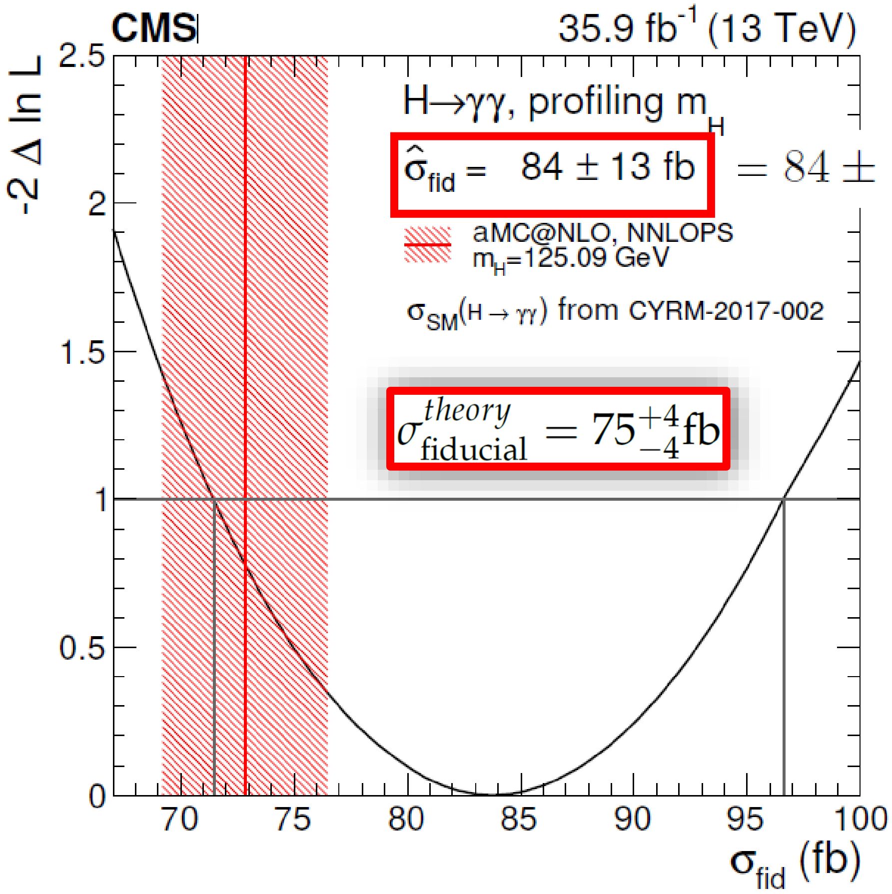
4. Fiducial cross-sections

- **Fiducial cross section** :
  - ✓ Fiducial volume to **minimize model dependency**
  - ✓ 3 untagged event categories based on expected **mass resolution**

Fiducial volume:
$p_T^{\gamma1(\gamma2)}/m_{\gamma\gamma} > 1/3\ (1/4)$
$|\eta^{\gamma1(\gamma2)}|<2.5$ excluding
$1.4442<|\eta^{\gamma1(\gamma2)}|<1.566$
$Iso_{gen1,2} < 10$ GeV ($\Delta R=0.3$)



$$= 84 \pm 11\,(\mathrm{stat}) \pm 7\,(\mathrm{syst})\ \mathrm{fb}$$

$$\sigma_{\mathrm{fiducial}}^{\mathit{theory}} = 75^{+4}_{-4}\mathrm{fb}$$

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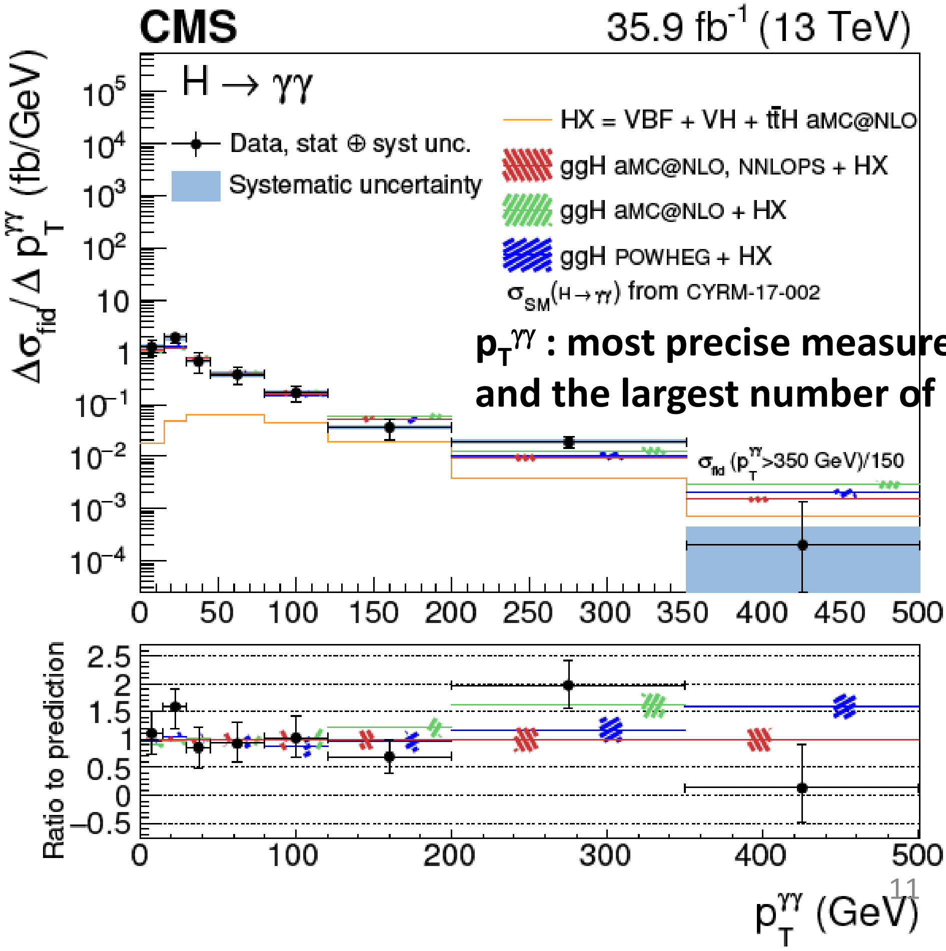
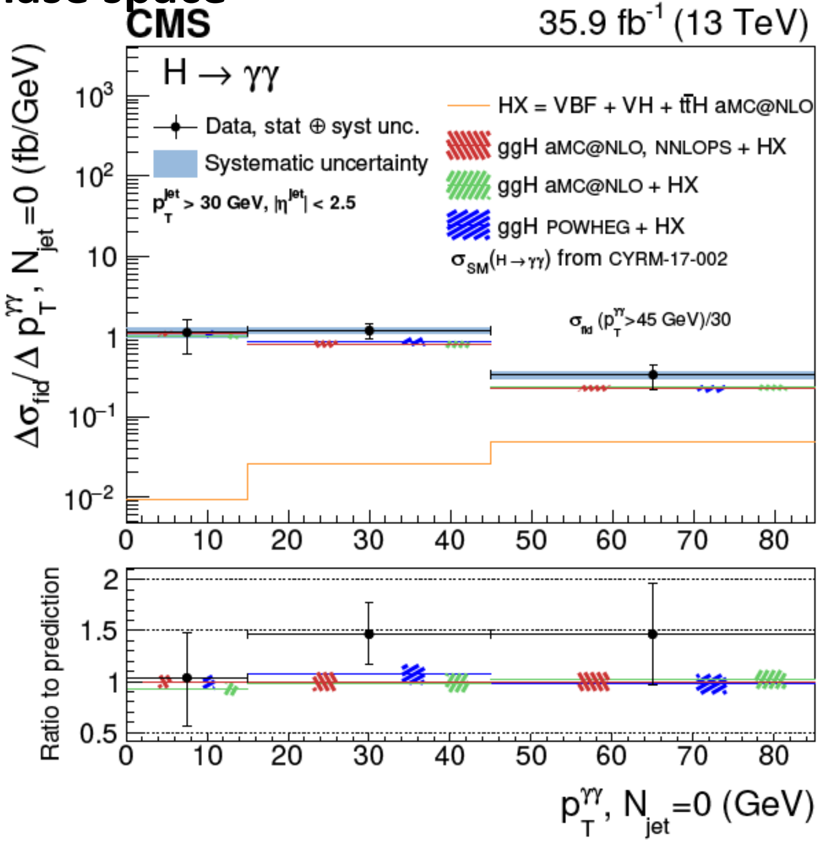
- **Differential fiducial cross sections**
  - ✓ **Single** differential XS with $p_T(\gamma\gamma)$, N(jets), $|y^{\gamma\gamma}|$, $|\cos\theta^*|$,... compared to **different simulation programs** (histograms)



$p_T^{\gamma\gamma}$: **most precise measurement and the largest number of bins**

4. Fiducial cross-sections (cont.)

- **Differential fiducial cross sections**
  - ✓ **Single** differential XS with pT(γγ), N(jets), $|y^{\gamma\gamma}|$, $|\cos\theta^*|$,…
  - ✓ **Double** differential XS with pT(γγ) and N(jets)
  - ✓ Differential cross section for **different regions of phase space**



Fiducial volume:
$pT^{\gamma1(\gamma2)}/m_{\gamma\gamma}$ > 1/3 (1/4)
$|\eta^{\gamma1(\gamma2)}|$<2.5 excluding
1.4442<$|\eta^{\gamma1(\gamma2)}|$<1.566
$Iso_{gen1,2}$ < 10 GeV (ΔR=0.3)

On top of these, **other cuts** are imposed depending on the observable under study

Jet:
PT>30GeV
ΔR(γ, jet)>0.4
|η|< 4.7 when two jets
|η|< 2.5 when 1 hadronic jet
|η|< 2.4 for b-tagged jets

Leptons:
PT>20GeV, |η|< 2.4 and not in the gap for electrons
ΔR(γ, l)>0.35

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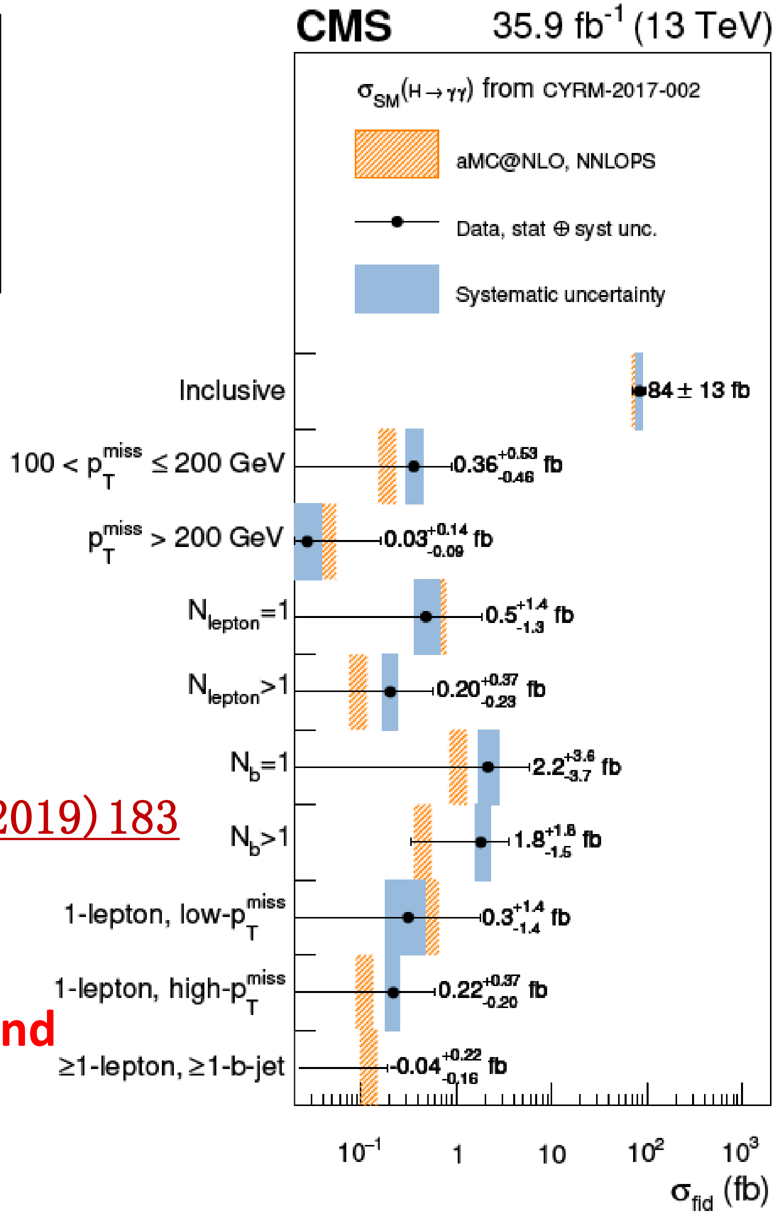
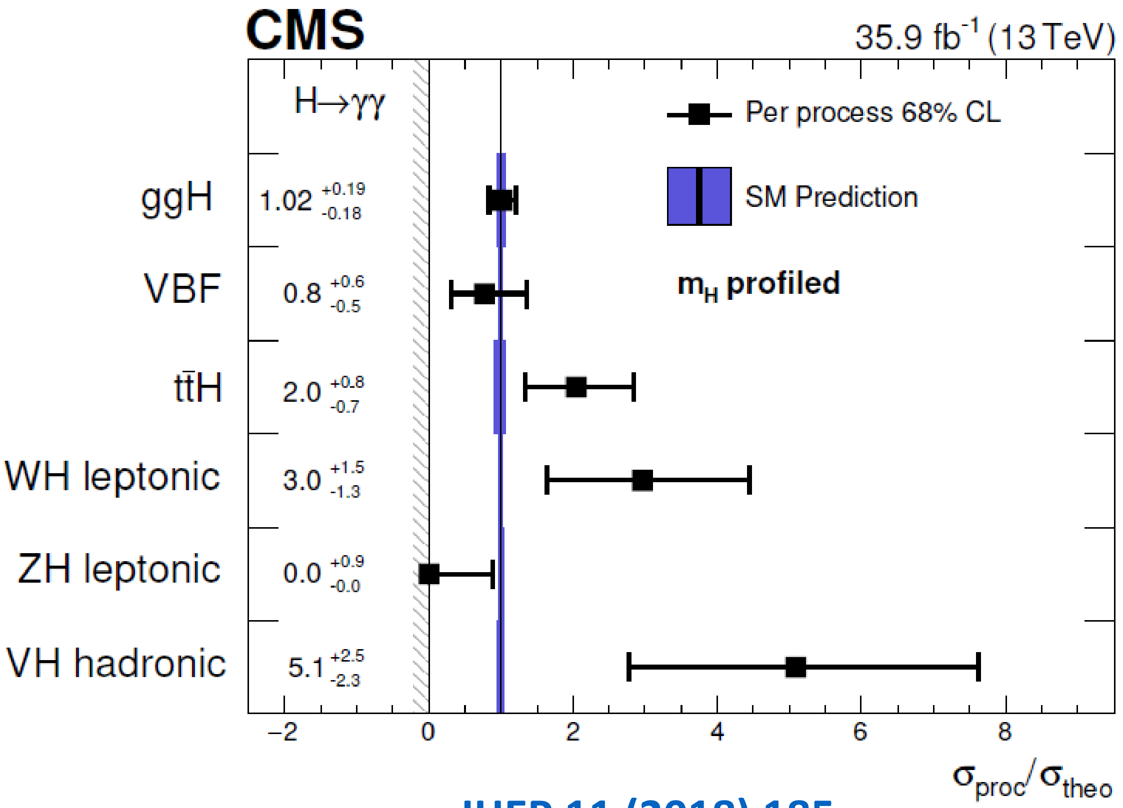


Measurements are found in agreement with the theoretical predictions

5. Simplified template cross sections

- **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 kinematic phase space (bins)

- **Stage 0 STXS** : compatible with SM
  - ✓ Higgs boson rapidity to be less than 2.5
  - ✓ Ratios are measured for the ggH, VBF, ttH, and VH production processes
  - ✓ VH split into WH leptonic, ZH leptonic, and VH hadronic



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5. Stage 1 STXS

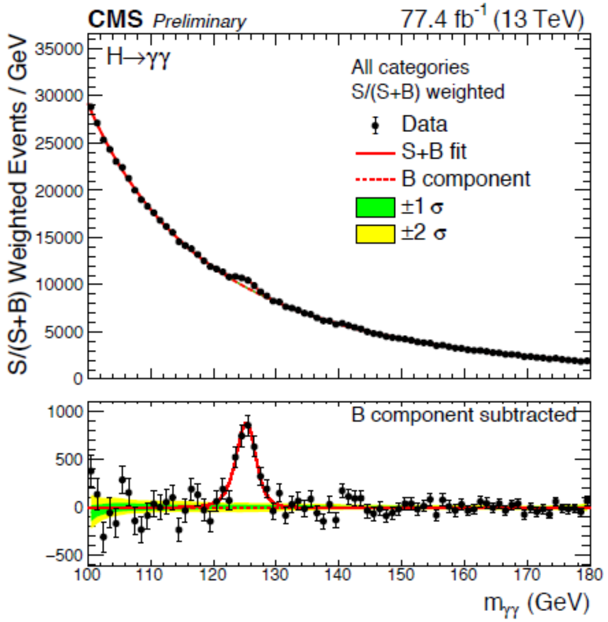
- **With 2016 + 2017 data sets**

CMS-PAS-HIG-18-029

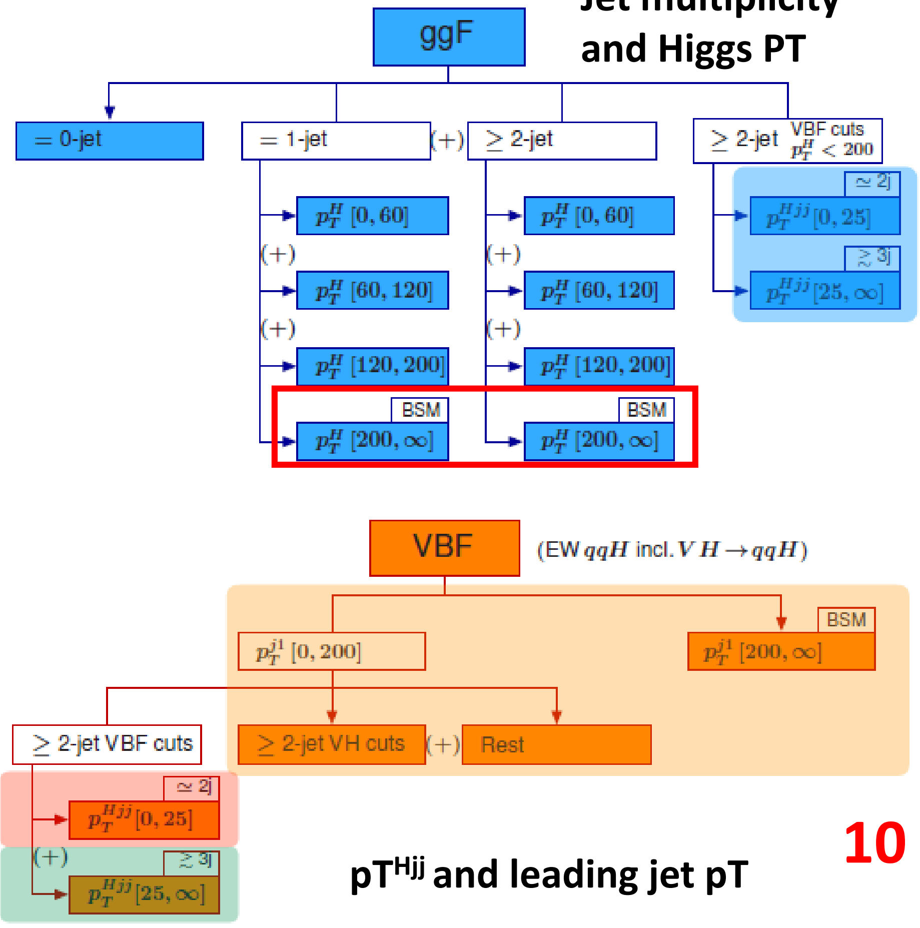
- **Target ggH & VBF production modes**
- **VBF and ggH categories**

$\Rightarrow$ split to match **stage1 bins**

$\Rightarrow$ split to improve **S/B**



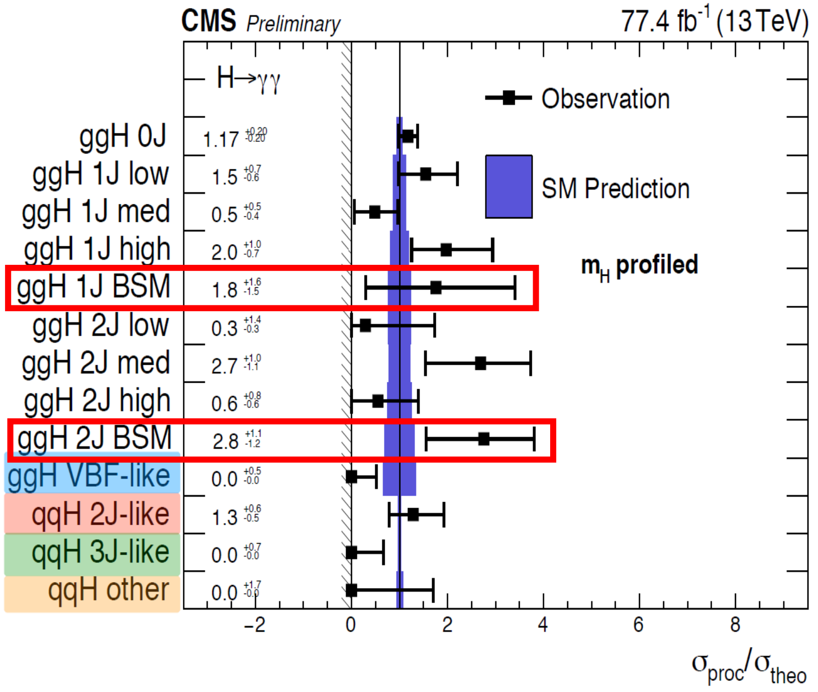
Jet multiplicity and Higgs PT



p_T^{Hjj} and leading jet pT

Inclusive σ/σ_{SM}

ggH = $1.15^{+0.15}_{-0.15}$ **VBF =** $0.8^{+0.4}_{-0.3}$



Better than earlier results of 35.9 fb^{-1} data:

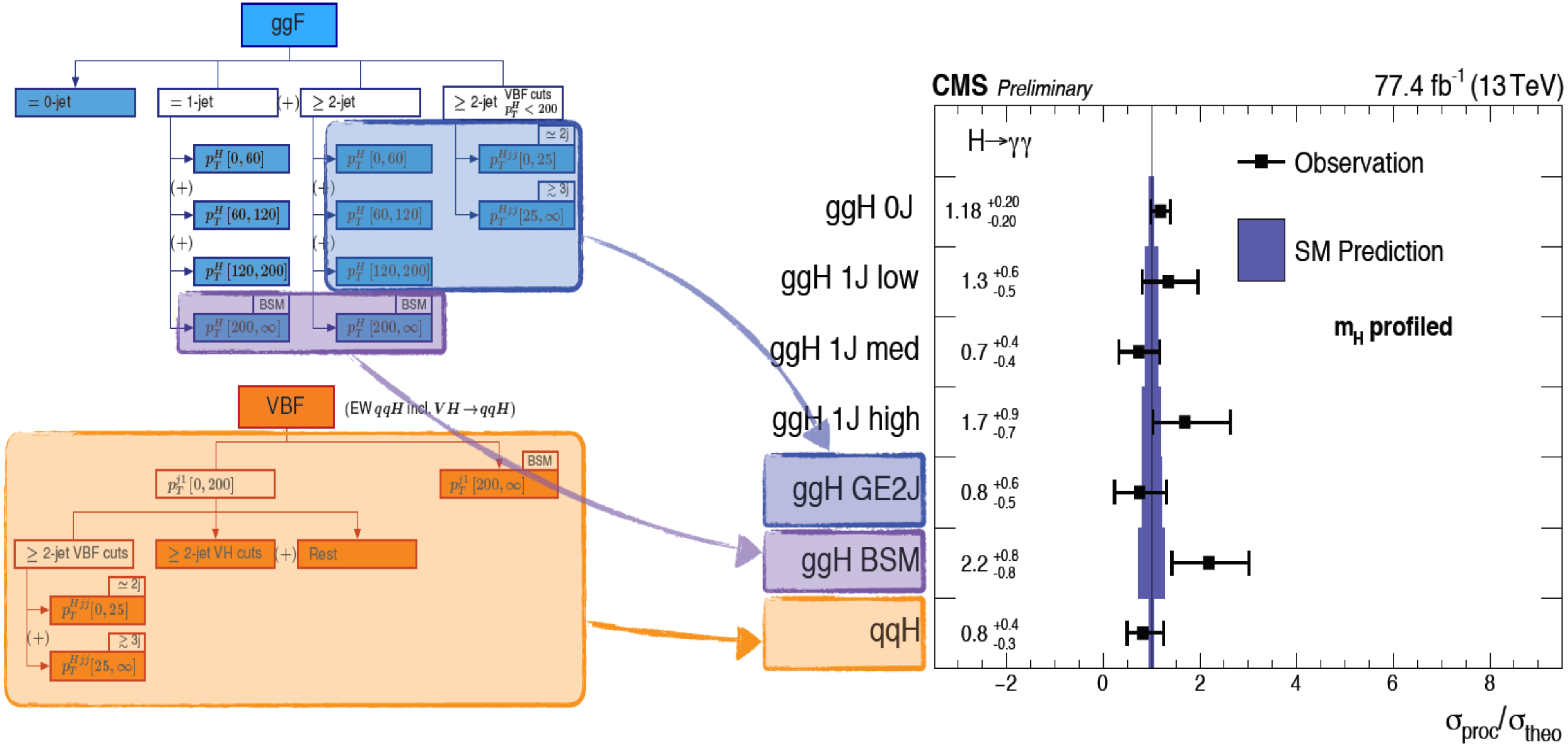
ggH=$1.10^{+0.20}_{-0.18}$, VBF=$0.8^{+0.6}_{-0.5}$

10 ggH + 3 VBF parameters

5. Stage 1 STXS (cont.)

- Some signal bins are merged to **reduce statistical uncertainty**
- Combined fit with **seven parameters** of interest
- Having the most granular possible set whilst maintaining an **uncertainty of less than 100%** of the SM prediction
- **qqH: same as stage 0**

CMS-PAS-HIG-18-029



6 ggH + 1 VBF parameters

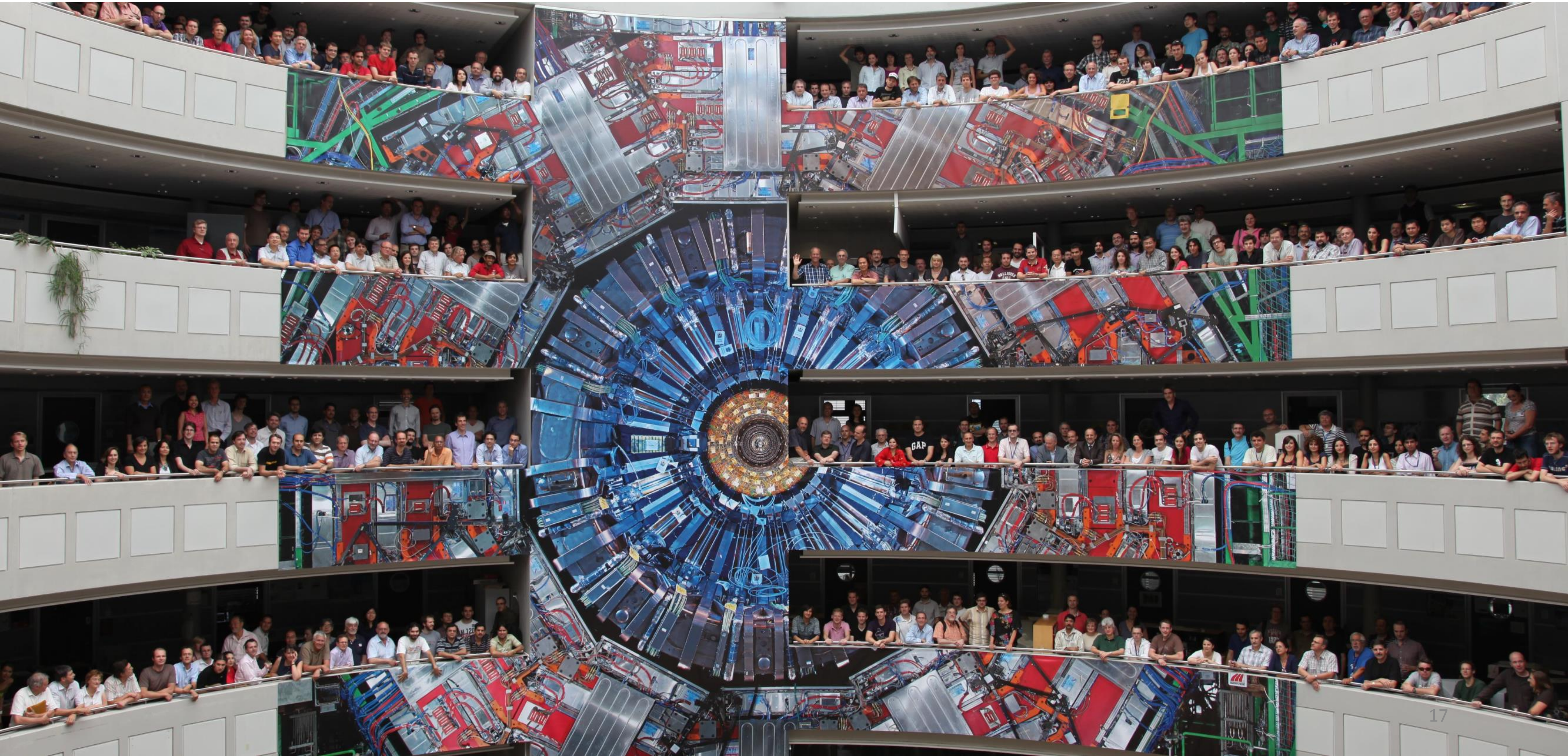
Summary

- **Higgs boson properties, measured in diphoton final states ($H\rightarrow\gamma\gamma$) at CMS, have been presented**
  - ✓ Measured **mass** with **2016 legacy data** and gave the **best precision result (0.12%) of Higgs boson mass** when combined with 2016 $H\rightarrow ZZ^* \rightarrow 4l$ and Run-1 results
  - ✓ Precision of measured **overall signal strength** is about 14% with 2016 data set
  - ✓ **Improved precision** in Higgs measurements with 77.4fb^{-1} instead of 35.9fb^{-1} :
    - ➔ ttH signal strength improved from ~40% precision to ~30% with 4.1σ observed
    - ➔ VBF signal strength improved from ~60% precision to ~40%
    - ➔ Results of STXS stage1

- **All results are compatible with the Standard Model**

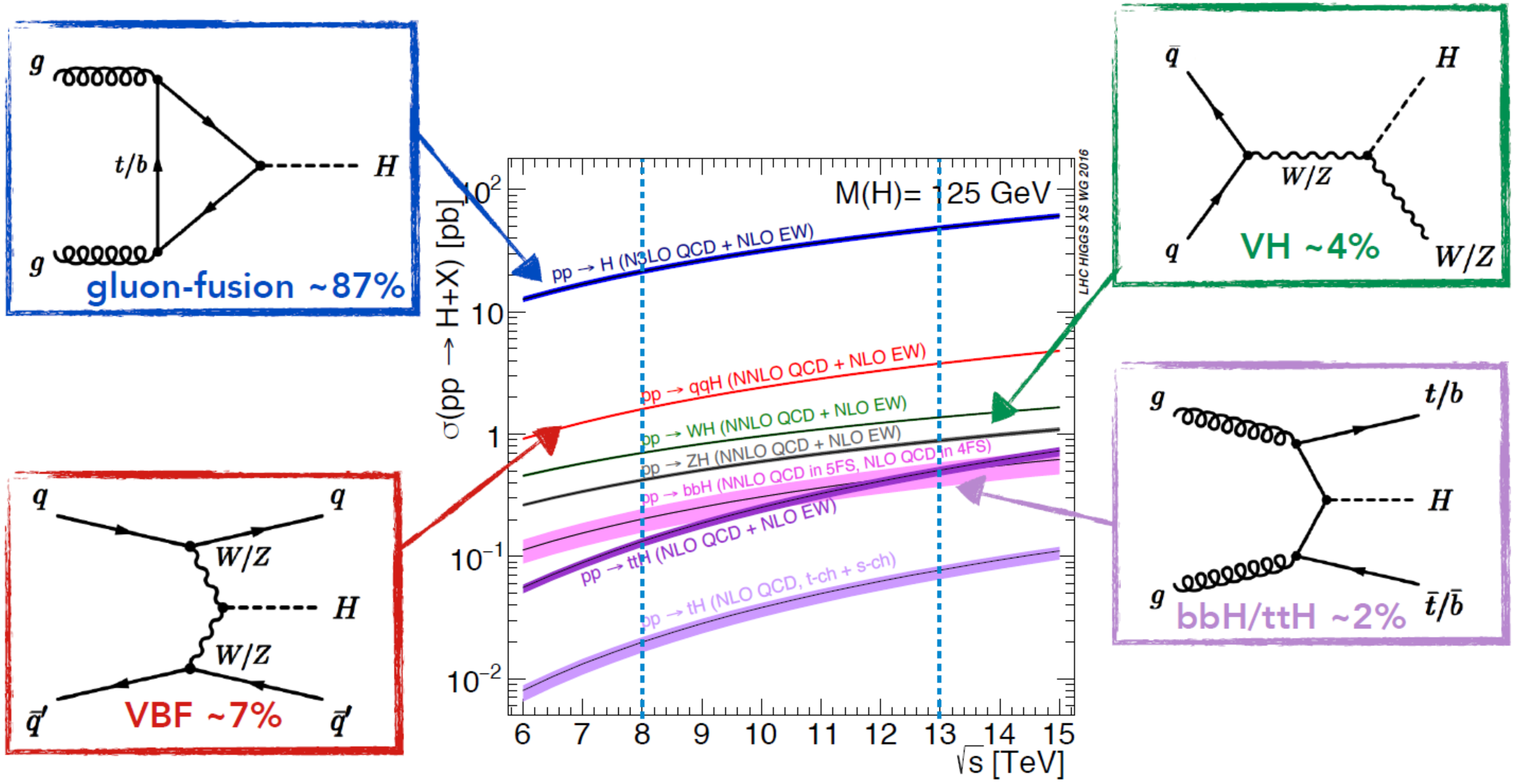
- All results are being updated with **full Run-2 dataset** → **Stay Tuned** !!
  - ✓ **ttH + CP** measurements with full Run-2 : will release the results soon
  - ✓ Updated **STXS** analysis : aim to release a PAS for Moriond
  - ✓ **Signal strength, differential cross sections, mass**, …

Thanks for your attention!



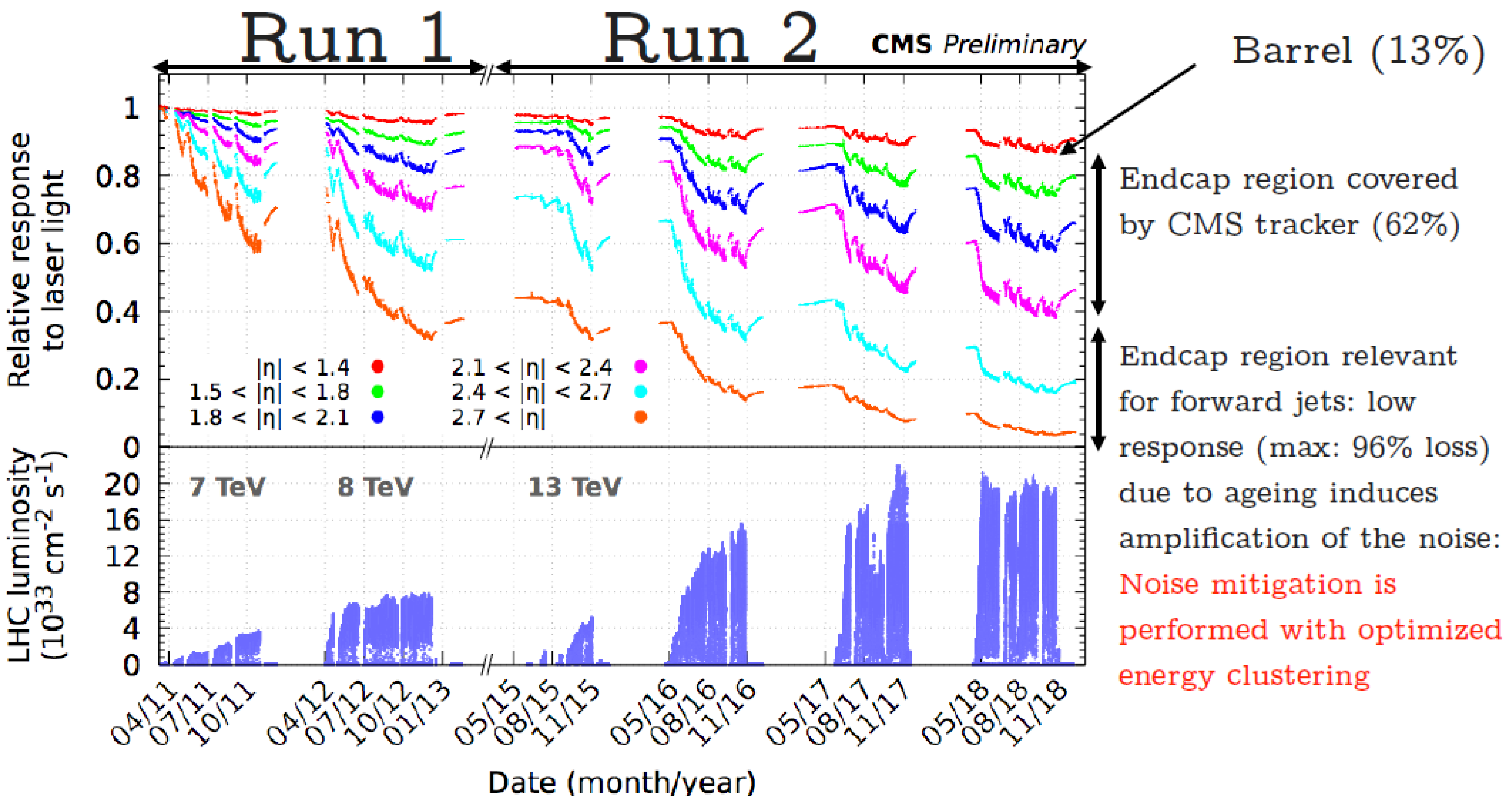
Backup slides

Higgs production



- **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**

ECAL response changes over Run 1 and Run 2



Significant response changes (crystal+photodetector) due to LHC irradiation

Monitoring of each channel via a dedicated laser system, is performed every 40 minutes and corrections are provided within 48 hours.

These are crucial to **maintain stable ECAL energy scale and resolution** over time

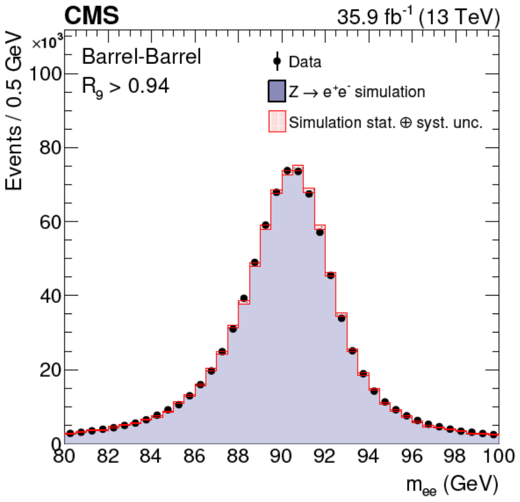
Some detailed Analysis strategy

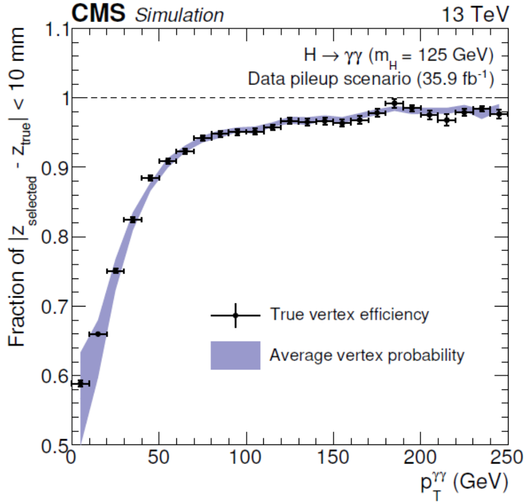
Analysis flow

- 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**

Common tools for different H→γγ measurements

Photon Energy scale and resolution validated with Z→ee





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

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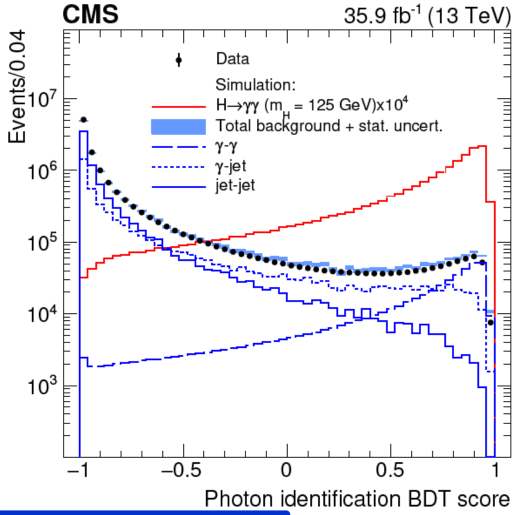
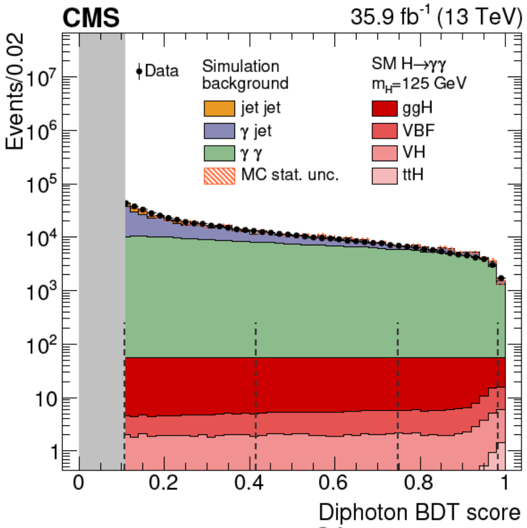
Photon ID BDT to discriminate prompt/fake photons



Diphoton BDT to discriminate signal and bkg



H→γγ categorization by productions

ttH (leptonic + hadronic)

- (sub-)lead-photon $pT/m_{\gamma\gamma}$ >1/2(1/4), at least one lepton ($\ell=\mu,e$) away from Z peak
- at least two jets with pT>25GeV, |η|<2.5
- at least one of the jet is b-tag

- At least 3 jets + 1 b-jet
- Train an MVA on MC ttH vs MC diphoton using the input variables : N_{jets}, lead b-tag , sub-lead b-tag, lead p_T

Changed later to complicated BDT for ttH discovery

VH leptonic

- $W \to \ell\nu$ or $Z \to \ell\ell$
- (sub-)lead-photon $pT/m_{\gamma\gamma}$ >1/2(1/4)
- at least one lepton ($\ell=\mu,e$) away from Z peak
- ΔR(γ,μ (e)) > 0.5 (0.2)
- diphoton MVA > 0.5
- MET > 45 GEV (WH leptonic)

VH Hadronic

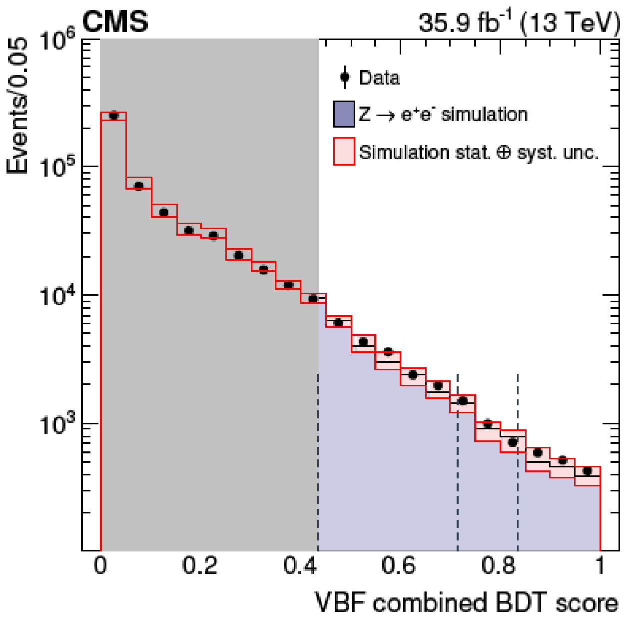
- $W \to jj$ or $W \to jj$
- (sub-)lead-photon $pT/m_{\gamma\gamma}$ >1/2(1/4)
- at least two jets
- p_T > 40 GeV, |η|<2.4, $|\cos\theta^*|$ < 0.5
- $60 < m_{jj}$ < 120 GeV

VH MET

- $W \to \ell\nu$ or $W \to \nu\nu$
- MET > 85 GeV
- ΔΦ(γγ,MET) > 2.4
- diphoton MVA > 0.79

VBF

- Require at least 2 jets with p_{T1} > 30GeV, p_{T2} >20 GeV, |η| < 4.7, m_{jj} >250 GeV
- A diphoton pair with (sub)lead $p_T/m_{\gamma\gamma}$ > 1/2(1/4)
- Construct a BDT to identify VBF dijet-like events using:
  - $p_T/m_{\gamma\gamma}$ of both photons, p_T of both jets, m_{jj}, $\Delta\eta_{jj}$, centrality variable, ΔΦjj,γγ, ΔRγj, ΔΦjj
- Final VBF classification combines dijet BDT with BDT estimating diphoton quality (see next slide)
- 3 VBF categories are then defined by sensitivity (VBF tag 0-1-2)



Remaining events fall into the untagged category : 4 untagged events in 2016

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Signal efficiency and fraction with 2016 data set

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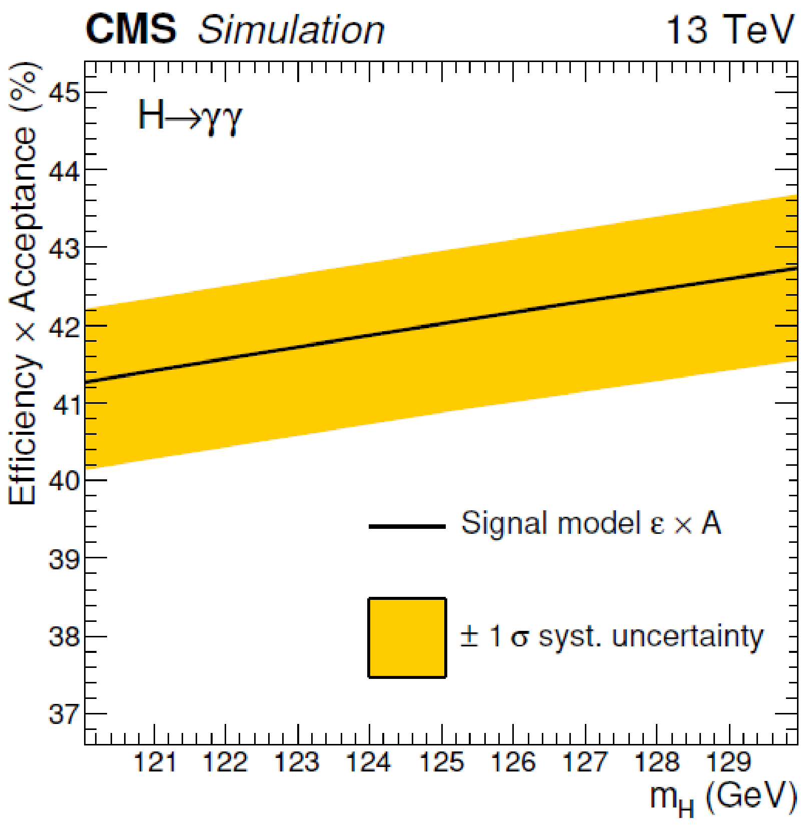
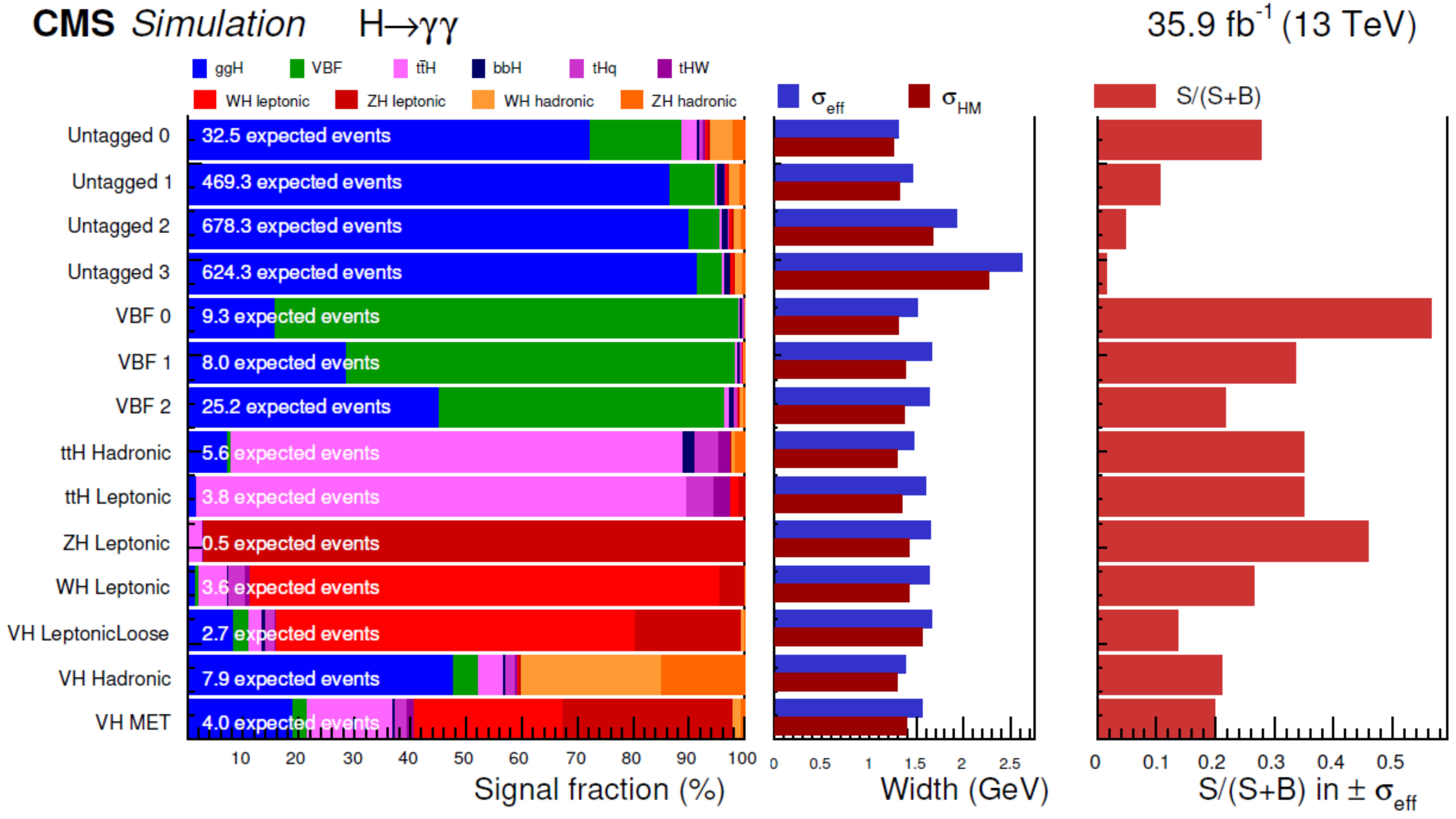
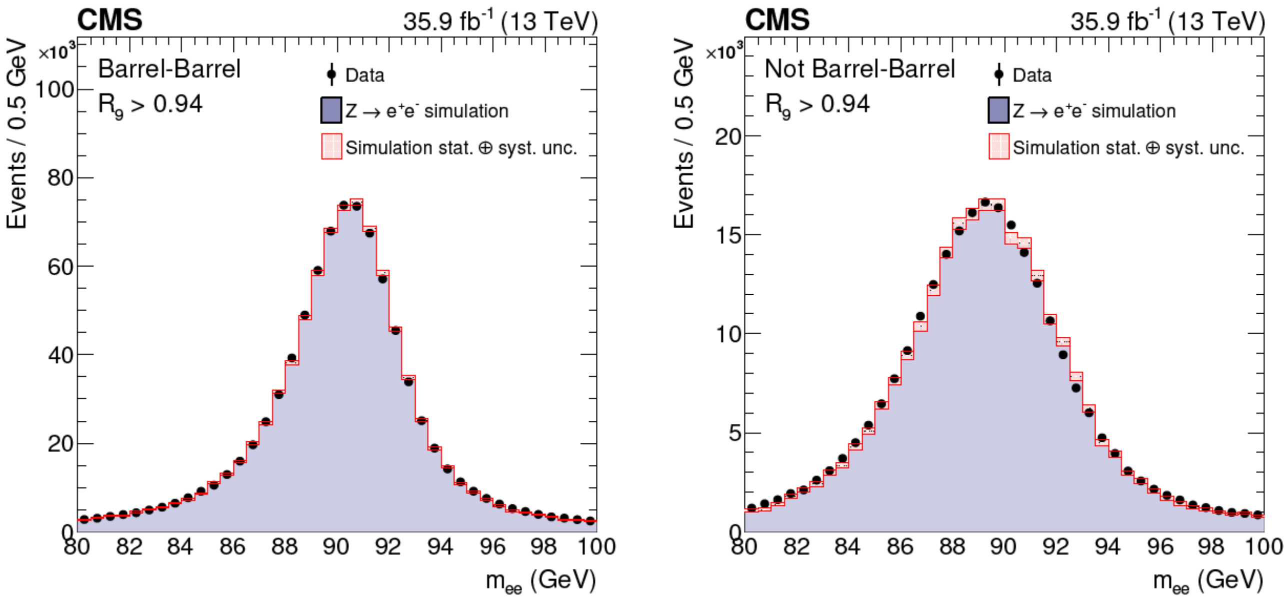




$m_{\gamma\gamma}$: Photon energy

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

- 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]



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

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

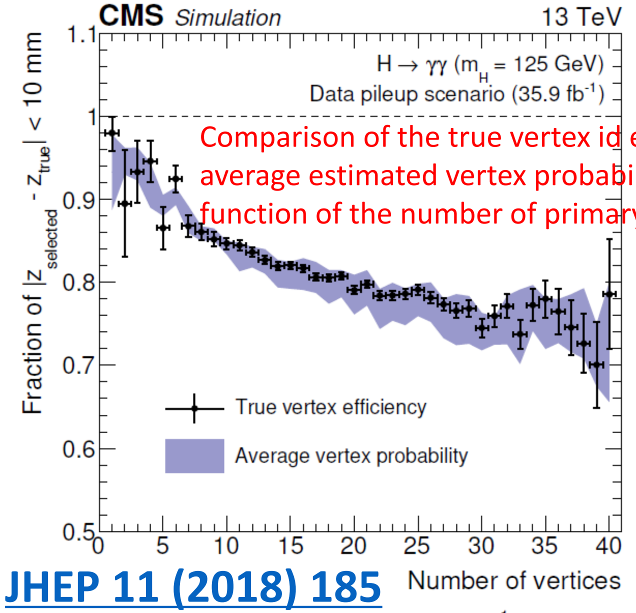
- **Multivariate approach (BDT) for vertex identification**
  - Vertex ID BDT: **kinematic correlations and track distribution imbalance**

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

  - 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



Averaged efficiency is about 81%

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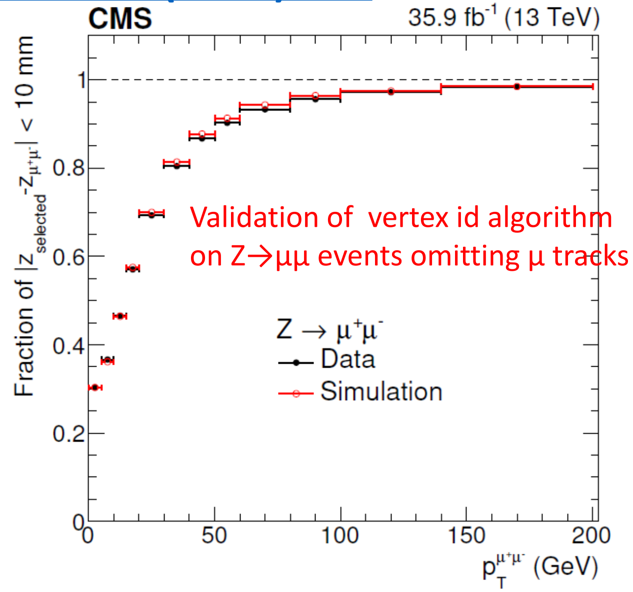

Photon identification

- **MVA based photon ID classifier (BDT)** to discriminate between prompt and fake photons
  - Shower shape variables: $\sigma_{i\eta i\eta}$, $cov_{i\eta i\phi}$, E2x2/E5x5, R9, η-width, ϕ-width, Preshower σ_{RR}
  - Isolation variables: PF Photon ISO, PF Charged ISO - wrt selected vertex and to the worst (largest isolation sum) vertex
  - ρ, η_{SC}, E_{RAW}

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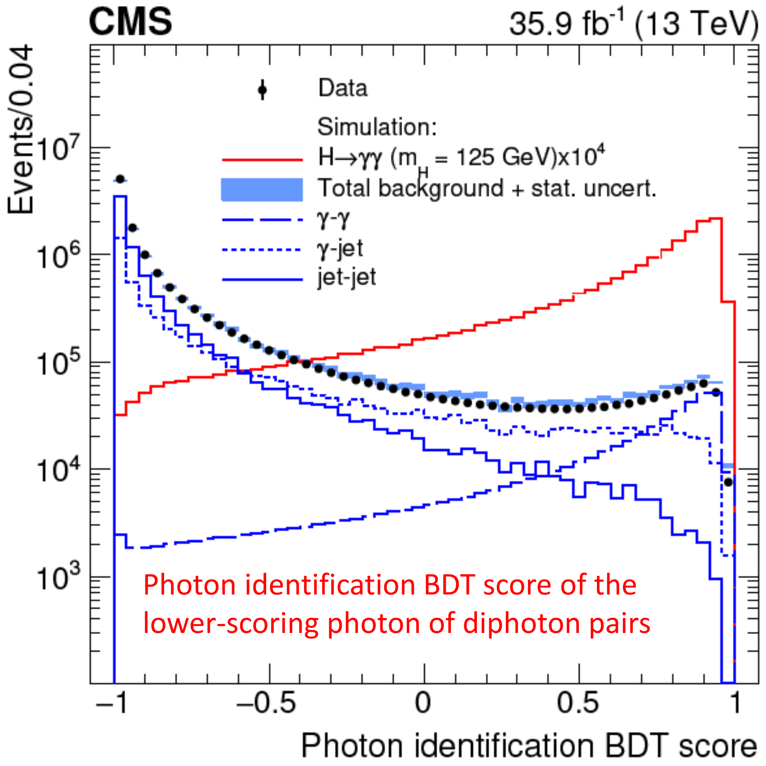
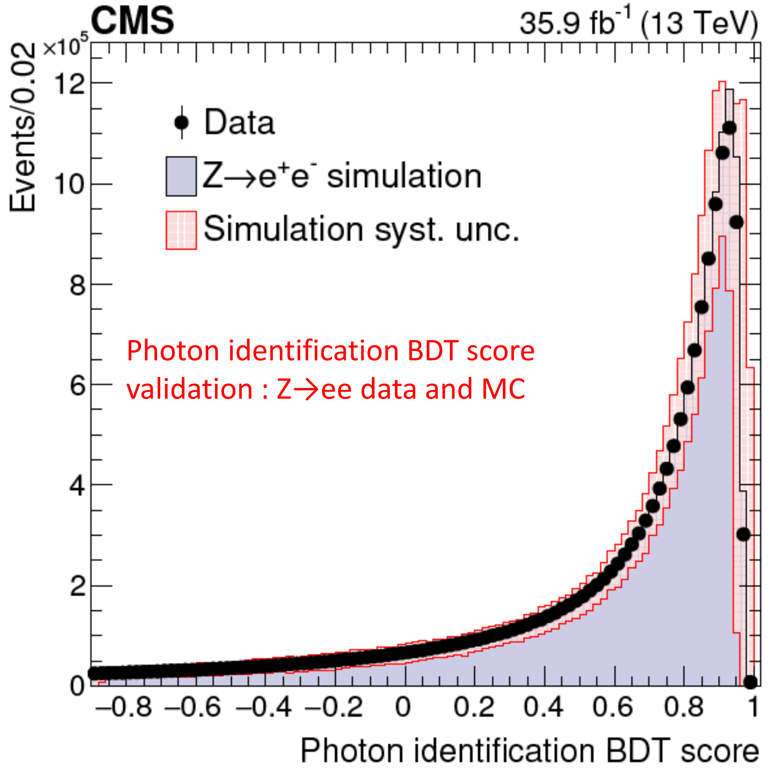




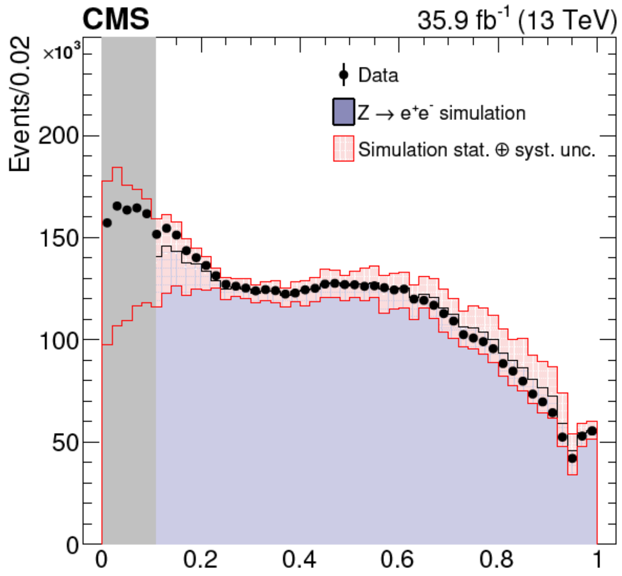
- Inputs and output of the MVA are **validated** on data and MC in **Z→ee** and **Z→μμγ** events

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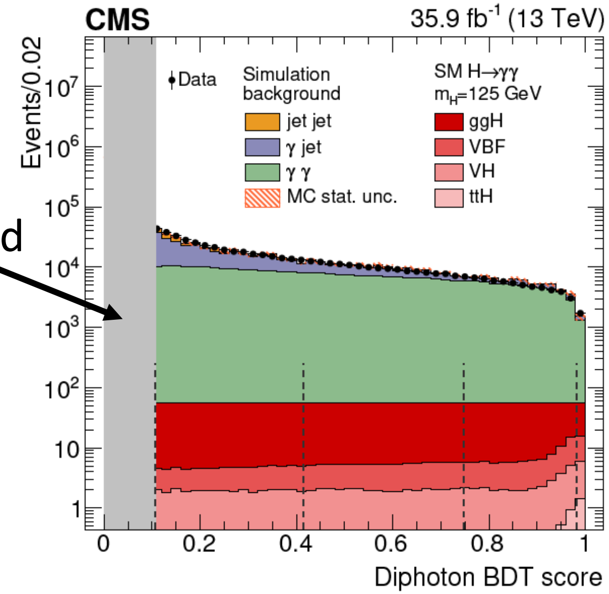
➢ **Validation** of Diphoton MVA is done on **Z→ee** events, with the electrons taken as photons

➢ 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

rejected



Higher BDT score gives better mass-resolution diphoton events

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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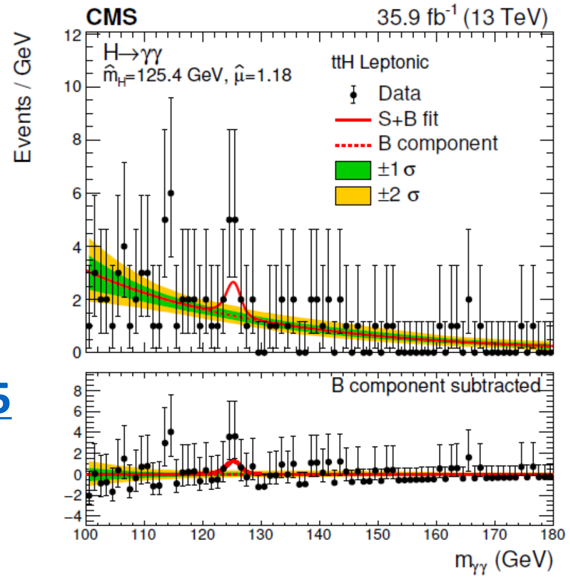
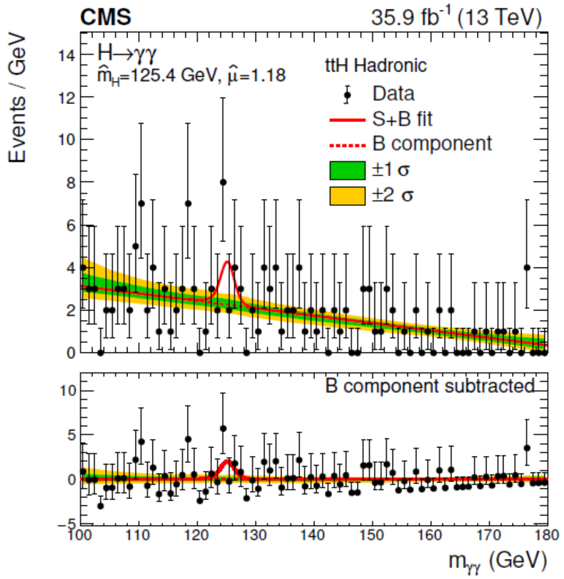
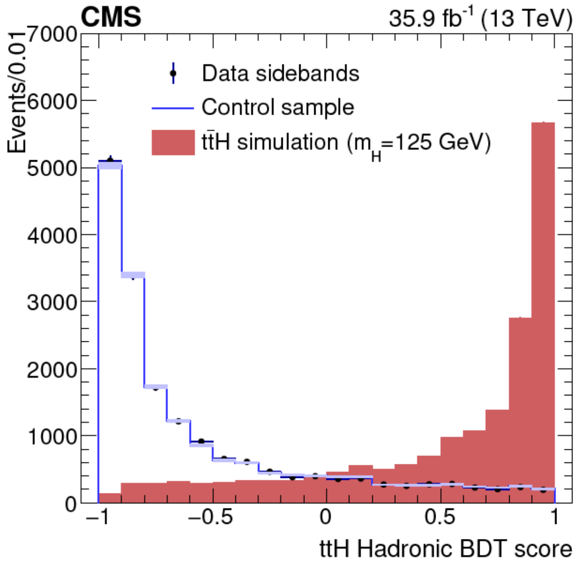






2016 H→γγ : VH

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

- **Muons**
  - p_T>20 GeV; $|\eta|$<2.4; "tight muon"; pf isolation < 0.25 (loose WP)
- **Electrons**
  - p_T>20 GeV; $|\eta|$<2.5; 1.442<$|\eta|$<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
  - $\Delta R(\gamma, l)$ >1.0
  - diphoton mva>0.28
  - <=2 jets

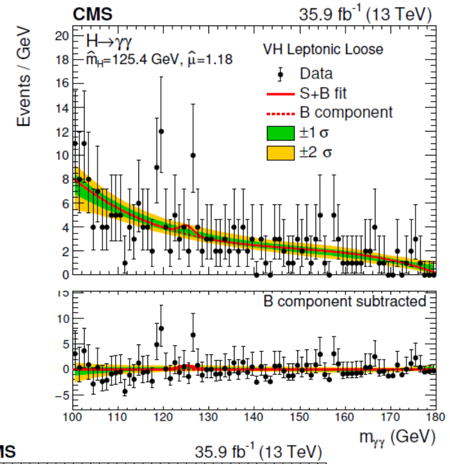
- **ZH leptonic:**
  - two leptons:
  - 70<m_{ll}<110 GeV
  - $\Delta R(\gamma, \mu(e))$ >0.5(1.0)
  - diphoton mva>0.107

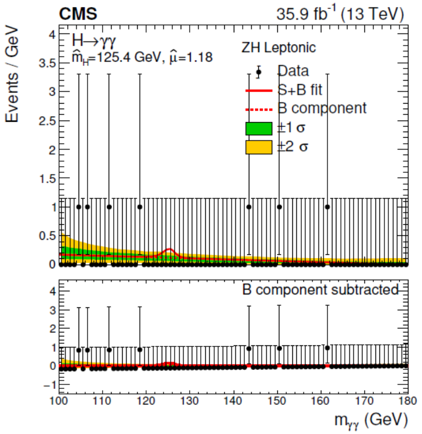
- **VH leptonic loose:**
  - one lepton:
  - p_T^{miss} < 45 GeV
  - $\Delta R(\gamma, l)$ >1.0
  - diphoton mva>0.28
  - <=2 jets

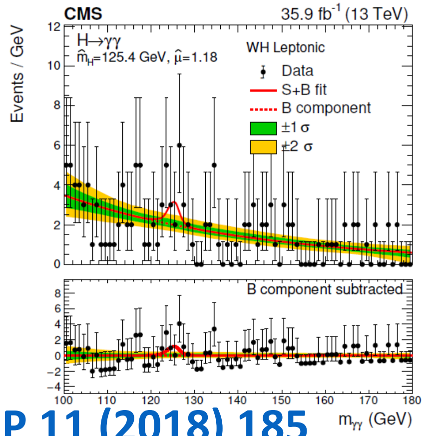
Diphoton MVA cuts were tuned

MET category

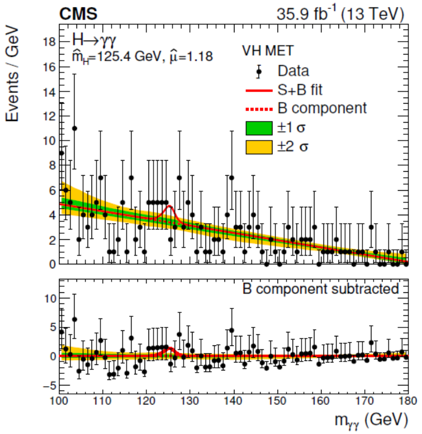
- $W \to l\nu$ (lepton out of acceptance) or $Z \to \nu\nu$
  - p_T^{miss} > 85 GeV
  - $\Delta\varphi(\gamma\gamma, p_T^{miss})$ >2.4
  - diphoton MVA > 0.790 (0.6 before flattening)

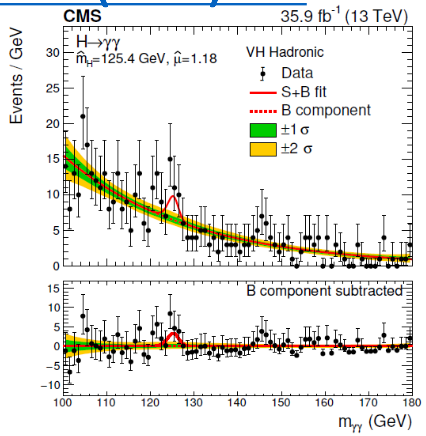






[JHEP 11 (2018) 185]





W->jj or Z->jj

hadronic category

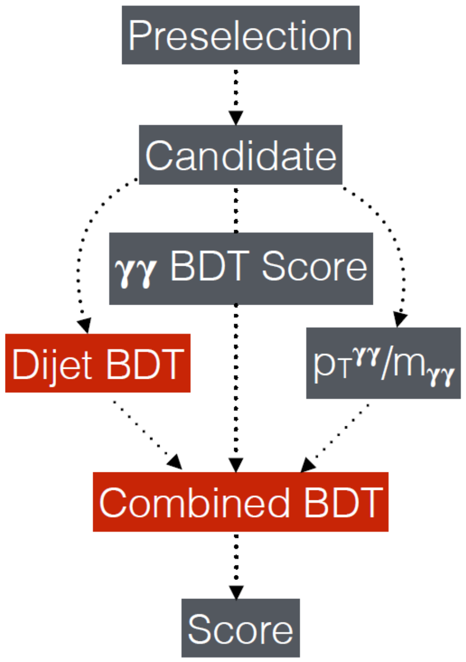
- **Photons**
  - (sub)leading $p_T/m_{\gamma\gamma}$>0.5(0.25)
  - $p_T^{\gamma\gamma}/m_{\gamma\gamma}$>1.0
- **Jets**
  - At least two jets
  - p_T > 40 GeV
  - $|\eta|$ < 2.4
  - 60<m_{jj} < 120 GeV
  - $|\cos\theta^*|$ < 0.5

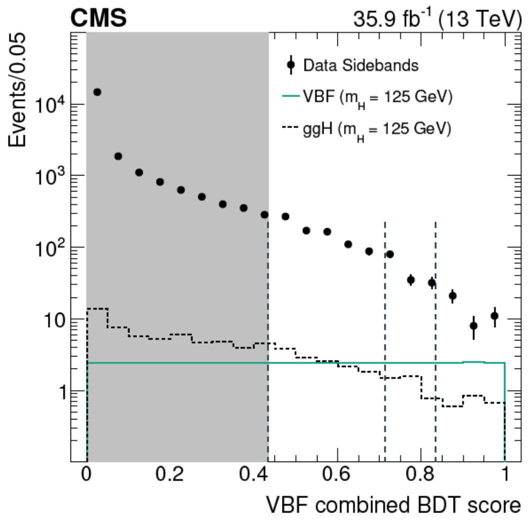
Diphoton MVA > 0.906

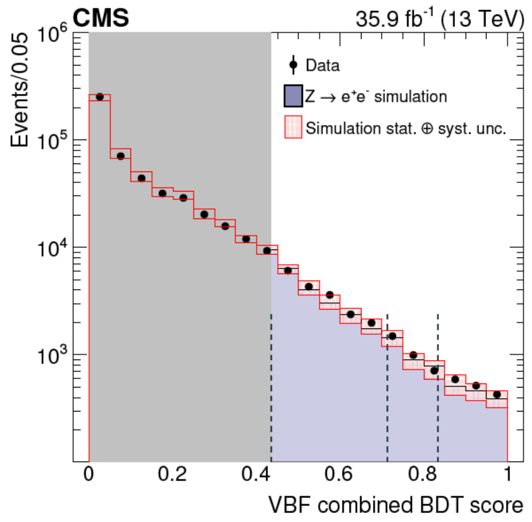
- before flattening (0.7)

2016 H→γγ : VBF Tag

- Preselection: Two jets with $pT_{j1}>40GeV$, $pT_{j2}>30GeV$, $|\eta|<4.7$, $m_{jj}>250GeV$
- 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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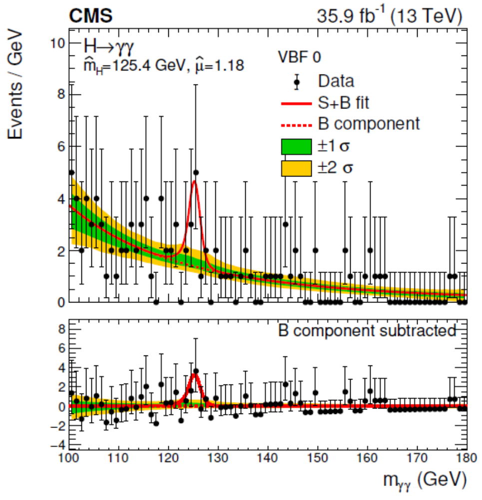
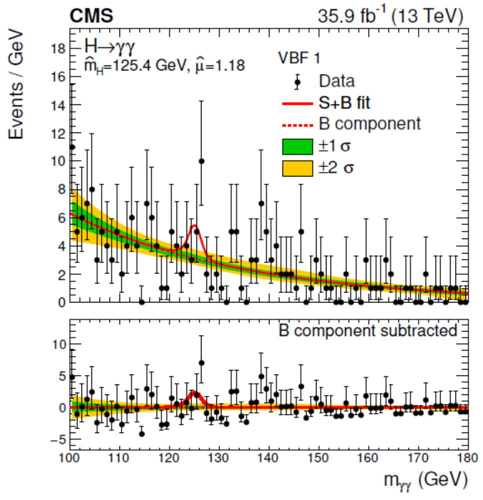
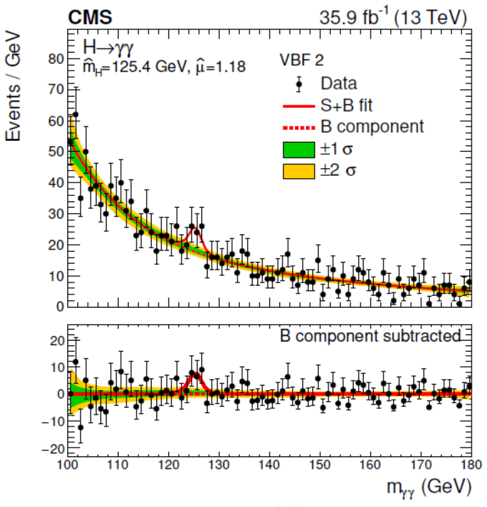






ttH observation

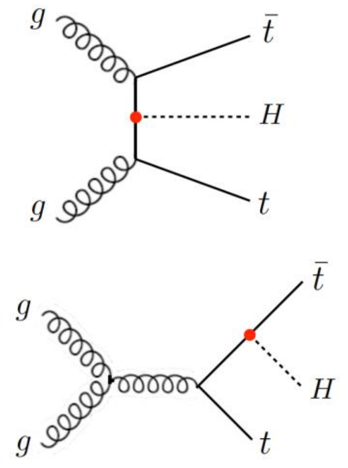
- **Largest coupling to the top quark**

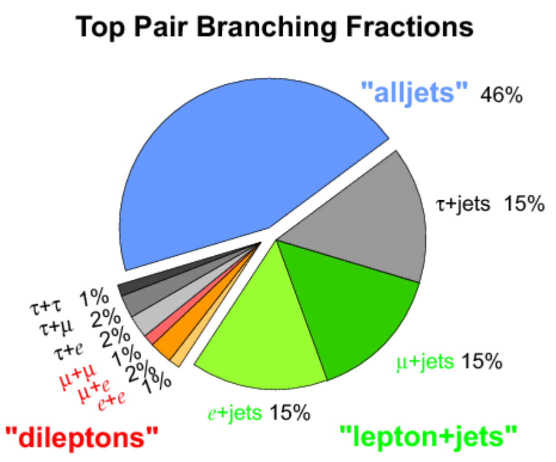
- **Very challenging**

  Complicated experimental signature

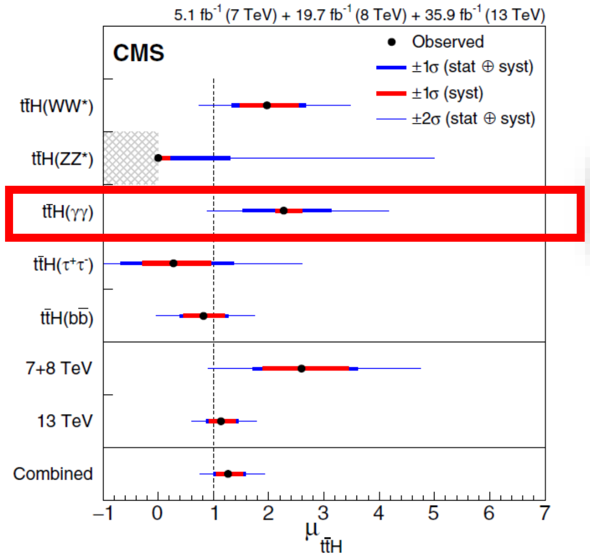
  Low cross section : σ_{ttH} = 507 fb (NLO QCD + NLO EW, 13TeV)

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





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



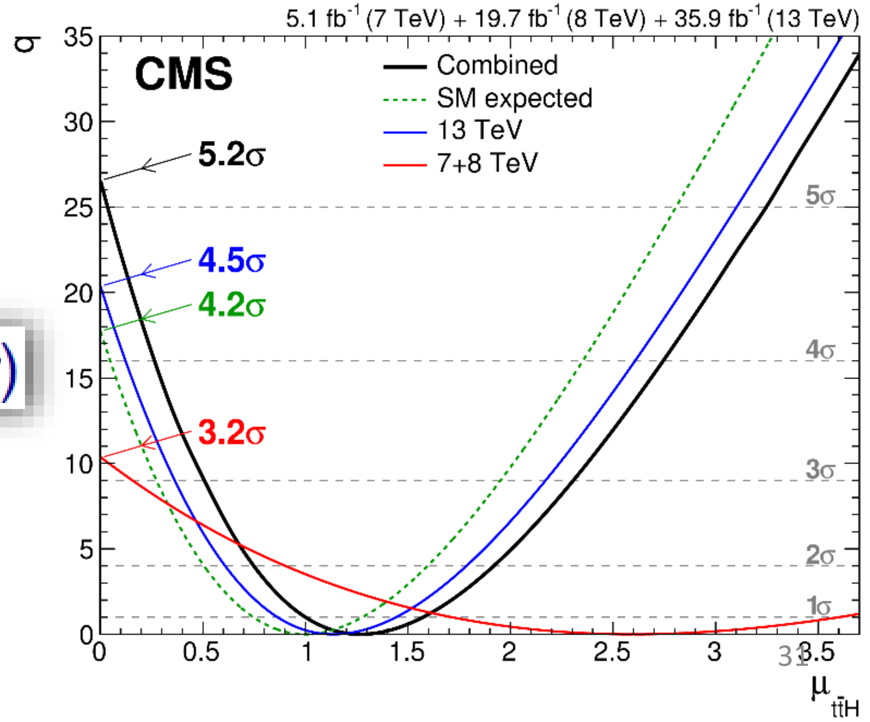
CMS Run1 + Run2 (2016 dataset)

Observed 5.2σ (exp 4.2σ)

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

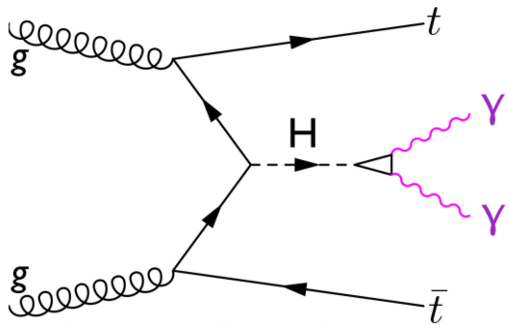
$$= 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{exp})^{+0.14}_{-0.13}(\text{th, B})^{+0.15}_{-0.07}(\text{th, S})$$

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



ttH→$\gamma\gamma$ measurement with 2017 data

- Very rare process but excellent mass resolution, very low background



- Use **BDT** to reject most non-ttH and non-resonant background

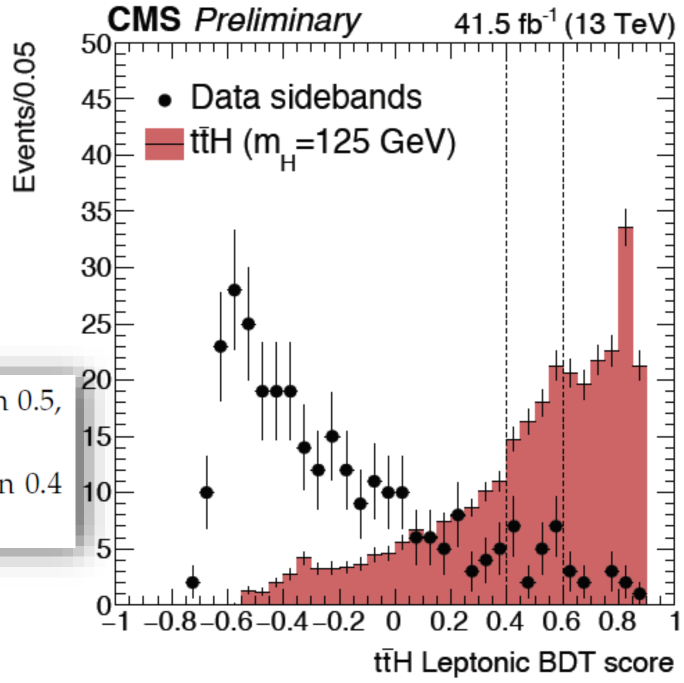
- fully leptonic: $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}\ell\nu_\ell\ell'\nu_{\ell'}$;
- semi-leptonic: $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}q\bar{q}\ell\nu_\ell$;
- fully hadronic: $t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}qq'\bar{q}\bar{q}'$.

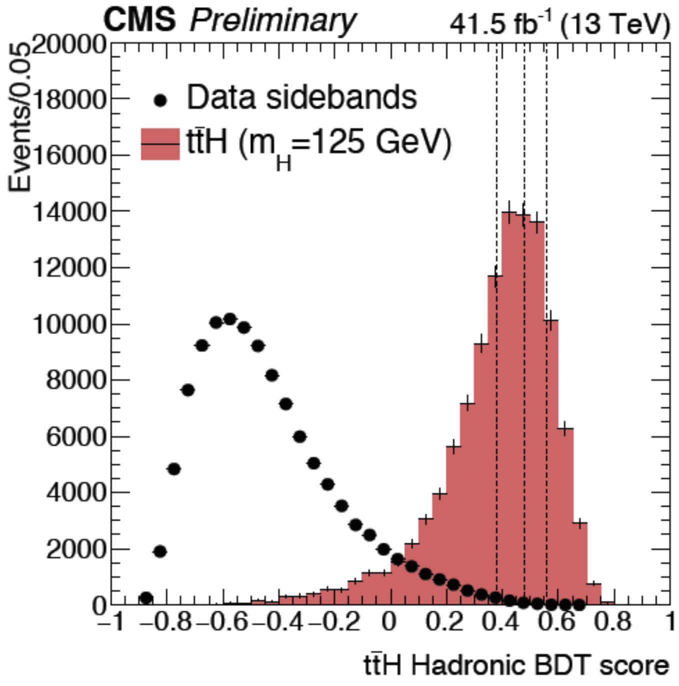
2 leptonic event classes

- 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.

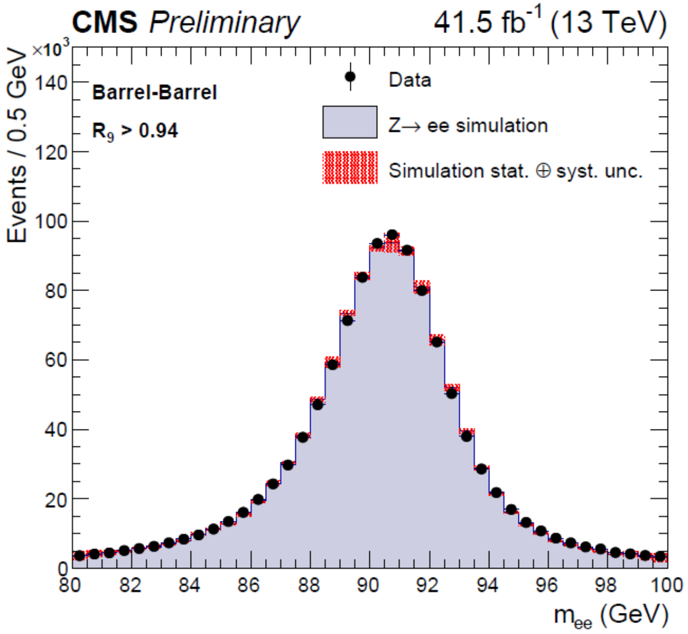
3 hadronic event classes

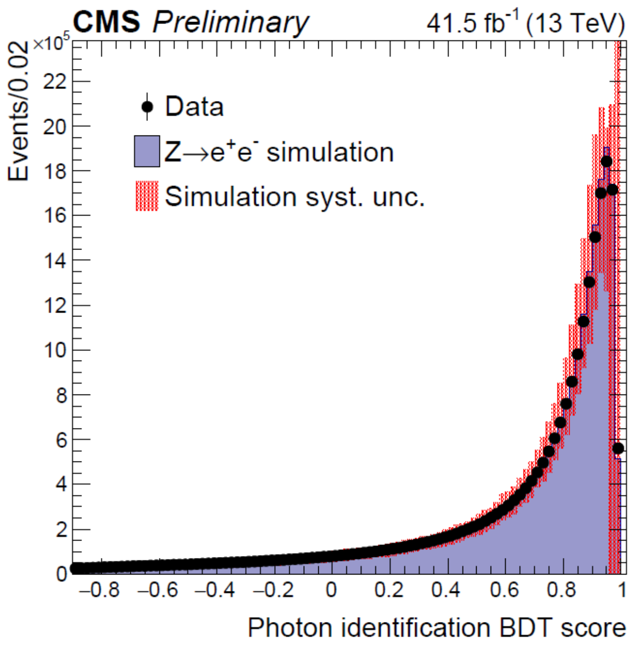
- TTH Hadronic 0: events with a BDT score greater than 0.56;
- TTH Hadronic 1: events with a BDT score between 0.48 and 0.56;
- TTH Hadronic 2: events with a BDT score between 0.38 and 0.48.





ttH→$\gamma\gamma$ with 2017 data





CMS-PAS-HIG-18-018

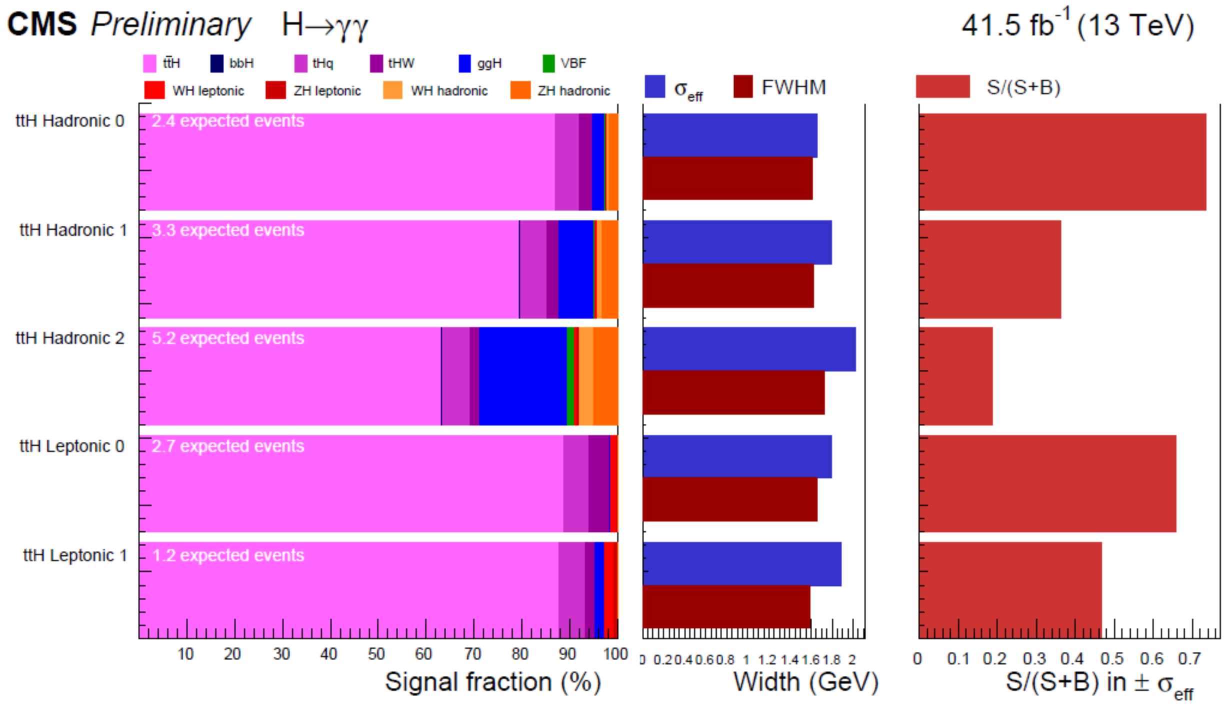
Input variables of leptonic BDT

- 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}.

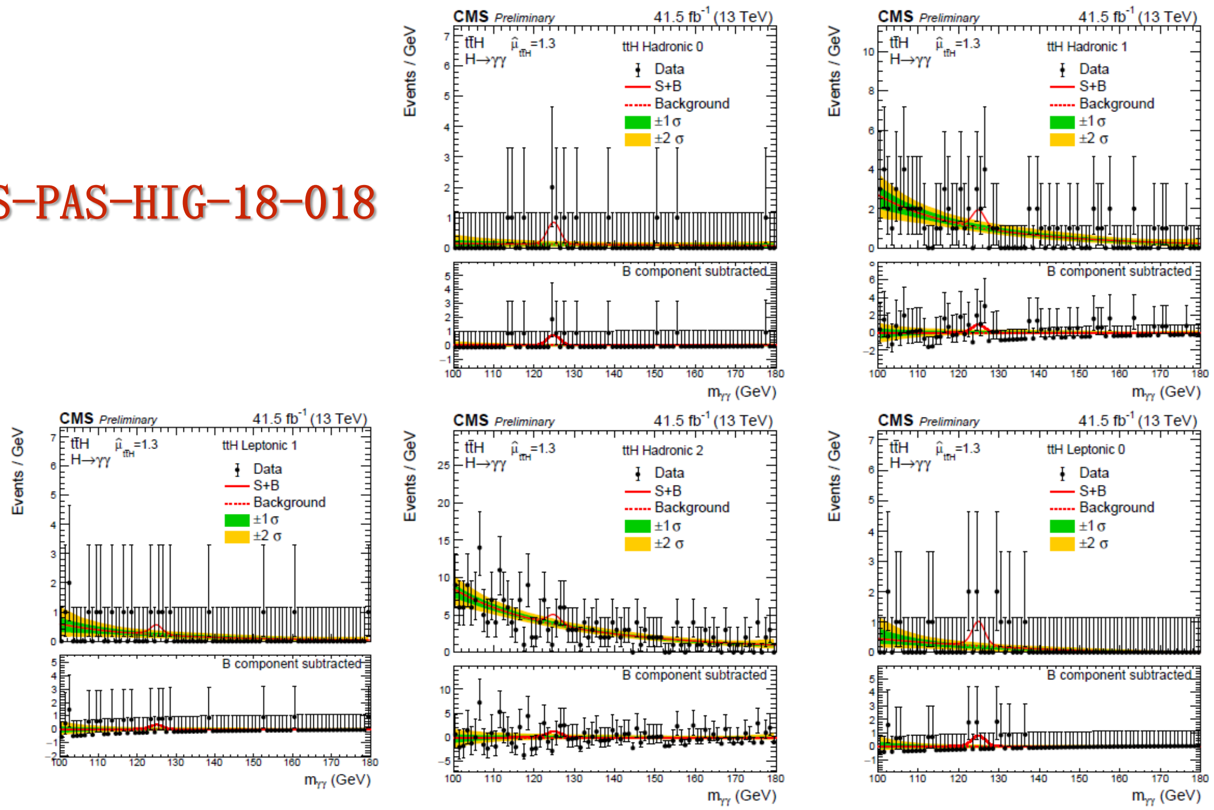
Input variables of hadronic BDT

- 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}.

ttH→γγ with 2017 data (cont.)



CMS-PAS-HIG-18-018



Event categories	SM 125 GeV Higgs boson expected signal													Bkg (GeV^{-1})
	Total	ttH	bbH	tHq	tHW	ggH	VBF	WH lep	ZH lep	WH had	ZH had	σ_{eff}	FWHM	
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

Basic idea of STXS

- Direct measurements (Run 1 m, CP-odd OO, ...)
  - ✓ Maximum sensitivity
  - ✓ Theory model, uncertainties and pre dictions are part of the measurement. If these change → redo measurement

- Differential fiducial measurements
  - ✓ Best model and theory independence
  - ✓ Less sensitive: measurements use simple cuts and avoid selections with a strong production mode/signal dependence

- STXS == compromise
  - ✓ Use “most sensitive analysis" to separate between Higgs production modes and against backgrounds
  - ✓ Extrapolate (unfold) to coarse kinematic regions for each Higgs production mode
  - ✓ Good sensitivity while keeping reduced theory dependence