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

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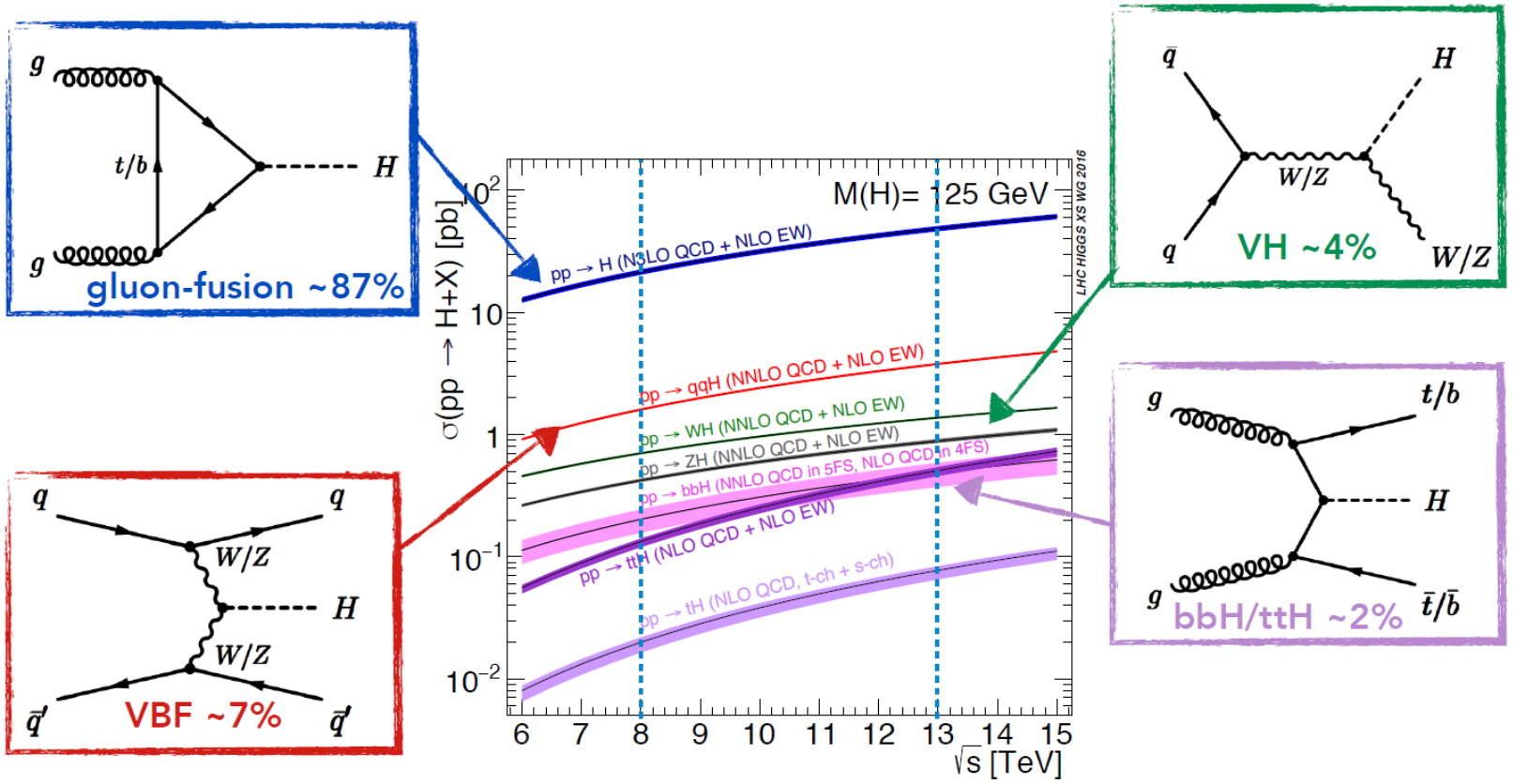
Outline

- SM Higgs production and H→$\gamma\gamma$ decay
- Analysis strategy and analysis elements
- Event categorization, signal and background modelling
- Measurement results : mass, signal strength and couplings
- Fiducial XS measurement
- Summary

Latest H→$\gamma\gamma$ results with all 2016 35.9 fb^{-1} data (HIG-16-040, HIG-17-015)

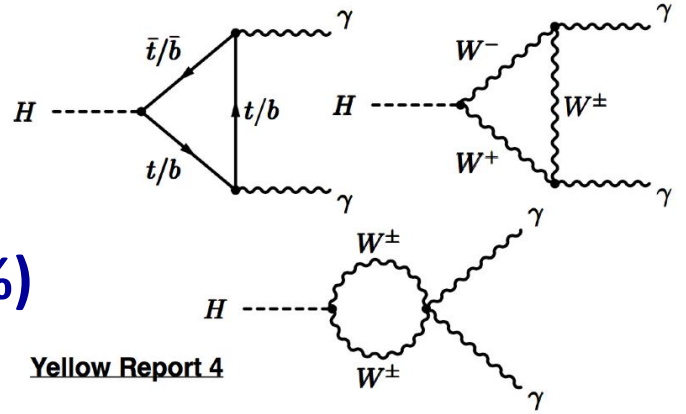
Higgs Production @ LHC



- **Significant increase in production cross section from 8 TeV (Run1 2012) to 13TeV (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**

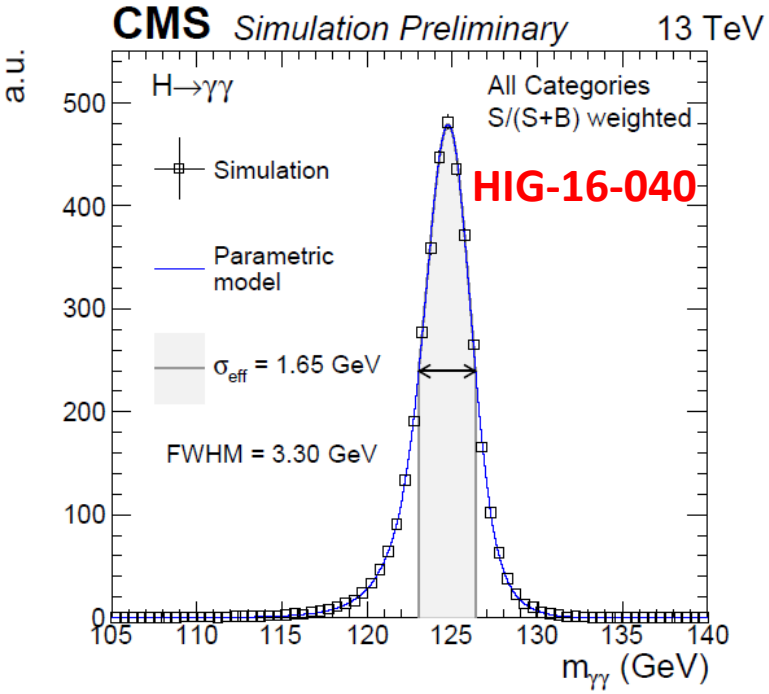
H→γγ Decay

- **Loop-induced decay : sensitive to BSM -** *new physics might contribute to the loop*



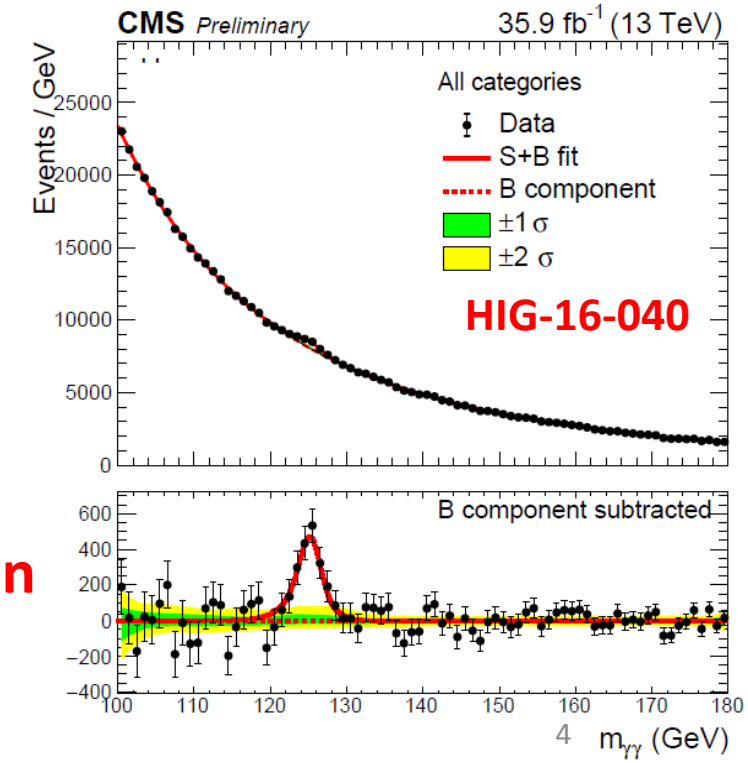
Yellow Report 4

- **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**



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

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



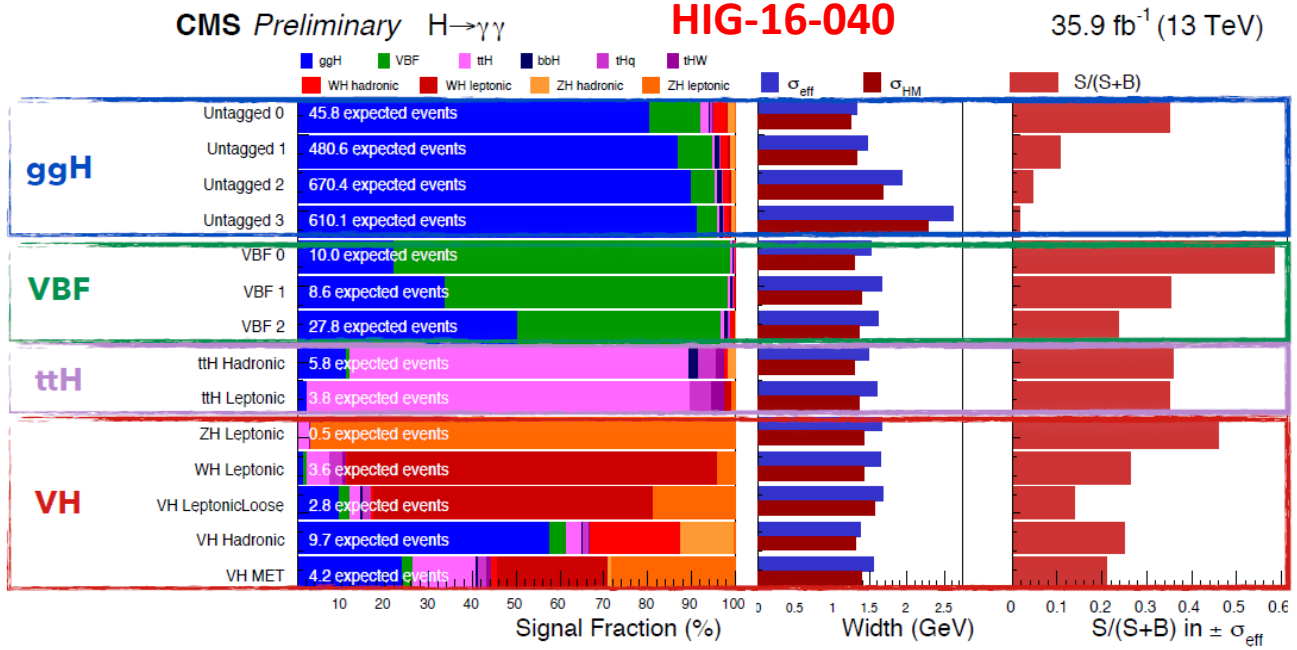
Analysis strategy

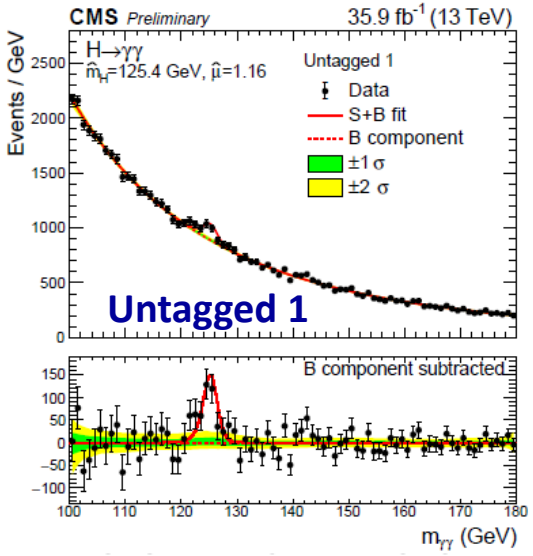
➢ **Well reconstructed and corrected photons energy** and higher **primary vertex** finding efficiency, to obtain good mass resolution ($\sigma_{m\gamma\gamma}$)

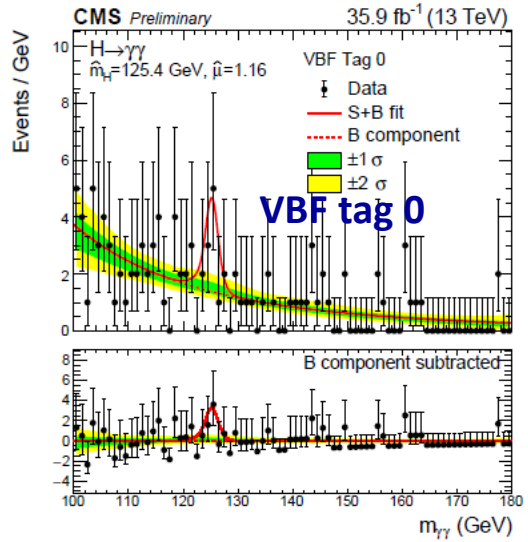
➢ To suppress background, have good rejection of fake photons by **photon identification with BDT** (Boosted Decision Tree)

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

➢ Extraction of signal through fit of **di-photon invariant mass** spectrum in ***each event class***



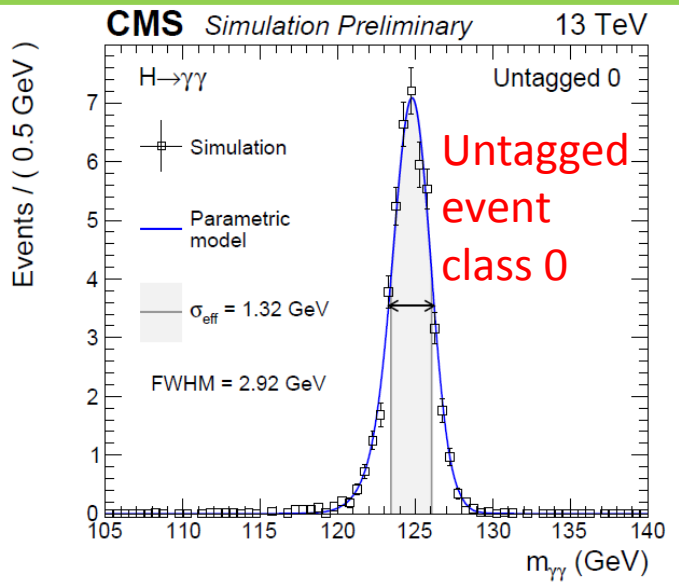


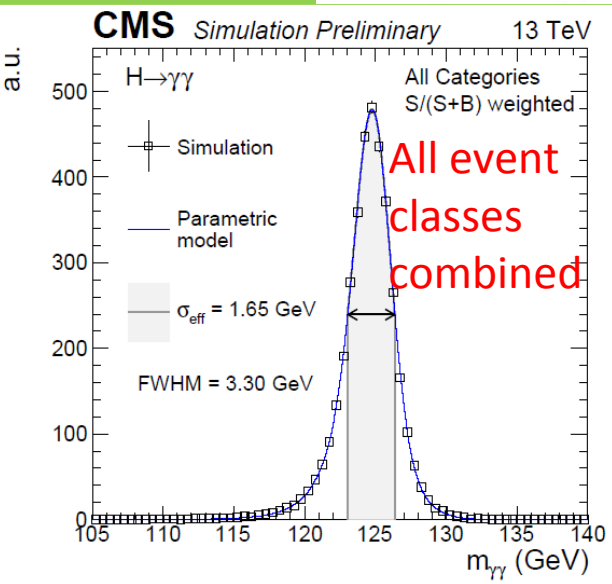


$m_{\gamma\gamma}$: Photon energy

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

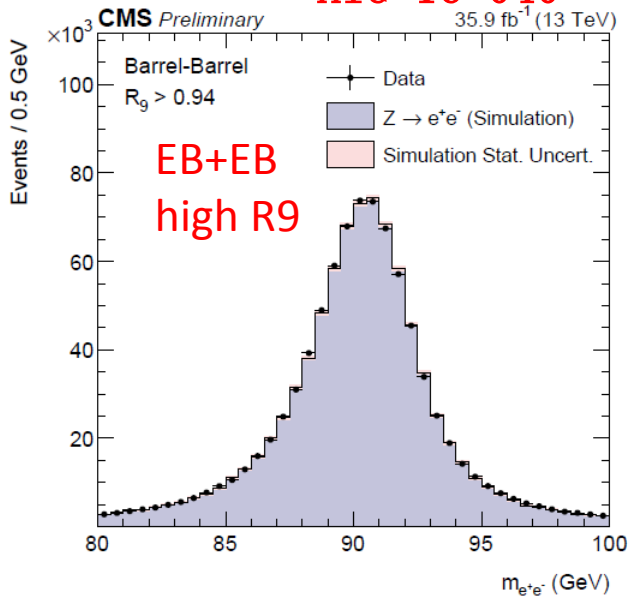
- Photons energy is computed from the sum of the energy of the **ECAL reconstructed hits, calibrated and corrected for several detector effects**
  - correction for **response changes** in time, $S_i(t)$
  - single-channel intercalibration (C_i)
  - **absolute scale** adjustment 2013 JINST 8 P09009





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

HIG-16-040



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

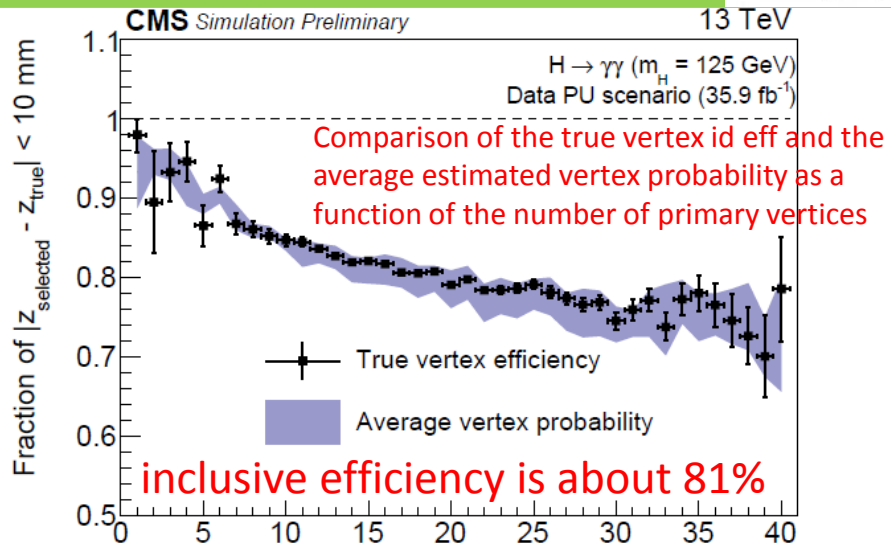
- **Multivariate approach (BDT) for vertex identification**
  - Vertex ID BDT: **kinematic correlations and track distribution imbalance**

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

  - 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



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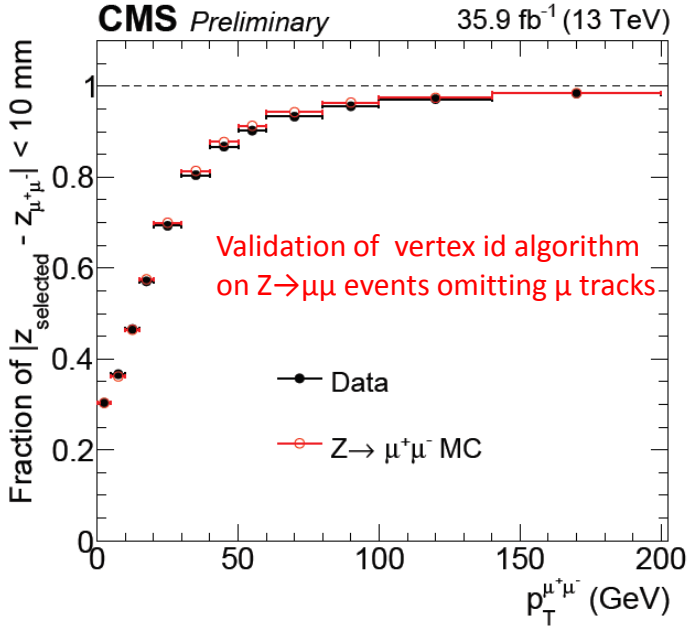
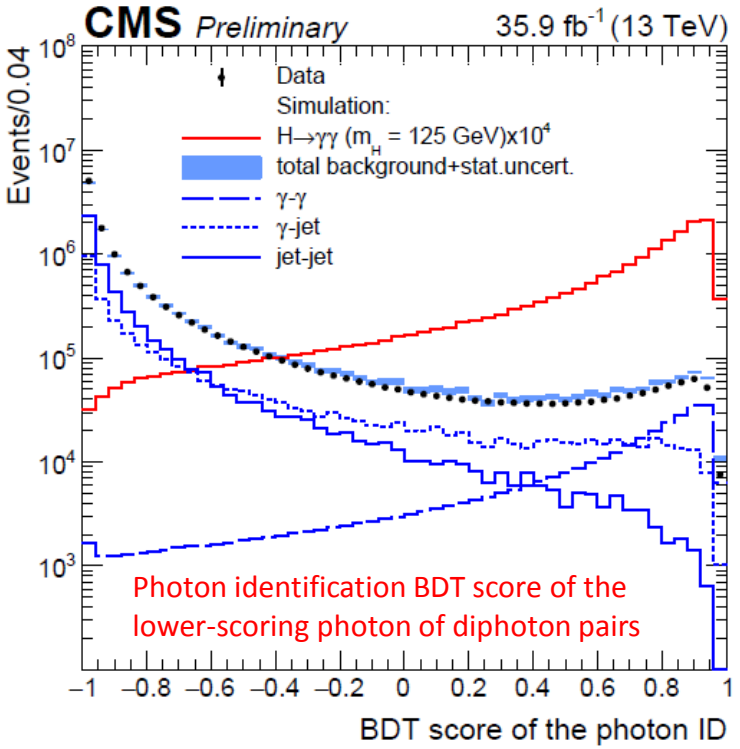
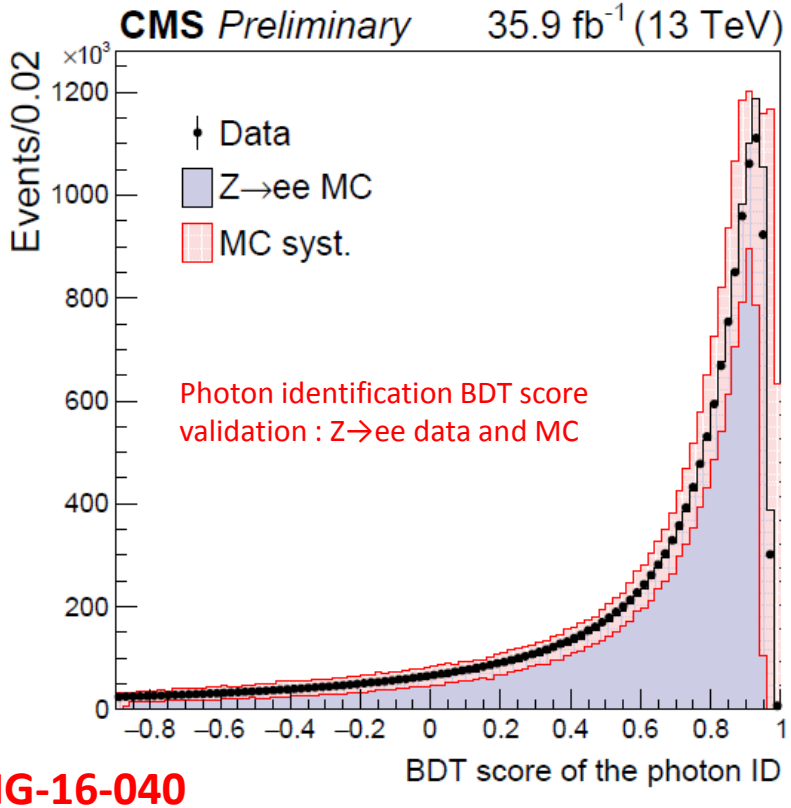


Photon identification

➢ **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, 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**

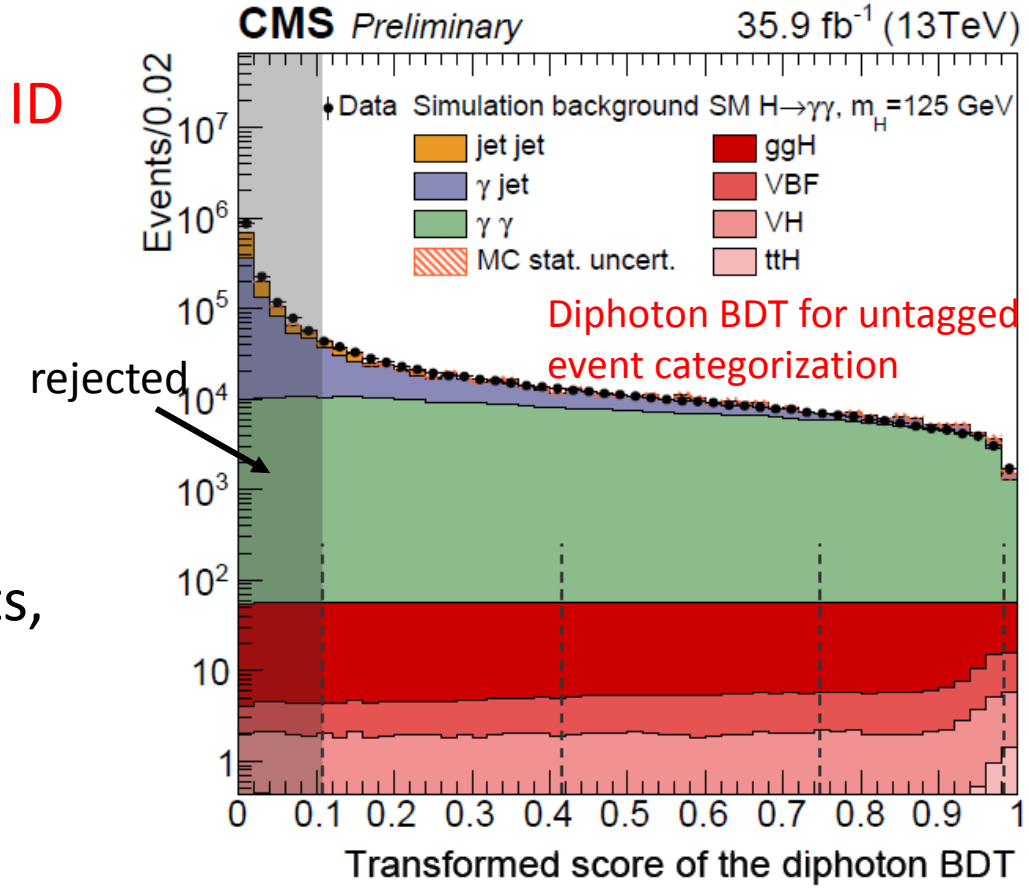
Diphoton BDT

➢ **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

➢ **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



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Higher BDT score gives better mass-resolution diphoton events

Event categorization

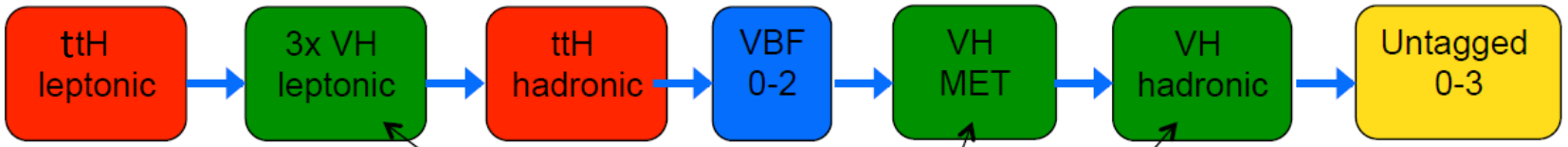
- Selected events are split into **14 categories** depending on **Higgs production modes** and kinematics, to improve the analysis sensitivity

- Top fusion (**ttH**): cut-based ***leptonic*** and mva-based ***hadronic*** (2cats)

- **VH**: **new in 2017**, cut-based method and split into ***leptonic, hadronic, MET*** (5cats)

- **VBF**: combined dijet + diphoton BDT with categories based on significance (3cats)

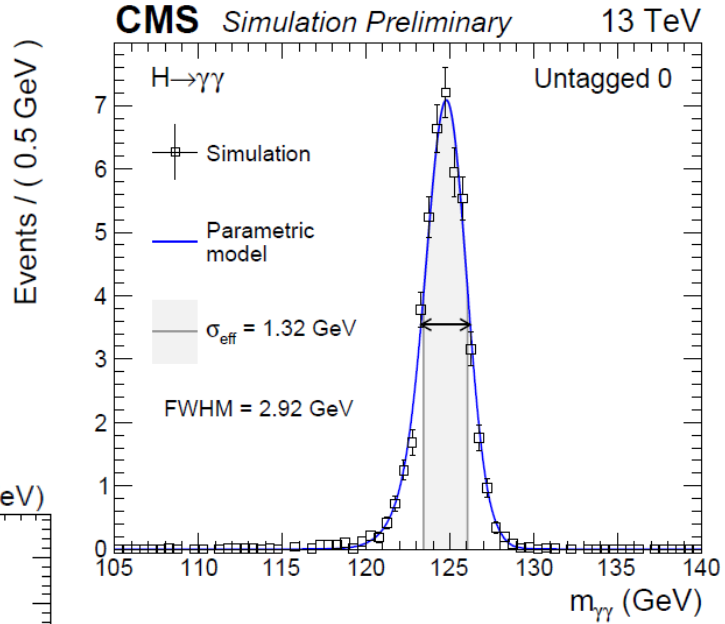
- **Untagged** (ggH): split by ***diphoton BDT score***, correspond to different S/B and invariant mass resolutions (4cats)



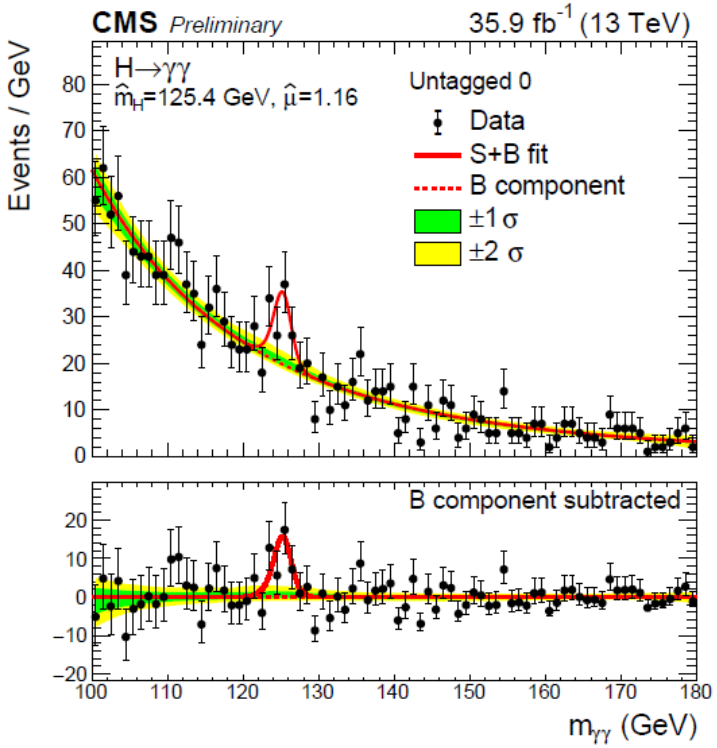
Order of event tagging

Signal and background modeling

- 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: *discrete profiling method* [2015 JINST 10 P04015]



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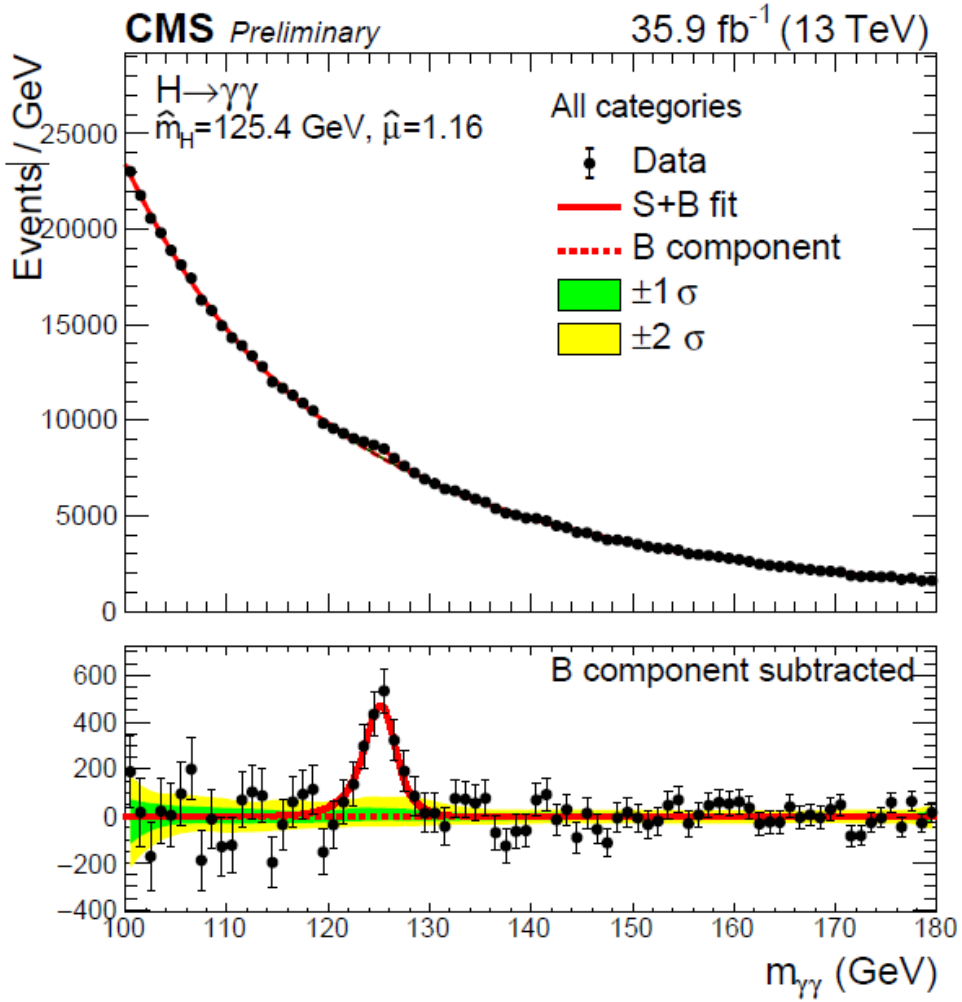
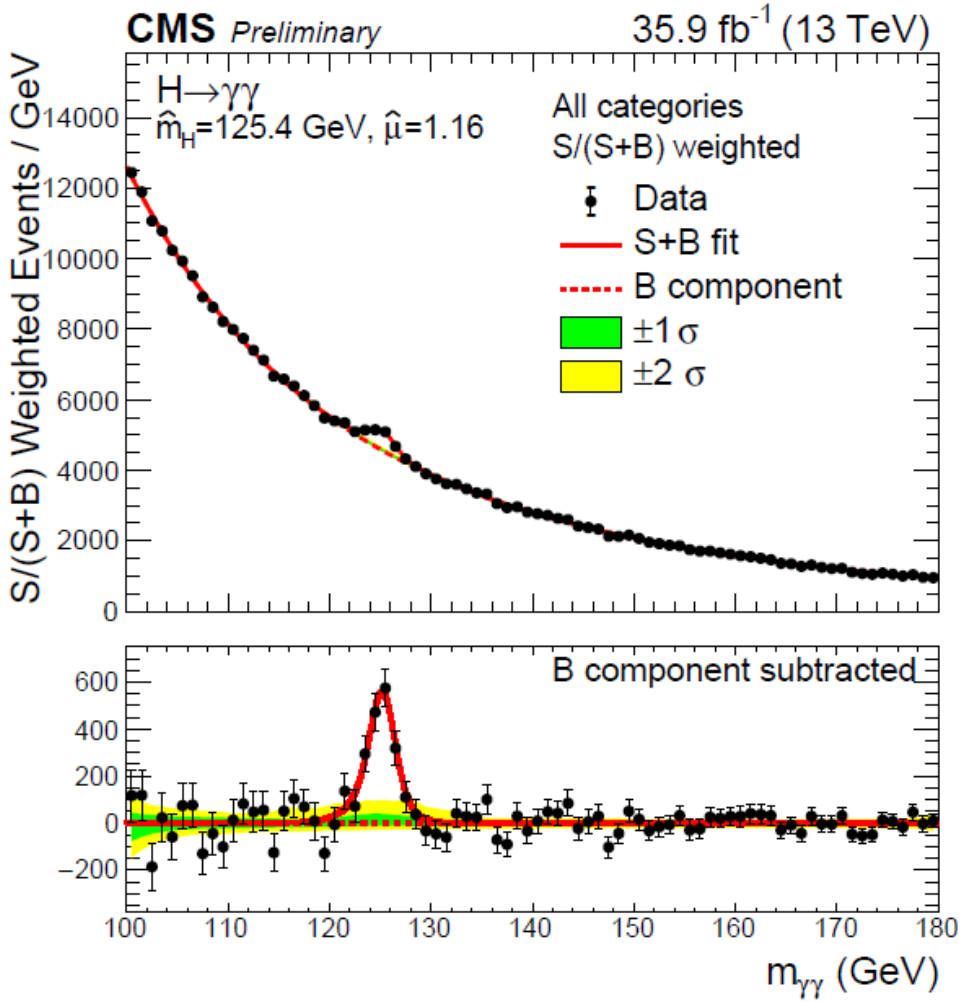
Mass

All categories



All categories (weighted by their sensitivity)



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

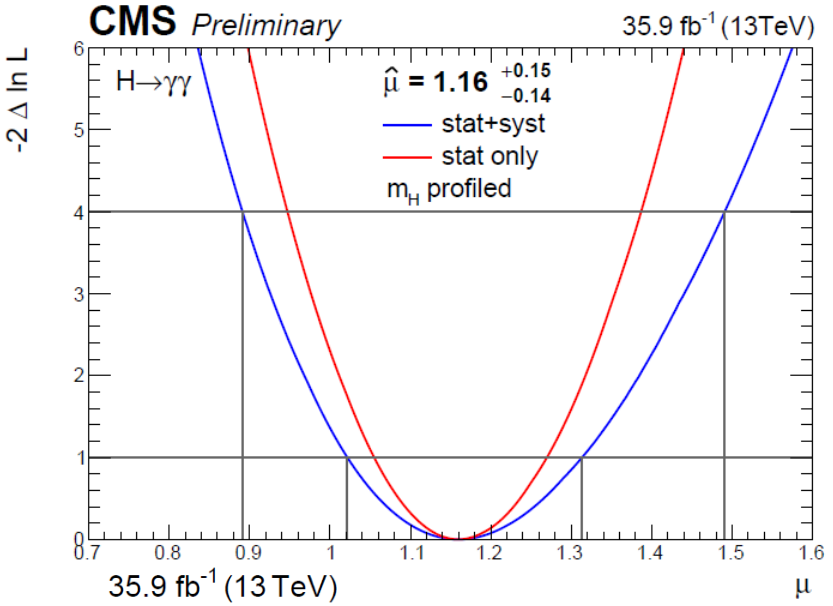
Signal strength

- Overall signal strength

$$\mu = 1.16^{+0.15}_{-0.14}(stat+syst) = 1.16^{+0.11}_{-0.10}(stat.)^{+0.09}_{-0.08}(syst.)^{+0.06}_{-0.05}(theo.)$$

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

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



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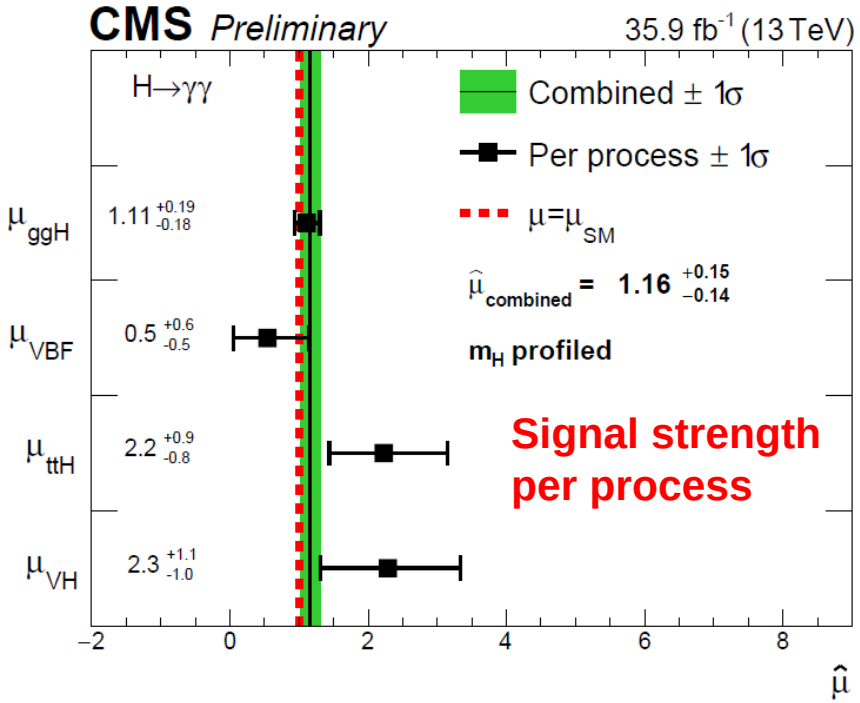
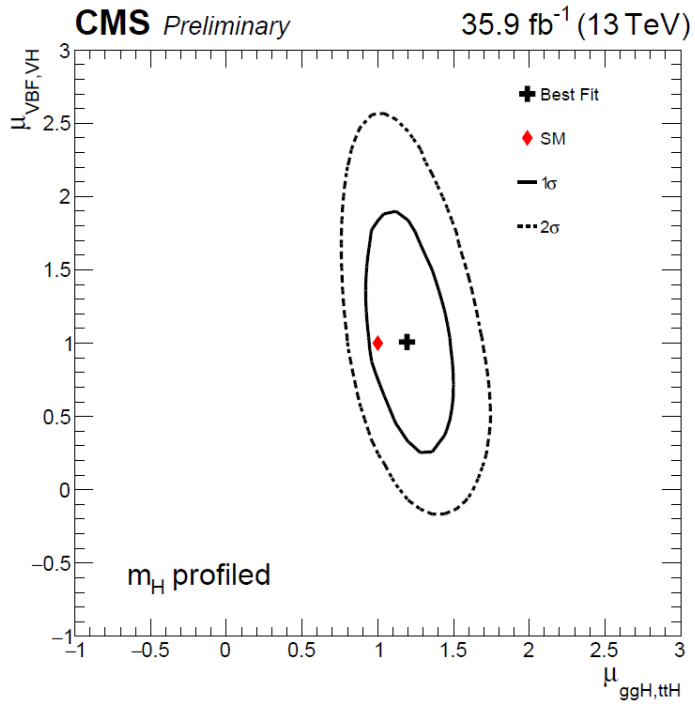


Significance
Observed(Expected)

VBF **1.1σ (1.9σ)**

ttH **3.3σ (1.5σ)**

VH **2.4σ (1.2 σ)**

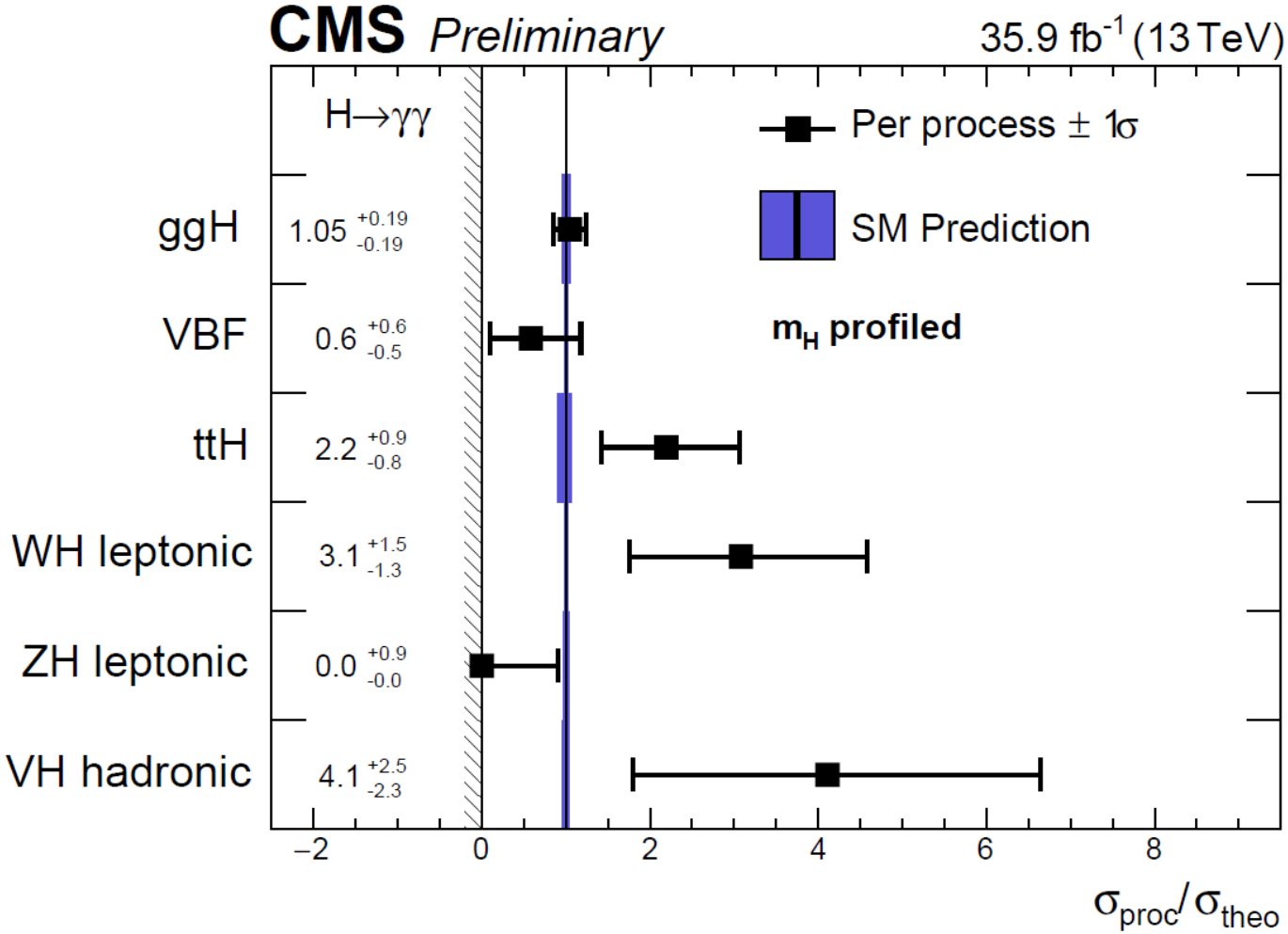


$$\mu_{ggH,t\bar{t}H} = 1.19^{+0.20}_{-0.18}$$

$$\mu_{VBF,VH} = 1.01^{+0.57}_{-0.51}$$

Cross section

Cross section ratios measured for each process in the Higgs Simplified Template Cross Section (STXS) framework, for profiled m_H, compared to the SM expectation and its uncertainties



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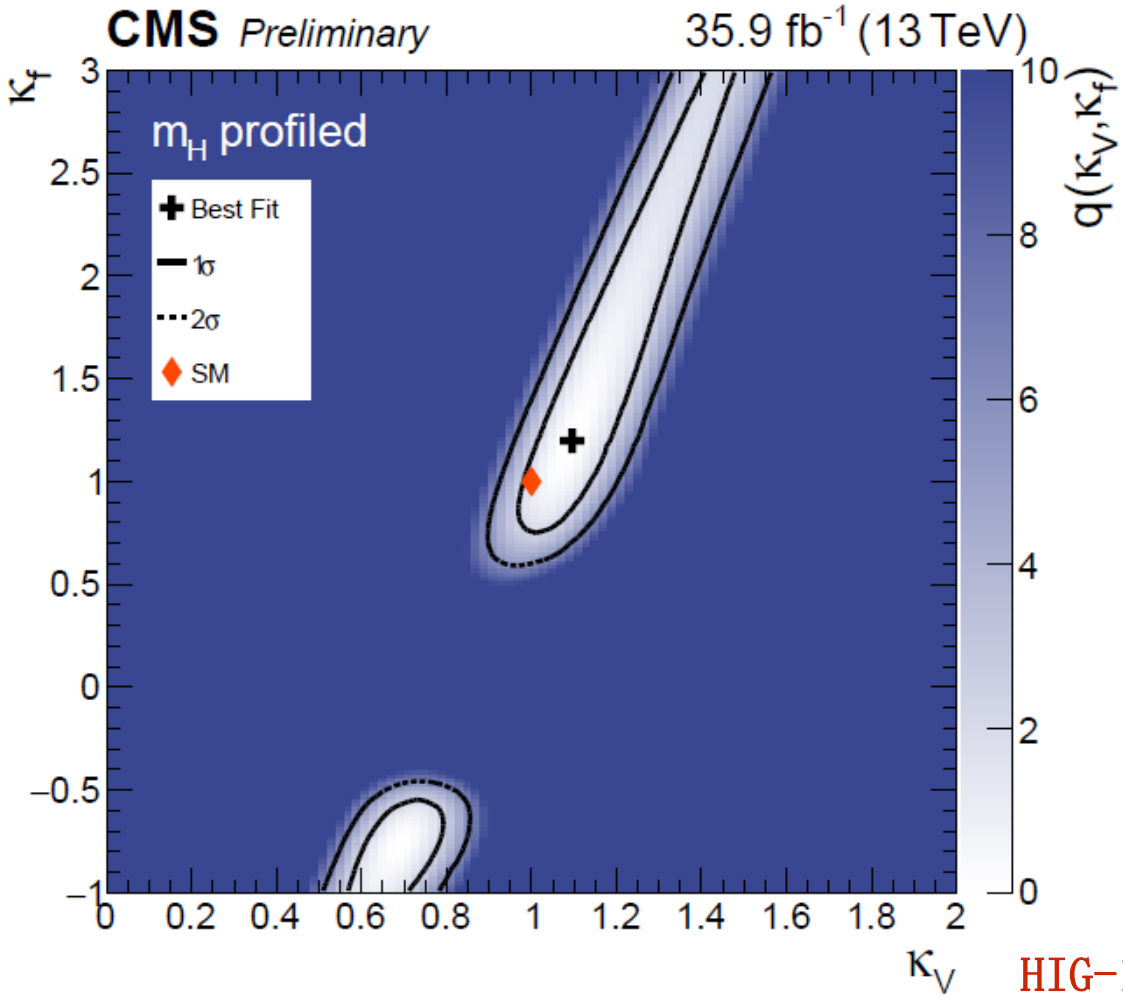
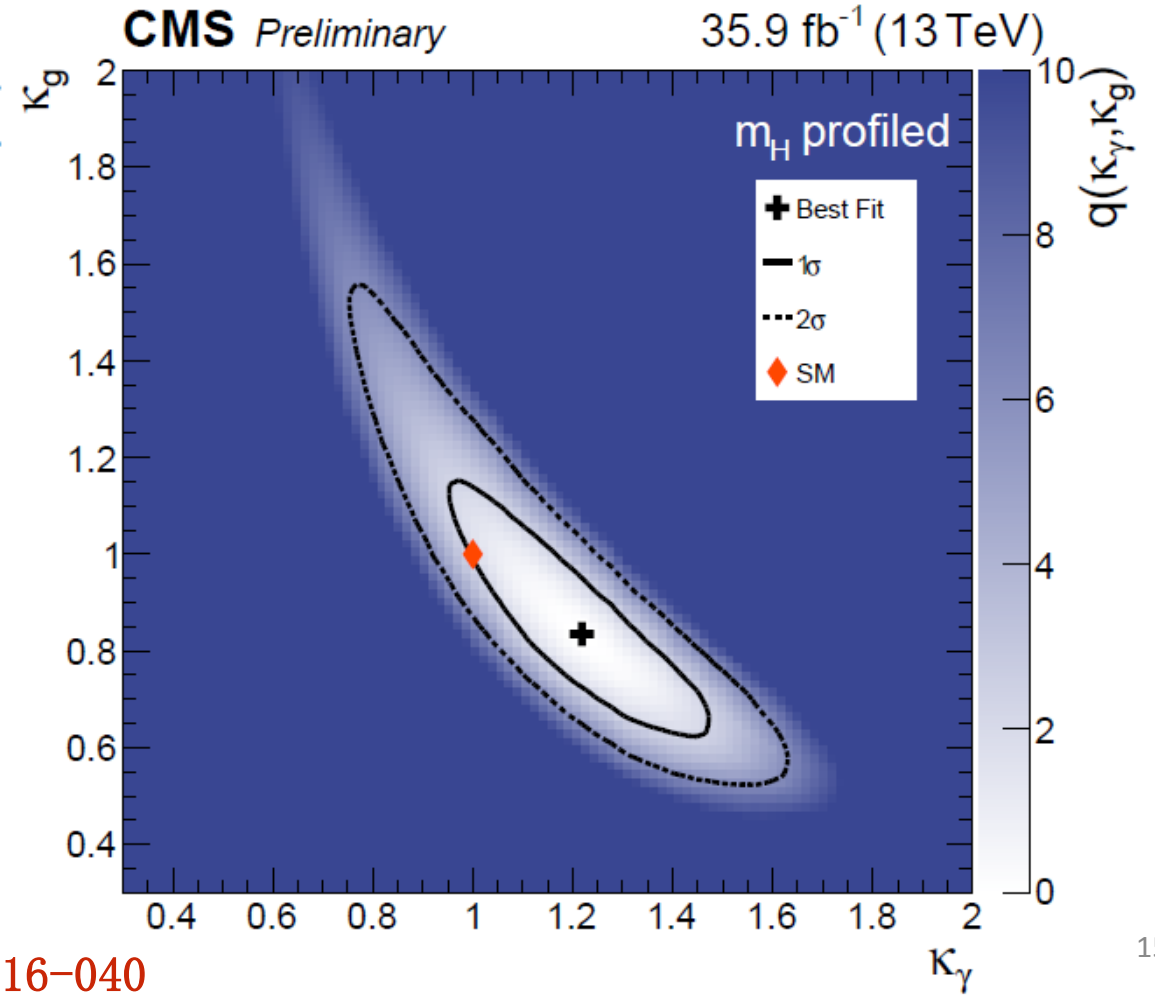
Coupling constants

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

Compatible with SM





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Fiducial cross section

- **3 untagged event categories** based on **expected mass resolution**
- **Results**: **most precise fiducial measurement so far**

$$\hat{\sigma}_{\text{fiducial}} = 84 \pm 11\ (\text{stat}) \pm 7\ (\text{syst})\ \text{fb}$$

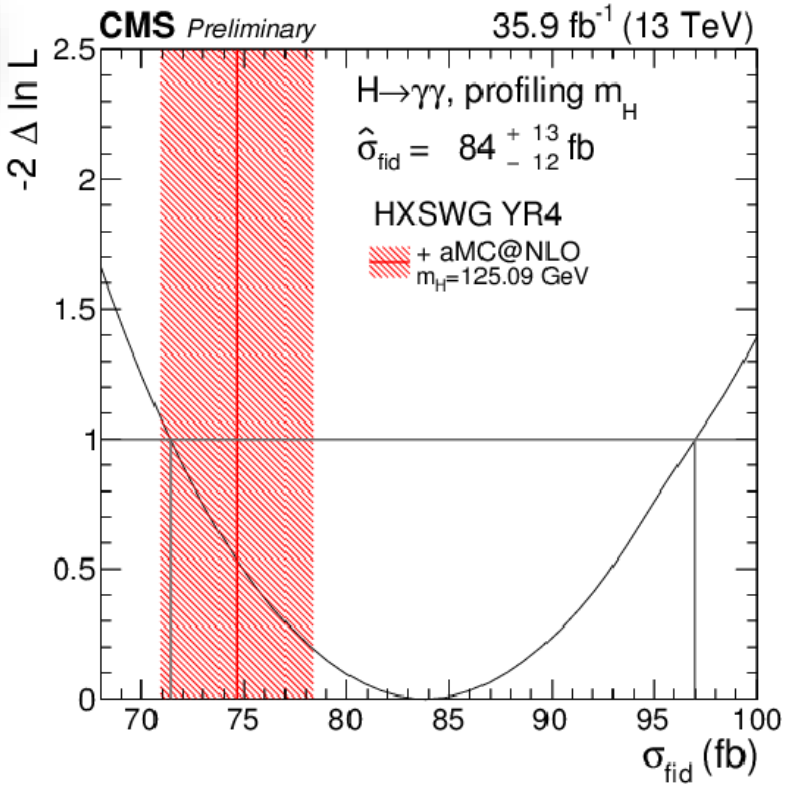
$$\sigma^{theory}_{\text{fiducial}} = 75^{+4}_{-4}\,\text{fb}$$

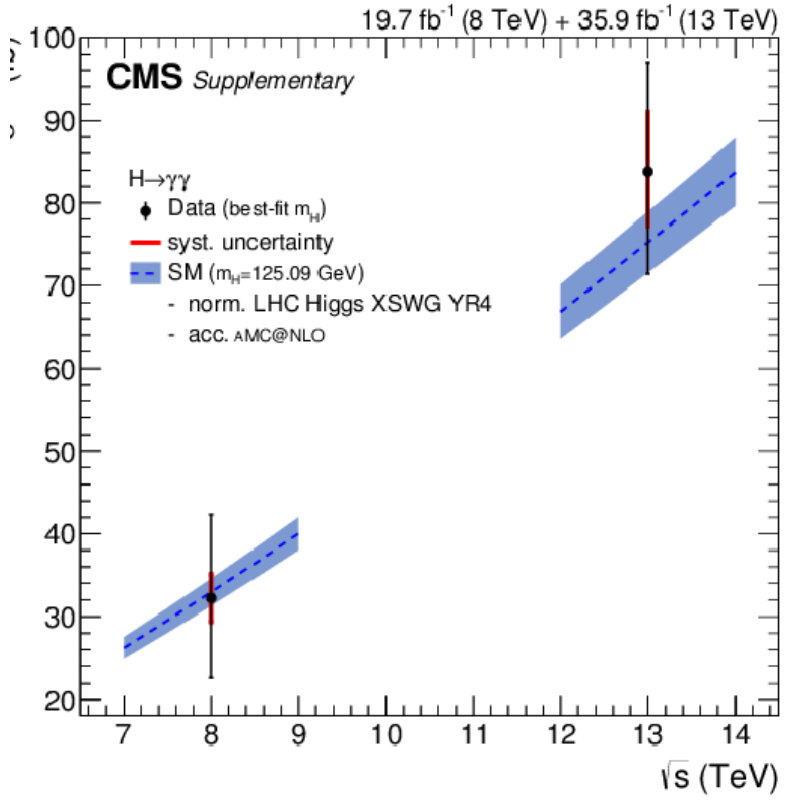
Fiducial volume:

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

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

$\text{Iso}_{\text{gen}1,2} < 10$ GeV (ΔR=0.3)





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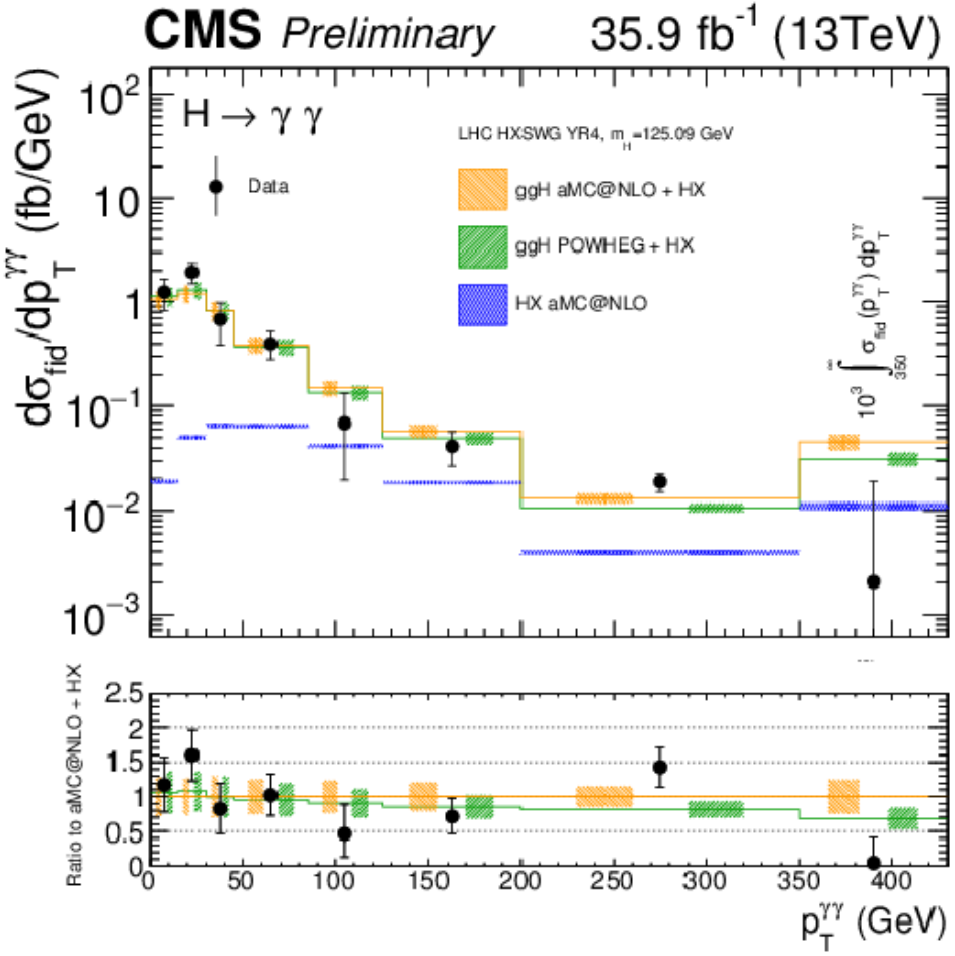
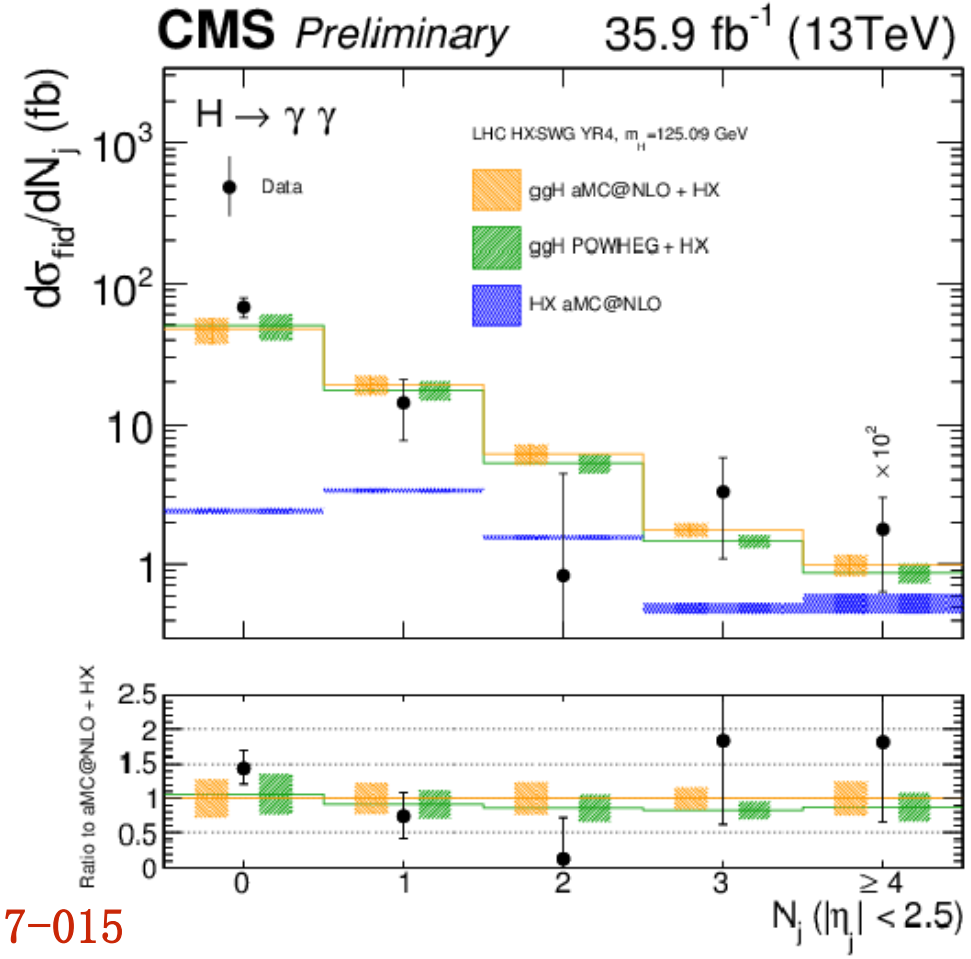
Differential fiducial cross section

- **Differential fiducial cross sections** are measured for **pT(γγ)** and **N(jets)**, compared with predictions from MADGRAPH aMC@NLO, **ggH powheg** + **other modes (VBF+VH+ttH, "HX") from MADGRAPH aMC@NLO**





HIG-17-015

Summary and outlook

- Latest results of Higgs measurements in diphoton decay (**H→$\gamma\gamma$**) from Run 2 data (35.9 fb^{-1}) collected by CMS detector at 13 TeV are presented

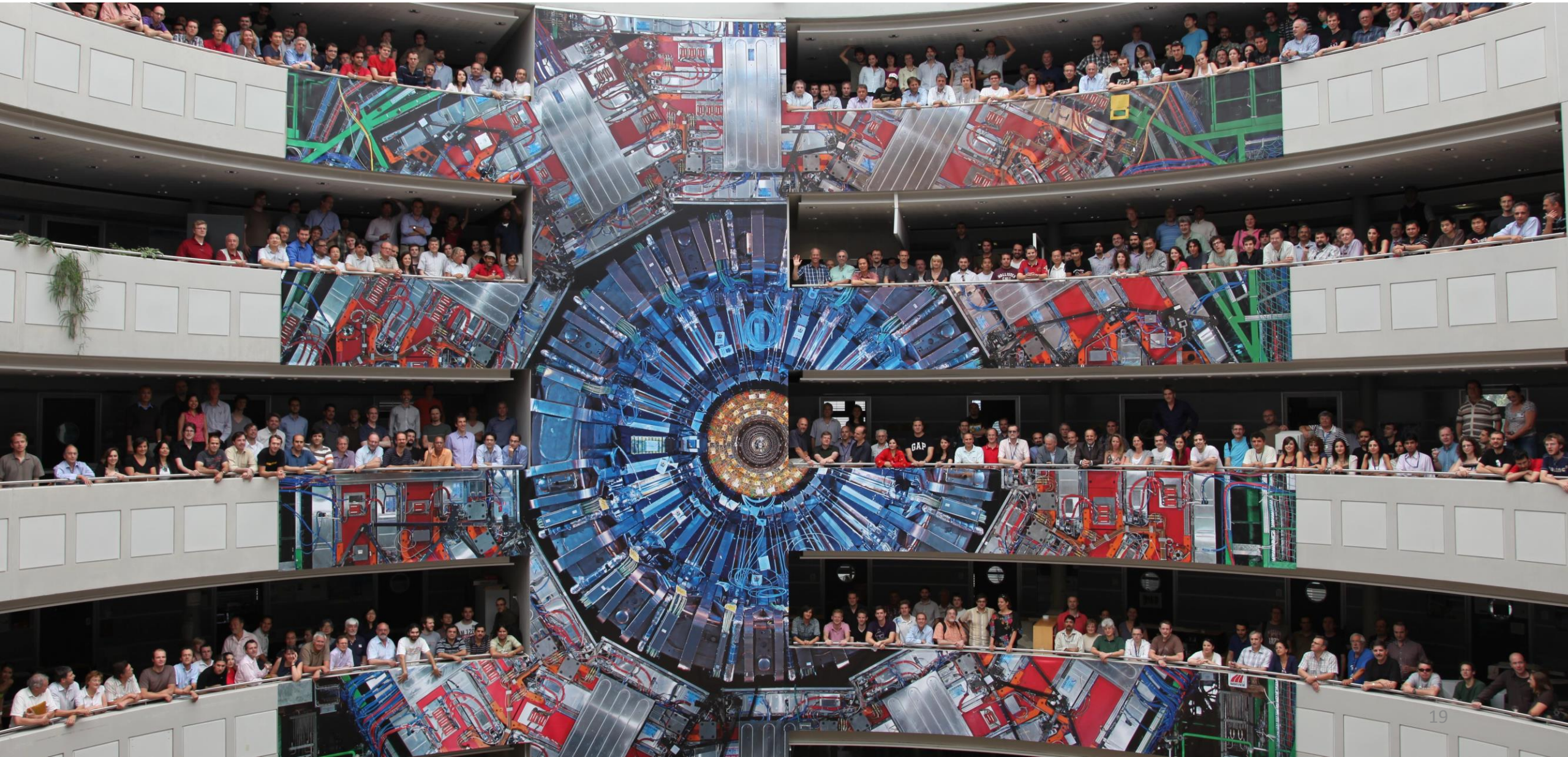
- Measurements of its properties are largely compatible with SM expectations

- Results are still statistically limited

- Expected > 100 fb^{-1} to be delivered by the end of Run2 (**the end of 2018**)
  - Improve precision on the measurements
  - Further optimization of analyses as well as interpretations of data

on the way

Thanks for your attention!



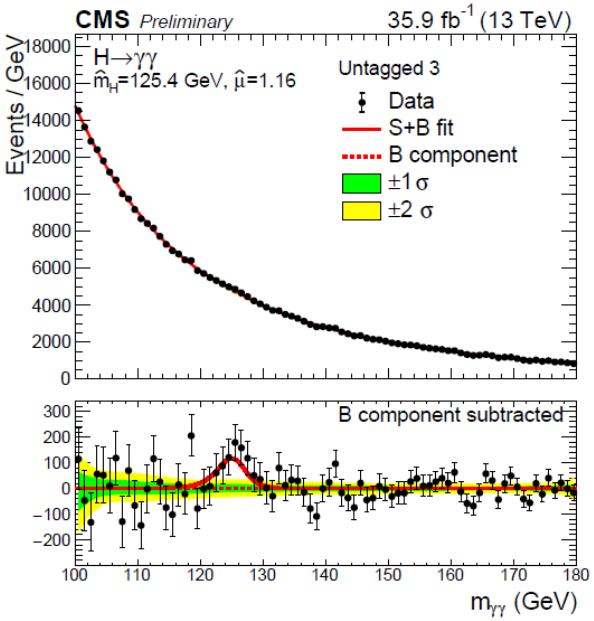
Backup slides

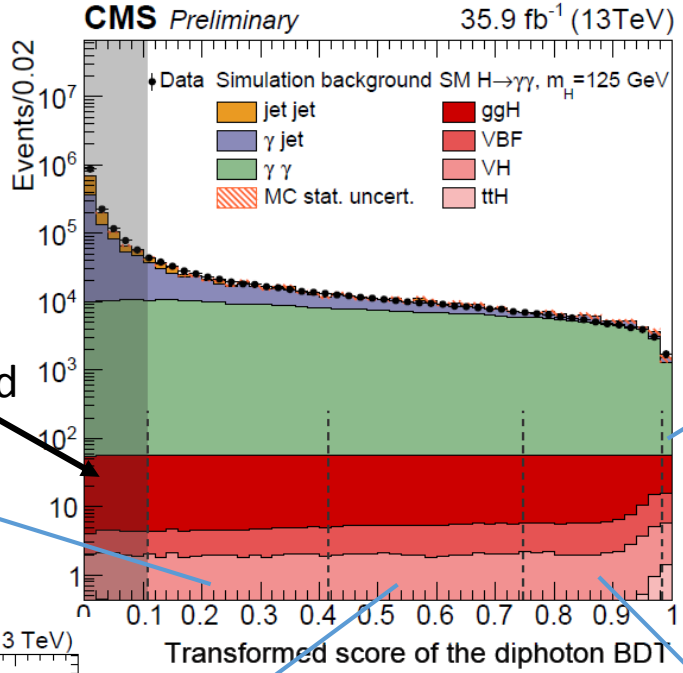
Vertex probability BDT

A second vertex-related multivariate discriminant, used in the diphoton BDT (see Section 6), is designed to estimate, event-by-event, the probability for the vertex assignment to be within 1 cm of the diphoton interaction point. The vertex probability BDT is trained on simulated $H \to \gamma\gamma$ events using the following input variables:

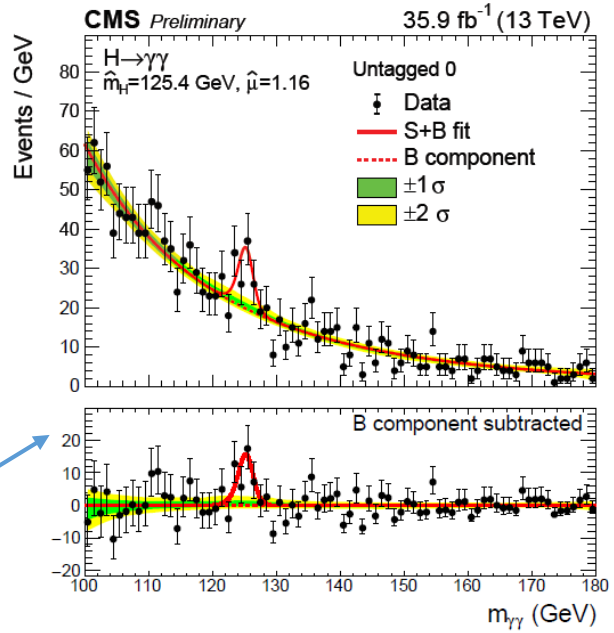
- the number of vertices in each event,
- the values of the vertex identification BDT score for the three most probable vertices in each event,
- the distances between the chosen vertex and the second and third choices,
- the transverse momentum of the diphoton system, $p_T^{\gamma\gamma}$,
- the number of photons with an associated conversion track.

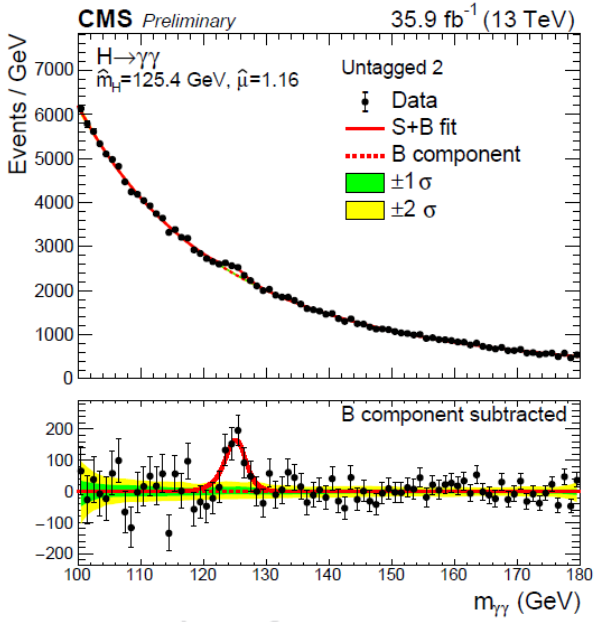
Untagged (ggH)





rejected





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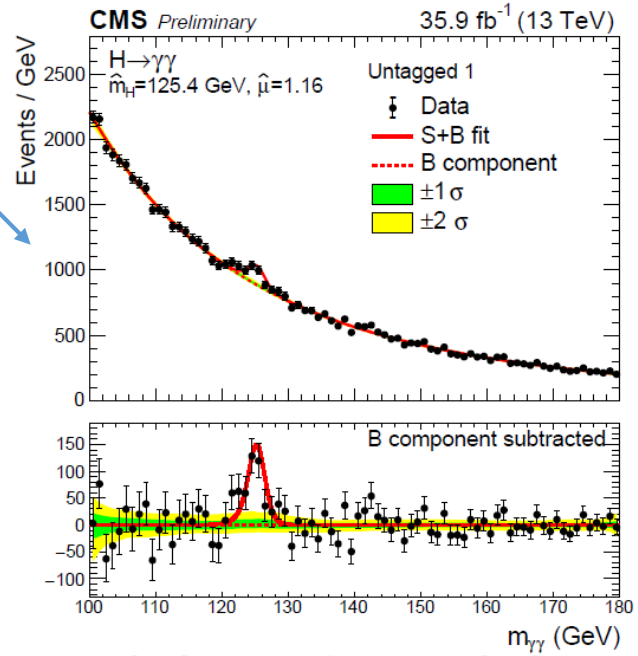


ttH

Objects

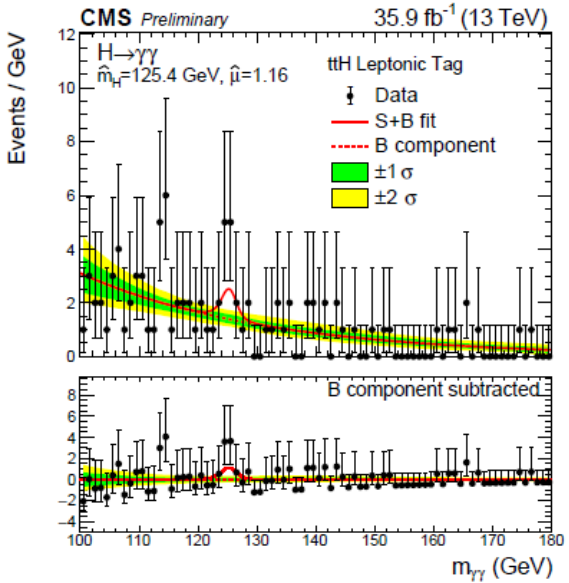
- **Jets**:
  - ak4PFCHS; pT>25 GeV; |η| <2.4
- **Bjets**:
  - PF CSV v2 (medium WP)
- **Muons**:
  - p_T>20 GeV; |η|<2.4; "tight muon"; miniIso<0.06
- **Electrons**:
  - p_T>20 GeV; |η|<2.5; 1.442<|η| <1.566; loose EGM ID

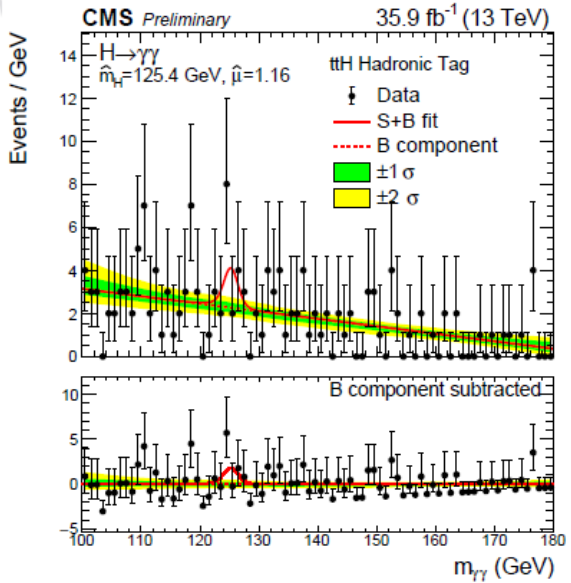
leptonic

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

- **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

HIG-16-040



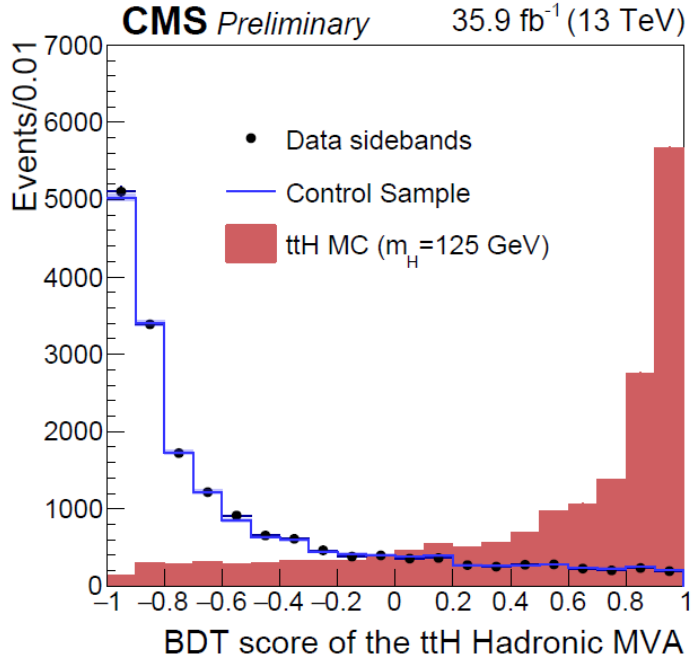


hadronic

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

- **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 μttH sensitivity



VH

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

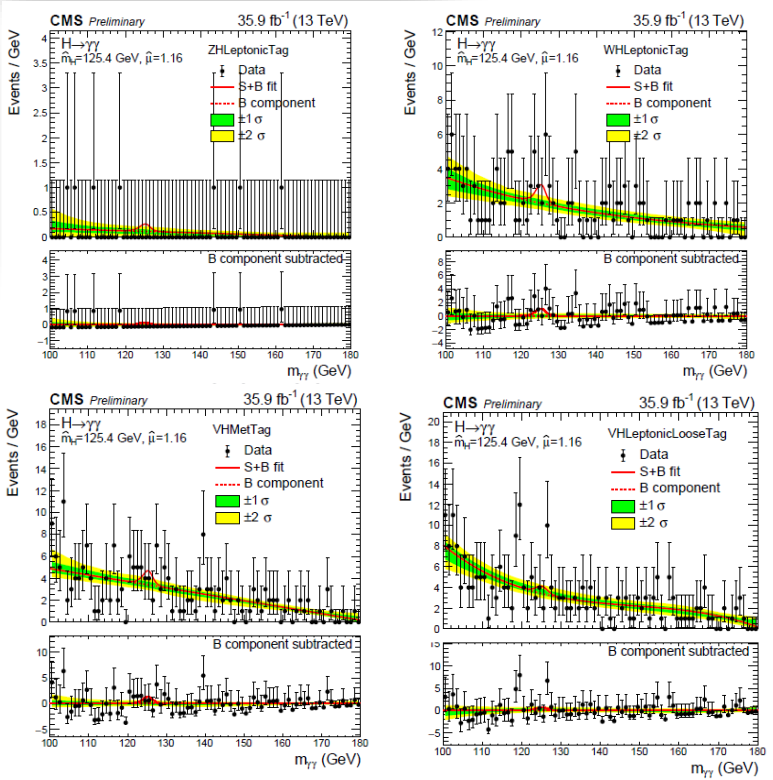
- **Muons**
  - p_T>20 GeV; |η|<2.4; "tight muon"; pf isolation < 0.25 (loose WP)
- **Electrons**
  - p_T>20 GeV; |η|<2.5; 1.442<|η|<1.566; loose EGM ID
- **Photons**
  - (sub)leading $p_T/m_{\gamma\gamma}$>0.375(0.25)

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

VH leptonic loose:
- 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

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)

hadronic category W->jj or Z->jj

- **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)

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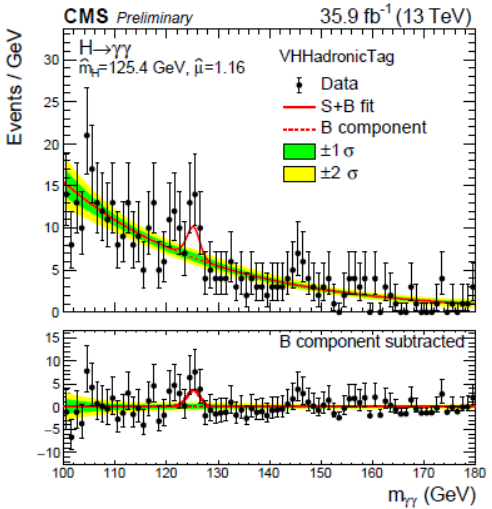

VBF Tag

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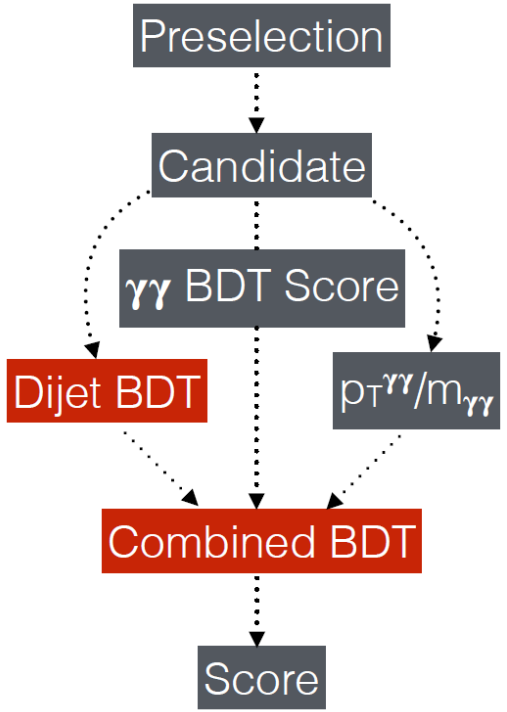
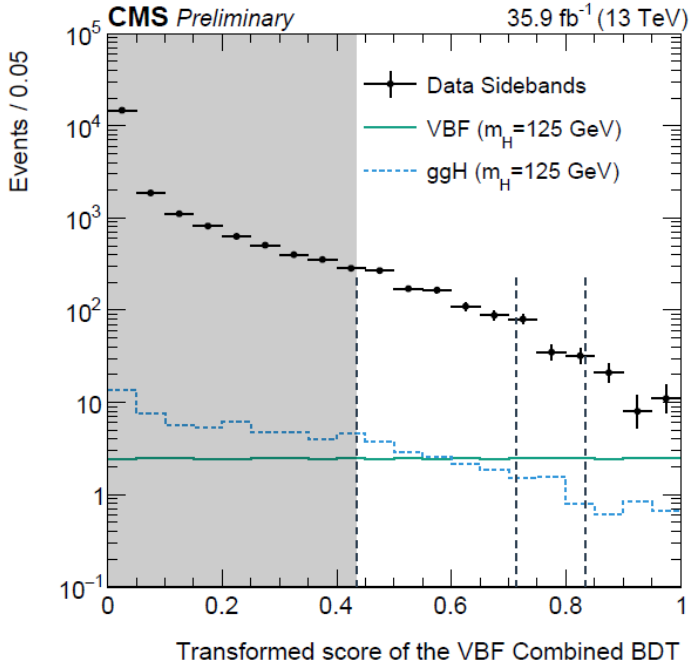
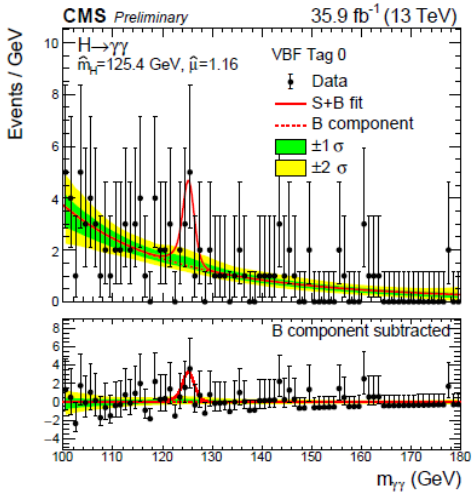
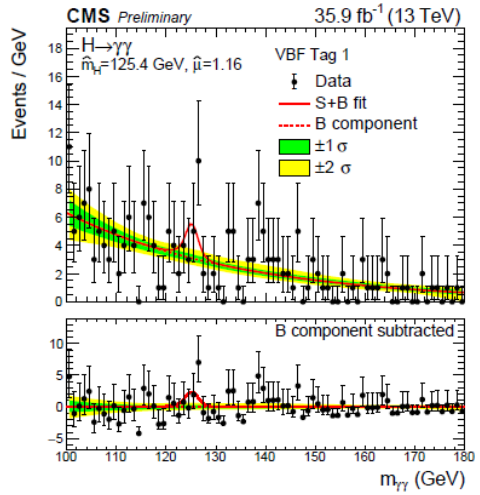
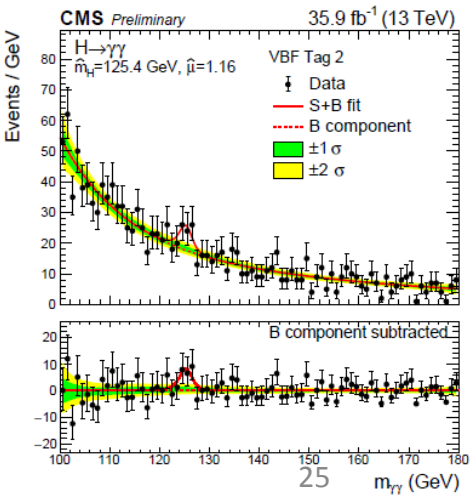
- Preselection (ICHEP): Two jets with pT_{j1}>30GeV, pT_{j2} >20GeV, |η|<4.7, m_{jj}>250GeV
- Main Structure: two parts, the Dijet BDT & Combined BDT
- Dijet BDT: separates VBF dijet from BG (incl. gluon fusion) using dijet kinematics
- Combined BDT: separates signal/BG diphotons using diphoton BDT, dijet BDT and scaled diphoton pT
- 3 VBF-tagged categories using the combined MVA with boundary optimisation: cuts on combined score are simultaneously optimised for max significance across all categories











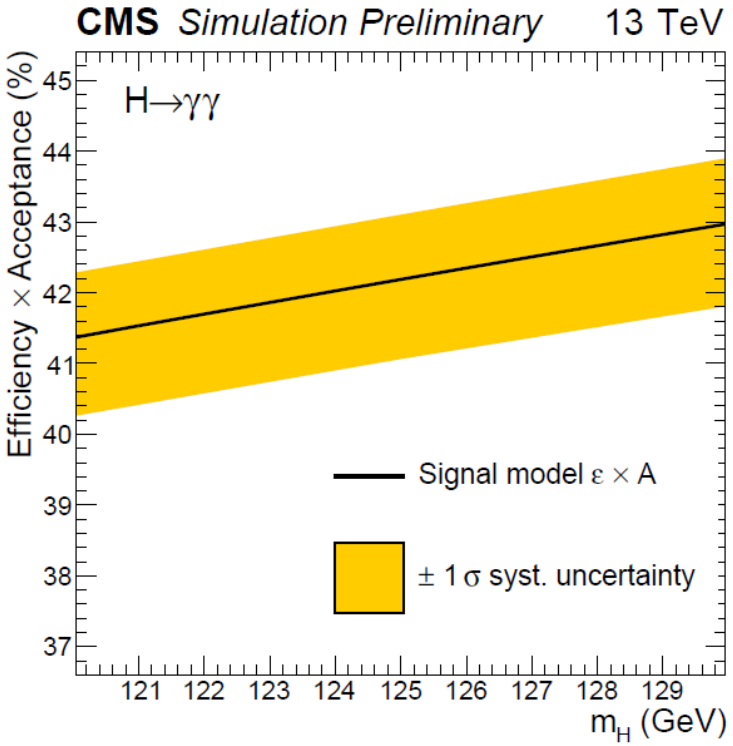
Signal efficiency and expected N_{evt}

- Kinematic selection
  - Leading photon : $E_T / m_{\gamma\gamma} > 1/3$
  - Subleading photon : $E_T / m_{\gamma\gamma} > 1/4$
  - Photons $|\eta| < 2.5$
- Preselection to be tighter than HLT, selections on photon ID MVA and diphoton BDT

	R_9	H/E	$\sigma_{\eta\eta}$	$\mathcal{I}_{ph}$	$\mathcal{I}_{tk}$
Barrel	$[0.5, 0.85]$	< 0.08	< 0.015	< 4.0	< 6.0
	> 0.85	< 0.08	–	–	–
Endcaps	$[0.8, 0.90]$	< 0.08	< 0.035	< 4.0	< 6.0
	> 0.90	< 0.08	–	–	–

Event Categories	SM 125 GeV Higgs boson expected signal													Bkg
	Total	ggH	VBF	ttH	bbH	tHq	tHW	WH lep	ZH lep	WH had	ZH had	σ_{eff}	σ_{HM}	(GeV^{-1})
Untagged 0	45.83	80.19 %	11.75 %	1.83 %	0.40 %	0.47 %	0.22 %	0.41 %	0.19 %	2.96 %	1.58 %	1.32	1.24	21.92
Untagged 1	480.56	86.81 %	7.73 %	0.56 %	1.15 %	0.13 %	0.02 %	0.47 %	0.27 %	1.81 %	1.04 %	1.47	1.32	924.21
Untagged 2	670.45	89.76 %	5.48 %	0.44 %	1.18 %	0.08 %	0.01 %	0.51 %	0.34 %	1.40 %	0.81 %	1.94	1.68	2419.53
Untagged 3	610.07	91.13 %	4.51 %	0.48 %	1.07 %	0.07 %	0.01 %	0.55 %	0.30 %	1.21 %	0.69 %	2.62	2.28	4855.00
VBF 0	10.01	21.69 %	77.09 %	0.34 %	0.35 %	0.29 %	0.03 %	0.03 %	0.00 %	0.19 %	-0.01 %	1.51	1.30	1.60
VBF 1	8.64	33.58 %	64.64 %	0.39 %	0.52 %	0.36 %	0.04 %	0.13 %	0.03 %	0.24 %	0.07 %	1.66	1.38	3.25
VBF 2	27.76	50.14 %	46.46 %	0.81 %	0.73 %	0.53 %	0.07 %	0.20 %	0.06 %	0.71 %	0.27 %	1.61	1.36	18.89
ttH Hadronic	5.85	10.99 %	0.70 %	77.54 %	2.02 %	4.13 %	2.02 %	0.09 %	0.05 %	0.63 %	1.82 %	1.48	1.30	2.40
ttH Leptonic	3.81	1.90 %	0.05 %	87.48 %	0.08 %	4.73 %	3.04 %	1.53 %	1.15 %	0.02 %	0.02 %	1.60	1.35	1.50
ZH Leptonic	0.49	0.00 %	0.00 %	2.56 %	0.00 %	0.02 %	0.13 %	0.00 %	97.30 %	0.00 %	0.00 %	1.65	1.43	0.12
WH Leptonic	3.61	1.26 %	0.59 %	5.18 %	0.18 %	3.03 %	0.73 %	84.48 %	4.33 %	0.12 %	0.09 %	1.64	1.43	2.09
VH LeptonicLoose	2.75	9.16 %	2.70 %	2.34 %	0.57 %	1.81 %	0.13 %	63.62 %	18.87 %	0.56 %	0.23 %	1.67	1.56	3.50
VH Hadronic	9.69	57.38 %	3.68 %	3.61 %	0.35 %	1.39 %	0.27 %	0.17 %	0.42 %	20.47 %	12.26 %	1.38	1.31	7.22
VH Met	4.25	23.63 %	2.46 %	14.45 %	0.41 %	2.00 %	1.14 %	25.17 %	28.60 %	1.32 %	0.82 %	1.55	1.38	3.49
Total	1883.77	86.96 %	7.09 %	1.00 %	1.09 %	0.15 %	0.04 %	0.81 %	0.42 %	1.55 %	0.89 %	1.95	1.62	8264.73

Table 3: The expected number of signal events per category and the percentage breakdown per production mode in that category. The σ_{eff}, computed as the smallest interval containing 68.3% of the invariant mass distribution, and σ_{HM}, computed as the width of the distribution at half of its highest point divided by 2.35 are also shown as an estimate of the $m_{\gamma\gamma}$ resolution in that category. The expected number of background events per GeV around 125 GeV is also listed.



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