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

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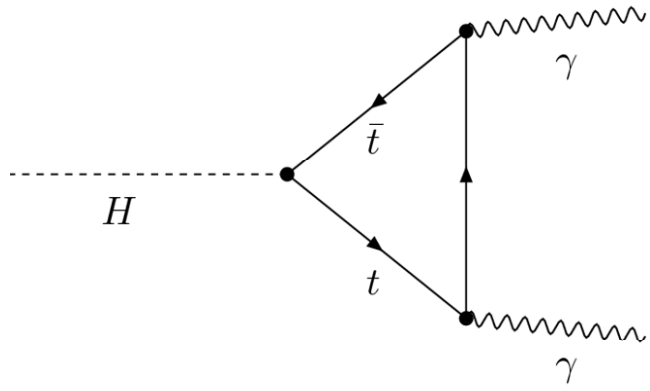
Outline

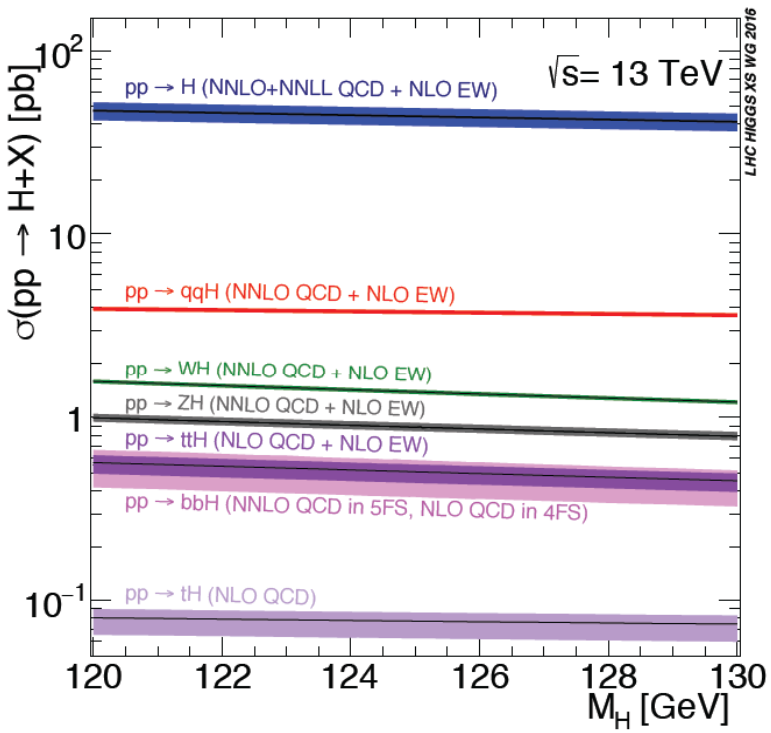
Based on the $H \rightarrow \gamma\gamma$ strategy and results with 12.9fb^{-1} data for ICHEP2016

- Introduction
- Analysis strategy and analysis elements
- Event categorization, Signal and Background Modelling
- Measurement results : significance, signal strength and couplings
- Fiducial XS measurement
- Summary

Introduction

- **Clean final state** with two highly **energetic photons**
- Final state **fully reconstructed** with **high resolution**
- Good mass resolution : **σ~ 1-2% $m_{\gamma\gamma}$**
- Very small branching fraction (**~0.2%)**





- **Large backgrounds** ($\gamma\gamma$, γj, jj)
- Search for a **narrow peak on a falling** background in mass distribution
- **Exclusive categories targeting:**
gluon-gluon fusion **(ggH),**
vector boson fusion **(VBF)**
and **ttH production modes**

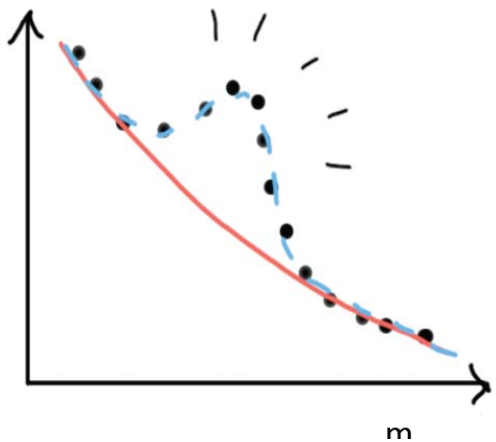
Analysis strategy and analysis elements

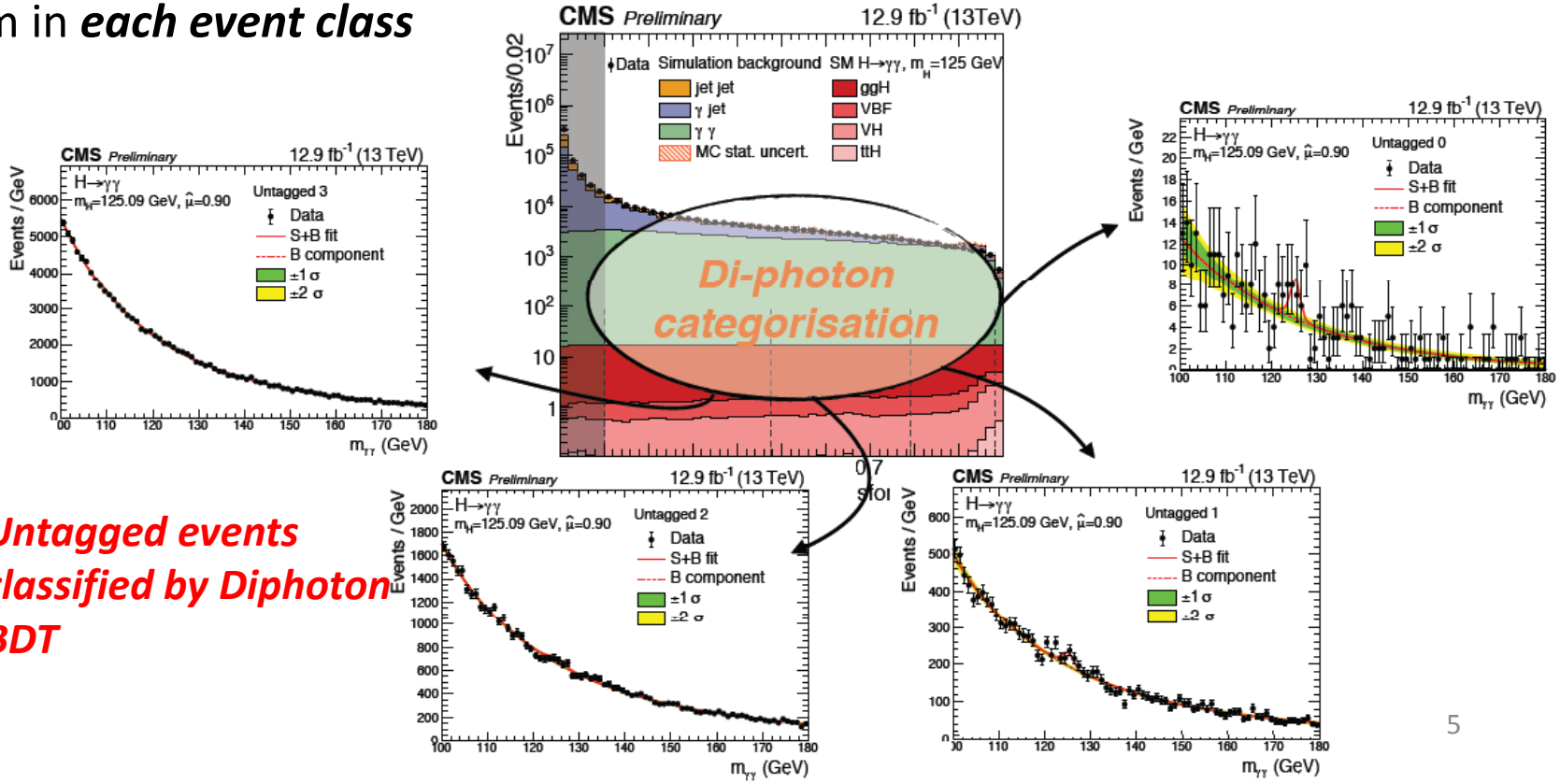
Analysis strategy

- **Photons energy reconstructed and corrected**, rejection of fake photons (**photon id**)

- **Events categorized** into **classes (production mechanism, mass resolution, S/B)** to improve the analysis sensitivity

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





Untagged events classified by Diphoton BDT

Event and photon selection

- **Double-photon trigger selection** based on **transverse energy**, **$m_{\gamma\gamma}$**, **isolation** and electromagnetic **shower shapes** variables

  HLT_Diphoton30_18 _R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90

- Minimal **pre-selection**, similar to but **tighter than trigger selections**
  - p_T>30 (20) GeV, $p_T/m_{\gamma\gamma}$ > 1/3 (1/4) for (sub)leading-p_T photon
  - |η|<2.5, removing 1.44<|η|<1.57, electron veto
  - either R_9>0.8, or charged hadron isolation < 20 GeV, or charged hadron isolation relative to p_T <0.3

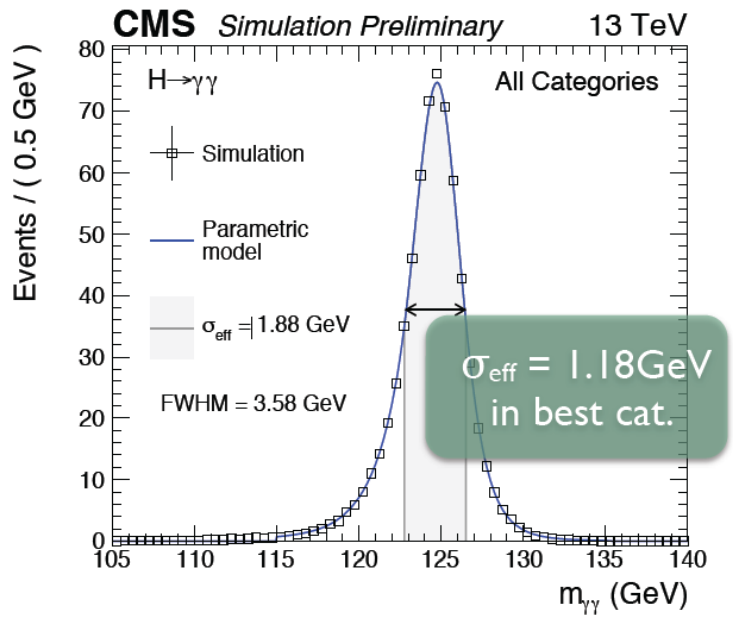
	H/E	$\sigma_{\eta\eta}$	R_9	photon iso.	tracker iso.
ECAL barrel; $R_9 > 0.85$	<0.08	–	>0.5	–	–
ECAL barrel; $R_9 \leq 0.85$	<0.08	<0.015	>0.5	< 4.0	< 6.0
ECAL endcaps; $R_9 > 0.90$	<0.08	–	>0.8	–	–
ECAL endcaps; $R_9 \leq 0.90$	<0.08	<0.035	>0.8	< 4.0	< 6.0

- **Efficiency** is measured **in MC** with **SFs** from data and simulation with tag & probe method with ***Z→ee and Z→μμγ***
  - ***Z→ee*** events used for all cuts other than electron veto
  - ***Z→μμγ*** events for electron veto

Photon energy

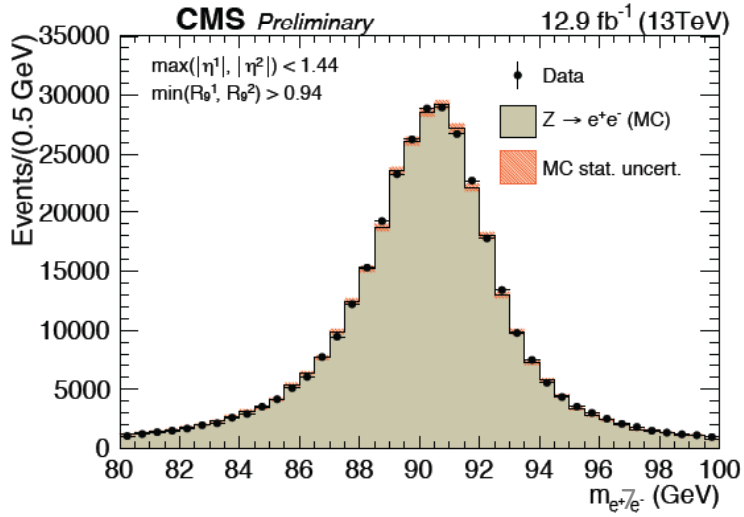
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$

- **Electro-magnetic calorimeter response**
  - corrected for **change in time**
  - **inter-calibrated** to be uniform in η/ϕ
  - adjustment of **absolute scale**



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

- **Scale vs time and resolution calibration: Z→ee peak** used as reference



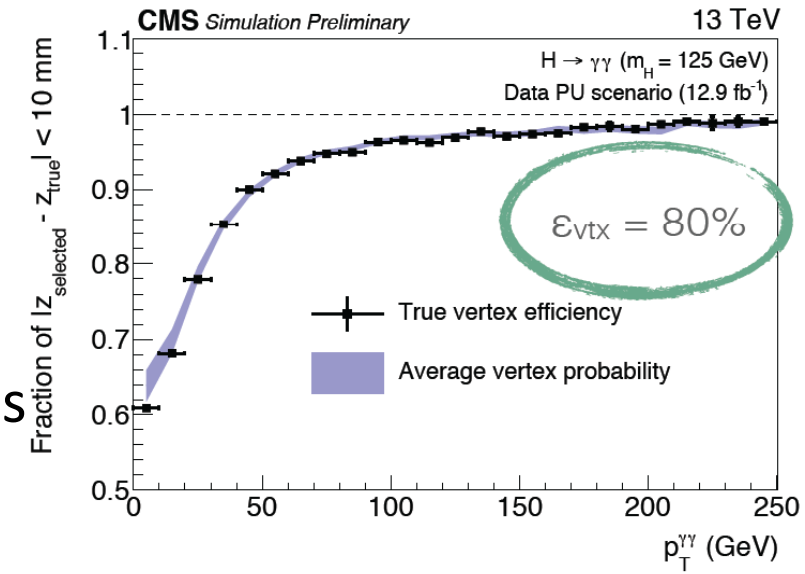
- **Corrected energies and resolutions used in the analysis**

Vertex identification

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

- Vertex assignment correct within **1 cm**

→ **negligible** impact on mass resolution

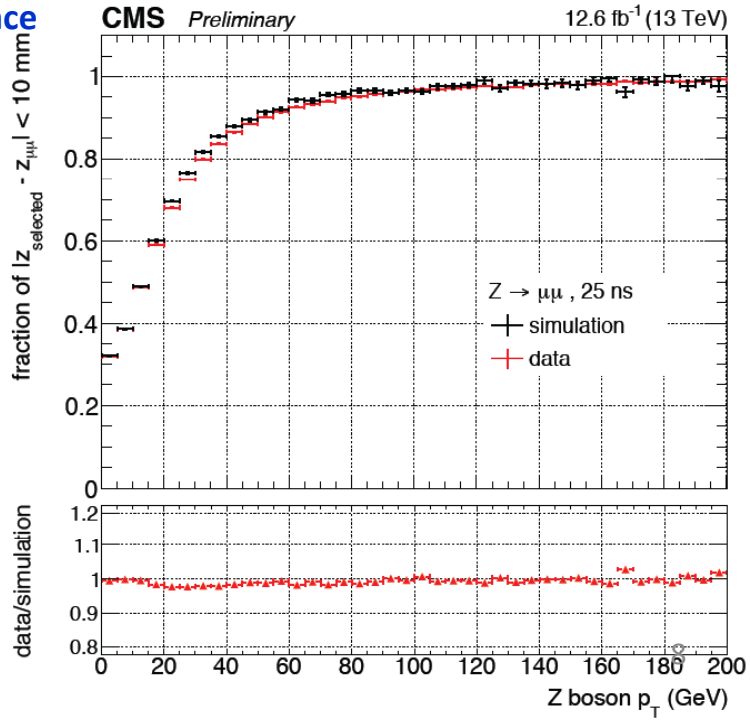


- No ionization in the tracker for photons
- **Multi-variate approach for vertex identification**
  - Vertex ID BDT: **kinematic correlations and track distribution imbalance**

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

  - if conversions are present **Conversion information** the number of conversions and 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. The variable

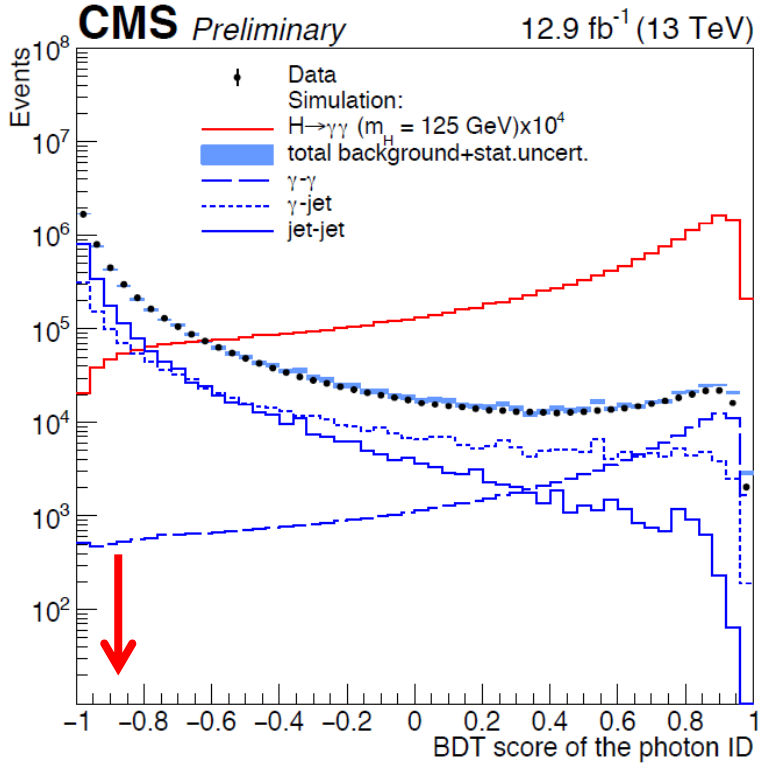
- Second MVA estimates **probability of correct vertex** choice, used for di-photon classification
- **Method validated** on Z→μμ (γ+j for converted γ) events, where vertex found after removing muon tracks

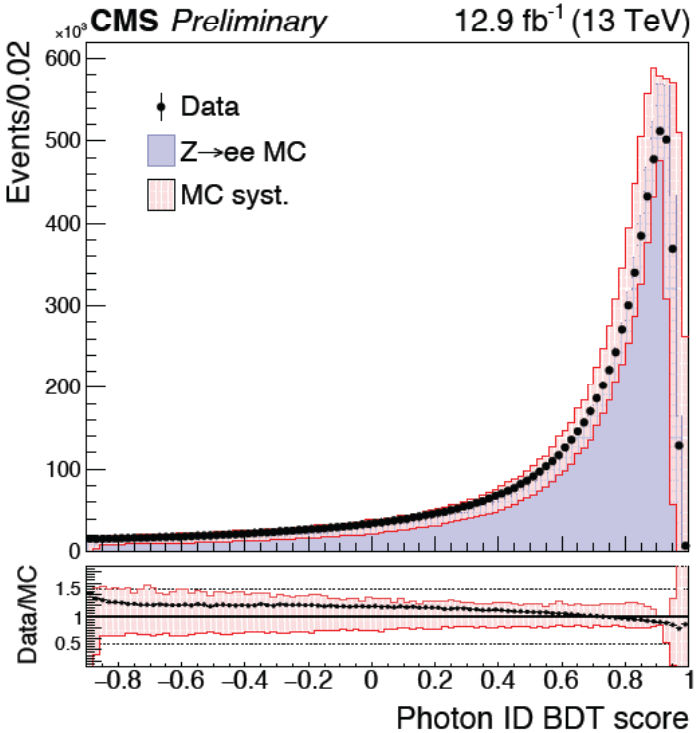


Photon identification

➢ **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, ERAW



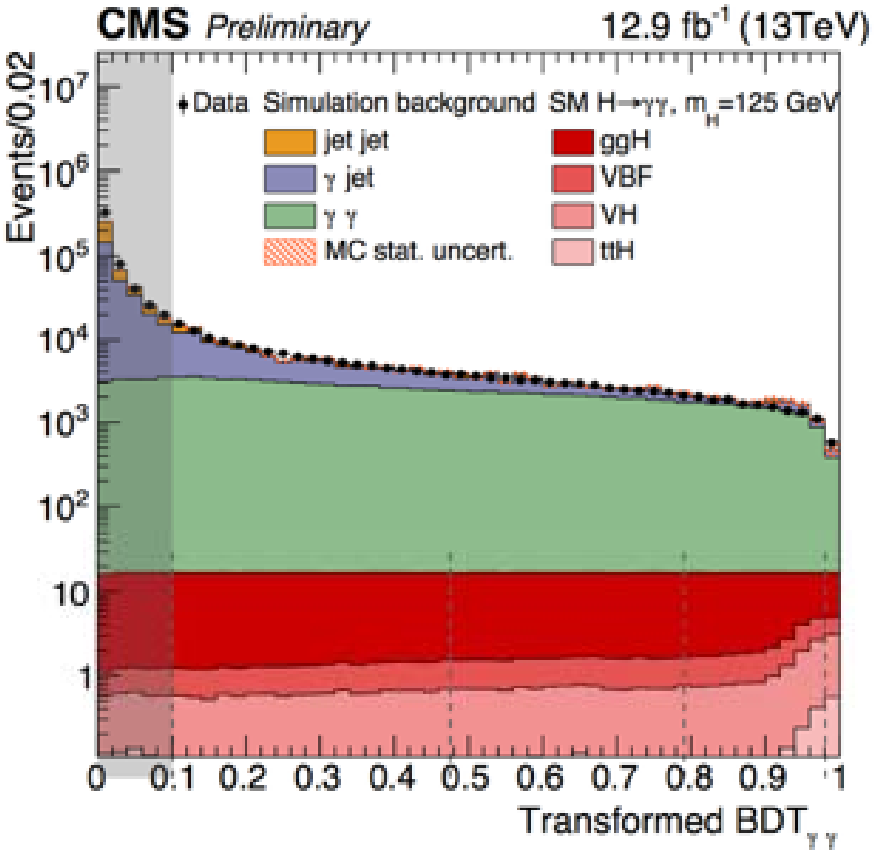


➢ Inputs and output of the MVA are **validated** on data and MC in **Z→ee** and **Z→μμγ** events

➢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



- **Input variables**:
  - 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

Higher BDT score gives better mass-resolution diphoton events

Event categorization, Signal and Background Modelling

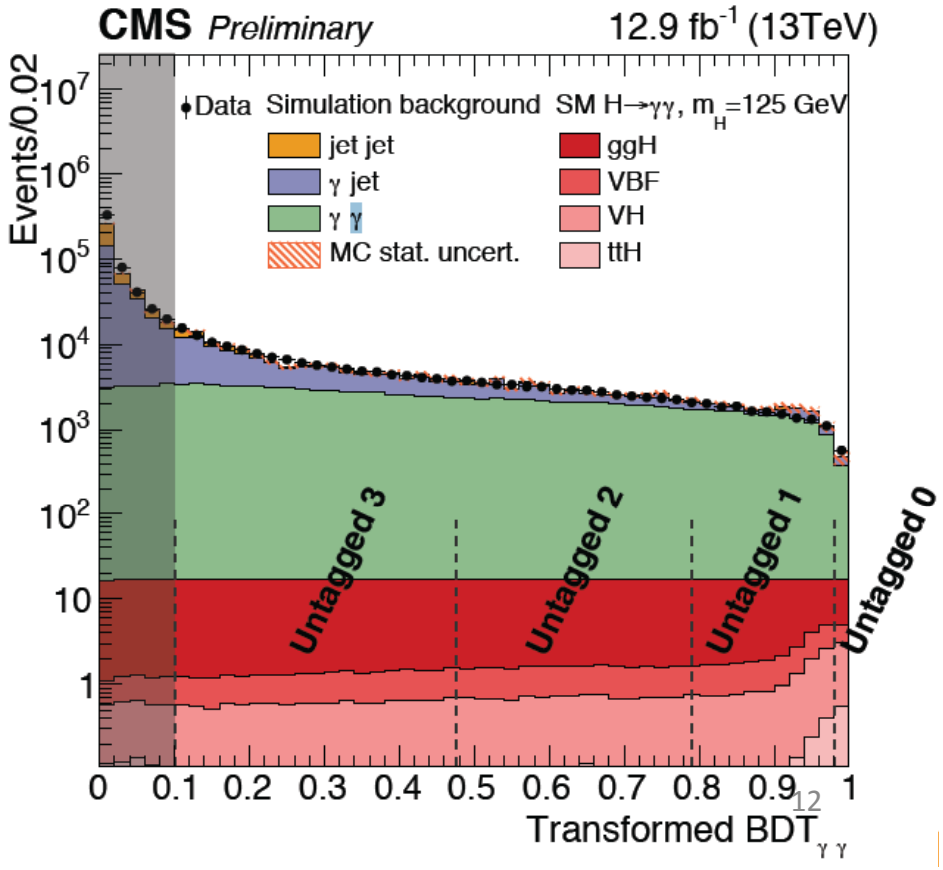
Event classification

- Events are **split** into different categories corresponding loosely to **Higgs production modes**

- **VBF- and ttH-specific categories** with additional selection criteria to identify topologies corresponding to respective production modes
  - ✓ **ttH**: **leptonic** and **hadronic** modes
  - ✓ **VBF**: Split into **2 sub-categories** based on sensitivity

- VH was not integrated into workflow could not happen in time. ***To be added in the future.***

- **4 Inclusive categories** ("Untagged 0-3"), mostly consisting of ggH events : corresponding to different **S/B** and invariant **mass resolution**

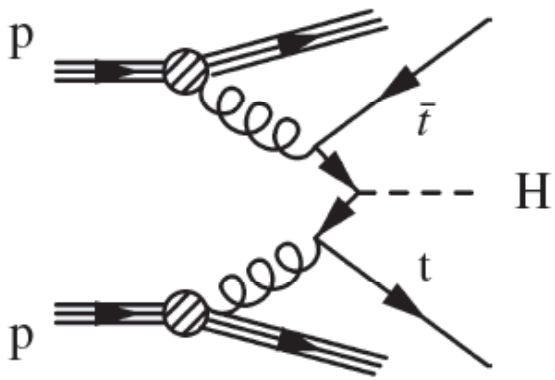


Tagged events

ttH: leptonic tag

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

- (sub)lead pT/$m_{\gamma\gamma}$ > 1/2(1/4)
- at least one lepton (ℓ=e,μ), away from Z peak
- ≥ 2 jets
- ≥ 1 b-jet



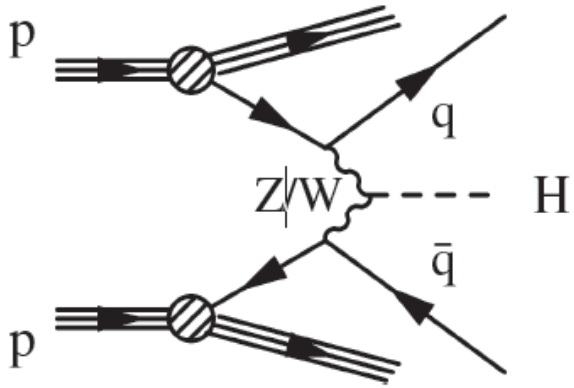
ttH: hadronic tag

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

- (sub)lead pT/$m_{\gamma\gamma}$ > 1/2(1/4)
- 0 leptons
- ≥ 5 jets
- ≥ 1 b-jet

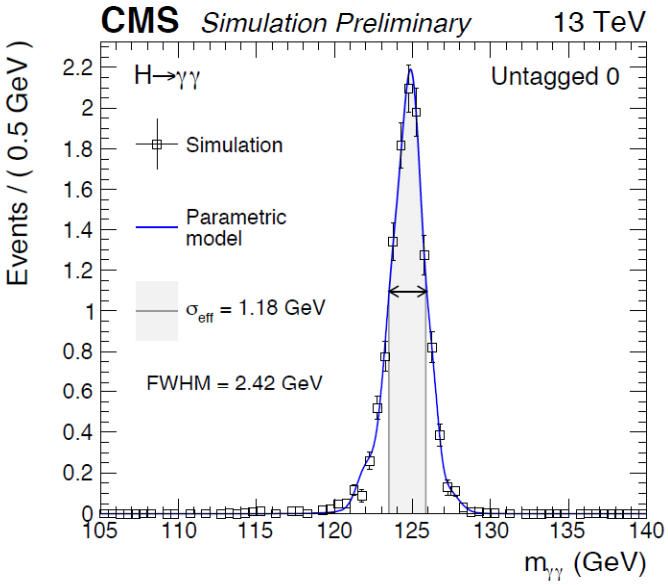
VBF tag

- Identify events with **2 jets** through a MVA
  - inputs: pT/$m_{\gamma\gamma}$ of both photons, pT of both jets, m_{jj}, $\Delta\eta_{jj}$, Zeppenfeld variable, $\Delta\phi_{\gamma\gamma jj}$
- 2 jets with p_{T1} > 30GeV, p_{T2} >20 GeV, |η| < 4.7, m_{jj} >250 GeV
- **VBF Classification** BDT combines di-jet and diphoton BDT: 2 data categories (**VBF tag 0-1**)

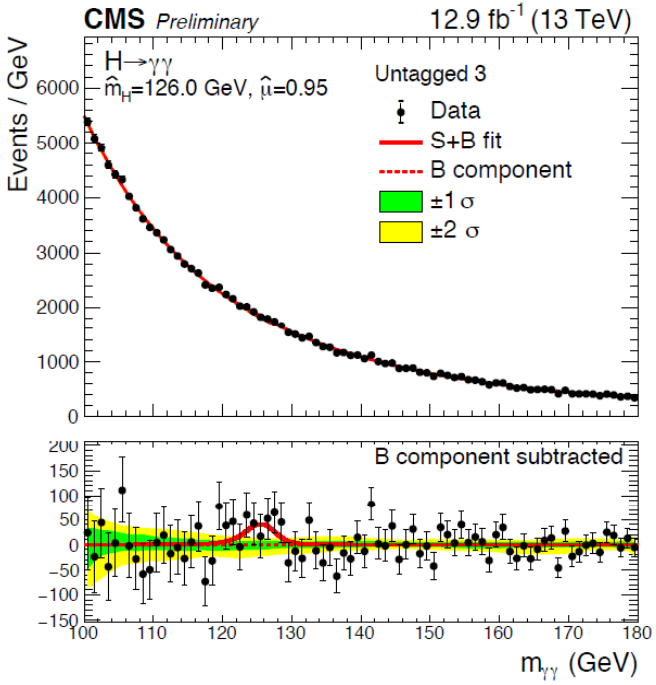


Signal and background models

- Fully parametric **signal** model from **MC** simulation
  - ✓ physical nuisances allowed to float
  - ✓ **corrections** and data/MC efficiency **scale factors** applied

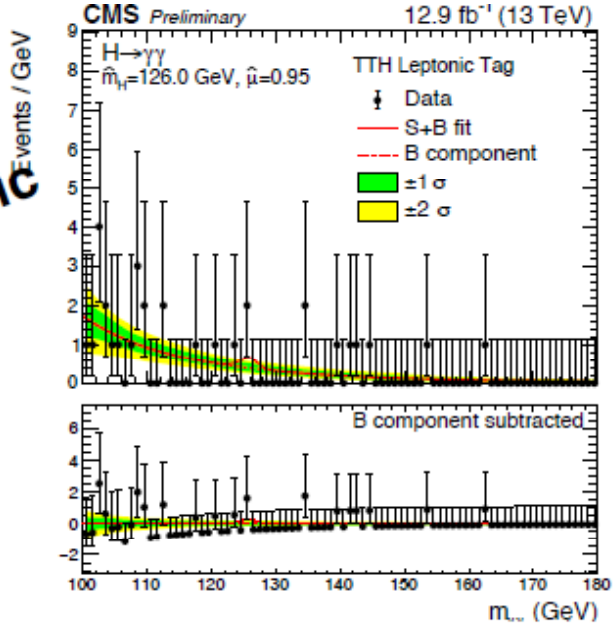


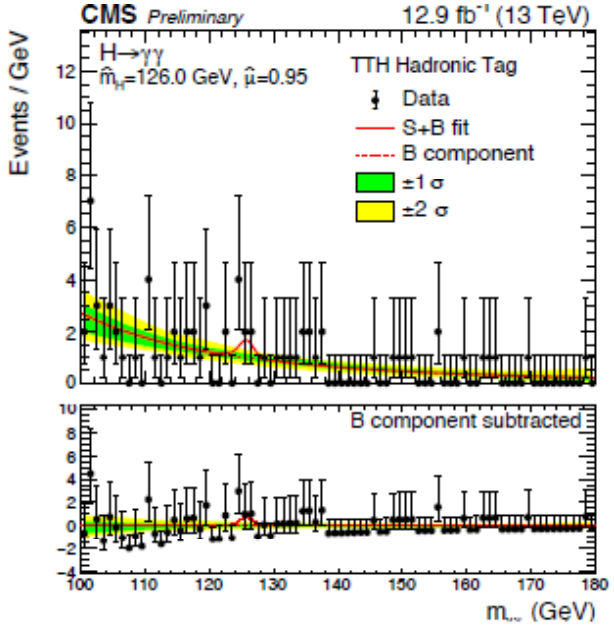
- Background model **data driven**
  - ✓ For each category, use **different functional forms** (sums of ***exponentials***, sums of **power law** terms, ***Laurent*** series and ***polynomials***)
  - ✓ Background functional forms treated as **discrete nuisance** parameter



Mass spectra : tagged events

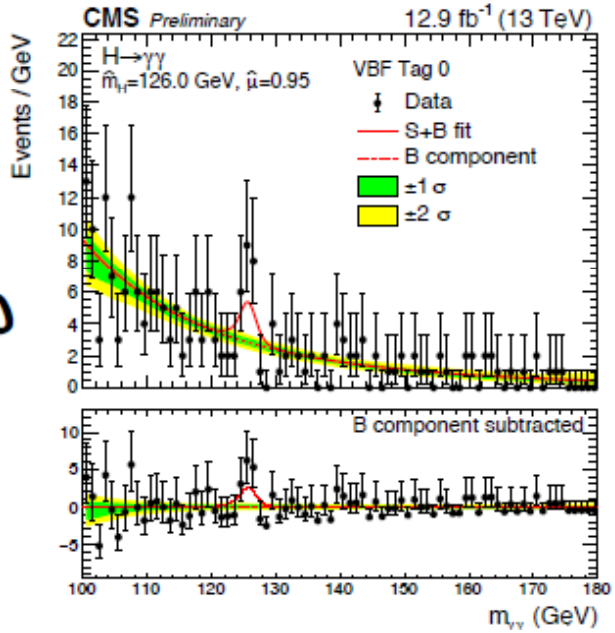
ttH leptonic

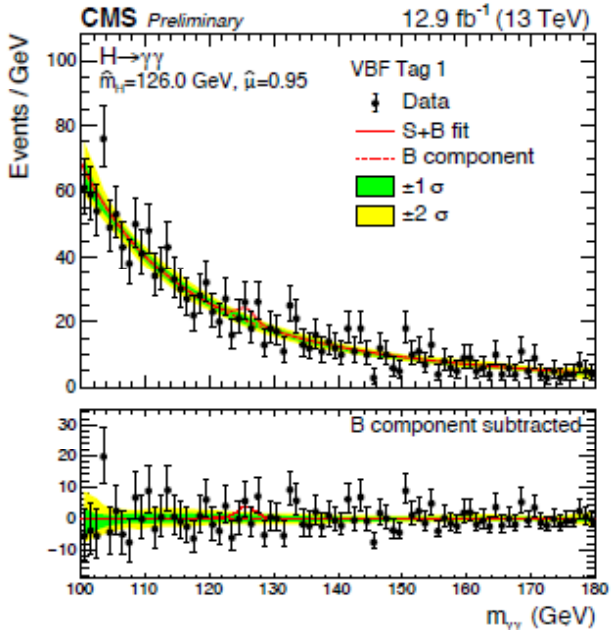




ttH hadronic

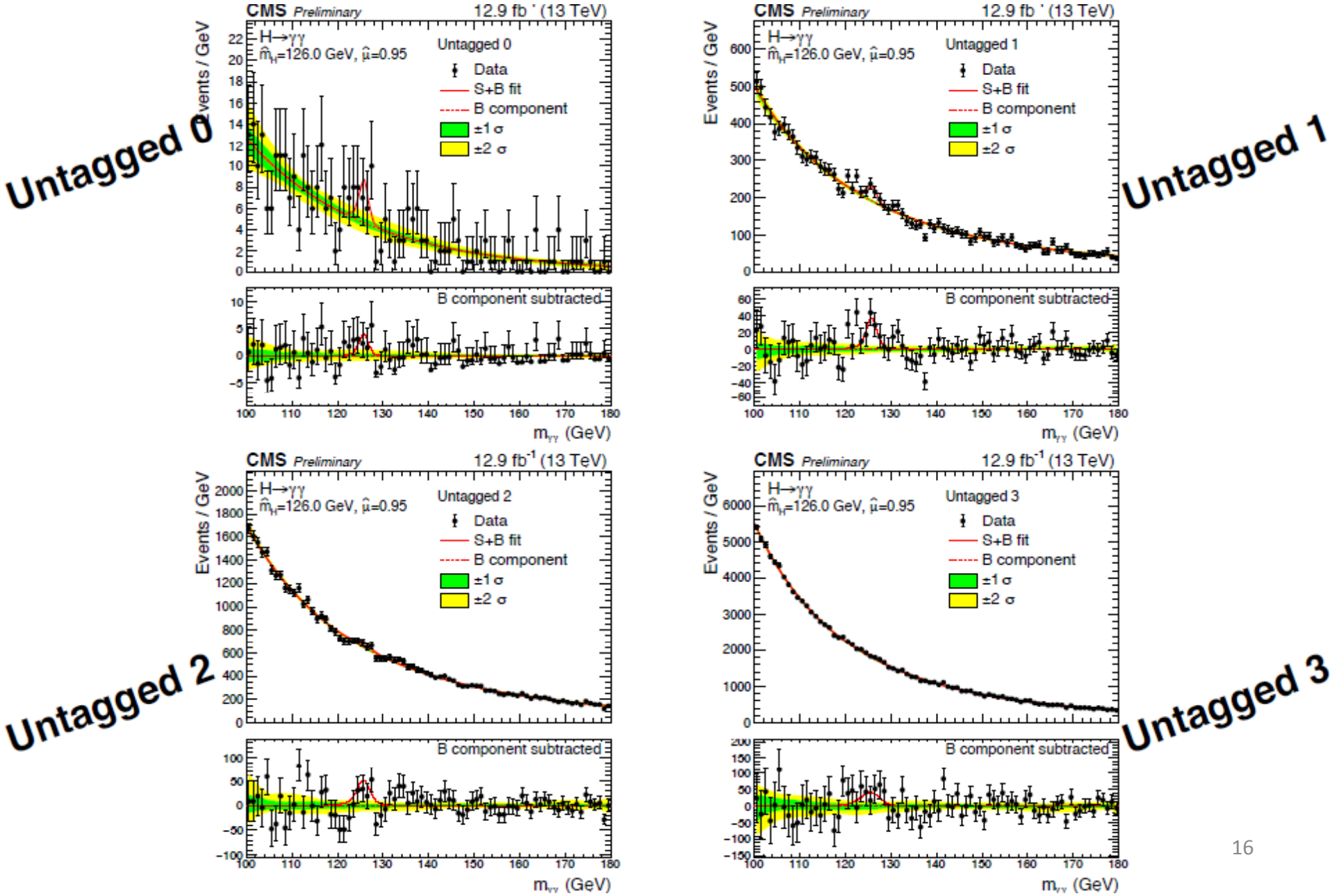
VBF tag 0



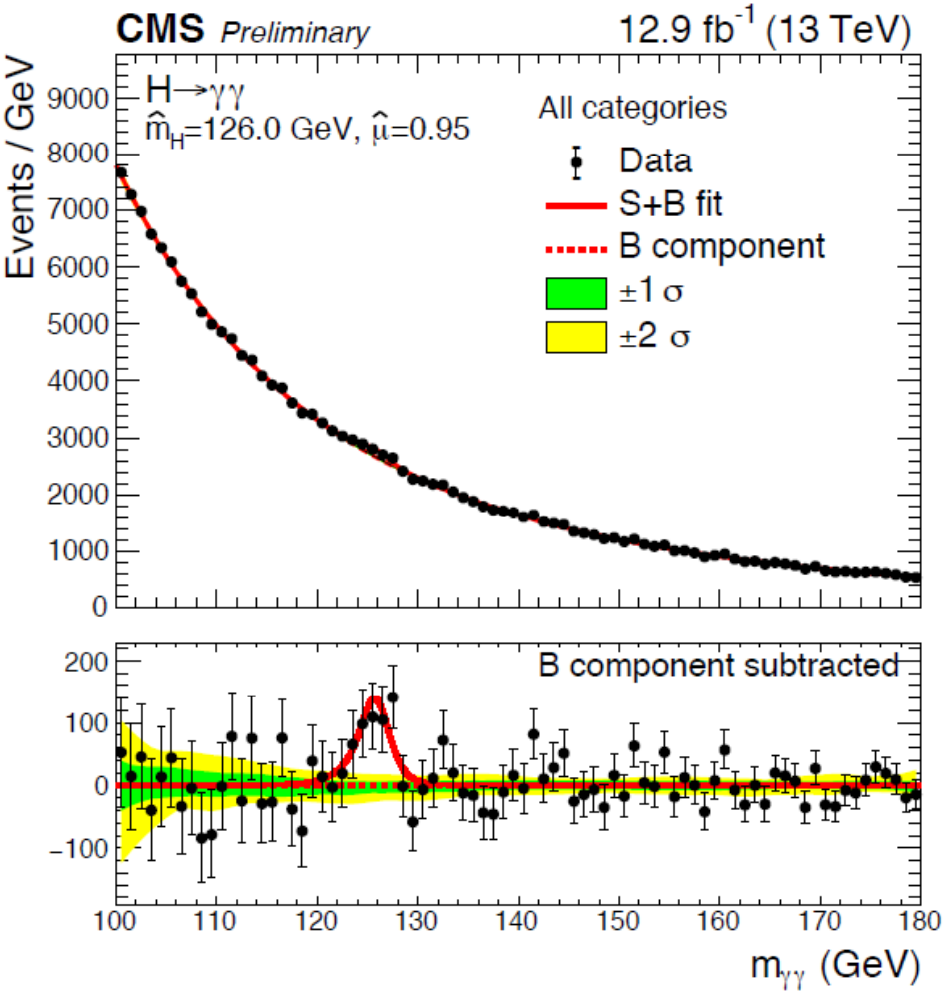


VBF tag 1

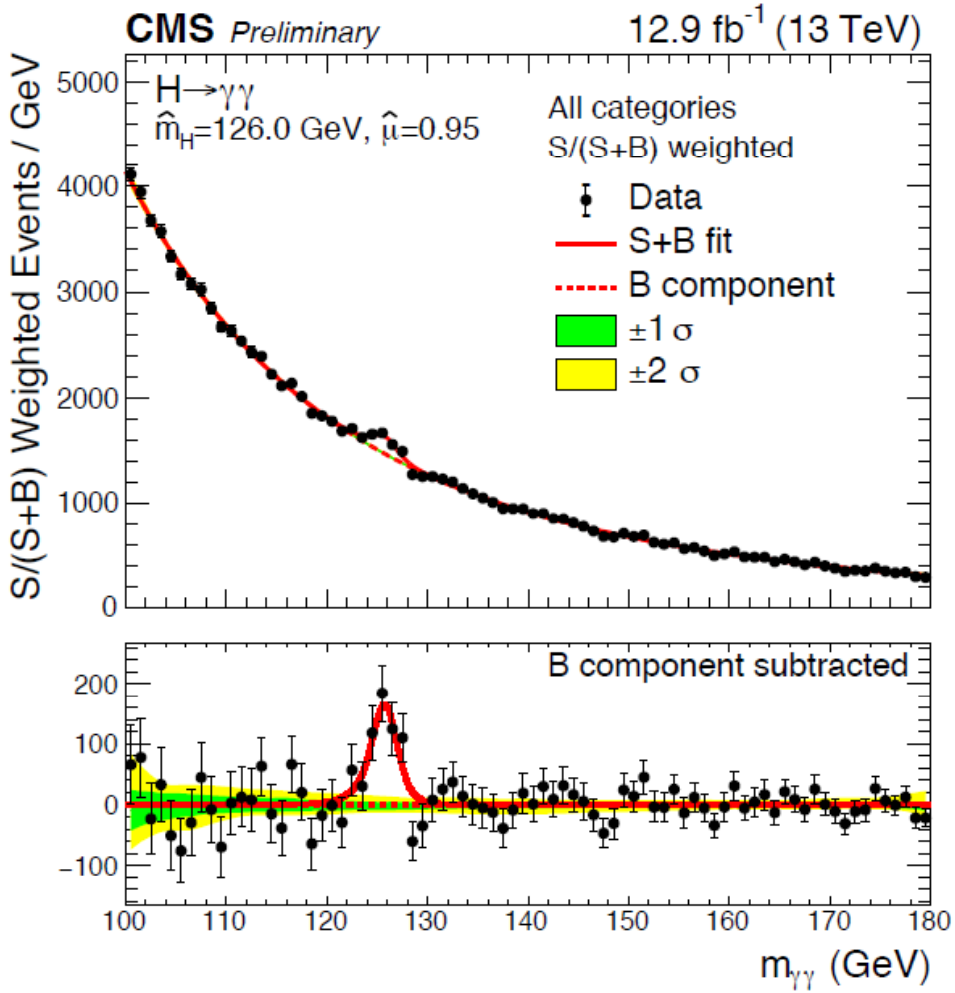
Mass spectra : untagged events



Mass spectra : all categories



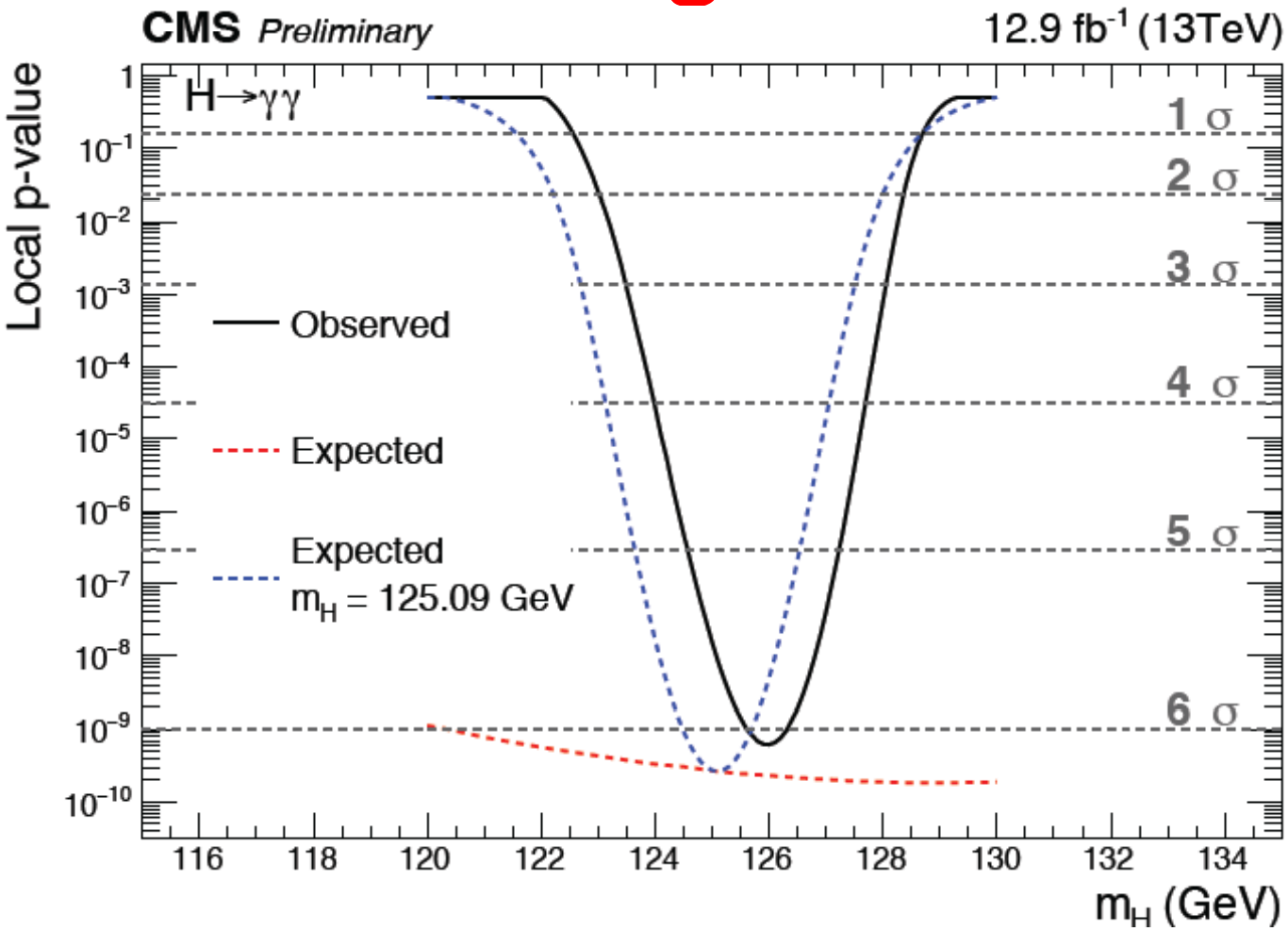
Unweighted



Weighted

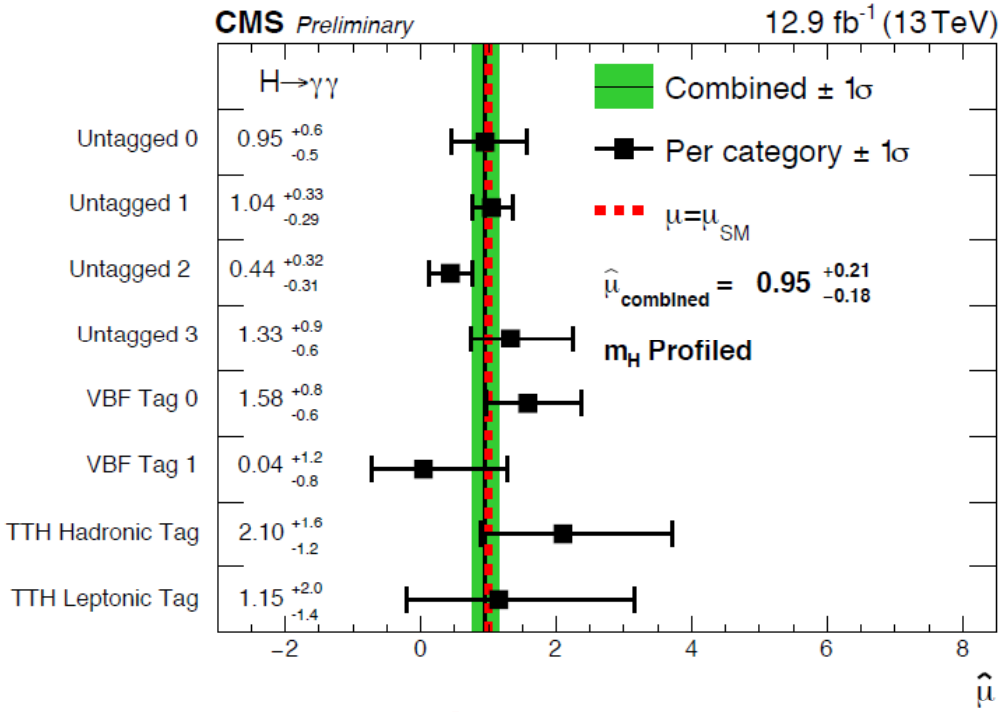
Measurement results : significance, signal strength and couplings

Results : significance

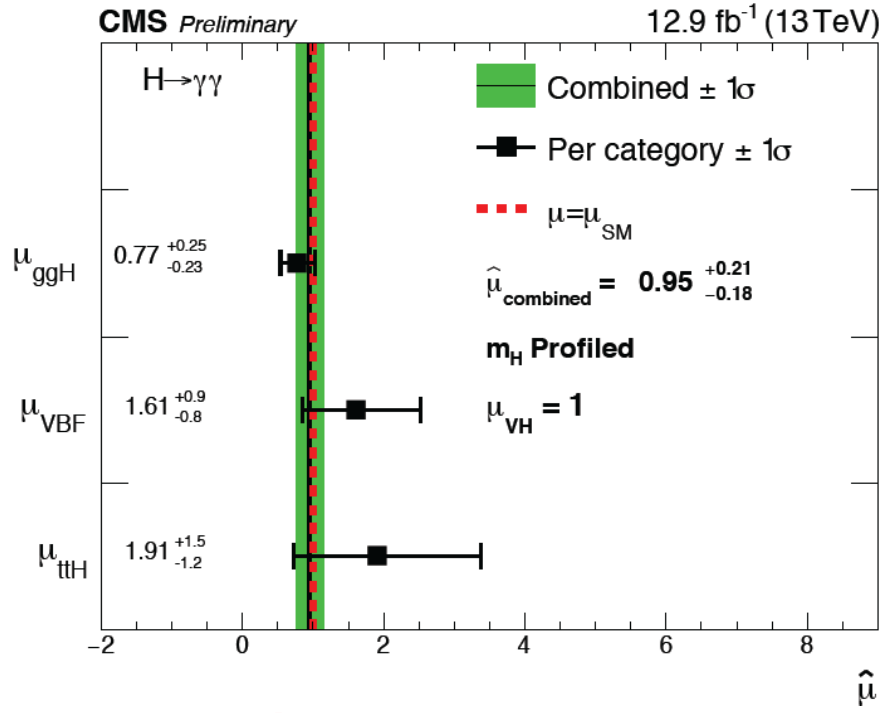


- **Significance** at **125.09 GeV** : **5.6σ** observed (6.2σ expected)
- **Maximum** observed significance is **6.1σ** at 126.0 GeV

Results : signal strength (I)



Per category



Per process

- **Best-fit signal strength**

$$\hat{\sigma}/\sigma_{SM} = 0.95^{+0.21}_{-0.19} = 0.95 \pm 0.17(stat.)^{+0.08}_{-0.05}(theo.)^{+0.10}_{-0.07}(syst.)$$

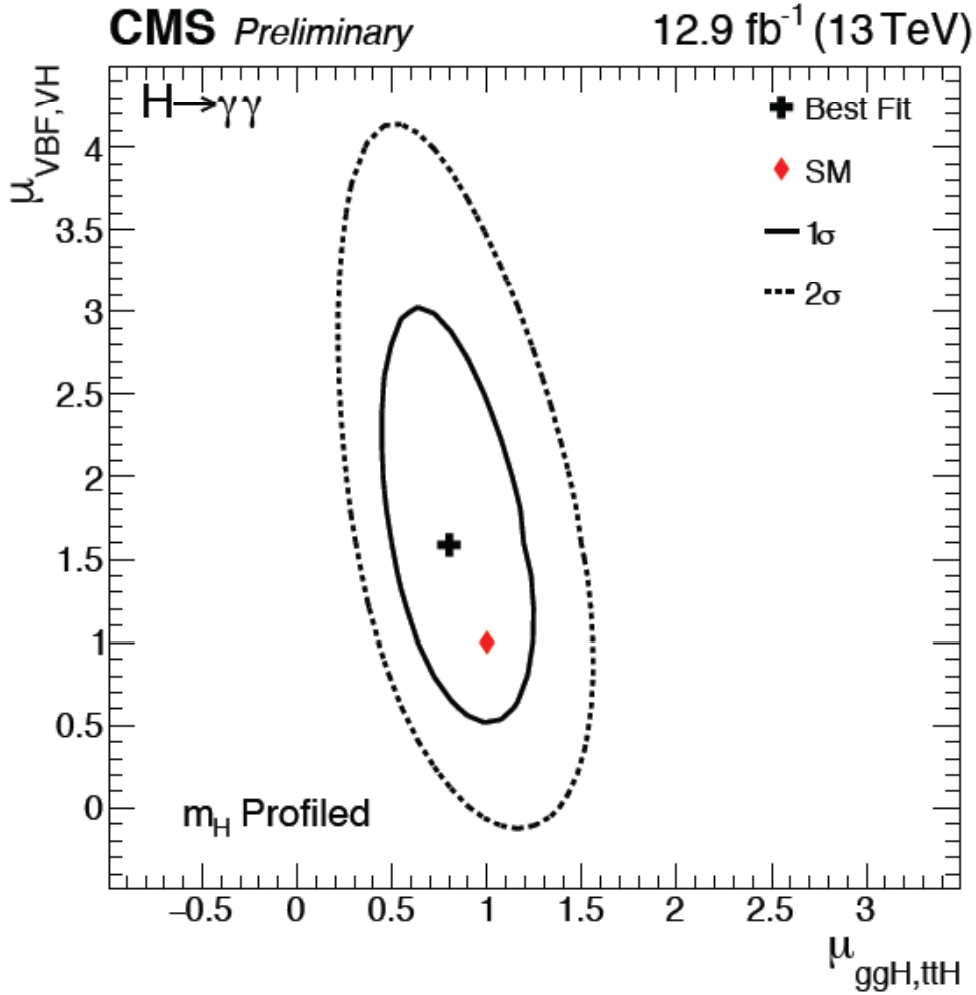
- Signal strengths measurements **compatible with SM**

Results : signal strength (II)

Signal strength measured is measured in **bosonic** and **fermionic** components

$$\hat{\mu}_{VBF,VH} = 1.59^{+0.73}_{-0.45}$$

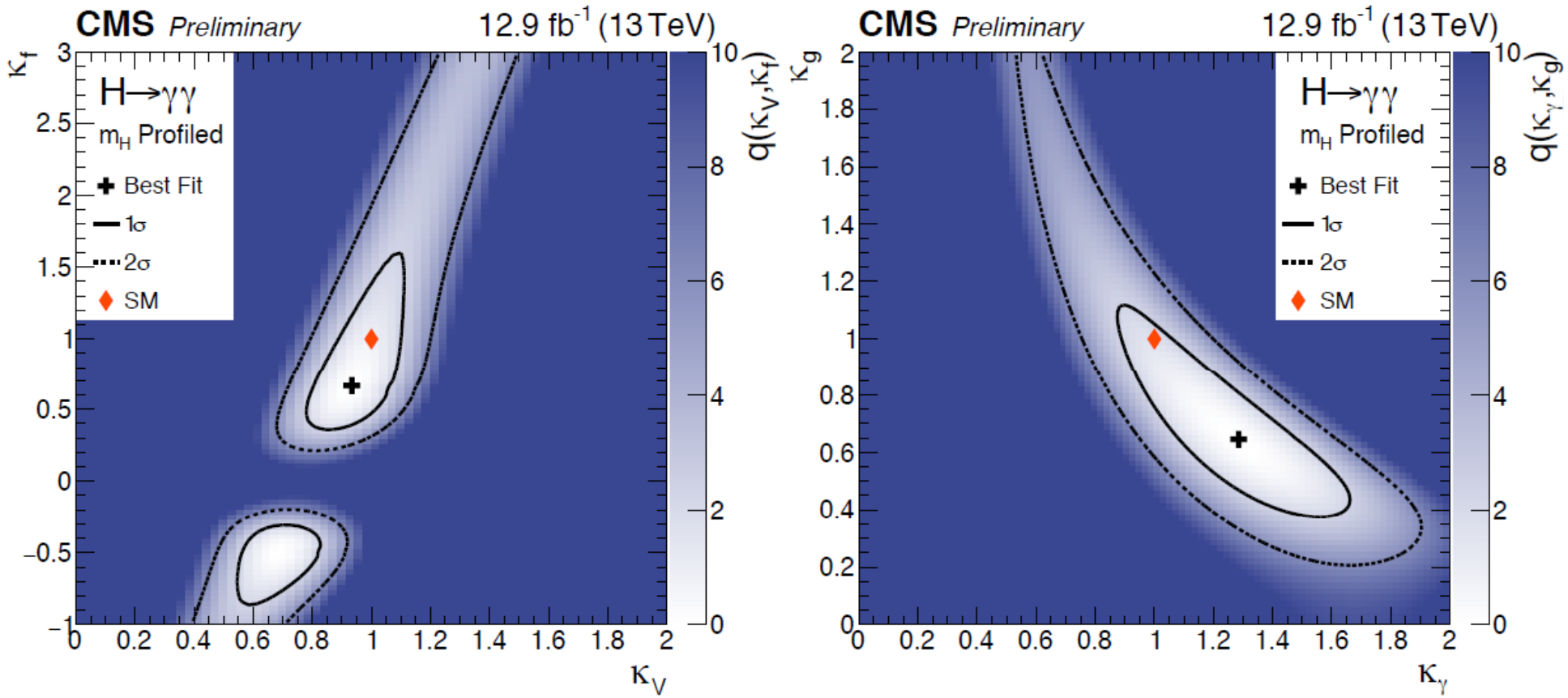
$$\hat{\mu}_{ggH,t\bar{t}H} = 0.80^{+0.14}_{-0.18}$$



Compatible with SM

Results : couplings

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



Compatible with SM

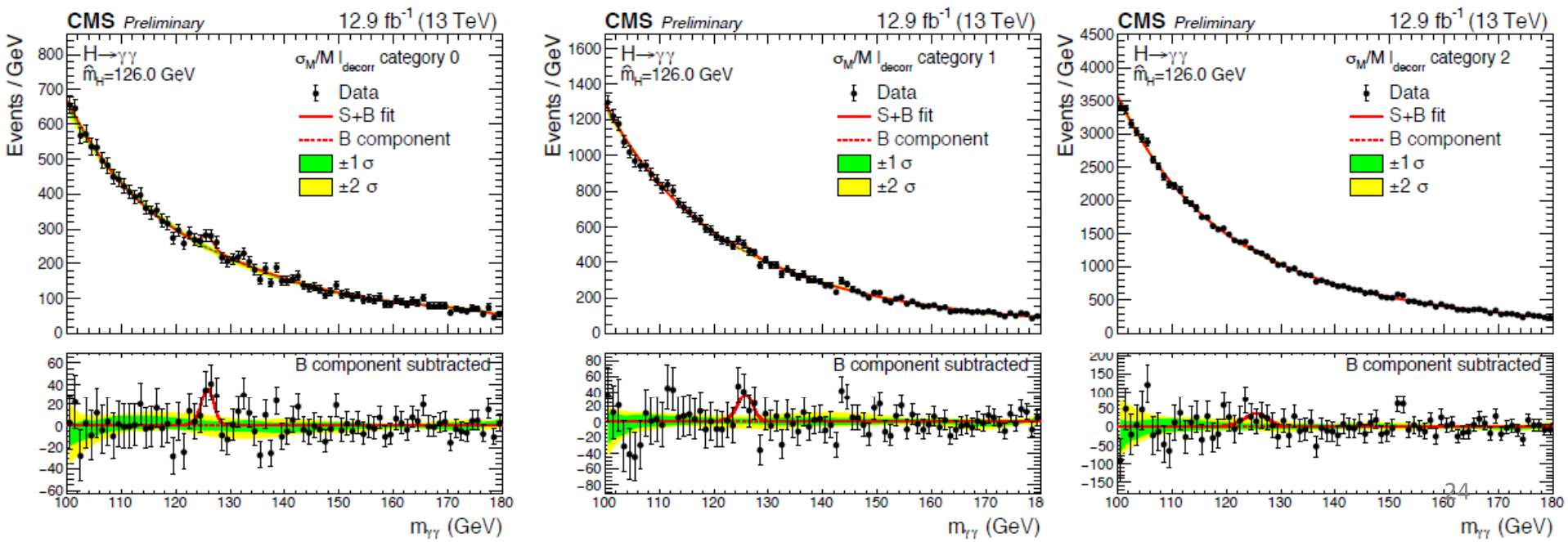
Fiducial XS measurement

Fiducial XS Measurement : Strategy

- Fiducial region is defined using **generator-level properties** of particles: ***$pT^{GEN}/m_{\gamma\gamma}^{GEN}$, η^{GEN}, $Isolation^{GEN}$***

- Follows a **similar strategy** to the main analysis

- **Different event categorization: 3 mass resolution categories**



Fiducial XS Measurement : Result

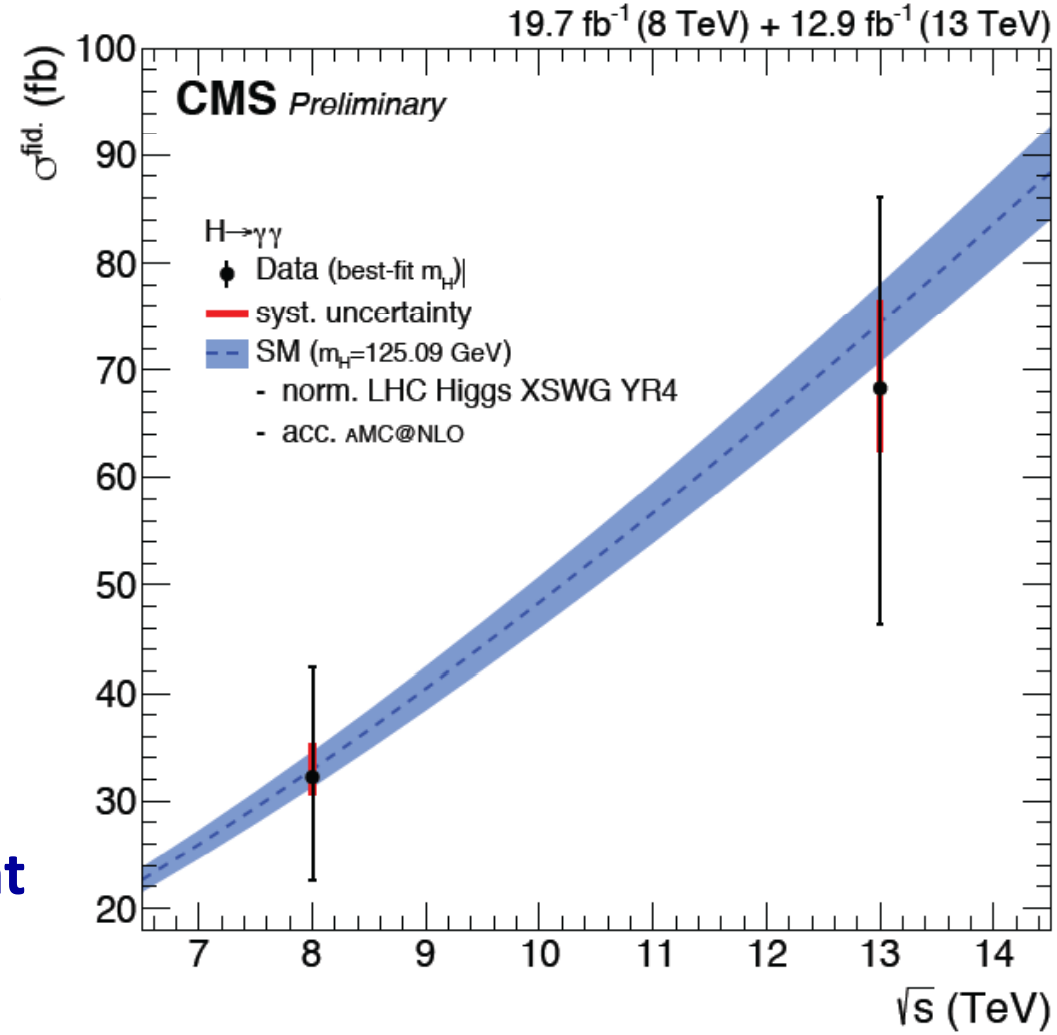
- **Fiducially cross section measured profiling m_H:**

$$\hat{\sigma}_{fid} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$$

- **Theoretical prediction for m_H=125.09 GeV**

$$\sigma^{th.}_{fid} = 73.8 \pm 3.8\text{fb}$$

- **Good data/theory agreement**



Summary

- CMS **H→γγ** results using **12.9/fb** of **13 TeV** collision data collected in **2016** have been presented

- **Observation** (**6.1σ** peak significance) of the Higgs boson in the **diphoton** channel

- Best fit **signal strength** is $\hat{\sigma}/\sigma_{SM} = 0.95^{+0.21}_{-0.19}$

- **Bosonic and fermionic** components of signal strength are observed $\hat{\mu}_{VBF,VH} = 1.59^{+0.73}_{-0.45}$ $\hat{\mu}_{ggH,t\bar{t}H} = 0.80^{+0.14}_{-0.18}$

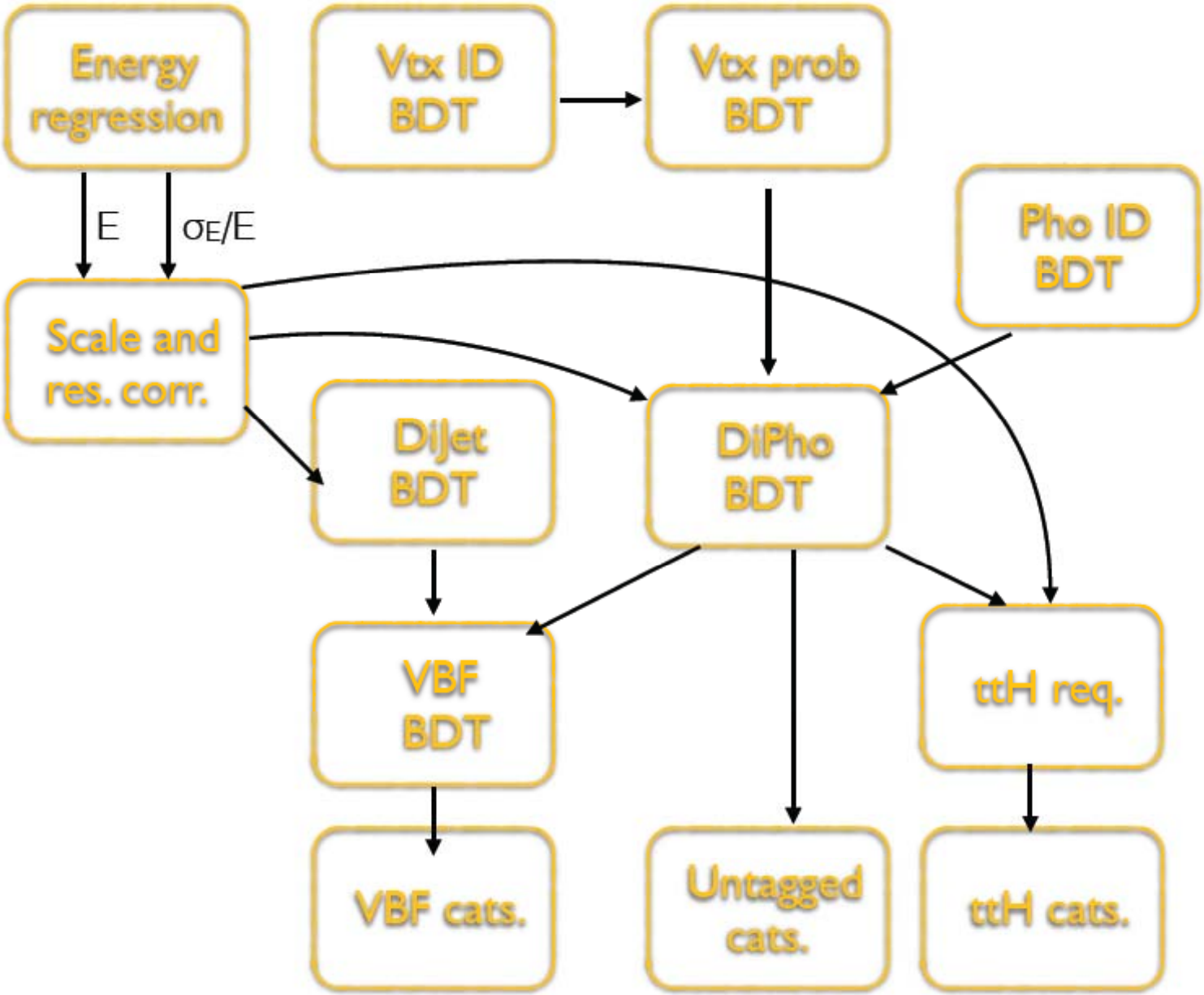
- **Fiducial cross-section** is measured to be $\hat{\sigma}_{fid} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$

- **Consistency with SM! Waiting for Moriond17…**

Thanks for your attention!

BACKUP

Analysis flowchart

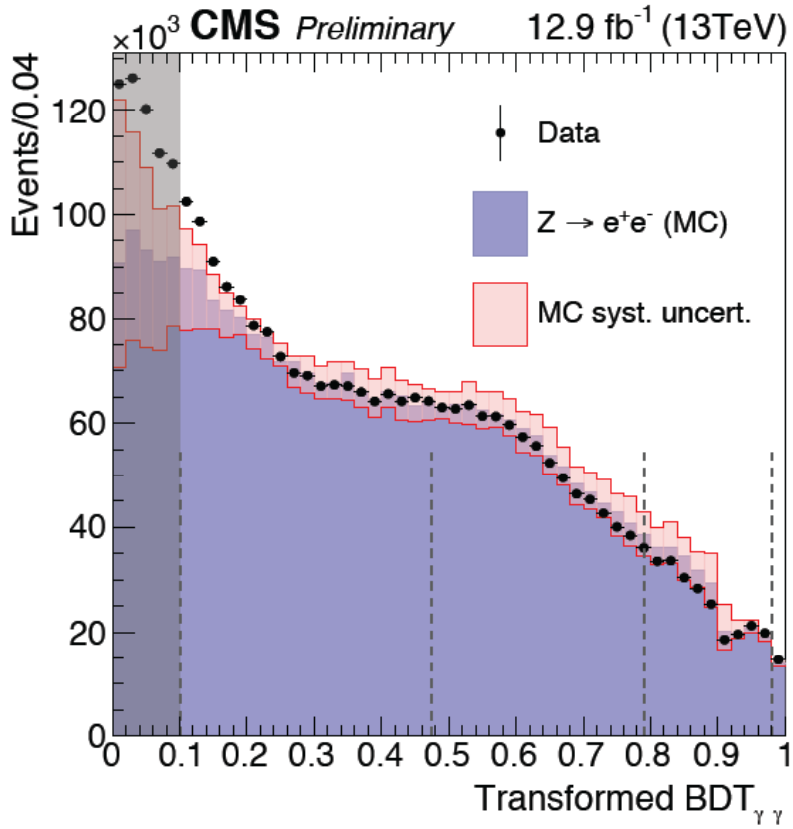


Diphoton BDT

- Inputs
- Systematic uncertainties

- the relative transverse momenta of both photons, $p_T^{1(2)}/m_{\gamma\gamma}$;
- the pseudorapidities of both photons, $\eta^{1(2)}$;
- the cosine of the angle between the two photons in the transverse plane, $\cos(\phi_1 - \phi_2)$;
- the relative diphoton mass resolution, under the hypothesis that the mass has been reconstructed using the correct primary vertex, $\sigma_m^{right}/m_{\gamma\gamma}$;
- the relative diphoton mass resolution, under the hypothesis that the mass has been reconstructed using an incorrect primary vertex, $\sigma_m^{wrong}/m_{\gamma\gamma}$;
- the per-event probability estimate that the correct primary vertex has been used to reconstruct the mass, taken from $BDT_{VTX\ PROB}$;
- the $BDT_{\gamma\ ID}$ score for both photons.

- Impact on $BDT_{\gamma\gamma}$ of systematic uncertainties associated to:
  - relative energy resolution (±5% relative shift)
  - photon ID BDT (± 0.03 shift plus linearly increasing term)
- Z→ee events with electrons reconstructed as photons



ttH selection details

- leading photon $p_T > m_{\gamma\gamma}/2$;
- sub-leading photon $p_T > m_{\gamma\gamma}/4$;
- at least one lepton with $p_T > 20$ GeV: electrons must be within the ECAL fiducial region and pass the recommended criteria for loose requirements on the same observables as described in [27]. In addition the electron should satisfy $|m(e,\gamma) - m_Z| > 10$ GeV, where m_Z refers to the Z boson mass. Muons are required to have $|\eta| < 2.4$ and to pass a tight selection based on the quality of the track, the number of hits in the tracker and muon system, and the longitudinal and transverse impact parameters of the track with respect to the muon vertex; additionally, it has to satisfy a requirement on the relative isolation with pileup correction, based on the transverse momentum of the charged hadrons, transverse energy of the neutral hadrons and photons in a cone of $R = 0.4$ around the muon;
- all selected leptons (ℓ) are required to have $\Delta R(\ell,\gamma) > 0.4$;
- at least two jets in the event with $p_T > 25$ GeV, $|\eta| < 2.4$, and $\Delta R(\text{jet},\gamma) > 0.4$ and $\Delta R(\text{jet},\ell) > 0.4$;
- at least one of the jets in the event has to be identified as b jet according to the CSV tagger medium requirement [28].
- $\text{BDT}_{\gamma\gamma}$ output > -0.4. Too few events are available to optimise this selection for signifiance, so this choice is made simply to remove most of the events with low $\text{BDT}_{\gamma\gamma}$ score.

➢ Leptonic tag →

➢ Hadronic tag ↓

- leading photon $p_T > m_{\gamma\gamma}/2$;
- sub-leading photon $p_T > m_{\gamma\gamma}/4$;
- no leptons defined according to the leptonic tag;
- at least five jets in the event with $p_T > 25$ GeV and $|\eta| < 2.4$;
- at least one of the jets in the event has to be identified as a b-jet according to the CSV tagger medium requirement [28];
- a minimum value of $\text{BDT}_{\gamma\gamma}$ output. The value is a compromise between significance optimisation and the need of a minimum number of events to fit the background.

Diphoton MVA cut set to 0.5

Yields per event class : 12.9 fb^{-1}

Event Categories	SM 125GeV Higgs boson expected signal								Bkg
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	(GeV^{-1})
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	1.47	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	2.17	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	1.33	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	1.40	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	1.52	2762.65

Systematic uncertainties

- **Theory uncertainties** (PDFs, αS, QCD scale, underlying event and parton shower, H→γγ branching fraction)

- **ggH contamination** in VBF and ttH tagged categories

- **Trigger** efficiency, **integrated luminosity**, **vertex** efficiency, **preselection**

- Non-unformity of light collection, non-linearity, detector simulation, modeling of the material budget, shower shape corrections

- Photon energy **scale and resolution**

- **BDT_γ ID** and per-photon **energy resolution**

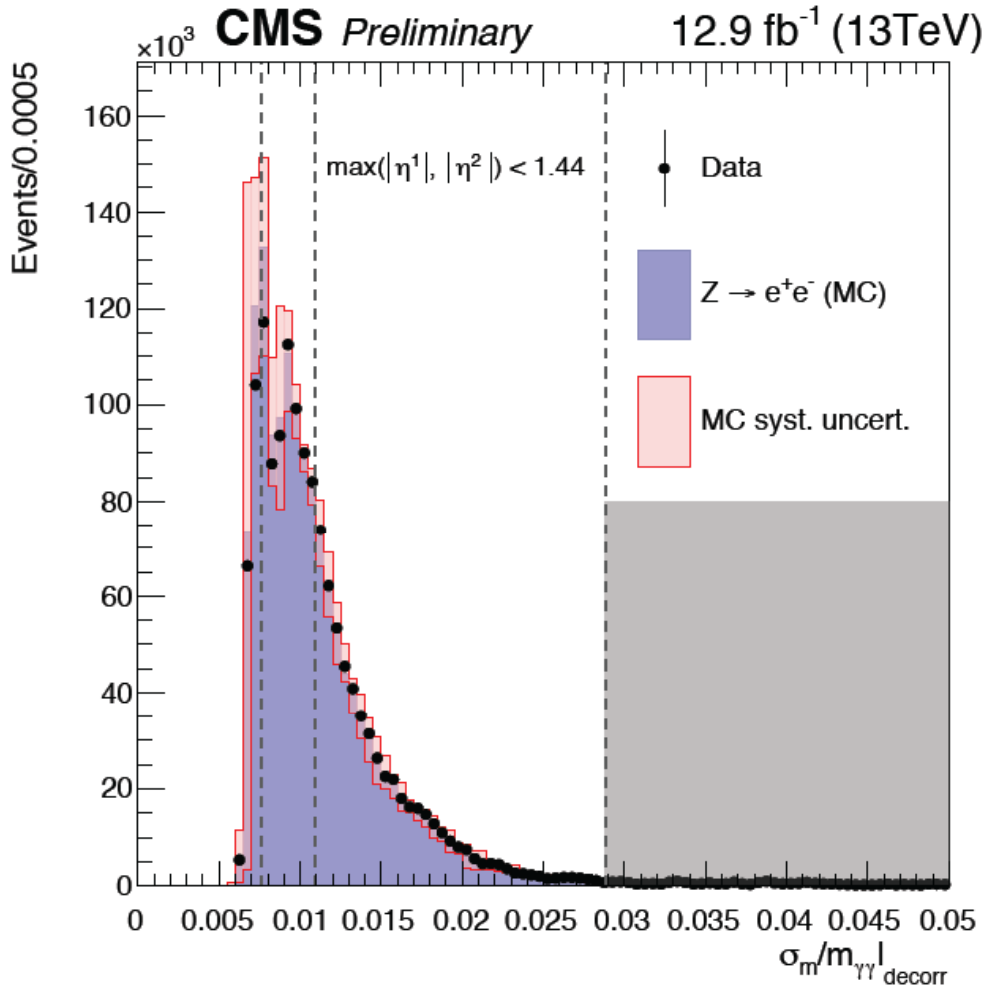
- **Jet** energy scale and smearings

- **b-tagging** efficiency, **gluon-splitting** fraction, **parton shower**, ID efficiency for **e and μ**

Fiducial cross section : categorization

- **Categorization: 3 mass resolution categories**

- Categorization is validated on Z→ee with electrons reconstructed as photons



Mass : Run 1 combination