Observation of $H \rightarrow \gamma\gamma$ at CMS using 2016 data at $\sqrt{s}=13$ TeV

Public analysis summary: CMS-PAS-HIG-16-020

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on behalf of the CMS Collaboration.

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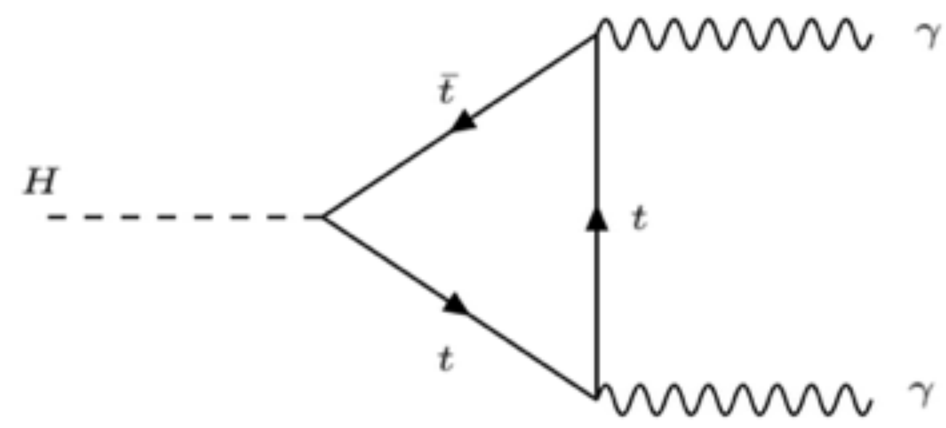
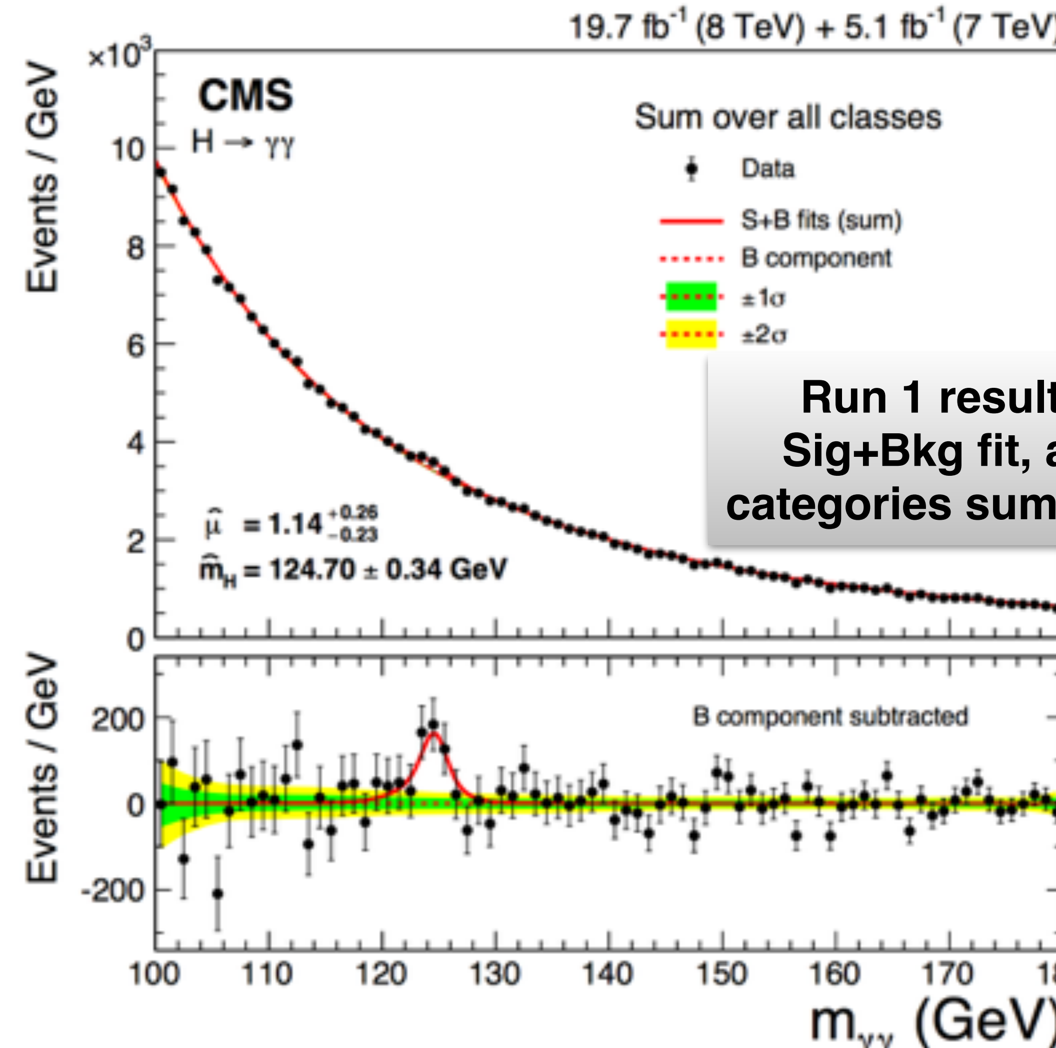
Higgs Hunting 2016, Paris.
Young Scientists Forum - Part 1

Introduction

- **H→γγ: key role** in **discovery** of the Higgs.
- Clean final state: **two highly energetic photons**. However, **low branching fraction** (~0.2%) and large **irreducible background.**
- In a nutshell: Look for 'bump' on diphoton invariant mass (mγγ) spectrum.
- General strategy: **categorise events by resolution and production topology** (using additional objects in the event).
- This talk presents first results with **12.9 fb^{-1}** of prompt data collected by CMS in 2016 at **√s=13 TeV**.
- Increased Higgs cross-section (XS): **similar statistical sensitivity to Run 1 analysis.**



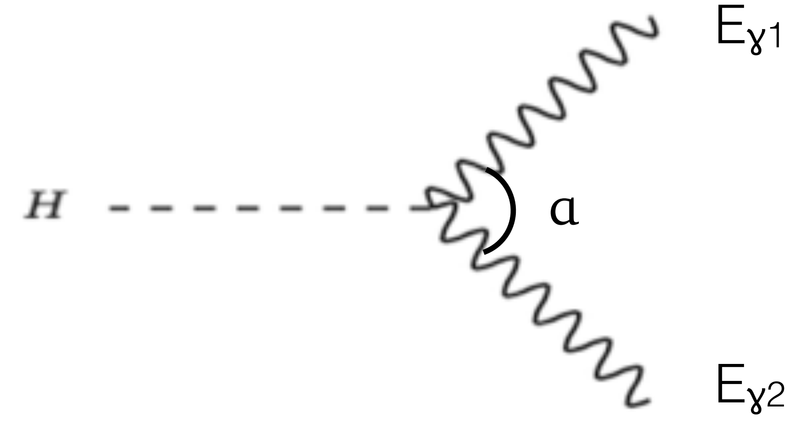


Run 1 result: Sig+Bkg fit, all categories summed

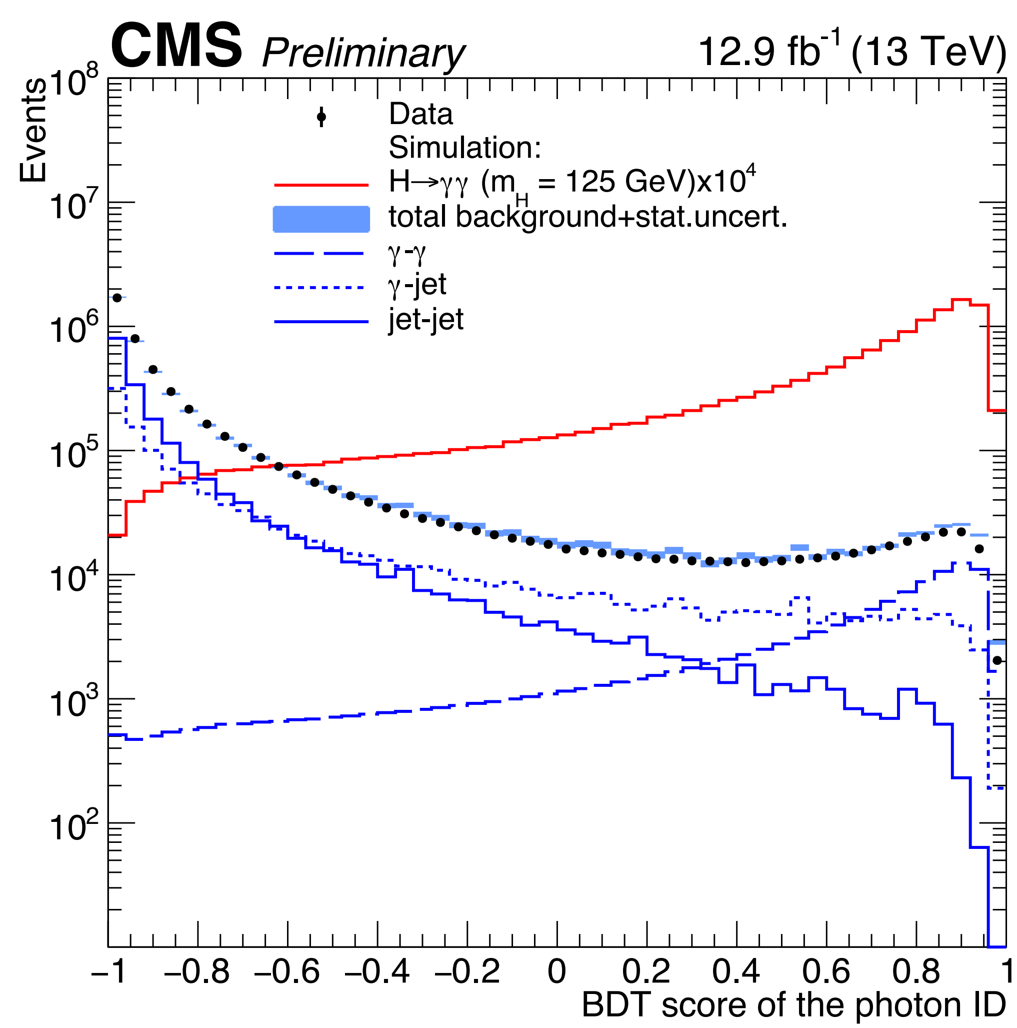
Vertex ID and photon/diphoton ID

Vertex ID

- **Vertex assignment important for $m_{\gamma\gamma}$ resolution.** $|z_{chosen} - z_{true}| < 1$ cm ⇒ angular contribution negligible wrt energy resolution.
- **Vertex ID uses Multivariate approach (BDT):** exploits tracks recoiling from $\gamma\gamma$ system and conversion tracks. Estimate of vertex probability extracted for use in diphoton classification.



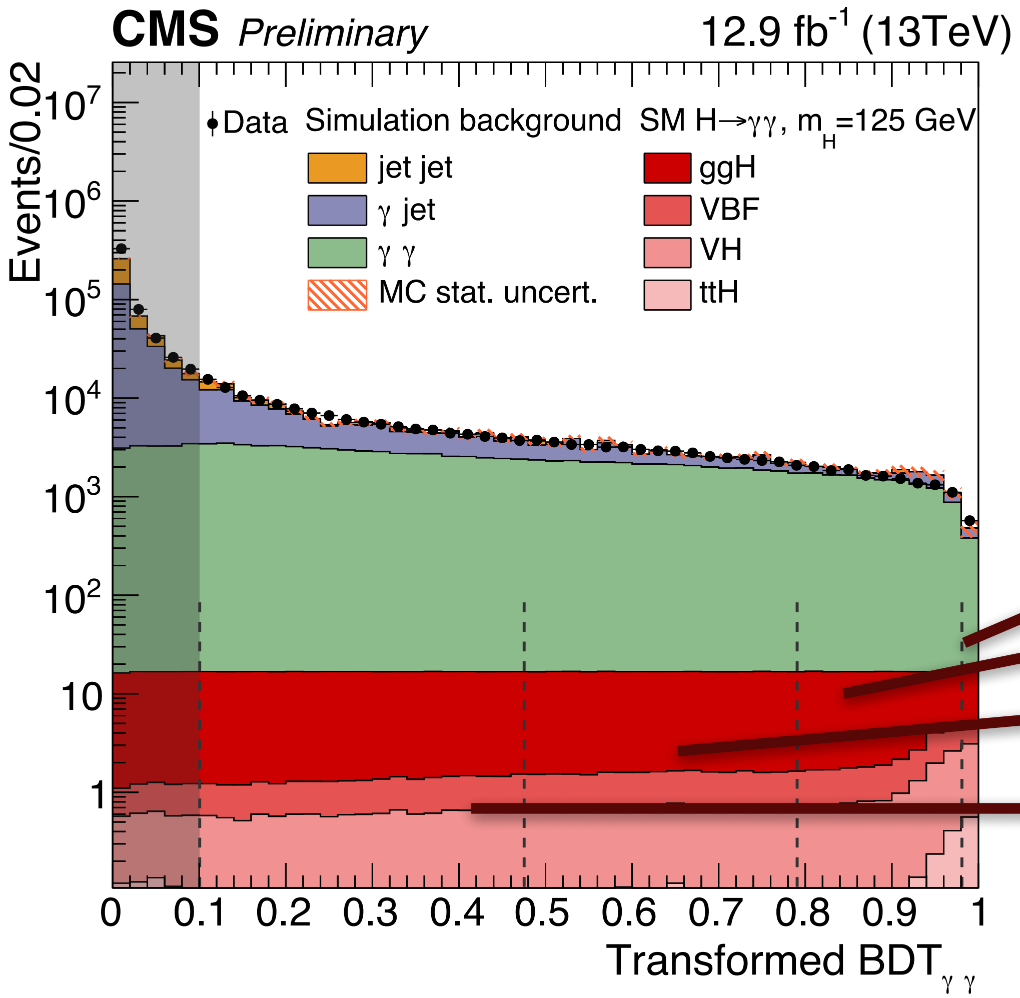
$$m_H = m_{\gamma\gamma} = \sqrt{2E_{\gamma1}E_{\gamma2}(1 - \cos\alpha)}$$



Photon ID and diphoton pairs

- Photon ID selects **prompt photons against $\pi^0/\eta \rightarrow \gamma\gamma$ and electrons.**
- **Multivariate approach** combining shower shape and isolation variables.
- A further **BDT is used to identify signal-like diphoton pairs:** kinematics, high photon ID scores, correct vertex probability and **good mass resolution.**

Event categorisation



- TTH Leptonic
- TTH Hadronic

Target ttH (~0.5 pb)
Events categorised by top decay

- VBF Tag 0
- VBF Tag 1

Target VBF (~3.8 pb).
Events categorised by sensitivity

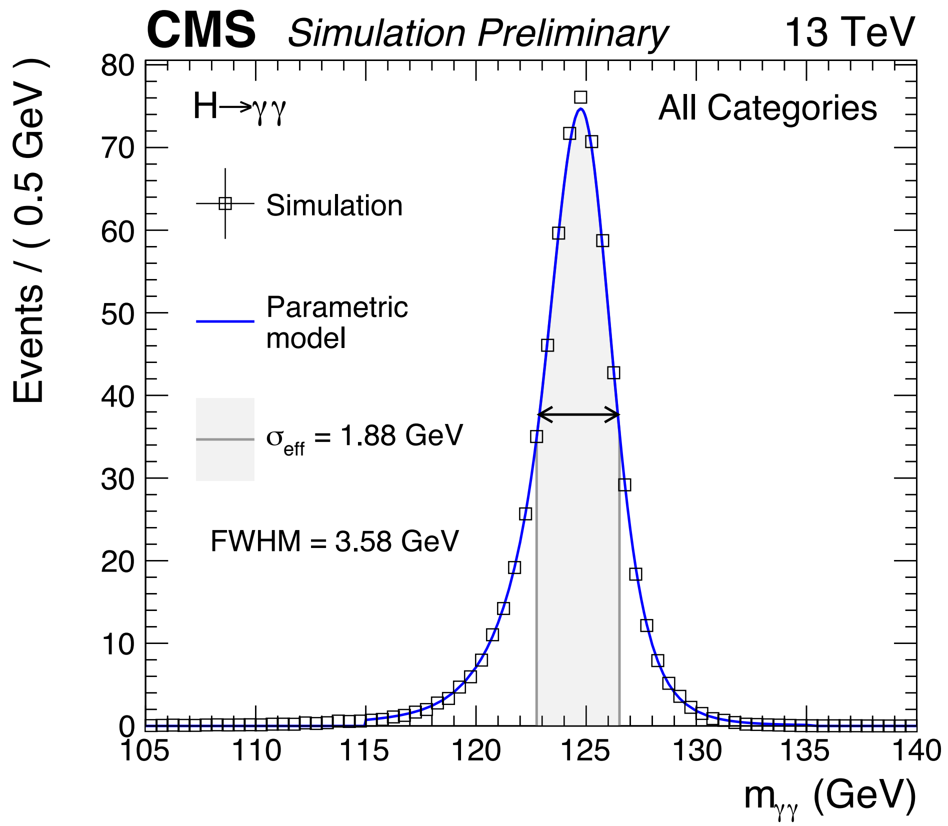
- Untagged 0
- Untagged 1
- Untagged 2
- Untagged 3

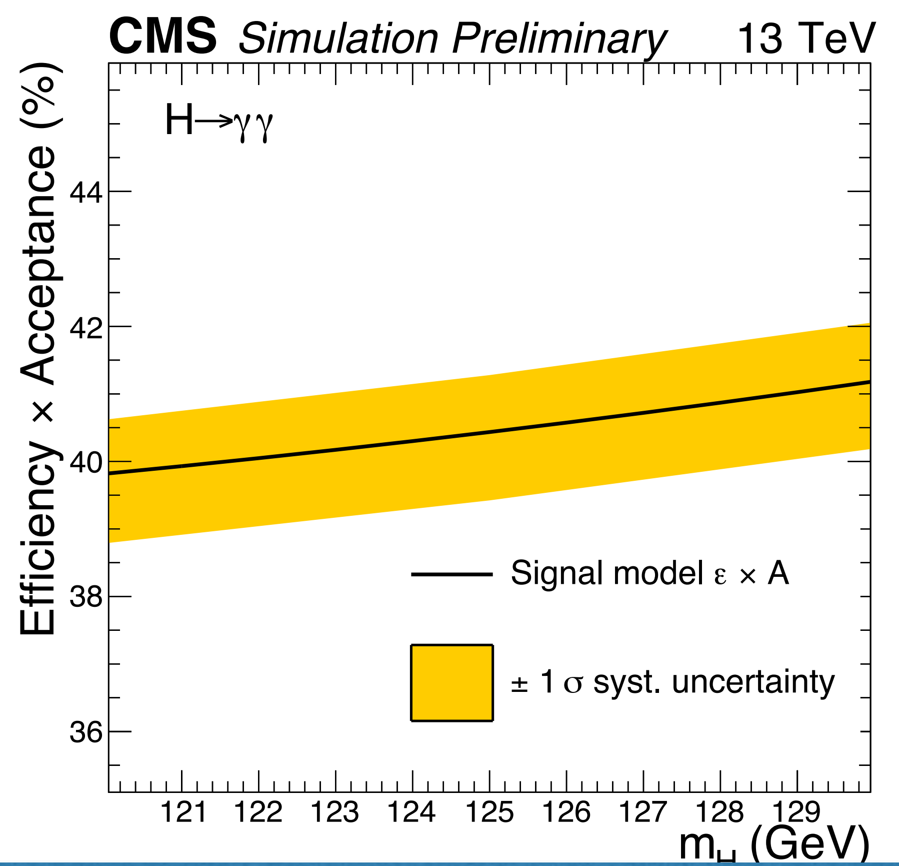
Inclusive categories, mostly populated by **ggH (~49 pb)** and **VH (~2 pb)**.
Events categorised by sensitivity using BDT.

- Events with additional objects characteristic of specific production modes are tagged, and remaining events are categorised using $BDT_{\gamma\gamma}$.
  - **TTH:** look for **hadronic or leptonic decays of tops quarks.**
  - **VBF:** Distinctive 2-jet + 2-photon signature, **use BDTs to identify VBF jets and split VBF Tags by mass resolution.**
  - **Inclusive categories** split by **mass resolution using $BDT_{\gamma\gamma}$** output.

Signal and Background Modelling

- **Signal Model:** For each category/process, **fit sum of Gaussians to $m_{\gamma\gamma}$ distribution**, separately for:
  - **Vertex correctly identified:** mass resolution dominated by energy resolution.
  - **Vertex incorrectly identified:** mass resolution dominated by uncert. on vertex position.
  - **Smooth parametric model** in each process/ category. **Interpolated between 7 mass points** in the range 120-130 GeV.

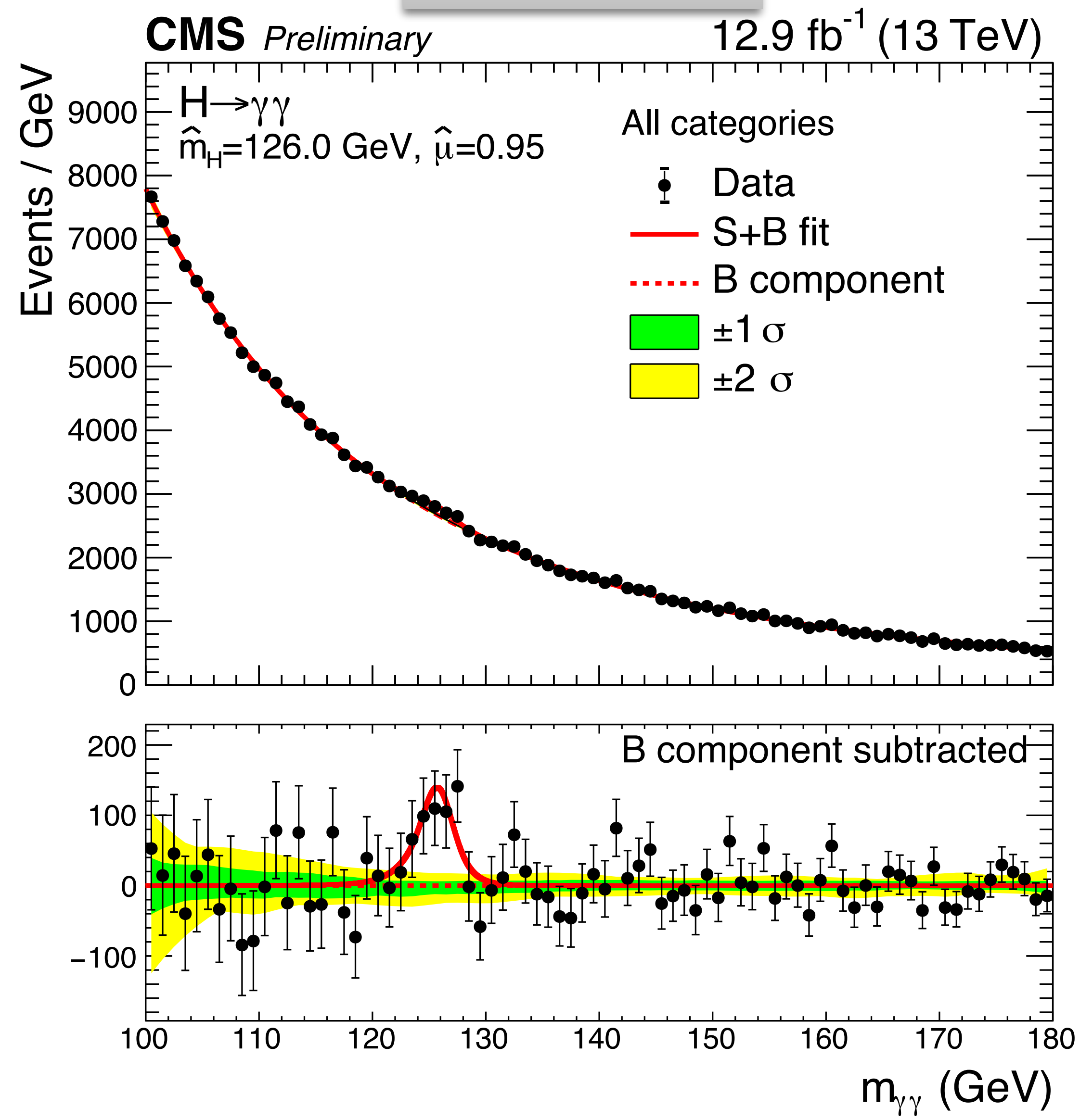




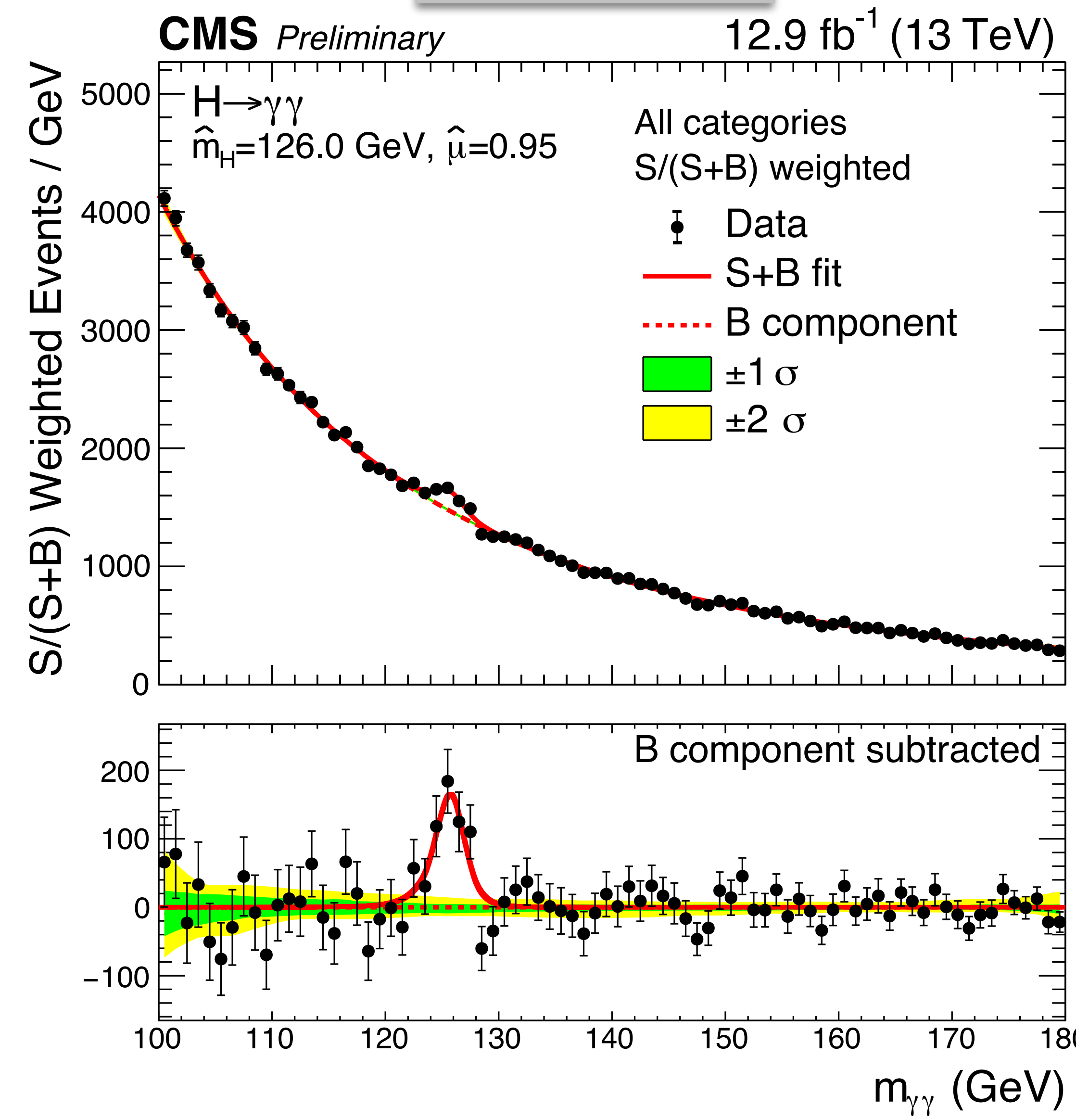
- **Background model: data-driven method.** Sidebands used to determine background shape under signal peak in $m_{\gamma\gamma}$ distribution.
  - Treat choice of background function as discrete parameter in final minimisation.

Diphoton mass spectrum
All categories summed

Unweighted

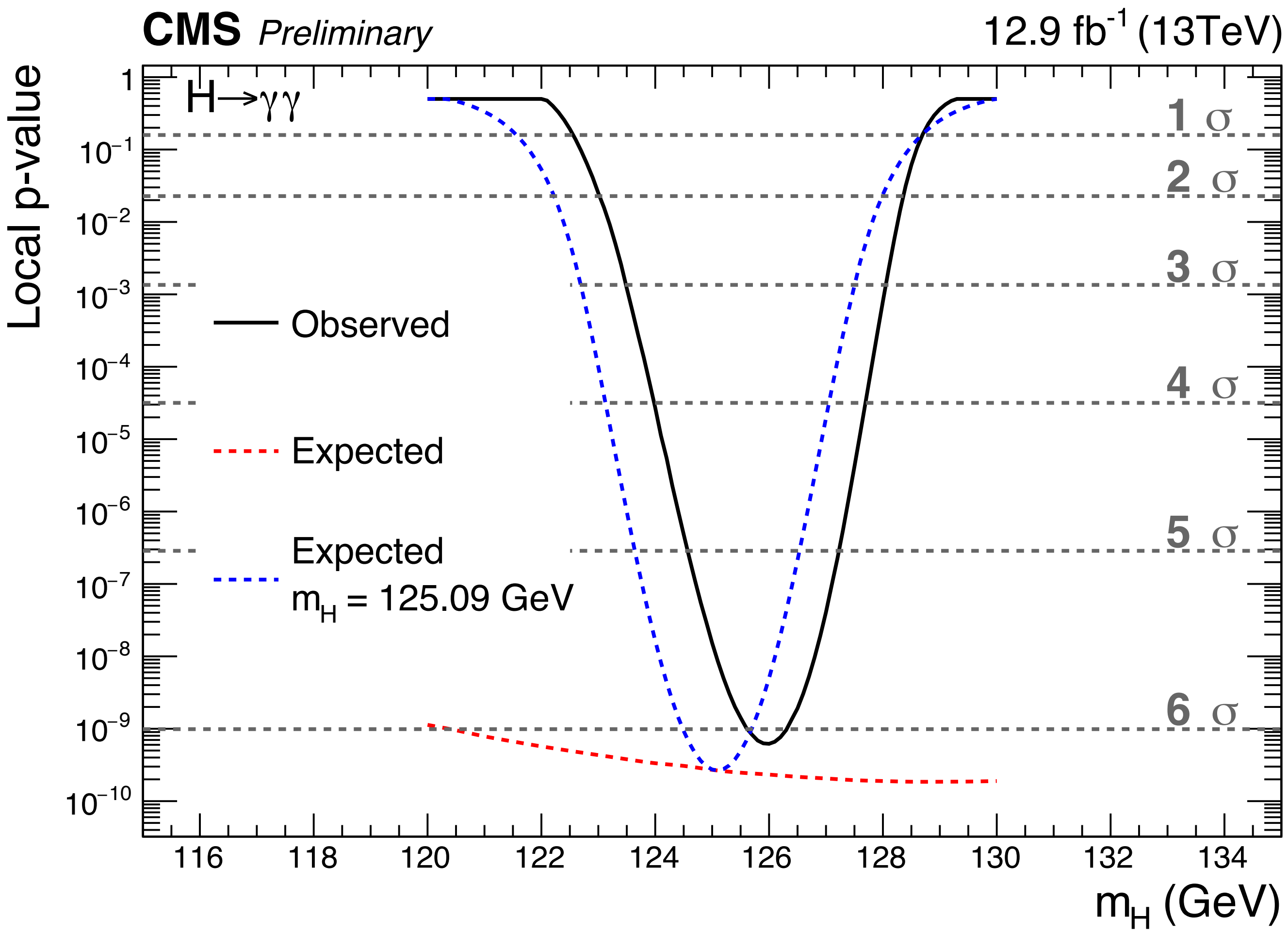


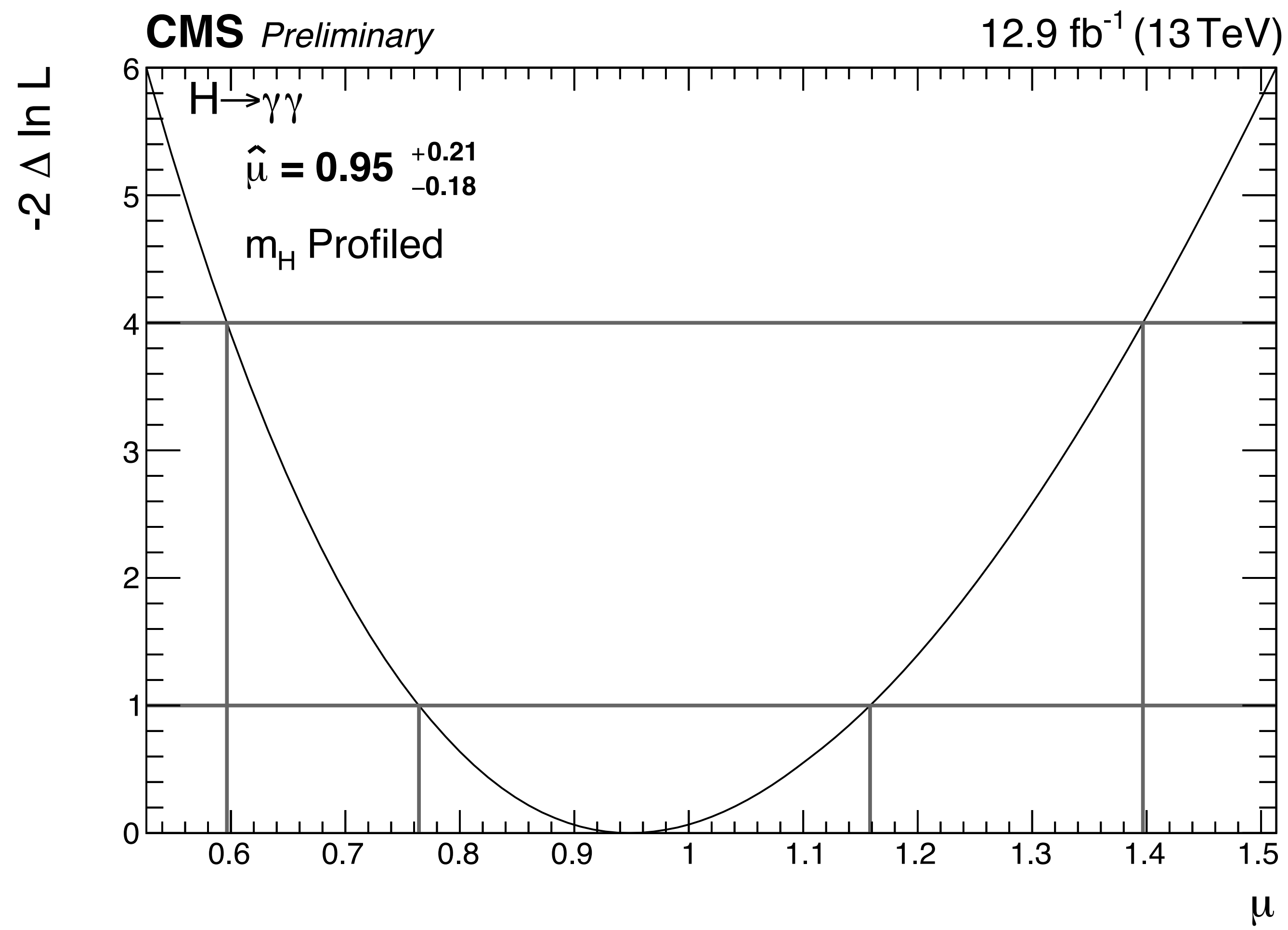
Weighted



- **Invariant mass spectrum.** Background-only and signal-plus-background fits to the data are shown.
- **Clear Higgs signal,** visible by eye when background subtracted. Applying the weighting by sensitivity makes the peak even more obvious.

P-value and signal strength



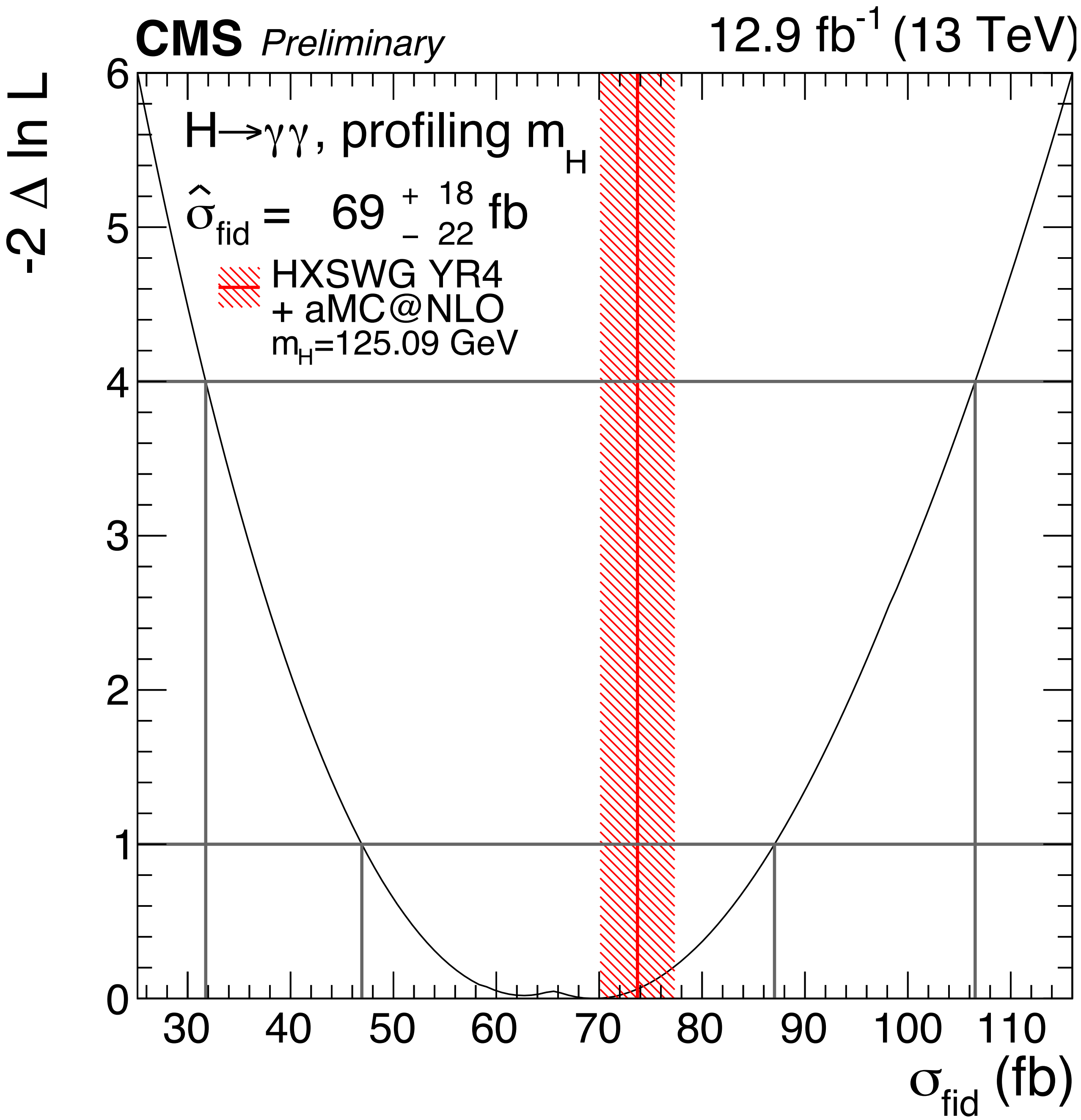


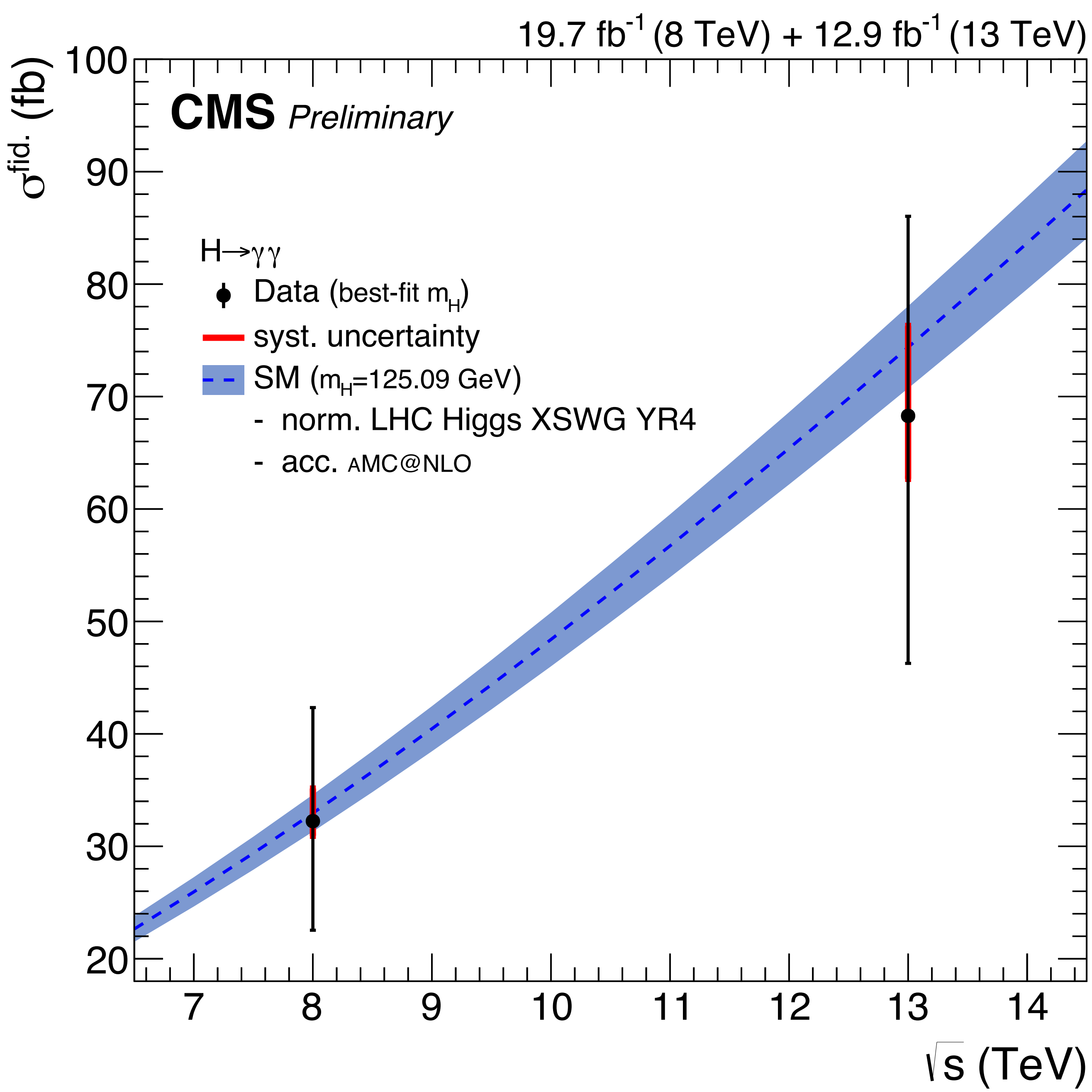
- We report an **observation with significance 5.6σ** where 6.2σ was expected for the SM Higgs boson at m_H=125.09 GeV.
  The maximum significance of 6.1σ is observed at 126 GeV.
- Best fit signal strength (XS*BR) relative to SM, for profiled M_H, is found to be:

$$\hat{\mu} = 0.95 \pm 0.20 = 0.95 \pm 0.17\,(\text{stat.})\,^{+0.10}_{-0.07}\,(\text{syst.})\,^{+0.08}_{-0.05}\,(\text{theo.})$$

Imperial College London

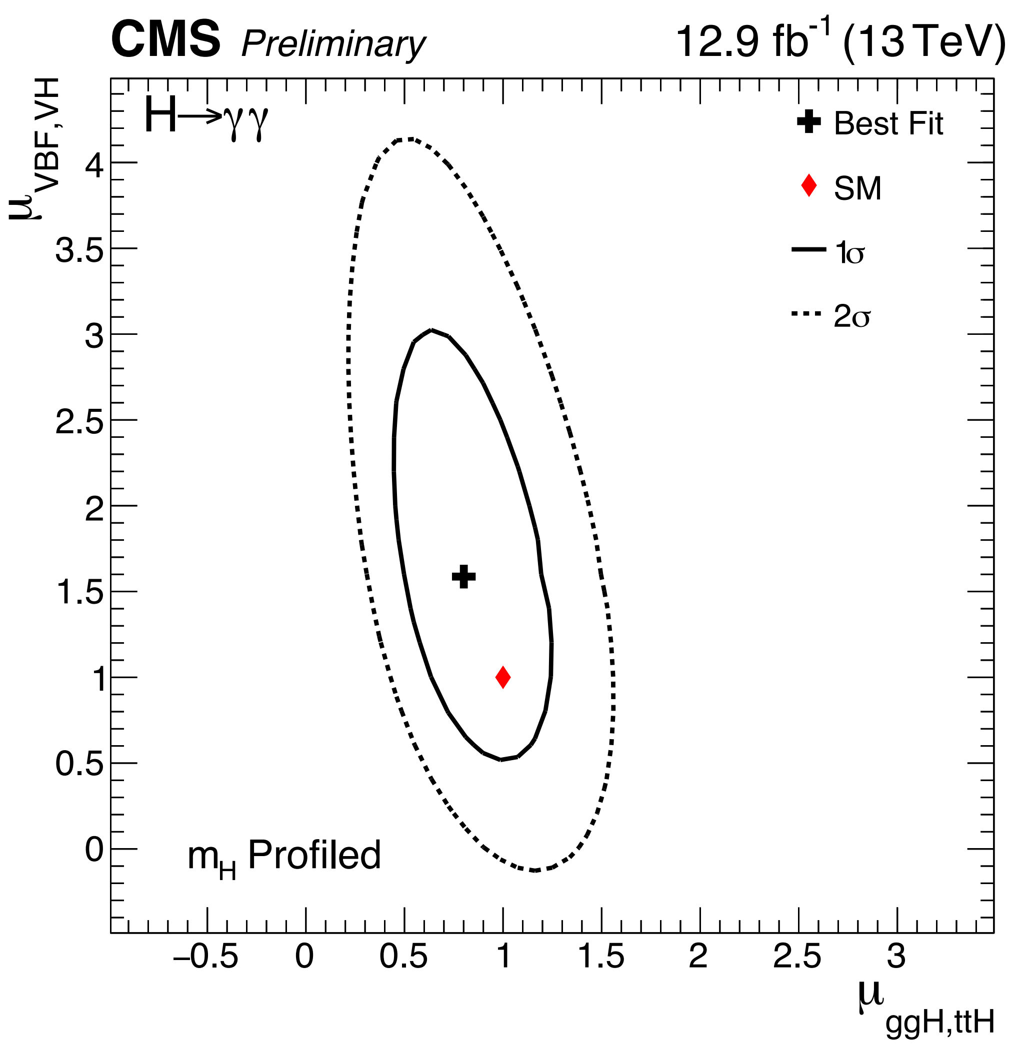
Fiducial Cross-section measurement

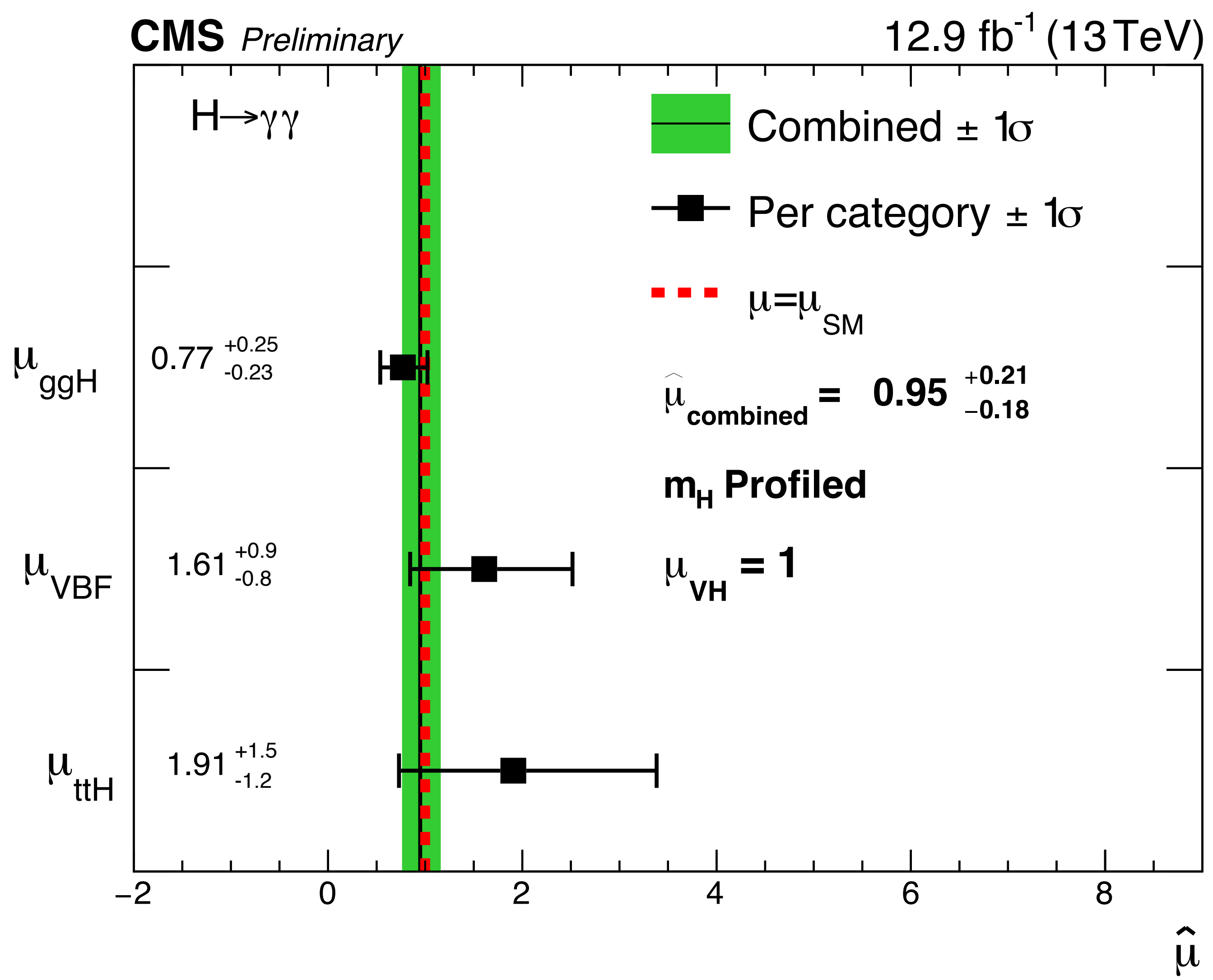




- Measurement of fiducial cross section using different categorisation scheme.
- Consistency with SM observed.

Production rate modifier



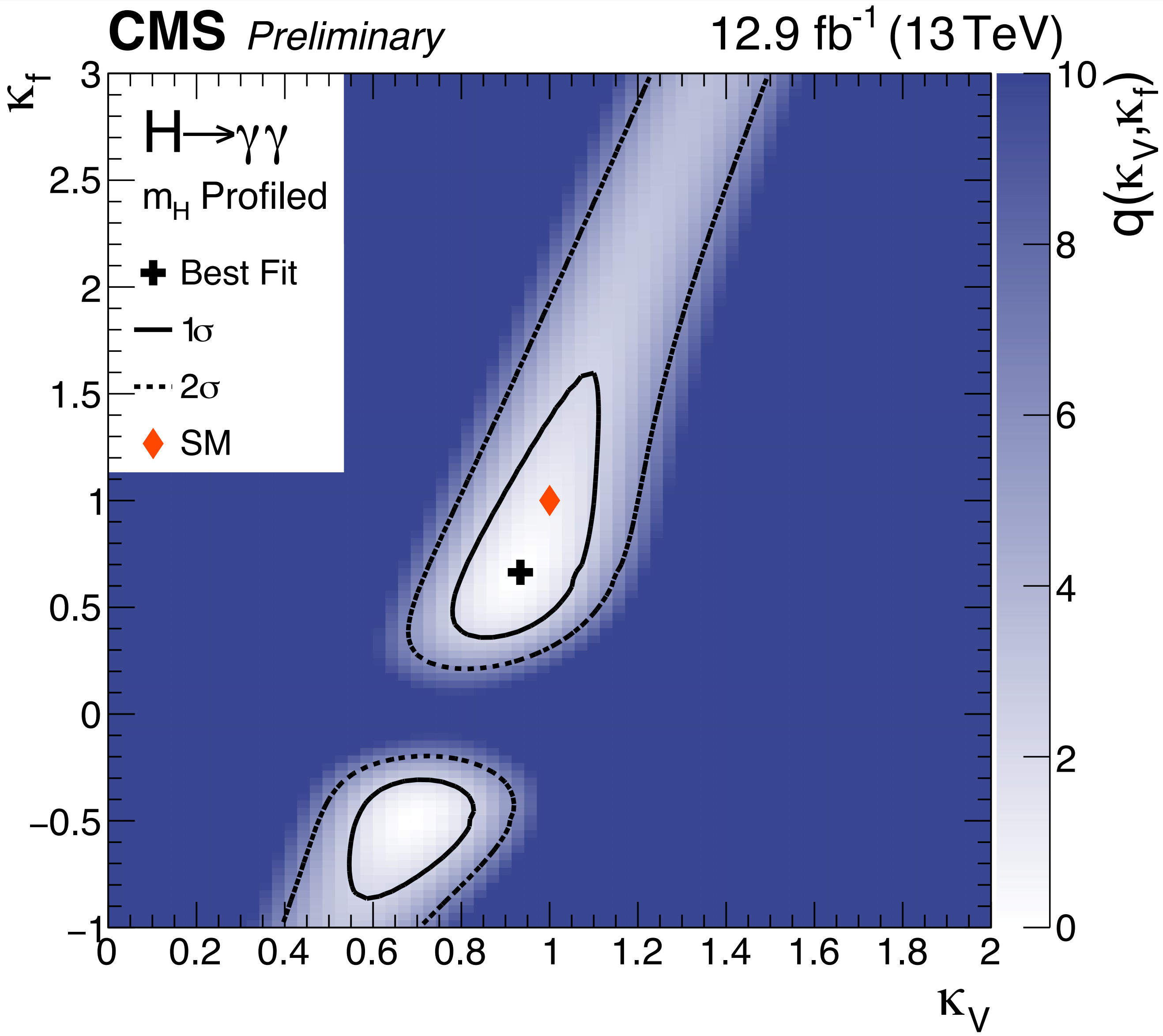


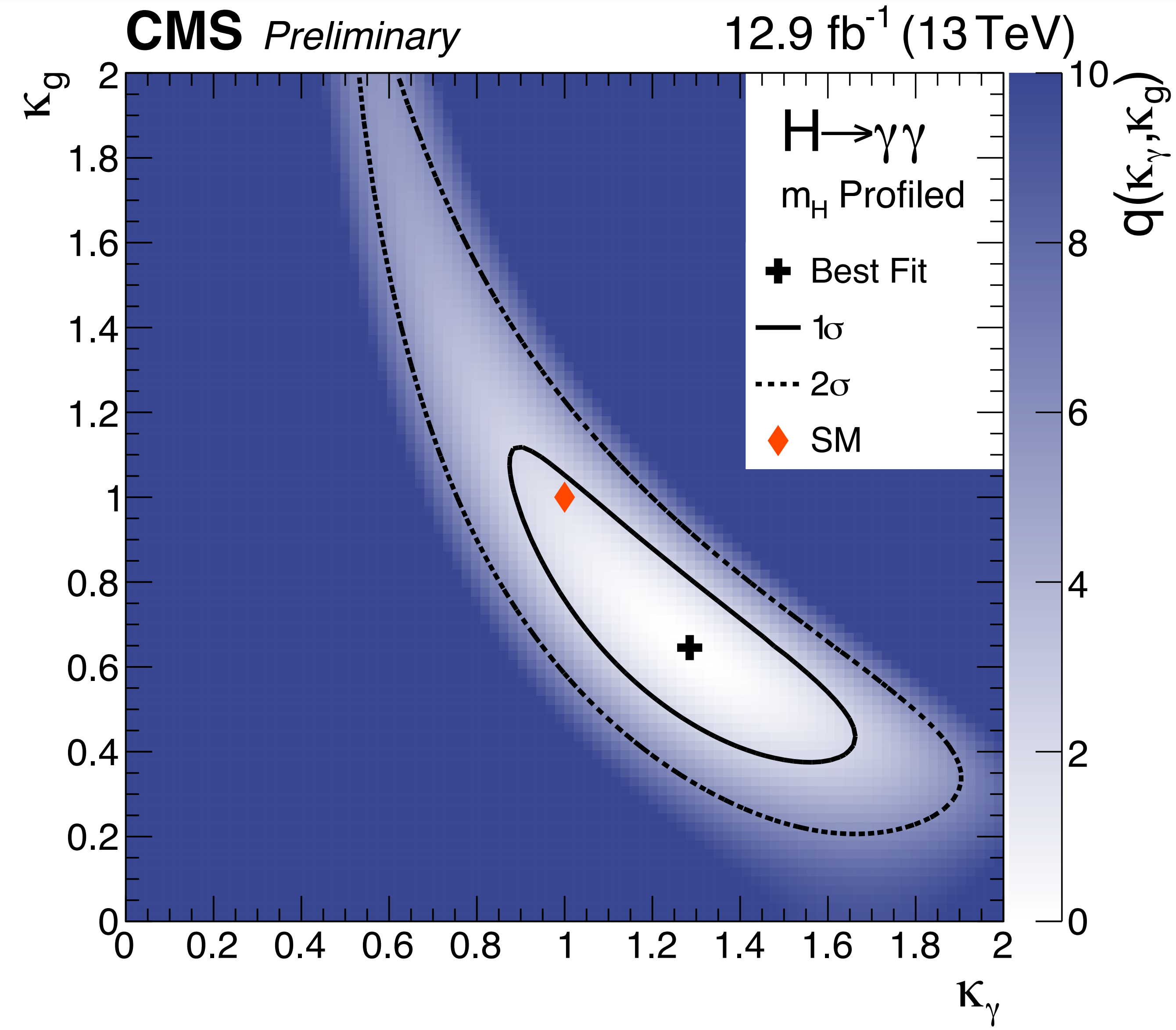
- Best fit signal strength **split into bosonic and fermionic production modes**:

$$\mu_{ggH,t\bar{t}H} = 0.80^{+0.14}_{-0.18} \text{ and } \mu_{VBF,VH} = 1.59^{+0.73}_{-0.45}$$

- Also **split the signal strength by individual production mode:** consistent with SM.

Coupling strength modifiers





- ***κ***$_\gamma$, ***κ***$_g$, ***κ***$_V$, ***κ***$_f$ measure strength of Higgs coupling to particles relative to SM. For Higgs couplings via loops, an effective coupling is defined.
- Results **consistent with SM expectation.**

Summary and Conclusions

- CMS has prepared its **first results using the 2016 13 TeV** dataset with **12.9 fb^{-1}. Roughly equivalent to Run 1 dataset in terms of sensitivity.**
- We report an **observation of the Higgs boson with over 5σ significance in the diphoton decay channel.**
- The measured signal strength is consistent with the SM expectation, with overall uncertainty of ~20%:

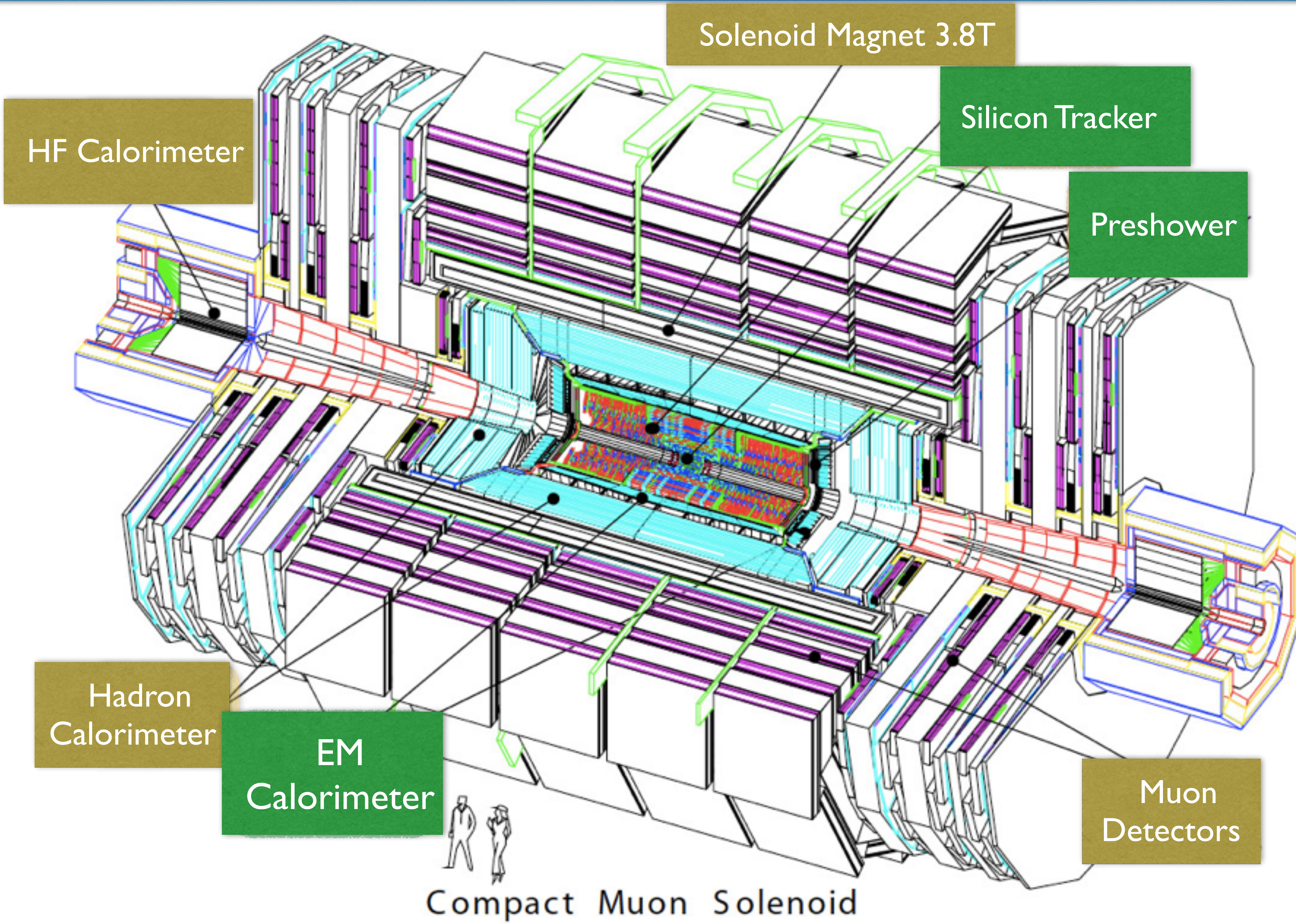
$$\widehat{\mu} = 0.95 \pm 0.20 = 0.95 \pm 0.17\,(\text{stat.})\,^{+0.10}_{-0.07}\,(\text{syst.})\,^{+0.08}_{-0.05}\,(\text{theo.})$$

- Fiducial XS measurement performed - in line with SM expectation.
- **Consistency with SM** when splitting signal strength into production modes.
- Best-fit values of Higgs coupling strength modifiers for gluons, photons, vector bosons and tops are found to be consistent with SM expectation.
- **Higgs physics:** begin transitioning **from discovery to precision measurement era.**

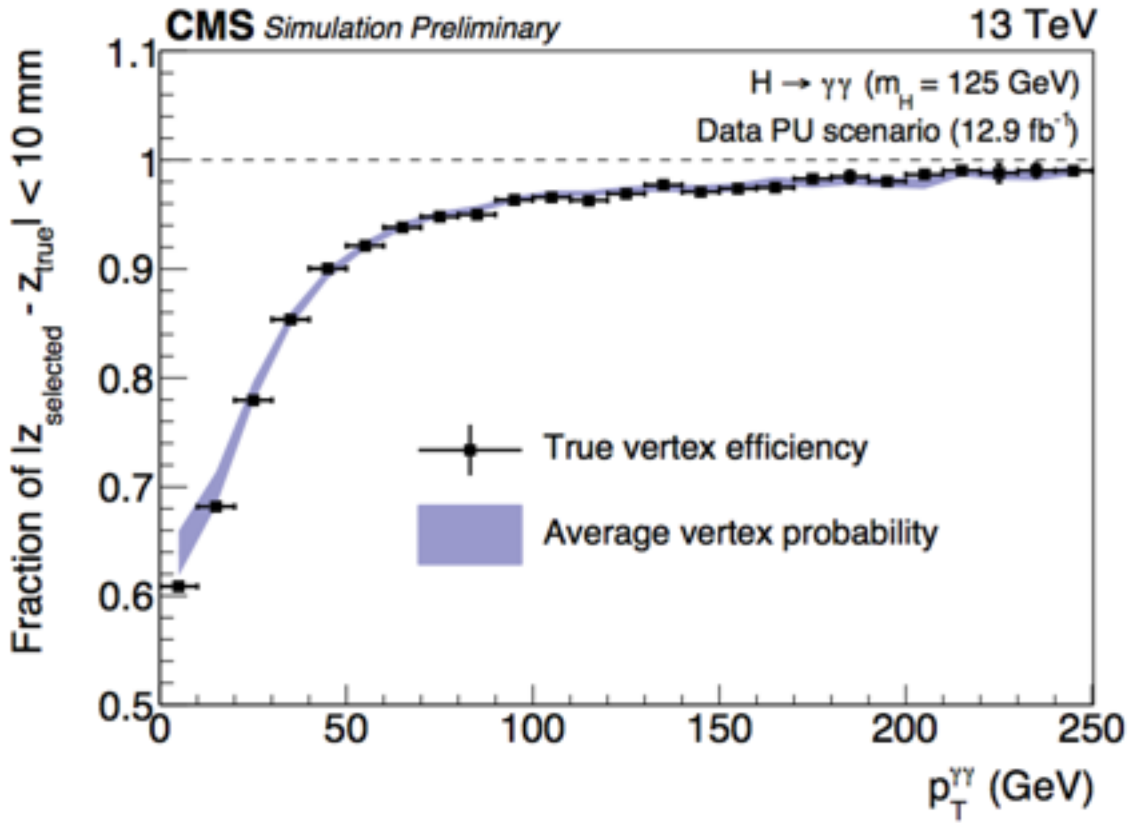
BACKUP

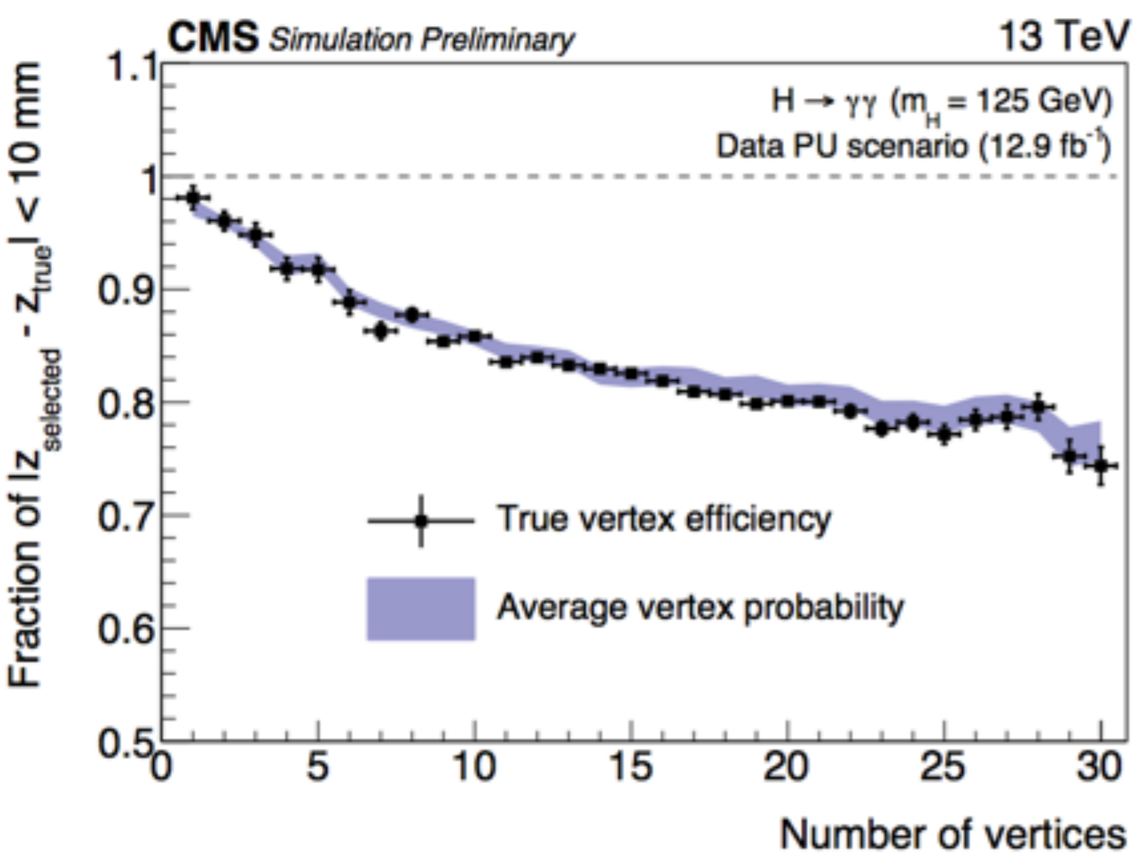
BACKUP

The CMS detector



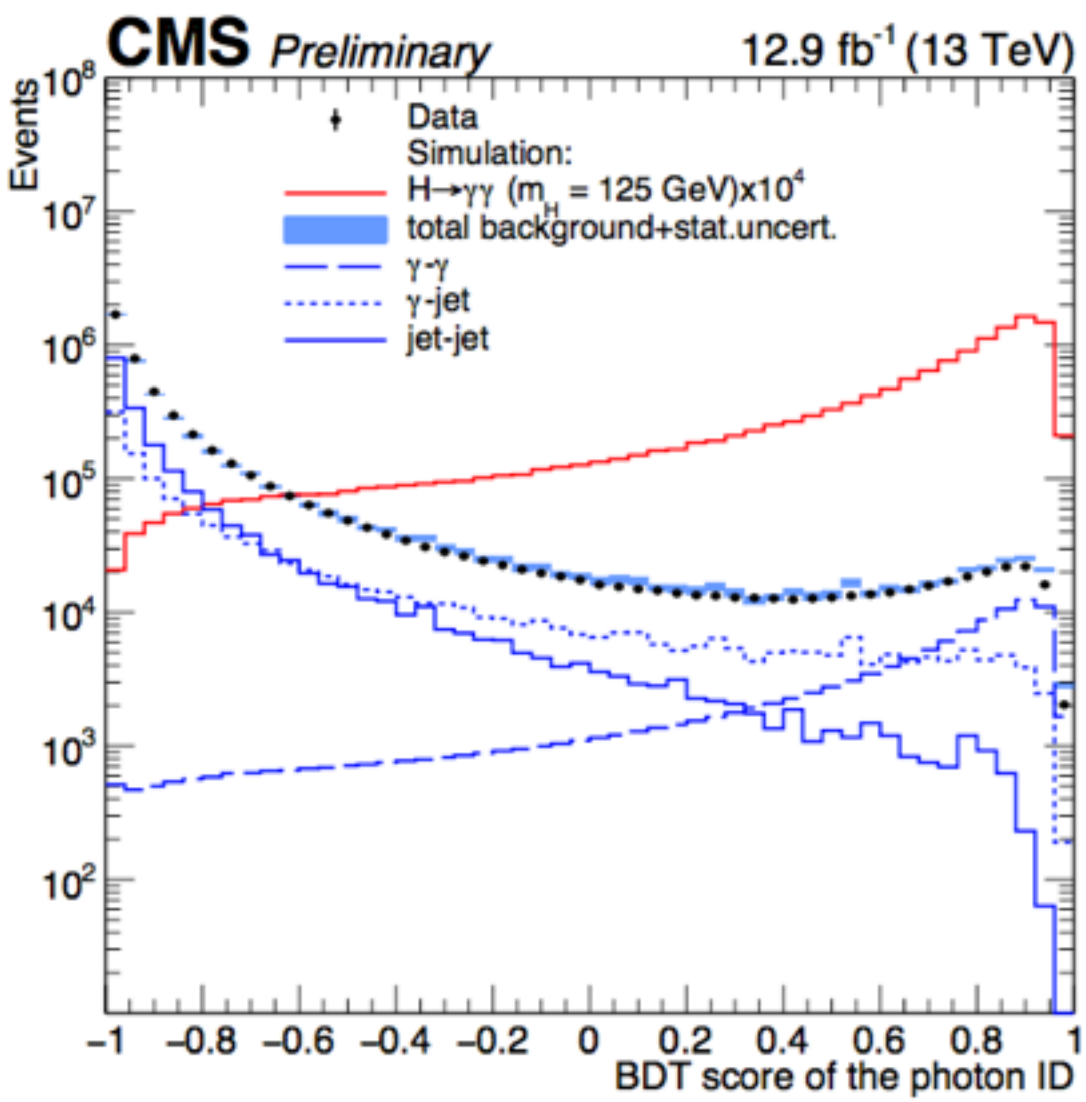
Vertex ID

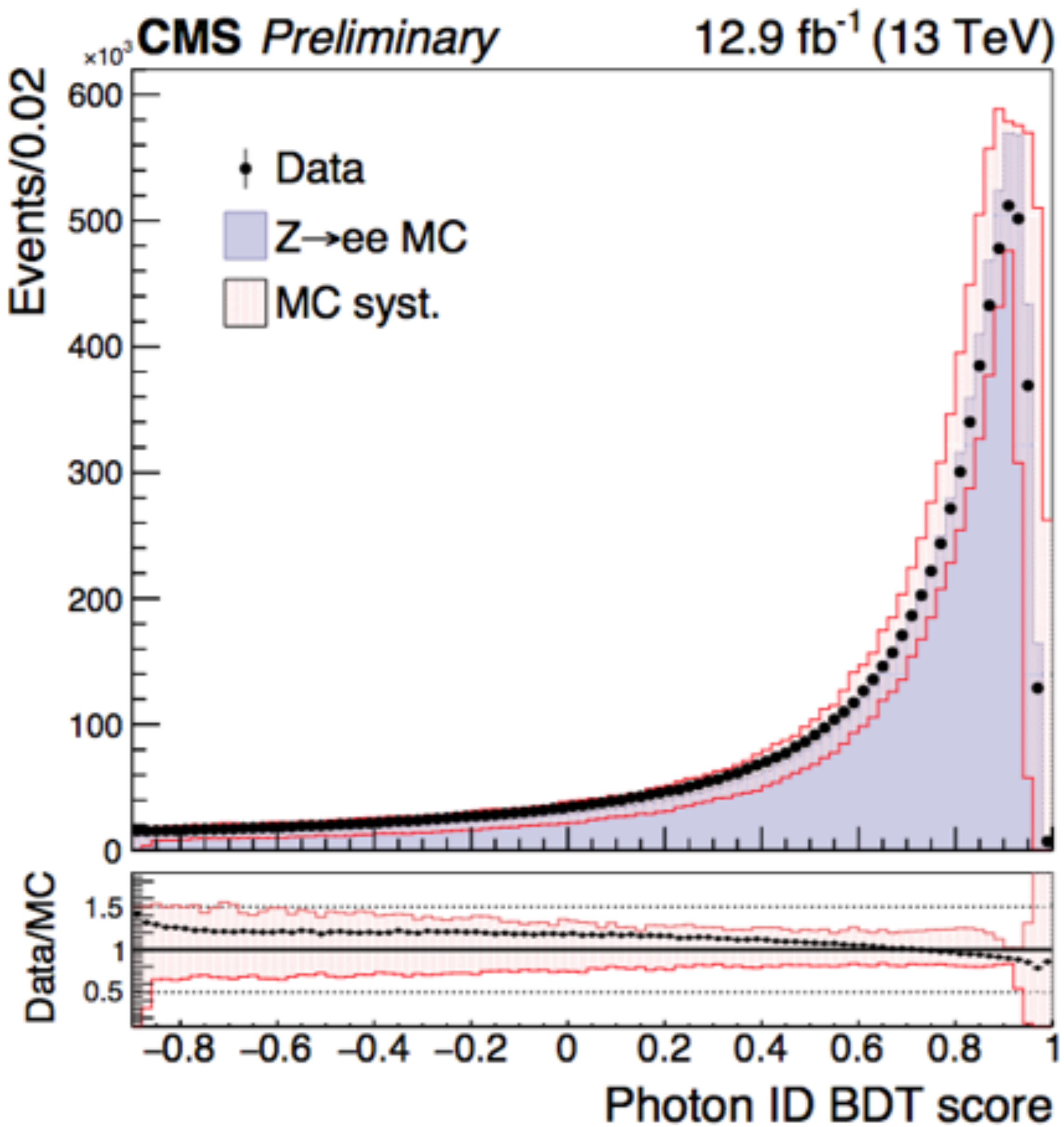




- Inputs to the vertex ID BDT.
  - ptasym
  - ptbal
  - sumpt2
  - pull
- correct vertex (dZ<1cm)
- incorrect vertex (dZ >1cm)

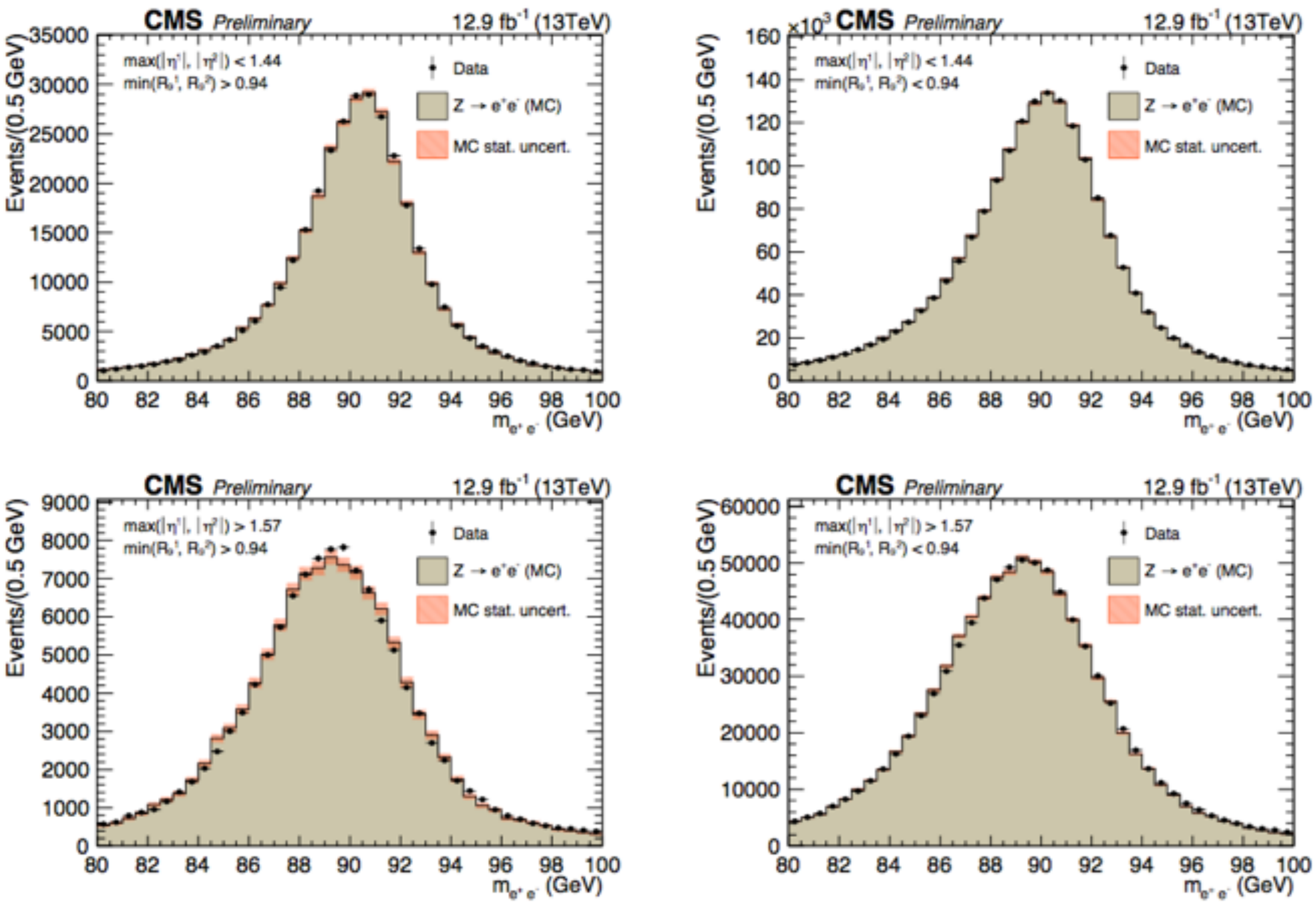
Photon ID





- Distribution of BDTɣ ID score for signal and background.
- Comparison of Distribution of BDTɣ ID score in data and MC using Z→ee events where electrons are reconstructed as photons.

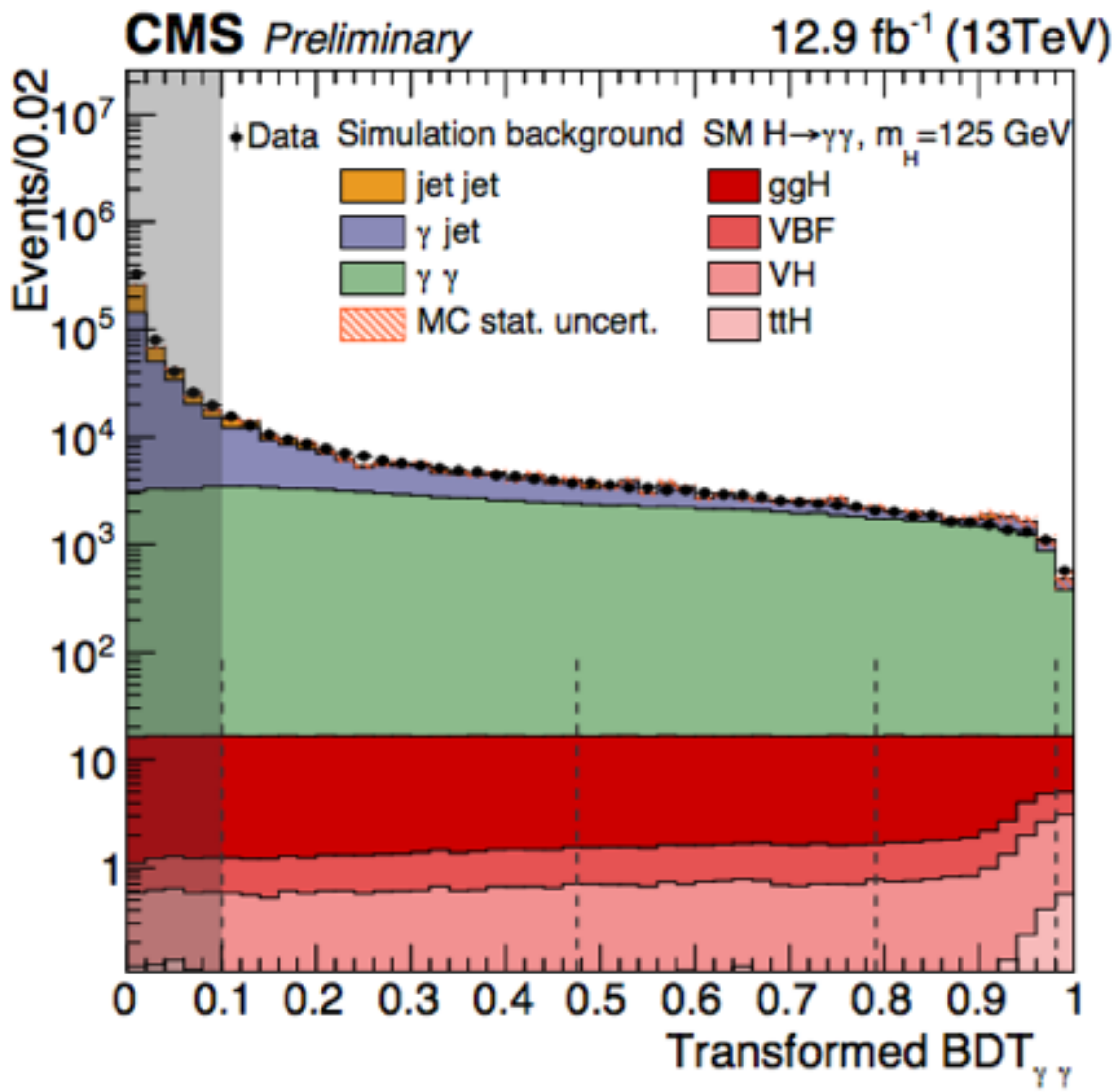
Energy Reconstruction

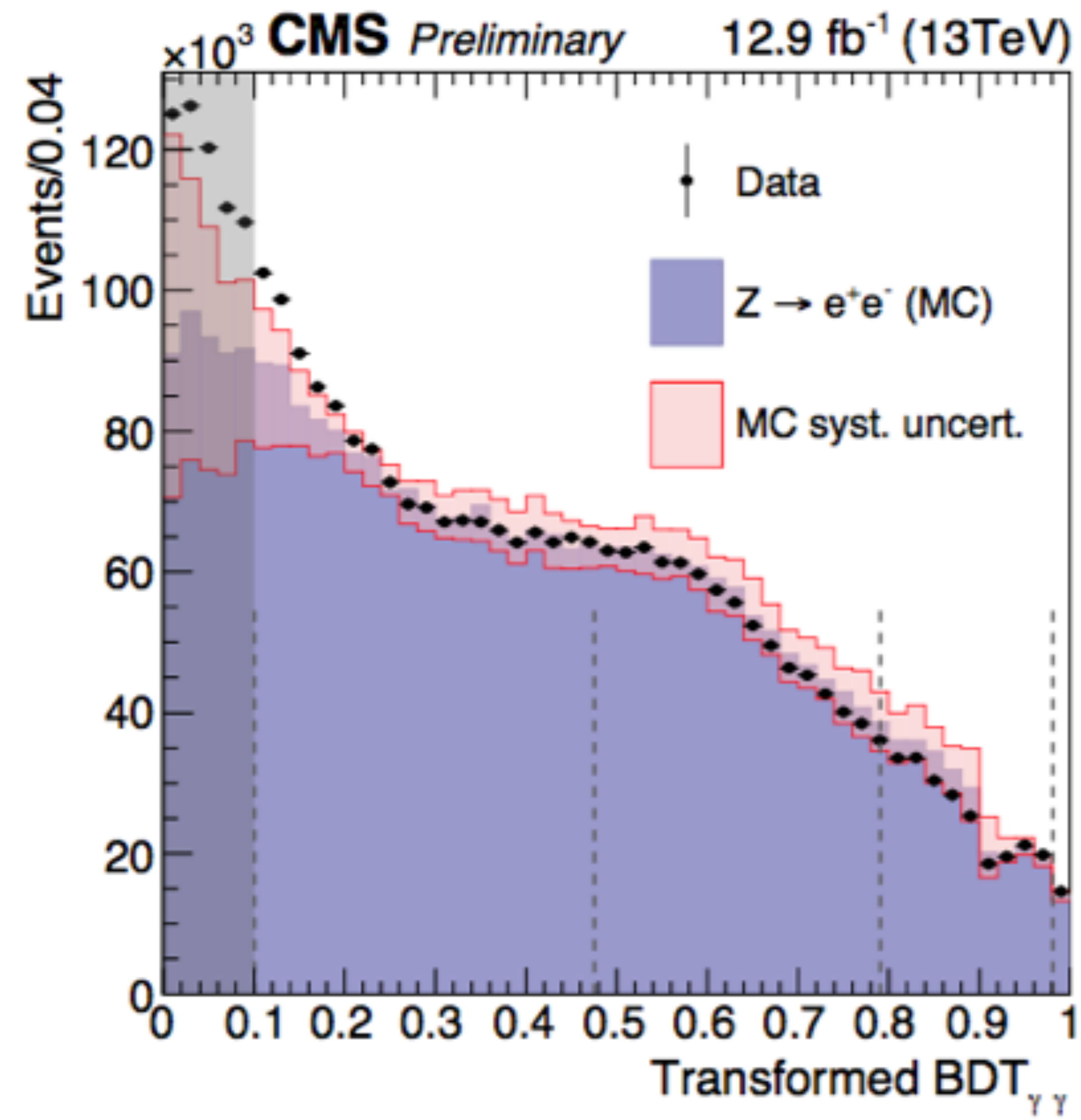


data vs MC comparison for invariant mass of Z→ee electrons reconstructed as photons.

Events split into |η| and R_9 categories. (R9 is the ratio of the amount of energy in a 3x3 array of ECAL crystals around the seed divided by the total energy in the supercluster. High R_9 (>0.94) photons are likely to be unconverted, while Low R_9 photons are likely to have undergone $\gamma \rightarrow e^+e^-$).

Diphoton MVA





- Distribution of BDTγγ score for signal and background.
- Comparison of Distribution of BDTγγ score in data and MC using Z→ee events where electrons are reconstructed as photons.

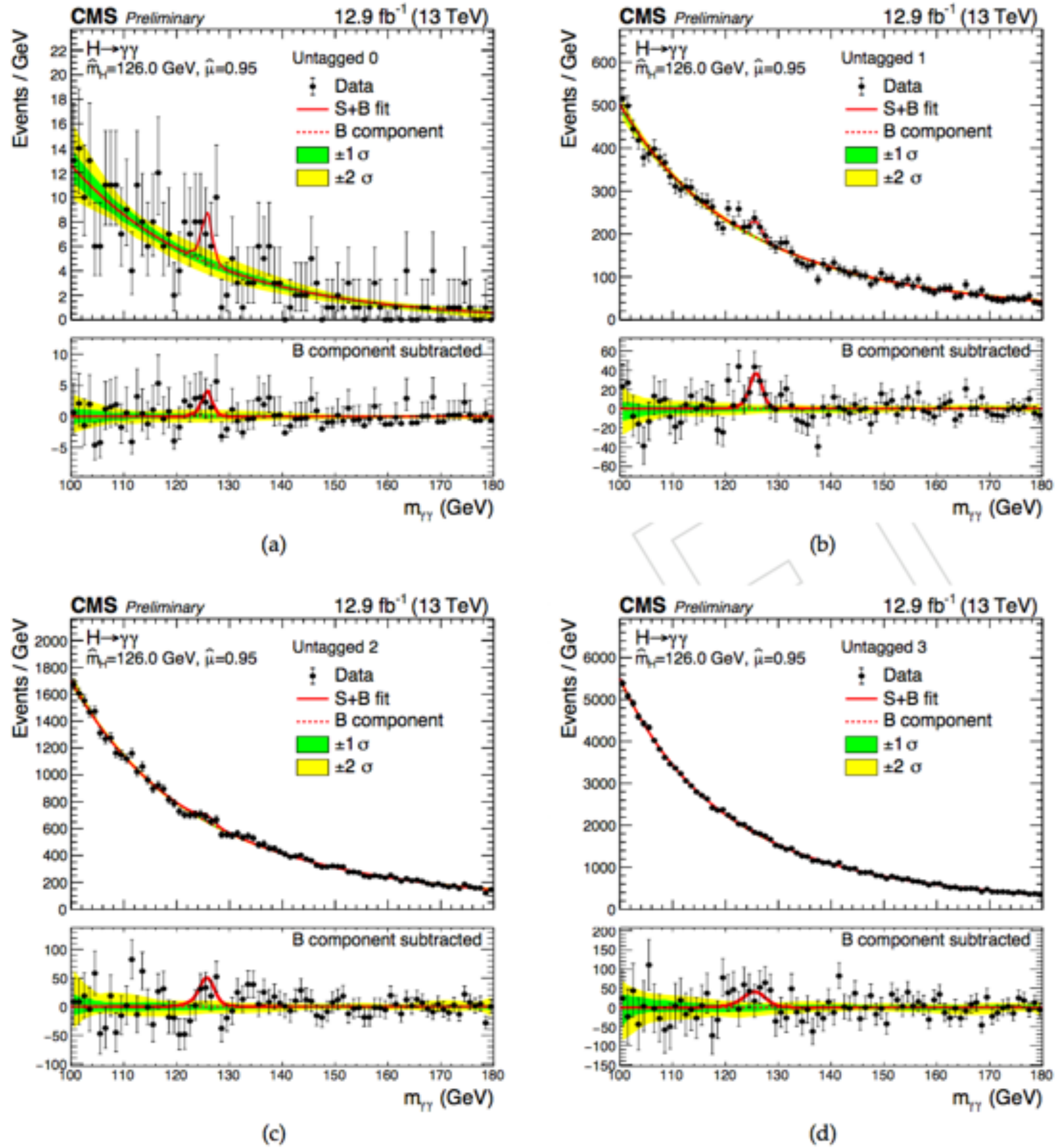
Diphoton Selection and Event Classification

- Diphotons split into categories, exploiting different S/B ratios and mass resolution => maximum sensitivity:
  - TTH categories: make cuts on photon quality and requirements on bTags, Jets and absence/presence of leptons .
  - VBF categories: use an MVA to identify VBF-like events with dijets. A further MVA using the diphoton and dijet MVAs as inputs is used to classify VBF events by sensitivity into VBFTags 0 and 1.
  - Untagged categories: mostly populated by ggH, bring the largest contribution to analysis' sensitivity. Category boundaries defined by Diphoton MVA.
- Event tagging sequence is defined as follows:

ttHLeptonic → **ttHHadronic** → **VBF0-1** → **Untagged0-3**

Background Model Plots Unblinded

- Data and Signal + Background Fits shown, in the scenario where **m_H is profiled.**
- Figures also show the Background-subtracted distributions.
- Uncertainty bands achieved by throwing toys from the post-Fit distributions and finding locations of relevant quantiles.



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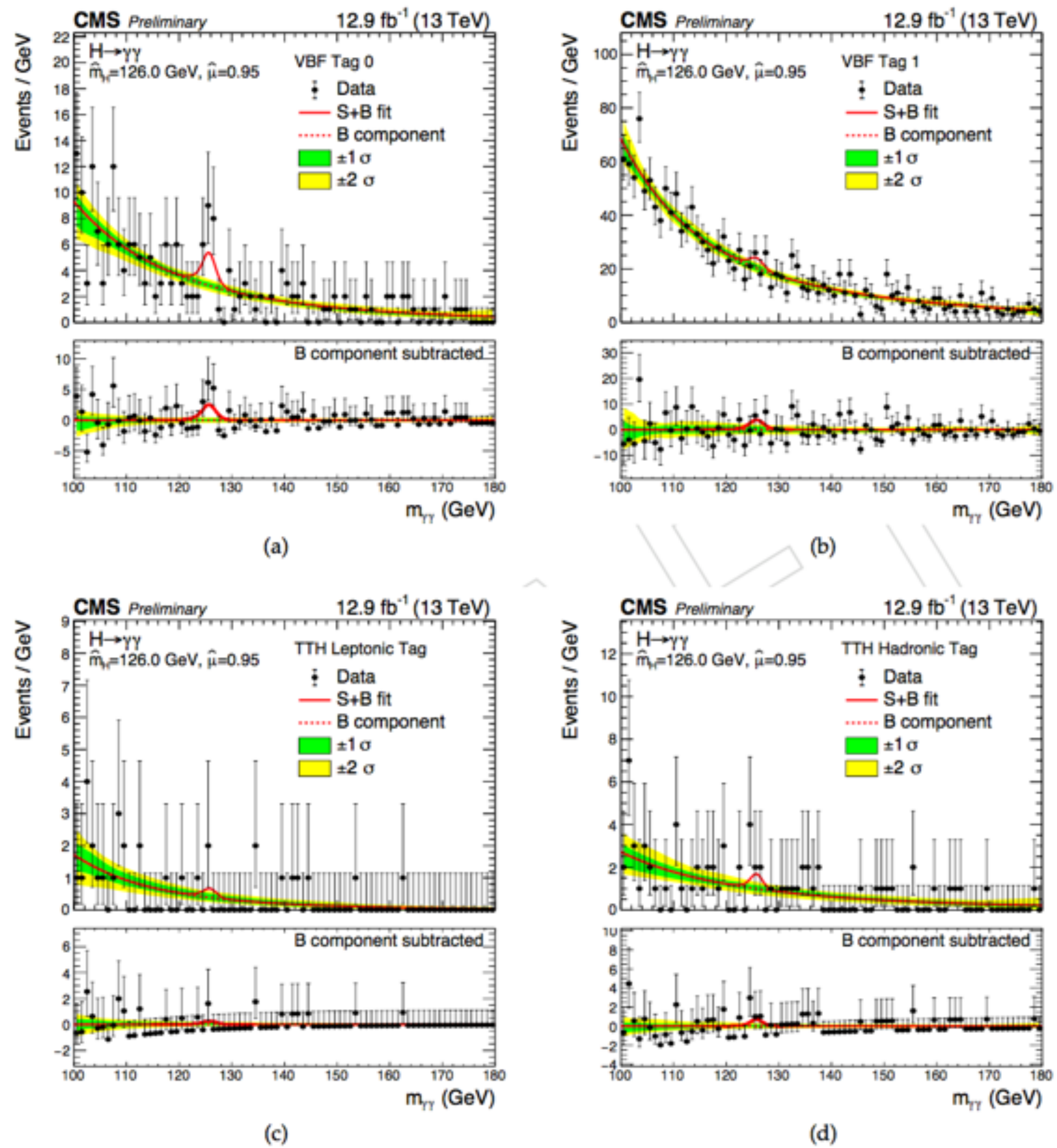
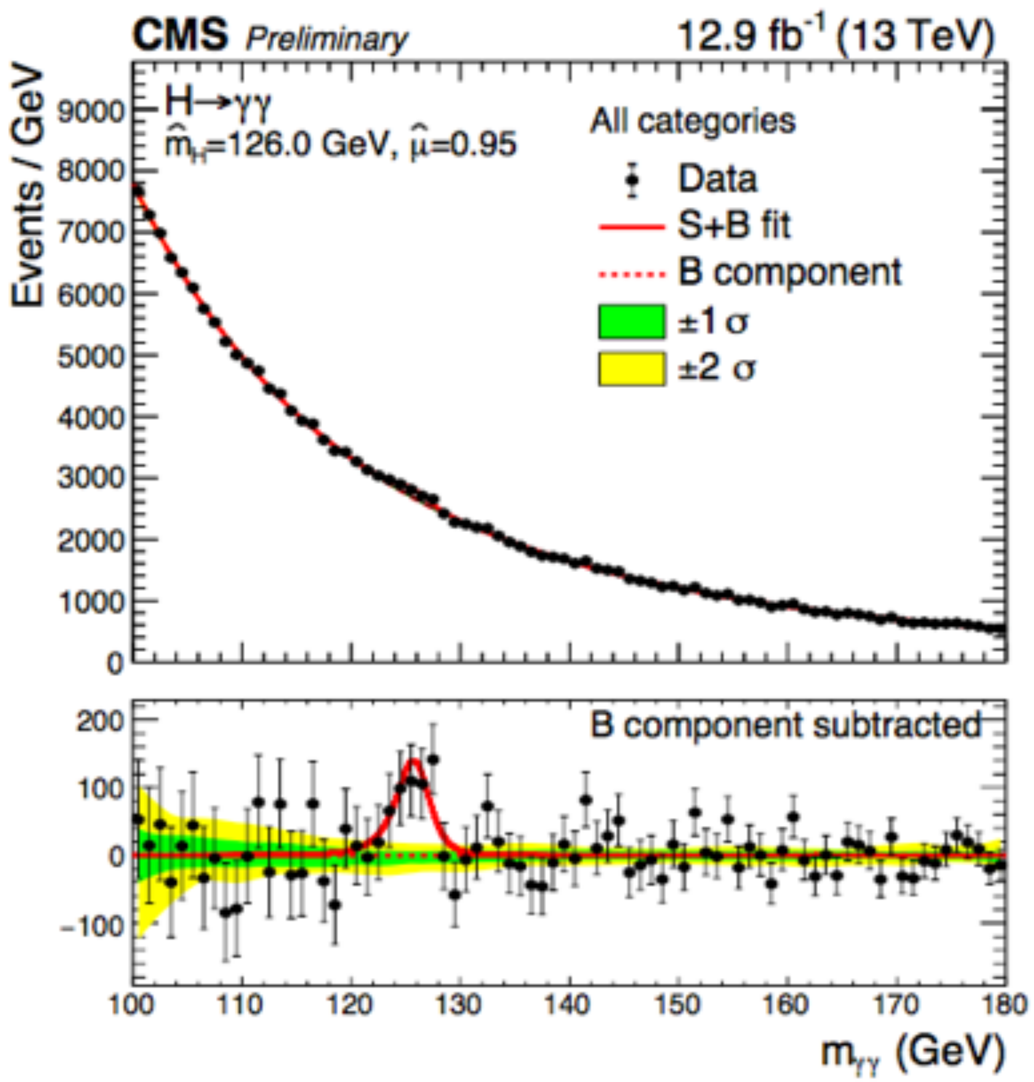


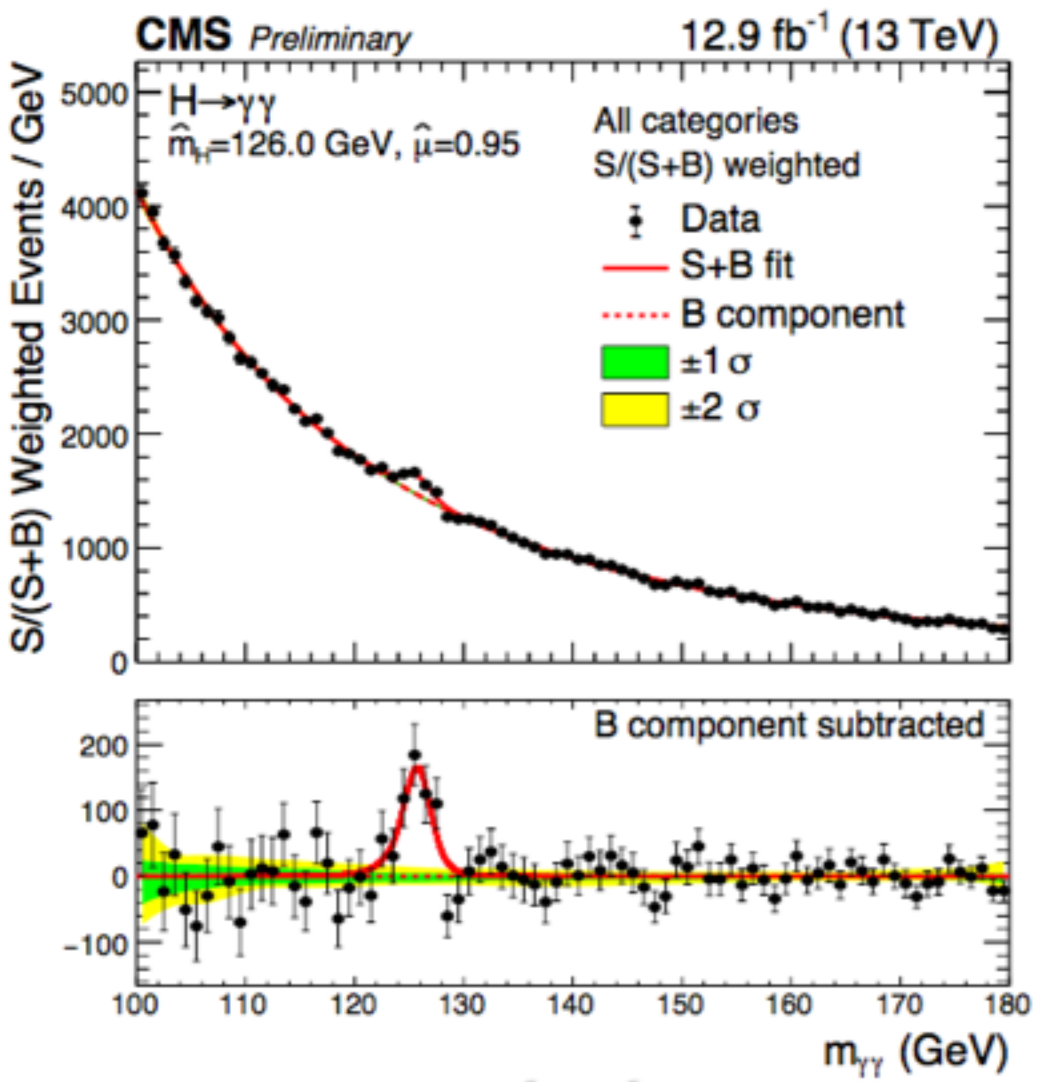
Weighted S/S+B and P-Value

Unweighted

Weighted



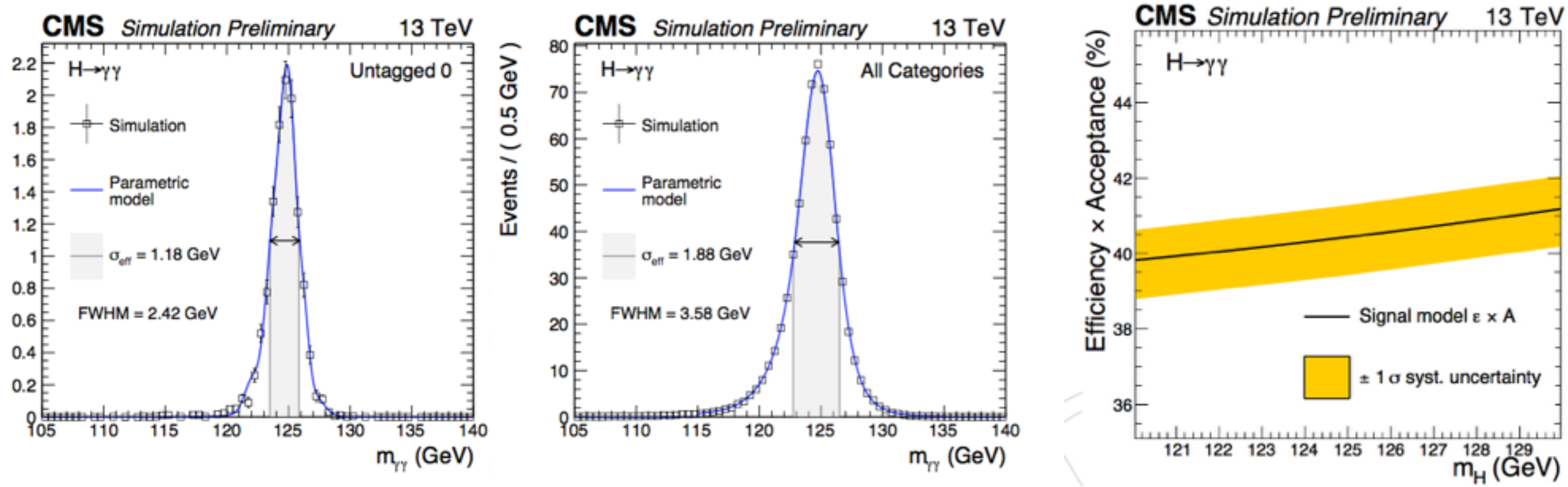
(a)



(b)

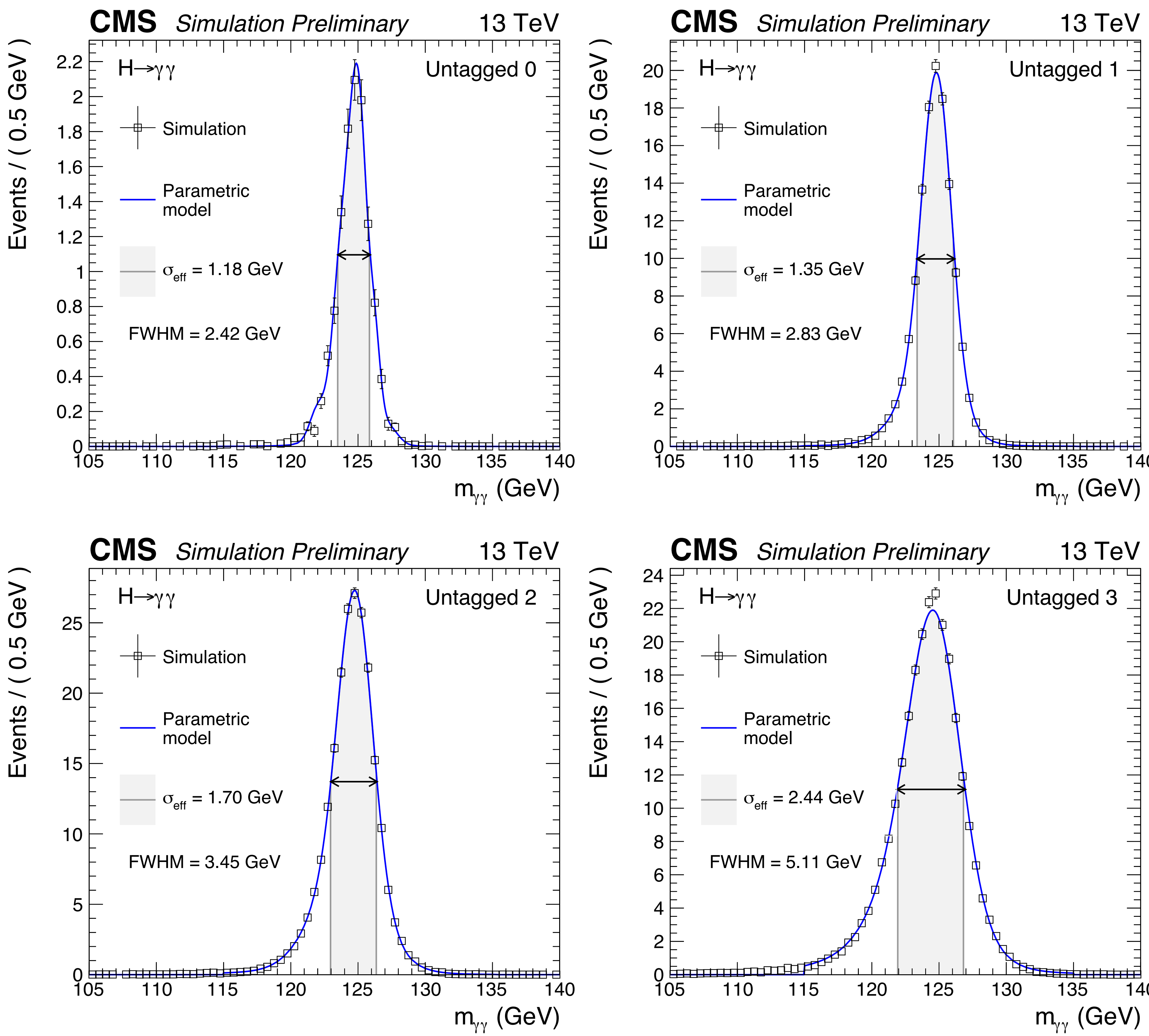
- Shown here is the total invariant mass distribution where we reweight using the factor S/(S+B) in a 1GeV window around the point.

Signal Model

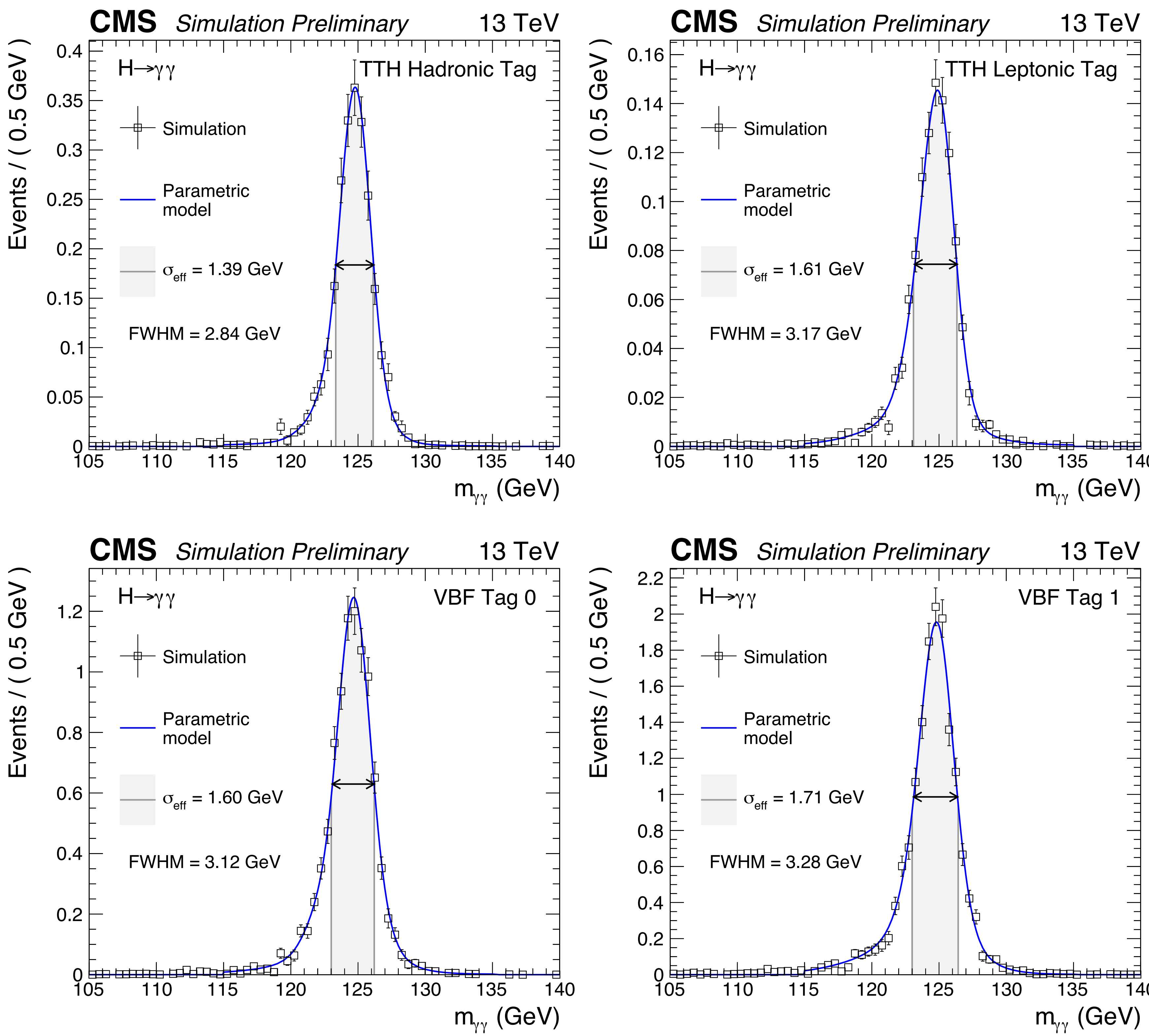


Event Categories	SM 125GeV Higgs boson expected signal								Bkg (GeV^{-1})
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	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

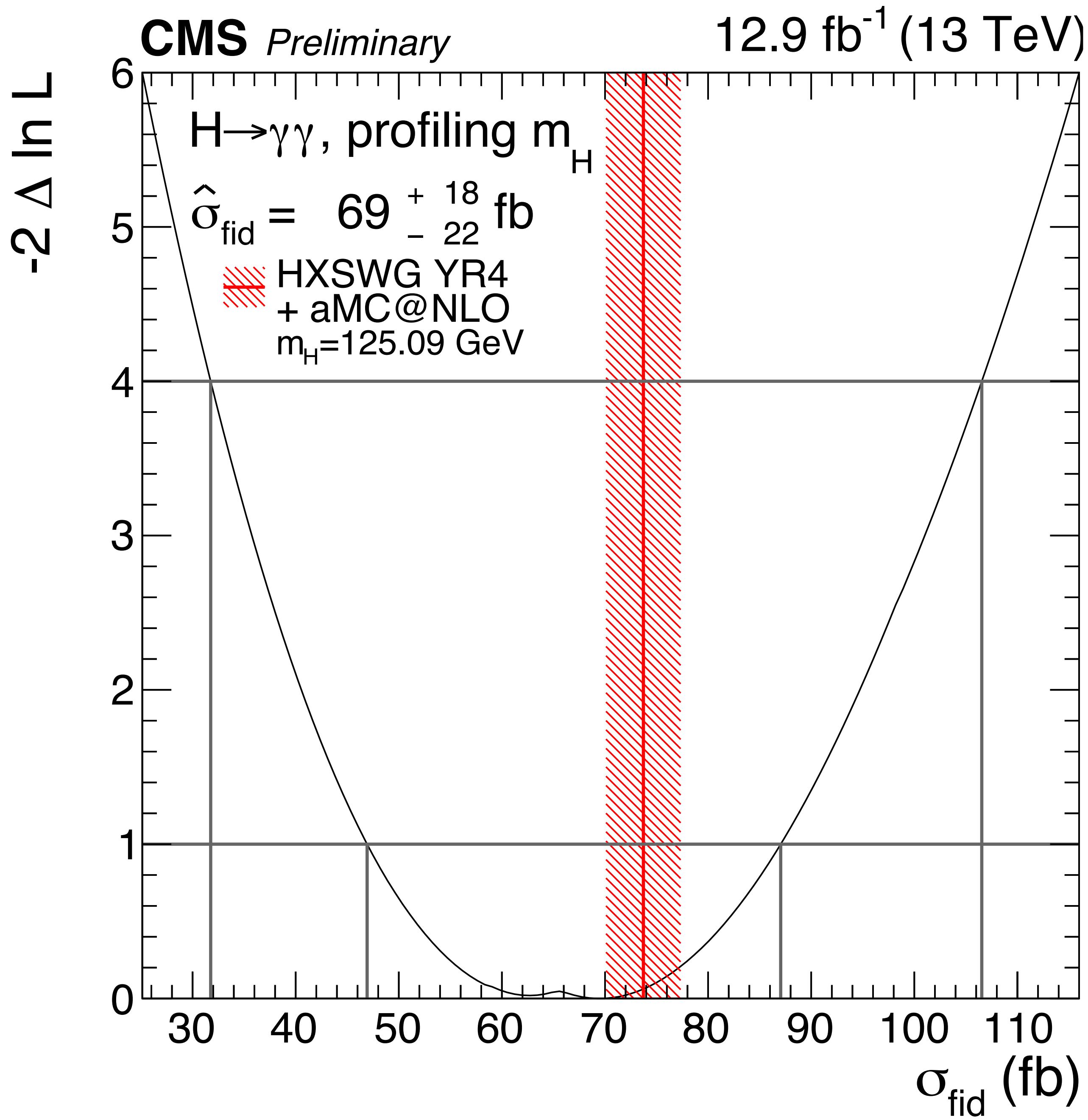
Signal Model

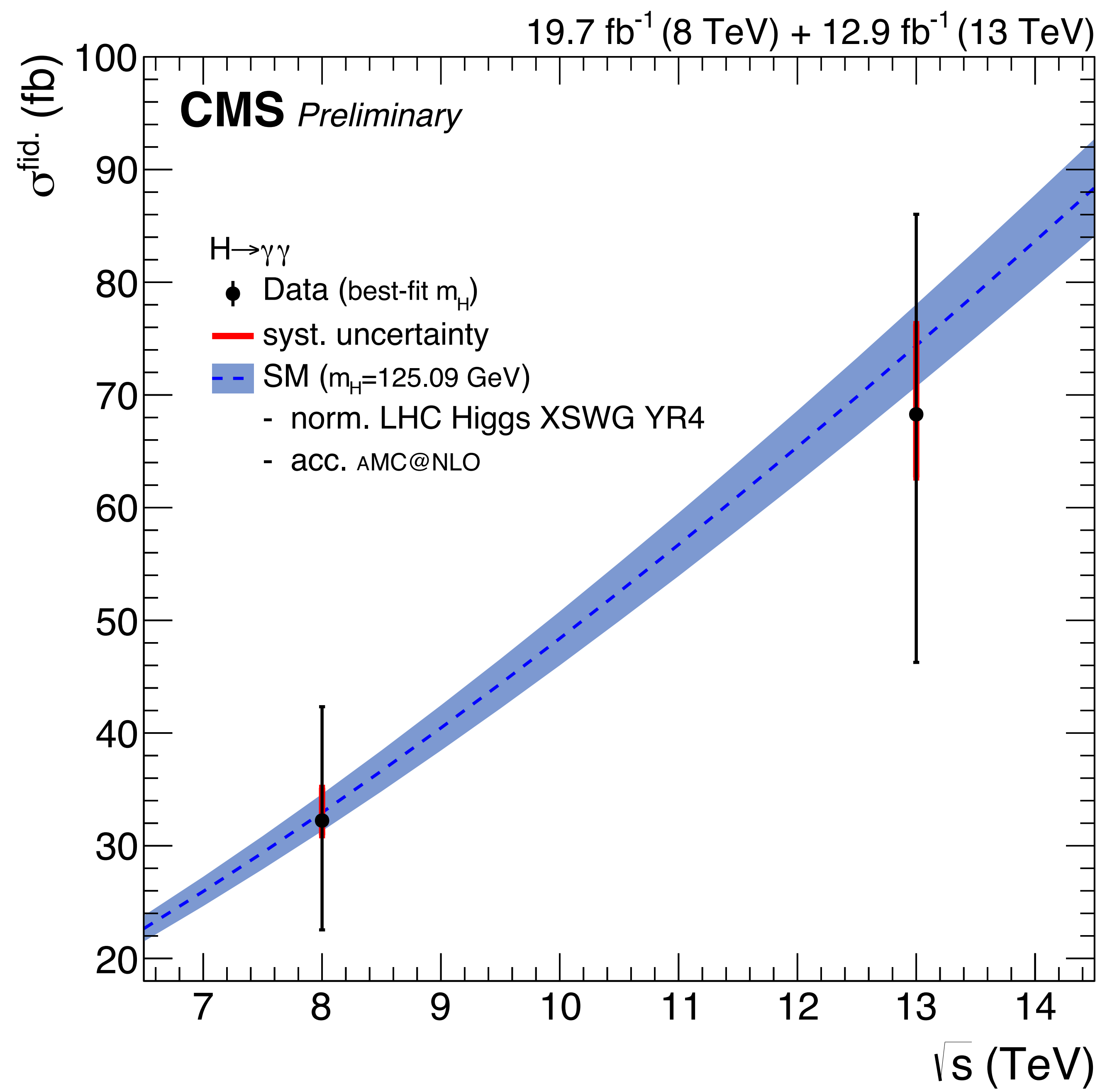


Signal Model



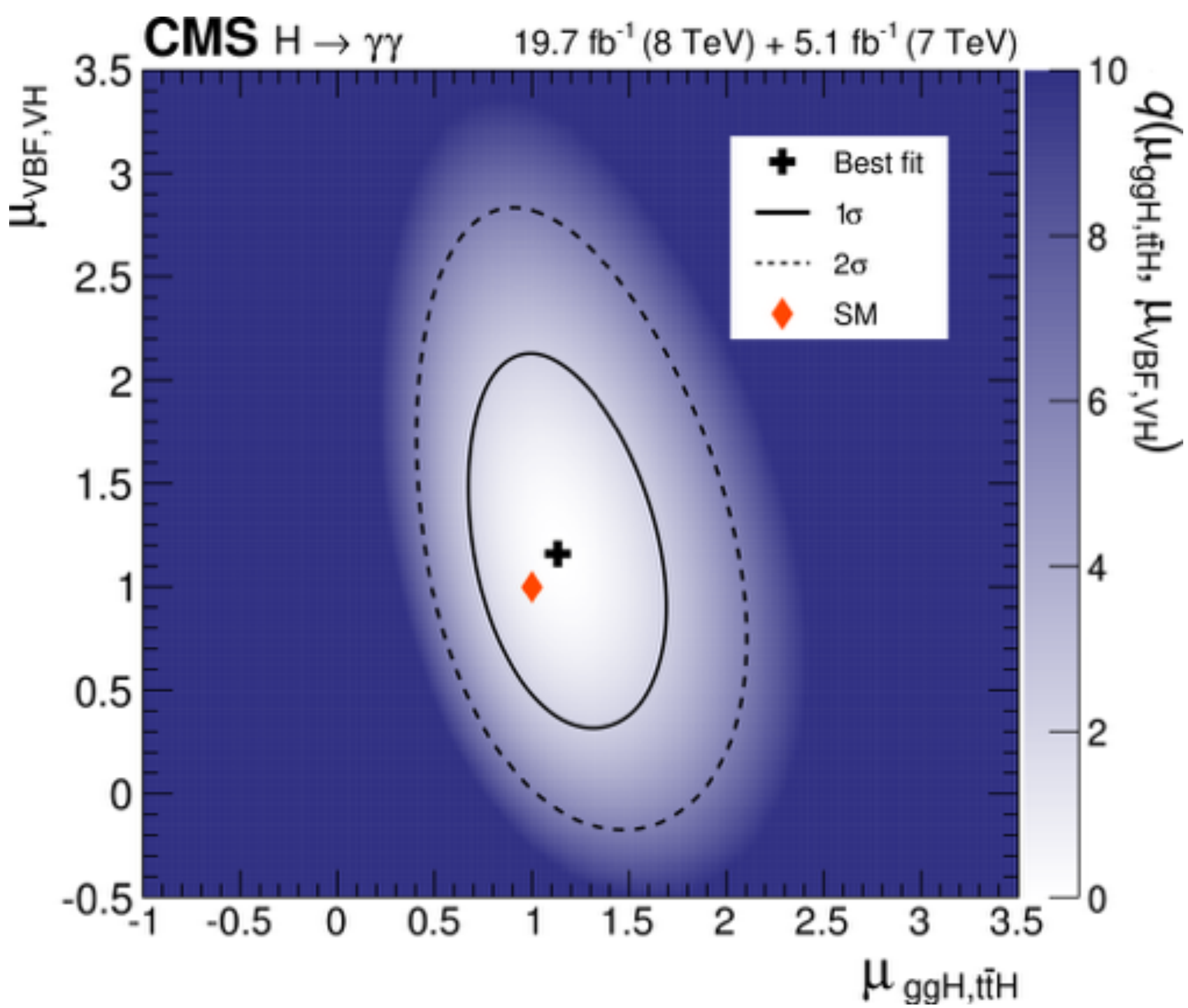
Fiducial XS measurement



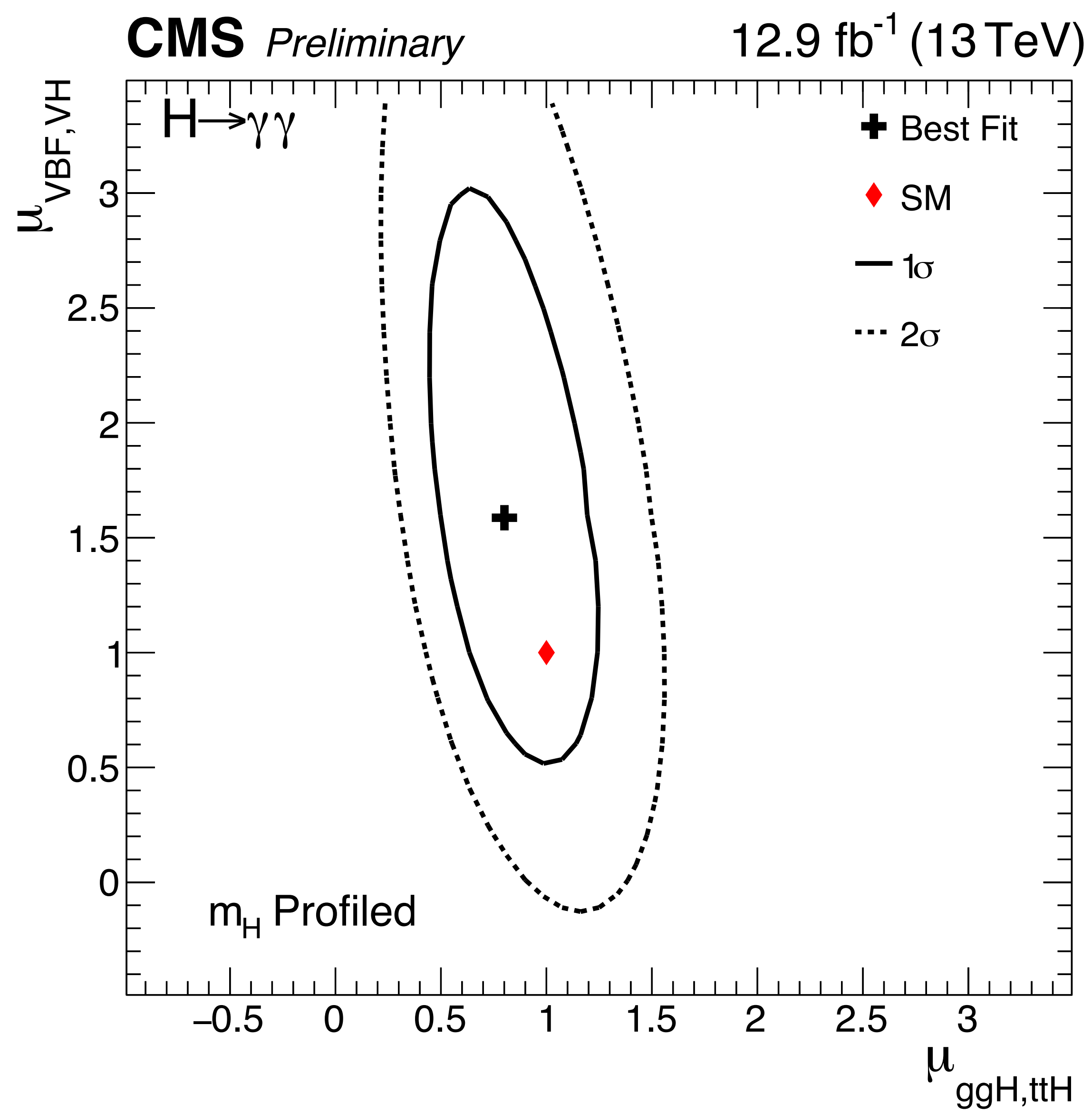


$\mu_{ggH,ttH}$ vs $\mu_{VBF,VH}$
Run1 vs Run2

Run 1



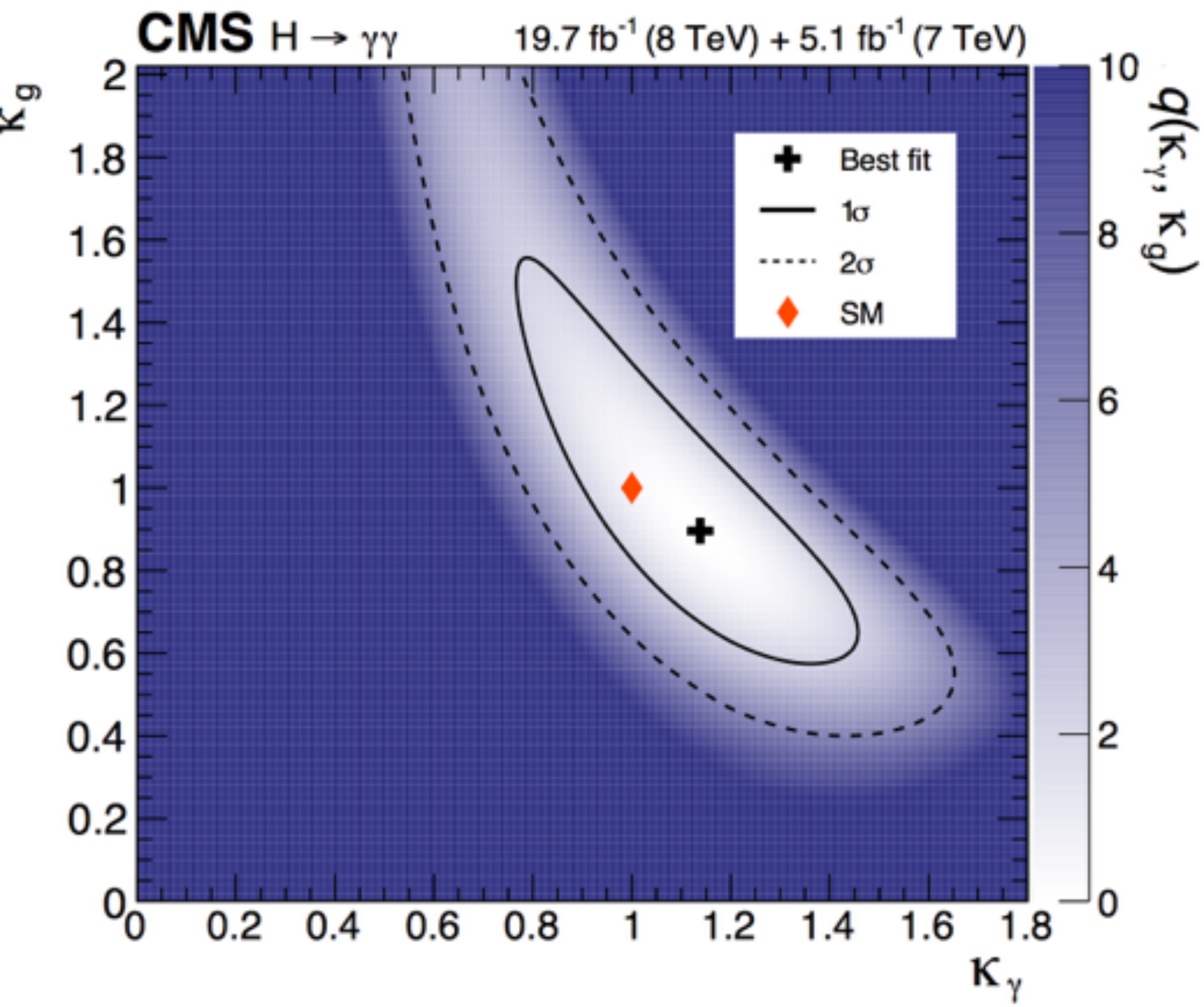
Run 2



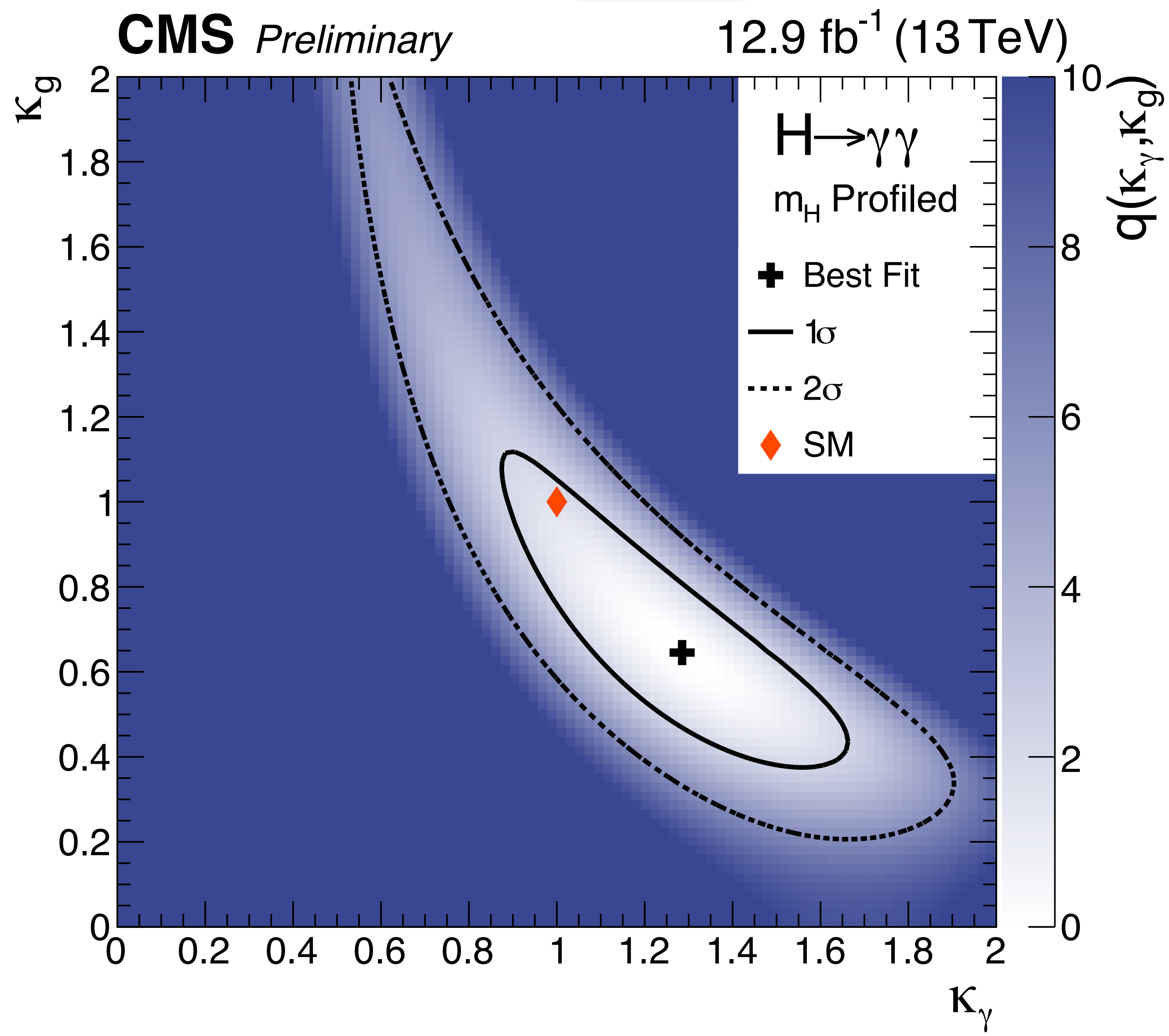
Figures shows with same axis ranges

κ_g VS κ_γ
Run1 vs Run2

Run 1

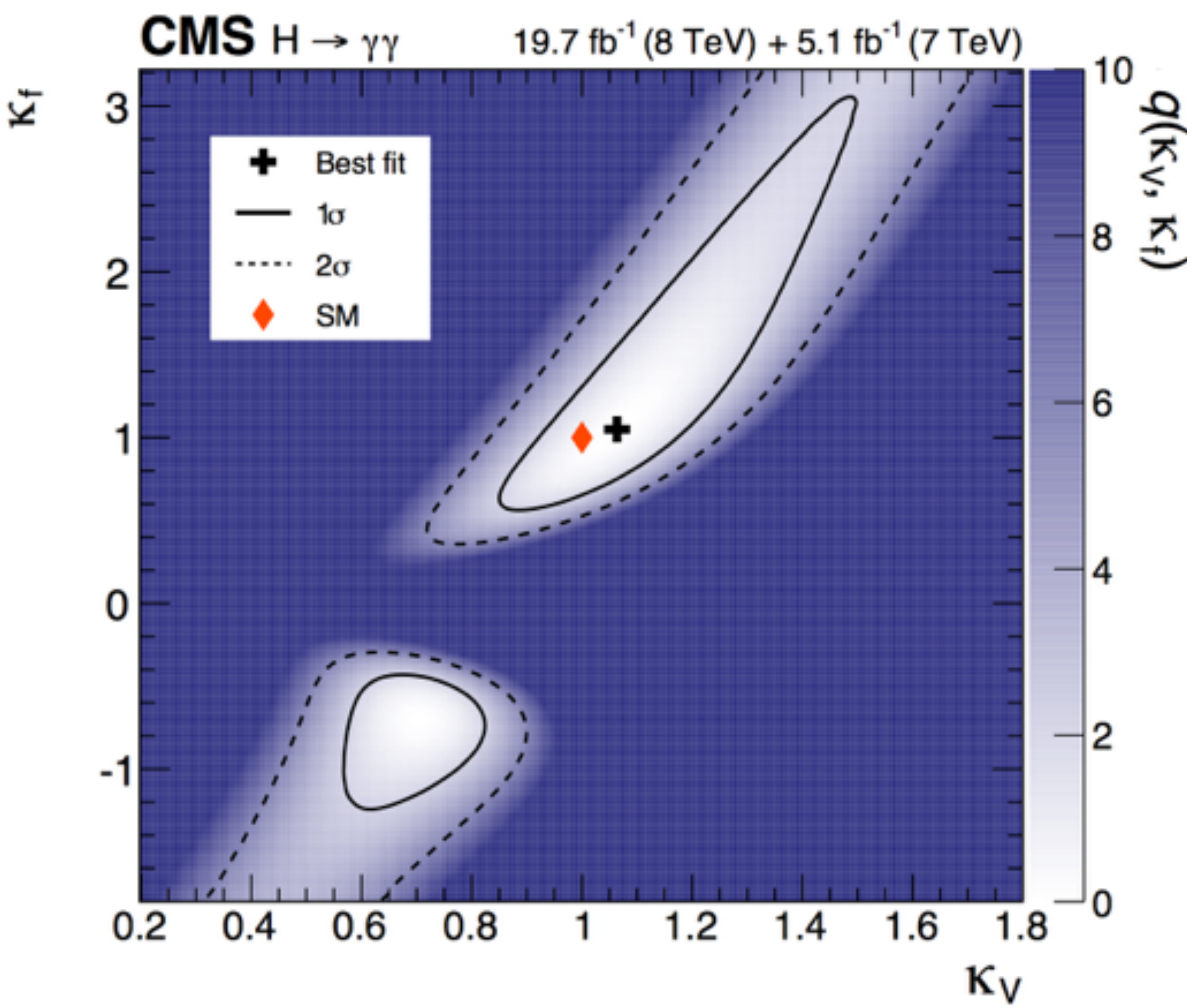


Run 2

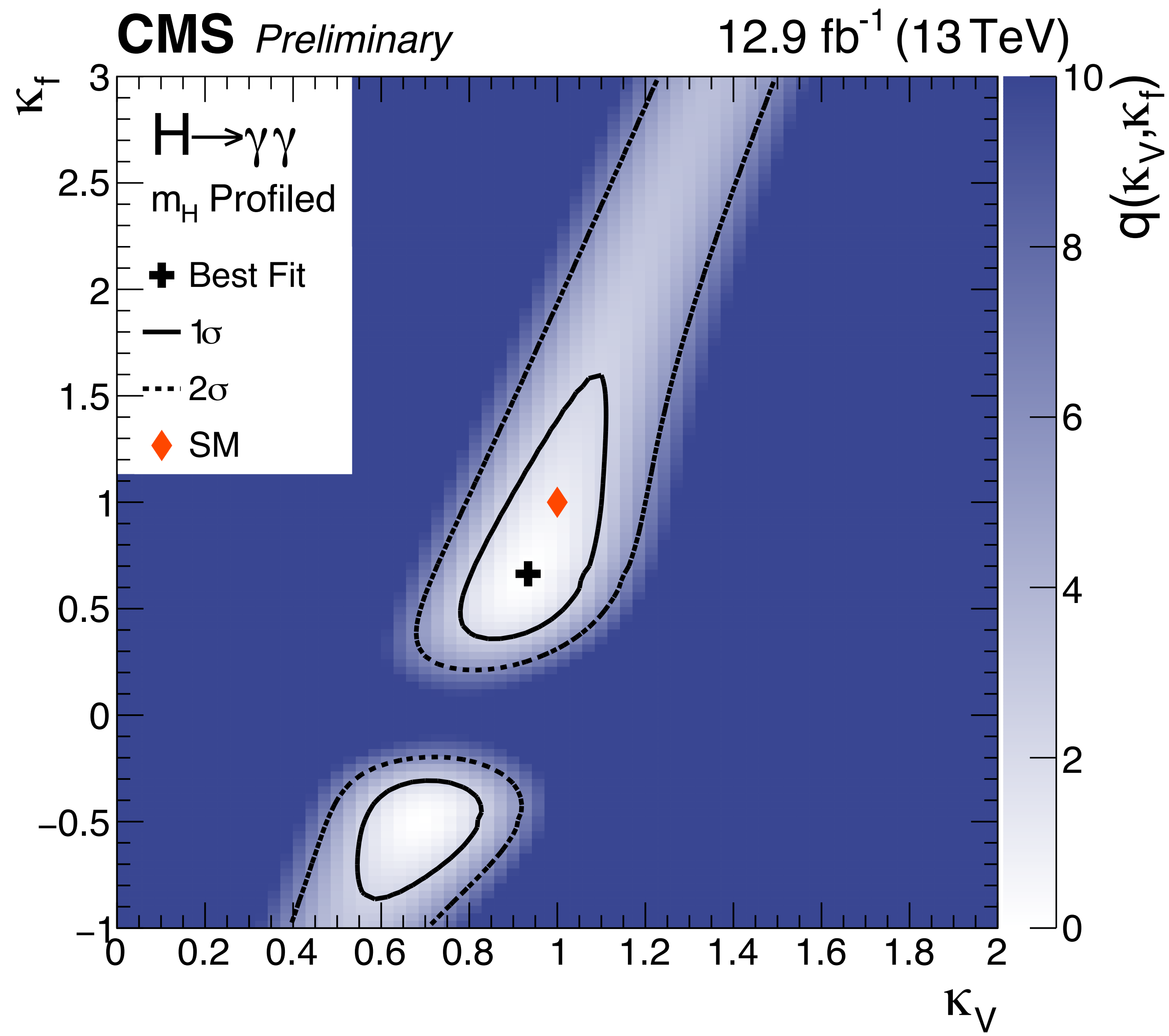


κ_g VS κ_γ
Run1 vs Run2

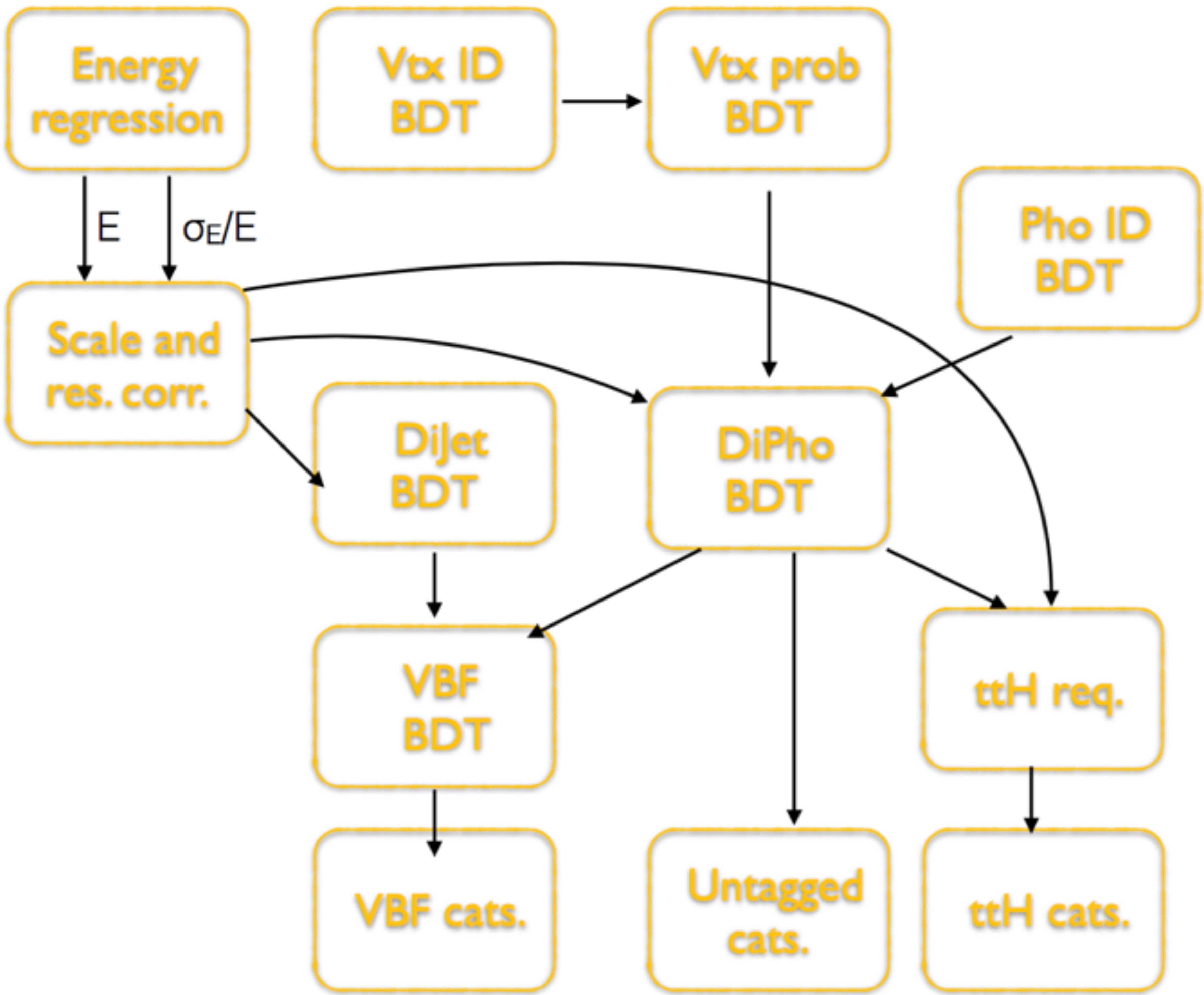
Run 1



Run 2



Analysis Flowchart



Mass Measurement

- **Observed best fit is at m_H=126.0 GeV.**
- Obtained from prompt-reconstructed data.
- Statistical uncertainty ~0.3 GeV.
- Systematic uncertainty ~0.2-0.4 GeV.
- Details of the systematic uncertainties on the mass require further refinement and are still under study.