Higgs Measurements with H→γγ at CMS

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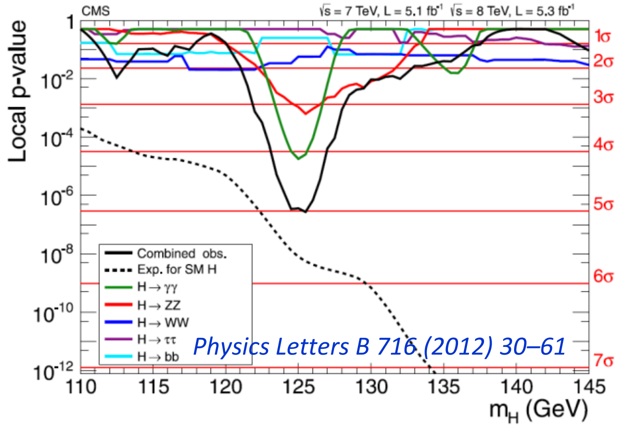
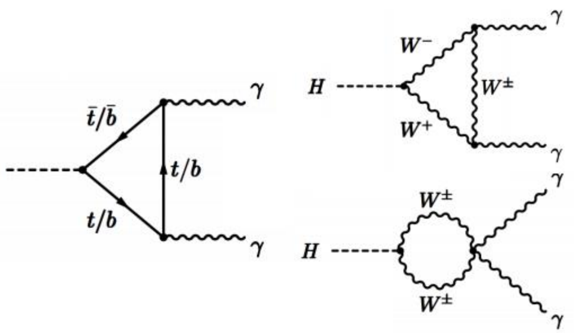
CLHCP2020-pre

该二维码7天内(11月9日前)有效，重新进入将更新

Higgs Boson decaying into $\gamma\gamma$

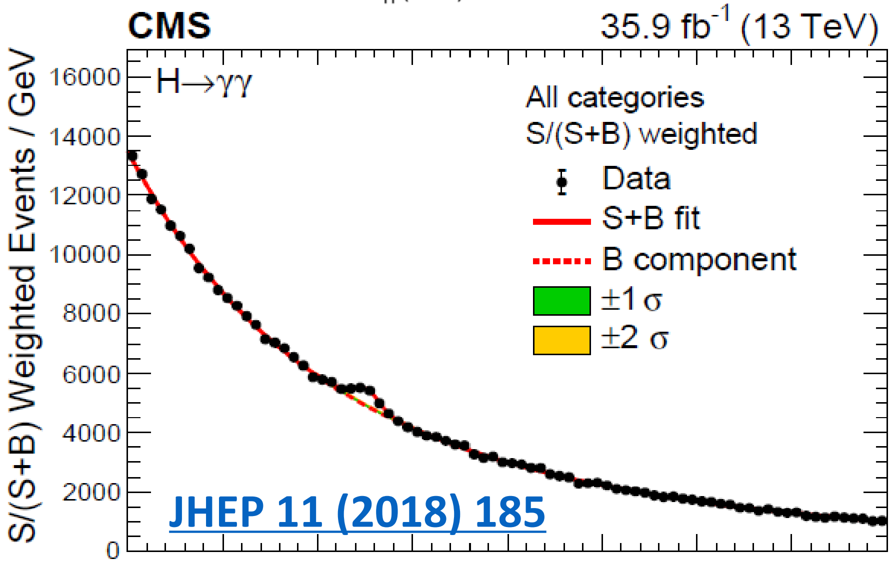
- At LHC, $H \rightarrow \gamma\gamma$ channel plays a **key role** first in the **discovery of the Higgs boson**, and then in the **measurements of Higgs boson properties** and also in **searches for new physics**





- **Small branching fraction** (0.2%), but clean final state with two highly **energetic and isolated photons, so** final state can be **fully reconstructed with excellent mass resolution** (1-2%)

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

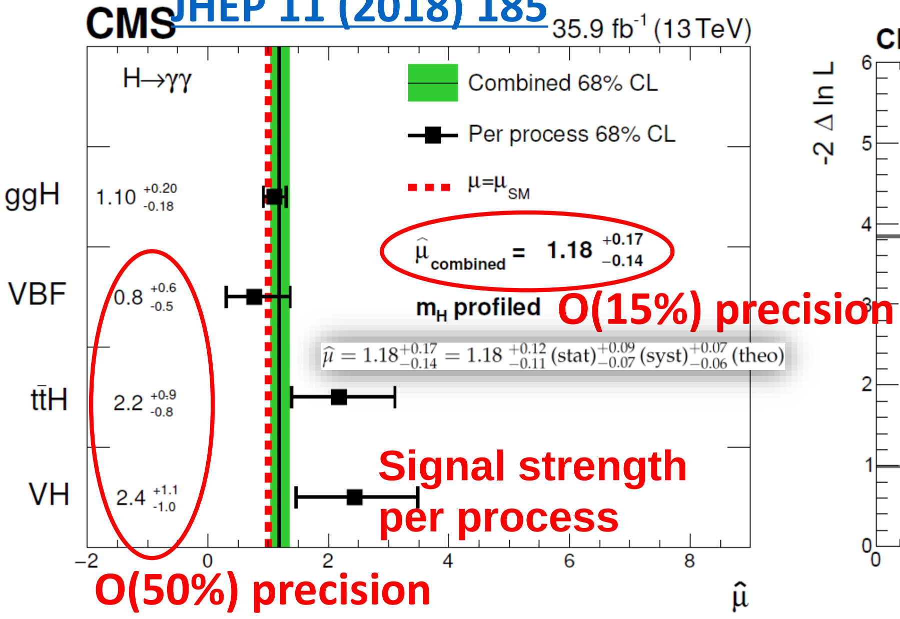


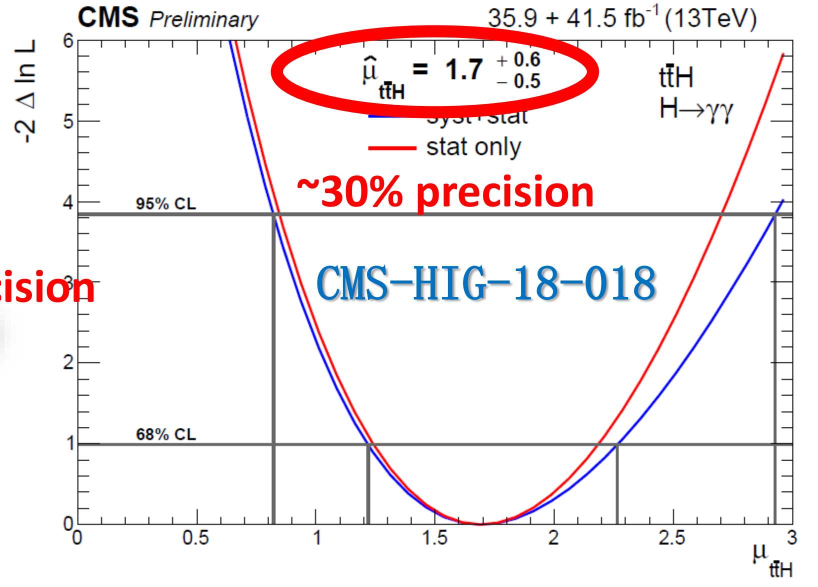
Search for a narrow peak on a larger falling background in mass distribution

H→γγ measurements in Run2

- **2016 data** : Signal strength, STXS stage 0, coupling modifier
- **2016+2017 data: ttH** (CMS-HIG-18-018), ggH + VBF STXS stage 1.0 (CMS-HIG-18-029)

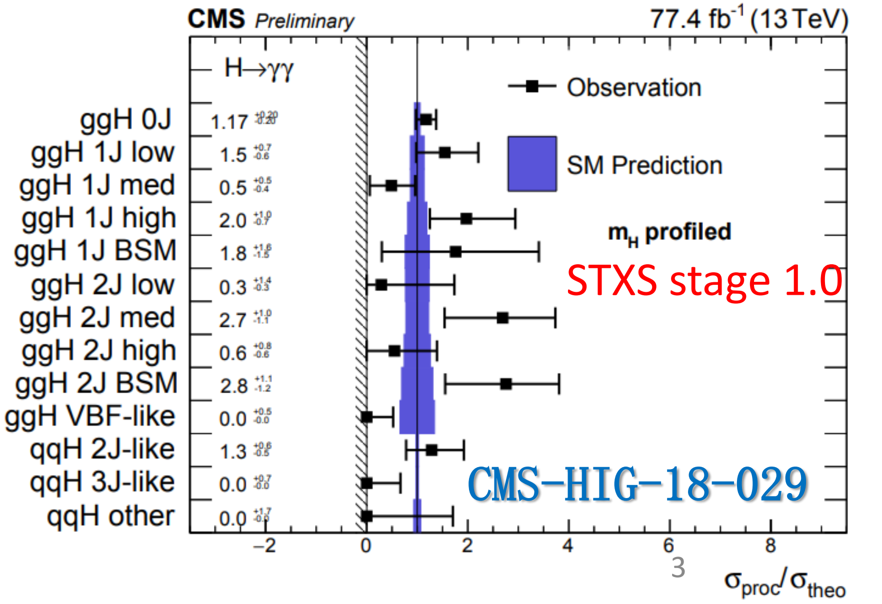
JHEP 11 (2018) 185





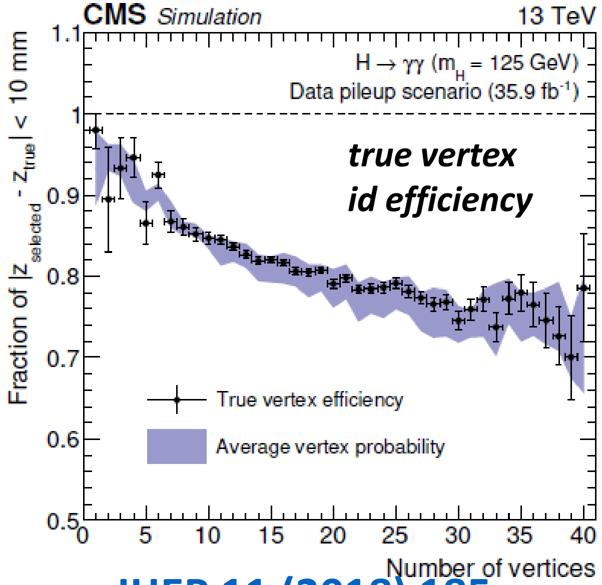
This talk will present some latest results from measurements of Higgs boson properties with H→γγ

1. Higgs mass with 2016 legacy data [Phys. Lett. B 805 (2020) 135425]
2. ttH production + CP with full Run2 dataset (2016 + 2017 + 2018) [Phys. Rev. Lett. 125, 061801]
3. Signal strength, STXS stage 1.2, coupling modifier with the full Run 2 dataset [CMS-HIG-19-015]



General analysis strategy

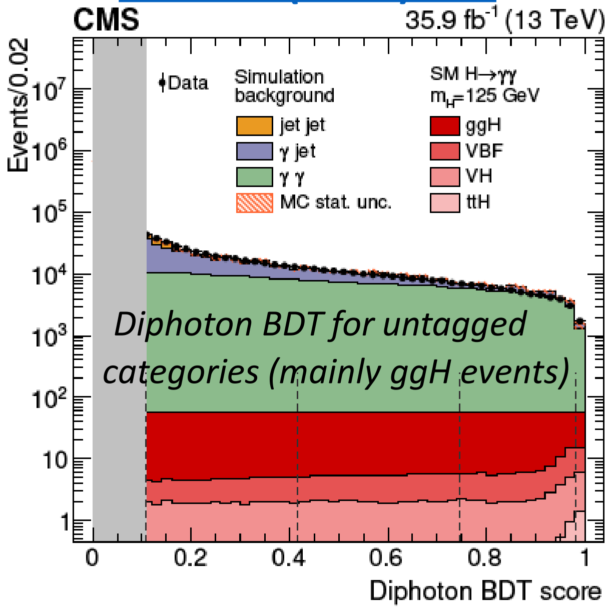
- **Signal mass reconstruction** $m^2_{\gamma\gamma} = E_{\gamma_1} E_{\gamma_2}(1 - \cos\alpha)$
  - ✓ select/reconstruct two **photons** with precise **photon energy corrected** with a **multivariate regression technique**
  - ✓ Find the **primary vertex** of the Higgs decay with ***MVA BDT***



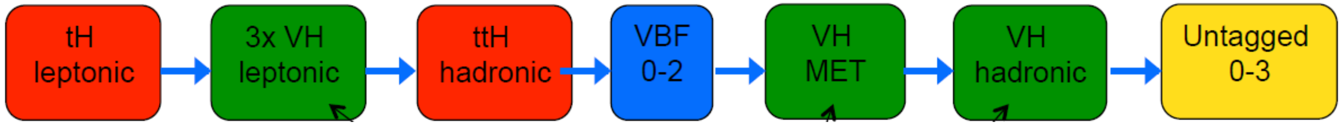
[JHEP 11 (2018) 185]

- **Background suppression**: **photon identification *BDT***

- **Various BDT/DNN** for different production models, e.g. **Diphoton BDT** based on kinematics including mass resolution, **to separate Higgs signal from background**



- **Event categorization according to production models, BDT/DNN scores** (such as diphoton BDT) and **different S/B**, to **improve the analysis sensitivity**



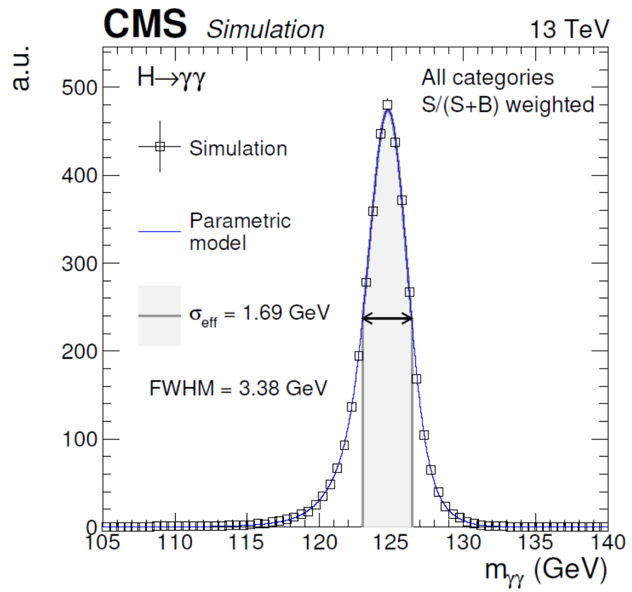
eg in2016 dataset ([JHEP 11 (2018) 185]): 14 non-overlapping categories in total

General analysis strategy (cont.)

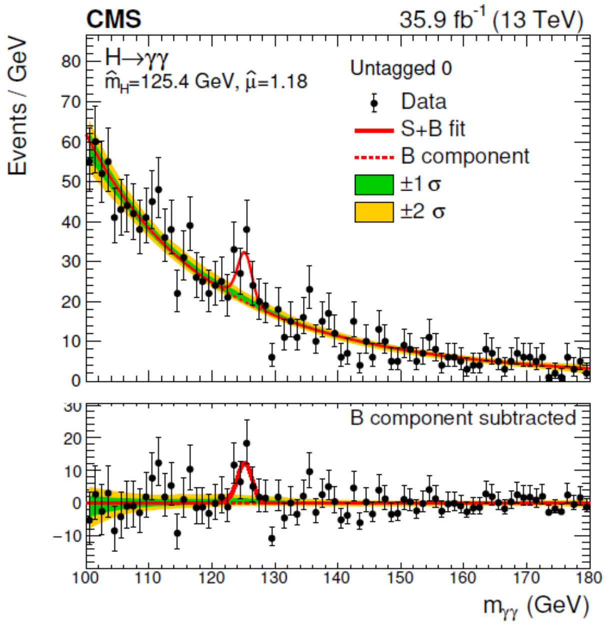
- **Signal modeling :** full parametric **signal** model from **MC** simulation
  - ✓ All the corrections (reweighting, data/MC SFs, …) applied
  - ✓ ***Sum of n-Guassian*** *functions (n<=5) or* **double-sided Crystal Ball plus Gaussian** (ttH full Run2)
  - ✓ Physical nuisances allowed to float

- **Bkg modeling : "data-driven"**
  - ✓ For each event category, use **different functional forms** selected from 4 families (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



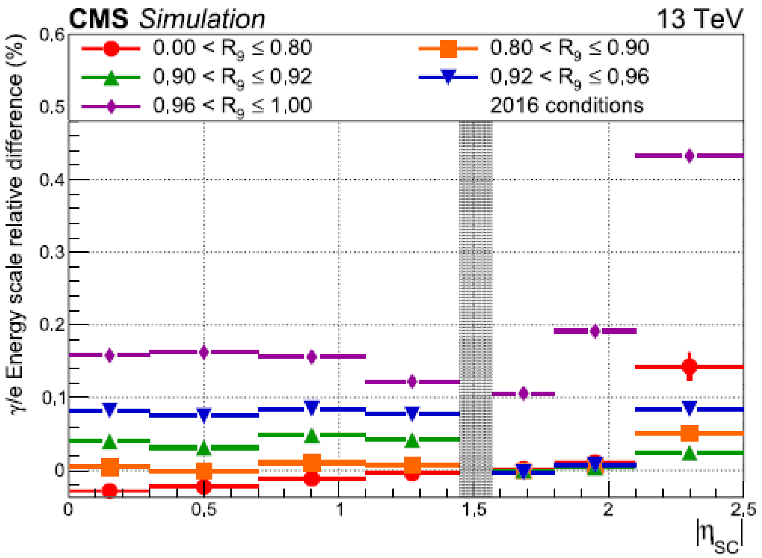
JHEP 11 (2018) 185

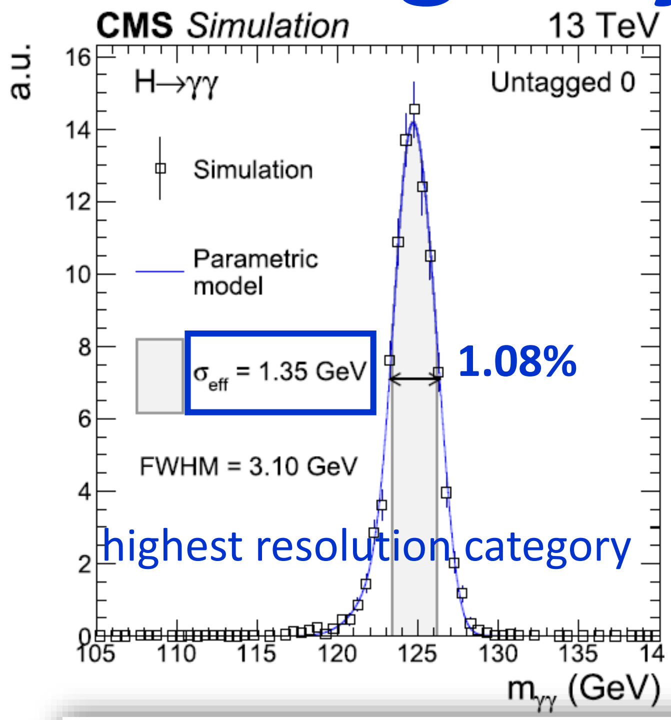


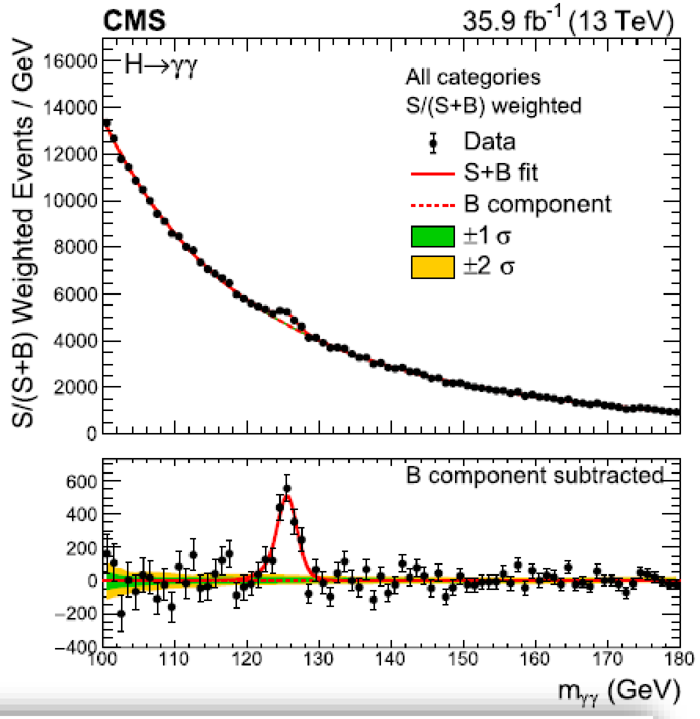
Higgs mass with 2016 legeacy data

- **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**

*Systematic uncertainty due to **e/γ energy scale difference***







$$m_{\mathrm{H}} = 125.78 \pm 0.26\ (0.18\ (\mathrm{stat}) \pm 0.18\ (\mathrm{syst}))\ \mathrm{GeV}$$

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

Phys. Lett. B 805 (2020) 135425

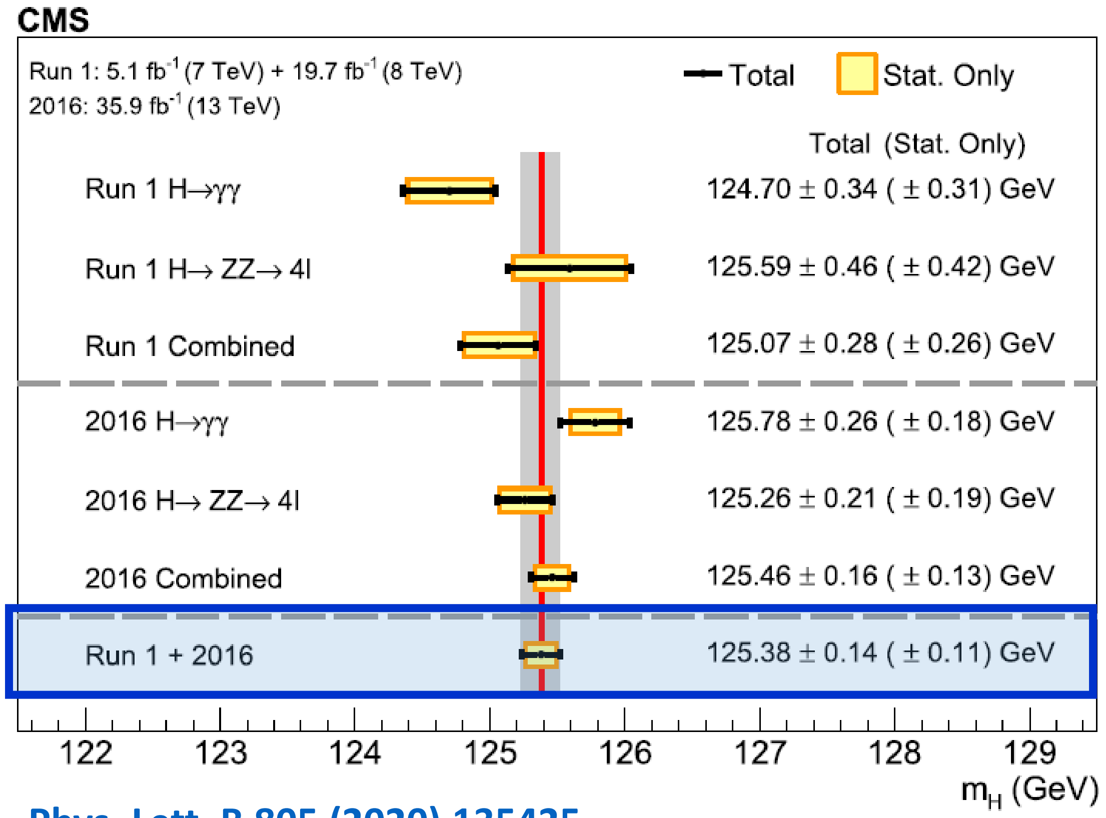
Higgs mass from 2016 + Run1

- Combination with the **H→ZZ* → 4l** mass measurement with the 2016 data set, then with the **Run 1** data set
- Published in the same H→γγ paper

m_H = 125.38 ± 0.14 GeV

(0.11(stat.)±0.09(syst.))

best mass precision ~ 0.11%



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See also the talk from Chengguang Zhang (IHEP/CAS)

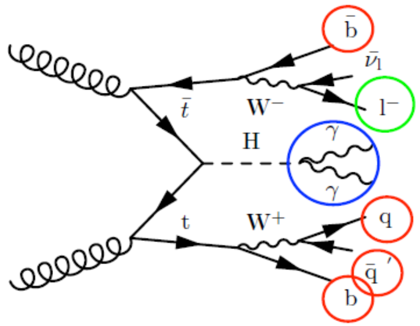
ttH, H→γγ with full Run2 data

- Both **leptonic** and **hadronic** channels included
- A dedicated **BDT discriminant** ("BDT-bkg") is employed in each channel to distinguish between **ttH sig** and **bkg events**

Backgrounds: $\gamma(\gamma)$+jets, tt+jets, tt+$\gamma(\gamma)$, Z+γ, W+γ

BDT scores validated in **mass side-bands** (100-120GeV and 130-180GeV), and **control regions** that target **tt + Z events**

Leptonic Channel

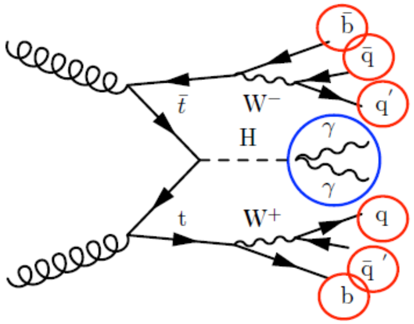


- # e/μ ≥ 1

- Loose photon ID
- 100 < $m_{\gamma\gamma}$ < 180 GeV
- (sub)leading photon $p_T/m_{\gamma\gamma}$ > 1/3(1/4)

- ≥ 1 jet

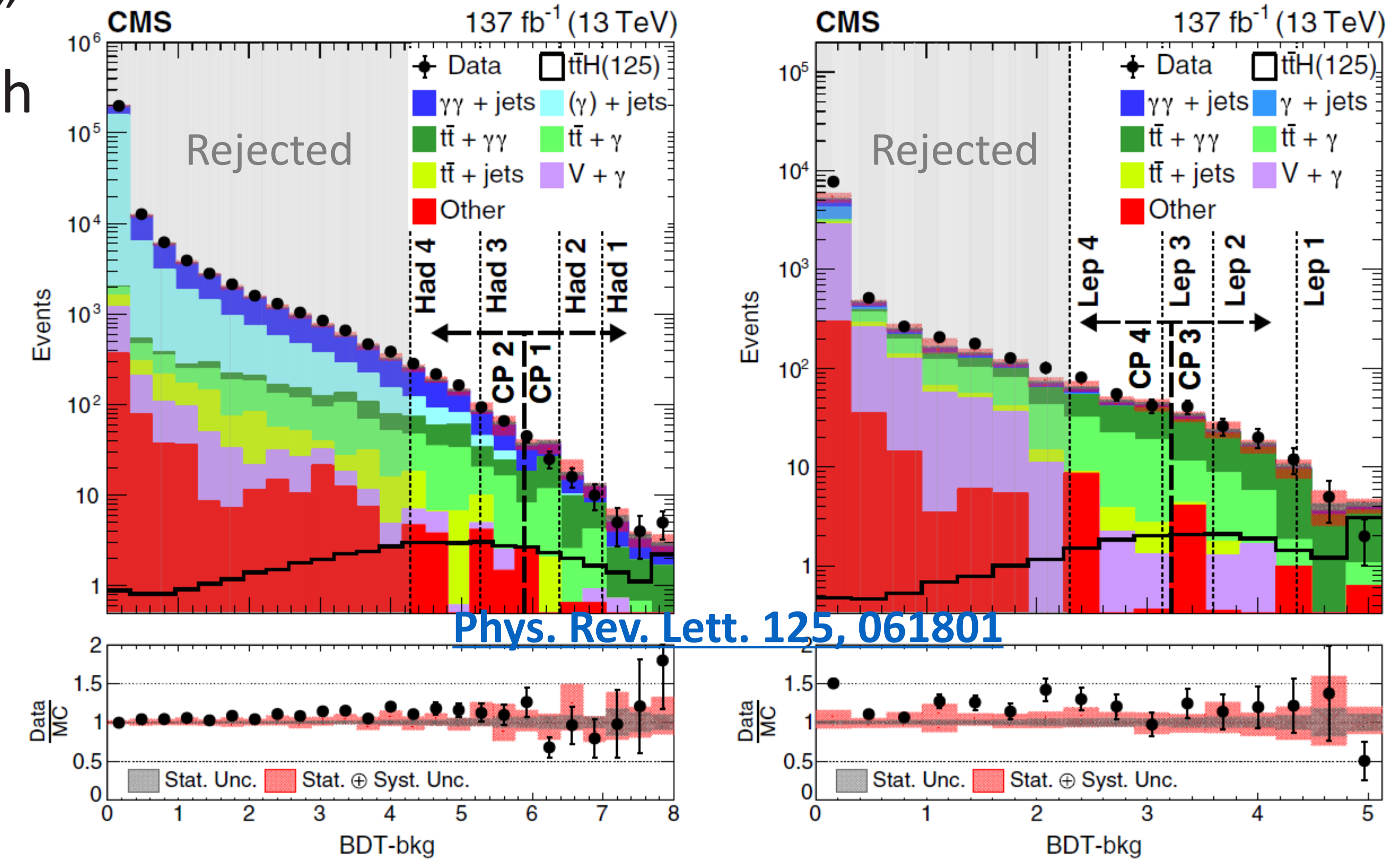
Hadronic Channel



- # e/μ == 0

- Loose photo
- 100 < $m_{\gamma\gamma}$ < 180 GeV
- (sub)leading photon $p_T/m_{\gamma\gamma}$ > 1/3(1/4)

- ≥ 3 jets, ≥ 1 b-tagged jets



Phys. Rev. Lett. 125, 061801

ttH signal strength : 8 categories

Results of ttH→γγ with full Run2 data

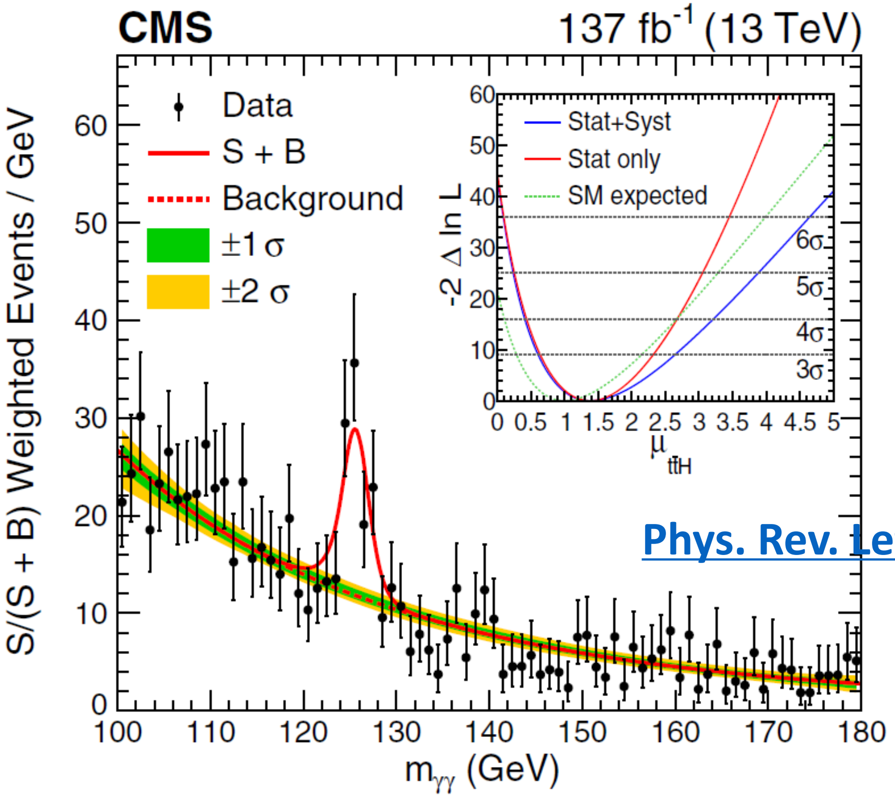
$$\sigma_{t\bar{t}H}\mathcal{B}_{\gamma\gamma} = 1.56^{+0.34}_{-0.32}\ \text{fb} = 1.56^{+0.33}_{-0.30}(\text{stat})^{+0.09}_{-0.08}(\text{syst})\ \text{fb}$$

~20% precision

$$\mu_{t\bar{t}H} = 1.38^{+0.36}_{-0.29} = 1.38^{+0.29}_{-0.27}(\text{stat})^{+0.21}_{-0.11}(\text{syst})$$

Observed (expected) **significance 6.6σ** (4.7σ)

→ First observation of ttH with a single channel



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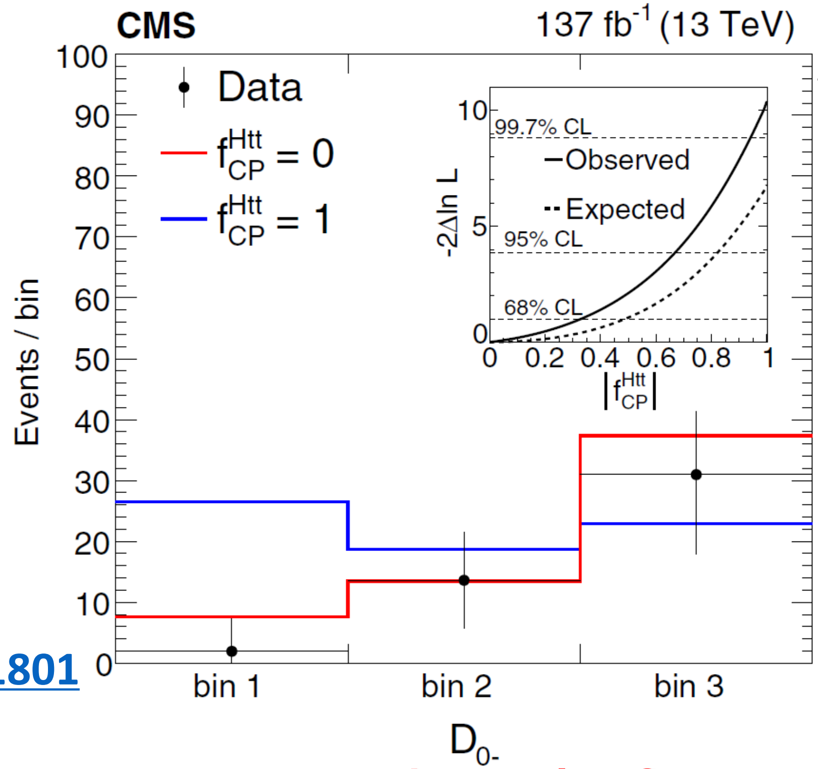
CP structure : $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\text{sign}(\tilde{\kappa}_t/\kappa_t)$

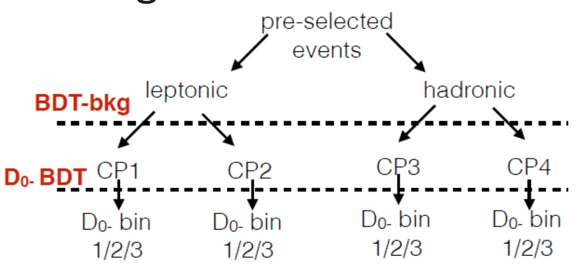
κ_t CP-even Yukawa couplings
$\tilde{\kappa}_t$ CP-odd Yukawa couplings

$f_{CP}^{Htt} = 1$ Pure pseudo-scalar (CP-odd) model of CP structure
$f_{CP}^{Htt} = 0$ Pure scalar model (CP-even) of CP structure
$f_{CP}^{Htt} = 0.72$ Equal CP-even/CP-odd contributions



Train a BDT (D_{0-}) to distinguish CP-even and CP-odd contributions

12 categories



CP-odd excluded at 3.2σ (obs)

$$f_{CP}^{Htt} = 0.00 \pm 0.33$$

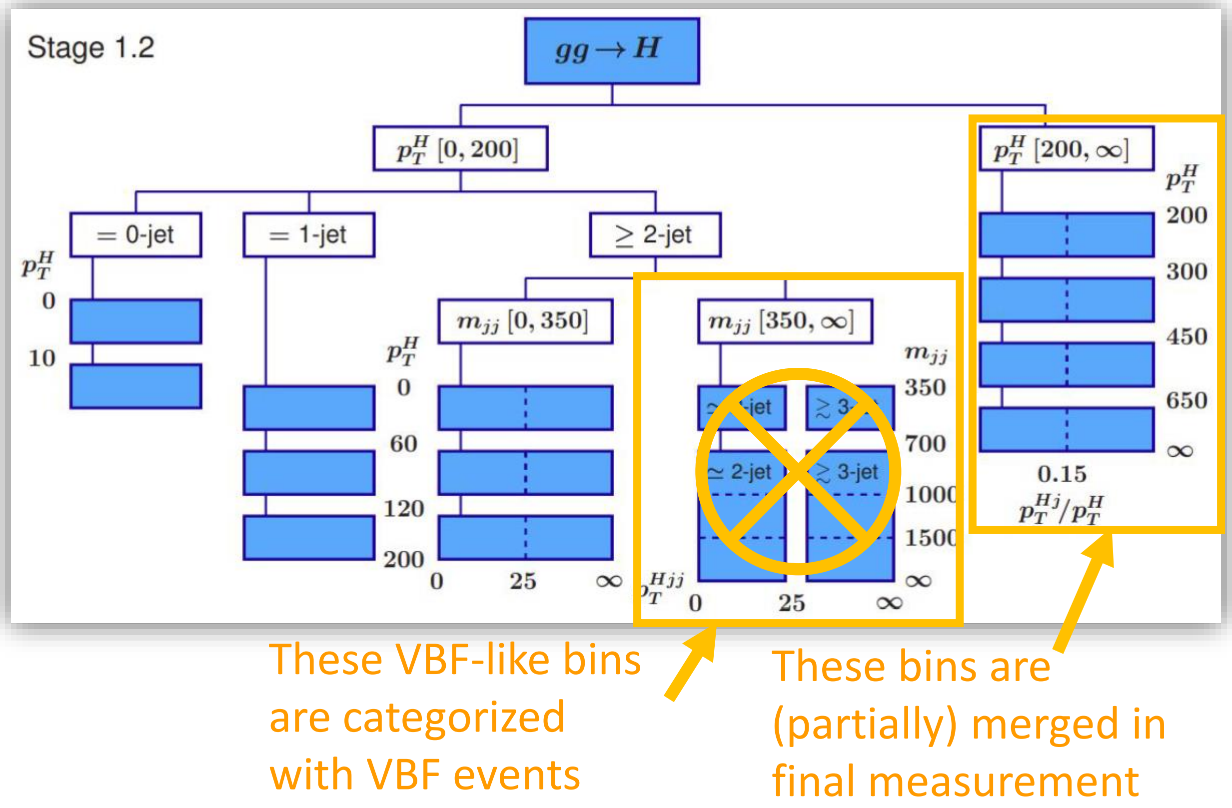
See details from Renqi Pan (ZJU)

STXS measurements with full Run2

- **Higgs Simplified Template Cross Section (STXS) framework** used to **maximize the measurement precision and the sensitivity to BSM contributions**

- **Analysis strategy with full Run2 data**
  - ✓ Phase spaces that target different **Higgs production mode (ggH, VBF, VH, tH, ttH)** are further divided to explore as many stage 1.2 STXS bins as possible
  - ✓ Allows measurements to be performed across all these **major Higgs production modes**
  - ✓ Also provides sensitivity to measure **signal strength modifiers** (μ) and **coupling modifiers** (κ) in the κ-framework
  - ✓ Extract cross section, μ and κ by performing a **simultaneous fit** to the $m_{\gamma\gamma}$ distribution in each category

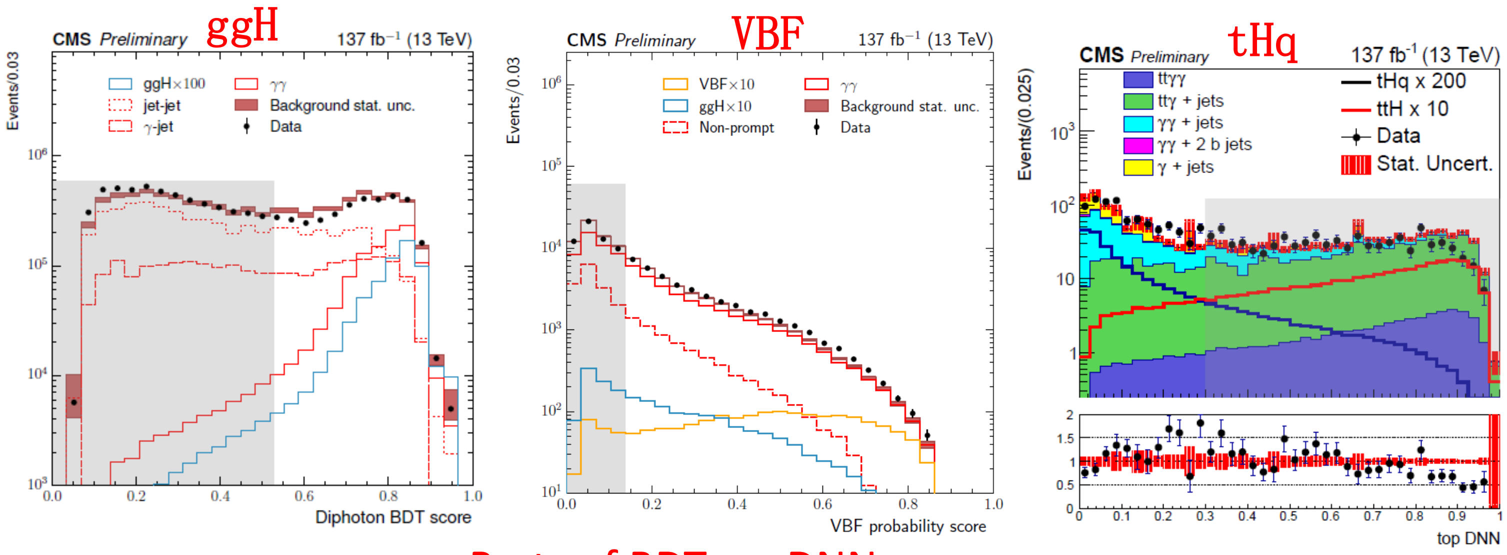
An example of bin definition for ggH at stage 1.2



- **Certain STXS bins are merged** due to low statistics

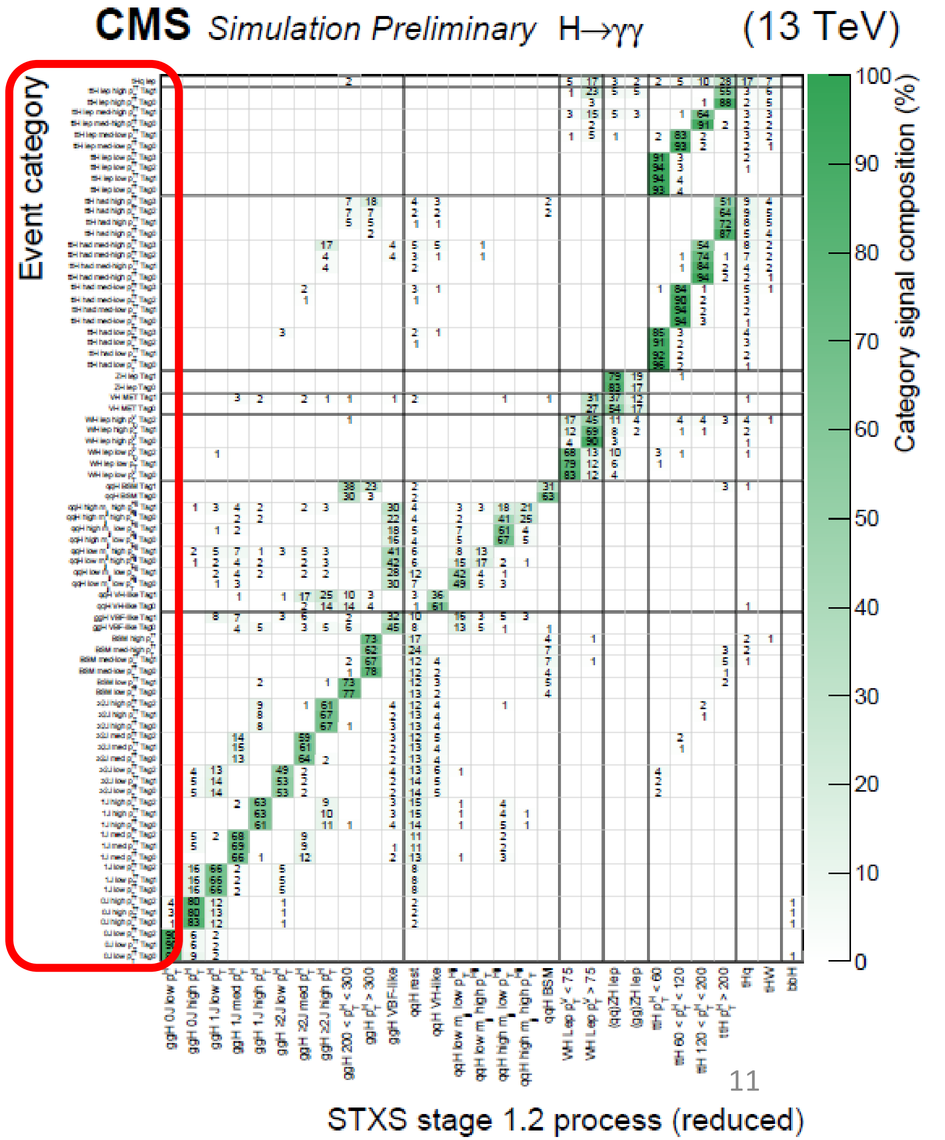
Event categorization for STXS

- Each considered **STXS region** is divided into analysis categories using dedicated BDTs or DNNs → To **reject background** and **maximize expected sensitivity**



Parts of BDTs or DNNs scores

81 analysis categories are considered



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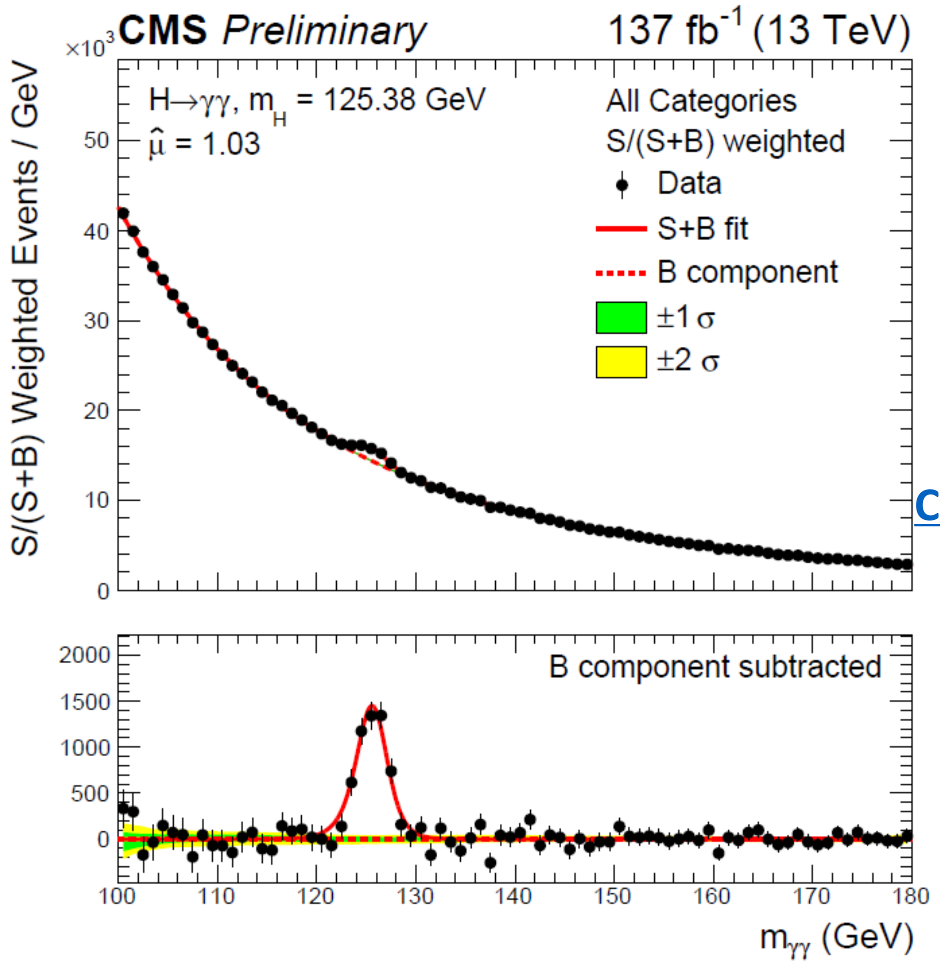
To avoid ambiguity (one event passes selection criteria for > 1 analysis category)

- ✓ Define a priority: analysis category **with lower expected signal yield has higher priority**
- ✓ Events that could enter more than one analysis category are assigned to the category with the **highest priority**

Signal strength with full Run2

$$\mu = 1.03^{+0.11}_{-0.09} = 1.03^{+0.07}_{-0.05}\,(\text{theo})^{+0.04}_{-0.03}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{stat})$$

~10% precision



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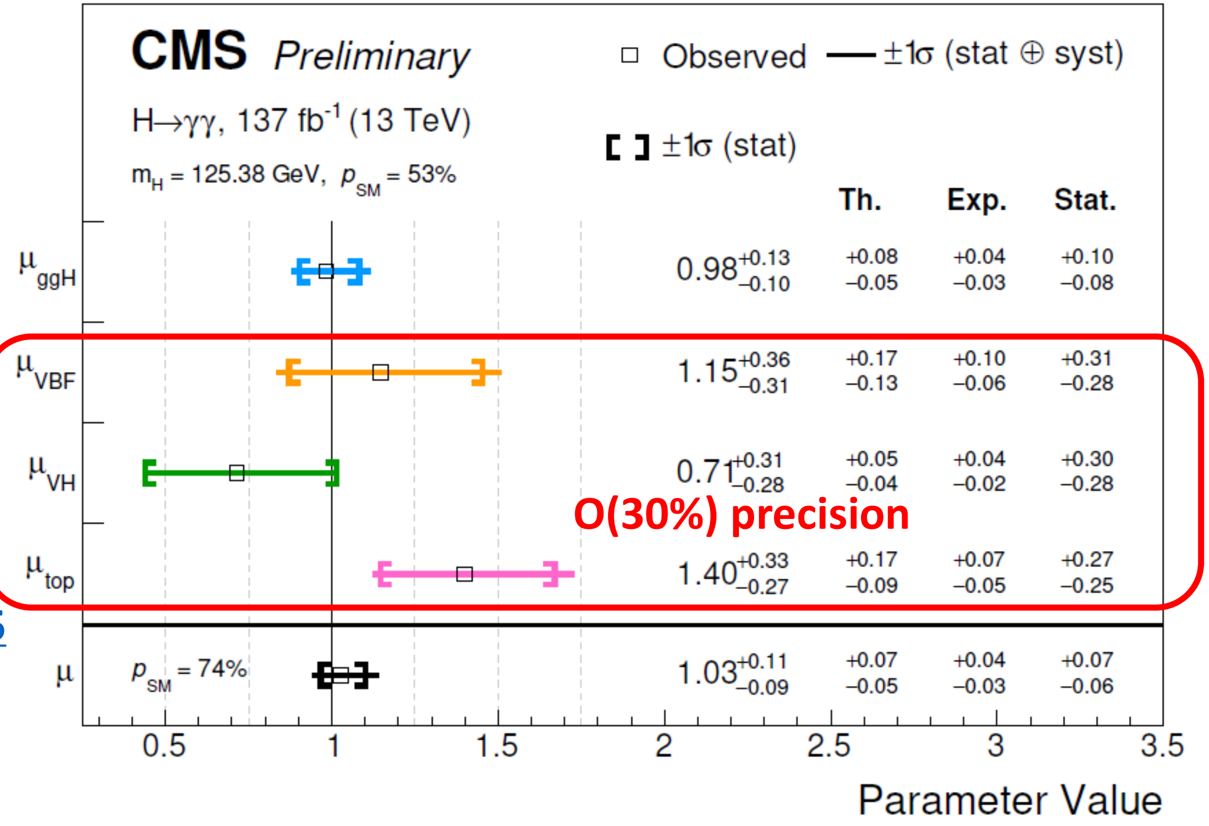
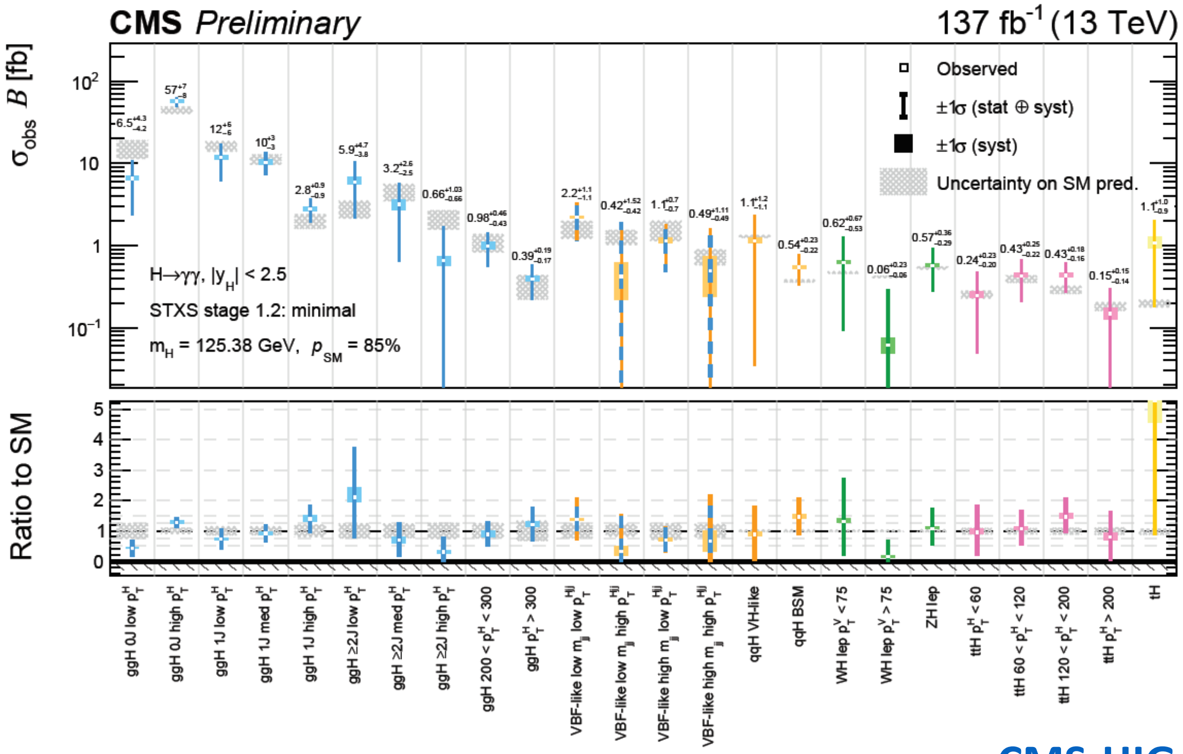
μ per production mode



STXS results with full Run2

➢ minimal merging scheme :

- ✓ STXS bins merge **as few STXS bins as possible** to satisfy **correlations** between bins $\lesssim$ **0.75**
- ✓ **24** parameters of interest

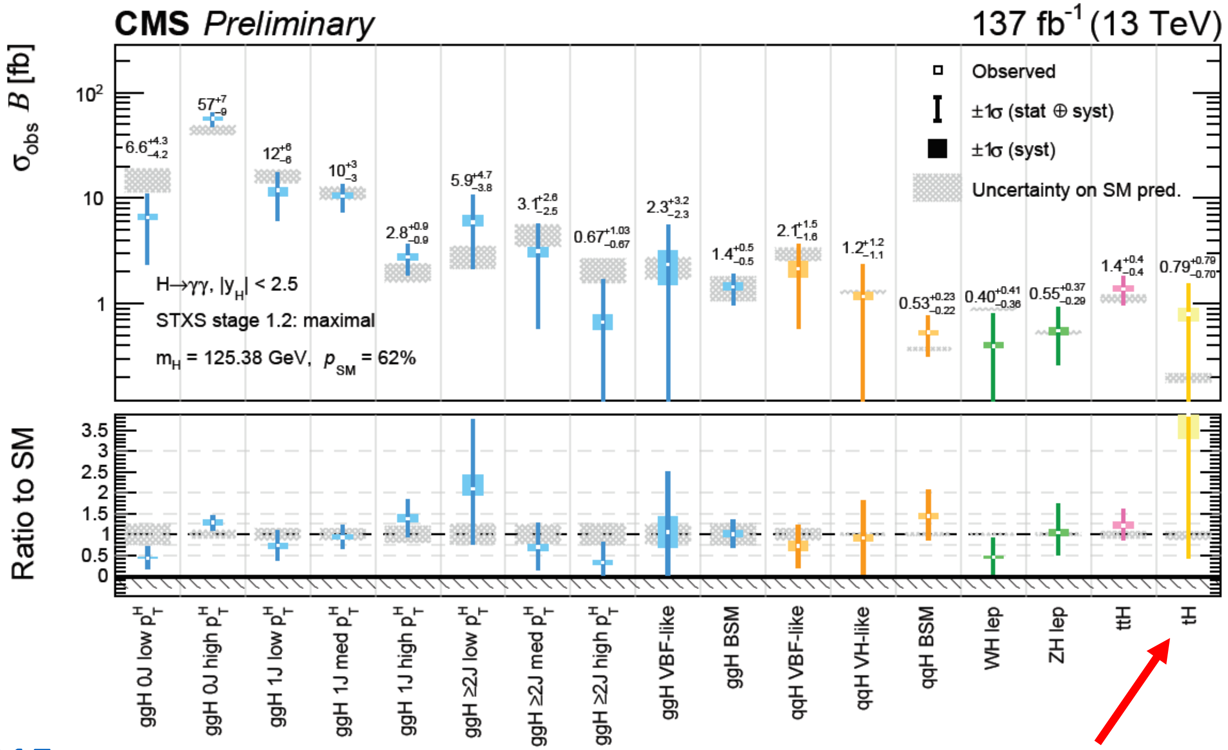


Measured XS in each bin is compatible with SM within ~1σ of the uncertainties

[CMS-HIG-19-015](CMS-HIG-19-015)

➢ maximal merging scheme

- ✓ STXS bins **merged until expected uncertainty is <150%** of SM prediction
- ✓ **17** parameters of interest



- ◆ observed (expected) limit on **tH production** at 95% CL: **12**(9) times SM prediction
- ◆ σ(tH)* BR(H→γγ): $0.8^{+0.8}_{-0.7}$ fb

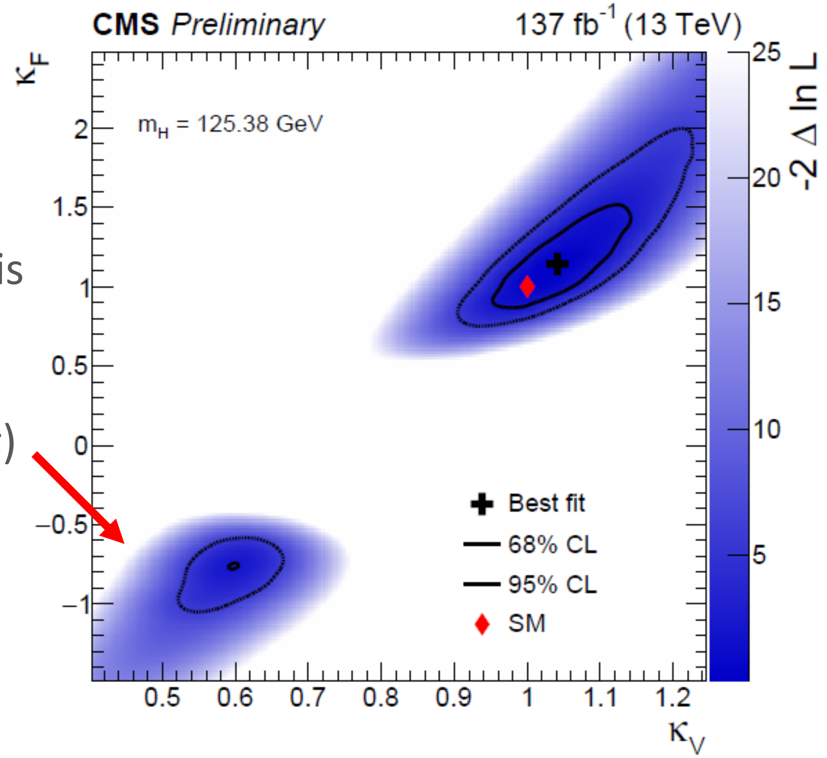
Coupling modifiers with full Run2

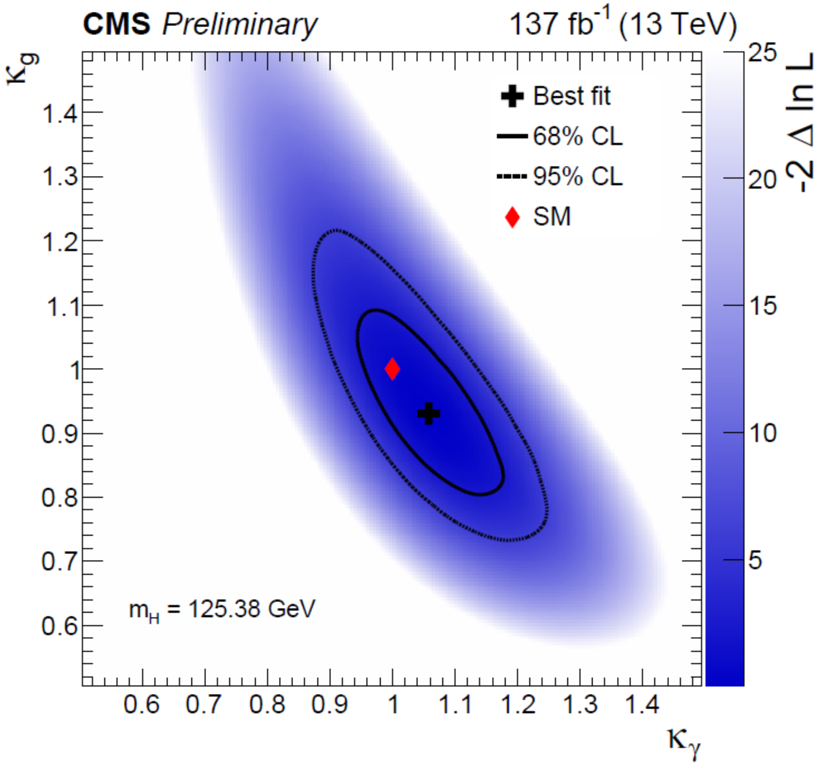
"κ framework" : measurements of **coupling modifiers** to **vector bosons** and **fermions** **(κ_V, κ_f)** and to **photons** and **gluons** **(κ_γ, κ_g)**

Compatible with SM

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

Region with **negative κ_f** is observed (expected) to be **excluded** with a significance of **1.0σ**(2.3σ)





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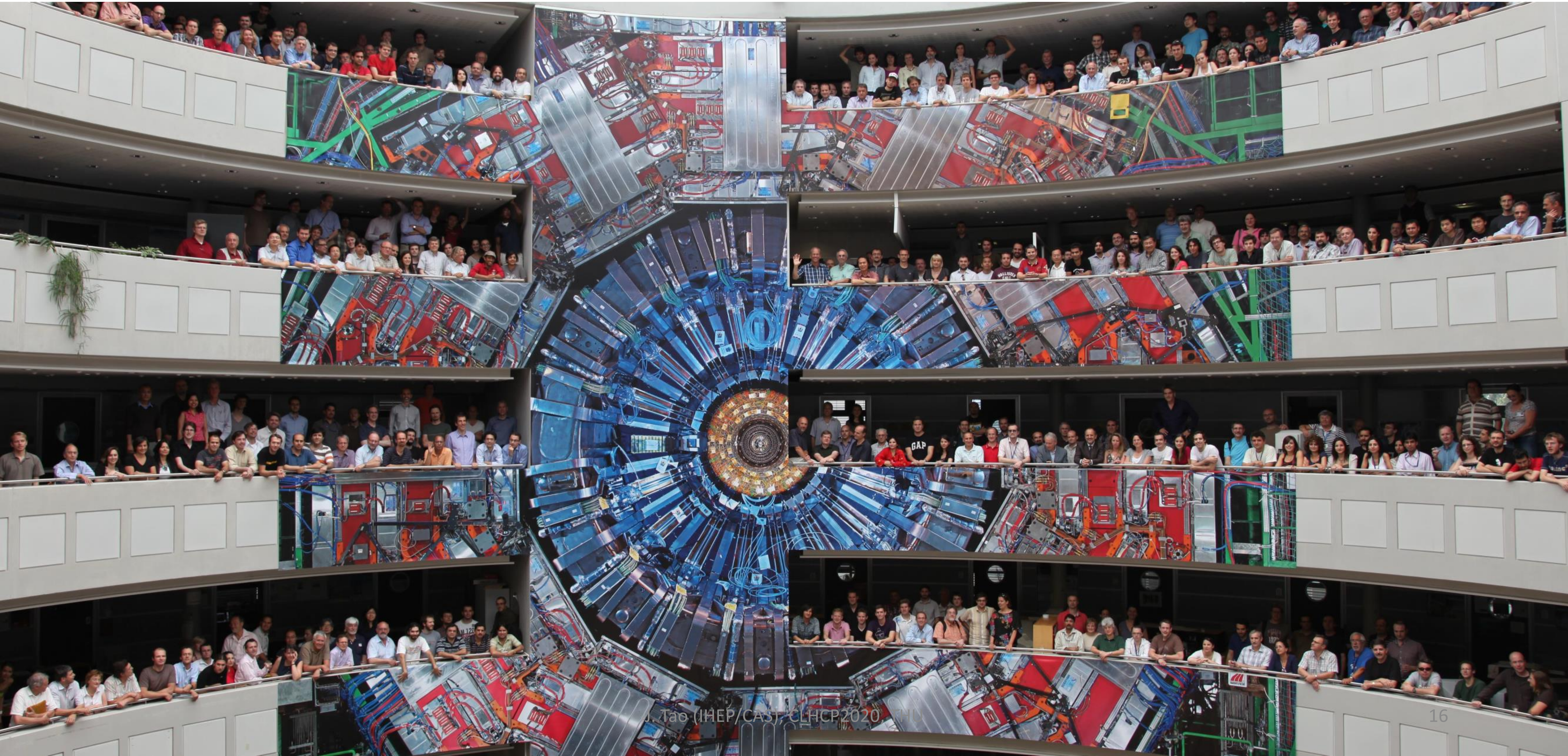
unresolved κ model : effective scaling factors of the ggH and H→γγ loops

Summary

- **Higgs mass measured from $H\to\gamma\gamma$ with 2016 legacy data, and combinations** with 2016 $H\to ZZ^* \to 4l$ and Run-1 results
  - ✓ **best precision result (~0.11%) of Higgs boson mass**
- **ttH, $H\to\gamma\gamma$ measurements with full Run2 data**
  - ✓ **first observation (6.6σ) from a single decay channel**
- **Signal strength and STXS with full Run2 data**
  - ✓ **Overall signal strength ~10% precision**
  - ✓ **All STXS and coupling modifier results are compatible with SM**
- Higgs properties with **$H\to\gamma\gamma$** are being updated with **full Run-2 Ultra-legacy data: Stay Tuned!**

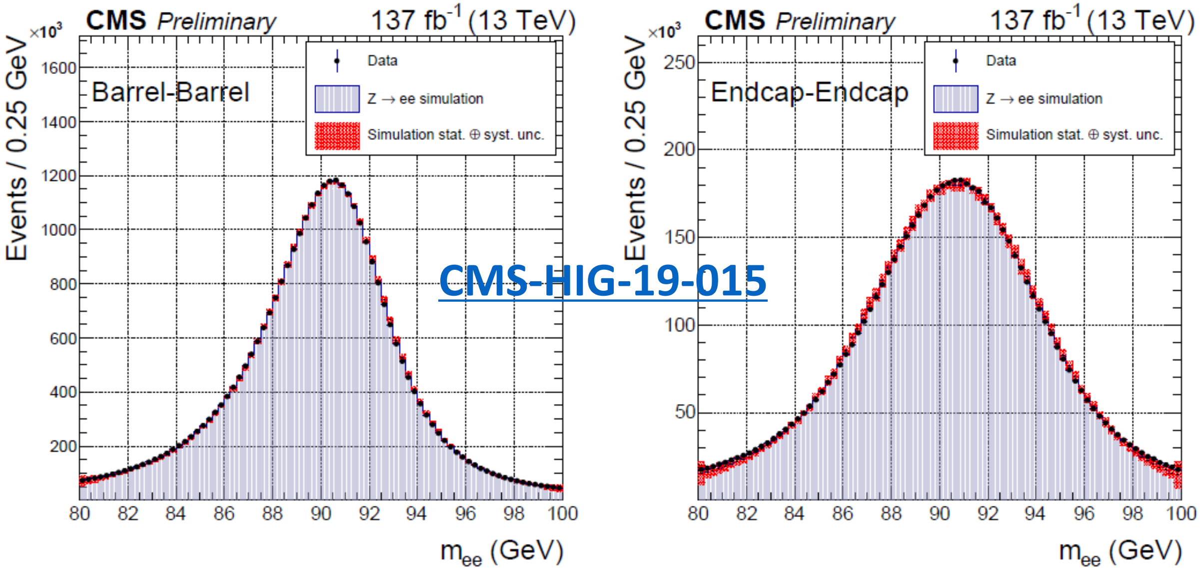
Thanks for your attention!



Backup slides

Photon energy

- Correct photon energy with a **multivariate regression technique** to account for reconstruction effect
  - ✓ Also predicts its uncertainty
- Use **Z→ee events to derive** additional corrections (with electrons reconstructed as photons)
  - ✓ To correct drift of energy scale in data over time as a function of LHC fill
  - ✓ To correct energy scale (resolution) in data (simulation)
    -> By aligning dielectron mass distribution between data and simulation
- Use **Z→μμγ FSR photons to validate** energy scale (resolution) in data (simulation) (CMS-EGM-17-001)



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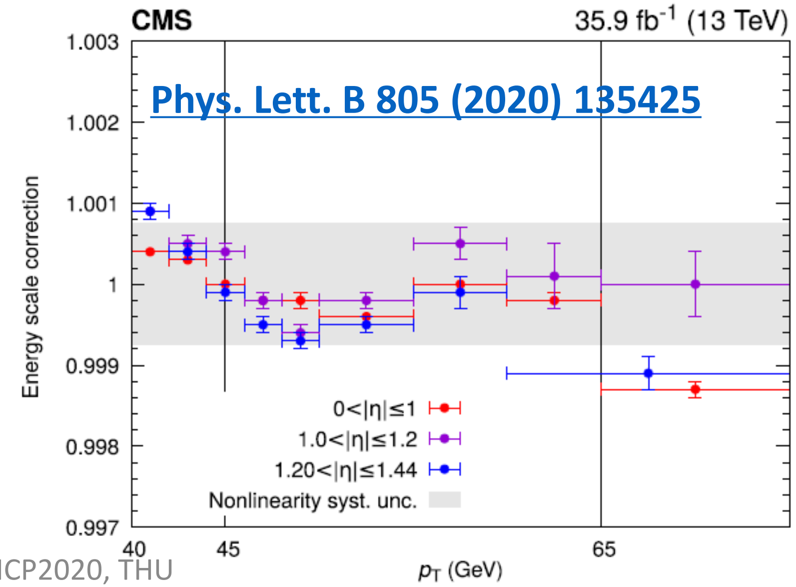
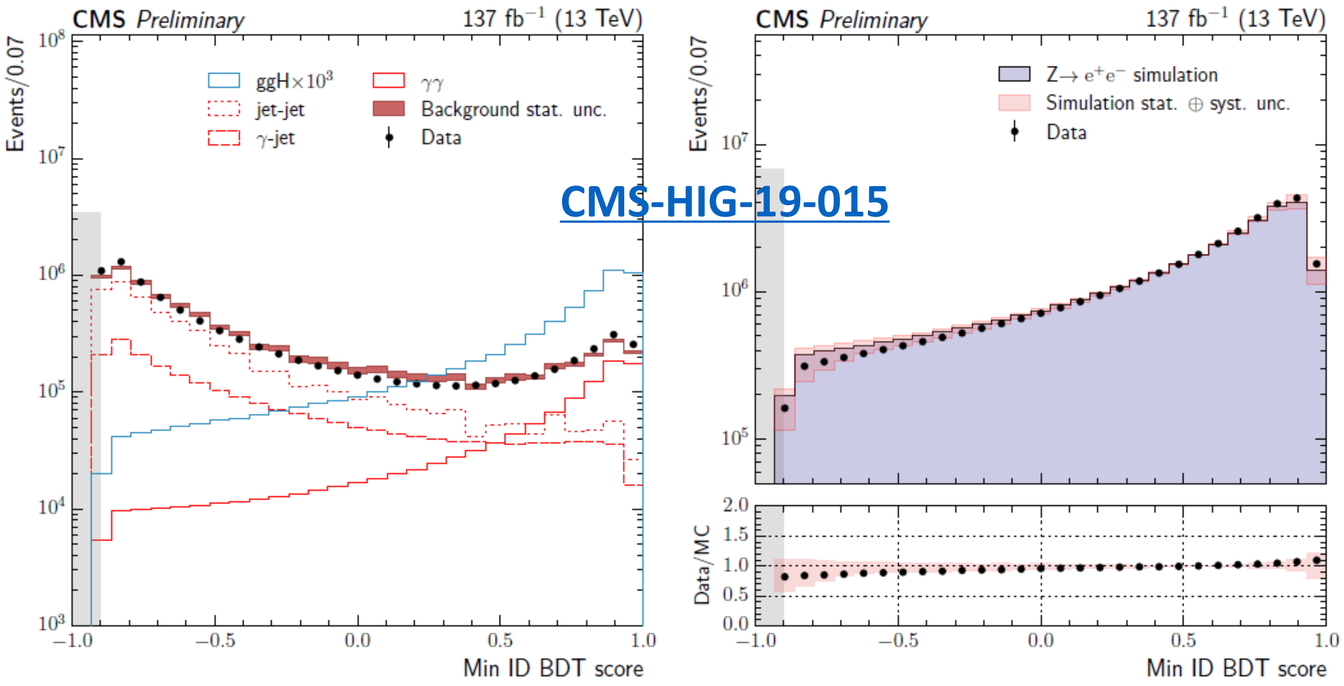


Phys. Lett. B 805 (2020) 135425

Energy scale corrections as a function of the *p*T of the photon [2016 legacy data]

Photon identification

- Use **a ID BDT** to separate genuine photons from jets mimicking a photon
- Trained on **γ+jet simulation**, input variables include:
  - ✓ Shower shape/isolation variables, photon energy and η, variables sensitive to pileup
- Use a chained quantile regression method with electrons from Z → ee, to **correct shower shape and isolation variable's distributions** in simulation to agree with data
- Use **electrons from Z → ee data/MC** and **FSR photons from Z→μμγ data/MC** to validate the inputs and output of photon ID BDT



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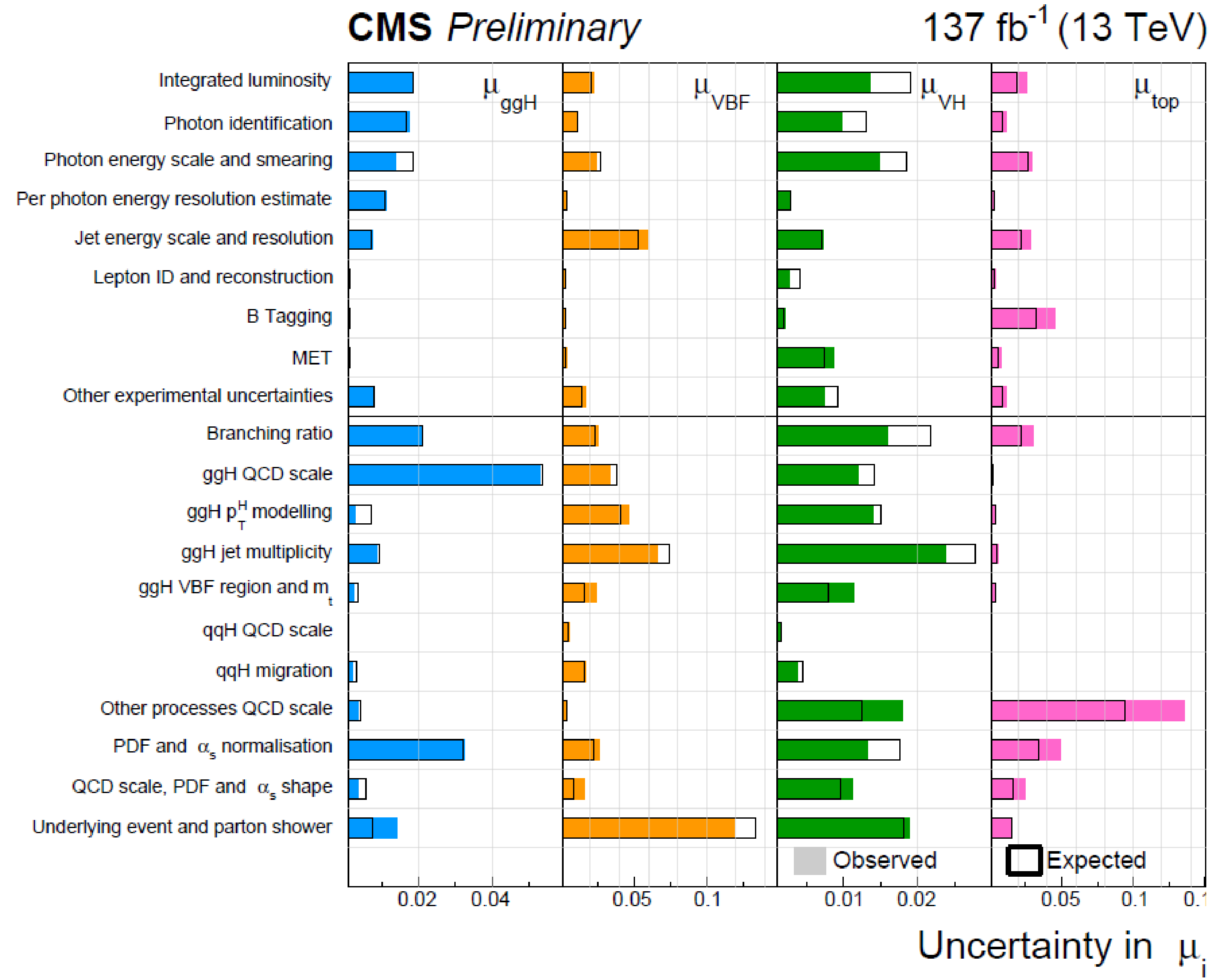
- After a **looser cut on photon ID BDT (>-0.9),** the scores of two photon are **used as one of the input of diphoton BDT** used for untagged event (mainly from ggH production) categorization

Uncertainties on signal strength



Uncertainties per production mode

[CMS-HIG-19-015]