Measurements of Higgs boson properties and search for new resonances in $\gamma\gamma$ final state at CMS

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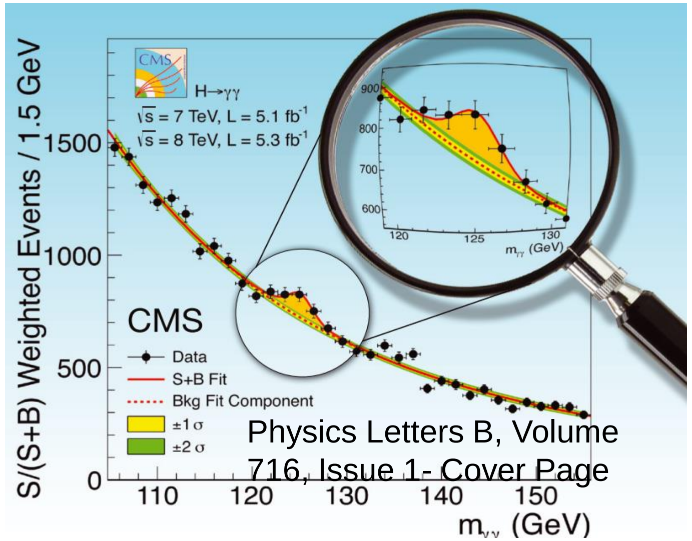
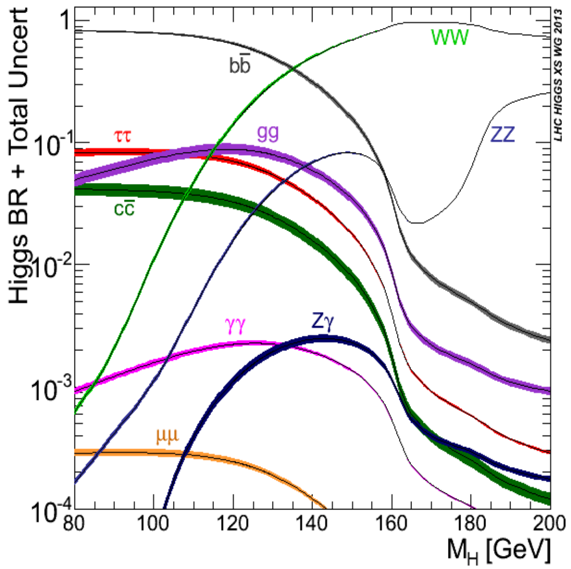
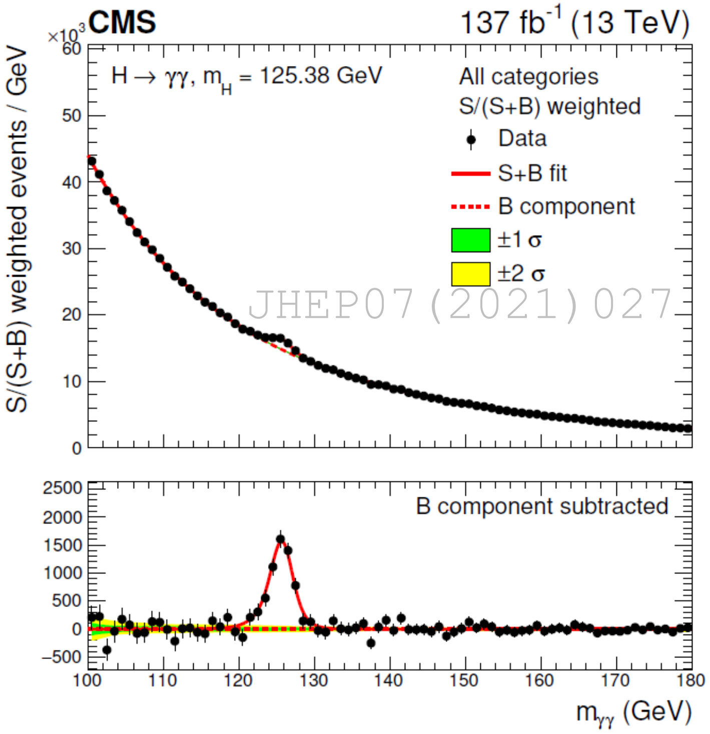
Introduction

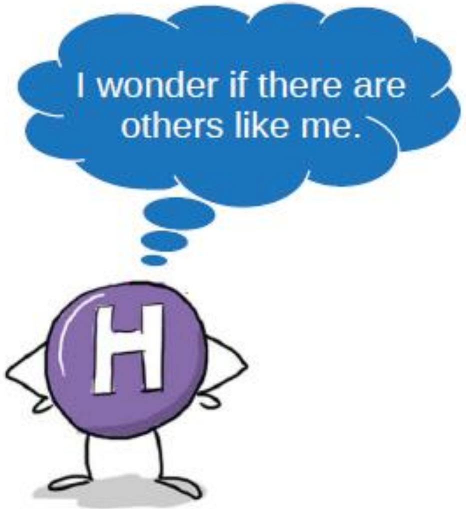
- **$H\to\gamma\gamma$** is one of the most important channels for the **discovery of Higgs boson** and **measurements of its properties**
  - ✓ Small branching fraction (~0.23%) and large bkg, clean final state **fully reconstructed** with high energy resolution and **$m_{\gamma\gamma}$ resolution (1-2%)**





- γγ final state also important for **additional resonances searches**
  - ✓ Direct search for **$X\to\gamma\gamma$** (high mass, **low mass**)
  - ✓ **Exotic decays** of Higgs boson with the new scalar (a/A) decaying into diphoton ($H\to aa\to\gamma\gamma\gamma\gamma$, **$H\to Za\to ll\gamma\gamma$**)
  - ✓ **Multi-Higgs resonances**: **X→HH/HY** with one H/Y decaying into **γγ** (see Zhenxuan's talk)





Selected results in this talk

Analysis Strategy

Samples (data, MC) → **Data events passing (diphoton) HLT-paths**

For example in 125 GeV H→γγ analyses

HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90 (2016)

HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90 (2017 and 2018).

HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90 (2022)

Trigger efficiency is measured from Z →ee events using the tag-and-probe technique (JHEP 10 (2011) 132)

For example in (very) low-mass BSM H→γγ analyses

HLT_Diphoton30EB_18EB_R9Id_OR_IsoCaloId_AND_HE_R9Id_DoublePixelVeto_Mass55_v
HLT_Diphoton30PV_18PV_R9Id_AND_IsoCaloId_AND_HE_R9Id_DoublePixelVeto_Mass55 (2016)

HLT_Diphoton30PV_18PV_R9Id_AND_IsoCaloId_AND_HE_R9Id_PixelVeto_Mass55 (2017)

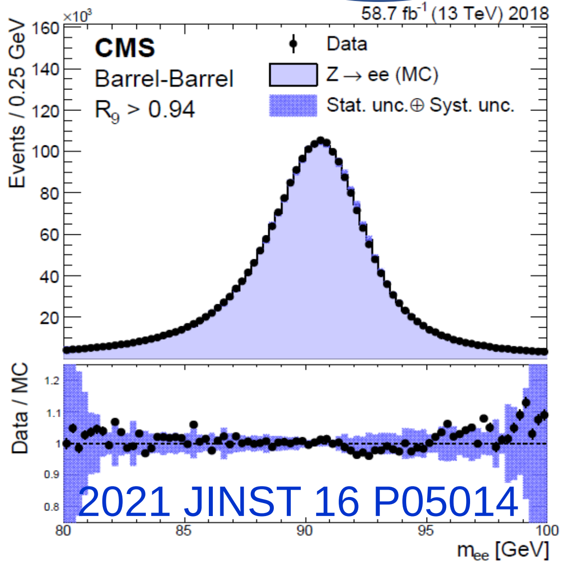
HLT_Diphoton30_18_R9IdL_AND_HE_AN_IsoCaloId_NoPixelVeto (2018, 2022)

Analysis Strategy

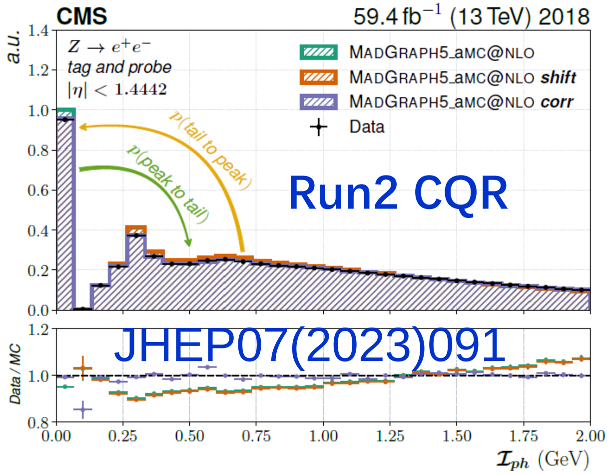
Samples (data, MC) → **Data events passing (diphoton) HLT-paths** → **Preselection to mimic HLT, photon ID MVA cut (>-0.9) , electron-veto, photon $p_T/M_{\gamma\gamma}$ …**

Per object strategy

Energy Scale and Resolution Corrections, corrections on MC simulated photon shower shapes and isolations



Energy scaling and smearing: using Z→ ee events with electrons reconstructed as photons



MC corrections

Run2: ***Chained Quantile Regression*** (arXiv:1211.6581, extremely complicated and time-consuming)

Run3: ***Normalizing flow*** (arXiv:2403.18582)

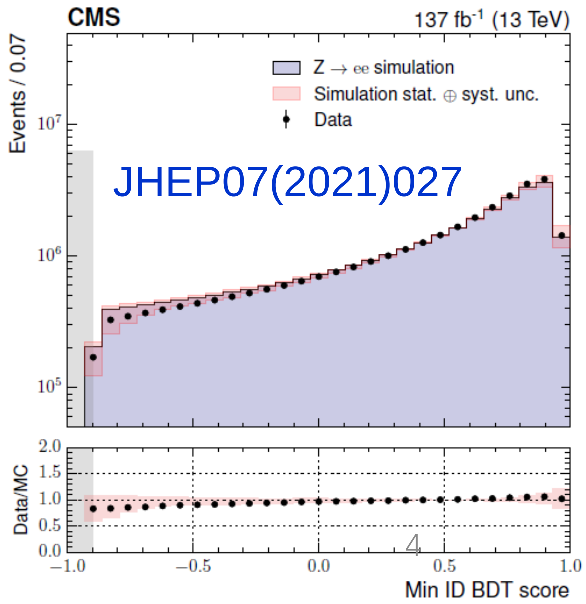
Photon ID MVA trained to distinguish prompt photons from jets

Validated on Z→ee and Z→μμγ

A dedicated Vertex ID MVA to select the primary vertex (Run2)

Validated on $Z\to\mu\mu$ events, by refitting vertices ignoring the muon tracks

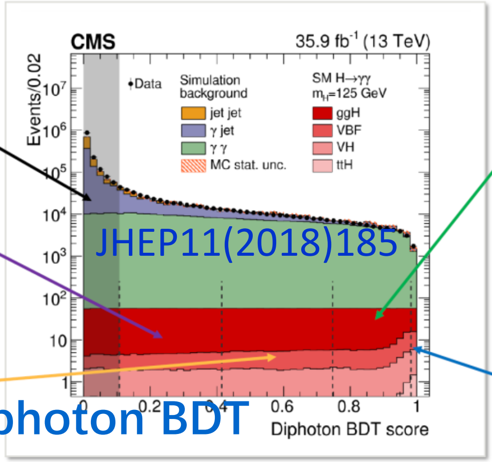
Run 3: "0th vertex" corresponding to the hardest scattering in the event, evaluated using tracks



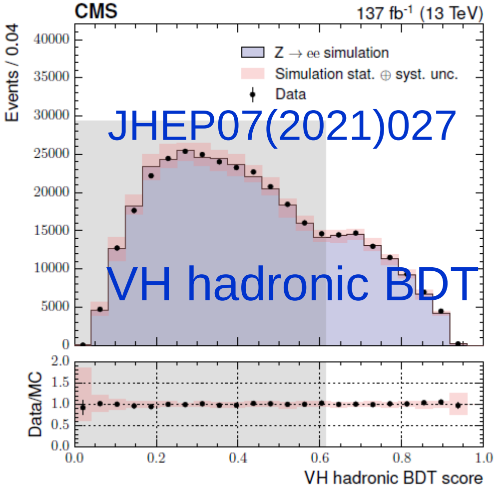
Analysis Strategy

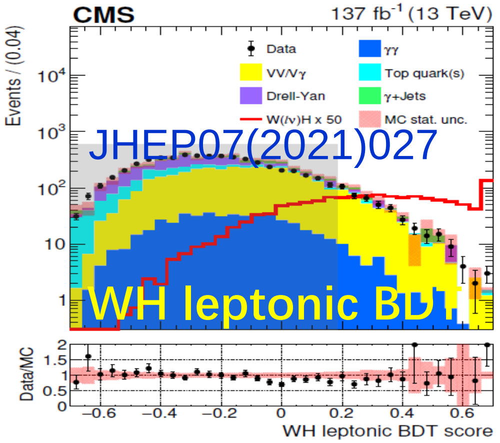
Samples (data, MC) → **Data events passing (diphoton) HLT-paths** → **Preselection to mimic HLT, photon ID MVA cut (>-0.9), electron-veto, photon $p_T/M_{\gamma\gamma}$ …**

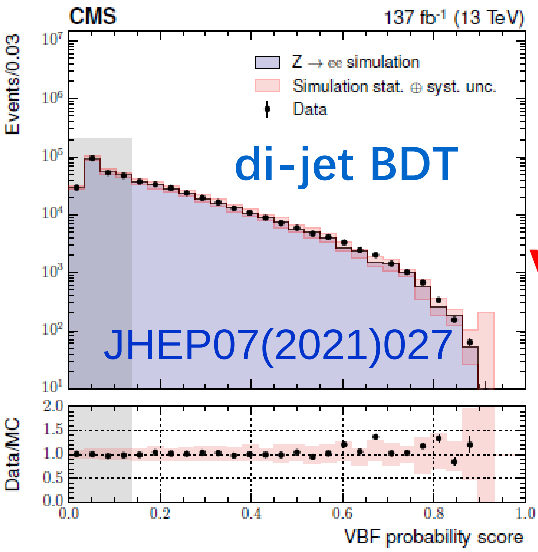
Event categorization on production modes, mass resolution and S/B to improve the analysis sensitivity

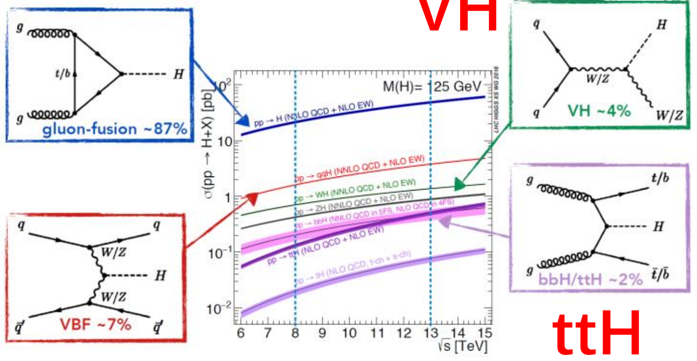


ggH

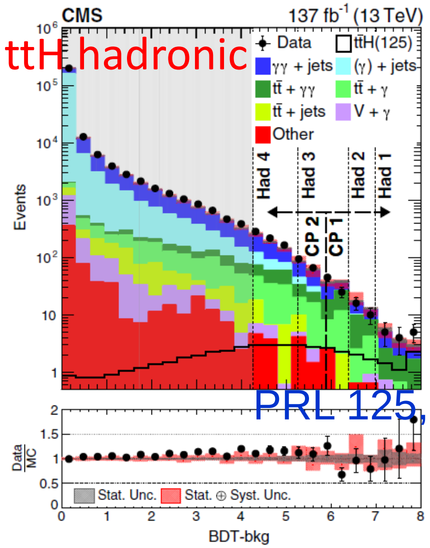


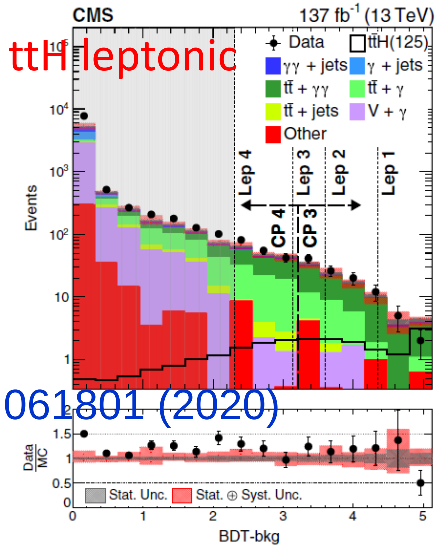






2D: di-jet BDT and diphoton BDT
Or combine BDT (HIG-16-040, LM HIG-20-002)





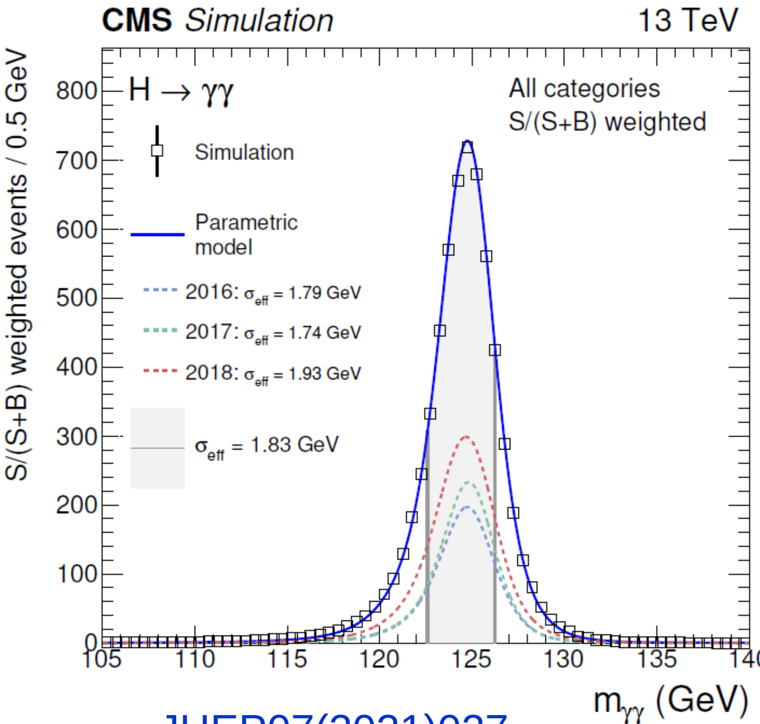
PRL 125, 061801 (2020)

Several different machine learning (ML) algorithms

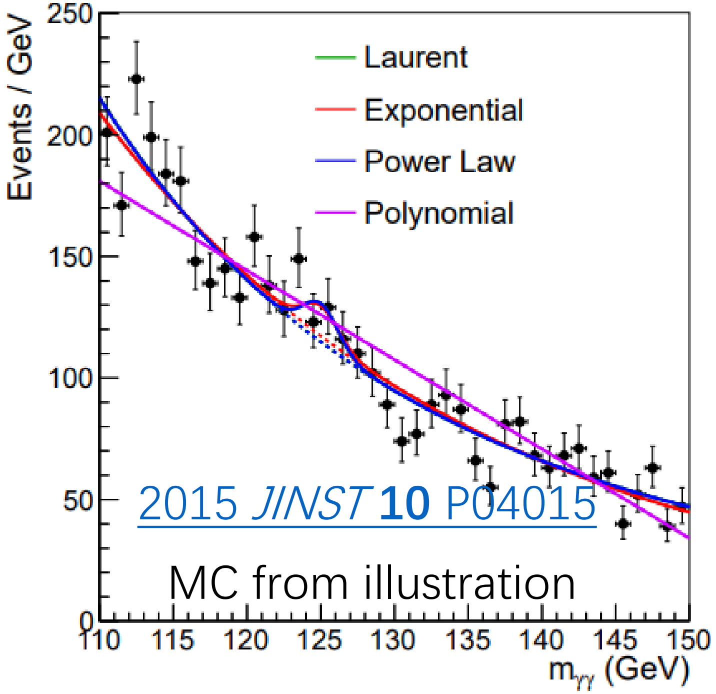
Analysis Strategy

Samples (data, MC) → **Data events passing (diphoton) HLT-paths** → **Preselection to mimic HLT, photon ID MVA cut (>-0.9) , electron-veto, photon $p_T/M_{\gamma\gamma}$ …** → **Event categorization** on **production modes**, **mass resolution** and **S/B** to improve the analysis sensitivity → Sig and bkg modeling based on $m_{\gamma\gamma}$

Signal model derived from MC simulation, with corrections (trigger eff, data/SFs, …)



JHEP07(2021)027



2015 *JINST* **10** P04015

MC from illustration

Background model derived from data, using the envelope method (discrete profiling method, 2015 *JINST* **10** P04015)

Analysis Strategy

Samples (data, MC)

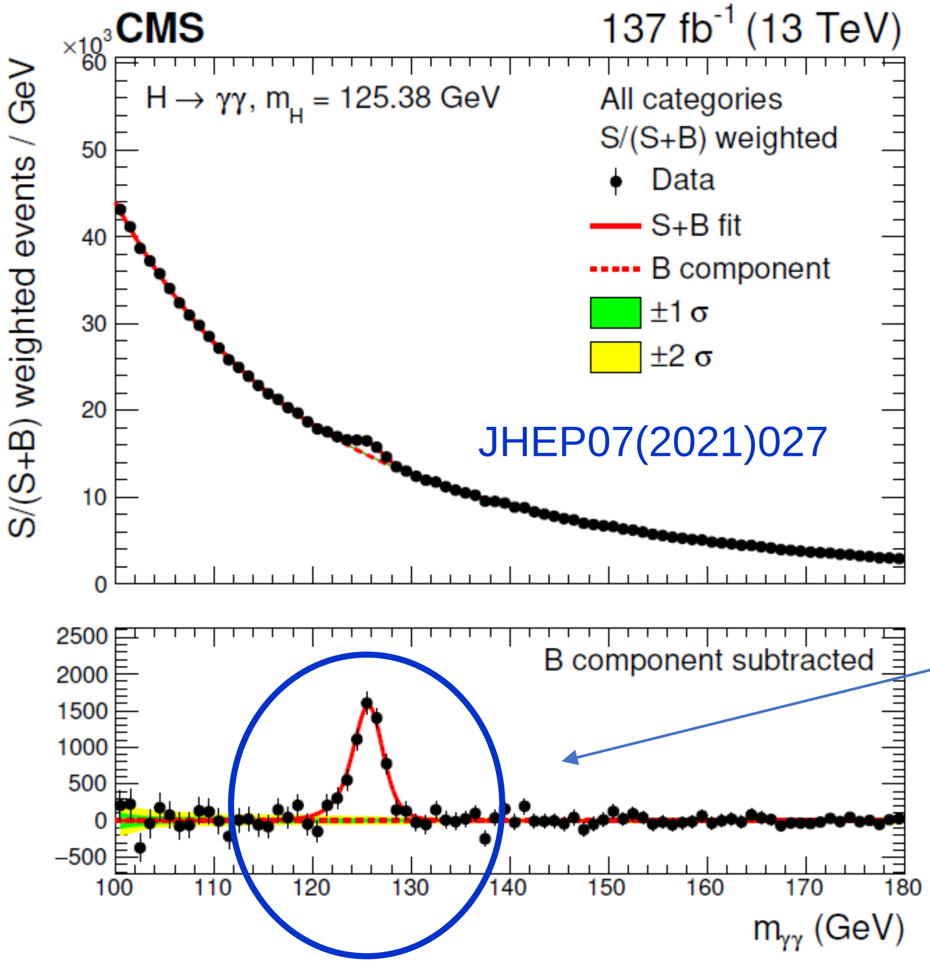
Data events passing (diphoton) HLT-paths

Preselection to mimic HLT, photon ID MVA cut (>-0.9) , electron-veto, photon $p_T/M_{\gamma\gamma}$ …

Event categorization on **production modes**, **mass resolution** and **S/B** to improve the analysis sensitivity

Sig and bkg modeling based on $m_{\gamma\gamma}$

Results



***Signal is extracted** by a simultaneous maximum-likelihood fit to the **diphoton mass** in all event classes*

125 GeV Higgs boson: mass, signal strength, cross sections (inclusive, differential, STXS), couplings and anomalous couplings, CP,⋯

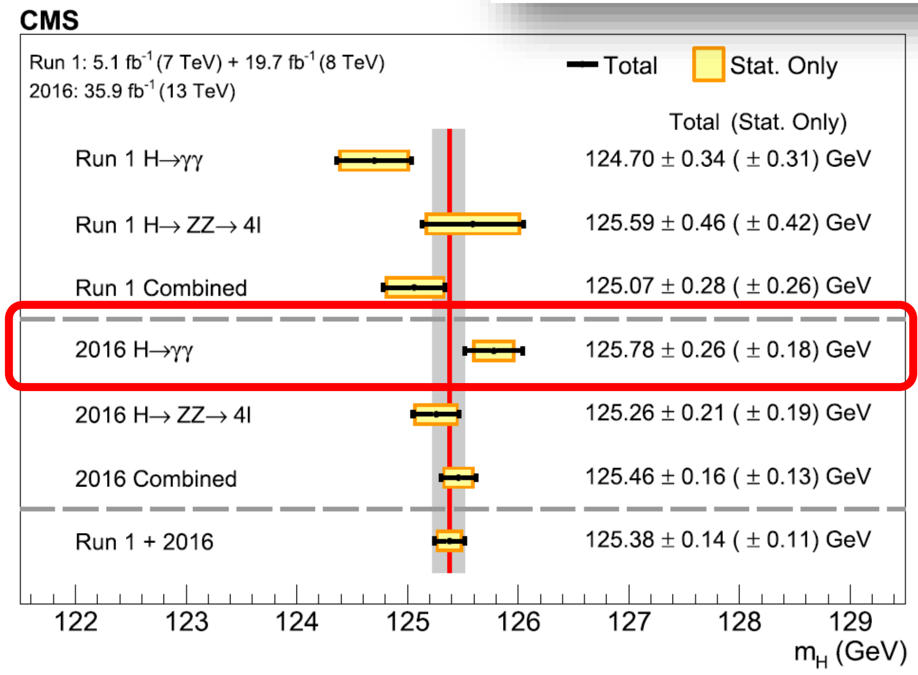
BSM Higgs: upper limits and significances

H→γγ : mass

- Measurement with 2016 data: 4 untagged event classes + 3 VBF classes (see details in Chenguang's talk)

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

Precision at per-mille level



The observed impact of the different uncertainties on the measurement of m_{H}.

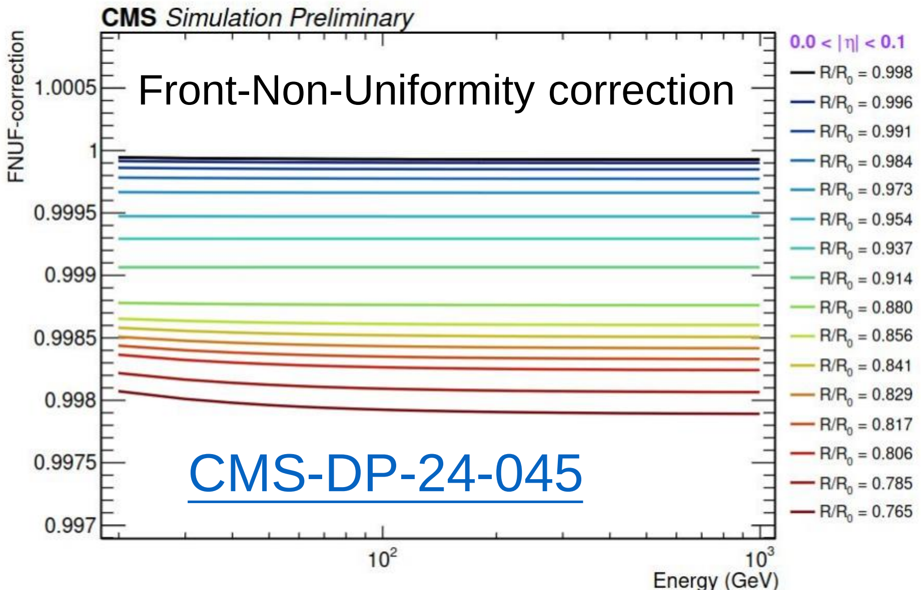
Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_{T} dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

Phys. Lett. B 805 (2020) 135425

Large uncertainty from the **non-uniformity of the light collection** along the length of the ECAL crystals

- In view of **full Run 2** analysis **this effect is corrected: significantly reduced uncertainty**, full Run2 measurement in progress

New for full Run2



CMS-DP-24-045

H→γγ fiducial cross sections

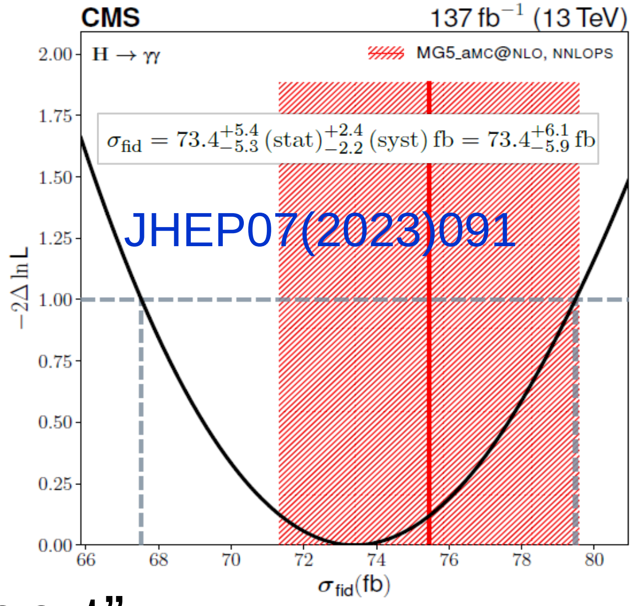
- Fiducial cross sections aim at providing a set of **model independent** results
- **CMS** released the its **first Run3 H→γγ measurements for ICHEP2024** with 2022 data (details in Chengyang's talk)
- **Fiducial volume (Run2)**

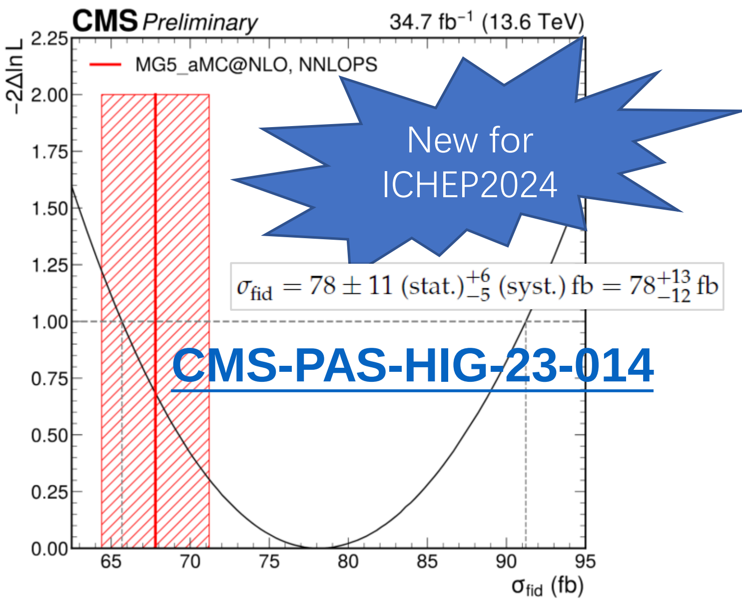
Observable	Selection
$p_T^{\gamma_1}/m_{\gamma\gamma}$	$>1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma}$	$>1/4$
$\mathcal{I}_{\text{gen}}^{\gamma}$	<10 GeV
$\lvert\eta^{\gamma}\rvert$	<2.5

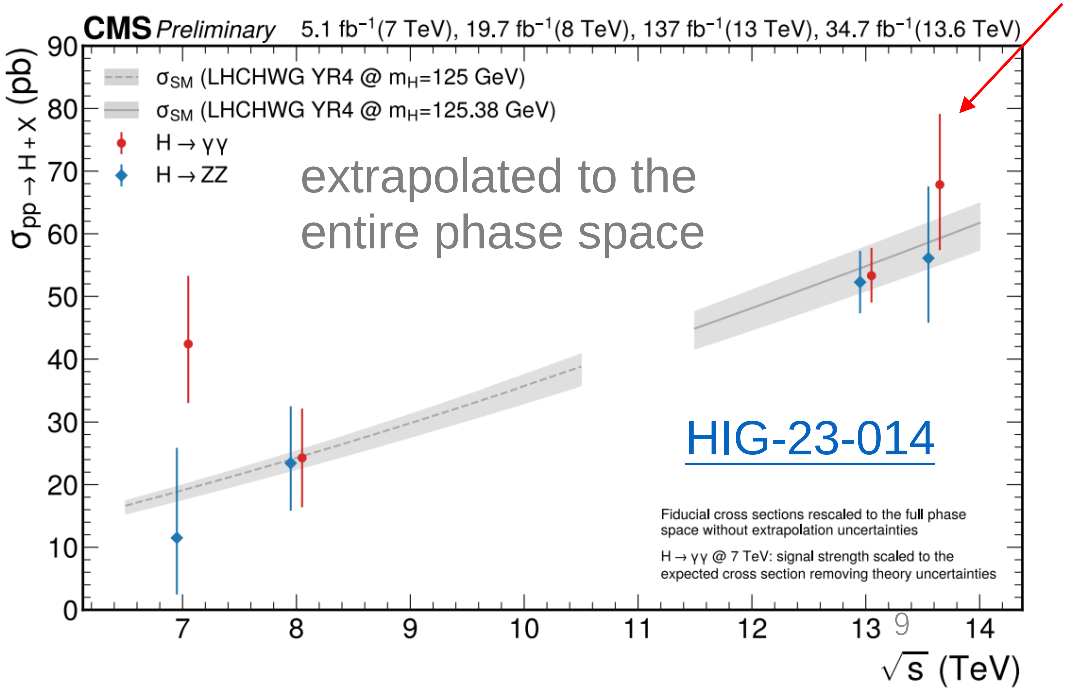
Run3 "geometric cut"

$$\sqrt{p_T^{\gamma_1} p_T^{\gamma_2}}/m_{\gamma\gamma} > 1/3$$

to improve perturbative convergence in the fiducial phase space [JHEP11(2021)220]







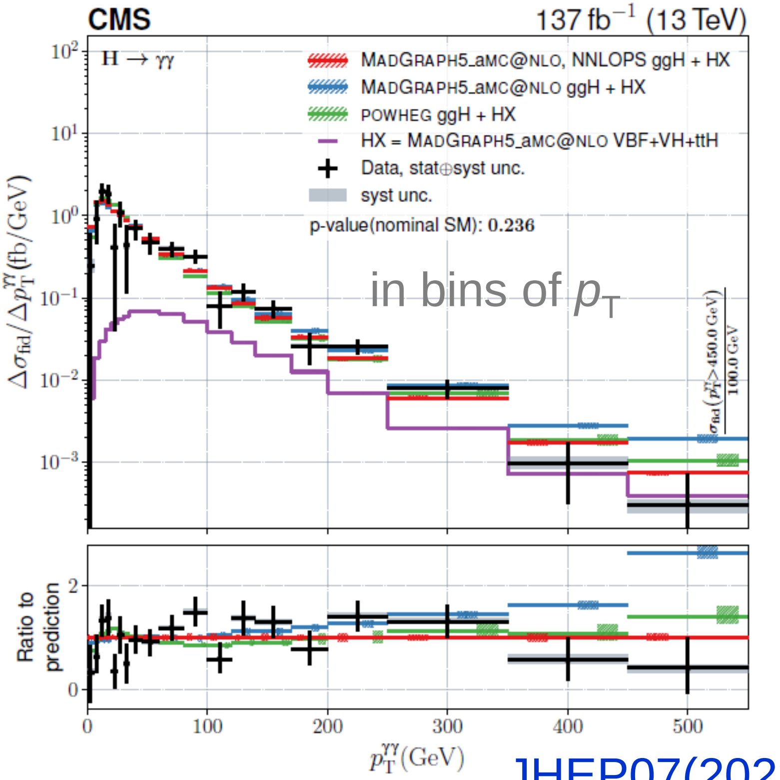
in agreement with the SM predictions

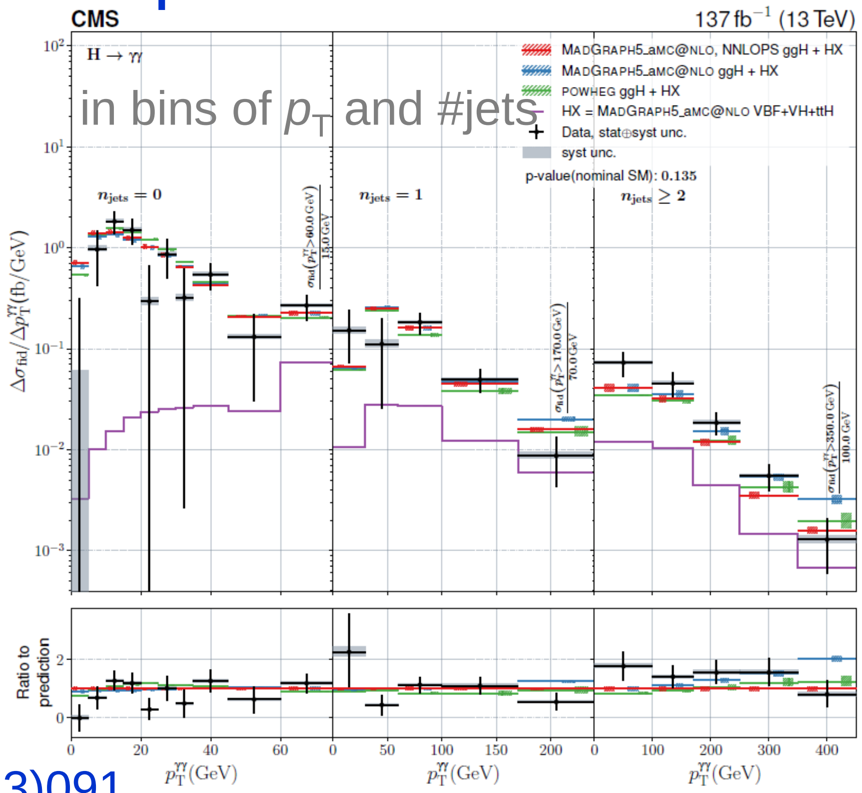
H→γγ differential fiducial XS

- **Fiducial XS measured as a function of observables**
  - ✓ **Full Run2** (JHEP07(2023)091): **~20 observables** of the diphoton system as well as jets; numbers of jets, leptons, and b-tagged jets; **two double-differential** XS measurements
  - ✓ 2022 data (CMS-PAS-HIG-23-014): **3 differential observables** Higgs p_T and |y|, N_{jet}

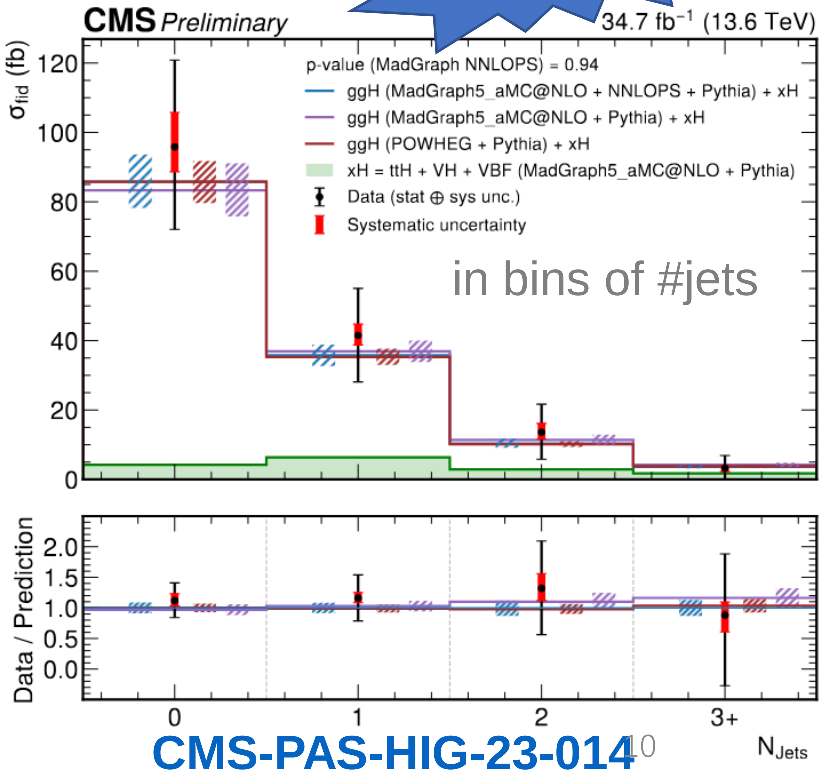
New for ICHEP2024

In agreement with the SM prediction within the uncertainties





JHEP07(2023)091



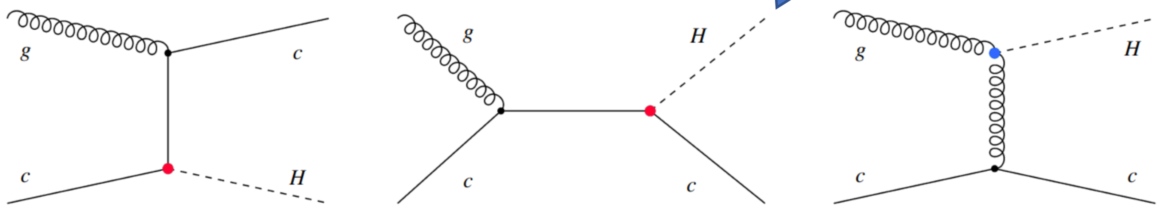
CMS-PAS-HIG-23-014

First search for cH, H→γγ

- Provide a unique opportunity **to probe the Higgs boson-charm quark coupling**
- **Two BDT classifiers** to distinguish **cH** and **ggH**, to distinguish **cH** and the **continuous bkg**
- **Upper limits on the cH signal strength < 243 (355) $\times\ \sigma_{SM}$** obs. (exp.) at 95% CL
- **Constraints on H-c quark coupling modifier $|\kappa_c|$ < 38.1** ($|\kappa_c|$< 72.5) obs. (exp.) at 95% CL

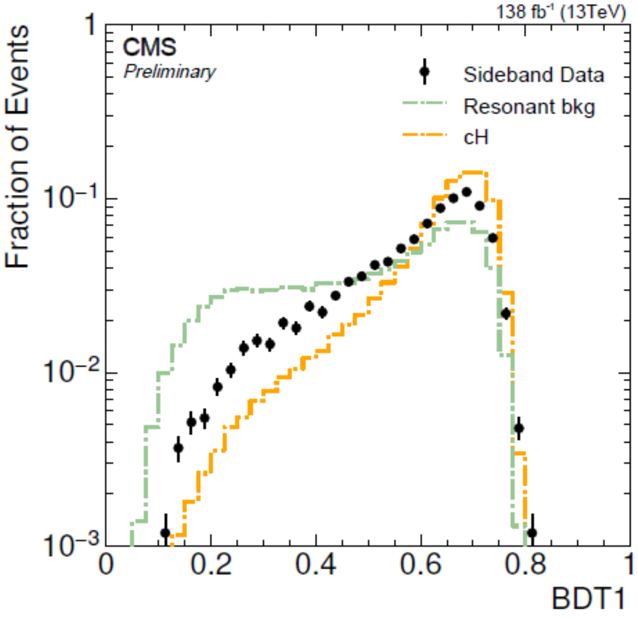
CMS-PAS-HIG-23-010

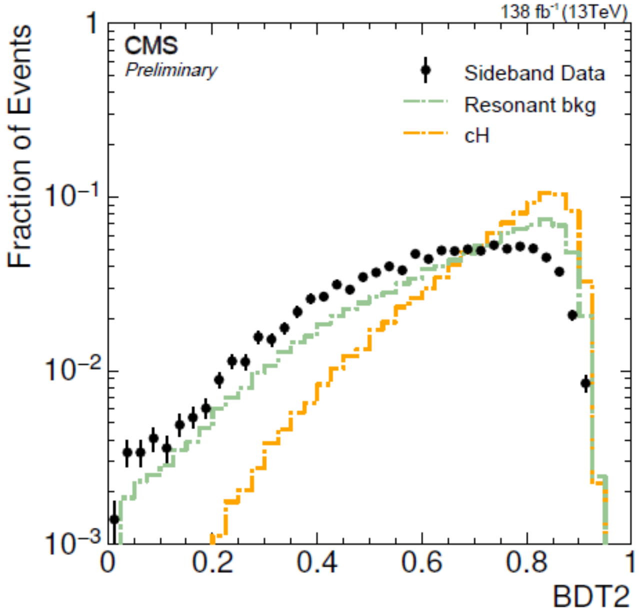
New for ICHEP2024

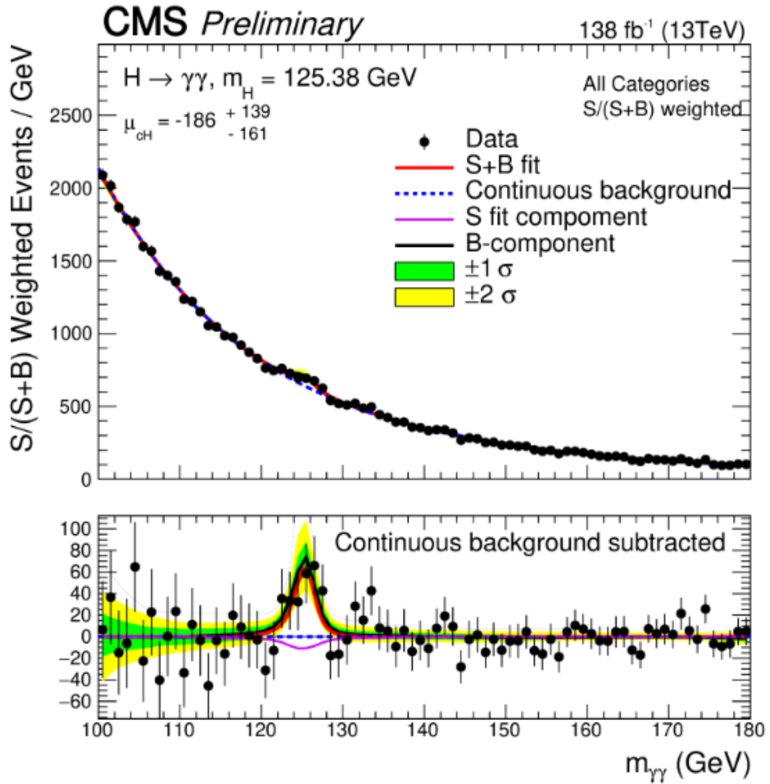


c-tagging (CvsL score>0.25)

Tagger	CvsL
DeepJet	$\frac{P(c)}{P(c)+P(uds)+P(g)}$







Dominated by the statistical uncertainty of data, sub-dominated by theoretical uncertainties on cH signal and resonant bkg

BSM: low-mass H→γγ

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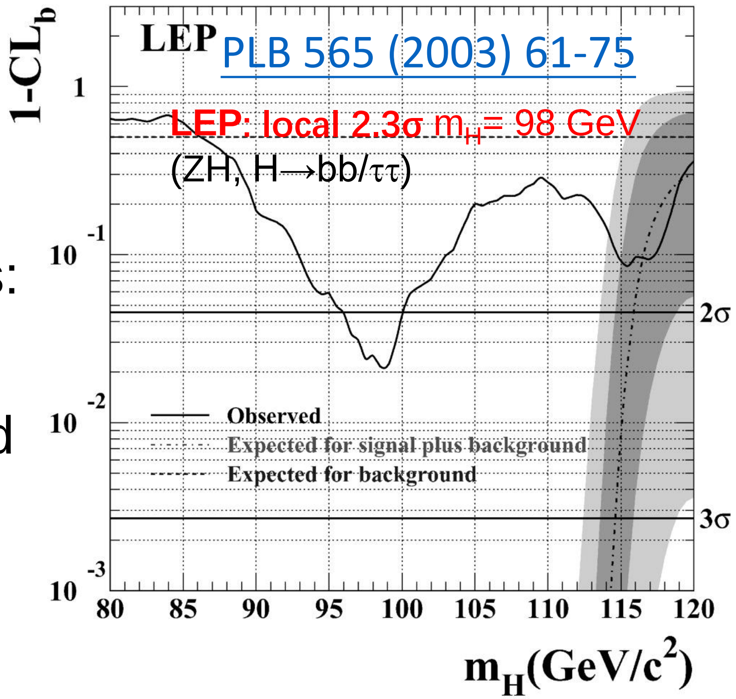
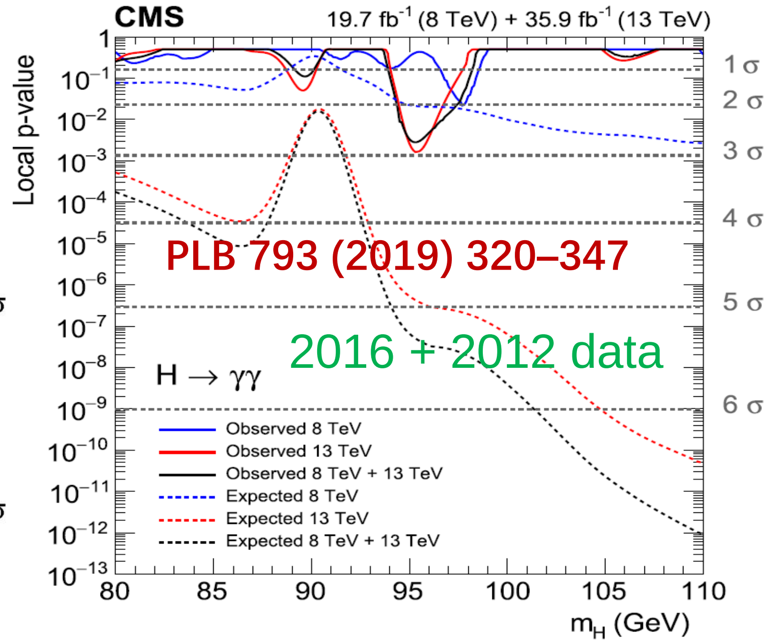
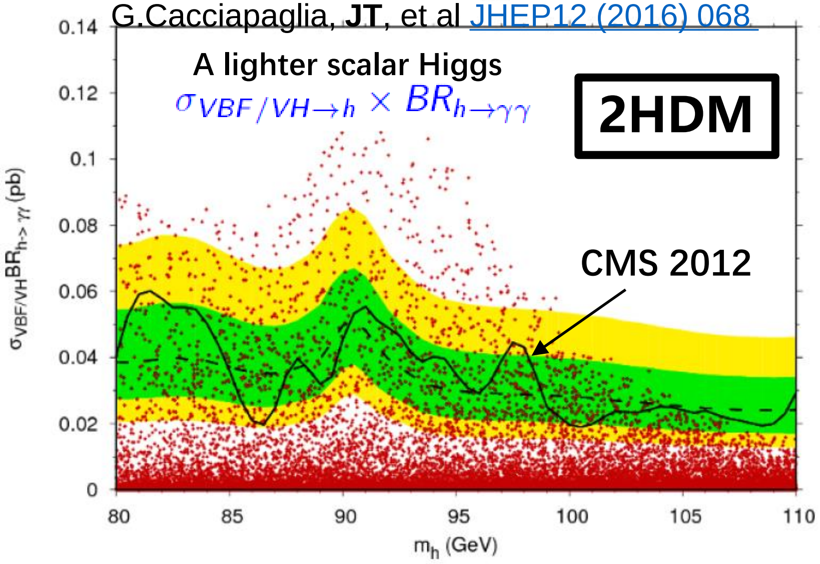
- Many BSM models (e.g. 2HDM, NMSSM) predict additional Higgs bosons, Some of which could have masses < 125 GeV
- Final LEP SM Higgs boson search results: 2.3σ local excess at m_H = 98 GeV
- Discovery of **extra Higgs boson(s)** would be an unequivocal sign of new physics





- We have **performed the LM h→γγ search since Run1 at CMS**
  - ✓ 2012 data (**HIG-14-037**, PAS only) : ~2σ local at 97.5 GeV
  - ✓ 2016 + 2012 data (**HIG-17-013, PLB 793 (2019) 320–347**)**:** 2.8σ local (1.3σ global) significance at 95.3 GeV
- Performed **interpretations with several BSM**



NMSSM: J. Fan, **JT(*)**, et al., Chin. Phys. C 38 (2013) 073101

2HDM: G.Cacciapaglia, **JT**, et al JHEP12 (2016) 068

NMSSM: **JT** et al., Chin. Phys. C 42 (2018) no.10, 103107

Georgi-Machacek model: C. Wang, **JT(*)** et al., Chin. Phys. C 46 (2022) 8, 083107

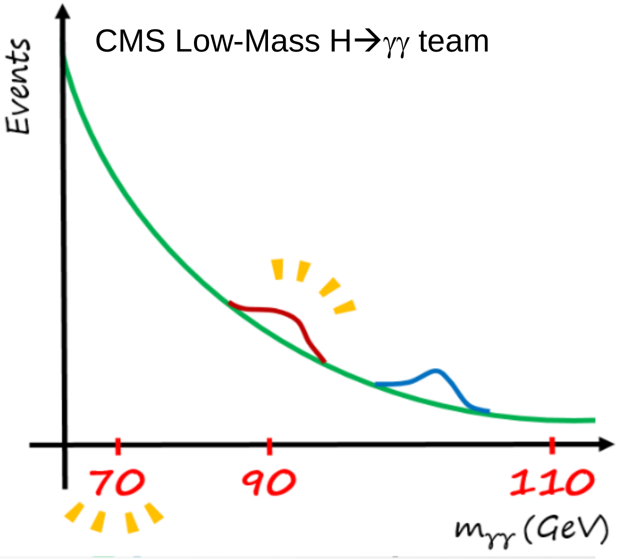
Low-mass H→γγ

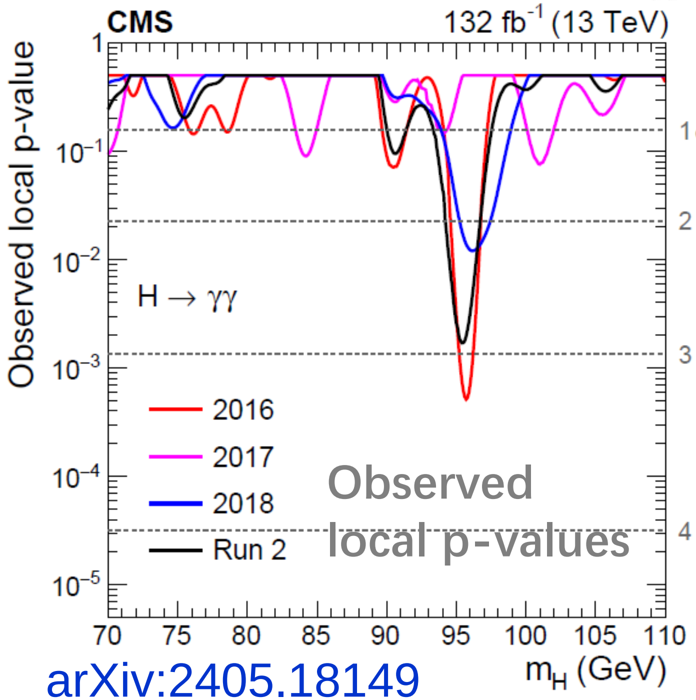
- Analysis strategy is similar as SM **H→γγ** except for **relic Drell-Yan (Z→ee)**, in the diphoton mass spectrum
  - ✓ Dedicated **HLT** paths then event (pre-) **selections**
  - ✓ Dedicated **DY suppression** strategy and modeling (a double-sided Crystal Ball function + an exponential)
  - ✓ **Retrained photon ID MVA** and **diphoton BDT** training, optimization of **event categorization**

- **Modest excess with ~2.9σ local (1.3σ global) significance at $m_{\gamma\gamma}$ = 95.4 GeV**
  - ✓ excess did not grow with luminosity, but remains intriguing

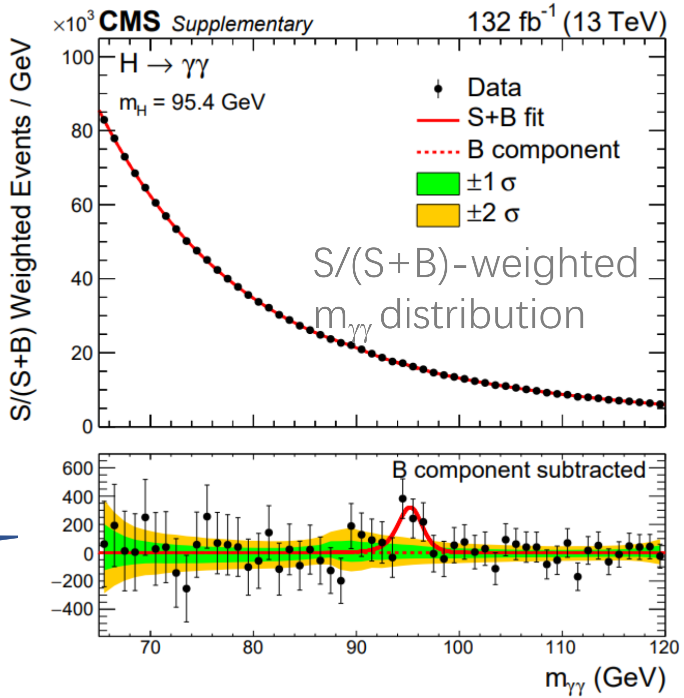
More results and interpretations

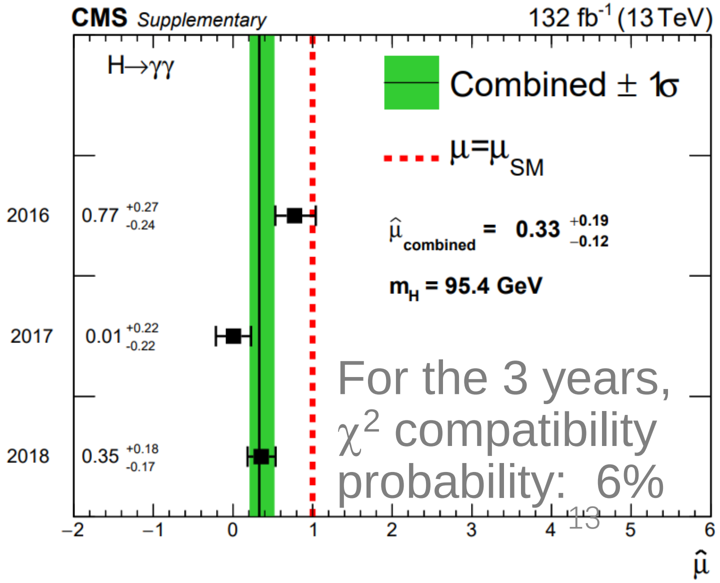
Accepted by Phys. Lett. B (Oct. 2024)





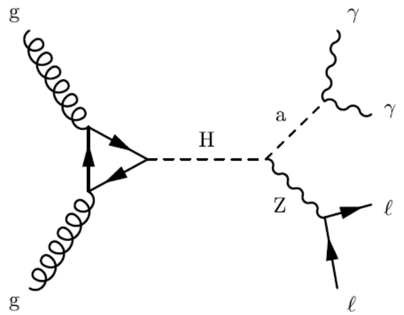
arXiv:2405.18149



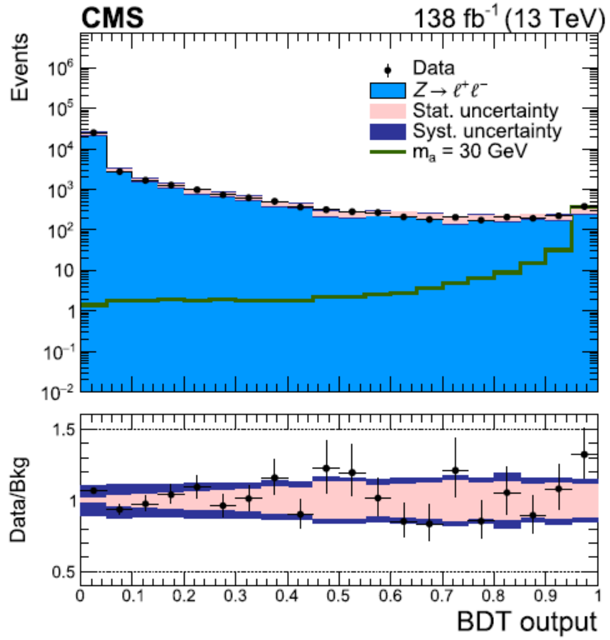


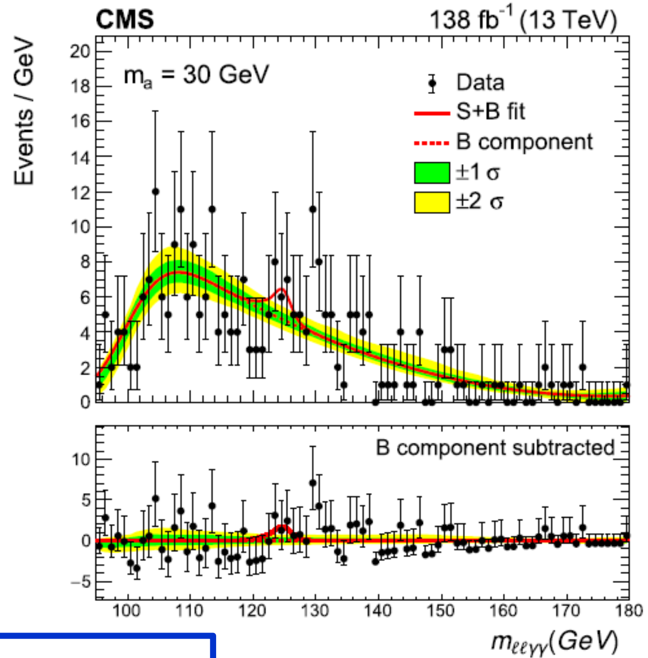
Exotic decays of H: H→Za→ll+γγ

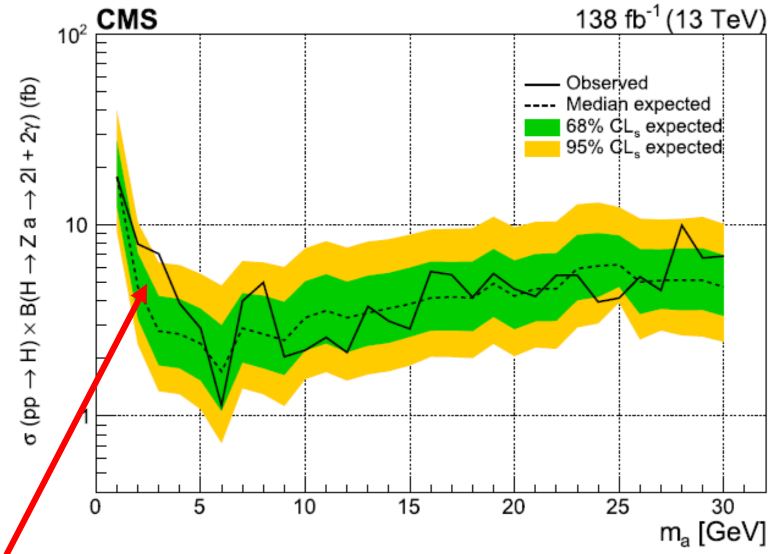
- **Two photon resolved** case with $m_a \in [1, 30]$ GeV, with **Z→μμ or ee**
- Developed **dedicated photon ID** by removing $\boldsymbol{\sigma_{i\eta i\eta}}$ and **PF Photon Isolation** from official cut-based photon ID
- Trained an **event BDT** for event categorization to improve the sensitivity
- Use **llγγ invariant mass** spectrum to extract signal in data
- **Statistical uncertainties dominate**



Phys. Lett. B 852 (2024) 138582







First LHC result in the H→Za→llγγ final state

2.6σ (1.3σ) local (global) significance at m_a=3 GeV

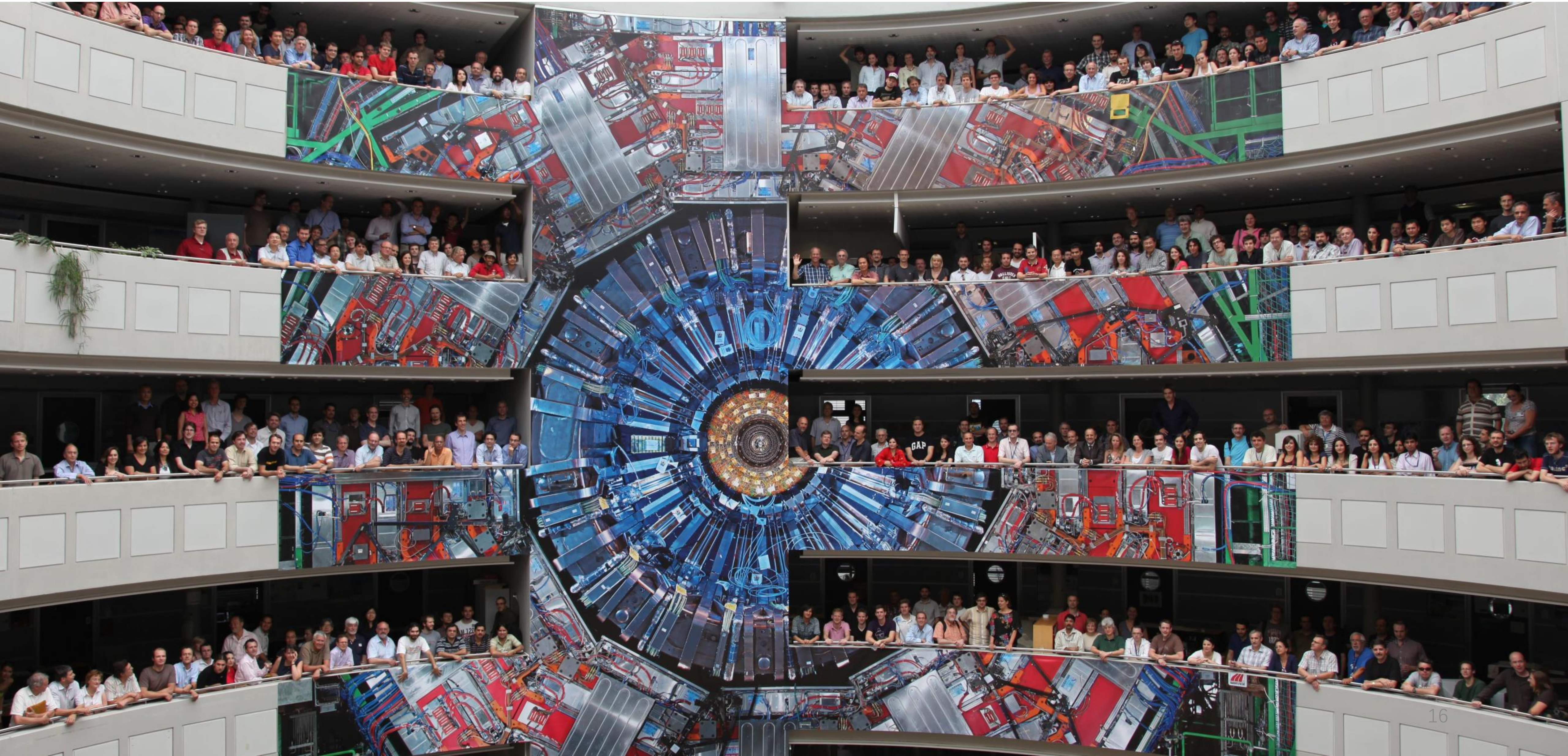
Summary

- **Measurements of Higgs boson properties with H→γγ** were performed with **Run2 13TeV 138 fb^{-1}** and **2022 13.6 TeV 34.7 fb^{-1} data** (fiducial XS): **all results are compatible with the Standard Model**

- **No direct evidence of new physics yet, but mild excesses** (2-3σ) in **low-mass H→γγ** and exotic decays of Higgs boson with **H→Za→llγγ**

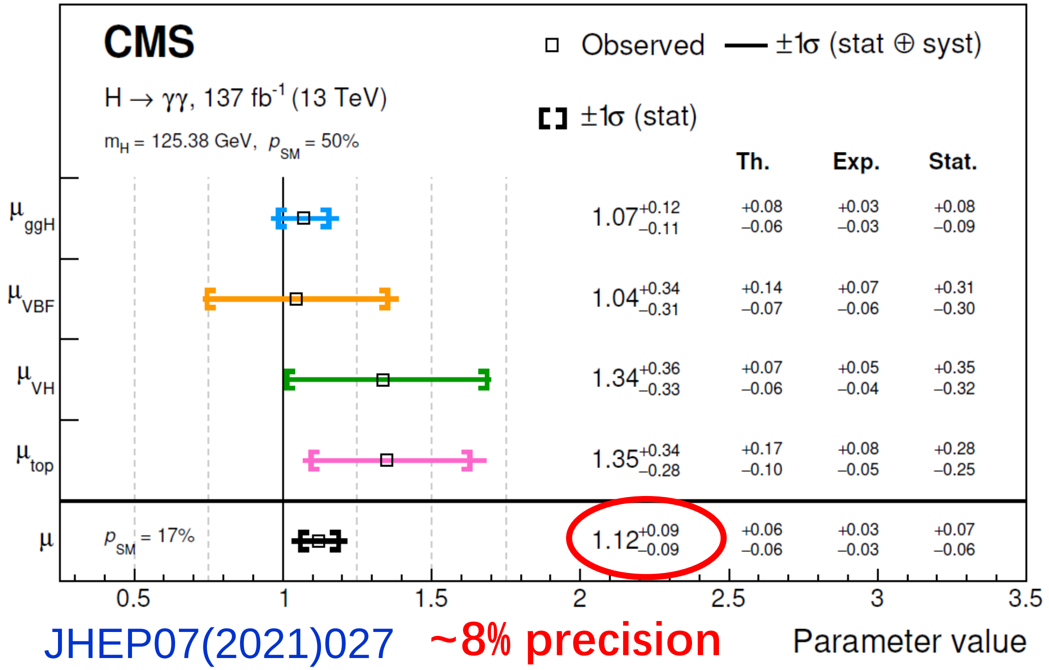
- **More Run2** (H→γγ Higgs mass and anomalous couplings, very low-mass H→γγ,…) **and Run3 results** (H→γγ STXS, low-mass H→γγ,…) **are coming … stay tuned!**

Thanks for your attention!



Backup

H→γγ : signal strength and couplings



JHEP07(2021)027 **~8% precision**

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

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu^f = \frac{\mathcal{B}^f}{\mathcal{B}^f_{SM}}$$

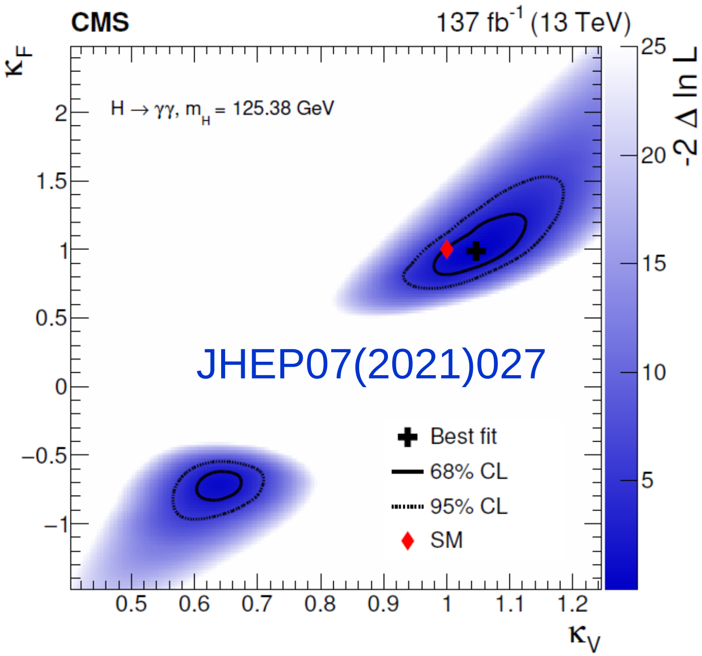
$$\mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{SM}} = \mu_i \times \mu^f$$

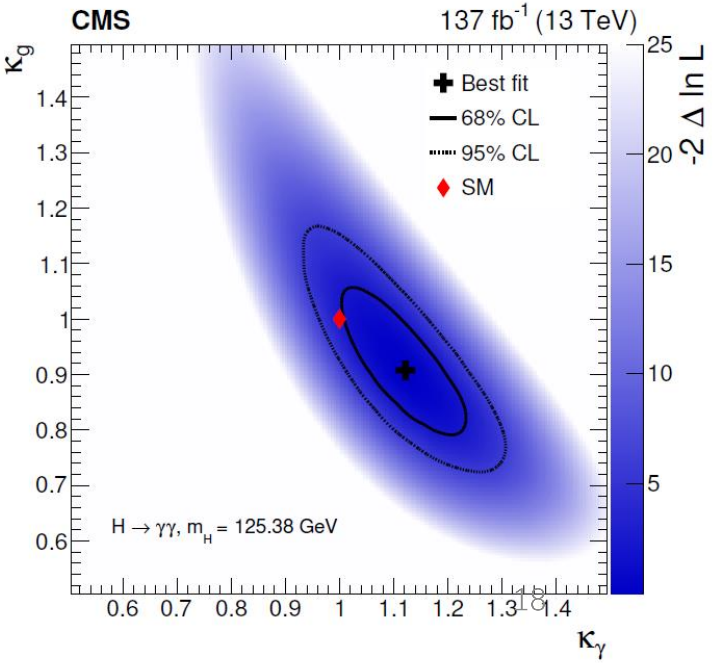
in agreement with the SM predictions

Production and decay parametrized in terms of **coupling modifiers** (κ-framework) :
measurements of **coupling modifiers** to **vector bosons** and **fermions** (**κ_V, κ_f**) and to **photons** and **gluons** (**κ_γ, κ_g**)

$$\sigma(i \to H \to f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$

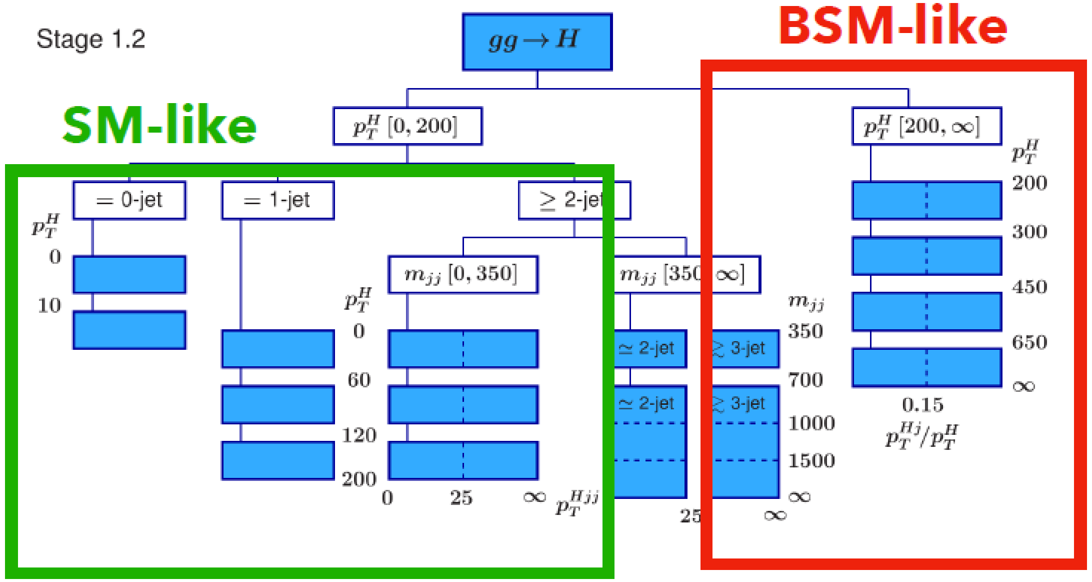
$$\sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$

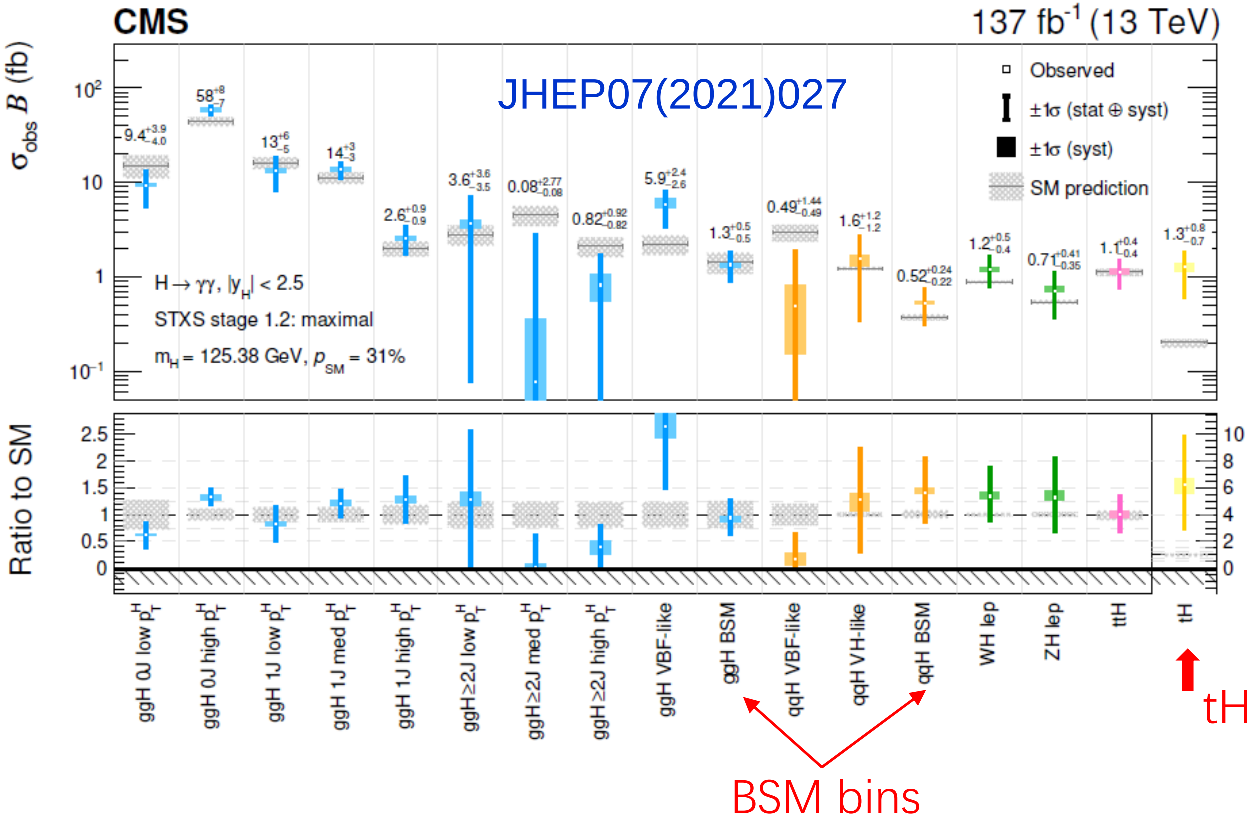




H→γγ simplified template cross sections

The primary goal of STXS framework is to **minimize the measurement dependence on theory predictions** without losing sensitivity, also **maximize sensitivity to beyond SM physics**





- **"Maximal" merging scenario (17 POI)**: STXS bins are merged until their **expected uncertainty is less than 150%** of the SM prediction
  - ✓ Measurement of ttH and tH simultaneously
  - ✓ **First and best tH measurement**

All σ results are in agreement with the SM predictions

ttH, H→γγ and CP

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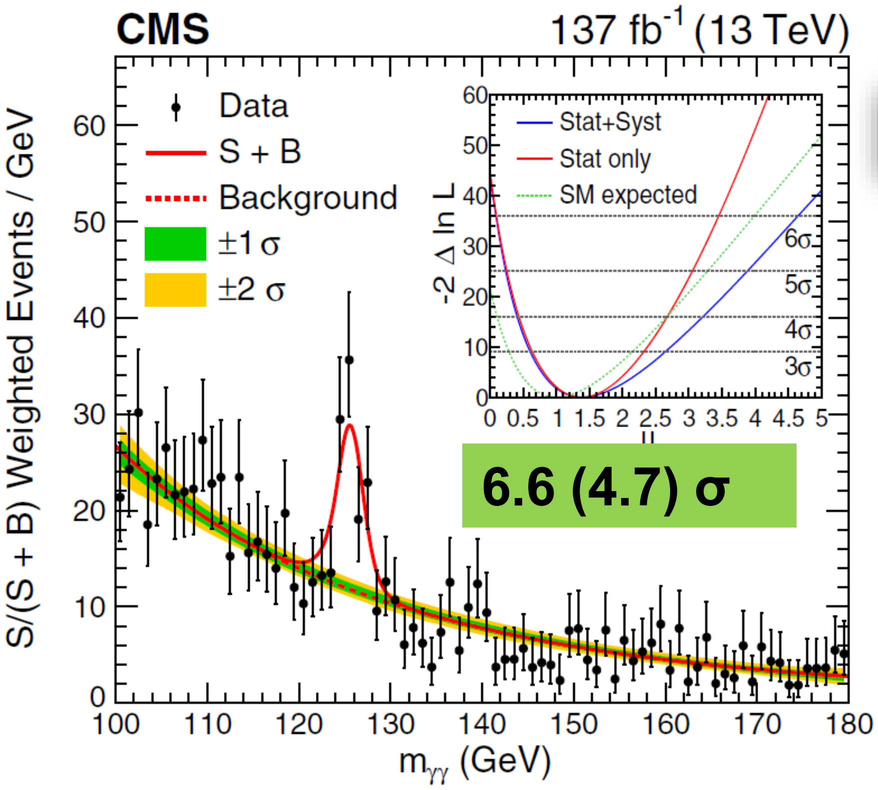
- Presented the **first single-channel observation** of the **ttH process**, along with **the first measurement of the CP structure** of the Htt coupling
  - ✓ Signal strength: **Two BDTs** with each for each leptonic or hadronic channel to distinguish between ttH and bkg events (8 categories)
  - ✓ CP: **a BDT** to distinguish CP-even and CP-odd contributions

pure CP-odd model of the Htt coupling is excluded at 3.2σ



$$\mu_{t\bar{t}H} = 1.38^{+0.36}_{-0.29}$$

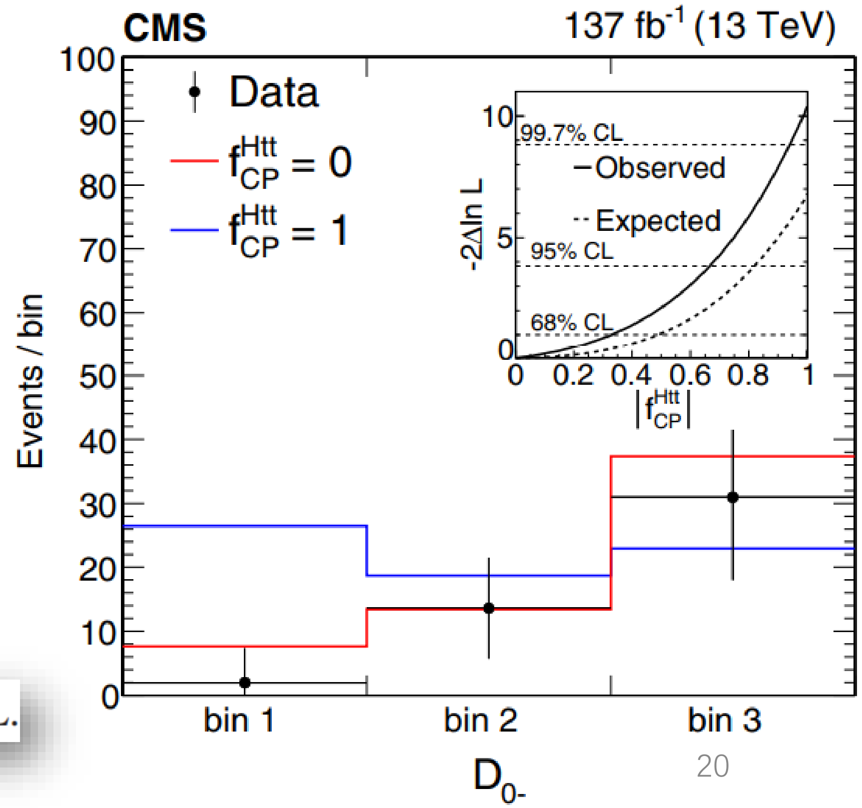
$$= 1.38^{+0.29}_{-0.27}(\text{stat})^{+0.21}_{-0.11}(\text{syst})$$

~20% precision

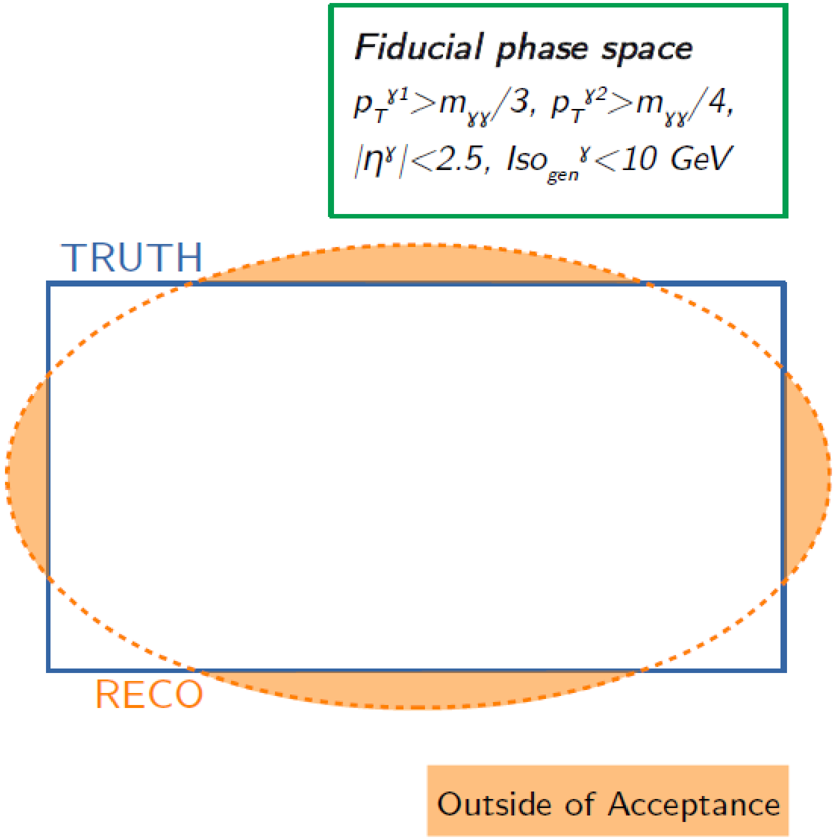
PRL 125, 061801 (2020)

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

$$f_{CP}^{Htt} = 0.00 \pm 0.33 \text{ at } 68\% \text{ C.L.}$$



H→γγ fiducial XS



Maximum Likelihood Unfolding

- $H \rightarrow \gamma\gamma$ uses maximum likelihood fits to fiducial cross sections with profiled nuisances
- Unfolding through full detector **response matrix K**, parameterized as a function of nuisances, included in the likelihood

$$\mathcal{L}_{ij}(\text{data}|\Delta\vec{\sigma}^{\text{fid}},\vec{n}_{\text{bkg}},\vec{\theta}_{\text{S}},\vec{\theta}_{\text{B}}) = \prod_{l=1}^{n_{m_{\gamma\gamma}}}\left(\frac{\sum_{k=1}^{n_b}\Delta\sigma_k^{\text{fid}}K_k^{ij}(\vec{\theta}_{\text{S}})S_k^{ij}(m^l_{\gamma\gamma}|\vec{\theta}_{\text{S}})L + n^{ij}_{\text{OOA}}S^{ij}_{\text{OOA}}(m^l_{\gamma\gamma}|\vec{\theta}_{\text{S}}) + n^{ij}_{\text{bkg}}B^{ij}(m^l_{\gamma\gamma}|\vec{\theta}_{\text{B}})}{n^{ij}_{\text{sig}}+n^{ij}_{\text{bkg}}}\right)^{n^{lij}_{\text{ev}}}$$

- ML unfolding allows accounting of **bin migrations** and **correct modeling of systematic uncertainties** in all regions of the phase space.
- In $H \rightarrow \gamma\gamma$ **no explicit regularization procedure** was needed so far, performed **ML unfolding** was sufficient

Correction of light collection non-uniformity

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- Light collection efficiency as a function of depth (z) simulated (CMS-DP-24-045) to determine energy scale corrections → dedicated uncertainty assigned to the correction

Take into account the impact of the radiation on the difference of the shower profiles

Energy scale correction factor F

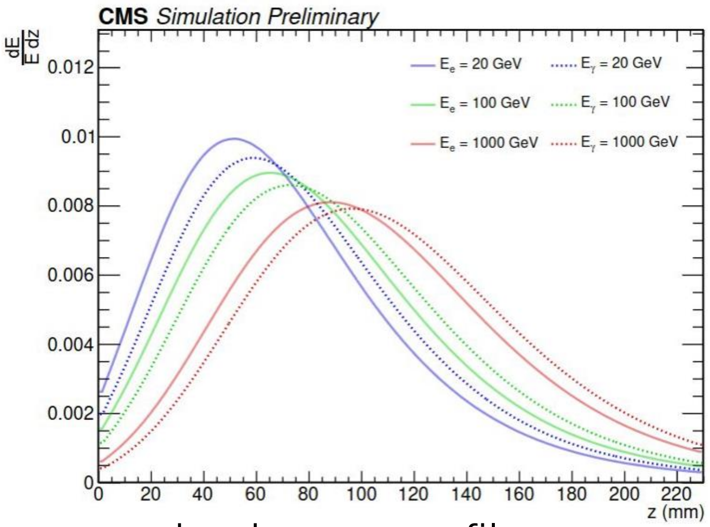
$$F = \frac{S^e}{S^\gamma} = \frac{\dfrac{\int E^e_{\text{dep}}(z) \times \text{LCE}(z;\, \text{R}/\text{R}_0, \eta)\, \text{d}z}{\int E^e_{\text{dep}}(z)\, \text{d}z}}{\dfrac{\int E^\gamma_{\text{dep}}(z) \times \text{LCE}(z;\, \text{R}/\text{R}_0, \eta)\, \text{d}z}{\int E^\gamma_{\text{dep}}(z)\, \text{d}z}}$$

- S_e (S_γ): ECAL response to electrons (photons)
- $E_{dep}(z)$: shower profile in $PbWO_4$ (Geant4)
- $LCE(z)$: Light Collection Efficiency, simulated with Fluka+Light-tracing (Litrani code)
- R/R_0: ECAL laser response measured in data → per-run corrections possible

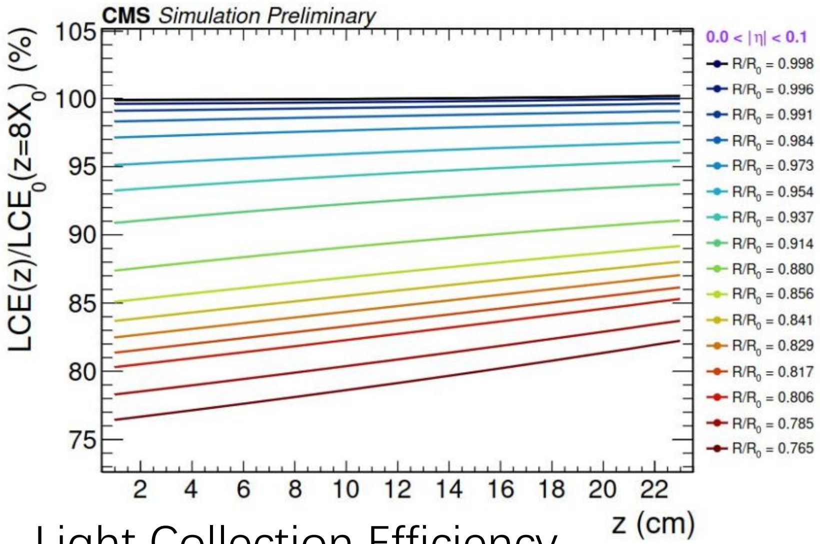
- Key elements include electron/photon shower profiles (Geant4) and light collection efficiency in ECAL (Fluka + Litrani) depending on crystal transparency
- This approach should significantly reduce uncertainty in full Run 2 mass measurement

different scenarios of crystal transparency, R/R0

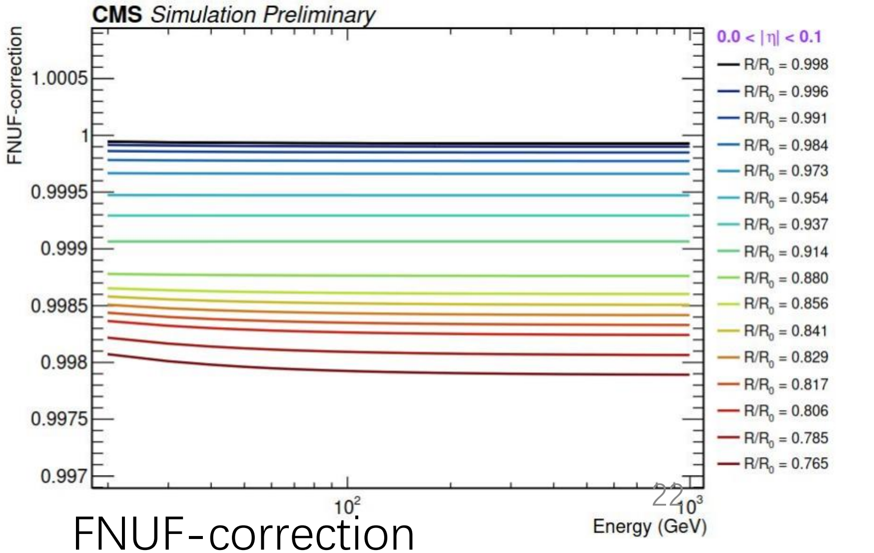
CMS-DP-24-045



e and γ shower profiles



Light Collection Efficiency

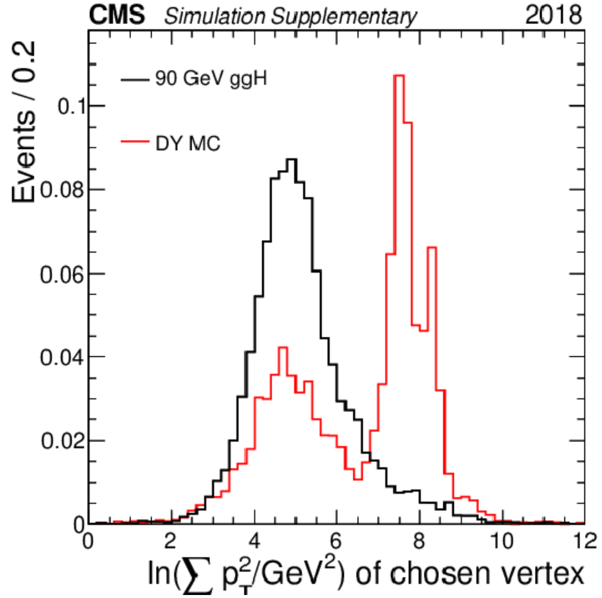


FNUF-correction

SM-like LM H→γγ search with full Run2

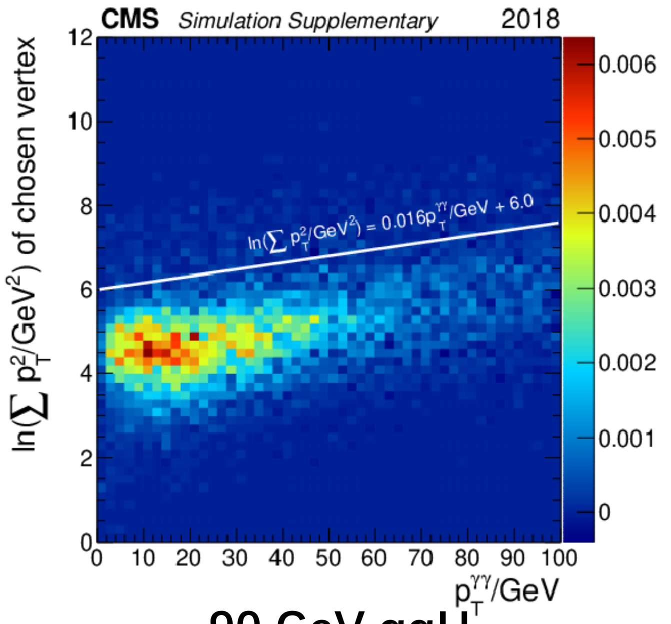
- **Major changes** wrt prior version (*PLB 793 (2019) 320*) (2012+2016 data):
  - ✓ A Kinematic **diphoton BDT** (*pt/m$_{\gamma\gamma}$, η , cos($\phi_{\gamma1}$-$\phi_{\gamma2}$), both Photon ID MVA scores, mass resolutions wrt correct and incorrect vertices, vertex probability*) for **sig and bkg discrimination retrained and reoptimized** for events categorization, **for low-mass case**
  - ✓ **Relic DY (Z→ee) veto** (based on pixel detector hits) **reinforced with:**
    - Rejection of photon candidates also reconstructed as electrons
    - Maximum value of **ln (Σp_T^2/GeV^2)** [tracks in chosen vertex] **as function of $p_T^{\gamma\gamma}$ (GeV)**:

      $\ln(\Sigma p_T^2) < 0.016\, p_T^{\gamma\gamma} + 6$
  - ✓ **2017/18**: events with additional jets selected for class targeting VBF process
  - ✓ **2016**: data reanalyzed with an **improved calibration (legacy data)**

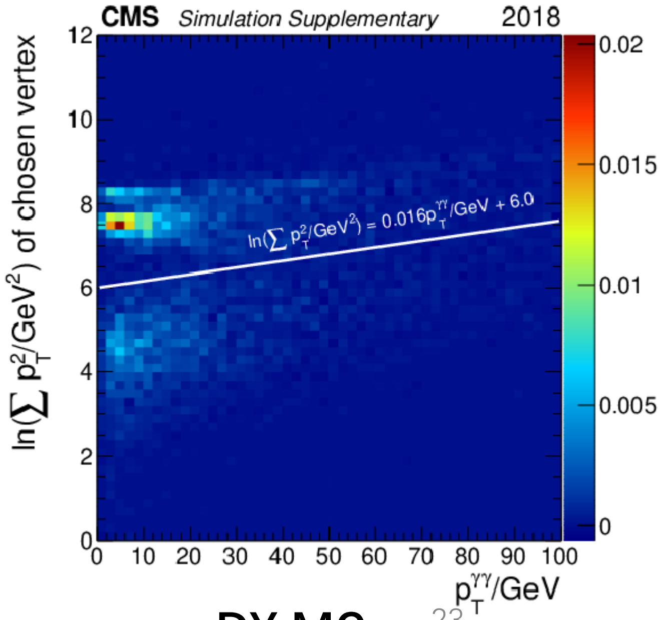


Public results

The 2 additional cuts can reject ~60%-70% of the relic DY events while keeping ~92% 90GeV signal efficiency in 2016-2018 analysis, on top of pixel seed e-veto

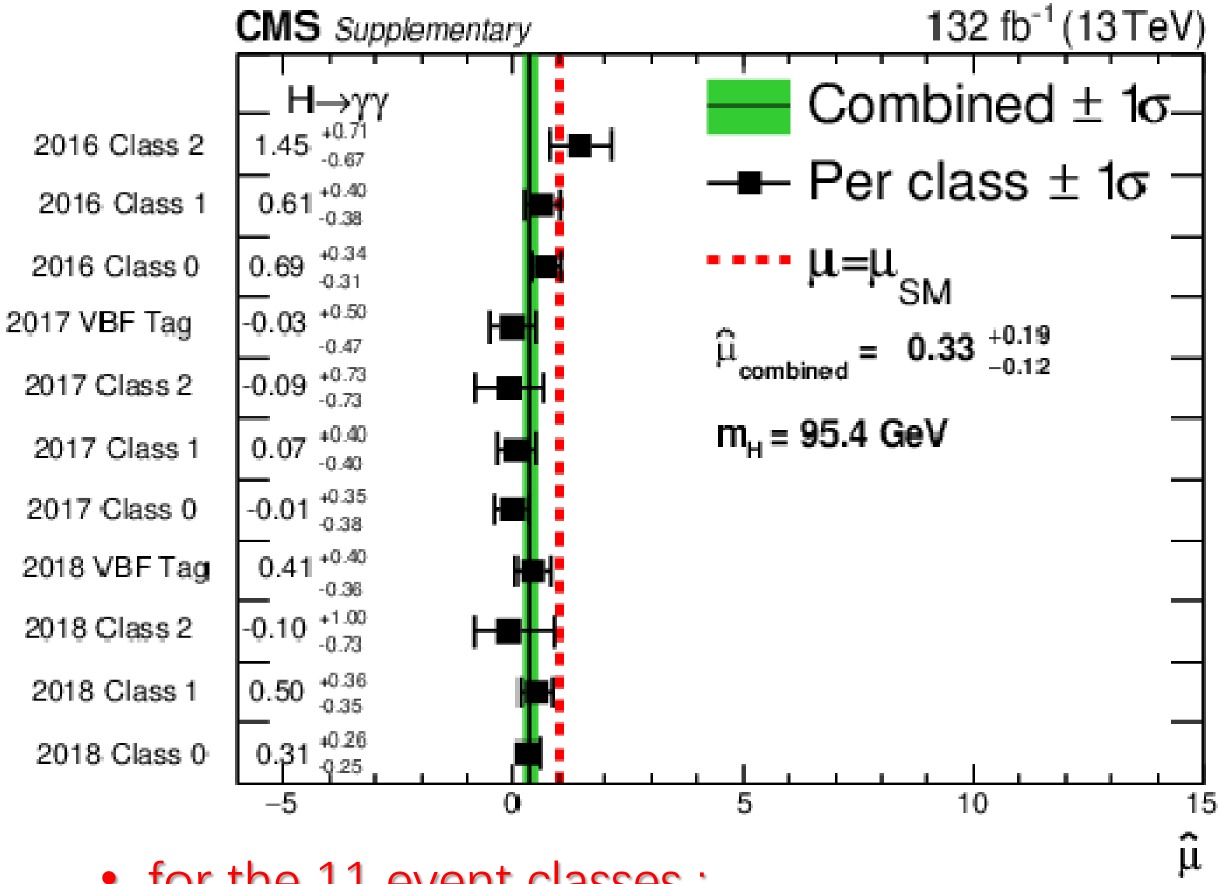


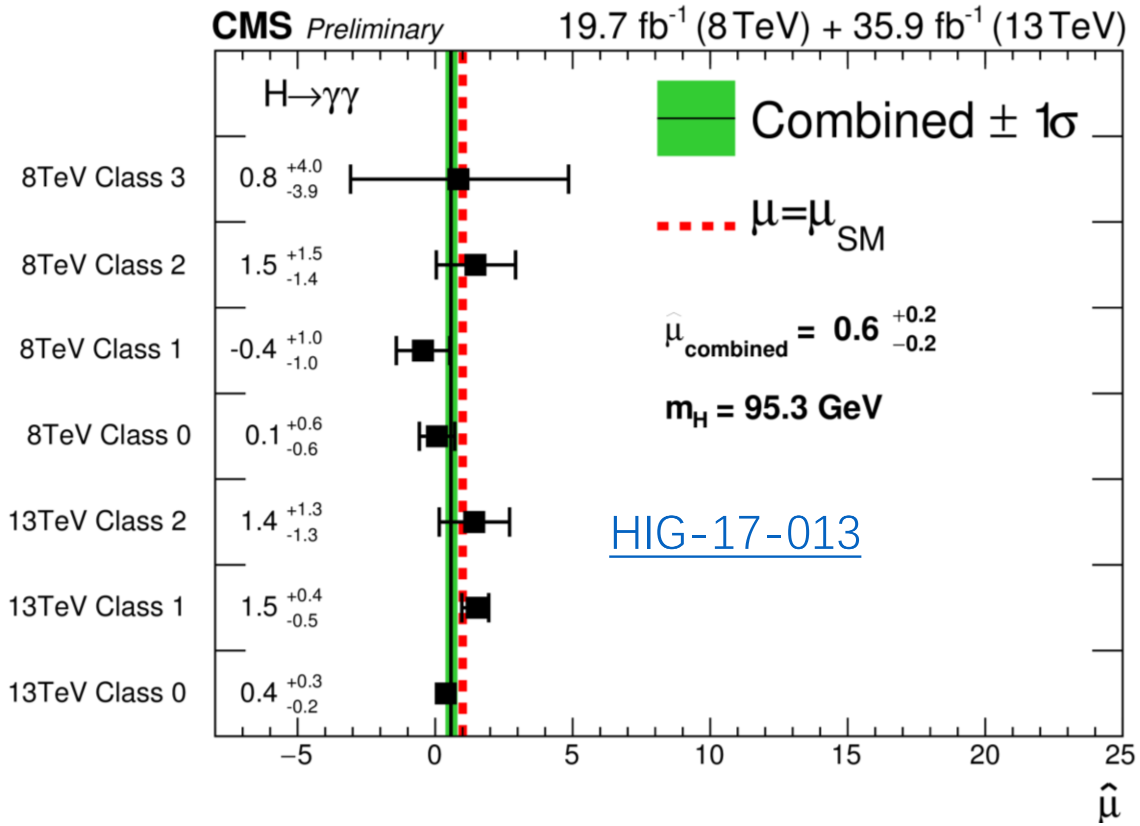
90 GeV ggH



DY MC

LM H→γγ 'signal' strength compatibility



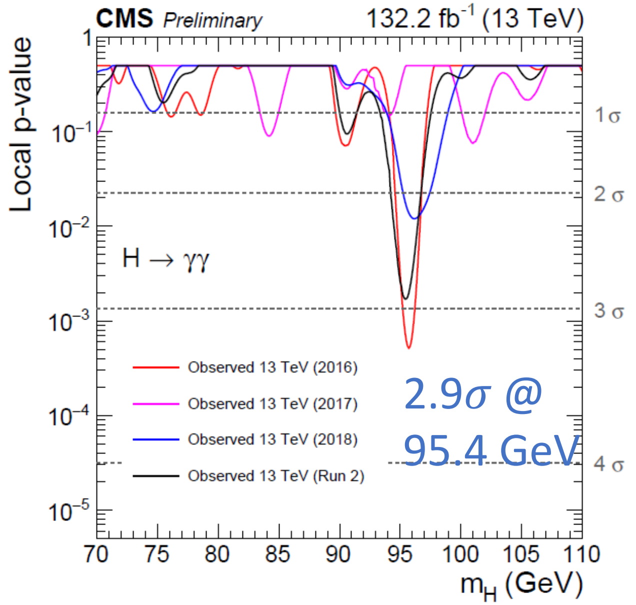


HIG-17-013

- for the 11 event classes :
  χ^2 compatibility probability: 68%

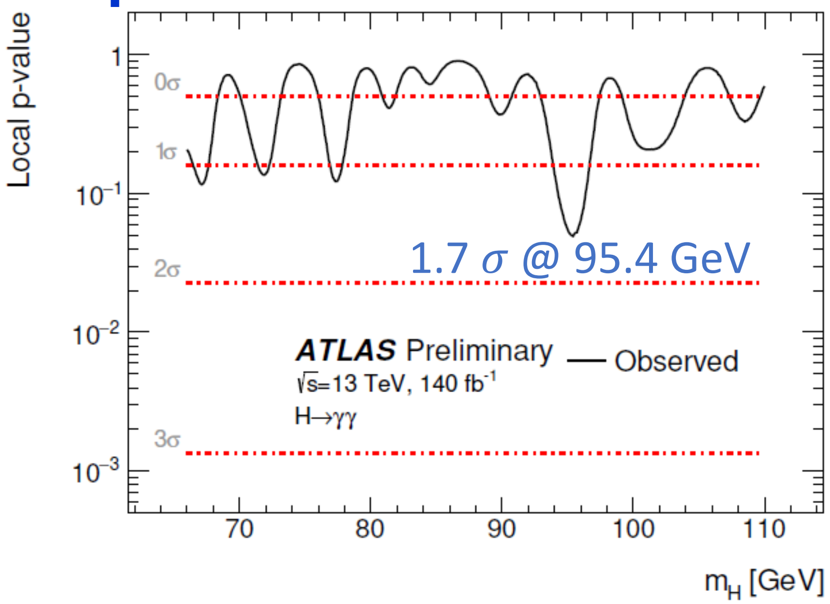
HIG-20-002
Public results

HIG-20-002: comparison with ATLAS



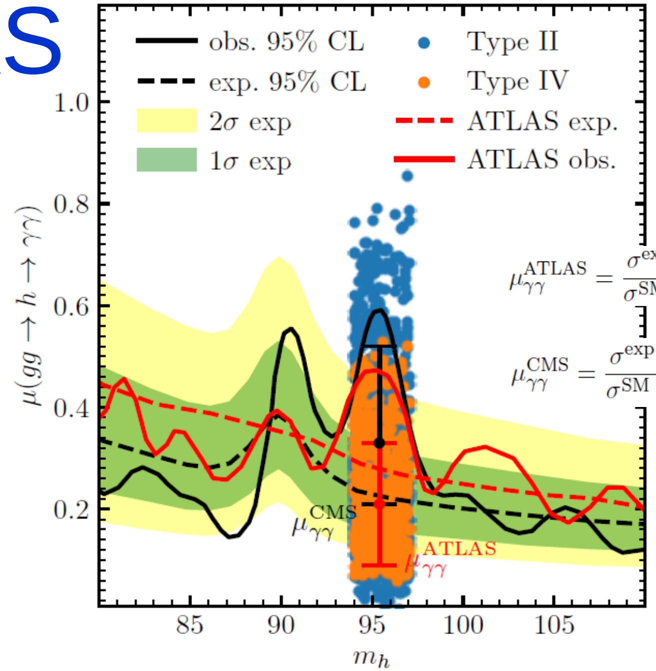
CMS-PAS-HIG-20-002

March, 2023 (Moriond)



ATLAS-CONF-2023-035

June 6, 2023

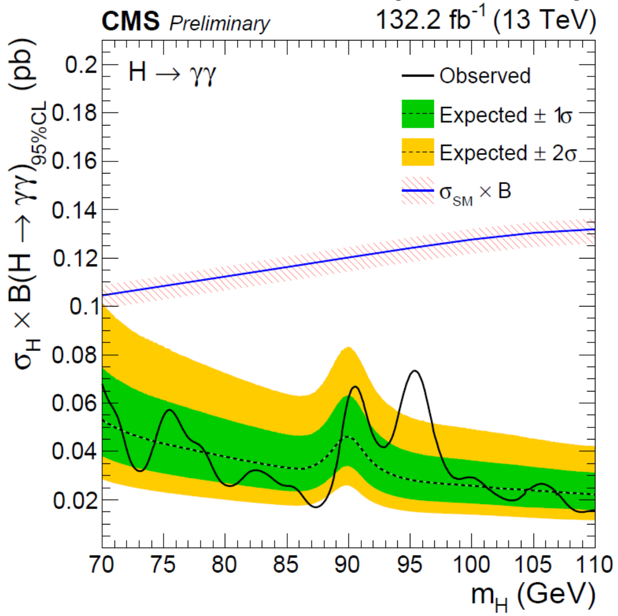


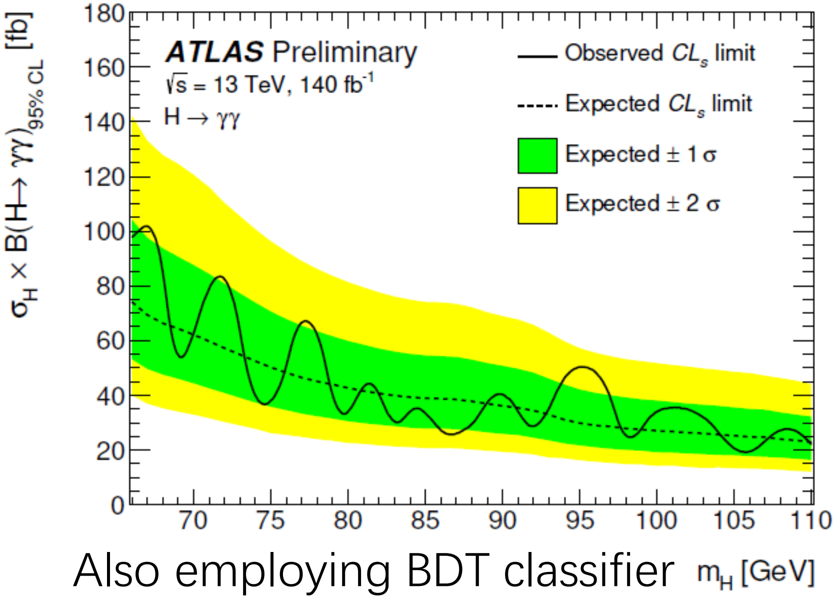
Extension of the 2HDM by a complex singlet (S2HDM)

$$\mu_{\gamma\gamma}^{\rm ATLAS} = \frac{\sigma^{\rm exp}(gg \to \phi \to \gamma\gamma)}{\sigma^{\rm SM}(gg \to H \to \gamma\gamma)} = 0.21^{+0.12}_{-0.12}$$

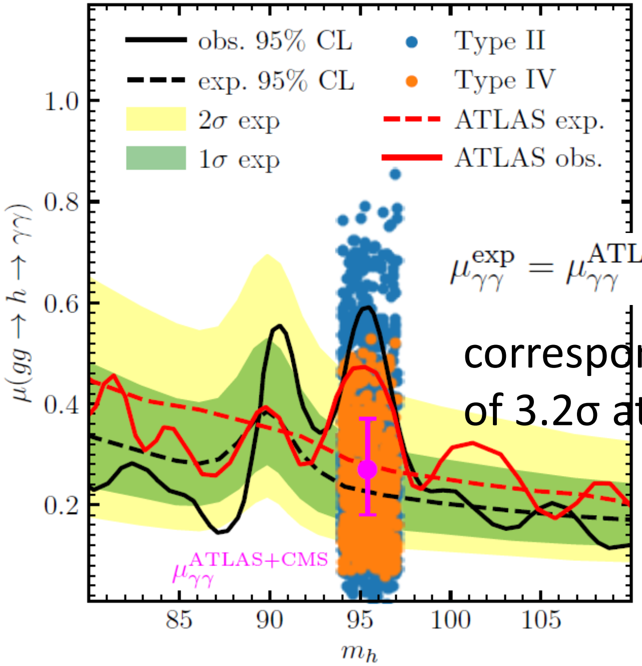
$$\mu_{\gamma\gamma}^{\rm CMS} = \frac{\sigma^{\rm exp}(gg \to \phi \to \gamma\gamma)}{\sigma^{\rm SM}(gg \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

arXiv:2306.03889





Also employing BDT classifier

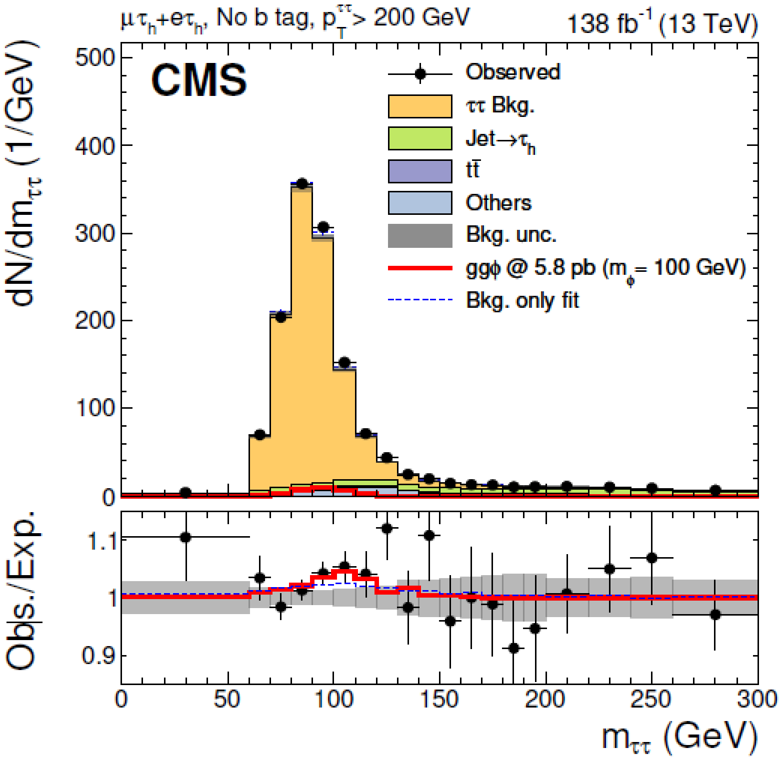


$$\mu_{\gamma\gamma}^{\rm exp} = \mu_{\gamma\gamma}^{\rm ATLAS+CMS} = 0.27^{+0.10}_{-0.09}$$

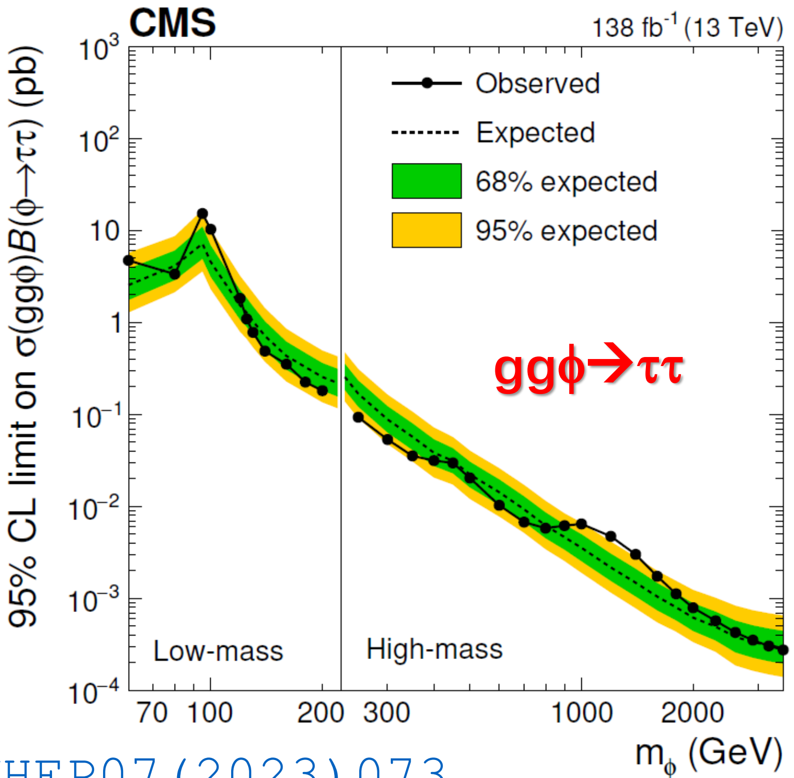
corresponding to an excess of 3.2σ at 95.4 GeV

Search for neutral scalar $\phi \rightarrow \tau\tau$

- $\tau\tau$ final state: identified with **higher purity than b; well estimated $\tau\tau$ bkg**; typically **larger BR**; …
- Production via **gluon fusion** ($gg\phi$) or **in association with b** quarks ($bb\phi$)
- Performed in 4 $\tau\tau$ final states : $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$
- Event categorization : split into **no b-tag (N_{bjets}=0)** and **b-tag** categories
  - ✓ For no b-tag category split events based on **reconstructed $p_T^{\tau\tau}$**



"Low-mass" (60–250 GeV): fitting on $m_{\tau\tau}$ to extract signal



JHEP07(2023)073

3.1σ(2.7σ) local (global) @ 100 GeV

2.6σ(2.3σ) local (global) @ 95 GeV

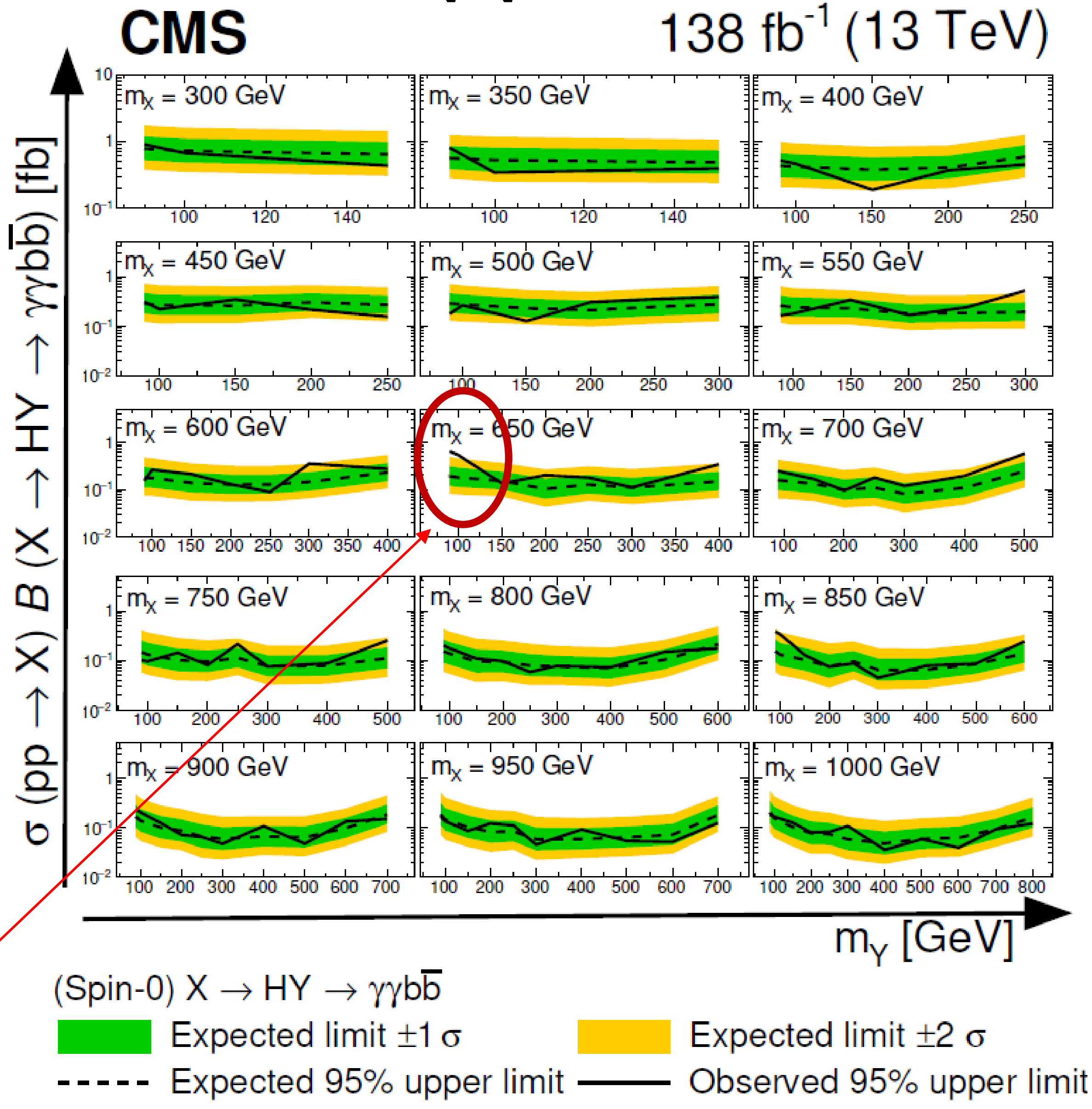
2.8σ(2.2σ) local (global) @ 1.2 TeV

Not seen in bbϕ production

$X \rightarrow HH/YH \rightarrow bb\gamma\gamma$

- Search for **a new boson X** decays into **two spin-0 bosons**, with **2γ** and **2b quarks**
  - Relatively **large signal purity in H→γγ**
  - Large branching fraction of decaying into bb
- Focus on X decays into an H(→γγ) and **a new spin-0 boson Y**(→bb) in this talk
- BDT (DNN) scores to separate signals and non-resonant (resonant) backgrounds
- Six BDT training accounts for different signal **m_X-m_Y** mass ranges
  - 3 event classes based on BDT output
- A parametric fit in the **($m_{\gamma\gamma}$, m_{jj})** plane is performed for signal extraction

3.8σ local (2.8σ global) for m_X = 650 GeV and **m_Y = 90 GeV**



JHEP05(2024)316

X → HH/YH → $\tau\tau\gamma\gamma$

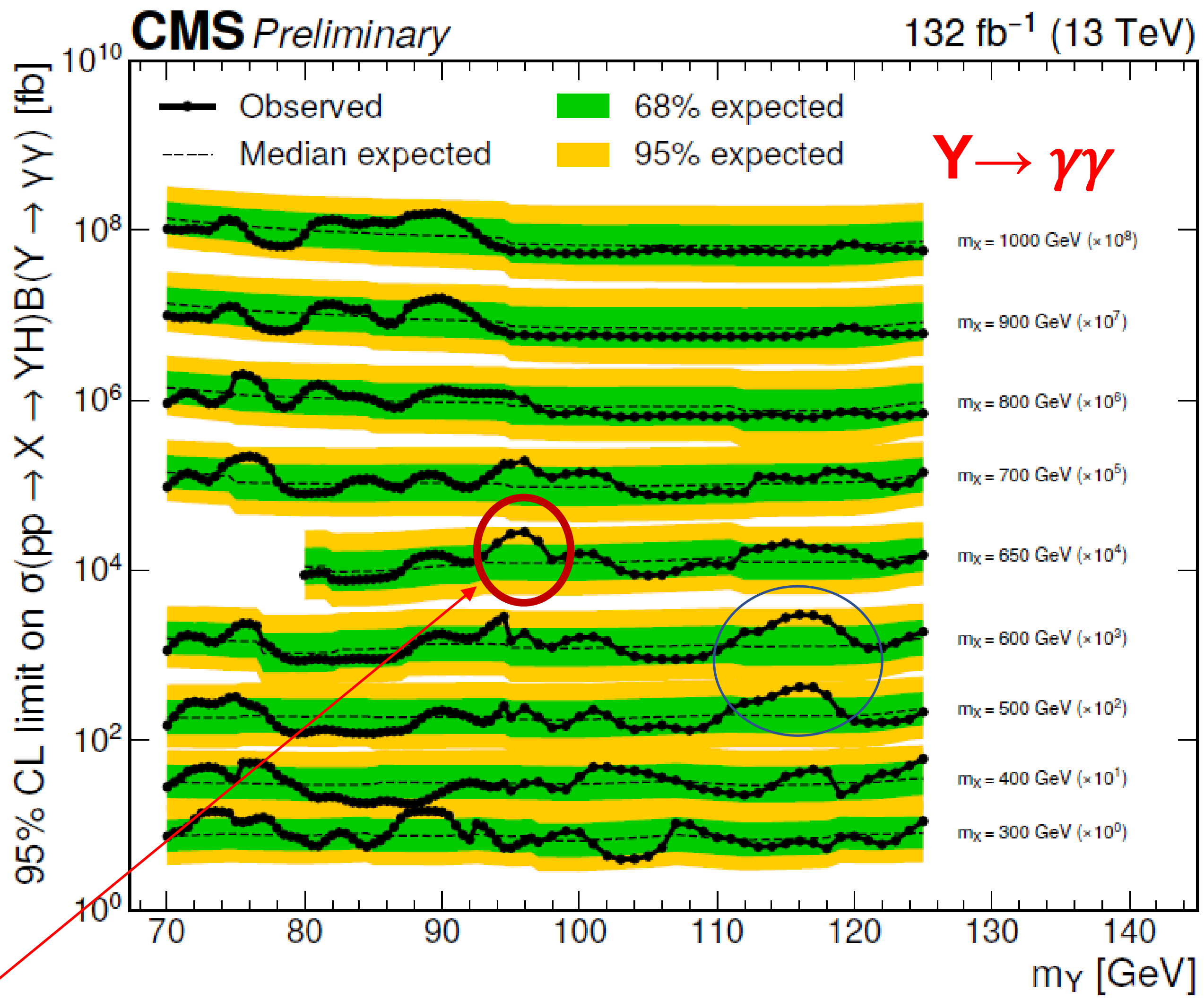
- Diphoton pair offers a clean experimental signature to **trigger** on with **a good mass resolution**, whilst the additional **tau leptons** in the event help further **isolate signal from bkg**

- **Three search channels of X →YH → $\tau\tau\gamma\gamma$:**
  - ✓ X → Y($\tau\tau$) H($\gamma\gamma$)
  - ✓ Low-mass X → Y($\gamma\gamma$) H($\tau\tau$) (Y mass 70-125 GeV)
  - ✓ High-mass X → Y($\gamma\gamma$) H($\tau\tau$) (Y mass 125 -800 GeV)

- A Parametric Neural Network (pNN) trained to identify sig from bkg and for event categorization

Y→ $\gamma\gamma$: the largest local significance of **3.4σ** (0.1σ global) @ **m_X = 525 GeV**, **m_Y = 115 GeV**

local 2.3σ @ m_X = 650 GeV, m_Y = 95 GeV is interesting

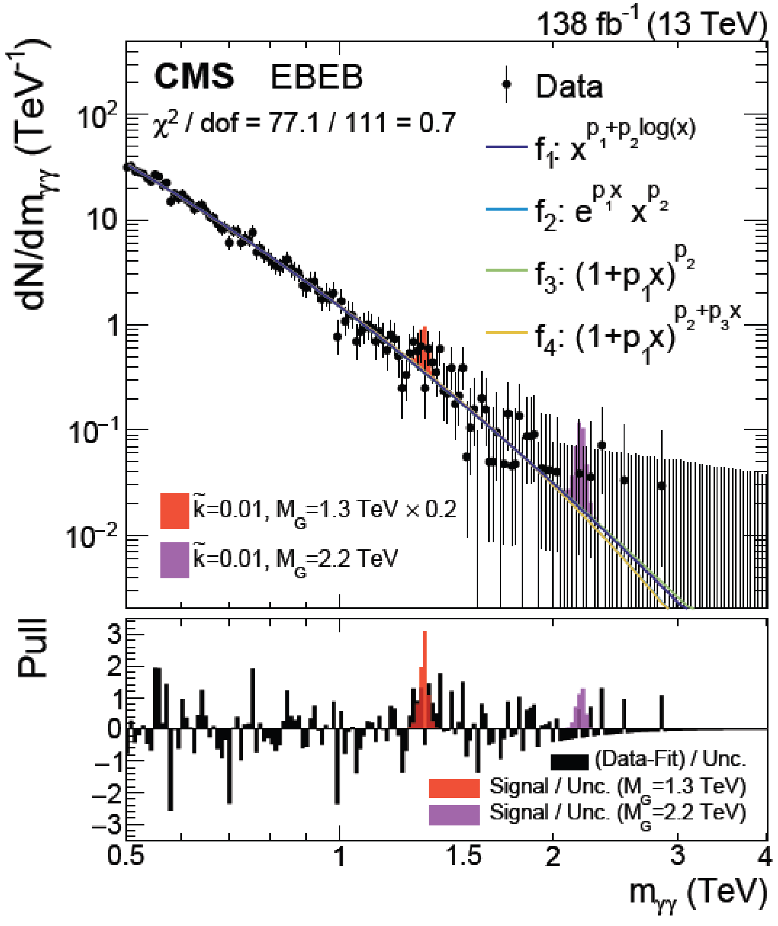


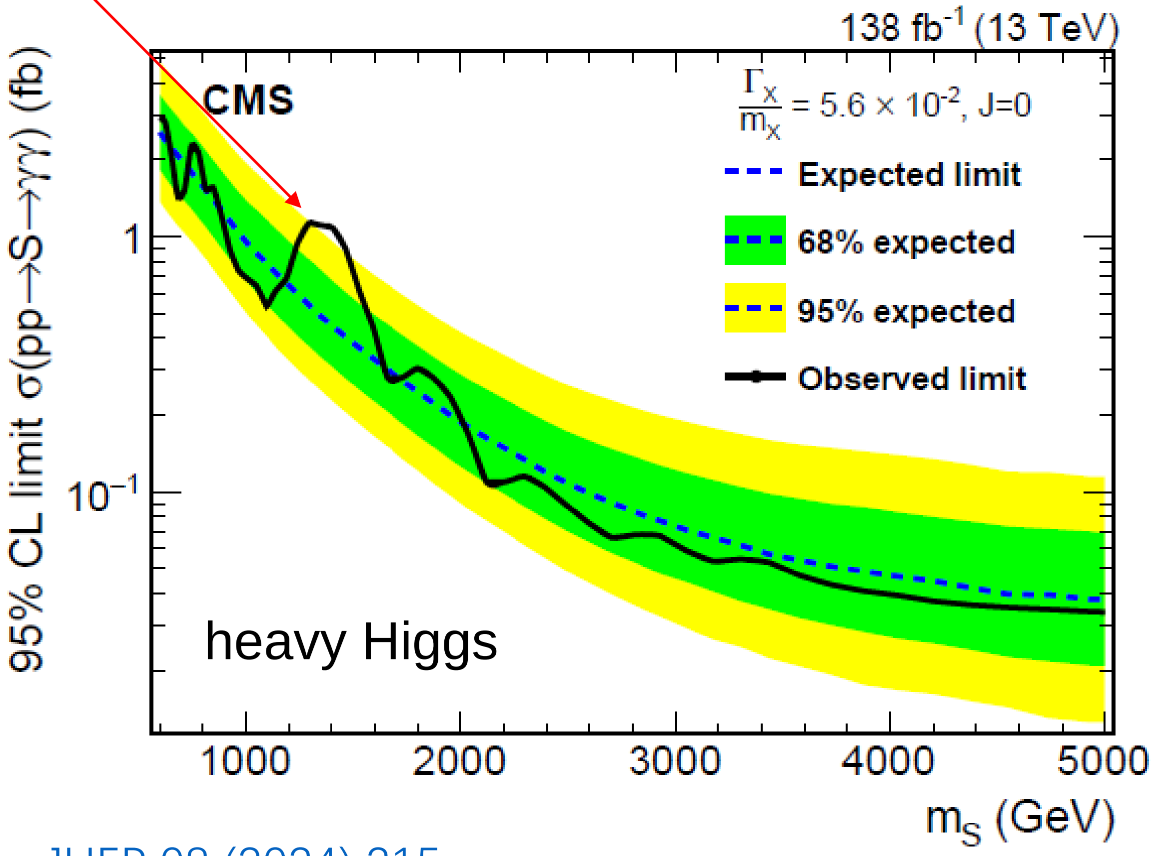
CMS-PAS-HIG-22-012

High mass X→γγ

- X→γγ: **bump search in the diphoton mass spectrum (> 500 GeV)**
- Two channels: EB+EB, EB+EE

2.6σ (0.8σ) local (global) excess @ ~1.3 TeV for the broad resonance model





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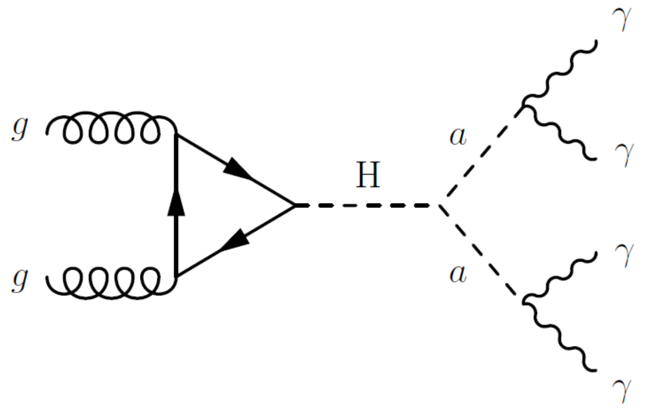
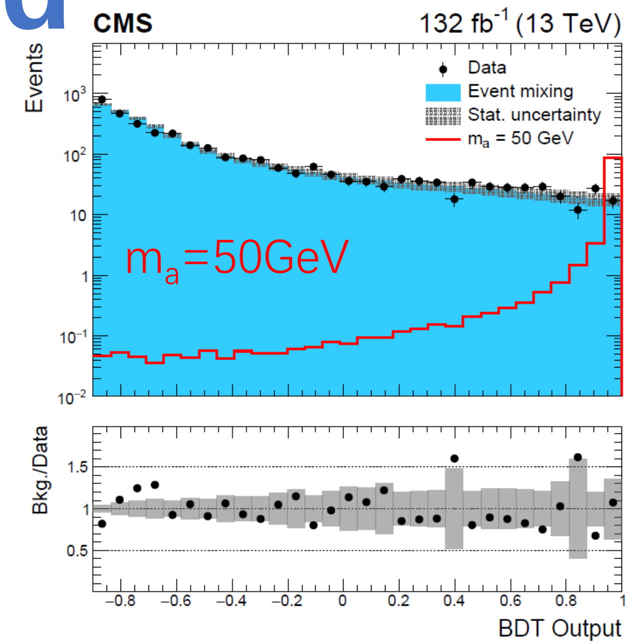
H→aa→γγγγ resolved

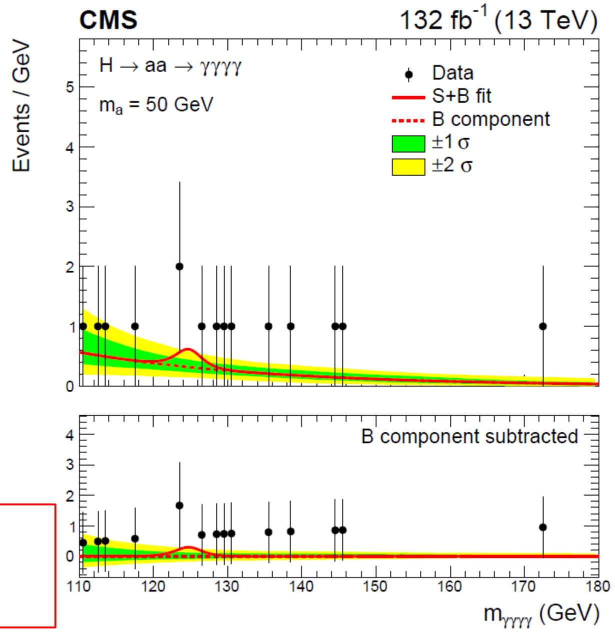
- Probes pseudoscalar masses (m_a) in the range **15-62 GeV**
- **Four well-isolated photons** in the final state
- Dedicated **primary vertex (PV) BDT** is trained on simulated H→aa→γγγγ events, to select PV with highest BDT score
- To improve the sensitivity, a **4-photon event classifier** is trained to separate sig events from bkg events: **a single category** optimized based on the BDT output, for each m_a
- Signal is extracted from **$m_{\gamma\gamma\gamma\gamma}$ distribution** in data (100-180 GeV)
- **No significant deviation** : **95% CL upper limit** $\sigma_H B(H \to aa \to \gamma\gamma\gamma\gamma)$: **0.26-0.80** (0.24-1.0) **fb** observed (exp.)

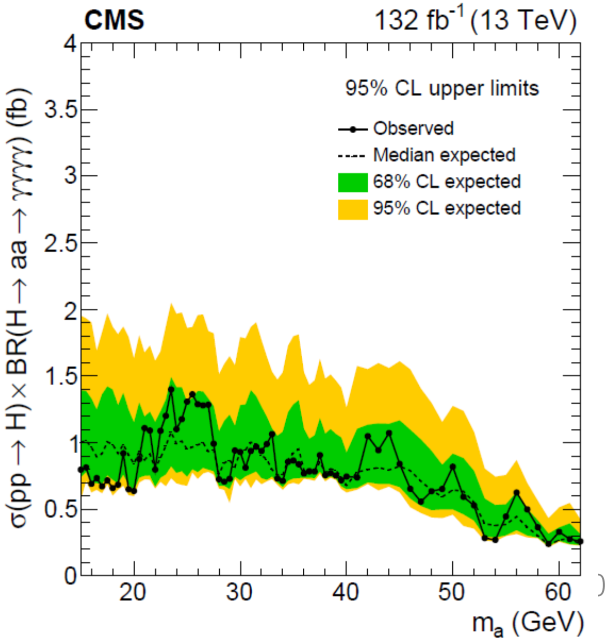
CMS-PAS-HIG-21-003

[JHEP 07 (2023) 148]





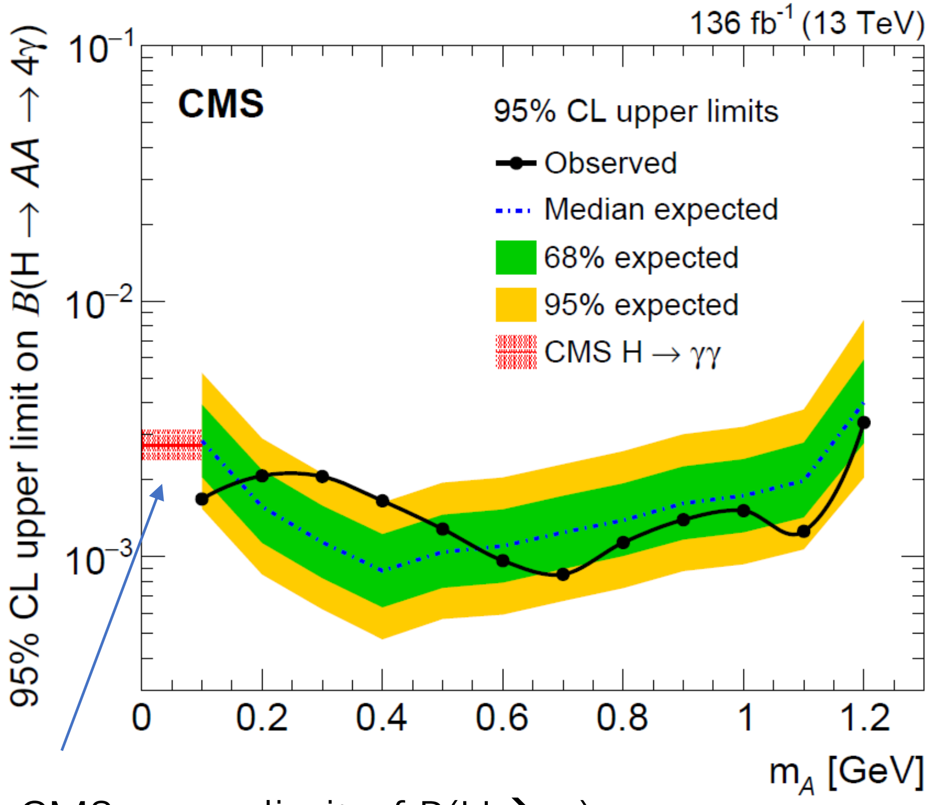




First CMS search in this channel

H→AA→γγγγ boosted

- **Search range of $m_A \in [0.1, 1.2]$ GeV**
- Two collimated γ reconstructed as single Γ: $110 < m_{\Gamma\Gamma} <$ 140GeV
- Deep-learning used to reconstruct m_Γ of collimated di-γ
- Signal templates built in $m_{\Gamma 1}$ - $m_{\Gamma 2}$ plane
- Backgrounds
  - ✓ H→γγ from MC
  - ✓ Prompt-diphoton and QCD/γ + j from **data in $m_{\Gamma\Gamma}$ sideband** regions (100-110 GeV and 140-180 GeV)



CMS upper limit of B(H→γγ)

- **No excess observed** : upper limits on the branching fraction B(H → AA → 4γ) of **(0.9-3.3) × 10^{-3}** at 95% CL

- **Upper limit on B interpreted for long-lived A at m_A = 0.1 (0.4) GeV**
  - ✓ 1.6 (0.9) times the prompt-decay UL for $c\tau_0$ = 1 mm
  - ✓ 30 (3) times the prompt-decay UL for $c\tau_0$ = 10 mm

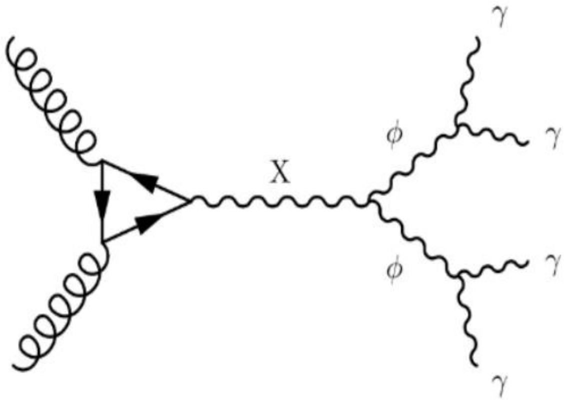
Best constraints for this decay mode in the studied m_A range

Boosted multi-photon $X \to \phi\phi \to 4\gamma$

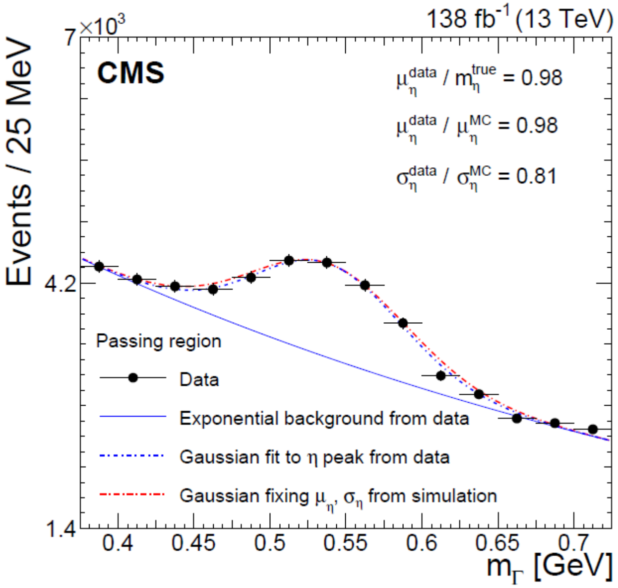
- **Highly boosted ϕ** resulting in merged photon pairs : need new ML analysis techniques

Analysis Regime:

- 300 GeV < M_X < 3000 GeV
- 0.005 < α < 0.025 $\quad \alpha = M_\phi / M_X$
- Barrel Only

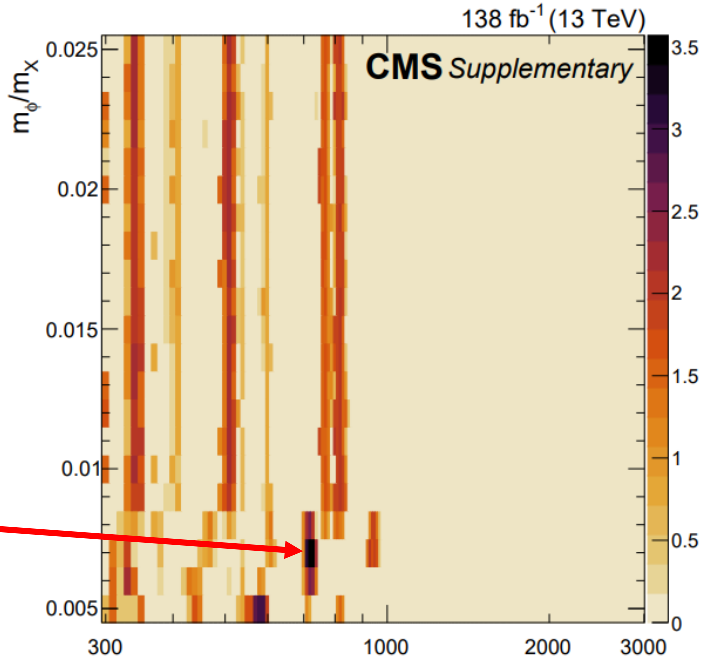


CMS-EXO-22-022, *arXiv:2405.00834*



- **Two convolutional neural networks**
  - **Classification NN1:** selects diphotons from single photons and hadrons
  - **Regression NN2:** predicts the diphoton mass (m_Γ)
  - Validations of CNN: $\eta \to \gamma\gamma$
- **Final search is a bump hunt in $M_{\Gamma\Gamma}$** (reconstructed X or four-photon mass)

3.57σ (1.07σ) local (global) excess @ m_X = 720 GeV, m_ϕ = 5.04 GeV



public-results