Search for light Higgs bosons in the diphoton channel at CMS

Junquan Tao （IHEP/CAS）

陶军全 （中科院高能所）

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

References:

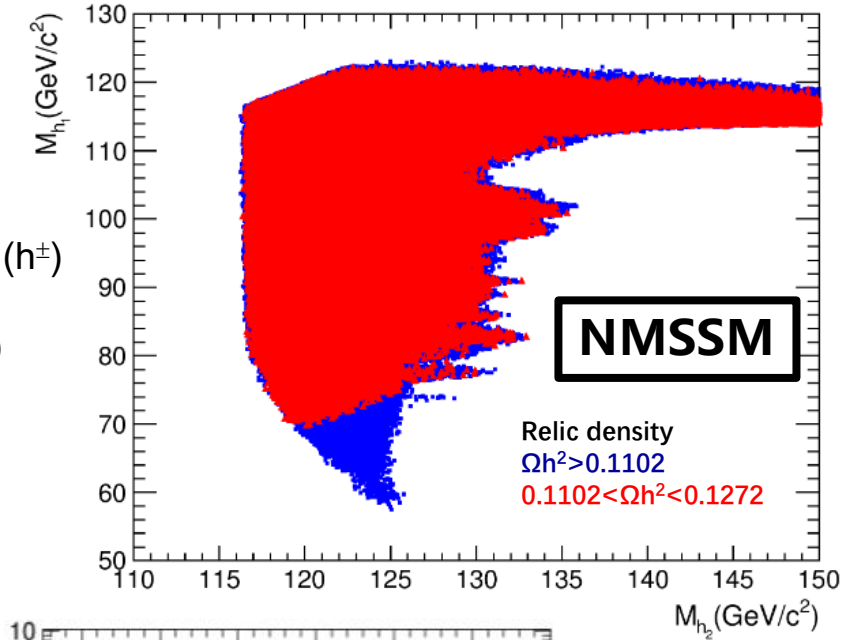
Low-mass (70-110 GeV) H→γγ with **Run2** data: PLB 860 (2025) 139067 published in January 2025

Vey low-mass (10-70 GeV) H→γγ with **Run2** data : CMS-PAS-HIG-24-014 released in 03/2025 (La Thuile)

Motivations : theory

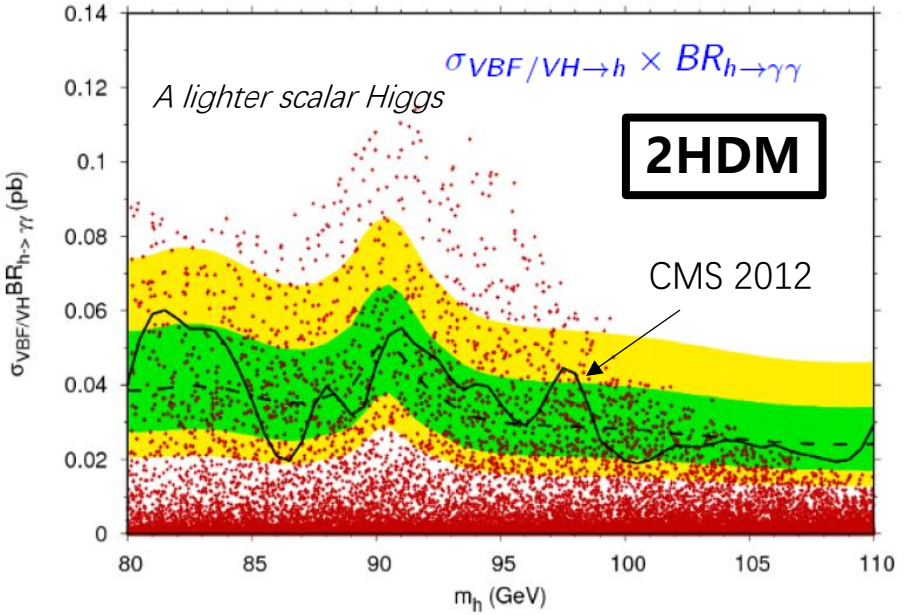
- Many **BSM models** (e.g. NMSSM, 2HDM, GM models) provide a Higgs boson that is compatible with the LHC observed 125 GeV boson, and predict additional Higgs bosons with some of which could **have masses below 125 GeV**
  - ✓ **Next-to-minimal supersymmetric model (NMSSM):** 3 CP-even (h_i), 2 CP-odd (a_i), 2 charged ($h^{\pm}$)
  - ✓ **Two Higgs Doublet Models (2HDM)**: 2 CP-even (h, H), 1 CP-odd (a), 2 charged ($H^{\pm}$)
  - ✓ **Georgi-Machacek (GM) model**: 2 singlet(h, H), 3 triplet(H_3^0, $H_3^{\pm}$) and 5 fiveplet (H_5^0, $H_5^{\pm}$, $H_5^{\pm\pm}$) mass eigenstates

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

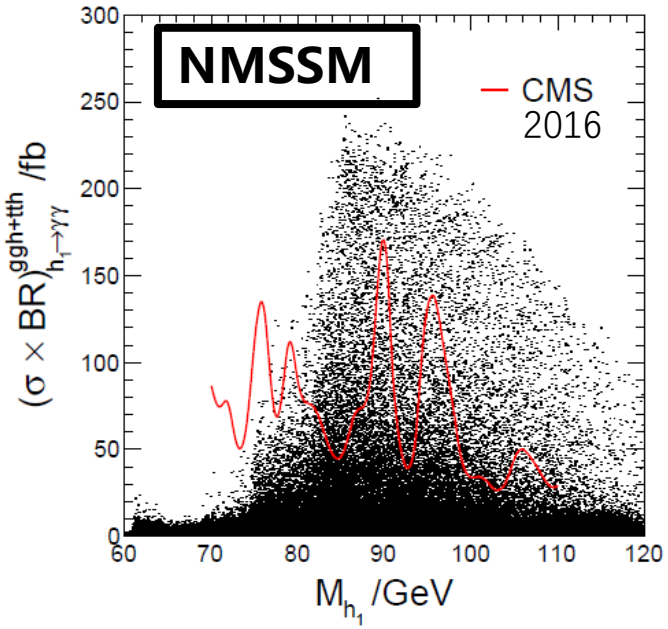


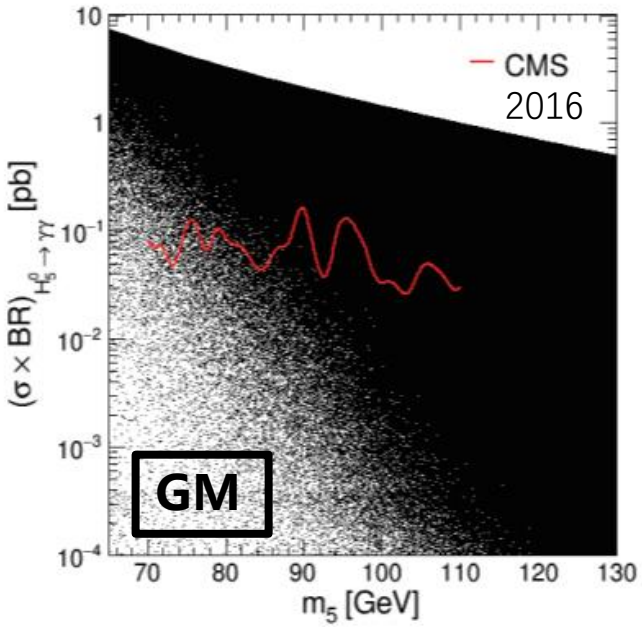
- **Discovery of a second Higgs boson would be an unequivocal sign of new physics**

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



JT et al., Chin. Phys. C 42 (2018)10, 103107

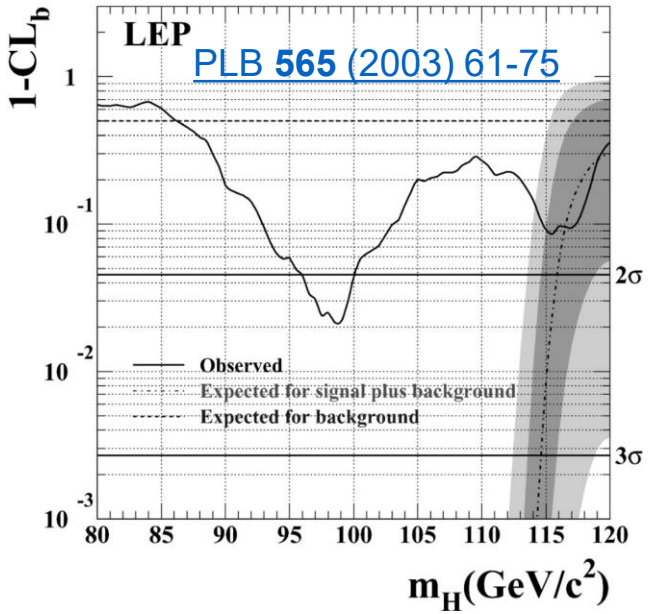


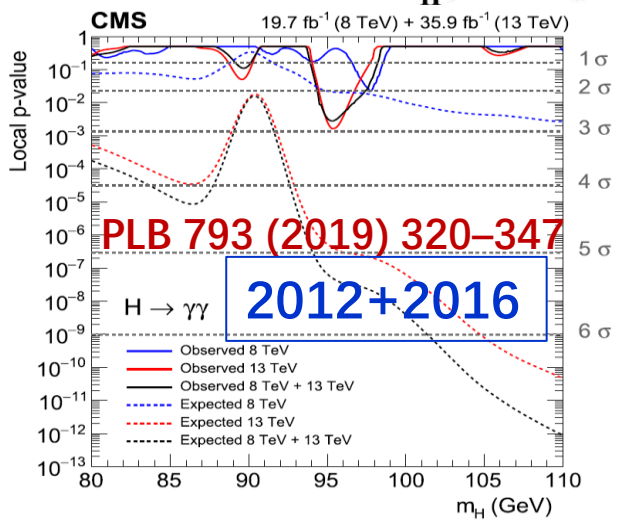


*C. Wang, **JT(*)** et al., Chin. Phys. C 46 (2022) 8, 083107*

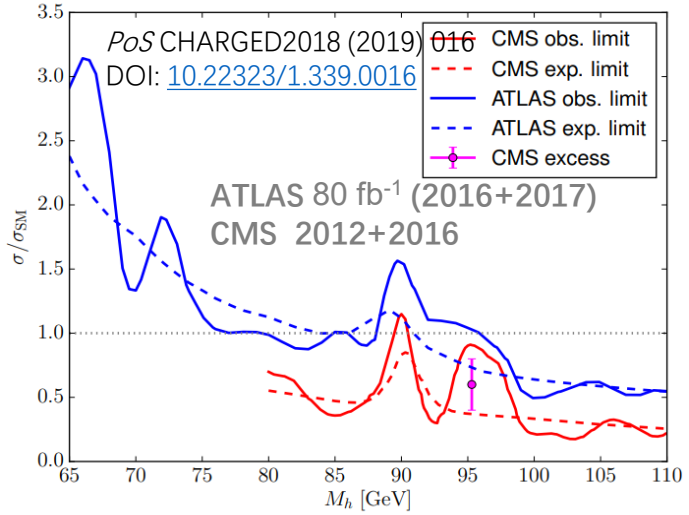
Motivations: experiments

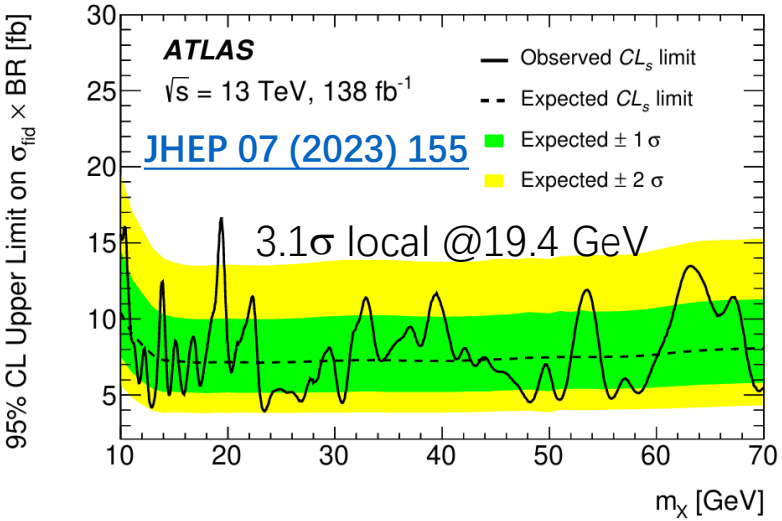
- Final **LEP** SM Higgs boson search results: >2σ excess at m_H= 98 GeV





- **Performed LM H→γγ** searches since Run1 at **CMS**
  - ✓ **2012 data** (CMS-PAS-HIG-14-037): **~2σ** local significance at **97.5 GeV**
  - ✓ **2016+2012 data** (PLB 793 (2019) 320):**2.8σ local (1.3σ global)** significance at **95.3 GeV**
- **ATLAS**
  - ✓ **LM** with Run2 80 fb^{-1}(ATLAS-CONF-2018-025) : not exclude 2012+2016 CMS observed excess
  - ✓ **Very LM** with Run2 138 fb^{-1}(**JHEP 07 (2023) 155**)



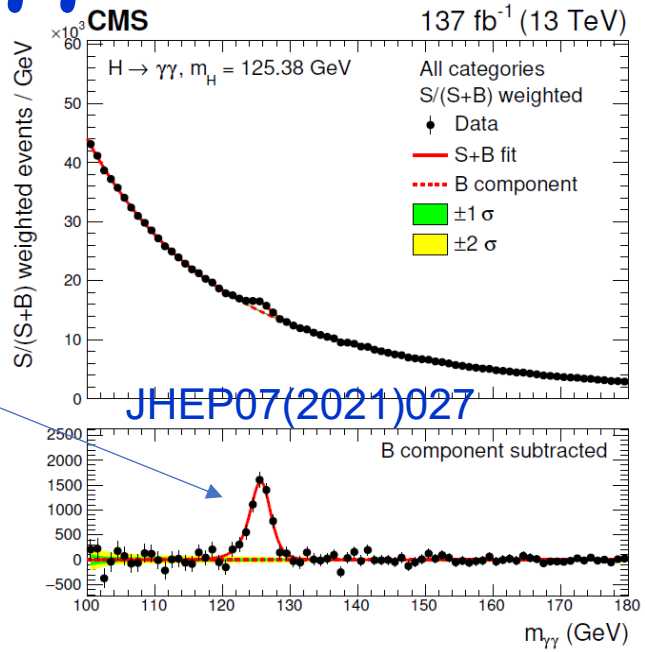


CMS full Run2 LM (PLB 860 (2025) 139067) : first LHC full Run 2 result of additional Higgs boson search in the mass range [70,110] GeV

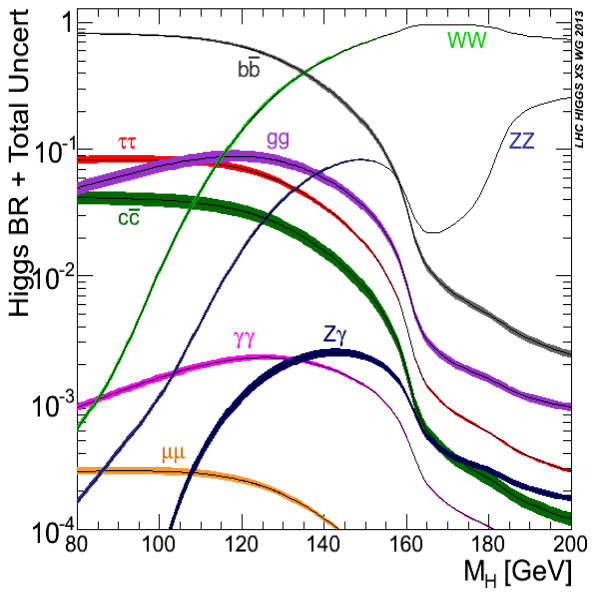
ATLAS released/published full Run2 LM results just after CMS: JHEP 01 (2025) 053

Light H→γγ search

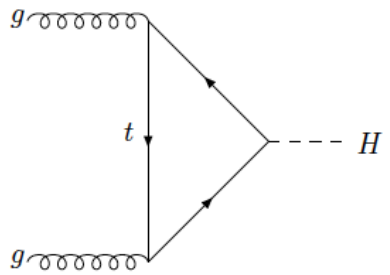
- γγ final state is important for both H_{125} measurements and **additional resonances searches :** clean final state **fully reconstructed** with high energy resolution and **high $m_{\gamma\gamma}$ resolution** (1-2%)
  - ✓ **Large backgrounds** including continuum γγ (irreducible) and fakes from γj and jj (reducible)

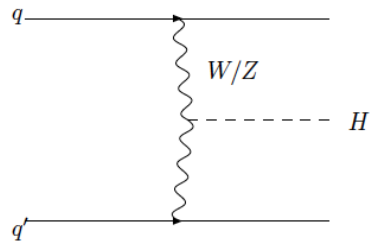


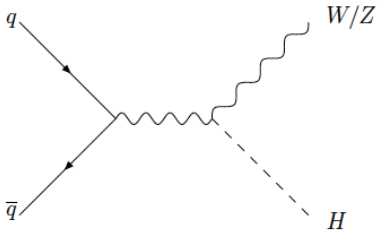
JHEP07(2021)027

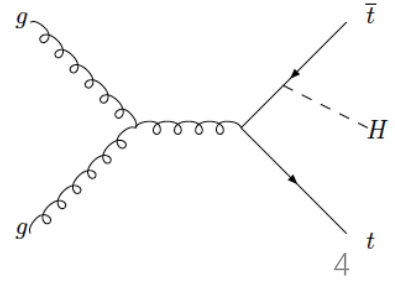


- **"SM-like" production modes:** gluon fusion (ggH), vector boson fusion (VBF), in association with a W or Z boson (VH), or with a tt pair (ttH)



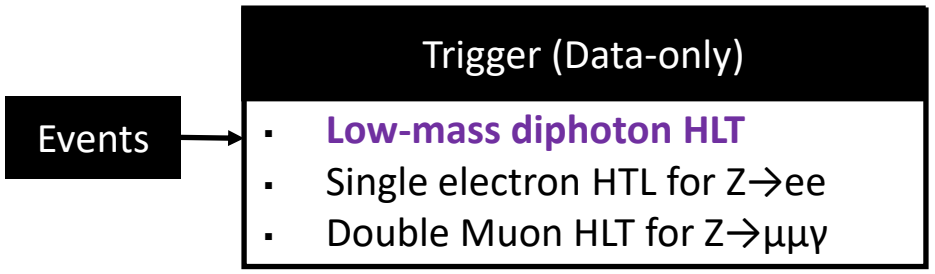






- **Cross sections and BR from** LHC Higgs Working Group YR4
- **Data samples**: Run2 132.2 fb^{-1} data
  - ✓ lost ~5 fb^{-1} as HLT path absent from start of 2018 data-taking, so 54.4 fb^{-1} data in 2018 (VLM)

Analysis workflow



- Direct search for **narrow signal peak** over **smoothly-falling background,** except for **relic Drell-Yan** in the low mass (**[70, 110] GeV**) **H→γγ analysis**
- Many **techniques** inherited from **SM H→γγ analysis** (Fabio's talk) but with **dedicated updates and optimizations in (very) low-mass case**

In 125 GeV H→γγ analyses

HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90 (2016)

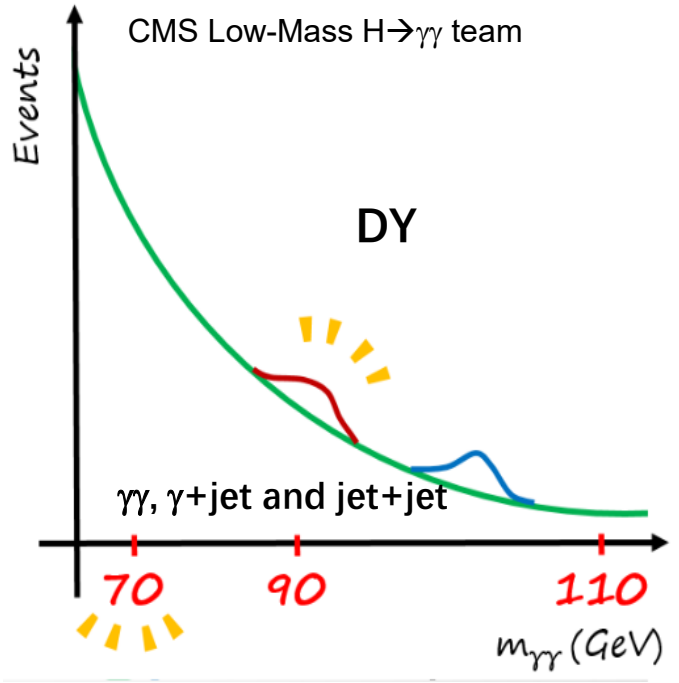
HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90 (2017 and 2018)

In (very) low-mass BSM H→γγ analyses

HLT_Diphoton30EB_18EB_R9Id_OR_IsoCaloId_AND_HE_R9Id_DoublePixelVeto_Mass55_v7
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)



- **2016** data reanalyzed with **improved calibration (legacy data)**
  - ✓ In 2016+2012 data (PLB 793 (2019) 320): ReReco 2016 data

Analysis workflow

Events

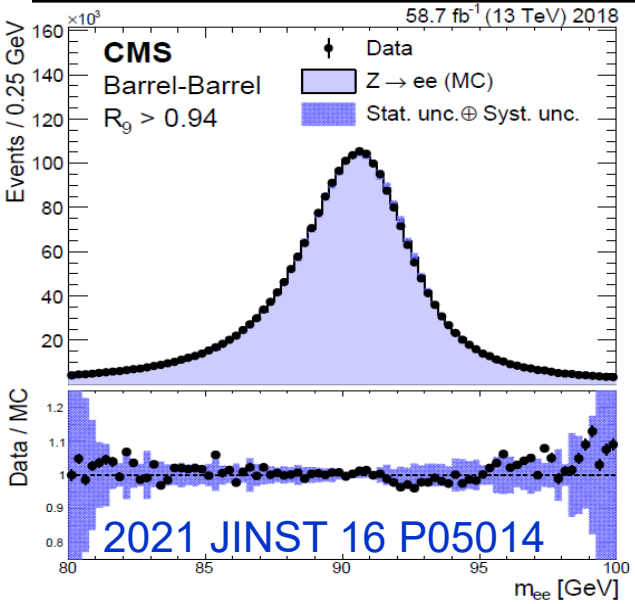
Trigger (Data-only)

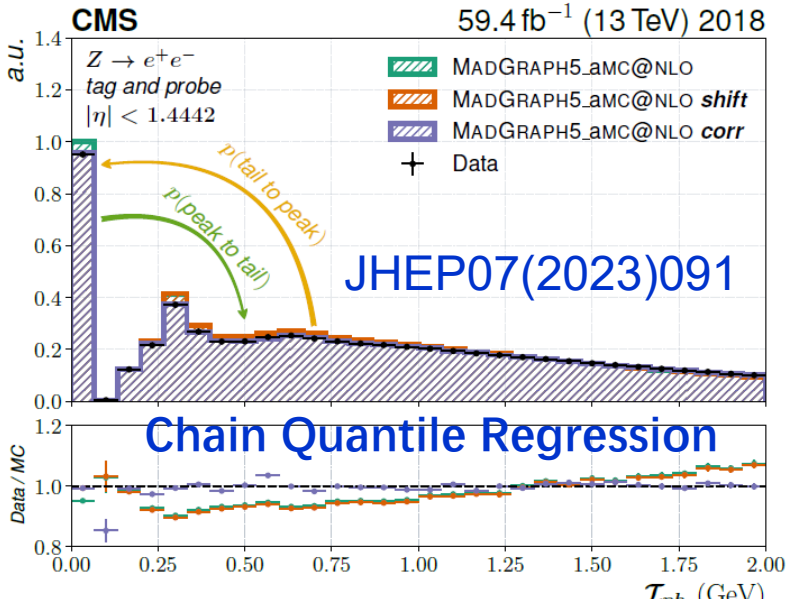
- **Low-mass diphoton HLT**
- Single electron HTL for Z→ee
- Double Muon HLT for Z→μμγ

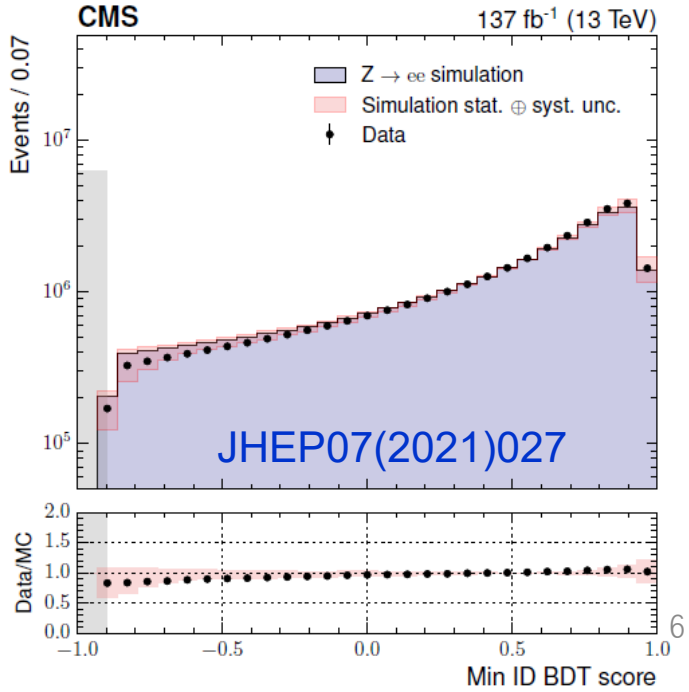
Correction & Weighting

- Energy scaling and smearing (S+S) corrections
- MC corrections (Run2 CQR)
- Re-evaluation of photon ID MVA

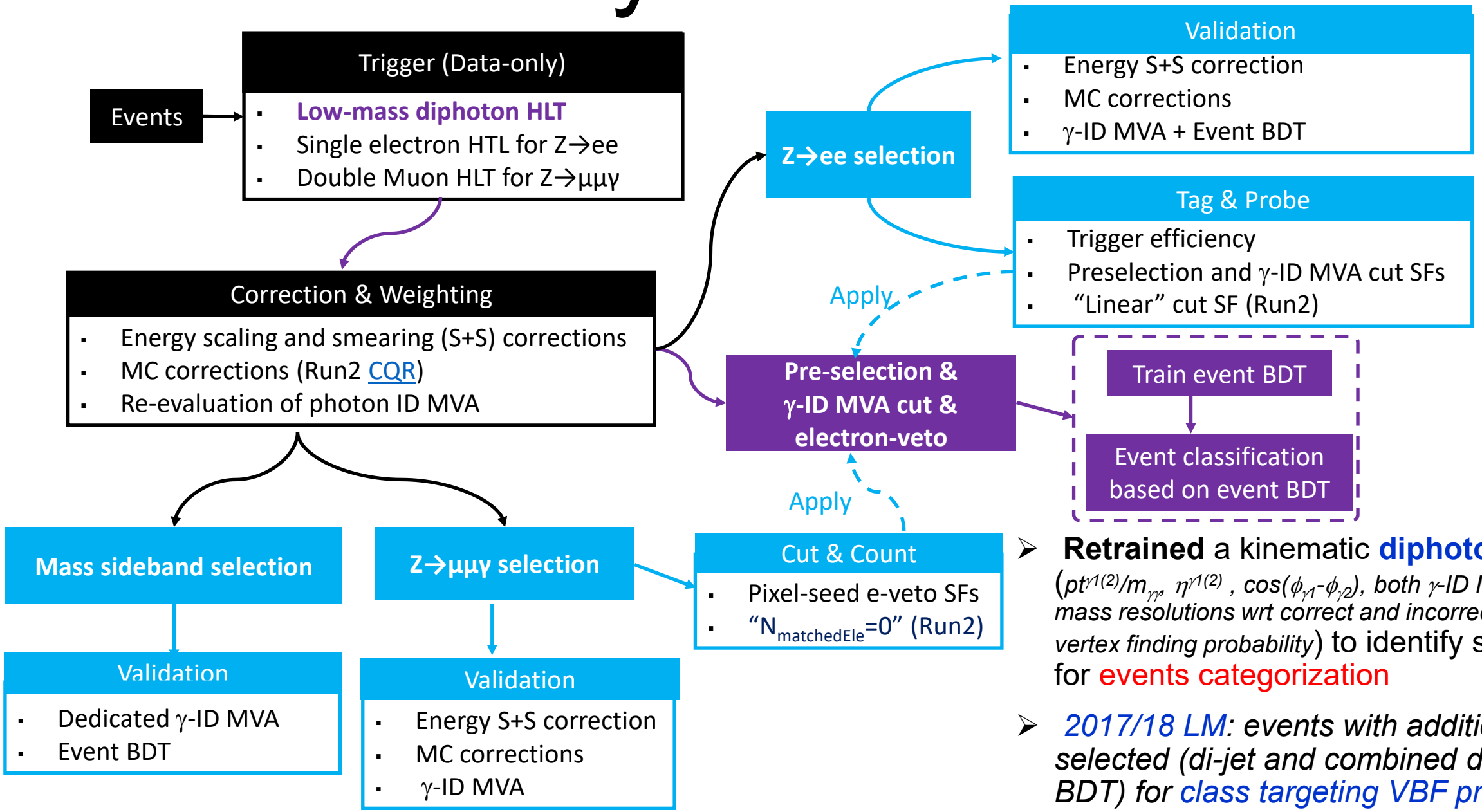
- Many **techniques** inherited from **SM H→γγ analysis** (Fabio's talk) but with **dedicated updates and optimizations in (very) low-mass case**







Analysis workflow



- **Retrained** a kinematic **diphoton BDT** ($pt^{\gamma 1(2)}/m_{\gamma\gamma}$, $\eta^{\gamma 1(2)}$, $\cos(\phi_{\gamma 1}-\phi_{\gamma 2})$, *both γ-ID MVA scores, mass resolutions wrt correct and incorrect vertices, vertex finding probability*) to identify signal and for events categorization
- *2017/18 LM: events with additional jets selected (di-jet and combined di-jet + γγ BDT) for class targeting VBF process*

Analysis workflow

Events

Trigger (Data-only)
- **Low-mass diphoton HLT**
- Single electron HTL for Z→ee
- Double Muon HLT for Z→μμγ

Correction & Weighting
- Energy scaling and smearing (S+S) corrections
- MC corrections (Run2 CQR)
- Re-evaluation of photon ID MVA

Z→ee selection

Validation
- Energy S+S correction
- MC corrections
- γ-ID MVA + Event BDT

Tag & Probe
- Trigger efficiency
- Preselection and γ-ID MVA cut SFs
- "Linear" cut SF (Run2)

Apply

Pre-selection & γ-ID MVA cut & electron-veto

Apply

Cut & Count
- Pixel-seed e-veto SFs
- "$N_{matchedEle}$=0" (Run2)

Mass sideband selection

Validation
- Dedicated γ-ID MVA
- Event BDT

Z→μμγ selection

Validation
- Energy S+S correction
- MC corrections
- γ-ID MVA

Train event BDT

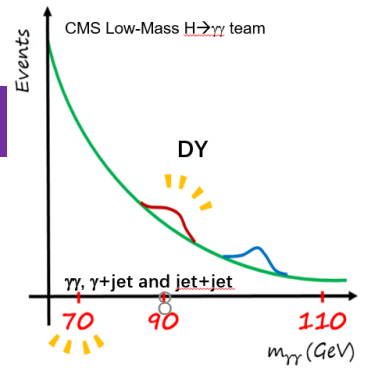
Event classification based on event BDT

DY suppression

Signal/Background modeling

Statistical analysis

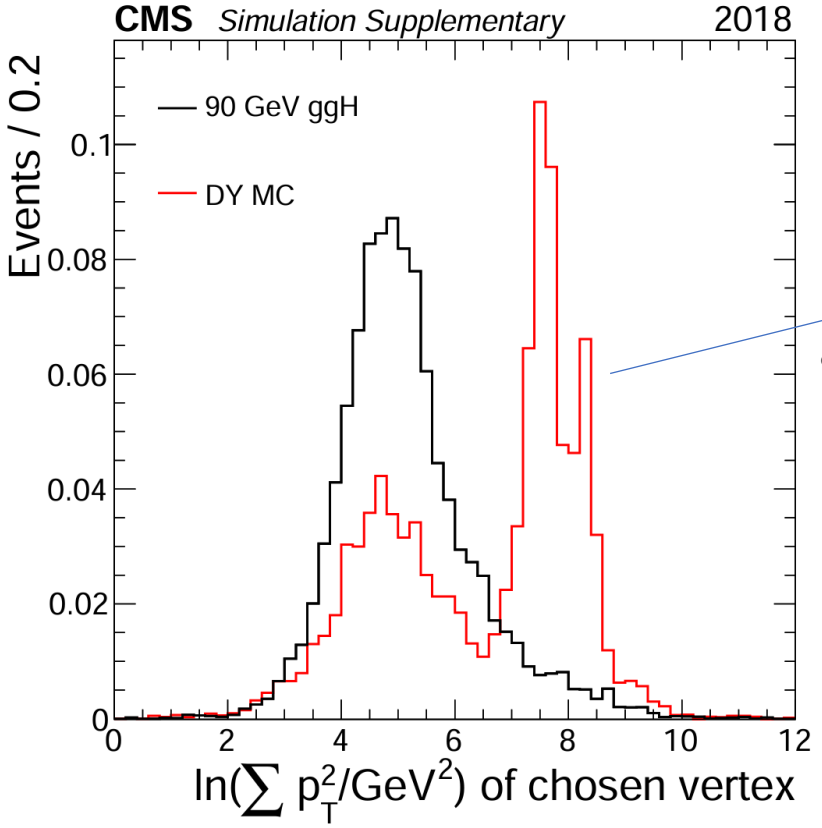
➢ **Dedicated Drell-Yan suppression** strategy in **LM analysis**

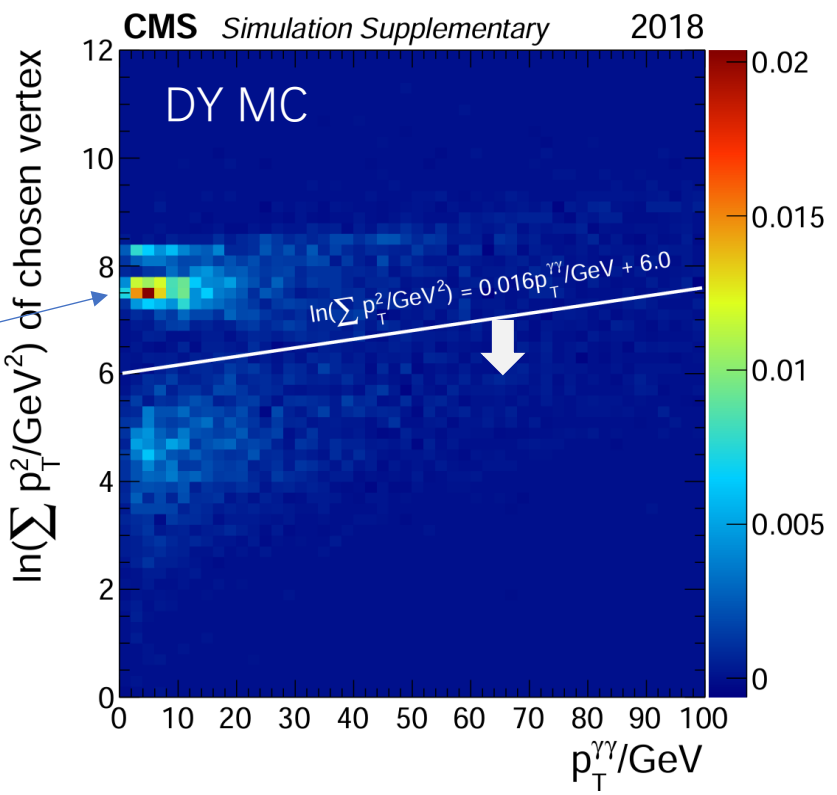


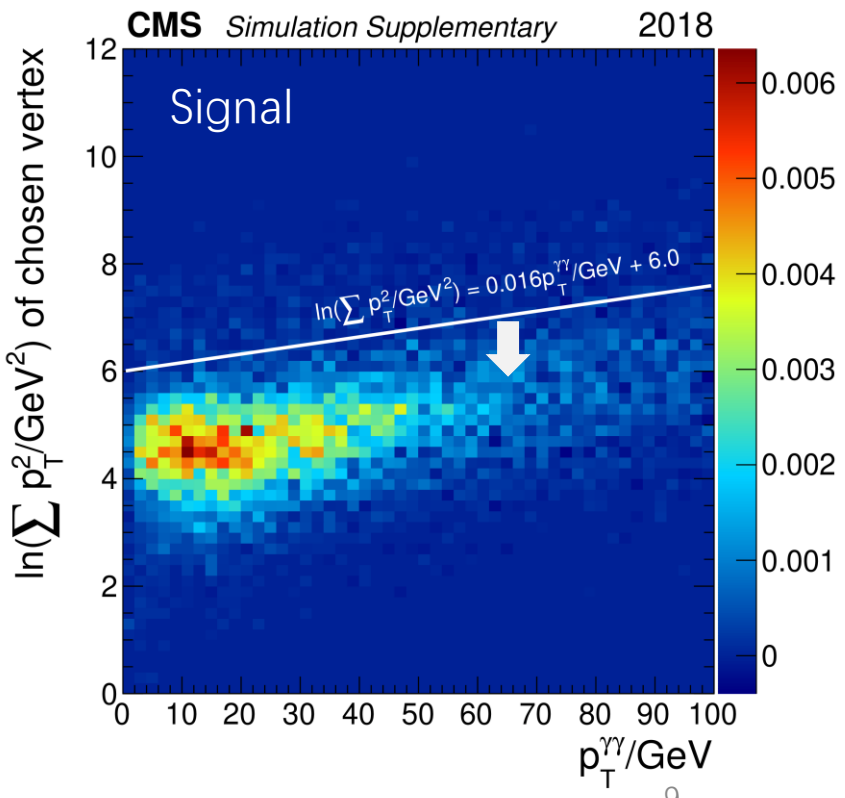
LM H→γγ : DY suppression

- **Relic Drell-Yan veto** (**no pixel detector hit to veto electrons**) reinforced with:
  - ✓ **Rejection** of **photon candidates also reconstructed as electrons**
  - ✓ Maximum value of **ln ($\Sigma p_T^2/GeV^2$)** [tracks in chosen vertex] **as function of $p_T^{\gamma\gamma}$:** ln ($\Sigma p_T^2/GeV^2$) < 0.016 $p_T^{\gamma\gamma}$ /GeV+ 6.0 ("Linear" cut)

Improved strategy wrt analysis with 2016+2012 data (PLB 793 (2019) 320); Ongoing Run3 analysis, ML



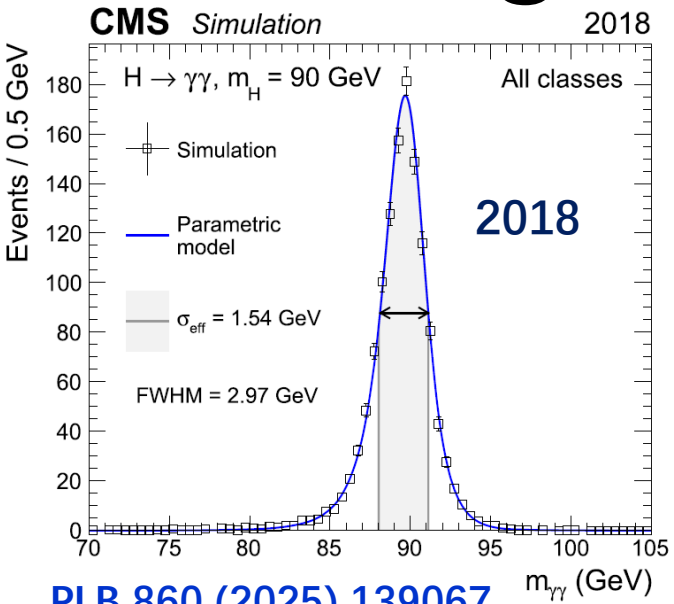




HIG-20-002 Supplementary

LM H→γγ : signal and bkg modeling

- **Signal modeling** (sum of Gaussian functions): event classes x production modes x correct/incorrect vertex; simultaneous signal fitting then interpolation



- **Background modeling** (discrete profiling, arXiv:1408.6865): *sums of continuous functions* (different families/orders) with *"DCB+exponential" for relic DY* (normalization floating)

$$Nf \times Exp(x) + N(1-f)(DCB(x)+exp(x)) = Nf \times \sum_{i=0}^{M} \beta_{2i} e^{\beta_{2i+1} x} + N(1-f)(DCB(x)+exp(x))$$

$$Nf \times Pow(x) + N(1-f)(DCB(x)+exp(x)) = Nf \times \sum_{i=0}^{M} \beta_{2i} x^{\beta_{2i+1}} + N(1-f)(DCB(x)+exp(x))$$

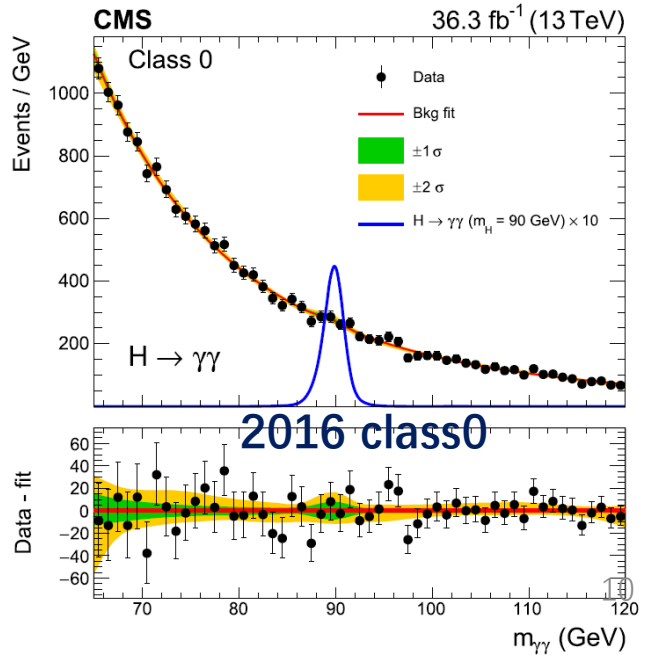
$$Nf \times Ber(x) + N(1-f)(DCB(x)+exp(x)) = Nf \times \sum_{i=0}^{M} \beta_i b_{i,M} + N(1-f)(DCB(x)+exp(x))$$

$$\text{with} \quad b_{i,M} = \binom{M}{i} x^i (1-x)^{M-i}$$

$$Nf \times Lau(x) + N(1-f)(DCB(x)+exp(x)) = Nf \sum_{i=0}^{M} \beta_i x^{-\alpha_i} + N(1-f)(DCB(x)+exp(x))$$

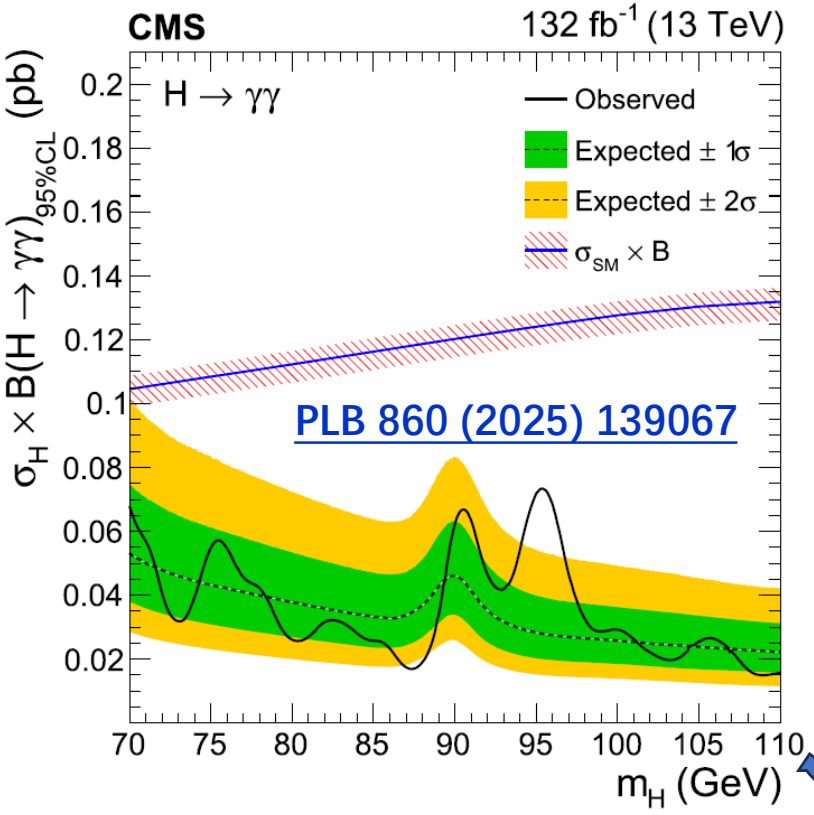
$$\text{with} \quad \alpha_i = 4,5,3,6,2,7,\ldots \quad \text{for} \quad i = 0,1,2,3,4,5,\ldots$$

PLB 860 (2025) 139067

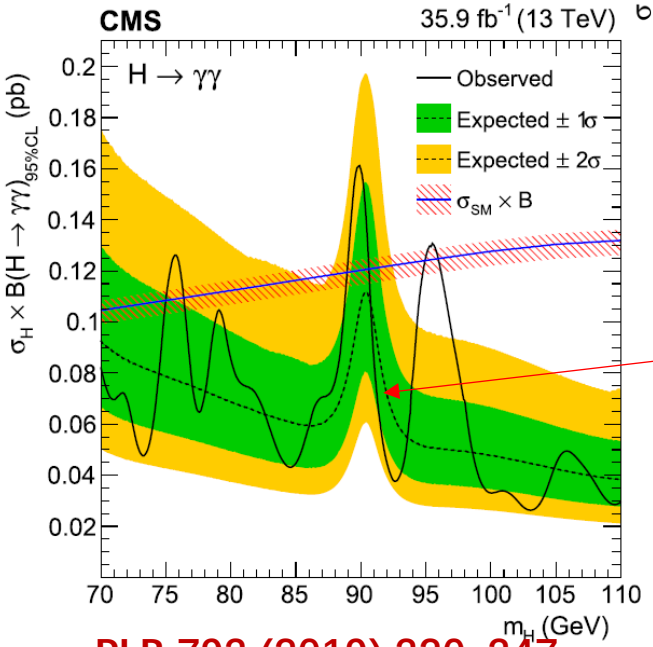


LM H→γγ Run2: upper limits on σ X B

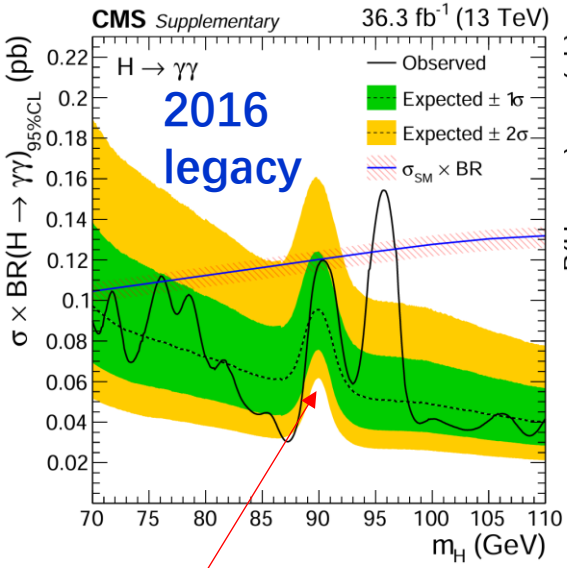
- **Observed absolute 95% CL UL on σ X B between 15-73 fb** (22-53 fb expected)

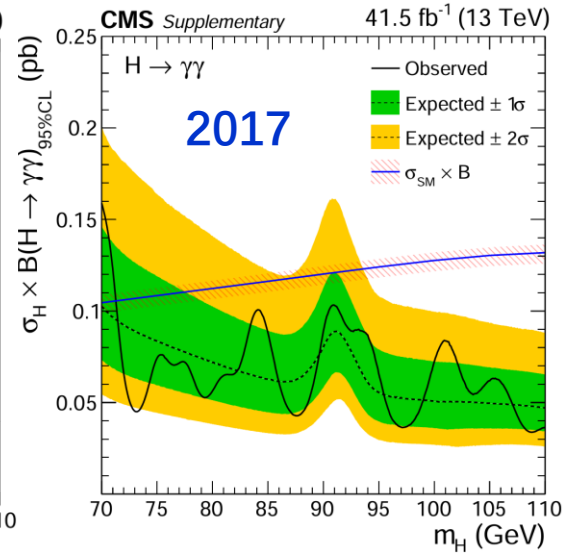


PLB 860 (2025) 139067

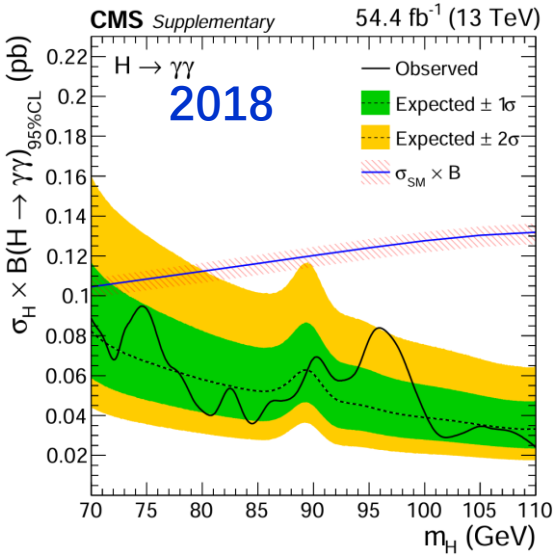


PLB 793 (2019) 320–347
(ReReco 2016 data)





HIG-20-002 Supplementary



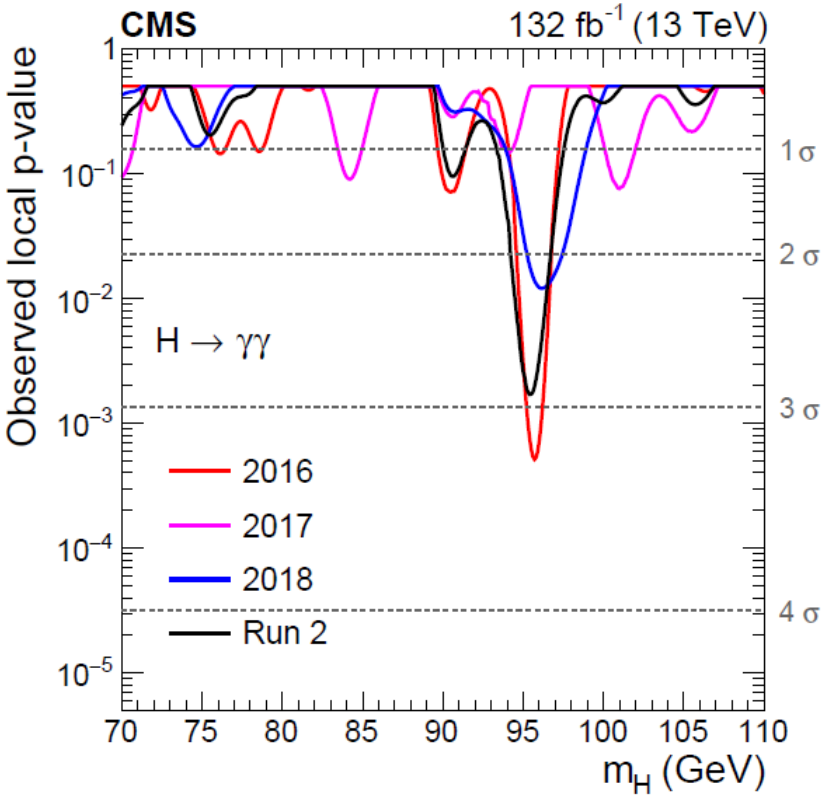
Performance against DY in the Z pole mass region is **improved**

- **Results of each year**

✓ **Much improved** compared to previous 2016 results
[26-161 fb (obs.) , 37-110 fb (exp.)]

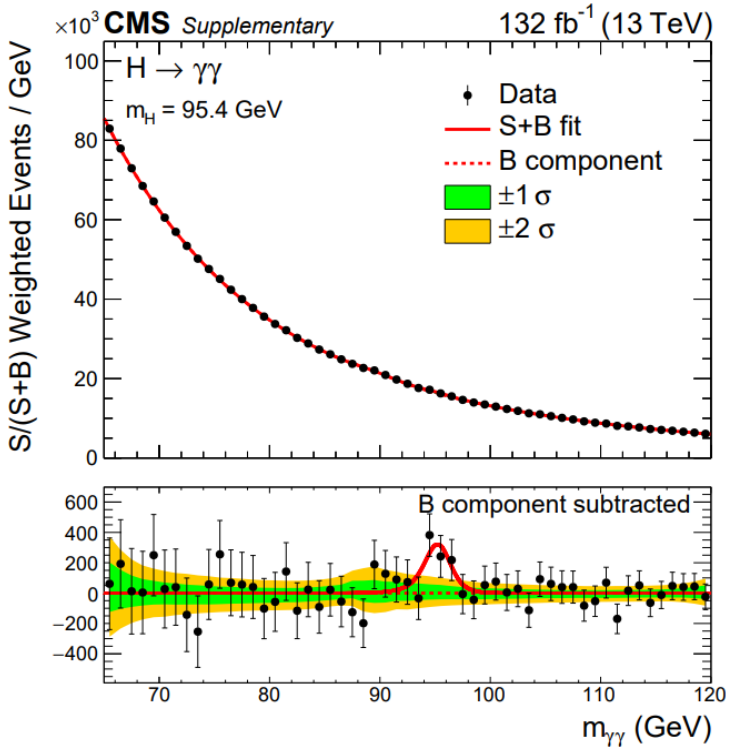
LM H→γγ Run2 Results

- **Observed local p-values** for 2016, 2017, 2018 and combination



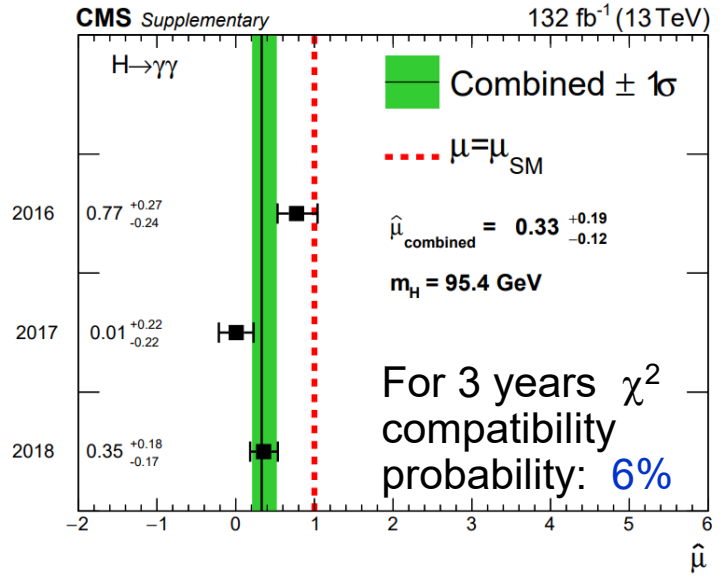
PLB 860 (2025) 139067

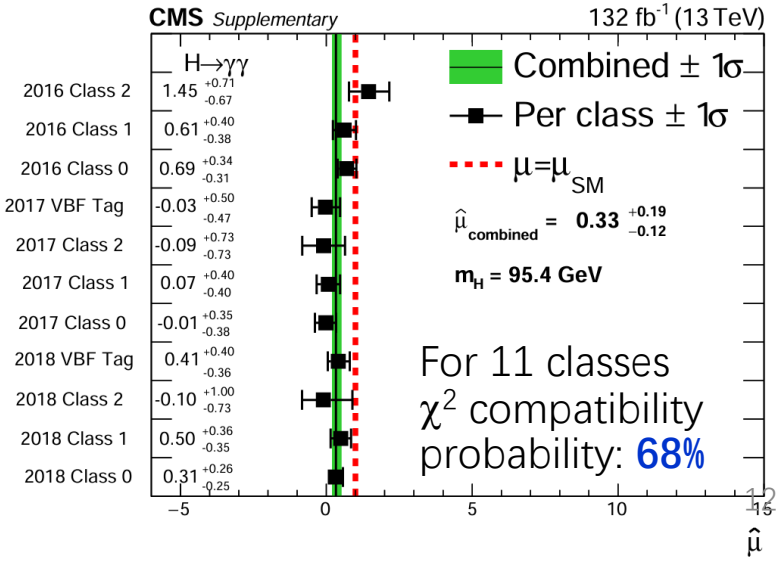
- **S/(S+B)-weighted $m_{\gamma\gamma}$ distribution** with S+B fit for m_H = 95.4 GeV



PLB 860 (2025) 139067

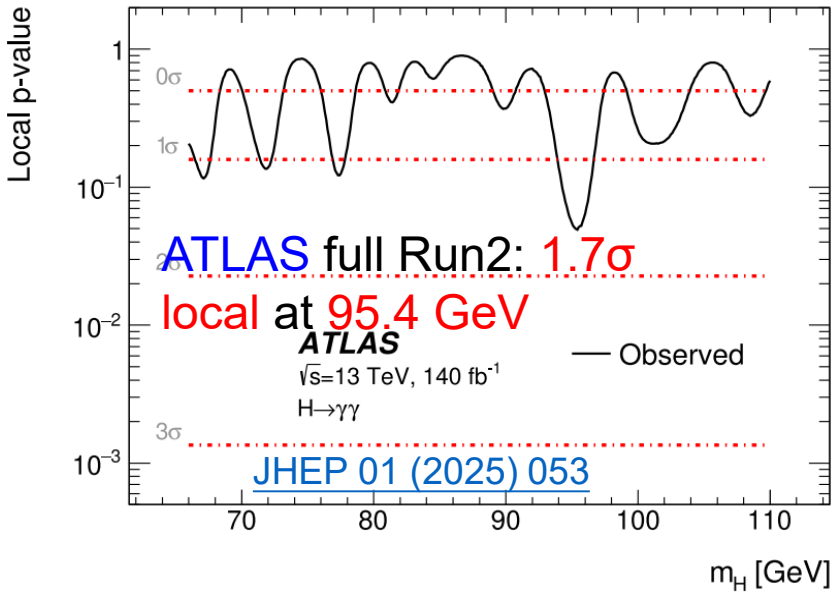
- 'Signal' strengths μ : fixing m_H = 95.4 GeV HIG-20-002 Supplementary

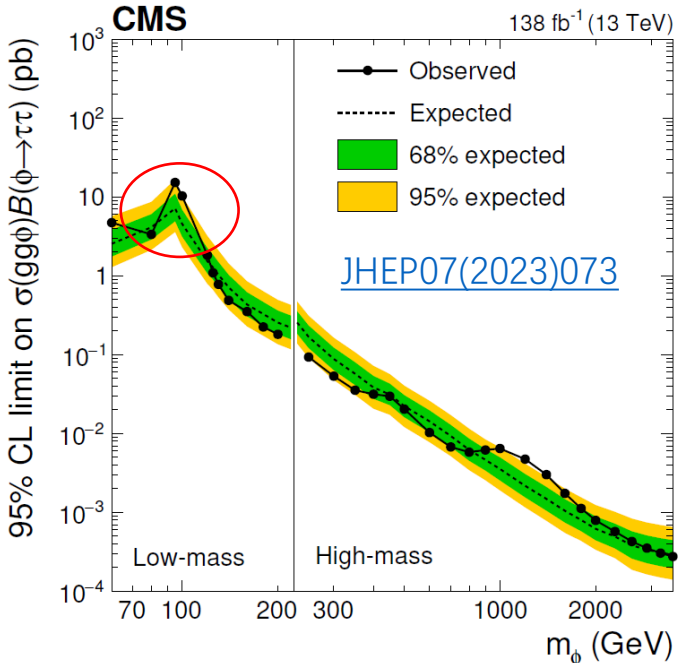


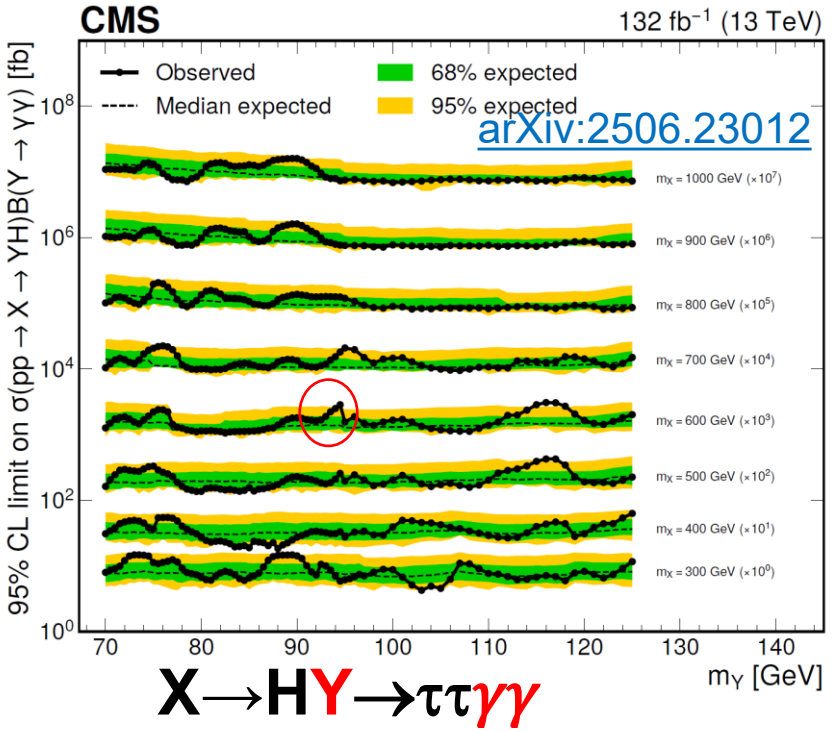


- **Excess with ~2.9σ local (1.3σ global) significance at $m_{\gamma\gamma}$= 95.4 GeV**

~95 GeV excess







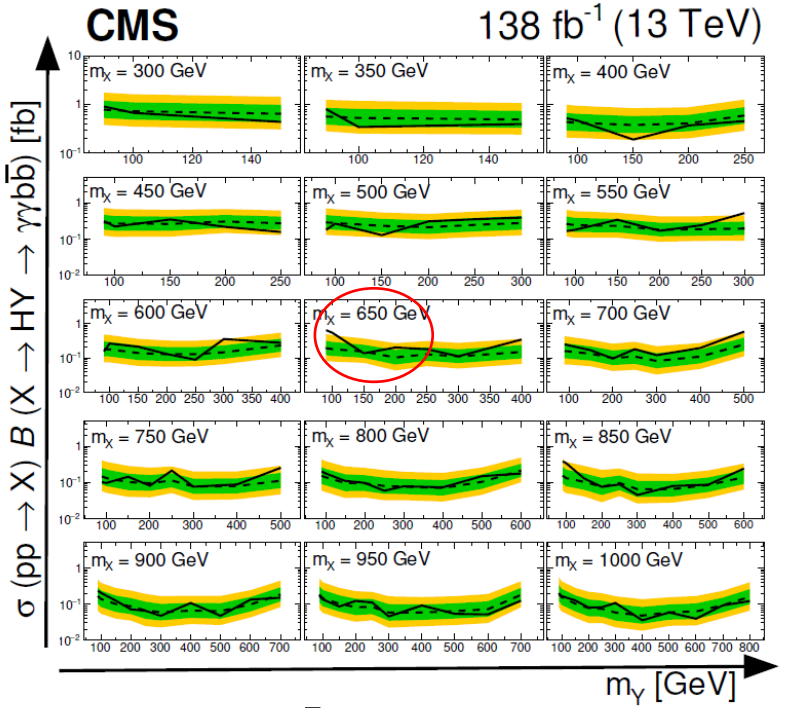
X→HY→ττγγ

2.5σ local @ m_X = 600 GeV, m_Y = 95 GeV

ggϕ→ττ

2.6σ (2.3σ) local (global) @ 95 GeV

JHEP05(2024)316



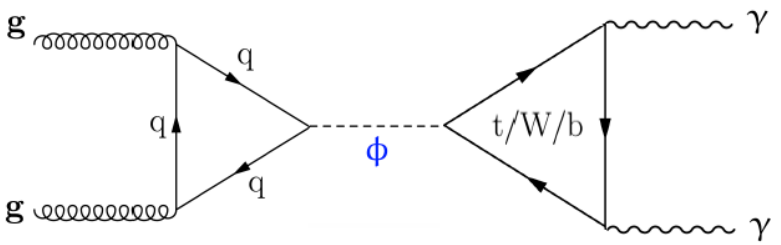
X → HY → γγbb

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

Searches for X→HY: Shaowei's talk

Search for [10,70] GeV H→γγ

- **Released** in March 2025 for "**La Thuile 2025**"

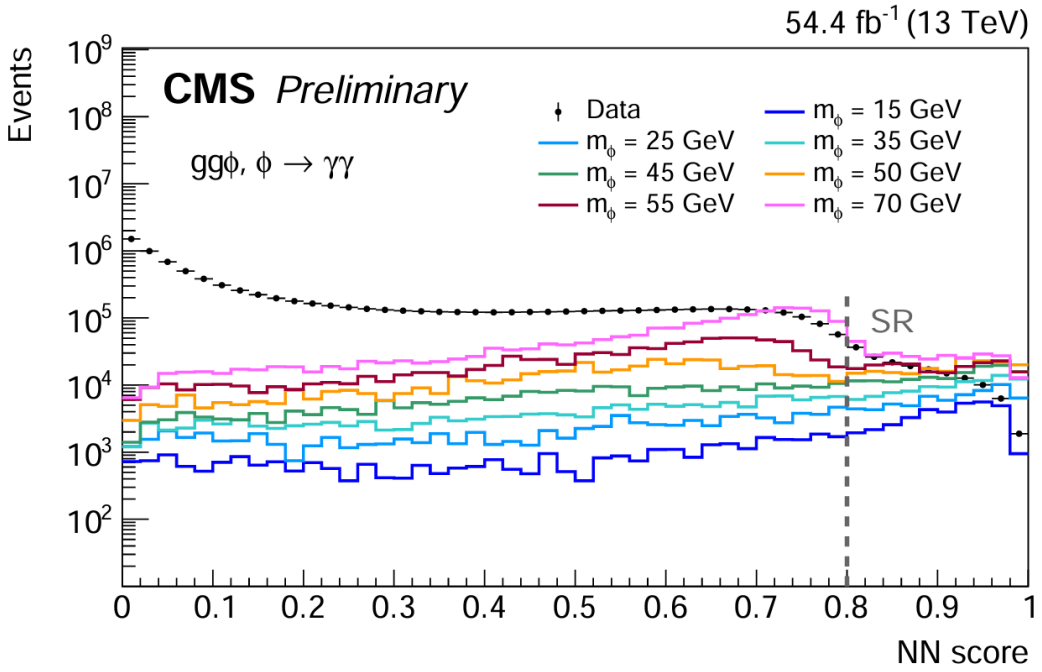


- Motivated by GeV-scale **Axion-like particles** (**ALP**s), and performed using **2018 data** without any diphoton mass cut in the HLT trigger

CMS-PAS-HIG-24-014

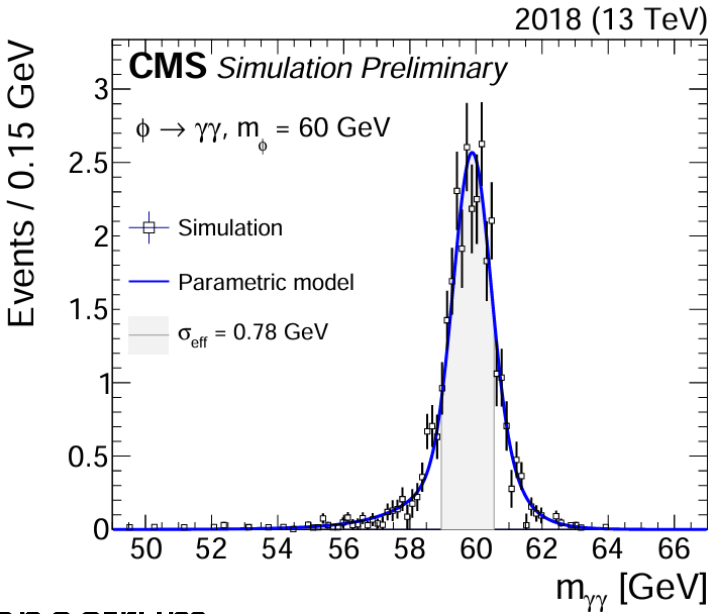
- Many elements (such as trigger efficiencies, pre-selections) inherited from the **Run2 low-mass H→γγ analysis** as introduced in previous slides

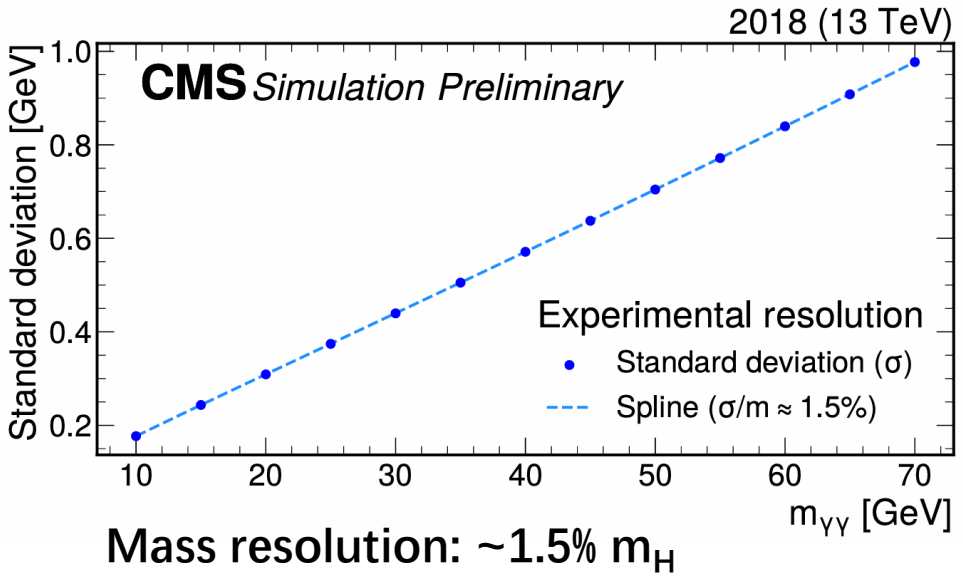
- A neural network (**NN**) is employed to enhance the selection of events with a high sig-to-bkg ratio and good mass resolution
  - ✓ Variable inputs include photon kinematics and diphoton features along with discrete mass hypothesis
  - ✓ Signal region (SR) : **NN score>0.8** with highest sensitivity



[10,70] GeV H→γγ: sig and bkg modeling

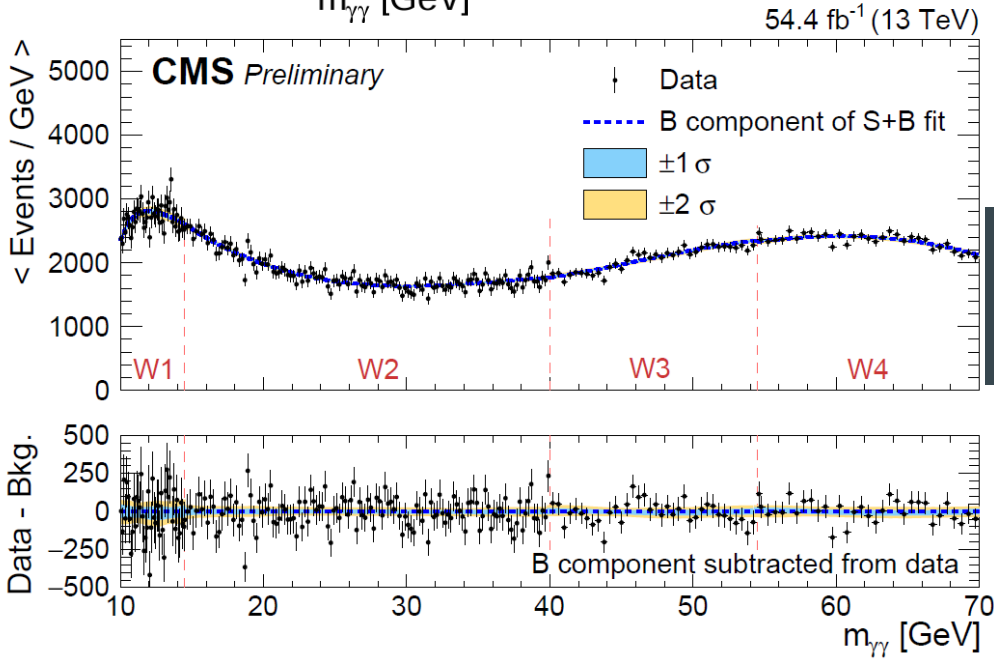
- **Signal model**: Double Crystal ball + Gaussian





Mass resolution: ~1.5% m_H

- **Background model**: mass spectrum divided into four sub ranges, with the discrete profiling method applied in each one
  - ✓ **Two distinct turn-on features** : **one ~50 GeV** driven by the photon pT trigger thresholds, and **another ~12 GeV** arising from the photon isolation criteria starting to be inefficient for close-by objects from highly boosted diphoton candidates

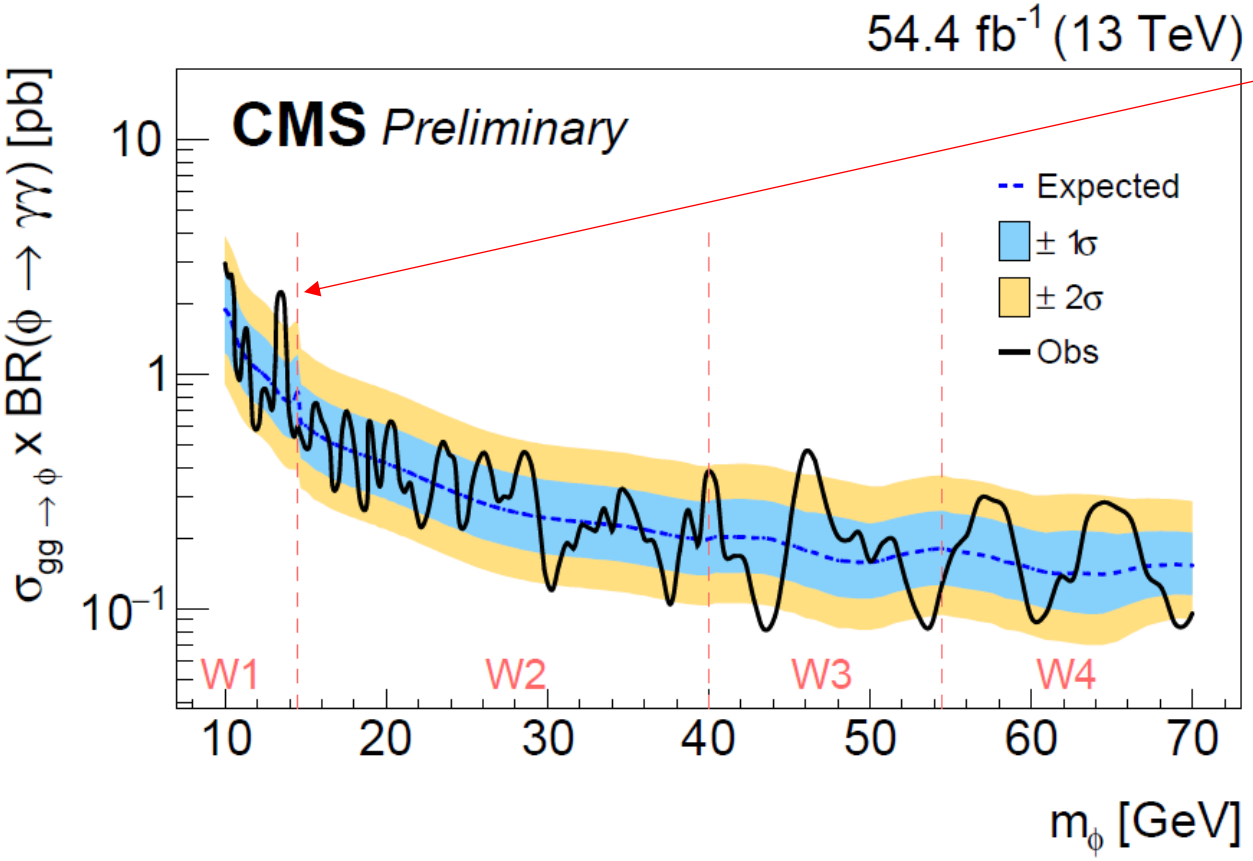


CMS-PAS-HIG-24-014

Envelope of functions includes:
- Bernstein 2-4
- Exponential 3
- Power Law 3

Results of search for [10,70] GeV H→γγ

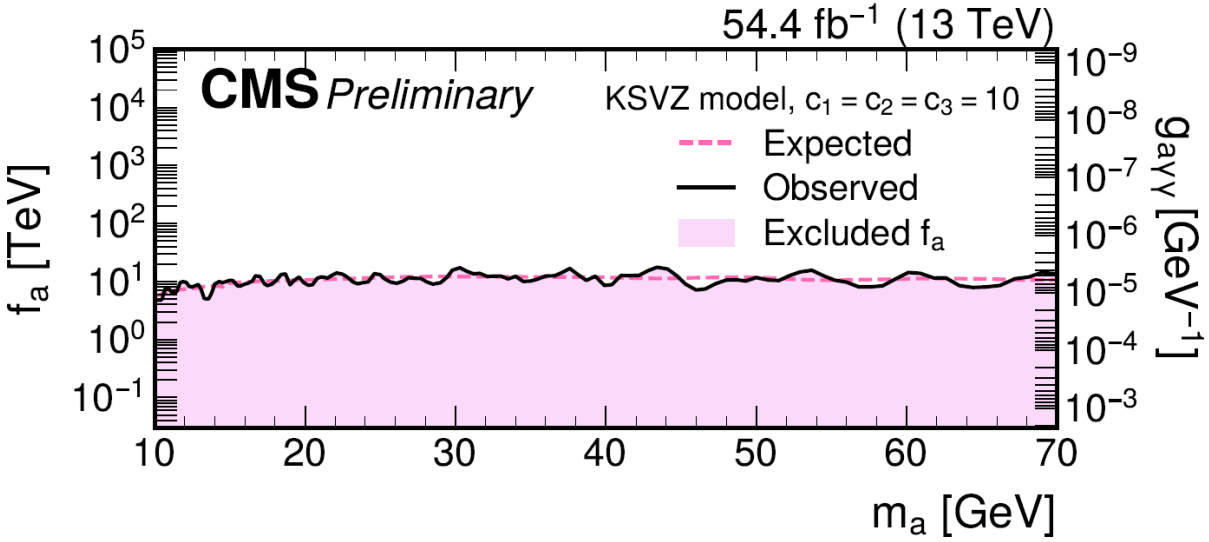
Obs. and exp. 95% UL on the gluon fusion production cross section of a narrow diphoton resonance



CMS-PAS-HIG-24-014

Most significant excess at **13.6 GeV** with **3.47σ (1.9σ) local (global)** significance

Interpretation in the context of the ALP model: constraints on the ***ALP decay constant f_a*** ,and the corresponding upper limits on ***the coupling $g_{a\gamma\gamma}$***



$$g_{a\gamma\gamma} \equiv \alpha_{EM} \cdot E/(\pi \cdot f_a)$$

with $E = (c_2 + 5/3 \cdot c_1)$ [arXiv:1710.01743]

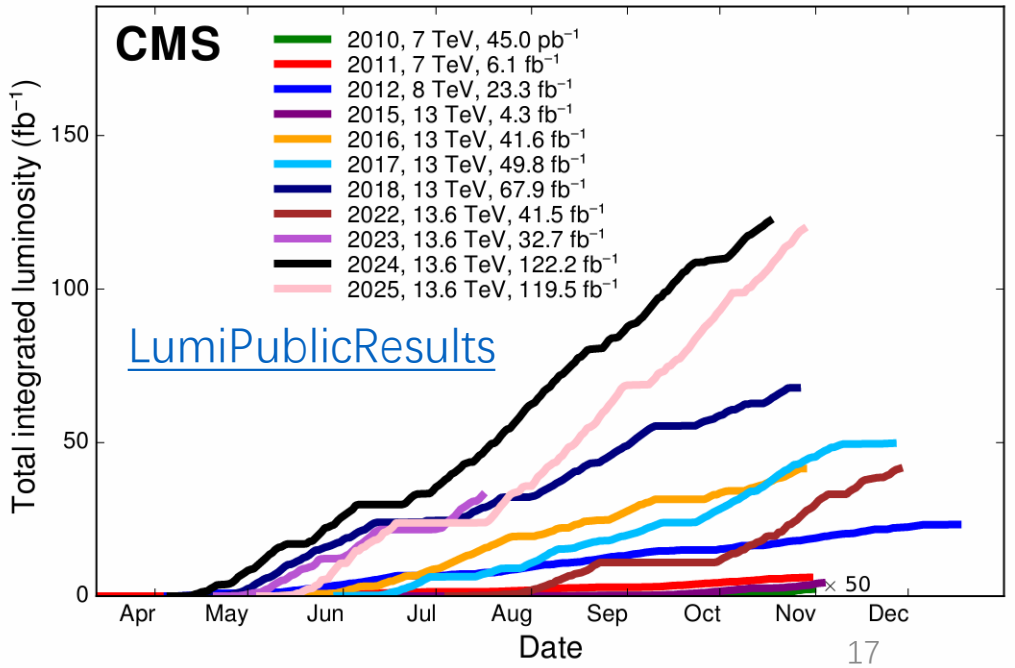
Summary

- **Results of search for light Higgs bosons decaying into $\gamma\gamma$ channel using Run2 data are presented**
  - ✓ LM (70-110 GeV) results with full Run2 data (PLB 860 (2025) 139067): first search for $\gamma\gamma$ resonances in this mass range with full Run 2 data !
  - ✓ VLM (10-70 GeV) results with 2018 data (CMS-PAS-HIG-24-014) : released for "La Thuile 2025"

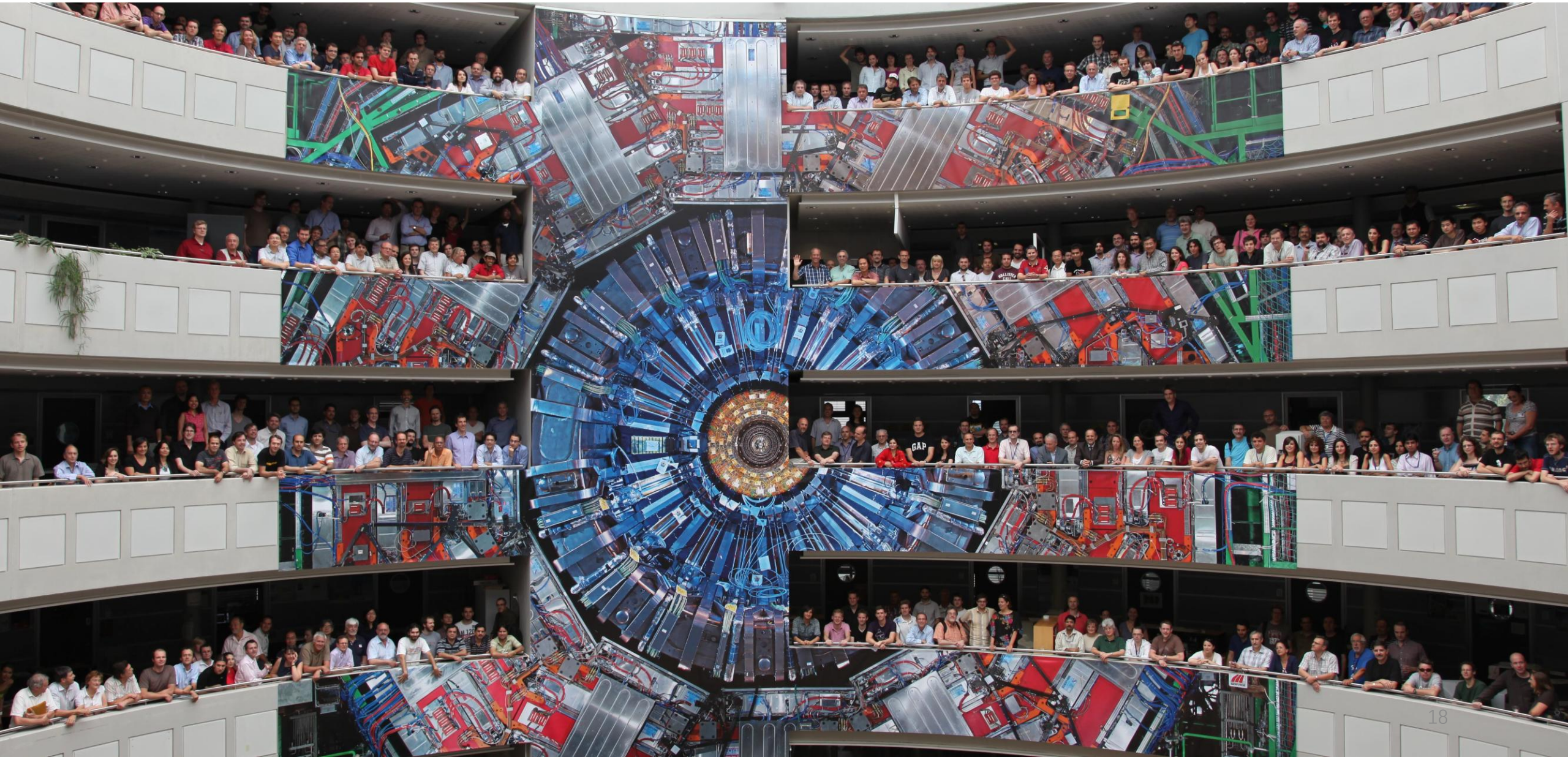
- **No strong evidence** for the existence of extra Higgs bosons found so far, but some **modest excesses** in the searching ranges
  - ✓ **2.9σ** (1.3σ) local (global) significance at $m_{\gamma\gamma}$=95.4 GeV
  - ✓ **3.47σ** (1.9σ) local (global) significance at $m_{\gamma\gamma}$=13.6 GeV

- Analysis with **Run3 data** is ongoing…more (Run3 ~300 fb^{-1}) data will be included to conclude on the nature of the excesses in Run2

- **Stay tuned!**



Thanks a lot for your attention!

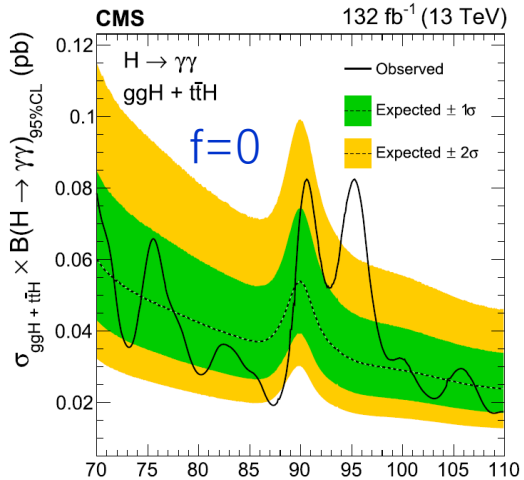


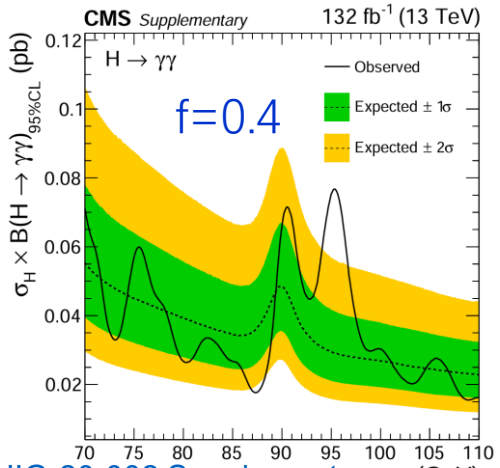
LM H→γγ Run2 Results Interpretations

- **Limits** assuming different proportions of *ggH+ttH* and *VBF+VH* cross sections

$$\sigma = (1-f) \times (\sigma_{SM}^{ggH} + \sigma_{SM}^{t\bar{t}H}) + f \times (\sigma_{SM}^{VH} + \sigma_{SM}^{VBF})$$

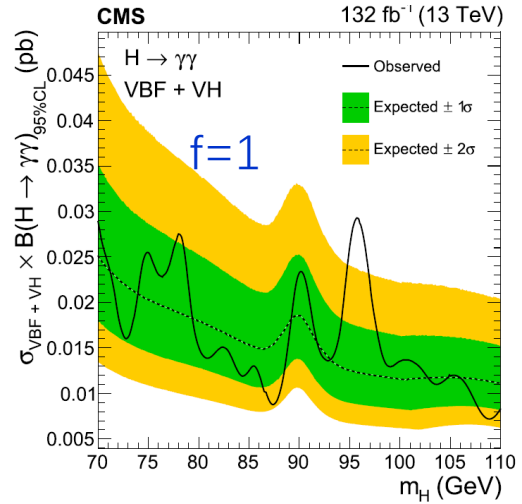
with f = 0, 0.1, 0.2, ⋯, 0.9, 1.0

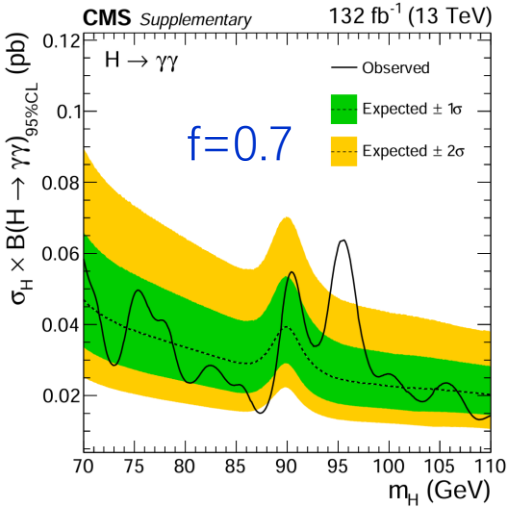




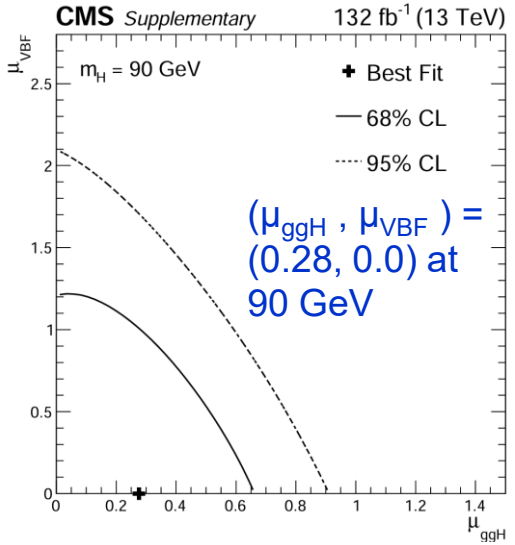
PLB 860 (2025) 139067

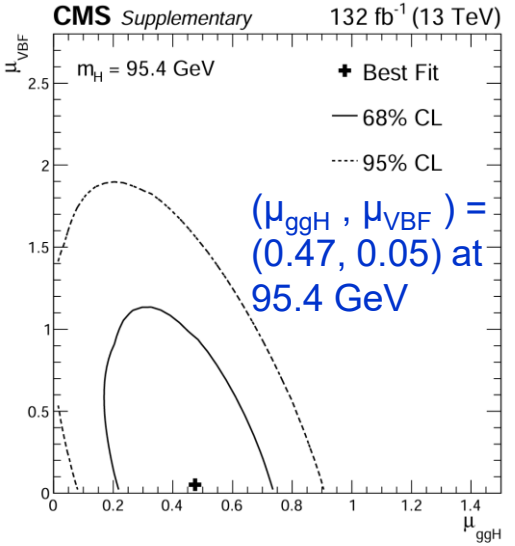
HIG-20-002 Supplementary



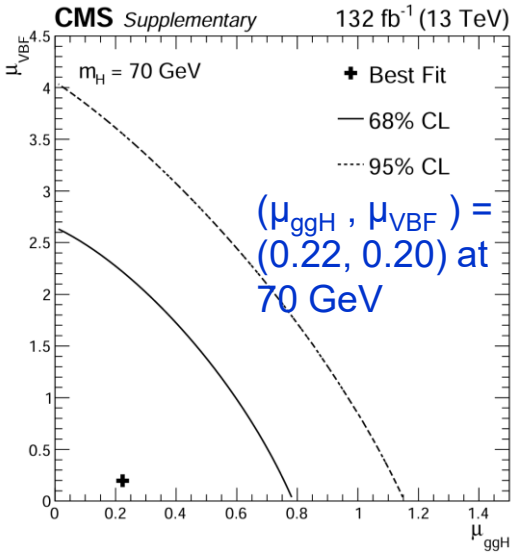


- **Maximum likelihood estimates as a function of μ_{ggH} versus μ_{VBF} at different mass points**





HIG-20-002 Supplementary



More interpretations