Higgs boson property measurements with H→γγ at CMS

Jie Xiao (IP2I-Lyon)

On behalf of the CMS collaboration

In particular the joint IP2I+IHEP team

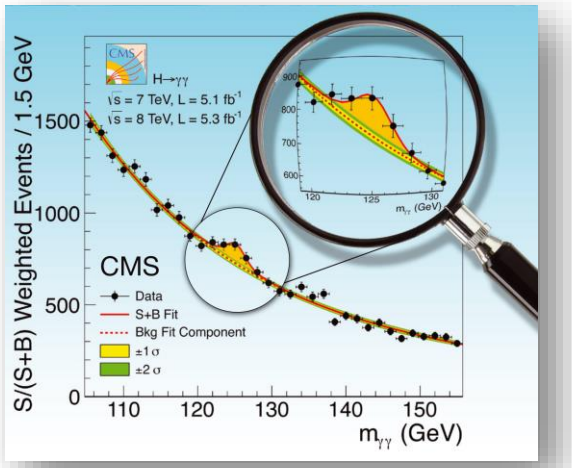
Susan Gascon-Shotkin, Junquan Tao, Morgan Lethuillier, Antoine Lesauvage, Guoming Chen, Jiawei Fan, Sijing Zhang, Aamir Shahzad, …

Overview

- Recent analyses based on **H→γγ** are introduced
- All the analyses used the full **Run2** data collected by the CMS detector
- Included analyses:
  - *HIG-19-015*: SM H→γγ signal strengths & STXS — Publication: *JHEP07(2021)027*
  - *HIG-19-016*: SM H→γγ differential and fiducial x-sec — Publication: *JHEP07(2023)091*
  - *HIG-21-014*: Search for non-resonant HH→WWγγ
  - *HIG-19-018*: Search for non-resonant HH→bbγγ — Publication: *JHEP03(2021)257*
  - *HIG-21-011*: Search for resonant X→HH/HY→bbγγ — Accepted by JHEP

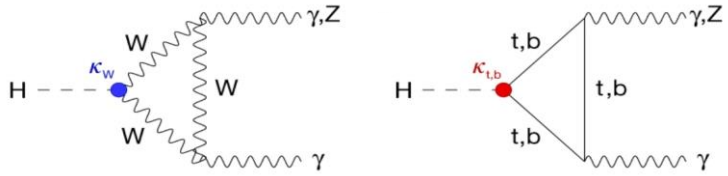
Introduction of H→γγ decay channel

- One of the **golden channels** in the Higgs observation
  - Small branching ratio
    - ~ 0.23 %
  - Clean final state

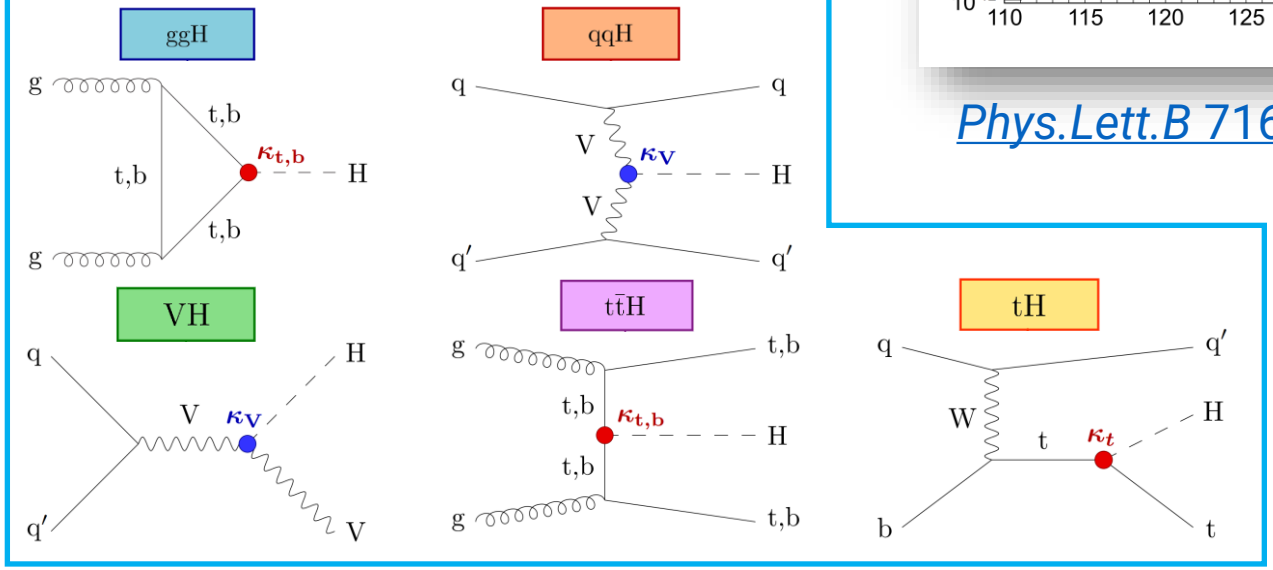


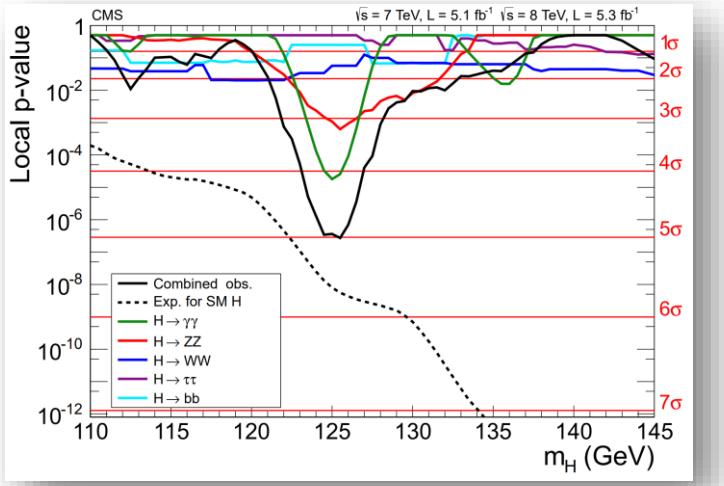
[Phys.Lett.B Vol.716 Iss.1]

H→γγ decay channel



Higgs production channel

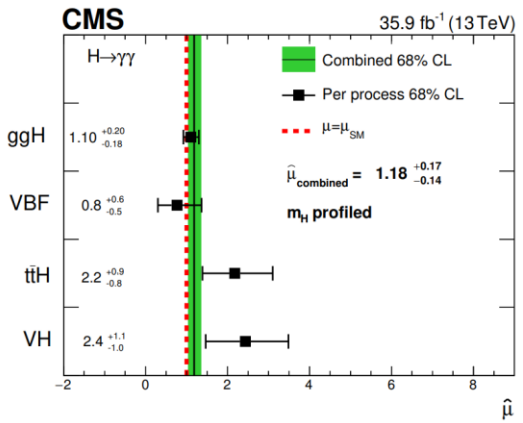


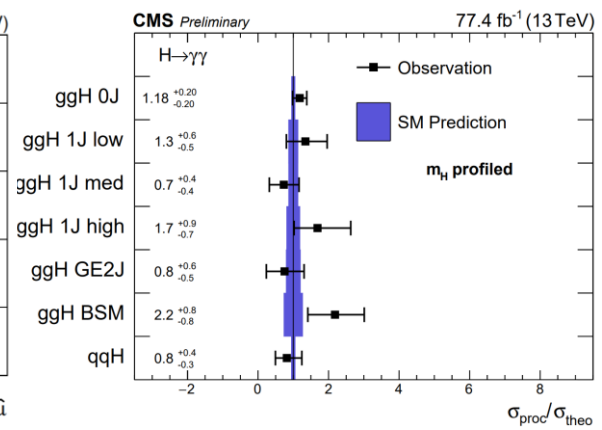


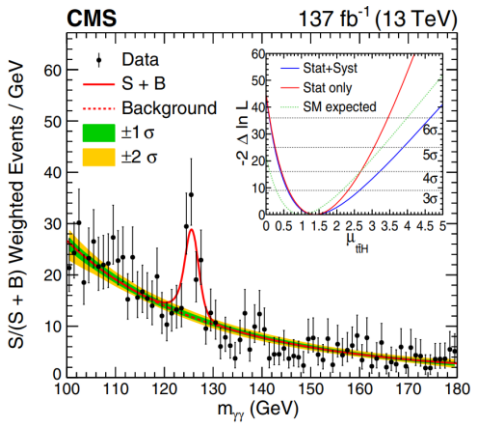
[Phys.Lett.B 716 (2012) 30-61]

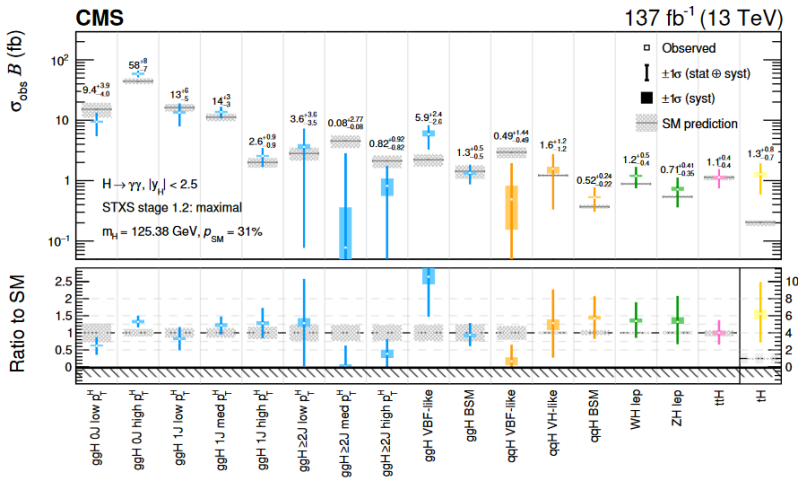
Roadmap of the Run2 H→γγ analysis at CMS

HIG-16-040	*HIG-18-029*	*HIG-19-013*	*HIG-19-015*
2016 ggH, VBF, VH, ttH	2016+2017 ggH+VBF STXS Stage 1.0	Full Run2 ttH	Full Run2 ggH, VBF, VH, ttH, tH STXS Stage 1.2





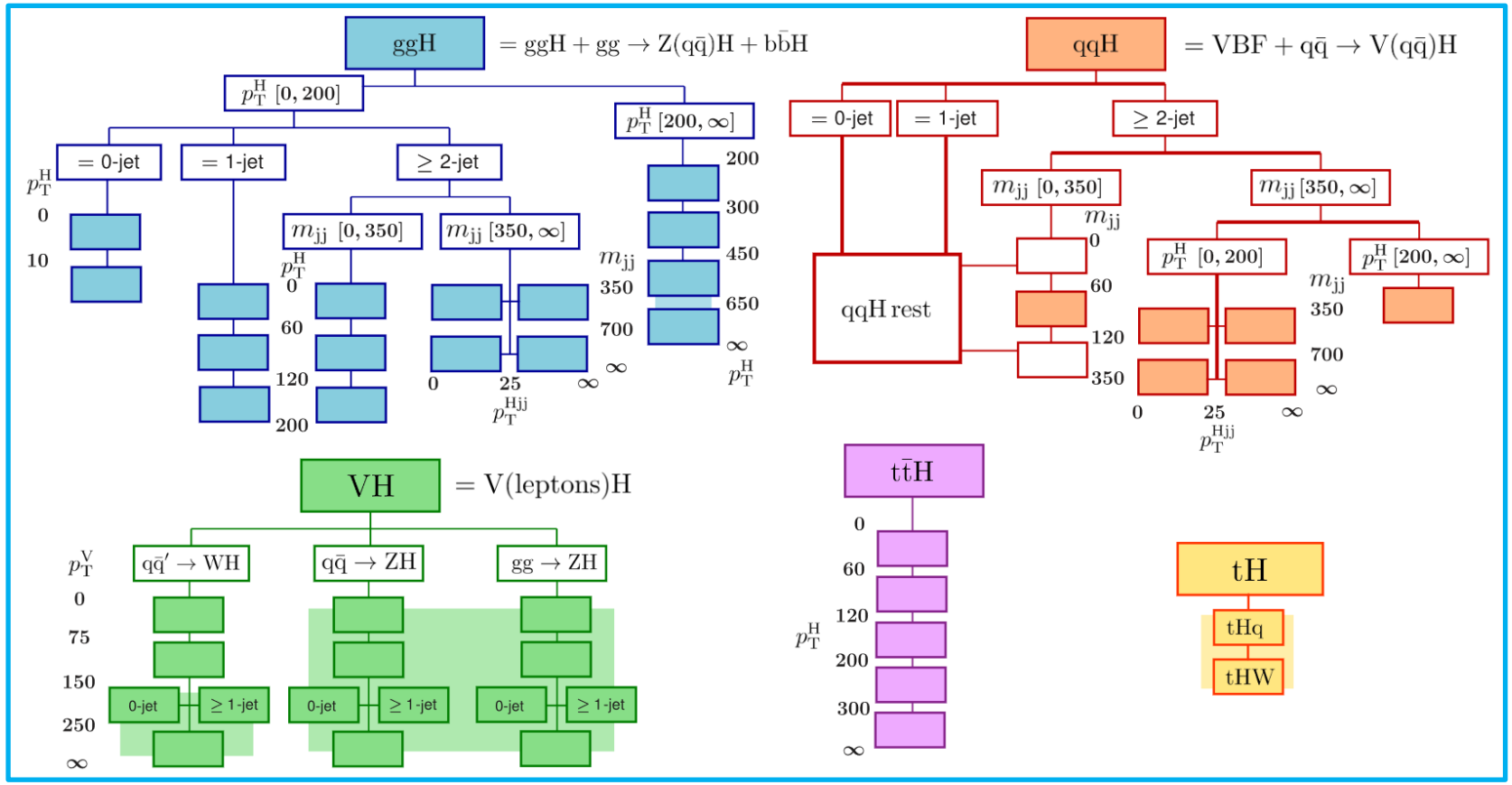




- Evolving from measuring 4 signal strengths (μ) in *HIG-16-040* to over 20 parameters in *HIG-19-015*

Simplified template cross sections (STXS)

- STXS: developed to provide a natural way to evolve Higgs coupling measurements
  - Separate more cleanly measurement steps
  - Reduce the theory dependencies
  - More finely-grained
  - Allow global combination
- Recommended binning
  - Stage 1.2

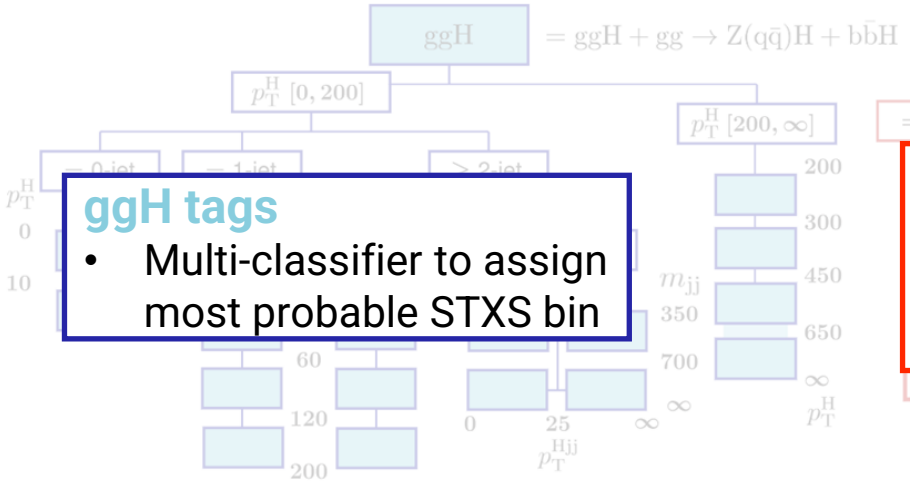


SM H→γγ signal strengths & STXS

HIG-19-015

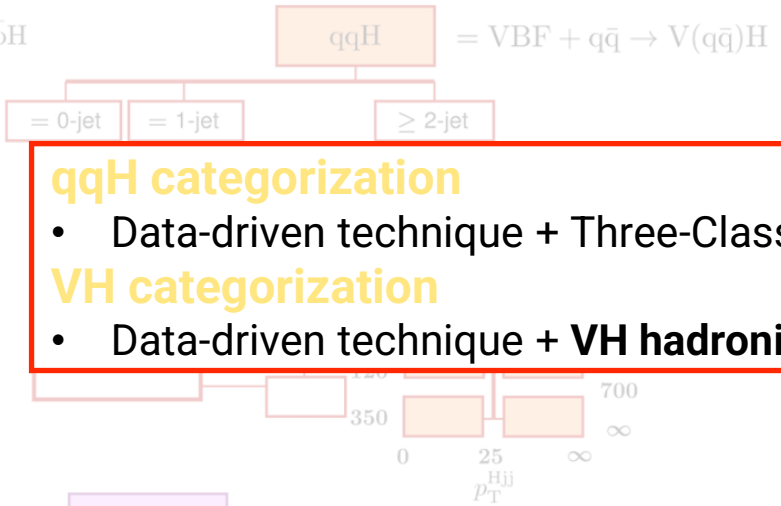
Definition of the categories

HIG-19-015



ggH tags

- Multi-classifier to assign most probable STXS bin

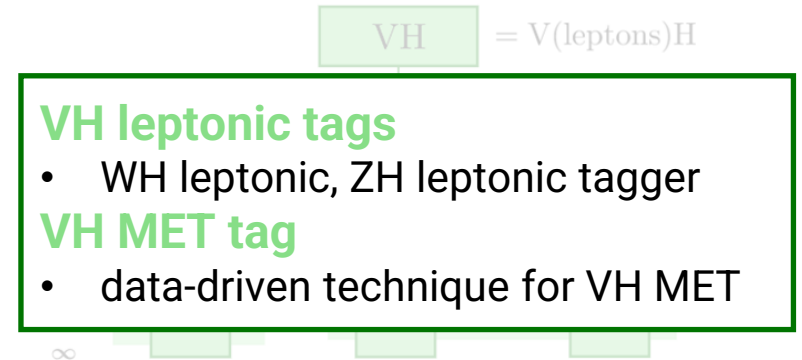


qqH categorization

- Data-driven technique + Three-Class BDT: **qqH tags**

VH categorization

- Data-driven technique + **VH hadronic tag**

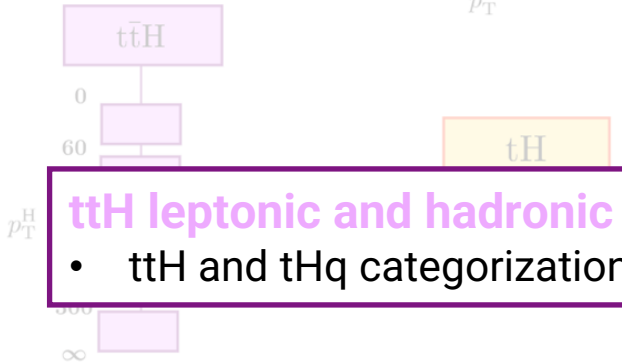


VH leptonic tags

- WH leptonic, ZH leptonic tagger

VH MET tag

- data-driven technique for VH MET

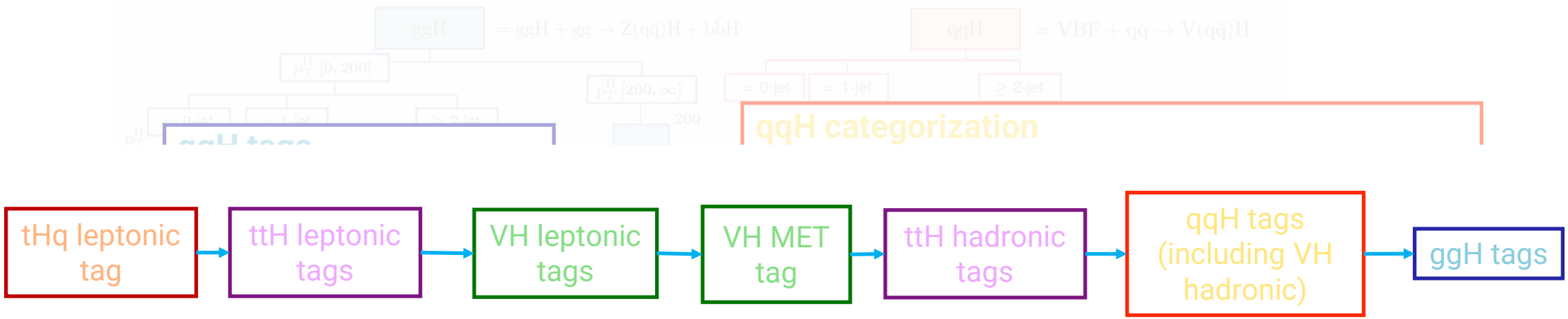


ttH leptonic and hadronic tags

- ttH and tHq categorization followed HIG-19-013

Definition of the categories

HIG-19-015

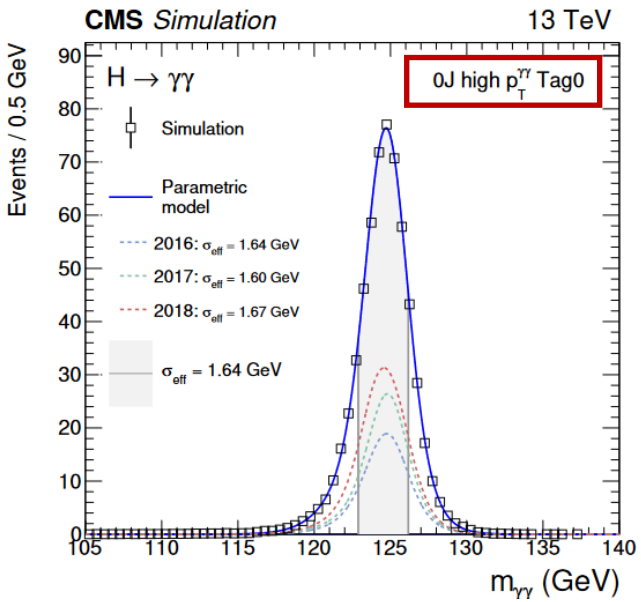


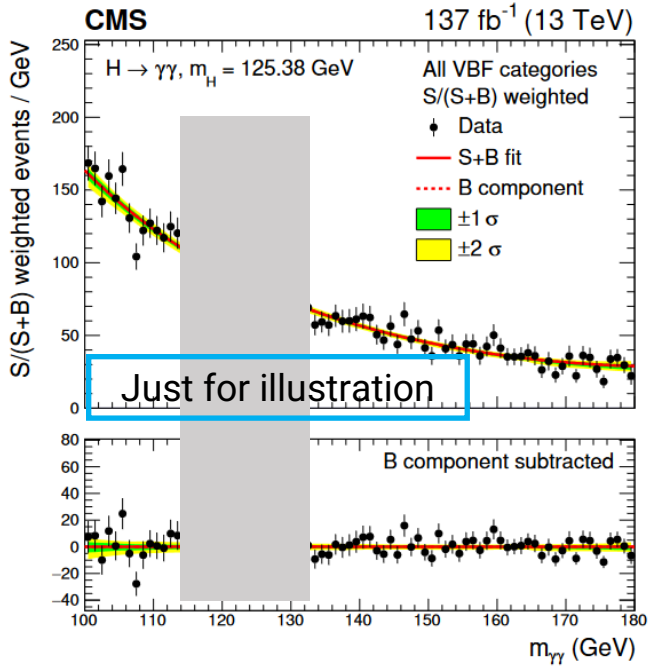
- An event might pass the selection criteria for more than one analysis category
- A **priority sequence** is defined to unambiguously assign each event to only one analysis category
- A **higher priority** assigned **to** analysis categories with a **lower expected signal yield**

Signal & Background modeling

HIG-19-015

- Signal model built separately in each category from the simulation
- Using a sum of at most five **Gaussian** functions



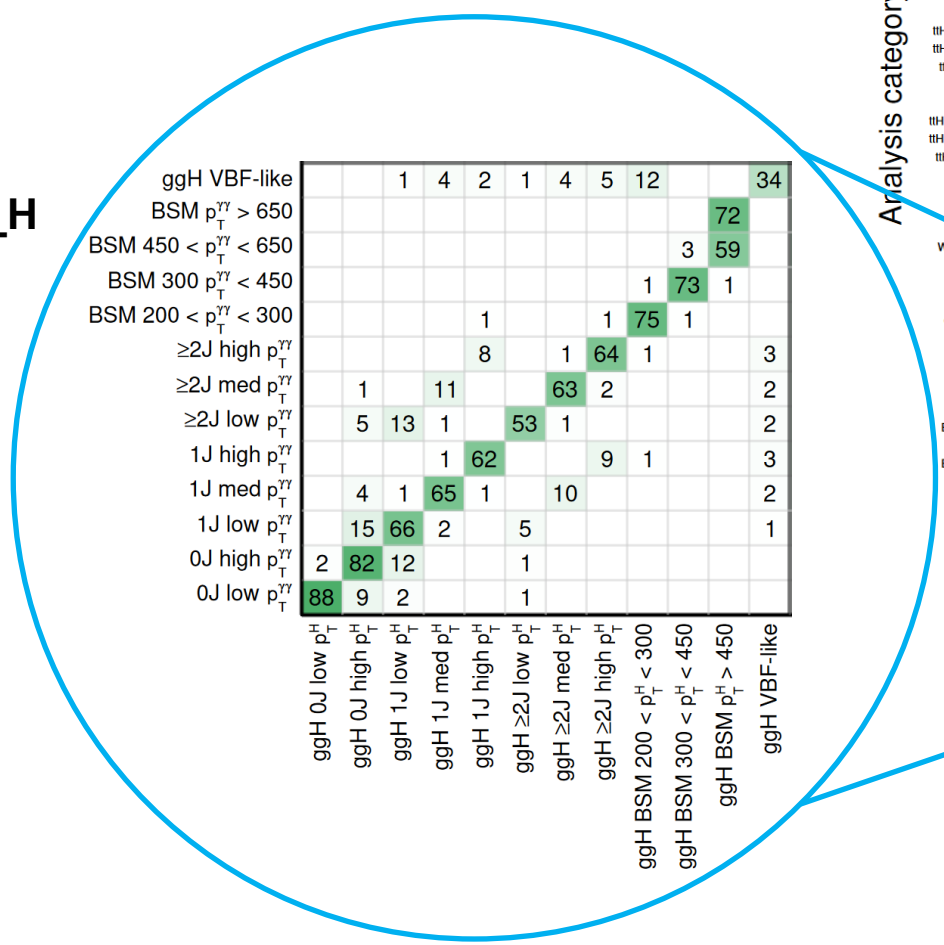


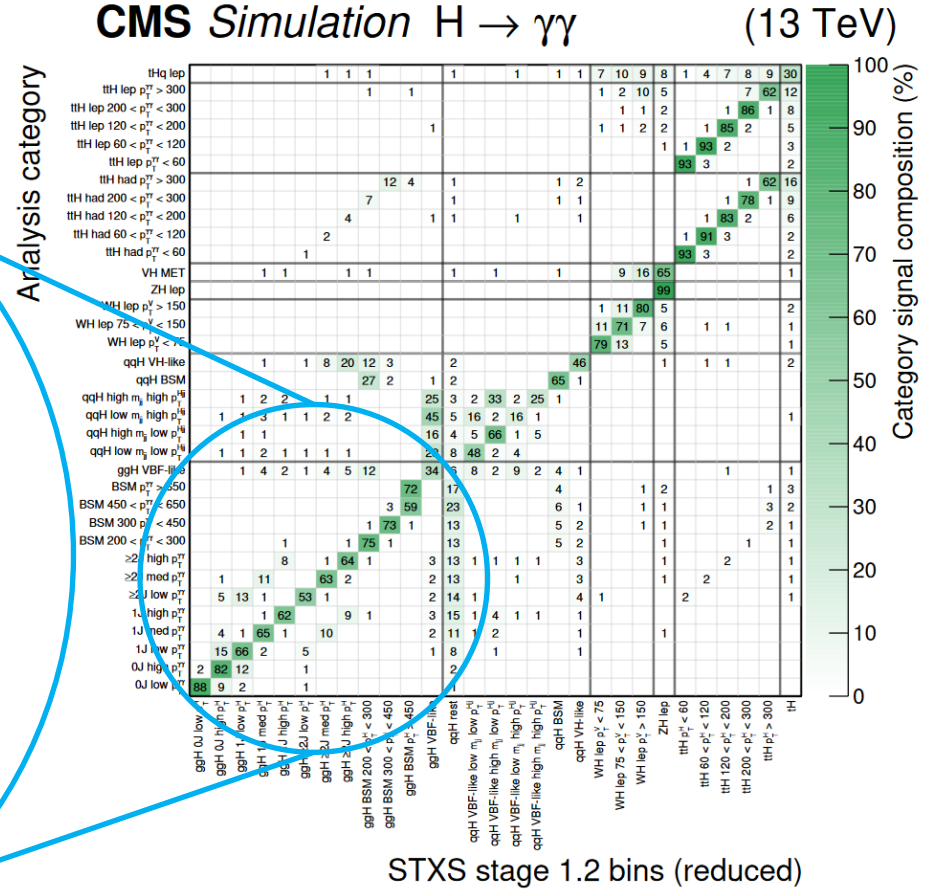
- Background derived from data side-band using **discrete profiling method** [paper]
  - Choice of background pdf type treated as discrete nuisance parameter
  - Likelihood scanned with all different choices of background pdf type
- A more detailed example, see Junquan's talk

Category composition

HIG-19-015

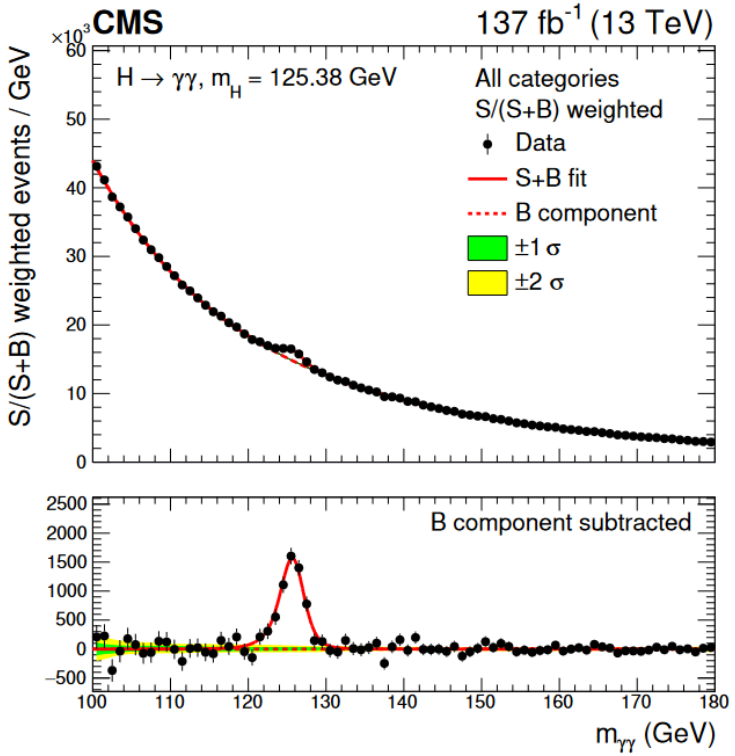
- Percentage contribution of total signal yield in each category from each process
- Entries in each row sum to 100%
- Fairly diagonal in $\mathbf{p_T^H}$

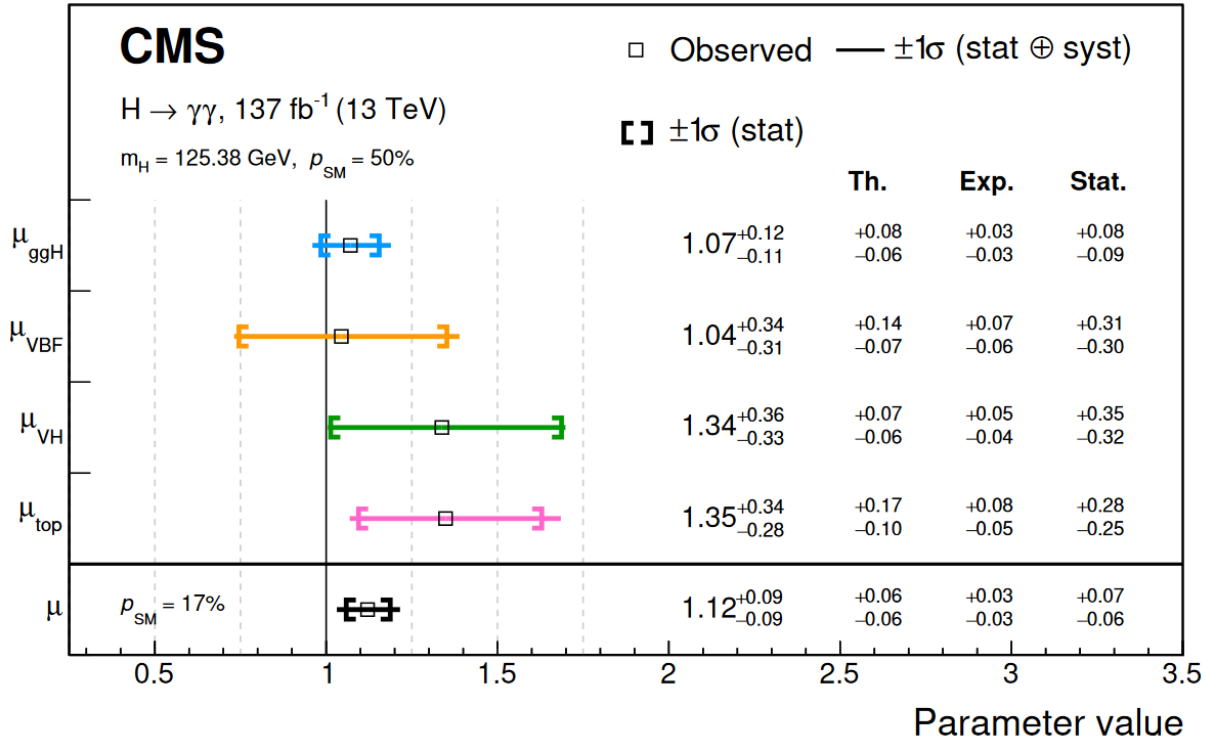




Results - Signal strength modifiers

HIG-19-015





- Common signal strength modifier (μ)
  - Ratio of observed (σ_H×diphoton BR) to SM prediction

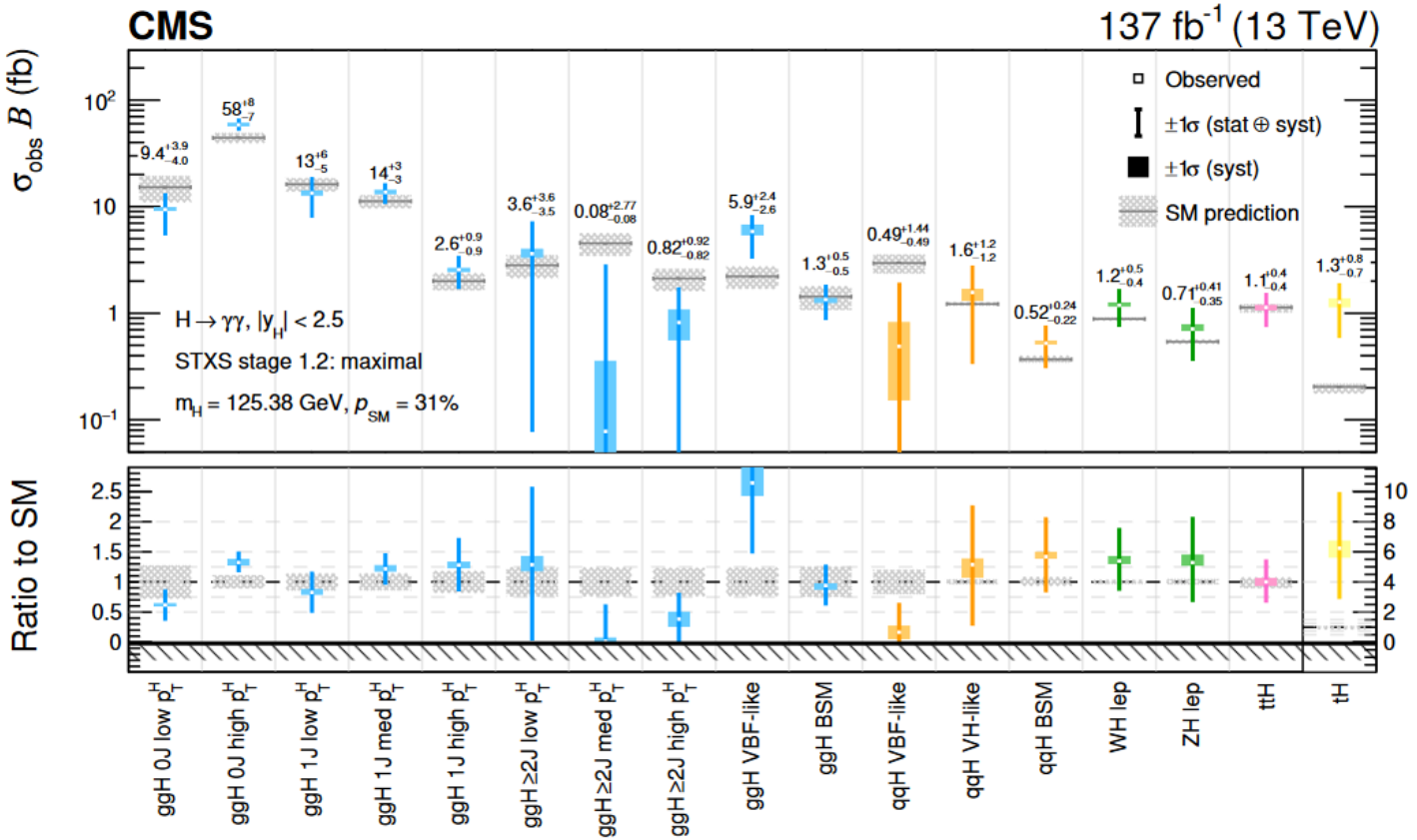
$$\mu = 1.12^{+0.09}_{-0.09} = 1.12^{+0.06}_{-0.06}\,(\text{theo})^{+0.03}_{-0.03}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{stat})$$

- Signal strength modifiers **per production mode**
  - μ_{VH} (VH hadronic + VH leptonic)
  - μ_{VBF} (VBF production)
  - μ_{top} (ttH + tHq + tHW)
  - μ_{ggH} (ggH + bbH)
- ggH is **syst-limited**, while others are **stat-limited**

Results - STXS fit

HIG-19-015

- Fits performed to extract **cross-sections (σ)** in the **STXS 1.2 bins**
- Merging scenarios - **maximal merging scenario**
  - 17 parameters to fit, STXS bins merged until uncertainty is < 150% of SM prediction



SM H→γγ differential and fiducial cross-sections

HIG-19-016

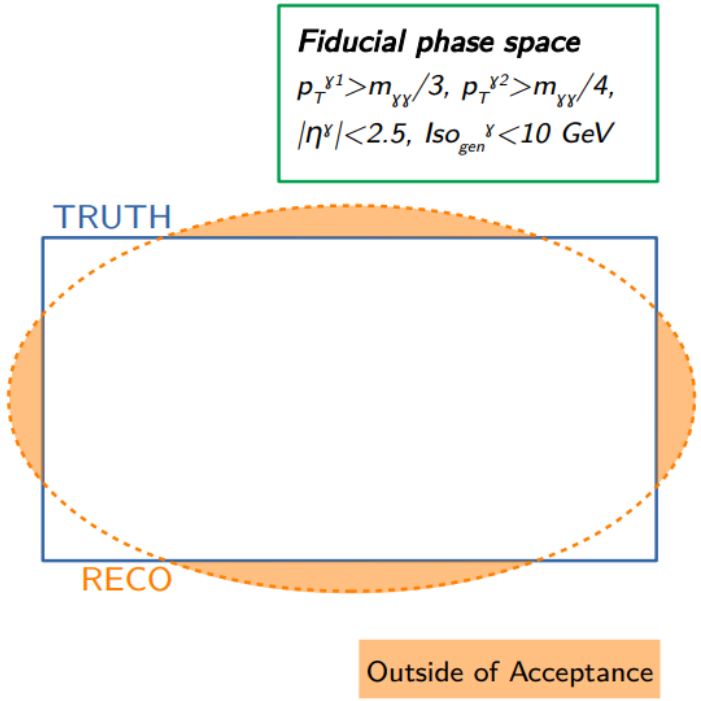
Fiducial phase space definitions

HIG-19-016

- **Inclusive** and **differential fiducial phase spaces** are defined at particle level (simulation truth)
- Phase space defined such that it follows **detector configuration** and **event selection** as close as possible

- Two definitions do not align perfectly
- Outside of Acceptance (OOA) component treated as production process, signal strength fixed to SM prediction

- Fiducial phase space requirements applied to all phase spaces
- VBF-enriched phase space for differential measurement w.r.t. dedicated 2-jet observables
- Dedicated fiducial x-sec measurements in 3 special phase spaces



Fiducial phase space

- $p_T^{\gamma 1} > m_{\gamma\gamma}/3$
- $p_T^{\gamma 2} > m_{\gamma\gamma}/4$
- $|\eta^{\gamma}| < 2.5$
- $Iso_{gen}^{\gamma} < 10$ GeV

1 jet phase space

- $>= 1$ Jet
- $\eta^{j1} < 2.5$
- $p_T^{j1} > 30$ GeV

2 jet phase space

- $>= 2$ Jets
- $\eta^{j1,j2} < 4.7$
- $p_T^{j1,j2} > 30$ GeV

VBF-enriched phase space:

- $>=2$ Jets
- $|\Delta\eta^{j1,j2}| > 3.5$
- $m^{j1j2} > 200$ GeV

Dedicated fiducial xs measurement

ttH-like phase space:

- $>= 1$ lepton
- $>= 1$ b-jet

VH-like phase space:

- 1 lepton
- $p_T^{Miss} < 100$ GeV

WH-like phase space:

- 1 lepton
- $p_T^{Miss} > 100$ GeV

Maximum Likelihood Unfolding

HIG-19-016

- Unfolding through full detector response matrix ***K***
  - Parameterized as a function of nuisances in the **likelihood**

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

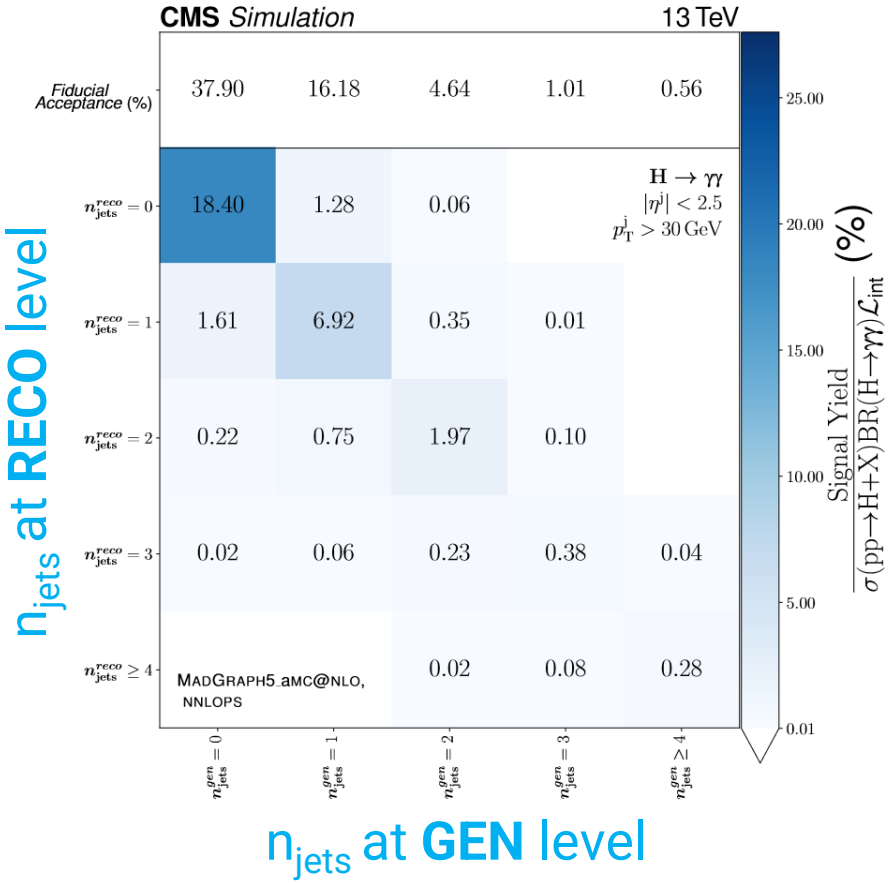
POIs

Signal

Outside of Acceptance (OOA)

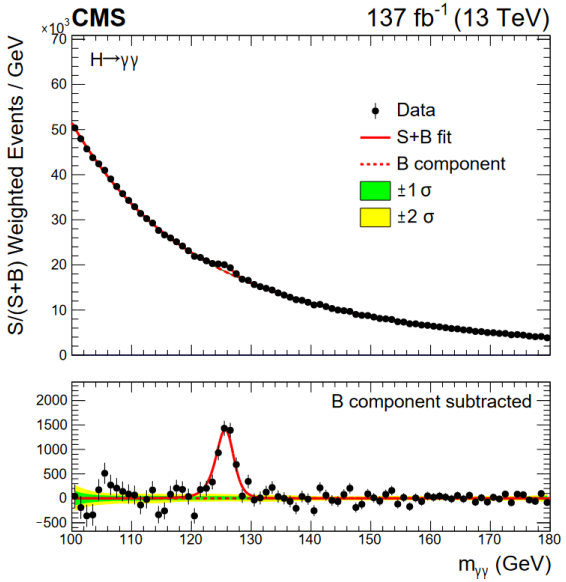
Background

Response matrix ***K***



Results - Fiducial cross-section

HIG-19-016

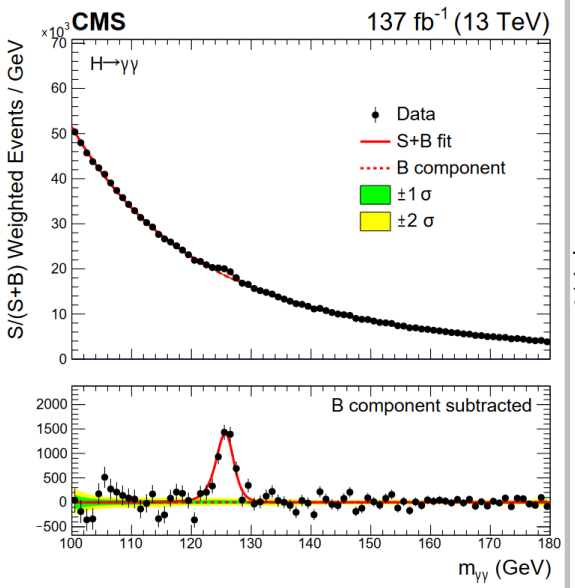


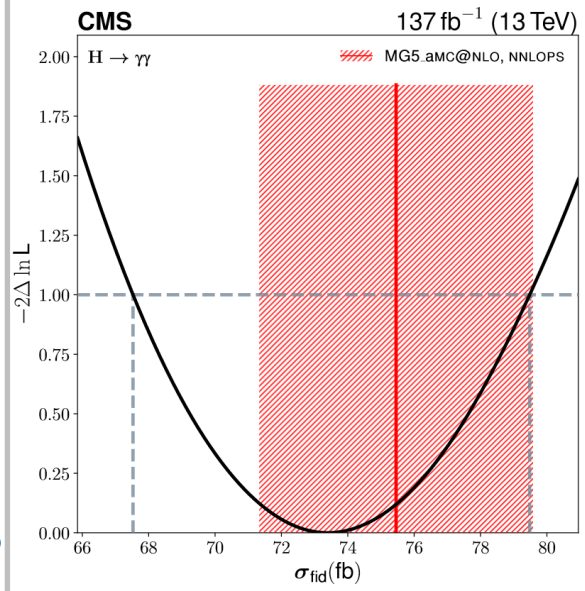
Inclusive fiducial fit

- Same analysis framework with *HIG-19-015*
- Same signal/background modeling strategy

Results - Fiducial cross-section

HIG-19-016





Inclusive fiducial fit

- Same analysis framework with HIG-19-015
- Same signal/background modeling strategy

Observed fiducial x-sec

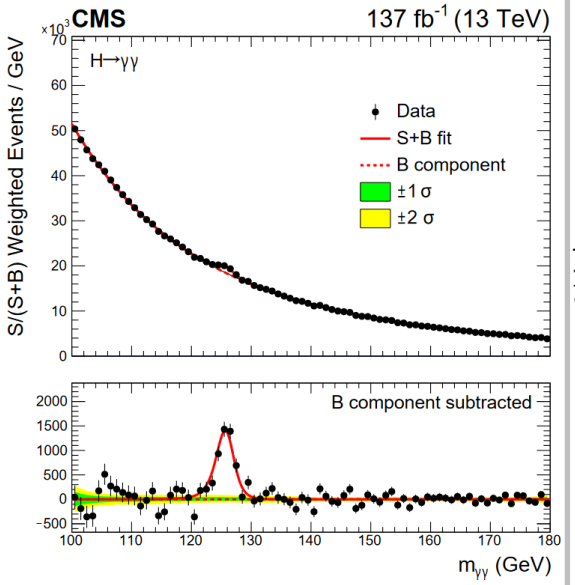
$$\sigma_{\text{fid}} = 73.4^{+5.4}_{-5.3}\,(\text{stat})^{+2.4}_{-2.2}\,(\text{syst})\ \text{fb}$$

$$= 73.4^{+6.1}_{-5.9}\ \text{fb}$$

agree with **expectation** of 75.4 ± 4.1 fb

Results - Fiducial cross-section

HIG-19-016



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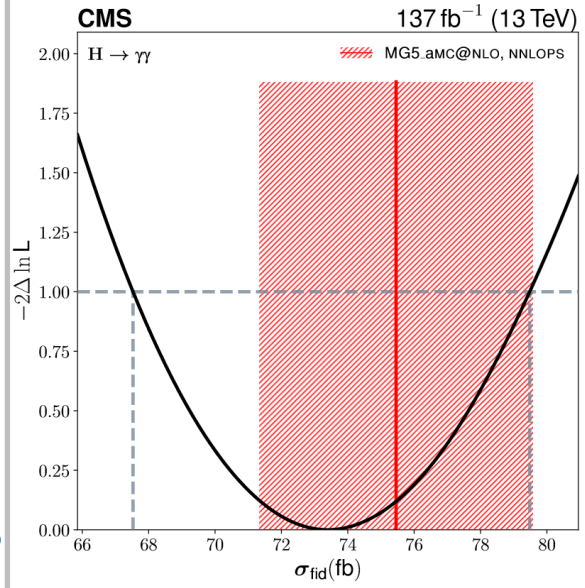

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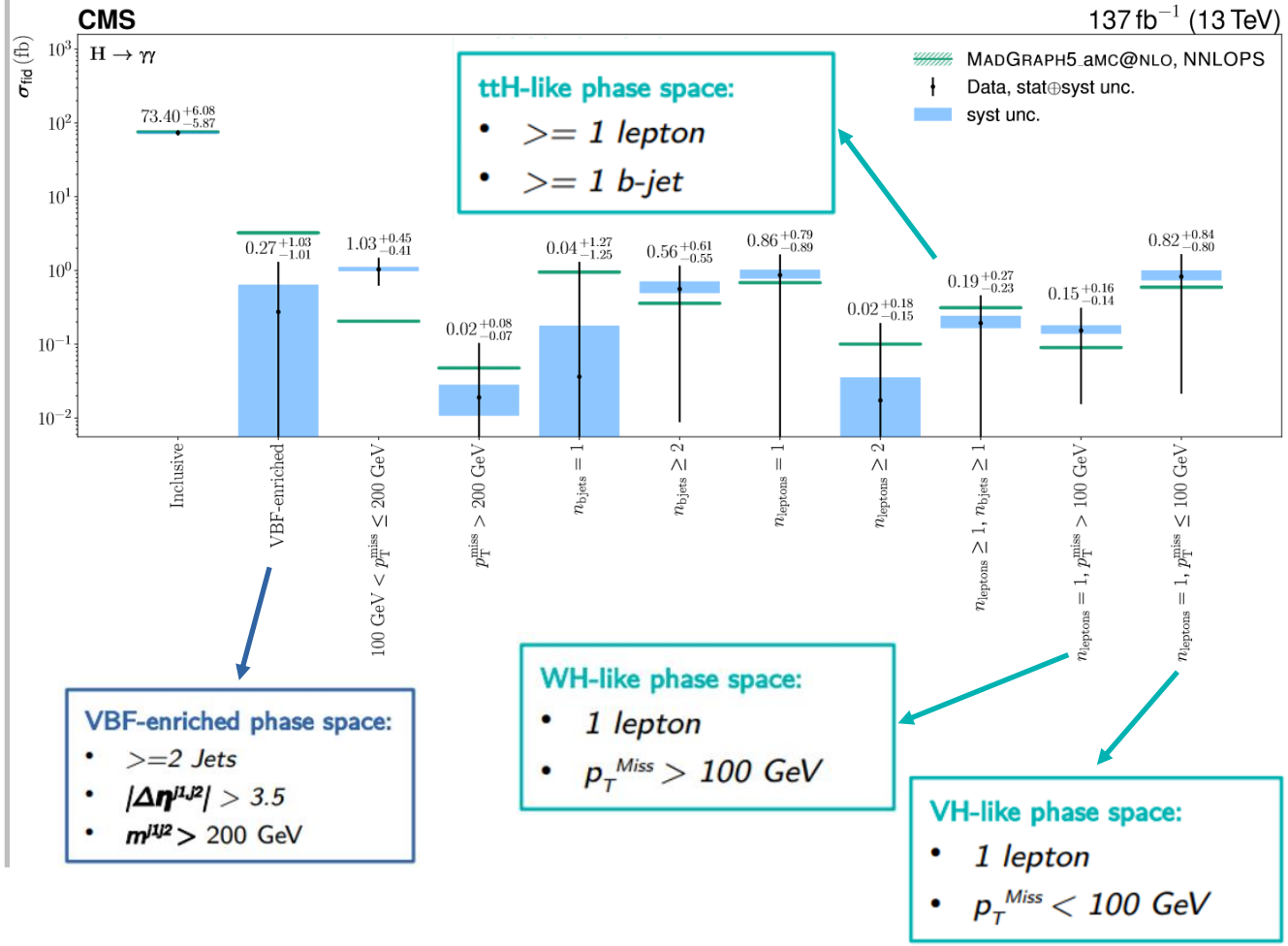
$$= 73.4^{+6.1}_{-5.9}\ \text{fb}$$

agree with **expectation** of 75.4 ± 4.1 fb

X-secs in **dedicated** regions of the **fiducial phase space**



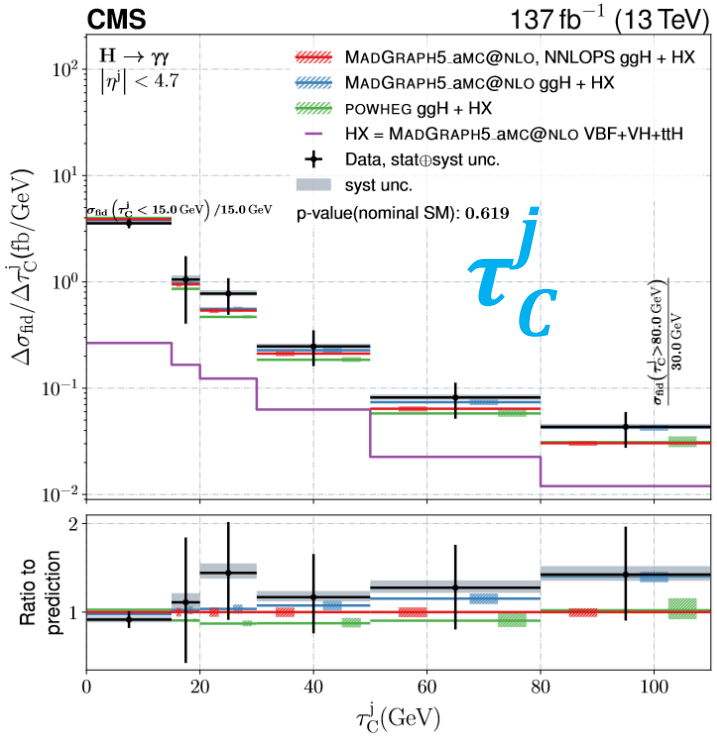
Results - Differential fiducial x-sec

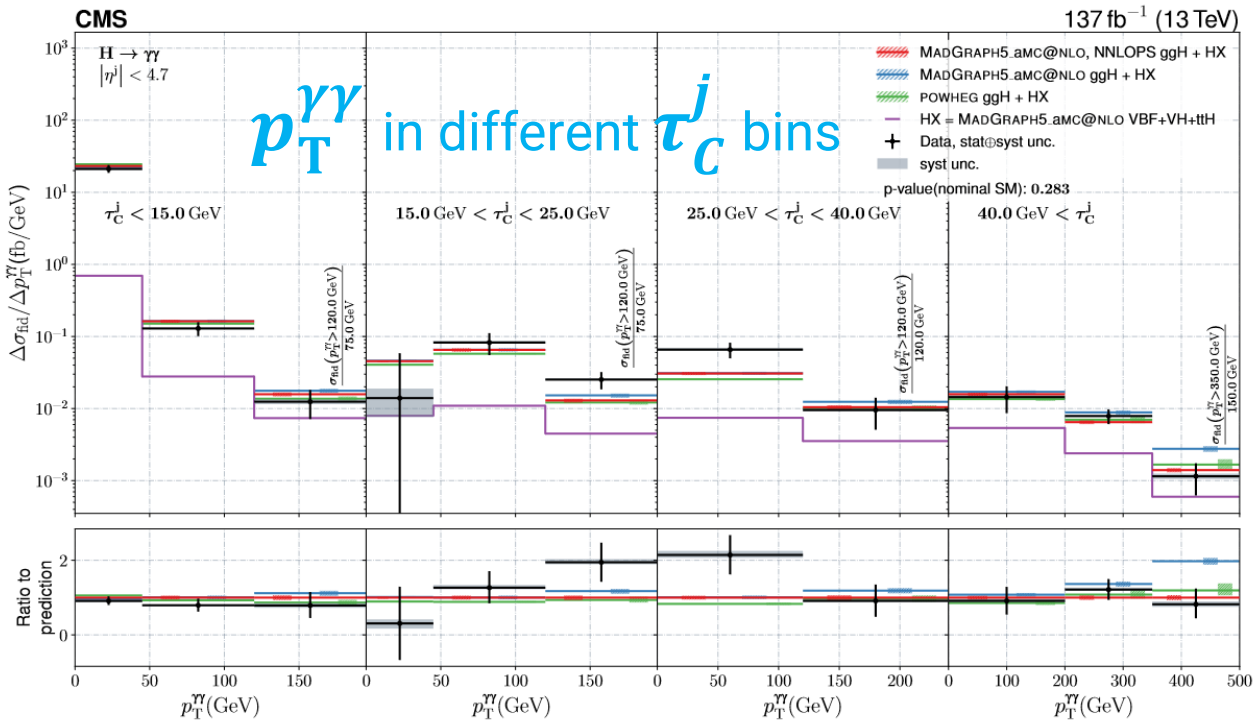
HIG-19-016

- Fiducial x-sec also measured as function of **20 observables**, **2 double differential** measurements
- Example of $\tau_{C,j} = \max_j \left(\frac{\sqrt{E_j^2 - p_{z,j}^2}}{2\cosh(Y_j - Y_H)} \right)$, jet−pT weighted by a rapidity dependent function

PRD **91**, 054023

  - Binning in $\tau_{c,j}$ does not spoil **resummation** → flat pT cut cannot be treated correctly when resumming logs





Search for non-resonant HH→WWγγ

HIG-21-014

HH production

HIG-21-014

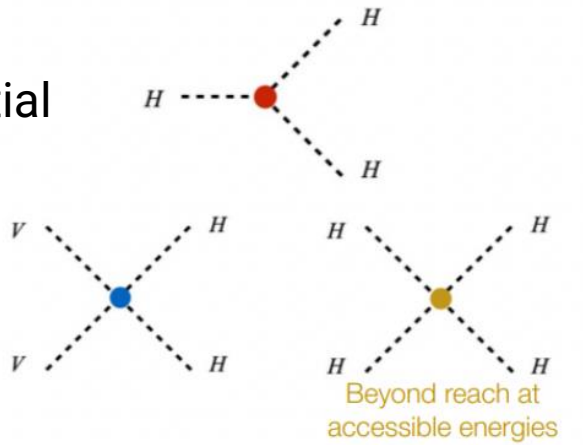
- Higgs potential: **self-couplings λ** is crucial for understanding the field potential

$$V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4 = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$$

Mass-term | λ_3, trilinear self-coupling | λ_4, quartic self-coupling

plus effect of cov. derivative on ϕ in $\mathcal{L}_H$

C_{2V}, VVHH coupling



HH production

HIG-21-014

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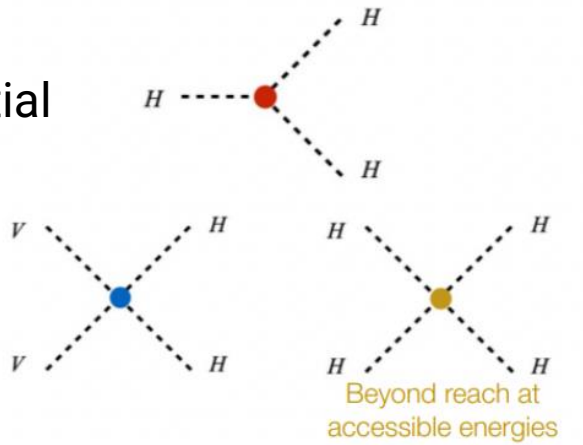
plus effect of cov. derivative on ϕ in $\mathcal{L}_H$

Mass-term | λ_3, trilinear self-coupling | λ_4, quartic self-coupling | C_{2V}, VVHH coupling

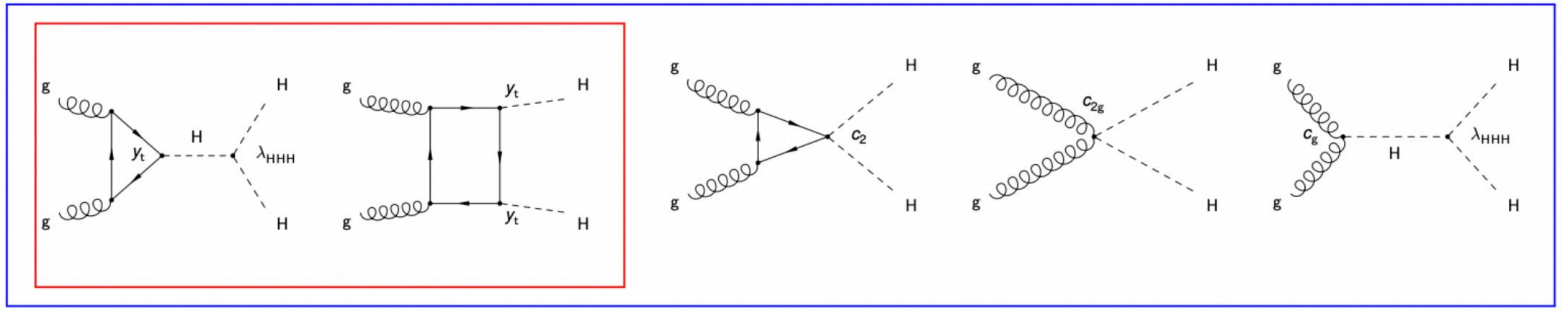


- Effective Field Theory (**EFT**) is also powerful to catch BSM

$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v} H^2)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v} H^2) G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}, \quad \lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}, \quad \kappa_t = \frac{y_t}{y_t^{SM}}, \quad y_t^{SM} = \frac{\sqrt{2} m_t^2}{v}$$

SM (k_λ=1, k_t=1, $c_{2g} = c_g = c_2$=0) **BSM**



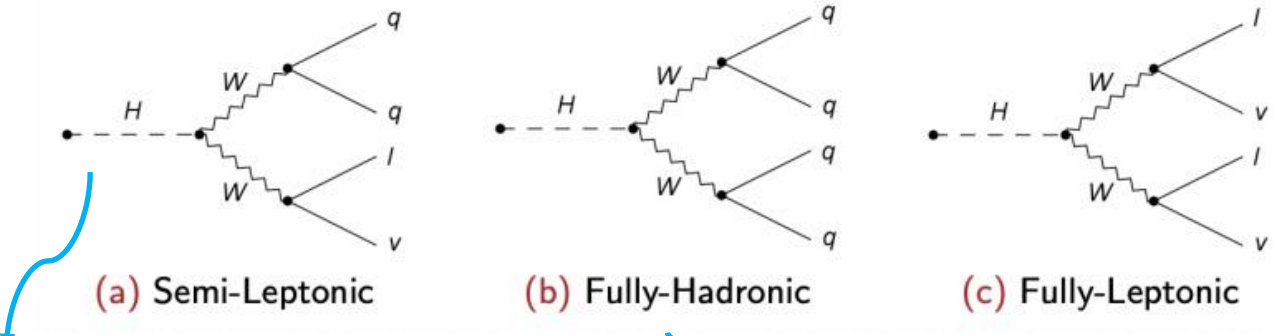
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
1b	3.94	0.94	$\frac{-1}{3}$	0.75	-1
2b	6.84	0.61	$\frac{1}{3}$	0.0	1.0
3b	2.21	1.05	$\frac{-1}{3}$	0.75	-1.5
4b	2.79	0.61	$\frac{1}{3}$	-0.75	-0.5
5b	3.95	1.17	$\frac{-1}{3}$	0.25	1.5
6b	5.68	0.83	$\frac{1}{3}$	-0.75	-1.0
7b	-0.10	0.94	1.0	0.25	0.5

Test 20 EFT benchmarks

Event categorization & fitting

HIG-21-014

- Consider **three** categories of the **H(γγ)H(WW)** events according to the W decay modes

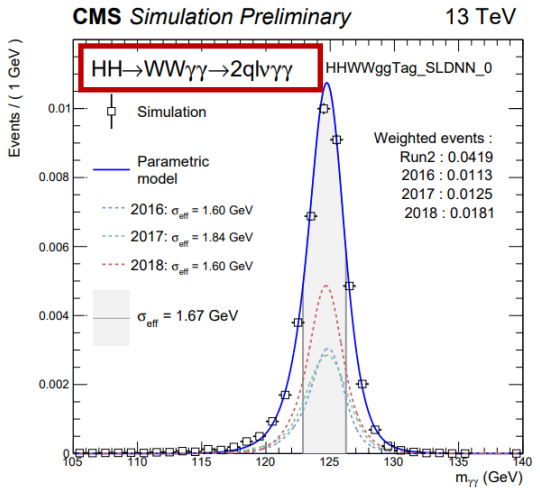


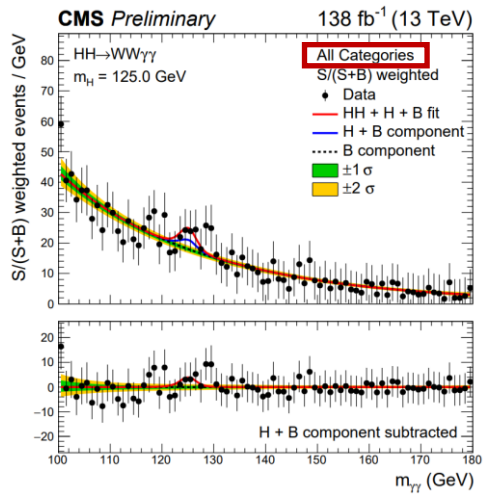
Cut-based
Clean final state and low stats

Two Binary DNNs
- **WWγγ** DNN to separate HH from all backgrounds
- **bbγγ killer DNN** to reject HH bb events

Multi-Class DNN
To separate HH , H and continuum background

- Use **same analysis framework** with HIG-19-015
  - Same signal and background modeling method
  - Fit to $\mathbf{m_{\gamma\gamma}}$ to extract upper limits

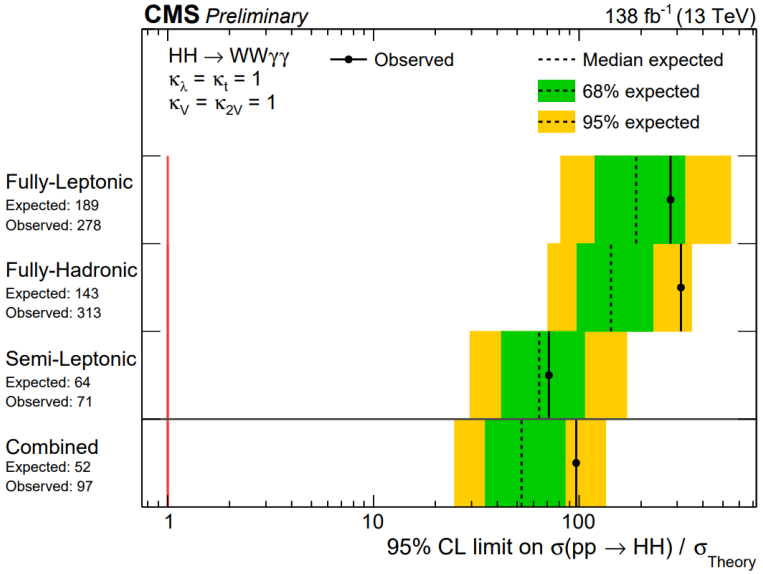




Results

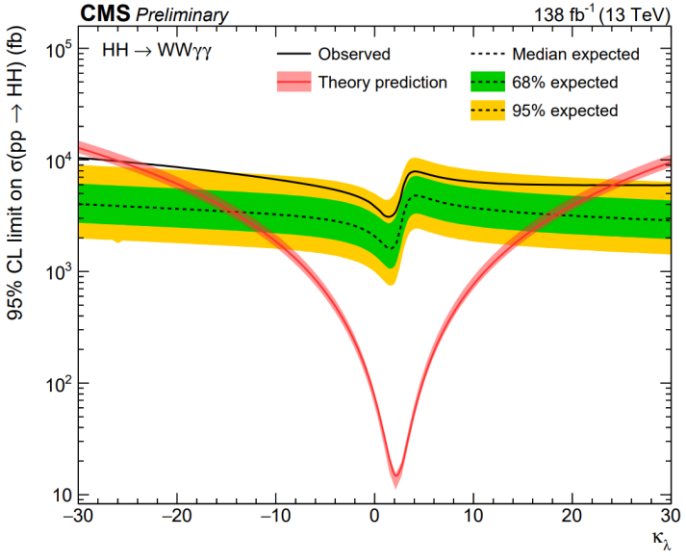
[HIG-21-014]

HH gluon fusion production with respect to SM σ_{NLO} = 31.05 fb

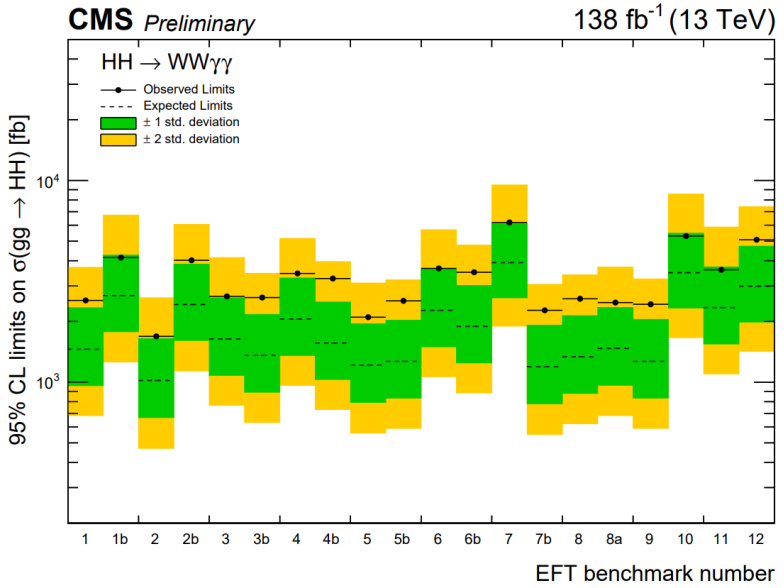


Observed: 96.8
Expected median: 52.5
Expected ± 1σ: [35.0, 85.6]
Expected ± 2σ: [24.8, 134.8]

κ_λ scan for Run2



95% CL range
Observed: -25.8 < κ_λ < 24.1
Expected: -14.4 < κ_λ < 18.3



95% CL limits on **HH gluon fusion production** for 20 EFT benchmarks

Search for non-resonant/resonant HH→bbγγ

HIG-19-018

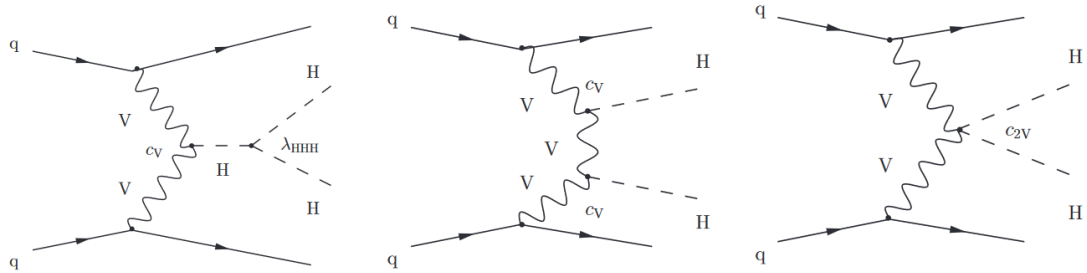
HIG-21-011

Search for non-resonant HH→bbγγ

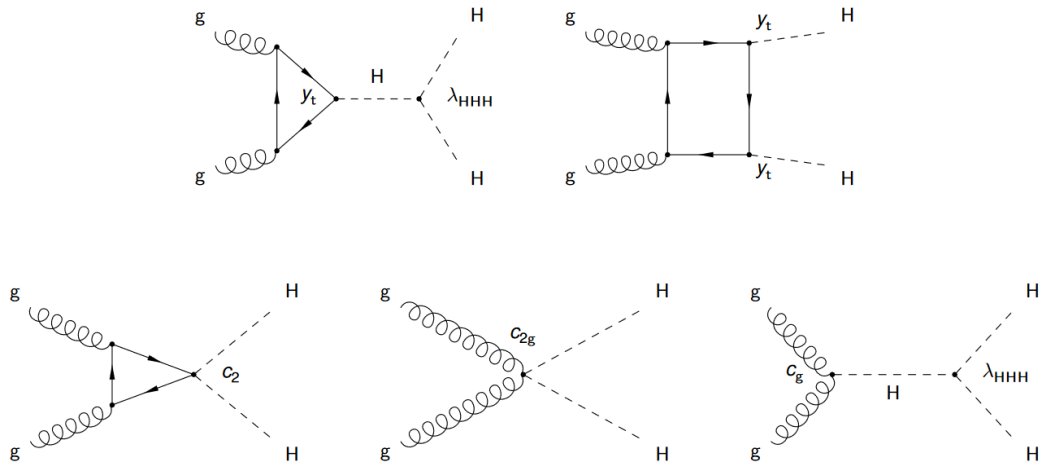
HIG-19-018

- Similar goals with the HH→WWγγ *HIG-21-014*
  - Set limits on the **coupling parameters**
  - Constraint the **EFT benchmarks**
- **VBF HH** production is considered
  - Constraint $\mathbf{c_v}$, $\mathbf{c_{2v}}$
- **ttH production** is included in fitting to improve the constraints

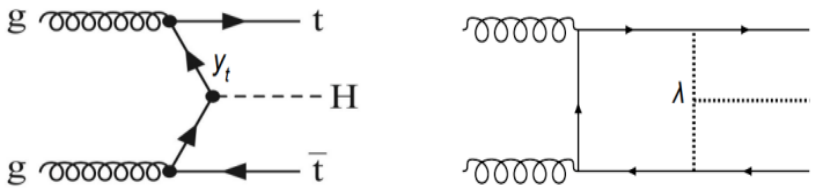
VBF HH production



ggHH production

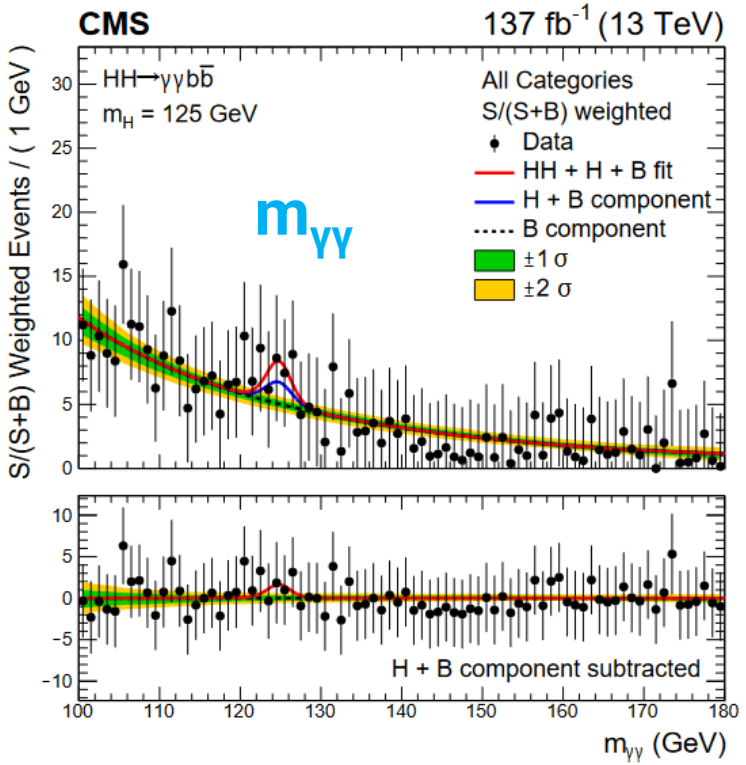


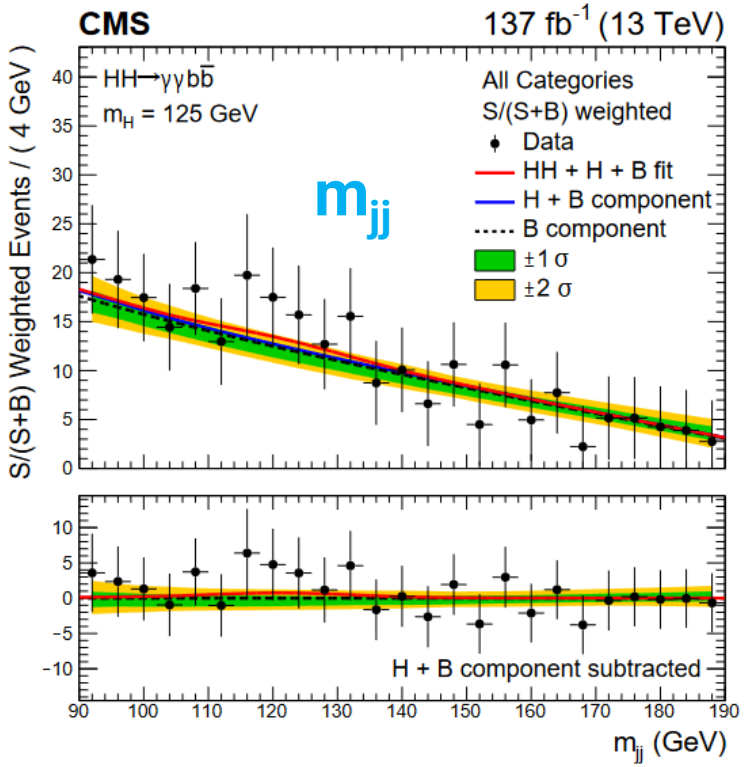
ttH production



Fit strategy

- Fit is performed in both $\mathbf{m_{\gamma\gamma}}$ and $\mathbf{m_{jj}}$



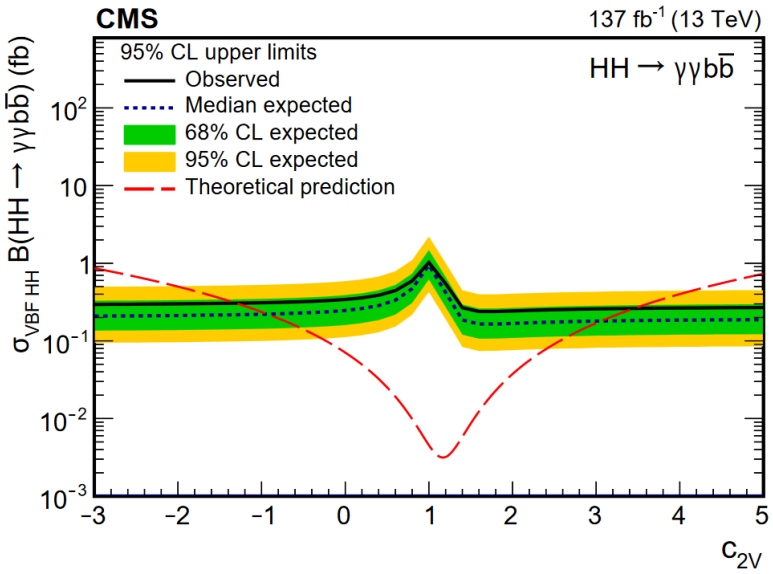


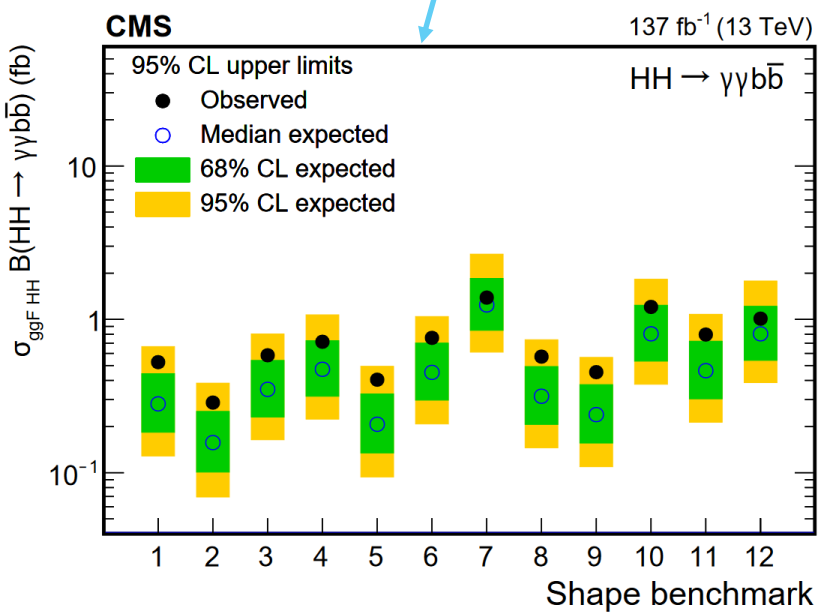
Results

HIG-19-018

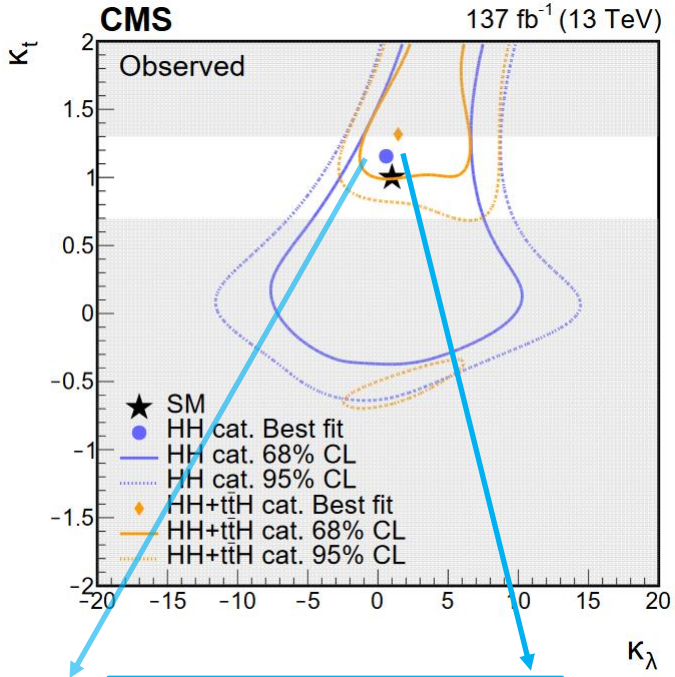
95% CL upper limits on the product of the **ggF HH production cross section and B(HH → γγbb)** for EFT benchmarks

C_{2V} scan for Run2





NLL contours at 68 and 95% CL in the (κ_λ, κ_t) plane



95% CL range

Observed: $-1.3 < C_{2V} < 3.5$

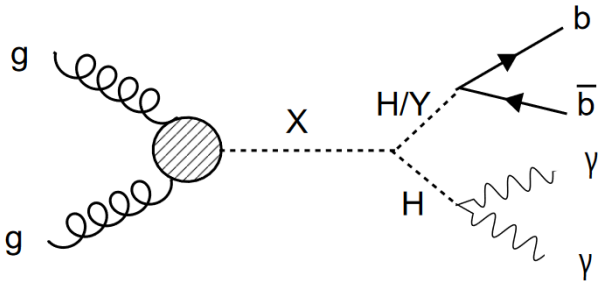
Expected: $-0.9 < C_{2V} < 3.1$

HH categories (κ_λ=0.6, κ_t=1.2)

HH+ttH categories (κ_λ=1.4, κ_t=1.3)

Search for resonant X→HH/HY→bbγγ

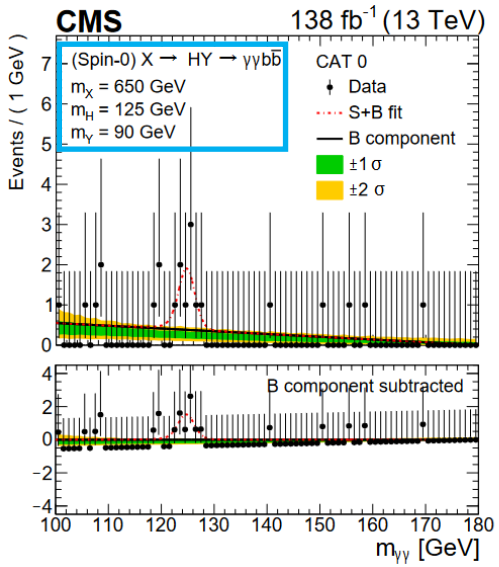
HIG-21-011

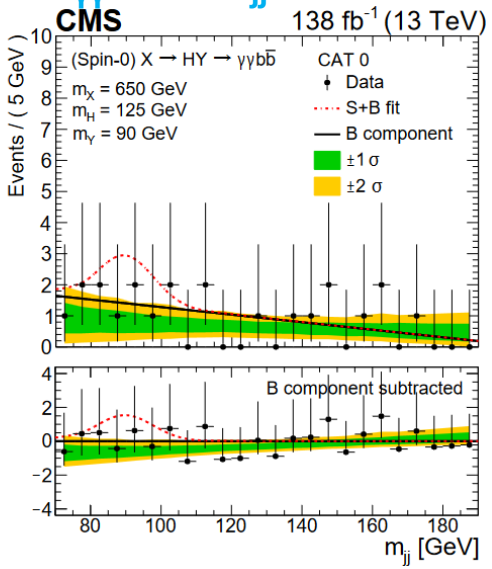


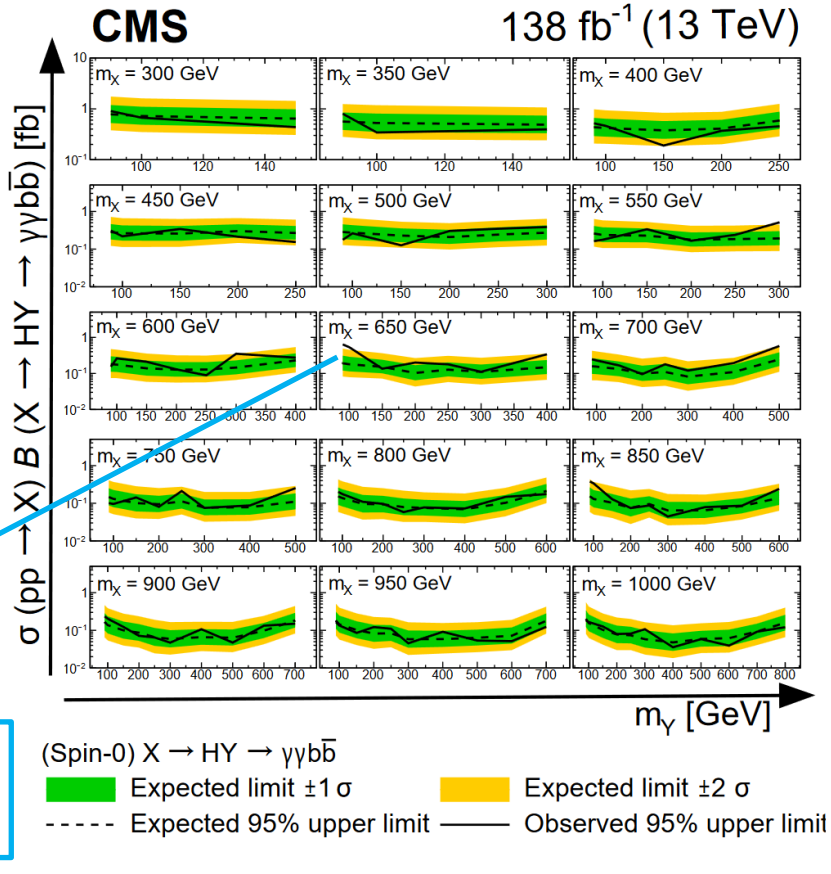
Motivated by multiple BSM theories

- Warped extra dimension (**WED**) model (X→ HH)
- Next-to-minimal supersymmetric model (**NMSSM**)
- Two-real-scalar-singlet model (**TRSM**) (X→ YH)

Fit to both $m_{\gamma\gamma}$ and m_{jj}







A local (global) significance of 3.8 (2.8) standard deviations

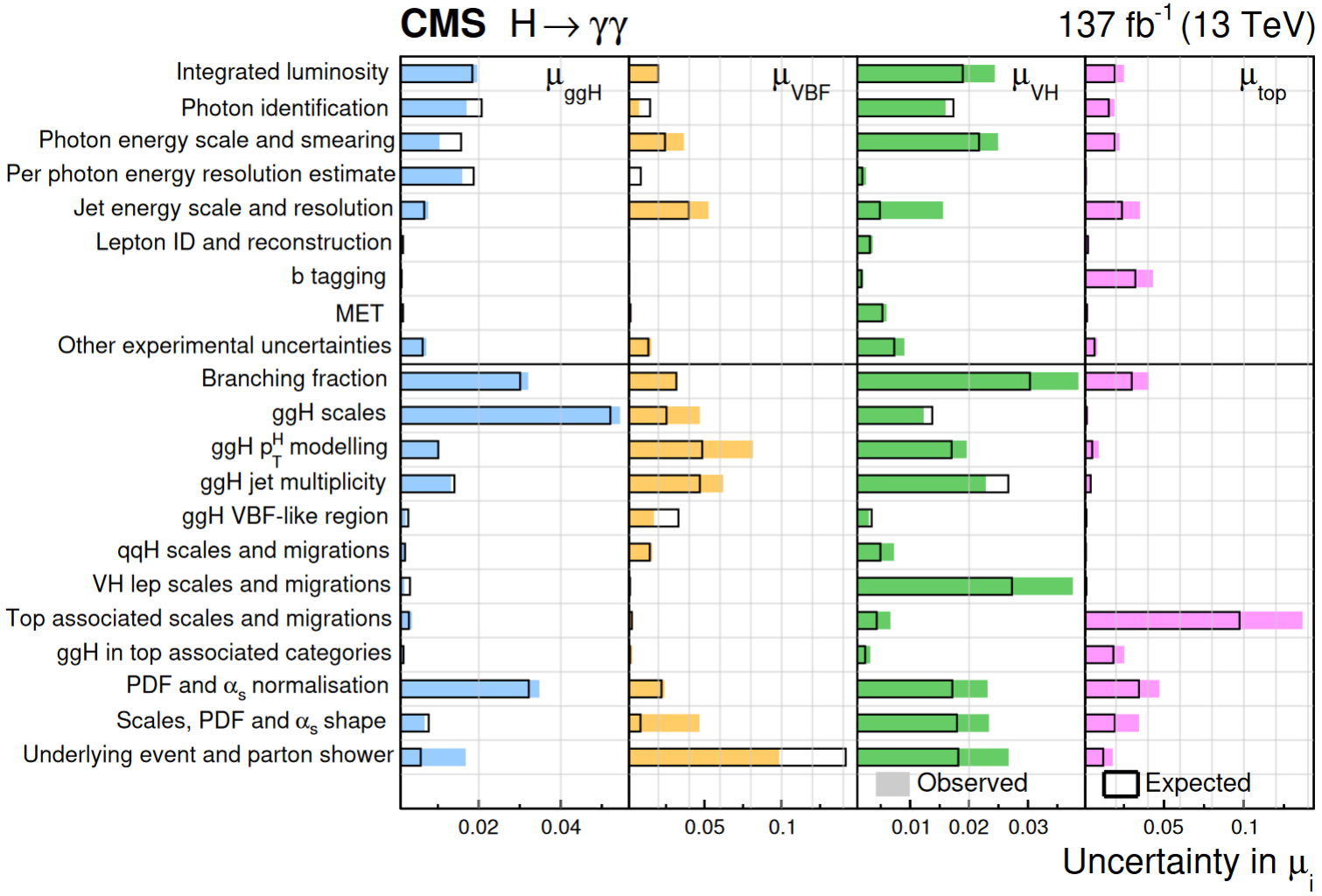
Summary

- Present Run2 **single and double Higgs** measurements **with one Higgs decays to diphoton**
- Detailed **Higgs properties** studies and **validation with theory predictions** are performed
  - *HIG-19-015*: SM H→γγ signal strengths & STXS
  - *HIG-19-016*: SM H→γγ differential and fiducial cross sections
- Non-resonant HH productions with diphoton in the final state are useful to **constrain couplings** and explore **EFT settings**
  - *HIG-21-014*: Search for non-resonant HH→WWγγ
  - *HIG-19-018*: Search for non-resonant HH→bbγγ
- Search for additional particles could benefit from resonant HH productions with diphoton in the final state
  - *HIG-21-011*: Search for resonant X→HH/HY→bbγγ
- Analysis groups from China and France work together to make contributions on relevant analyses

Backup

Run2 STXS H→γγ systematics

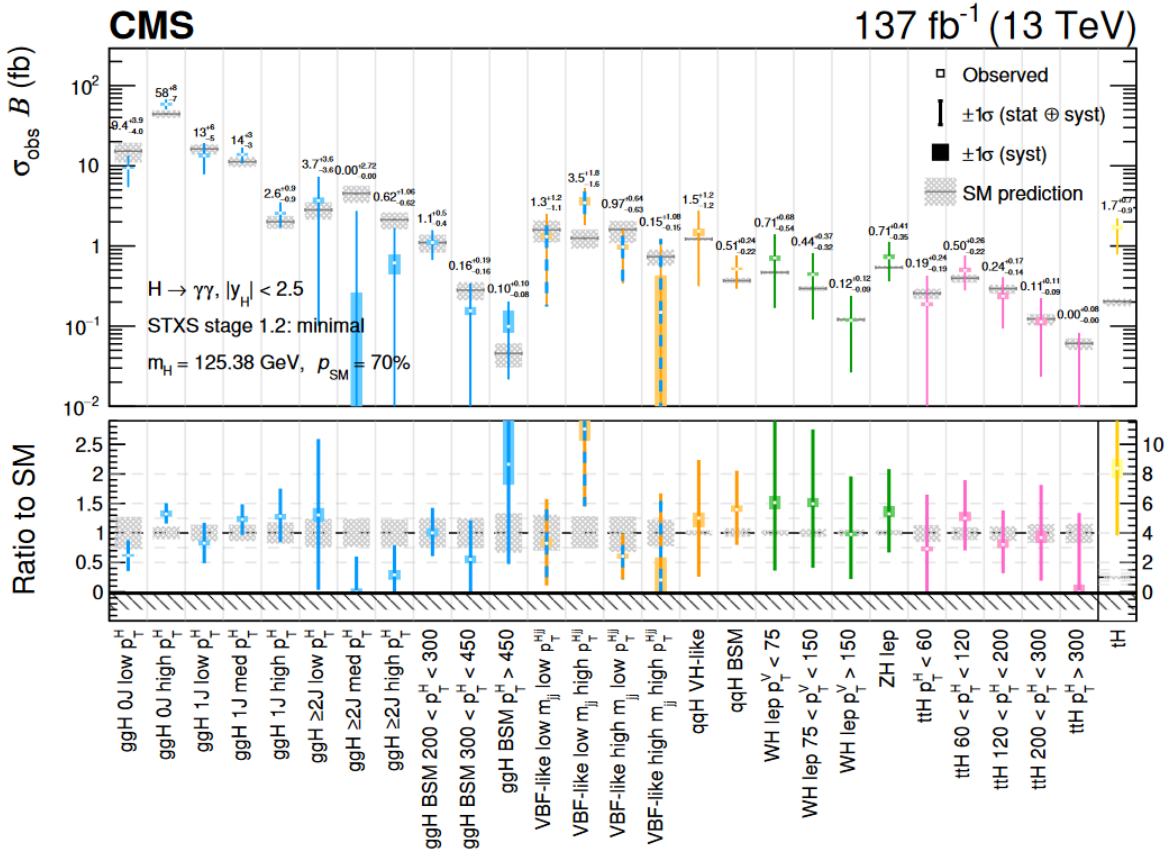
HIG-19-015



Results - STXS fit

HIG-19-015

- Fits performed to extract **cross-sections (σ)** in the **STXS 1.2 bins**
- Merging scenarios - minimal merging scenario
  - 24 parameter fit, merges as few bins as possible to satisfy correlations $\lesssim 0.75$

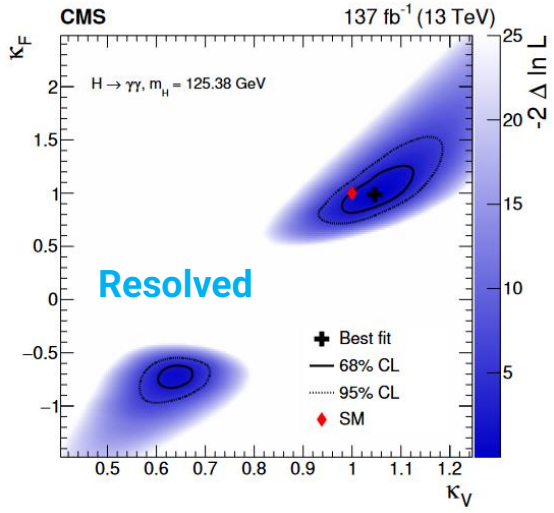


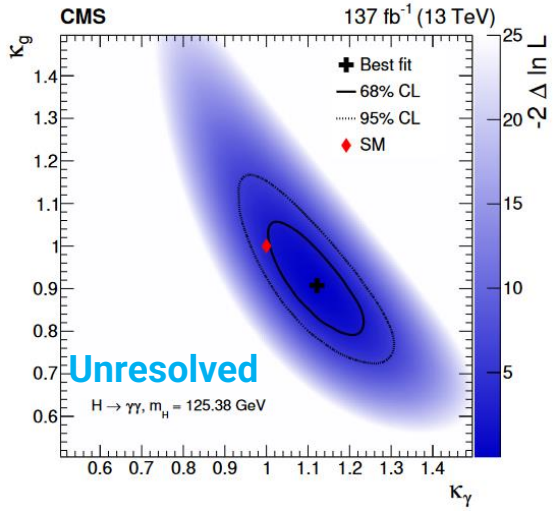
Results - Coupling modifiers

HIG-19-015

- Parameterize deviations from SM in Higgs couplings to other particles
- **Resolved** κ model
  - Scaling of ggH and H→γγ loops resolved into SM components in terms of other κ parameters
  - **2D scan** of κ_V and κ_f: universal coupling modifiers to vector bosons/fermions - other κ parameters fixed to unity
  - Data still favors positive κ_f: - exclude negative κ_f with 1.0 (2.4) σ confidence
- **Unresolved** κ model
  - Parameterize deviations in ggH and H→γγ loops using effective coupling modifiers (κ_g, κ_γ)
  - Other κ parameters fixed to unity

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}$$





Observables

HIG-19-016

Diphoton

p_T $|y^{\gamma\gamma}|$

NEW

$|\phi_\eta^*|$ $\cos(\Theta^*)$

Leading jet

p_T^{j1} $|\Delta\Phi^{\gamma\gamma,j1}|$

$|y^{j1}|$ $|\Delta y^{\gamma\gamma,j1}|$

2nd jet, jj-System

p_T^{j2} $|\Delta\Phi^{j1,j2}|$ $|\eta^{j1j2}-\eta^{\gamma\gamma}|$ m^{j1j2}

$|\Delta\Phi^{\gamma\gamma,j1j2}|$ *Also measured in VBF-like phase space* $|\Delta\eta^{j1,j2}|$ $|y^{j2}|$

VBF-like phase space:

2 jets, $|\Delta\eta^{j1,j2}|>3.5$, $m^{j1j2}>200$ GeV

$\phi_\eta^* = \tan(\phi_{acop}/2) * \mathrm{sech}((\eta_1-\eta_2)/2)$

$\phi_{acop} = \pi - \Delta\phi$

Details: Higgs Tools Handbook

Double differential

p_T vs N_{Jets}

NEW

p_T vs $\tau_{c,j}$

Event-level observables

p_T^{miss} N_{BJets}

$N_{Leptons}$ N_{Jets}

Jet Rapidity observable

$\tau_{c,j}$

NEW

Sensitive to Resummation (theory slides)

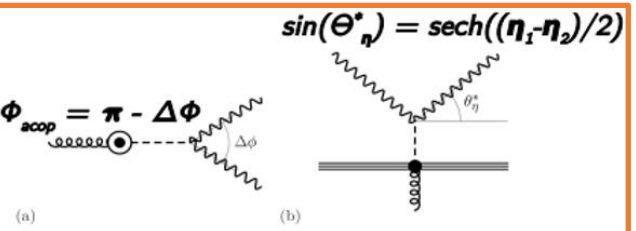
$$\tau_{C,j} = \max_j \left(\frac{\sqrt{E_j^2 - p_{z,j}^2}}{2\cosh(Y_j - Y_H)} \right)$$

New observables

HIG-19-016

$|\Phi_\eta^*|$ $\Phi_\eta^* = \tan(\Phi_{acop}/2) * \mathrm{sech}((\eta_1-\eta_2)/2)$ $\Phi_{acop} = \pi - \Delta\Phi$

$\sin(\Theta^*_\eta) = \mathrm{sech}((\eta_1-\eta_2)/2)$

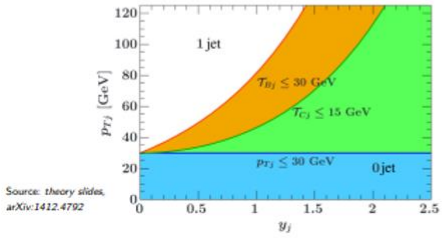


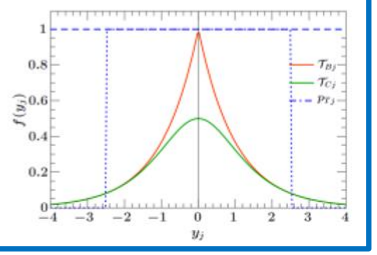
- Handle on low-p_T region of the Higgs
- Measures deviation from "back-to-backness"
- Minimizes the impact of experimental uncertainties

$T_{c,j}$

$$\tau_{C,j} = \max_j \left(\frac{\sqrt{E_j^2 - p_{z,j}^2}}{2\cosh(Y_j - Y_H)} \right)$$

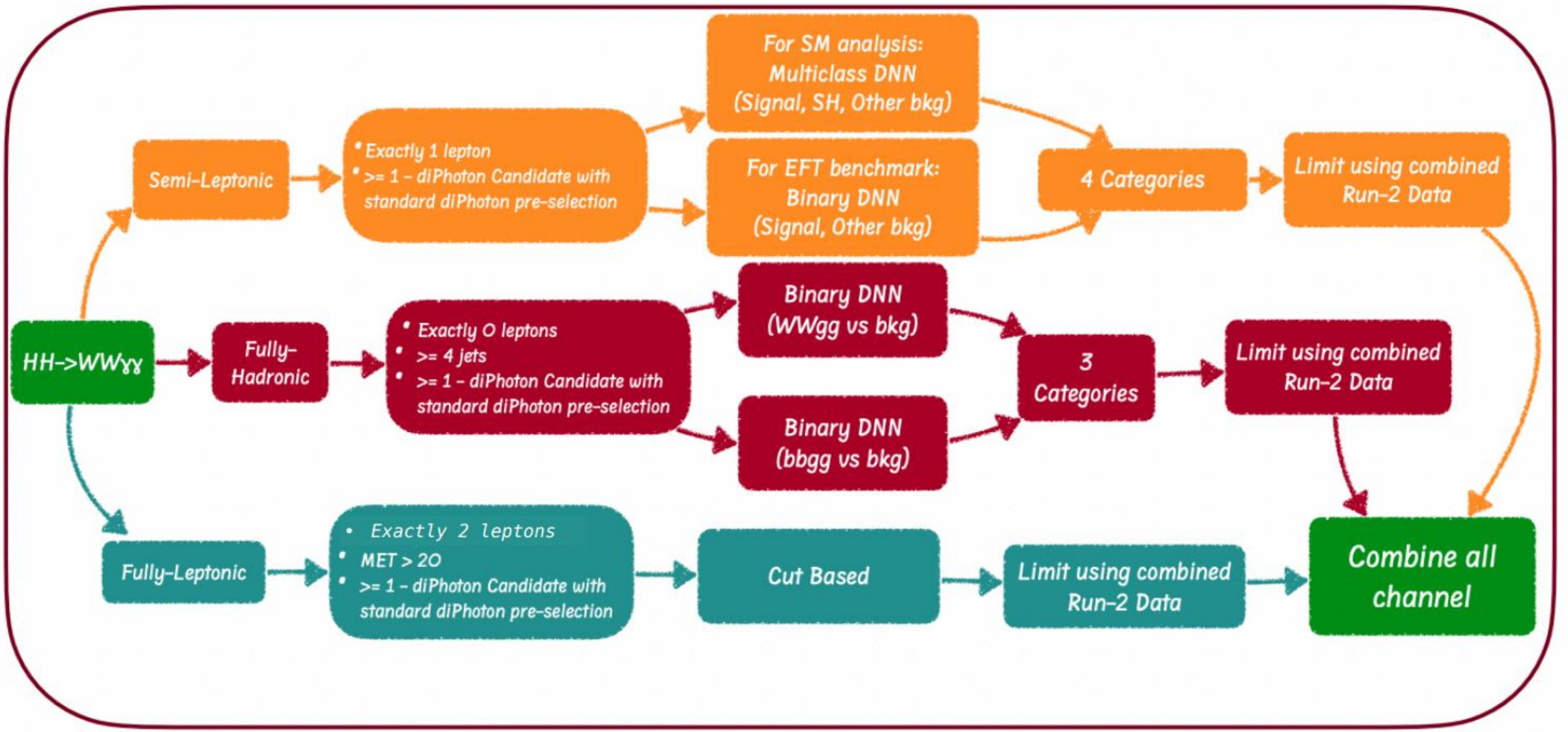
- Jet-p_T weighted by a rapidity dependent function $\mathcal{T}_{fj} = p_{Tj}\, f(y_j)$,
- Preserves theoretical interpretability
- Binning in $\tau_{c,j}$ does not spoil resummation
- → flat p_T cut cannot be treated correctly when resumming logs
- Using $|\eta| < 4.7$ Jets, as inclusive as possible
- Reordering jets in $\tau_{c,j}$
  → using max of $\tau_{c,j}$ of 5 pt leading jets
- $p_T > 30$ GeV, equivalent to $\tau_{c,j} > 15$ GeV, i.e. 0-jet PS equivalent to $\tau_{c,j} < 15$ GeV





Analysis Strategy: Summary flowchart

HIG-21-014



Event categories

HIG-19-018