Higgs Differential and STXS cross sections in CMS

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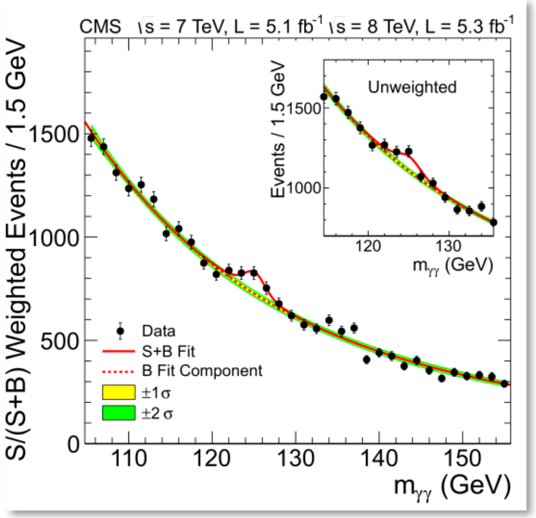
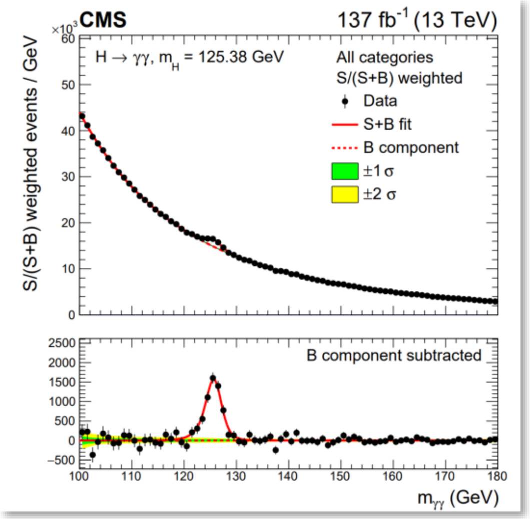
ON BEHALF OF THE CMS COLLABORATION

10 years!

- It's been (almost) 10 years since the discovery of the Higgs boson by ATLAS and CMS
- We've not been standing still during this time!
- With run 2 of the LHC especially, we have definitively entered the precision era for Higgs physics
- **Enough data for differential and STXS cross sections**



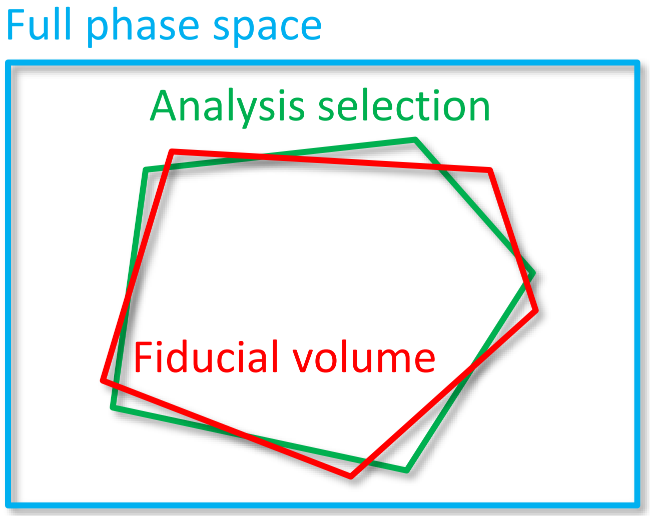
Discovery → Run 2



Going differential

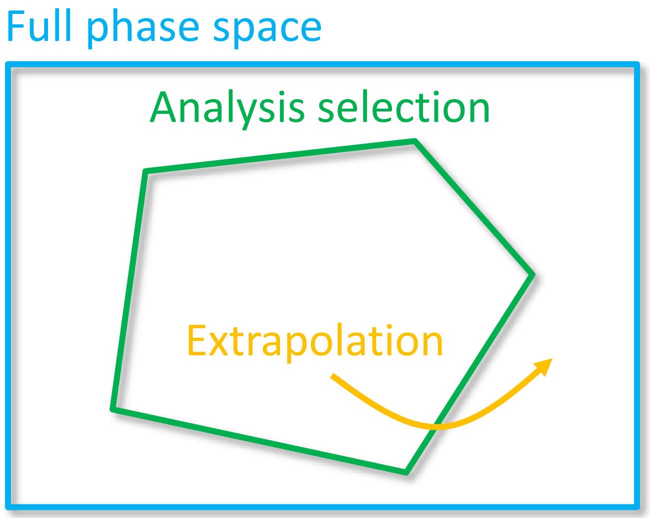
- Differential cross section measurements are stringent tests of the Standard Model (SM)
- Reduce dependence from model assumption/modelling uncertainties
- Presenting 2 complementary approaches: fiducial differential and Simplified Template Cross Sections (STXS)

Fiducial differential



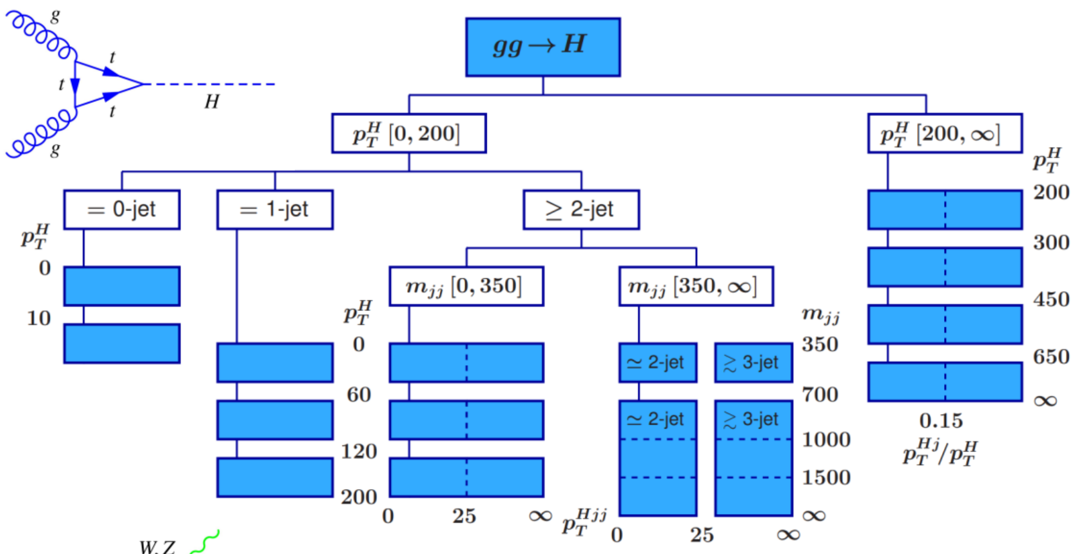
- ✓ Measurement limited to a subset of phase space
- ✓ Small extrapolation uncertainty
- ✗ Fiducial volume is **analysis-dependent**

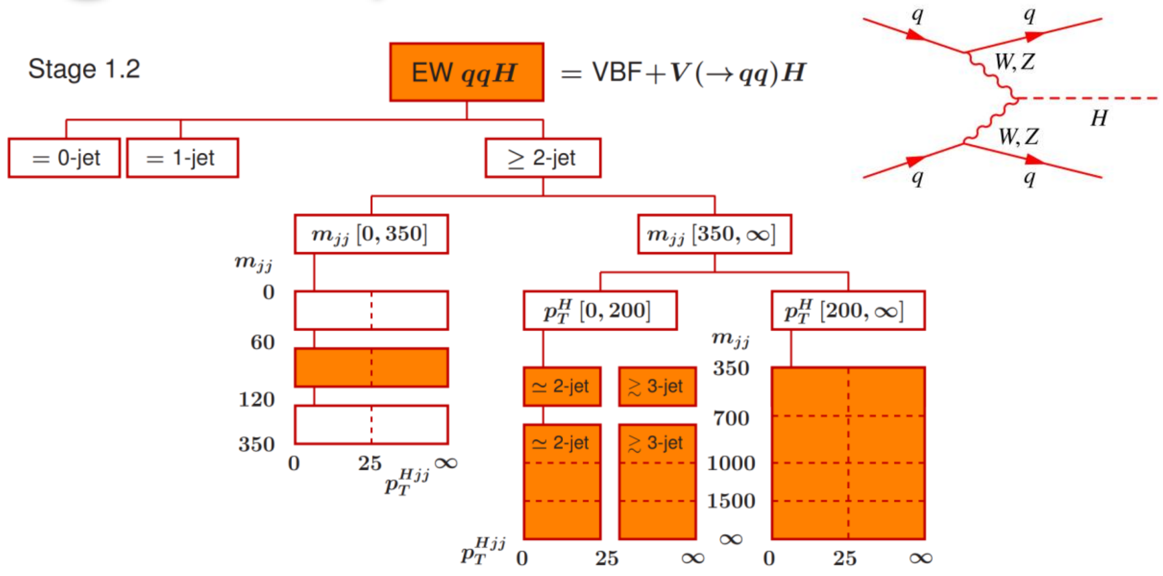
STXS

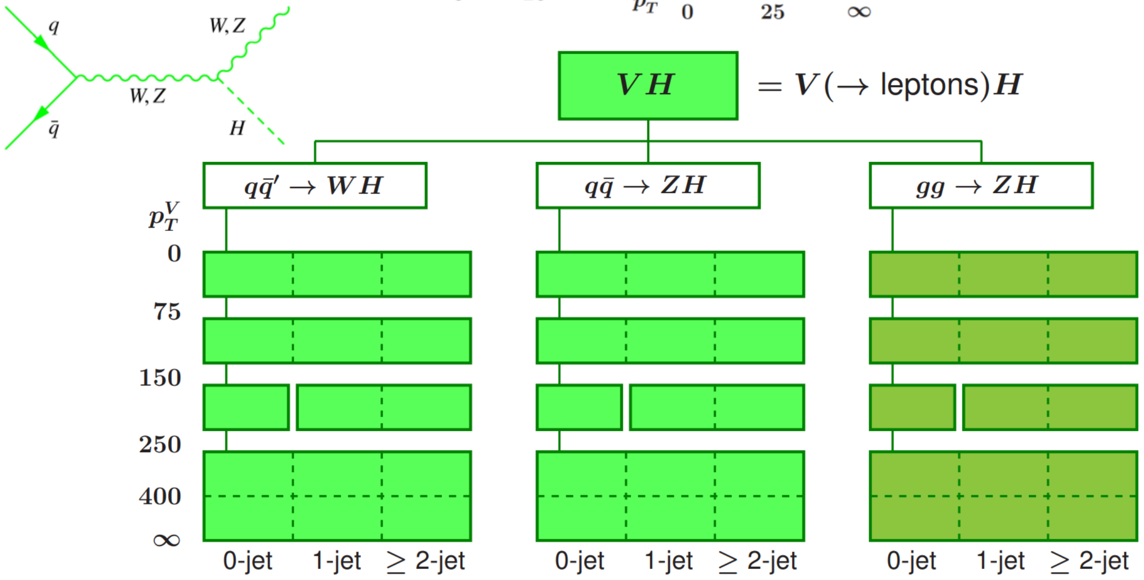


- ✓ Differential measurement in **pre-defined bins**
- ✓ Straightforward combination between channels
- ✗ Potentially large extrapolation uncertainties

Definition of STXS bins (stage 1.2)







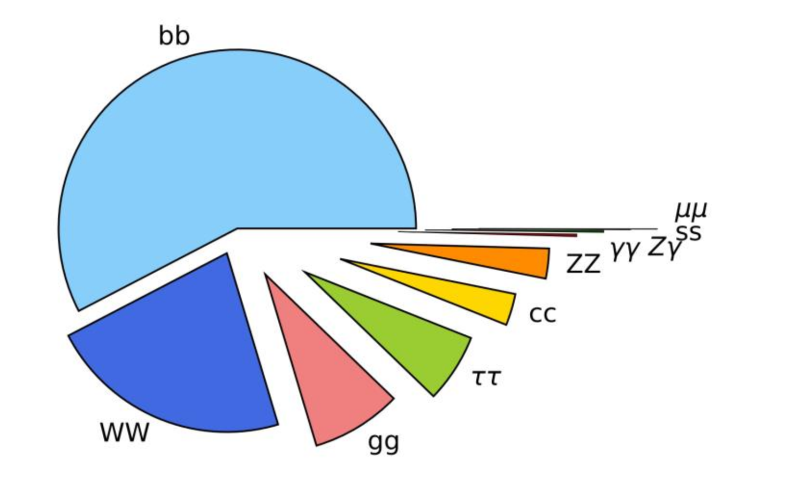
- Bins defined independently for the different Higgs production modes
- Different analyses will be sensitive to different bins
- Bins can be “merged” (i.e., measured as a single bin)

Results from CMS

Channel	Fiducial differential	STXS
$H \rightarrow WW$	10.1007/JHEP03(2021)003	CMS-PAS-HIG-20-013
$H \rightarrow \tau\tau$	10.1103/PhysRevLett.128.081805	arXiv:2204.12957 (sub to EPJC)
$H \rightarrow \gamma\gamma$	CMS-PAS-HIG-19-016	10.1007/JHEP07(2021)027
$H \rightarrow ZZ$	10.1140/epjc/s10052-021-09200-x	10.1140/epjc/s10052-021-09200-x
$H \rightarrow bb$	10.1007/JHEP12(2020)085	–

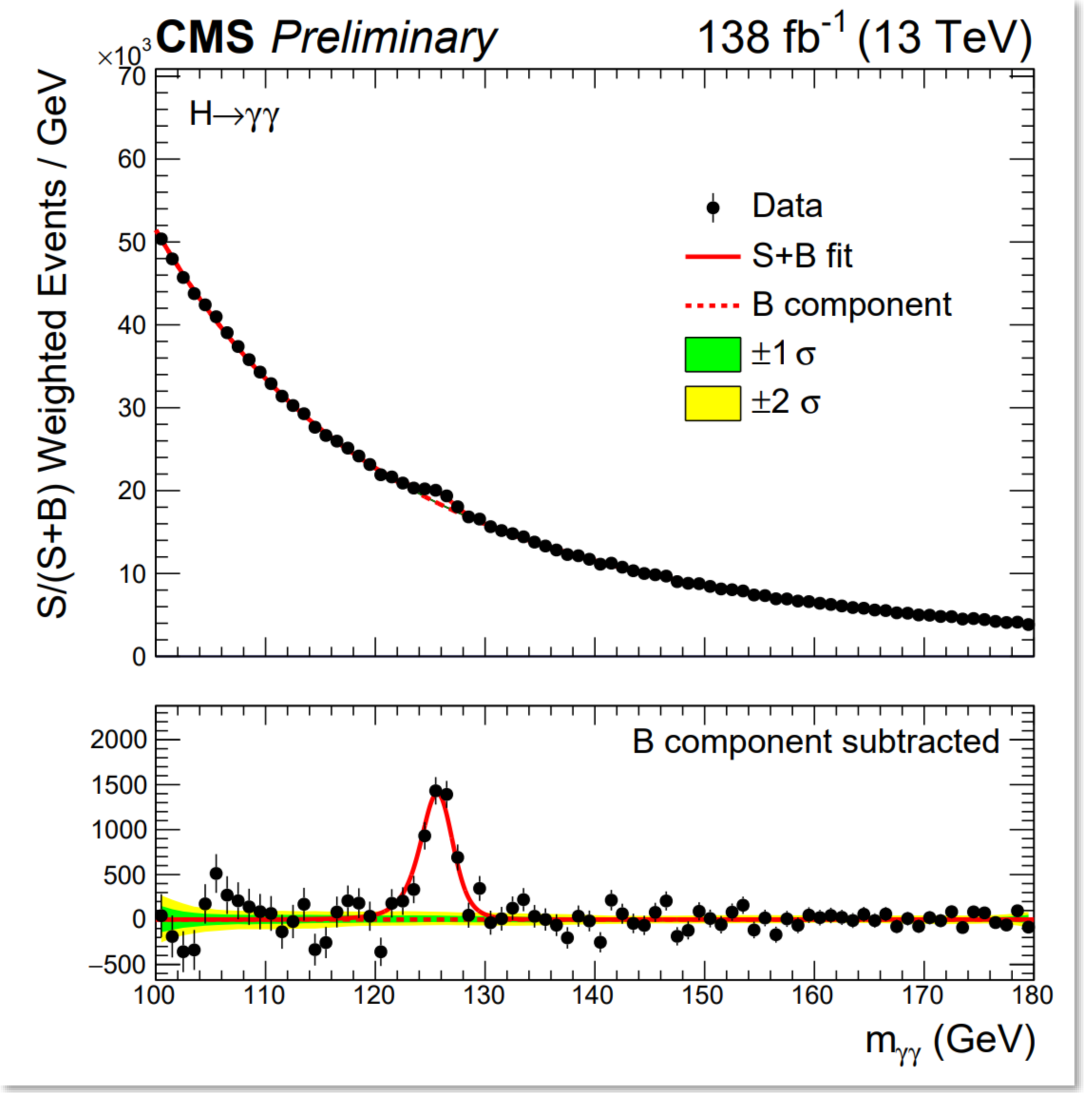
Covered in this talk

- CMS has produced an extensive set of measurements covering a variety of decay modes
- **All results are on the full LHC Run 2 data set of $138\ \mathrm{fb}^{-1}$ at 13 TeV**



H → γγ – overview

- Low branching ratio is offset by a very clean final state
- Access to the full invariant mass of the system m_H
- One of the primary channels for precision physics in the Higgs sector!
- Extensive set of results:
  - Inclusive fiducial cross sections
  - Differential fiducial cross sections as a function of 20 observables, some also in VBF-enriched selections
  - 2 double differential cross sections



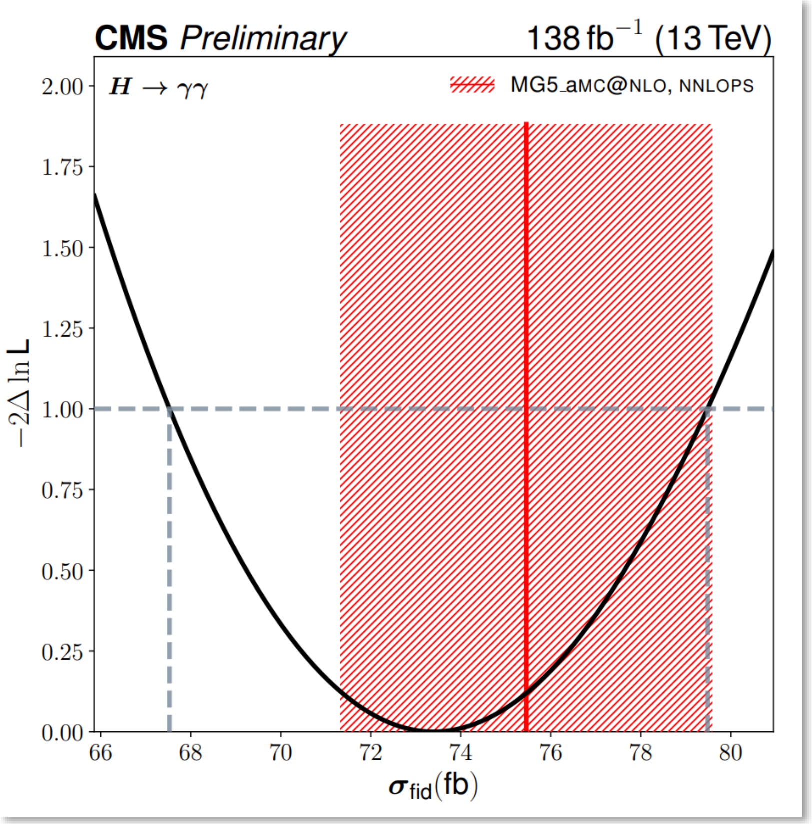
Fiducial volume

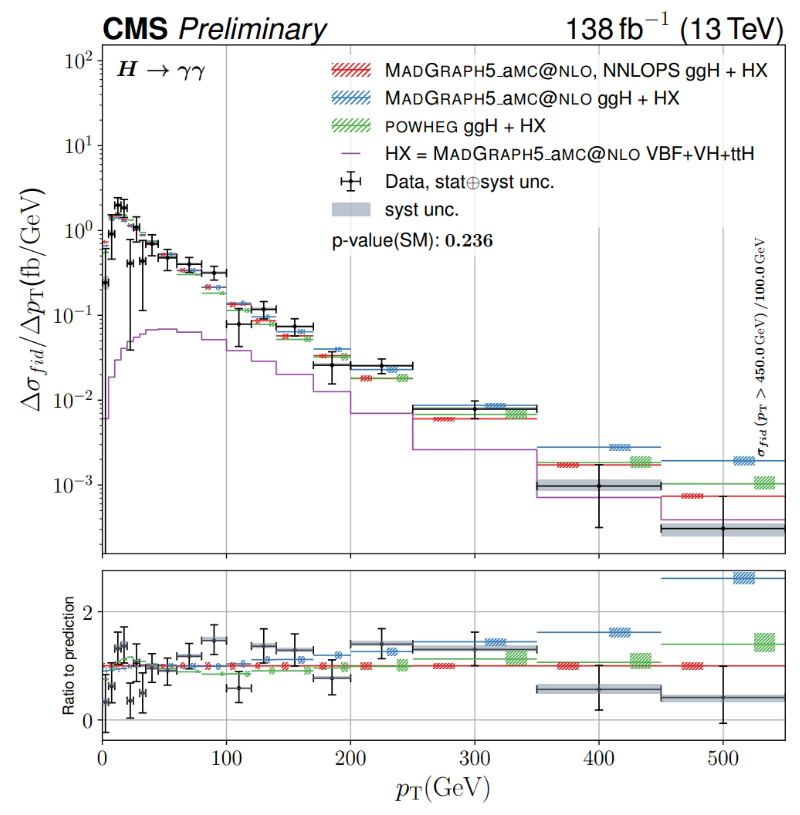
Observable	Selection
$p_T^{\gamma_1}/m_{\gamma\gamma}$	$> 1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma}$	$> 1/4$
$\mathcal{I}_{gen}^{\gamma}$	$< 10\,\mathrm{GeV}$
$\lvert\eta^{\gamma}\rvert$	< 2.5

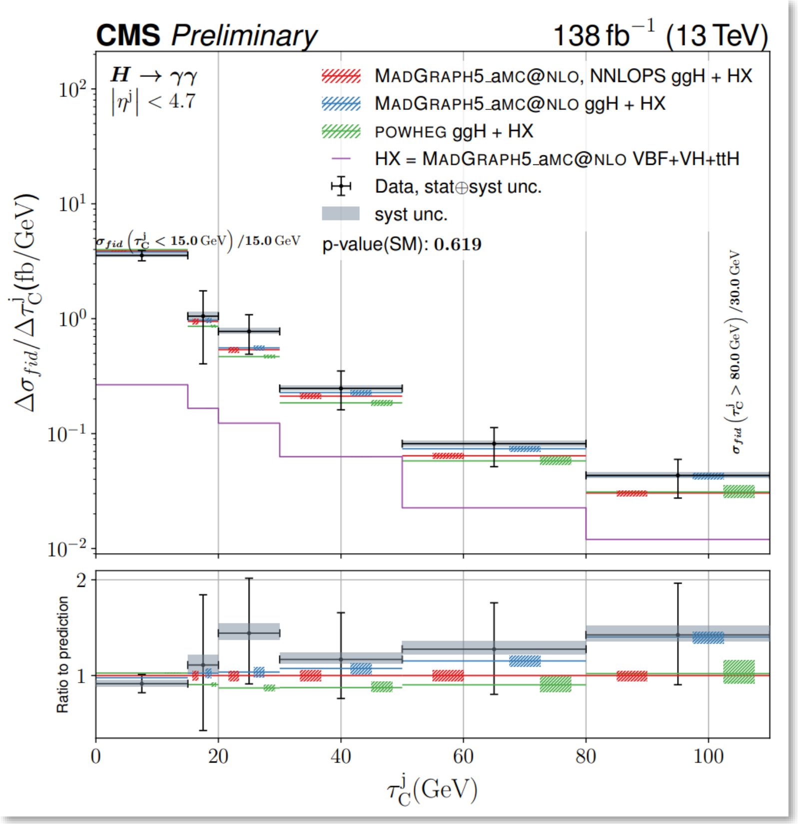
Total hadronic energy within $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ from the photon → mimics the reco level photon ID MVA

$H \to \gamma\gamma$ – results

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







$$\sigma_{fid} = 73.40^{+5.4}_{-5.3}(\text{stat})^{+2.4}_{-2.2}(\text{syst})\ \text{fb}$$

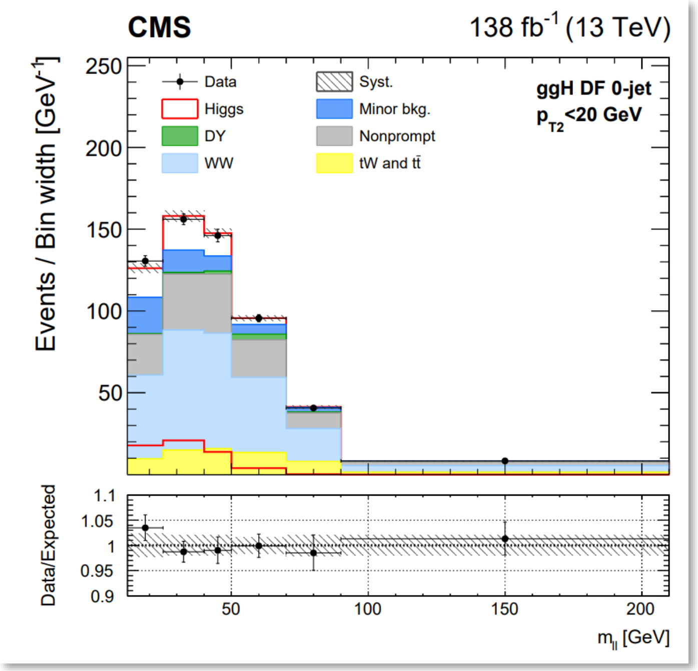
- Showing just a few examples from the extensive set!
- Measuring variables sensitive to couplings, BSM (p_T^H) and QCD effects (τ_C^j)

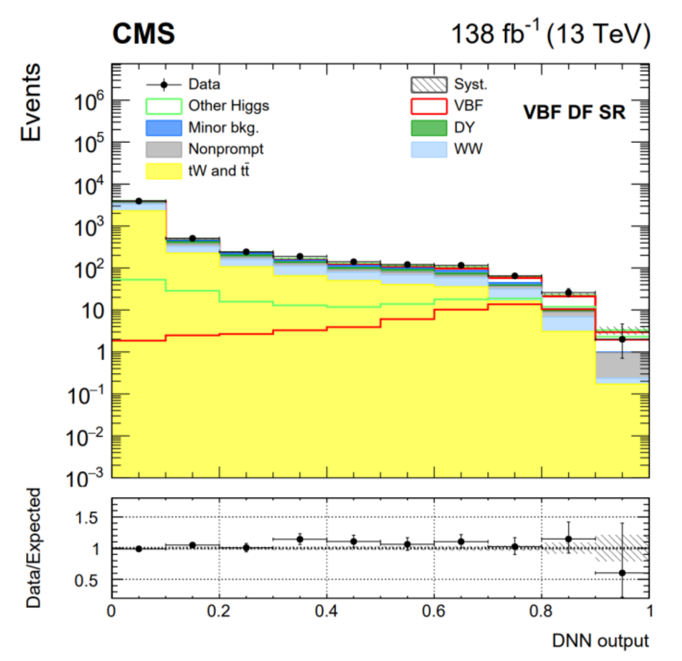
H → WW – overview

- H → WW has the second highest BR
- Gives access to leptonic final states → lower background
- Require at least one of the W bosons from the Higgs to decay leptonically $(W \to \ell\nu_\ell)$
- Leptonic final state also has neutrinos
- Cannot reconstruct invariant mass m_H, rely on other variables for the fit

Main backgrounds

Top quark production
$DY \to \ell\ell$
Nonresonant WW
Nonprompt leptons

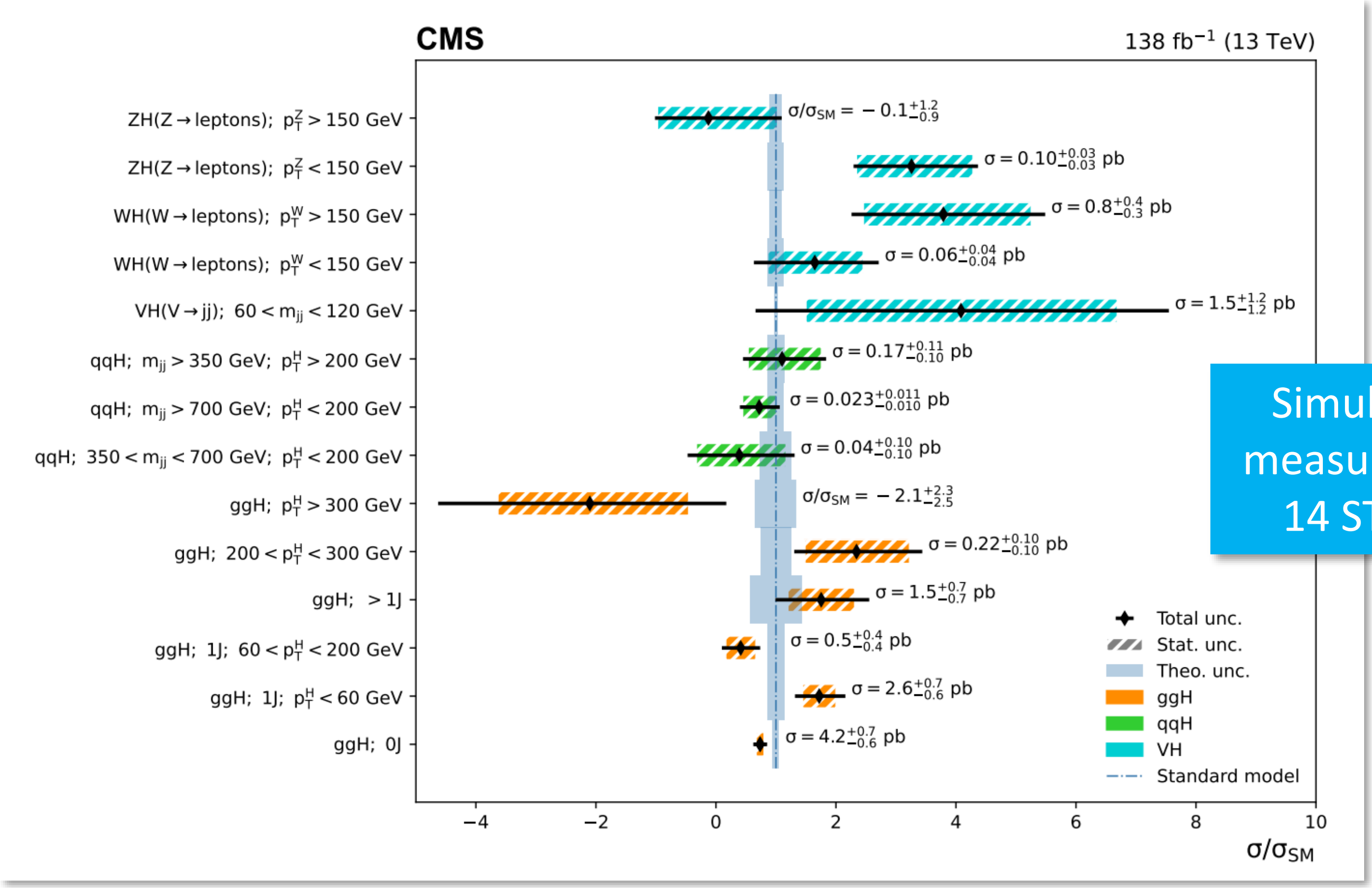




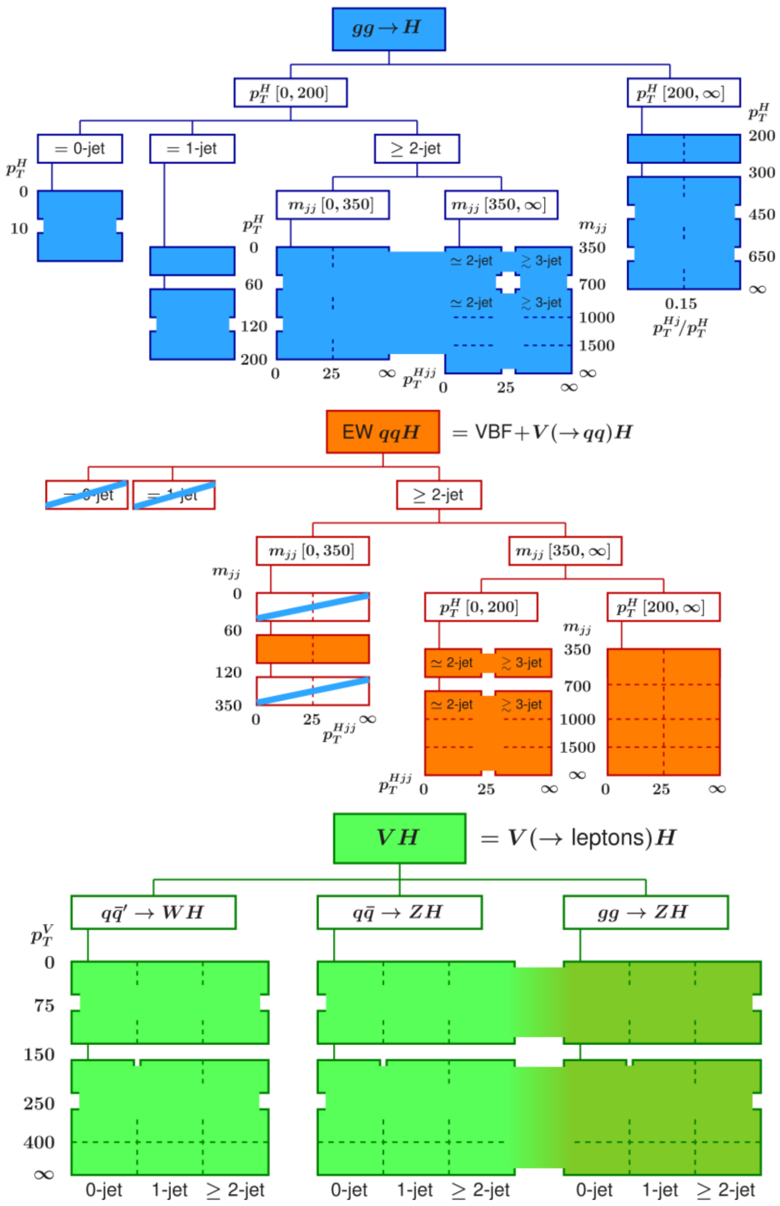
Target ggH, VBF, VH production modes for STXS

New measurements in the ggH and VBF channels + combination with VH channels reported in [CMS-PAS-HIG-19-017]

H → WW – results



Simultaneous measurement of 14 STXS bins



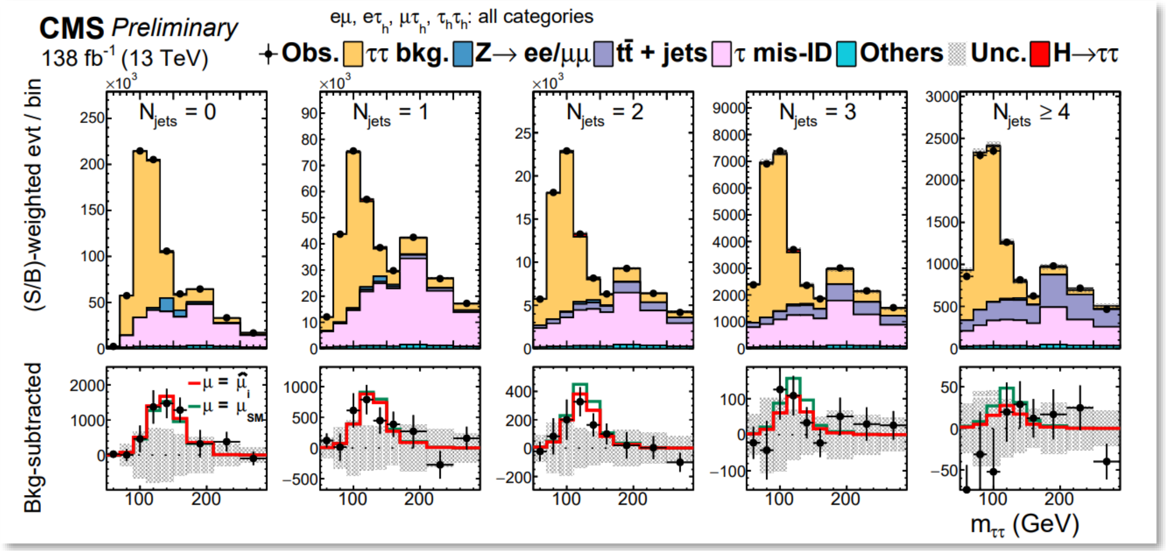
- Among the most precise measurements in low p_T^H STXS bins to date!
- Sizeable correlations because of migration effects
- Some bins merged together for lack of sensitivity

H → $\tau\tau$ fiducial differential – overview

- The analysis measures p_T^H, N_{jets} and $p_T^{j_1}$ distributions
- Relatively large BR ($\sim 6\%$) makes this channel competitive, especially in the high p_T^H, N_{jets} regions
- All decay combinations of the $\tau\tau$ system considered, apart from $ee + 4\nu$ and $\mu\mu + 4\nu$
- **First differential measurement in this channel!**

Main backgrounds

- $Z \rightarrow \tau\tau, t\bar{t}$, di-boson production
  - Events with two τ leptons estimated with embedded samples
  - Di-muon events in data with muons replaced with simulated τ leptons
- Jets misidentified as τ_h
  - Misidentification probability estimated in data



— SM expectation

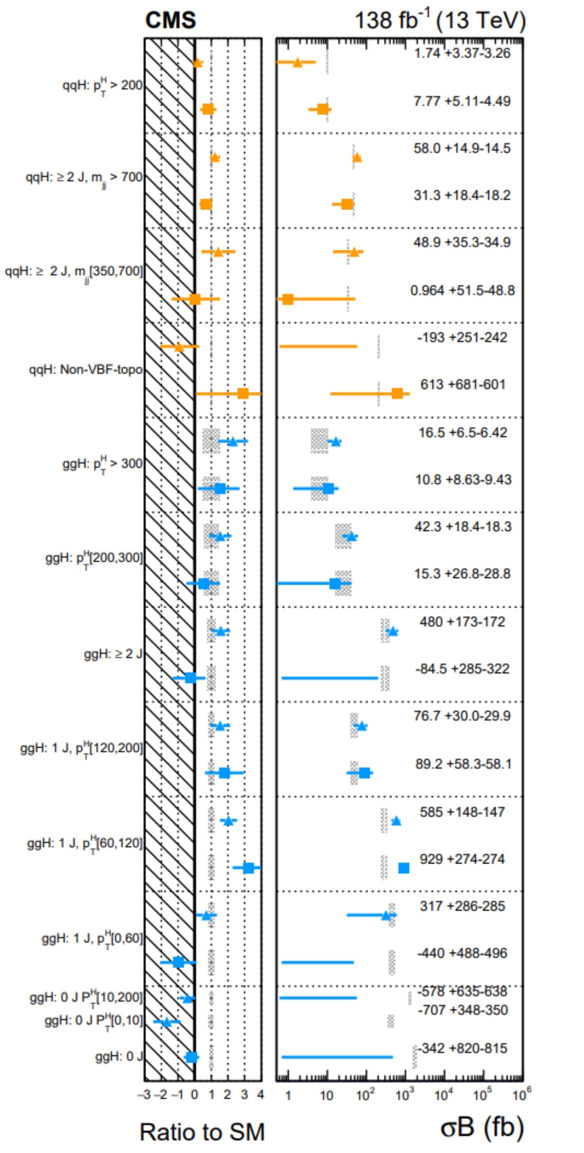
— Fit result

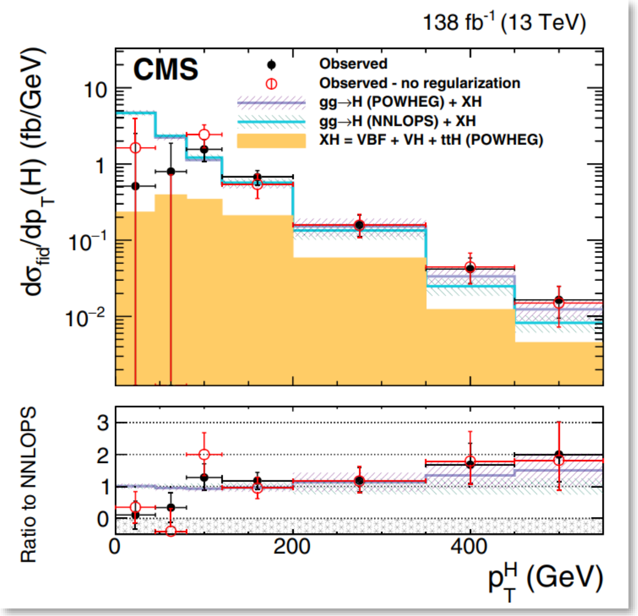
The fit is done on the mass of the $\tau\tau$ system ($m_{\tau\tau}$), reconstructed with a simplified matrix-element algorithm

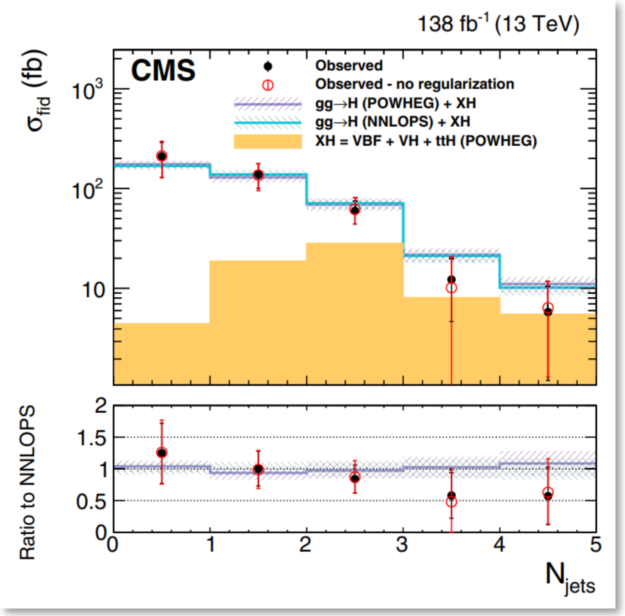
H → ττ – results

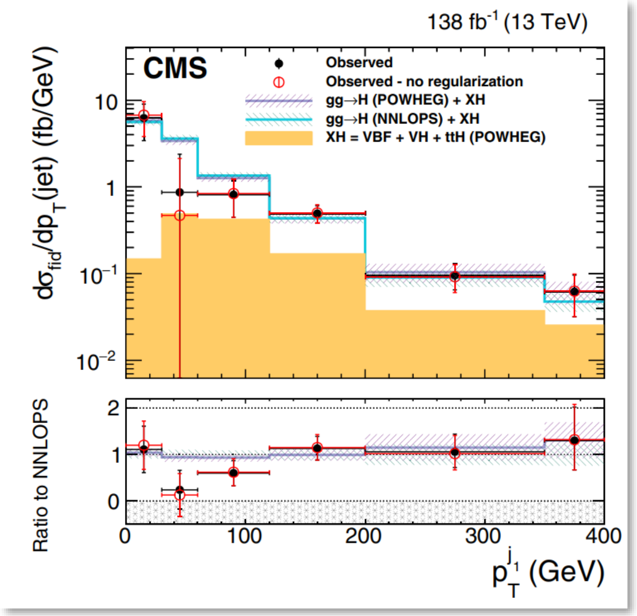
- Measurement inclusive in production modes
- Great sensitivity in high p_T^H and N_{jets} bins!
- Good agreement with SM expectation:
  - $p(p_T^H) = 17\%, p(N_{jets}) = 71\%, p\left(p_T^{j_1}\right) = 45\%$
- Fiducial cross section extracted from fit to N_{jets}:
  - $\sigma^{fid} = 426 \pm 102$ fb $\left(\sigma_{SM}^{fid} = 408 \pm 27 \text{ fb}\right)$

STXS results from dedicated inclusive analysis, more details in Nick's talk



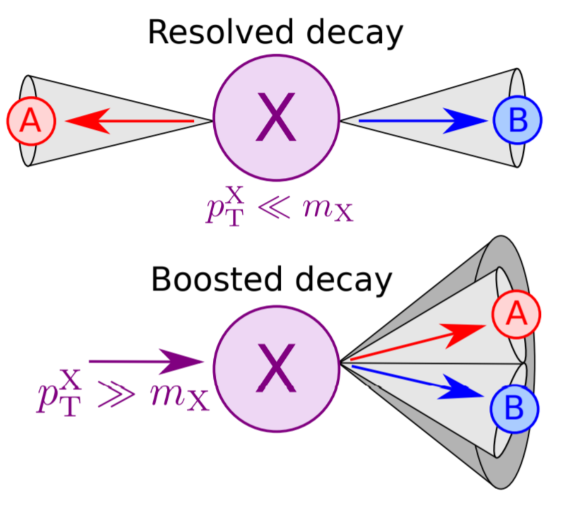


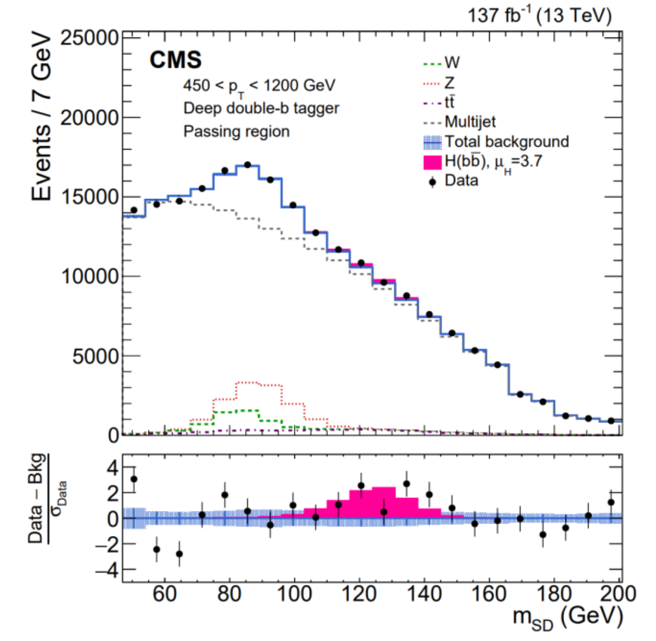


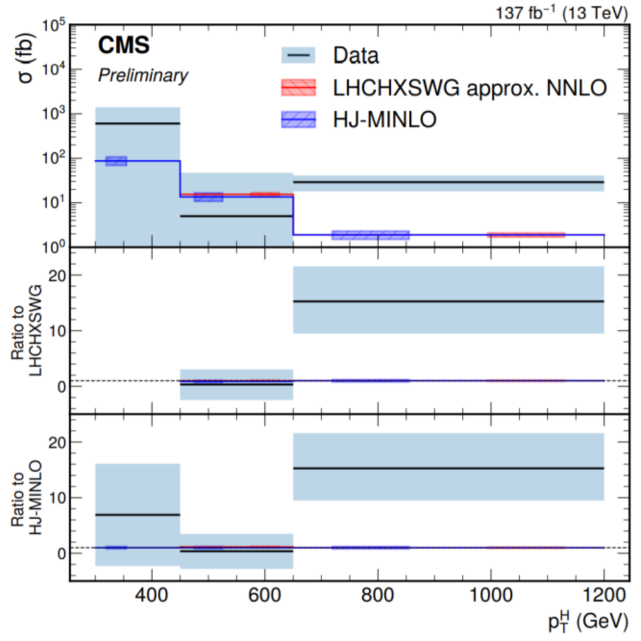


H → bb

- Very high multijet (QCD) background
- $\mathrm{BR}(\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}) = 58\% \longrightarrow$ highest in the SM
- **Mitigates natural cross section decrease at high p_T^H**
- Target the boosted jet topology i.e., a large radius jet with a 2 sub-jet structure



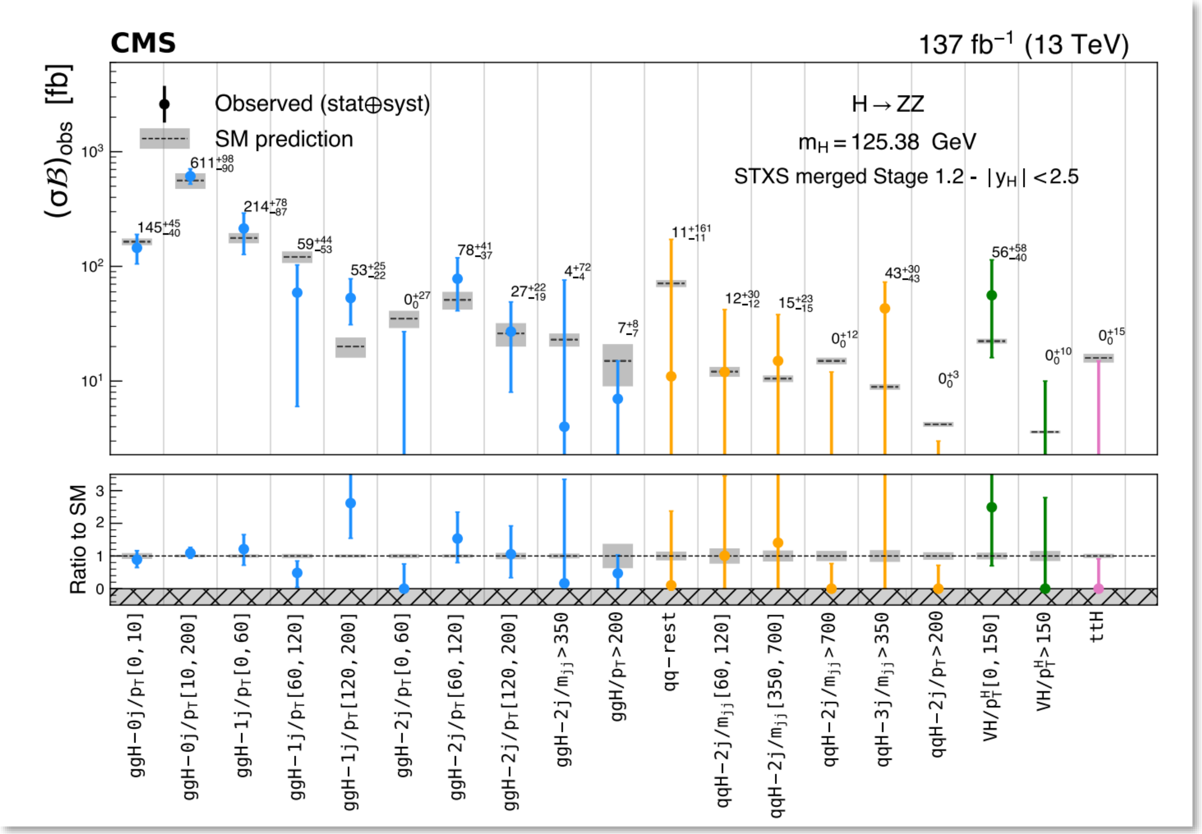


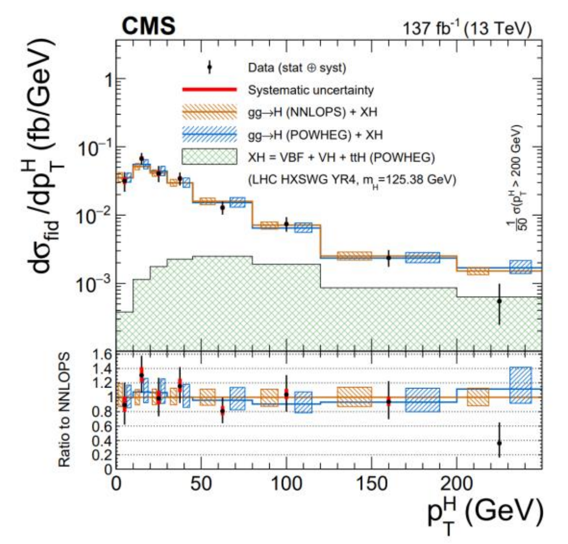


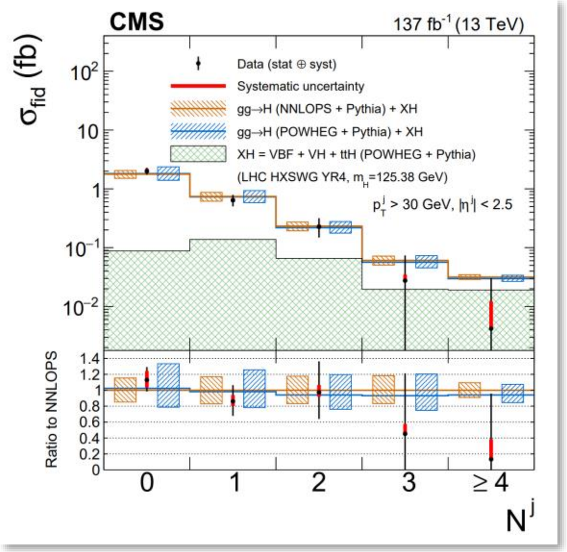
- Signal extracted by fitting the (soft drop groomed) jet mass distribution
- Require $p_T^{j_1} > 450$ GeV, dedicated MVA tagger
- Target gluon fusion, other modes treated as background
- 2.6σ excess in highest p_T^H bin, reduced to 1.8σ when considering all bins simultaneously

$H \rightarrow ZZ$

- Low BR but clean final state with 4 charged leptons
- Main backgrounds: nonresonant $ZZ/Z\gamma$, $Z + \text{jets}$, $t\bar{t}$, WZ production
- Extensive set of results: 19 STXS bins, 4 differential cross sections ($p_T^H, N_{jets}, |y_H|, p_T^{j_1}$)
- Fit on the invariant mass of the 4-lepton system







Fiducial volume

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell^-} > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

Conclusions

- 10 years after its discovery, we have entered the era of precision characterization of the Higgs boson
- The LHC and its experiments continue to exceed expectation in their potential for precision physics
- CMS delivered a comprehensive set of STXS and fiducial differential cross section measurement on Run 2, with more to come
- WW, ZZ, $\gamma\gamma$, $\tau\tau$ and bb decays covered
- Looking forward for Run 3 starting this summer, and HL-LHC further down the line!

Backup

Unfolding

Results unfolded to particle level within likelihood fit

True for all analyses discussed in this talk

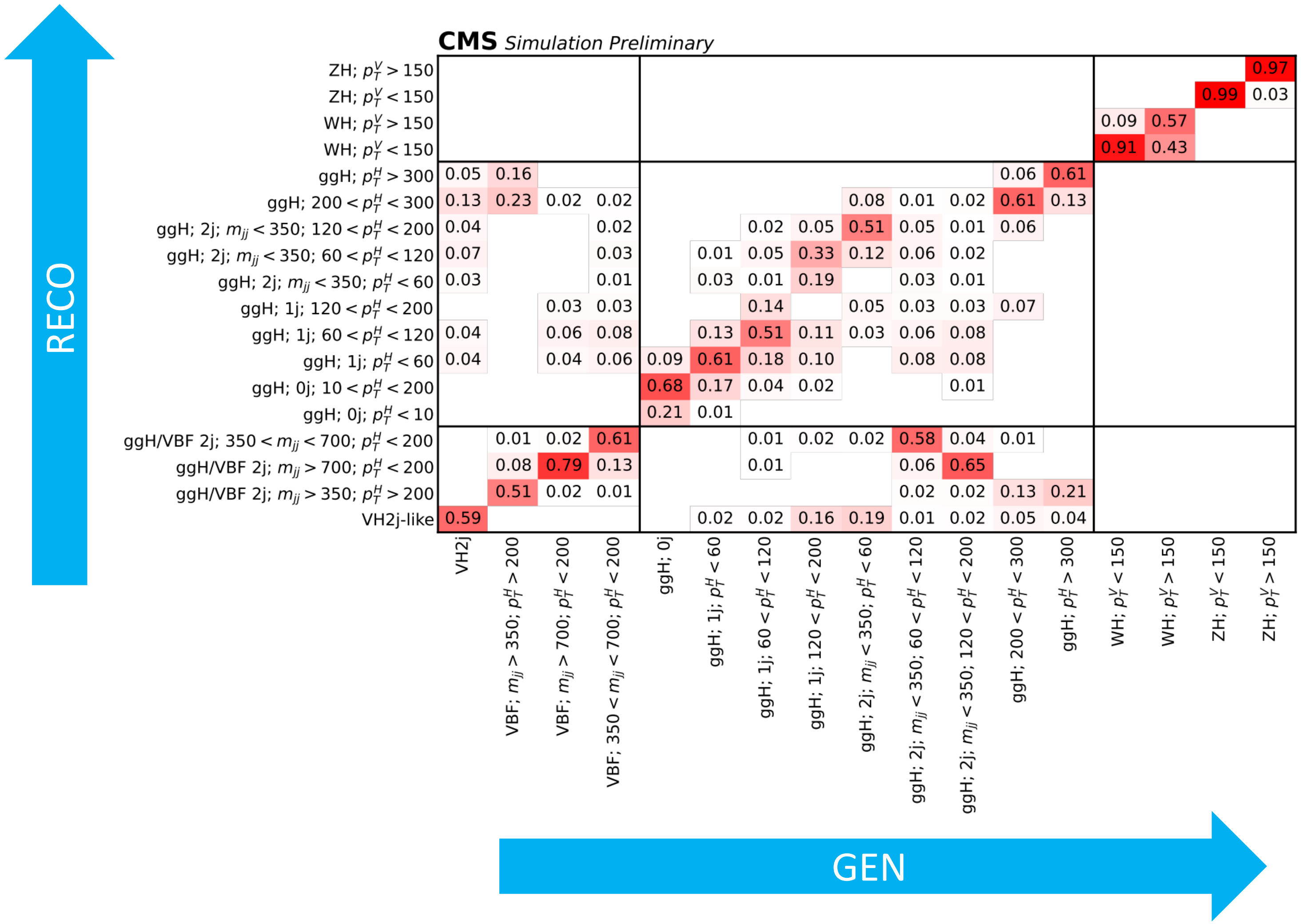
$$\mathcal{L} = \prod_i Poisson\left(n_i; \sum_j R_{ij}(\theta)\,\mu_j + b_i\right) \cdot \mathcal{C}(\theta) \cdot \mathcal{K}(\mu)$$

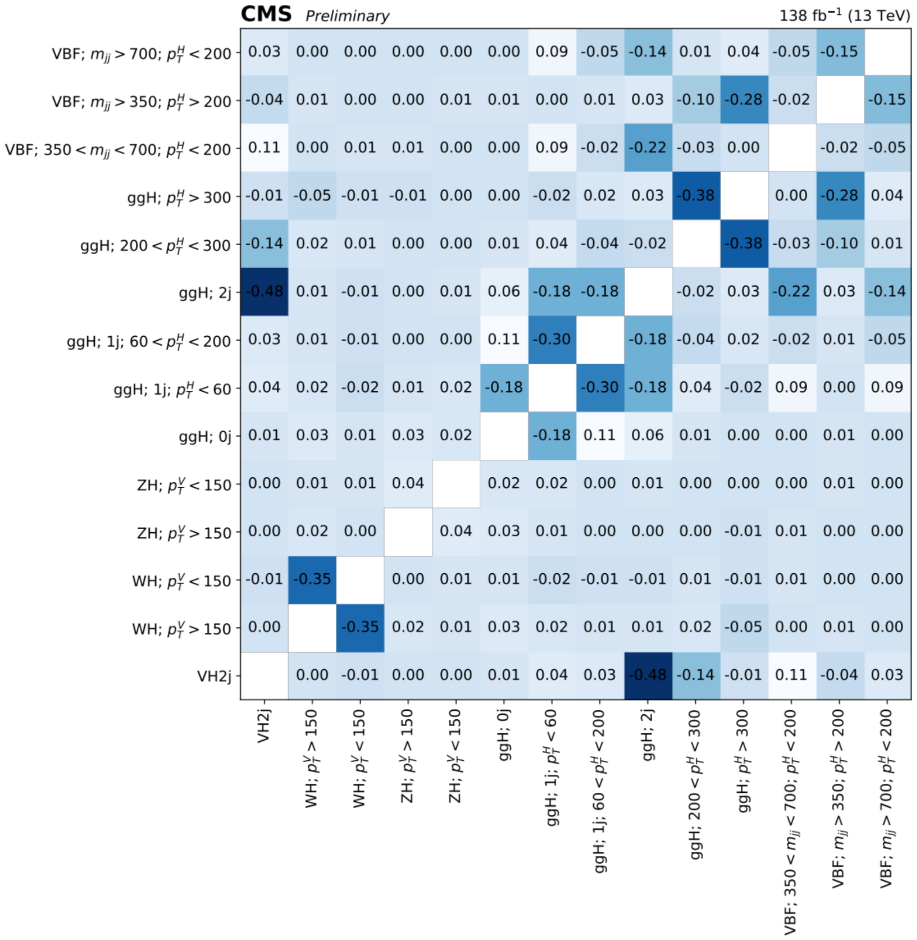
Migration matrix

Particle level signal strength

Regularization term (optional), Tikhonov scheme in this analysis

H → WW migrations and correlations

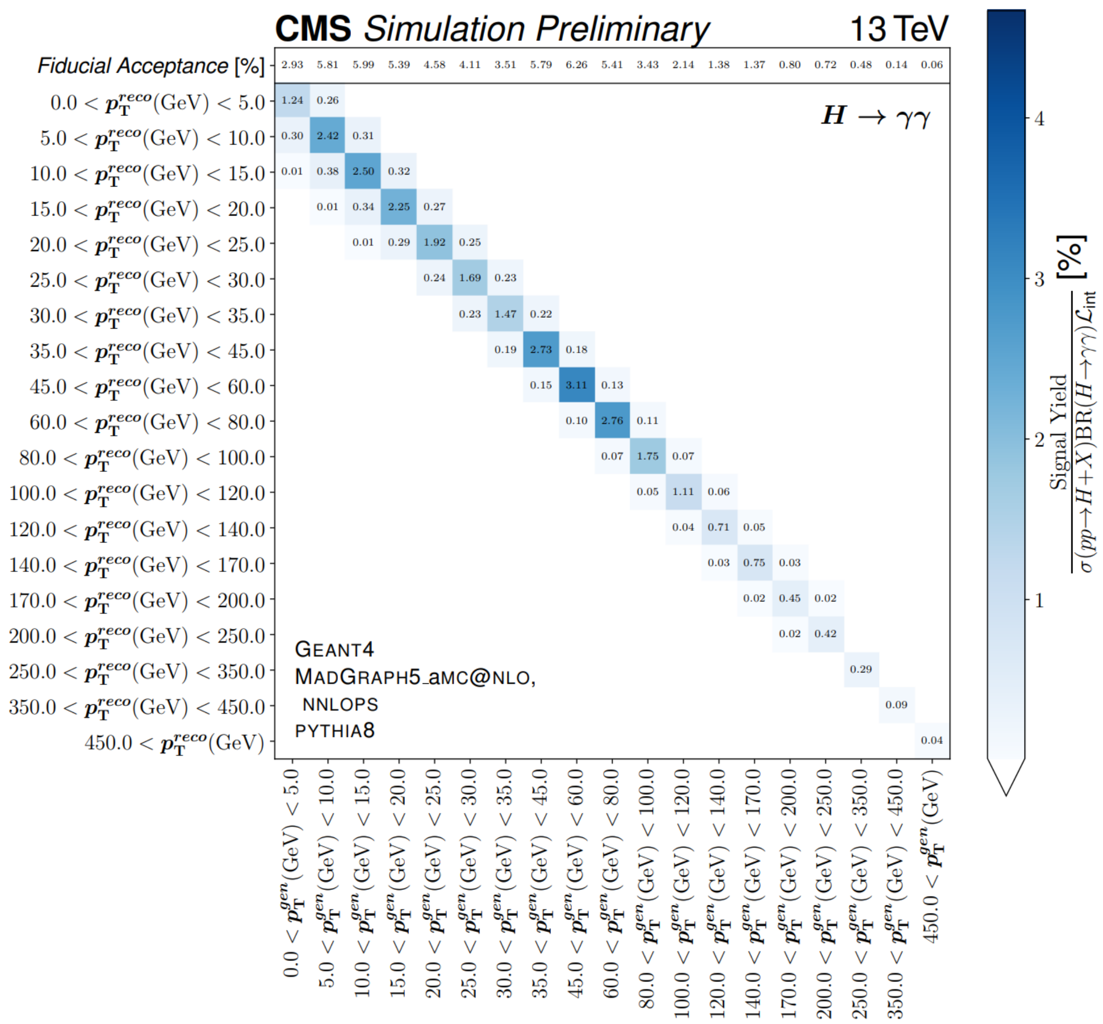


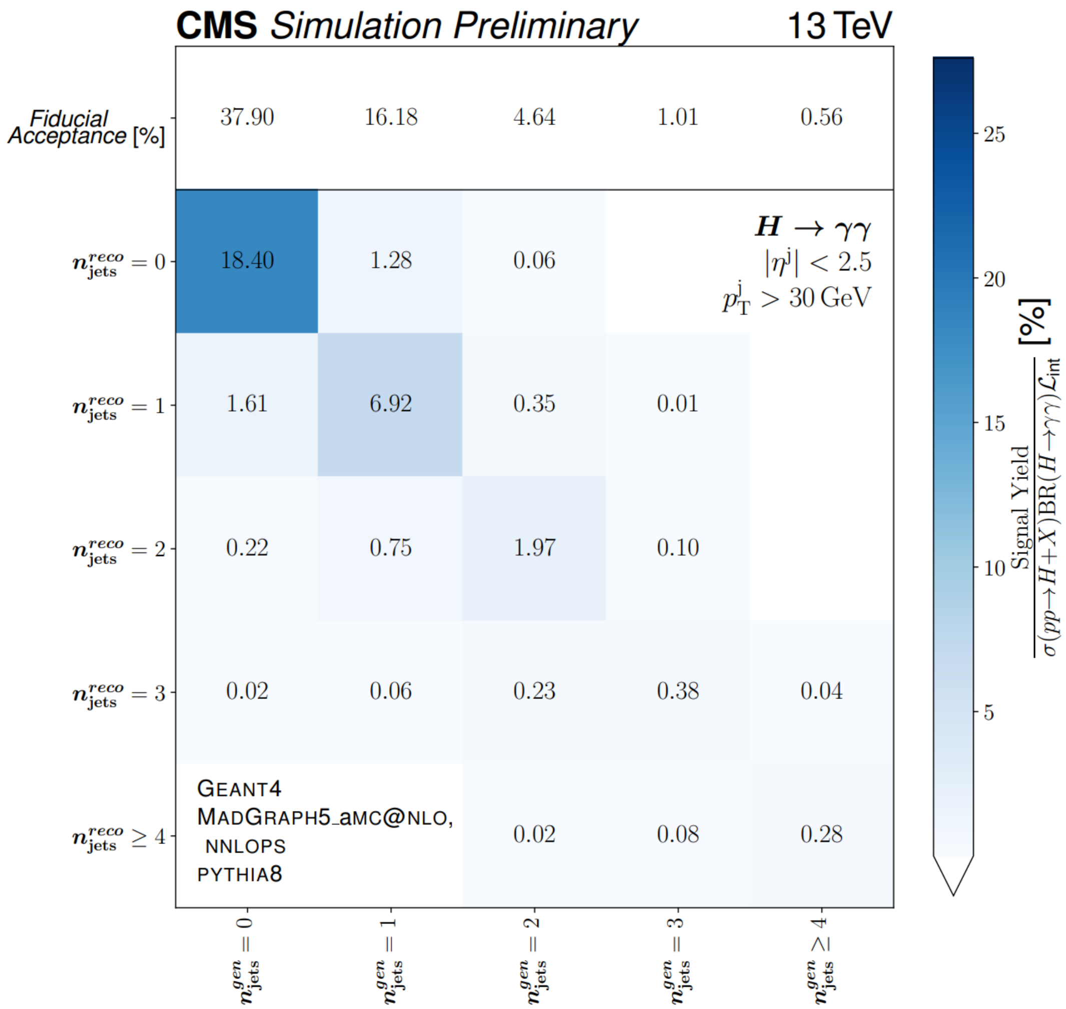


$\mathrm{H} \rightarrow \gamma\gamma$ fiducial selections

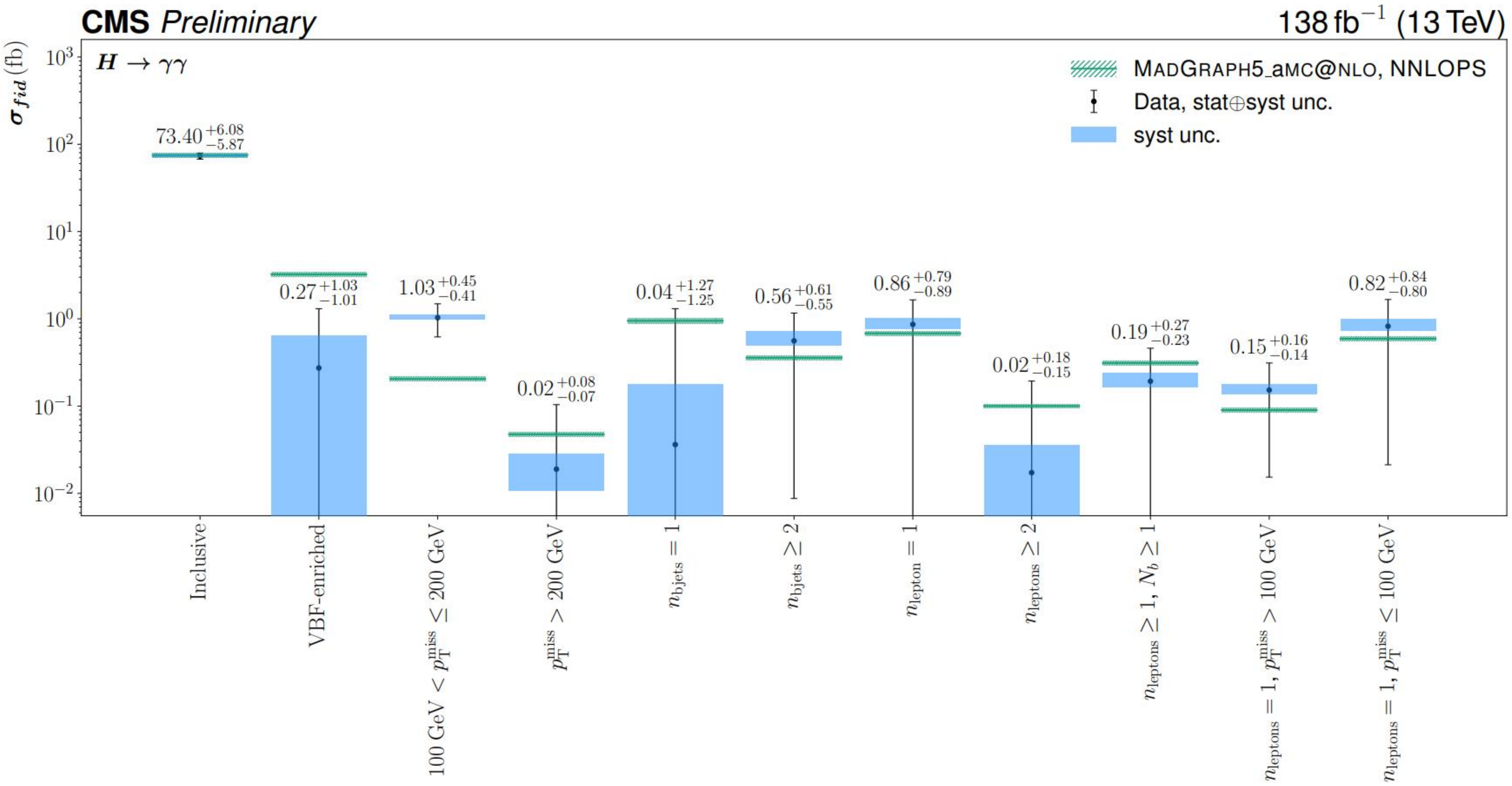
Phase Space Region	Observable	Bin boundaries							
	$p_T^{\gamma\gamma}$	0	5	10	15	20	25	30	35
		45	60	80	100	120	140	170	200
		250	350	450	∞				
	n_{jets}	0	1	2	3	≥ 4			
	$\|y^{\gamma\gamma}\|$	0.0	0.1	0.2	0.3	0.45	0.6	0.75	0.90
		2.5							
Baseline	$\|\cos(\theta^*)\|$	0.0	0.07	0.15	0.22	0.35	0.45	0.55	0.75
$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$		1.0							
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$\|\phi_\eta^*\|$	0.0	0.05	0.1	0.2	0.3	0.4	0.5	0.7
$\|\eta^\gamma\| < 2.5$		1.0	1.5						
$\mathcal{I}_{gen}^{\gamma} < 10\,\mathrm{GeV}$		2.5	4.0	∞					
	$p_T^{\gamma\gamma}, n_{jets} = 0$	0	5	10	15	20	25	30	35
		45	60	∞					
	$p_T^{\gamma\gamma}, n_{jets} = 1$	0	30	60	100	170	∞		
	$p_T^{\gamma\gamma}, n_{jets} > 1$	0	100	170	250	350	∞		
	n_{jets}^{b}	0	1	≥ 2					
	n_{leptons}	0	1	≥ 2					
	p_T^{miss}	0	30	50	100	200	∞		
	$p_T^{j_1}$	30	40	55	75	95	120	150	200
		∞							
	$\|y^{j_1}\|$	0.0	0.3	0.6	0.9	1.2	1.6	2.0	2.5
1-jet	$\|\Delta\phi_{\gamma\gamma,j_1}\|$	0.0	2.0	2.6	2.85	3.0	3.07	π	
Baseline + ≥ 1 jet	$\|\Delta y_{\gamma\gamma,j_1}\|$	0.0	0.3	0.6	1.0	1.4	1.9	2.5	∞
$p_T^{j} > 30$ GeV	τ_C^{j}	< 15	15	20	30	50	80	∞	
$\|\eta^{j}\| < 2.5$	$p_T^{\gamma\gamma}, \tau_{Cj} < 15$ GeV	0	45	120	∞				
	$p_T^{\gamma\gamma}$, 15 GeV $\leq \tau_C^{j} <$ 25 GeV	0	45	120	∞				
	$p_T^{\gamma\gamma}$, 25 GeV $\leq \tau_C^{j} <$ 40 GeV	0	120	∞					
	$p_T^{\gamma\gamma}$, 40 GeV $\leq \tau_C^{j}$	0	200	350	∞				
	$p_T^{j_2}$	30	40	65	90	150	∞		
2-jets	$\|y^{j_2}\|$	0.0	0.6	1.2	1.8	2.5	3.5	5.0	
Baseline + ≥ 2 jets	$\|\Delta\phi_{j_1,j_2}\|$	0.0	0.5	0.9	1.3	1.7	2.5	π	
$p_T^{j} > 30$ GeV	$\|\Delta\phi_{\gamma\gamma,j_1j_2}\|$	0.0	2.0	2.7	2.95	3.07	π		
$\|\eta^{j}\| < 4.7$	$\|\bar{\eta}_{j_1j_2} - \eta_{\gamma\gamma}\|$	0.0	0.2	0.5	0.85	1.2	1.7	∞	
	m^{jj}	0	75	120	180	300	500	1000	∞
	$\|\Delta\eta_{j_1j_2}\|$	0.0	0.7	1.6	3.0	5.0	∞		
VBF-enriched	$p_T^{\gamma\gamma}$	0	30	60	120	200	∞		
2-jets + $n_{\mathrm{jets}} \geq 2$	$p_T^{j_2}$	30	40	65	90	150	∞		
$\Delta\eta^{jj} > 3.5$	$\|\Delta\phi_{j_1,j_2}\|$	0.0	0.5	0.9	1.3	1.7	2.5	π	
$m^{jj} > 200\,\mathrm{GeV}$	$\|\Delta\phi_{\gamma\gamma,j_1j_2}\|$	0.0	2.0	2.7	2.95	3.07	π		

H → γγ migrations





$H \to \gamma\gamma$ fiducial cross sections



$H \rightarrow ZZ$ STXS selection

Reconstructed event category	1st categorization step	Number of jets	Kinematical requirements (GeV)	Targeted production bin
Untagged-0j-$p_T^{4\ell}[0, 10]$	Untagged	0	$0 < p_T^{4\ell} < 10$	ggH-0j/$p_T[0, 10]$
Untagged-0j-$p_T^{4\ell}[10, 200]$	Untagged	0	$10 < p_T^{4\ell} < 200$	ggH-0j/$p_T[10, 200]$
Untagged-1j-$p_T^{4\ell}[0, 60]$	Untagged	1	$0 < p_T^{4\ell} < 60$	ggH-1j/$p_T[0, 60]$
Untagged-1j-$p_T^{4\ell}[60, 120]$	Untagged	1	$60 < p_T^{4\ell} < 120$	ggH-1j/$p_T[60, 120]$
Untagged-1j-$p_T^{4\ell}[120, 200]$	Untagged	1	$120 < p_T^{4\ell} < 200$	ggH-1j/$p_T[120, 200]$
Untagged-2j-$p_T^{4\ell}[0, 60]$	Untagged	2	$0 < p_T^{4\ell} < 60$, $m_{jj} < 350$	ggH-2j/$p_T[0, 60]$
Untagged-2j-$p_T^{4\ell}[60, 120]$	Untagged	2	$60 < p_T^{4\ell} < 120$, $m_{jj} < 350$	ggH-2j/$p_T[60, 120]$
Untagged-2j-$p_T^{4\ell}[120, 200]$	Untagged	2	$120 < p_T^{4\ell} < 200$, $m_{jj} < 350$	ggH-2j/$p_T[120, 200]$
Untagged-$p_T^{4\ell} > 200$	Untagged	–	$p_T^{4\ell} > 200$	ggH/$p_T > 200$
Untagged-2j-$m_{jj} > 350$	Untagged	2	$m_{jj} > 350$	ggH-2j/$m_{jj} > 350$
VBF-1jet-tagged	VBF-1jet-tagged	–	–	qqH-rest
VBF-2jet-tagged-$m_{jj}[350, 700]$	VBF-2jet-tagged	–	$p_T^{4\ell} < 200$, $p_T^{4\ell jj} < 25$, $350 < m_{jj} < 700$	qqH-2j/$m_{jj}[350, 700]$
VBF-2jet-tagged-$m_{jj} > 700$	VBF-2jet-tagged	–	$p_T^{4\ell} < 200$, $p_T^{4\ell jj} < 25$, $m_{jj} > 700$	qqH-2j/$m_{jj} > 700$
VBF-3jet-tagged-$m_{jj} > 350$	VBF-2jet-tagged	–	$p_T^{4\ell} < 200$, $p_T^{4\ell jj} > 25$, $m_{jj} > 350$	qqH-3j/$m_{jj} > 350$
VBF-2jet-tagged-$p_T^{4\ell} > 200$	VBF-2jet-tagged	–	$p_T^{4\ell} > 200$, $m_{jj} > 350$	qqH-2j/$p_T > 200$
VBF-rest	VBF-2jet-tagged	–	$m_{jj} < 350$	qqH-rest
VH-hadronic-tagged-$m_{jj}[60, 120]$	VH-hadronic-tagged	–	$60 < m_{jj} < 120$	qqH-2j/$m_{jj}[60, 120]$
VH-rest	VH-hadronic-tagged	–	$m_{jj} < 60$ or $m_{jj} > 120$	qqH-rest
VH-leptonic-tagged-$p_T^{4\ell}[0, 150]$	VH-leptonic-tagged	–	$p_T^{4\ell} < 150$	VH-lep/$p_{TH}[0, 150]$
VH-leptonic-tagged-$p_T^{4\ell} > 150$	VH-leptonic-tagged	–	$p_T^{4\ell} > 150$	VH-lep/$p_{TH} > 150$
$t\bar{t}$H-leptonic-tagged	$t\bar{t}$H-leptonic-tagged	–	–	ttH
$t\bar{t}$H-hadronic-tagged	$t\bar{t}$H-hadronic-tagged	–	–	ttH