Measurements of Higgs boson cross sections and differential distributions in bosonic final states at the CMS experiment

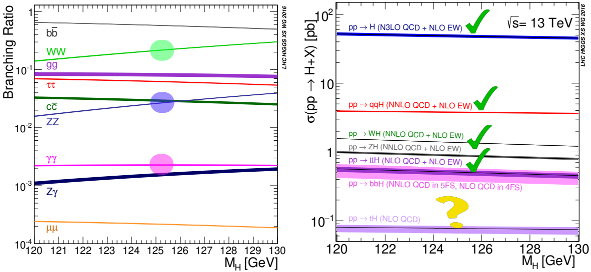
J. Langford

On behalf of the CMS Collaboration

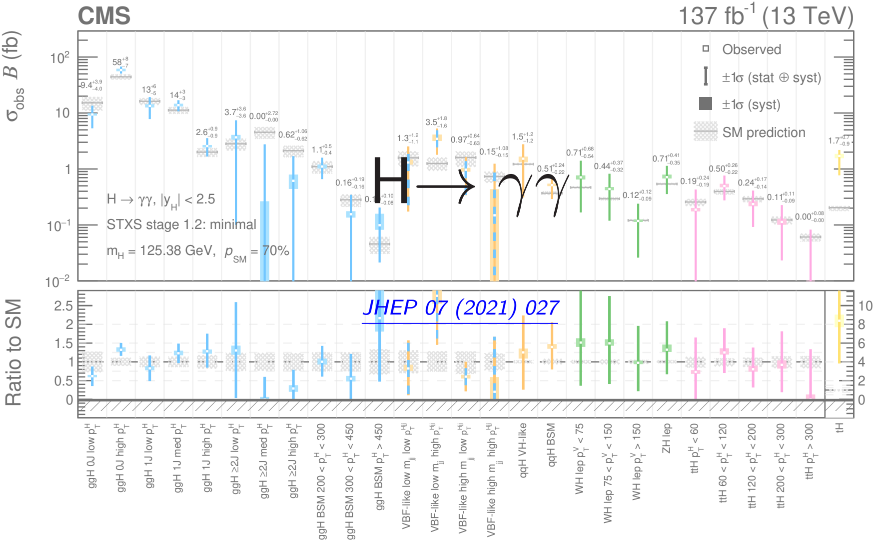
EPS 2021

Introduction

- Bosonic final states provide clean signatures for precision measurements

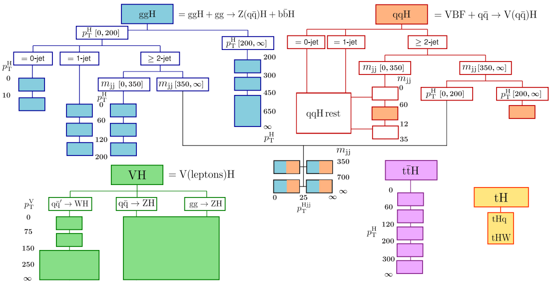


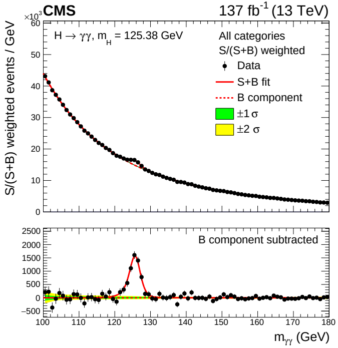
- Measured four dominant production modes with $> 5\sigma$ sensitivity
  - wealth of Run 2 data permits measurements in different kinematic regions
    - ⇒ sensitive to new physics affecting shape of Higgs boson distributions
    - ⇒ STXS vs fiducial differential ▸ Back-up
  - + rarer processes e.g. single-top production (tH)
- Most recent **cross section measurements** by CMS in bosonic final states
  - all based on 137 fb^{-1} of p-p collision data collected during Run 2 (2016-2018)
  - signal strengths, κ's etc covered in talk by Ulascan


CMS
137 fb-1 (13 TeV)
σobs B (fb)
Ratio to SM
Observed
±1σ (stat ⊕ syst)
±1σ (syst)
SM prediction
H → γγ, |yH| < 2.5
STXS stage 1.2: minimal
mH = 125.38 GeV, pSM = 70%
H → γγ
JHEP 07 (2021) 027
ggH 0J low pTH
ggH 0J high pTH
ggH 1J low pTH
ggH 1J med pTH
ggH 1J high pTH
ggH ≥2J low pTH
ggH ≥2J med pTH
ggH ≥2J high pTH
ggH BSM 200 < pTH < 300
ggH BSM 300 < pTH < 450
ggH BSM pTH > 450
VBF-like low mjj low pTHjj
VBF-like low mjj high pTHjj
VBF-like high mjj low pTHjj
VBF-like high mjj high pTHjj
qqH VH-like
qqH BSM
WH lep pTV < 75
WH lep 75 < pTV < 150
WH lep pTV > 150
ZH lep
ttH pTH < 60
ttH 60 < pTH < 120
ttH 120 < pTH < 200
ttH 200 < pTH < 300
ttH pTH > 300
tH

H→ $\gamma\gamma$: overview

- Small branching fraction: $\sim$0.2%
- Clean, fully-reconstructed final state of two isolated photons
  - benefit from excellent diphoton mass resolution: 1-2%
- Measure cross sections in kinematics bins of the **STXS** framework (stage 1.2)
  - sensitive to all major Higgs production modes: ggH, VBF + VH had, VH lep, ttH, tH
  - $\sigma \cdot \mathcal{B}$ extracted in fit to diphoton invariant mass spectrum ($m_{\gamma\gamma}$)

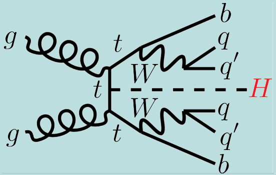




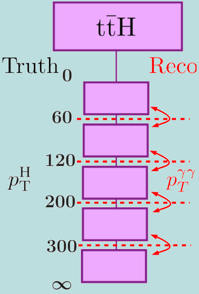
H→ $\gamma\gamma$: analysis strategy

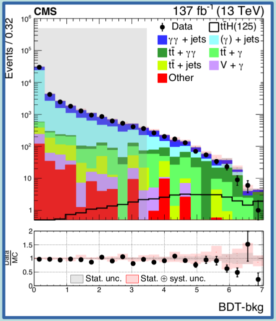
- Construct orthogonal event categories enriched in events from kinematic bins
  1. Isolate events from given H production mode: ggH, VBF, VH, ttH, tH
     $\Rightarrow$ requires tagging on additional objects: jets, charged leptons, MET
  2. Split events into kinematic regions. Either...
     $\Rightarrow$ aligning cuts on equivalent reco-level quantities e.g. $p_T^{\gamma\gamma} \Leftrightarrow p_T^H$
     $\Rightarrow$ ggH: multiclass BDT to predict kinematic bin $\Rightarrow$ reduces correlations!
  3. Further improve S-vs-B discrimination with dedicated BDTs/DNNs

e.g. ttH Hadronic



- 0 leptons
- ≥3 jets (≥1 b tagged)





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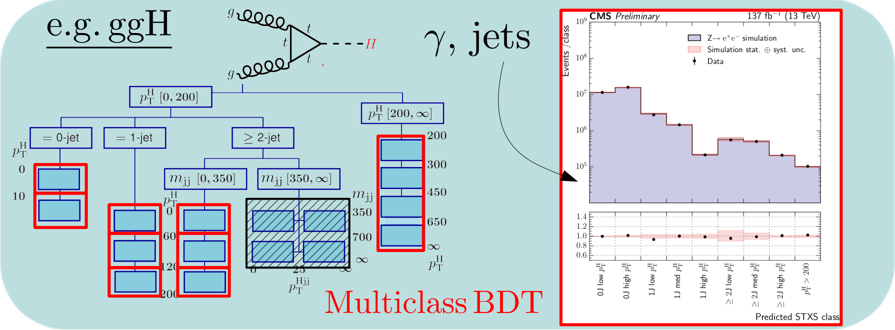

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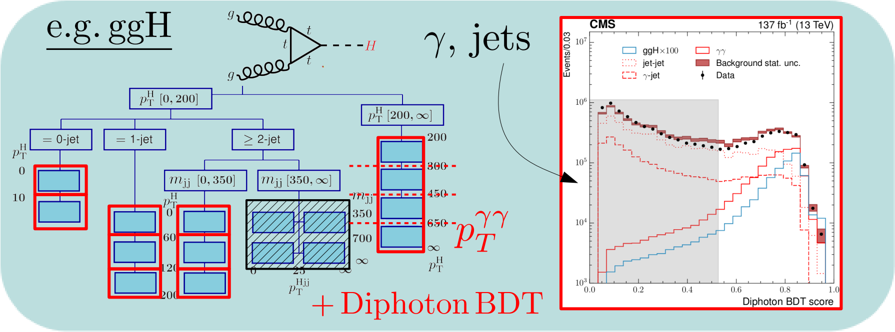

* bad data/MC agreement does not matter: bkg modeled directly from data

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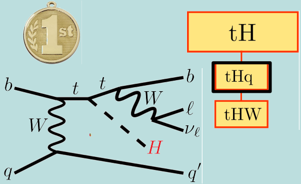
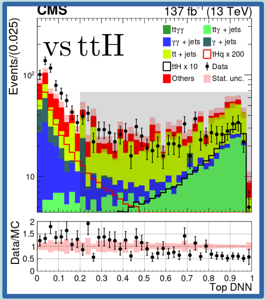
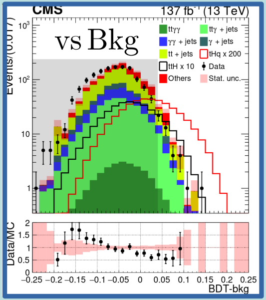
e.g. tHq Leptonic



- 1 isolated electron/muon
- $\geq$2 jets ($\geq$1 b tagged)





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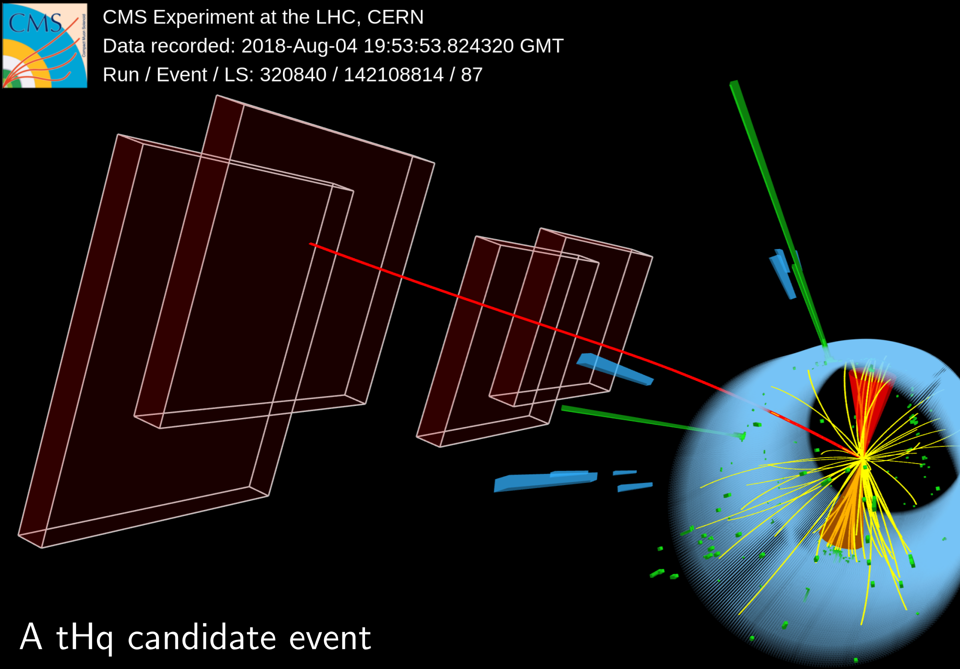
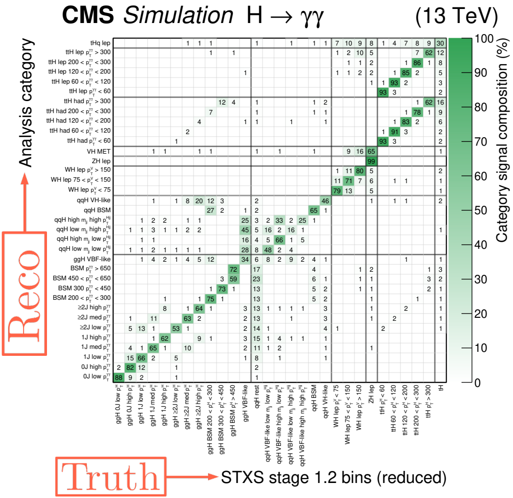
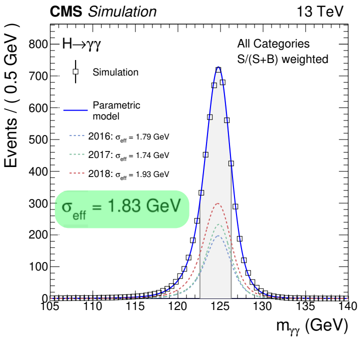


A tHq candidate event

H→ $\gamma\gamma$: extracting the results

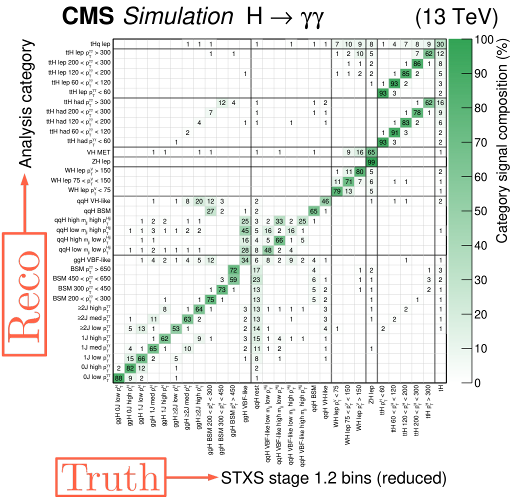
- Simultaneous binned likelihood fit to $m_{\gamma\gamma}$ spectrum in 80 event categories
  - S: from simulation, model each (STXS bin, category, data-taking year) separately
  - B: from data, discrete profile likelihood method

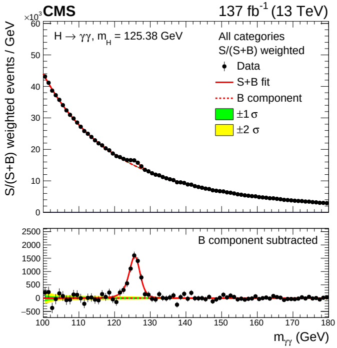




H$\rightarrow \gamma\gamma$: extracting the results

- Likelihood: $\mathcal{L} = \prod_{\text{j=cat}} \prod_{m_{\gamma\gamma}} \text{Poisson}(n| \sum_i s_{ij}(\theta)\mu_i + b_j) \cdot \mathcal{C}(\theta)$
  - Systematics: lnN nuisance params (θ) affecting shape and norm of signal
  - unfold confusion matrix (i.e. the detector) $\Rightarrow$ measure $\sigma \cdot \mathcal{B}$ (truth) in 27 bins

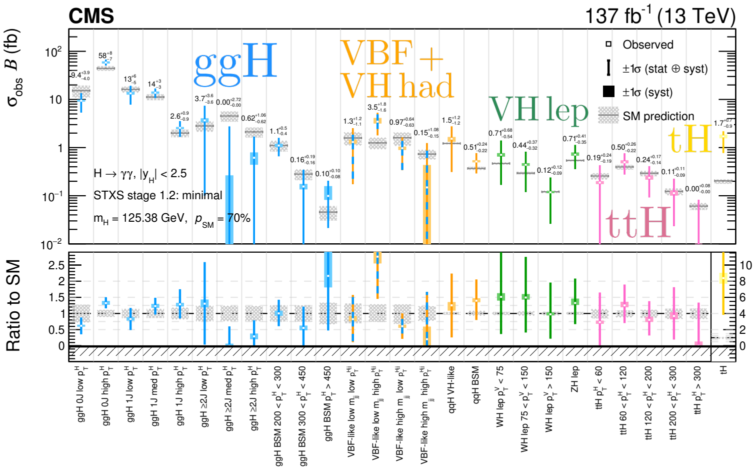




H→ $\gamma\gamma$: results

Correlations between params

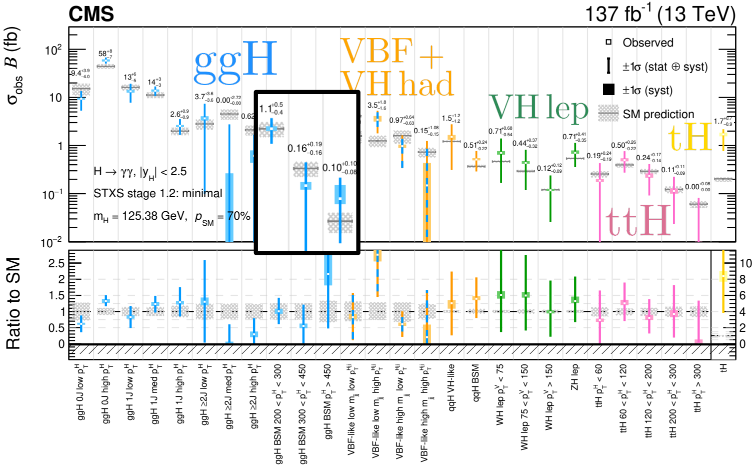
- One of most granular H cross section measurements to-date
  - overall good agreement with SM: global p-value of 70%
  - cross section measurements also provided in coarser kinematic binning Maximal



H→ $\gamma\gamma$: results

▸ Correlations between params

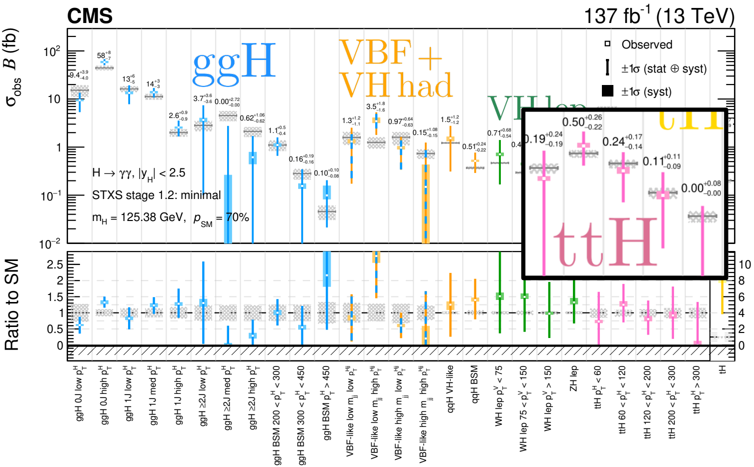
- ggH high p_T^H region particularly sensitive to BSM physics
  - $(200 < p_T^H < 300$ GeV) region measured with high precision ($\pm 40\%$)
  - uncertainties comparable to theory uncertainty in SM prediction!



H→ $\gamma\gamma$: results

Correlations between params

- First published measurement of **ttH** production in kinematic bins
- Observe excess in single-top production: 1.6σ w.r.t. SM prediction
  - competitive upper limit of tH: 14 (8) × SM @ 95% C.L.



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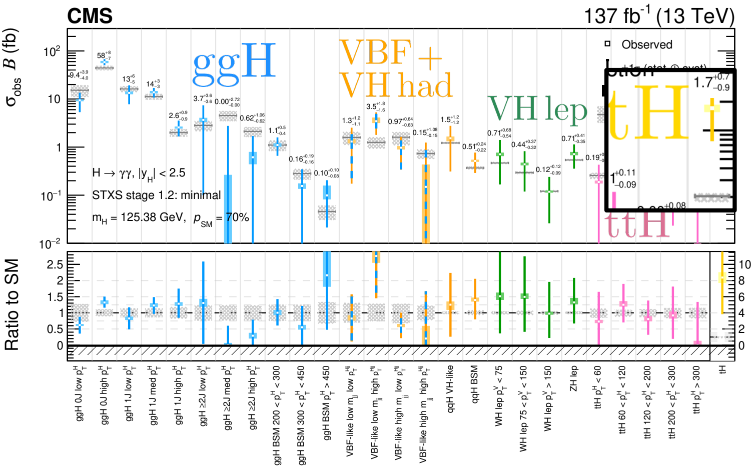
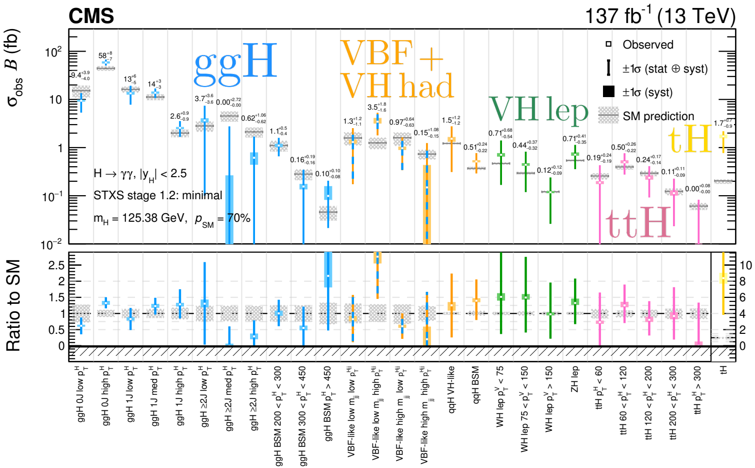


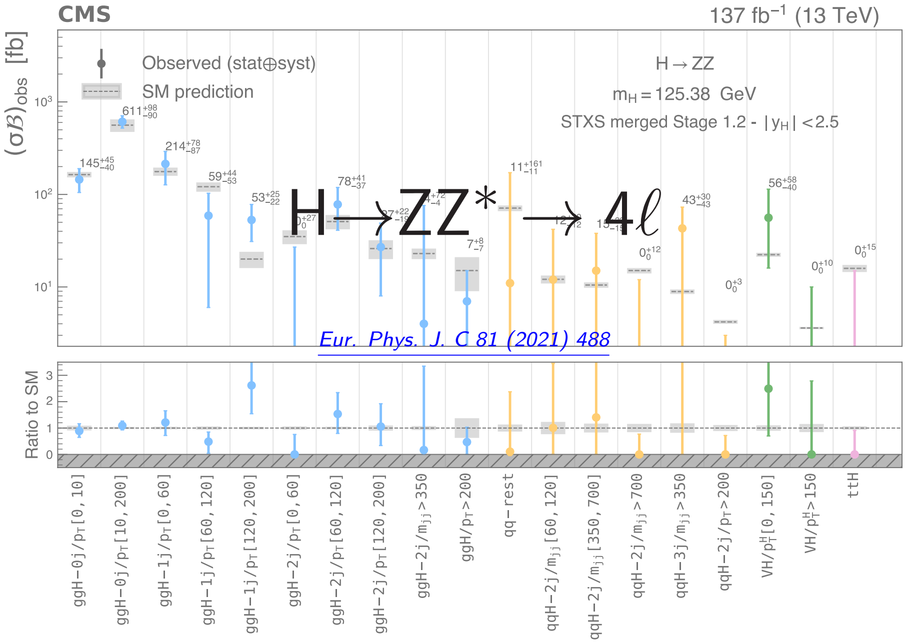
H→ $\gamma\gamma$: results

▸ Correlations between params

- Significantly improved results with respect to previous H→ $\gamma\gamma$ analyses
  - larger statistics, improved analysis techniques, reduced systematics
  - STXS stage 1.2 $\sigma \cdot \mathcal{B}$ remain statistically limited: room for improvement!



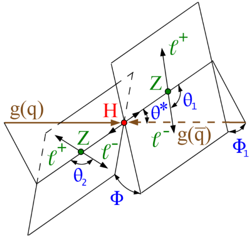
$H \to ZZ^* \to 4\ell$



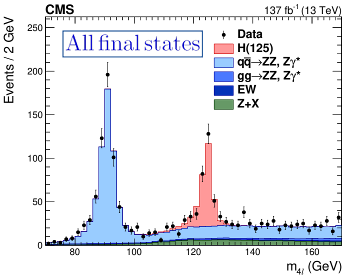
[Eur. Phys. J. C 81 (2021) 488]()

H→ZZ* → 4ℓ : overview

- Low $\mathcal{B}$ fraction (0.012%) compensated by fully reconstructed final state
  - provides extremely high S/B with which to perform precision measurements
  - + access to full Higgs boson kinematics



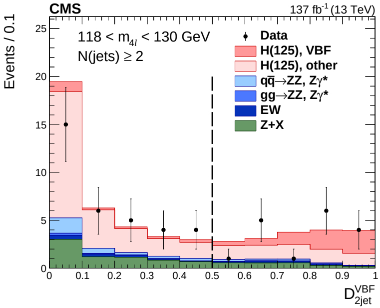
- Decay channels: 4e, 4μ, 2e2μ
  - group same-flavour opposite-charge leptons
  - build Z candidates: $12 < m_{\ell\ell(\gamma)} < 120$ GeV
  - apply series of ▸ Selection cuts
- Dominant bkgs: non-resonant ZZ/Zγ
  - shape and norm from MC simulation
  - also triboson, ttV, ttVV from simulation
  - subdominant component from misidentified leptons in Z+jets, tt+jets etc.
  - estimated from dedicated control regions

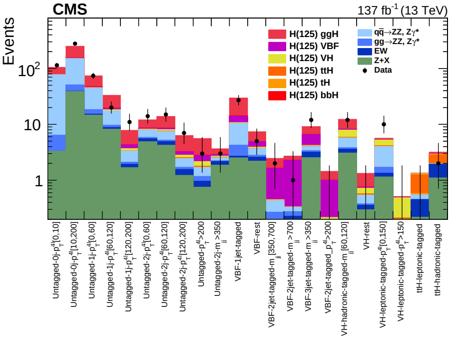


- STXS + ▸ Fiducial differential cross sections
  - targeted prod modes: ggH, qqH, VH lep, ttH

H→ZZ* → 4ℓ : STXS analysis strategy

- MELA: construct matrix-element based kinematic discriminants, $\mathcal{D}$
  1. Categorisation: split events into mutually exclusive production mode categories
     - ⇒ e.g. $\mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}}$ isolate VBF 2-jet events
     - ⇒ split production mode categories into 22 kinematic regions: STXS
     - ⇒ using equivalent reco quantities e.g. $p_T^{4\ell} \Leftrightarrow p_T^H$
  2. Kinematic: separate H→ 4ℓ signal from SM background processes
     - ⇒ $\mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}}/\mathcal{D}^{\mathrm{VBF+dec}}_{\mathrm{bkg}}/\ \mathcal{D}^{\mathrm{VH+dec}}_{\mathrm{bkg}}$ used along with $m_{4\ell}$ as fitting observables





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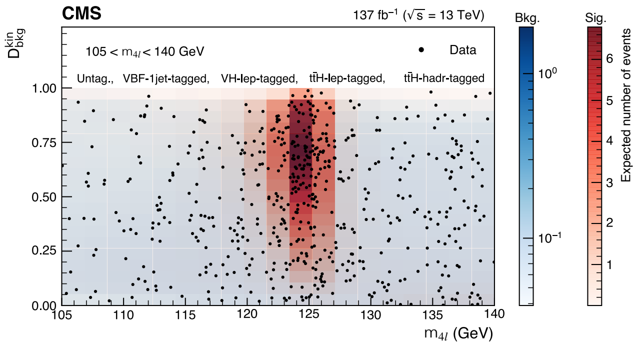
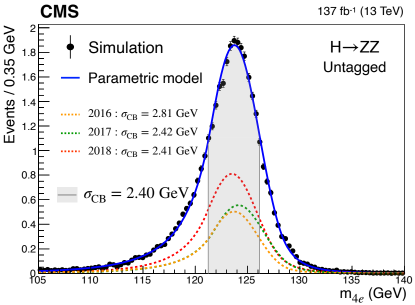
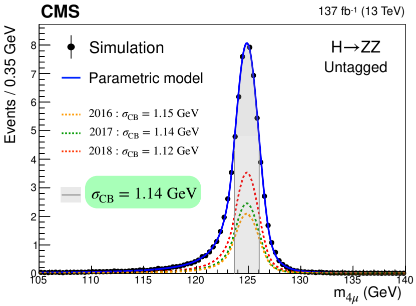


$H \to ZZ^* \to 4\ell$: STXS results

- Two-dimensional likelihood fit in $(m_{4\ell}, \mathcal{D}_{\rm bkg})$ in all 22 analysis categories
  - $\mathcal{P}(m_{4\ell})$: unbinned analytic model for each (STXS bin, category, decay channel)
  - $\mathcal{P}(\mathcal{D}_{\rm bkg}|m_{4\ell})$: binned template, conditional on value of $m_{4\ell}$
  - Systematic included which affect shape and normalisation of S + B models
- Use likelihood to unfold $\sigma \cdot \mathcal{B}$ in 19 independent kinematic regions Merging scheme
  - again good agreement with SM, stat uncertainties dominate





H→ZZ* → 4ℓ : STXS results

▸ Corrections ▸ Per-production mode

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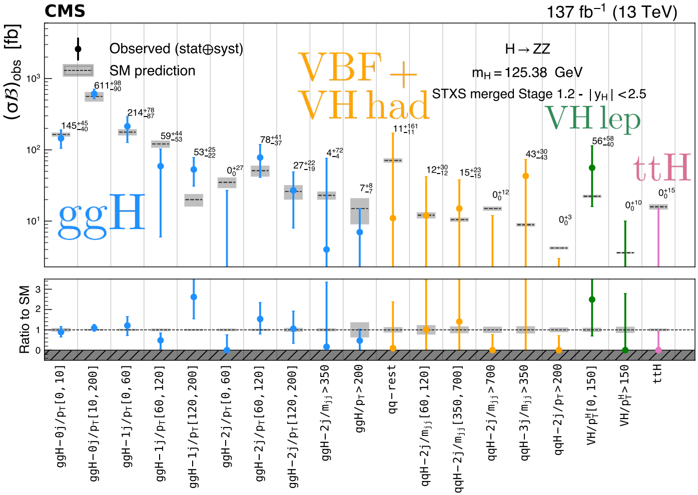
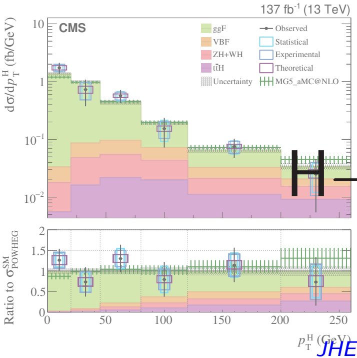
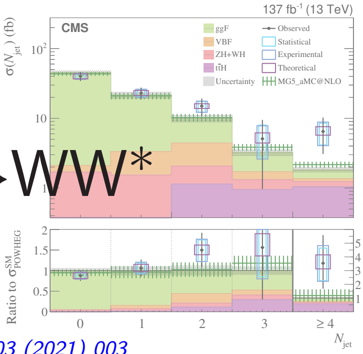


H→WW*





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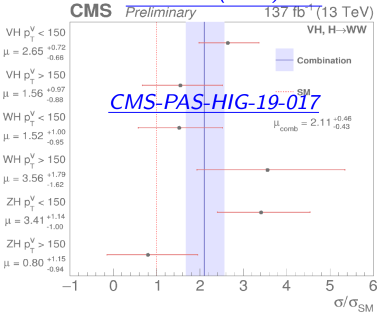


[CMS-PAS-HIG-19-017]

H→WW* : fiducial differential overview

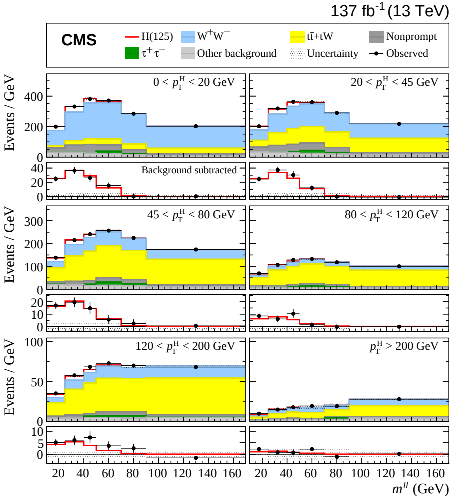
- Leptonic final state has best sensitivity with decent $\mathcal{B}$ fraction (1%)
  - $WW^* \to e\nu\mu\nu$ channel only: suppress Drell-Yan bkg ▸ Selection criteria
  - **but** neutrinos! cannot fully reconstruct kinematics

- Bkg: non-res WW and tt (dominant)
  - MC simulation, norm from data
  - + (data-driven) mis-identified leptons, DY($\tau\tau$), Diboson/Triboson (small)

- ▸ Fiducial cross section measurement
  - differential in p_T^H and N_{jet}
  - larger migrations due to p_T^{miss}

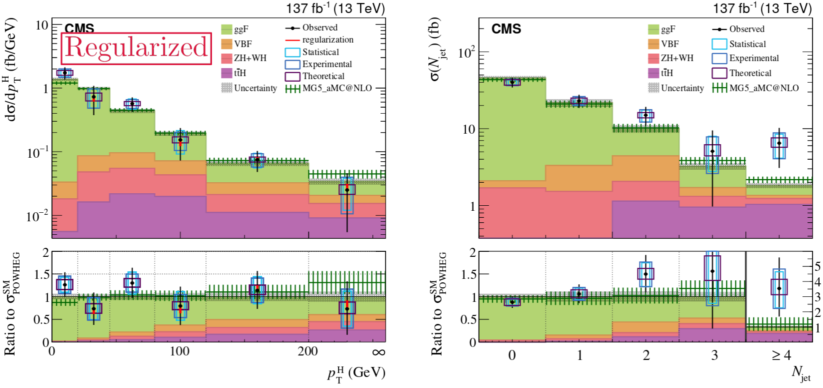
- 2D likelihood fit in ($m_{\ell\ell}$,m_T^H)
  - S + B templates per differential bin
  - S also split by truth-level bin

  ⇒ **unfold** response of detector in fit



H→WW* : fiducial differential results

- Regularization for p_T^H fit: smooths measured distribution ▸ Details
  - reduces ▸ Correlations between measured cross sections
- Good agreement with POWHEG (v2) and MG5@NLO predictions

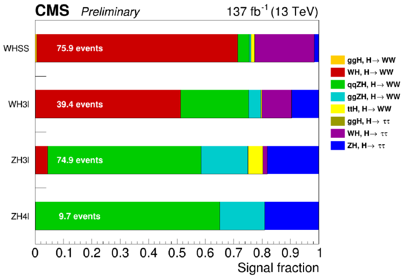


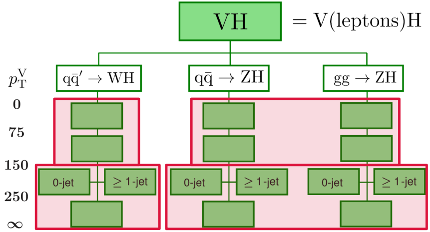
- Uncertainties: stat. and (experimental) syst components comparable in size
  - (both) grow with increasing p_T^H (total: 20→85%) and N_{jet} (total: 15→90%)
  - inclusive σ_{fid} is syst limited: $\sigma_{\text{fid}}/\sigma_{\text{fid}}^{\text{SM}} = 1.05 \pm 0.05(\text{stat.}) + 0.08(\text{exp.}) + 0.07(\text{th.})$

H→WW* : via VH production

inclusive in talk by Ulascan

- Final states in which V (+ at least one W) decays leptonically
  - WHSS: $2\ell 2\nu qq$, WH3ℓ: $3\ell 3\nu$, ZH3ℓ: $3\ell\nu qq$, ZH4ℓ: $4\ell 2\nu$
- Measure inclusive + **VH lep STXS** using dedicated approach in each channel
  - baseline selection ⇒ event categorisation + data control regions
  - split categories into four kinematic bins by reconstructed p_T^V
  - simultaneous binned template fit: $\tilde{m}_H$ or BDT (depends on channel)





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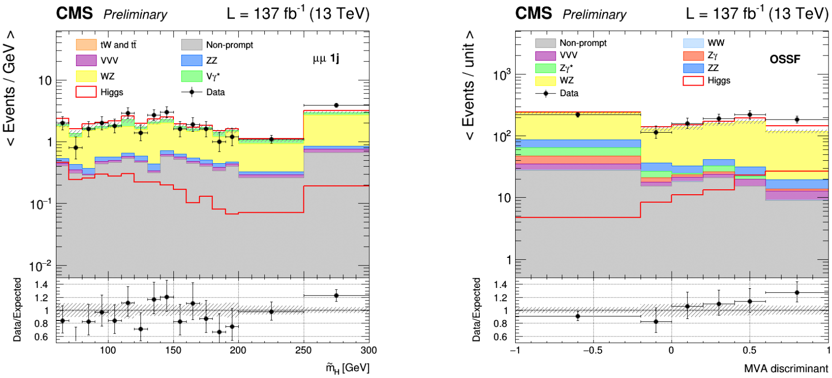

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  - split categories into four kinematic bins by reconstructed p_T^V
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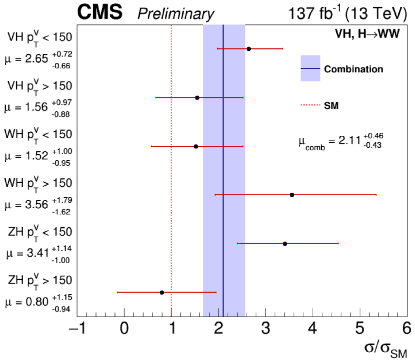
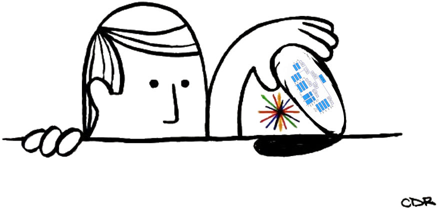


- No significant deviation from SM, uncertainties are large

Summary

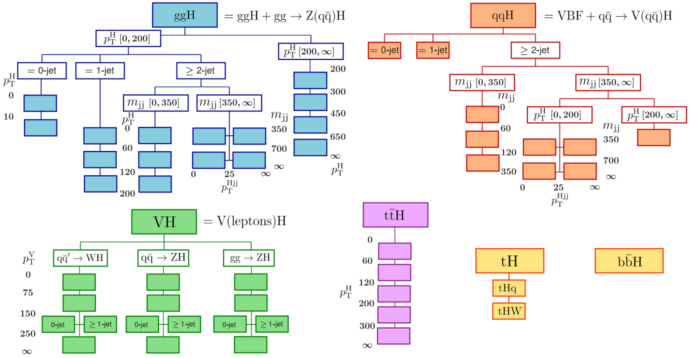
- During Run 2 we have entered precision era of Higgs physics
  - opened up possibility to measure H production in different kinematic regions
  - $+$ can target rarer processes e.g. tH
- Covered most recent CMS H cross section measurements: $\gamma\gamma$, ZZ, WW
  - all based on full Run 2 dataset (137 fb^{-1})
  - STXS and fiducial differential cross sections
  - in agreement with SM but uncertainties still large in places
- As Run 3 approaches: must continue effort to pin down the Higgs sector
  - leave no stone/region of phase space unturned



Back-Up Slides

Simplified template cross sections

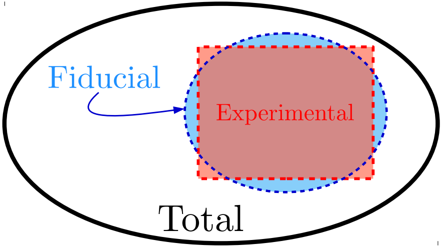
- **Mantra**: optimised for sensitivity, whilst minimising theory dependence



- Events split by production then by (truth) kinematics: p_T^H, $N_{\rm jet}$, m_{jj}, p_T^V, p_T^{Hjj}
  - bin boundaries chosen according to theory modeling / sensitivity / isolate BSM
  - evolves in stages of increasing granularity: currently stage 1.2
  - no selection on H decay products: enables combination across channels
  - more sophisticated analysis techniques permitted e.g. BDT, DNN, ...

Fiducial (differential) cross sections

- **Mantra**: optimised for theory/model independence



Observable	Condition
Lepton origin	Direct decay of $H \to W^+W^-$
Lepton flavors; lepton charge	$e\mu$(not from τdecay); opposite
Leading lepton p_T	$p_T^{l_1} > 25\,\text{GeV}$
Trailing lepton p_T	$p_T^{l_2} > 13\,\text{GeV}$
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m^{ll} > 12\,\text{GeV}$
p_T of the dilepton system	$p_T^{ll} > 30\,\text{GeV}$
Transverse mass using trailing lepton	$m_T^{l_2} > 30\,\text{GeV}$
Higgs boson transverse mass	$m_T^{H} > 60\,\text{GeV}$

- Define fiducial phase space (truth) to closely match experimental phase space
  - reduces extrapolation into phase space not measured in detector
  - measure differential cross section (in fiducial region) in bins of some quantity

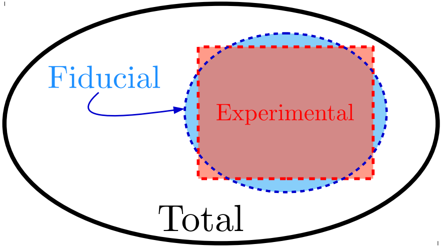
    $\Rightarrow$ e.g. p_T^H, N_{jet}, ...

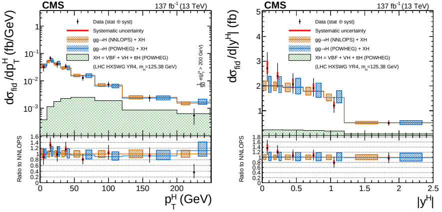
    $\Rightarrow$ unfold to truth-level: account for detector response matrix (truth $\Leftrightarrow$ reco)

    $\Rightarrow$ correct for non-fiducial effects
  - typically use simple variables in analysis for signal extraction e.g. $m_{4\ell}$

Fiducial (differential) cross sections

- **Mantra**: optimised for theory/model independence





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  - reduces extrapolation into phase space not measured in detector
  - measure differential cross section (in fiducial region) in bins of some quantity

    ⇒ e.g. p_T^H, $N_{\rm jet}$, ...

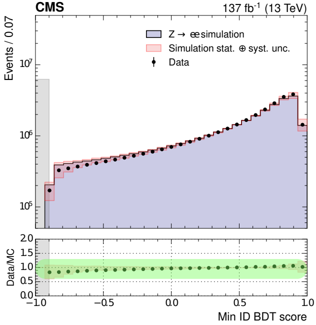
    ⇒ unfold to truth-level: account for detector response matrix (truth ⇔ reco)

    ⇒ correct for non-fiducial effects
  - typically use simple variables in analysis for signal extraction e.g. $m_{4\ell}$

H→ $\gamma\gamma$: chained quantile regression

- Improved shower shape corrections using **chained quantile regression**
  - train 21 BDTs: predict points along CDF of shower shape/isolation variable
  - correct variable in simulation by mapping to CDF in data
  - photon ID features ordered into chain:

    $\Rightarrow$ next feature BDT(s) include previously corrected variable
  - additional stochastic morphing for isolation variables
  - vastly improved agreement in photon ID output score



- Reduces dominant systematic in analysis: 5% ⇒ 2%

Likelihood unfolding

- Product over Poisson terms in analysis region, j:

Observed events

Background estimate

Regularization (optional)

$$\mathcal{L}(\boldsymbol{\mu};\boldsymbol{\theta}) = \prod_j \text{Poisson}\left(n_j; s_j(\boldsymbol{\mu};\boldsymbol{\theta}) + b_j(\boldsymbol{\theta})\right)\mathcal{N}(\boldsymbol{\theta})\mathcal{K}(\boldsymbol{\mu})$$

Signal estimate

$$s_j(\boldsymbol{\mu};\boldsymbol{\theta}) = \sum_{i=1}^{N}\left[A_{ji}(\boldsymbol{\theta})\mu_i L_j \sigma_i\right]$$

Constraint term

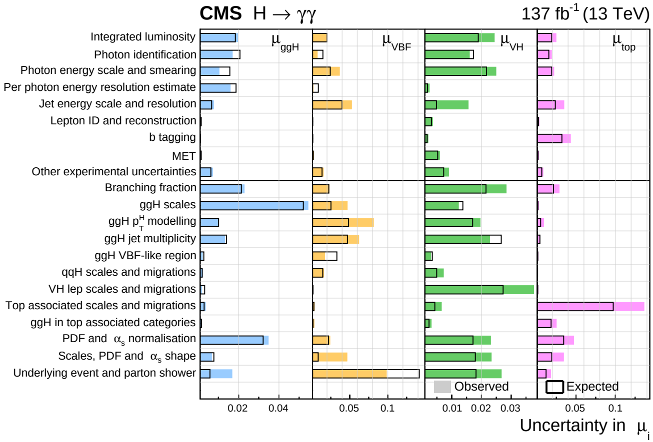
Response matrix

- **Response matrix**: describes number of events of type i in region j
  - maximum likehood fit will unfold the effect of the detector

    $\Rightarrow$ measure truth-level cross section, σ_i

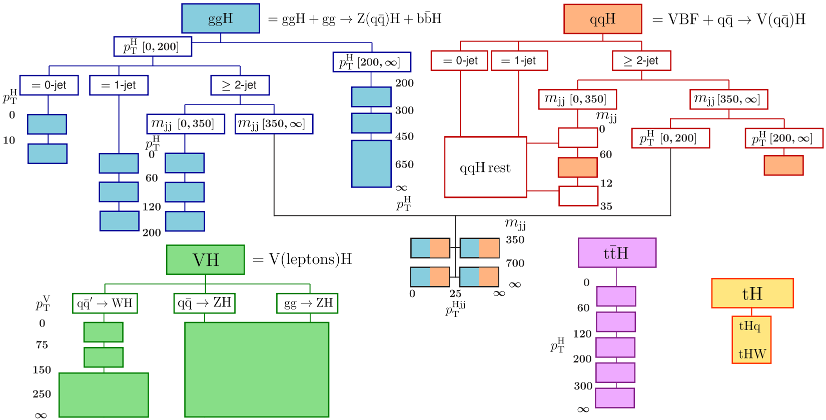
H→ $\gamma\gamma$: systematic uncertainties

- Nuisance parameters: two types
  - shape: impact mean and width of S model (typically related to γ energy)
  - yield: both experimental and theoretical contributions
- N.B. normalisation theory uncertainties not included in cross section meas.

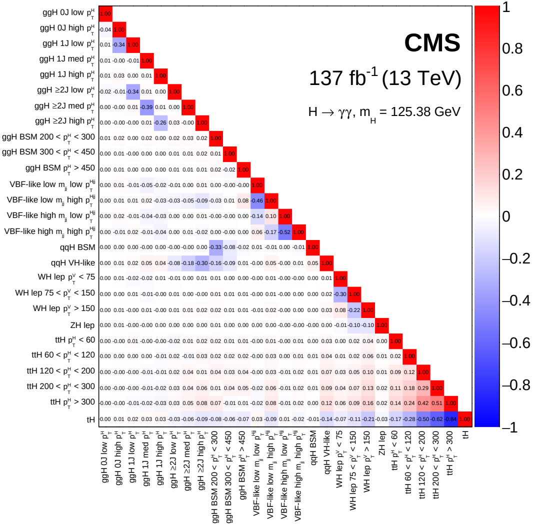


H→ $\gamma\gamma$: merging schemes

- Insufficient sensitivity to all STXS bin splittings in H→ $\gamma\gamma$ alone
  - define two merging schemes with varying granularity
  - e.g **minimal merging**: 27 kinematic regions as parameters of interest (main body)

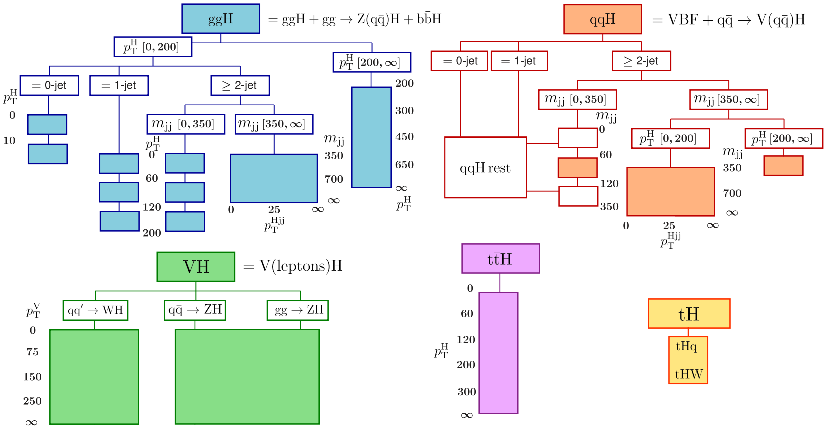


H$\rightarrow \gamma\gamma$: minimal merging correlations

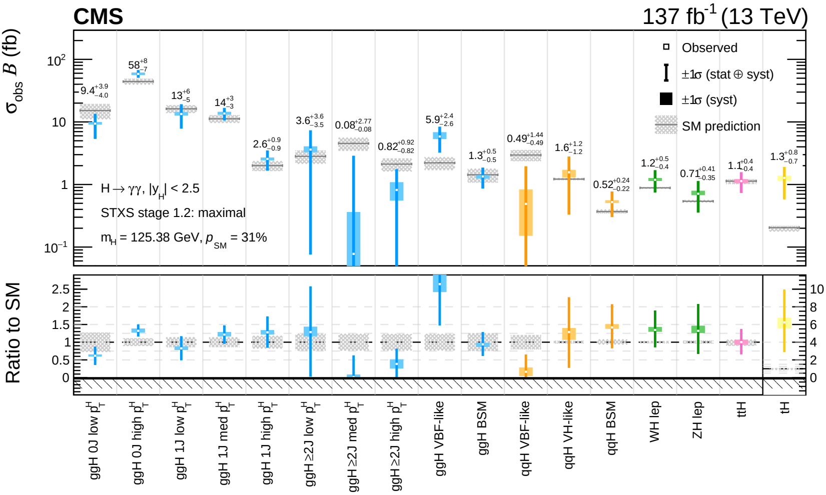


H$\rightarrow\gamma\gamma$: merging schemes

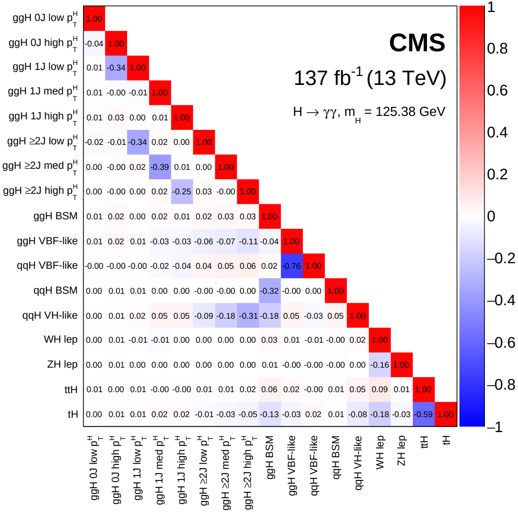
- Insufficient sensitivity to all STXS bin splittings in H$\rightarrow\gamma\gamma$ alone
  - define two merging schemes with varying granularity
  - e.g **maximal merging**: 17 kinematic regions as parameters of interest



H→ $\gamma\gamma$: maximal merging results



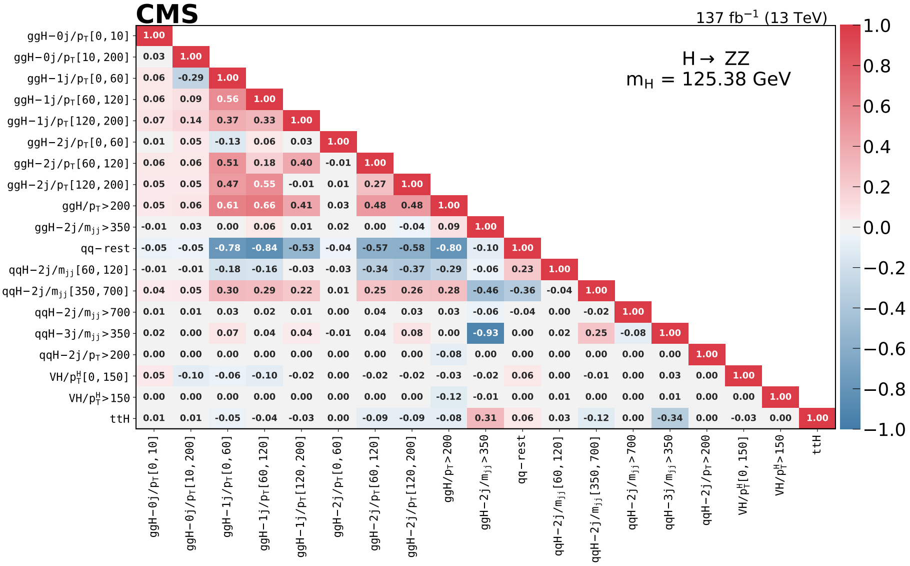
H→ $\gamma\gamma$: maximal merging correlations



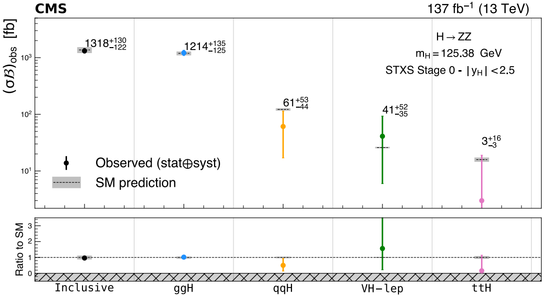
H→ZZ* → 4ℓ : selection cuts

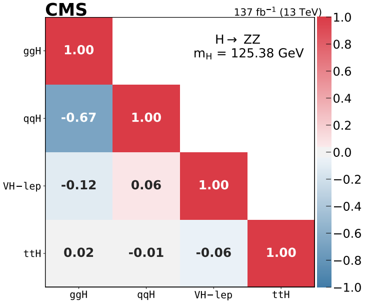
- Muons: $p_T > 5$ GeV, $|\eta| < 2.4$
  - also include low-p_T muons which may not penetrate entire muon system
  - isolation requirements to remove muons from hadron decays
- Electrons: $p_T > 7$ GeV, $|\eta| < 2.5$
  - multivariate electron identification and isolation algorithm
- FSR recovery
- Impact parameter requirements w.r.t. primary vertex
- Build ZZ candidates from pairs of same flavour opposite charge leptons GeV
  - Z_1 with mass closest to nominal Z boson mass, Z_2 as other one
  - Z_1 invariant mass > 40 GeV
  - All leptons separated by $\Delta R > 0.02$
  - At least two leptons with $p_T > 10$ GeV + at least one with $p_T > 20$ GeV
  - All pairs of leptons to have $m_{\ell+\ell-} > 4$ GeV
  - $m_{4\ell} > 70$ GeV
- For multiple ZZ candidates: choose candidate with highest $\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}$
  - if two candidates from same four leptons: choose Z_1 closest to m_Z

H→ZZ* → 4ℓ : correlations

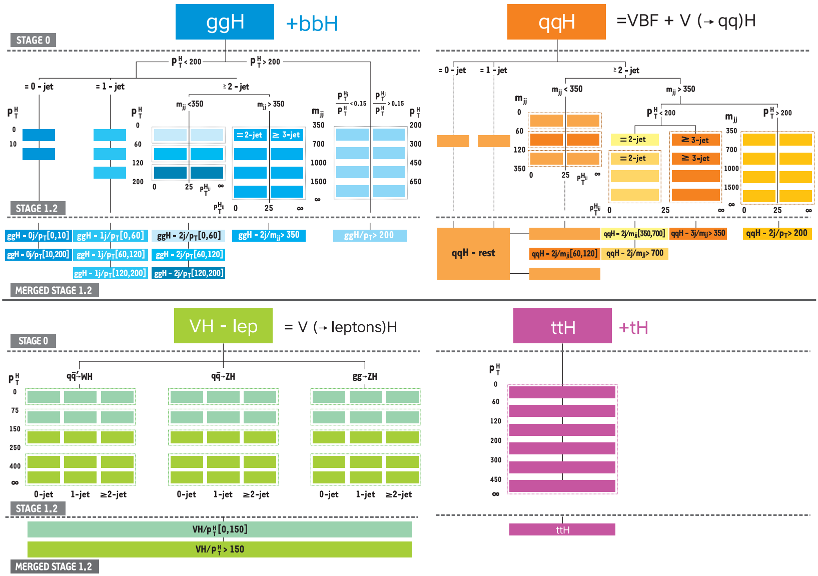


H→ZZ* → 4ℓ : stage 0 cross sections

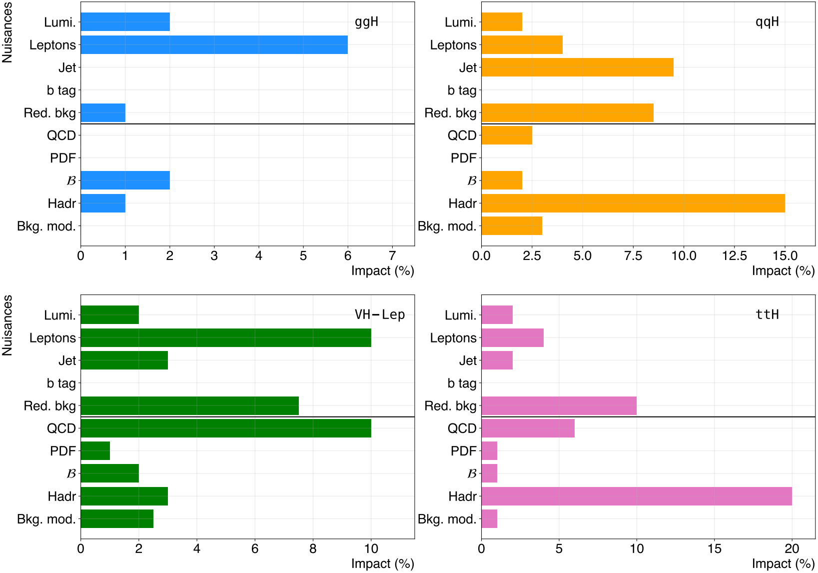




H→ZZ* → 4ℓ : merging scheme



H→ZZ* → 4ℓ : systematics



$H \to ZZ^* \to 4\ell$: fiducial phase space

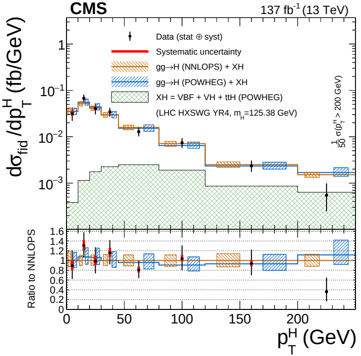
Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,GeV$
Next-to-leading lepton p_T	$p_T > 10\,GeV$
Additional electrons (muons) p_T	$p_T > 7(5)\,GeV$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5\ (2.4)$
Sum of scalar 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	$105 < m_{4\ell} < 140\,GeV$

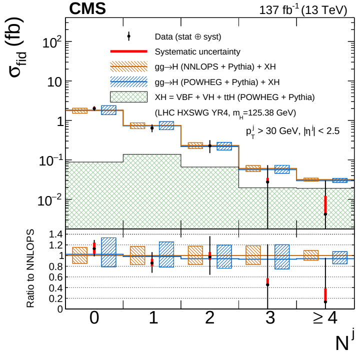
$H \rightarrow ZZ^* \rightarrow 4\ell$: fiducial differential results

- Signal extracted in 1D fit ($m_{4\ell}$) in tight fiducial phase space ▸ Definition
  - inclusive, per-channel, and differential in p_T^H, $|Y_H|$, N_{jet}, p_T^{j1}
  - systematic comparable to stat uncertainty for inclusive measurement

Fiducial cross section, σ_{fid} $\quad \sigma_{\text{fid}}^{\text{SM}} = 2.84 \pm 0.15$ fb

$2e2\mu$ (fb)	4μ (fb)	$4e$ (fb)	Inclusive (fb)
$1.31^{+0.20}_{-0.19}$	$0.78^{+0.10}_{-0.10}$	$0.76^{+0.18}_{-0.16}$	$2.84^{+0.34}_{-0.31} = 2.84^{+0.23}_{-0.22}\,(\text{stat})^{+0.26}_{-0.21}\,(\text{syst})$





H→WW* : selection criteria

- Two opposite flavour ($e\mu$), opposite charged leptons
  - criteria on lepton isolation + transverse/longitudinal impact parameters
  - track algorithm to reject electrons from photons conversions
  - $p_T^{\ell 1} > 25$ GeV, $p_T^{\ell 2} > 13$ GeV
  - $|\eta^e| < 2.5$, $|\eta^\mu| < 2.4$
  - require additional leptons in event to have $p_T < 10$ GeV
- $p_T^{\text{miss}} > 30$ GeV, $p_T^{\ell\ell} > 30$ GeV, $m^{\ell\ell} > 12$ GeV
- $m_T^H > 60$ GeV, $m_T^{\ell 2} = \sqrt{2 p_T^{\ell 2} p_T^{\text{miss}} (1 - \cos\Delta\phi(\vec{p}_T^{\ell 2}, \vec{p}_T^{\text{miss}}))} > 30$ GeV
- No b-tagged jets with $p_T > 20$ GeV
- Categorise events in ($p_T^{\ell 2}$, flavour of leptons):

p_T^H

Binning (GeV):	0–20	20–45	45–80	80–120	120–200	>200
Categorization:	$4\mathcal{W}$	$4\mathcal{W}$	$4\mathcal{W}$	$3\mathcal{W}$	$2\mathcal{W}$	$2\mathcal{W}$

N_{jet}

Binning:	0	1	2	3	≥4
Categorization:	$4\mathcal{W}$	$4\mathcal{W}$	$2\mathcal{W}$	$1\mathcal{W}$	$1\mathcal{W}$

H→WW* : fiducal phase space

Observable	Condition
Lepton origin	Direct decay of $\mathrm{H} \to \mathrm{W}^{+}\mathrm{W}^{-}$
Lepton flavors; lepton charge	$\mathrm{e}\mu$(not from τdecay); opposite
Leading lepton p_{T}	$p_{\mathrm{T}}^{l_1} > 25\,\mathrm{GeV}$
Trailing lepton p_{T}	$p_{\mathrm{T}}^{l_2} > 13\,\mathrm{GeV}$
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m^{ll} > 12\,\mathrm{GeV}$
p_{T} of the dilepton system	$p_{\mathrm{T}}^{ll} > 30\,\mathrm{GeV}$
Transverse mass using trailing lepton	$m_{\mathrm{T}}^{l_2} > 30\,\mathrm{GeV}$
Higgs boson transverse mass	$m_{\mathrm{T}}^{\mathrm{H}} > 60\,\mathrm{GeV}$

H→WW* : systematics

- Nuisances (lnN) model changes in template shape and normalisation
- Experimental: trigger efficiency, lepton reconstruction and identification efficiency, lepton momentum scale, jet energy scale, p_T^{miss} uncertainty, b tagging efficiency (17 nuisances), estimation of non-prompt lepton background in calculation of fake factors, integrated luminosity
- Theoretical: choice of PDFs, missing higher orders in perturbative expansion (scale variations), event migrations between jet multiplicity bins, modeling of pileup, underlying event, parton shower, individual background systematics
- Uncertainty in fiducial cross section of each bin excluded from fits
- Unfolding bias is checked

Regularization

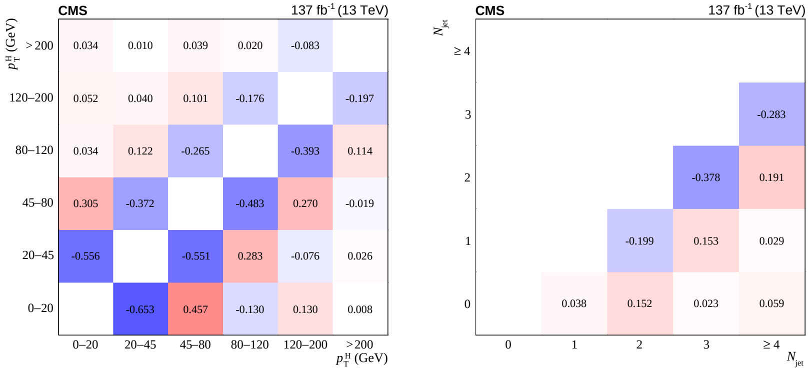
- Remove unphysical fluctuations in neighbouring bins of distribution
- Add penalty term to the likelihood of the form:

$$\mathcal{K}(\boldsymbol{\mu}) = \prod_{i=2}^{N-1} \exp\left(\frac{-\left[(\mu_{i+1} - \mu_i) - (\mu_i - \mu_{i-1})\right]^2}{2\delta^2}\right)$$

  - penalizes large variations in signal strengths of neighbouring bins
  - acts as smoothing constraint on the unfolded distribution
- δ: controls strength of regularization
  - value optimised by minimising the global correlation coefficient in Asimov fit
  - optimal value = 2.50
- Not required on N_{jet} distribution as discrete

H→WW* : correlations

- Large correlations due to large gen-to-reco bin migrations (p_T^{miss})
  - regularized p_T^H (top left) shows smaller correlations than unregularized (bottom right)



VH H$\to$WW* : selection (1)

	WHSS	WH3l	ZH3l	ZH4l
Number of leptons with $p_T > 10$ GeV	2	3	3	4
Number of jets with $p_T > 30$ GeV	≥ 1	0	≥ 1	—

- WHSS

	Preselection			
Lepton p_T (GeV)	$> 25, 20$			
Third lepton veto	Yes			
$m_{\ell\ell}$ (GeV)	> 12			
$\Delta\eta_{\ell\ell}$	< 2.0			
B jet veto	DeepCSV, medium WP, applied to all jets with $p_T > 20$ GeV			
p_T^{miss} (GeV)	> 30			
$\tilde{m}_H$ (GeV)	> 50			
	1j $e\mu$ SR	2j $e\mu$ SR	1j $\mu\mu$ SR	2j $\mu\mu$ SR
Jets with $p_T > 30$ GeV	==1	≥ 2	==1	≥ 2
m_{jj} (GeV)		< 100		< 100
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)			> 15	> 15

- WH3ℓ

	Preselection			
Lepton p_T (GeV)	$> 25, 20, 15$			
Fourth lepton p_T (GeV)	< 10			
$ch_{\ell\ell\ell}$	± 1			
$\min(m_{\ell\ell})$ (GeV)	> 12			
Jets with $p_T > 30$ GeV	0			
B jet veto	DeepCSV, loose WP, applied to all jets with $p_T > 20$ GeV			
	OSSF SR	SSSF SR	WZ CR	$Z\gamma$ CR
OSSF lepton pair	Yes	No	Yes	Yes
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)	> 20		< 20	< 20
p_T^{miss} (GeV)	> 40		> 45	< 40
$m_{\ell\ell\ell}$ (GeV)			> 100	$[80, 100]$

VH H→WW* : selection (2)

- ZH3ℓ

	Preselection			
Lepton p_{T} (GeV)	$> 25, 20, 15$			
Fourth lepton p_{T} (GeV)	< 10			
$\mathrm{ch}_{\ell\ell\ell}$	± 1			
$\min(m_{\ell\ell})$ (GeV)	> 12			
b jet veto	DeepCSV, medium WP, applied to all jets with $p_{\mathrm{T}} > 20$ GeV			
$\lvert m_{\ell\ell} - m_{\mathrm{Z}} \rvert$ (GeV)	< 25			
$\lvert m_{\ell\ell\ell} - m_{\mathrm{Z}} \rvert$ (GeV)	> 20			
	1j SR	2j SR	1j WZ CR	2j WZ CR
Jets with $p_{\mathrm{T}} > 30$ GeV	==1	≥ 2	==1	≥ 2
$\Delta\varphi(\ell p_{\mathrm{T}}^{\mathrm{miss}}, j(j))$	$< \pi/2$	$< \pi/2$	$> \pi/2$	$> \pi/2$

- ZH4ℓ

	Preselection		
Lepton p_{T} (GeV)	$> 25, 15, 10, 10$		
Fifth lepton p_{T} (GeV)	< 10		
$ch_{\ell\ell\ell\ell}$	0		
$\min(m_{\ell\ell})$ (GeV)	< 12		
$\lvert m_{\ell\ell}^{Z} - m_{\mathrm{Z}} \rvert$ (GeV)	< 15		
B jet veto	DeepCSV, loose WP, applied to all jets with $p_{\mathrm{T}} > 20$ GeV		
	XSF SR	XDF SR	ZZ CR
X pair flavor	Same	Different	
$m_{\ell\ell\ell\ell}$ (GeV)	> 140		
$m_{\ell\ell}^{X}$ (GeV)	[10,60]	[10,70]	[75,105]
PUPPI $p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 35	> 20	< 35