
# Recent Higgs results from CMS with the full LHC run 2 dataset

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ON BEHALF OF THE CMS COLLABORATION

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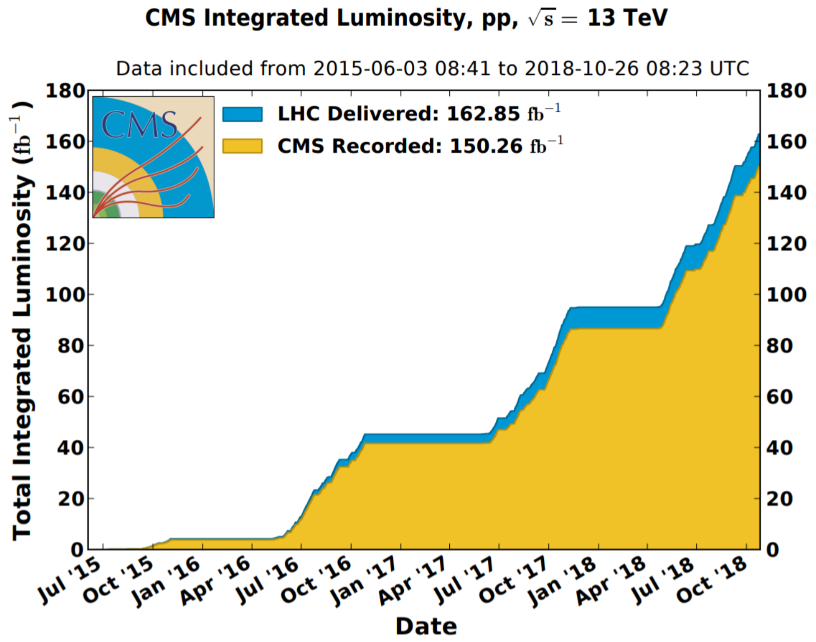
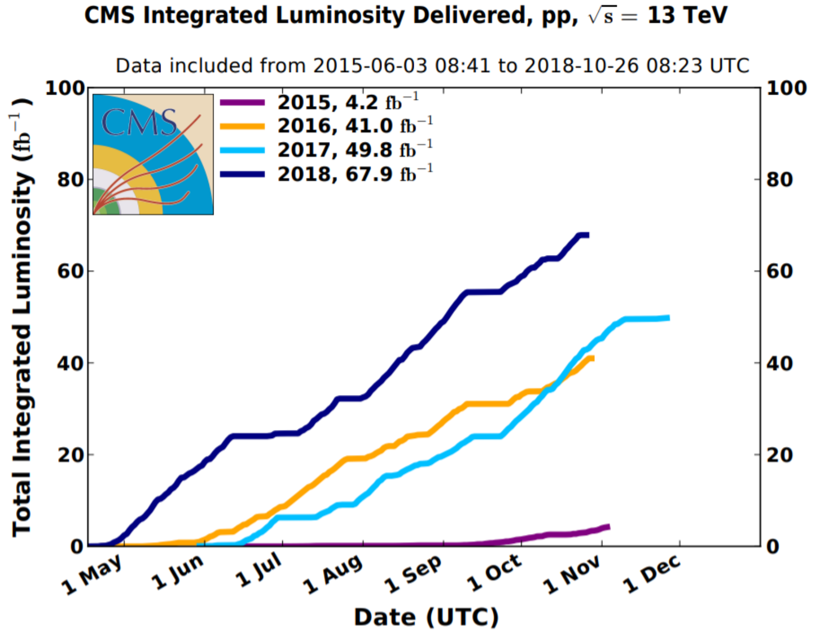
# Run 2 of the LHC

- The LHC performed admirably during run 2, delivering $163\ \mathrm{fb}^{-1}$ of integrated luminosity
- CMS was able to record with great efficiency: $137\ \mathrm{fb}^{-1}$ of "good for physics" data at $13\ \mathrm{TeV}$
- This unprecedented dataset has allowed to reach new levels of precision in Higgs physics
- Better measurements of couplings to vector bosons and 3rd generation fermions
- Possibility of precise and multi-dimensional differential cross sections
- First evidence of Higgs decaying to 2nd generation fermions!

Presenting just a small subset of the Higgs results by CMS in no particular order, many other available and more coming still!



# CMS run 2 Higgs results

| Public document | Analysis | Submitted to journal/published | Covered in this talk |
|---|---|---|---|
| CMS PAS HIG-19-001 | $H \to ZZ \to 4\ell$ | | ☑ |
| CMS PAS HIG-19-002 | $H \to$ WW differential | ✉ | ☑ |
| CMS PAS HIG-19-003 | $ggH(H \to bb)$ boosted | ✉ | ☑ |
| CMS PAS HIG-19-006 | $H \to \mu\mu$ | | ☑ |
| CMS PAS HIG-19-007 | $H \to Z_D Z_D$ | | |
| CMS PAS HIG-19-008 | ttH multilepton | | ☑ |
| CMS PAS HIG-19-009 | $H \to ZZ \to 4\ell$ anomalous couplings | | |
| CMS PAS HIG-19-010 | $H \to \tau\tau$ | | ☑ |
| CMS PAS HIG-19-012 | $H \to Z\rho, H \to Z\phi$ | ✉ | |
| CMS PAS HIG-19-015 | $H \to \gamma\gamma$ | | ☑ |
| CMS PAS HIG-20-004 | $HH \to bbZZ(ZZ \to 4\ell)$ | | |
| CMS PAS HIG-20-006 | CP violation in $H \to \tau\tau$ | | |
| 10.1103/PhysRevLett.125.061801 | ttH di-photon | ✉ | ☑ |

☑ Covered in this talk

✉ Submitted to journal/published

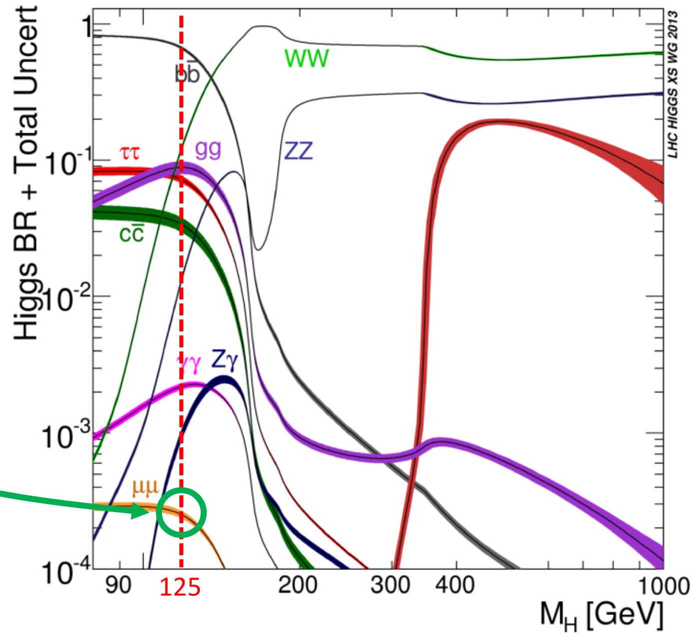
- CMS Higgs group very prolific
- Covering mainly SM Higgs
- Many other interesting results I'm unable to cover today
- Further results are in the works, stay tuned!

# First evidence for $\mathrm{H} \to \mu\mu$

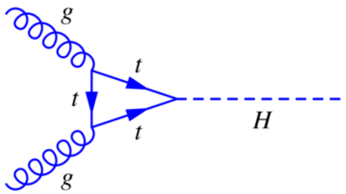
CMS PAS HIG-19-006

# The H → μμ decay channel

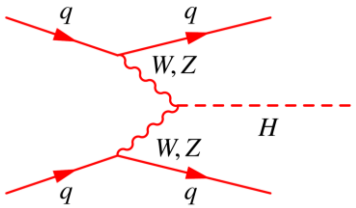
- $\mathcal{B}(H \to \mu\mu) = 2.18 \times 10^{-4}$ in the SM ⟶ challenging measurement
- Muons are precisely reconstructed by the CMS detector
- Clean final state, allows to reconstruct the full Higgs mass
- First 2nd generation fermion to be directly observed interacting with the Higgs boson!
- The analysis targets the 4 major Higgs production mechanisms



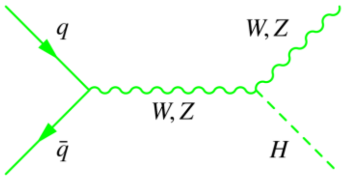

$ggH$



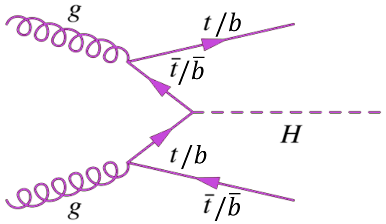

$VBF$




$VH$




$t\bar{t}H$



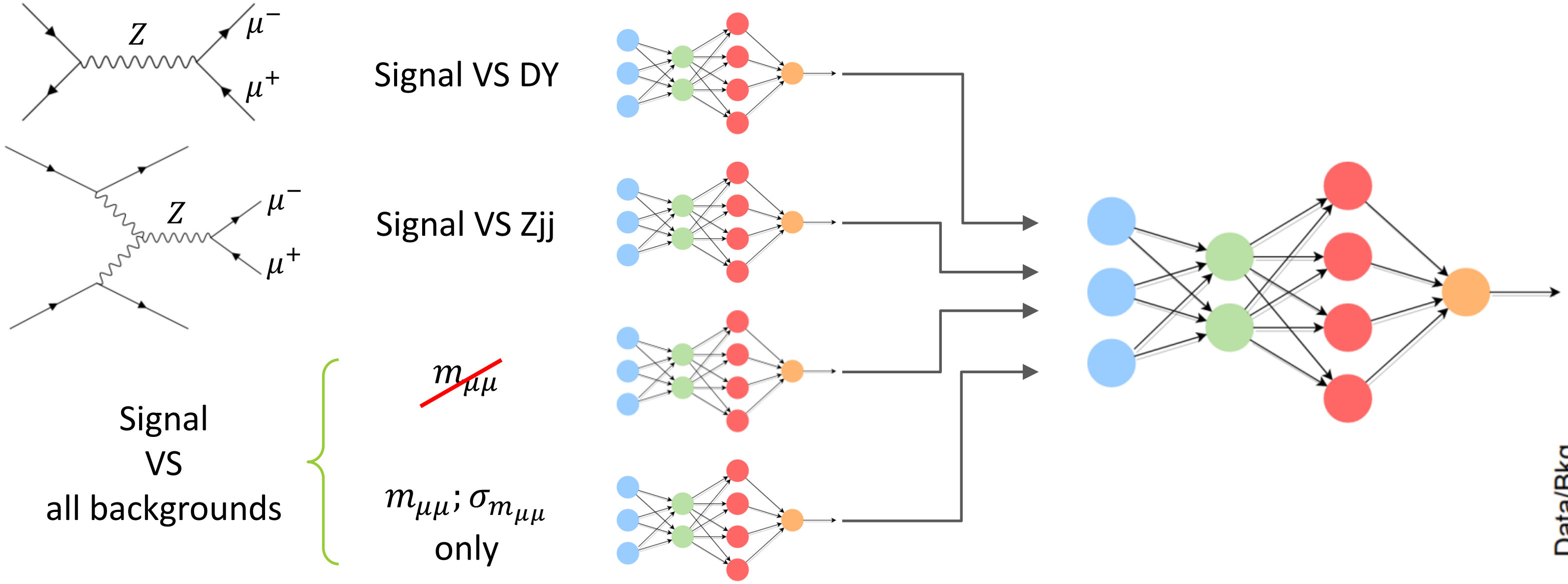

Decreasing cross section

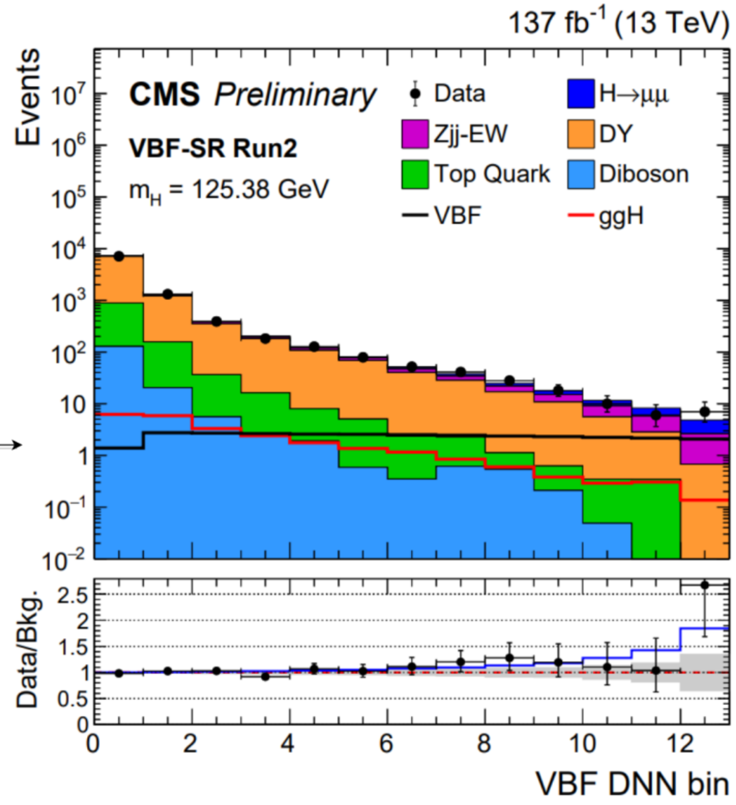
# Machine learning discriminants

- Aim to separate signal from background as much as possible
  - ggH, VH, ttH ⟶ Boosted Decision Trees (BDTs)
  - VBF ⟶ Deep Neural Network (DNN)
- Will focus on VBF as an example
  - 4 separate DNNs are trained, and their output is fed to a 5th DNN

**DNN input variables**

$$m_{\mu\mu};\ \sigma_{m_{\mu\mu}};\ p_T^{\mu\mu};\ y_{\mu\mu};\ \phi_{CS};\ \cos\theta_{CS}$$
$$\overleftrightarrow{p}_{j_1};\ \overleftrightarrow{p}_{j_2};\ m_{jj};\ \Delta\eta_{jj};\ qgl$$
$$\min(\Delta\eta_{\mu\mu,j_i});\ z^*;\ R(p_T);\ H_T$$



# Results

- Results are extracted via a simultaneous binned maximum likelihood fit in all categories
  - VBF: DNN output
  - ggH, VH, ttH: $m_{\mu\mu}$

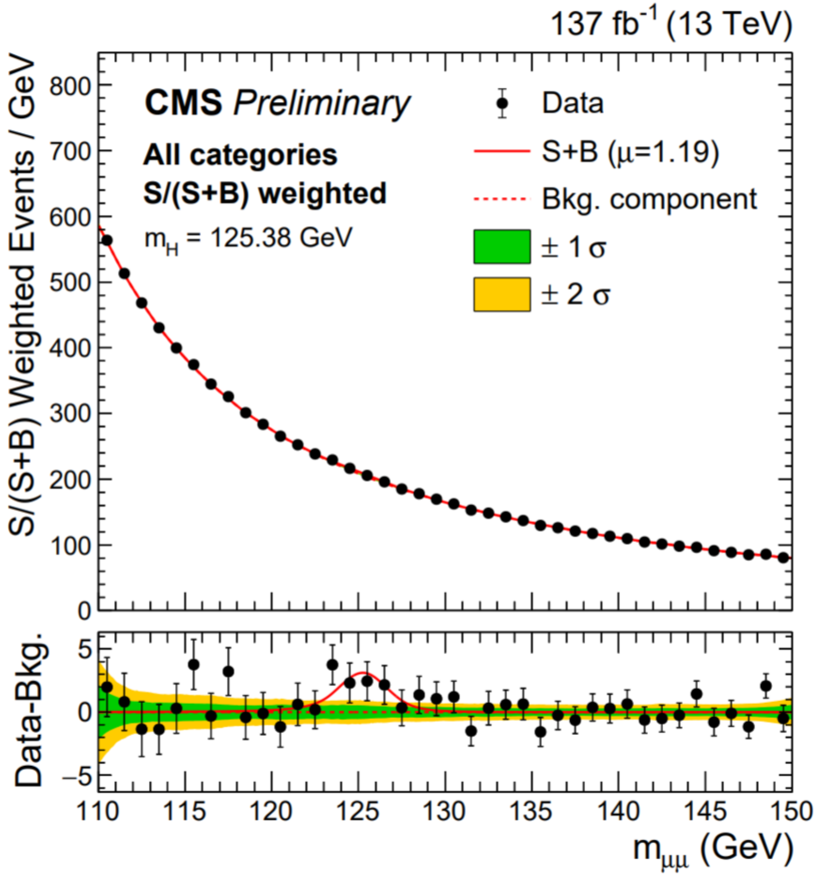
$\hat{\mu} = 1.19^{+0.41}_{-0.39}(stat)^{+0.17}_{-0.16}(syst)$

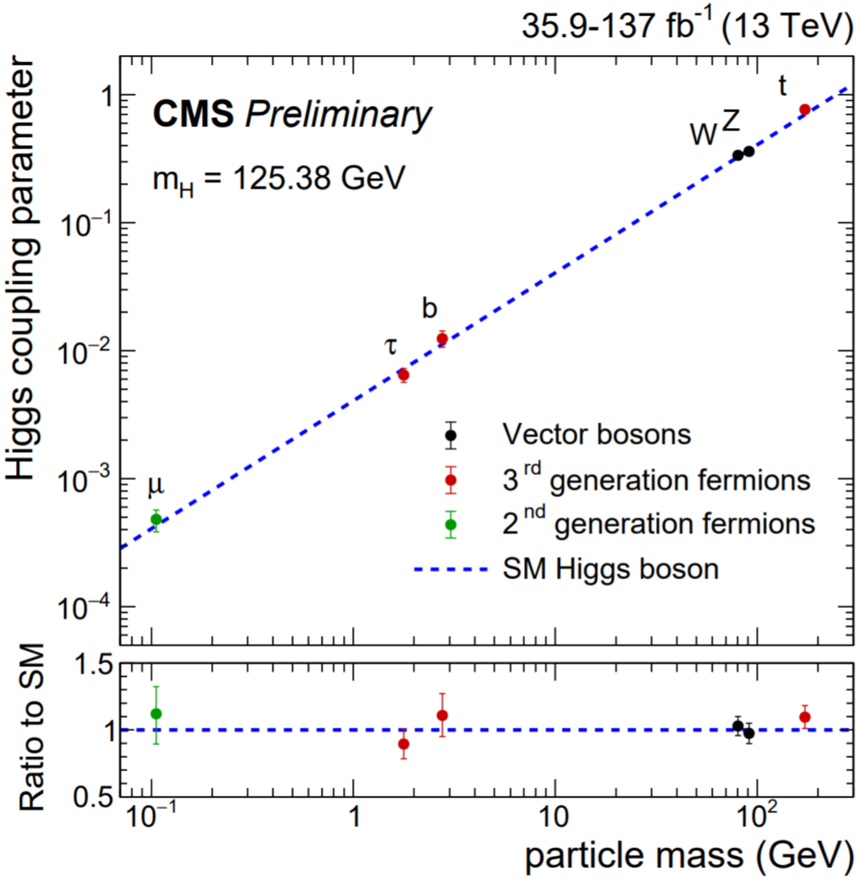
Assuming SM cross sections

$0.8 \times 10^{-4} < \mathcal{B}(H \to \mu\mu) < 4.5 \times 10^{-4}$

$3.0(2.5\ exp)\ \sigma$ significance

Most precise measurement to date!



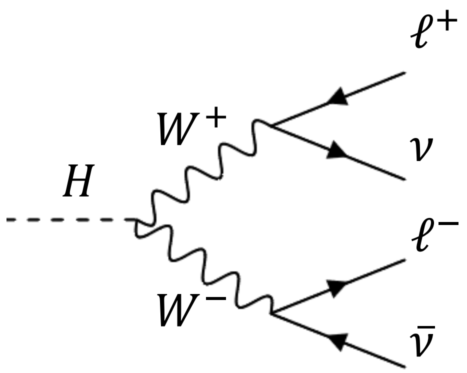



# $H \rightarrow WW$ differential

ARXIV:2007.01984 - (SUBMITTED TO JHEP)

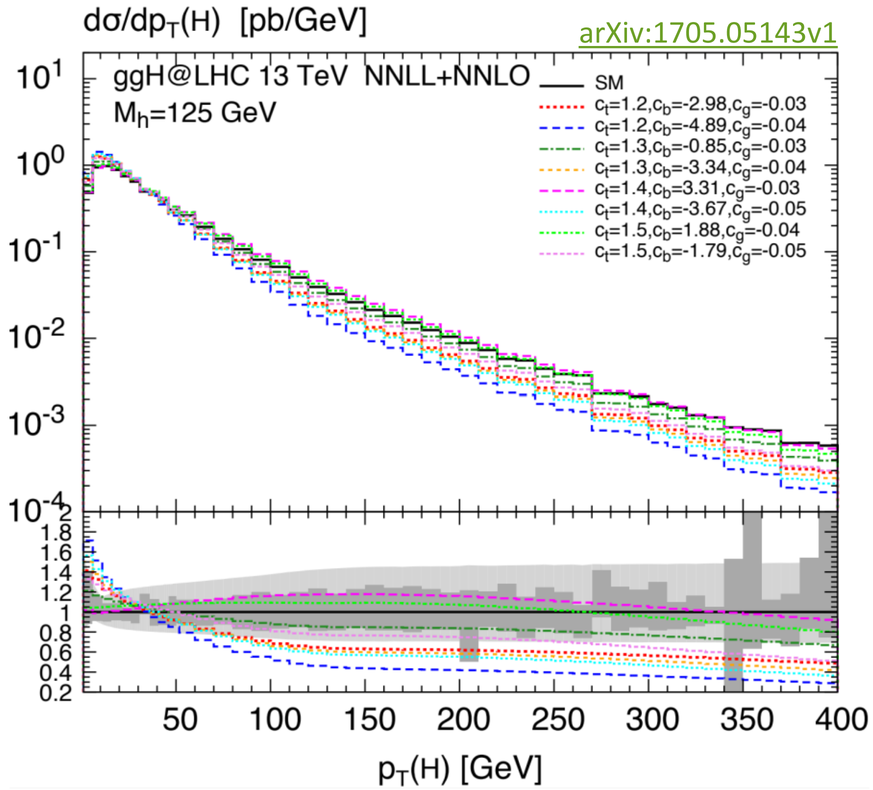
# The H → WW decay channel

- Second highest total branching ratio, highest to a leptonic final state
- Final state with 2 leptons and 2 neutrinos provides best sensitivity
- Neutrinos are undetected, resulting in missing transverse energy (MET)
- No access to full kinematics of the diboson system




Two differential cross sections measured: $d\sigma/dp_T^H$ , $\sigma(N_{jets})$

arXiv:1705.05143v1




- Precision test for the SM, indirect probe for new physics
- Differential cross sections are as model agnostic as it gets
- Main backgrounds: $t\bar{t}$, $WW$, $Z \to \tau\tau$, non-prompt leptons

# Analysis strategy

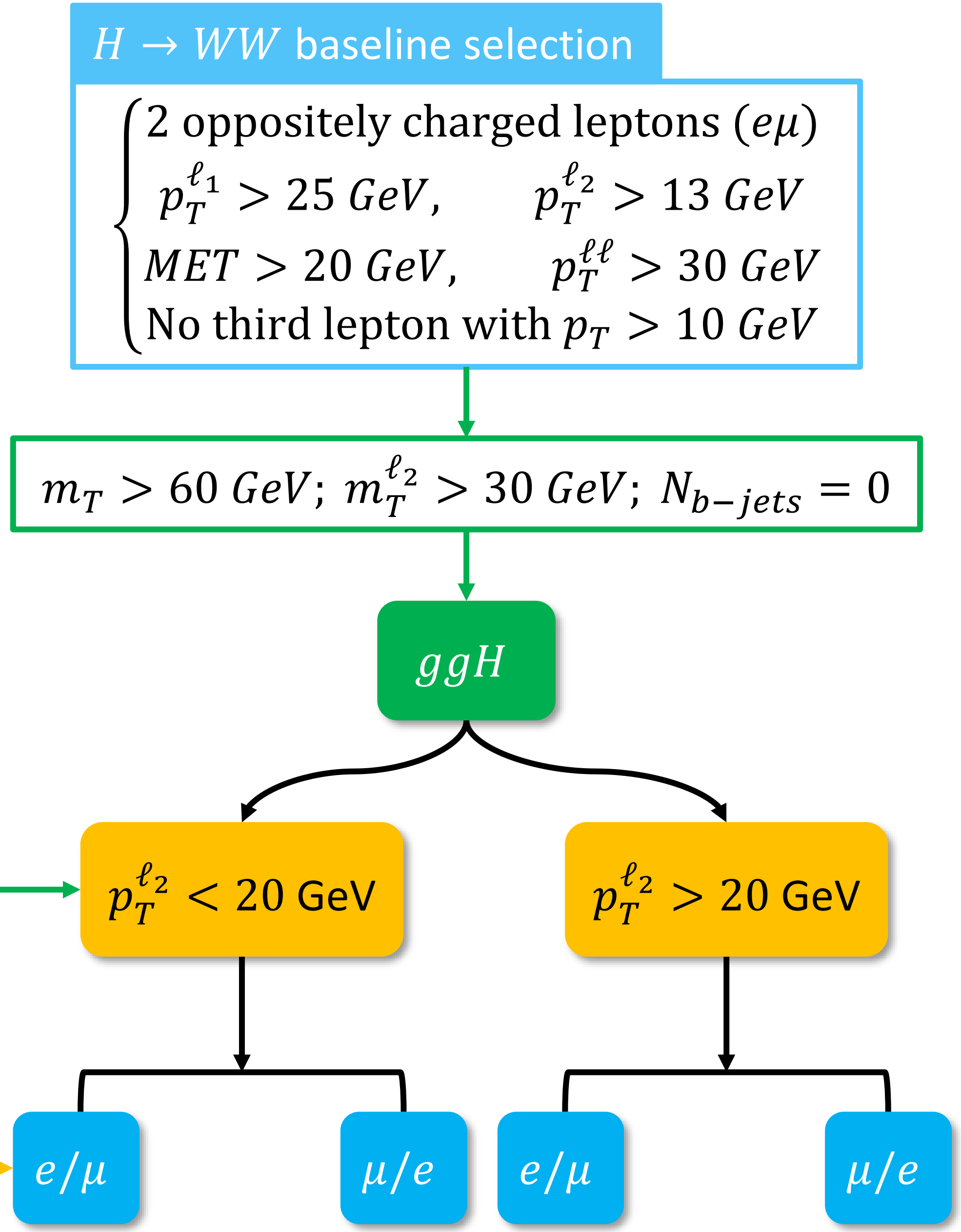
- Main target is the ggH production mode
- Further subcategorization to enhance sensitivity, gradually relaxed for higher $p_T^H/N_{jets}$ bins (lower statistics)
- $Z \to \tau\tau$, $t\bar{t}$ backgrounds normalized from data in dedicated phase space regions; $WW$ normalized in signal region
- Both reconstructed and particle level phase space binned in $p_T^H/N_{jets}$, **simultaneous regularized unfolding within fit**
- Low $p_T^H$ binning driven by MET resolution

$\boldsymbol{p_T^H}$ binning:
$[0, 20, 45, 80, 120, 200, \infty]$

$\boldsymbol{N_{jets}}$ binning:
$[0, 1, 2, 3, \geq 4]$

Low $p_T^{\ell_2}$ regions have less $WW$, $t\bar{t}$ contamination $\Longrightarrow$ higher S/B

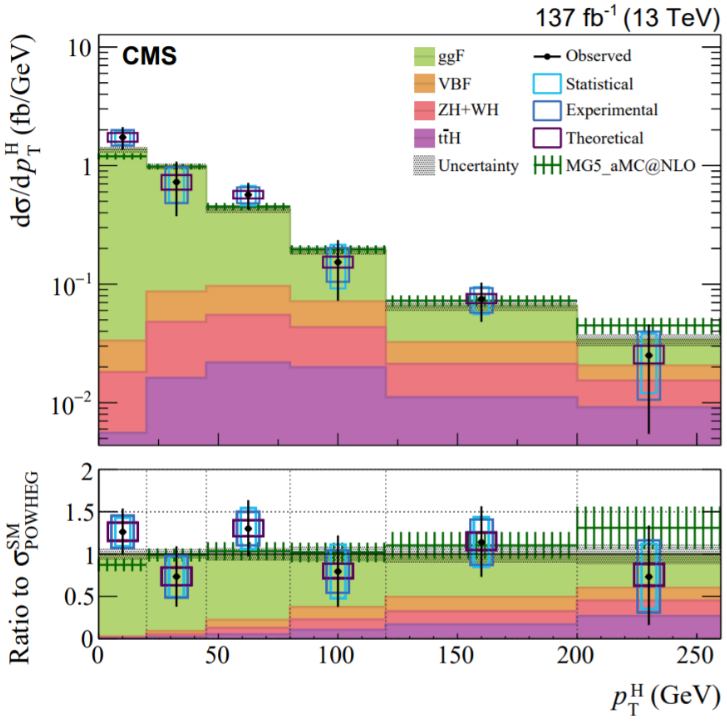
Non-prompt leptons primarily from mis-id of electrons

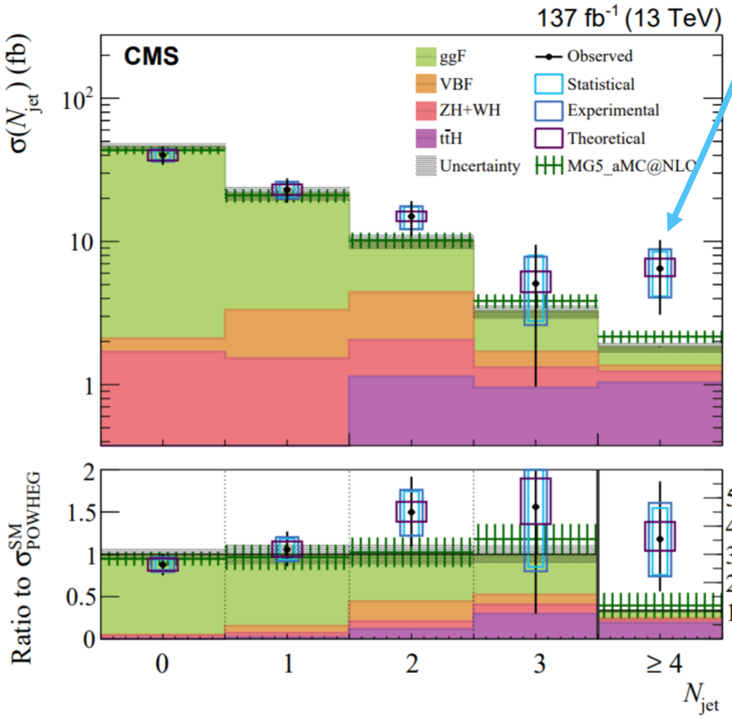


# Results

- Good agreement with the SM
- 15-20% error in lower $p_T^H/N_{jets}$ bins

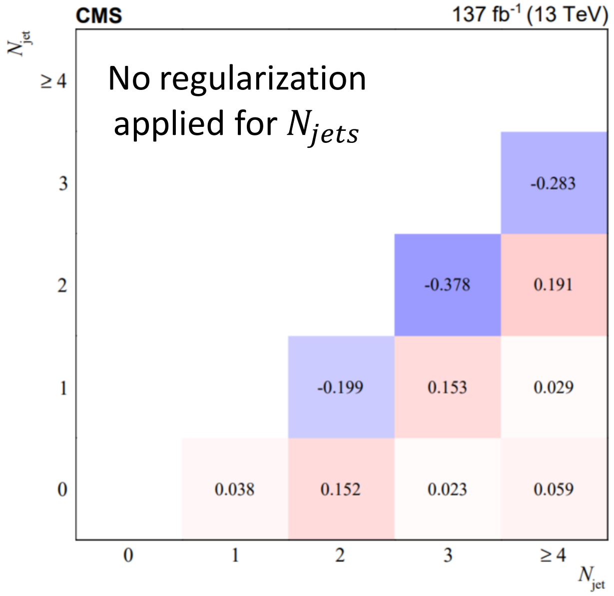
Largest discrepancy at a 1.4$\sigma$ level

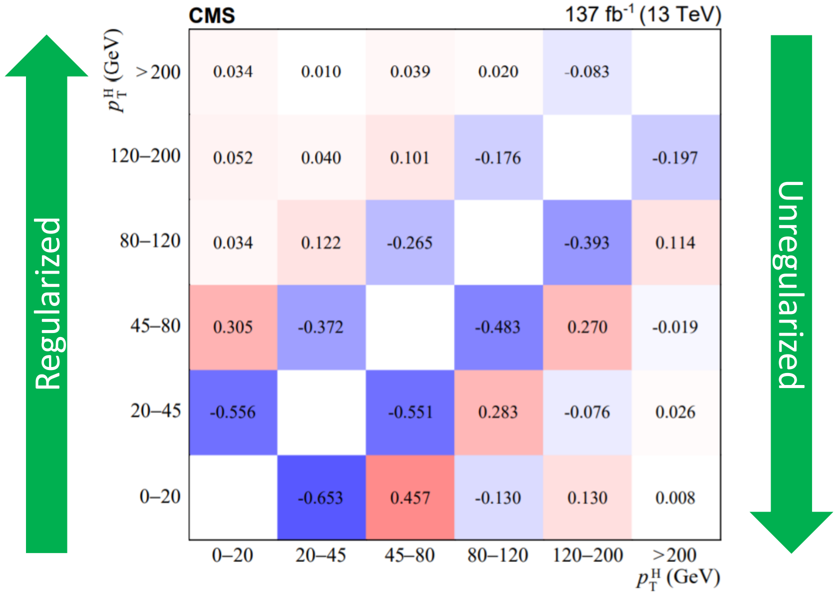



$$\mu^{\text{fid}} = 1.03^{+0.12}_{-0.11} \left( ^{+0.05}_{-0.05}\,(\text{stat.})\, ^{+0.08}_{-0.07}\,(\text{theo.})\, ^{+0.03}_{-0.03}\,(\text{lumi.})\, ^{+0.07}_{-0.07}\,(\text{exp.}) \right)$$

$$\sigma^{\text{fid}} = 85.0^{+9.9}_{-9.3}\ \text{fb}$$



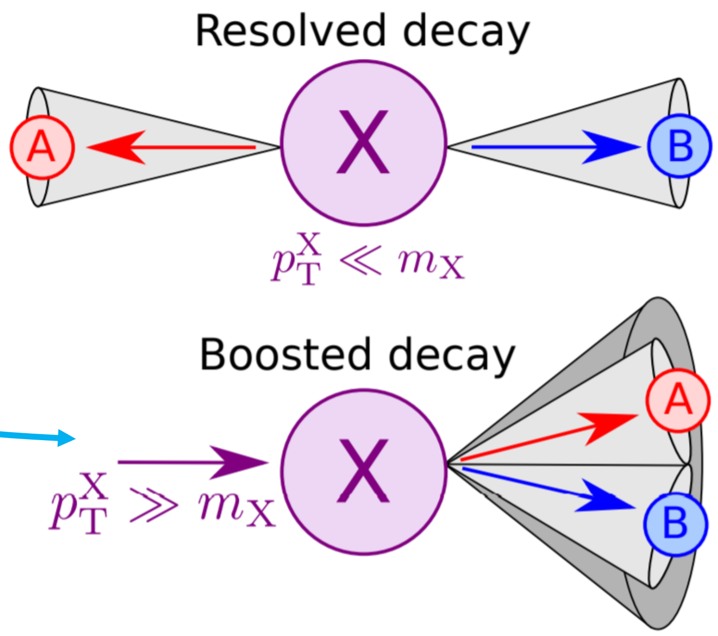



# Boosted $\mathrm{H} \rightarrow \mathbf{bb}$ run 2

CMS PAS HIG-19-003

# The $H \to bb$ channel and strategy

- $BR(H \to b\bar{b}) = 58\% \longrightarrow$ highest in the SM
- Very high multijet (QCD) background
- Important channel in high $p_T^H$ phase space due to high BR
- Results in boosted jet topology, i.e. 2 jets reconstructed as one



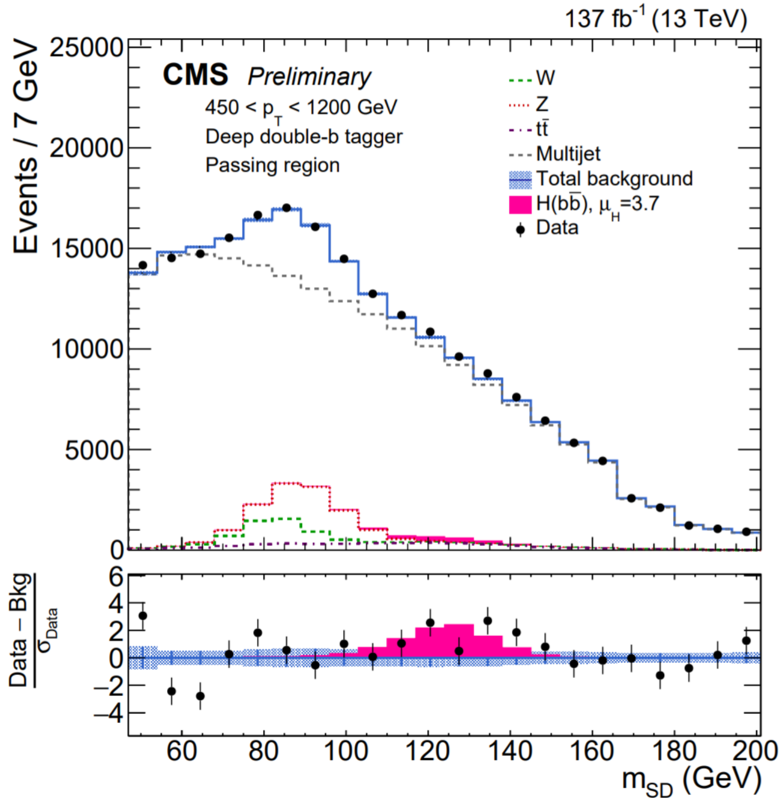

**Events with 1 AK8 jet consistent with a 2-prong substructure are selected**

- Events with isolated leptons, high MET or a b-tagged AK4 jet in the opposite direction to the AK8 jet are vetoed
- Events are binned in $p_T^H$ from 450 GeV to 1.2 TeV

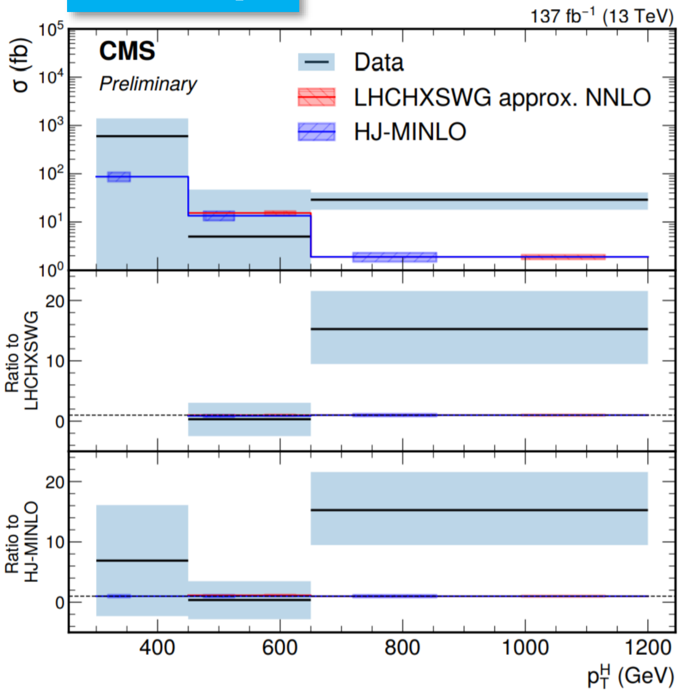
**A DNN is trained to recognize jets consistent with the $H \to b\bar{b}$ decay**

# Results

- Maximum likelihood fits on the jet mass distribution
- Both inclusive as well as differential (in $p_T^H$) measurements provided
- Likelihood unfolding to particle level distribution




$d\sigma/dp_T^H$




Inclusive signal strength

$$\mu_H = 3.68 \pm 1.20(\text{stat})^{+0.63}_{-0.66}(\text{syst})^{+0.81}_{-0.46}(\text{theo})$$

2.5(0.71 exp) $\sigma$ w.r.t. background

1.8 $\sigma$ w.r.t. SM

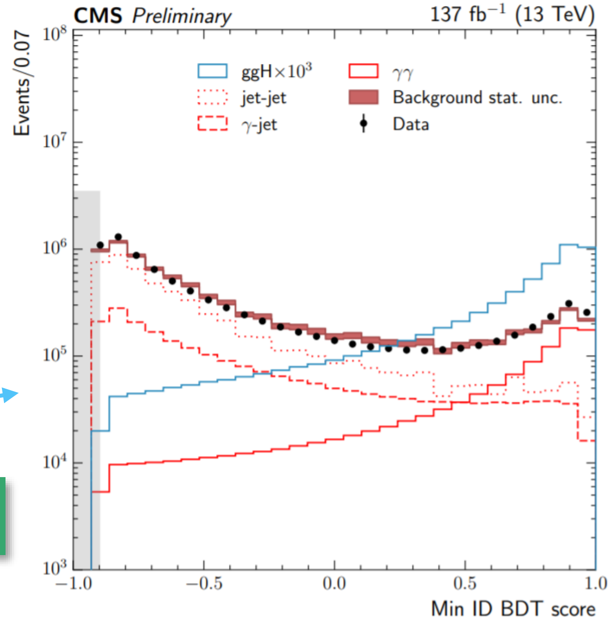
# $H \rightarrow \gamma\gamma$ run 2 results

CMS PAS HIG-19-015

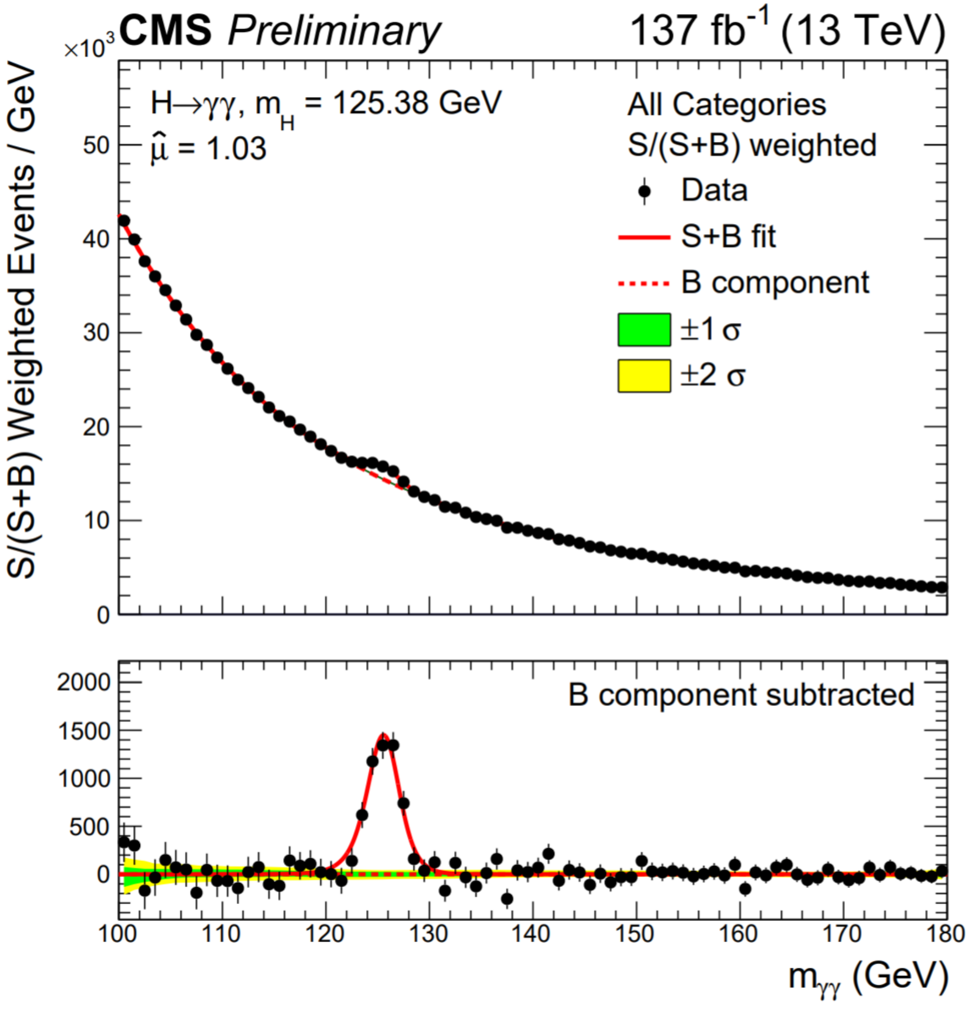
# The H → γγ decay channel

- Relatively small SM branching ratio (~0.2%) is offset by very clean diphoton final state
- The full 4-momentum of the diphoton pair is accessible
- Excellent diphoton mass ($m_{\gamma\gamma}$) resolution of 1-2%
- Main backgrounds: SM diphoton production (dominant), $\gamma$ + jets, dijet (with misidentified jets)

A BTD discriminant is trained to separate genuine photons from jets



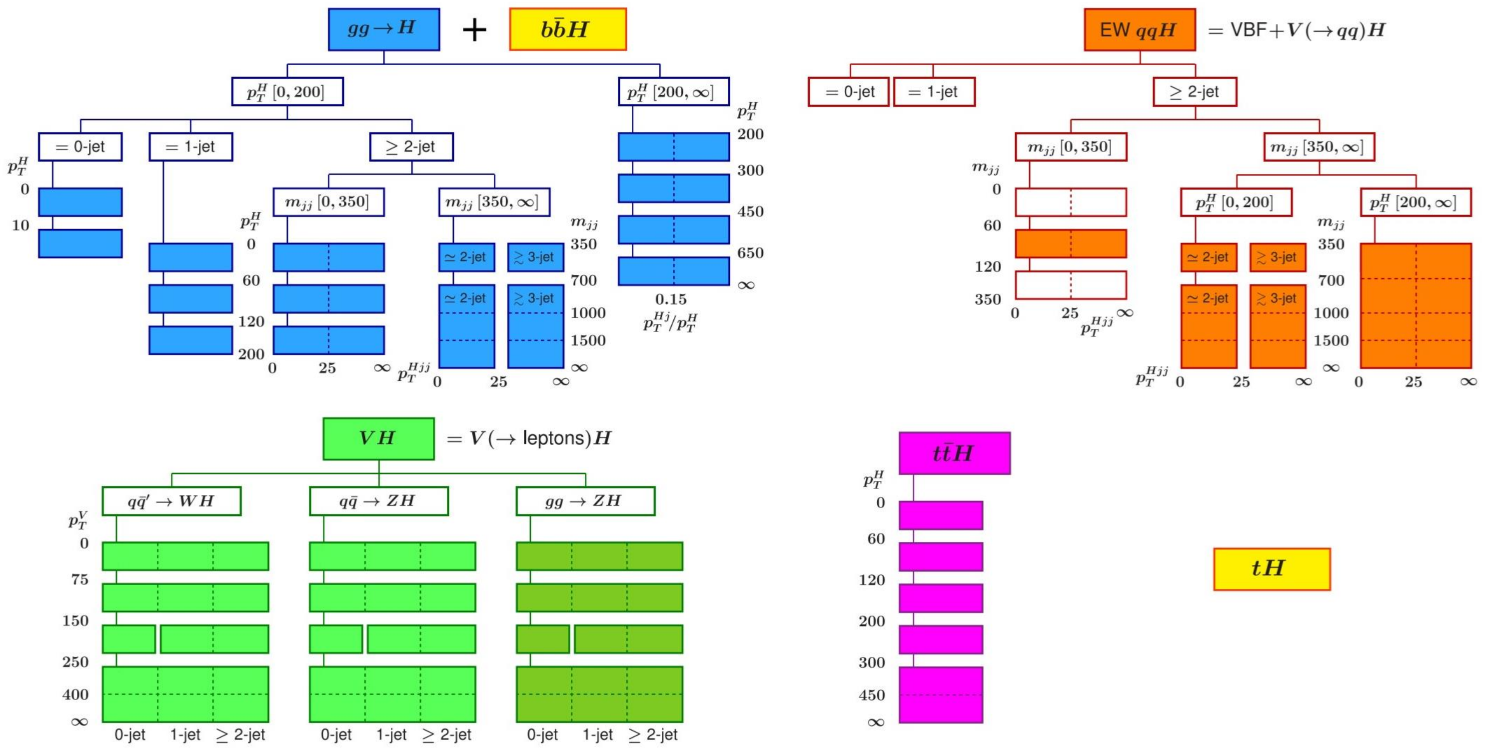

The diphoton baseline is measured in data



# Analysis strategy

- Simplified Template Cross Section (STXS) 1.2 framework is targeted (some bins are merged for enhanced sensitivity)

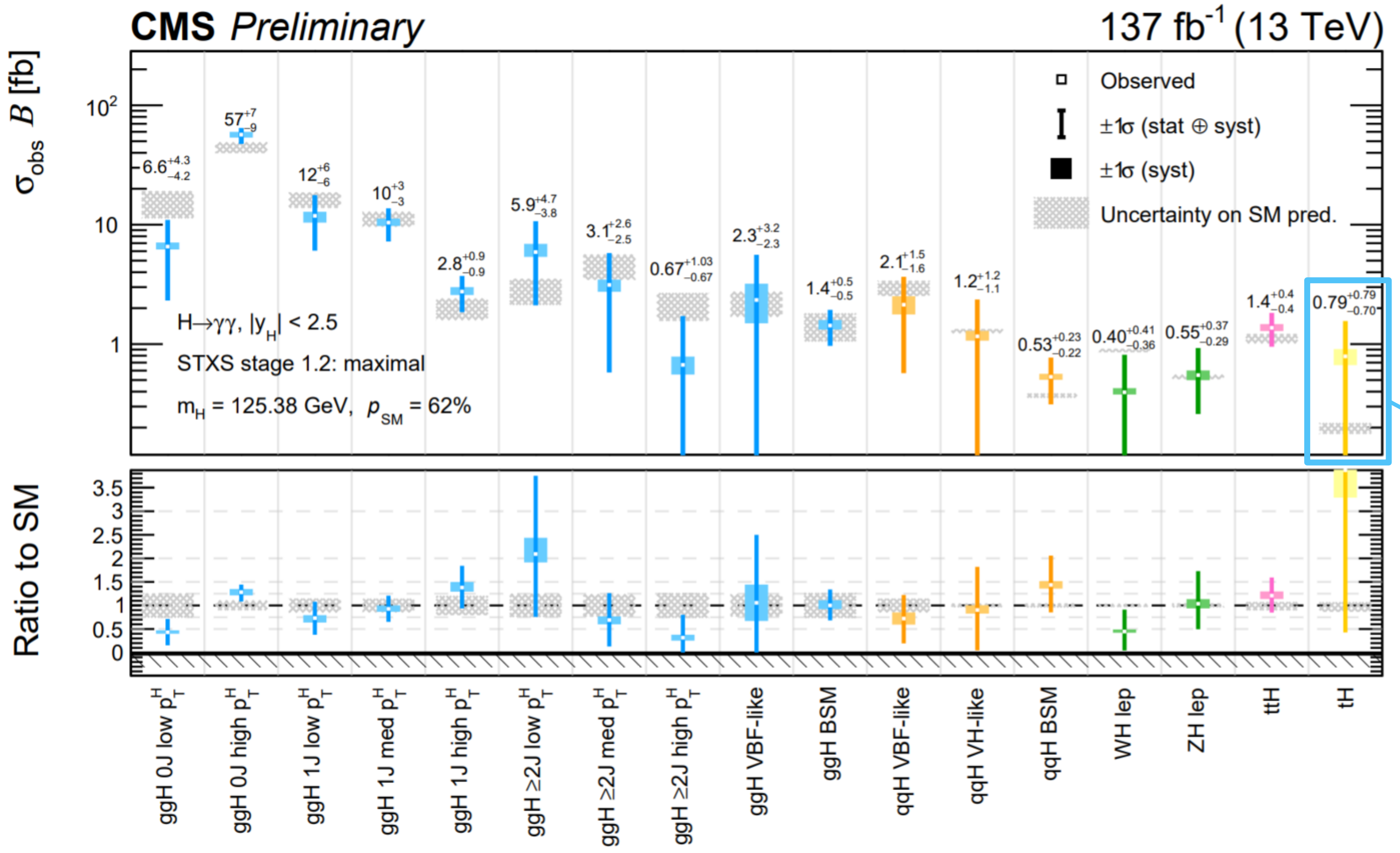
- Particle level phase space split in orthogonal "bins" based on Higgs kinematics
- A Boosted Decision Tree (BDT) is used to categorize reconstructed events in the corresponding STXS bins
  - Better performance (5-10%) w.r.t. kinematic cuts by leveraging correlations
- Allows for different interpretations of the dataset:
  - STXS, signal strength/coupling modifiers
- A binned maximum likelihood fit on the $m_{\gamma\gamma}$ distribution is used to extract results




81 categories in the fit

# Results - STXS

- In each STXS bin, a dedicated BDT or DNN is used to achieve maximal separation between signal and background
- Both a “maximal” and a “minimal” merging scheme are explored; tradeoff between uncertainty and model dependence

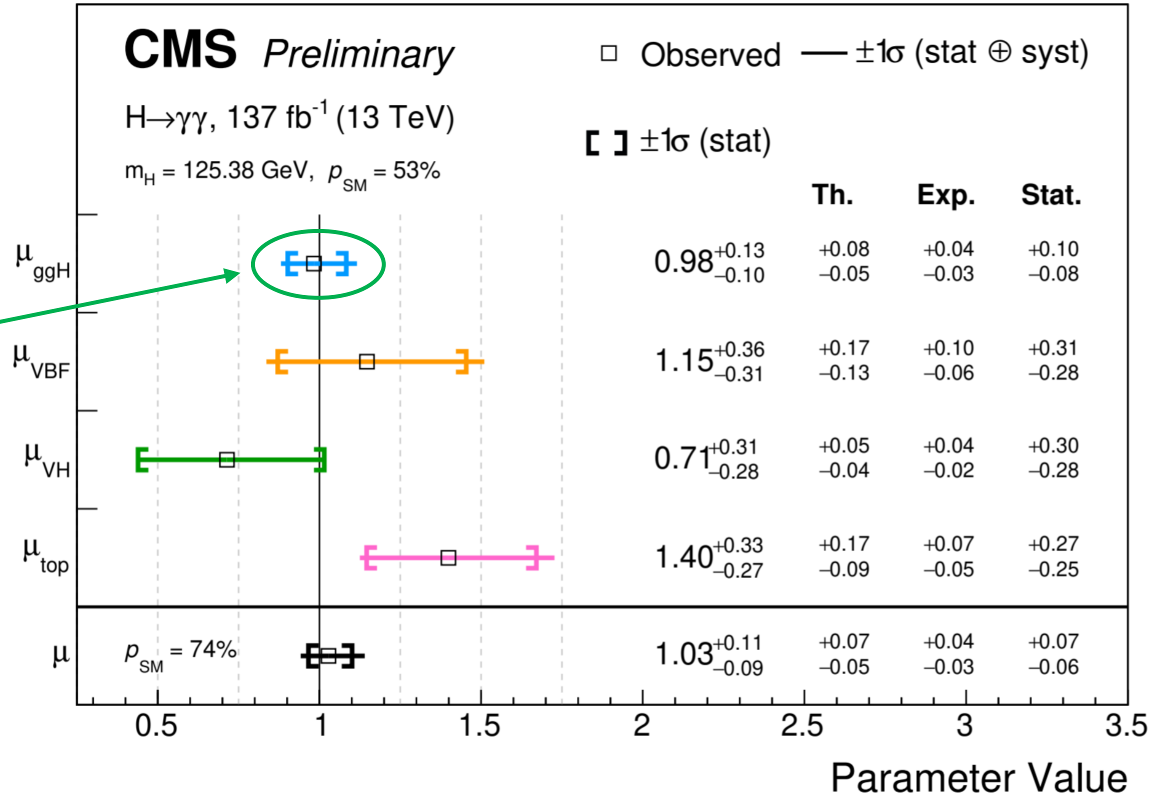


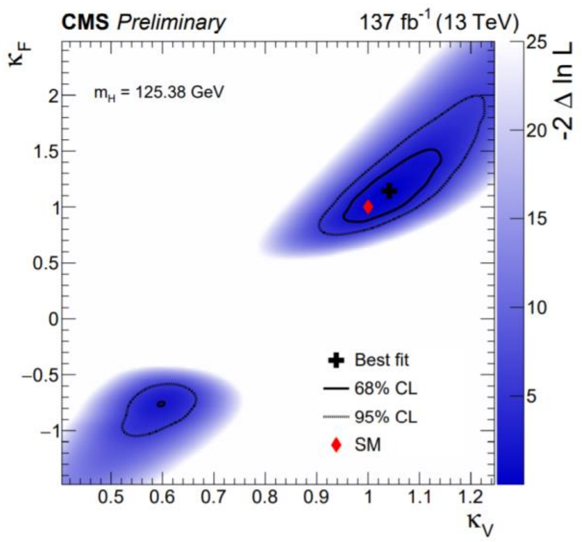

- Only maximal merging shown here
- STXS bins are merged until all expected uncertainties are below 150% of the SM prediction
- All cross sections agree with the SM within uncertainties

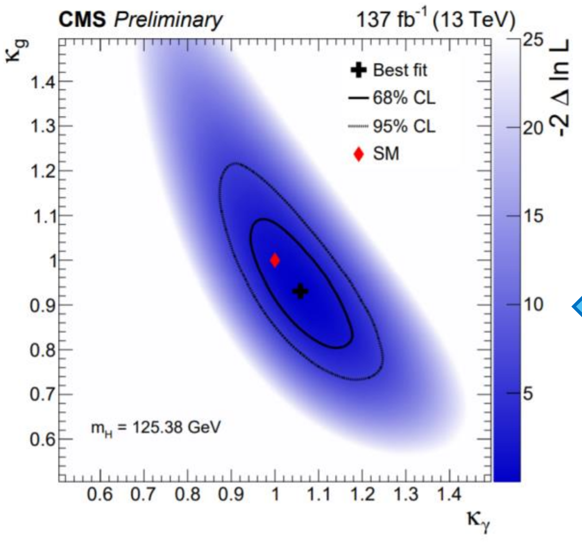
Most precise $tH(H \rightarrow \gamma\gamma)$ measurement to date

# Results - signal strength and coupling modifiers

- Each production mode is scaled independently
- The $H \to \gamma\gamma$ channels is sensitive to all primary production modes
- Full agreement with the SM
- Uncertainty on $\mu_{ggH}$ is starting to be driven by systematics




- Coupling modifiers follow the kappa framework
- Left: Higgs couplings to fermions/bosons, i.e. resolving the $H \to \gamma\gamma$ effective vertex
- Right: effective couplings to gluons and photons

# $H \to ZZ \to 4\ell$ run 2

CMS PAS HIG-19-001

# The H → ZZ → 4ℓ decay channel

- Relatively low branching ratio but very clean final state
  - Main backgrounds: SM ZZ, Z+jets
- Access to full Higgs system kinematics
- 4 final states targeted: $4\mu, 4e, 2\mu 2e$
- Categorization aims at all major production modes
- Matrix element technique is used both for categorization and signal extraction

Signal(background) probability calculated from matrix element

$$\mathcal{D}^{\text{kin}}_{\text{bkg}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\text{bkg}}(\vec{\Omega}^{\text{H}\to 4\ell}|m_{4\ell})}{\mathcal{P}^{gg}_{\text{sig}}(\vec{\Omega}^{\text{H}\to 4\ell}|m_{4\ell})}\right]^{-1}$$

## Preselection

$$\begin{cases} \text{4 isolated leptons} \\ Z \text{ candidates formed from } e^+e^-, \mu^+\mu^- \text{ pairs} \\ \max(m_Z) > 40\ GeV \end{cases}$$

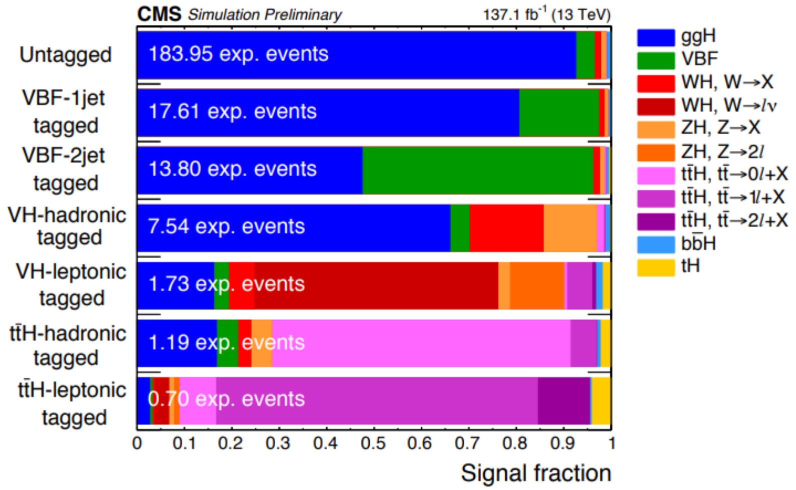
$$\mathcal{D}_{\text{2jet}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\text{VBF}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\text{WH}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\text{WH}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\text{1jet}} = \left[1 + \frac{\mathcal{P}_{\text{HJ}}(\vec{\Omega}^{\text{H+J}}|m_{4\ell})}{\int d\eta_J \mathcal{P}_{\text{VBF}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\text{ZH}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\text{ZH}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

Matrix element discriminants + additional leptons/jets kinematics




STXS sub-categorization in ggH, VBF, VH tagged regions

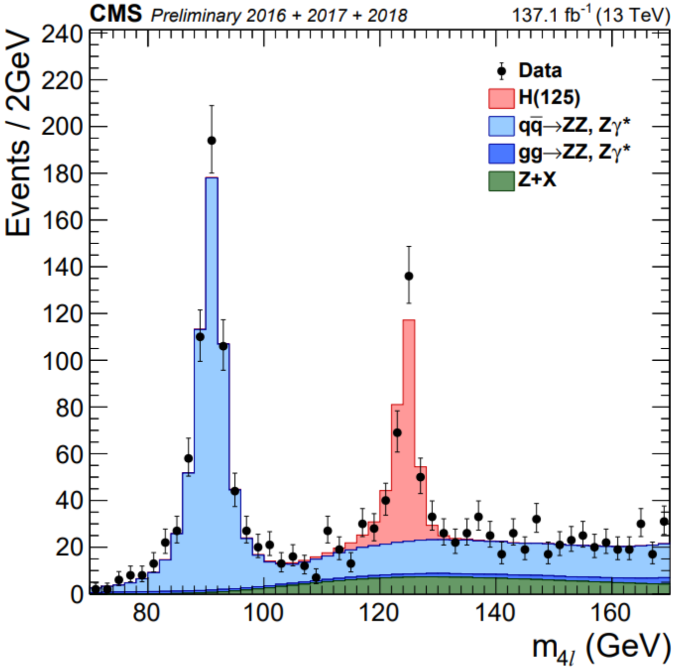
# Results - signal strengths and STXS

- Simultaneous fit in all categories with 2D likelihood

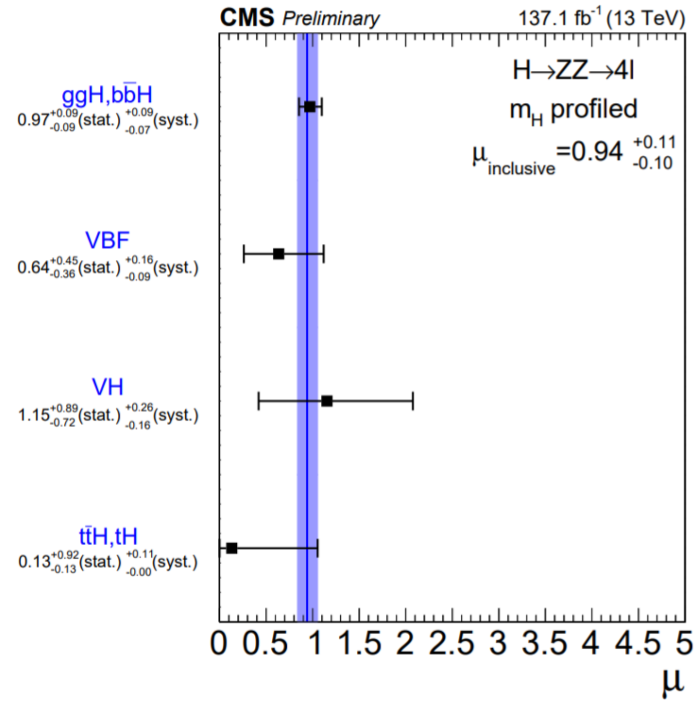
$$\mathcal{L}_{2D} = \mathcal{L}(m_{4\ell})\mathcal{L}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4\ell})$$

Unbinned

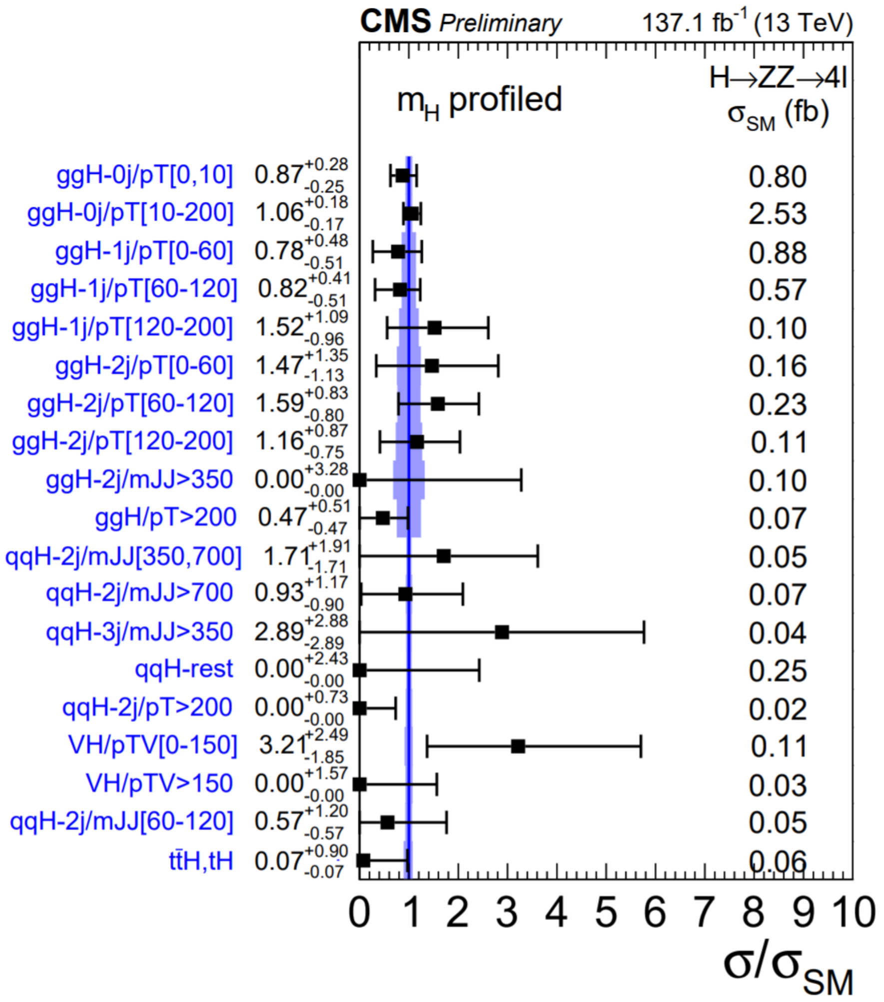
2D template




## Production modes




## STXS

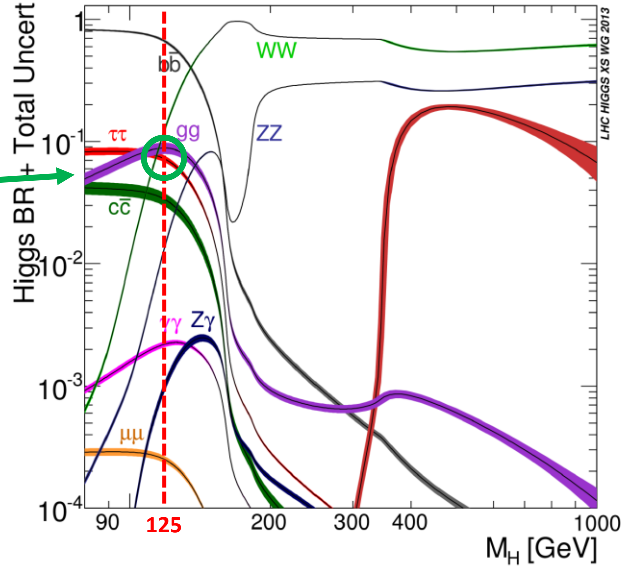


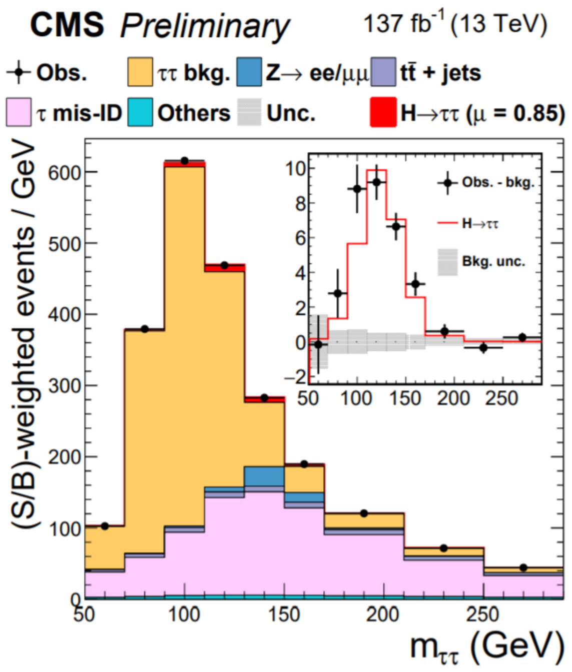
# $H \rightarrow \tau\tau$ run 2 results

CMS PAS HIG-19-010

# The H → ττ decay channel

- Second largest branching ratio in fermionic Higgs decays, cleaner w.r.t. $b\bar{b}$
- Analysis targets $\tau_h\tau_h,\ e\tau_h,\ \mu\tau_h,\ e\mu$ final states, stage 1.2 STXS in ggH, VBF
- $m_{\tau\tau}$ reconstructed with 15-20% accuracy



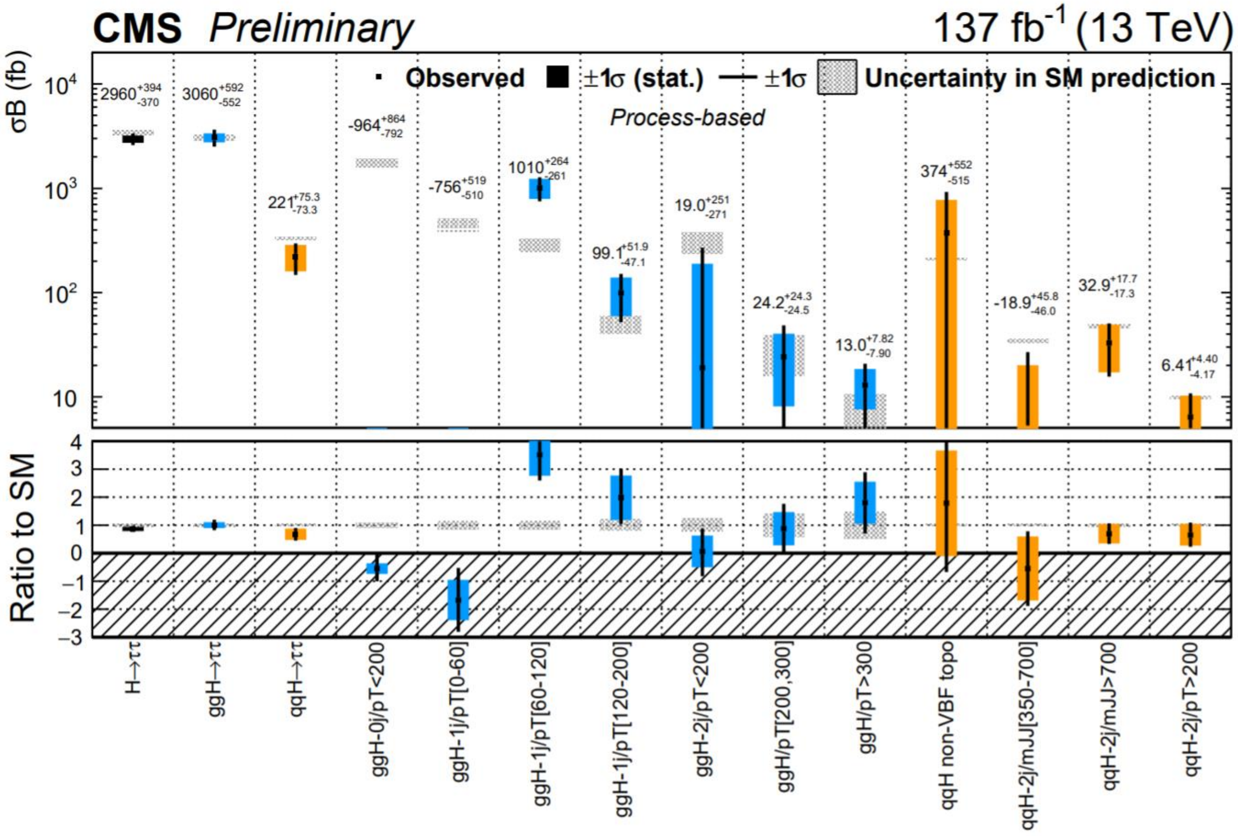




Fit variables

| Final state | Category | Selection | Observables |
|---|---|---|---|
| $\ell\tau_h$, $e\mu$ | 0-jet | 0 jet | $m_{\tau\tau}$, $\tau_h$ $p_T$ ($\ell\tau_h$)<br>$m_{\tau\tau}$ ($e\mu$) |
| | VBF low $p_T^H$ | $\geq 2$ jets, $m_{jj} > 350\,\mathrm{GeV}$, $p_T^H < 200\,\mathrm{GeV}$ | $m_{\tau\tau}$, $m_{jj}$ |
| | VBF high $p_T^H$ | $\geq 2$ jets, $m_{jj} > 350\,\mathrm{GeV}$, $p_T^H > 200\,\mathrm{GeV}$ | $m_{\tau\tau}$, $m_{jj}$ |
| | Boosted 1 jet | 1 jet | $m_{\tau\tau}$, $p_T^H$ |
| | Boosted $\geq 2$ jets | Not in VBF, $\geq 2$ jets | $m_{\tau\tau}$, $p_T^H$ |
| $\tau_h\tau_h$ | 0-jet | 0 jet | $m_{\tau\tau}$ |
| | VBF low $p_T^H$ | $\geq 2$ jets, $\Delta\eta_{jj} > 2.5$(2.0 for 2016),<br>$100 < p_T^H < 200\,\mathrm{GeV}$ | $m_{\tau\tau}$, $m_{jj}$ |
| | VBF high $p_T^H$ | $\geq 2$ jets, $\Delta\eta_{jj} > 2.5$(2.0 for 2016),<br>$p_T^H > 200\,\mathrm{GeV}$ | $m_{\tau\tau}$, $m_{jj}$ |
| | Boosted 1 jet | 1 jet | $m_{\tau\tau}$, $p_T^H$ |
| | Boosted $\geq 2$ jets | Not in VBF, $\geq 2$ jets | $m_{\tau\tau}$, $p_T^H$ |

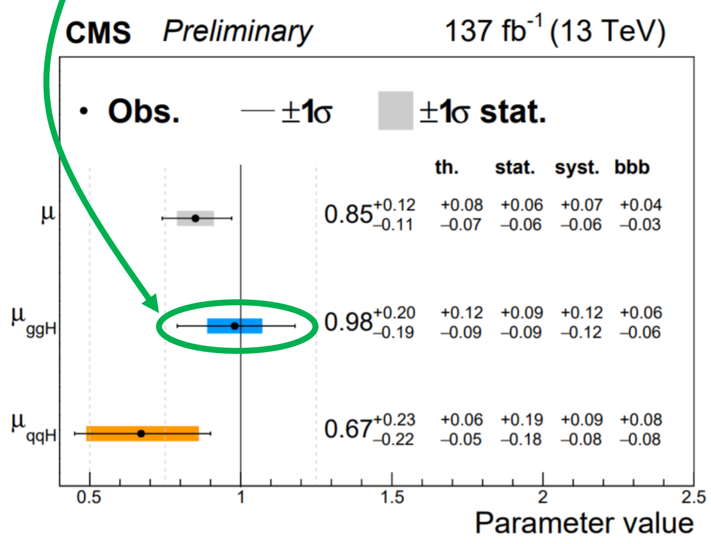
# Results

- Production mode signal strength/coupling modifiers and STXS results provided
- Binned maximum likelihood fit on different variables depending on phase space region (see previous slide)

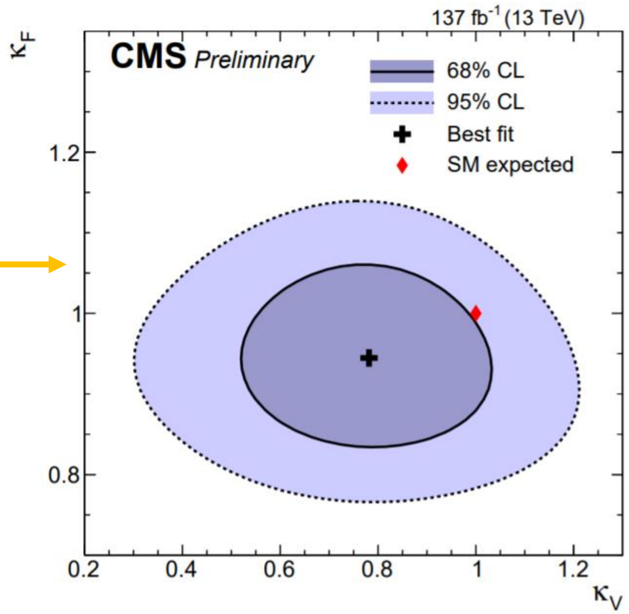



STXS

Driven by systematics




Coupling modifiers to fermions $(\kappa_f)$ and bosons $(\kappa_V)$

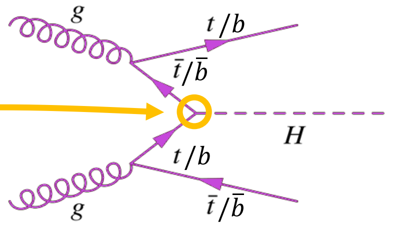


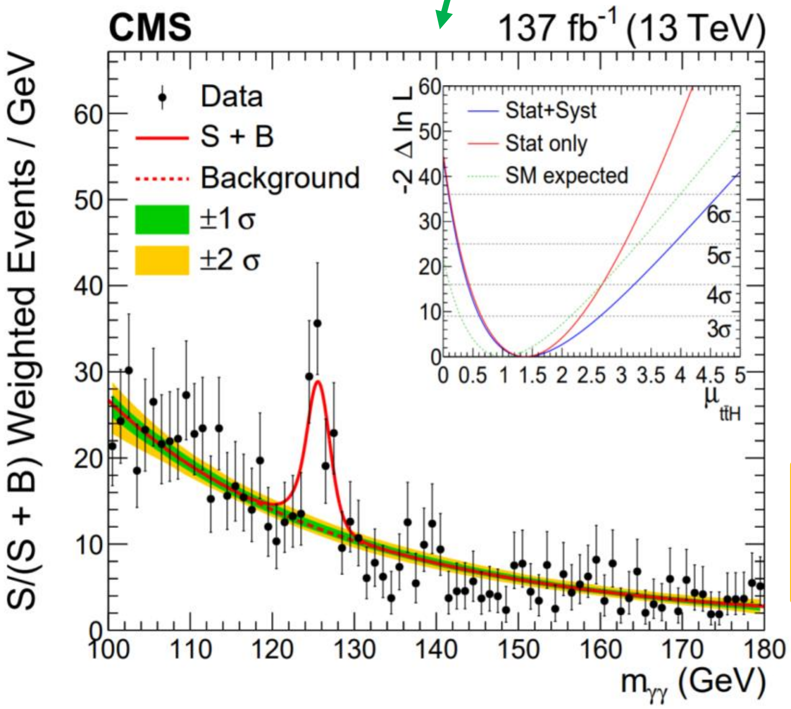
# ttH di-photon and multi-lepton final states

10.1103/PHYSREVLETT.125.061801; CMS PAS HIG-19-008

# ttH(H → γγ) and multilepton

- Dedicated measurements for the $ttH$ production channel
- Direct access to H coupling to fermions
- Measured in both diphoton an multilepton final states

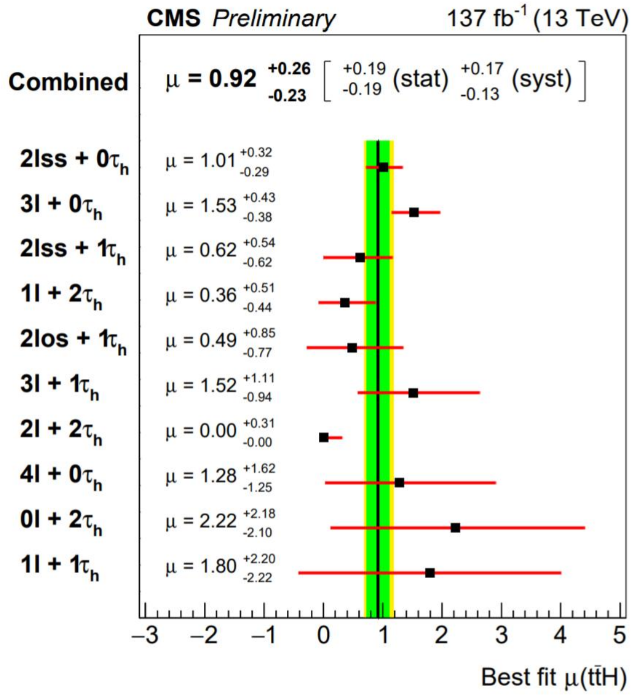



$\mu_{ttH} = 1.38^{+0.36}_{-0.29}$

$6.6(4.7\ exp)\ \sigma$

First observation of $ttH(H \rightarrow \gamma\gamma)$!




$H \rightarrow WW, H \rightarrow ZZ,$
$H \rightarrow \tau\tau$ targeted

35 sub-categories

$\mu_{ttH} = 0.92^{+0.26}_{-0.23}$

# Conclusions

- The remarkable run 2 dataset provided by the LHC is enabling unprecedented reach in Higgs physics
- Substantial improvements across channels
- New observations!
- Many more results I could not cover, and still more to come soon

# Thank you for your attention

# Backup

# Hμμ - event selection

**$H \to \mu\mu$ baseline selection**

$$\begin{cases} 2\ isolated, oppositely\ charged\ muons \\ p_T^{lead} > 26(29^*)\ GeV, \quad p_T^{subl} > 20\ GeV \\ |\eta| < 2.4 \end{cases}$$

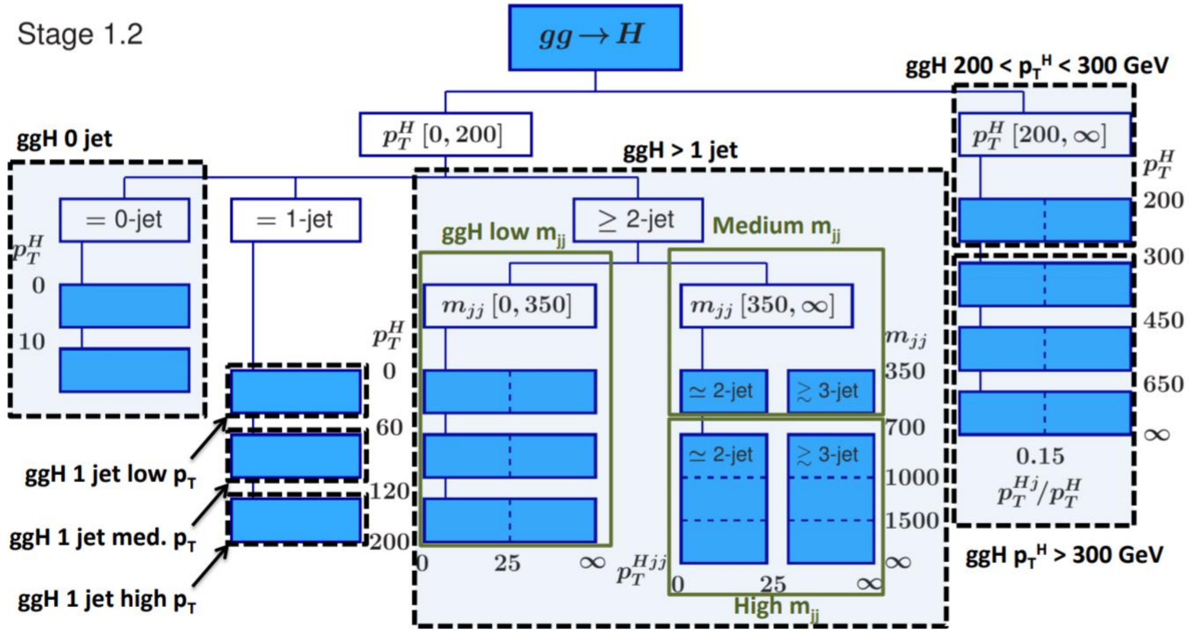
- $N_{b-jet} = 1, 2$ → ttH like
- $N_{b-jets} = 0$; $N_{leptons} > 2$
  - $N_{leptons} = 3$ → WH like
  - $N_{leptons} = 4$ → ZH like
- $N_{b-jets} = 0; N_{jets} \geq 2$; $m_{jj} > 400\ GeV; |\Delta\eta_{jj}| > 2.5$ → VBF like
- Other → Gluon fusion like

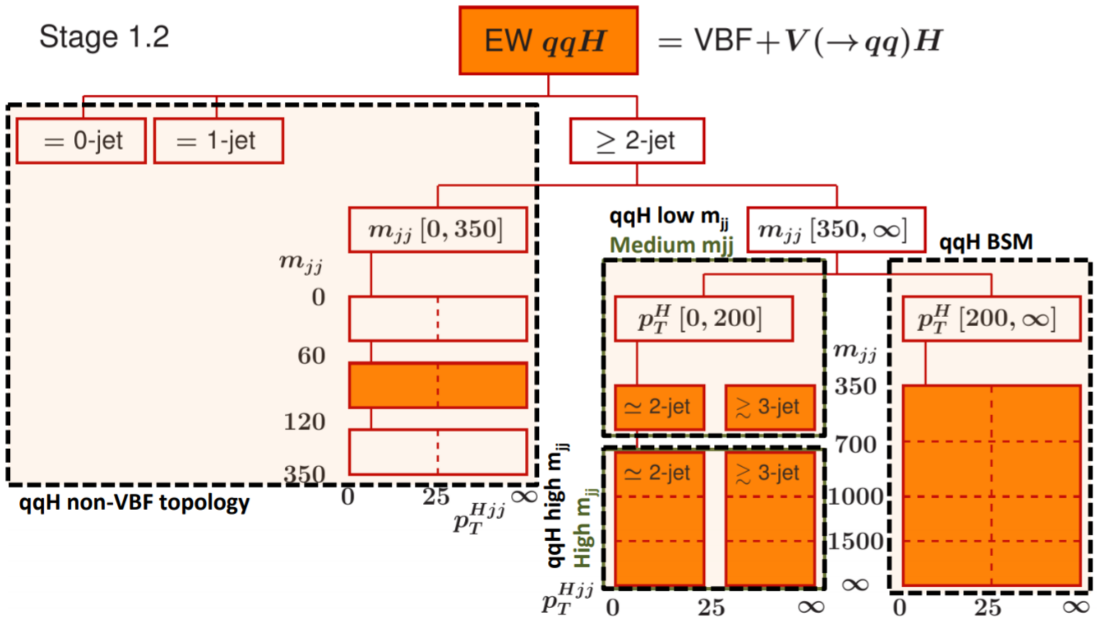
- 96% of dimuon events contained in ggH region ($\sigma_{ggH} \simeq 10 \times \sigma_{VBF}$)
- VBF selection however reduces contribution from off-shell $Z \to \mu\mu$ events
- VBF drives the sensitivity of the analysis

Further subdivision of phase space in each category with multivariate techniques

*2017 dataset

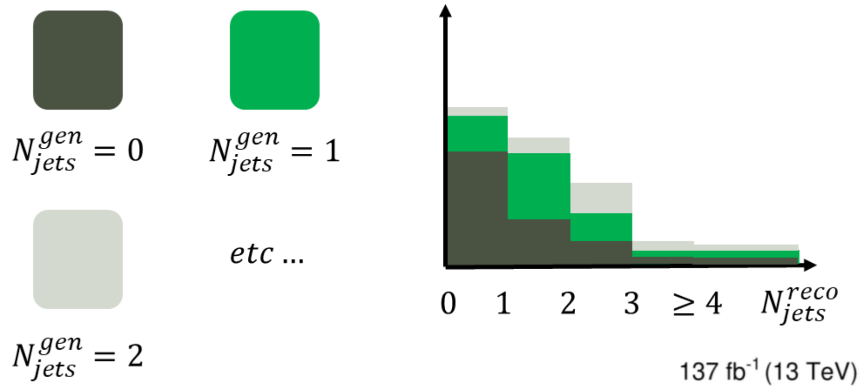
# H → ττ - STXS setup



# HWW - Signal extraction and unfolding

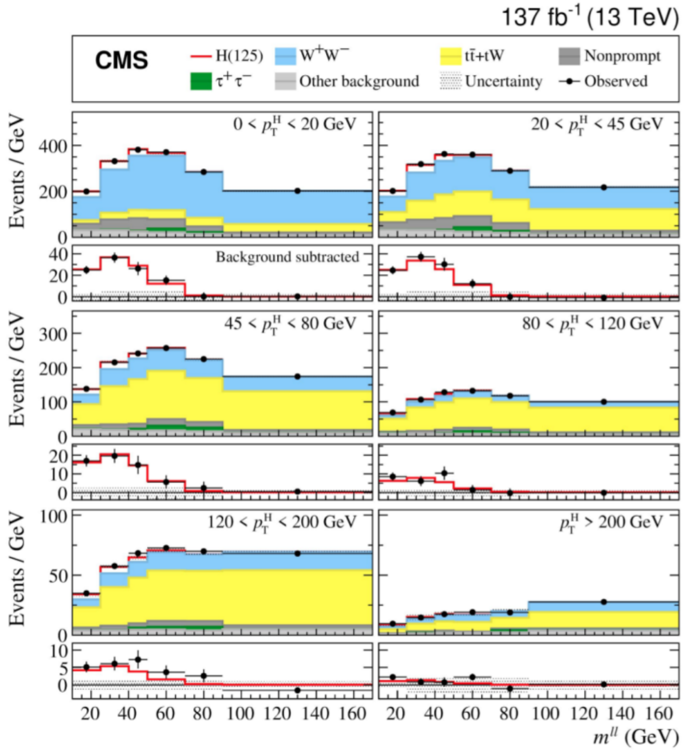
- Binned maximum likelihood fit to the 2D $(m_T, m_{\ell\ell})$ distribution
- Result is unfolded to a particle level fiducial phase space
- Particle level bins are treated as separate signal sources
  - Detector response function implicitly built into the fit
  - Result is automatically unfolded, no further procedures required
  - Natural propagation of systematic uncertainties to unfolded distributions
- Regularization term included for $p_T^H$ due to substantial MET smearing




$$\mathcal{L}_{unreg}(\vec{\mu}, \vec{\theta}) = \prod_{j=1}^{N_{bins}^{reco}} Poisson\left(n_j; s_j(\vec{\mu}, \vec{\theta}) + b_j(\vec{\theta})\right) \cdot \mathcal{N}(\vec{\theta}) \cdot \mathcal{K}(\vec{\mu})$$

$$s_j(\vec{\mu}, \vec{\theta}) = \sum_{i=1}^{N_{bins}^{gen}} \left[R_{ij}(\vec{\theta})\mu_i L \cdot \left(\sigma_i^{fid} + \sigma_i^{non-fid}\right)\right]$$

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



# Simplified Template Cross Sections (STXS)

- Framework designed to enhance sensitivity to the structure of the Higgs sector
- Measure **cross sections** (not signal strengths) in mutually exclusive regions of phase space (bins)
- Unfolded to particle level, i.e. corrected for detector response
- Built with scalability in mind: different stages with increasing granularity
- Minimizes theory dependence while maximizing experimental sensitivity, isolate new physics
- Targets $ggH, VBF, VH, ttH, tH, bbH$ production modes