Higgs Boson Cross Sections and Coupling Measurements at CMS

EPS-HEP 2025

Ralf Schmieder on behalf of the CMS Collaboration

July 7, 2025

Analyses covered in this Talk

- HIG-PAS-24-003: VVH(bb) Run 2
- HIG-PAS-24-019: WH(ττ) Run 2
- HIG-PAS-24-008: Boosted H(WW) Run 2
- HIG-PAS-23-015: ttH Run 2
- HIG-PAS-21-018: Combination Run 2
- HIG-23-014: H($\gamma\gamma$) Run 3
- HIG-24-013: H(4ℓ) Run 3

Higgs Boson Couplings

- The Higgs boson (H) is responsible for electroweak spontaneous symmetry breaking

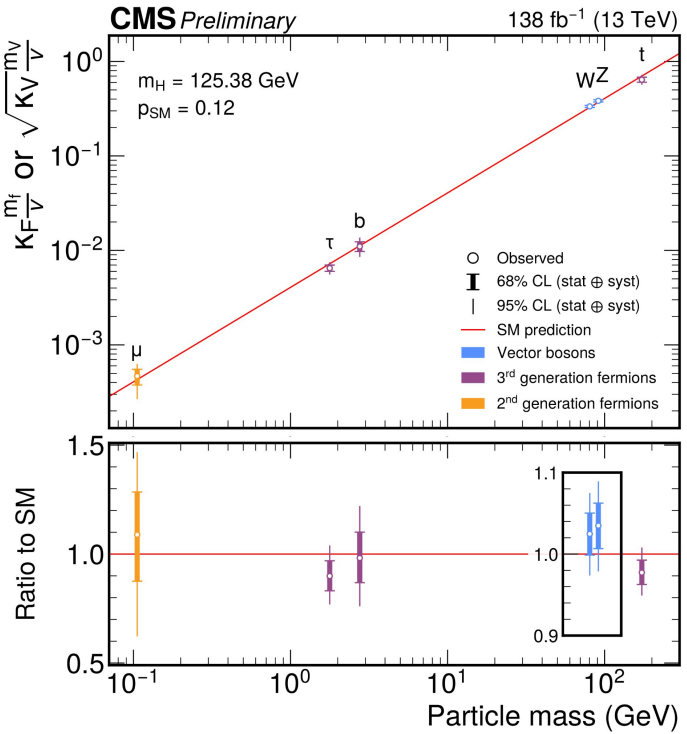
$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger (D_\mu \phi) - \sum_f g_f (\bar{\psi}_L \phi \psi_R + h.c.) - V(\phi)$$

- Gives mass to vector bosons (V) through gauge couplings and vacuum expectation value:

$$m_W = \frac{vg}{2}$$

- Fermion masses determined by Yukawa couplings:

$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

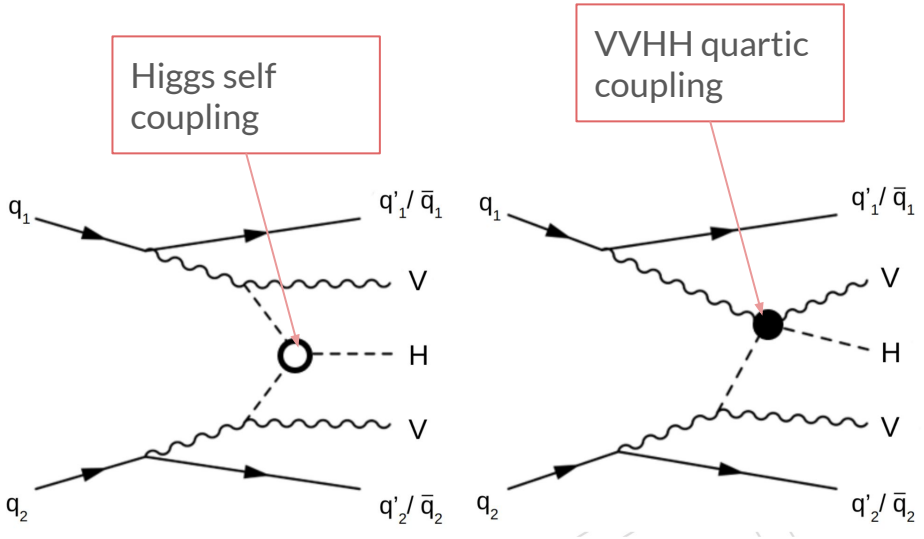


HIG-PAS-21-018

VVH(bb) - Introduction

NEW!

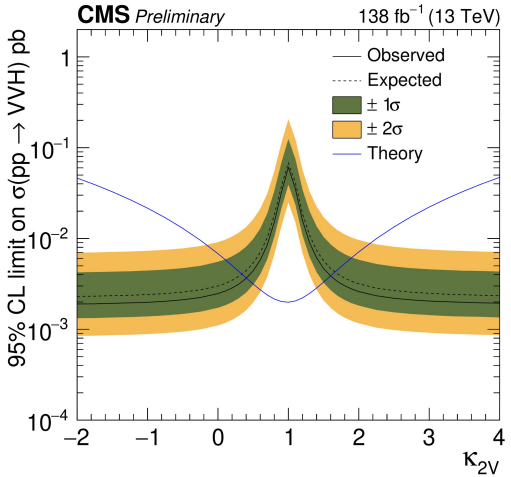
- Run 2 search for VVH production via VBS
- Analysis probes quartic VVHH couplings (κ_{2V}, κ_{2Z}, κ_{2W}) complementing di-H analyses
- Six final states considered:
  - 0ℓ (boosted, semi-boosted)
  - 1ℓ
  - 2ℓ (ss/os WW, Z)
- Boosted signal topology: two forward jets (VBS) and H(bb) as a single large-radius jet
- DNNs and BDTs are used for signal discrimination
- All background estimated by data via ABCD method



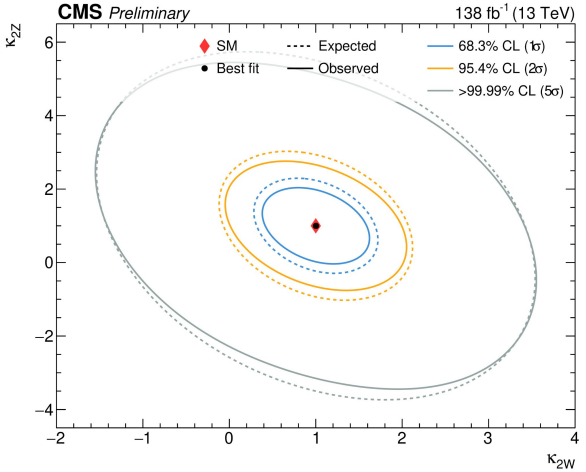
HIG-PAS-24-003

VVH(bb) - Results

- In each final state the four ABCD regions are part of the fit
- One bin counting experiment in each final state
- Analysis constraints the coupling modifiers to
  - $\kappa_{2V} \in [0.41,1.49]$
  - $\kappa_{2Z} \in [0.17,1.83]$
  - $\kappa_{2W} \in [-0.37,2.37]$
- Current tightest limits on κ_{2Z} and κ_{2W}



NEW!



HIG-PAS-24-003

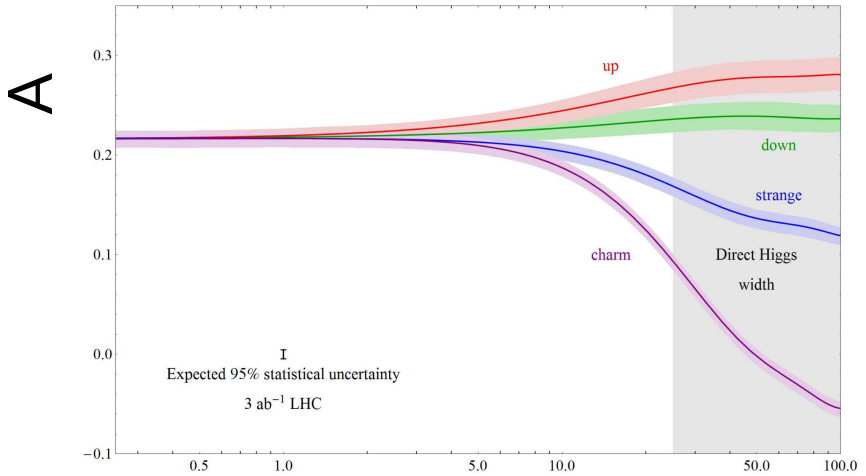
WH($\tau\tau$) - Introduction

NEW!

- Run 2 measurement of $\sigma(W^+H)$, $\sigma(W^-H)$, $\sigma(WH)$ and charge asymmetry (A) in $W(\nu\ell)H(\tau\tau)$
- A in WH production:

$$A = \frac{\sigma(W^+H) - \sigma(W^-H)}{\sigma(W^+H) + \sigma(W^-H)}$$

- A sensitive to Yukawa couplings
- Final states: $\ell\ell\tau_h$, $\ell\tau_h\tau_h$
- Major backgrounds: WZ and jet faking ℓ,τ_h
- DNN to classify signal and background events



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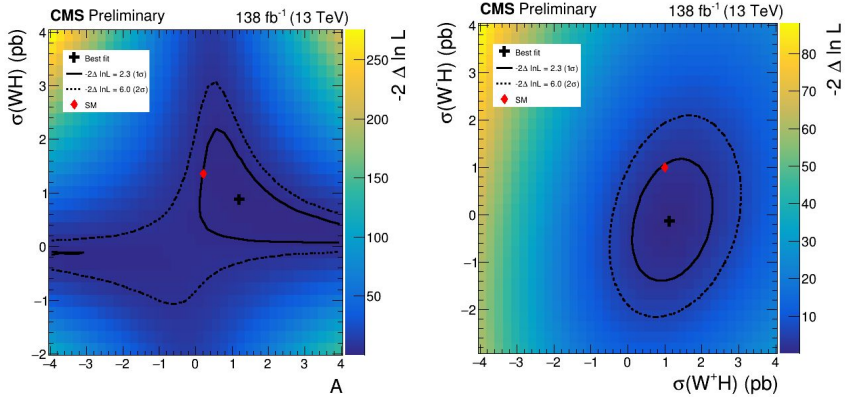
$$\tilde{\kappa}_f = \frac{m_f(\mu=125\ \text{GeV})}{m_b(\mu=125\ \text{GeV})}\kappa_f$$

WH($\tau\tau$) - Result

NEW!

- First measurement of A, σ(W^+H), σ(W^-H)
- WH(WW) is treated as a signal in fit
- All results within SM expectation
- Results can be interpreted in terms of Yukawa couplings

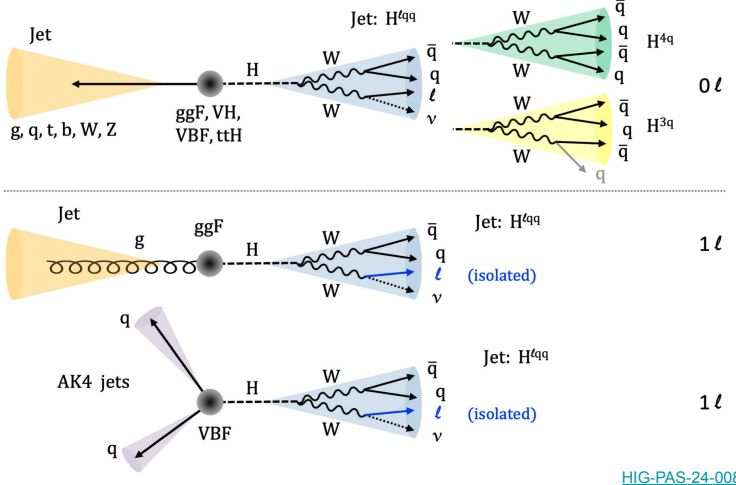
Quantity	Observed	Expected	Theory
$\sigma(W^+H)$ [pb]	$0.96^{+0.61}_{-0.58}$	$0.83^{+0.61}_{-0.58}$	0.83 ± 0.02
$\sigma(W^-H)$ [pb]	$-0.05^{+0.46}_{-0.44}$	$0.53^{+0.51}_{-0.49}$	0.53 ± 0.01
$\sigma(WH)$ [pb]	$0.96^{+0.86}_{-0.82}$	$1.36^{+0.90}_{-0.84}$	1.36 ± 0.03
A	$1.18^{+0.00}_{-0.75}$	$0.22^{+0.66}_{-0.56}$	0.22 ± 0.01
$\mu(W^+H)$	$1.16^{+0.74}_{-0.70}$	$1.00^{+0.73}_{-0.69}$	
$\mu(W^-H)$	$-0.15^{+0.87}_{-0.83}$	$1.00^{+0.96}_{-0.91}$	
$\mu(WH)$	$0.71^{+0.63}_{-0.60}$	$1.00^{+0.65}_{-0.62}$	



HIG-PAS-24-019

Boosted H(WW) - Introduction

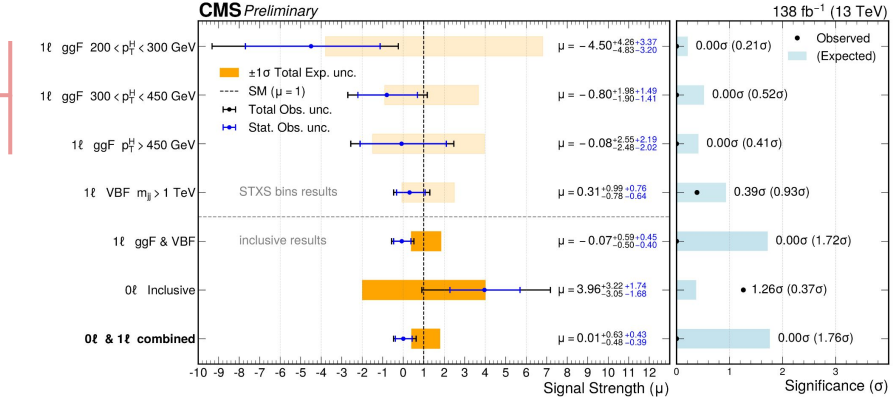
- First measurement of boosted H(WW) with semileptonic and full hadronic decays (Run 2)
- Sensitive probe of BSM physics
- For H-p_T>250 GeV, W bosons merged to a single large-radius jet
- Categories:
  - 0ℓ: inclusive
  - 1ℓ: ggF, VBF
- DNN classifier for large-radius jets to identify signal
- Dedicated control regions for tt, W+jets, QCD in each final state



HIG-PAS-24-008

Boosted H(WW) - Results

- Observed full inclusive signal strength: $\mu_H = 0.01^{+0.61}_{-0.46}$
- All results compatible with SM expectation
- Differential cross sections are provided for STXS framework in the 1ℓ final state



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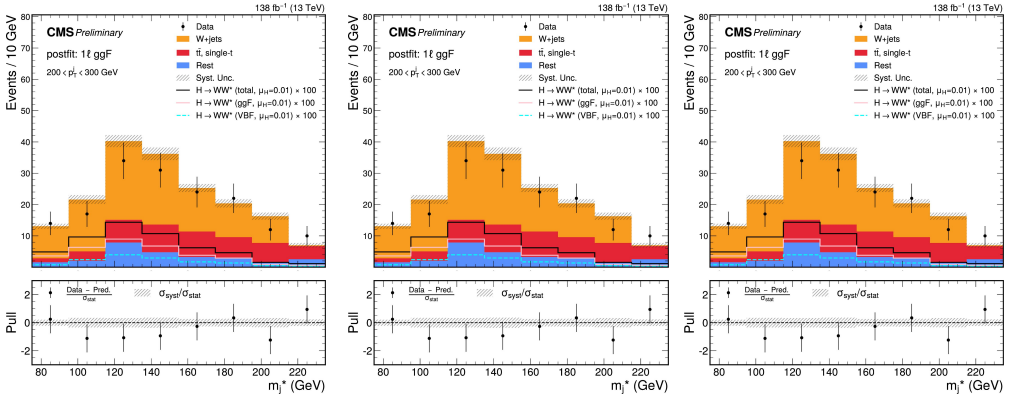
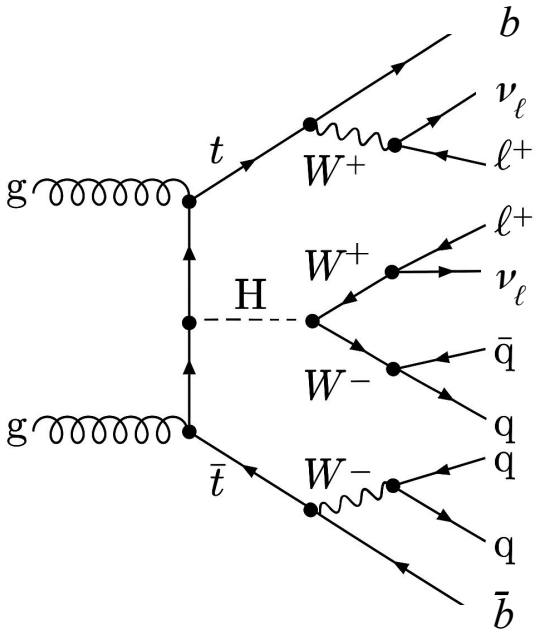


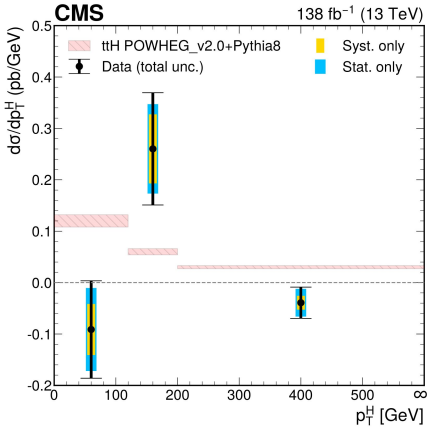
Differential ttH production - Introduction

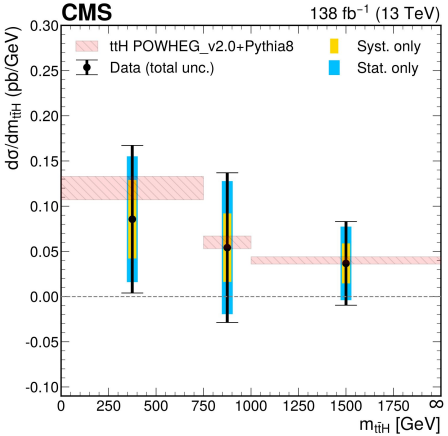
- Run 2 cross section measurement, targeting multi-lepton final states with
  - $H \rightarrow WW \rightarrow \ell\nu\ell\nu \mid \ell\nu qq'$
  - $H \rightarrow \tau\tau \rightarrow \ell\nu\tau_h \mid \ell\nu\ell\nu$
  - $2\ell ss+0\tau_h$, $2\ell ss+1\tau_h$, $3\ell+0\tau_h$
- Differential measurement sensitive to BSM effects
  - three H-p_T and m_{ttH} bins
- Constraint on κ_λ, complementary to HH searches
- DNN regression to estimate H-p_T
- DNN classifier for each final states



Differential ttH production - Results

- Fit to all DNN output distributions and a 3ℓ and 4ℓ CR to constrain irreducible backgrounds (ttW, ttZ)
- H-p_T and m_{ttH} cross section measurements consistent with SM with p-values of 2% and 52%
- H self coupling: $\kappa_\lambda = 40\ ^{+83.5}_{-56.4}$ @95% CL
- First ttH differential measurement by CMS

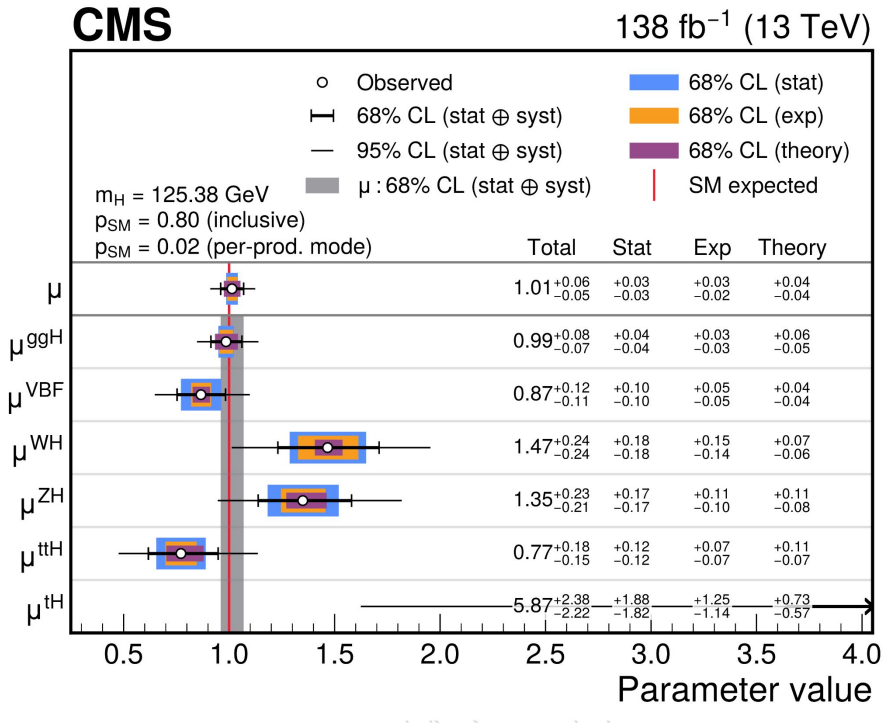




HIG-PAS-23-015

Combined Measurements of H Production and Decay - Results

- Detailed talk about this combination results on Wednesday
- Result using single parameter of interest (POI):
  - $\mu_H = 1.014\ ^{+0.055}_{-0.053}$
- Covers STXS, branching fractions, κ-framework, constraints on κ_λ, BSM interpretation

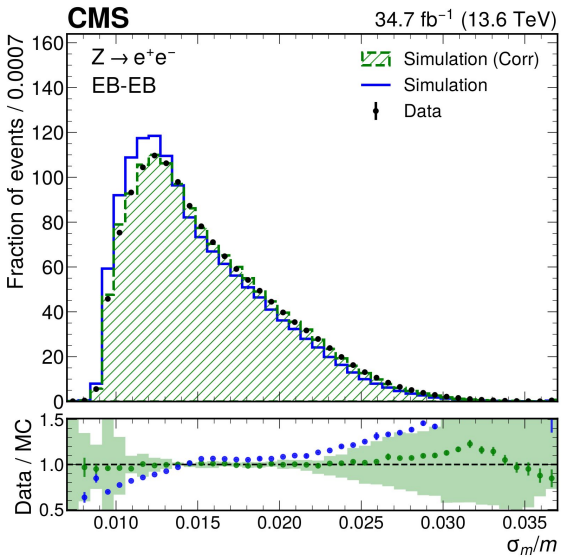


HIG-PAS-21-018

H(γγ) - Introduction

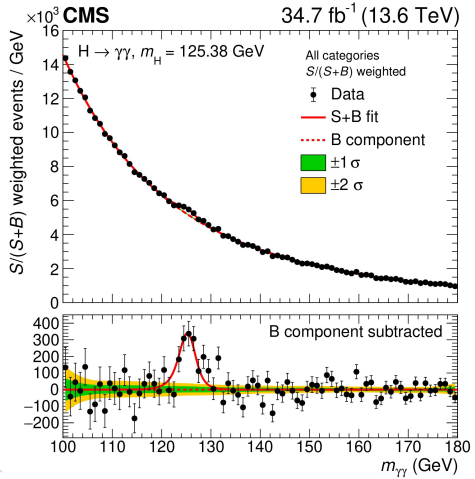
- First H(γγ) analysis using CMS Run 3 data
- Use of novel and innovative analysis techniques
  - NN to improve γ energy resolution σ_E
  - Data/MC corrections of γ shower shape, isolation and σ_E via normalizing flows → reducing systematic uncertainties
- Inclusive and differential fiducial cross section measurement with an integrated luminosity of 34.7 fb^{-1}

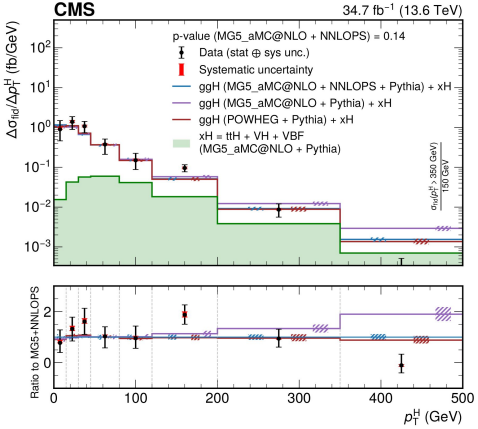
Data-MC comparison before and after correcting σ_E

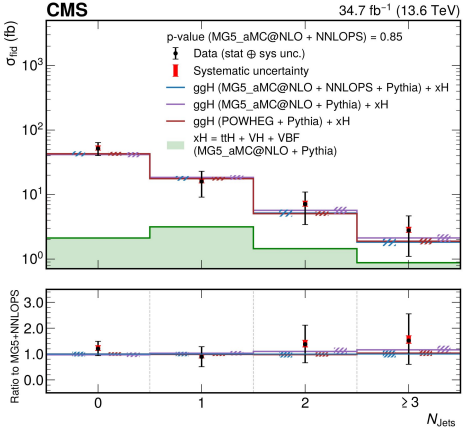


H(γγ) - Results

- Inclusive result compatible with SM expectation:
  σ_{fid} = 74 ± 12 fb (67.8 ± 3.8 fb)
- Differential cross sections also agree with SM expectation



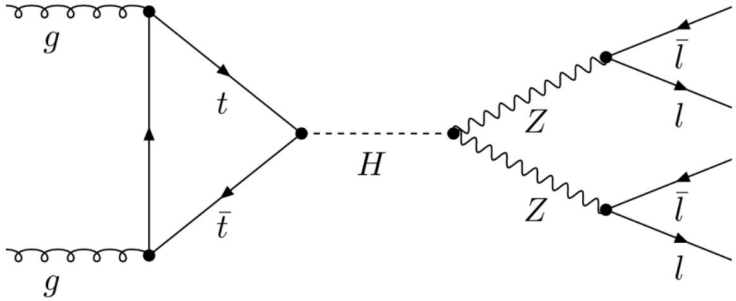




arXiv:2501.17755

H(4ℓ) - Introduction

- First H(4ℓ) analysis using CMS Run 3 data
- Inclusive and differential fiducial cross section measurement with an integrated luminosity of 34.7 fb^{-1}
- Low branching fraction (1.3×10^{-4}) but clear 4ℓ signature
- Fit to $m_{4\ell}$ distribution to extract σ_{fid}
- Three final states considered: 4μ, 4e, 2e2μ

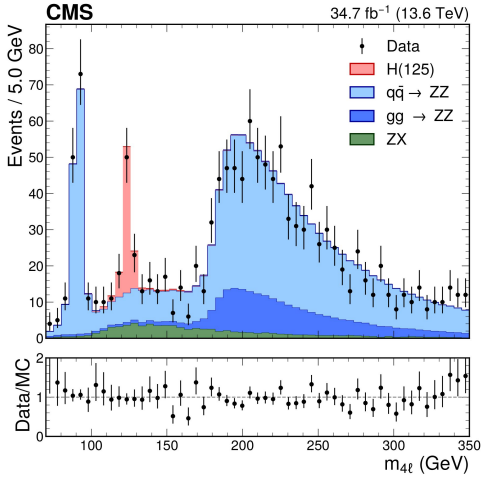


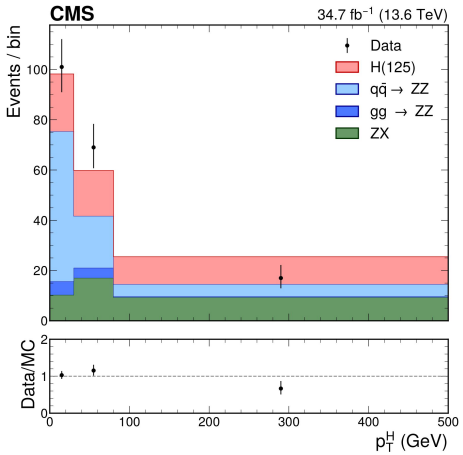
H(4ℓ) - Results

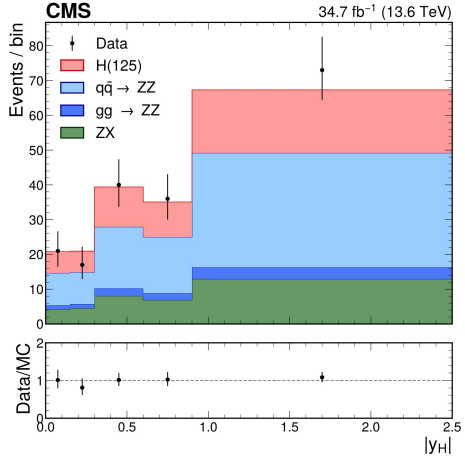
- Inclusive result compatible with SM expectation of 3.09 $^{+0.27}_{-0.24}$ fb:

$$\sigma_{\text{fid}} = 2.89^{+0.53}_{-0.49}\,(\text{stat})\,^{+0.29}_{-0.21}\,(\text{syst})\,\text{fb}$$

- Differential cross sections also agree with SM expectation







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Conclusions

- We are in the era of precision measurements of H boson properties
- H coupling to a lot of particles well established
- Sophisticated analysis techniques open undiscovered phase spaces and improve precision
- Differential measurements are able to constrain BSM and H self coupling
- First H-related Run 3 measurements

Backup

Additional Material - VVH(bb)

- Full hadronic:
  - Boosted: all V are large-radius jets
  - Semi-boosted: one V reconstructed by two small-radius jets
- Semi-leptonic: Two large-radius jets, and one isolated lepton
- 2 lepton: WW: one large-radius jet, ZZ: two large radius jets
- Higgs jet id'd via NN trained on X(qq) (highest score for X(bb))
- Orthogonality via lepton count
- Dominant systematic: factorization scale μ_F, closure uncertainties on ABCD method
- Benchmark model for the 95% CL plot with κ_{2V}
- Best fit for κ_{2Z} κ_{2W} at (1,1) due to lower counts than the expected background
- Tightest constraints on κ_{2V} from di-H [0.67, 1.38]

Additional Material - Boosted H(WW)

- p_T-dependent isolation variable
- Veto of further leptons and large-radius jets to suppress VH in the one lepton final state
- Particle Transformer algorithm, calibrated via Lund jet plane (2D-space to map the jet's internal structure)
    - Tagger designed to id broad range of H induced jets
    - WW kinematics asymmetric (challenging)
- 0-lepton: 2 or 3 large-radius jets required
- 1-lepton: VBF: two small-radius jets (high Δη, high di-jet mass), MET close to the jet, veto further V jets | ggF: all other events
- Major systematics: Tagger efficiency, background normalization
- Backgrounds:
    - 0l: QCD estimated by rhalphabet method (like FF)
    - 1l: W+Jets(CR by cut on tagger), tt (#b-jets>0)

Additional Material - ttH

- Veto of same-flavour os lepton events close to Z mass
    - Reduces backgrounds from: ttZ, tZ, WZ, DY
- Two b jets required (loose)
- Reducible backgrounds: charge mis-assignement, jet faking leptons, estimated data driven

Additional Material - H(γγ)

- Two γ selected within $m_{\gamma\gamma} \in [100,180]$ GeV
- σ_E around 1-4%
- BDT regression improves resolution, accounting for shower leakage, dead cystals, energy thresholds
- Photon var correction: Z->ee events using TnP
- Events categorized on per-event $m_{\gamma\gamma}$-resolution estimator σ_m/m (σ_E) in three bins
- Backgrounds: non resonant di-γ, γ+jet → modelled by exponential function
- Fiducial cross sections measured in p_T^H, $|y^H|$, N_{jets}, p_T(leading jet)
- Fit to $m_{\gamma\gamma}$ in the three $m_{\gamma\gamma}$-resolution categories
- Result with 16% uncertainty comparable with ATLAS

Additional Material - H(4ℓ)

- At least two pairs with same-flavour os within the Z mass window
- Leptons from taus are not considered
- Electron selection efficiency is highest uncertainty