Latest CMS results in the $H \rightarrow ZZ \rightarrow 4\ell$ channel

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On behalf of CMS Collaboration

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The $H \rightarrow ZZ \rightarrow 4\ell$ channel

- **Golden channel**: important for the discovery and study of $H$ properties
  - Clear 4 lepton signature provides large S/B
  - Complete reconstruction of the final state decay products
  - But very small Branching fraction (0.012%)

- Results presented in this talk:
  - CMS-PAS-HIG-21-009 **New!**
The $H \rightarrow ZZ \rightarrow 4l$ Channel

- Selection:
  - $4l$ (e, $\mu$)
  - $Z$ candidate
  - $ZZ$ candidate
  - **best $ZZ$** candidate chosen (if more than 1) with:
    - Kinematic discriminant (MELA pkg)
    - Highest $p_T$ of $Z_2$ (for differential cross sections)

- Background:
  - $ZZ$ estimated from MC
  - $Z+X$ (reducible) from data

- Additional objects for event categorization

- Matrix element discriminants and multidimensional ML fits to extract results
The $H \rightarrow ZZ \rightarrow 4l$ RESULTS

Signal Strengths

STXS

Fiducial Differential Cross Sections

New!

Signal strengths

- Defined as ratio of the measured cross section and the SM expectation
- Inclusive: $\mu = 0.94 \pm 0.07^{+0.07}_{-0.06} \text{(stat)} +^{0.06}_{-0.05} \text{(th)} +^{0.07}_{-0.06} \text{(exp)}$
- Consistent with SM expectations

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Simplified Template Cross Sections (STXS)

- Kinematic regions based on the production modes of the Higgs → Built to maximize sensitivity to isolate BSM effects while reducing theory dependence

- Dedicated categories to measure STXS Stage 1.2: splitting based on number of jets and kinematic selections ($p_T^H$)

- Some STXS bins merged to avoid large uncertainties or high correlations (reduces model-independence)
Simplified Template Cross Sections (STXS)

- Good sensitivity to ggH process
- Because of low statistics, some bins merged and result to be fit to 0
- Consistent with SM expectations

Fiducial Differential Cross sections

- **Fiducial volume** defined to match experimental selections → achieve model-independence
- Large number of **new observables** considered
- Differential xsec **bin boundaries** chosen to:
  - Be aligned for the combination with other channels
  - Have enough data for low expected uncertainties
  - Ensure a good level of S/B
- **Improved** event reconstruction, object calibration, systematics estimate
- **Interpretation** of $p_T^H$ spectrum ($k_\lambda$, $k_b$, $k_c$)

New results! → Alessandro’s talk
Inclusive Fiducial Cross Section

\[ \sigma^{\text{fid}} = 2.73^{+0.22}_{-0.22} \text{(stat)}^{+0.15}_{-0.14} \text{(syst)} \text{ fb} \]
\[ = 2.73^{+0.22}_{-0.22} \text{(stat)}^{+0.12}_{-0.12} \text{(electrons)}^{+0.06}_{-0.05} \text{(lumi)}^{+0.04}_{-0.04} \text{(bkg)}^{+0.03}_{-0.02} \text{(muons)} \text{ fb} \]

- Overall precision of 10%
- Good agreement with SM expectations
- 40% decrease of systematic uncertainties w.r.t. previous measurements!
- Systematic component dominated by electron reconstruction efficiency

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138 fb\(^{-1}\) (13 TeV)

-2\Delta ln L

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**Inclusive Fiducial Cross Section: Floating ZZ Normalization**

**New strategy** investigated: measure the ZZ irreducible bkg normalization together with the inclusive fiducial xsec

- Standard approach: ZZ shape and normalization from MC
- Useful to:
  - Reduce uncertainty on ZZ normalization
  - Be **sensitive to possible BSM effects in the bkg**

- Results consistent with standard approach
- But not yet enough data to profit from this method in differential measurements
Production Observables

- New bin boundaries choice
- \( p_T^H \) spectrum measurement precision improved
- jets phase space extension (up to \(|\eta_j| < 4.7\)) thanks to improved CMS jet reconstruction

\[ \rightarrow \text{more variables in the paper} \]
Production Observables

- New observables
- Information on di-jet and H+jet system
- First bin contains events for which the observables are not defined

→ more variables in the paper

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**Production Observables**

- **New observables**
- Jet transverse momentum weighted by a function of jet rapidity
- Useful to test QCD resummation
- 0-jet phase space redefinition

\[
\tau_C^{\text{max}} = \max_j \left( \frac{\sqrt{E_j^2 - p_{zj}^2}}{2 \cosh(y_j - y_H)} \right)
\]

\[
\tau_B^{\text{max}} = \max_j \left( m_T^{i} e^{-|y_j - y_H|} \right)
\]

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**Decay Observables**

- 7 parameters fully describing the $H\to 4l$ decay:
  - Z masses ($m_{Z1}, m_{Z2}$)
  - Angular variables for fermion kinematics ($\Phi, \cos \theta_1, \cos \theta_2$)
  - Angular variables connecting production and decay ($\Phi_1, \cos \theta^*$)

- New observables
- Results divided for identical ($4e+4\mu$) and different ($2e2\mu$) flavour final states
  → highlight sensitivity of identical flavour final state to interference effects

→ more variables in the paper
**Decay Observables: ME Discriminants**

- **New observables**
- **ME discriminants** sensitive to HVV anomalous couplings
- Results compared to different BSM hypotheses
- Presented separately for identical (4e+4μ) and different (2e2μ) flavour final states

Sensitive to possible CP-violation effects

→ more variables in the paper
**Double Differential Observables**

- **New** observables
- Large set of observables to improve characterization of the decay channel and maximize coverage of different phase space regions

→ more variables in the paper
- NLO EW corrections induce dependence of single-H cross sections on $\lambda_{HHH}$ → extract information from $p_T^H$ spectrum
- Large contribution from ttH and VH
- H cross section parametrized as function of $k_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$:
  - Cross section and BR fixed to SM values
  - Scaling function $\mu(\lambda)$ in each bin of $p_T^H$ spectrum for all production mechanisms
- Observed (expected) limits at 95% CL:
  
  \[-5.5 \ (7.7) \ < \ k_\lambda \ < \ 15.1 \ (17.9)\]

Competitive with many limits from HH direct searches!
**INTERPRETATION**

- **ggH** $p_T^H$ **spectrum** used to set constraints on $k_b$, $k_c$ coupling modifiers
  → Quadratic polynomials to parametrize simultaneous variations of H couplings in each bin

- Observed (expected) 95% CL limits assuming **branching fractions dependent on** $k_b$, $k_c$
  - $-1.1 (-1.3) < k_b < 1.1 (1.2)$
  - $-5.3 (-5.7) < k_c < 5.2 (5.7)$

- Observed (expected) 95% CL limits if treating $H \rightarrow ZZ$ branching fraction as unconstrained parameters in fit
  - $-5.6 (-5.5) < k_b < 8.9 (7.4)$
  - $-20 (-19) < k_c < 23 (20)$
Summary

- H→ZZ→4l is a fundamental channel to study the Higgs boson
- Most recent full Run2 results presented, overall good agreement with SM
- Super fresh results from differential fiducial cross section measurements
  - Comprehensive characterization of the H→4l channel
  - Many new observables considered
  - 3 interpretation performed
  - Improved event reconstruction, object calibration, systematics estimate
    → Very precise measurements (10% inclusive)!

The precision exploration of the scalar sector has just started!
Production Observables

CMS Preliminary

138 fb$^{-1}$ (13 TeV)

$\frac{d\sigma_{\text{fid}}}{dy_H}$ (fb)

Data (stat. @ syst. unc.)
- p-value(PowHiggs): 0.85
- Systematic uncertainty

$gg \rightarrow H$ (amcatnloFXFX + JHUGen + Pythia) + XH
$gg \rightarrow H$ (NNLOPS + JHUGen + Pythia) + XH
$gg \rightarrow H$ (POWHEG + JHUGen + Pythia) + XH

$XH = VBF + VH + ttH$ (POWHEG + JHUGen + Pythia)
(LHCHWG YR4, $m_H = 125.38$ GeV)

CMS Preliminary

138 fb$^{-1}$ (13 TeV)

$\sigma_{\text{fid}}$ (fb)

Data (stat. @ syst. unc.)
- p-value(PowHiggs): 0.48
- Systematic uncertainty

$gg \rightarrow H$ (amcatnloFXFX + JHUGen + Pythia) + XH
$gg \rightarrow H$ (NNLOPS + JHUGen + Pythia) + XH
$gg \rightarrow H$ (POWHEG + JHUGen + Pythia) + XH

$XH = VBF + VH + ttH$ (POWHEG + JHUGen + Pythia)
(LHCHWG YR4, $m_H = 125.38$ GeV)

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Production Observables
**Decay Observables**

[Graph and data plots showing decay observables for Higgs boson production and decay.]
Sensitive to possible BSM contribution from heavy H bosons
**Double Differential Observables**

\[ p_T^H, y^H \]

**CMS Preliminary**

138 fb\(^{-1}\) (13 TeV)

\[ \frac{d^2\sigma}{dp_T^H dy_H} (fb/GeV) \]

- Data (stat. \& sys. unc.)
- Systematic uncertainty
- gg\(\rightarrow\)H (amcatnloFXFX + JHUGen + Pythia) + XH
- gg\(\rightarrow\)H (NNLOPS + JHUGen + Pythia) + XH
- gg\(\rightarrow\)H (POWHEG + JHUGen + Pythia) + XH
- XH = VBF + VH + t\(\bar{t}\)H (POWHEG + JHUGen + Pythia)

\[ (LHCHWG YR4, m_H=125.38 \text{ GeV}) \]

- Ratio to NNLOPS

\[ p_T^H (GeV) \]

**CMS Preliminary**

138 fb\(^{-1}\) (13 TeV)

\[ \frac{d^2\sigma}{dp_T^H dN_{jets}} (fb/GeV) \]

- Data (stat. \& sys. unc.)
- Systematic uncertainty
- gg\(\rightarrow\)H (amcatnloFXFX + JHUGen + Pythia) + XH
- gg\(\rightarrow\)H (NNLOPS + JHUGen + Pythia) + XH
- gg\(\rightarrow\)H (POWHEG + JHUGen + Pythia) + XH
- XH = VBF + VH + t\(\bar{t}\)H (POWHEG + JHUGen + Pythia)

\[ (LHCHWG YR4, m_H=125.38 \text{ GeV}) \]

- Ratio to NNLOPS

\[ p_T^H (GeV) \]

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INTERPRETATION

Credits:
Alessandro Tarabini
$\mu_i^f = \mu_i \times \mu_f = \frac{\sigma_{NLO}^{M}}{\sigma_{SM}^{NLO}} \frac{BR(H\rightarrow ZZ)}{BR_{SM}(H\rightarrow ZZ)} = \frac{1+k_{\lambda}C_{1,i}+\delta Z_H}{(1-(k_{\lambda}^2-1)\delta Z_H)(1+C_{1,i}+\delta Z_H)} \times \left[ 1 + \frac{(k_{\lambda}-1)(C_{1}^{\Gamma ZZ}-C_{1}^{\Gamma tot})}{1+(k_{\lambda}-1)C_{1}^{\Gamma tot}} \right]$

$\delta Z_H = -1.536 \times 10^{-3}$ universal quantity

$C_{1}(p_n)$ dependent on H production model and kinematics

$C_{1}^{\Gamma ZZ} = 0.0082$

$C_{1}^{\Gamma tot} = 2.5 \times 10^{-3}$
**INTERPRETATION**

\[
\sigma_{ggH} = \left| \sum_i A_i k_i \right|^2 = A k_b^2 + B k_c^2 + C k_t^2 + D k_b k_c + E k_b k_t + F k_c k_t
\]

set \( k_t = 1 \)

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6 \\
\end{bmatrix} = \begin{bmatrix}
\kappa_{b,1}^2 & \kappa_{c,1}^2 & \kappa_{t,1}^2 & \kappa_{b,1} \kappa_{c,1} & \kappa_{b,1} \kappa_{t,1} & \kappa_{c,1} \kappa_{t,1} \\
\kappa_{b,2}^2 & \kappa_{c,2}^2 & \kappa_{t,2}^2 & \kappa_{b,2} \kappa_{c,2} & \kappa_{b,2} \kappa_{t,2} & \kappa_{c,2} \kappa_{t,2} \\
\kappa_{b,3}^2 & \kappa_{c,3}^2 & \kappa_{t,3}^2 & \kappa_{b,3} \kappa_{c,3} & \kappa_{b,3} \kappa_{t,3} & \kappa_{c,3} \kappa_{t,3} \\
\kappa_{b,4}^2 & \kappa_{c,4}^2 & \kappa_{t,4}^2 & \kappa_{b,4} \kappa_{c,4} & \kappa_{b,4} \kappa_{t,4} & \kappa_{c,4} \kappa_{t,4} \\
\kappa_{b,5}^2 & \kappa_{c,5}^2 & \kappa_{t,5}^2 & \kappa_{b,5} \kappa_{c,5} & \kappa_{b,5} \kappa_{t,5} & \kappa_{c,5} \kappa_{t,5} \\
\kappa_{b,6}^2 & \kappa_{c,6}^2 & \kappa_{t,6}^2 & \kappa_{b,6} \kappa_{c,6} & \kappa_{b,6} \kappa_{t,6} & \kappa_{c,6} \kappa_{t,6}
\end{bmatrix} \begin{bmatrix}
A \\
B \\
C \\
D \\
E \\
F
\end{bmatrix}
\]