8 years ago…

- ATLAS and CMS both first observed the Higgs boson.
- Theorized in summer of 1964
- Francois Englert and Peter Higgs were awarded the 2013 Nobel Prize in physics for this prediction.
Full LHC Run 2

- With LHC’s exceptional performance from 2015-2018 each experiment has ~140/fb of proton-proton collision data at 13 TeV, from which to harvest Higgs bosons!
  - LHC operated at twice design (!) luminosity in 2018!
  - Very impressive! Thank you LHC!

Overview

- Review of the new SM Higgs boson measurements shown at ICHEP 2020
  - Start at the largest coupling
  - End with the first evidence of second generation coupling ($H \to \mu\mu$ in CMS)
- A few words on HH and self-coupling
- Sample of new BSM searches
ATLAS, CMS and the theory community have been working together in the LHC Higgs Working Group to setup a common framework for Higgs boson measurements in Run 2.

- Reduce theory uncertainty and model dependence on measured bins
- Each Higgs boson production mode is split into numerous templates by kinematic features that are highly correlated with reconstruction-level objects.

<table>
<thead>
<tr>
<th>ggH</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathbf{87%})</td>
<td>(\mathbf{7%})</td>
<td>(\mathbf{4%})</td>
<td>(\mathbf{1%})</td>
</tr>
<tr>
<td>(p_T(H))</td>
<td>(N_{\text{jets}})</td>
<td>(p_T(V))</td>
<td>(p_T(H))</td>
</tr>
<tr>
<td>(N_{\text{jets}})</td>
<td>(M_{jj}, p_T(H+jj)) (if (N_{\text{jets}}&gt;1))</td>
<td>(N_{\text{jets}})</td>
<td>(p_T(H))</td>
</tr>
<tr>
<td>(M_{jj}, p_T(H+jj)) (if (N_{\text{jets}}&gt;1, \text{VBF-like}))</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The di-photon signal is very well reconstructed and triggerable because of the precision of the CMS and ATLAS electromagnetic calorimeters.

- Pre-select events with two isolated photon candidates

- Since this Higgs decay signature directly anchors the trigger and reconstruction, both experiments can probe all four of the production channels (and single top+Higgs production too!).

- Identify isolated electrons and muons as well as jets with minimally sufficient $p_T$.

**Classify**

**Optimize categories per class**

**Fit the data per category**
Assuming SM coupling and excluding theory uncertainties both experiments achieve about 8\% uncertainty on the signal strength of $H \rightarrow \gamma\gamma$ production.

**ATLAS**

\[ (\sigma \times B_{\gamma\gamma})_{\text{obs}} = 127 \pm 10 \text{ fb} = 127 \pm 7 \text{ (stat.)} \pm 7 \text{ (syst.) fb} \]

**CMS**

\[ \mu = 1.03^{+0.11}_{-0.09} = 1.03^{+0.07}_{-0.05} \text{ (theo)}^{+0.04}_{-0.03} \text{ (syst)}^{+0.07}_{-0.06} \text{ (stat)} \]
ATLAS H→γγ STXS Results

- With such large datasets and signal yields, we are measuring the Higgs boson’s kinematics differentially.
- From 44 target bins, 27 merged bins are measured.
- CMS has similar results.
- Compatibility with SM p-value 60%.

For more information, please see parallel talks:
- ICHEP talk for ATLAS by L. Mijovic
- ICHEP talk for CMS by H. Mei
**ttH MultiLepton, CMS**

- Higgs decays of $H \rightarrow WW$, $H \rightarrow ZZ$ and $H \rightarrow \tau\tau$ with 2-4 leptons (e, $\mu$, $\tau$, $\text{Hadron}$) are targeted.
  - In both $ttH$ and $tH$ production
  - Number of jets and b-jets are used for further categorization.
  - BDTs and ANNs are used to separate signal from background in these categories.

---

**ICHEP talk by S. Sanchez Cruz**

**HIG-19-008**
**Key backgrounds are freely-floated in the full fit.**

- All are quite in agreement with simulation expectations.

**Results for ttH are also very much in agreement with the SM expectations.**
This analysis is anchored in an electron-muon pair arriving from the leptonic decays of 2Ws.

VBF topology is ensured by requiring that there are at least two jets and that the di-jet mass is greater than 120 GeV.

Controls regions employed/fit to constrain normalization
- Z+jets
- Top quark
- A DNN is utilized to isolate VBF signal process
- This is a major improvement to the analysis

\[ \mu_{VBF} = 1.04^{+0.24}_{-0.20} \]

\[ +0.13 \text{ (stat.)} +0.09 \text{ (exp syst.)} +0.17 \text{ (sig. theo.)} +0.08 \text{ (bkg. theo.)} \]

\[ -0.12 \text{ (stat.)} -0.08 \text{ (exp syst.)} -0.12 \text{ (sig. theo.)} -0.07 \text{ (bkg. theo.)} \]

**Observed (exp) significance**

**7.0σ (6.2σ)**

ICHEP talk by L. Mijovic. ATLAS-CONF-2020-045
New results from CMS take advantage of:
- Full Higgs decay information in ZZ4l (angular distributions)
- Full Run 2 dataset

Results interpreted as both:
- Anomalous amplitude couplings
- Effective Field Theory

Anomalous couplings to gluons
- Compatible with SM

ICHEP talk by S. Kyriacou
H1G-19-009
**V(leptonic) H \rightarrow bb, ATLAS**

- Trigger and categorize on the leptonic decay products of W/Z
- Isolate signal regions requiring two b-jets and train BDTs in all signal regions.
- Fit together with numerous control regions targeting background processes.

<table>
<thead>
<tr>
<th></th>
<th>Obs</th>
<th>Exp</th>
</tr>
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<tbody>
<tr>
<td>WH</td>
<td>4.0σ</td>
<td>4.1σ</td>
</tr>
<tr>
<td>ZH</td>
<td>5.3σ</td>
<td>5.1σ</td>
</tr>
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</table>

**Total signal strength**

\[ \text{Tot.} (\text{Stat., Syst.}) = 1.02^{+0.18}_{-0.17} = (+0.12, +0.14, -0.11, -0.13) \]

![Graph showing signal strengths](image-url)
The $H\gamma$ final state is forbidden in $ggH$ and so it provides an opportunity to measure other production modes without contamination given enough data.

This analysis requires a high $p_T$ photon at the level1 trigger and then 4 jets ($E_T > 35$ GeV) at the high level trigger.

- At least two of these jets must have large (>700 GeV) invariant di-jet mass.
- Final selection also include lepton vetoes and two b-jets.
- A BDT is used to categorize events, while background is estimated in a fit to the data.
- Uncertainty dominated by statistics (~0.8), bkg norm (~0.5) and spurious signal (~0.25).

**NEW!**

\[
\mu_H = 1.3 \pm 1.0
\]

Obs (exp) 1.3σ (1.0σ)
Multiple decay channels are considered in this cut-based analysis.

- $\mu \eta, \eta \tau, \tau \eta, \eta \eta$ in ggH and VBF

**DeepTau ID** provided better efficiency and lower fake rates in the updated analysis.

**NEW!**

Tau embedding in $Z \rightarrow \mu \mu$ data events critical to $Z \rightarrow \tau \tau$ estimates

Replace real $\mu$ with simulated $\tau$
The CMS Preliminary results for the H → ττ - CP Violation Search show a significant exclusion of CP-odd H → ττ at more than 3 sigma C.L. The analysis uses the expression:

\[ \tan \phi_{TT} = \frac{\tilde{\kappa}_T}{\kappa_T} = \frac{CP\ odd}{CP\ even\ (SM)} \]

The observed value of \( \phi_{TT} \) is (4 ± 17 (stat) ± 2(bin-by-bin) ± 1(syst) ± 1(theory))°.

The ICHEP poster by M. Hassanshahi highlights this result with a new exclusion for CP-violating H → ττ decays.
**H\rightarrow\mu\mu, CMS and ATLAS**

- Select events with two well-isolated opposite-signed muons.
- Classify events on the topology of the production modes.
  - ggH, VBF, VH and ttH are targeted by both collaborations.
  - VBF, VH, and ttH topologies are new features in both analyses.

**Isolate signal with binary BDT or DNN output**

**Extract signal strength and background shape in fit to data**

This is the analysis strategy for all ATLAS categories and for CMS in ggH, VH, and ttH.

- VBF in CMS has separate treatment.
Unlike all other analysis regions, the uncertainty on the prediction of background from simulation is better than the estimate from directly fitting the data.

- Sensitivity increases by ~20%
- Uncertainties on Drell-Yan (amc@NLO) and electroweak Z+di-jet (MadGraph+herwig) simulation

- Normalization motivated by theory
  - Substantiated by CMS SM precision measurements
  - EPJC 78, (Jul. 2018), 589
- Shape differences from:
  - Different parton showering simulations
At $m_H = 125.09$ GeV, ATLAS reports an observed (expected) excess with a significance of $2.0\sigma$ ($1.7\sigma$).

$\mu = 1.2 \pm 0.6$

**NEW!**

ICHEP talk by H. Borecka-Bielska

ATLAS-HIGG-2019-14

CMS observes (expects) $3.0\sigma$ ($2.5\sigma$) at 125.38 GeV

Including the Run 1 analysis in the combination increased significance 1% on expected and observed.

$$\mu = 1.19^{+0.41}_{-0.39} \text{(stat)} + 0.17 \text{(sys)}$$

First evidence of $H \rightarrow \mu\mu$ process!
**Updated Combination, ATLAS**

- 29 merged STXS bins
- Floating SM coupling fits (kappa-framework)
- Limits on BSM
- First observation of WH!
- Constraints of two-Higgs-doublet models in the \((\cos(\beta - \alpha), \tan \beta)\) plane for the

<table>
<thead>
<tr>
<th></th>
<th>ZZ  (\rightarrow 4l)</th>
<th>(\gamma\gamma)</th>
<th>bb</th>
<th>(\mu\mu)</th>
<th>(\tau\tau)</th>
<th>WW</th>
<th>multi-llep</th>
<th>inv</th>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
</tr>
<tr>
<td>WH</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>ZH</td>
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<td>(tH)</td>
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<td>✓</td>
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**ICHEP talk by M. Klein, ATLAS-CONF-2020-027**

\[ \mu = 1.06 \pm 0.07 \]

Overall signal strength

1.06 ± 0.04 (stat.) ± 0.03 (exp.) \(^{+0.05}_{-0.04} \) (sig. th.) ± 0.02 (bkg. th.)

**ATLAS Preliminary**

\(\sqrt{s} = 13\text{ TeV}, 24.5 \times 139\text{ fb}^{-1}\)

\(m_H = 125.09\text{ GeV}, |y_H| < 2.5\)

\(p_{SM} = 86\%\)

<table>
<thead>
<tr>
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<th>Syst.</th>
<th>SM</th>
</tr>
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<tbody>
<tr>
<td>ggF</td>
<td>1.00</td>
<td>± 0.07</td>
<td>± 0.05</td>
<td>± 0.05</td>
</tr>
<tr>
<td>VBF</td>
<td>1.15</td>
<td>(± 0.18)</td>
<td>(± 0.17)</td>
<td>(± 0.12)</td>
</tr>
<tr>
<td>WH</td>
<td>1.20</td>
<td>(± 0.23)</td>
<td>(± 0.17)</td>
<td>(± 0.15)</td>
</tr>
<tr>
<td>ZH</td>
<td>0.98</td>
<td>(± 0.22)</td>
<td>(± 0.16)</td>
<td>(± 0.15)</td>
</tr>
<tr>
<td>(tH+tH)</td>
<td>1.10</td>
<td>(± 0.21)</td>
<td>(± 0.16)</td>
<td>(± 0.15)</td>
</tr>
</tbody>
</table>

Cross-section normalized to SM value
Very compatible with SM

VBF+MET alone constrains $\text{BR}(H \rightarrow \text{inv}) < 0.13$ at 95% CL
Self-coupling with HH+H (best $\kappa_\lambda$)

- The future of the LHC Higgs program is probing the Higgs potential.
- That future is now!
- Right now we constrain $\kappa_\lambda=\lambda/\lambda_{SM}$ with:
  - Double Higgs searches
  - Single Higgs searches

### Analysis

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<td>$HH \rightarrow b\bar{b}b\bar{b}$</td>
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<td>$HH \rightarrow b\bar{b}\tau^+\tau^-$</td>
<td>36.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>30.1</td>
</tr>
</tbody>
</table>

### Models

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_\lambda +\sigma$</th>
<th>$\kappa_\lambda -\sigma$</th>
<th>$\kappa_\lambda$ [95% CL]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\lambda$-only</td>
<td>$4.6^{+3.2}_{-3.8}$</td>
<td>$1.0^{+7.3}_{-3.8}$</td>
<td>[-2.3, 10.3] [95% CL]</td>
</tr>
<tr>
<td>Generic</td>
<td>$5.5^{+3.5}_{-5.2}$</td>
<td>$1.0^{+7.6}_{-4.5}$</td>
<td>[-3.7, 11.5] [95% CL]</td>
</tr>
</tbody>
</table>

- $\kappa_\lambda = \kappa_2 = \kappa_3 = \kappa_4 = 1$
Based strongly on CMS $H \rightarrow ZZ \rightarrow 4l$ analysis

- Add two jets compatible with $b$-jets
- Cut tightly on 4l mass

$HH \rightarrow bbZZ \rightarrow bb4l$ in CMS

- Obs at 95% CL: $-9 < k_\lambda < 14$
- Exp at 95% CL: $-10.5 < k_\lambda < 15.5$

First results with this channel in the non-resonant HH search at LHC!
BSM Higgs

- New full Run 2 ATLAS searches
  - \( ZZ \rightarrow 4l + llv \), high mass (ATLAS-CONF-2020-032)
  - \( \gamma \gamma \), high mass (ATLAS-CONF-2020-037)
  - \( H^+ \rightarrow tb \) (ATLAS-CONF-2020-039)

\[ \sigma \times BR < 3.6 \text{ pb at 95\% CL (} m_{H^+} = 200 \text{ GeV)}\]
\[ \sigma \times BR < 35 \text{ fb at 95\% CL (} m_{H^+} = 2 \text{ TeV)}\]

Largest deviation: 3.29\( \sigma \) (local) \[ 1.3\sigma \] (global) at \( m_x = 684 \text{ GeV} \)
Upper limits for the narrow-width assumption: 12.5 fb (162 GeV) to 0.03 fb (3 TeV)
The excellent performance of the LHC has delivered an enormous dataset, from which we are elucidating precise features of the Higgs boson.

The lower mass particles with proportionally smaller couplings are coming into view.

First evidence of H→μμ!

CMS 3σ observed, ATLAS 2σ observed, μ=1.2 for both

The global signal strength has reached a statistical precision of 4% challenging the theory error on the prediction.

Both experiments are exploring more detailed kinematic regions sensitive to BSM effects through STXS.

Ahead we look forward to understanding the Higgs potential itself.

Hoping for the unexpecting, I look forward to the future.
Thank you!
Be safe.
Questions?
Bibliography

- Full Run 2 results
  - CMS, HIG-19-015, Hgg, STXS
  - ATLAS, HIGG-2018-25, Hgg, STXS
  - CMS, HIG-19-001, HZZ4l, STXS
  - ATLAS, HZZ4l, STXS
  - ATLAS, Hµµ
  - CMS, Hµµ
  - CMS, HIG-19-010, Hττ, STXS
  - CMS, HIG-20-006, Hττ, CP
  - CMS, tH multi-lepton
  - ATLAS, VBF+γ H→bb
- STXS
  - https://arxiv.org/abs/1906.02754 (Stage 1.1)
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGfiducialAndSTXS#Recommended_binning_Stage_1_2 (Stage 1.2)
- Higgs observation
- HH, κλ
  - ATLAS, H+HH
Higgs Boson Mass Measurements

- Given the excellent resolution in the 4l and γγ channels CMS and ATLAS have both made very precise measurements of the mass.
- The Higgs mass completes the SM predictions for coupling strengths and cross sections for single Higgs boson production.

ICHEP talk by A. Laudrain
Standard Higgs Boson Mass Choices

- Given the excellent resolution in the 4l and $\gamma\gamma$ channels CMS and ATLAS have both made very precise measurements of the mass.
- The Higgs mass completes the SM predictions for coupling strengths and cross sections for single Higgs boson production.

ICHEP talk by A. Laudrain
Run 2 $H \rightarrow ZZ^* \rightarrow 4l$ Mass, ATLAS

- Updated result is fully compatible with previous ATLAS results and combinations.
- Many target bins: 43 total bins (44 for ATLAS with tHW, tHqb)
- Some STXS signal regions are inaccessible (e.g. low yield) or too similar from some other bins.
  - These bins are left unmeasured or merged with adjacent or similar bins.
  - Merging schemes are uniquely constructed per analysis.

10 bins (4 rest bins) | 15 bins | 5 bins (+1 tH bin)
Both collaborations train BDTs in STXS events classes.

Further division into categories based on the score (see dashed lines below).
For all categories the invariant mass distributions are then fit to extract signal and background estimates simultaneously.

Below are the fit results with fitted signal modifiers for each production mode (ATLAS VH → WH+ZH).

All channels in both experiments have visible excess above fitted background.
**H→γγ Overall Results**

- Assuming SM coupling and excluding theory uncertainties both experiments achieve about 8% uncertainty on the signal strength of H→γγ production.

**ATLAS**

\[(\sigma \times B_{γγ})_{\text{obs}} = 127 \pm 10 \text{ fb} = 127 \pm 7 \text{ (stat.)} \pm 7 \text{ (syst.) fb}\]

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\[\mu = 1.03^{+0.11}_{-0.09} = 1.03^{+0.07 \text{ (theo)}}_{-0.03 \text{ (syst)}}^{+0.04 \text{ (syst)}}_{-0.06 \text{ (stat)}}\]
Of the 43 target bins, 17 bins are measured.

STXS bins are merged until their expected uncertainty is less than 150% of the SM prediction.

Good agreement with the SM.

- **ggH**
  - Merge all 2 jet bins with $m_{jj}>350$ GeV
  - Merge all bins with $p_T(H) > 200$ GeV

- **VBF**
  - Reduced to three bins in total
  - Only 1 bin per process for WH, ZH, tth, and tH
  - "Rest bins" of VBF fixed to SM

- Minimal splitting scheme shown in backup
Of the 43 target bins, 24 bins are measured.

Selected by ensuring correlations among parameters is less than 0.75.

Good agreement with the SM.

VBF and ggH main di-jet topology bins are measured together.

More merging the VlePH sector

WH \( p_T \) (V) split at 75 GeV

“Rest bins” of VBF fixed to SM

Maximal splitting scheme already shown
New results from CMS take advantage of:

- Full Higgs decay information in ZZ4l (angular distributions)
- Full Run 2 dataset
- Results interpreted as both Anomalous amplitude couplings
- Effective Field Theory
- Two dimension projection of EFT fit of coupling involving Z

\[ \delta c_z, c_{zz}, c_{z\square}, \text{ and } \tilde{c}_{zz} \]
- Largest difference in \[ \delta c_z \]
- Compatible with SM

ICHEP talk by S. Kyriacou

HICP-19-009
Self-coupling with HH+H (best $\kappa_\lambda$)

- The future of the LHC Higgs program is probing the Higgs potential.
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<td>obs.</td>
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| | $1.0^{+7.6}_{-4.5}$ | $[-6.2, 11.6]$ | exp.

[ICHEP talk by M. Swiatkowski] [ATLAS-CONF-2019-049]
Based strongly on CMS $H \rightarrow ZZ \rightarrow 4l$ analysis
- Add two jets compatible with $b$-jets
- Cut tightly on $m_{4l}$ mass

**HH$\rightarrow bbZZ \rightarrow bb4l$ in CMS**
- Observed at 95% CL: $-9 < k_\lambda < 14$
- Expected at 95% CL: $-10.5 < k_\lambda < 15.5$

First results in any non-resonant HH search in this channel at LHC!
VBF

Samples for $\tilde{Z}jj$-EW

- MadGraph+Herwig simulation (nominal)
- Madgraph+Pythia with dipole recoil ON as alternative/syst

In data-driven method statistical uncertainty is 60%

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total uncertainty</td>
<td>+0.44 -0.42</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>+0.41 -0.39</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+0.17 -0.16</td>
</tr>
<tr>
<td>Size of simulated samples</td>
<td>+0.07 -0.06</td>
</tr>
<tr>
<td>Total experimental uncertainty</td>
<td>+0.12 -0.10</td>
</tr>
<tr>
<td>Total theoretical uncertainty</td>
<td>+0.10 -0.11</td>
</tr>
</tbody>
</table>
$H \rightarrow \mu\mu$, CMS, VBF SRs per Year

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

CMS Preliminary
VBF-SR 2016
$m_H = 125.38$ GeV

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

CMS Preliminary
VBF-SR 2017
$m_H = 125.38$ GeV

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

CMS Preliminary
VBF-SR 2018
$m_H = 125.38$ GeV
H\rightarrow\mu\mu, CMS Categories

**CMS Preliminary**

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

- ggH-cat1: 267.6 expected events
- ggH-cat2: 311.5 expected events
- ggH-cat3: 131.4 expected events
- ggH-cat4: 125.8 expected events
- ggH-cat5: 53.8 expected events
- VBF DNN-bin-1-5: 11.8 expected events
- VBF DNN-bin-6-9: 4.5 expected events
- VBF DNN-bin-10-11: 4.0 expected events
- VBF DNN-bin-12-13: 6.6 expected events
- ttHhad-cat1: 7.6 expected events
- ttHhad-cat2: 1.3 expected events
- ttHhad-cat3: 1.1 expected events
- ttHlep-cat1: 1.0 expected events
- ttHlep-cat2: 0.8 expected events
- WH-cat1: 1.7 expected events
- WH-cat2: 1.1 expected events
- WH-cat3: 0.1 expected events
- ZH-cat1: 0.3 expected events
- ZH-cat2: 0.0 expected events

**Signal composition (%)**

**S/(S+B) (%)**

**S/\sqrt{B}**
The hypotheically allowed Yukawa couplings are:

\[ \mathcal{L}_Y = -\frac{m_\tau}{v} \kappa_\tau \bar{\tau} \tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau \]

Where the first term is CP-even (SM) and the second is CP-odd.

The aim of this type of search is to measure the ratio of the coupling strengths where:

- 0° is CP-even
- 90° is CP-odd

Only $\tau h \tau$ and $\mu \tau h$ channels are considered.

The system is boosted to the zero momentum frame (ZMF) of the charged decay products.

The angle, $\phi_{CP}$, is measured as shown. This angle is sensitive to $\Phi_{\tau\tau}$.

DNN for signal isolation; $\Phi_{CP}$, shape is in each bin

\[ \tan \phi_{\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau} \]
# ttH Multilepton Systematics, Fit Results

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \mu_{tH}/\mu_{tH}$ [%]</th>
<th>$\Delta \mu_{lH}/\mu_{lH}$ [%]</th>
<th>$\Delta \mu_{lW}/\mu_{lW}$ [%]</th>
<th>$\Delta \mu_{HZ}/\mu_{HZ}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiency</td>
<td>2.3</td>
<td>8.1</td>
<td>1.2</td>
<td>1.9</td>
</tr>
<tr>
<td>$e, \mu$ reconstruction and identification efficiency</td>
<td>2.9</td>
<td>7.1</td>
<td>1.7</td>
<td>3.2</td>
</tr>
<tr>
<td>$\tau_h$ identification efficiency</td>
<td>4.6</td>
<td>9.1</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>$b$ tagging efficiency and mistag rate</td>
<td>3.6</td>
<td>13.6</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Misidentified leptons and flips</td>
<td>6.0</td>
<td>36.8</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>3.4</td>
<td>8.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>MC and sideband statistical uncertainty</td>
<td>7.1</td>
<td>27.2</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Theory-related sources</td>
<td>4.6</td>
<td>18.2</td>
<td>2.0</td>
<td>4.2</td>
</tr>
<tr>
<td>Normalization of MC-estimation processes</td>
<td>13.3</td>
<td>12.3</td>
<td>13.9</td>
<td>11.3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.2</td>
<td>4.6</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>20.9</td>
<td>48.0</td>
<td>5.9</td>
<td>5.8</td>
</tr>
</tbody>
</table>
ttH Multilepton Systematics, Fit Results

CMS Preliminary 137 fb⁻¹ (13 TeV)

pp → tH + tH
H → WW/ZZ/ττ

Observed

- 68% CL region
- 95% CL region

• Best fit
• SM expected

CMS Preliminary 137 fb⁻¹ (13 TeV)

pp → tH + tH
H → WW/ZZ/ττ

Observed

- 68% CL region
- 95% CL region

• Best fit
• SM expected
General Analysis Strategy

- **Resolved-jet topology**
  - Higgs decay products resolved in two AK4 (R=0.4) jets (di-jet)
  - Probe larger fraction of the available signal cross-section (95% of events have $p_T(V)<200$ GeV)
  - DeepCSV tagger (CvsL, CvsB)

- **Merged-jet topology**
  - A single AK15 (R=1.5) jet to reconstruct the $H\rightarrow cc$ decay
  - Allows to better exploit the correlations between the two charms
  - DeepAK15 tagger

### Final results: combination of the two topologies to maximize the sensitivity

<table>
<thead>
<tr>
<th>Channel</th>
<th>Resolved-jet</th>
<th>Merged-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\nu\nu)H(cc)$: 0L</td>
<td>$p_T(Z) &gt; 170$ GeV</td>
<td>$p_T(V) &gt; 200$ GeV</td>
</tr>
<tr>
<td>$W(\ell\nu)H(cc)$: 1L</td>
<td>$p_T(W) &gt; 100$ GeV</td>
<td>$p_T(V) &gt; 200$ GeV</td>
</tr>
<tr>
<td>$Z(\ell\ell)H(cc)$: 2L</td>
<td>$p_T(Z) &gt; 50$ GeV</td>
<td>$p_T(V) &gt; 200$ GeV</td>
</tr>
</tbody>
</table>
**VH(H→cc) Combination**

- **Combination:**
  - Resolved-jet: \( p_T(V) < 300 \) GeV
  - Merged-jet: \( p_T(V) > 300 \) GeV
  - Systematics: correlated, but: \( c/cc\)-tagging efficiency & PDF, \( \mu_R, \mu_F \) for \( V+jets \)

- **Validation with \( VZ(Z→cc) \)**
  - \( \mu_{VZ(Z→cc)} = 0.55^{+0.86}_{-0.84} \)
  - 0.7\( \sigma \) obs. (1.3\( \sigma \) exp.)

- **95% C.L. Exclusion Limits**

<table>
<thead>
<tr>
<th>Combination</th>
<th>Resolved-jet ( p_T(V) &lt; 300 ) GeV</th>
<th>Boosted-jet ( p_T(V) &gt; 300 ) GeV</th>
<th>Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.</td>
<td>45(^{+18}_{-13})</td>
<td>73(^{+34}_{-22})</td>
<td>0L</td>
</tr>
<tr>
<td>Obs.</td>
<td>86</td>
<td>75</td>
<td>1L</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2L</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All. Ch.</td>
</tr>
<tr>
<td>Obs.</td>
<td>86</td>
<td>75</td>
<td>83</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>110</td>
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<td>93</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>

- **L. Mastrolorenzo – Higgs Coupling 2019**

- **CMS (13 TeV)**
  - 35.9 fb\(^{-1}\)
  - Observed vs. Median expected
  - Combination
  - \( \mu_{VH(H→cc)} = 0.7\sigma \)
Two Higgs doublet models

125 GeV Higgs boson is (so far) consistent with SM predictions

However an extended Higgs sector is strongly motivated
(Hierarchy problem, baryon asymmetry, dark matter/energy...)

Many BSM theories require 2 Higgs doublets $\phi_1$ and $\phi_2$ (2HDMs)

2 important free parameters: $\alpha$ and $\tan \beta$
(mixing angle of h and H, and ratio of the VEVs of $\phi_1$ and $\phi_2$)
$$\mathcal{L}_{\text{hvv}} = \frac{h}{v} \left[ (1 + \delta c_w) \frac{g^2 v^2}{2} W^+_{\mu} W^-_{\mu} + (1 + \delta c_z) \frac{(g^2 + g'^2) v^2}{4} Z_{\mu} Z_{\mu} \right. $$

$$+ c_{ww} \frac{g^2}{2} W^+_{\mu \nu} W^-_{\mu \nu} + \tilde{c}_{ww} \frac{g^2}{2} W^+_{\mu \nu} \tilde{W}^-_{\mu \nu} + c_{w \Box} g^2 \left( W^-_{\mu} \partial_{\nu} W^+_{\mu \nu} + \text{h.c.} \right) $$

$$+ c_{gg} \frac{g_s^2}{4} G^a_{\mu \nu} G^a_{\mu \nu} + c_{g g} \frac{e^2}{4} A_{\mu \nu} A_{\mu \nu} + c_{z \gamma} \frac{e \sqrt{g^2 + g'^2}}{2} Z_{\mu \nu} A_{\mu \nu} + c_{zz} \frac{g^2 + g'^2}{4} Z_{\mu \nu} Z_{\mu \nu} $$

$$+ c_{z \Box} g^2 Z_{\mu} \partial_{\nu} Z_{\mu \nu} + c_{g \Box} g g' Z_{\mu} \partial_{\nu} A_{\mu \nu} $$

$$+ \tilde{c}_{gg} \frac{g_s^2}{4} G^a_{\mu \nu} \tilde{G}^a_{\mu \nu} + \tilde{c}_{g g} \frac{e^2}{4} A_{\mu \nu} \tilde{A}_{\mu \nu} + \tilde{c}_{z \gamma} \frac{e \sqrt{g^2 + g'^2}}{2} Z_{\mu \nu} \tilde{A}_{\mu \nu} + \tilde{c}_{zz} \frac{g^2 + g'^2}{4} Z_{\mu \nu} \tilde{Z}_{\mu \nu} $$
