Higgs boson at CMS

Christophe Ochando (LLR/CNRS/Ecole Polytechnique) on behalf of the CMS Collaboration

September 17th 2018
LHC Days 2018, Split
Standard Model Lagrangian: 2 main parts:

- **Gauge:** based on symmetries, elegant
- **Higgs mechanism:** Ad-hoc… but necessary to describe reality (gives mass to elementary particles, allows unitarity, …)

\[ \mathcal{L} = - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \slashed{D} \psi + D_\mu \Phi^\dagger D^{\mu} \Phi - V(\Phi) + \bar{\psi}_L Y \Phi \psi_R + h.c. \]

Completely defines the production and decay modes of the Higgs boson.
Reminder: Higgs production & decay at colliders

**Main production Modes**

(for mH=125 GeV, LHCXSWG 4)

- **Glusion fusion (ggH)**
  - 48.58 pb

- **Vector Boson Fusion (VBF)**
  - 3.78 pb

**Main decay Modes**

- **Associated production with Vector Boson (VH)**
  - 1.373 pb (WH)
  - 0.8839 pb (ZH)

- **Associated production with quarks (ttH, bbH)**
  - 0.5071 pb (ttH)
  - 0.488 pb (bbH)

![Diagram of Higgs production and decay](image-url)
At that time, one of the claim was:
- ~20 fb-1 @ 14 TeV needed for discovery in H->ZZ->4l
- We actually did it with less than 20 fb-1… at 8 TeV (production cross section divided by ~2)
  • Thanks to big improvements in theoretical calculations and experimental techniques

Where are we now?
Higgs coupling to gauge bosons

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} D\Phi \psi + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) + \bar{\Psi}_L \gamma \Phi \Psi_R + h.c. \]

Coupling to Gauge bosons.

Main decay modes used for discovery in 2012
Moving to (precise) measurements…

H→γγ, H→ZZ→4l, H→WW→2l2ν: short summary

- **H→γγ**: 2 high pT photons,
  - signal as high resolution peak on top of falling background. Low S/B.
- **H→ZZ→4 leptons (e or μ)**: 4 isolated primary leptons (down to 5 GeV!),
  - signal as a high resolution peak over ~small background. But small statistics.
- **H→WW→2l2ν**: 2 opposite sign leptons + Missing ET from neutrinos.
  - Large yield but no full reconstruction of Higgs boson mass

- With increasing luminosity, move from inclusive analysis (for discovery) to categories targeting rare production modes (+ increase S/B):
  - Asking for additional leptons, (b-)jets, MET, kinematics, …
  - … with simple cuts, BDT’s or Matrix Element techniques

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**CMS Simulation**

- **Untagged 0**: 32.5 expected events
- **Untagged 1**: 492.3 expected events
- **Untagged 2**: 678.3 expected events
- **Untagged 3**: 624.3 expected events
- **VBF 0**: 9.3 expected events
- **VBF 1**: 8.0 expected events
- **VBF 2**: 25.2 expected events
- **ttH Hadronic**: 5.5 expected events
- **ttH Leptonic**: 3.8 expected events
- **ZH Leptonic**: 0.5 expected events
- **ZH Hadronic**: 2.7 expected events
- **WH Leptonic**: 0.9 expected events
- **VH Leptonic/Loose**: 4.9 expected events
- **VH MET**: 4.9 expected events

**35.9 fb⁻¹ (13 TeV)**
H→γγ, H→ZZ→4l, H→WW→2l2v: Spectrum

We’ve come a long way since the discovery...

~8 Higgs events

From early Run I to Run II

~80 Higgs events

2016+2017 (77.4 fb⁻¹)

2016 (~36 fb⁻¹)


Submitted to Phys. Lett. B
Simplified Template Cross-section

- Measurement of the fiducial cross-section in the “stage-0” simplified template cross-section framework, for various signal processes (ggH, VBF, VH, ttH) [aim at minimizing dependence to theory]
  - Signal processes defined requiring $|y_H|<2.5$ at generator level
  - SM prediction for signal cross sections taken from LHC Higgs XS WG (YR4)

<table>
<thead>
<tr>
<th>Process</th>
<th>$rac{\sigma}{\sigma_{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$1.18^{+0.12}<em>{-0.11} (\text{stat})^{+0.09}</em>{-0.07} (\text{syst})^{+0.07}_{-0.06} (\text{theo})$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$1.06^{+0.10}<em>{-0.10} (\text{stat})^{+0.08}</em>{-0.06} (\text{syst})^{+0.07}_{-0.05} (\text{theo})$</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$1.28^{+0.10}<em>{-0.10} (\text{stat})^{+0.11}</em>{-0.11} (\text{syst})^{+0.10}_{-0.07} (\text{theo})$</td>
</tr>
</tbody>
</table>

Now dominated by systematic (exp+theo) uncertainties
Increasing luminosity of Run II now allows precision measurement on differential cross-section.
- Combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ measurements (also boosted $H \rightarrow bb$ for high $p_T$)

$p_T(H)$
Sensitive to perturbative QCD modelling, production mode, yukawa couplings, etc.

$N(\text{jets})$
Test of modelling QCD radiation, production mechanism

$Y(H)$
Probes of PDFs, production mode, etc.

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

$\Delta \sigma(p_T^H) / \Delta p_T^H$ (pb/GeV)

Ratio to prediction

$\Delta \sigma(N(\text{jets}))$ (pb)

Ratio to prediction

$\Delta \sigma(|y_H|)$ (pb)

Ratio to prediction

30-40% precision up to 350 GeV

20% precision in 0-jet bin

30-50% precision across the spectrum

Measurement largely dominated by statistics! Great improvements to come
Differential cross-sections (2/2)

- Higgs pT spectrum very sensitive to modifications of the couplings
  - Can give information on couplings not possible via inclusive measurements

- Couplings to b, c & top quarks in k-framework

Results are dependant on the assumptions about Branching Ratios
(here, assume BR scaling with couplings)
Higgs boson mass measurement

ATLAS + CMS Run I (~25 fb-1 each, 7+8 TeV)

\[ m_H = 125.09 \pm 0.24 \text{ GeV} \]

\[ = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV} \]

(1.9 per-mille precision)

CMS Run II (~36 fb-1 each, 13 TeV)

\[ m_H = 125.26 \pm 0.21 \text{ GeV} \]

\[ = 125.26 \pm 0.20 \text{ (stat)} \pm 0.08 \text{ (syst)} \text{ GeV} \]

Most precise LHC measurement of \( m_H \) (1.7 per-mille!)
Higgs boson width (4.1 MeV @ 125 GeV) not directly measurable due to limitations from detector resolution (~1 GeV)
- Can be probed by analysing on-shell & off-shell distributions:

On-shell: \[ \frac{g_{\text{prod}} g_{\text{dec}}^2}{m_H^2 r_H^2} \, dq_H^2 \propto \mu_{\text{prod}} \]

Off-shell: \[ \frac{g_{\text{prod}} g_{\text{dec}}^2}{(q_H^2 - m_H^2)^2} \, dq_H^2 \propto \mu_{\text{prod}} \cdot 1_H \]

Anomalous couplings enhance off-shell yield, change m_{4l} & other kinematics
Run I + Run II combination

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_H$ (MeV)</td>
<td>$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]</td>
<td>$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]</td>
</tr>
</tbody>
</table>

Best LHC result
Higgs coupling to fermions

\[ \mathcal{L} = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{\Psi} D \Psi + D_\mu \Phi \dagger D^\mu \Phi - V(\Phi) + \bar{\Psi}_L Y \Phi \Psi_R + h.c. \]

- Can be probed:
  - Indirectly (through loop diagrams)
  - Directly (tree-level diagrams)

- Observation of coupling to taus announced on May 2017
  - first single experiment observation of coupling to leptons
    - Combining Run I + Run II
    - Run II now reaches >5 sigmas alone as well (ggH+VBF+ new VH)

- What about quarks?

phys. lett. b 779 (2018) 283
**ttH overview**

**ttH:** directly probe top Yukawa coupling at tree level through associated production

**RunII ttH analysis in CMS:**
Final states combine Higgs & Top decay

**Top Pair Branching Fractions**
- "alljets" 46%
- τ+jets 15%
- μ+jets 15%
- "dileptons"
- "lepton+jets"

**H→bb** 58.1%

- H→WW 21.5%
- H→ZZ... other 11.3%
- H→γγ 0.2%
- H→ττ...

*High purity, low yield*

*Low purity, high yield*
H → γγ

H → WW, ZZ, ττ
"multi-leptons"

H → bb

Significance: 3.2 σ (2.8 σ)

μ = \frac{σ}{σ_{SM}} = 2.2^{+0.9}_{-0.8}

Significance: 1.6 σ (2.2 σ)

μ = \frac{σ}{σ_{SM}} = 0.72^{+0.45}_{-0.45}
Observation of $ttH$

- Grand combination of all $ttH$ analyses (multileptons, $bb$, $\gamma\gamma$) from Run I + Run II (2016)
  - Inclusive signal theory and some background theory uncertainties are treated as correlated
  - Experimental uncertainties largely uncorrelated

**Measured signal strength**

$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.26^{+0.31}_{-0.26}$$

**Significance:** 5.2 $\sigma$ observed

(4.2 $\sigma$ expected)

**Observation $ttH$ by the CMS Collaboration**

First single experiment observation (paper submitted April 8th)

**Table:**

- ttH(WW*)
- ttH(ZZ*)
- ttH($\gamma\gamma$)
- ttH($\tau\tau$)
- ttH($bb$)
- 7+8 TeV
- 13 TeV
- Combined

**Graph:**

- Observed
- $\pm$1 $\sigma$ (stat $\oplus$ syst)
- $\pm$2 $\sigma$ (syst)
- Combined

- 5.1 fb$^{-1}$ (7 TeV) + 19.7 fb$^{-1}$ (8 TeV) + 35.9 fb$^{-1}$ (13 TeV)
- CMS

- 5.2 $\sigma$ observed

VH→bb (2017 data)

- Highest BR (58%) but low S/B
- 3 channels with 0, 1 and 2 leptons
  - Target: Z(→νν)H, W (→lν)H and Z(→ll)H

- Require large boost for vector boson to increase S/B
- Large usage of MVA for b-tagging, b-jet energy regression or final discriminant (Deep Neural Network with b-jet properties, di-jet kinematics, event topology)
- Control of backgrounds (V+bb, ttbar, VZ, …) is critical!

2017 (41.3 fb⁻¹)

![CMS Simulation Supplementary](chart.png)
Observation of $H \rightarrow bb$

- Grand combination of all Run I + Run II CMS $H \rightarrow bb$ measurements: VH, boosted $ggH$, VBF and $ttH$
  - Most sources of systematic uncertainty are treated as uncorrelated
  - Theory uncertainties are correlated between all processes and data sets

$\leq 5.1 \text{ fb}^{-1} (7 \text{ TeV}) + \leq 19.8 \text{ fb}^{-1} (8 \text{ TeV}) + \leq 77.2 \text{ fb}^{-1} (13 \text{ TeV})$

\begin{itemize}
  \item ggF
  \item VBF
  \item $ttH$
  \item $WH$
  \item $ZH$
  \item Combined
\end{itemize}

\begin{itemize}
  \item $\frac{\sigma}{\sigma_{SM}} = 1.04 \pm 0.20$
  \item Significance: $5.6 \sigma$ observed ($5.5 \sigma$ expected)
\end{itemize}

Measurement of the $H \rightarrow bb$ decay by the CMS collaboration

More details in Luca Mastrolorenzo’s talk
Combination

- Grand combination of 11 analyses from 2016 (~36 fb⁻¹)
  - 265 event categories, 5500+ nuisance parameters, ...

Most generic parameterization: one signal strength per prodxdecay mode

\[ \mu_i^f = \frac{\sigma_i \cdot B_i^f}{(\sigma_i)^{SM} \cdot (B_i^f)^{SM}} = \mu_i \times \mu_f \]

Assuming SM predictions for Branching Ratios

Reduction in uncertainties wrt Run I:
- ~33% on ggH
- ~50% on ttH

Dominated by systematic uncertainties!

\[ \mu = 1.17^{+0.10}_{-0.10} \]
\[ = 1.17^{+0.06}_{-0.06} \text{ (stat.)}^{+0.06}_{-0.05} \text{ (sig. th.)}^{+0.06}_{-0.06} \text{ (other sys.)} \]

See talk by Karsten Koeneke
Couplings to bosons:
Observed in July 2012

Couplings to (τ) leptons:
Observed in May 2017

(direct) Coupling to top:
Observed in April 2018

Run II (≥ 2015) gave a clear boost to the exploration of the scalar sector
Couplings to gauge bosons (resp. 3rd generations fermions) known to ~10 (resp. ~20) %
What are the next milestones?
**Next target: Coupling to 2\textsuperscript{nd} generation**

\[ \text{H} \rightarrow \mu\mu: \] first channel accessible at LHC to probe 2\textsuperscript{nd} generation couplings

- **Clean signature**: high resolution peak from 2 high pT isolated muons
- But SM backgrounds (Drell-Yann, top, VV) very large. \( S/B \approx 0.01 \)
- Use kinematics & muon resolution information into BDT
  - + additional jet activity, b-jets and MET to distinguish between production modes

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**Observed (Expected) 95% CL limit on \( B(\text{H} \rightarrow \mu\mu) \):** 2.92 (2.16) \( \times \) SM

Can we claim 3\( \sigma \) Evidence for Run III?
Next target: Higgs self-coupling

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \slashed{D} \Psi + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) + \bar{\Psi}_L \hat{Y} \Phi \Psi_R + h.c. \]

\[ V(\Phi) = -\mu |\Phi|^2 + \lambda |\Phi|^4 \]

- Can probe the Higgs potential via di-Higgs production
  - Quadri-linear coupling not accessible at LHC…

\[ \sigma(gg \rightarrow HH) = (33.4 \pm 5.9) \text{ fb} \]

1/500 vs single H production…

(due to destructive interference)

Can be enhanced by BSM contributions (non-SM top coupling, …)
Constraints on HH

\[ \sigma_{HH} < 22 \times \text{SM} \ (13 \text{ expected}) \]

Approaching the x10 SM sensitivity…

Constraint on tri-linear coupling:

\[-11.8 < k_{\lambda} < 18.8 \]
\[-7.1 < k_{\lambda} < 13.6 \text{ exp.} \]
@ 95 CL

See talk by Dinko Ferencek
We have come a long way since the starting of the LHC 10 years ago…

- The Higgs boson has been found, with a mass of ~125 GeV (1.7 per mille precision!)
  - Its total width has been constrained to a few MeV (NEW)
  - All production modes have been observed.
  - The coupling to gauge boson is now entering a precision era.
  - The Run II results proves the existence of a new type of interaction, Yukawa couplings to up and down fermions (for the 3rd generation)
  - Couplings to 2nd generation is within reach
  - Sensitivity to Di-Higgs is approaching 10 times the SM predictions

- But the scalar sector is not just an “era of precision”. It remains the best portal we have to new physics:
  - Search for Dark Matter via “invisible” decay
  - Searches for extended scalar sector
  - Searches for rare or forbidden decay (H→Zγ, H→τν, …)
  - Link with Cosmology ?
  - Etc…

We must not underestimate our ignorance about the Higgs sector
We must not undersell the value of exploring and establishing it

G. Salam, LHCP 2018 “Theory vision” talk
Luminosity vs Results

Run 1
\( \sqrt{s} = 7-8 \text{ TeV} \)

Long Shutdown 1

Run 2
\( \sqrt{s} = 13 \text{ TeV} \)

>150 fb\(^{-1}\) delivered by LHC
~36-77 fb\(^{-1}\) analysed

H → ZZ → 4l CMS-PAS-HIG-18-001, HIG-18-002
VH → bb arXiv:1808.08242

H → γγ arxiv:1804.02716
H → WW arxiv:1806.05246
2016 Differential Xsec CMS-PAS-HIG-17-028

H → μμ arXiv:1807.06325
2016-HH Combo CMS-PAS-HIG-17-030
2016 H-combo CMS-PAS-HIG-17-031
BACK UP SLIDES
- Higgs boson discovery with bosonic decays,
  - now also observation with taus
- $m_H = 125.09$ with 0.2% precision (dominated by statistics!)
- 0+ state favoured over other $J^{PC}$ hypothesis
- narrow width ($\Gamma_H < \sim 20$ MeV @ 95% CL)
- Couplings to third-generation fermions and W/Z known with 10-30% precision.
- Slight excess in $ttH$ (3\,$\sigma$)... slight deficit in $b\bar{b}$ decay (-2.5\,$\sigma$)...
CMS analysis: HVV couplings

\[ A(HVV) \sim \left[ a_1 - e^{i\phi_{\Lambda Q}} \frac{q_H^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}} \frac{(\kappa_1 q_{\tilde{V}1}^2 + \kappa_2 q_{\tilde{V}2}^2)}{\Lambda_1^2} \right] m_{\tilde{V}}^2 \varepsilon_{\tilde{V}1}^* \varepsilon_{\tilde{V}2}^* + a_2 f_{\mu\nu}^{(1)} f_{\mu\nu}^{(2)} + a_3 f_{\mu\nu}^{(1)} f_{\mu\nu}^{(2)} \]

\[ = a_2 f_{\mu\nu}^{(1)} f_{\mu\nu}^{(2)}, \mu\nu + a_3 f_{\mu\nu}^{(1)} f_{\mu\nu}^{(2)}, \mu\nu \]

→ Any anomalous coupling can be described with an effective on-shell cross sectional fraction and a phase defined for $2f2f'$ decay:

\[ f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \]
\[ \phi_{ai} = \tan^{-1}(a_i / a_1) \]

→ $f_{\Lambda Q}$ observable only from off-shell. Others can be measured from either on-shell or off-shell.

→ Formalisms used by ATLAS are equivalent with different ways of parameterizing AC couplings.
### CMS results: $f_{ai} \cos(\phi_{ai})$

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<tr>
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<th>Observed</th>
<th>Expected</th>
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<tr>
<td>$f_{a3} \cos(\phi_{a3})$</td>
<td>$-0.0001^{+0.0005}_{-0.0015}$ $[-0.16, 0.09]$</td>
<td>$0.0000^{+0.0019}_{-0.0019}$ $[-0.082, 0.082]$</td>
</tr>
<tr>
<td>$f_{a2} \cos(\phi_{a2})$</td>
<td>$0.0004^{+0.0026}_{-0.0007}$ $[-0.006, 0.025]$</td>
<td>$0.0000^{+0.0030}_{-0.0023}$ $[-0.021, 0.035]$</td>
</tr>
<tr>
<td>$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$</td>
<td>$0.0000^{+0.0035}_{-0.0008}$ $[-0.21, 0.09]$</td>
<td>$0.0000^{+0.0012}_{-0.0006}$ $[-0.059, 0.032]$</td>
</tr>
<tr>
<td>$f_{\Lambda 1}^{Z\gamma} \cos(\phi_{\Lambda 1}^{Z\gamma})$</td>
<td>$0.0000^{+0.355}_{-0.009}$ $[-0.17, 0.61]$</td>
<td>$0.0000^{+0.009}_{-0.010}$ $[-0.10, 0.34]$</td>
</tr>
</tbody>
</table>

**On-shell results**

**On-shell + off-shell combination**

<table>
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<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{a3} \cos(\phi_{a3})$</td>
<td>$0.0000^{+0.0005}_{-0.0011}$ $[-0.0067, 0.0050]$</td>
<td>$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$</td>
</tr>
<tr>
<td>$f_{a2} \cos(\phi_{a2})$</td>
<td>$0.0005^{+0.0025}_{-0.0008}$ $[-0.0029, 0.0129]$</td>
<td>$0.0000^{+0.0011}_{-0.0017}$ $[-0.0100, 0.0117]$</td>
</tr>
<tr>
<td>$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$</td>
<td>$0.0001^{+0.0020}_{-0.0010}$ $[-0.0150, 0.0501]$</td>
<td>$0.0000^{+0.0010}_{-0.0010}$ $[-0.0152, 0.0158]$</td>
</tr>
</tbody>
</table>

### Different HVV couplings

<table>
<thead>
<tr>
<th>Parameter (MeV)</th>
<th>Unconstrained Parameter</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_H$</td>
<td>$f_{a3} \cos(\phi_{a3})$</td>
<td>$2.4^{+2.7}_{-1.8}$ $[0.02, 8.38]$</td>
<td>$4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>$f_{a2} \cos(\phi_{a2})$</td>
<td>$2.5^{+2.9}_{-1.8}$ $[0.02, 8.76]$</td>
<td>$4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$</td>
<td>$2.4^{+2.5}_{-1.6}$ $[0.06, 7.84]$</td>
<td>$4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$</td>
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</table>
Measurements

Cross-sections

- Signal strengths
- Inclusive
  - Used for discovery
  - Now limited by systematics
- Per process
  - Mostly stat-limited
  - Also use Simplified Template Cross-Section (STXS) framework

- Couplings
  - Usually $\kappa$ framework
- Differential
  - Shape information; strongly stat-limited

Mass

- Only $\gamma\gamma$ and $ZZ$ contribute
- Requires excellent understanding of systematic uncertainties
Simplified Template Cross-section (STXS) framework aims to minimise measurements’ dependence on theory.
Fiducial cross-section
- Optimized for maximal theoretical independence
- Fiducial in Higgs decay
- Smallest acceptance corrections
- Simple signal cuts
- "Exact" fiducial volume
- Targeted object definitions
- Agnostic to production mode
Can be done with single and differential distributions
Only feasible in HZZ, H\(\gamma\gamma\), HWW
Combination not straightforward

Simplified templates cross section
- Target maximum sensitivity, while keeping theoretical dependence as small as possible
- Cross section split by production mode
- Cross section divided in exclusive regions of phase space (bins)
- Larger acceptance corrections
- Abstracted fiducial volumes
- Inclusive in Higgs decay
- Allows complex event selections, categorisation
Common abstracted object definitions
Can be done in all decay modes
Explicitly designed for combination
Signal Extraction via Matrix Element Methods (MEM):
- Event-by-event discriminator built upon Matrix Elements. Combined with reco level info.

\[
w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4 \left( p_1^\mu + p_2^\mu - \sum_{k \geq 2} p_k^\mu \right) \cdot \frac{f(x_1, \mu_F) f(x_2, \mu_F)}{x_1 x_2 s} \cdot \left| M_\alpha(p_k^\mu) \right|^2 \cdot W(\Phi' | \Phi_\alpha)
\]

- **MEM weights** used in ttH→multileptons (see later) as input to BDT.

- **Matrix Element Likelihood Analysis** (H→ZZ→4l):
  - Simplified MEM. No integration, no transfer function
  - ME from JHUGen or MCFM
  - Several discriminants (see later) built to separate:
    - gg vs qq→4 leptons
    - ggH vs VBF or VH or ttH
    - Different J^{PC} hypothesis, …

\[
D_{bkg}^{kin} = \left[ 1 + \frac{P_{bkg}^{q\bar{q}}(\Omega^{H\rightarrow4\ell} | m_{4\ell})}{P_{sig}^{q\bar{q}}(\Omega^{H\rightarrow4\ell} | m_{4\ell})} \right]^{-1}
\]
Two types of per-process signal strength measurement
- traditional signal strengths: theory uncertainty included in the measurement
- Stage 0 STXS: factorise theory uncertainty on overall yield
- Significance of ttH observed to be 3.3σ (1.5σ expected)
Hgg: impact of systematics

- Inclusive signal strength on point of becoming systematics-limited
- Important contributions from both theoretical and experimental uncertainties
ZZ candidates classified into 7 categories:
- Hunt for H(125) production modes
- New ttH categories
- Selection based on number of jets, b-tags, extra leptons and cuts on the 3 matrix-element based production discriminants (D_{2jet}, D_{1jet} and D_{VH})
Good data/MC agreement over the whole $m_{4l}$ range in all 3 final states (4e, 4µ, 2e2µ)
\[ \mu = 1.06 \pm 0.10 \text{(stat)}^{+0.08}_{-0.06} \text{(exp. syst)}^{+0.07}_{-0.05} \text{(th. syst)} \]

\[ \mu_{VBF,VH} = 0.60^{+0.62}_{-0.49} \]

\[ \mu_{ggH,ttH,bbH, t\bar{t}H} = 1.12^{+0.16}_{-0.18} \]
- Define simplified fiducial regions for maximally model-independent results
- New $H\rightarrow\gamma\gamma$ fiducial and differential result recently submitted to JHEP
Signal Strength

Signal strengths

Parameters scale cross sections and BRs relative to SM

\[ \mu_i = \frac{\sigma_i}{\sigma_{i,SM}} \quad \mu^f = \frac{BR^f}{BR_{SM}^f} \]

Scaling of generic \( i \rightarrow H \rightarrow f \) process

\[ \mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR_{SM}^f)} = \mu_i \times \mu_i^f \]

Most immediate quantity: ratio of observed “rate” with respect to the expected results

Production: ratio of cross-sections

Decay: ratio of branching fractions

Many systematic uncertainties and theory assumptions cancel out in the ratio

• Easy to interpret
• Deviation from SM immediately visible
• Can decouple production and decay mechanisms
• Only effects modifying the absolute normalisation are visible, no sensitivity to shapes

No immediate relation with the width, each signal strength is independent from each other, but possible reinterpretation in the k-framework
Single Top + Higgs

\[
\sigma_{tH} \propto \left( \frac{\kappa_t}{y_t} \right) \left( \frac{g_{\text{HVV}}}{g_{\text{HVV}}^{\text{SM}}} \right)
\]

- Very small production cross section in SM (t-channel = \sim 71 \text{ fb})
- But enhanced by factor \sim 10 if sign(\kappa_t/\kappa_v) opposite to SM \Rightarrow \sigma_{tH} > \sigma_{ttH}
- So can be used with present Run-2 dataset to constraint relative sign of \kappa_t and \kappa_v.

[B. Stieger, ICHEP2018 talk]
Single Top + Higgs

- **NEW CMS Run-2 combination** of:
  - $tH, H \to$ Multi-leptons ($WW/ZZ/TT$)
  - $tH, H \to bb$
  - $ttH, H \to \gamma\gamma$ (use $ttH$ categories)

- Data favors $\text{sign}(\kappa_t/\kappa_\gamma) = 1$ at 1.5$\sigma$ level ($\sim 4\sigma$ expected)
- Complementary to constraints from $H \to \gamma\gamma$ and $gg \to ZH$ production
- Assuming SM $ttH$ yield and SM $tH$ acceptance, can constrain $\sigma(tH)$:

  $\mu_{tH} < 26.5 \ (13.6 \ exp.)$