Higgs boson physics at the LHC

Selected results from ATLAS and CMS
On July 4\textsuperscript{th}, 2012

The ATLAS and CMS experiments announced the observation of a new, narrow resonance with a mass around \( \sim 125 \text{ GeV} \).

The discovery was driven by identifying its decay into pairs of vector bosons: the \( \gamma\gamma \), \( Z(*)Z \) and \( W(*)W \) decay channels.

With additional data collected afterwards, the observation has been further confirmed in several independent channels.

Combining ATLAS+CMS results, its coupling to fermions is now established at \( >5\sigma \) level.

\textbf{Studying the properties of this particle aims at establishing whether this new particle is the Standard Model Higgs boson responsible for the Electroweak gauge symmetry breaking, or whether new physics beyond the SM is at play.}

\textbf{A selected sample of results from ATLAS and CMS is presented here.}

Impressive amount of information: ATLAS+CMS have produced more than 100 published papers each!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHiggs
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
Introduction/Outline

- Reaching for the 125 GeV Higgs boson at the LHC
  - machine and detector performances
  - SM Higgs production and decay modes

- Selected topics on SM Higgs observables
  - mass, width
  - spin/CP characterisation
  - evidence for decay/coupling to fermions
  - signal strengths
  - search for rare Higgs decay modes

- Combined ATLAS+CMS studies of SM Higgs couplings
  - methodology
  - constraints on fermionic and bosonic couplings
  - global test of EWSB coupling patterns
  - constraints on BSM contributions

- A few topics on non-SM Higgs(es) searches

- A first look at the Higgs with 13 TeV data

- Prospects for Run 2 LHC running (and beyond)

- Conclusions
Identifying the SM Higgs boson at the LHC : production

In decreasing order :

• gluon fusion (ggH)
• vector-boson fusion (VBF)
• W associated prod. (WH)
• Z associated prod. (ZH)
• tt/bb associated production (ttH/bbH)
• (+other minor modes)

Diagrams borrowed from Denegri, Guyot, Höcker, Roos, “L’aventure du grand collisionneur LHC - Du big bang au boson de Higgs”, EDP Sciences 2014
Identifying the SM Higgs boson at the LHC: decay

\[ H \rightarrow b \bar{b} \]
dominant decay (~57\% BR)
huge backgrounds from QCD jets

\[ H \rightarrow W^+W^- \text{ and } H \rightarrow \tau^+\tau^- \]
subdominant (~22\%, ~6\% resp.)
incomplete reconstruction

\[ H \rightarrow Z(*)Z \]
penalty from \( BR(Z \rightarrow l^+l^-)^2 \)
very clean, fully reconstructed

\[ H \rightarrow \gamma\gamma : \]
• (interfering) W- and top- loops
• very small BR
• Huge bkgs. from QCD photons and jets
• fully reconstructed final state -> access to mass measurement
**Mass measurement with $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$**

### Combined ATLAS+CMS result
- using diphoton and four-lepton results
- consistent treatment of systematics
- impressive ±0.2% accuracy

### Impressive improvements wrt previous results
- final Run-1 calibrations on $e, \gamma, \mu$
- most detailed detector simulations

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**ATLAS and CMS**

**LHC Run 1**

- **ATLAS** $H \rightarrow \gamma\gamma$  
  $126.02 \pm 0.51$ (±0.43±0.27) GeV

- **CMS** $H \rightarrow \gamma\gamma$  
  $124.70 \pm 0.34$ (±0.31±0.15) GeV

- **ATLAS** $H \rightarrow ZZ \rightarrow 4l$  
  $124.51 \pm 0.52$ (±0.52±0.04) GeV

- **CMS** $H \rightarrow ZZ \rightarrow 4l$  
  $125.59 \pm 0.45$ (±0.42±0.17) GeV

- **ATLAS+CMS** $\gamma\gamma$  
  $125.07 \pm 0.29$ (±0.25±0.14) GeV

- **ATLAS+CMS** $4l$  
  $125.15 \pm 0.40$ (±0.37±0.15) GeV

- **ATLAS+CMS** $\gamma\gamma+4l$  
  $125.09 \pm 0.24$ (±0.21±0.11) GeV

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Testing the $0^+ \text{ Spin-CP }$ hypothesis

Effective amplitude formalism:
- SM, CP-even coupling
- BSM energy scale
- anomalous CP-even (odd) couplings

$H \rightarrow \gamma\gamma$: only $\cos\theta^*$ angle available

$H \rightarrow Z(\gamma^*)Z(\gamma^*) \rightarrow 4l$: complete 8D phase space available (3 masses 5 angles)

$H \rightarrow WW \rightarrow l\nu l\nu$: dilepton and transverse masses

ATLAS and CMS:
- all hypotheses other than $0^+$ strongly disfavored
Fiducial and differential cross-sections with $H \rightarrow WW$

Analyses assume SM production modes:

- mass-related variables as discriminant, extract *unfolded* signal distributions
- Higgs kinematics, jet multiplicities, jet kinematics ...
  - sensitive to Higgs production, CP, PDFs, parton radiation ...
- comparison to theoretical predictions
- previous published results on $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$
- most recent: $H \rightarrow WW$

\[\text{arXiv:1604.02997} \]

\[\text{arXiv:1606.01522} \]
Search for Higgs decays to fermions: \( H \to \tau\tau \)

Final state is not fully reconstructed: relatively poor sensitivity to Higgs boson mass

Tau lepton not stable: several (leptonic, hadronic) decay sub-channels combined

Exploit VBF topology to enhance signal sensitivity

Driving the evidence:

- ATLAS @125 GeV: 4.4\( \sigma \) observed (3.3\( \sigma \) expected)
- CMS @125 GeV: 3.4\( \sigma \) observed (3.7\( \sigma \) expected)
- Combined: 5.5\( \sigma \) observed (5.0\( \sigma \) expected)

arXiv:1606.02266
Search for Higgs decays to fermions: $H \rightarrow bb$

- Poor sensitivity to Higgs boson mass: limited by jet energy resolutions
- Overwhelming QCD backgrounds: tag signal using (W,Z)H associated production (other analyses using VBF or ttH tag also available)
- Combine many discriminant inputs into a single BDT...difficult analyses, with room for improvements...
  ...full potential will require larger datasets (Run-2 & beyond)

Driving the evidence:
- ATLAS @ 125 GeV: 1.7σ observed (2.7σ expected)
- CMS @ 125 GeV: 2.0σ observed (2.5σ expected)
- Combined: 2.6σ observed (3.7σ expected)

arXiv:1606.02266
Higgs coupling to fermions: search for $ttH$

Higgs $ttH$ production: direct measurement of the top-Higgs Yukawa coupling

Combine several Higgs and top final states with various advantages/challenges i.e. $H \rightarrow bb$ has large rate, poor S/B while $H \rightarrow \gamma\gamma$ has best S/B but poor rate

...challenging analyses ...

...their Run-2 potential will benefit from $x3.8$ increase in rate at 13 TeV

Driving the evidence:

- **ATLAS @125 GeV**: 2.7σ observed (1.6σ expected)
- **CMS @ 125 GeV**: 3.6σ observed (1.3σ expected)
- **Combined**: 4.4σ observed (2.0σ expected)
Signal strengths: final states and production modes

\[ n_{\text{Signal}}^k = \left( \sum_i \mu_i \sigma_{i,SM} \times A_{if}^k \times \varepsilon_{if}^k \right) \times \mu_f B_{f,SM} \times \mathcal{L}^k \]

\( \sigma/\sigma(\text{SM}) \) per production mode (assuming SM BR's) and \( BR/BR(\text{SM}) \) per decay mode (assuming SM \( \sigma \)'s)

- check compatibility of individual/combined strengths
  - to be compared both to SM value, null value and among channels
  - overall agreement with the SM
- Combined ATLAS+CMS:
  \[ \mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07} \text{ (stat)}^{+0.04}_{-0.04} \text{ (expt)}^{+0.03}_{-0.03} \text{ (thbgd)}^{+0.07}_{-0.06} \text{ (thsig)} \]
Scalar couplings: derivation framework

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \left\{ \begin{array}{c} \kappa_{g}^{2} \left( \kappa_{b}, \kappa_{t}, m_{H} \right) \\ \kappa_{g}^{2} \end{array} \right\}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF} \left( \kappa_{W}, \kappa_{Z}, m_{H} \right)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_{W}^{2}$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_{Z}^{2}$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_{t}^{2}$$

Detectable decay modes

$$\frac{\Gamma_{WW(\ast)}}{\Gamma_{WW}^{SM(\ast)}} = \kappa_{W}^{2}$$

$$\frac{\Gamma_{ZZ(\ast)}}{\Gamma_{ZZ}^{SM(\ast)}} = \kappa_{Z}^{2}$$

$$\frac{\Gamma_{bb}}{\Gamma_{bb}^{SM}} = \kappa_{b}^{2}$$

$$\frac{\Gamma_{\tau^{\pm}\tau^{\pm}}}{\Gamma_{\tau^{\pm}\tau^{\pm}}^{SM}} = \kappa_{\tau}^{2}$$

$$\frac{\Gamma_{YY}}{\Gamma_{YY}^{SM}} = \left\{ \begin{array}{c} \kappa_{b}^{2} \left( \kappa_{b}, \kappa_{t}, \kappa_{\tau}, \kappa_{W}, m_{H} \right) \\ \kappa_{y}^{2} \end{array} \right\}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \left\{ \begin{array}{c} \kappa_{b}^{2} \left( \kappa_{b}, \kappa_{t}, \kappa_{\tau}, \kappa_{W}, m_{H} \right) \\ \kappa_{y}^{2} \left( \kappa_{y} \right) \end{array} \right\}$$

Total width

$$\frac{\Gamma_{H}}{\Gamma_{H}^{SM}} = \left\{ \begin{array}{c} \kappa_{H}^{2} \left( \kappa_{H}, m_{H} \right) \\ \kappa_{H}^{2} \end{array} \right\}$$

Currently undetectable decay modes

$$\frac{\Gamma_{tt}}{\Gamma_{tt}^{SM}} = \kappa_{t}^{2}$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{cc}}{\Gamma_{cc}^{SM}} = \kappa_{c}^{2}$$

$$\frac{\Gamma_{ss}}{\Gamma_{ss}^{SM}} = \kappa_{s}^{2}$$

$$\frac{\Gamma_{\mu^{\pm}\mu^{\pm}}}{\Gamma_{\mu^{\pm}\mu^{\pm}}^{SM}} = \kappa_{\mu}^{2}$$

Modified couplings: parameterized in terms of scale factors $\kappa$

- single-resonance assumption
- narrow width assumption
- no change of tensor structure in fields and couplings

Example: diphoton from gluon fusion

$$(\sigma \cdot BR) (gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_{g}^{2} \cdot \kappa_{y}^{2}}{\kappa_{H}^{2}}$$
Scalar couplings: derivation framework

- One modifier per production mode
- One modifier per decay channel
- One modifier for the Higgs width

Not enough inputs to constrain the complete modifier space:
- Perform specific benchmark tests on subsamples of modifiers, e.g.
  - by equating all bosonic (fermionic) modifiers
  - by profiling out modifiers for channels with no sensitivity
  - by fixing some modifiers to their SM value ($\kappa=1$)
Fermionic vs. bosonic couplings

A two-parameter benchmark model, under the following assumptions:

One single modifier $\kappa_V$ for all vector boson couplings

One single modifier $\kappa_f$ for all fermions

Destructive W- and top- mediated interference in $H \rightarrow \gamma\gamma$ loops:
dominant sensitivity to the relative sign of fermionic/bosonic couplings
(tH and ggZH also contribute)

$\kappa^2_\gamma \approx 1.59 \cdot \kappa^2_W - 0.66 \cdot \kappa_W \kappa_t + 0.07 \cdot \kappa_t^2$

$\kappa^2_g \approx 1.06 \cdot \kappa_t^2 - 0.07 \cdot \kappa_t \kappa_b + 0.01 \cdot \kappa_b^2$

ATLAS+CMS: in agreement with SM expectation
**Testing for coupling ratios**

(most) model-independent test accessible within the kappa framework

- check for ratios of couplings: \( \lambda_{ij} = \kappa_i / \kappa_j \)
- allow deviations on vertex loop couplings or on the total Higgs width

**ATLAS+CMS**: overall agreement with SM expectation
Run-1 conclusion on SM Higgs

Couplings to SM particles fitted independently, assuming:

- no invisible decays
- no undetected decays
- no BSM in loops

Couplings-masses trend nicely follows the expected SM EWSB pattern

arXiv:1606.02266
Testing potential BSM contributions in loops

Benchmark model testing the following scenarios:

- Loop couplings to non-SM particles
- with/without invisible/undetectable decay channels

Run-1 results compatible with BR(BSM)=0
(dominant uncertainty is statistical)

arXiv:1606.02266
Sizable increases in production cross-sections:
in the x2.2 – x3.8 range for Higgs production
(up to much larger factors for some BSM processes)
(and backgrounds increase as well)

<table>
<thead>
<tr>
<th></th>
<th>√s=7 TeV</th>
<th>√s=8 TeV</th>
<th>√s=13 TeV</th>
<th>Ratio 13/8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>15.3 pb</td>
<td>19.4 pb</td>
<td>44.1 pb</td>
<td>2.27</td>
</tr>
<tr>
<td>VBF</td>
<td>1.25 pb</td>
<td>1.6 pb</td>
<td>3.8 pb</td>
<td>2.38</td>
</tr>
<tr>
<td>ttH</td>
<td>88.6 fb</td>
<td>133 fb</td>
<td>507 fb</td>
<td>3.81</td>
</tr>
<tr>
<td>tt</td>
<td>177 pb</td>
<td>253 pb</td>
<td>832 pb</td>
<td>3.29</td>
</tr>
</tbody>
</table>
First results at 13 TeV: $H(125) \rightarrow ZZ \rightarrow 4l$ (and higher-masses)

Results from 2015 data-taking: 2.8 to 3.2 fb$^{-1}$

Preliminary results on $H(125)$ production cross-section at 13 TeV

High-mass ZZ resonance search: no events above ~700 GeV (yet)
First results at 13 TeV: $H \rightarrow \gamma\gamma$

Results from 2015 data-taking: 2.7 to 3.2 fb$^{-1}$

Preliminary results on $H(125)$ production cross-section at 13 TeV

High-mass diphoton resonance searches: needs own, dedicated slides
(more details in A. De Roeck’s talk)
Results from 2015 data-taking: 2.7 to 3.2 $\text{fb}^{-1}$

Preliminary results on $H(125)$ production cross-section at 13 TeV
Limited by statistics, will improve quickly with 2016 data!
First results at 13 TeV: high-mass diphoton resonance searches

Two benchmark models

- **Spin-0 search**
  analysis strategy similar to SM diphoton

- **Spin-2 search**
  looser selection on photon kinematics

Both analyses find a local excess around 750 GeV

- global significances: both at 2.1σ (after LEE)
- best fit for a wider resonance (Γ/m in the 6%-8% range)
First results at 13 TeV: high-mass diphoton resonance searches

Spin-0 and spin-2 models
Uses 2015 data with magnet on/off
local excess around 750 GeV
best fit for a narrow resonance
Combining with 8 TeV data: global significance 1.6σ (after LEE)
Future prospects: looking ahead at Run2 and HL-LHC

Vast improvement over Run1 in sight!

Prospective studies in two steps:
- Run2+Run3: 300 fb⁻¹
- HL-LHC: 3000 fb⁻¹

With HL-LHC:
- Reach rare channels, i.e. expect >5σ for $H \rightarrow \mu\mu$
Future prospects: looking ahead at Run2 and HL-LHC

Vast improvement over Run1 in sight!

Prospective studies in two steps:
• Run2+Run3: 300 fb⁻¹
• HL-LHC: 3000 fb⁻¹

With HL-LHC:
• (few-)percent-level precision on most couplings
• Hint at Higgs self-couplings?

\(\Delta \lambda_{XY} = \Delta \left( \frac{\kappa_X}{\kappa_Y} \right)\)
Conclusions

- ATLAS and CMS have established the existence of a Higgs boson
  - Clear observation through its decay to pairs of bosons
  - Combining ATLAS+CMS: evidence for its decay to pairs of fermions at the >5σ level

- Many new results on properties with ever-improving precision
  - ATLAS+CMS: Higgs mass measured with a few permil accuracy
  - spin/CP: the SM 0+ hypothesis favoured by Run 1 data

- ATLAS+CMS coupling analysis:
  - no significant deviation from SM is observed on Run 1 data

- Large, ongoing program of searches for deviation(s) from SM or for extra states in the Higgs sector

- No evidence for BSM physics in Higgs analyses with Run 1 data

- Since 2015: first, promising, exciting Higgs and BSM results at 13 TeV!
  - data is being collected at steady pace
  - looking forward for exciting Run-2 results on Higgs and BSM!
La Habana, Jul 20 2016

Higgs boson physics at the LHC

José Ocariz – LPNHE et Univ. Paris Diderot

BACKUP (+partly outdated material)
LHC Run-1 proton-proton collision data recorded by ATLAS and CMS:

- 7 TeV in 2011
- 8 TeV in 2012

In total, >28 fb^-1 delivered to each experiment

Pileup: price for high luminosity
Large number of collisions per bunch crossing!
\( <\mu> = 21, \mu's \text{ up to } \sim 40 \text{ (2012)} \)

Average data-taking efficiency: both experiments above 90%
Run-II started: 13 TeV collisions!
From (7)8 TeV to 13 TeV: what does it mean?

- Globally speaking, production cross-sections increase
- The actual amounts depend on the processes ... and background rates increase as well
From (7)8 TeV to 13 TeV: what does it mean?

Cross section ratios: 14 (13) TeV / 8 TeV

- Minimum bias: 1.2
- ZZ: 2.1
- WH: 2.1
- t (s-channel): 2.2
- H (ggF): 2.6
- H (VBF): 2.6
- t (t-channel): 2.8
- tt: 3.9
- ttH: 4.7
- Stop pair (0.7 TeV): 11
- Stop pair (0.9 TeV): 16
- Gluino pair (1.5 TeV): 72
- Gluino pair (2.5 TeV):
- Z' SSM (3 TeV): 13
- Q* (4 Tev)
- QBH (6 TeV): 5700 (13 / 8: 2700)

And: pp \rightarrow H^{\pm}(500) + X: 14 TeV/8 TeV \sim 7

For the some BSM processes, rates can increase by significant amounts and can even reach amazing numbers!
Hypothesis-Testing based on Profile Likelihood Ratio test statistic $q(\mu) :$

$$q(\mu) = -2 \ln \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}$$

- $\mu$ : parameter(s) of interest
- $\theta$ : nuisance parameters

- Asymptotics: $q(\mu)$ is $\chi^2$ distributed ($n\text{DoF} = \text{dimensionality of POI's}$)

- Higgs couplings:
  - test (combinations of) scale factors (signal strengths) $\mu_i$ and $\mu_f$

$$n_{\text{Signal}}^k = \left( \sum \mu_i \sigma_i,SM \times A_{i,f}^k \times \varepsilon_{i,f}^k \right) \times \mu_f B_{f,SM} \times L^k$$

- Production strength
- Acceptance, Efficiency
- Decay strength
- Luminosity
Constraints on Higgs width from off-shell production

\( \Gamma_{SM} = 4.2 \text{ MeV} \): out of reach of exp. mass resolutions ...
\( \Gamma_H \) from ratio of on- vs. off- shell signal rates

\[ H \rightarrow ZZ \rightarrow 4l \] , \( H \rightarrow ZZ \rightarrow ll\nu\nu \) (ATLAS+CMS)
and \( H \rightarrow WW \rightarrow e\nu\mu\nu \) (ATLAS)

Continuum \( gg\rightarrow VV \) at LO: dependence on K-factors ratio

Assuming same couplings on- and off- shell:

**CMS**: \( \frac{\Gamma_H}{\Gamma_{SM}} < 5.7 \) @95% C.L. (8.5 exp.)

**ATLAS**: \( \Gamma_H < 22.7 \text{ MeV} \) @95% C.L. (33.0 MeV exp.)
Analyses assume SM production modes:

- use mass as discriminant variable, extract unfolded signal distributions
  - Higgs kinematics, jet multiplicities, jet kinematics ...
  - sensitive to Higgs production, CP, PDFs, parton radiation ...
- Compare with theoretical predictions

**Fiducial and differential cross-sections with $H \to ZZ$**

Analyses assume SM production modes:

- use mass as discriminant variable, extract unfolded signal distributions
- Higgs kinematics, jet multiplicities, jet kinematics ...
- sensitive to Higgs production, CP, PDFs, parton radiation ...
- Compare with theoretical predictions
Fiducial and differential cross-sections with $H \rightarrow \gamma\gamma$

Analyses assume SM production modes:

- use mass as discriminant variable, extract unfolded signal distributions
- Higgs kinematics, jet multiplicities, jet kinematics ...
- sensitive to Higgs production, CP, PDFs, parton radiation ...
- Compare with theoretical predictions

**Direct search for rare dilepton SM Higgs decays**

**SM prediction at** \( m_H = 125 \text{ GeV} : BR(H \rightarrow \mu\mu) = 0.02\% 

**Overwhelming background rates (mostly Drell-Yan)**

à la \( H \rightarrow \gamma\gamma \) strategy:
- exploit dimuon mass resolution to maximise sensitivity
- categorisation to exploit different S/B performances

95% C.L. limits on \( \sigma / \sigma_{SM} \):
- **ATLAS**: < 7.0 (7.2)
- **CMS**: < 7.4 (6.5)

Great physics potential to be unveiled at Run 2

With \( H \rightarrow ee \) limits (CMS) and \( H \rightarrow \tau\tau \) evidence:
Exclusion of “universal” leptonic couplings
Run-1 searches for low- and high-mass diphoton resonances

ATLAS
search range: \(65 < m(X \to \gamma\gamma) < 600 \text{ GeV}\)
narrow-width approximation
signal @125 GeV treated as background

CMS
search range: \(150 < m(X \to \gamma\gamma) < 850 \text{ GeV}\)
both narrow- and wide-width, up to \(0.1 \times m(X)\)
spin-0 and spin-2 acceptances tested

results presented as limits on \(\sigma \times BR(X \to \gamma\gamma)\)
Run-1 searches for high-mass diboson resonances

- CMS search: combined $WW\rightarrow l\nu l\nu$, $l\nu qq'$; $ZZ \rightarrow llll$, $l\nu l\nu$, $l\nu qq$

Assuming SM couplings and decays:
95\% C.L. exclusion in the $145 \text{ GeV} < m_H < 1 \text{ TeV}$ range
Also interpreted as bounds on EW singlet parameters

arXiv:1504.00936
Direct search for invisible decays of (a) Higgs

An invisible decay, yielding large missing transverse energy, tagged using mostly:

- **VBF**: two-jets with large pseudorapidity gap
- **VH**: with $Z \rightarrow ll$ or $Z \rightarrow bb$

![Graph showing CMS 95% CL limits for different Higgs decay modes](image_url)
ATLAS Simulation Preliminary

\( s = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1} ; \int L dt = 3000 \text{ fb}^{-1} \)

\( \Delta \lambda_{XY} = \Delta \left( \frac{K_X}{K_Y} \right) \)

Future prospects: looking ahead at Run2 and HL-LHC

- Same systematic uncertainties as today (Scenario 1, conservative)
- Experimental syst. scaled by \( 1/\sqrt{L} \), theory syst. halved (Scenario 2, ambitious)

CMS Projection

CMS-NOTE-2013-002
### Overview of the decay channels: per experiment

<table>
<thead>
<tr>
<th>Channel</th>
<th>References for individual publications</th>
<th>Signal strength $[\mu]$ from results in this paper (Section ??)</th>
<th>Signal significance $[\sigma]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>[91], [92]</td>
<td>ATLAS: $1.14^{+0.27}<em>{-0.25}$, CMS: $1.11^{+0.25}</em>{-0.23}$</td>
<td>ATLAS: 5.0, CMS: 5.6</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>[93], [94]</td>
<td>ATLAS: $1.52^{+0.40}<em>{-0.34}$, CMS: $1.04^{+0.32}</em>{-0.26}$</td>
<td>ATLAS: 7.6, CMS: 7.0</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>[95,96], [97]</td>
<td>ATLAS: $1.22^{+0.23}<em>{-0.21}$, CMS: $0.90^{+0.23}</em>{-0.21}$</td>
<td>ATLAS: 6.8, CMS: 4.8</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>[98], [99]</td>
<td>ATLAS: $1.41^{+0.40}<em>{-0.36}$, CMS: $0.88^{+0.30}</em>{-0.28}$</td>
<td>ATLAS: 4.4, CMS: 3.4</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>[100], [101]</td>
<td>ATLAS: $0.62^{+0.37}<em>{-0.37}$, CMS: $0.81^{+0.45}</em>{-0.43}$</td>
<td>ATLAS: 1.7, CMS: 2.0</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>[102], [103]</td>
<td>ATLAS: $-0.6^{+3.6}<em>{-3.6}$, CMS: $0.9^{+3.6}</em>{-3.5}$</td>
<td>ATLAS: 2.7, CMS: 3.6</td>
</tr>
<tr>
<td>$ttH$ production</td>
<td>[104,105,77], [107]</td>
<td>ATLAS: $1.9^{+0.8}<em>{-0.7}$, CMS: $2.9^{+1.0}</em>{-0.9}$</td>
<td>ATLAS: 2.7, CMS: 3.6</td>
</tr>
</tbody>
</table>
### Overview of the decay channels: combined

<table>
<thead>
<tr>
<th>Production process</th>
<th>Measured significance ($\sigma$)</th>
<th>Expected significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>5.4</td>
<td>4.6</td>
</tr>
<tr>
<td>$WH$</td>
<td>2.4</td>
<td>2.7</td>
</tr>
<tr>
<td>$ZH$</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>$VH$</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td>$ttH$</td>
<td>4.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Measured significance ($\sigma$)</th>
<th>Expected significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>5.5</td>
<td>5.0</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>2.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>