EXTENDING HIGGS MEASUREMENT CAPABILITIES

MARÍA CEPEDA (CIEMAT)
In other words: what can we learn about Higgs physics in Run3 and in the HL-LHC?
Main lines of research at current and future colliders

- **Detailed studies of the Higgs boson** (only possible at colliders) → a "guaranteed deliverable"
- **Searches for new physics**: directly through observation of new particles and indirectly through precise measurements revealing deviations from SM expectations

H is not just "another particle":
- Profoundly different from all elementary particles discovered previously
- It got almost no properties; carries a different type of "force"
- Related to the most obscure sector of SM
- Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)
  → It provides a unique door into new physics, and calls for a very broad and challenging experimental programme which will extend for decades

Every problem of the SM originates from Higgs interactions

\[ L = \lambda \psi \bar{\psi} + \mu H^2 - \lambda H^4 - V_0 \]

- Flavour
- Naturalness
- Stability

- Precision measurements of couplings (as many generations as possible, loops, ...)
- Forbidden and rare decays (e.g. \( H \rightarrow \tau \psi \)) → flavour structure and source of fermion masses
- \( H \) potential (\( HH \) production, self-couplings) → EWSB mechanism
- Exotic decays (e.g. \( H \rightarrow E_T^{\text{miss}} \)) → new physics?
- Other \( H \) properties (width, CP, ...)
- Searches for additional H bosons, etc.

Fabiola Giannotti @ LHCP 2021
Let’s recap…

- Main Higgs production & decay modes observed
- So far, excellent agreement with the Standard Model prediction, but more precision is needed: just the tip of the iceberg explored so far
- Similar performance in CMS and ATLAS: Single experiment partial Run2 results more precise already than Run1 ATLAS+CMS
- Existing results span from 36 fb\(^{-1}\) to the full Run2 data set → large phase space to explore and exploit
What to ask the boson?

- Is its production rate, where we measure it, at the correct SM level?
- How do we characterize it? (mass, width, spin)
- How well can we model its behaviour?
- Does it couple to SM particles at the appropriate level?
- Does it couple to itself?
- Does it decay unusually?
- Are there more Higgses?
- Higgs as a tool for discovery

Larger datasets → rarer / more complex production and decay modes become accessible
Precise differential measurements possible
HL-LHC ?
So long Run2…

• The 2nd run of the LHC marked the conclusion of an extremely successful data taking period.

• With the third run about to start, we are still working on finishing the analysis of the close to 150 fb$^{-1}$ of 13TeV pp collisions available for analysis.
What Next?

LHC / HL-LHC Plan

Here we are!
What Next?

• We have only exploited a small fraction of the data of the full LHC program (~5%)!

• Rich physics program: from studying in detail the SM (sp. the Higgs sector!) to extending our capabilities to search for new physics

• Unexplored phase spaces and signatures, and rare processes will become accessible

• Opportunities come with challenges: High Pileup!

HL-LHC (Nominal): 14 TeV, $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 3000 fb$^{-1}$, PU ~140

HL-LHC (Ultimate): 14 TeV, $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 4000 fb$^{-1}$, PU ~200

(Design Luminosity: $10^{34} \text{ cm}^{-2}\text{s}^{-1}$)
With High Lumi comes High Pileup

CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-14 09:56:16.733952 GMT
Run / Event / LS: 283171 / 142530805 / 254
Precision physics at the HL-LHC?

- High statistics does not come for free: extremely challenging conditions
  - High luminosity → 200 soft pp interactions per crossing
  - Detector elements and electronics are exposed to high radiation dose

- Extensive **upgrade** program by ATLAS and CMS underway, with the goal of at least maintaining the current performance despite the hard conditions
  - Effective pileup mitigation & extended capabilities with new algorithms
  - Increased detector acceptance
  - Increased spatial granularity to resolve signals from individual particles
  - Precise timing measurements to provide an additional dimension for discrimination
**CMS Phase-2 upgrades**

**L1-Trigger/HLT/DAQ [CMS-TDR-021 / 022]**
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

**Calorimeter Endcap [CMS-TDR-019]**
- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS

**Barrel Calorimeters [CMS-TDR-015]**
- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/γ at 30 GeV, for vertex localization (H → γγ)
- ECAL and HCAL new Back-End boards

**Muon systems [CMS-TDR-016]**
- DT & CSC new FE/BE readout
- RPC back-end electronics
- Extended GEM coverage to η ≈ 3
- New GEM/RPC 1.6 < η < 2.4

**Tracker [CMS-TD-014]**
- P_t module design for tracking in L1-Trigger
- Extended coverage to η ≈ 3.8
- Much reduced material budget
- Si-Strip and Pixels increased granularity

**MIP Timing Detector [CMS-TDR-020]**
- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes
### ATLAS Upgrades

<table>
<thead>
<tr>
<th>System</th>
<th>Phase-I</th>
<th>Phase-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon</td>
<td>New Small Wheels (NSW)</td>
<td>Muon chambers for inner barrel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous readout.</td>
</tr>
<tr>
<td>Tracking</td>
<td></td>
<td>All-silicon Inner Tracker (ITk) w.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(</td>
</tr>
<tr>
<td>Calorimeters</td>
<td>Level-1 (L1) trigger</td>
<td>LAr: Continuous readout</td>
</tr>
<tr>
<td></td>
<td>electronics Liquid Argon (LAr):</td>
<td>Tile Calorimeter (TileCal):</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous readout</td>
</tr>
<tr>
<td>Timing</td>
<td>Trigger hardware</td>
<td>High-Granularity Timing Detector (HGT)D</td>
</tr>
<tr>
<td></td>
<td>Higher purity e/γ triggers</td>
<td>L1 rate increased: 1 MHz</td>
</tr>
<tr>
<td></td>
<td>Lower forward muon fake rate</td>
<td>High Level Trigger increased: 10 kHz</td>
</tr>
</tbody>
</table>
Precision physics at the HL-LHC?

- Studies of detector performance with fully simulated Monte Carlo samples in HL-LHC conditions allow us to have an understanding of the expected future performance of the detectors.
- These studies, performed extensively in the ATLAS&CMS Technical Design Reports, are critical to support our updated physics prospects (both those based on projections of Run2 analysis and those directly using fast/parameterized simulations of the HL-LHC performance)
- With new detector significant improvements are expected. Aim to at least maintain current performance as observed in Run2 for all physics objects.
**Triggering in High Lumi Conditions**

- ATLAS and CMS undergoing a complete upgrade of the Trigger and DAQ systems for better coverage & performance, despite the high PU.

- Exploit state of the art techniques (sophisticated FPGA-based algorithms, increased granularity and acceptance, L1 tracking): maintain Run2 thresholds and explore new phase spaces
The HL-LHC and the Higgs

What do we need to know? Where will the HL-LHC impact?

• Precision Measurements

• Rare decays

• Di-Higgs production ➔ self coupling

• BSM Higgs searches
The HL-LHC/HE-LHC Workshop: 2018 Yellow Reports

SM & TOP - CERN-LPCC-2018-03

BSM - CERN-LPCC-2018-05

Higgs - CERN-LPCC-2018-04

Flavor - CERN-LPCC-2018-06

Heavy Ions - CERN-LPCC-2018-07
The 2018 prospects are still the latest in many (Higgs) cases, but physics does not stop and the full Run2 analyses (published or underway) already incorporate advances and new ideas that have not yet been projected to the end of the LHC.

Global effort ongoing for Snowmass to expand and update these studies!
The Particle Physics Community Planning Exercise (a.k.a. “Snowmass”) is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them. (Learn more about the history and spirit of Snowmass here "How to Snowmass" written by Chris Quigg). The P5, Particle Physics Project Prioritization Panel, will take the scientific input from Snowmass and develop a strategic plan for U.S. particle physics that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field.

• “Snowmass Day”, on September 24, 2021

• **EF01**: EW Physics: Higgs Boson properties and couplings

• **EF02**: EW Physics: Higgs Boson as a portal to new physics

Higgs Couplings @ HL-LHC
How well should we measure the **Higgs Couplings**?

Reminder from Sally’s intro:

**SMALL CORRECTIONS EXPECTED IN MANY BSM MODELS**

If new physics is at 1 TeV:

<table>
<thead>
<tr>
<th></th>
<th>$\delta k_V$</th>
<th>$\delta k_b$</th>
<th>$\delta k_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet</td>
<td>&lt;6%</td>
<td>&lt;6%</td>
<td>&lt;6%</td>
</tr>
<tr>
<td>2HDM (large $t_R$)</td>
<td>~1%</td>
<td>~10%</td>
<td>~1%</td>
</tr>
<tr>
<td>MSSM</td>
<td>~.001%</td>
<td>~1.6%</td>
<td>~-.4%</td>
</tr>
<tr>
<td>Composite</td>
<td>~-3%</td>
<td>~-(3-9)%</td>
<td>~-9%</td>
</tr>
<tr>
<td>Top Partner</td>
<td>~-2%</td>
<td>~-2%</td>
<td>~1%</td>
</tr>
</tbody>
</table>

Patterns of deviations can pinpoint specific BSM physics

- Generically new physics effects on couplings $\sim \frac{v^2}{M^2} \sim \mathcal{O}(6\%)$ for M=1 TeV
- Only now are we approaching sensitivity where we expect deviations

Can we get to the % level with the LHC?
How to study the HL-LHC reach?

1. Full simulation MC study based on up-to-date knowledge of the future detectors

2. Full analysis using a parameterised approach to model detector performance (eg: Delphes)

3. Extrapolation of the current published Run2 studies, taking into account what we know of the future performance

Each approach has pros and cons (MC statistics available, necessity to simplify the analysis methods, feasibility of doing a full fledged full study, implementation of realistic future performance, realism of the simplified detector performance...
Full MC study?

- Examples of “Full simulation MC study based on up-to-date knowledge of the future detectors” are found in the Detector TDRs!

- Focus on detector performance with full simulation updates that complement the physics reach shown in the studies presented here

- Usually not the full analysis: target the critical performance areas to understand sensitivity
What does it mean to do a projection?
How well will we understand the detectors and the experimental uncertainties in the future?

- Two complementary scenarios given for each of the updated projections:
  - S1 - Systematic uncertainties used in Run2 analysis (assumes no changes, good or bad)
  - S2 - Estimates of ultimate performance for experimental uncertainties (assumes improvements: improved detectors, huge calibration dataset to study performance in detail)

<table>
<thead>
<tr>
<th>Source</th>
<th>Component</th>
<th>Run 2 uncertainty</th>
<th>Projection minimum uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Photon ID</td>
<td></td>
<td>0.5–2%</td>
<td>0.25–1%</td>
</tr>
<tr>
<td>Hadronic tau ID</td>
<td></td>
<td>6%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Absolute</td>
<td>0.5%</td>
<td>0.1–0.2%</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>0.1–3%</td>
<td>0.1–0.5%</td>
</tr>
<tr>
<td></td>
<td>Pileup</td>
<td>0–2%</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>Method and sample</td>
<td>0.5–5%</td>
<td>No limit</td>
</tr>
<tr>
<td>Jet flavour</td>
<td></td>
<td>1.5%</td>
<td>0.75%</td>
</tr>
<tr>
<td>Time stability</td>
<td></td>
<td>0.2%</td>
<td>No limit</td>
</tr>
<tr>
<td>Jet energy res.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MET scale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-Tagging</td>
<td>b-/c-jets (syst.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>light mis-tag (syst.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b-/c-jets (stat.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>light mis-tag (stat.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated lumi.</td>
<td></td>
<td>2.5%</td>
<td>1%</td>
</tr>
</tbody>
</table>
How well will we understand **theory uncertainties**?

- Theoretical uncertainties will become more and more important (dominant in cases) as statistics increase and our handle on experimental uncertainties gets better.
- In practice, the improvements depends heavily on the process under study.
- The data of the LHC will feed into our understanding of some of these uncertainties: eg, PDFs.
- Complex question. To simplify, two complementary scenarios given for each of the updated projections:
  - S2 - Assumes improvement upon YR4: flat factor of 1/2
Uncertainties @ 3000 fb$^{-1}$

**ATLAS** Preliminary
Projection from Run 2 data
\( \tilde{t}'s = 14 \text{ TeV, } 3000 \text{ fb}^{-1} \)
\( H \rightarrow \gamma \gamma, |y_H| < 2.5 \)

- **ggF+bbH**:
  - Total: $1.00 \pm 0.04$ (±0.02, ±0.03)
  - Stat: $1.00$ (±0.04, ±0.08)
  - Syst: $1.00$ (±0.08, +0.05, -0.04)

- **VBF**:
  - Total: $1.00 \pm 0.09$ (±0.05, ±0.06)

- **VH**:
  - Total: $1.00 \pm 0.07$ (±0.05, ±0.06)

**Postfit impact**

- jet flavour composition VBF
- UEPS VBF
- QCD scale $ggF$, VBF-like 2j
- QCD scale $ggF$, jet-bin 1→2
- photon isolation efficiency
- QCD scale $ggF$, $p_T^H < 120$
- QCD scale $ggF$, $p_T^H < 60$
- jet pileup $\rho$-topology
- JER
- jet flavour response VBF

**S2, VBF (on xsecxBR)**
Combining & Projecting

* Individual projections are also checked, detector upgrades are folded in, uncertainties are adapted to the S1/S2 scenarios
Two Experiments?

**ATLAS and CMS**

**Stat. + Exp.**

**HL-LHC Projection**

- $B^\gamma\gamma$
- $B^{ZZ}$
- $B^{WW}$
- $B^{\tau\tau}$
- $B^{bb}$
- $B^{\mu\mu}$
- $B^Z$
- $B^{\gamma}$

**Expected relative uncertainty**

3000 fb$^{-1}$

**ATLAS and CMS**

**Stat. + Exp.**

**HL-LHC Projection**

- $\sigma_{ggH}$
- $\sigma_{VBF}$
- $\sigma_{WH}$
- $\sigma_{ZH}$
- $\sigma_{ttH}$

**Expected relative uncertainty**

3000 fb$^{-1}$

Very compatible results. Few percent precision in almost all cases.
Combining both experiments

All main decay x production modes $\gamma\gamma$, WW, ZZ, $\tau\tau$, bb, $\mu\mu$, $Z\gamma$ x ggF, VBF, WH, ZH, ttH

Individual experiment result combination to obtain the ATLAS and CMS sensitivity: LHC reach

Theoretical systematics assumed fully correlated, experimental uncertainties uncorrelated
Combined LHC Reach

\[ \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \text{ per experiment} \]

\begin{align*}
\text{Importance of Theory / MC understanding: specially important for background modelling}
\end{align*}
Precision of 2-4% can be reached for the non-statistically dominated modes.
LHC (partial) Run2 vs HL-LHC

- ATLAS [11]: 36.1-79.8 fb⁻¹
- CMS [12]: 35.9 fb⁻¹
- HL-LHC [14]: 2x3000 fb⁻¹

- $|\kappa_W| > 0.983$
- $|\kappa_Z| > 0.987$
- $\Delta\kappa_g^{HL} = \pm 0.022$
- $\Delta\kappa_\gamma^{HL} = \pm 0.017$
- $\Delta\kappa_t^{HL} = \pm 0.028$
- $\Delta\kappa_b^{HL} = \pm 0.026$
- $\Delta\kappa_\tau^{HL} = \pm 0.016$
- $\Delta\kappa_\mu^{HL} = \pm 0.044$
- $\Delta\kappa_{Z\gamma}^{HL} = \pm 0.100$

- $\text{Br}_{inv}^{HL} < 0.019$
- $\text{Br}_{unt}^{HL} < 0.041$

*Higgs@FC WG*

July 2019. Kappa3, $|\kappa| \leq 1$
Evolution with statistics?

• Measurements became systematically limited rather fast in almost all cases -> challenge
• Most Coupling modifier uncertainties projected to reach ~4-6% precision by the end of Run 3, and 2-4% after 3000 fb⁻¹ at HL-LHC
What about after the HL-LHC?

• Reaching a precise understanding of Higgs physics is at the core of all future accelerator physics programs (CLIC, ILC, FCC, CEPC,…)

• “Higgs factories” (ee colliders) can exploit their clean measurements (very different from pp).

• High energy machines -> probing high pt, enhances sensitivity to new physics

More in P. Azzi and M. Selvaggi’s classes!

Higgs@FC WG
Kappa-3, 2019

All future colliders combined with HL-LHC
Uncertainty values on $\Delta \kappa$ in %.
Limits on Br (%) at 95% CL.
Analysis evolve!

**tH Analyses at LHC: Massively Complex!**

- 7 TeV
  - Data
  - Background fit
  - $\mu = 1.4$
  - $\tilde{t}H, H \rightarrow \gamma\gamma, m_H = 125.4$ GeV
  - 7 TeV hadronic category

- 8 TeV
  - Data
  - Background fit
  - $\mu = 1.4$
  - $\tilde{t}H, H \rightarrow \gamma\gamma, m_H = 125.4$ GeV
  - 8 TeV hadronic category

- 13 TeV, Partial Run II
  - Data
  - Continuum Background
  - Total Background
  - Signal + Background
  - All categories
  - $m_H = 125.09$ GeV
  - $\mu = 1.4$
  - In(1+S/B) weighted sum

M. Cepeda (CIEMAT)
23/24 August 2021 - SLAC
Analysis evolve!

13TeV, full Run2
Snapshots

• The projections of the sensitivity of the HL-LHC have improved over the years (same as Run2 analysis have)

• Improvements wrt to old projections due to:
  • Theoretical uncertainties (currently from “YR4”, old ones from “YR3”: improved predictions, up to a factor of 2!)
  • Global fit / coherent study of all decay modes
  • Better understanding of performance at HL-LHC
  • Improvements in analyses!
Going further: ratios

If uncertainties are a bottleneck: exploit ratios.

Improved precision through cancelation of uncertainties
Thinking globally

• Anticipating the EFT lectures tomorrow: we need to stop thinking about measuring Higgs couplings in isolation and only in the kappa framework.

• Slow move to EFT approaches that eventually will involve all precision data available.
Global Fits: EFT

Higgs couplings + DY + Diboson observables

95% probability limits on the new physics interaction scale

eg: compositeness $f>1.6$ TeV, mass scale 20TeV
What about after the HL-LHC?

- Moving away from just focusing on the kappa framework
- Global Fits, EFT: incorporate all our knowledge
Higgs Measurements
Higgs Mass

- Only free parameter in the SM
- Already precisely measured by CMS and ATLAS:
  - CMS: 0.11% (4l+Diphoton, 2016)
  - ATLAS: 0.2% (4l, full Run2)
- The precision with which we can measure $m_H$ is directly linked to precision with which we can reconstruct (energy scale and resolution) photons and leptons
- How well can we measure $m_H$ in the future? And how well do we *need* to measure it?

<table>
<thead>
<tr>
<th></th>
<th>Statistical precision [MeV]**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2</td>
<td>~100</td>
</tr>
<tr>
<td>Run 3</td>
<td>~ 60</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>~ 10</td>
</tr>
</tbody>
</table>

R. Chatterjee for Snowmass, assuming the physics object scale and resolution can be maintained at current levels
• Impact of the $m_H$ uncertainty on the HZZ decay width: In lepton colliders, $m_H$ needs to be improved to around 10 MeV to avoid any limitation on ZZ/WW couplings.

• HL-LHC reach dependent on muon pt momentum calibration with high statistics: 10-20 MeV plausible.

• ZH recoil at lepton colliders: statistically limited.

<table>
<thead>
<tr>
<th>Collider Scenario</th>
<th>Strategy</th>
<th>$\delta m_H$ (MeV)</th>
<th>Ref.</th>
<th>$\delta(\Gamma_{ZZ^*})$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC Run-2</td>
<td>$m(ZZ), m(\gamma\gamma)$</td>
<td>160</td>
<td>[93]</td>
<td>1.9</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>$m(ZZ)$</td>
<td>10-20</td>
<td>[13]</td>
<td>0.12-0.24</td>
</tr>
<tr>
<td>ILC$_{250}$</td>
<td>ZH recoil</td>
<td>14</td>
<td>[3]</td>
<td>0.17</td>
</tr>
<tr>
<td>CLIC$_{380}$</td>
<td>ZH recoil</td>
<td>78</td>
<td>[95]</td>
<td>0.94</td>
</tr>
<tr>
<td>CLIC$_{1500}$</td>
<td>$m(b\bar{b})$ in $H\nu\nu$</td>
<td>$30^{16}$</td>
<td>[95]</td>
<td>0.36</td>
</tr>
<tr>
<td>CLIC$_{3000}$</td>
<td>$m(b\bar{b})$ in $H\nu\nu$</td>
<td>23</td>
<td>[95]</td>
<td>0.28</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>ZH recoil</td>
<td>11</td>
<td>[96]</td>
<td>0.13</td>
</tr>
<tr>
<td>CEPC</td>
<td>ZH recoil</td>
<td>5.9</td>
<td>[2]</td>
<td>0.07</td>
</tr>
</tbody>
</table>
**Higgs Width**

- From couplings: $\Gamma_H$ if $k_V \leq 1 \rightarrow 5\%$ precision at 95% CL

- **4L Offshell:** 25% precision at 68% CL (20% assuming CMS+ATLAS: ±0.8 MeV)

- GammaGamma interference study: <40-50 $\Gamma_{SM}$ (old, ATLAS), reduction of the on-shell rate by 2% (Campbell, Carena, Harnik, Liu)

---

- **Figure 17:** Likelihood scans for projections on $G^a$.
- **Table 10:** Summary of the 95% CL intervals for limits in either $G^a_3$ or $G^a_4$.

Completely different picture in lepton colliders. Stay tuned for the recoil method, remember these numbers.
Differential Distributions
How well do we understand Higgs Kinematics?

- **Differential Cross Sections**

  - **STXS**: measuring cross sections in specific bins of phase-space with high precision

  ![Graph showing differential cross sections](image)

- **CMS**

  - Observed
  - $\pm 1\sigma$ (stat $\oplus$ syst)
  - $\pm 1\sigma$ (syst)
  - SM prediction

  ![Graph showing CMS results](image)

- **Higgs Kinematics**

  - $m_H = 125.38$ GeV, $\sigma_{SM} = 31\%$

  ![Graph showing Higgs Kinematics](image)
How high we can reach in Higgs Pt?

High Pt Regime: extremely interesting and challenging. BSM effects?
Differential @ HL

- Exploit the large dataset and go beyond inclusive measurements

Expected precision of ~ 10% for $p_T(H) > 350$ GeV, statistically limited
Indirect Constraints

New physics modifies kinematics: obtain constraints on new physics from the precise measurement of differential distributions.
Rare production modes

- Further characterisation of the kinematics of the boson: rarer production modes (tth) x differential measurements provide further insight

- Example: can be used to constrain the Higgs self coupling in an alternative way to the traditional HH analysis
Rare Decays
Rare decays

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Final states</th>
<th>13 TeV $\mathcal{L}$ [fb$^{-1}$]</th>
<th>BR (SM)</th>
<th>$\sigma_{\mu} \times$ BR(H decays)</th>
<th>ATLAS/CMS references</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\bar{c}$</td>
<td>$J/\psi\gamma$</td>
<td>139, 35.9</td>
<td>2.9%</td>
<td>$26 \times$ SM, $70 \times$ SM</td>
<td>ATLAS-CONF-2021-021, JHEP 03 (2020) 131</td>
</tr>
<tr>
<td>invisible</td>
<td>$J/\psi\gamma$</td>
<td>139, 35.9</td>
<td>$\sim 10^{-3}$</td>
<td></td>
<td>ATLAS-CONF-2020-052, PLB 793 (2019) 520</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$\mu^+\mu^-$</td>
<td>139, 137</td>
<td>$\sim 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BR(H decays)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Final states</th>
<th>13 TeV $\mathcal{L}$ [fb$^{-1}$]</th>
<th>BR (SM)</th>
<th>$\sigma_{\mu} \times$ BR(H decays)</th>
<th>ATLAS/CMS references</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho\gamma$</td>
<td>$\pi^+\pi^-\gamma$</td>
<td>35.6</td>
<td>$\sim 10^{-5}$</td>
<td>$8.8 \times 10^{-4}$</td>
<td>JHEP 07 (2018) 127</td>
</tr>
<tr>
<td>$\phi\gamma$</td>
<td>$K^+K^-\gamma$</td>
<td>137</td>
<td>$\sim 10^{-6}$</td>
<td>$4.8 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$Z\rho$</td>
<td>$\mu^+\mu^- + \pi^+\pi^-$</td>
<td>137</td>
<td>$\sim 10^{-6}$</td>
<td>$(1.04-1.31) \times 10^{-2}$</td>
<td>JHEP 11 (2020) 039</td>
</tr>
<tr>
<td>$Z\phi$</td>
<td>$\mu^+\mu^- + K^+K^-$</td>
<td>137</td>
<td>$\sim 10^{-6}$</td>
<td>$(3-4) \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$Z\eta_c$</td>
<td>$\mu^+\mu^- +$, had</td>
<td>139</td>
<td>$\sim 10^{-5}$</td>
<td>$(\sigma \times BR = 110, pb)$</td>
<td>PRL 125 (2020) 221802</td>
</tr>
<tr>
<td>$Z\psi$</td>
<td>$\mu^+\mu^- +$, had</td>
<td>139</td>
<td>$\sim 10^{-6}$</td>
<td>$(\sigma \times BR = 100, pb)$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi\gamma$</td>
<td>$\mu^+\mu^-\gamma$</td>
<td>36.1, 35.9</td>
<td>$\sim 10^{-6}$</td>
<td>$3.5 \times 10^{-4}$, $7.6 \times 10^{-4}$</td>
<td>PLB 786 (2018) 134, EPJC 79 (2019) 94</td>
</tr>
<tr>
<td>$\psi(2S)\gamma$</td>
<td>$\mu^+\mu^-\gamma$</td>
<td>36.1</td>
<td>$\sim 10^{-6}$</td>
<td>$2.0 \times 10^{-3}$</td>
<td>PLB 786 (2018) 134</td>
</tr>
<tr>
<td>$Y(nS)\gamma$</td>
<td>$\gamma\gamma$</td>
<td>36.1</td>
<td>$\sim 10^{-9}$</td>
<td>$(4.9, 5.9, 5.7) \times 10^{-4}$</td>
<td>PLB 797 (2019) 134811</td>
</tr>
<tr>
<td>$J/\psi\gamma$</td>
<td>$4\mu$</td>
<td>37.5</td>
<td>$\sim 10^{-9}$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>PLB 801 (2020) 135148</td>
</tr>
</tbody>
</table>

So far, no evidence of physics beyond the SM in studies of rare decays of the Higgs boson

Summary by Imma Riu @ LHCP2021

- At HL-LHC: Larger statistics : huge impact in rare modes
Coupling to the second generation: Hmm

- Highlight of 2020: evidence for the coupling to the second generation!
- Statistically limited: Run3 and HL-LHC hugely important
- Upgrades also very important: CMS example, tracker upgrade brings on resolution improvements
- Prospects for (combined) branching ratio and coupling measurement @ HL → ~8% & 4% uncertainty@3000fb⁻¹ respectively
How charming is the Higgs?

• Coupling to the second generation quarks?

• Difficult measurement: not only a matter of statistics. Exploit VH channel, and rely on c-tagging developments.

• Run II? ~ 30xSM @ 95 % CL (ATLAS-CONF-2021-021)

• HL-LHC?: $\mu$(ZH, Hcc, ATLAS)<6.3 @ 95% CL, 3000fb-1, 14 TeV (Best fit: $\Delta\mu=3.2$)
Improvements in tagging?

• How well can we distinguish c-jets from b-jets and light jets?
  • Future innovations in tagging can have a large impact in this area
  • Tracker upgrades
• And a reminder: not only a CMS+ATLAS game: LHCb!

LHCb: 50xSM projected, but factoring in detector upgrades 5-10XSM could be achieved, LHCb-CONF-2016-006
H→ZGamma?

Searches for the $H \rightarrow Z\gamma$ Decay Mode

$|H^2| W^\mu_\nu W^{\mu\nu}$

Field tensor coupling not measured yet!

$\sim 2.3\%$ of $Br(\gamma\gamma)$

ATLAS analysis with full dataset

- 6 Categories:
  - VBF enriched (BDT based)
  - ggf high photon pT (relative to the $Z\gamma$ system mass)
  - ggf high pT (dilepton) - ee and $\mu\mu$
  - ggf low pT (dilepton) - ee and $\mu\mu$

- Fit of an analytic continuous background for a peaking signal!

$2.0 \pm 0.9$ (stat.) $^{+0.9}_{-0.7}$ (syst.) $= 2.0^{+0.9}_{-0.7}$ (tot.)

Expected $2.1\sigma$

Observed $3.2\sigma$

Precision at HL-LHC also would need to be reappraised!

HL-LHC $\sim 10\%$

Very good example of how analysis improvements outpace the projections!
Exclusive decays

- $H \rightarrow J/\psi \gamma$ (ATLAS) -> probe $c$ coupling
- $H \rightarrow \Phi\gamma / \rho\gamma$ (ATLAS) -> probe light-quark couplings.

<table>
<thead>
<tr>
<th>mode</th>
<th>collider energy</th>
<th>$\mathcal{R}_{V\gamma,ZZ^*}$</th>
<th>Yukawa range ($\kappa_V = \kappa_{\gamma\gamma}^{\text{eff}} = 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \gamma$</td>
<td>14 TeV</td>
<td>$0.47\sqrt{L_3}$</td>
<td>$16 - 67L_3^{1/4} &lt; \kappa_c &lt; 16 + 67L_3^{1/4}$</td>
</tr>
<tr>
<td></td>
<td>27 TeV</td>
<td>$0.28\sqrt{L_3}$</td>
<td>$16 - 52L_3^{1/4} &lt; \kappa_c &lt; 16 + 52L_3^{1/4}$</td>
</tr>
<tr>
<td></td>
<td>100 TeV</td>
<td>$0.12\sqrt{L_3}$</td>
<td>$16 - 33L_3^{1/4} &lt; \kappa_c &lt; 16 + 33L_3^{1/4}$</td>
</tr>
<tr>
<td>$\phi\gamma$</td>
<td>14 TeV</td>
<td>$0.33\sqrt{L_3}$</td>
<td>$11 - 46L_3^{1/4} &lt; \kappa_s &lt; 11 + 46L_3^{1/4}$</td>
</tr>
<tr>
<td></td>
<td>27 TeV</td>
<td>$0.20\sqrt{L_3}$</td>
<td>$11 - 35L_3^{1/4} &lt; \kappa_s &lt; 11 + 35L_3^{1/4}$</td>
</tr>
<tr>
<td></td>
<td>100 TeV</td>
<td>$0.083\sqrt{L_3}$</td>
<td>$11 - 23L_3^{1/4} &lt; \kappa_s &lt; 11 + 23L_3^{1/4}$</td>
</tr>
<tr>
<td>$\rho\gamma$</td>
<td>14 TeV</td>
<td>$0.60\sqrt{L_3}$</td>
<td>$44 - 93L_3^{1/4} &lt; 2\kappa_u + \kappa_d &lt; 44 + 93L_3^{1/4}$</td>
</tr>
<tr>
<td></td>
<td>27 TeV</td>
<td>$0.36\sqrt{L_3}$</td>
<td>$44 - 72L_3^{1/4} &lt; 2\kappa_u + \kappa_d &lt; 44 + 72L_3^{1/4}$</td>
</tr>
<tr>
<td></td>
<td>100 TeV</td>
<td>$0.15\sqrt{L_3}$</td>
<td>$44 - 47L_3^{1/4} &lt; 2\kappa_u + \kappa_d &lt; 44 + 47L_3^{1/4}$</td>
</tr>
</tbody>
</table>
Summary of rare Yukawa Couplings

- Indirect constraints (e.g., from differential distributions, off-shell couplings, or from the global coupling fits) complement the direct searches.

- The combined LHC (ATLAS+CMS+LHCb) reach for kappa_c could reach the ~1 level.
Rare Decays: Light Yukawa

- Constraints on light Yukawa obtained from the upper limits on $\text{BR}_{\text{unt}}$

- Hee: very challenging. FCCee documentation: SM sensitivity could be reached in a five year run with a dedicated run at $\sqrt{s}=m_H$
Higgs&Flavour

- FCNC constraints to be improved by an order of magnitude at HL-LHC, and further in the future (projections not available for all future colliders)

- LFV could be improved by more than an order of magnitude in future colliders (based on the mumu and tautau improvements)
HH Hunting
Higgs Self Coupling: HH

Can we access the Higgs self-coupling $\lambda$ with the LHC?

Remember Caterina’s class:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

$$V(\nu + h) = V_0 + \frac{1}{2}m_h^2\nu^2 + \frac{m_h^2}{2\nu^2}\nu h^3 + \frac{1}{4}\frac{m_h^2}{2\nu^2}h^4$$

$$\lambda = \frac{m_h^2}{2\nu^2} = 0.13$$

Marumi’s summary

<table>
<thead>
<tr>
<th>exp.</th>
<th>$WW\gamma\gamma$</th>
<th>$bb\gamma\gamma$</th>
<th>$bb\tau\tau$</th>
<th>$bbWW$</th>
<th>$bbbb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \times Br$</td>
<td>0.1 %</td>
<td>0.26 %</td>
<td>7 %</td>
<td>25 %</td>
<td>34 %</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$&lt;747 \ (386)$</td>
<td>$&lt;4.1 \ (5.5)$</td>
<td>$&lt;4.7 \ (3.9)$</td>
<td>-</td>
<td>$&lt;13 \ (21)$</td>
</tr>
<tr>
<td>CMS</td>
<td>-</td>
<td>$&lt;7.7 \ (5.2)$</td>
<td>$&lt;30 \ (25)$</td>
<td>$&lt;79 \ (89)$</td>
<td>$&lt;3.7 \ (7.3)$</td>
</tr>
</tbody>
</table>
HH: Benchmark @ HL-LHC

• $\sigma \sim 39.5$ fb@14TeV $\to$ HL-LHC benchmark
  • Can we access the Higgs self-coupling $\lambda$?
  • Low cross section: destructive interference

• Expanding list of final states w. Run2 & extrapolated to HL-LHC: from the classical 2b2gamma & 2b2tau to rarer modes like bbZZ
DiHiggs: 3000fb$^{-1}$

Combined significance of a single experiment: roughly 3 standard deviations

Combining the ATLAS and CMS results a significance of 4 standard deviation can be achieved (including systematic uncertainties).

<table>
<thead>
<tr>
<th></th>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATLAS</td>
<td>CMS</td>
</tr>
<tr>
<td>$HH \rightarrow bbbb$</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>$HH \rightarrow bb\tau\tau$</td>
<td>2.5</td>
<td>1.6</td>
</tr>
<tr>
<td>$HH \rightarrow bb\gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>$HH \rightarrow bbVV(ll\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
</tr>
<tr>
<td>$HH \rightarrow bbZZ(4l)$</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>combined</td>
<td>3.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Combined

4.5

Combined

4.0
DiHiggs: 3000fb$^{-1}$

- Combined: 4$\sigma$ and 50% uncertainty on $\kappa_\lambda$
- Second minimum of the negative log-likelihood excluded at 99.4% CL
Indirect Constraints & Global Fits

Single Higgs studies (led by ttH) also yield constraints on the self coupling.
Beyond High Luminosity?

**Di-Higgs:**
- HL-LHC: ~50% or better?
- Improved by HE-LHC (~15%), ILC500 (~27%), CLIC1500 (~36%), CLIC3000 (~9%), FCC-hh (~5%)
- ILC 1000 - 10%

**Single-Higgs:**
- Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC (~21% if FCC-ee has 4 detectors)
- Exclusive analysis: too sensitive to other new physics to draw conclusion
Higgs and BSM?

- Dark Matter
  - Higgs portal
  - Higgs DM mediator

- Inflation
  - Higgs inflation
  - Inflaton vs Higgs

- Phase transitions
  - Baryogenesis
  - gravitational waves

- UV sensitivity
  - Naturalness
  - heavy new physics
  - Relaxation

- Fate of the Universe
  - Stability

Similar story for Axions and ALPs, scalars are versatile

V. Sanz
Higgs Invisible

Connection between Higgs & Dark Matter!

Run2 Limit ~10% @ 95%CL (sensitivity dominated by the VBF channel)

From the global coupling fit @ HL-LHC, if $B_{BSM} \geq 0$ (any invisible or undetected states): $B_{BSM} < 2.5\% @ 95\% CL$

What about the direct searches?
VBF Higgs Invisible @ HL?

Delphes analysis: full reoptimization of the analysis for 200PU to handle the impact of PU in MET
Higgs Invisible

Connection between Higgs & Dark Matter!

Run2 Limit ~10% @ 95%CL (sensitivity dominated by the VBF channel)

From the global coupling fit @ HL-LHC, if $B_{BSM} \geq 0$ (any invisible or undetected states): $B_{BSM} < 2.5\% @ 95\% CL$

What about the direct searches?

**VH: ATLAS, 2013:** $<8\% @ 95\%CL$

**VBF: CMS, 2018:** $<3.8\% @ 95\%CL$

$\rightarrow$ Combined reach $<2.5 \% @ 95\% CL @ HL-LHC$
Comparison with DM searches?

- **M. Cepeda (CIEMAT)**

---

![Comparison with DM searches](image)

---

<table>
<thead>
<tr>
<th>fit setup</th>
<th>quantity</th>
<th>HL-LHC S1</th>
<th>HL-LHC S2</th>
<th>LHeC</th>
<th>LHeC ⊕ HL-LHC S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\kappa, \text{BR}_{\text{inv}}))</td>
<td>(\kappa^2(1 - \text{BR}_{\text{inv}}))</td>
<td>(\geq 0.933)</td>
<td>(\geq 0.958)</td>
<td>(\geq 0.959)</td>
<td>(\geq 0.967)</td>
</tr>
<tr>
<td></td>
<td>(\text{BR}_{\text{inv}} (\kappa = 1))</td>
<td>(\leq 6.7%)</td>
<td>(\leq 4.2%)</td>
<td>(\leq 4.1%)</td>
<td>(\leq 3.3%)</td>
</tr>
<tr>
<td>((\kappa, \kappa_g, \kappa_\gamma, \text{BR}_{\text{inv}}))</td>
<td>(\kappa^2(1 - \text{BR}_{\text{inv}}))</td>
<td>(\geq 0.930)</td>
<td>(\geq 0.954)</td>
<td>(\geq 0.959)</td>
<td>(\geq 0.966)</td>
</tr>
<tr>
<td></td>
<td>(\text{BR}_{\text{inv}} (\kappa = 1))</td>
<td>(\leq 7.0%)</td>
<td>(\leq 4.6%)</td>
<td>(\leq 4.1%)</td>
<td>(\leq 3.4%)</td>
</tr>
</tbody>
</table>

* remember this is from 2018

---

**Robens, Stefaniak**

---

M. Cepeda (CIEMAT)
Other Exotic Higgs Decays

• Despite the good agreement with the SM so far, there is plenty of room for BSM Higgs decays

• Example: \( h \rightarrow aa/ss \) searches (2HDM+S)

\[ B_u < 19\% \]

\[ B_r = B_u = 0 \]

\[ \rho_{SM} = 92\% \]

\[ m_H = 125.09 \text{ GeV}, \ |y_H| < 2.5 \]

\[ \text{68\% CL} \]

\[ \text{95\% CL} \]

\[ \sigma(h)B(h \rightarrow aa \rightarrow 2b2\tau) \]

\[ m_a \text{ (GeV)} \]

Other Exotic Higgs Decays

• Despite the good agreement with the SM so far, there is plenty of room for BSM Higgs decays

• Example: $h \to aa/ss$ searches (2HDM+S)

\[ B_u < 19\% \]

Long Lived Searches?

Upgraded detectors: extended opportunities to look for long lived Higgs decays

Example: exploit the upgraded L1 trigger to expand the phase space we can probe
Extended Higgs Sector

Are there more Higgs bosons? Can we find them at the HL-LHC?

Benchmark channel: Htautau

Comparison of direct Htautau limits and indirect constraints from the couplings extrapolations

$H/A \rightarrow \tau^+\tau^-$ expected exclusion (95% C.L.)

- ATLAS 3 ab$^{-1}$ $\oplus$ CMS 3 ab$^{-1}$
- ATLAS 36.1 fb$^{-1}$ [JHEP 01(2018)055]
- CMS 35.9 fb$^{-1}$ [JHEP 09(2018)007]

$m(125)$ rates $M_h \neq (125 \pm 3)$ GeV
- ATLAS 36.1 fb$^{-1}$ $\oplus$ CMS 35.9 fb$^{-1}$
- ATLAS 3 ab$^{-1}$ $\oplus$ CMS 3 ab$^{-1}$

Plot by T. Stefaniak et al

$M_h^{125}$ scenario with YR18 syst. uncert.
Extended Higgs Sector

Very wide landscape of searches beyond the tautau benchmark

CMS FTR-18-040 (H→ZZ→llqq)

Heavy Scalar Singlet

CERN-ESU-004
Brief note before finishing…

• Repeated from the introduction: **probing the Higgs boson at high $p_T$** enhances the sensitivity to new physics -> not fully captured in the analyses presented here -> further room for BSM studies
What about the HE-LHC?

- The HE-LHC will extend the HL-LHC reach in direct searches for new particles, approximately doubling the reach in mass → high impact on BSM Higgs studies.

- In terms of SM Higgs, it will enhance statistically limited processes and enable the access to very large transverse momenta.

- As an hypothesis, assuming an additional factor of 1/2 reduction of theoretical uncertainties plus the increase in cross section yields clear improvements in the global fit results.

- Once again, special focus on HH reach: precision of 10% to 20% on \( \kappa \lambda \) could be achieved from just the combination of the two main decay modes (\( \text{bb} \tau \tau \) and \( \text{bb} \gamma \gamma \)).

---

Fit by J. De Blas et al using CMS/ATLAS projections.
How well will we know the Higgs by the end of the LHC program?

- Is its production rate, where we measure it, at the correct SM level?
- How do we characterize it? (mass, width, spin)
- How well can we model its behaviour?
- Does it couple to SM particles at the appropriate level?
- Does it couple to itself?
- Does it decay unusually?
- Are there more Higgses?
- Higgs as a tool for discovery

The HL/HE-LHC datasets will allow us to fully characterise the Higgs boson.
Will new physics be able to still hide after the scrutiny?
Conclusions

• Higgs studies are central to the HL(HE)-LHC program:
  • Measurement of the Higgs couplings possible to few percent
  • Differential distributions and fiducial cross sections: probing interesting phase spaces and reducing dependence on theoretical uncertainties
  • High statistics: rare processes become accessible
  • Enhanced sensitivity to New Physics involving Higgs bosons

• Huge program, plenty of opportunities for new ideas