Lecture 3

Rare decays, rare production, diHiggs modes and the Higgs self coupling

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Outline

Lecture 1 (Run 1 landmark results): Introduction, the discovery of the Higgs boson and diboson channels
- The Standard Model
- The three pillars of Higgs physics
- The LHC and the LHC experiments
- Performance achievements and goals
- The discovery and the channels
- Entering the precision era: fiducial cross section definitions
- Simplified template cross sections
- Differential fiducial and unfolded cross sections
- The Higgs natural width at the LHC
- The mass of the higgs boson

Lecture 2 (Run 2 landmark results): Fermion channels and combination of Higgs boson measurements
- Higgs signal predictions and modelling
- Run 2 headlines on the Yukawa couplings to the third generation fermions:
  - Yukawa coupling to taus
  - Yukawa coupling to the top quarks
  - Yukawa coupling to b quarks
- Simplified template cross sections in sermonic channels
- The profiling paradigm
- Precision challenges and ancillary measurements
- Combining channels
- The kappa framework
- The SMEFT framework and first results

Lecture 3 (Run 3 and HL-LHC expected landmarks): Rare decay modes, searches for an extended Higgs sector and the quest to measure the Higgs self coupling
- Evidence for the second generation Yukawa coupling to muons
- Evidence for the $\gamma\gamma^*$ decay of the Higgs boson
- Other rare decays
  - Search for the $Z\gamma$ decay
  - Searches for quarkonia ($\rho, \phi, J/\Psi$) and a photon
  - The two electrons decay channel
- LFV decays
- FCNC top decays involving a Higgs boson
- Invisible decays of the Higgs boson
- Searches for extended Higgs sector (additional Higgs bosons)
- Searches for di-Higgs production and the trilinear Higgs self coupling
- Interpretation
New evidences for Higgs decay modes
Evidence for $H \rightarrow \mu^+\mu^-$
Evidence for Second Generation Yukawa Coupling

Very challenging, various ways to constrain

- Approximately 2k events produced but very small signal-to-noise ~0.2 (inclusive)
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity through the separation in production modes.

CMS analysis overview

- All production modes ggF, VBF, VH, ttH
- Improvements in mass resolution through Brem recovery
- DNN/BDT discriminants in all categories / Sideband region used to control backgrounds
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Summary of all categories

Estimate the background parameters through a fit of an analytical form!

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Evidence for Second Generation Yukawa Coupling

Search in ATLAS

Similar analysis with several categories aiming at ggF, VBF, VH and tH production modes.

Interesting to note the variations of the s/b and significance in the various categories.

In this case as well fit of an analytic smoothly falling background.

Summary spectrum of all categories together.

Results

\[ \mu = 1.2 \pm 0.6 \]

Expected \( 1.7\sigma \)

Observed \( 2.0\sigma \)
Superb achievement!

- Splendid plot of kappa combination assuming no additional states in the decay (total width varying only according to the coupling strengths of Higgs to SM particles)

- With 300 fb^{-1} Additional, at Run 3 a combined significance should nearly reach observation sensitivity!

- Foreseen precision at HL-LHC 5% will need to be reappraised (given the large analysis improvements with the full dataset)
Evidence for $H \rightarrow \gamma \ell^+ \ell^-$

Underlying BSM dynamics that could affect the $R_{K^*}$ ratio could also affect the $\ell \ell \gamma$ rate.

\[
R_{K^*} \equiv \frac{\text{Br}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\text{Br}(B \rightarrow K^{(*)}e^+e^-)}
\]

Interesting decay observable as a Forward-Backward asymmetry of the lepton w.r.t. flight direction, sensitive to CP violation in the interference between the $Z\gamma$ and $\gamma^{(*)}\gamma$ couplings.

A very interesting channel studied in two regimes, at the Z resonance ($Z\gamma\gamma^*$) often referred to as $\gamma^{(*)}\gamma$ but this neglects important contributions to the $\gamma \ell^+ \ell^-$ decay!


Phys. Rev. D 90
The key experimental challenge (see previous mass plot) is to go to low dilepton mass) this required a new reconstruction technique:

Merged electron reconstruction where a calorimeter (electron-like) cluster is associated to two tracks and conversions are carefully rejected!
Evidence for $H \rightarrow \gamma \ell^+ \ell^-$
Evidence for $H \rightarrow \gamma \ell^+\ell^-$

- Analysis carried out in ggF and VBF production modes signatures categories enriched with simple cuts!
- 3 x 3 categories (VBF, high $p_T$ ggF, low $p_T$ ggF) $\otimes$ (ee resolved, ee merged, $\mu\mu$)
- Contributions from $J/\psi$ are removed with a mass cut
Evidence for $H \rightarrow \gamma \ell^+ \ell^-$

- Analysis carried out in ggF and VBF production modes signatures categories enriched with simple cuts!
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- Contributions from $J/\psi$ are removed with a mass cut

$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5 \text{ (stat.)} \pm^{+0.2}_{-0.1} \text{ (syst.)}$$
$$\mu_{\text{exp}} = 1.0 \pm 0.5 = 1.0 \pm 0.5 \text{ (stat.)} \pm^{+0.2}_{-0.1} \text{ (syst.)}$$

Expected $2.1\sigma$
Observed $3.2\sigma$
Evidence for $H \rightarrow \gamma \ell^+ \ell^-$

- Analysis carried out in ggF and VBF production modes signatures categories enriched with simple cuts!
- 3 x 3 categories (VBF, high pT ggF, low pT ggF) $\otimes$ (ee resolved, ee merged, $\mu\mu$)
- Contributions from $J/\psi$ are removed with a mass cut

In this case the HL-LHC O(3%) projection will need to be fully reappraised!
Searches for the $H \rightarrow Z\gamma$ Decay Mode

**Z-photon**

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

Field tensor coupling not measured yet!

A priori straightforward similar search for a leptonic (electrons and muons) decaying Z and a photon.

$\sim 2.3\%$ 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!
Searches for the $H \rightarrow Z\gamma$ Decay Mode

Z-photon $|H^2|W^{\alpha\mu}W_{\mu\nu\alpha}$

Field tensor coupling not measured yet!

A priori straightforward similar search for a leptonic (electrons and muons) decaying $Z$ and a photon.

ATLAS analysis with full dataset

- 6 Categories:
  - VBF enriched (BDT based)
  - ggF high photon $p_T$ (relative to the $Z\gamma$ system mass)
  - ggF high $p_T$ (dilepton) - ee and $\mu\mu$
  - ggF low $p_T$ (dilepton) - ee and $\mu\mu$
  - Fit of an analytic continuous background for a peaking signal!

2.0 ± 0.9(stat.)$^{+0.4}_{-0.3}$(syst.) = 2.0$^{+1.0}_{-0.9}$(tot.)

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

Expected 1.2σ

Observed 2.2σ

HL-LHC ~10%
What about the electron Yukawa?

The soft limit of the photon is covered by the $H \rightarrow e^+e^-$ decay channel, sensitive to the electron Yukawa. The Branching fraction in the SM:

$$\text{Br}(H \rightarrow e^+e^-) \sim 5 \times 10^{-9}$$

Though one could hope that this would be large, it is suppressed by $m_e^2$.

The limits obtained with a dimuon-like analysis yields a

$$\text{Br}(H \rightarrow e^+e^-) < 3.4 \times 10^{-4}$$

Probe large electron e-Yukawa coupling from $B \rightarrow e^+e^-$ (where B is a pseudo-scalar) which is helicity suppressed from other contributions than the Higgs exchange (potentially sensitive to large Higgs contributions).

Perhaps possible at $e^+e^-$ collider in the s-channel $e^+e^- \rightarrow h$ (requires special run and monochromatization of beams to compensate for horizontal blow up from Bremstrahlung).

Probes of light quark and electron Yukawas in atomic physics (through isotopic shift spectroscopy in atomic clock transitions, which are the most precise frequency measurements!)

Provisional 2018-58
More on the CP violation in the fermion couplings

The pseudoscalar coupling of the Higgs boson to fermions not probed directly (yet)

\[ \frac{\lambda_f}{\sqrt{2}} \left( \kappa_f h \bar{\psi}_f \psi_f + i \tilde{\kappa}_f h \bar{\psi}_f \gamma_5 \psi_f \right) \]

Non zero \( \tilde{\kappa}_f \) implies CP violation in the Yukawa interaction

However indirect probes through electron (and neutron) EDM Very suppressed in the SM (where it arises at four loops)

A good probe for NP BSM!

From J. Brod., U. Haisch and J. Zupan 2013

\[ \frac{d_e}{e} \propto G_F m_e \left[ C_1 \kappa_e \tilde{\kappa}_t + C_2 \tilde{\kappa}_e \kappa_t \right] \]

ACME II limit: \[ \left| \frac{d_e}{e} \right| < 1.1 \times 10^{-29} \text{ cm} \]

Assuming electron Yukawa SM \( \tilde{\kappa}_t < 0.001 \)

This constraint is model dependent, still interesting to probe directly in ttH production channel (next slide).

Also a priori possible using the bbH production mode.

The electron EDM constraint is weaker for taus \( \tilde{\kappa}_\tau < 0.3 \)

First attempts to constrain this coupling using tau polarisation observables (see Lecture 2 as well)

\[ H \to \tau^+ \tau^- \to \rho^+ \nu_\tau \rho^- \bar{\nu}_\tau \]

Sensitivity of \( \sim 0.3 \) at 68\% CL at HL-LHC
Analysis overview

Using the powerful ttH in the subsequent $H \rightarrow \gamma \gamma$ mode in the fully hadronic and leptonic top decay modes
- BDT for top reconstruction
- Background rejection BDT
- CP BDT to separate CP-even and CP-odd (using kinematic variables of the photons and reconstructed tops)

Signal of course “seen” again with similar strength and significance

$\alpha < 43^\circ \ (63^\circ \ exp.)$

CP-even preferred vs CP-Odd also at ~4σ level
A Closer Look at the Yukawa Sector
Analysis similar to the VH(bb) but tagging charm quark jets instead and applying a b-tag veto!

\[
(W \rightarrow \ell \nu, Z \rightarrow \ell \ell, \nu \nu)
\]

\[
(H \rightarrow c\bar{c})
\]

Observation of VH(bb):

ATLAS
\[
\begin{align*}
\text{Run: } & 350440 \\
\text{Event: } & 1105654304 \\
\text{2018-05-16 23:55:11 CEST}
\end{align*}
\]
H(cc) in the SM is only 3%  
**Charm tagging is key!**

The challenging Yukawa coupling to charm

Very challenging!

**Important control of peaking**  
Bkg. W(cc) and Z(cc)

**c-tagging efficiency**  
(with b-tag veto) ~25-30%

**b rejection**  
(with b-tag veto) ~10

**light rejection**  
(with b-tag veto) ~50
More Decays with to Quarkonia and a Photon

Current limits

Neubert et al., 2015

\[ \text{Br}(J/\Psi \gamma) = 2.95 \times 10^{-6} \]

\[ J/\psi \]

Potentially sensitive to charm Yukawa

\[ \mu^+ \mu^- \gamma \]

\[ \sim 100 \times \text{SM} \]

Does not include the subsequent branching to muons (6%)

\[ \text{Br}(\phi \gamma) = 2.31 \times 10^{-6} \]

\[ \phi \]

Potentially sensitive to strange Yukawa

\[ K^+ K^- \gamma \]

\[ \sim 200 \times \text{SM} \]

No Kaon tagging based on the \( \phi \) mass only

\[ \text{Br}(\rho \gamma) = 1.68 \times 10^{-5} \]

\[ \rho \]

Potentially sensitive to light Yukawa

\[ \pi^+ \pi^- \gamma \]

\[ \sim 50 \times \text{SM} \]

Paradoxically closest limit to SM sensitivity

\[ \text{Br}(\rho \gamma) \]

Measuring the Higgs decays to quarkonia and a photon do not give exclusive access to the Yukawa

\[ \text{Measuring the Higgs decays to quarkonia and a photon do not give exclusive access to the Yukawa} \]

\[ H \]

\[ \Psi \gamma \]

\[ \phi \gamma \]

\[ \rho \gamma \]

\[ K^+ K^- \gamma \]

\[ \sim 200 \times \text{SM} \]

\[ \sim 100 \times \text{SM} \]

\[ \sim 50 \times \text{SM} \]

\[ K^+ K^- \gamma \]

\[ \text{Highly non trivial interpretation as a value of } \kappa_c \text{ of } \sim 100 \text{ requires a } \kappa_t \sim 20 \text{ i.e. a non perturbative top Yukawa!} \]
Very challenging, various ways to constrain
- VH(cc) direct detection, relies on ability to distinguish b and c jets, using charm tagging (based on the charm decay length comprised between b jets and light jets) based on deep neural network techniques.
- Differential cross sections (as discussed previously in lecture 1)
- Charmonium-photon exclusive decays
- WH production charge asymmetry (PDFs)
- Search for Hc production

![Graph showing light-jet rejection efficiency](attachment:light-jet-rejection.png)

**Potential sensitivity to charm Yukawa**

Also limits on Upsilon-gamma

Sensitivity to gamma-gamma*(top loop) and interference

Example of new idea in ratios where many TH uncertainties will cancel, of course in this case sensitive to PDFs.

\[ A = \frac{\sigma(W^+ h) - \sigma(W^- h)}{\sigma(W^+ h) + \sigma(W^- h)} \]
Summary on Flavors
(at HL-LHC with comments on HE-LHC)

First and Second generation Yukawas

- Extremely challenging at HL-LHC (most stringent constraint coming from the couplings fit assuming no BSM width).

- For the charm Yukawa direct search (using charm tagging) is not far behind!

- Then comes sensitivity to coupling combination through width offshell.

- Exclusive searches still only marginally sensitive.

- New emerging ideas to be explored with such large datasets.
More rare decays and production Modes
More rare decays and production Modes

Lepton flavor violating decays

Flavor changing neutral current decays of the top quark

Single top associated production

Tree level interference between W and top

Various decay channels of the Higgs boson (diphoton, bb)
In the **Standard Model** the Yukawa couplings are diagonalised as the mass matrix: **no flavour non-diagonal terms.**

Non diagonal terms can arise in dimension 6 operators in a SM EFT

\[
\frac{\phi^\dagger \phi}{\Lambda^2} \left( \lambda_{ij} F_L^i \phi^d_j f_{dR} + \lambda_{ij} F_L^i \phi^c_j f_{uR} \right)
\]

In this case the Yukawa-masses relation is broken, and di- and tri-Higgs terms will be generated!

\[
Y_{ij} \sim \frac{m_{ij}}{v} + \frac{v^2}{\Lambda^2} c_{ij}
\]

As in 2HDMs unless carefully assuming that one Higgs doublet couples to a type of fermion at a time (Natural Flavour Conservation rule - yielding types I - IV 2HDMs)!

Not a necessary condition to match the Kaon, B and muon decays data

**Cheng and Sher Ansatz**

\[
\lambda_{ij} \sim \frac{\sqrt{m_i m_j}}{v}
\]

This Ansatz works well with most constraints (light quarks and leptons), but for higher masses the Higgs data can be of interest (experimental goal).

Going beyond this Ansatz requires fine tuning and this is thus called the « Naturalness Limit »

**Defines a good experimental goal!**
Lepton Flavor Violating Couplings

Simplest channel at the LHC is the $e\mu$ but it is way more constrained by $\mu \to e\gamma$ experiment (MEG)

$$\text{Br}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

$$\text{Br}(H \to e\mu) < O(10^{-8})$$

Depending on assumptions on the diagonal $e$ and $\mu$ Yukawa

The **Naturalness Limit** in the case of the tau and mu couplings is much larger corresponding to $\text{Br} \sim 0.4\%$

$\tau\mu$ channel studied at Run 1 and Run 2 by ATLAS and CMS, with analyses in both the hadronic and leptonic decay channels of the tau (with analyses similar to the $H \to \tau^+\tau^-$ channels).

The *raise and fall* of the Cheng and Sher ansatz (see *slides*)

Limit on $e\mu$ LFV Branching at 95%CL:

$\text{Br} < 6.1 \times 10^{-5}$ Only factor ~10 from « naturalness » limit

CMS result with 36 fb$^{-1}$

$$\text{Br}(H \to \tau\mu) < 0.25\%$$
Flavor changing neutral current decays of the top quark is strongly suppressed (by the GIM mechanism)

\[ B(t \rightarrow Hq) \]  
SM Branching \( \sim 10^{-15} \)

Therefore an excellent channel to look for New Physics!

Various decay channels of the Higgs boson
\( (\gamma\gamma, \text{bb, WW}) \)

Tree level interference between top Yukawa and VVH production: single-top and Higgs associated production:

\[ \propto 3.3 \times \kappa_W^2 - 5.1 \kappa_W \kappa_t + 2.8 \kappa_i^2 \]

Allows to further constrain the relative sign of the top Yukawa coupling w.r.t. hVV

CMS analysis in combination between the multi lepton, bb and \( \gamma\gamma \) channels

Excludes values of \( \kappa_t < -0.9 \) at 95% CL

The discrepancy between observed and expected limits around is caused by the fact that the predicted \( \text{ttH} \) cross section vanishes while the data favors larger than expected yields for \( \text{ttH} \).

Similar result from yesterday's multi lepton analysis!
Invisible decays of the Higgs boson
Invisible decays of the Higgs boson

**Very small rate in the SM (0.1%)**

Large variety of accessible modes

- VH where the V is leptonic and hadronic
- VBF is the most sensitive channel *challenge is the estimate of the V-jets backgrounds: estimated from control regions using W, Z and photon-jet events*.
- ggH (from mono-jet)
- Recently include ttH

**ATLAS VBF search** [ATLAS-CONF-2020-008]

Key aspect in this analysis is the control of the main Z-jets background (use of control regions)

\[ \text{Br(inv.)} < 13\% \text{ (@ 95% CL)} \]
Invisible decays of the Higgs boson

CMS combination

Including VBF, ggF, VH modes


\( Br(\text{inv.}) < 0.19 \ (0.15) \)

at 95% CL

ATLAS combination

Including VBF and tth modes and Run 1 results

ATLAS-CONF-2020-052

\( Br(\text{inv.}) < 0.11 \ (0.11) \)

at 95% CL

Limits are now at 9% on invisible branching at 90% CL

Interpretation in terms of WIMP-Nucleon cross section limits: very nice complementarity with direct searches!
Searches for an Extended Higgs Sector

Covered in more detail by Nausheen and Jessie
Very large number of searches (see concise summary and much more in Nausheen and Jessie’s lectures!)

- Direct "BSM Higgs searches" for an extended Higgs sector (MSSM, 2HDM, NMSSM, Georgi-Machacek Triplets, additional singlets, etc…)

- Still large improvement in the sensitivity with the HL-LHC ~1 TeV

- Challenge: Extend the direct search coverage in the more difficult regions (e.g. intermediate tan beta region and high mass requires improving searches such as top-pair (taking into account the interference with the continuum background).
Very large number of searches (see concise summary and much more in Nausheen and Jessie’s lectures!)

ATLAS Preliminary
hMSSM, 95% CL limits
Run 2, \( \sqrt{s} = 13 \text{ TeV} \)
- Observed
- - Expected

July 2021

ATLAS Higgs Searches

<table>
<thead>
<tr>
<th>CP-even ( H )</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Other experiments</th>
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<tbody>
<tr>
<td>( H \to \gamma \gamma )</td>
<td>[371]</td>
<td>[372]</td>
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<tr>
<td>( H \to \gamma \gamma ) (low mass)</td>
<td>[371]</td>
<td>[373]</td>
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<td>( H \to ZZ \to 4\ell )</td>
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<td>( H \to ZZ \to \ell \ell \nu \nu )</td>
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<td>( H \to ZZ \to \ell \ell q\bar{q} )</td>
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<td>( H \to WW \to \ell \ell \nu \nu )</td>
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<td>( H \to WW \to \ell \ell q\bar{q} )</td>
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<td>[383]</td>
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<tr>
<td>( H \to VV \to \ell \ell q\bar{q} (JJ) )</td>
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<td>( H \to VV ) combination</td>
<td>[385]</td>
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<tr>
<td>( H \to hh \to b\bar{b}t\bar{t}, b\bar{b}b\gamma, 4b )</td>
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<td>( \gamma \gamma W W^<em>, b b W W^</em>, W W^* W W^<em>, b b Z Z^</em> )</td>
<td>[386, 387]</td>
<td>[388–390]</td>
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<tr>
<td>CP-odd ( A ) (and/or CP-even ( H ))</td>
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<th>CMS</th>
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<tr>
<td>( H^\pm \to \tau^\pm \nu )</td>
<td>[411, 412]</td>
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<td>( H^\pm \to cs )</td>
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<tr>
<td>( a \to \mu^+ \mu^- )</td>
<td>[422]</td>
<td>[423]</td>
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<tr>
<td>( h \to a a \to 4 \mu, 4 \tau, 2 \mu 2 \tau, 4 \gamma, )</td>
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<td>( bbq, b\tau \tau )</td>
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<td>[426] (TeV)</td>
<td>(LEP)</td>
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<td>( T_{1_{2,3}} \to a \gamma )</td>
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<td>[428] (LEP)</td>
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Physics Rev. D 101 (2020) 012002
BSM Higgs Searches

Very large number of searches (see concise summary and much more in Nausheen and Jessie’s lectures!)

Difficult intermediate and high mass region, above the $t\bar{t}$ threshold

Searches for a high mass $t\bar{t}$ resonance is particularly difficult due to the interference between the signal searched and the background.

Analysis done at 8 TeV, not yet performed at 13 TeV

HH or charged Higgs searches are also important in this region and lower $\tan \beta$
BSM Higgs Searches

Very large number of searches (see concise summary and much more in Nausheen and Jessie’s lectures!)

SUSY could modify the couplings of the Higgs

From the combination of all channels presented in Lecture 3, from constraints on up versus down Yukawa and coupling to vector bosons, limits in the MSSM parameter space can be set.

Example where the kappa formalism can be directly used (couplings of the Higgs boson are modified and the gauge invariance is restored by other Higgs sector states that are not at reach!)
Higgs Self Coupling

Covered in more detail by Caterina
The Higgs self coupling is key in understanding the shape of the Higgs potential. Probing the potential would shed light, beside the electroweak symmetry breaking, on whether there could be an EW phase transition in the early universe, or the stability of the vacuum.

Measuring the di-Higgs production would provide a unique and direct probe of the Higgs boson self-coupling.

Very similar analysis as the Off-shell Higgs couplings!

Incredibly small cross section ~1000 times smaller than Higgs production! **Huge challenge!** but still more than 100k event will be produced at HL-LHC!

**Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!
Di-Higgs boson production

Latest result using the full Run 2 data set in the $b\bar{b}\gamma\gamma$ channel

Various regions defined from a BDT based on photon and jet kinematics, and separated in two regions in HH mass (high and low important to discriminate HH components and constrain the trilinear coupling).
Di-Higgs boson production

**Latest result** using the full Run 2 data set in the $b\bar{b}\gamma\gamma$ channel

Key aspect in the measurement of $\lambda$ is the HH invariant mass distribution

Limits on HH production at 4.1 obs. (5.5 exp.) x SM at 95% CL

Yields constraints on the trilinear coupling at $[-1.5,6.7]$ at 95% CL

**Very interesting improvements** w.r.t. previous results!
Di-Higgs boson production

Many more channels have been investigated (e.g. CMS)

\[ HH \rightarrow b\bar{b}\gamma\gamma \]
Limits on HH production at **7.7 obs.** (5.2 exp.) x SM at 95% CL

Constraints on the trilinear coupling at **[-3.3,8.5]** at 95% CL

\[ HH \rightarrow b\bar{b}b\bar{b} \]
Limits on HH production at **3.7 obs.** (7.3 exp.) x SM at 95% CL

Constraints on the trilinear coupling at **[-2.5,9.5]** at 95% CL

**Summary** in terms of limits on HH production

<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 \text{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>

**Full data results in all channels and their combinations eagerly awaited!!**
Indirect constraints on Higgs Self Coupling

Indirect constraints from combined STXS

Combination with ATLAS STXSs

- Several production processes (ggF, VBF, VH, thh)
- Several decay processes (diphoton, ZZ, yy)
- Trilinear coupling on wave function renormalisation

Direct/Indirect currently comparable, direct HH searches will dominate at higher luminosities, but complementarity still necessary to fix $\kappa_t$

$-2.3 < \kappa_1 < 10.3$

Indirect constraints from differential measurements (e.g. ttH)

ttH Process (with subsequent decay to diphoton)

$-4.1 < \kappa_1 < 14.1$

Possible to disentagle effect of trilinear from other coupling modifications from the differential ttH measurements!

Global fit  S. di Vita, C. Grojean et al.

In a global EFT Flat directions exist in the single-Higgs production (including all relevant operators) and the HH results are necessary to resolve them.

However, the inclusion of single-H differential measurements does not seem improve greatly the trilinear measurement with the full statistics.
Towards a Measurement of the Higgs Self Coupling

Indirect constraints from combined STXS

First specific VBF-HH search in the 4b final state, with as main interpretation a limit on the $c_{2V}$

---

Strong variation of cross section (and acceptance) yield quite strong constraints at 95% CL:

$-1.0 < c_{2V} < 2.7$  Done also by CMS in other channels since!

---

At HL-LHC

Current estimates yield an observation of an HH signal at 4$\sigma$

50% level constraints on the Higgs boson self coupling!

$0.5 < \kappa_\lambda < 1.5$

Already impressive, must try all we can to improve!!

F. Dreyer and A. Karlberg

Uses the latest N3LO-QCD estimate of the VBF-HH cross section!
Indirect constraints from combined STXS

First specific VBF-HH search in the 4b final state, with as main interpretation a limit on the $c_{2V}^V$,

Strong variation of cross section (and acceptance) yield quite strong constraints at 95% CL:

$$-1.0 < c_{2V} < 2.7$$

Probing 1st order phase transition and GW signals

The sensitivity of HL-LHC to the trilinear coupling could constrain models which would predict strongly first order EW phase transition!

In these cases, signals of stochastic background (e.g. collisions of bubbles) in the phase transition could potentially be detected by next generation interferometers like eLISA*.

*eLISA: evolved LISA
What have we learned?
What have we Learned from all coupling measurements?

All couplings of the Higgs boson (within the Standard Model and except the self coupling) were known before the discovery of the Higgs boson!

- From coupling measurements (to gauge bosons, third and soon second generation fermions)
  - Vector bosons ~8\% → 1-2\% precision at HL-LHC
  - Fermions ~10-20\% → 2-3\% precision at HL-LHC
  - Self coupling ~[-2,7] x SM → 50\% precision at HL-LHC

- Boson and fermion couplings are not CP-odd (mixing with CP-even still possible)

Within an already excellent precision, no significant deviation from the Standard Model hypothesis has been found so far!
Running of the Higgs self coupling:

\[ V(\phi) = -m^2 \phi \dagger \phi + \lambda (\phi \dagger \phi)^2 \]

\[ m_H = \sqrt{2\lambda v} \]

\[
32\pi^2 \frac{\partial \lambda}{\partial \mu} = 24\lambda^2 - \frac{6g_t^4}{y_t^4} - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4
\]

Dominant term for large values of the Higgs boson quartic coupling

The simplified differential equation can be solved and derive a so-called « triviality » bound.

Dominant term for small values of the Higgs boson quartic coupling

The simplified differential equation can be solved and derive a so-called « vacuum stability » bound.
What have we Learned from Knowing its Mass?

Running of the Higgs self coupling, assuming SM only at high scale

\[ V(\phi) = -m^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2 \]

\[ m_H = \sqrt{2\lambda} \]

With the discovery of the Higgs for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

Near vanishing coupling at the Planck scale

Interpretation more sensitive to precision on the top quark mass is more

Electroweak Measurements consistent at quantum corrections level (also assumes SM)

Precision measurements allow to make predictions!!
Assuming the SM, the top quark mass and Higgs boson mass were (approximately) known before being discovered!
Conclusions

- **The discovery of the Higgs boson** compatible with the SM Higgs boson has sealed the triumph of the Standard Model and is an immense success of the LHC.

- The parameter that was unknown until prior to the LHC (Higgs boson mass) is now one of the most precisely measured parameters at the LHC (0.1% level).

- The Higgs physics program has blossomed and the boundaries of what is possible in Higgs properties measurements have been greatly expanded.

- Every new Higgs physics branch offers plenty of novel opportunities for further developments.

- The pursuit of precision at LHC will be key in its Higgs physics program (and in general at the LHC) - and will require efforts from both the Experimental and Theory communities.