Higgs WG Summary

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UNIVERSITY OF BIRMINGHAM

June 20, 2018

HL-LHC June Workshop
Some Useful Information

- HL-LHC Workshop TWiki page
- WG2 TWiki page
- WG2 conveners: Maria Cepeda, Stefania Gori, Philip Ilten, Marumi Kado, Francesco Riva
- WG mailing list is hllhc-wg2@cern.ch
- mailing list membership constitutes the draft author list
- sign up and/or check the list here
- e-groups will be made shortly for each chapter of the report
- Overleaf document (ask for editing link)

- October 2017 CERN workshop
- April 2018 FNAL workshop
- this June 2018 CERN workshop
- list of WG2 (Higgs) meetings
Introduction

Goals

• **Higgs Yellow Report**
  1. provide improved benchmarks
  2. provide a synthesis of the opportunities for Higgs physics at HL/HE-LHC
  3. provide a strong and as exhaustive as possible reference to the community

• this workshop
  1. the progress in each section (in particular HE projections)
  2. collect and discuss all areas where choices are needed
  3. organise integration of experimental results
  4. liaise between all participants to ensure good communication between authors
Introduction

Yellow Report (YR) Outline

1. Introduction: Main goals and timeline
2. Precision Higgs physics
3. Di-Higgs production and Higgs self couplings
4. Other high energy probes
5. The higgs boson mass and width
6. Invisible decays of the Higgs boson
7. Higgs flavor and rare decays
8. Global view of Higgs couplings at the HL/HE-LHC
9. BSM Higgs
**Wishlist Summary**

- nice summary by Marianna, *et. al.* from May meeting
- legend: previous study, 2017 TDR study, to be done/expanded

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(✓) what about $B^+ \rightarrow K^+ \chi(\mu\mu)$ from LHCb?
1. Precision Higgs physics
5. Higgs mass and width
8. Global view of Higgs couplings at the HL/HE-LHC
• editors: Predrag Milenovic (CMS), Michael Duehrssen-Deblin (ATLAS), Simone Alioli (theory))

1 Channels reach in diboson decays, including fiducial and differential measurements
2 Channels reach in main Yukawa couplings, including fiducial and differential measurements
3 Special focus on direct and indirect probe of top Yukawa coupling (Alessandro Calandri)
4 Progress on TH uncertainties: what to expect?
5 Impact from PDFs and alphaS on Higgs measurements
6 Progress on Higgs specific MC (Prestel, Hoeche, Maltoni, Alioli)
7 HE Cross-sections (Grazzini et al.)
8 Higgs couplings precision overview
9 Probes using differential distributions of CP sensitive observables (Yu, Piccinini et al.)
10 Interpretation in terms of Composite Higgs models (Vecchi)
11 Interpretation in terms of SUSY models (Wagner, Shah)
12 Kappa-formalism and the nonlinear EFT (Krause, Cata)
Higgs Mass and Width Yellow Report Outline

- editors: Meng Xiao (CMS)

1. Theory review (Melnikov, Caola)
2. Measurement of the Higgs boson mass
3. Mass shift from the diphoton interference: constraints on the width (Dixon)
4. Direct constraints from the Higgs boson lineshape
5. Direct constraints from the Higgs boson lifetime measurements
6. Width from off-Shell higgs boson couplings
7. Width from the diphoton interference rate (Z.Liu)
Higgs Couplings

Overview

- Higgs coupling measurements are a top priority from the 2013 European strategy, see talk by Tatsuya Nakada

  The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

- previous Run 1/2 analyses have shown projections were not accurate enough

- provide a new benchmark that is accurate, not necessarily precise, for the HL-LHC

- re-appraisal in several channels necessary

- provide a rough estimate for HE-LHC coupling measurements
Accurate, Not Necessarily Precise

- extrapolate from Run 2 analyses when possible
  - increased luminosity
  - increased centre-of-mass energy (14, 15 and 27 TeV)
  - reconstruction performance with new detector
  - different PU conditions (200)
  - different systematic scenarios
- agreement almost all systematics
  - theory uncertainties centralised by LHC Higgs XS working group, see talk by Fabrizio Caola
  - experimental uncertainties discussed in detail, see talk by Meenakshi Narain and Simone Griso

\[ \sqrt{s} = 14 \text{ TeV}; \int \text{L} \text{d}t = 300 \text{ fb}^{-1}; \int \text{L} \text{d}t = 3000 \text{ fb}^{-1} \]
collaboration with LHC Higgs XS Working Group
first meeting this week, common meetings to come
provide cross sections (14 and 27 TeV)

decide on theory systematic scenarios for HL/HE-LHC
  similar predictions as arXiv:1610.07922
  consider possible future theory development
  define scale variation, PDF, $\alpha_s$, etc. uncertainty
  one baseline scenario and one optimistic scenario

especially done but needs to be written down
Experimental Wishlist and Uncertainties

- uncertainties discussed in detail in two dedicated meetings and during this workshop, *e.g.* talk by Meenakshi Narain and Simone Griso
- dominant uncertainties identified and discussed with experts
  - signal modelling at all levels, *e.g.* cross-sections, Monte Carlo
  - Background modelling (*WW*, *t* and *V+jets* mostly)
  - jet energy scale and resolution
  - photon energy scale and resolution (and scale), *w*
  - flavor tagging
- some uncertainty improvements automatically handled in profiling
  - validity of model needs to be confirmed by collaborations
- wishlist, *e.g.* *possible* studies, discussed and solidified
**Practical Example**

- extrapolate expected sensitivity from current framework
  - already can see change in hierarchy
  - many uncertainties can be constrained by data
  - theory and experimental uncertainties via prescriptions
  - 1% luminosity uncertainty
Mass Width

- we do want a mass prediction, even if use case not entirely clear
- projections of direct width measurements
- fiducial ratio measurement $\gamma\gamma/4\ell$ for width
- constraints on width and mass shift from $\gamma\gamma$ interference
- discuss off-shell Higgs measurements on the width
- provide synthesis of all the measurements
HE-LHC Considerations

- high energy running scenario specified (27 TeV and 15 ab$^{-1}$), but detectors are not
- experiments will perform basic extrapolation (energy and luminosity, not pile-up and detector performance) for a few analyses e.g. HH
- projections will rely on combined theory and experimental input
- high energy studies have been organised within sections, needs reinforcement
Remarks

- overall couplings benchmark using the main channels combination
- provide an ATLAS-CMS combined statement about the couplings
- more specific discussions in the YR on specific questions
  - how precisely top Yukawa can be measured directly (\(ttH\) and \(tH\) analyses)
  - access charm Yukawa (\(VH(cc)\), rare decays, differential)
  - effort on lighter Yukawas (rare decays, differential, \(WH\) charge asymmetry)
Di-Higgs production and Higgs self couplings
Yellow Report Outline

- editors: Cadamuro (CMS), Wardrope (ATLAS), Riembau (theory)

1. SM calculation (Dawson, Heinrich et al.)
2. Double Higgs measurements and trilinear coupling (ATLAS and CMS)
3. Indirect probes of the trilinear coupling through differential distributions measurements (CMS)
4. Indirect probes through single Higgs boson production (Maltoni, Pagani, Zanderighi et. al, Englert; see di-Higgs meeting)
5. HE prospects (Goncalves and Plehn, Homiller and Meade)
6. Theory implications, including a critical view of the validity of direct and indirect trilinear couplings measurements (di Vita, Riembau, Vanthalon; see di-Higgs meeting)
Self Couplings

Differential Distributions

- see talk by Jonathon Langford (based on arXiv:1709.08649):

Signal extraction and interpretation

1. **Uncertainties for differential cross-sections**: $ttH$ and $VH$ @HL-LHC

2. **Sensitivity to $\kappa_\lambda$**
   - 1D likelihood scan with $\kappa_\lambda$ as POI
   - 2D scan of $\kappa_\lambda$ vs $\kappa_t$?

**Important towards final sensitivity**

- Systematics
  - experimental: YR2018
  - theoretical

- Theoretical assumptions
  - only $\lambda_3$ variations
  - impact of EW unc close to SM
  - role of QCD higher order effects

3. **Combination with HH**
   - 1D $\kappa_\lambda$ scan, increased sensitivity
   - global fit: constraints from standard single-Higgs measurements

$\mathbf{p_T(H)}$ for $ttH \rightarrow bjj bjj \gamma \gamma$
Mass Effects vs Parton Shower Effects

- for details see talk by Gudrun Heinrich
- shower effects are large but orders of magnitude less than Born-improved HEFT
High Energy

- **$HH$** discovery at 27 TeV requires $2.3 a b^{-1}$ (rather than $2.8 a b^{-1}$) and $0.2 a b^{-1}$ at 100 TeV
- photon and jet mass resolution critical for detector design
- see talk by Dorival Gonçalves based on arXiv:1802.04319
4 Other high energy probes
• editors: Francesco Riva (theory)

1. Measuring Offshell couplings
2. tth differential measurements (Maltoni, Vryonodou)
3. WH/ZH at high energy/luminosity (Spannovski, Mccoulough)
4. WW/WZ at high energy/luminosity (Elias-Miro, Panico, Azatov)
5. VBF longitudinal VBS and di-Higgs (Rojo, Bishara, Contino)
6. Same-sign WW scattering (Kalinowski, Kozow, Pokorski, Rosiek, Szleper, Tkaczyk)
tails of energy distributions, \( e.g. p_T \) and \( m \), become interesting when \( \delta_{\text{stat}} \gg \delta_{\text{syst}} \)

- for the HL-LHC this translates to a linear improvement

some BSM-EFT effects grow with energy, \( \sim E^2/\Lambda^2 \)

- going from 100 GeV to 1 TeV increases effect by \( \mathcal{O}(100) \)
- new distributions become available with high statistics
Vector and Higgs

- see talk by Rick Sandeepan Gupta
- \( VV \) and \( HV \) processes are connected by symmetry and constrain the same high energy observables
  \[
  \Phi \equiv \left( \frac{G^+}{H+iG} \right) \sqrt{2}
  \]
- BSM in \( HZ \) with \( Z \to \ell\ell \) and \( H \to bb \)
- \( ZH \to G^0H \)
- what about \( Z \to \nu\nu \) and \( WH? \) \( VH \) mass distributions?
Double Vector Bosons

- $WW \rightarrow G^+G^-$
- $WZ/\gamma \rightarrow G^+G^0$
- BSM in longitudinal vectors
  - $WZ/WW$ semi-leptonic
  - systematics in polar angle distributions?

- BSM in transverse vectors
  - $WZ/W\gamma$
    - leptonic/semi-leptonic
  - systematics in azimuthal distributions?
Top BSM and VBF

- $p_T$ spectrum sensitive new physics, see talk by Thomas Klijnsma
- projected 5% uncertainty for $\gamma\gamma$, 5 – 10% for $ZZ$, < 5% combined
- better to consider single overflow bin?

ATLAS-TDR

- study on $ttH$ differential measurements by Maltoni and Vryonodou
- study on $WW \rightarrow HHWW$ by Rojo, Bishara, and Contino
7 Higgs flavor and rare decays
• editors: Kostas Nikopoulos (ATLAS), Alexander Schmidt (CMS), Lorenzo Sestini (LHCb), Yotam Soreq (theory)

1. Flavor aspects Yukawa modifications in flavor models (Bishara)
2. Exclusive Higgs decays (Soreq)
3. Flavor tagging (charm and strange) (Schlaffer)
4. LFV decays of the Higgs
5. Yukawa constraints from Higgs distributions (Soreq)
6. CP violation in Higgs couplings ($\tau, ttH$) (Harnik)
Higgs to Inclusive Charm

- see talk by Elliot Reynolds for more details
- ATLAS measurement of $ZH \rightarrow \ell\ell cc$: arXiv:1802.04329
- current limit is roughly $100 \times \text{SM}$
- projection now available, roughly $6 \times \text{SM}$

\[ \text{ATLAS Simulation} \]
\[ \sqrt{s} = 13 \text{ TeV}, t\bar{t} \]

- $c$-jet rejection
- Light-jet rejection

\[ \text{Events / 10 GeV} \]

\[ \text{Data} / \text{Bkgd.} \]

\[ \text{ATLAS} \]
\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]
2 $c$-tags, $p_T^Z \geq 150 \text{ GeV} \]

\[ \text{Data} \]
- Pre-fit
- Fit Result
- $Z + \text{jets}$
- $t\bar{t}$
- $ZZ$
- $ZW$
- $ZH(b\bar{b})(100\times\text{SM})$

\[ \text{m}_{c\bar{c}} \text{[GeV]} \]

\[ \text{ATLAS Simulation} \]
\[ \sqrt{s} = 13 \text{ TeV}, t\bar{t} \]

- $c$-jet efficiency 41%
- $c$-jet efficiency 30%
- $c$-jet efficiency 20%
- 41% efficiency WP
Higgs to Inclusive Charm

- LHCb measurement of $VH \to ccl$: LHCb-CONF-2016-006
- current limit is roughly $6400\times$ SM
- rough projection of $4\times$ SM
- detailed study underway including $H \to bb$
Differential Cross-sections

- see talk by Thomas Klijnsma
- $p_T$ spectrum sensitive to couplings (low) and top mass (high)
- rapidity spectrum depends on gluon PDF

![Graph](image_url)

\[
\frac{(1/\sigma)d\sigma/dp_T,h)_{SM}}{(1/\sigma)d\sigma/dp_T,h)}
\]

\[
\Delta \chi^2 = 2.3 \quad \Delta \chi^2 = 5.99
\]

LHC Run I

HL-LHC

Ilten Higgs Working Group Summary 32 / 46
Charge Asymmetry

- see talk by Felix Yu for theory overview on Higgs flavour

\[ A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)} \]

RG effects calculated using RunDec [hep-ph/0004189]
Central: NNPDF2.3NLO
Shading: uncorrelated scale uncertainty

Expected 95\% statistical uncertainty
3 ab\(^{-1}\) LHC

Direct Higgs width

Charmed
Strange
Down
Up
Lepton Flavour Violation

- search by CMS for $H \rightarrow \tau\mu$ and $H \rightarrow \tau\tau$ : arXiv:1712.07173
- search by CMS for $H \rightarrow e\mu$ and $H \rightarrow e\tau$ : arXiv:1607.03561
- projections of results underway

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Higgs Working Group Summary
search by ATLAS for $H/Z \rightarrow Q\bar{Q}\gamma$: arXiv:1501.03276

projections by ATLAS for HL-LHC: ATL-PHYS-PUB-2015-043

no plans for CMS or LHCb projections

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$H \rightarrow \phi\gamma$ and $H \rightarrow \rho\gamma$

- search by ATLAS for $H/Z \rightarrow \rho/\phi\gamma$:
  - arXiv:1712.02758
- ATLAS projections are underway
- no plans for CMS or LHCb projections

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6 Invisible Decays
8 BSM Higgs
Invisible Decays Yellow Report Outline

- editors: **Anne Marie Magnan** (CMS), **Benjamin Nachman** (ATLAS)

1. Main channels for direct searches
2. Interpretation and combination with precision Higgs boson measurements (**Stefaniak, Robens**)
3. Higgs portal interpretations (**Stefaniak, Robens**)

Ilten

Higgs Working Group Summary
BSM Higgs Yellow Report Outline

- BSM editors: Martin Flechl (CMS), Lei Zhang (ATLAS), Martino Borsato (LHCb), Stefania Gori (theory)

1. Searches for additional Higgs bosons in fermionic final states ($\tau$, $b$, $\mu$, and $t$)
2. Searches for additional Higgs bosons in diboson final states
3. Searches for intermediate mass Higgs bosons (60 GeV – 120 GeV) (Heinemeyer)
4. Searches for low mass Higgs bosons (up to 60GeV)
5. Covering the MSSM and 2HDMs (J.M.No)
6. Covering Twin Higgs models (Redigolo)
7. Interference effects in heavy Higgs searches (M. Carena, Z.Liu)
8. New techniques for reconstructing highly boosted heavy Higgs bosons (Klimek)
Experiment Projections

- see talk by Ben Nachman
- two different scenarios
  - theory uncertainty drops by 50%, experimental uncertainty drops with luminosity up to a bound
  - experimental uncertainties are not bounded
- challenges include systematics, trigger, pile-up, quark-gluon tagging, and vertexing
- timing information can provide benefits
Precision and Invisible

- see talk by Tim Stefaniak
- theory interpretations in terms of minimal Higgs portal, standard model plus complex scalar singlet, etc.
- what to assume for the Higgs couplings and Higgs invisible decays at the HE-LHC?
## Experimental Projections

- see overview of projections in talk by Lei Zhang

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**Legend:**
- Past studies, Wishlist for 2018
MSSM and 2HDM

- overview of theory status given in talk by Andrea Thamm and talk by Sven Heinemeyer
- new heavy Higgs phenomenology projections in talk by Radovan Dermisek
Exotic Higgs Decays

- updates on phenomenology study given in talk by Andrea Thamm
- considers $H \rightarrow aa$, here $m(a) = 10$ GeV
Conclusions
Final Remarks

• we have our work cut out for us!
• need to be efficient but also rely on common sense
• modus operandi of accurate but not necessarily precise
• individual meetings per section and sub-section beginning
• discussion from this workshop has been very useful
• communication between theory and experiment is critical
• writing should be happening now, very rough drafts are fine!