Higgs @HL/HE-LHC

S. Jézéquel (LAPP-IN2P3)

On behalf of the Higgs Working group (WG2)
Higgs target in YR18

* Provide most complete picture of Higgs physics @ HL/HE-LHC
  * Update expected HL-LHC (3 ab$^{-1}$ @ 14 TeV) results
  * Include new topics (appeared in Run-2 analysis or new ideas)
  * Combine ATLAS-CMS results when statistically limited
  * HE-LHC (15 ab$^{-1}@ 27$ TeV) : First publication of expected performances

* Driven by
  * Final ATLAS/CMS detector optimisation for HL-LHC
  * Better understanding of particle/object reconstruction performances
    * Upgraded detector vs pileup ($<\mu> = 200$) vs trigger (5-7x nominal luminosity)
  * Improved analysis methods developed for Run-2 (2015+2016 data : 36 fb$^{-1}$)
  * Improved theoretical calculations and tools
  * Request from CERN management to evaluate physics potential of HE-LHC
WG2 - "Higgs and Electroweak symmetry breaking"

Contacts:
- Maria Cepeda (CMS), Philip Ilten (LHCb), Marumi Kado (ATLAS)
- Theorists: Stefania Gori, Francesco Riva

Informations: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2

Mailing list to join effort: hllhc-wg2@cern.ch
Experimental timeline : 2016-2017

- Technical Design Reports (TDR) for sub-detector upgrades @ HL-LHC
  - Final detector optimisation associated with particle/object performances
  - Demonstrate benefit from detector upgrades on benchmark physics channels (HL-LHC vs Run2 comparisons)
  - Analysis teams priority : Publish results with Run-2 data

→ Only few HL-LHC PUB notes
Experimental timeline : YR 18@ HL-LHC

- Do exhaustive and accurate review of physics channel performances
- Coherent approach between ATLAS/CMS and explore LHCb
- Benefit from recent analysis developments for Run2 publications
- Optimise available manpower

Methodology :
- Extrapolate Run2 results @ 14 TeV with HL-LHC integrated luminosity
- When possible : apply HL-LHC detector performances
  - Few benchmark channels to validate Run-2 extrap. with fullsim/Delphes
- Agree on scenarios for experimental systematics uncertainties
  - Conservative : Current Run-2
  - Optimistic : Define constant term limiting gain from high luminosity
- Quantify impact of theoretical systematics uncertainties : cross-section, jet modeling, ...
Activity on theory side
- Compute some inclusive and differential cross-sections @ 27 TeV
- Estimation of physics achievements with detector performances assumptions

Activity on experimental side
- Reminder: Priority for LHC experiments is to complete HL-LHC prospects
  → Only few selected analysis @ HE-LHC might be done by LHC exp. teams
    - HH: maybe
    - Others: probably not

Contribution only as extension of HL-LHC approach assuming same detector performances even if:
- Pileup per bunch-crossing: **200** (HL-LHC) → **800** (HE-LHC)
- Completely different detectors
Meetings among experiments: Already started

- List analysed physics channels per experiment
- Define coherent approach among experiments to prepare combination
  - Common data format
  - Build conservative and optimistic scenarios for experimental systematics uncertainties
- First target: Apply this approach in Proto PUB notes
Higgs chapter in YR 18

Vol. 1: Synthesis of results (150 pages)

1. Introduction
2. Precision Higgs physics
3. Di-Higgs production and Higgs self coupling
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 with HE/HL-LHC
9. BSM Higgs
10. Conclusions and outlook

Vol. 2: Collection of PUB notes

Adressed in this presentation
Others in backup
Detailed outline
in WG2 Twiki
Quick review of subjects addressed in this workshop

More detailed presentations during the Higgs session
1. Collaboration with LHC Higgs XS WG

- Platform for publication of most precise SM cross-section computations
  - Present LHC studies (13 TeV)
  - Future HL-LHC (14 TeV) / HE-LHC (27 TeV)

- Overlap between SM (WG1) and Higgs

- First meeting with Steering Committee last January
- Open meeting last week at CERN (link)

- Coordinated effort to decide on TH systematics scenarios
  - Define conservative/optimistic scenarios
2. Higgs cross-sections and couplings

信号强度精度 $\mu = \sigma / \sigma_{SM}^*$

- 当前公共结果基于Run-1外推，加上少数早期Run-2研究以及基于完整模拟的具体研究

- YR18：从Run-2结果重新外推
  - $\mu$, $\kappa$, $\kappa$ 比率（非系统误差受限）
  - 预期获得显著增益

- 之前外推方法主要受系统误差影响
  - TH/Exp系统误差情景需要重新考虑
    - 例子：ggF NNLO $\rightarrow$ N3LO
      (G. Salam报告在ECFA 16)
      - QCD比例尺误差：$(+7.4, -7.9) \rightarrow 3.9\%$
      - PDF和$\alpha_s$误差：$(+7.1, -6.0) \rightarrow 3.2\%$

$\mu = \sigma / \sigma_{SM}^*$

<table>
<thead>
<tr>
<th>$L$ (fb$^{-1}$)</th>
<th>$\kappa_\gamma$</th>
<th>$\kappa_W$</th>
<th>$\kappa_Z$</th>
<th>$\kappa_t$</th>
<th>$\kappa_t$</th>
<th>$\kappa_{Z\gamma}$</th>
<th>$\kappa_{H\gamma}$</th>
<th>$\text{BR}_{SM}$</th>
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<tbody>
<tr>
<td>300</td>
<td>$[5, 7]$</td>
<td>$[4, 6]$</td>
<td>$[4, 6]$</td>
<td>$[6, 8]$</td>
<td>$[10, 13]$</td>
<td>$[14, 15]$</td>
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<td>$[41, 41]$</td>
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<tr>
<td>3000</td>
<td>$[2, 5]$</td>
<td>$[2, 5]$</td>
<td>$[2, 4]$</td>
<td>$[3, 5]$</td>
<td>$[4, 7]$</td>
<td>$[7, 10]$</td>
<td>$[2, 5]$</td>
<td>$[10, 12]$</td>
</tr>
</tbody>
</table>
2. Differential cross-section

* Benefit from large dataset and go beyond inclusive measurement

* Sensitive to $\kappa_b/\kappa_c$ (low $p_T$) and $\kappa_t$/BSM (high $p_T$) with statistical limitation

* YR 18: Combination between experiments and interpretation
3. DiHiggs @ HL-LHC

- **Context:**
  - 120 k events produced
  - High background (bbbbb, bbττ) or low B.R. (bbgg)
- **Targets:**
  - First observation of HH production
  - Measure $\lambda_{HHH}$ and $\kappa_t$ (top-Yukawa coupling)

- Strong dependance on $p_T(4\text{jets})$ trigger threshold
- Precision limited by QCD multijet uncertainty
### 3. DiHiggs @ HL-LHC (2)

<table>
<thead>
<tr>
<th>Channel</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH → bbbb</td>
<td>$Z(\sigma_{HH}(SM))=0.39\sigma$</td>
<td>$-4.1 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 8.7$ @95 % C.L.</td>
</tr>
<tr>
<td>HH → bbττ</td>
<td>1.6 $\times$SM</td>
<td>0.6 $\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-4.0 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 12.0$ @95 % C.L.</td>
</tr>
<tr>
<td>HH → bbγγ</td>
<td>1.43 $\sigma$</td>
<td>1.5 $\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.2 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 6.9$ @95 % C.L. (stat only)</td>
</tr>
<tr>
<td>HH → WWbb</td>
<td>0.45 $\sigma$</td>
<td></td>
</tr>
<tr>
<td>tt(HH → bbbb)</td>
<td></td>
<td>0.35 $\sigma$</td>
</tr>
</tbody>
</table>

* Most results will be updated for YR18 mainly based on Run2 extrapolation
  - Improve significance for HH production
  - Benefit from kinematic distributions ($m_{HH}$) for couplings ($\lambda,...$)
* Combination to be done: Channels and experiments (+ single H ?)
3. DiHiggs @ HE-LHC

- Gain compared to HL-LHC
  - Signal cross-section: $\times 4$
    - Same factor or lower for background
  - Integrated luminosity: $\times 5$
  - Possibility to observe rare final states
  - Reduction of stat. error by factor $\sim 4$

- Recent theory study on HE-LHC prospect (arXiv:1802.04319)
  - $\sim 30\%$ precision in $\lambda$ just from $HH \rightarrow b\bar{b}\gamma\gamma$
4. ttH : Top-Higgs Yukawa coupling

- Benchmark channel for HL-LHC
- First evidence of ttH production with Run-2 data (ATLAS+CMS)
- Addressing systematics uncertainties : critical
- YR 18 : Complete overview of decay channels

Extrapolated from 12.9 fb⁻¹ @13 TeV
4. VH, VBF/VBS

* VH: First observations @ Run-2
  - ATLAS: $\mu = 1.20^{+0.42}_{-0.36}$
  - CMS: $\mu = 1.06^{+0.31}_{-0.29}$

* Vector Boson Fusion/Scattering:
  - Probe for ElectroWeak Symmetry Breaking
  - Benchmark for forward detector optimisation (TDR)

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**ATLAS Simulation**

\[ \text{Events / 325 GeV} \]

- WW, Z-jets, Single Top, W+jets, Z+H, WZ/ZZ, ggH, VBF H

**ATLAS TDR-025**

\[ VBF \text{ ZZ} \rightarrow 4 \ell : \text{ATL-PHYS-PUB-2016-008} \]
7. Rare decays: $H \rightarrow \mu \mu$

- Probe for fermion of second generation
- 0.02 % branching ratio

- Benchmark for detector upgrade
- Run-1 → Phase 2: Gain 65 % in $m_{\mu\mu}$

- Expected precision: $\mu \sim 8 \%$ / $\kappa_\mu \sim 5 \%$
7. LHCb : $H \to bb$ and $H \to cc$

* Search for leptonic $W/Z+ H \to bb/cc$ final states (Forward production)
* LHCb angular acceptance → Challenging for integrated cross sections and uncertainties

First publication $H \to cc$ from LHCb → Possible reach 5 xSM @ 300 fb$^{-1}$

Extrapolation $H \to J/\Psi \gamma$ @ HL-LHC : 15 xSM @ 3000 fb$^{-1}$ (ATLAS)

$ZH \to cc$ @ Run-2 (arxiv:1802.04329): $\mu < 110 \ (150^{+80}_{-40})$ @ 95 % C.L. (ATLAS)
7. Exotics decay

- B.R. \((H \rightarrow \text{exotics})\) still allowed at 5 % level by Higgs fits @ HL-LHC

- Many Run-2 analysis published recently targeting new exotic decays but extrapolations to HL-LHC still to be done
  - Invisible
  - Lepton Flavor Violation (LFV)
  - Displaced vertices
Existing prospects for direct searches: $H \rightarrow \mu\mu$, $H \rightarrow \tau\tau$, $A \rightarrow ZH$

Results revisited with Run2 expertise

Not done

- Search for scalars in other final states (ex: Low mass $\gamma\gamma$)
- Search for $H \rightarrow t\bar{t}$
9. High mass Higgs $\rightarrow \tau\tau$

* Most sensitive final state for direct search of additional Higgs boson predicted by MSSM

Model independent:
- limit on ggF or bbH

Model dependent: $m_A - \tan \beta$

Limited by statistics especially at high mass
## Expected coverage by LHC experiments

<table>
<thead>
<tr>
<th>Category</th>
<th>CMS</th>
<th>ATLAS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Couplings Studies</td>
<td>✓ ✓ ★</td>
<td>✓ ✓ ★</td>
<td></td>
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<tr>
<td>Differential CrossSections</td>
<td>✓ ★</td>
<td>✓ ★</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>CPV</td>
<td>✓ ★</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Rare Decays</td>
<td>μμ, cc</td>
<td>Zγ,J/ψγ,FCNCμμ,ργ,cc</td>
<td>Hcc/Hbb</td>
</tr>
<tr>
<td>Exotic Decays</td>
<td>LFV; Invisible, DarkSusy; 4jets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DiHiggs</td>
<td>✓ ✓ ★</td>
<td>✓ ✓ ★</td>
<td></td>
</tr>
<tr>
<td>Additional Scalars</td>
<td>A→Zh, high mass ττ, low mass γγ</td>
<td>μμ, ZZ, A→Zh, ττ, WW</td>
<td></td>
</tr>
</tbody>
</table>

**Legend:** Past Studies, 2017 TDRs, Wishlist for 2018

Stay tuned: CMS public page, ATLAS public page

**Courtesy M. Cepeda**

**Higgs at LHeC : U. Klein**
10. Conclusion

HL-LHC: First Higgs factory

- Higgs couplings and differential cross-sections: Precision regime
- Rare decays accessible
- Probe to New Physics

2012-2014: First attempt to estimate Higgs physics potential (Run-1 based)
2016-2017: Transition period (Upgrade TDRs, Run-2 analysis, theory dev.)
- Source of many improvements

2018: Common effort to:
- Recompute expected Higgs physics performances
  - Define conservative and optimistic scenarios for syst. uncertainties
  - Document results in YR18

HE-LHC physics potential: Based on scratch program recycling HL-LHC tools

Presentations in Higgs session:

Opportunity for lively discussions → Input for final work
Backup
1. Introduction: Main goals and timeline

2. Precision Higgs physics
   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
   4. Progress on TH uncertainties: what to expect?
   5. Impact from PDFs and alphaS on Higgs measurements.
   6. Progress on Higgs specific MC.
   7. Higgs couplings precision overview.
   8. Probes using differential distributions of CP sensitive observables (and other dimension -6).
   9. Interpretation in terms of Composite Higgs and the MSSM.

3. Di-Higgs production and Higgs self couplings
   1. SM calculation
   2. Double Higgs measurements and trilinear coupling.
   3. Indirect probes of the trilinear coupling through differential distributions measurements.
   4. Indirect probes through single Higgs boson production.
   5. Theory Implications (including a critical view of the validity of direct and indirect trilinear couplings measurements.

4. Other high energy probes
   1. Measuring Offshell couplings
   2. tth differential measurements
   3. WH/ZH at high energy/luminosity
   4. WW WZ at high energy/luminosity
   5. VBF
   6. longitudinal VBS and di-higgs

5. The higgs boson mass and width
   1. Theory review
   4. Direct constraints from the Higgs boson lineshape.
   5. Direct constraints from the Higgs boson lifetime measurements.
   6. Width from Off-Shell higgs boson coupling.
   7. Width from the diphoton interference rate.

6. Invisible decays of the Higgs boson
   1. Main channels for direct searches.
   2. Interpretation and combination with precision Higgs boson measurements.
   3. Higgs portal interpretations.

7. Higgs flavor and rare decays
   1. Flavor aspects Yukawa modifications in flavor models
   2. Exclusive Higgs decays
   3. Flavor tagging (charm and strange) exp mostly
   4. LFV decays of the Higgs exp mostly (CMS can try to cover this)
   5. Yukawa constraints from Higgs distributions
   6. CP violation in Higgs couplings (tau, tH) exp mostly

8. BSM Higgs
   1. Searches for additional Higgs bosons in fermionic final states (taus, b's, muons and tops)
   2. Searches for additional Higgs bosons in diboson final states.
   3. Searches for intermediate mass Higgs bosons (60 GeV - 120 GeV)
   4. Searches for low mass Higgs bosons (up to 60 GeV).
   5. Covering the MSSM, 2HDMs and the NMSSM, composite Higgs.
   6. Searches for unconventional signatures of additional Higgs bosons.
   7. Searches for exotic decays of the Higgs boson.

9. Conclusions and outlook
ECFA scenarios

- **ECFA S1**: All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be unchanged with respect to the reference analysis;
- **ECFA S1+**: All systematic uncertainties are kept constant with integrated luminosity. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account [4];
- **ECFA S2**: Theoretical uncertainties are scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are not taken into account;
- **ECFA S2+**: Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account [4].

[https://cds.cern.ch/record/2266165/files/FTR-16-002-pas.pdf]
H couplings

**ATLAS Simulation Preliminary**

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

### H → γγ
- (comb.)
  - (0j)
  - (1j)
- (VBF-like)
- (WH-like)
- (ZH-like)
- (tth-like)

### H → ZZ
- (comb.)
  - (VH-like)
  - (tth-like)
- (VBF-like)
- (ggF-like)

### H → WW
- (comb.)
  - (0j)
  - (1j)
- (VBF-like)

### H → Zγ
- (incl.)

### H → bb
- (comb.)
  - (WH-like)
  - (ZH-like)

### H → ττ
- (VBF-like)

### H → μμ
- (comb.)
  - (incl.)
  - (tth-like)

\[ \Delta \mu/\mu \]

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**ATL-PUB-PHYS-2014-016**
2. Coupling: $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$

Update based on 12.9 fb$^{-1}$ of data at 13 TeV
Effect of high pileup and detector performance considered based on the CMS Upgrade TP (LHCC-P-008)
2. Cross-sections @Run2: \( H \rightarrow ZZ \) and \( H \rightarrow \gamma\gamma \)

**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

\( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ \rightarrow 4l \)

\( m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \)

**CMS Preliminary**

35.9 fb\(^{-1}\) (13 TeV)

- Observed
- \( \pm 1\sigma \) (stat+sys.)
- \( \pm 2\sigma \) (stat+sys.)
- SM prediction

**Stage 0 Simplified Template Cross Sections**

- \( |y_H| < 2.5 \)

- \( t\bar{t}H \)
2. Width

Off-shell measurements

\( gg \rightarrow VV, \, gg \rightarrow H^* \rightarrow VV \)

Interference in

\( gg \rightarrow \gamma\gamma, \, gg \rightarrow H \rightarrow \gamma\gamma \)

\( \Delta m_H, [\text{MeV}] \)

\( \Gamma_H \sim <40-50 \Gamma_{SM} \)

ATL-PHYS-PUB-2015-024
2. Anomalous couplings

\[ A(HVV) \sim \left[ a_{1}^{VV} + \frac{\kappa_{1}^{VV} q_{1}^{2} + \kappa_{2}^{VV} q_{2}^{2}}{(\Lambda_{1}^{VV})^{2}} \right] m_{V_{1}}^{2} \epsilon_{V_{1}}^{*} \epsilon_{V_{2}}^{*} + a_{2}^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_{3}^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}. \]

Parametrisation of anomalous couplings:

\[ f_{ai} = \frac{|a_{i}|^{2} \sigma_{i}}{\sum |a_{j}|^{2} \sigma_{j}} \quad \phi_{ai} = \text{arg} \left( \frac{a_{i}}{a_{1}} \right) \]

Reach percent level but still stat. limited
2. Differential xsection

**ATLAS Simulation**

\[ H \rightarrow ZZ^* \rightarrow 4l \]

14 TeV, 3000 fb\(^{-1}\)

- Expectation HL-LHC
- Syst. uncertainties
- Total unc. Run 2, 30 fb\(^{-1}\)
- PowHeq (q\(g\)) + XH
- XH = V3F, WH, ZH, H\(+H\), bbH

**CMS Phase-2 Simulation**

3000 fb\(^{-1}\), 14 TeV, 200 PU

- Z+X
- Z\(\gamma^*, ZZ\)
- \(m_{\gamma^*}=125\) GeV

CMS-TDR-17-003

118 < \(m_{\gamma^*}\) < 130 GeV
3. DiHiggs @ HL-LHC

HH production at 14 TeV LHC at (N)LO in QCD

$M_H=125$ GeV, MSTW2008 (N)LO pdf (68%cl)

$\sigma_{(N)LO}[fb]$ vs $\lambda/\lambda_{SM}$

- $pp \rightarrow HH$ (EFT loop-improved)
- $pp \rightarrow HHjj$ (VBF)
- $pp \rightarrow ttHH$
- $pp \rightarrow WHH$
- $pp \rightarrow ZHH$
- $pp \rightarrow jjHH$

MadGraph5_aMC@NLO
3. Cross-sections HH and background
3. HH → bbbb

ATLAS Preliminary
$\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$

ATL-PHYS-PUB-2016-024

Background uncertainty scale relative to current level

ATLAS Simulation Preliminary
5% C.L. exclusion limit on $\sigma/\sigma_{SM}$
$\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$

ATLAS Pixel TDR

(a) No Systematics

(b) With Systematics
7. Rare decays

Expected branching ratio limit (no syst.) :
\[ \mathcal{B}(H \to J/\Psi \gamma) < (44^{+19}_{-12}) \times 10^{-6} \] @ 95% C.L.

Standard Model expectation : \((2.9 \pm 0.2) \times 10^{-6}\)
7. Rare decays: $H \rightarrow$ light quarks

*Probe for fermion of second/first generation*

![Graph showing Higgs boson decay](chart.png)

**Table:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Final state</th>
<th>Exp. SM $\times 10^{-6}$</th>
<th>Run2 limit @ 95% C.L. $\times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \rho \gamma$</td>
<td>$\pi^+\pi^- \gamma$</td>
<td>$16.8 \pm 0.8$</td>
<td>880</td>
</tr>
<tr>
<td>$H \rightarrow \phi \gamma$</td>
<td>$K^+K^- \gamma$</td>
<td>$2.31 \pm 0.11$</td>
<td>480</td>
</tr>
</tbody>
</table>

arXiv:1712.02758
9. Other BSM searches