Latest Results from the LHC and Prospects for HL-LHC

Karl Jakobs
University of Freiburg / Germany

Joint Kavli IPMU – ICEPP Symposium, 18th June 2018
Latest Results from the LHC and Prospects for HL-LHC

- Status of LHC Data Taking in Run 2
- A summary of recent results from the LHC
  Where do we stand? Focus on Higgs boson physics
- Prospects for HL-LHC
  With focus on Higgs boson physics

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**Data taking in Run 2**

- Excellent performance of the accelerator and of the experiments
- The ATLAS and CMS experiments have recorded \( >100 \text{ fb}^{-1} \) in Run 2 (\( \sqrt{s} = 13 \text{ TeV} \)); High data taking efficiency
- Stiff luminosity slope in 2018, better running conditions than in 2017 (no luminosity levelling necessary)
Data taking in Run 2

\[ \int L dt = 100.8 \text{ fb}^{-1} \]

\begin{align*}
2015: & \langle \mu \rangle = 13.4 \\
2016: & \langle \mu \rangle = 25.1 \\
2017: & \langle \mu \rangle = 37.8 \\
2018: & \langle \mu \rangle = 39.2 \\
Total: & \langle \mu \rangle = 33.0
\end{align*}
Pileup in 2017

A clear event with four identified muons, however, from two independent har scattering events in the same bunch crossing (see z-vertex reconstruction)
The Physics Messages from the LHC  
- a summary from the first 8 years-

(i) The Standard Model has been tested at the highest energies

High LHC intensities (excellent machine and detectors)  
→ rarer and rarer processes are being explored

(ii) A Higgs boson has been discovered (2012)

The properties of the discovered Higgs boson are in agreement with the predictions of the Standard Model  
-within the present uncertainties-

(iii) No Physics Beyond the Standard Model has been discovered (yet)
The mission of the LHC for the next decade (HL-LHC)

(i) Continue the direct searches for Physics Beyond the Standard Model at the highest energies

→ Address more complex scenarios

(ii) Exploration of the Higgs sector

- Does the discovered Higgs particle have the properties as predicted in the Standard Model? (higher precision, access to rare decay modes)

- Investigation of the Higgs boson self-coupling
  → Higgs boson potential

(iii) Precision Measurements

- Precision measurements of Standard Model processes and parameters
- Measurement of rare processes
Summary of recent results from the LHC

Di-jet event with the highest di-jet invariant mass of $m_{jj} = 9.3$ TeV recorded during 2017
Double differential jet production cross sections, as a function of $p_T$ and rapidity $y$ (full 2015 data set, $\sqrt{s} = 13$ TeV)

- Also at the highest energies explored so far, the data are well described by NLO perturbative QCD calculations (NLOJet++)
- Latest comparisons to NNLO predictions (NNLOJet) [J. Currie, N. Glover, T. Pieres, Phys. Rev. Lett. 118 (2017)] → improved agreement, however, scale dependent
Search for new phenomena in di-jet events

• First publication on complete Run-2 (2015+2016) dataset: 37.0 fb$^{-1}$ at $\sqrt{s} = 13$ TeV

95% CL exclusion limits:

- Excited quarks: $m_{q^*} > 6.0$ TeV (5.8 TeV exp.)*
- Add. gauge bosons: $m_{W^*} > 3.6$ TeV (3.7 TeV exp.)
- Quantum Black Holes: $m_{BH} > 8.9$ TeV (8.9 TeV exp.)
- Contact Interactions:
  - $\Lambda > 13.1$ TeV ($\eta_{LL} = +1$)
  - $\Lambda > 21.8$ TeV ($\eta_{LL} = -1$)

*pre-LHC limit on excited quarks from the Tevatron: 0.87 TeV
Huge progress also on the theoretical side: (N)NLO QCD / el.weak corrections
Status of Higgs Boson measurements
Results of Searches for $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ at 13 TeV

- Impressive signals in these high-resolution bosonic decay channels 
  (Data collected during 2015 and 2016 in Run 2 at 13 TeV)

- Observation with a significance of $> 5\sigma$ in each channel
H → γγ signals for various categories

a) untagged categories
(expected to be dominated by gluon fusion)

b) VBF categories
(tag-jet configuration, Δη, m_{jj})

c) VH categories
(one-lepton, E_{T}^{miss}, low-mass di-jets)

d) ttH categories
(lepton, jets, b-jet(s))
Differential cross-section measurements

- Data are well described by theoretical calculations (within large uncertainties)
- Such measurements will become important ingredients for future measurements of Higgs boson parameters (Effective Field Theories)
H → WW* → ℓν ℓν signal

- Large branching fraction, however, also severe backgrounds (no mass peak, due to neutrinos)
- → Rely on lepton/jet kinematics  (→ transverse mass $M_T$, di-lepton invariant mass $m_{ll}$, $\theta_{ll}$)

* Very significant excesses visible in the “transverse mass” and $m_{ll}$ distributions

ATLAS: gluon fusion  $6.3\sigma$ observed  (5.2$\sigma$ expected)
CMS: total  $9.1\sigma$ observed  (7.1$\sigma$ expected)
**Couplings to fermions?**

- **Quarks**
  - u, c, t, d, s, b
  - up, charm, top, down, strange, bottom

- **Leptons**
  - e, μ, τ
  - electron, muon, tau
  - νₑ, νₘ, νₜ
  - electron neutrino, muon neutrino, tau neutrino

- **Forces**
  - Z, γ, W, g
  - Z boson, photon, W boson, gluon

**Search for** $H \rightarrow ττ$ **and** $H \rightarrow bb$ **decays, and ttH production**

Couplings to bosons well established in Run 1 and nicely confirmed in Run 2.
**Couplings to quarks and leptons?**

- Search for $H \rightarrow \tau\tau$ and $H \rightarrow bb$ decays;

- Challenging signatures due to jets ($bb$ decays) or significant fraction of hadronic tau decays

- Vector boson fusion mode essential for $H \rightarrow \tau\tau$ decays

- Associated production WH, ZH modes have to be used for $H \rightarrow bb$ decays

- Exploitation of multivariate analyses
Couplings to Fermions: $H \rightarrow \tau\tau$

- Search for $H \rightarrow \tau\tau$ with $\tau\tau$ decaying in $e\mu$, $\mu\tau$, $\tau_h\tau_h$, and $\tau_h\tau_h$
- Largest background from $Z \rightarrow \tau\tau$ and hadronic multi-jet events
- Search in categories aiming at $ggH$ and VBF production

Observation of $H \rightarrow \tau\tau$

Significance:
- CMS: 5.9\(\sigma\)
- ATLAS: 6.4\(\sigma\)

(combination of Run-1 and Run-2 data)
Search for $H \rightarrow bb$ decays

- $H \rightarrow bb$ mode dominates Higgs decays (BR~58%)
- Most sensitive channel exploits VH, $H \rightarrow bb$ (V=W/Z)
- Combined ATLAS+CMS significance 2.6$\sigma$ (3.7$\sigma$ expected) from LHC Run-1

- Combination of Z and W final states characterised by lepton multiplicity: (2-lepton ($Z \rightarrow \ell\ell$), 1-lepton ($W \rightarrow \ell v$), and 0-lepton ($Z \rightarrow vv$))

Combination of result with ATLAS Run-1 gives 3.6$\sigma$ observed (4.0$\sigma$ expected)
Search for ttH Production

- Direct access to top-Yukawa coupling
- Rich decay topologies; final states with leptons, jets, b-jets, photons
- Combination of all channels leads to $4.2\sigma$ observed ($3.8\sigma$ expected) (Phys. Rev. D97 (2018) 072003)

- In addition, Run-1 sensitivity of $2.7\sigma$ observed ($1.8\sigma$ expected) (JHEP08 (2016) 045)

- Measured production and decay rates consistent with SM expectation
Observation of ttH production


Observation of ttH production:
(combination of Run-1 and Run-2 data)

\[ \mu = 1.26^{+0.31}_{-0.26} \]

Significance: 5.2\(\sigma\) (obs.), 4.2\(\sigma\) (exp.)
Including the 2017 data for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$

**Observation of $ttH$ production with larger significance**

$\mu = 1.32^{+0.28}_{-0.26}$

Significance: $6.3\sigma$ (obs.), $5.1\sigma$ (exp.) (Run-1 + Run-2 data)

*Higgs signal appears in $\gamma\gamma$ final states*
Combined ATLAS & CMS Higgs analysis — Run-1 legacy

ATLAS & CMS Run-1 combination of Higgs coupling measurements

[ arXiv:1606.02266 ]

Higgs production processes

<table>
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<th>Process</th>
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<th>CMS</th>
<th>ATLAS+CMS</th>
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Higgs decay processes

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<tr>
<td>Wγ</td>
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</table>

Agreement among experiments

Overall signal strength (Run-1): \( \mu = 1.09 \pm 0.11 \) (A & C)

Run-2: \( 1.17 \pm 0.10 \) (CMS, all channels, 0.06 stat/syst/sig),
\( 1.09 \pm 0.12 \) (ATLAS, ZZ* + γγ)

Note that the least model-dependent observables at the LHC are ratios of couplings
Search for Physics beyond the Standard Model

@ Hitoshi Murayama, IPMU Tokyo & Berkeley
Search for Supersymmetry
-Important new results with complete 2015-2016 dataset-

Gluino mass limit beyond 2 TeV, $m(\chi^0) = 0$

Data well described by expectations from SM processes

Results on dedicated searches for stop quarks

- Weaker mass limits for partners of the top quark (lower production rate, $t\bar{t}$ background)
- However, significant progress, with mass limits $\sim$1 TeV (light neutralinos), including coverage for complex decay scenarios
Results on electroweak SUSY production

The 95% CL exclusion limits on \( \chi_1^+ \chi_1^- \), \( \chi_1^\pm \chi_2^0 \) and \( \chi_2^0 \chi_3^0 \) production with either SM-boson-mediated or \( \ell \)-mediated decays, as a function of the \( \chi_1^\pm \), \( \chi_2^0 \) and \( \chi_3^0 \) masses. The production cross-section is for pure wino \( \chi_1^+ \chi_1^- \) and \( \chi_1^\pm \chi_2^0 \), and pure higgsino \( \chi_2^0 \chi_3^0 \).
Electroweak SUSY sensitivity beyond LEP limits

Interesting limits for electroweak SUSY production with compressed mass states (left): First direct Higgsino constraints from ATLAS (combination of several analyses)

(right): Exclusion of slepton masses up to 190 GeV
**ATLAS Exotics Searches** - 95% CL Upper Exclusion Limits

**Status:** July 2017

\[ \int \mathcal{L} \, dt = (3.2 - 37.0) \, \text{fb}^{-1} \]

\[ \sqrt{s} = 8, 13 \text{ TeV} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets(^\dagger)</th>
<th>( E_{\text{miss}}^{\text{miss}} )</th>
<th>Limit</th>
<th>Reference</th>
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<td>-</td>
<td>36.7</td>
<td>(\ell, \gamma ) mass</td>
</tr>
<tr>
<td>Bulk RS GUK + ( WW \to q\bar{q}v\nu )</td>
<td>1 e, \mu</td>
<td>1 J</td>
<td>Yes</td>
<td>36.1</td>
<td>(\ell, \gamma ) mass</td>
</tr>
</tbody>
</table>

**Extra dimensions**

**Gauge bosons**

**SM Z \to t\bar{t}**

**Higgs boson**

**Extra dimensions**

**DM**

**CI – ICEPP Symposium, K. Jakobs, 18th May 2017**

**QQ, BB, TT**

**CI quark**

**CI gluon**

**CL u/f**

**Axial-vector mediator (Dirac DM)**

**Vector mediator (Dirac DM)**

**Scalar LQ 1st gen**

**Scalar LQ 2nd gen**

**Scaler LQ 3rd gen**

**VLO TT \to Ht + X**

**VLO TT \to Zt + X**

**VLO TT \to Wh + X**

**VLO BB \to Hb + X**

**VLO BB \to Zb + X**

**VLO BB \to Wh + X**

**VLO QQ \to WjWj**

**Excited fermions**

**LHiggs Majorana\( \nu \)**

**Other**

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ \sqrt{s} = 13 \text{ TeV} \]

*Only a selection of the available mass limits on new states or phenomena is shown.*

\(\dagger\) Small-radius (large-radius) jets are denoted by the letter \(j\) (J).
The next steps
Phase-II:
The High-Luminosity LHC

LHC / HL-LHC Plan

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Expected integrated luminosity of LHC and HL-LHC

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\mathcal{L}_{\text{inst}}$ [10^{-34} cm^{-2}s^{-1}]</th>
<th>$\mu$ [fb^{-1}]</th>
<th>$\int \mathcal{L}$ per year [fb^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>5</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>Ultimate</td>
<td>7.5</td>
<td>200</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

We are here

[Graph showing the expected integrated luminosity for LHC and HL-LHC with various configurations and years.]

© P. Ferreira da Silva at Moriond EW, 2016
Expected integrated luminosity of LHC and HL-LHC

HL-LHC: Configuration | $\mathcal{L}_{\text{inst}} \left[10^{34} \text{cm}^{-2} \text{s}^{-1}\right]$ | $\langle \mu \rangle$ | $\int \mathcal{L} \text{ per year} [\text{fb}^{-1}]$
---|---|---|---
Baseline | 5 | 140 | 250
Ultimate | 7.5 | 200 | >300

HL-LHC inclusive Higgs sample will be 23 times larger (30 times for 4 ab$^{-1}$) than that expected for full Run-2 (~150 fb$^{-1}$ at 13 TeV)

With 3 ab$^{-1}$: 190 million H and 120 thousand HH (ggF) produced (SM)
All six TDRs of the ATLAS Phase-II Upgrade programme have been presented by ATLAS, reviewed and approved by the LHCC and UCG, and finally approved by the CERN Research Board.

… but also a huge amount of work ahead of us..
14 TeV / 13 TeV cross-section ratios

Minimum bias 1.02
W 1.08
Z 1.09
ZZ 1.11
t (s-channel) 1.10
t (t-channel) 1.14
Wt 1.18
WH 1.10
H (ggF) 1.13
H (VBF) 1.13
HH 1.19
tt 1.18
ttZ 1.20
ttH 1.21
stop pair (0.9 TeV) 1.37
gluino pair (2.0 TeV) 1.73
Z' SSM (4 TeV) 1.40
q* (6 TeV) 2.0
QBH (9 TeV, n=6) 5.3
Methodology of HL-LHC studies

- The experiments use full or parameterised fast simulation tuned to full simulation of upgraded detectors, together with overlaid pileup and simplified analyses to explore HL-LHC reach

- Alternatively, current full analyses are extrapolated to HL-LHC energy and conditions

  - In both cases bold assumptions on evolution of theoretical uncertainties made

  - Both methods suffer from caveats. Many studies are conservative

  - Most of the studies shown here will be updated for the HL-LHC Yellow report; under preparation, will appear by end of this year

  - All studies shown here for 3 ab\(^{-1}\) and assuming 200 or 140 pileup events on average per bunch crossing
Prospects for standard SUSY searches

ATLAS Simulation Preliminary

HL-LHC 95% C.L. exclusion limits for gluinos up to ~ 3 TeV
Prospects for standard SUSY searches (cont.)

ATLAS Simulation Preliminary

$\bar{\chi}^0_1 - m_0 < \bar{\chi}^0_2 \rightarrow \bar{\chi}^0_1 Z \bar{\chi}^0_1$

$\sigma_{bg} = 30\%$

HL-LHC 95% C.L. exclusion limits for charginos / neutralinos up to ~ 1.1 TeV
Prospects for standard SUSY searches (cont.)

HL-LHC 95% C.L. exclusion limits for stops up to ~ 1.5 TeV
Higgs physics programme at the LHC in a nutshell

Higgs boson properties:
- Mass (well known), width (through interference measurements)
- Spin ($0^+$ established), CP (odd admixture possible) — not discussed today

Rare Higgs boson decays:
- Observation of $H \rightarrow \mu\mu, H \rightarrow Z\gamma$, HH production (constraint on Higgs boson self coupling)
- Search for very rare (e.g., $H \rightarrow M\gamma$, $M=J/\psi, \phi, \rho$), difficult ($H \rightarrow cc$) or anomalous decays (invisible or new particles, or flavour violating)

Higgs boson couplings:
- Study of Higgs boson production and anomalous couplings by differential cross-section measurements
- Global and partially global coupling fits: experiments moving from “kappa” interpretation to EFT

New physics in Higgs boson production or other scalar states:
- Search for anomalous FCNC through top decays, Higgs production via SUSY cascades, etc.
- Search for additional scalar particles
Coupling to 2nd generation: Higgs decay to $H \rightarrow \mu\mu$ (BR: 0.022% in SM)

Upgraded detectors feature improved di-muon mass resolution

→ Cross-section times branching fraction measurement to ~13% (ATLAS), 10% (CMS) precision for 3 ab$^{-1}$

Challenging data-driven Drell-Yan background determination
Rare loop decay to $H \rightarrow Z\gamma$ (BR: 0.15% in SM, 0.010% with $Z \rightarrow ee, \mu\mu$)

Large background from $Z$ production with radiative photons

Observation with combined ATLAS & CMS dataset expected with $3 \text{ ab}^{-1}$

Combined statistical precision of about 15% on cross-section

Challenging data-driven background determination

Also searches for, eg, $H \rightarrow J/\psi \gamma$ with expected sensitivity of 15 times SM prediction (BR: $2.9 \times 10^{-6}$)
Di-Higgs boson production

HH cross section predicted to 40 ± 2 fb at 14 TeV, i.e., >1000 times smaller than for single Higgs production

**Sophisticated analyses needed, room for innovation;**
Extrapolation uncertainty in continuum background prediction

Best channels: bbγγ (BR = 0.26%), bbττ (7.3%), bbbb (33%), bbWW, 25% → combination

Currently (36 fb$^{-1}$ at 13 TeV) for bbγγ: $\mu_{HH} < 19$ ($17_{\exp}$) [CMS, using LO signal simulation, some effect on acceptance]

Projection to HL-LHC (bbγγ, 2017): ~1.5σ significance, CMS combines w/ bbττ in HL-LHC TP (2015): 1.9σ

It is not yet established which of the three main channels will be best

The bbbb channel strongly depends on the lowest jet $p_T$ trigger threshold and on top background modelling

Combining ATLAS and CMS in all channels, hoping for analysis improvements, and including new channels may give 3σ HH sensitivity with 3 ab$^{-1}$
Constraints on Higgs trilinear self coupling $\lambda_{HHH}$

Constraint on $\lambda_{HHH}$ by simulating NLO MC HH samples for different $\lambda_{HHH}$ values. Effects on total HH cross section and acceptance

Projection to HL-LHC ($bb\gamma\gamma$, 2017)

95% CL limit: $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ ($bb\gamma\gamma$)

These analyses use only inclusive rates. Fitting differential variables such as $m_{HH}$, $p_{T,H}$ close to threshold should allow to improve the constraint on $\lambda$ (but hard for $bb\bar{b}\bar{b}$ channel, so $bb\gamma\gamma$ and $bb\tau\tau$ might be best for $\lambda$)

[See, e.g., 1607.07441]

$\lambda_{HHH}$ also affects single-H production at NLO through internal H loops

→ Complementary information from differential H cross-section measurements

LO diagrams contributing with negative interference to SM HH production

Box diagram dominates inclusive production

Sensitivity to H self coupling rises at low $m_{HH}$
Off-shell coupling measurement

Both CMS and ATLAS have constrained the Higgs off-shell coupling and through this obtained upper limits on the Higgs total width $\Gamma_H$. Current limit $\Gamma_H < 22$ MeV at 95% CL ($\Gamma_{H,SM} = 4.1$ MeV).

The method uses the independence of off-shell cross section on $\Gamma_H$ and relies on identical on-shell and off-shell Higgs couplings. One can then determine $\Gamma_H$ from measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$

\[
\mu_{\text{off-shell}}(\hat{s}) = \frac{\sigma_{\text{gg} \rightarrow H* \rightarrow VV}^{\text{off-shell}}(\hat{s})}{\sigma_{\text{gg} \rightarrow H* \rightarrow VV}^{\text{off-shell, SM}}(\hat{s})} = \kappa_{g,\text{off-shell}}^2(\hat{s}) \cdot \kappa_{V,\text{off-shell}}^2(\hat{s})
\]

\[
\mu_{\text{on-shell}} = \frac{\sigma_{\text{gg} \rightarrow H \rightarrow ZZ}^{\text{on-shell}}}{\sigma_{\text{gg} \rightarrow H \rightarrow ZZ}^{\text{on-shell, SM}}} = \frac{\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{Z,\text{on-shell}}^2}{\Gamma_H / \Gamma_{H,SM}^{\text{SM}}}
\]

With $L_2 = 3000$ fb$^{-1}$, one may find:

\[
\mu_{\text{off-shell}}^{(L_2)} = 1.00^{+0.43}_{-0.50} \text{ (stat+sys)}
\]

\[
\Gamma_H^{(L_2)} = 4.2^{+1.5}_{-2.1} \text{ MeV (stat+sys)}
\]

ATLAS: ATL-PHYS-PUB-2015-024

Large theory uncertainty (~30%) from gg $\rightarrow$ ZZ
Constraints on invisible Higgs boson decays

If dark matter (DM) is a thermal relic of the early universe and it is light enough so the Higgs can decay to it, it leads to invisible Higgs decays.

Such decays can be detected through Higgs VBF, ZH or ISR-jet production, or in a model-dependent way through the coupling fit (e.g., assuming SM couplings to SM particles).

Best limit of ~3% on $H \rightarrow$ invisible branching fraction at 3 ab$^{-1}$ (reminder: current limit: 24%)

However, systematics limited, so difficult extrapolation.

An extrapolation of the combined coupling fit under SM hypothesis gives $H \rightarrow$ invisible limits of 9% (13% when including theory uncertainties).

ATL-PHYS-PUB-2014-017
Higgs boson couplings — ATLAS (Status 2014)

Higgs signal strengths (left) and ratios of coupling modifiers (right), compared to current precision (orange).
Conservative extrapolation: does not include improved detector design, large theoretical uncertainties, simplified analyses.

4–5% for main channels, 10~20% on rare modes.
Conclusions

• The LHC and the experiments (ATLAS, CMS, LHCb, and ALICE) challenge the validity of the Standard Model at the high-energy frontier with ever increasing precision

• In order to exploit the full potential of the LHC, massive upgrades are needed for the accelerators and the experiments

• The HL-LHC will make a strong impact on Higgs property measurements. It has sensitivity to discover rare Higgs decays to $\mu\mu$ and $Z\gamma$, and to study couplings to bosons and third generation fermions to a few percent precision

• Di-Higgs production can likely be seen, but a significant measurement of Higgs self-coupling seems beyond reach. However, important constraints can be obtained.

• Higgs measurements in conjunction with other SM sectors such as diboson and top will allow to obtain coherent information in the framework of EFT or model extensions of the SM.

• Precision measurements in the SM sector will contribute to these constraints