The HL-LHC physics program

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for the ATLAS & CMS Collaborations

Workshop on Future High Energy Circular Colliders
Beijing, 16-17, December, 2013
Contents

• LHC operation schedule

• Challenges at High Luminosity LHC (HL-LHC) and detector upgrade plans

• Physics prospects for HL-LHC
  • Higgs properties and couplings
  • Higgs self-coupling
  • Searches for SUSY
  • Rare processes
The Large Hadron Collider (LHC)

- Circumference: 27 km
- Design values
  - $\sqrt{s} = 14$ TeV
  - $L = 2 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$
LHC roadmap

2009
LHC startup, $\sqrt{s} \approx 900$ GeV

$\sqrt{s} = 7+8$ TeV, $L \sim 6 \times 10^{33}$ cm$^{-2}$s$^{-1}$, bunch spacing 50 ns

2010

2011

2012

2013
LS1

Go to design energy, nominal luminosity - Phase 0

$\sqrt{s} = 13$–$14$ TeV, $L \sim 1 \times 10^{34}$ cm$^{-2}$s$^{-1}$, bunch spacing 25 ns

2014

2015

2016

2017

2018
LS2

2019

2020

2021

2022

2023
LS3

2024

2025

HL-LHC Phase II upgrade: Interaction Region, crab cavities?

... 2035?

$\sqrt{s} = 14$ TeV, $L \sim 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, luminosity levelling

From LHCC Open meeting, 03.12.2013
High Luminosity LHC

**HL-LHC conditions**

- Increased LHC instantaneous luminosity
- Large number of pileup events (μ) in the same bunch crossing

⇒ Luminosity leveling at $L = 5 \times 10^{34}$ (cm$^{-2}$s$^{-1}$) with $\langle \mu \rangle = 140$

<table>
<thead>
<tr>
<th></th>
<th>Peak L (cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Until 2012</td>
<td>$7 \times 10^{33}$</td>
</tr>
<tr>
<td>After Phase-1 upgrade</td>
<td>$2.5 \times 10^{34}$</td>
</tr>
<tr>
<td>After Phase-2 upgrade</td>
<td>$2 \times 10^{35}$ (*)</td>
</tr>
</tbody>
</table>

(*) Maximum peak luminosity achievable by the machine

- ATLAS and CMS detectors must be upgraded to cope with high pileup condition
- Inner trackers must be replaced due to radiation damage
- Need new detectors (both hardware and software) to keep similar performance as now
ATLAS detector upgrade plans

**Phase-0**
- Insertable B-layer (IBL)
- L1 topological trigger
- Fast Track Trigger (FTK)

**Phase-1**
- High granularity at L1 calorimeter trigger
- New small wheel for L1 endcap muon trigger

**Phase-2**
- New silicon tracker (ITK)
- L0/L1 trigger scheme (500/100 kHz)

Work on detector consolidation is ongoing: cooling, power supply, electronic, etc.
CMS detector upgrade plans

Phase-0
- 4th muon endcap station
- Detector consolidation

Phase-1
- New L1 trigger system
- New pixel detector
- HCAL upgrade (photo-detector and electronics)

Phase-2
- Details to be defined in Technical Proposal (2014)
- New tracker with L1 track trigger capability (pT>2.5 GeV)
- DAQ/HLT upgrade to have 1 MHz at L1 and 10 kHz recording rate
- Replace endcap & forward calorimeters
- Possible extension of muon coverage
- Possible EM preshower system to have photon pointing
Detector performance for HL-LHC physics studies

- **ATLAS**
  - Parameterize the detector response based on GEANT4 full simulation
    - The simulation includes the currently proposed layout of the upgraded tracker
  - $\langle \mu \rangle = 140$ ($\langle \mu \rangle = 50$) is assumed for $3,000 \text{ fb}^{-1}$ ($300 \text{ fb}^{-1}$)

- **CMS**
  - Studies scale current analysis
  - Assumes detector upgrades maintain current performance
  - Fast detector simulation using DELPHES
  - Cross checked with full simulation in some cases
Detector performance (1)

- CMS muon $p_T$ resolution comparison between full simulation and DELPHES fast simulation
- Good agreement is observed

- Parameterization of ATLAS muon $p_T$ resolution based on full simulation
- Better performance is obtained with ITK than with the current ID
Detector performance (2)

Parameterization of $E_T^{\text{miss}}$ resolution

**b-tagging**

- 70% efficiency as a typical working point
- 0.05% mis-tag rate at $\langle \mu \rangle = 140$

![Graphs of $E_T^{\text{miss}}$ resolution and b-tagging efficiency](image)
Physics after the Higgs discovery

• Measurements of properties and couplings of the Higgs boson
  • Couplings to various particles including rare decay modes
  • Natural width (very difficult, \( \Gamma_H = 4.2 \text{ MeV} \))
  • BSM Higgs search

• Investigation of Electroweak symmetry breaking (EWSB)
  • Higgs self-coupling measurement
  • Vector boson scattering

• Searches for physics beyond the SM
  • Strong motivation due to the evidence of dark matter from cosmology
  • Supersymmetry (SUSY)
  • Rare decays
Higgs results in LHC Run-1

- A resonance is observed in $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ$ decay modes
- Mass: $126.0 \pm 0.4(stat) \pm 0.4(sys)$ GeV (ATLAS), $125.3 \pm 0.4(stat) \pm 0.5(sys)$ (CMS)
- Spin/parity of 0$^+$ is strongly favored
- Constraints on the signal strength in various final states
  - $\rightarrow$ Constraints on the couplings
### Latest results on Higgs signal strength

**ATLAS Prelim.**

$m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{\text{statistical}}$</th>
<th>$\sigma_{\text{syst.incl.theo.}}$</th>
<th>Total uncertainty</th>
<th>$\pm 1\sigma$ on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.22</td>
<td>0.22</td>
<td>0.24</td>
<td>0.18</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>0.35</td>
<td>0.32</td>
<td>0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow l\nu l\nu$</td>
<td>0.20</td>
<td>0.21</td>
<td>0.23</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Combined**

$H \rightarrow \gamma\gamma, ZZ^*, WW^*$

$\mu = 1.33^{+0.21}_{-0.18}$

**CMS Preliminary**

$m_H = 125.7$ GeV

$p_{SM} = 0.65$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$1.15 \pm 0.62$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$1.10 \pm 0.41$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$0.77 \pm 0.27$</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$0.68 \pm 0.20$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$0.92 \pm 0.28$</td>
</tr>
</tbody>
</table>

**Graph:**

- $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L \leq 19.6$ fb$^{-1}$

- ATLAS-CONF-2013-079
- ATLAS-CONF-2013-106

**Legend:**

- $\mu = 0.2^{+0.7}_{-0.6}$
- $\mu = 1.4^{+0.5}_{-0.4}$
- $\mu = 1.10^{+0.41}_{-0.28}$
- $\mu = 0.77^{+0.27}_{-0.18}$
- $\mu = 0.68^{+0.20}_{-0.13}$
- $\mu = 0.92^{+0.28}_{-0.15}$

**Signal strength (\(\mu\))**

- $0$ to $2.5$
$H \rightarrow ZZ^{(*)}$ channel with 3,000 fb$^{-1}$

- Red histogram shows the distribution with wider $\eta$ acceptance ($|\eta| < 4$)

CMS-PAS-FTR-13-003

- $H \rightarrow ZZ^{(*)}$ can be observed in the $ttH$ production mode with 3,000 fb$^{-1}$

ATLAS-PUB-2013-014
$H \rightarrow WW(\ast)$ channel with 300 and 3,000 fb$^{-1}$

- Feasibility was studied by extrapolating the study for 8 TeV to 14 TeV, using smearing functions.
- The background ($t\bar{t}$ and $WW$) increases in 3,000 fb$^{-1}$ due to the higher pileup.
- Measurement of $H \rightarrow WW(\ast)$ is still possible.

ATLAS-PUB-2013-009
$H \rightarrow \mu\mu$ channel

- Direct verification of the Higgs coupling to 2nd generation leptons
- ATLAS (CMS) expects >6$\sigma$ (>5$\sigma$) significance
- Coupling measurement with 10-20% precision
$H \rightarrow Z\gamma$ channel

- Sensitive to new charged particles in the loop
- Large background due to radiative $Z$ decay but the measurement is possible

**Graphs:**
- Top-left: ATLAS Simulation Preliminary
  - $\sqrt{s} = 14$ TeV
  - $L dt = 3000$ fb$^{-1}$
  - $H \rightarrow Z\gamma, Z \rightarrow ee$
  - Background
  - SM Signal $\times 20$
- Top-right: ATLAS Simulation Preliminary
  - $\sqrt{s} = 14$ TeV
  - $L dt = 3000$ fb$^{-1}$
  - $H \rightarrow Z\gamma, Z \rightarrow \mu\mu/ee$
  - Background
  - SM Signal
  - B-only fit

**Table:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$ee\gamma$ inclusive</th>
<th>$\mu\mu\gamma$ inclusive</th>
<th>$ee\gamma$ VBF</th>
<th>$\mu\mu\gamma$ VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1465</td>
<td>1667</td>
<td>21.5</td>
<td>23.2</td>
</tr>
<tr>
<td>B</td>
<td>$4.05 \times 10^5$</td>
<td>$4.84 \times 10^5$</td>
<td>609</td>
<td>726</td>
</tr>
<tr>
<td>S/B (%)</td>
<td>0.36</td>
<td>0.35</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>VBF/(VBF+$ggF$)</td>
<td>0.09</td>
<td>0.09</td>
<td>0.55</td>
<td>0.55</td>
</tr>
</tbody>
</table>
Coupling measurement

- Fit the scale factors ($\kappa_i$) for the couplings with respect to their SM value
  - Width ($\Gamma_i$) scales with $\kappa_i^2$

\[
\sigma \cdot B (i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}
\]

- Measure ratios of coupling scale factors which are independent of the total width

Constraints on the universal fermion (boson) coupling scale factor $C_F$ ($C_V$)
Summary of the coupling measurement

ATLAS Simulation Preliminary

- $\int L dt = 300$ fb$^{-1}$
- $\int L dt = 3000$ fb$^{-1}$

$\sqrt{s} = 14$ TeV

$Y^- |_{\kappa^-}$

$\mu$, $\tau$, $Z$, $W$, $t$, $g$

$m_X$ [GeV]
HZZ vertex structure

- In a general expression, the HZZ vertex may contain CP-even (CP-odd) terms with coefficients $g_2$ ($g_4$).
- Set constraints using the angular distribution of the decay products of Z bosons.
- Large improvement with 3,000 fb$^{-1}$
Measurement of the total width

- The natural width of Higgs particle is $\Gamma_H = 4.2$ MeV
  - Much smaller than detector resolution
- There is an interference of signal and background amplitudes in $H \to \gamma\gamma$ and $H \to ZZ$
  - Shifts the mass peak to lower value

L. J. Dixon, Y. Li, PRL 111 (2013) 111802
Higgs width from $H \to \gamma\gamma$

- Mass shifts for $\Gamma_H = 1 \times \Gamma_{H_{SM}}$ and $\Gamma_H = 200 \times \Gamma_{H_{SM}}$
- A 95% C.L. upper limit can be set
  - $220 \times \Gamma_{H_{SM}}$ with 300 fb$^{-1}$
  - $40 \times \Gamma_{H_{SM}} \sim 160$ MeV with 3,000 fb$^{-1}$
- Current limit by CMS: 6.9 GeV (without using the interference technique)
Two Higgs Double Model (2HDM)

- 2HDM introduces 5 physical Higgs particles ($h, H, H^\pm, A$)
- Search for heavy Higgs bosons in decay modes: $H \rightarrow ZZ$ or $A \rightarrow Zh$
  - Performed by ATLAS & CMS for Type I-IV models

$H \rightarrow ZZ \rightarrow 4l$
- Derive the limit on $\sigma \cdot Br$ for each $m_H$
- Exclude the parameter region if $\sigma \cdot Br$ is excluded
- Exclusion limit set for $200 \text{ GeV} < m_H < 1 \text{ TeV}$

ATLAS-PUB-2013-016
CMS-PAS-FTR-13-024
Higgs self-coupling measurement

• In order to determine the parameters of the SM completely, a measurement of the Higgs self-coupling is essential
  • Higgs potential and the EWSB mechanism
  • Measurement of double Higgs production
  • Destructive interference between diagrams with triple Higgs coupling and other diagrams

<table>
<thead>
<tr>
<th>$\sigma_{HH} \text{ (fb)}$</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda = 0$</td>
<td>71</td>
</tr>
<tr>
<td>$\lambda = \lambda_{SM}$</td>
<td>34</td>
</tr>
<tr>
<td>$\lambda = 2 \cdot \lambda_{SM}$</td>
<td>16</td>
</tr>
</tbody>
</table>
Double Higgs production yields

Event yields of various channels

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching ratio (%)</th>
<th>Yield with 3 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>33.4</td>
<td>34,000</td>
</tr>
<tr>
<td>$b\bar{b}W^+W^-$</td>
<td>25.0</td>
<td>25,500</td>
</tr>
<tr>
<td>$b\bar{b}\tau\tau$</td>
<td>7.36</td>
<td>7,500</td>
</tr>
<tr>
<td>$W^+W^-W^+W^-$</td>
<td>4.66</td>
<td>4,750</td>
</tr>
<tr>
<td>$b\bar{b}ZZ$</td>
<td>3.09</td>
<td>3,150</td>
</tr>
<tr>
<td>$ZZW^+W^-$</td>
<td>1.15</td>
<td>1,170</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>0.26</td>
<td>265</td>
</tr>
</tbody>
</table>

- Very challenging due to low yield and contributions from irreducible backgrounds ($t\bar{t}H, ZH$, etc.)
- Ongoing studies suggest some sensitivity to constrain the triple Higgs coupling
- Also, several phenomenological papers suggest this possibility
Vector boson scattering

- Vector boson ($V = W^\pm, Z, \gamma$) scattering involves:
  - Triple gauge couplings
  - Quadratic gauge coupling
  - Higgs boson propagator in s- and/or t-channel
- The interference of all contributions $\rightarrow$ unitarity
- Deviation of VVH coupling from the SM value $\rightarrow$ violates unitarity
- Higher dimensional operators $\rightarrow$ new physics

**ZZ scattering**

ATLAS Simulation Preliminary

$\int L = 3000 \text{fb}^{-1}$

- VBS ZZ (SM)
- SM VBS ZZ + $C_{W} = 15/\text{TeV}^2$
- SM ZZ QCD

**ATLAS**

Simulation Preliminary

$3000 \text{fb}^{-1}$

$300 \text{fb}^{-1}$

ATLAS-PUB-2013-006

CMS-PAS-FTR-13-006
SUSY Search
SUSY search at HL-LHC

- Limits set by Run-1 LHC: $m_{\tilde{q}} < 0.7$ TeV, $m_{\tilde{g}} < 1.3$ TeV
- Less stringent limits on sleptons, 3rd generation squark, weak gauginos
  - → Accessible at HL-LHC

![Graph showing cross section vs. mass for different processes such as gluino, squark, weak gaugino production.](graph.png)

Followed prescriptions in 1206.2892 [hep-ph]
Weak gaugino production (1)

- Direct production of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$
- Signature:
  - 3 leptons (>10 GeV)
  - $E_T^{miss} > 50$ GeV
  - $b$-jet veto

Excluded chargino mass (for massless LSP) is increased by 300 GeV by going from 300 fb$^{-1}$ to 3,000 fb$^{-1}$
Weak gaugino production (2)

- $5\sigma$ exclusion region from CMS
  - Extend the mass range up to 700 GeV with 3,000 $fb^{-1}$
  - Assuming 100% or 50% branching ratios of $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$
Stop pair production

Signature:
- Fully hadronic top decay:
  - 0-lepton, >6 jets with 2 $b$-tagged, $E_T^{miss}$
- Semi-leptonic top decay:
  - 1-lepton, >4 jets with 1 $b$-tagged, $E_T^{miss}$

5$\sigma$ discovery up to 1.2 TeV at 3,000 fb$^{-1}$ (200 GeV gain from 300 fb$^{-1}$)
Gluino production

- Large production cross section
- Gluino masses up to 2.2 (1.8) TeV and LSP mass up to 500 (400) GeV can be discovered with 3,000 (300) fb$^{-1}$

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$: Multijet, $E_T^{miss}$

In case gluino decays preferentially to top
- $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$: Multijet, $E_T^{miss}$, 1-lepton
FCNC with top decay

- $\text{Br}(t \rightarrow Wb) \sim 100\%$ in SM
- Flavor changing neutral current (FCNC) decay is highly suppressed
  - $\text{Br}(t \rightarrow Zq) \sim 10^{-14}$ (SM)
  - $\text{Br}(t \rightarrow cH) \sim 3 \times 10^{-17}$ (SM)
- Search for or $llq$ or $c\gamma\gamma$ final states
- ATLAS & CMS studies show sensitivity of $10^{-4}$ can be achieved in these channels with 3,000 fb$^{-1}$
  - Predicted by several extensions of SM (2HDM, RPV SUSY etc.)

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM-III</th>
<th>FC-2HDM</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow u\gamma$</td>
<td>$3.7 \times 10^{-16}$</td>
<td>$7.5 \times 10^{-9}$</td>
<td>—</td>
<td>—</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow uZ$</td>
<td>$8 \times 10^{-17}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>—</td>
<td>—</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow uH$</td>
<td>$2 \times 10^{-17}$</td>
<td>$4.1 \times 10^{-5}$</td>
<td>$5.5 \times 10^{-6}$</td>
<td>—</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$t \rightarrow c\gamma$</td>
<td>$4.6 \times 10^{-14}$</td>
<td>$7.5 \times 10^{-9}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-9}$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow cZ$</td>
<td>$1 \times 10^{-14}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-10}$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$t \rightarrow cH$</td>
<td>$3 \times 10^{-15}$</td>
<td>$4.1 \times 10^{-5}$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$\sim 10^{-5}$</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>
Conclusion

• There is a well-defined LHC roadmap including the High Luminosity LHC

• Detector upgrade R&D is in progress
  • Expect to have similar performance as the current detector even with higher pileup

• Many measurements are possible at HL-LHC
  • Higgs coupling to various particles
  • Natural width
  • Sensitivity to Higgs self-coupling
  • Vector boson scattering
  • Extension of search region for SUSY particles
  • Measurements of rare processes
Backup slides