Physik am Large Hadron Collider

-Von der Entdeckung des Higgs-Teilchens zur Suche nach Neuer Physik-

Prof. Karl Jakobs
Physikalisches Institut
Universität Freiburg
Key questions of particle physics

1. **Mass**
   - What is the origin of mass?
   - Does the Higgs particle exist?

2. **Unification**
   - Can the interactions be unified?
   - Are there new types of matter, e.g. supersymmetric particles?
   - Are they responsible for the Dark Matter in the universe?

3. **Flavour**
   - Why are there three generations of particles?
   - What is the origin of the matter-antimatter asymmetry (Origin of CP violation)

Answers to some of these questions are expected on the TeV energy scale, i.e. at the LHC
Nobel-Preis für Physik 2013:
Francois Englert und Peter Higgs

“... for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of sub-atomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.”
The Large Hadron Collider

CMS

ALICE

LHCb

ATLAS
Data taking at the LHC (2010-2012)

Steve Meyers at “Physics at LHC 2012”:

“The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics.”

Until end 2012:

> $10^{15}$ pp collisions

$\sim 10^{10}$ pp collisions recorded

$25 \cdot 10^6 Z \rightarrow \mu\mu$ decays produced
Data taking at the LHC (2010-2012)

- Excellent LHC performance
  Peak luminosities $> 7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ (world record, 2012)

- Excellent performance of the experiments:
  - Data recording efficiency $\sim 93.5\%$
  - Working detector channels $>99\%$
  - Speed of data analysis

Until end 2012:

- $> 10^{15} \text{ pp collisions}$
- $\sim 10^{10} \text{ pp collisions recorded}$
- $25 \times 10^6 \text{ } Z \rightarrow \mu\mu \text{ decays produced}$
Since 30. March 2010: collisions at 7/8 TeV
(....first interesting physics events)

- Jets at high energy ~0.5 TeV
  (scattered quarks, gluons)
Double differential cross sections, as a function of $p_T$ and rapidity $y$ (full 2011 data set)

\[ y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \tanh^{-1} \left( \frac{p_z}{E} \right) \]
Double differential cross sections, as a function of $p_T$ and rapidity $y$ (full 2011 data set)

- Data are well described by NLO perturbative QCD calculations (NLOJet++), within the experimental and theoretical uncertainties
Towards precision tests of QCD at the LHC

\[ \alpha_s(m_Z) = 0.1185 \pm 0.0019 \text{ (exp)} +0.0060 \text{-}0.0037 \text{ (theo)} \]
In addition: Sensitivity to New Physics

- Di-jet mass spectrum provides large sensitivity to new physics
  
  e.g. resonances decaying into qq, excited quarks q*, ....

CDF (Tevatron), L = 1.13 fb⁻¹: \(0.26 < m_{q*} < 0.87 \text{ TeV}\)
\(\sqrt{s} = 1.96 \text{ TeV}\)

ATLAS (LHC), L = 0.000315 fb⁻¹: exclude (95% C.L) q* mass interval
\(0.30 < m_{q*} < 1.26 \text{ TeV}\)
\(\sqrt{s} = 7 \text{ TeV}\)

ATLAS (LHC), L = 20.3 fb⁻¹, 8 TeV: exclude (95% C.L.) \(m_{q*} < 4.09 \text{ TeV}\)
(For theorists: \textbf{LHC: = Long and Hard Calculations})
Production of $W$ and $Z$ bosons at the LHC

Theoretical predictions (NNLO accuracy) in very good agreement with the experimental measurements
Top Quarks mass: precision physics

ATLAS + CMS: \( m_t = 173.29 \pm 0.95 \) GeV

World combination: \( m_t = 173.34 \pm 0.76 \) GeV

Precision: \( \pm 0.55\% \) (LHC), \( \pm 0.44\% \) (world)

Top quark mass measurement from cross section:

\[
m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6} \text{ GeV}
\]
Evidence for El. weak $W^\pm W^\pm jj$ production

- Higgs boson needed in the SM to regularise VV scattering at high energies;
- Key experimental process: $W^\pm W^\pm$ scattering

VBS enhancement by cutting on mass ($m_{jj}$) and rapidity separation $\Delta y_{jj}$

ATLAS: $3.6\sigma$ for el. weak production

CMS: $2.0\sigma$ (expected: about $3.0\sigma$)
Discovery of a Higgs boson at the LHC

Expected number of decays in the data:

\[ m_H = 125 \text{ GeV} \]

\[ \sim 950 \, H \rightarrow \gamma\gamma \]

\[ \sim 60 \, H \rightarrow ZZ^* \rightarrow 4 \ell \]

\[ \sim 9000 \, H \rightarrow WW^* \rightarrow \ell\nu \ell\nu \]
The Brout-Englert-Higgs Mechanism


R. Brout (1964)
P. Higgs (1964)
The Brout-Englert-Higgs Mechanism

Complex scalar (spin-0) field $\phi$ with potential:

$$V(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2$$

For $\lambda > 0$, $\mu^2 < 0$:

“Spontaneous Symmetry Breaking”

→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV
→ Higgs Boson (mass not predicted, except $m_H < \sim 1000$ GeV)
→ Particles acquire mass through interaction with the Higgs field
The Brout-Englert-Higgs Mechanism

Complex scalar (spin-0) field $\phi$ with potential:

$$V(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2$$

For $\lambda > 0$, $\mu^2 < 0$: “Spontaneous Symmetry Breaking”

- Couplings proportional to mass
Higgs Boson Production at the LHC

*) LHC Higgs cross-section working group;
(N)NLO calculations: Huge theory effort
Higgs Boson Decays

*) LHC Higgs cross-section working group
The first serious studies

EXPERIMENTAL REVIEW OF THE SEARCH FOR THE HIGGS BOSON

Daniel Froidevaux

This review will limit its scope to the search for the Standard Model Higgs boson, \( H \), at the LHC, for \( \sqrt{s} = 16 \text{ TeV} \). Integrated luminosities of \( 10^8 \text{ pb}^{-1} \) per year of running will be used throughout, unless otherwise stated.

The search for charged Higgs bosons will be covered by the top physics working group [1], and the search for scalar or pseudoscalar neutral Higgs bosons from the Minimal Supersymmetric Standard Model has been summarised in a theoretical overview [2], since no detailed experimental simulations have yet been carried out in this context.

This review would not have been possible without the work of many people, theorists and experimentalists, who have participated in the Higgs working group studies for the Aachen workshop over a relatively short period of about 9 months. It will be divided into four main chapters:

1. \( H \rightarrow ZZ, ZZ* \rightarrow 4 \text{ leptons} \)
   M. Della Negra, D. Froidevaux, K. Jakobs, R. Kinnunen, R. Kleiss, A. Nisai and T. Sjöstrand

2. Intermediate mass Higgs
   a) \( H \rightarrow \gamma\gamma, \) \( WH \) with \( W \rightarrow \ell\nu, H \rightarrow \gamma\gamma, \) and \( ZH \) with \( Z \rightarrow \ell\ell, H \rightarrow \gamma\gamma \)
   This topic is reviewed in detail in the summary given by C. Seez [3]. Only the main conclusions will be discussed here.
   b) \( H \rightarrow \tau\tau \)
   F. Anselmo, K. Bos, L. DiLella and B. Van Eijk
   c) \( WH \) with \( W \rightarrow \ell\nu, H \rightarrow jj \) or \( bb \) and \( ZH \) with \( Z \rightarrow \ell\ell, H \rightarrow jj \) or \( bb \)
   L. Poggiali

3. \( H \rightarrow ZZ \rightarrow 2\ell 2\nu, H \rightarrow ZZ, ZZ* \rightarrow 2\ell jj, H \rightarrow WW \rightarrow 2\ell jj \) for \( m_H \) large
   U. Baur, D. Froidevaux, E.W.N. Glover and M.H. Seymour
Conclusions on the Higgs boson discovery potential

Intermediate mass Higgs range $120 < m_H < 2 m_Z$:

(i) “In this mass range, the Higgs boson can be detected in the channel $H \rightarrow ZZ^* \rightarrow ℓℓ\ellℓ$, provided the detector can identify low energy isolated electrons and muons.”

(ii) “With an integrated luminosity of $10^5$ pb$^{-1}$, a signal from $H \rightarrow γγ$ decays can be observed for $80 < m_H < 150$ GeV. This, however, imposes severe constraints on the detector design.”

(iii) “None of the other possible channels, which have been studied, provides any hope to discover a Higgs boson in this mass range.”
Further major physics steps

(i) The $H \rightarrow WW^*$ decay channel:

1997: M. Dittmar and H. Dreiner, $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ as the dominant search mode at the LHC from $m_H = 150 – 180$ GeV, Phys. Rev. D55 (1997) 167.
1999: Established in ATLAS and CMS Physics TDRs

(ii) The $qqH \rightarrow qq\tau\tau$ decay mode:

1999: D. Rainwater, D. Zeppenfeld: Vector boson fusion production at low mass, $qqH \rightarrow qq WW$, $qqH \rightarrow qq\tau\tau$
2003: ATLAS Vector boson fusion paper, EPJ-C

(iii) H \rightarrow bb revival

Little Higgs models

Composite Higgs bosons

More Higgs bosons

Ausgeschmierte Higgs

MSSM Higgs bosons

Dark Higgs

SUSY Higgs

Heidi Higgs

No Higgs at the LHC
Result of the ATLAS search for $H \rightarrow \gamma\gamma$


p-value for consistency of data with background-only: $\sim 10^{-13}$ (7.4$\sigma$ observed)

Measured signal strengths:
ATLAS: $\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}} = 1.17 \pm 0.27$
CMS: $\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}} = 1.14 \pm 0.26$

Background

Higgs signal (main production process via gluon fusion) (mass can be reconstructed from $\gamma\gamma$)
Reconstructed mass spectra from 4ℓ decays

**ATLAS**

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

- **Data**
- **Signal** \( (m_\ell = 125 \text{ GeV}, \mu = 1.51) \)
- **Background** \( ZZ^* \)
- **Background** \( Z + \text{jets}, W \)
- **Systematic uncertainty**

**CMS**

\[ m_\ell = 126 \text{ GeV} \]

**Measured signal strengths:**

**ATLAS:** \( \mu = 1.44^{+0.40}_{-0.33} \)

**CMS:** \( \mu = 0.93^{+0.29}_{-0.23} \)

**Significance in each experiment:** \( > 6\sigma \)
ATLAS $H \rightarrow WW^* \rightarrow \ell\nu \ell\nu$ signal

- Very significant excess in the “transverse mass” distribution visible (6.1σ)
- Signals for both gluon-fusion (ggF) and vector-boson fusion (VBF) production

Measured signal strengths:

ATLAS: $\mu_{\text{ggF}} = 1.02^{+0.29}_{-0.26}$
VBF: $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$

CMS: $\mu = 0.72^{+0.20}_{-0.18}$
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.
Evidence for $H \rightarrow \tau\tau$ decays

**Measured signal strengths:**

**ATLAS:** $\mu = 1.43 \pm 0.43 -0.37$ (4.5$\sigma$)

**CMS:** $\mu = 0.78 \pm 0.27$ (3.2$\sigma$)

$m_{\tau\tau}$ distribution, events weighted by $\ln (1+S/B)$

One of the most important LHC results in 2014
Results on the search for $H \rightarrow bb$ decays

Signal strengths:

**ATLAS:** $\mu = 0.50 \pm 0.36$

**CMS:** $\mu = 1.0 \pm 0.5$

- Reference signal from WZ, and ZZ with $Z \rightarrow bb$ seen
- Positive, but non-conclusive Higgs boson signal contribution observed

Reconstructed $m_{bb}$ signals (after subtraction of major backgrounds)
Properties of the New Particle

Is it the Higgs Boson of the Standard Model?
Signal strength in individual decay modes

-normalised to the expectations for the Standard Model Higgs boson-

**ATLAS Preliminary**

$m_H = 125.36$ GeV

- $H \rightarrow \gamma \gamma$
  - $\mu = 1.17^{+0.27}_{-0.27}$

- $H \rightarrow ZZ^* \rightarrow 4l$
  - $\mu = 1.44^{+0.40}_{-0.33}$

- $H \rightarrow WW^* \rightarrow l\nu l\nu$
  - $\mu = 1.09^{+0.23}_{-0.21}$

- $W,Z H \rightarrow b\bar{b}$
  - $\mu = 0.5^{+0.4}_{-0.4}$

- $H \rightarrow \tau\tau$
  - $\mu = 1.4^{+0.4}_{-0.4}$

Total uncertainty

$\pm 1\sigma$ on $\mu$

**Signal strengths:**

**ATLAS:** $\mu_{\text{ges}} = 1.30 \pm 0.17$ (prel.)

**CMS:** $\mu_{\text{ges}} = 1.00 \pm 0.14$ (new)

**ATLAS**

$\sqrt{s} = 7$ TeV $\int L dt = 4.5$-4.7 fb$^{-1}$

$\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

**CMS**

$m_H = 125.03 \pm 0.27$ (stat) $\pm 0.14$ (syst) GeV

**Data are consistent with the hypothesis of the Standard Model Higgs boson**

**If ATLAS and CMS combined: clear evidence for coupling to fermions**
Spin and CP

- Standard Model Higgs boson: \( J^P = 0^+ \)

  - Strategy is to falsify other hypotheses (0\(^-\), 1\(^-\), 1\(^+\), 2\(^-\), 2\(^+\))

- Angular distributions of final state particles show sensitivity to spin

Data strongly favour the spin-0 hypothesis of the Standard Model

(Alternatives can be excluded with confidence levels > 99%)
CMS results on Higgs boson couplings

For the first time, non-universal, mass-dependent couplings observed

\[ \lambda \] = Yukawa coupling for fermions

\[ \sqrt{g/2v} \] = couplings for W/Z bosons

\( (M, \varepsilon) \) fit

68% CL

95% CL

--- SM Higgs

For the first time, non-universal, mass-dependent couplings observed

arXiv:1412.8662
Physics Beyond the Standard Model

Hitoshi Murayama, IPMU Tokyo & Berkeley
Supersymmetry

New Quantum number: R-parity: \( R_p = (-1)^{B+L+2s} \)

- +1 SM particles
- -1 SUSY particles

R-parity conservation: SUSY particles produced in pairs
Decays into the Lightest SUSY Particle (LSP)

Final states with jets, \( E_T^{\text{miss}} \), (and leptons)
Why do we like SUSY so much?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

\[ \Delta m_H = f(m_B^2 - m_f^2) \]

\[ \rightarrow m_{\text{SUSY}} \sim 1 \text{ TeV} \]

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter

The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data
Search for Squarks and Gluinos

\[ E_T^{\text{miss}} / \sqrt{H_T} = \text{missing transverse energy normalized to the square root of the total transverse energy (H}_T) \text{ seen in the event} \]

Data are in agreement with predictions from Standard Model processes.
Limits of light squark and gluino masses

mSUGRA / CMSSM interpretation: $\tan \beta = 30, A_0 = -2m_0, \mu > 0$

For equal mass light-flavour squarks (of first and second generation) and gluinos with masses below about 1650 GeV are excluded.
The special role of top squarks (stops)

- The partners of the top (bottom) quarks might be the lightest squarks, whereas all other squarks might be too heavy to be produced at the LHC;

- Light stops could solve the so-called “hierarchy” problem (cancellation of large quantum corrections to the Higgs boson mass) “Natural SUSY”
• Weaker mass limits for partners of the top quark (lower production rate, tt background)

• Parameter coverage not yet complete!
Is SUSY dead?

• “Under attack from all sides, but not dead yet.”

• Some of the simplest models are ruled out, however, interpretations rely on many simplifying assumptions.

• Plausible “natural” scenarios still not ruled out;

  Light stop and/or R-parity violating scenarios have fewer constraints.

• Search for Charginos and Neutralinos (el.weak production) needed at high luminosity / energy
Results from other Searches for New Physics

**Leptoquarks**
- Stopped gluino (cloud)
- HSCP gluino (cloud)
- HSCP stop (cloud)
- $q\rightarrow 3\ell$ HSCP
- Neutralino, cτ=25 cm, ECAL time

**Long-Lived Particles**
- J+MET, SI DM=100 GeV, λ
- J+MET, SD DM=100 GeV, λ
- γ+MET, SI DM=100 GeV, λ
- γ+MET, SD DM=100 GeV, λ
- H+MET, λ=1, SI DM=100 GeV, λ
- H+MET, λ=1, SD DM=100 GeV, λ
- H+MET, λ=1, SD DM=100 GeV, λ

**RS Gravitons**
- RS1(γγ), k=0.1
- RS1(σ, uu), k=0.1
- RS1(σ, pp), k=0.1
- RS1(WW→jj), k=0.1

**Dark Matter**
- ADD (σ, nED=4, MS
- ADD (σ, nED=4, MS
- ADD (γ+MET, nED=4, MD
- ADD (γ+MET, nED=4, MD
- QBH, nED=4, MD=4 TeV
- NR BH, nED=4, MD=4 TeV
- Jet Extinction Scale
- String Scale (σ)

**Heavy Gauge Bosons**
- SSM Z(ττ)
- SSM Z(χχ)
- SSM Z(bb)
- SSM Z(σ, uu)
- SSM W(χχ)
- SSM W(bb)
- SSM W(WZ→llll)
- SSM W(WZ→llll)

**Excited Fermions**
- $e^+$ ($M=λ$)
- $μ^+$ ($M=λ$)
- $q^+$ (gg)
- $q^+$ (gy)
- $b^+$

**Multijet Resonances**
- coloron(σ, pp)
- coloron(σ, uu)
- gluino(σ, pp)
- gluino(σ, uu)

**Compositeness**
- dijets, λ+ LL/RR
- dijets, λ- LL/RR
- dimuons, λ+ LL/RR
- dimuons, λ- LL/RR
- dielectrons, λ+ LL/RR
- dielectrons, λ- LL/RR
- single $e$, $A_{HnCM}
- single $μ$, $A_{HnCM}
- inclusive jets, λ+
- inclusive jets, λ-
Direct Search for Dark Matter using Monojet signature

- Coupling of weakly interacting massive particles (WIMPs) is described as a contact interaction using an effective field theory approach;
- WIMP assumed to be either a Dirac fermion or a scalar; Limits given for different operators

- Interesting complementary approach to understand the nature of dark matter;
- Close collaboration with astroparticle physics community and theory needed to understand the validity of the approach and the “translation” of results
What next?

- The LHC will resume operation at an increased energy (at $\sqrt{s} = 13 – 14$ TeV) in March / May 2015 (higher energy and higher luminosity)

- A new energy range will be explored !!

Major physics topics:
(i) Extend the searches for New Physics

(ii) Precise measurements of the Higgs boson profile

(iii) Additional Higgs bosons?

(iv) Scattering of vector bosons

(v) Precision measurements ($m_W$, $m_{top}$, Higgs couplings)
Conclusions

• With the operation of the LHC at high energies, particle physics has entered a new era

• Performance of the LHC and the experiments is superb

• A milestone discovery announced in July 2012

  Strong evidence that the new particle is the long-sought Higgs boson of the Standard Model;
  We moved from the discovery to the measurement phase;

• So far no signals from New Physics, however, only a small fraction of the parameter space at reach at the LHC has been explored;
• Higgs particle might be portal to new physics

• Exciting times ahead of us, with new, unexplored energy regime in reach