The LHC: challenges on the way to the Higgs discovery

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Felicitas Pauss
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4 July 2012: CERN press conference
“CERN experiments observe particle consistent with long-sought Higgs boson”

“A historic milestone – but only beginning of a full exploitation of LHC physics potential”
2013 Nobel Prize in Physics

to François Englert & Peter Higgs

“For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic 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”

François Englert  Peter Higgs

CERN, July 2012
The LHC: challenges on the way to the Higgs discovery

How did it all start?

What were the challenges?
- physics motivation / goals
- choice of technologies
- time schedule and milestones
- financing, upper limit of costs (“design-to-cost”)
- management (number of institutes and collaborators increasing)

What is next?

.... will focus on ATLAS and CMS ......
The LHC Project: how it all started ....

1984  Lausanne workshop official starting point for work at the LHC:
      $E_{cm} = 18\ \text{TeV}$ ?, $L = 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$ ?

1987  La Thuile workshop: comparison of LHC, CLIC ($e^+e^-$), e-p option
      LHC: $E_{cm} = 16\ \text{TeV}$, $L = 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1} \rightarrow 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$ (D. Treille)
      e-p: 1.3 - 1.8 TeV, CLIC: 2 TeV

Conclusion: La Thuile workshop (CERN-TH.4682/87; March 1987)
            J. Ellis, F. Pauss (convener of WG beyond SM)

"It seems to us inevitable that a pp collider in the LHC/SSC range will be built in Europe and/or the United States. Such a machine certainly has very great physics capabilities ..... (also strongly encouraged R&D for CLIC)
The LHC Project: how it all started ....

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\[ E_{cm} = 18 \text{ TeV} , \ L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \ ? \]

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e-p: 1.3 - 1.8 TeV, CLIC: 2 TeV

End 1980’s  the first embryonic collaborations started

1990  Aachen workshop: LHC physics and instrumentation
\[ E_{cm} \sim 16 \text{ TeV} , \ L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

1992  Evian workshop presentation of EoI (in March)
proto-collaborations
LoI presentation at CERN (in October)

1995  LHC conceptual design: 14 TeV, \( L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

1993  SSC cancelled (87 km, 40 TeV)
Physics motivation / goals — as in the late 1980’s before the start of LEP

**Particle masses?**

**Dark Matter?**

**Unification of forces?**

**Matter-Antimatter Asymmetry?**

LHC ➔ Answers to open questions
Back in 1964: 3 important publications

1) F. Englert and R. Brout, June 1964: *Broken Symmetry and the Mass of Gauge Vector Mesons*

2) P. Higgs, August 1964: *Broken Symmetries and the Masses of Gauge Bosons*

3) G. Guralnik, T. Kibble, C. Hagen, October 1964: *Global Conservation Laws and Massless Particles*

Back in 1975: first comprehensive phenomenological investigations ....

J. Ellis, M.K. Gaillard, D.V. Nanopoulos: *A Phenomenological Profile of the Higgs Boson*

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
Open Questions in SM and Possible Solutions (late 80’s)

**Higgs sector:** is Higgs mechanism in SM correct description? $m_H = ?$
- Hierarchy problem: EW scale $\sim 10^2$ GeV; Planck scale $\sim 10^{19}$ GeV
- Naturalness problem/fine tuning: Rad. correct.: $m_{Higgs} \sim \Lambda$ (Higgs is scalar !!)

Standard Model

successful for ever?
Open Questions in SM and Possible Solutions (late 80’s)

Supersymmetry
- new particles at ~ TeV scale; light Higgs;
- unification of Forces, DM candidate

Standard Model

Composite Models
- new contact interactions

Z’
- concentrated on novel/speculative Z’, which mixes with Z

Leptoquarks
- studied J=0, Q=-1/3 LQs

For all proposed solutions: new particles should appear at TeV scale or below

Louisville 1987
Conveners: J.Ellis, F.Pauss
Experimental Challenges at LHC

LHC: $E_{cm} = 14$ TeV, Luminosity $\mathcal{L}_{\text{Design}} = 10^{34}$ cm$^{-2}$s$^{-1}$

Every 25 ns on average about 1000 charged particles produced in $\eta < 3$
($\theta \sim 4^\circ$ w.r.t. beam axis)

- Require high granularity, i.e. many channels $O(10^7)$ (no pixel detector)
- Require fast (25 ns!) , radiation hard detectors and electronics

All charged tracks ($B = 4$ T)

Charged tracks with $p_T > 2$ GeV

Higgs decay into 4 $\mu$

- Trigger: 40 MHz collision rate $\rightarrow O(100$ Hz)
- Data volume per year: 10 Petabytes $\rightarrow$ GRID computing
Which technology? ↔ R&D

Magnet:
- toroid
- solenoid
- or both?

Calorimetry:
- sampling
- scintillating crystals

Tracking:
- gas (MSGC)
- TRT
- silicon

Many years of intense R&D
1992: **EoI** (Evian workshop) ➔ **LoI** (CERN)

Evian meeting: also first ideas about b-physics and heavy ion physics
.... from 4 to 2 experiments ...

Period of negotiations ....
.... from 4 to 2 experiments ...

Period of negotiations ....
Dec 1994: Council approves LHC project, initially for construction in two stages ‘missing magnet machine’

1996: single-stage construction approved

Technical Proposals (TPs):
- 1994: ATLAS and CMS
- 1995: ALICE
- 1998: LHCb

Approval of experiments:

February 1996

February 1996

February 1997

September 1998

“We are ready for an unforeseen event that may or may not occur” (A. Gore)
Construction starts ........

1998

Civil engineering work for the ATLAS experiment

About 10 years later ....
Construction starts .......

1998

Gallo-Roman ruins and coins discovered at CMS dig site → 6 months delay

2006
Construction starts ..........

Civil Engineering at ATLAS (Point 1):
Cavern delivered in April 2003

Civil Engineering at CMS (Point 5):
Cavern delivery in July 2004
Barrel toroid system: eight 25m-long, 5m-wide, 100 ton superconducting coils
Field \(~0.5\) T; \(~1\)GJ stored energy
Closing CMS for the first time in July 2006

19.14 kA, 2.5 GJ stored energy, sufficient to melt 18 t of gold

~ 25 million cosmic events recorded

SC Magnet: 4 Tesla, l = 13 m, Ø = 6 m, weight > 10'000 tons
Lowering of heavy elements into cavern

Lowering of central and heaviest element (~ 2000 t) on 28 February 2007 ……

Lowering of the last heavy element on 22 January 2008
Technical Coordination, TriDAS, ....

Marzio Nessi

Alain Herve

Austin Ball

Sergio Cittolin
Schedule: towards first collisions at the LHC

- Schedule (Aachen workshop 1990): start civil engineering in 1992; commissioning in 1998; LEP + LHC concurrent operation
- 1995: start LHC project, duration 10 years (2005 first collisions)

2007: DG (RA) confirms LHC start-up in May 2008:
2008: $E_{cm} = 10$ TeV: 40 physics days, $L_{peak} = 5 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, $L_{deliv} \sim 20 \text{ pb}^{-1}$
2009: $E_{cm} = 14$ TeV: 150 physics days, $L_{peak} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, $L_{delive} \sim 2.5 \text{ fb}^{-1}$

10 Sept 2008: first protons circulating in the LHC ring

- 19 Sept 2008: incident in sector 3-4
- Nov 2009: 2 beams circulating
- March 2010: collisions at $E_{cm} = 7$ TeV

See talk by L. Evans
December 2011 (run @ 7 TeV: ~5 fb⁻¹)

ATLAS und CMS see “hints” in 120 - 130 GeV mass region

2012 run @ 8 TeV:
December 2012: ~25 fb⁻¹
December 2011 (run @ 7 TeV: ~5 fb⁻¹)

ATLAS und CMS see “hints” in 120 - 130 GeV mass region

2012 run @ 8 TeV:
December 2012: ~25 fb⁻¹
4 July 2012: Discovery

July 2014: ICHEP 2014

one Higgs → 4e produced in $10^{13}$ pp collisions
Impressive scientific output from Run1@LHC

Standard Model Production Cross Section Measurements

- ATLAS Preliminary
- LHC pp $\sqrt{s} = 7, 8$ TeV
- Run 1

- Theory
- Data

- LHC pp $\sqrt{s} = 7$ TeV
  - Theory
  - Data $4.5 - 4.7$ fb$^{-1}$

- LHC pp $\sqrt{s} = 8$ TeV
  - Theory
  - Data $20.3$ fb$^{-1}$

- $W \rightarrow \ell \nu \sim 100$ M Events
- $Z \rightarrow \ell \ell \sim 10$ M Events
- $t\bar{t} \rightarrow \ell + X \sim 0.4$ M Events
Impressive scientific output from Run1@LHC

- Leptoquarks
  - $W \rightarrow l\nu$: $\sim 100$ M Events
  - $Z \rightarrow l^+l^-$: $\sim 10$ M Events
  - $t\bar{t} \rightarrow l^+X$: $\sim 0.4$ M Events

- RS Gravitons
- Lepton Flavors

- Heavy Gauge Bosons

- Excited Fermions
  - $e^*$ ($M=\Lambda$), $\mu^*$ ($N=\Lambda$)
  - $q^*$ ($Q_3$), $q^*$ ($Q_4$)
  - $b^*$

- Multijet Resonances
  - coloron($jj$) x 2
  - coloron($4j$) x 2
  - gluino($3j$) x 2
  - gluino($jjb$) x 2

- Large Extra Dimensions
  - ADD ($\nu\nu$, $nED=4$, MS)
  - ADD ($\nu\mu$, $nED=4$, MS)
  - ADD ($t\bar{t}+b\bar{b}$, $nED=4$, MD)
  - QCD ($Q_{BH}$, $nED=4$, MD=4 TeV)
  - Jet Extinction Scale

- Compositeness
  - dijets, $A^+ LL/RR$
  - dijets, $A^-$ $LL/RR$
  - dimuons, $A^+ LLIM$
  - dimuons, $A^- LLIM$
  - dielectrons, $A^+ LLIM$
  - dielectrons, $A^- LLIM$
  - single $e$, $\Lambda$ HnCM
  - single $\mu$, $\Lambda$ HnCM
  - inclusive jets, $A^+$
  - inclusive jets, $A^-$

CMS Exotica Physics Group Summary – IHEP, 2014
Impressive scientific output \iff\text{impressive detector performance}

Examples

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 3.1$ pb$^{-1}$

78 pp collisions
Physics motivation / goals – in 2014

After long shut-down - start in 2015 with an essentially new machine!

\[ E_{CM} \sim 13 \text{ TeV} \rightarrow 14 \text{ TeV} \]

Data taking till Q2 2018

Important for the long term future of LHC / CERN – and of particle physics

LHC \(\leftrightarrow\) Answers to open questions \(\rightarrow\) still valid!
Sir Ben Lockspeiser

“Scientific research lives and flourishes in an atmosphere of freedom – freedom to doubt, freedom to enquire and freedom to discover. These are the conditions under which this new laboratory has been established.”
The foundations for CERN’s success

- European scientists and political leaders with visionary minds created CERN 60 years ago:
  - Building strong links between scientists of large and small countries
  - Tying together human and financial resources for a common scientific goal
  - Realization of long-term goals with strong support from all Member States

To meet the challenges posed by the increasing global (and competitive) nature of frontier facilities, a clear scientific vision and strong political support is needed for a bright future of CERN.
3rd International Conference on New Frontiers in Physics

New Frontiers in Physics
ICNFp 2014

28 July - 6 August 2014, Kolymbari, Crete, Greece
http://indico.cern.ch/event/icnf2014

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Main topics of the Conference
High Energy Particle Physics
Heavy Ion Physics
Superconductivity, Critical Phenomena
Quantum Physics, Quantum Entanglement
Quantum Field Theory, String Theory
Cosmology, Astrophysics, Gravity
Mathematical Physics

Thank you !!!

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