CERN and the Large Hadron Collider
The Big Bang Machine

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Introduction
The Physics program of the Large Hadron Collider
Higgs Discovery
Dark Matter & supersymmetry?
Extra space dimensions?
Matter versus anti-matter?
Summary
CERN: The European Laboratory for Particle Physics

- CERN is the European Organization for Nuclear Research, the world’s largest Particle Physics Centre, near Geneva, Switzerland.
- It is now commonly referred to as European Laboratory for Particle Physics.
- It was founded in 1954 and has 21 member states + several observer states.
- CERN employs ~4000 people + hosts ~11000 visitors from >500 universities.
- Annual budget ~ 1000 MCHF/year (2014)

Where the World Wide Web was born...
What is the world made of?
What holds the world together?
Where did we come from?
Accelerators are Powerful Microscopes

They make high energy particle beams that allow us to see small things.

\[ \lambda = \frac{h}{p} \]

- wavelength
- Planck constant
- momentum
- energy

seen by low energy beam of particles (poorer resolution)

seen by high energy beam of particles (better resolution)
Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.

- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang.
The Structure of Matter

Quarks and electrons are the smallest building blocks of matter that we know of today.

Are there still smaller particles?

The Large Hadron Collider will address this question!
The Fundamental Forces of Nature

Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity

together they make the Sun shine

Gravity: holds planets and stars together
The “Standard Model”

Over the last 100 years: combination of Quantum Mechanics and Special Theory of relativity along with all new particles discovered has led to the Standard Model of Particle Physics.

The new (final?) “Periodic Table” of fundamental elements:

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time.

A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin
The Hunt for the Higgs

Where do the masses of elementary particles come from?

Massless particles move at the speed of light -> no atom formation!!

The key question (pre-2012):
Does the Higgs particle exist?
If so, where is the Higgs?

We do not know the mass of the Higgs Boson

Scalar field with at least one scalar particle

\[ L_{\text{Higgs}} = (\partial_{\mu} \phi)^* (\partial^{\mu} \phi) - V(\phi) \]
\[ V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 \]

Note: NOT the mass of protons and neutrons

It could be anywhere from 114 to ~700 GeV
The Higgs Field and the Cocktail Party

By David Miller

Imagine a cocktail party

This is the Higgs field

Enters a famous person...

He is slowed down on his way to the drinks!!
This Search Requires.......

1. Accelerators: powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles.

2. Detectors: gigantic instruments that record the resulting particles as they “stream” out from the point of collision.

3. Computing: to collect, store, distribute and analyse the vast amount of data produced by these detectors.

4. Collaborative Science on Worldwide scale: thousands of scientists, engineers, technicians and support staff to design, build and operate these complex “machines”.

The Large Hadron Collider = a proton proton collider

A 27 km ring -- 100m underground

7 TeV + 7 TeV
(3.5/4 TeV + 3.5/4 TeV)

1 TeV = 1 Tera electron volt
= $10^{12}$ electron volt

Primary physics targets
• Origin of mass
• Nature of Dark Matter
• Understanding space time
• Matter versus antimatter
• Primordial plasma

The LHC produced collisions from 2010 till beginning of 2013
LHC will restart in 2015 with collisions at an energy of 13 TeV
The LHC is an Extraordinary Machine

Colder than the empty space in the Universe: 1.9K ie above absolute zero

The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun
Experiments at the LHC
Physics requirements drive the design!

Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task. Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Such an experiment has ~ 100 Million read-out channels!!
The Higgs Hunters @ the LHC

The ATLAS experiment

The CMS experiment

These experiments use different technologies for their detector components
The CMS Collaboration: >3200 scientists and engineers, >800 students from ~190 Institutions in 42 countries.

UC-Davis is an very active Member of CMS.

About 1/8th of the collaboration
Experiments were anticipated to produce about **15 Million Gigabytes** of data each year (~20 million CDs!)

The total volume in eg ATLAS is 5 billion detector events and several billion Monte Carlo events amounting to 100 Million Gigabytes of data in 3 years.

LHC data analysis requires a computing power equivalent to ~100,000 of today's fastest PC processors.

=> Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity.

GRID Computing
The Science Questions…

The Higgs Particle
Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem
  – need high energy:
    \[ E = mc^2 \]
  – need lots of data
non-deterministic and very rare
order 1 in \(10^{10}\)

* for us finding the Higgs it was
48 years = 1,513,728,000 sec
Higgs Boson Searches (simulation)

Low $M_H < 140$ GeV/c$^2$

Medium $130 < M_H < 500$ GeV/c$^2$

High $M_H > 500$ GeV/c$^2$

Simulation

$p \rightarrow H \rightarrow \gamma \gamma$

$H \rightarrow ZZ \rightarrow \ell \ell jj$

$H (150$ GeV$) \rightarrow Z^0 Z^0 \rightarrow 4\mu$
A Collision with two Photons

A Higgs or a ‘background’ process without a Higgs?

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced 15 Higgses/minute with present luminosity
A real collisions: ZZ→ 4 muons
Physicists hope to find the Higgs boson, key to unified field theory, this year

The suspense was building up...

Fabrice Coffrini/Agence France-Presse via Getty Images - A superconducting solenoid magnet, the largest of its kind, is part of the Large Hadron Collider, which is searching for the Higgs boson.
July 4\textsuperscript{th} 2012

- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

Followed live around the world...
July 2012: Results

Higgs → 2 photons!!

Higgs → 2Z → 4 leptons!!

Higgs → 2W → 2l2ν!!
July 4th 2012
The discovery of a new particle
July 2012: Results

Both experiments see an excess ~125 GeV in the $\gamma\gamma$, ZZ and WW channel

→ Final result by adding up all the channels

Shown is the compatibility with a ‘background only hypothesis’

CMS and ATLAS observe a new boson with a significance of about 5 sigma (1 chance in 3 million to be wrong!!)

5 fb$^{-1}$/2011 and 5 fb$^{-1}$/2012
We called the new particle a “higgs-like” particle
Update with the Full 2012 Data Sample

Increased data sample with a factor of ~3

The particle is clearly still with us, now with a significance of $>10\sigma$ !!

We now enter the phase of measuring the properties of the new particle
The Birth of a Particle

"History" of the data accumulation during the last two years

ATLAS

CMS

\( \sqrt{s} = 7 \text{ TeV} \int L dt = 0.02 \text{ fb}^{-1} \) Apr 18, 2011

ATLAS Preliminary

\( H \rightarrow \gamma\gamma \) channel

Data

Background-only

CMS Preliminary

\( \sqrt{s} = 7 \text{ TeV}; L = 0.0 \text{ fb}^{-1} \)

Data

\( m_H = 126 \text{ GeV} \)

\( Z^\gamma, ZZ \)

\( Z + X \)
The discovery of the new particle has been confirmed with more added collisions in 2012.

Signals in the fermion-channels start building up

We tested the spin: it is compatible with a $0^+$ state and not with a $0^-$ or spin 2 states

The mass is measured better with time, now in the range 125-126 GeV. A naïve average gives 125.6 GeV

The couplings to Bosons and Fermions are consistent with the SM predictions (but these are not very precise yet; Surprises possible…)

March 2013: We call it now “a Higgs particle”
Tuesday 8 October 2013

Francois Englert

Peter Higgs

Congratulations!!!!
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. 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".

UC-Davis is a member of CMS
Many questions are still unanswered:

- What explain a Higgs mass $\sim 126$ GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ...
Other Questions…

Are there Extra Space Dimensions?

Or Micro Black Holes?
The Gravitational force becomes strong!

Problem: \( m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^2} = \) 246 GeV

\[ M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV} \]

No signal found yet
New Planck scale is larger than 3 TeV
Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein’s general theory on relativity

If the Planck scale is in ~TeV region: can expect Quantum Black Hole production

Quantum Black Holes are harmless for the environment: they will decay within less than $10^{-27}$ seconds ⇒ SAFE!

Simulation of a Quantum Black Hole event

Black holes with mass of up to 5 TeV are excluded
Black Holes Hunters at the LHC...
Other Questions...

Dark Matter at the LHC?

Are we supersymmetric?
Dark Matter in the Universe

Astronomers found that most of the matter in the Universe must be invisible Dark Matter.

‘Supersymmetric’ particles?
SUSY Searches: No signal yet to date...

So far NO clear signal of supersymmetric particles has been found so far. SUSY particles must be heavier than 1000 GeV.

We can exclude regions where the new particles could exist.

Searches will continue for the next years.
The properties and subtle differences of matter and antimatter using mesons containing the beauty quark, will be studied further in the LHCb experiment.
Primordial Plasma

Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe.

Hundreds of particles in the detector

Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today.

A recorded lead lead collision in the CMS detector
The Physics Program at LHC

Data taking started in 2010
Now we have more than 300 reviewed scientific papers per experiment!
Mostly measurements of the strong and electroweak force at 7/8 TeV and Searches

- Are quarks the elementary particles? So far yes
- Do we see supersymmetric particles? Not yet
- Do we see extra space dimensions? Not Yet
- Do we see micro-black holes? No

-> The Discovery of a Higgs-like particle!!
Electro-weak phase transition (Higgs,...)

QCD phase transition (quark gluon plasma)

LHC studies the first $10^{-10}$ - $10^{-5}$ seconds...
Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought fundamental scalar boson, postulated in 1964.

March 2013: The full statistics of 2011+2012 (about a factor 3 more data) confirms the existence of the new particle.

The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it now “a Higgs particle”. This is a brand new fundamental particle, as we never seen before.

This Higgs boson is ‘very light’ which suggest new physics Beyond the Standard Model will be needed. Supersymmetry? Extra Dimensions? Other? The next years @ the LHC will tell...

We are on the verge of a revolution in our understanding of the Universe and our place within it. UC-Davis and many other US-scientist participate!!

This is only the beginning!!!
The Physics Program at LHC

Data taking started in 2010
Now we have more than 300 reviewed scientific papers per experiment!
Mostly measurements of the strong and electroweak force at 7/8 TeV and Searches

- Are quarks the elementary particles?
- Do we see supersymmetric particles/Dark Matter?
- Do we see extra space dimensions?
- Do we see micro-black holes?

-> The Discovery of a Higgs-like particle!!
A Recorded Heavy Ion Collision
Are Quarks Elementary Particles?
Supersymmetry: a new symmetry in Nature?

SUSY particle production at the LHC

Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab
Are Quarks Elementary Particles?

Rutherford experiment: Unexpected backscattering of $\alpha$-particles: Evidence for the structure of atoms!! (1911)
Are Quarks Elementary Particles?

Quarks remain elementary particles after these first results.
The discovery of the Higgs made the headlines worldwide

Hawking lost $100 bet over Higgs boson

'God Particle' 'Discovered': European Researchers Claim Discovery of Higgs Boson-Like Particle

HOW THE HIGGS COULD BECOME ANNOYING
Yes, the discovery of the Higgs boson is thrilling and game-changing. But it could also introduce some aggravating situations.

Discovery of Higgs Boson Bittersweet News in Texas

Scientists Set The Higgs Boson To Music

3 Ways the Higgs Boson Discovery Will Impact Financial Services

Higgs boson researchers consider move to Cloud computing

"Within another decade the Cloud will be where grid computing is now"

What Comes After Higgs Boson?

Higgs boson discovery could make science fiction a reality

Discovery of the 'God particle' could make science fiction a reality, and answer one of the most basic questions of our universe: How did light become matter — and us?
What is Next?

The work is not over yet: Many questions still remain unanswered:

- Is it THE Standard Model Higgs boson or a messenger of New Physics?
- How can we explain a Higgs mass ~ 126 GeV? What stabilizes the mass?
- What explains the mass pattern of the particles that we observe?
- What is Dark Matter and Dark energy? Supersymmetry at higher masses??
- Where is the antimatter in the Universe? How did it disappear??

Need for precision measurements with ~100x the present statistics
LHC upgrade! Experiment upgrades!! (Other machines?)
Bringing the Nations Together

“...the promotion of contacts between, and the interchange of, scientists...”
Detecting Supersymmetric Particles

Supersymmetric particles decay and produce a cascade of jets, leptons and missing (transverse) energy due to escaping ‘dark matter’ particles.

Very clear signatures in CMS and ATLAS.

LHC can discover supersymmetric partners of the quarks and gluons as heavy as 2 to 3 TeV.

The expected cross sections are huge!! ⇒ ~10,000 particles per year.
Silicon detector for a Compton camera in nuclear medical imaging

Thin films by sputtering or evaporation

Radio-isotope production for medical applications

Medipix: Medical X-ray diagnosis with contrast enhancement and dose reduction

Radiography of a bat, recorded with a GEM detector
Applications of Grid Computing

Multitude of applications from a growing number of domains

- Archeology
- Astronomy & Astrophysics
- Civil Protection
- Computational Chemistry
- Earth Sciences
- Financial Simulation
- Fusion
- Geophysics
- High Energy Physics
- Life Sciences
- Multimedia
- Material Sciences
- ...

Infrastructure used by >10000 researchers
CERN as an Educator

- Apprentices
- Academic Training
- Exhibitions
- Visits
- Outreach
- Technical Training
- Conferences
- Accelerator School
- Fellows
- CERN-Latin America School
- Summer Students
- Science on Stage
- Teachers programmes
- Doctoral Students
- Physics School
- Computing School
- Technical Students
- Microcosm
- Language Training
- Communications Training
- Management Training
Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought Higgs boson, postulated in 1964.

March 2013: The full statistics of 2011+2012 (about a factor 3 more data) confirms the existence of the new particle.

The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it from now onwards “a Higgs particle”. This is a brand new particle, as we never seen before.

This Higgs boson is likely to carry the ‘genetic code’ for the physics Beyond the Standard Model. Present studies do not yet reveal any BSM signatures but have only a ~20% precision.

We are on the verge of a revolution in our understanding of the Universe and our place within it. We expect more discoveries at the LHC (Supersymmetry, Extra dimensions, other?)

This is only the beginning!!!
Following the data released by ATLAS and by CMS last March, we now call it a Higgs boson (instead of a Higgs-like boson).
The LHC is an Extraordinary Machine

Colder than the empty space in the Universe: 1.9K i.e above absolute zero

The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun
Physicists hope to find the Higgs boson, key to unified field theory, this year

The suspense was building up...

A superconducting solenoid magnet, the largest of its kind, is part of the Large Hadron Collider, which is searching for the Higgs boson.
The Spin of the New Particle

A Higgs particle should be a spin $0^+$ state

- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

=> Particle is consistent with a $0^+$ state!!
The Dark Matter Connection

Results for direct searches and collider searches for Dark Matter
-> Spin dependent and spin independent cross sections of Dark Matter with ordinary matter (monojets searches)

Competitive limits with direct searches (under the effective theory assumptions)
Rare Decays: $B_s$ to $\mu\mu$ Decays

• A $B_s$ particle is a particle consisting of a beauty-quark and strangeness-quark, with a mass of $\sim 10$ GeV
• Three $B_s$ particles in a million will decay into two muons. This decay has been chased since 25 years.
• New physics modifies these Standard Models predictions

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) = 3.56 \pm 0.29 \times 10^{-9}$$

Observation:

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

Results from LHCb +CMS experiment combined
And it continues…

• European physics society prize in July for the ATLAS and CMS experiments…
• Prestigious Prince of Asturias Award two weeks ago for CERN and Englert & Higgs…
Consequences for our Universe?

Precise measurements of the top quark and first measurements of the Higgs mass:

Our Universe meta-stable? Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

Will our universe end in a "big slurp"? Higgs-like particle suggests it might
Searches at the Tevatron

In the last 10 years most information came from the Tevatron. This will be discussed in a separate lecture.

...An excess at $M_H \sim 120-135$ GeV!
What is Next?

Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other “sectors”

\[ \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y \]

Need for precision measurements with \( \sim 100 \times \) the present statistics

LHC upgrade! Experiment upgrades!! (Other machines?)
Aside: Profile likelihood Ratio, $p_0$ and $CL_s$

- Local significance $p_0$ to test background hypothesis.

- $CL_s = CL_{s+b}/CL_b$ (log-likelihood ratio) to test signal hypothesis.

3 sigma = “Evidence”
1 chance in 1000 to be wrong!

5 sigma = “Discovery”
1 chance in 3 million To be wrong!!!
Signal Strength

- Signal strength $\mu$ is the observed over Standard Model expected cross section.
- For $\mu = 1$ the production rate is compatible with Standard Model expectation.

ATLAS a bit above and CMS a bit below $\mu = 1$...
The Spin of the New Particle

A Higgs particle should be a spin $0^+$ state

- Study angular correlations in the decays of the particle; build likelihoods and test spin- and parity hypotheses
- Use the ZZ, 2-photon and WW final states

=>$\Rightarrow$ Particle is consistent with a $0^+$ state!!
Couplings to the New Particle

- Use information of all production and decay channels
- $\kappa_f$ and $\kappa_V$ are scale factors w.r.t. the Standard Model values for fermions and vector bosons

$\Rightarrow$ Couplings compatible Standard Model values, but large uncertainties
...Future data will decide...
8 October 2013: Prof. François Englert and Prof. Peter W. Higgs were jointly awarded the Nobel Prize in Physics "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"

This seminar will discuss the discovery of the particle…
Introduction: The LHC and the boson Hunter experiments

The birth of a new particle:

The discovery of a new kind of fundamental particle:

A Higgs Boson

Studies of its properties

What is next?

Summary

(*) I will mostly use that name throughout.
EWSB Heroics

The year is 1964

Electroweak Symmetry Breaking

François Englert  Robert Brout  Peter Higgs
Gerald Guralnik  Carl Hagen  Tom Kibble

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS
P. W. Higgs
Tayl Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

+ others could be mentioned, that have inspired those above
In 1964 Peter Higgs, and Francois Englert & Robert Brout introduce scalar fields as a solution to EWSB. Peter Higgs mentions as a side-remark that there should be a particle associated with these fields in his second paper.

Steve Weinberg picks up the idea for the Standard Model formulation at the end of the 60’s. Benjamin Lee coins at ICHEP 1972 the particle as ‘Higgs’ particle. The name stuck…

In recent years some new proposals have been tried such as:
- The Brout-Englert-Higgs particle (BEH particle)
- The Electro-weak fundamental scalar
- The Standard Model Boson (SMS)

None really got stuck so far: the Particle Data Group & community is used to 40 years of then name “Higgs particle”

We do call it the “Brout-Englert-Higgs Mechanism”

See eg. “The Particle at the End of the Universe” by Sean Carroll
Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
They orbit a 27km ring 11 000 times/second
A billion collisions a second in the experiments

Luminosity = # events/cross section/time

LHC operation is now stopped for 2 years, and the machine is being prepared for running at 13-14 TeV from 2015 onwards.
Power consumption ~ 100 MW = 60% of one Aswan Turbine

Aswan can power 20 LHCs
The Higgs Field

Another view of the Higgs field
Pre-LHC: Higgs Searches in 2010

• Searches for the Higgs particle started end of the ‘70’s and 80’s
• Stringent results came in the ‘90’s from the LEP and Tevatron accelerators

Precision Measurements (LEP...)

Tevatron p anti-p collisions at 1.96 TeV

• Direct exclusion: \( M_H < 114 \) GeV
• Results from quantum corrections: favorite mass \( M_H = 92 +/- 34 \) GeV

• Direct exclusion: \( M_H = 158-176 \) GeV

....Enter the LHC!
Higgs Search in 2011

November 2011: based on 50% of the data

ATLAS + CMS Preliminary, $\sqrt{s} = 7$ TeV

$L_{\text{int}} = 1.0-2.3$ fb$^{-1}$/experiment

95\% CL limit on $\sigma/\sigma_{\text{SM}}$

No sign of a new particle yet, but mass limited to 114.4 - 141 GeV or >476 GeV

Allowed

Excluded
All the data from 2011 was now analysed and the combination the decay channels showed the following:

- We see – for the first time-- an excess of events building up in a region over expectation from pure background. Cool!

  Is this the first sign of the ‘growing Higgs signal?’
<table>
<thead>
<tr>
<th>Neutral currents (1973)</th>
<th>A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charm (1974)</td>
<td>John ELLIS, Mary K. GAILLARD * and D.V. NANOPoulos **</td>
</tr>
<tr>
<td>Heavy lepton $\tau$ (1975)</td>
<td>CERN, Geneva</td>
</tr>
<tr>
<td>Attention to search for $W^\pm, Z^0$</td>
<td>Received 7 November 1975</td>
</tr>
<tr>
<td><strong>For us, the Big Issue: is there a Higgs boson?</strong></td>
<td></td>
</tr>
<tr>
<td>Previously $\sim$ 10 papers on Higgs bosons</td>
<td></td>
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<tr>
<td>$M_H &gt; 18$ MeV</td>
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</tbody>
</table>

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.
CERN: The European Laboratory for Particle Physics

- CERN is the European Organization for Nuclear Research, the world’s largest Particle Physics Centre, near Geneva, Switzerland.
- It is now commonly referred to as European Laboratory for Particle Physics.
- It was founded in 1954 and has 20 member states + several observer states.
- CERN employs >3000 people + hosts ~11000 visitors from >500 universities.
- Annual budget ~ 1200 MCHF/year (2013)

Where the World Wide Web was born...
The Origin of Particle Masses

- At ‘low’ energy the Weak force is much weaker than the Electromagnetic force: Electroweak Symmetry Breaking: EWSB
- The W and Z bosons are very massive (~ 100 proton masses) while the photon is massless.
- The proposed mechanism(*) in 1964 gives mass to W and Z bosons and predicts the existence of a new elementary ‘Higgs’ particle. Extend the mechanism to give mass to the Fermions via Yukawa couplings.

(*) Brout, Englert, Higgs, Kibble, Hagen and Guralnik, …

The Higgs (H) boson is the quantum of the new postulated field and has been searched for since decades at other particle colliders such as LEP and the Tevatron, and now at the Large Hadron Collider @ CERN
Blinding the Data

Not to have a bias in the analysis we decided to analyse the 2012 data blinded. The unblinding in CMS was on June 15th, 2012.

About 900 participants (400 persons in a room for 250 people, rest by video).

That day CMS knew whether they had a discovery or not...
Does this Particle Decay into Fermions?

- The BEH Mechanism was proposed in 1964 to give mass to the W and Z boson.
- Does it also give mass to the fermions? Does the particle couple to fermions?
- ⇒ Direct test: check for the decays $H \rightarrow \tau \tau$ and $H \rightarrow b$ quark pairs

Yes: A mild excess is building up also for these channels!!
The Mass of the Particle

Determine the mass from ZZ and 2-photon channels which show a peak!

\[ \hat{m}_H = 125.5 \pm 0.2^{\text{(stat)}} \pm 0.6^{\text{(syst)}} \text{ GeV} \]

\[ \hat{m}_H = 125.7 \pm 0.3^{\text{(stat)}} \pm 0.3^{\text{(syst)}} \text{ GeV} \]

ATLAS and CMS observe the same particle!! 😊
Signal Strength

- Signal strength $\mu$ is the observed over Standard Model expected cross section.
- For $\mu = 1$ the production rate is compatible with Standard Model expectation.

ATLAS a bit above and CMS a bit below $\mu = 1$...
The Dark Matter Connection

Results for direct searches and collider searches for Dark Matter

- Spin dependent and spin independent cross sections of Dark Matter with ordinary matter \((W/Z + \text{MET searches})\)

Competitive if DM-\(u\) quark coupling different from DM-\(d\) quark coupling
Search for Weakly Interacting Massive Particle (WIMPs) candidates in events with Missing Transverse Momentum
EG: SUSY searches, monojet and mono-photon Searches, W’ searches...

arXiv:1305.1605

+ CAST experiment, searching for axion DM
So far NO clear signal of supersymmetric particles has been found.

We can exclude regions where the new particles could exist.

Searches will continue for the next years.

$\mathbf{m_0}$ and $\mathbf{m_{1/2}}$ are SUSY parameters.

Masses of SUSY particles are larger than 1000 GeV!!!
So these particles are heavier than 1000 times the proton.
Explore other than the simplest/constrained SUSY models.
A Higgs...

Naturalness: Requires Top squarks $< \sim 1$ TeV, gluino $< \sim 1.5$ TeV...
So far no evidence found...
Various limits on sparticles: No 'light' Lightest SUSY Particle (LSP) so far

But could hide in contrived scenarios
# Searches for SUSY

## ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** EPS 2013

<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$ Jets</th>
<th>$E_{T}$ jets</th>
<th>$\int L , dt$ [fb$^{-1}$]</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSM</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$1.2$ TeV</td>
</tr>
<tr>
<td>MSUGRA/CMSM</td>
<td>0-3 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$1.1$ TeV</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$740$ GeV</td>
</tr>
<tr>
<td>$\tilde{b}$</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$1.3$ TeV</td>
</tr>
<tr>
<td>$\tilde{t}$</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$1.1$ TeV</td>
</tr>
<tr>
<td>$\tilde{Z}$</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$0.7$ TeV</td>
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<tr>
<td>$\tilde{g}$</td>
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<td>Yes</td>
<td>20.3</td>
<td>$1$ TeV</td>
</tr>
<tr>
<td>$\tilde{t}$</td>
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<td>Yes</td>
<td>20.3</td>
<td>$0.3$ TeV</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$0.1$ TeV</td>
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<tr>
<td>$\tilde{g}$</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$0.01$ TeV</td>
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<td>$\tilde{g}$</td>
<td>0-2 bjets</td>
<td>Yes</td>
<td>20.3</td>
<td>$0.001$ TeV</td>
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</tbody>
</table>

*similar results obtained by CMS*
Events with five jets of particles and large missing energy which could come from a possible dark matter particle

But a few events is not enough too prove we have something new
Higgs Production Channels vs Mass

We now have data on all production channels...

Higgs Production at the LHC

Higgs production in proton-proton collisions

area of largest interest
The five main decay channels:

- $H \to \gamma\gamma$: $110-150$ GeV/c$^2$, Data used: 7+8 TeV (fb$^{-1}$), $m_H$ resolution: 1-2%
- $H \to \tau\tau$: $110-145$ GeV/c$^2$, Data used: 4.9+19.6 fb$^{-1}$, 15%
- $H \to bb$: $110-135$ GeV/c$^2$, Data used: 5.0+19.0 fb$^{-1}$, 10%
- $H \to WW \to ll\nu\nu$: $110-600$ GeV/c$^2$, Data used: 4.9+19.5 fb$^{-1}$, 20%
- $H \to ZZ \to 4l$: $110-1000$ GeV/c$^2$, Data used: 5.1+19.6 fb$^{-1}$, 1-2%

Higgs boson couples to mass:

$\Gamma_{H\to f\bar{f}} \sim m_f^2$
Dark Matter Search Experiments

Dark Matter Experiments provide limits on cross section vs. WIMP mass

No established signal for Dark Matter yet

Search for Weakly Interacting Massive Particle (WIMPs)
The Other Dark Matter Connection

Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM). Use effective theory to relate measurements to Dark Matter studies.
The Dark Matter Connection

Results for direct searches and collider searches for Dark Matter

- Spin dependent and spin independent cross sections of Dark Matter with ordinary matter (monojets searches)

---

**Spin Dependent**

**Spin Independent**

Competitive limits with direct searches (under the effective theory assumptions)
The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders

The Higgs particle is the last missing particle in the Standard Model

proton → Higgs → proton

1993

The Higgs particle is the last missing particle in the Standard Model
The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders

The Higgs particle is the last missing particle in the Standard Model
ATLAS before closing...
Extra Space Dimensions

Problem:

\[ m_{EW} = \frac{1}{(G_F \sqrt{2})^2} = 246 \text{ GeV} \]

\[ M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV} \]

The Gravity force becomes strong!
Extra Dimensions at the LHC

Main detection modes at the experiments
- Collisions with Large missing (transverse) energy
- Resonance production in two particle distributions

LHC can detect extra dimensions for scales up to 5 to 9 TeV

No signal yet
If extra dimensions exist then the Planck scale is larger than 2-3 TeV
Search for Micro-black Holes

Extra Dimensions!

Evaporates in $10^{-27}$ sec

No evidence for micro black holes was found in the data so far.

But some do see some interesting events. These could be background.

Black holes with mass of up to 5 TeV are excluded (model dependent).
Searches for the Higgs Particle

A Higgs particle will decay immediately, e.g. in two heavy quarks or two heavy (W,Z) bosons.

Example: Higgs(?) decays into ZZ and each Z boson decays into μμ.

So we look for 4 muons in the detector.

But two Z bosons can also be produced in LHC collisions, without involving a Higgs!

We cannot say for on event by event (we can reconstruct the total mass with the 4 muons).
Does this new particle have all the properties that we expect a Higgs Boson to have?  (Summer 2012 5+5 fb⁻¹)  
– So far it seems to couple as expected to photons, heavy Z and W bosons, but at the time of the discovery it was not seen that they also couple to quarks or leptons

What are the quantum numbers of this new particle?
– EG Spin and Parity: for the SM Higgs we expect it to have spin = 0 and parity = +.

Is there more than one Higgs-like particle? Some theories beyond the Standard Model predict these…

Does it have ‘exotic’ properties?

Still a lot of questions to be answered in summer 2012!!
Let’s look at the new updates with full 2012 data (~ 25 fb⁻¹)