Status of LHC and the Higgs Search

Andrei Gritsan

Johns Hopkins University

August, 2011

JHU Quarknet Meeting
Finding the Higgs

- Higgs mechanism is responsible for generating mass of fundamental particles (discuss later how)

- Is it responsible for our mass? (discuss later why)

- Why have not we seen the Higgs? (A) it is too heavy for past experiments (B) it does not exist

- If Higgs is so important:
  - how do we find the Higgs?
  - or prove that it does not exist...
Produce the Higgs: Reaching Highest Energy

\[ mc^2 = E \]
CMS Experiment

36 Nations, 160 Institutions, 2008 Scientists and Engineers (November 2003)

**TRIGGER & DATA ACQUISITION**
- Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

**TRACKER**
- Austria, Belgium, CERN, Finland, France, New Zealand, Germany, Italy, Japan*, Switzerland, UK, USA

**CRYSTAL ECAL**
- Belarus, CERN, China, Croatia, Cyprus, France, Ireland, Italy, Japan*, Portugal, Russia, Serbia, Switzerland, UK, USA

**PRESHOWER**
- Armenia, Belarus, CERN, Greece, India, Russia, Taipeh, Uzbekistan

**RETURN YOKE**
- Barrel: Czech Rep., Estonia, Germany, Greece, Russia
- Endcap: Japan*, USA, Brazil

**SUPERCONDUCTING MAGNET**
- All countries in CMS contribute to Magnet financing in particular: Finland, France, Italy, Japan*, Korea, Switzerland, USA

**HCAL**
- Barrel: Bulgaria, India, Spain*, USA
- Endcap: Belarus, Bulgaria, Russia, Ukraine
- HO: India

**MUON CHAMBERS**
- Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain, Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA
- * Only through industrial contracts

**FORWARD CALORIMETER**
- Hungary, Iran, Russia, Turkey, USA

**Features**
- Total weight: 12500 T
- Overall diameter: 15.0 m
- Overall length: 21.5 m
- Magnetic field: 4 Tesla
Detecting Particles at CMS
Production of the Higgs

- Higgs interaction strength $\propto \text{mass of particles}$ of color-neutral & charge-neutral Higgs
- Does not interact with massless gluons directly $gg \rightarrow X$ only through a "loop"
- Very unlikely to interact with light quarks in proton $q\bar{q} \rightarrow X$ negligible
Decay of the Higgs

• Consider decay back to Standard Model particles

  X \rightarrow l^+l^-, q\bar{q}
  
  again very unlikely (light)

• Decay to fermions

• Decay to gauge bosons

  X \rightarrow \gamma\gamma, W^+W^-, ZZ, gg

  \gamma\gamma through a loop

  two likely channels WW, ZZ
  
  but Higgs mass \geq 2m_W
Next Steps

• If there is a Higgs
  – likely to appear as a ”resonance” on top of ”background”
  – ”background” = random combination of particles
Cartoon of an Experiment
Kinematics of $X \rightarrow ZZ$ and $WW$

- We can describe kinematics of decay and distinguish from others
By the end of June 2011 collected $\sim 1 \text{ fb}^{-1}$ of data
$\sim 100$ trillion proton-proton collisions
for comparison, in 2010 we had $\sim 0.04 \text{ fb}^{-1}$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$
Higgs at LHC: Candidate Events $H \rightarrow ZZ$

CMS Experiment at LHC, CERN
Data recorded: Sat Jun 25 08:34:20 2011 CEST
Run/Event: 167565 / 876658967
Lumi section: 829
Orbit/Crossing: 217104439 / 1377
Higgs at LHC: $H \rightarrow ZZ \rightarrow 4l$

- Perform statistical analysis of observed events
  - data are consistent with background only
  - can try to reject Higgs at 95% confidence

![Graph showing events and limits](image-url)
Higgs at LHC: $H \rightarrow ZZ \rightarrow 2l2q$

- Perform statistical analysis of observed events
  - data are consistent with background only
  - can try to reject Higgs at 95% confidence

![Graphs showing Higgs boson search results from CMS](image-url)
Combine all Higgs channels

- Higgs → γγ, ττ, WW, ZZ, with ZZ → 4l, 2l2q, 2l2ν

- reject Higgs at 95% confidence in large range of masses
Closing on the Higgs

- We are excluding large range of masses now
- Preparing new results by mid-August, LHC performs well
- Even better by the end of 2011, and in 2012
- We will either FIND or REJECT the SM Higgs hypothesis
  - both options are exciting
  - both will be only the first step to explain puzzles
    - (1) if Higgs found, still new discoveries expected to explain inconsistencies of the model
    - (2) if Higgs not found, even more expected to explain the mechanism of mass
What is the Higgs Particle?

- This answer is probably not very satisfying to see first:

  Higgs appears from introduction of this Lagrangian in the quantum field theory of particles

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu \phi)^2 - \left[ \frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda \phi^4 \right] \]
What is Higgs?

- There are several phenomena:
  - Peter Higgs
  - Higgs mechanism
  - Higgs field
  - Higgs particle (still elusive particle)

- People sometimes confuse these phenomena
  - especially the last two

- So far there is hard evidence only for the first:
  - 1964 article by Peter Higgs in Physics Review Letters

Andrei Gritsan, JHU
August, 2011
Why is it Higgs Mechanism?

- In fact, there are several names of the Higgs mechanism:
  - Brout-Englert-Higgs mechanism
  - Higgs-Brout-Englert-Guralnik-Hagen-Kibble mechanism
  - Anderson-Higgs mechanism
  - Higgs mechanism is just simpler
  - all for authors of independent papers on the topic

- Partly due to ironic history with the paper by Higgs:
  - rejected from European Physics Letters
    “of no obvious relevance to physics”
  - added a paragraph predicting a new particle
Spontaneous Symmetry Breaking

- Spontaneous symmetry breaking → Higgs mechanism
- 3 quark families → matter over antimatter asymmetry

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Yoichiro Nambu
1/2 of the prize

Makoto Kobayashi
1/4 of the prize

Toshihide Maskawa
1/4 of the prize
Symmetry spontaneously broken: pick $\phi = v$ at minimum of potential energy of Higgs field ($\mu^2 < 0$)

$$V(\phi_1, \phi_2, \phi_3, \phi_4) = \frac{1}{2} \mu^2 \left[ \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 \right] + \frac{1}{4} \lambda \left[ \ldots \right]^2$$

Higgs particle described by one field component

$$\eta = \phi_1 - v$$
What about other Higgs field components?

- The other field components $\phi_2$, $\phi_3$, $\phi_4$ “couple” to Weak Interaction bosons $Z$, $W^-$, $W^+$ and give them mass.

- Photon $\gamma$ is the same Weak Interaction boson but remains massless (does not couple to Higgs field).
All Elementary Particles get Mass from Higgs Field

- **Fermions** $S = \frac{\hbar}{2} \ (\text{matter})$

  - **leptons**
    - $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$
  - **quarks**
    - $u, c, s, d, b, t$

- **Bosons** $S = \hbar \ (\text{force carries})$:
  - **EM**
  - **strong**
  - massless (weak force bosons mass)

Andrei Gritsan, JHU  August, 2011
What is Higgs?

• Higgs mechanism
  – existence of Higgs field
  – spontaneous symmetry breaking and “gauge” invariance (interaction with $Z, W^\pm$)
  – gives mass to all elementary particles
  – predicts existence of Higgs particle

• Everything works perfectly, except:
  – we have not observed the Higgs particle yet

• Why:
  – Higgs particle is too heavy to produce (if it exists) (more than $100 \times$ proton mass)
  – hope to produce or exclude at Large Hadron Collider
  – still possible that Higgs mechanism is not correct
Do we have mass due to Higgs mechanism?

- Yes and no
  - we are not elementary particles...
What does give us mass? Molecules? Atoms?

Andrei Gritsan, JHU
August, 2011
What does make mass?

• What gives us mass?

Molecules

Atoms

Nucleus
• Three quarks make up a Baryon:
What Gives Mass to Baryons: Proton, Neutron,...

- Remember Einstein’s formula

\[ E = mc^2 \]

\[ m(u \text{ or } d) < 1\% \ m(\text{proton}) \]

Mostly energy of gluons and quarks inside gives proton mass

not really the Higgs mechanism
But Higgs Mechanism is Very Important

- Makes Weak Interactions weak: mass of $Z, W^-, W^+$

  \[ p + p \rightarrow d + e^+ + \nu_e \]

- Makes certain hierarchy of masses essential for our existence

Andrei Gritsan, JHU August, 2011
Hypothetical Scenario: Different Quark Mass

• Again, normally proton is stable and neutron decays:
  \[ m(n) > m(p) + m(e) + m(\nu_e) \]

• Why is \( m(n) > m(p) \)
  – \( m(p) = 938 \text{ MeV}, \ m(n) - m(p) = 1.3 \text{ MeV} \)
  – tiny difference makes a big difference!
  – naively expect \( m(p) > m(n) \) if \( u \) and \( d \) were the same
  – but \( m(d) > m(u) \)

• New scenario:
  – what if \( m(d) < m(u) \)
Hypothetical Scenario: Different Quark Mass

- If \( m(d) < m(u) \), proton decays:
  - Consequence: no Hydrogen, no \( H_2O \), no life
    - still have \( He^4 \), rapid \( nn \) fusion, instead of slower \( pp \)
We are likely to find more than just Higgs

- New (super)symmetry:
  \[ Q|\text{fermion}\rangle = |\text{boson}\rangle \]
  \[ Q|\text{boson}\rangle = |\text{fermion}\rangle \]

- Solve:

  1. natural light
     \[ H^0 \]

  2. dark matter
     \[ W^- W^+ Z \]
     lightest \( \tilde{\chi}_1^0 \)

  3. large matter/antimatter
     \[ g \gamma \]

- Just around the corner in mass...

Andrei Gritsan, JHU

August, 2011
BACKUP SLIDES
Another Scenario: Muonic World

- We would get a muonic atom:

\[ r = \frac{4\pi \epsilon_0 \hbar^2}{m_\mu e^2}, \text{ 200 smaller!} \]

Hydrogen radius

\[ r = \frac{4\pi \epsilon_0 \hbar^2}{m_e e^2} = 5 \times 10^{-11} \text{ m} \]
(1) Scenario: Muonic World

- However muonic hydrogen would decay:

- Not very interesting universe
  - filled with neutral “balls” of neutrons and neutrinos
(1) Scenario: Muonic World

- Normally neutron is not stable (life $\tau \sim 886$ seconds)
  \[ m(n) > m(p) + m(e) + m(\nu_e) \]

- But stable in the muonic world:
  \[ m(n) < m(p) + m(\mu) + m(\nu_\mu) \]
History of the Universe

Accelerators:
- CERN-LHC
- FNAL-Tevatron
- BNL-RHIC
- CERN-LEP
- SLAC-SLC

Key:
- $w, z$: bosons
- $\gamma$: photon
- $q$: quark
- $g$: gluon
- $e$: electron
- $\mu, \tau$: muon, tau
- $n$: neutrino

Inflation

BIG BANG

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
Composition of the Cosmos

Dark Energy: ~70%

Dark Matter: ~25%

Antimatter: 0%

Heavy elements: 0.03%

Neutrinos: 0.3%

Stars: 0.5%

Free hydrogen and helium: 4%

Dark matter: ~25%

Dark energy: ~70%
Look Beyond the Standard Model

- Why does matter dominate (Sakharov):
  - $CP$-asymmetry
  - baryon non-conservation
  - non-equilibrium

- Mysterious $H$iggs field
  - gives mass to particles

- Need something beyond the SM
  - large $CP$-asymmetry
  - dark matter
  - light $H$iggs