LHC: where are we?

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What is the LHC for?

Meant to address some of the most outstanding problems of particle physics today.

• Why do particles have mass?
  Possible answer: The Higgs boson

• Why is gravity so weak?
  Possible answers: supersymmetric particles, extra spatial dimensions, ....

• What is the nature of the Dark Matter?
  Possible answer: the lightest SUSY particle.

• The unexpected!
All behaviour of matter particles (fermions) can be explained in terms of few forces carried by exchange or carrier particles (bosons). Only one of its kind, what is it for?
Standard Model

- Describes the rules of interactions among particles.
- Also predicts results of experiments given various inputs (viz, mass, charge of particles).

(Forces Mediated by Gauge Bosons)

- $X$ is any fermion in the Standard Model.
- $X$ is electrically charged.
- $X$ is any quark.
- $U$ is a up-type quark; $D$ is a down-type quark.
- $L$ is a lepton and $\nu$ is the corresponding neutrino.
- $X$ is a photon or Z-boson.
- $X$ and $Y$ are any two electroweak bosons such that charge is conserved.

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Short-range interactions are mediated by massive particles

Long-range interactions are mediated by massless particles

Problem!

Weak interactions appear to be a gauge theory.

In a gauge theory, the W bosons must be massless.

Gauge symmetry is required to get the correct form of the interaction.

Gauge symmetry must be broken to get the W mass!
The idea is based on a phenomenon called **spontaneous symmetry-breaking**.

- The equations describing the system are invariant under some symmetry.
- The choice of ground state of the system (vacuum) breaks the symmetry.
- Close to the ground state (at low energy) the symmetry is not observable.
- Can observe the symmetry at high energies.
- Compare the situation of spin alignment in ferromagnet above and below the Curie temperature.
Low energy of excitations ➔ low temperatures.
High energy of excitations ➔ high temperatures.

Spontaneous symmetry-breaking is, therefore, always associated with a phase transition.

• When the universe was much hotter all the particles were massless.
• In the process of cooling down some of the symmetries are lost.

Electroweak symmetry breaking caused photon to remain massless while $W^\pm$ and $Z^0$ particles became massive.
Short range (1 fermi) of weak interaction incorporated at low energies.
The price of symmetry breaking: list of the fundamental particles got extended by (atleast) one new particle of spin 0.

→ *The Higgs Boson*

However, the Higgs particle has been elusive to the experiments until now. Since the mass of Higgs boson is an input to theory, experimentally the particle had to be hunted out.

**LHC is built to find the Higgs boson, OR, resolve the issue of mass generation of the carriers of weak interaction.**

Notably, the immensely complex LHC project has lived up to the expectations!!!
We have a discovery!  
4 July, 2012

How did it happen? LHC efforts started in the 2\textsuperscript{nd} half of 1980s.

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Mandate of the experiments:
1. Discover Higgs particle or rule out its existence.
2. Elucidate on physics at the new energy range of TeV.
3. Search for the candidate of the dark matter in the universe.

LHC: The Giant Marvel of Technology

2 major multipurpose experiments at LHC:
• A Toroidal LHC Apparatus (ATLAS)
• Compact Muon Solenoid (CMS)

• 80 Million electronic channels/experiment, ready for data/25 ns.
Interaction processes at LHC

- Production cross section of various types of processes varies over 12-13 orders of magnitude.

- Most of the processes are mundane (already understood) ⇒ interesting processes are rare and swamped by large number of backgrounds.

- Rich physics programme at LHC,

- Both machine and experiments performed much better than anticipated!
LHC motto: explore, search, measure

Collision of the protons occasionally collates sufficient energy so that heavy particles could be produced in the lab \((E = mc^2)\)

Subprocess energy: \(\sqrt{s'}\)
\[E^2 \sim s' = s \times x_1 \times x_2\]
\[x_i = p_i^2 / E_b\]
\[E_b = \text{beam energy}\]

Each constituent of proton carries only a fraction of the proton’s energy → effective energy \((\sqrt{s'}\) ) and hence the inelasticity of the event varies.

→ possibility of producing various new particles of different masses
→ Higgs of any mass within the allowed range could be produced at LHC
LHC operation

Event rate: \( dN/dt = \sigma \cdot L \)

Maximum \( L = 7.54 \times 10^{33} \text{ /cm}^2/\text{s} \)

\( \sigma \sim 10 \text{ pb} = 10^{35} \text{ cm}^2 \)

\( \Rightarrow \sim 750 \text{ Higgs events per sec.}! \)

Higgs discovery in 2012, based on data corr. to \( 10 \text{ fb}^{-1} \) \( \Rightarrow 10^{16} \text{ collisions} \)
The missing piece we have been after

A slice of CMS detector

- The detector can only “see” $\gamma, e^\pm, \mu^\pm, \pi^\pm, n, p, K$!
- Measure the position and energy-momentum with high resolution.
Excellent performance of detectors

Z$\rightarrow\mu\mu$ event from 2012 data with 25 reconstructed vertices

ATLAS

CMS

$\epsilon > 93\%$
Energetic muon

Z → ee

W → µ ν

Jets

Dijet Mass: 1636 GeV

Run: 142528
Event: 201376378
Jet 1 p_T: 739 GeV
Jet 2 p_T: 686 GeV
Precursor to discovery

2010: Pb+Pb 8.3 µb⁻¹
2011: Pb+Pb 150 µb⁻¹
2013: p+Pb 31 nb⁻¹
p+p@2.76~6 pb⁻¹

√s = 7 TeV, L = 36 pb⁻¹
√s = 7 TeV, L = 5 fb⁻¹
√s = 8 TeV, L = 20 fb⁻¹

Excellent performance on heavy ion front as well

2010: Pb+Pb 8.3 µb⁻¹
2011: Pb+Pb 150 µb⁻¹
2013: p+Pb 31 nb⁻¹
p+p@2.76~6 pb⁻¹

Data of 2010

√s = 7 TeV, Lₚ = 40 pb⁻¹

Proton-proton collisions
Re-discovering the Standard Model
The highest-mass central dijet event. The two central high-pT jets have an invariant mass of 4.69 TeV.
Dijet cross-section varying over 9 orders of magnitude measured in data described by theory ⇒ triumph of QCD perturbative theory
Foundation for Higgs search

Electroweak Measurements

Measurement of diboson coupling → gauge structure

- Good understanding of the detector + accurate theory predictions

Measurement of strong coupling $\alpha_s(M_z)$ at high momentum scale of 400-1400 GeV
Coming back to electroweak symmetry breaking

- Why photon is massless while W, Z particles are massive?
- What breaks the electroweak symmetry?

- Possible explanation: Brout-Englert-Higgs mechanism (1960s)

- With about 10 fb⁻¹ of data collected by each of ATLAS and CMS → 5 fb⁻¹ @ 7 TeV + 5 fb⁻¹ @ 8 TeV could search for the Higgs boson.

Standard Model predicts 200,000 Higgs boson produced in each expt. But majority of these events look similar to other processes!
→ $10^{15}$ minimum bias
→ $10^{12}$ dijet events with invariant mass $M_{jj}>100$ GeV
→ $3*10^9$ W+Jets events
→ ..
→ Discard most events judiciously, even some of yesterday’s discoveries!

Without grid computing the task would have been impossible.
Very few events possess tell-tale signatures

- Excellent mass resolution (~ 2 GeV)
- Higgs natural width ~ 5 MeV

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Different situation for $H \rightarrow ZZ^* \rightarrow 4$ leptons

Mass resolution $\sim 1 \%$
For discovery, $\sim 24$ signal, 1 background

With complete data collected by CMS

Continuum production of ZZ pair

Not discussing other bosonic decay modes of $H \rightarrow WW, Z \gamma$
Crucial to observe: Higgs to fermions

- Using production modes with topologies of 0, 1, 2 jets
- Channels searched for: $H \rightarrow bb, \tau\tau, \mu\mu$

For $H \rightarrow \tau\tau$, consider both lepton and hadron decay modes, best channel $\mu^+ + \text{hadron}$. Combine all channels with corresponding Signal to background ratio.

Mass: all $\tau \tau$ channels combined
$m_H = 120^{+9}_{-7} \text{ (stat+syst)} \text{ GeV}$

Significance: $2.93\sigma$ for $m_H = 120 \text{ GeV}$
$2.85\sigma$ for $m_H = 125 \text{ GeV}$
VH, H \rightarrow bb, V = W, Z \rightarrow \text{leptons}

- the largest number of Higgs decays
- but huge background (jets)
- b-jets identified through displaced tracks

\[ \rightarrow \text{Go to high } p_T \text{ where Higgs is enhanced.} \]

Significance from VH processes = 2.1\sigma
Mild excess observed in data.

For VBF process at 95\% CL, upper limit on $\sigma \cdot \text{BR}$
= 3.6 \cdot \text{SM (3.0 exp.)}

Combined Signal strength at 125 GeV: $\mu = 0.97 \pm 0.48$
Search for high mass Higgs

Heavy Higgs ruled out up to ~ 1 TeV
Summary of the results from the main channels

\[ m_H = 125.7 \pm 0.3^{(\text{stat})} \pm 0.3^{(\text{syst})} \text{ GeV} = 125.7 \pm 0.4 \text{ GeV} \]

Given \( m_H \), standard model can predict the cross section and Branching ratio of decay modes.

To check with the consistency of SM:

- Test production modes in various decay modes \( \text{wrt SM} \)
- Couplings to vector boson vs. to fermions

Data in good agreement with SM.
Interpretation of current measurements

Main questions now:
1. What is the spin and parity of the resonance?
2. How much is this signal compatible with the SM?

- Angular distribution of daughter particles can reveal the spin info of the mother.
- Use well measured channels with as much info as possible to discriminate spin values.

Data indicates strongly that it is a $0^+$ resonance.

Data also disfavors spin $2^+$ models.
$$\left( \sigma \cdot \text{BR} \right) \left( ii \rightarrow H \rightarrow ff \right) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{H}}$$

$\Gamma_{\gamma\gamma} \over \Gamma_{\gamma\gamma}^{\text{SM}} = \begin{cases} \kappa_{b}^{2}, \kappa_{t}^{2}, \kappa_{\gamma}^{2}, \kappa_{W}, m_{H} \\ \kappa_{b}^{2} \end{cases}$

$\frac{\sigma_{ggH}}{\sigma_{ggH}^{\text{SM}}} = \begin{cases} \kappa_{g}^{2}, \kappa_{b}, \kappa_{t}, m_{H} \\ \kappa_{g}^{2} \end{cases}$

➔ simplifies the problems to event yield only.
Measurement of couplings

Couplings via loops

gluons vs. photons

Measurements within 1.5\(\sigma\)

Observed uncertainty ~ 25 -30%

Results of all channels when considered together, are within 1\(\sigma\) of the SM prediction

Sensitivity of data towards new physics \(\Rightarrow\) decay to invisible mode < 55%

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Scattering of longitudinal vector bosons

Each diagram $\sim s^2$

Unitarity restored by scalar Higgs

- Could be managed by other means: other resonances, complex objects, multi-Higgs models, noHiggs, ..

- If the restoration is delayed at scale $M$, the scattering cross section will rise for range $m_W \ll \sqrt{s} \ll M$

$\Lambda_{SB} < 1\text{TeV}$
SB sector weakly coupled

$\Lambda_{SB} > 1\text{TeV}$
SB sector strongly coupled

Additionally there is $WW$ self interaction diagram also to be taken into account
Beyond standard model

No observation of physics beyond standard model as yet!
Searches are focused on finding
OR,
  excluding SUSY and non-SUSY models (extra dimensions, ...).

Main results till now:
- Coloured SUSY particles of first generation ruled out up to mass 1 TeV
- Natural SUSY probed up to a few hundred GeV of 3\textsuperscript{rd} generation spartners
- Exotica: heavy objects probed up to masses 2-3 TeV

Note:
- Probe into TeV scale has been limited by machine energy.
- LHC probes physics at TeV energy scale, typical rate: 10 – 0.01 pb
- Future operation of LHC probes well into TeV energy scale.
Searching for new physics through indirect evidence

\[ B^0_s \rightarrow \mu^+ \mu^- \]

- Dominant possible \( B^0_s \rightarrow \mu^+ \mu^- \) diagrams in the SM and MSSM
- Presence of SUSY Higgs, enhances standard model rate by large factor (@ high tan \( \beta \)).

Standard model prediction for branching ratio : \( 3.2 \pm 0.2 \times 10^{-9} \)
LHCb : \( 3.2^{+1.5}_{-1.2} \times 10^{-9} \)
LHC experiments combined upper limits only at 95% CL:
\[ \text{Br} (B^0_s \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-9}, \text{Br} (B^0 \rightarrow \mu^+ \mu^-) < 8.1 \times 10^{-10} \]

⇒ SUSY constrained highly.
Suppression of the individual $Y(nS)$ states in PbPb collisions with respect to their yields in $pp$ data has been measured.

$$\frac{Y(2S+3S)}{Y(1S)} \mid_{\text{PbPb}} = 0.31^{+0.19}_{-0.15} (\text{stat}) \pm 0.03 (\text{sys})$$

$$\frac{Y(2S+3S)}{Y(1S)} \mid_{\text{pp}}$$

$$\frac{Y(2S)}{Y(1S)} = 0.21 \pm 0.07 (\text{stat}) \pm 0.02 (\text{sys})$$

$$\frac{Y(3S)}{Y(1S)} = 0.06 \pm 0.06 (\text{stat}) \pm 0.06 (\text{sys})$$

Suppression indicates formation of new state of matter where $Y$ states experience a drag.

Significance of result $> 5 \sigma$.

Red: $Y$ events in PbPb collisions
Blue: expectation if the excited states were not suppressed wrt ground state
LHC Roadmap

- LHC startup, $\sqrt{s} = 900$ GeV
  - $\sqrt{s} \approx 7\sim8$ TeV, $L = 6 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, bunch spacing 50 ns
- Go to design energy, nominal luminosity
  - $\sqrt{s} = 13\sim14$ TeV, $L \approx 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- Injector and LHC Phase-1 upgrade to ultimate design luminosity
  - $\sqrt{s} = 14$ TeV, $L \approx 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- HL-LHC Phase-2 upgrade, IR, crab cavities?
  - $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, luminosity levelling

Under discussion presently
LHC Future

LHC 14 TeV operation during 2015-21 provides a plethora of motivations

- Double the reach for new particle mass
- Better measurement of Higgs properties
- Search for additional Higgs particles below or above 126 GeV
- Vector boson pair scattering at high energies (W,Z)
- Measurement of rare processes of standard model

Experimental challenges:

- Detectors must perform in high radiation and high pile-up environment
- Trigger criteria to accommodate all demands for above motivations.
- Computing has to be maximised for efficiency in throughput

Miles to go before we sleep!
New particle discovery potential

SuperSymmetric particles:
- Gluinos upto 1.7 TeV
- Stop: 750 - 950 GeV
- Sbottom: 600 - 700 GeV
- Electroweakinos: 500 - 600 GeV

New Vector Bosons:
- Exclude Z' upto ~ 6.5 TeV
- Discover W' @ 5s level upto 6 TeV
- Massive vector-like top quark upto 1.5 TeV.

At 5σ, with 300 fb⁻¹

At 5σ, with 3000 fb⁻¹
Higgs properties: projections for 300(0) fb\(^{-1}\)

CMS Projection (Prelim.)

Expected uncertainties on Higgs boson couplings

- \(\kappa_\gamma\)
- \(\kappa_V\)
- \(\kappa_g\)
- \(\kappa_b\)
- \(\kappa_l\)
- \(\kappa_t\)

300 fb\(^{-1}\) \(\Rightarrow\) 4-15 %

 CMS Projection (Prelim.)

Expected uncertainties on Higgs boson couplings

- \(\kappa_\gamma\)
- \(\kappa_V\)
- \(\kappa_g\)
- \(\kappa_b\)
- \(\kappa_l\)
- \(\kappa_t\)

3000 fb\(^{-1}\) \(\Rightarrow\) 2-10 %

Goal: ultimate precision of ~ 5% or better
Conclusion

• Finding a resonance at LHC, has been a giant leap for science.
• Most likely it is the Higgs boson of standard model.

• The discovery has established the main stream idea about the mechanism behind the mass generation of fundamental particles.

• Exploration of the high energy frontier provided by LHC has just started.
• The discovery has focused the future.
• LHC upgrades present several experimental challenges which must be addressed to.

• Coming years are going to be very promising ➔ stay tuned!
Backup
ttH production

Consider semileptonic decays of top
H → γγ, bb

Observed limit at 125 GeV: 3.3
Expected limit at 125 GeV: 3.1
(95% CL)

Sensitivity to 1-2•SM within reach with full data set/all channels!

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• Cornerstone of modern day particle physics.

• Quantum theory is invariant under constant phase transformations of wave function.
• The phase invariance is lost if the phase is a function of space-time

• Maxwell’s eqns. $E = -\nabla \phi - \partial A/\partial t$ and $B = \nabla \times A$.
$\Rightarrow$ invariant under $\phi' = \phi - \partial \Lambda/\partial t$ and $A' = A + \nabla \Lambda$, where $\Lambda$ is a function of $(x, t)$.

• If we introduce the electromagnetic field $(\phi, \Lambda)$ into the theory and identify the space-time dependent phase with $\Lambda(x, t)$, then the quantum theory is invariant under space-time dependent phase transformations.
Proton-Proton 1380 bunch/beam
Protons/bunch 2. $10^{11}$
Beam energy 4 TeV
Luminosity $7.5 \times 10^{33}$ /cm$^2$/s
Crossing rate 20 MHz
Total event rate $5.4 \times 10^8$ Hz
Higgs production <1 Hz

Selection of 1 in 10,000,000,000,000
Cartoon of CMS Detector

- Designed meticulously for hard collisions
- Serving well even for softer ones

Ticks:
- Pixels
- Tracker
- ECAL
- HCAL
- MUON Dets.
- Superconducting Solenoid

Total weight: 12500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla

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Higgs boson $\mu$ values

- CMS results from 10 fb\(^{-1}\) and extrapolated to 300 fb\(^{-1}\) with fixed systematic uncertainties with or w/o theory uncertainties

CMS Projection

Note sensitivity to $\mu\mu$, and ttH with 3000 fb\(^{-1}\)

**ATLAS** Simulation

$\sqrt{s} = 14$ TeV: \[\int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1}\]

$\int L dt = 300 \text{ fb}^{-1}$ extrapolated from 7+8 TeV

- $H \rightarrow \gamma \gamma$
- $ttH, H \rightarrow \mu \mu$
- $VBF, H \rightarrow \tau \tau$
- $H \rightarrow ZZ$
- $VBF, H \rightarrow WW$
- $H \rightarrow WW$
- $VH, H \rightarrow \gamma \gamma$
- $ttH, H \rightarrow \gamma \gamma$
- $VBF, H \rightarrow \gamma \gamma$
- $H \rightarrow \gamma \gamma$ (+j)
- $H \rightarrow \gamma \gamma$

- These dominant channels achieve 10-15% precision with 300 fb\(^{-1}\)
Standard Model cross section low, Branching ratio $\sim 0.1\%$
Large rate expected from physics beyond standard model
(contribution in loop at the decay, like in $\gamma\gamma$ channel)
Require 2 opposite sign same flavour leptons and a photon
Yield extracted using invariant mass distribution.
No excess: limit at $20 \times$ SM level
LHC Future: from here to there

Phase 1 upgrade

Long shutdown 1: 2013-14
Data: 2015-17
Long shutdown 2: 2018
Data: 2019-21
Long shutdown 3: 2022-23

L=1*10^{34}/cm^2/s

L=2*10^{34}/cm^2/s

L=5*10^{34}/cm^2/s
**Higgs production at LHC**

- **(a) $gg \rightarrow H$**
- **(b) VBF**
- **(c) $VH$**
- **(d) $t\bar{t}H$**

**Glueon-gluon fusion**

**Vector boson fusion**

**Associated productions with W, Z, top**

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Theoretical prediction of production rate of Higgs boson as a function of its mass.

Strong interaction corrections for the rate Higgs production in $gg \rightarrow H$ process are substantial.
Strategy for experimental Search

• Since the Higgs mass is not known, need to consider all the decay modes at different mass values.

• Divide the mass region according to the decay mode which is easy to identify and equip the detector accordingly.

1) For Higgs mass below 140 GeV look for
   \( H \to 2\gamma, \ H \to WW(*) , \ H \to ZZ(*) \)

2) For mass 140 -180 GeV, \( H \to WW, \ H \to ZZ(*) \)

3) Above 180 GeV, \( H \to ZZ \)

High demands on the detectors ➔ at lower values of Higgs mass, the natural width is very small, the detector resolution should be excellent.

For \( M_H = 125 \text{ GeV}, \Gamma_H = 4.2 \text{ MeV} \)

Branching ratios (%)

\( H \to WW^* : 23 \)
\( H \to ZZ^* : 2.9 \)
\( H \to bb : 56 \)
\( H \to cc : 2.8 \)
\( H \to \tau\tau : 6.2 \)
\( H \to \mu\mu : 0.021 \)
\( H \to gg : 8.5 \)
\( H \to \gamma\gamma : 0.23 \)
\( H \to \gamma Z : 0.16 \)