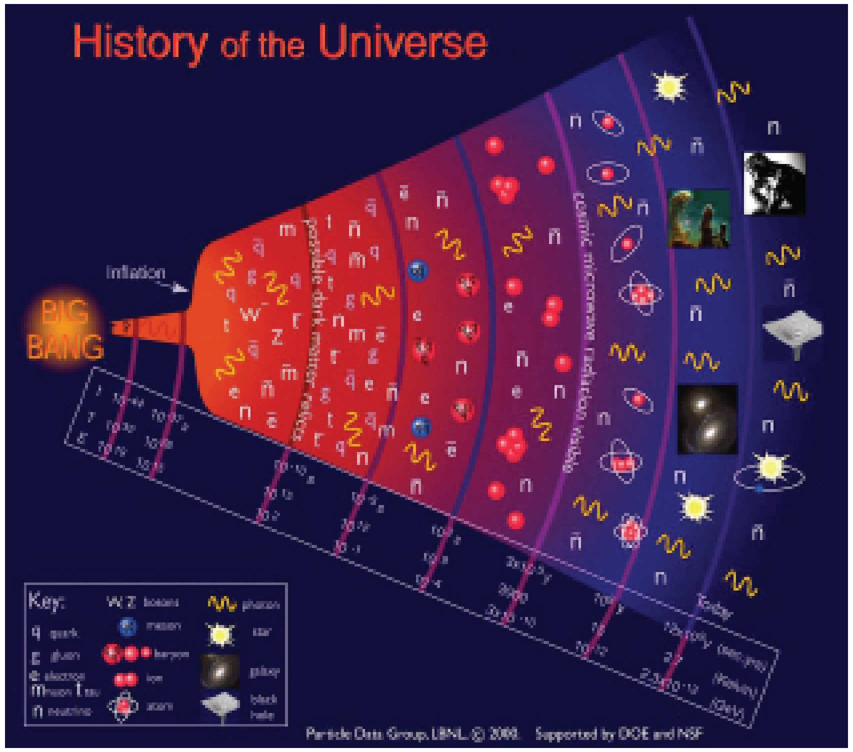
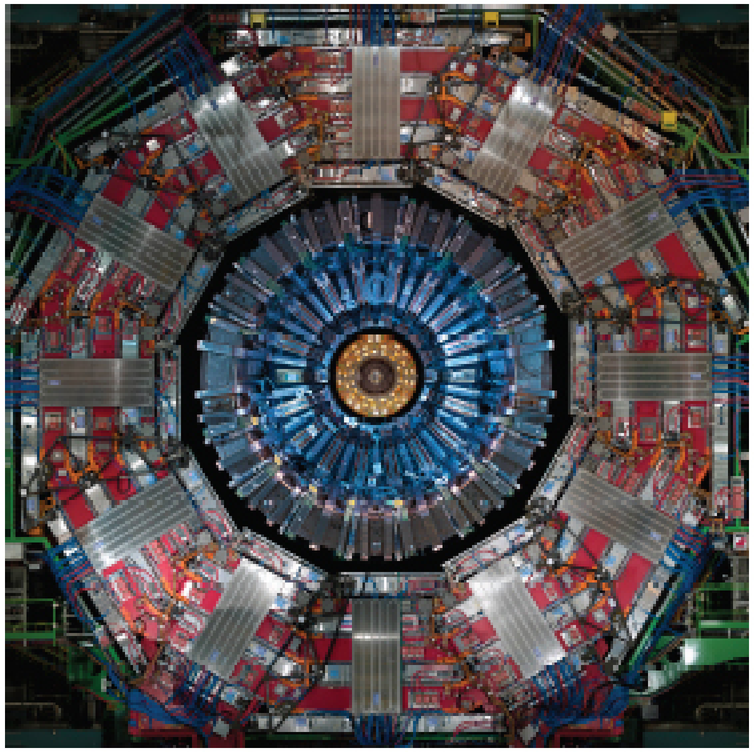
Exploring Nature Moments After the Big Bang

Prof. H. S. Hans Memorial Lecture
Panjab University
Chandigarh
5 March 2018

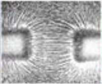


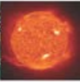


The Wonderful Variety of Nature



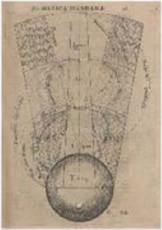






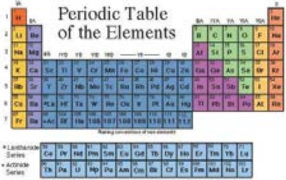
Elementary Constituents of Matter

Philosophy



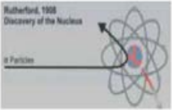
4 basic elements
Greek (450 BCE)
Other Ancients
Chinese
Indian (add vacuum)

Classical Mechanics



MENDELEEV
(19th century)
Periodic Table:
>100 basic elements

Quantum Mechanics



BOHR,
RUTHERFORD
(early 20th century)
2 basic elements:
electron, nucleus

Particle Physics

Particle physics is a modern name for centuries old effort to understand the laws of nature.

Aims to answer the two following questions:

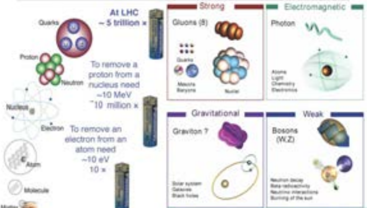
What are the elementary constituents of matter ?

What are the forces that control their behaviour at the most basic level?

Experimentally:

1. Make particles interact and study the products and properties of the result of the interaction
2. Measure the energy, direction and type of the products as accurately as possible
3. Reconstruct what happened during the collision

Matter and Forces



All known forces in the world can be attributed to these four interactions

Particle Accelerators

accelerate particles to extremely high energies.

High energies allow us to

i) Study the young universe (E= kT)
Revisit the earlier moments of our ancestral universe
(look further back in time ➔"powerful telescopes")

Boltzmann

ii) Discover new particles with high(er) mass ($E = mc^2$)

Einstein

de Broglie

iii) Look deeper into Nature (E α 1/size),
(look deeper ➔"powerful microscopes")

Observe phenomena and particles normally no longer observable in our everyday experience.

All in a controlled way - "in the laboratory"

The Standard Theory of Particle Physics

Over the last 100 years: the combination of
Quantum Mechanics and Special Theory of relativity
along with the plethora of particles discovered has led to the
Standard Model (Theory) of Particle Physics (SM).
The new (final?) "Periodic Table" of fundamental elements

- Matter is composed of
- Three families of **quarks**
- Three families of **leptons**
- Interactions (strong nuclear, electromagnetic, weak nuclear) are carried by exchange of **spin-1 bosons**

Classes of Fundamental Particles: Fermions and Bosons

Enrico Fermi

Two fermions with the same quantum numbers CANNOT co-exist in the same "space"

Satyendra Nath Bose

Two bosons with the same quantum numbers CAN co-exist in the same "space"

The Standard Theory of Particle Physics

Over the last 100 years: the combination of
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The new (final?) "Periodic Table" of fundamental elements

Quantum Field Theories of
3 of the 4 fundamental interactions

Very successful description of our visible universe (short distance)

The Standard Theory of Particle Physics

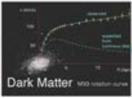
Over the last 100 years: the combination of **Quantum Mechanics and Special Theory of relativity** along with the plethora of particles discovered has led to the **Standard Model (Theory) of Particle Physics (SM).**

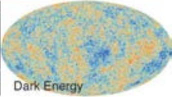
The new (final?) "Periodic Table" of fundamental elements

A crowning achievement of 20th Century Science

Before 2012 its most basic mechanism, that of granting mass to particles, was still missing. Quantum of the field is the Spin Zero Higgs boson.

The Science of the LHC





✓**Newton's unfinished business: what is the origin of mass..**? Mass gives our Universe substance!

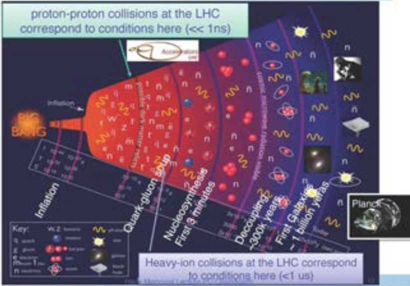
Science's little embarrassment… **what is 96% of the Universe made of**? Dark matter and dark energy?

Nature's favouritism… why is there no antimatter left in the universe?

The secrets of the Big Bang… what was matter like during the first second of the Universe's life? **How many space-time dimensions do we live in?**

Some of these go to the heart of our very existence !

Brief History of Our Universe



Studies in Particle Physics Require.......

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 a worldwide scale: thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

The Large Hadron Collider at CERN

The LHC Accelerator

Protons are accelerated by powerful electric fields to very (very) close to the speed of light (**superconducting r.f. cavities**)

And are guided around their circular orbits by powerful **superconducting dipole magnets**.

The dipole magnets operate at 8.3 Tesla (200'000 x Earth's magnetic field) & 1.9K (-271°C) in **superfluid helium**.

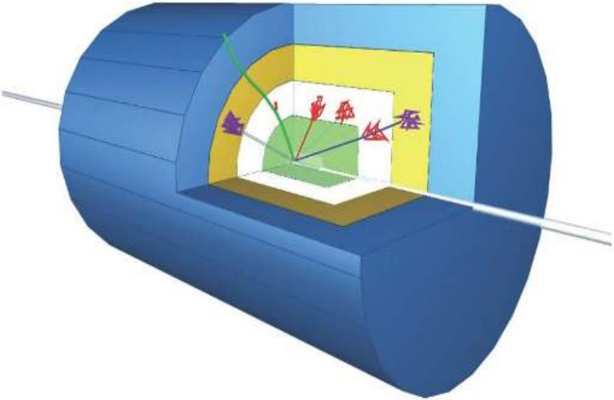
Protons travel in a tube which is under a better **vacuum**, and at a lower temperature, than that found in inter-planetary space.

Schematic of an HEP Detector

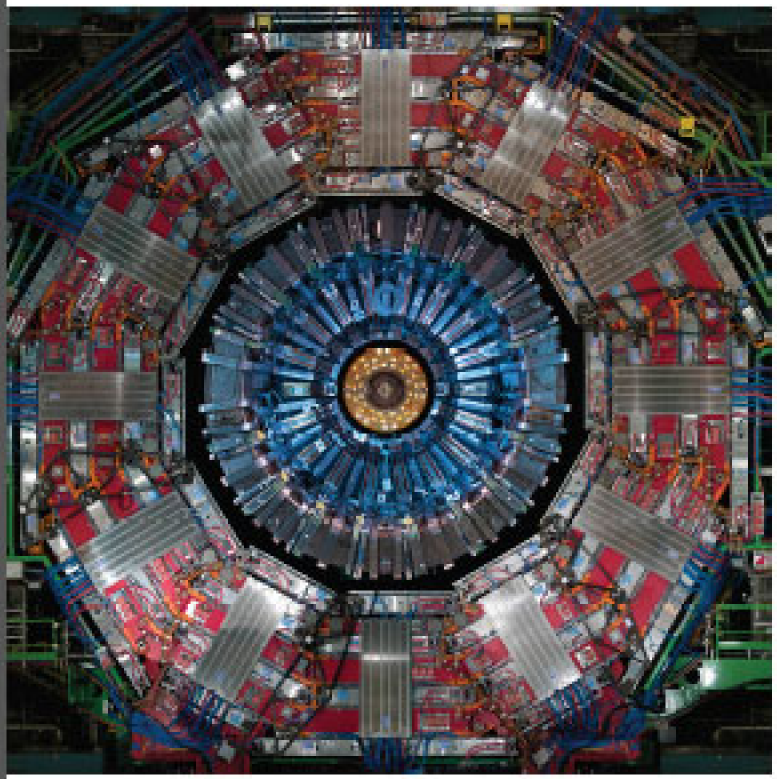
Physics requirements drive the design (e.g. search for the Higgs boson)

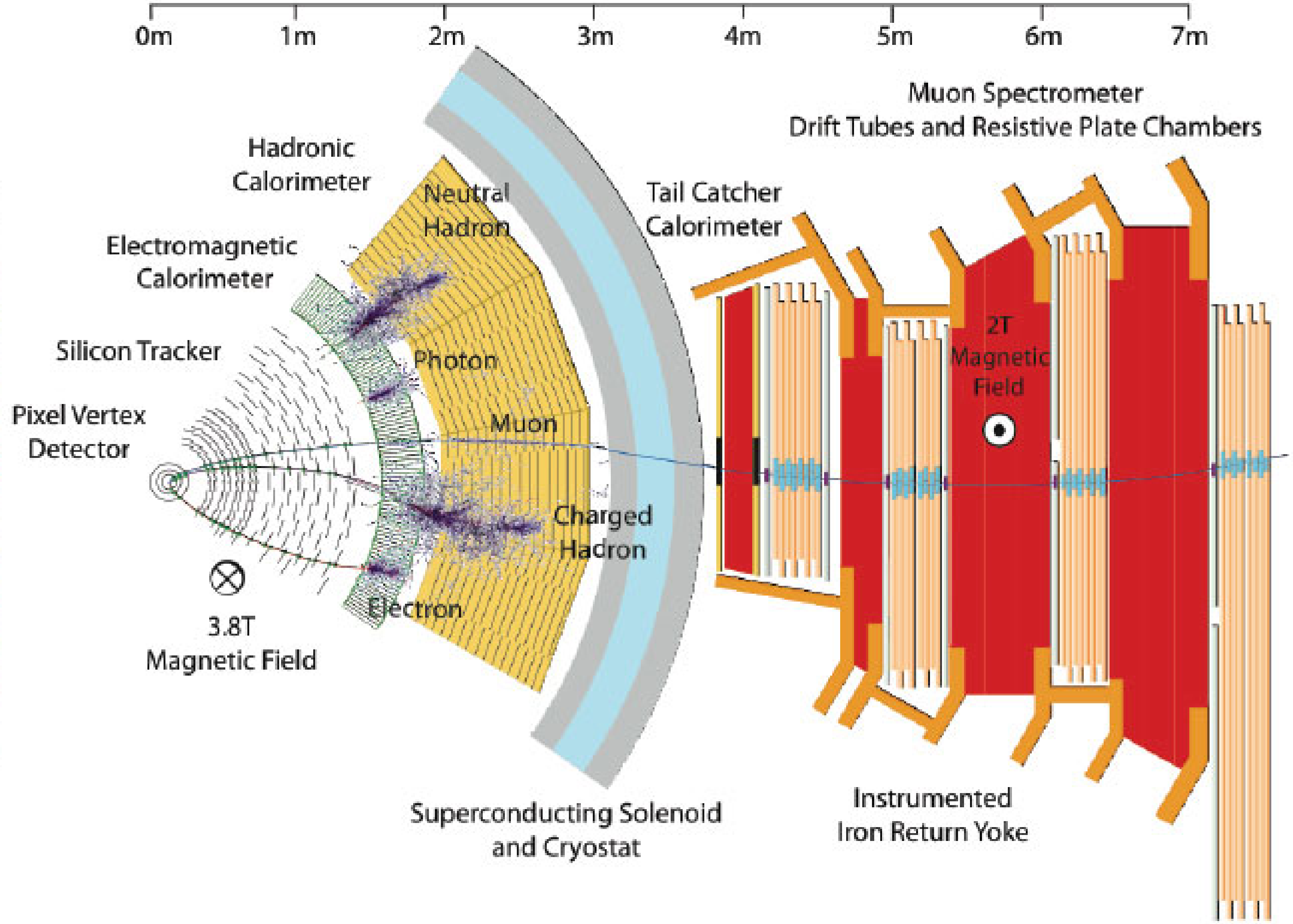
Analogy with a cylindrical onion:

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.



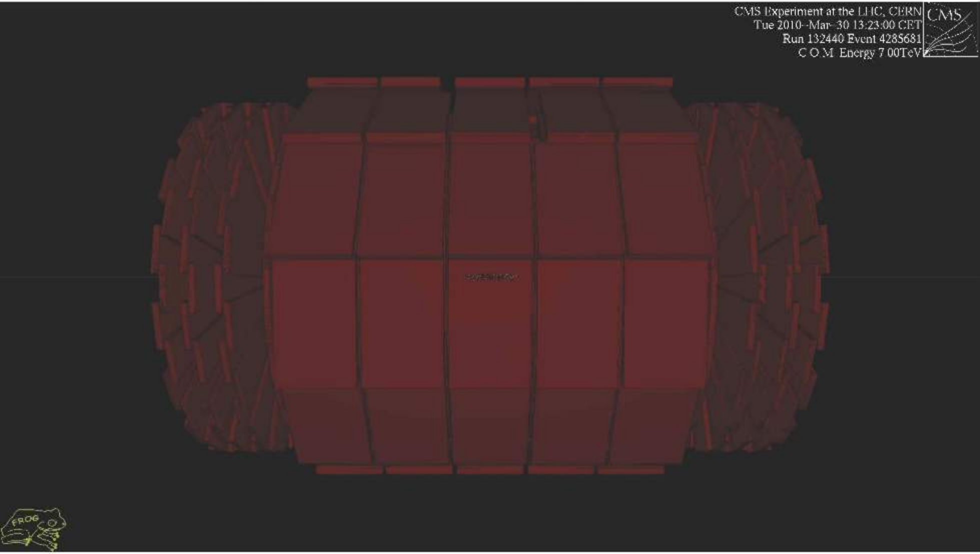
Measuring & Identifying Particles





Probing our Universe a few trillionths of second after Big Bang

Proton-proton Collisions at 7 TeV (7 trillion electron volts)



Experimental and Technological Challenge

1 billion proton-proton interactions per second

Bunches, each containing 100 billion protons, cross 40 million times a second in the centre of each experiment

Large Particle Fluxes

~ thousands of particles stream into the detector every 25 ns

⇨ **large number of channels (~ 100 M ch)**

⇨ ~ 1 MB/25ns i.e**. 40 TB generated per second !**

High Radiation Levels

⇨ radiation hard (tolerant) detectors and electronics

Extreme requirements in several domains

"If it doesn't exist and we need it, we will invent it"

Limited budgets!

Look at what exists, innovate and automate to drive costs down

CMS: Concept to Data Taking took ~ 20 Years!

3000 scientists from 40 countries
800 Ph. D. Students!

Silicon Tracker

Gas ionization chambers

CMS cut in mid-plane

Scintillating Crystals

Brass plastic scintillator

Example of Challenging Technologies: ECAL: Lead Tungstate Crystals

Physics Driving the Design
Measure the energies of photons from a decay of the Higgs boson **to a precision of ≤ 0.5%.**

Idea (1993 – few yellowish cm³ samples)

→ R&D (1993-1998: improve rad. hardness: purity, stoechiometry, defects)

→ Prototyping (1994-2001: large matrices in test beams, monitoring)

→ Mass manufacture (1997-2008: increase production, QC)

→ Systems Integration (2001-2008: tooling, assembly)

→ Installation and Commissioning (2007-2008)

→ Collision Data Taking (2009 onwards)

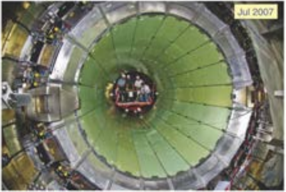
→ Discovery of a new heavy boson (2012)

Idea to Discovery
Δt ~ 20 years !!!

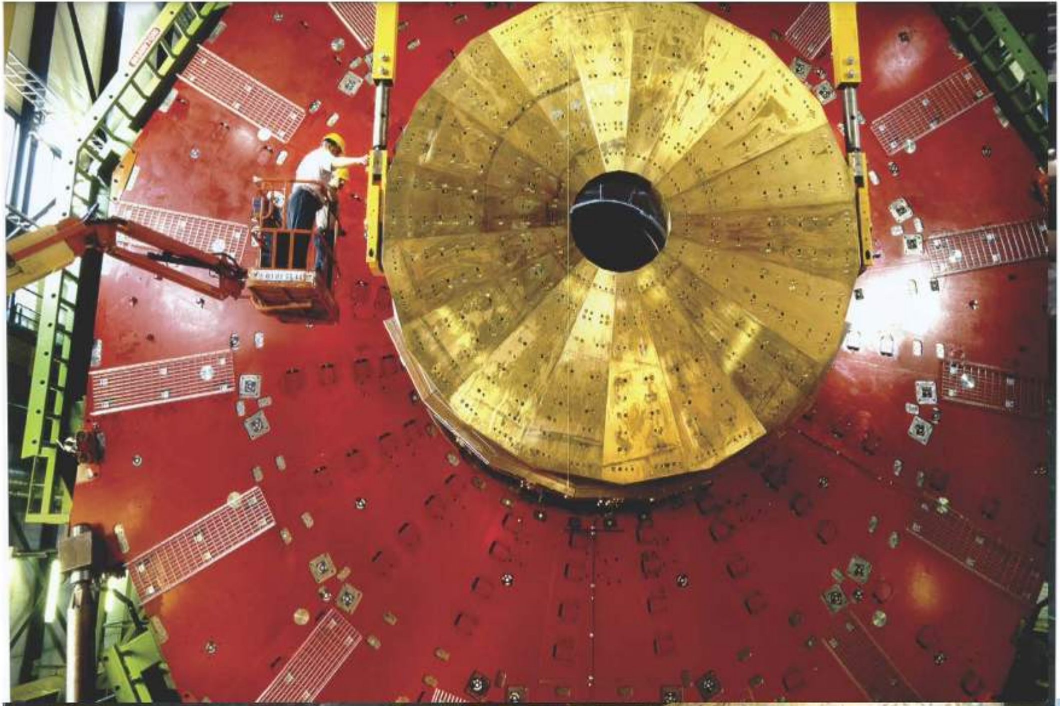
CMS Electromagnetic Calorimeter:
Lead Tungstate Scintillating Crystals

Total 36 Supermodules

CMS Electromagnetic Calorimeter:
15 years from Concept - Installation

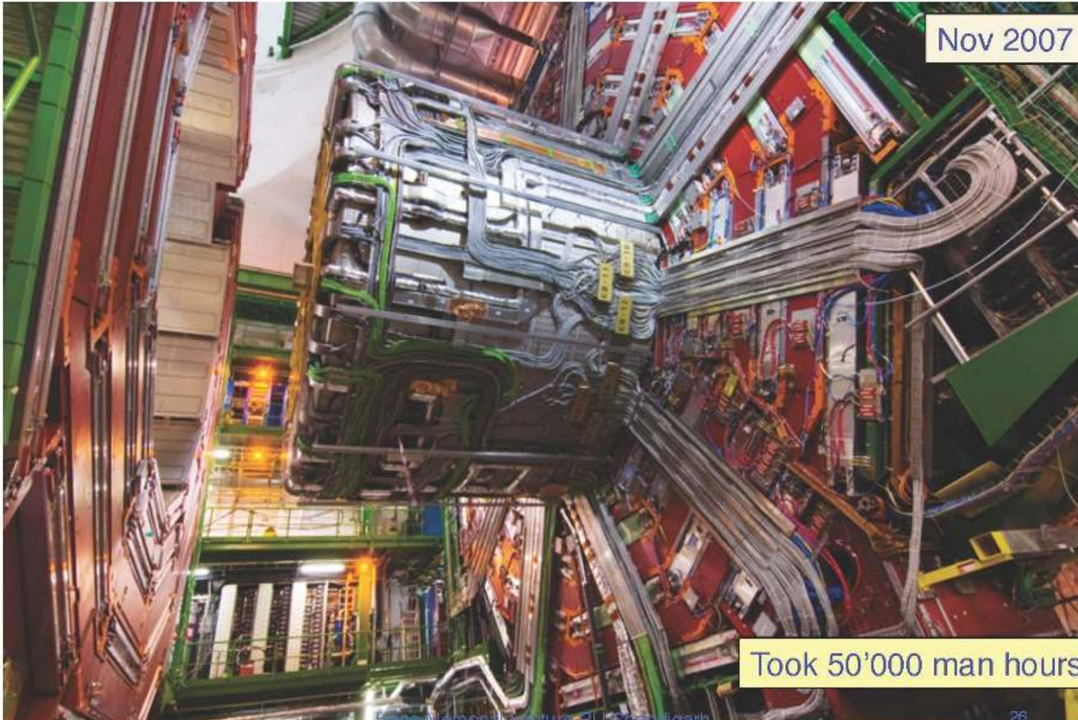


"Swords to Ploughshares"

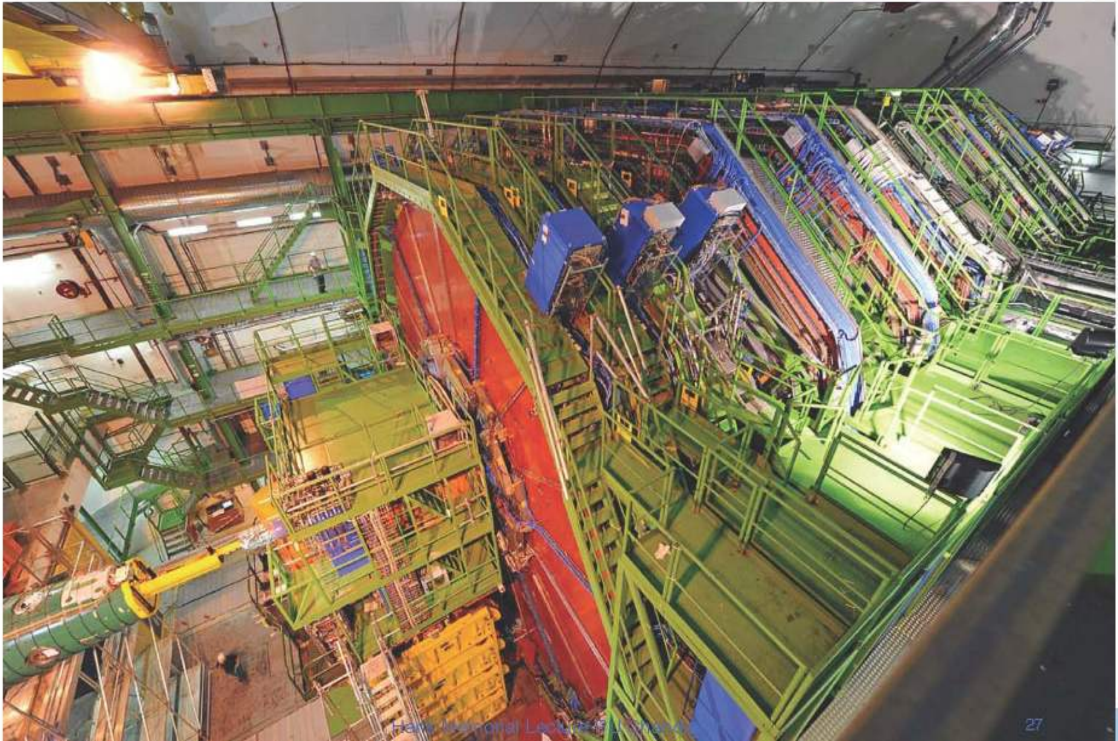


Spectacular Engineering Operations (Feb. 2007)

Cables, Pipes and Optical Fibres !



CMS Detector Closed (Sept 2008)



India in CMS (7th Largest Country)

Indian Member Institutes of CMS.
•BARC, TIFR (Mumbai), IISER Pune, Bhubaneshwar (IIT, NIESR), Chennai (IIT), **Panjab Univ. Chandigarh**, Kolkata (SINP), Delhi, IISc Bangalore

Detector construction:
- Outer Hadron Calorimeter (HO) (full responsibility)
- Si-Preshower detector (sensors made at BEL)

Operations: HO and HCAL

Physics: Conveners: SUSY Searches, B-Physics, $H \to \tau\tau$ (hadronic), ..
And studies in many physics topics
Core software, Data Quality, HCAL Detector performance, Computing –Tier 2

Upgrades: Phase 1: RPCs, GEMs, HCAL electronics
Phase 2: Si-strip Tracker, GEMs, HGCAL

Operation of an LHC Experiment

Analogy: 3D digital camera with 100 Mpix

40 million pictures per sec (which correspond to the happenings during the first ~1/10 of a billionth of a second after the Big Bang)

- Information: 10,000 encyclopedias per second

First selection of photographs: 100,000 / sec

- Each is up to ~ 1MB

And gets analyzed on a process farm with ~ 50000 CPU cores

Every second, record [store permanently] **1000 most interesting pictures**

Distribute the reconstructed data to institutes all over the world for physics analysis.

Fundamental Research Drives and Needs Innovation e.g. the WorldWideWeb

Declaration

The following CERN software is hereby put into the public domain:

- W 3 basic ("line-mode") client
- W 3 basic server
- W 3 library of common code.

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Geneva, 30 April 1993

W. Hoogland
Director of Research

H. Weber
Director of Administration

Fundamental Research Drives and Needs Innovation e.g. the WorldWideWeb

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Geneva, 30 April 1993

Pathway of an Innovation

Dirac's Equation $\left(\beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k c\right) \psi(\mathbf{x},t) = i\hbar \frac{\partial \psi(\mathbf{x},t)}{\partial t}$

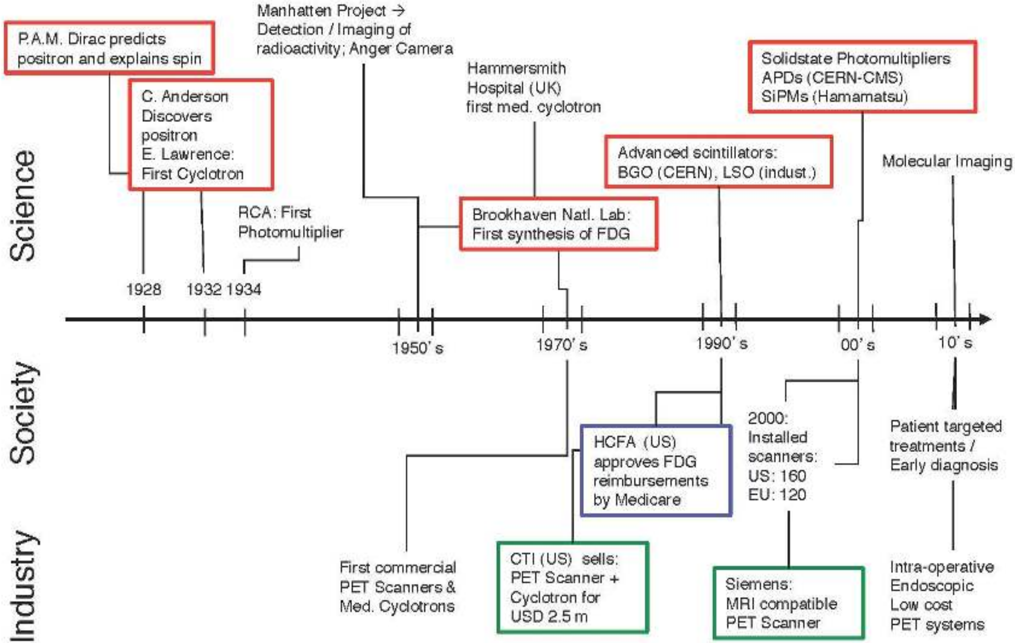
1928: Dirac's description of electrons consistent with Einstein's special relativity and quantum mechanics
Predicted existence of anti-particles (**e.g positron - basis of PET**) and explained spin (**basis of MRI**)

1932: Operation of first cyclotron, the anti-electron (positron) discovered

Radionuclides (e.g. fluorine18 (half-life ~110min) used in PET scanning are produced by cyclotrons in hospitals
PET cameras today use APDs (and Si PMs) and heavy scintillating crystals - now being combined with MRI scanners.

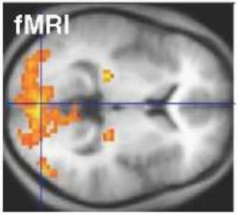
The scientific basis for all medical imaging (functional & physiological) is steeped in nuclear/particle physics

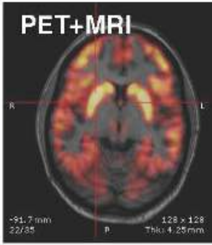
Positron Emission Tomography



PET and MRI

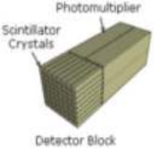
CT, MRI etc. scanners good at showing anatomical detail
PET makes metabolic activity visible
-determine how patients respond to drugs
- distinguish early Alzheimer's from other types of dementia?





Costs

PET (+CT today) ~ 2.5 M$ + 0.2M$/yr
Cyclotron ~ 2.0 M&
Infrastructure ~1.5 M&
Cost/Pet scan ~1'500$



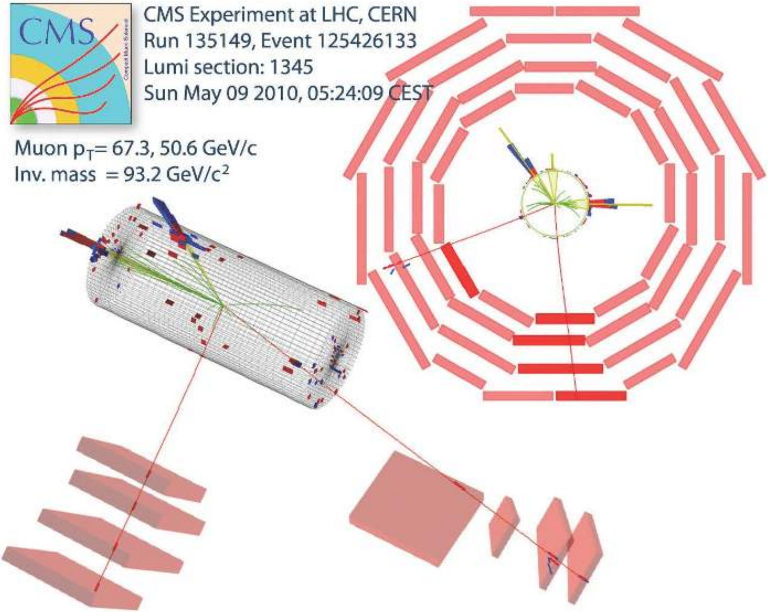
NB: 1 cyclotron can service many PET scanners
Of great benefit to reduce costs of PET scanners – here come in new technology (e.g. heavy scintillating crystals and SiPMs – aim to reduce cost/complexity.

Going to the Science

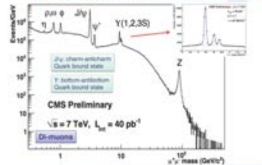
1. Do the experiments perform as designed?
2. Is known physics correctly observed?
3. Then look for new physics

We can only claim signals of new physics after having made measurements of already known physics that are consistent with the precise predictions of the Standard Model.

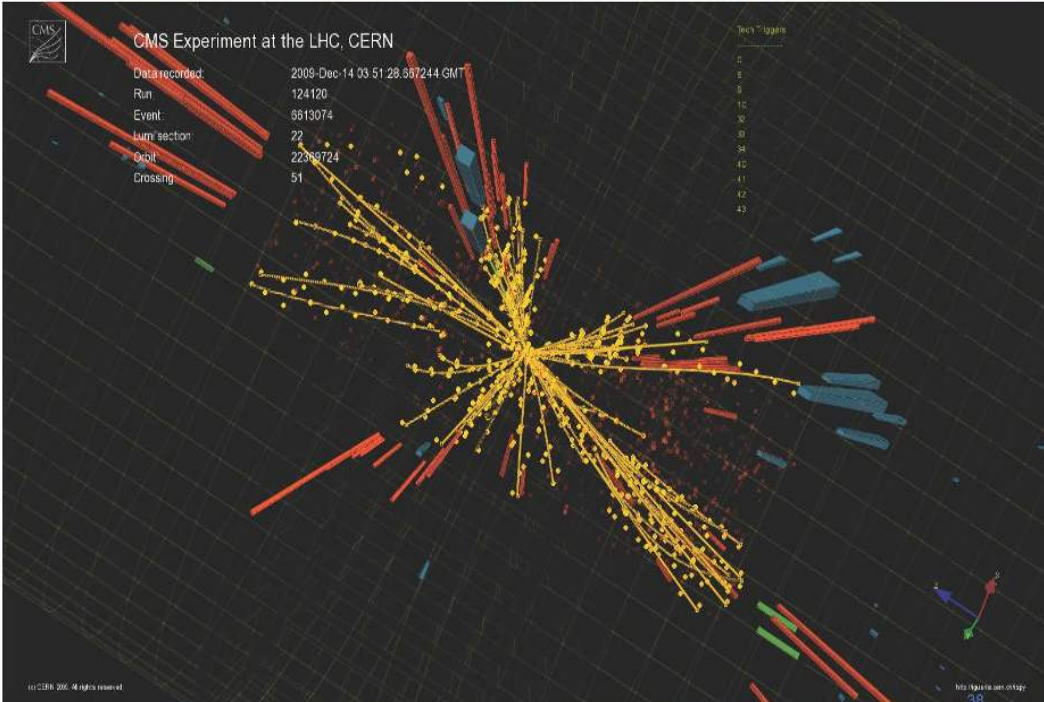
1. A Z boson decaying into $\mu^+ \mu^-$ pair



Performance of Experiments: CMS

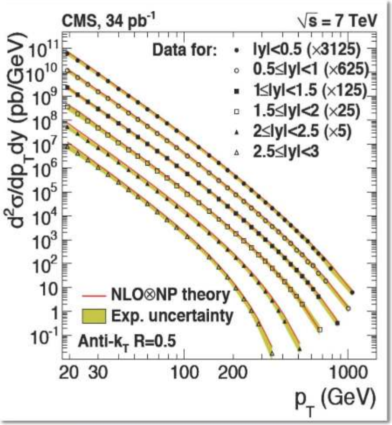


Quarks/gluons Production at the LHC

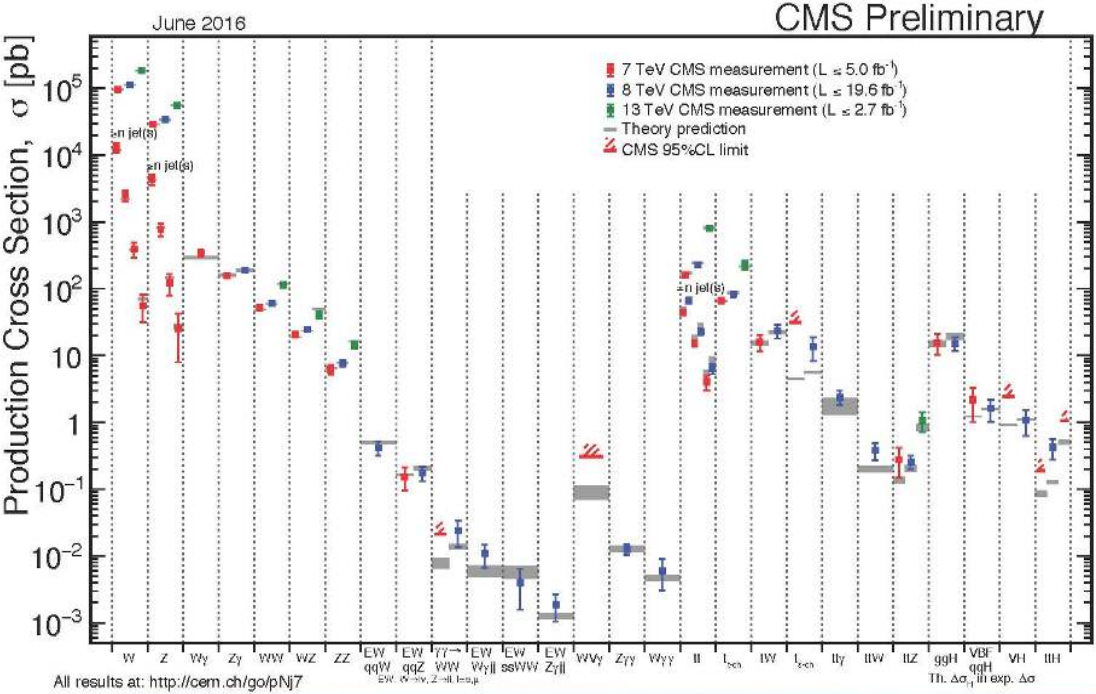


2. Testing Quantum Chromo Dynamics

Routinely and successfully analyse physics at the high energy frontier in terms of quarks and gluons!



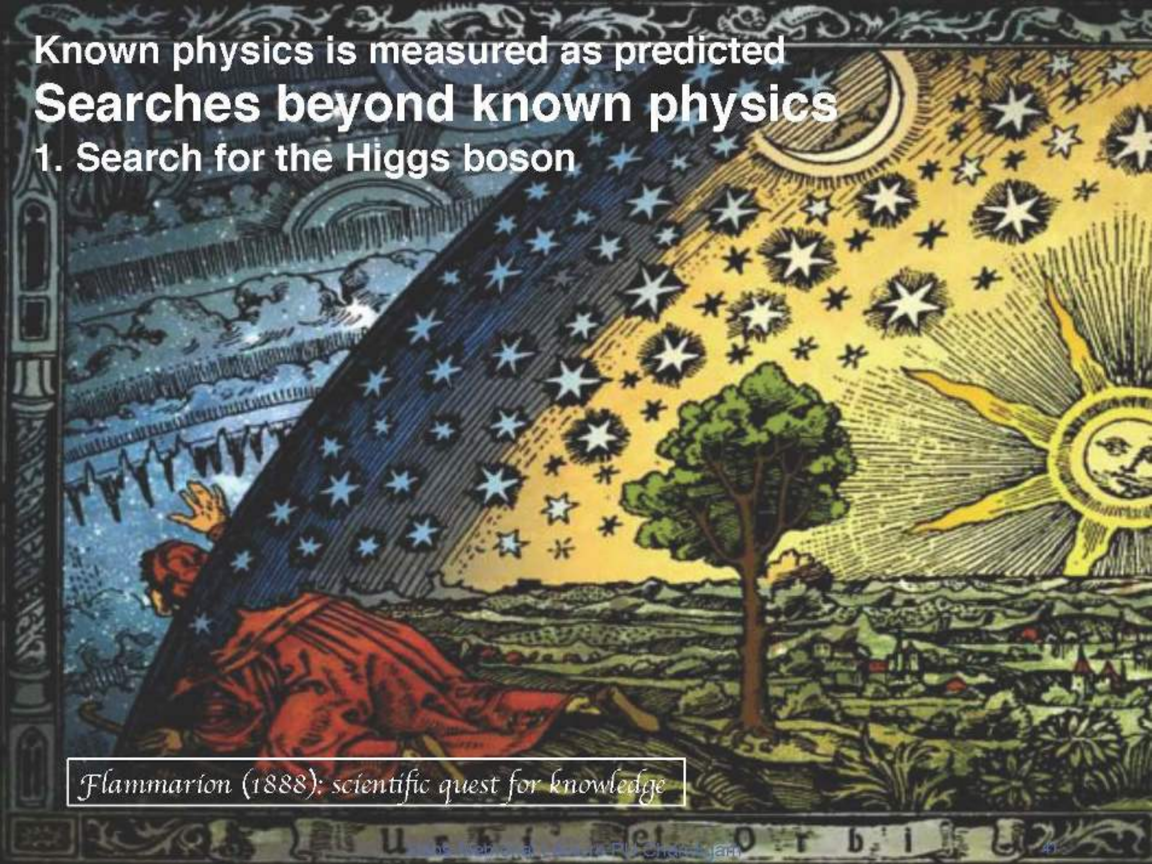
Standard Model (Electroweak) Measurements



Known physics is measured as predicted

Searches beyond known physics

1. Search for the Higgs boson



Flammarion (1888): scientific quest for knowledge

Mass gives our Universe substance!

To Newton: F= ma, w = mg
To Einstein: $E = mc^2$
Mass curves space-time

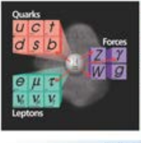
All of this is correct.
But how do fundamental objects become massive?
Simplest theory – all fundamental particles are massless !!

A bold intellectual conjecture (1964): a field pervades our entire universe. Particles interacting with this field acquire mass, the stronger the interaction the larger the mass

The field is a quantum field – its quantum is the Higgs boson. Finding the Higgs boson establishes the existence of this field.

So, how do we look for the Higgs boson?

The SM Higgs boson leaves very characteristic fingerprints
with well-defined couplings, decay rates and angular distributions of final products



Higgs lifetime (125 GeV): 10^{-22} s

So decay immediately so only see decay products in the detector

Higgs couples to mass:

Coupling to fermions (quarks and leptons)

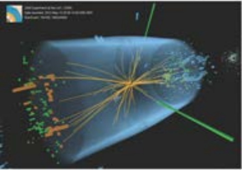
$H \to b\bar{b}$, $H \to \tau^+\tau^-$ $H \to \gamma\gamma$ $H \to ZZ \to 4l$

~55 % ~10% ~2/mille ~10^{-4}

at a mass of ~125 GeV
many decay modes are detectable
Makes it easier to establish whether or not it is a SM Higgs boson

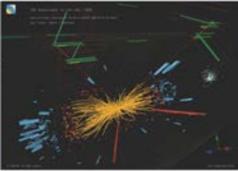
Run 1: The Higgs boson in e.g. CMS

CMS: H→γγ Channel



Expect: 450 events S/B ~ 3%

CMS: H→Z→4*l* Channel



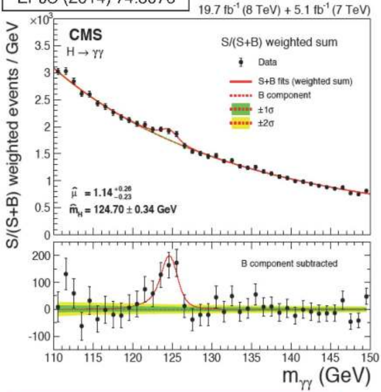
Expect: 20 events S/B ~ 1.5

2013

CMS (2014): H Decays to bosons

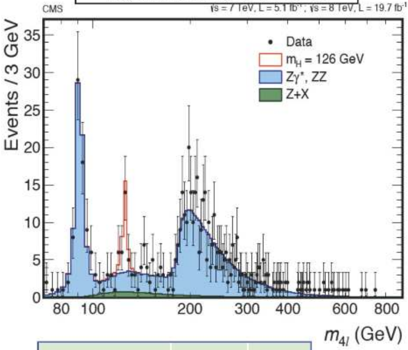
H→ 2γ Channel

EPJC (2014) 74:3076



H→Z→4*l* Channel

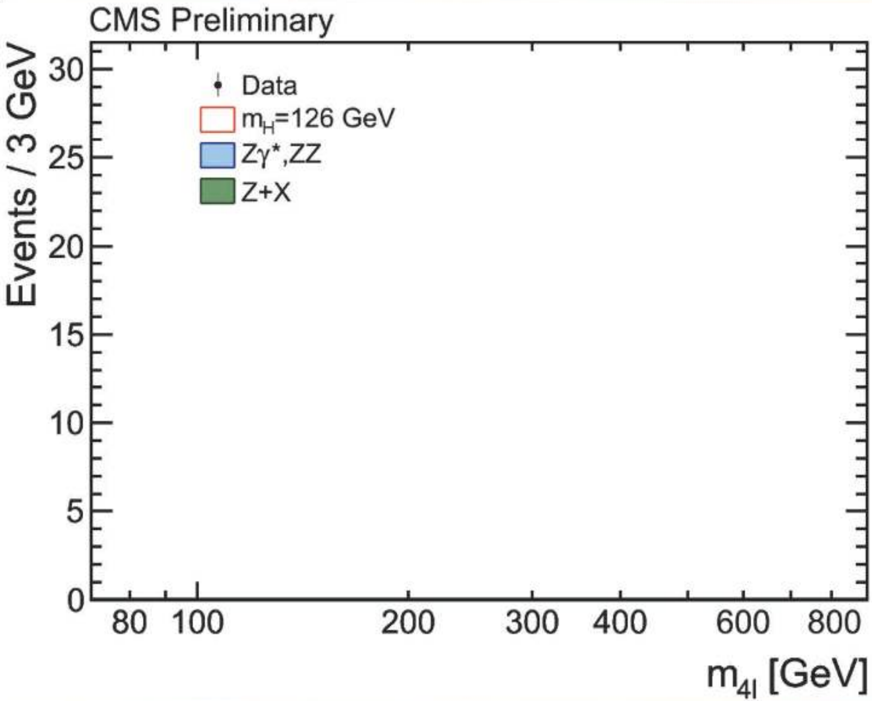
Phys. Rev. D89 (2014) 092007



Similar results from ATLAS

Significance	Exp	Obs
H→ 2γ	5.3 σ	5.6 σ
H→Z→4*l*	6.3 σ	6.5 σ

CMS $H \rightarrow ZZ^{(*)} \rightarrow 4l$ Channel Full Run 1 Dataset

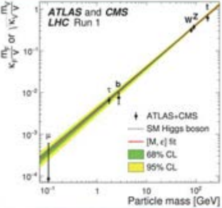


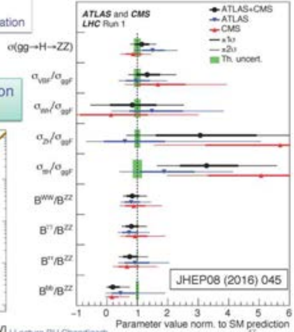
Combining all measurements so far ….

Signal Strength
Ratio of measured rate and the SM expectation

ATLAS+CMS
Ratio = 1.09 ± 0.11

Within errors the found Higgs boson looks like the SM Higgs boson





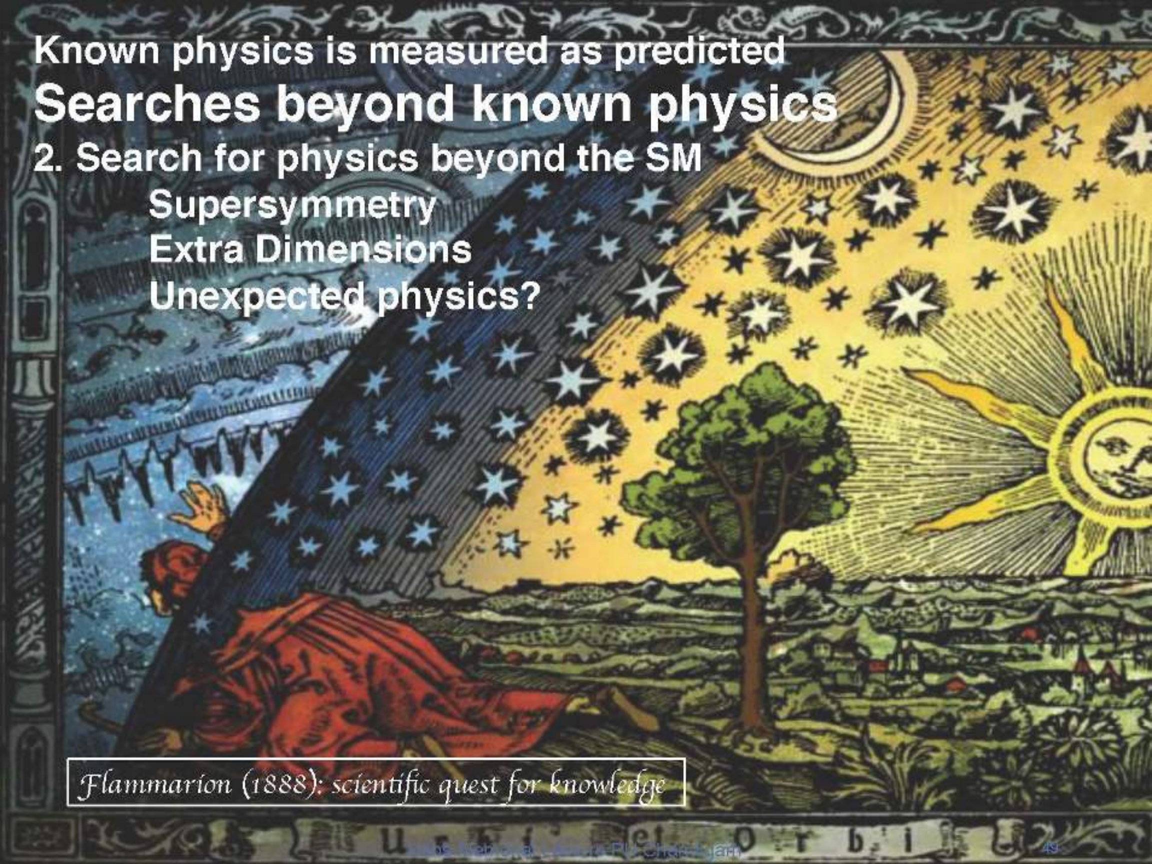
Discovery of the Higgs boson

Known physics is measured as predicted

Searches beyond known physics

2. Search for physics beyond the SM

- Supersymmetry
- Extra Dimensions
- Unexpected physics?



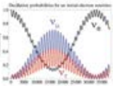
Flammarion (1888): scientific quest for knowledge

Moving Forward
Should we really expect new physics ?

Ample observational evidence for physics Beyond the SM

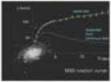
Neutrino mass (oscillations)

a QM phenomenon



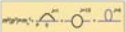
2015

Dark Matter



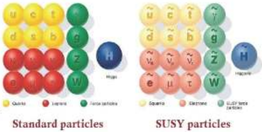
Matter-antimatter asymmetry

The lightness of the Higgs boson?



New Physics: Some Conjectures

Supersymmetry (SUSY)



Intimately relates matter particles and force particles.

SUSY predicts the existence of a partner for every known SM particle with spin differing by half a unit and 5 Higgs bosons!

The lightest particle of this species is a candidate for dark matter
Would address the issue of the "lightness" of the Higgs boson.

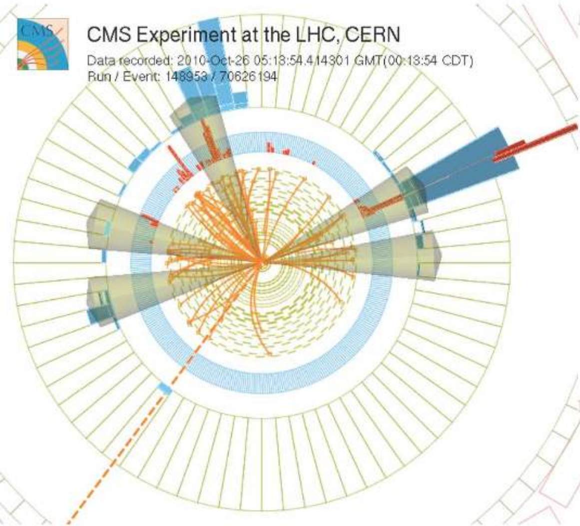
Superstring Theory

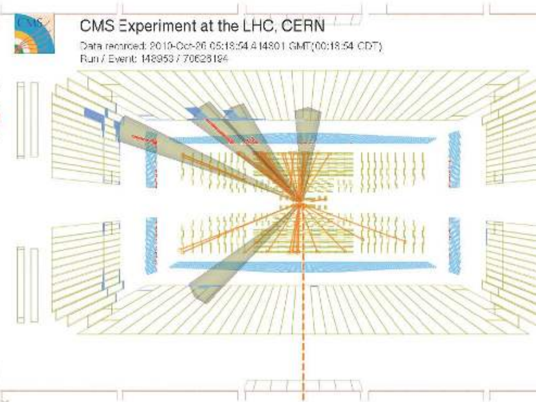
Can gravity be unified with the other forces? Supersymmetry helps.

Extra Dimensions

Number of space-time dimensions determines the observed form of a force
Tell-tale signs are new heavy Z-like particles.

Candidate Event for Supersymmetry at the LHC!





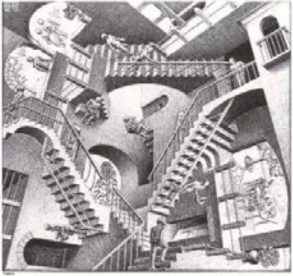
No evidence for Supersymmetry has been found so far.

Incorporating Gravity
How many space dimensions are there?

Law of Gravity
In 3-D(∞ large dim): $F = \frac{GMm}{r^2}$

e.g. in 2-D (∞ large dim): $F \propto \frac{1}{r}$

Number of space-time dimensions determines the observed form of a force



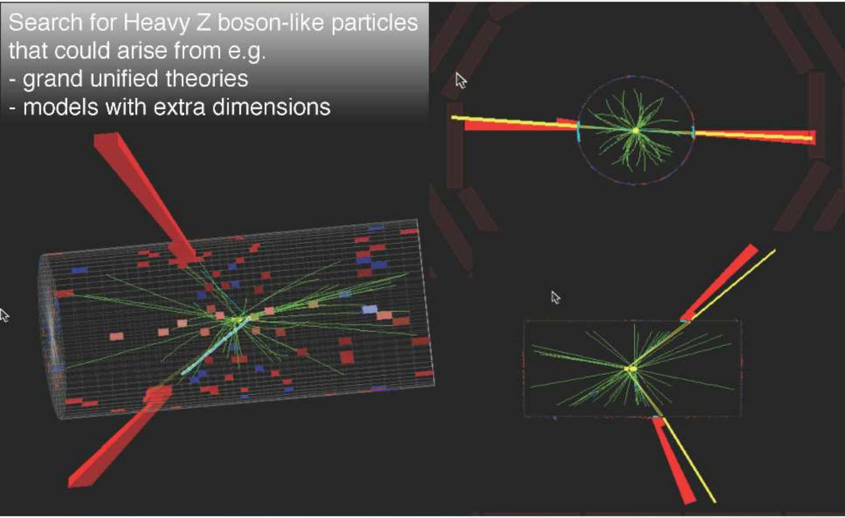
Gravity may propagate in 4+n dimensions, but we could see strong effects only at very small distances, perhaps reachable in pp collisions at the LHC

e.g. by finding new heavy Z-like particles

Path to combining gravity : Superstring theory ?
⇨dramatic concepts: supersymmetry, extra space-time dimensions ?

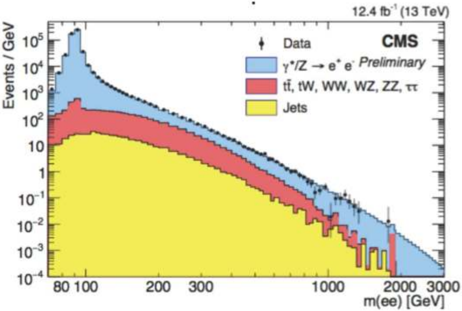
Searching for Extra Dimensions

Search for Heavy Z boson-like particles that could arise from e.g.
- grand unified theories
- models with extra dimensions



Search for New Physics

Searches for **compositeness** (do the particles of the SM have structure?), **extra dimensions** (some of these theories predict heavy resonances observable at the LHC), **new heavy gauge bosons**, leptoquarks (quark and lepton bound states), excited fermions, **black holes**, **dark matter particles**, and more.



CMS: ee and μμ
at 95% CL
$M(Z'_{SSM}) > 4.0$ TeV
$M(Z'_{\psi}) > 3.5$ TeV

No evidence for BSM physics has been found so far

Looking Ahead to Phase 1 and Phase 2 (HL-LHC)

Topmost Priority – exploitation of the full potential of the LHC
High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

1. Conduct detailed studies of the properties of the found Higgs boson.
LHC → HL-LHC - a Higgs factory! 100M produced with $3ab^{-1}$
How much does it contribute to restoring unitarity in VBF (closure test of SM), exotic decays, rare decays (e.g. $H \to \mu\mu$)

2. Search for new physics: resonances, supersymmetry, exotica, yet unknown. If new physics found in Phase 1, associated particle(s) will be heavy. Then conduct detailed studies in HL-LHC

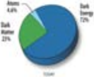
3. Look for deviations from the standard model – precision SM measurements (e.g. tens of millions of top pairs produced/yr)

The LHC Experiments will be Upgraded for Higher Luminosities
A programme of work for the next two decades

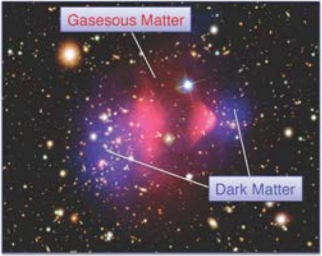
The Standard Models

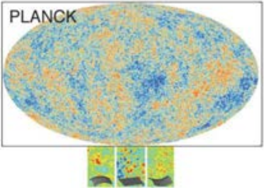
The Standard Model of Particle Physics

The Standard Model of Cosmology



The LHC and the Dark Side of the Universe





Simulation Closed Flat Open

Dark Matter appears to be made of weakly interacting massive particles.
Lightest SUSY particle has these properties !

Dark Energy?
One conjecture: remnant of some elementary scalar field analagous to the Higgs field?

Summary

- **Over the last 50 years, the "construction" of the Standard Model (SM) represents a towering intellectual achievement of humankind.**
- **This has allowed us to trace in much detail the evolution of our universe from moments after the Big Bang.**

- **At the LHC we have discovered the keystone of the SM – the Higgs boson** – it appears to be the one predicted by the SM. It now is being studied in great detail.
- **No evidence has yet been found for physics BSM.**
- **However, we are just at the start of the exploration of the Terascale.**

- **What further discoveries await us?**
  - Several of the open questions today are just as profound as those a century ago. LHC is the foremost place to look for new physics.

- **Discoveries in fundamental science invariably lead to paradigm shifting technologies**

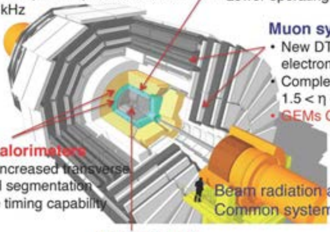
Only experiments reveal/confirm Nature's secrets

LHC Experiments will be Upgraded e.g. CMS

Trigger/HLT/DAQ
- Track information in Trigger (hardware)
- Trigger latency 12.5 μs - output rate 750 kHz
- HLT output 7.5 kHz

Barrel EM calorimeter
- New FE/BE electronics
- Lower operating temperature (8°C)

Muon systems
- New DT & CSC FE/BE electronics
- Complete RPC coverage $1.5 < \eta < 2.4$
- GEMs GE1/1, GE2/1, ME0



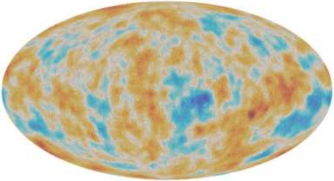
New Endcap Calorimeters
- Rad. tolerant - increased transverse and longitudinal segmentation - intrinsic precise timing capability

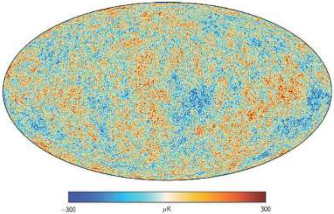
Beam radiation and luminosity
Common systems &infrastructure

New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout ($p_T \geq 2$ GeV) in Outer Tracker for Trigger
- Extended coverage to $\eta = 3.8$

Echoes from the Cosmos

PLANCK
Polarization and Temperature maps





PLANCK
Cosmological Parameters

Planck Collaboration Cosmological parameters[9]

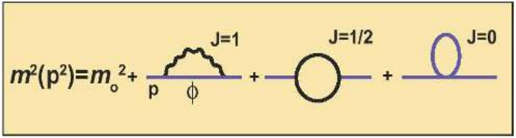
	Description	Symbol	Value
Independent parameters	Physical baryon density[note 1]	$\Omega_b h^2$	0.022 30 ±0.000 14
	Physical dark matter density[note 1]	$\Omega_c h^2$	0.1188 ±0.0010
	Age of the universe	t_0	13.799 ±0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$, $k_0 = 0.002$ Mpc^{-1}
	Reionization optical depth	τ	0.066 ±0.012
Fixed parameters	Total density	Ω_{tot}	1
	Equation of state of dark energy	w	−1
	Sum of three neutrino masses	$\sum m_\nu$	negligible
Calculated values	Hubble constant	H_0	67.74 ±0.46 km s^{-1} Mpc^{-1}
	Matter density	Ω_m	0.3089 ±0.0062
	Dark energy density	Ω_Λ	0.6911 ±0.0062
	Fluctuation amplitude at 8h^{-1} Mpc	σ_8	0.8159 ±0.0086
	Redshift at decoupling	z_*	1 089.90 ±0.23
	Age at decoupling	t_*	377 700 ±3200 years[12]
	Redshift of reionization	z_{re}	$8.8^{+1.2}_{-1.1}$

arXiv: 1502.01589 (2015)

The lightness of the Higgs boson?

What happens if extend validity of SM to scales $\Lambda >> 1/\sqrt{G_F}$?

Radiative corrections to the Higgs boson mass



$M_H^2 \rightarrow \mathbf{M_H^2}$ **(bare) + c** $\mathbf{\Lambda^2}$

Λ is the scale of the underlying theory (could be $M_{GUT} \sim 10^{15}$ GeV !)

Requires incredibly unnatural fine tuning to keep M_H small !!

What can be done ?

L_{SSB} does not contain an elementary Higgs boson

OR Cancel quadratic divergences (new symmetry e.g. supersymmetry,…)

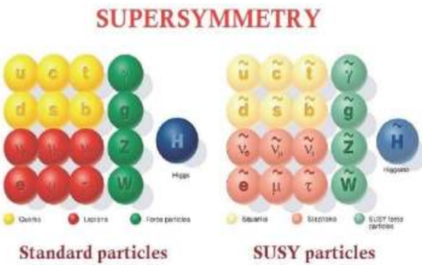
OR Some unknown new physics (exotica,…)

Supersymmetry

Invoke additional symmetry (e.g. Supersymmetry) to cancel divergences

bosons have fermion superpartners

fermions have boson superpartners



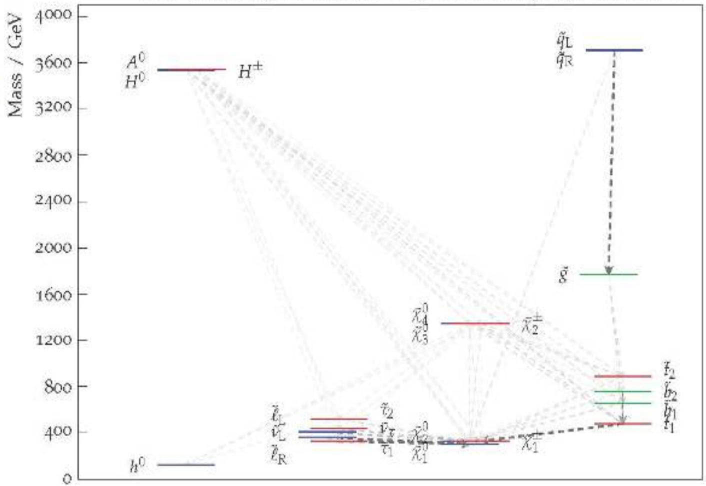
Minimal SUSY Model

gluinos, squarks, sleptons,
4 neutralinos, 2 charginos,
Higgs sector: h^0, H^0, A^0, $H^\pm$

SUSY is obviously broken

For SUSY to solve naturalness
$|M^2_{Higgs} - M^2_{sparticle}| \leq O(1\ TeV^2)$

An example SUSY (allowed) spectrum



Alas – SUSY has not yet turned up

Inclusive Searches

3rd Gen gluino med.

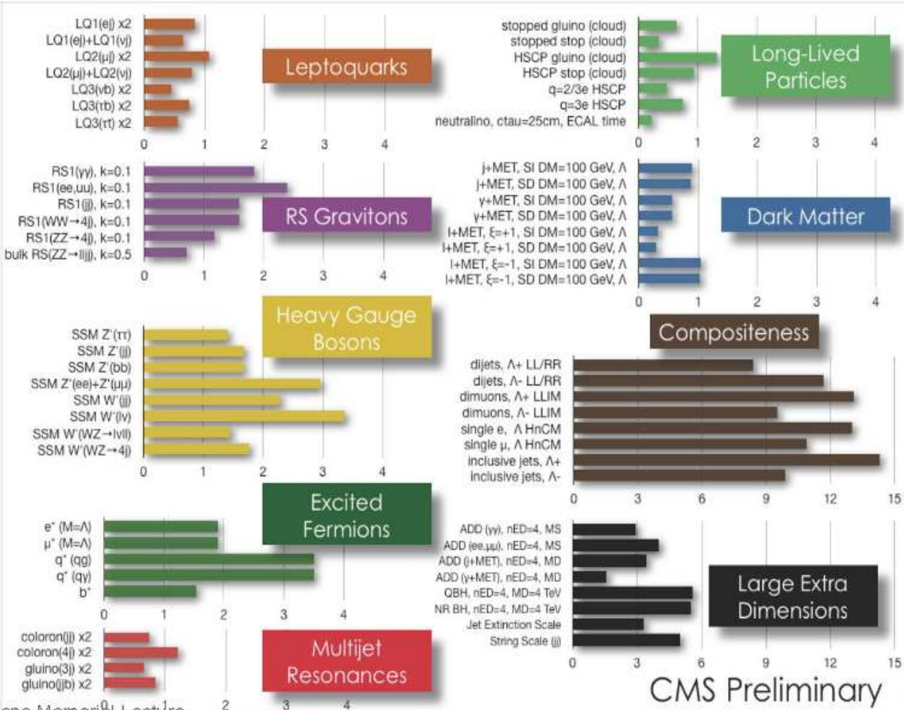
3rd Gen Direct

EW Direct

Long-lived

RPV

No Sign of "Exotic" Physics Either



Some of the Physics Questions from early 1990's

The Standard Model is incomplete when probed at the LHC.

Origin of mass

"Why is there something rather than nothing?" (Leibnitz 1697)

Even if the Higgs boson is found, all is not 100% well with ONLY the Standard Model. Why should we have found it?

A possible solution to postulate a new symmetry,

Supersymmetry – Relate matter particles to force particles!

Could allow understanding of the composition dark matter.

Why is there no anti-matter around?

How can gravity be incorporated into the SM?

Do we live in more than 3 space dimensions?

Superstrings? Find a pathway to a unified theory?

The unexpected. Most expect there to be new physics.

Timeline of the LHC Project

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future

1990 ECFA LHC Workshop, Aachen, Germany

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 **Letters of Intent** (ATLAS and CMS selected by LHCC)

1994 Technical Proposals Approved

1996 Approval to move to **Construction** (materials cost of 475 MCHF)

1998 Memorandum of Understanding for Construction Signed

1998 Construction Begins (after approval of Technical Design Reports)

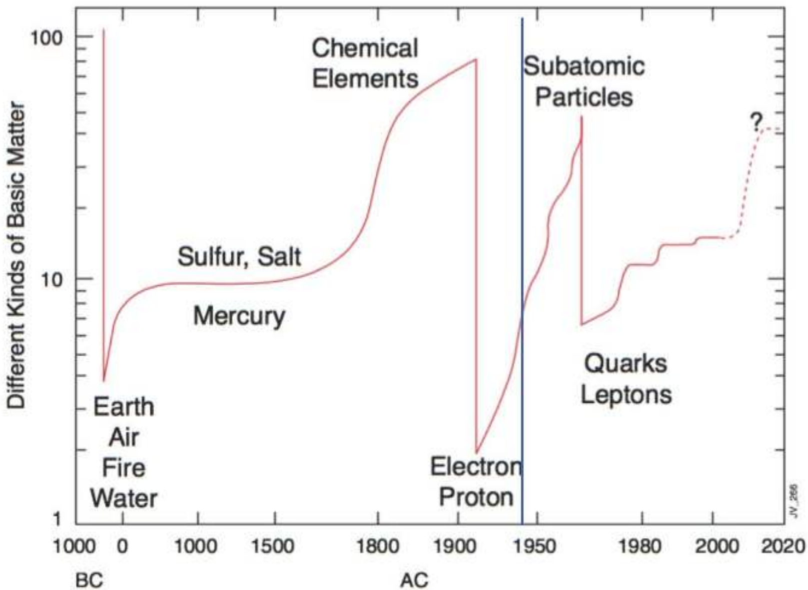
2000 ATLAS and CMS assembly begins above ground. LEP closes

2008 **ATLAS & CMS ready for First LHC Beams**

2009 First proton-proton collisions

2012 A new heavy boson discovered with mass ~125 × mass of proton

Elementary Constituents of Matter

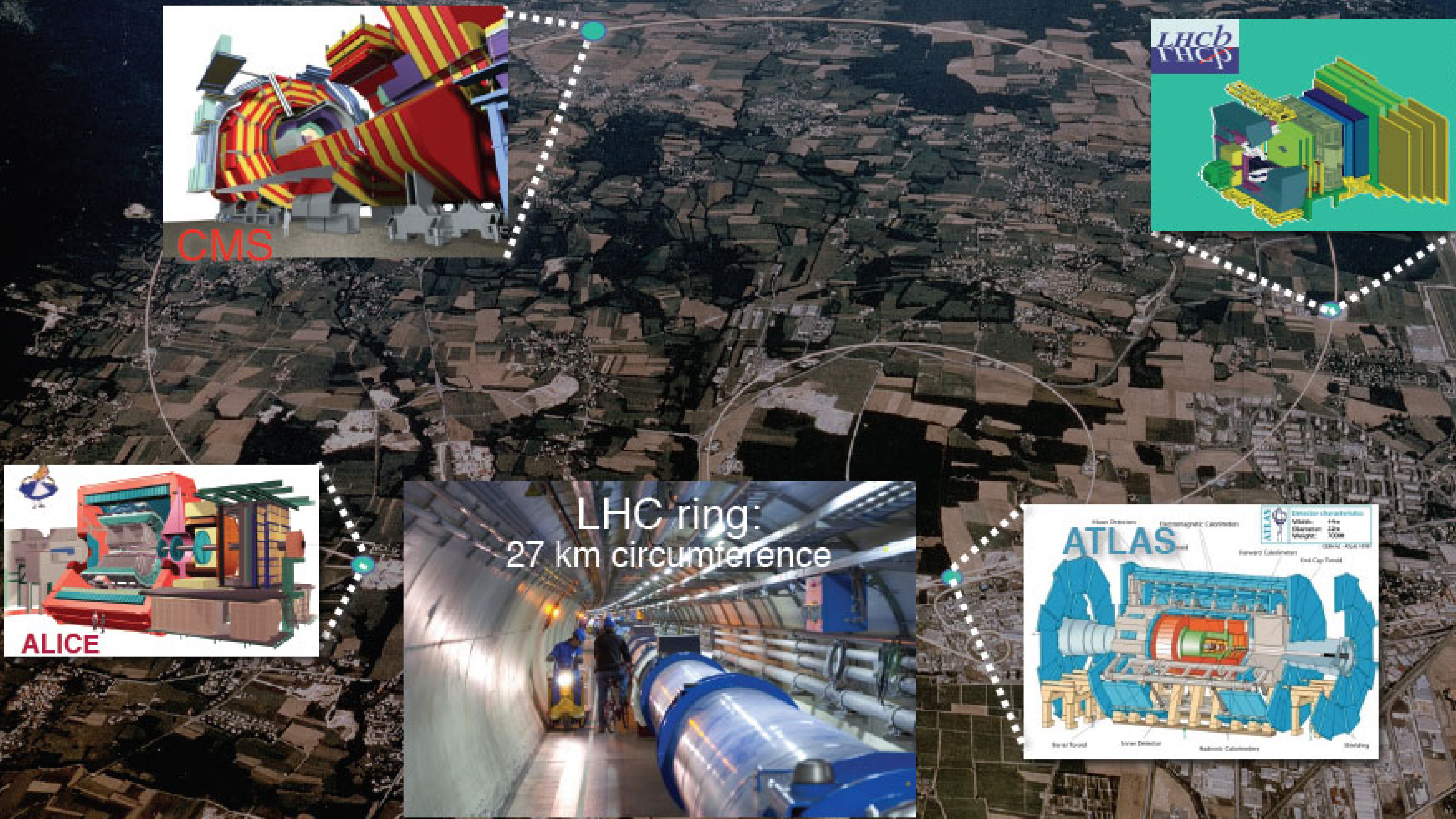


Main Experiments on the LHC

General-purpose (ATLAS and CMS) studying origin of mass, SUSY, …

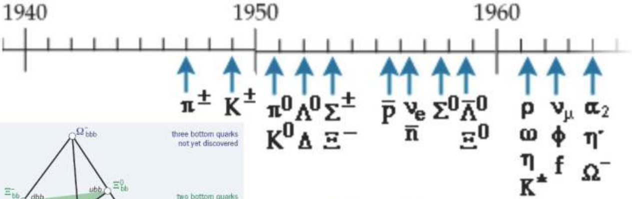
Dedicated (LHCb) studying origin of matter-antimatter asymmetry,…

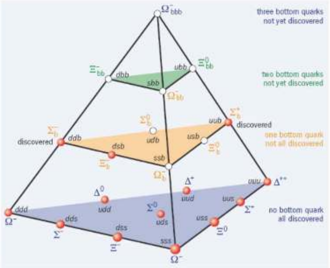
Dedicated (ALICE) studying general properties of quark-gluon fluid,…

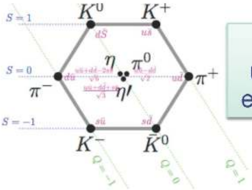


1950's and 1960's: Particle Explosion!

Dozens of "elementary particles" discovered implying neutrons and protons are not special; and turned out not to be elementary!







Explanation using mathematical entities called quarks

Lesson from Mendeleev's periodic table:

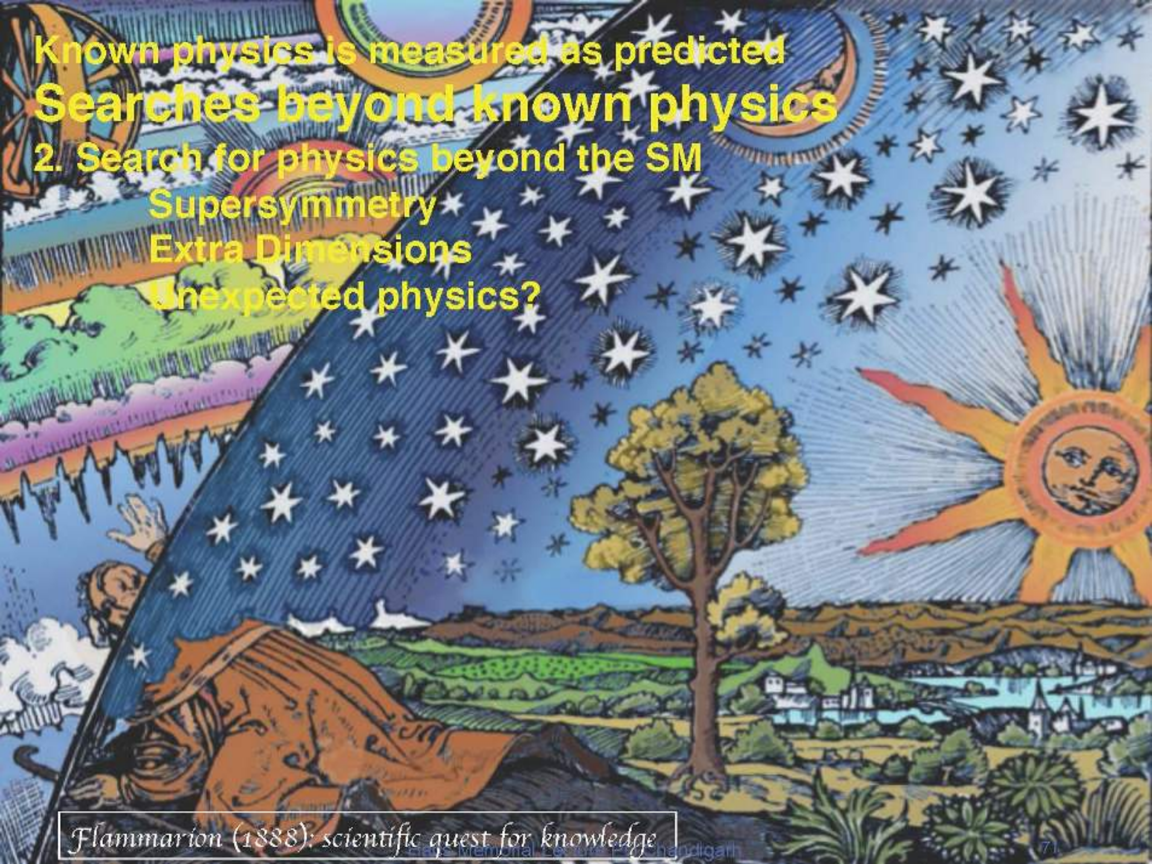
There was inner structure to atoms (electrons & nuclei)

Known physics is measured as predicted

Searches beyond known physics

2. Search for physics beyond the SM

- Supersymmetry
- Extra Dimensions
- Unexpected physics?



Flammarion (1888): scientific quest for knowledge

Known physics is measured as predicted

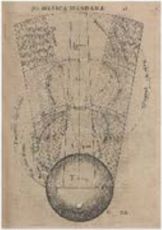
Searches beyond known physics

1. Search for the Higgs boson

Flammarion (1888): scientific quest for knowledge

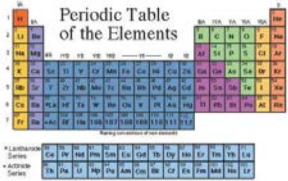
Elementary Constituents of Matter

Philosophy



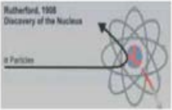
EMPEDOCLES
(492-432 B.C.)
4 basic elements
Earth, air, water, fire
Other Ancients
Chinese, Indian, ..

Classical Mechanics



MENDELEEV
(19th century)
Periodic Table:
>100 basic elements

Quantum Mechanics



BOHR,
RUTHERFORD
(early 20th century)
2 basic elements:
electron, nucleus

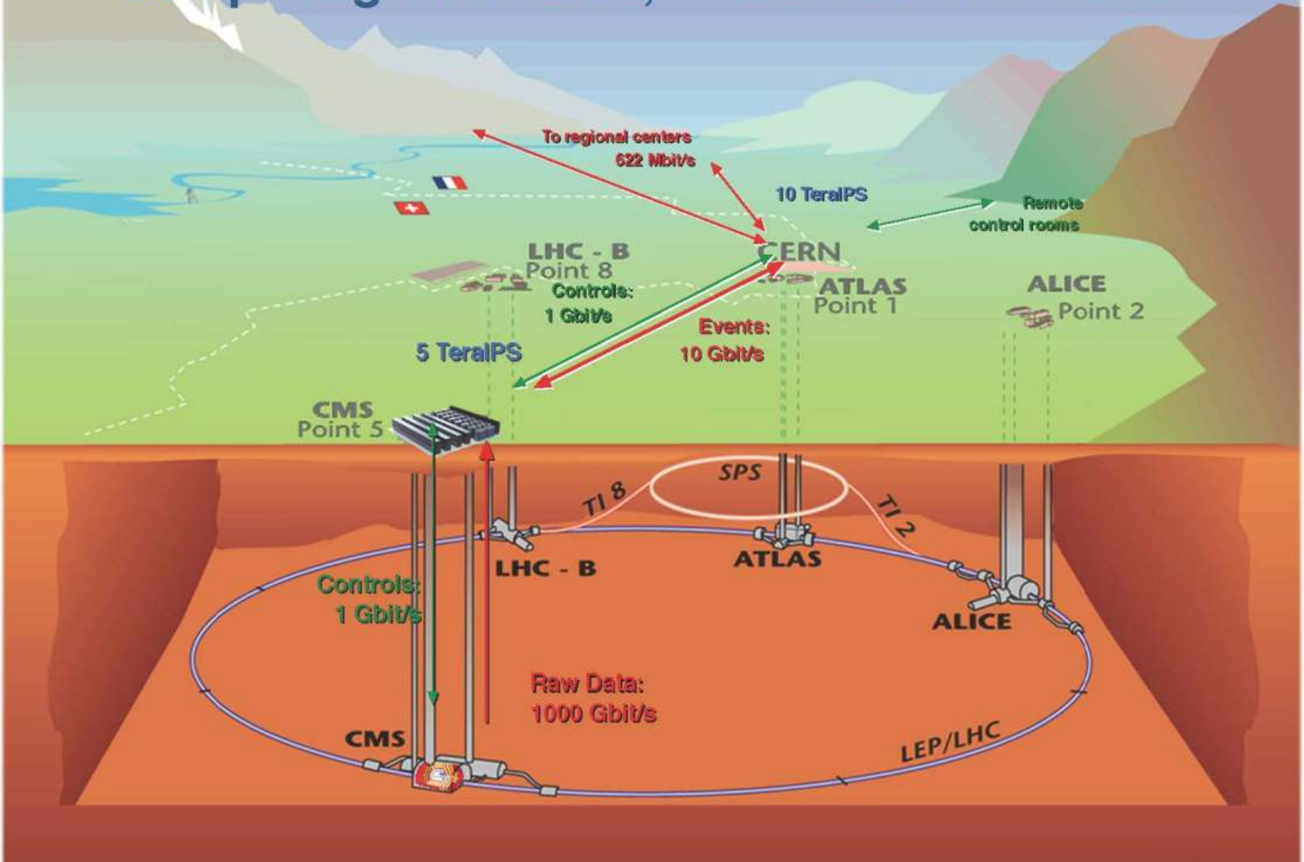
Discovery of the Higgs boson

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

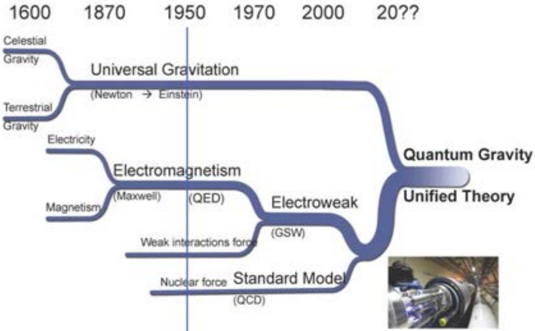
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle,

by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Computing: Networks, farms and data flows



Fundamental Forces: Laws of Nature



Physics Outlook: Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector
SM has an unproven element: the generation of mass
Higgs mechanism ->? or other physics ?
Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$
M_W, $M_Z \sim$ 100,000 MeV!

Transparency from the early 90's

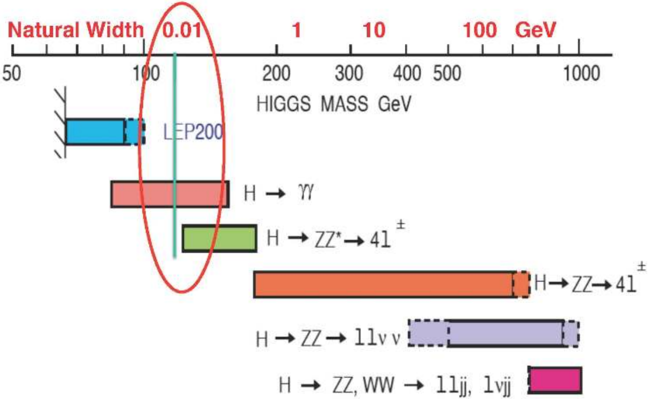
3. SM gives nonsense at LHC energies
Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!
Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter
Even if the Higgs boson is found all is not completely well with SM alone: next question is "Why is (Higgs) mass so low"?
*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV***)*

5. Search for new physics at the TeV scale
SM is logically incomplete – does not incorporate gravity
Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

20 Years ago: The design of ATLAS and CMS

SM Higgs Boson was used as a Physics Benchmark



Transparency from the 90's

Theory does not predict m_H

The favourable decay modes change with mass