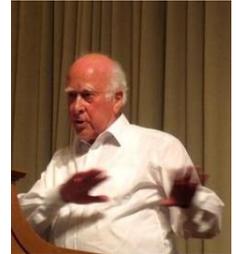


How the Higgs Boson was Discovered the physics & the fun

Frank E. Taylor
Physics Department
Laboratory for Nuclear Science
MIT
24 June 2013

Higgs Boson

- Where do electrons and other fundamental particles, such as quarks, get their mass?
 - The Higgs mechanism explains this
 - Proposed in 1964 by Englert-Brout, Higgs and others
 - The Higgs Boson* was predicted to come with the Higgs Field associated with the mechanism
 - Discovery announced simultaneously at CERN, Geneva Switzerland and Melbourne Australia July 4, 2012



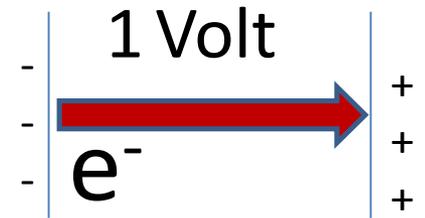
It took decades of theoretical and experimental work, culminating in the physics program at the Large Hadron Collider at CERN with huge teams of physicists and engineers, to make this key discovery.



* Satyendra Nath Bose (Bose-Einstein statistics)

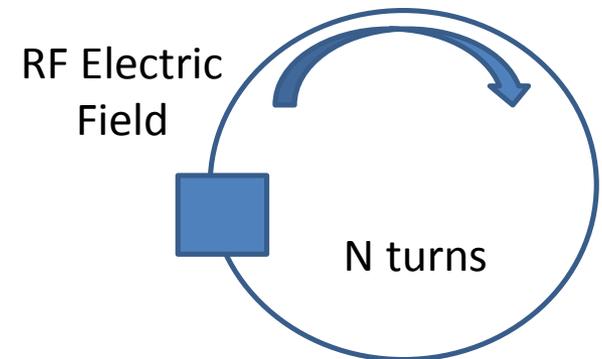
Energy Scales & Accelerators

- Units used are 'electron volts'
 - Amount of energy 1 electron (elementary charge) gains when it falls through 1 volt electric potential
- A few numbers:
 - Average kinetic energy room temperature 1/40 eV
 - Mass of the electron 0.51 MeV (10^6 eV)
 - Mass of proton 0.938 GeV (10^9 eV)
 - Mass of heaviest particle known (Top Quark) 271 GeV
 - Most energetic accelerator 7 TeV (10^{12} eV)
 - Most energetic cosmic rays $\sim 10^{20}$ eV



$$E=qV = 1 \text{ eV}$$

Magnet
'Racetrack'



$$E=NqV=7 \times 10^{12} = 7 \text{ TeV}$$

A few basic concepts

- It takes energy to produce mass (Einstein)

- $E = mc^2$

- Equation goes both ways

- Nuclear fusion energy from mass defect ($4M_p > M^4\text{He}$ by 0.7% 27 MeV)
 - Electron-Positron pair production by gamma rays

Special Theory of Relativity
speed of light constant in any reference frame

- It takes large energies to 'see' small things

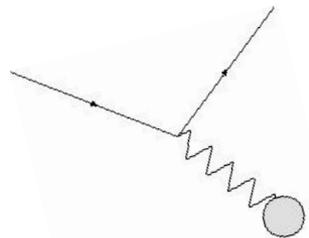
- Heisenberg's microscope

$$\Delta x \Delta p \gtrsim \hbar$$

Quantum Mechanics
particles behave like waves and
vice versa

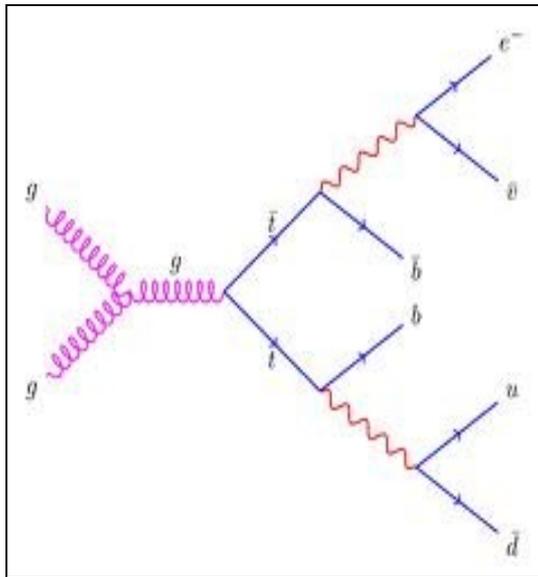
- If you want to localize something well you have to hit it with an energetic probe

- It takes a probe of 200 MeV to 'see' the diameter of a proton (10^{-13} cm)
 - It takes several GeV to 'see' the quarks inside the proton
 - If you want to see inside a coconut hit it hard with a hammer



A Little Theory

Feynman Diagram



time \longrightarrow

- A particle interacts with another particle by exchanging a particle
 - The exchanged particle carries the force
 - Imagine 2 hungry wolfs sharing a bone
 - Certain rules apply about who may interact with whom
 - Interactions are depicted by Feynman Diagrams that are used to calculate interaction probabilities and interaction cross sections
 - A major thrust of present theory is to try to unify forces
 - That quest takes high energy

The Standard Model

three generations of matter (fermions)					
	I	II	III		
mass→	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0	≈126 GeV/c ²
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
name→	up	charm	top	photon	Higgs boson
QUARKS	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	down	strange	bottom	gluon	
LEPTONS	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²	
	0	0	0	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	electron neutrino	muon neutrino	tau neutrino	Z boson	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²	
	-1	-1	-1	±1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	electron	muon	tau	W boson	
					GAUGE BOSONS

- Quarks bind with the strong force
 - Proton and Neutron have 3 quarks bound by exchange of gluons
- Leptons interact electromagnetically and through the weak force
- Gauge Bosons are exchanged
 - Mediates the force between particles
- Higgs Boson makes it all work
 - Responsible for mass of quarks, leptons and gauge bosons

What is the Higgs Boson

- Where do electrons and other fundamental particles, such as quarks, get their mass?
 - Higgs mechanism & Higgs Boson
 - A quasi-political explanation – David Miller, UK



Politician walks into crowded room
people clump & she acquires mass

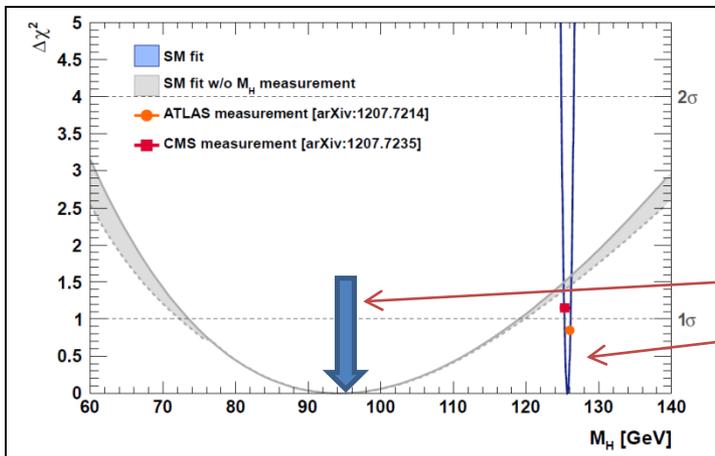


A rumor travels across
crowded room – Higgs Boson

<http://www.youtube.com/watch?v=C-pxHCJK7Yg>

Where to look for the Higgs ?

- The SM predicts how quarks and leptons interact
 - Using ever more complicated Feynman diagrams small effects can be predicted – then measured
 - Stepping stones of Experiments over the waters of Theory
 - In early times the Higgs mass was not constrained very well $1 \text{ GeV} < M_H < 1 \text{ TeV}$
 - By means of better determinations of parameters of the SM through experiment better predictions were made
 - The SM has been astoundingly correct ! Disappointingly so!

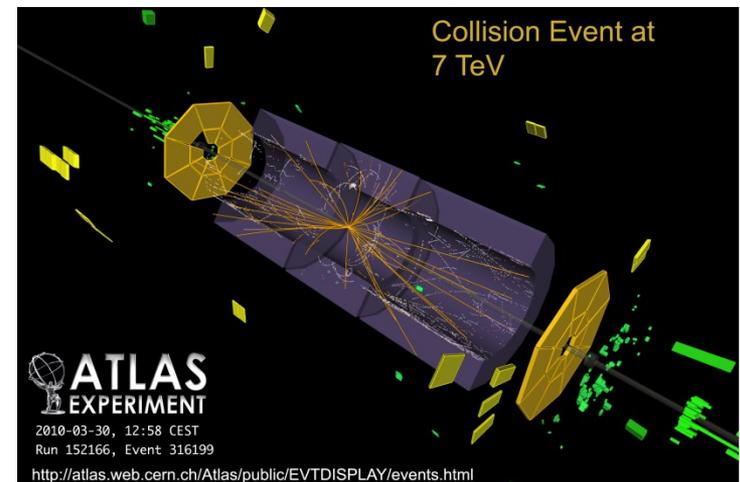


SM predicted mass of Top Quark (171 GeV).
It gave a strong indication of what the Higgs
Boson mass would be:

Predicted $\sim 95 \pm 20 \text{ GeV}$
Measured 125 GeV

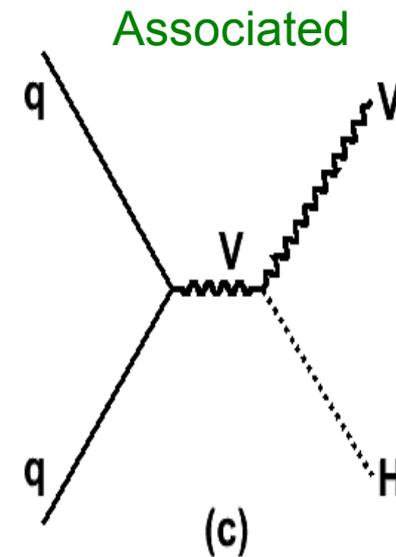
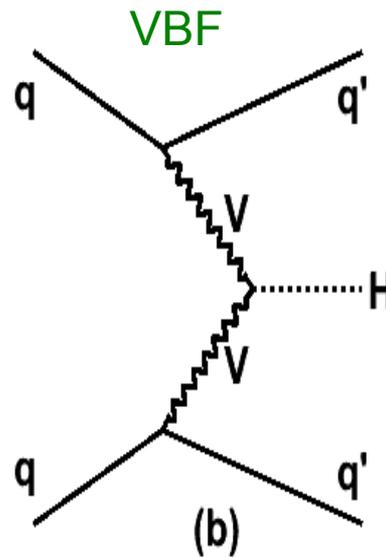
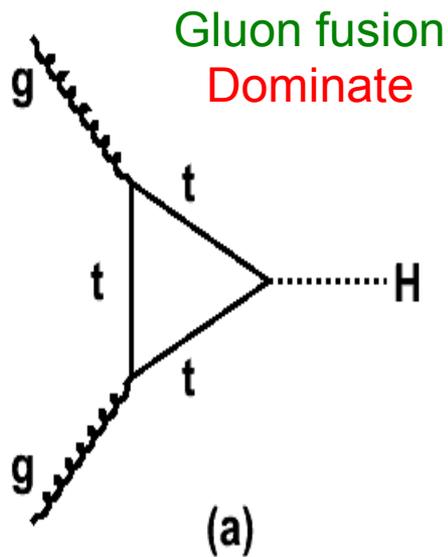
Production & Detection of Higgs

- With the growing confidence in the SM the production and decay rates of the Higgs could be predicted (Snowmass 1982)
 - Need high energy and high luminosity collisions
 - Make a proton-proton collider with energies 14 TeV. Head-on collisions are the most efficient way of reaching energies required. Thus the Large Hadron Collider (LHC) @ CERN (Geneva)
 - Need detectors to analyze the debris of the collisions in order to detect the Higgs out of the uninteresting events.
 - ATLAS & CMS Collaborations

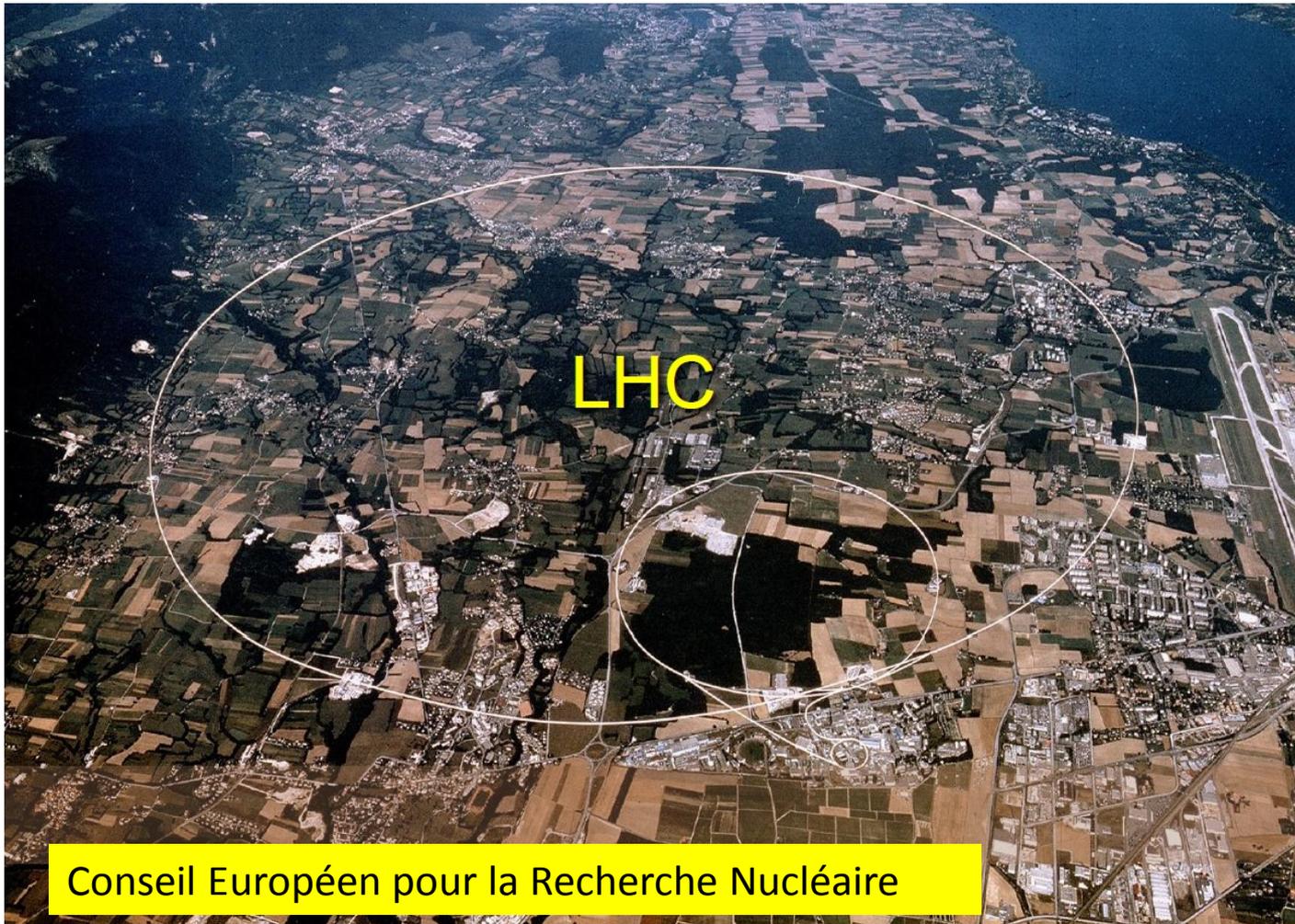


Higgs Production @ LHC

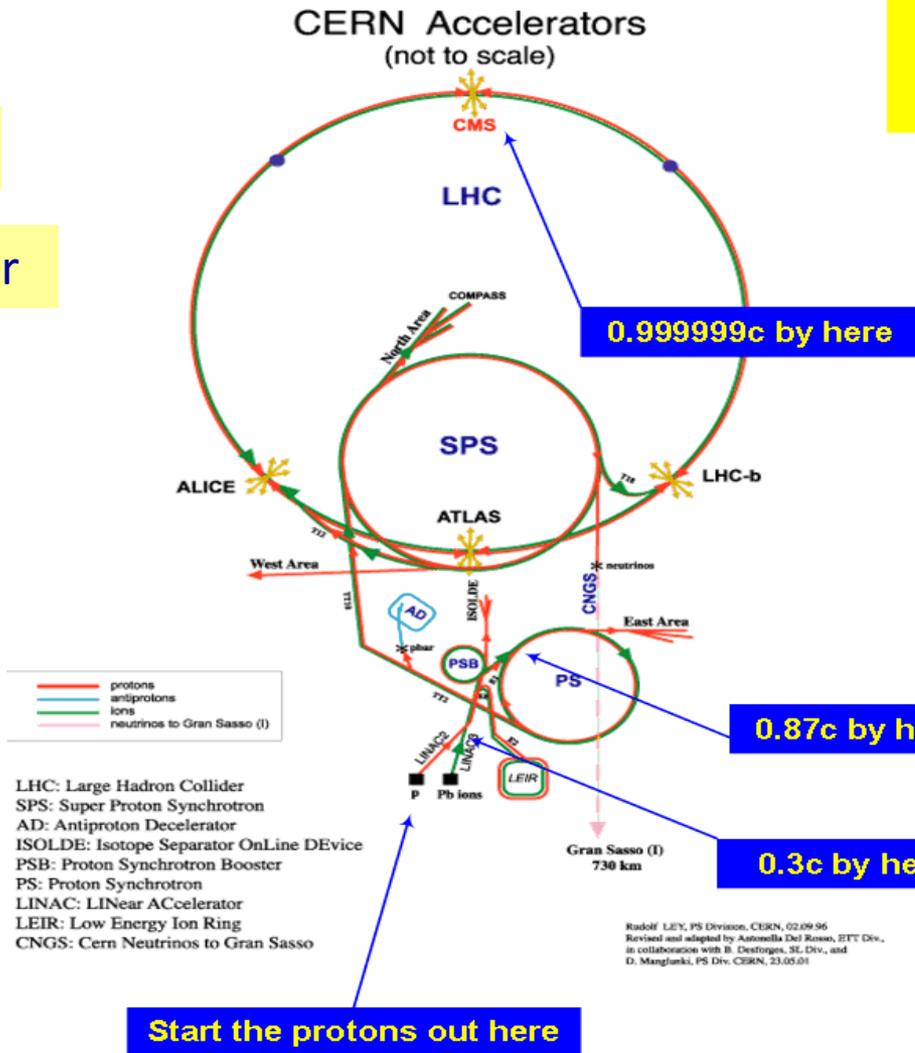
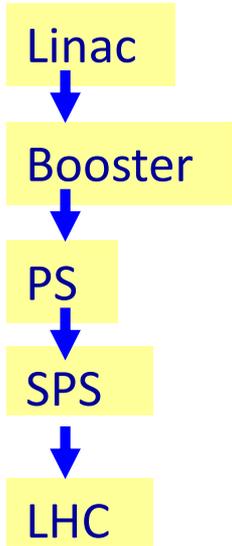
- Protons contain quarks and gluons
 - When protons collide with other protons the quarks inside can collide or the quarks with gluons or the gluons can hit each other
 - Some of those collisions can, quite rarely, produce a Higgs Boson



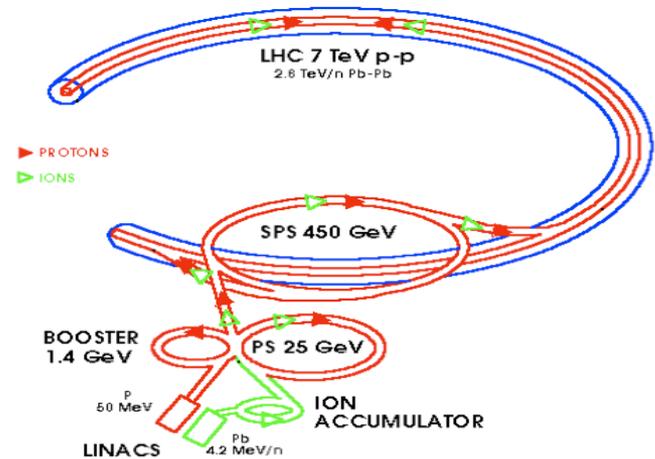
Large Hadron Collider CERN Geneva, Switzerland



The full LHC Accelerator Complex



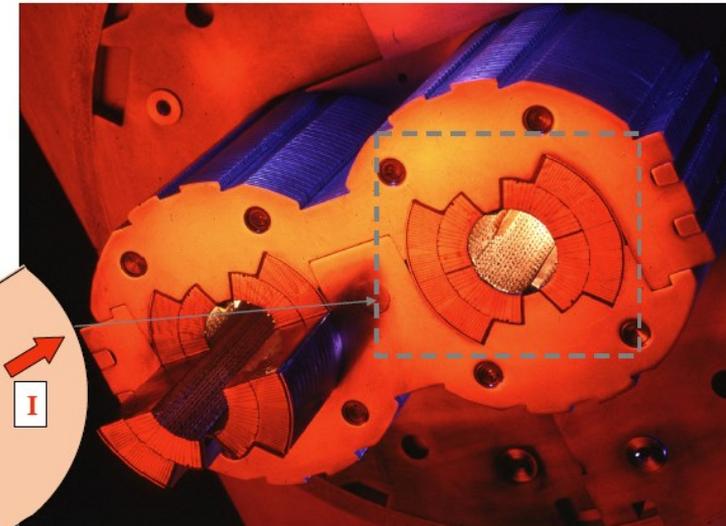
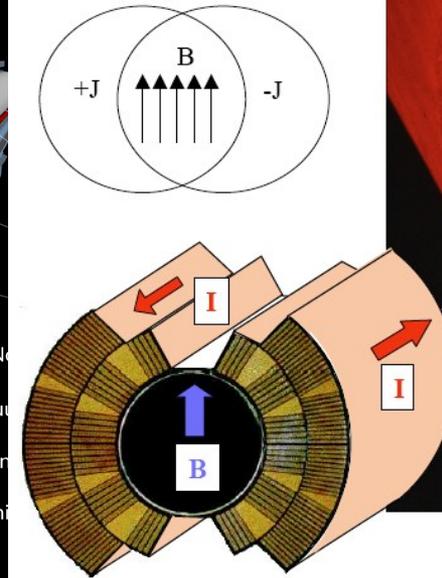
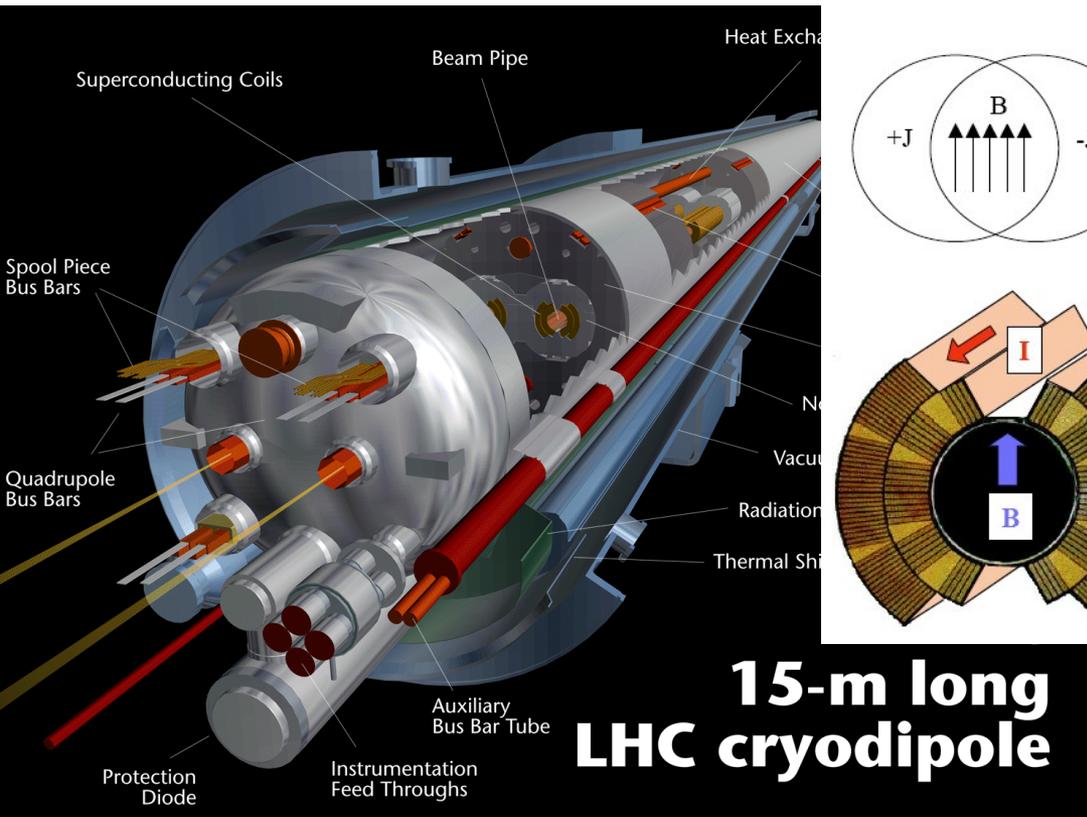
Built using existing infrastructure at CERN



Power Consumption ~ 700 GWh/y < 10% Geneva Canton

Radolf LEY, PS Division, CERN, 02/09/96
 Revised and adapted by Antonella Del Rosso, ETT Div.,
 in collaboration with B. Desforges, SL Div., and
 D. Manglani, PS Div. CERN, 23/05/01

LHC Accelerator Challenge: Dipole Magnets



Magnetic Field for Dipoles
 $p \text{ (TeV)} = 0.3 \text{ B(T)} R(\text{km})$

1.9 K (CMBR is about 2.7 K)

LHC magnets are cooled with pressurized superfluid helium ~ 125 tons

For $p = 7 \text{ TeV}$ and $R = 4.3 \text{ km}$
 $\Rightarrow B = 8.4 \text{ T}$
 $\Rightarrow \text{Current } 12 \text{ kA}$

Detectors have to find a needle in a Haystack

(few special grains of sand in an Olympic swimming pool filled with sand)

- Number of Higgs events was expected to be a very small fraction of the total number p-p interactions
 - Detectors have to be triggered on interesting events & and have to work in a high radiation environment

Process	Events (10 pb^{-1})
minimum bias	10^{12}
$W \rightarrow e\nu$	10^5
$Z \rightarrow ee$	10^4
$t\bar{t}$	10^3
Higgs (130 GeV)	10 ($\sigma \sim 10^{-11} \text{ MB}$)
Gluinos (1 TeV)	1



Factor of 10^{11}

The ATLAS Detector



37 Countries
169 Institutions
2500 Scientific Authors

45 m

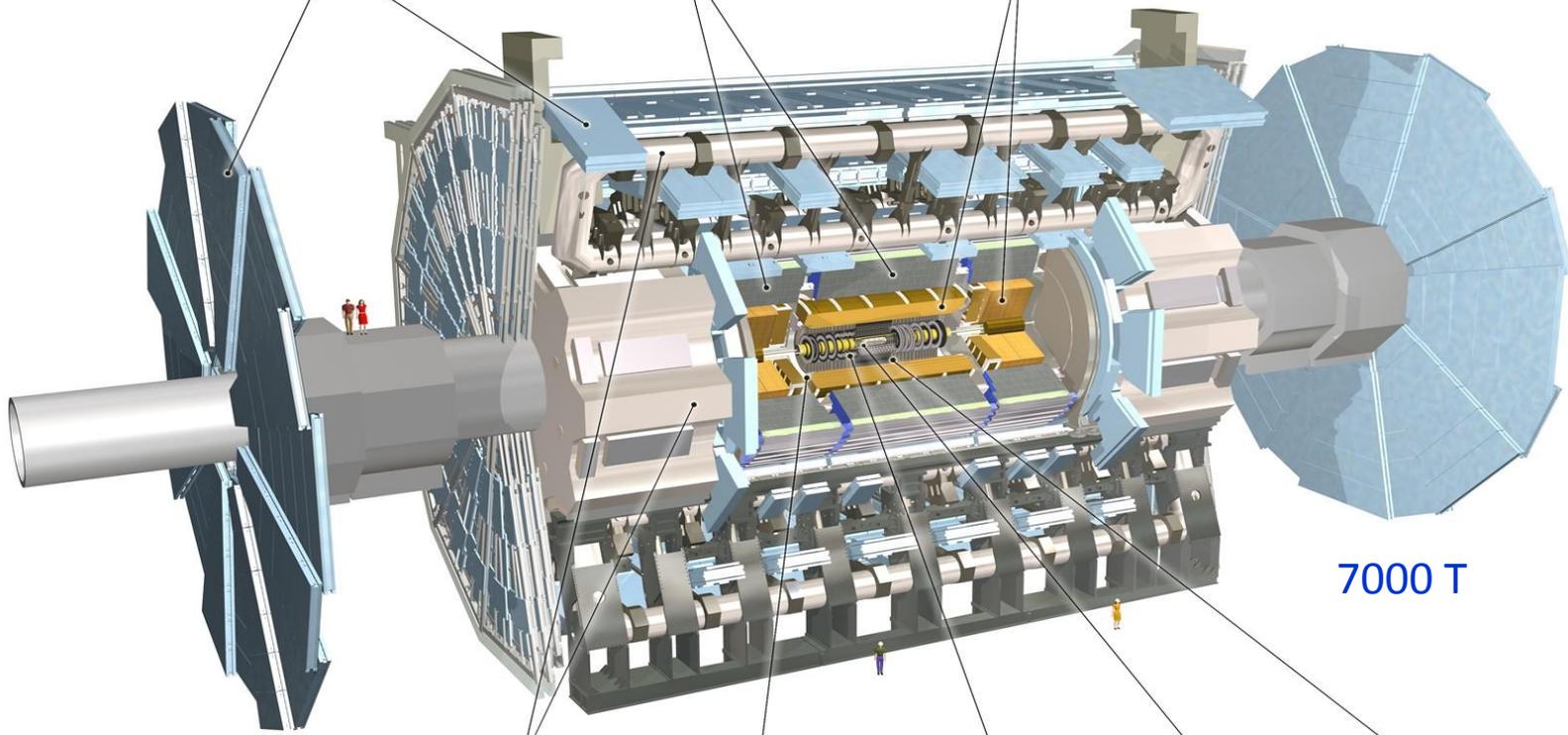
A Toroidal LHC Apparatus

Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeter

24 m



7000 T

Toroid Magnets

Solenoid Magnet

SCT Tracker

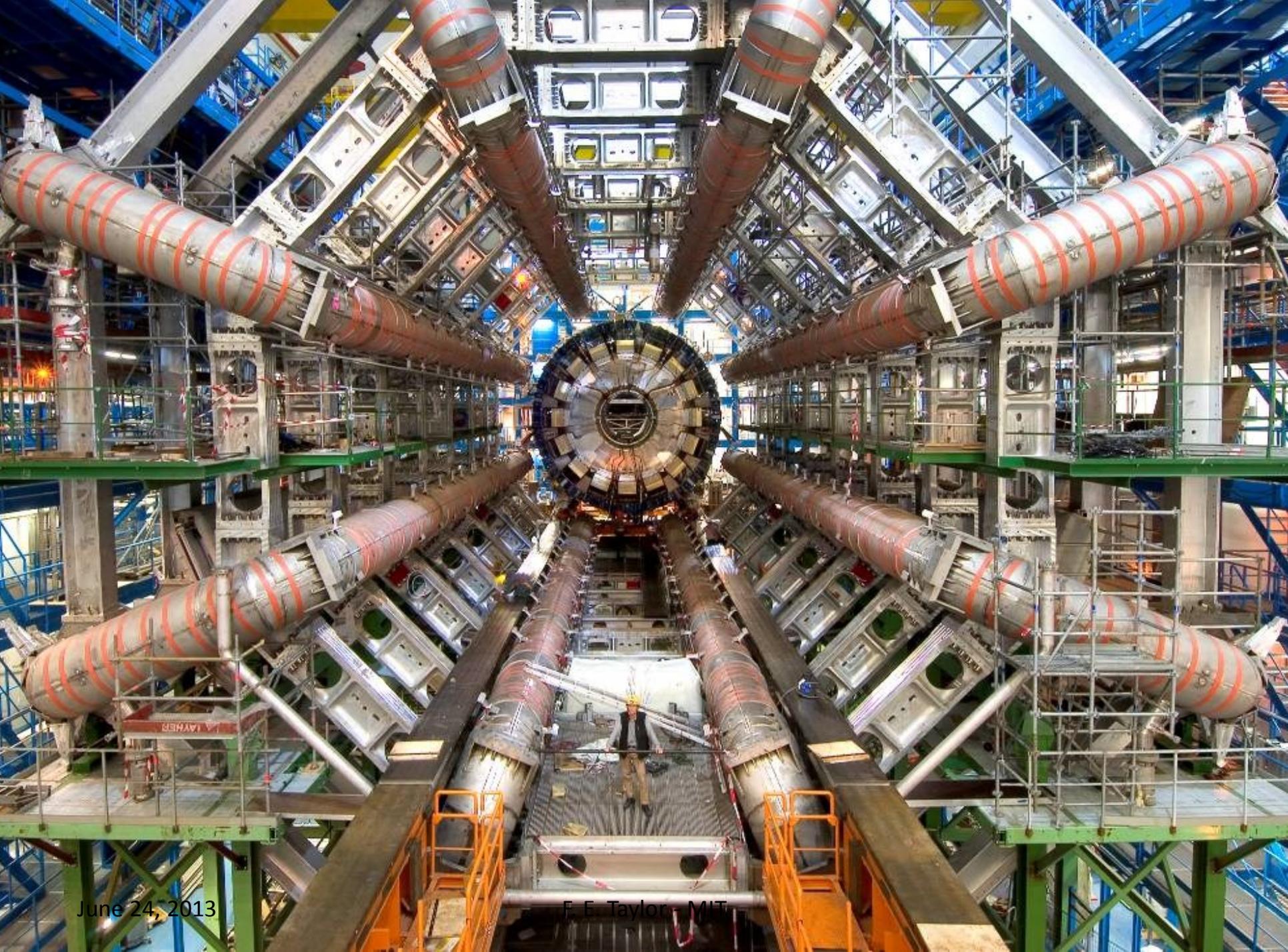
Pixel Detector

TRT Tracker

How ATLAS was built

- ATLAS was built by a large collaboration of some 3,000 physicists & engineers from 37 countries
 - The US contributed ~ \$163 M for construction are key parts of the detector*
 - Individual contribution were agreed upon and overall schedule worked out
 - The detector work was organized in systems, such as the magnets, inner tracking, calorimeters, muons, data acquisition, off-line computing
 - There were spokespersons, deputies, technical coordinators, system managers, funding resource coordinator, country leaders, university group leaders
- US work started in 1994 and was completed in 2005
 - Commissioned in 2007 / first collisions in 2008 / first real data 2010

* **US DOE & US NSF – many thanks**



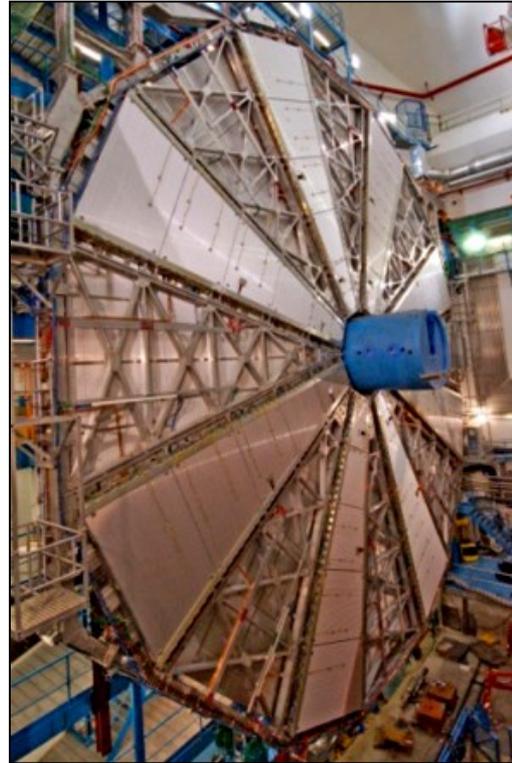
June 24, 2013

F. E. Taylor, MIT

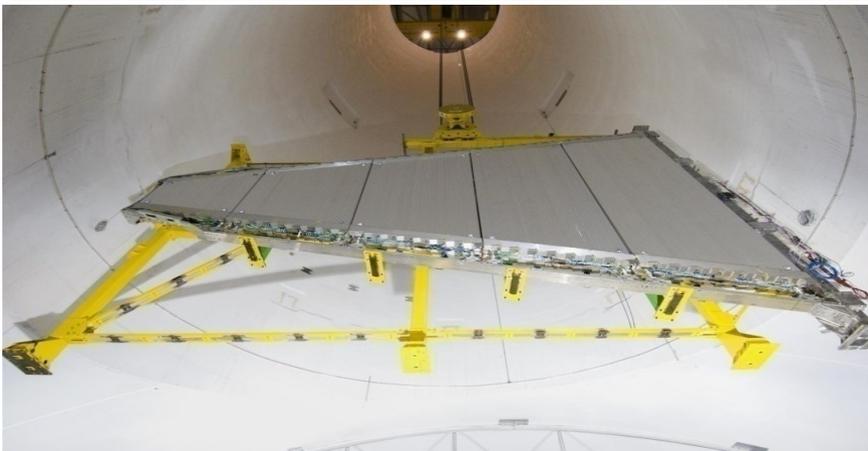
Muons – A window to Physics

- Muons are a major component of cosmic rays
 - Easy to filter from other particles
 - ATLAS has a huge muon detector (& CMS)
 - Many windows with ‘Lepton’ Signatures (e, μ , τ)
 - Leptons (μ^\pm) are decay products of:
 - Standard Model Higgs (H \rightarrow 4 μ^\pm Golden Mode)
 - Supersymmetry (120 parameters)
 - Randall - Sundrum resonances
 - W' and Z'
 - Extra Dimensions & String Theory
- Other theoretical possibilities – no experimental evidence yet

Construction of EC Muon System



MDT Big
Wheels
installed



32 MDT Sectors - Tracking
72 TGC Sectors - Triggering

Small Wheel Assembly @ CERN

Collaborating
Countries
US, Israel, Japan,
Armenia, Serbia,
Spain, Bulgaria, Italy,
Slovakia, Pakistan,
Belgium, France and
Germany



June 24, 2013

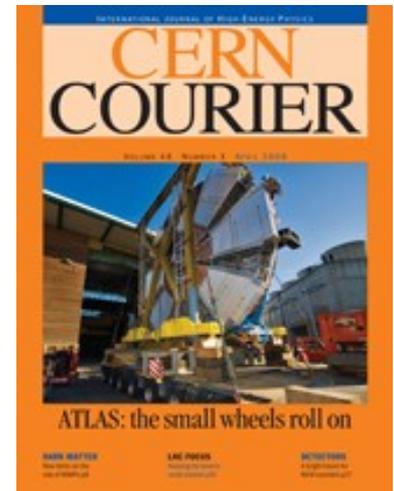
F. E. Taylor - MIT

20

Transport & Installation of Small Wheels



<http://news.nationalgeographic.com/news/2008/03/080303-AP-switzerland.html>

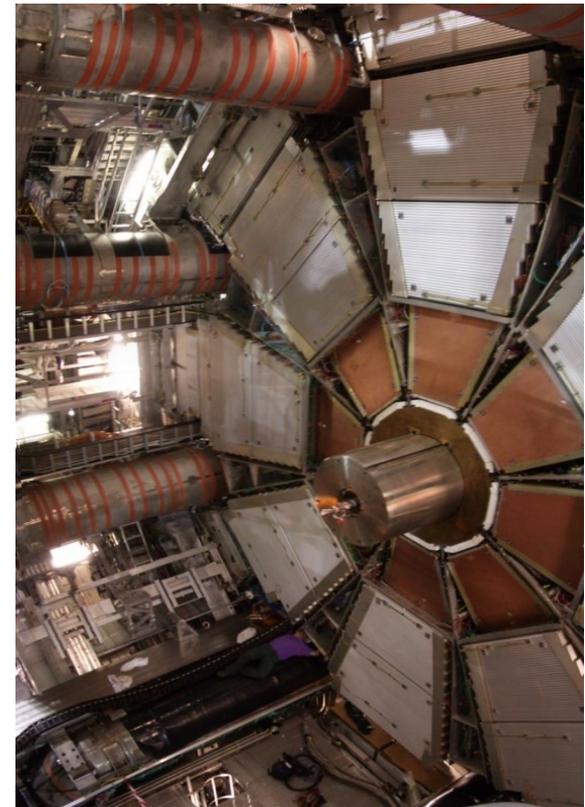


ATLAS Boston Muon Consortium

- Consortium formed after demise of the SSC '93
 - Boston, Brandeis, Harvard, MIT, Tufts
 - Built 80 of the 240 (US) precision tracking chambers
 - Factory located at Harvard



14
years



p-p Collision Events

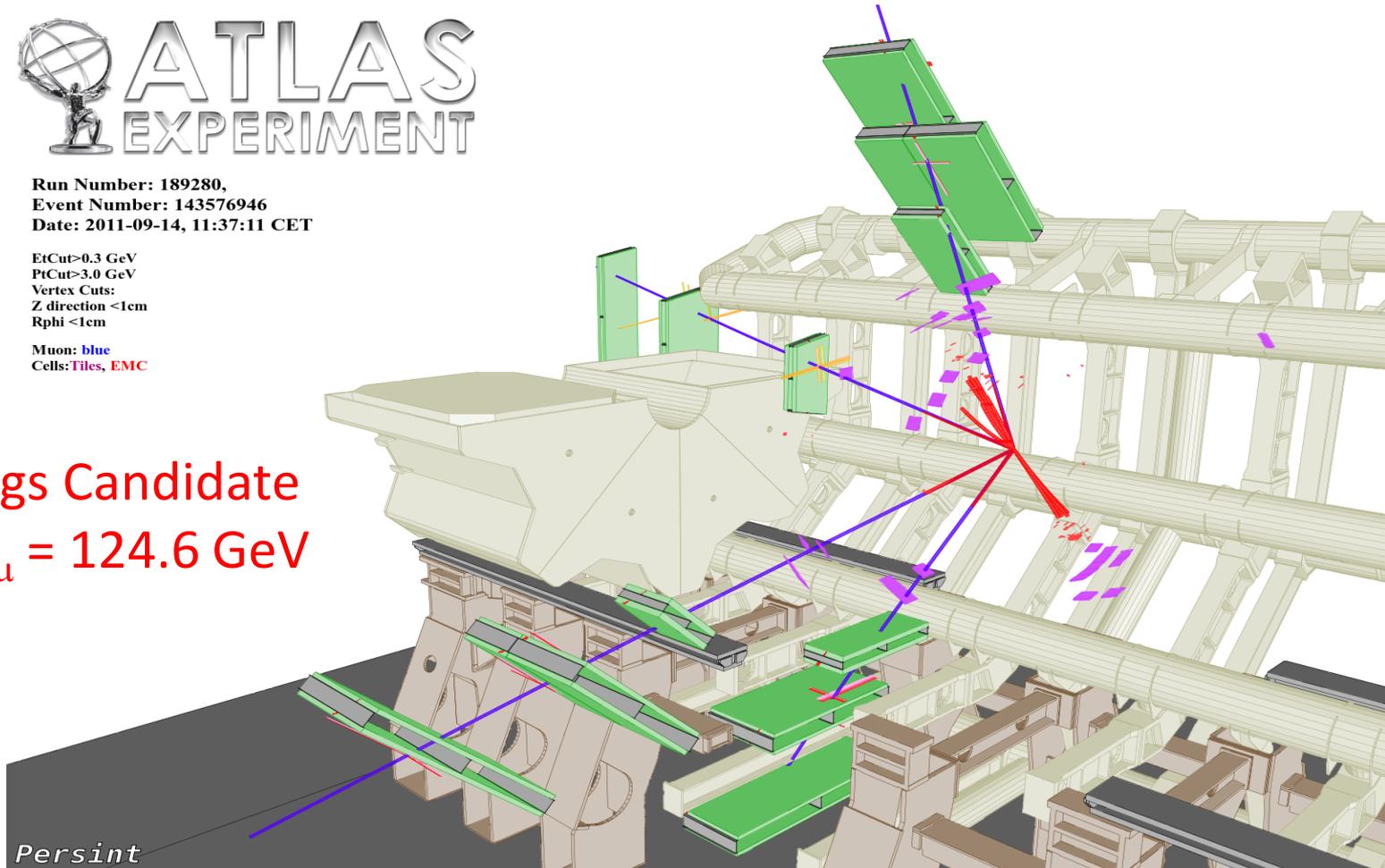


Run Number: 189280,
Event Number: 143576946
Date: 2011-09-14, 11:37:11 CET

EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm

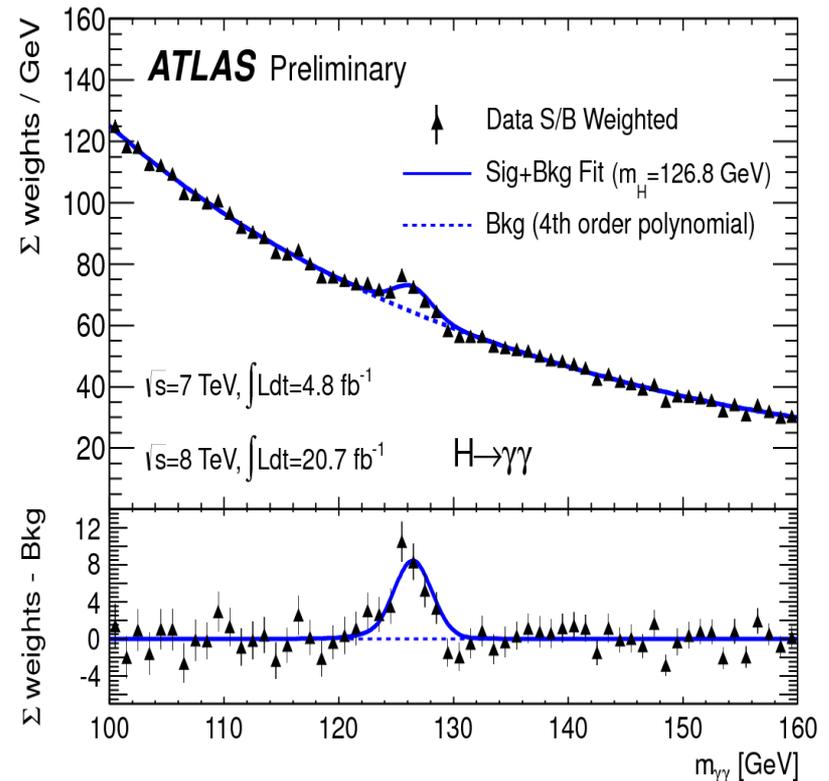
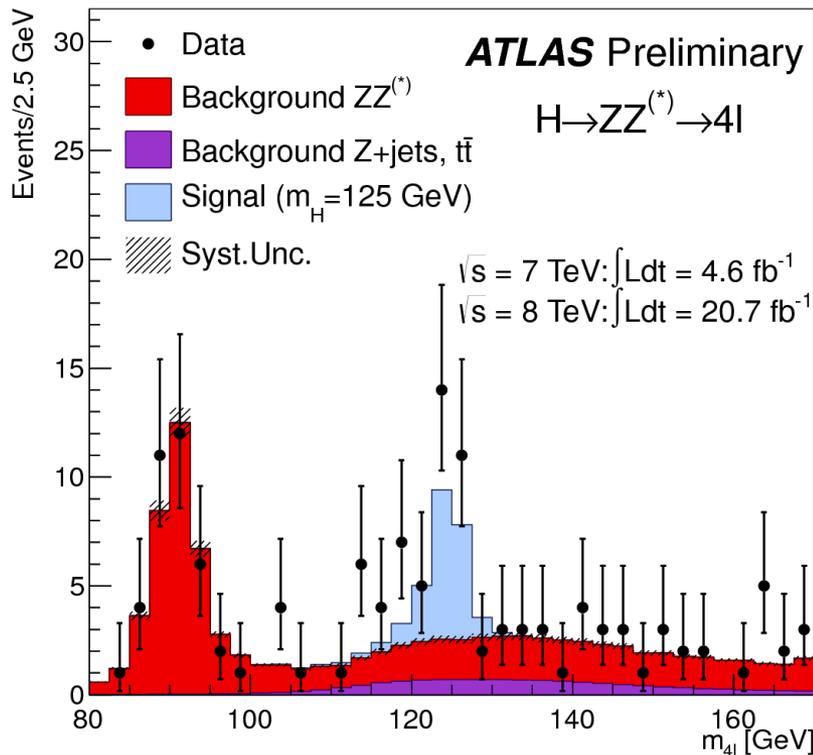
Muon: blue
Cells: Tiles, EMC

Higgs Candidate
 $M_{4\mu} = 124.6 \text{ GeV}$



Observation of Higgs Boson

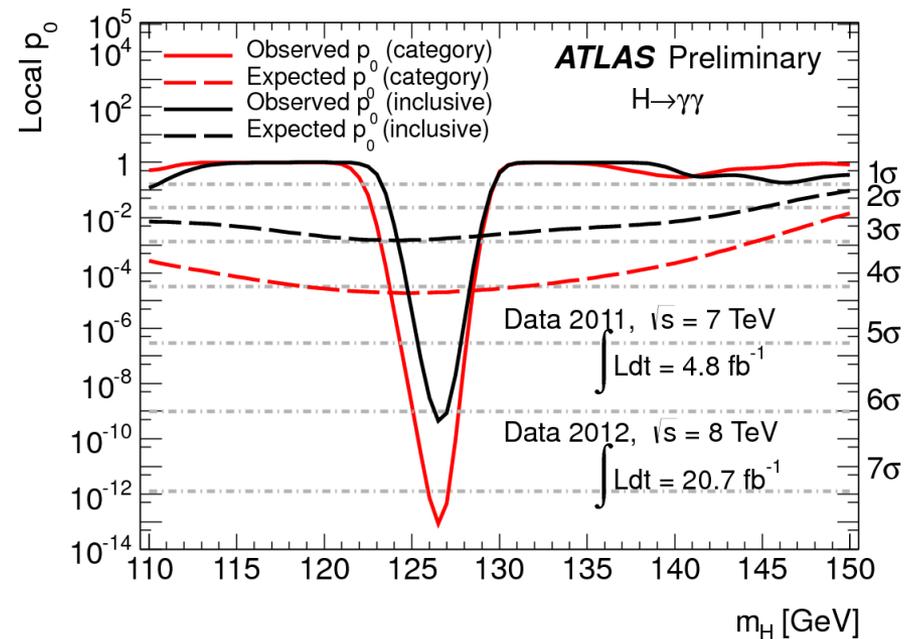
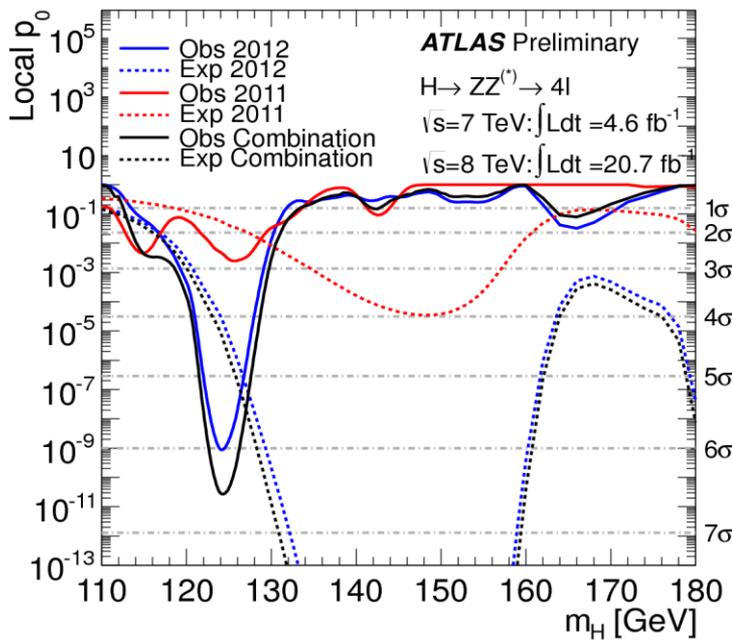
- A 'mass bump' at $M = 125$ GeV !
 - Particle is consistent with the SM Higgs – a neutral scalar



The Data

Dramatically incompatible with not existing
(6 to 7 σ)

- <http://www.atlas.ch/photos/plots.html>



The Standard Model - Again

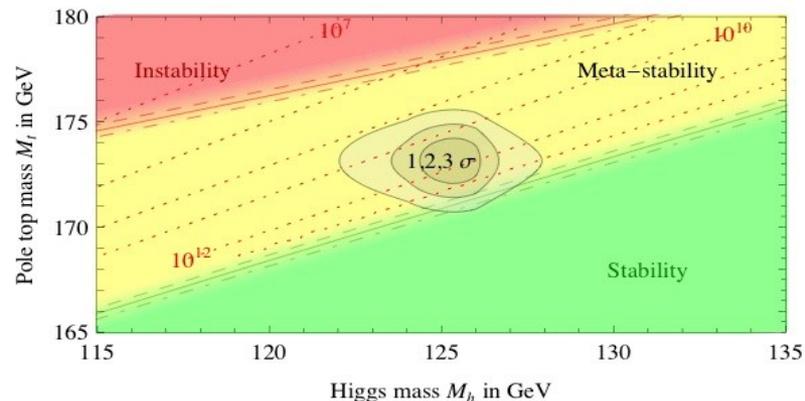
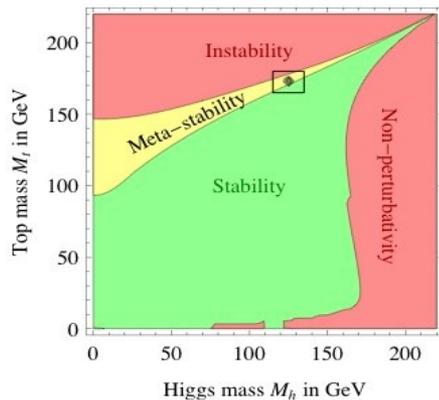
three generations of matter (fermions)				
	I	II	III	
mass→	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name→	u up	c charm	t top	γ photon
				≈ 126 GeV/c ² H Higgs boson
QUARKS	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
LEPTONS	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W W boson

The 'last' SM particle has now been observed at roughly the mass predicted by earlier experiments. The properties (spin and decay modes) are in agreement with expectation.

This is a major scientific triumph although anomalies are much more interesting. We don't know yet if this is really the complete picture.

Physicist's Vacuum

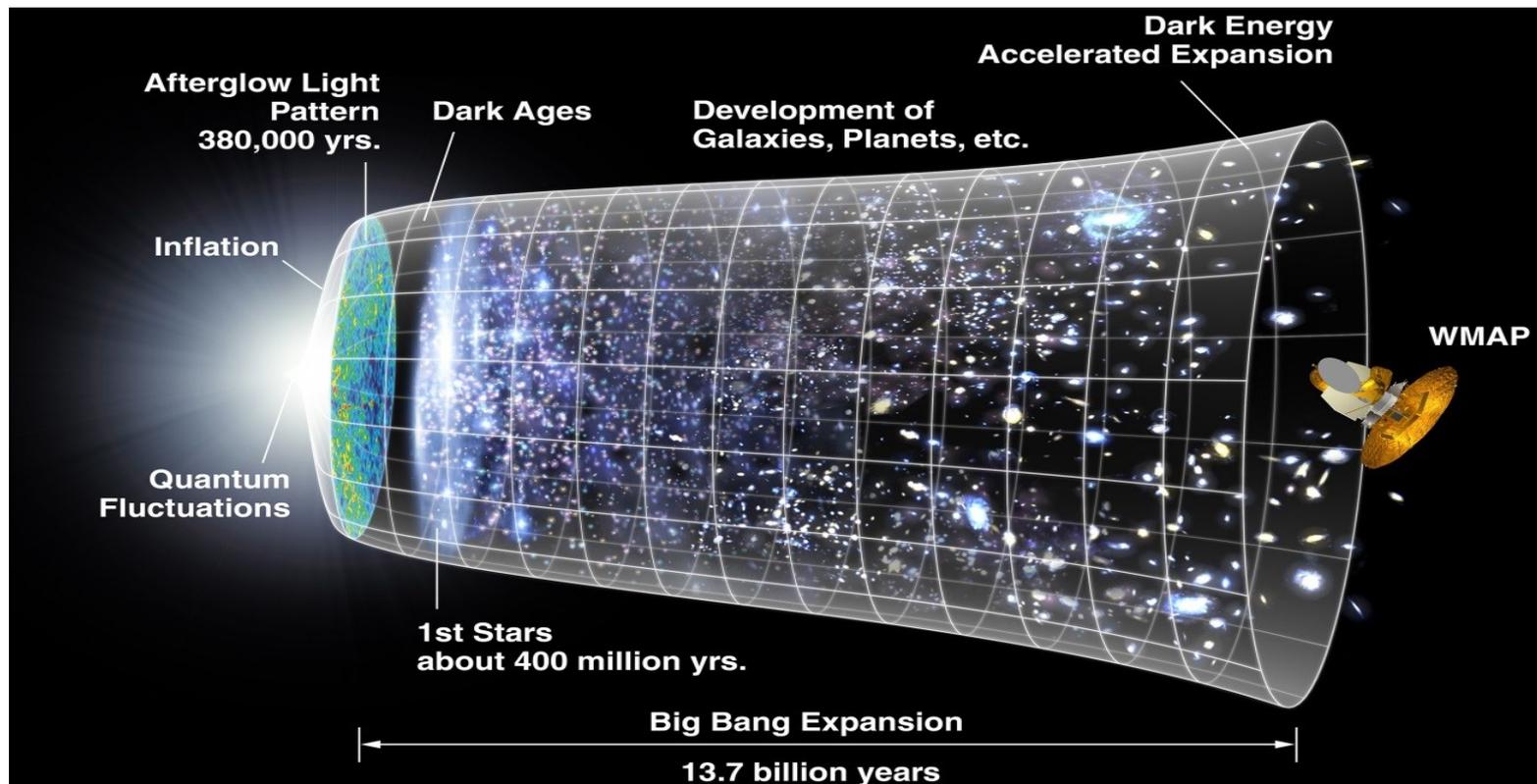
- Space (vacuum) is not empty – a sea of virtual particles
 - Remember Heisenberg's Uncertainty Principle)
 - The Higgs couples with other particles and with itself. The strength of these interactions should be finite up to extremely high energies (Planck scale)
 - Depending on the values of these couplings the vacuum could be unstable, stable or metastable



Vacuum seems to be metastable! Don't worry but this may be a hint for a deeper understanding

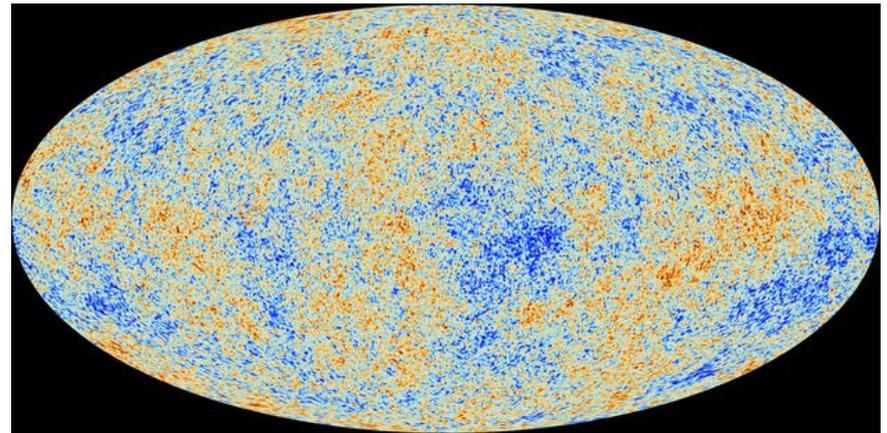
Cosmic Picture

- High energy physics has something to do with the very early age of the universe when the temperature was hot enough to make bosons and quarks in a kind of primordial 'soup'



Cosmic Connections

- WMAP and Planck Satellites measure the blackbody radiation from Big Bang
 - Composition of Universe
 - Baryonic matter 4.6 %
 - Neutrinos < 1% (3 species)
 - Cold Dark matter 24%
 - Dark Energy 71%
 - Age of Universe 13.8×10^9 years
 - Expansion (Hubble) constant $69 \text{ km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1}$
 - Geometry of Universe is Euclidean Flat and will expand forever

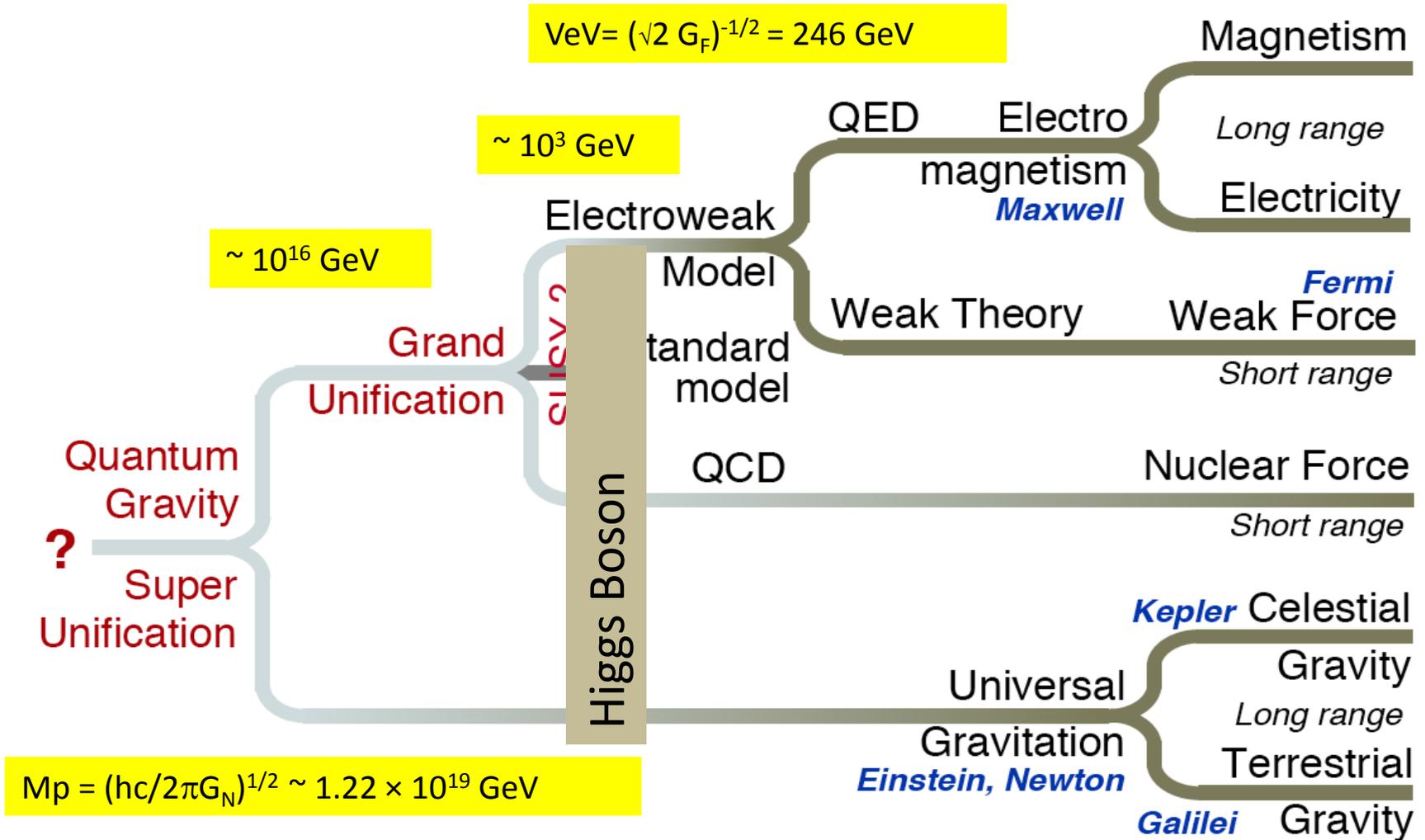


Standard Model of quarks etc. accounts for only 4.6% of Universe. What is the other stuff?

What's Next

- Data suggest that the Higgs Boson is consistent with the minimal standard model prediction
 - The significance of scientific research is measured not only by the quality of its results but also by the quality of the questions it raises
 - This result leads to a focus of questions that were being asked before the discovery
- What's next?
 - Both experiment & theory will march forward
 - There are 25 free parameters in the Standard Model
 - There are 120 free parameters in Supersymmetric Models
 - The LHC and experiments are being upgraded
 - The physics program is planned to continue until ~ 2030
 - And there are dreams of other accelerators

Unification of Forces



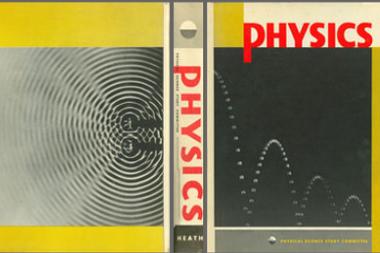
High School Physics – My Story

- PSSC Physics (1956) and Sputnik (1957)
 - My world was ‘analog’ (electronics, telescope, photography, doing experiments in basement, Scientific American Amateur Scientist ...)

MIT Institute Archives & Special Collections

Physical Science Study Committee, 1956

In 1956 a group of university physics professors and high school physics teachers, led by MIT's Jerrold Zacharias and Francis Friedman, formed the Physical Science Study Committee (PSSC) to consider ways of reforming the teaching of introductory courses in physics. Educators had come to realize that textbooks in physics did little to stimulate students' interest in the subject, failed to teach them to think like physicists, and afforded few opportunities for them to approach problems in the way that a physicist should. In 1957, after the Soviet Union successfully orbited *Sputnik*, fear spread in the United States that American schools lagged dangerously behind in science. As one response to the perceived Soviet threat the U.S. government increased National Science Foundation funding in support of PSSC objectives.



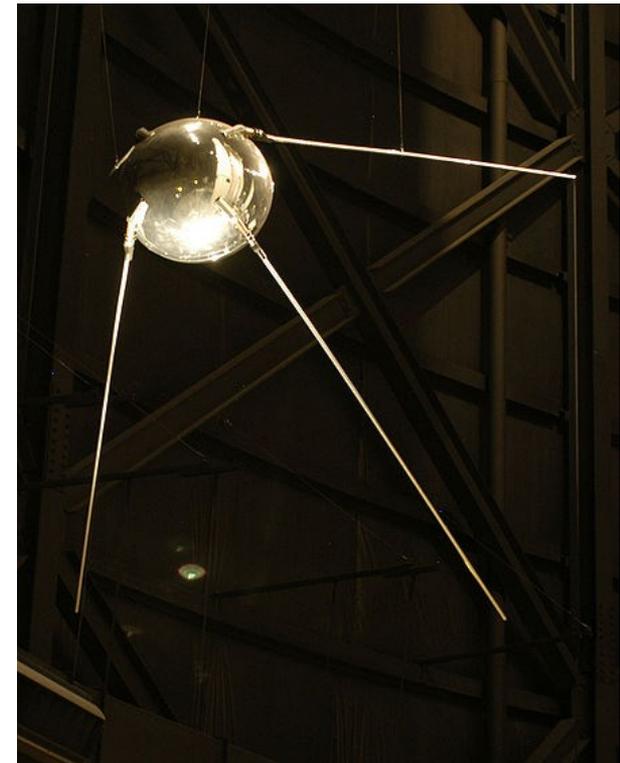
Teaching materials created by the PSSC were designed to emphasize fundamental principles in physics, encouraging engagement and understanding as opposed to memorization, making the subject more attractive to students. The first edition of the high school textbook *Physics* appeared in 1960, followed by many subsequent editions. Films, teacher guides, standardized tests, and recommendations for inexpensive experimental apparatus (especially designed by the PSSC) were available for use in conjunction with the book. The motion pictures illustrated phenomena that were too complex, or took too long, for practical demonstration in a classroom. [Sample pages](#) from the "PSSC Physics Teacher's Guide, Advanced Topics" describe some of the reasons behind innovative approaches to specific components of the course. The front cover of the textbook shows a multiple flash photograph of a bouncing ball by Berenice Abbott. "In our study of mechanics," the caption explains, "we shall study motions of bodies that range in size from enormous suns...to the minute particles in atoms...[and will] find a few basic ideas, such as momentum and energy, that clarify our understanding at any scale." The back cover photograph, also by Abbott, is of a ripple tank and it illustrates wave interference patterns.

Information about the Physical Science Study Committee can be found in the Physical Science Study Committee Oral History Collection (MC 602), the Jerrold Zacharias Papers (MC 31), the Educational Services Incorporated Records (MC 79), the Physical Science Study Committee Records (MC 626), and other sources available for research in the MIT Institute Archives and Special Collections reading room, 14N-118.

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[Sample pages from teacher's guide](#)

Object of the Month: September 2006; corrected June 2012



High School & High Energy Physics

- High Energy Physics as a discipline of study deals with both basic and arcane concepts
 - Some of these concepts are ideal subjects to teach science students
 - There are many outreach web sites for educators and students to get further information – such as
 - <http://atlas.ch/>
 - <http://cms.web.cern.ch/>
 - <http://home.web.cern.ch/>
 - <http://education.web.cern.ch/education/>
 - http://www.youtube.com/watch?v=tVF_iOgkAGM

Angels & Demons

June 24, 2013

F. E. Taylor - MIT

Dan Brown & Movie
with Tom Hanks

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