



The Frontier of High Energy Physics and the Large Hadron Collider

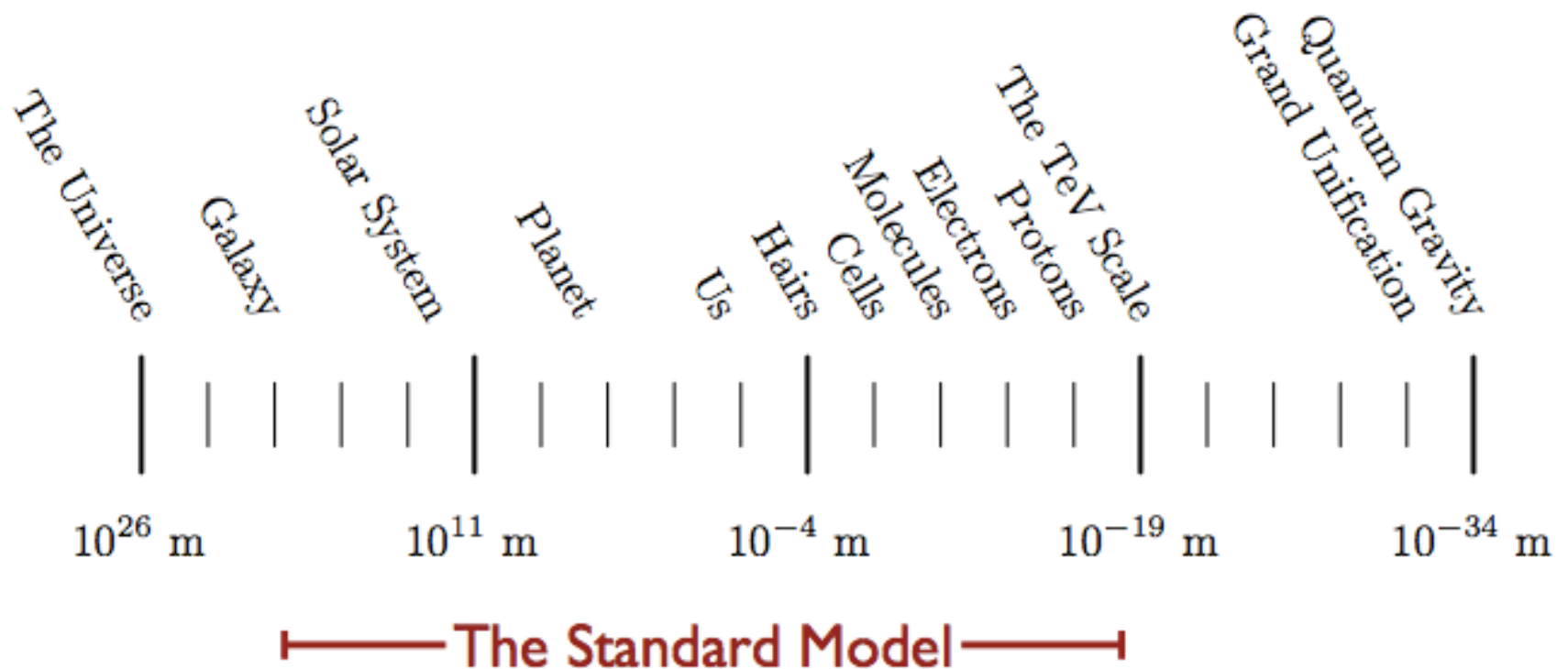
Kalanand Mishra, **Fermilab**



PIPS-2013, Universitas Padjadjaran, May 8, 2013

Outline

- Particle Physics and the Standard Model
- The Large Hadron Collider and its detectors
- The search for the Higgs boson
- Practical applications, conclusion, and outlook

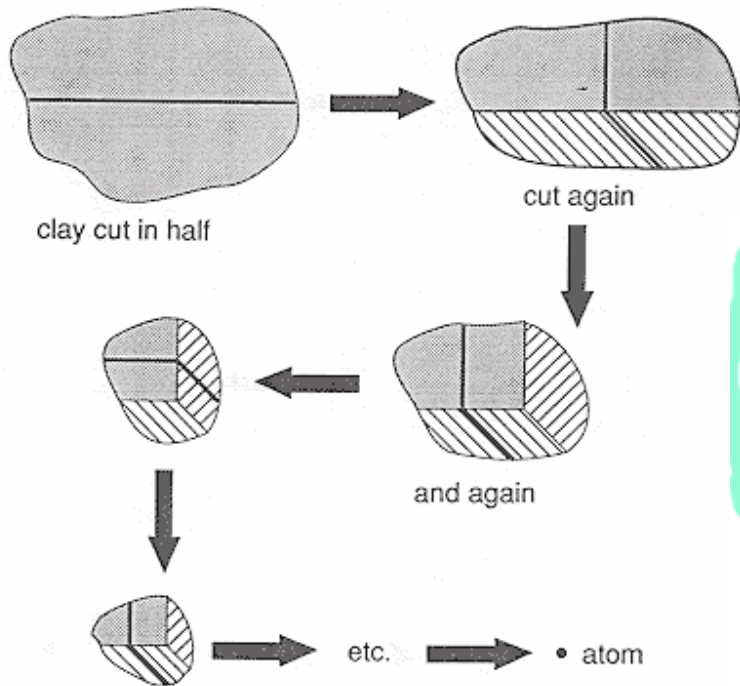


What is the Universe Made of?

Early speculation on the building blocks, 500 BC



Around 300 BC:



Hmmm ... I wonder if I could keep cutting this in half forever?
...Probably not, before long it would be too small to see. It would become invisible... Ah Ha! Invisible, indivisible..

The "Atom"

eureka !!!

Democritus' concept of the atom



Next Breakthrough Came After Two Millennia

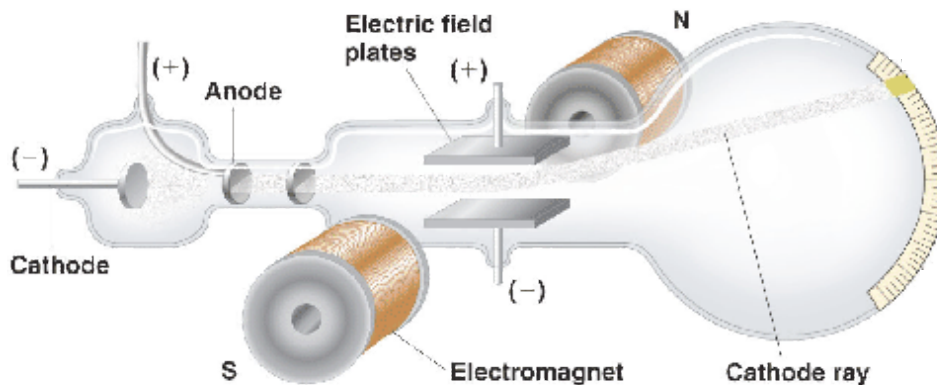
Periodic Table

Helium **Neon**

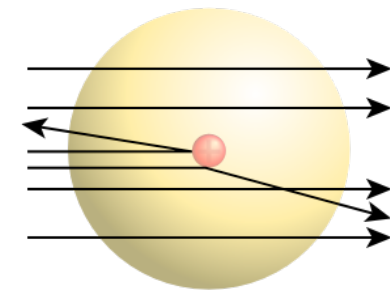
All atoms are made of protons, neutrons and electrons

**Atoms and
Simplicity
1869**

Discovery of electron – Thompson 1897



Nuclei – Rutherford 1908



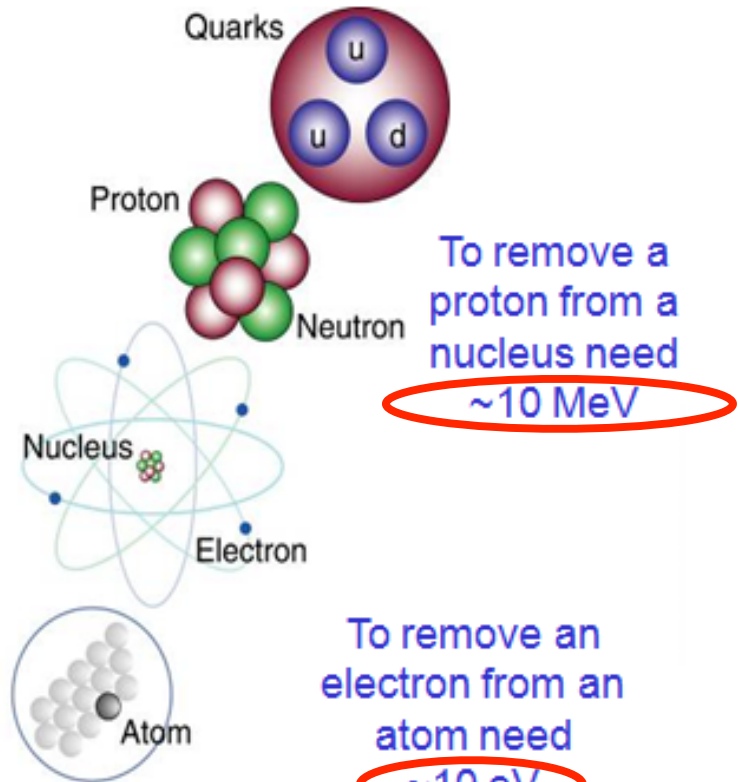
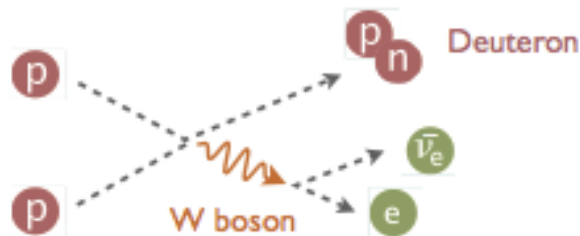
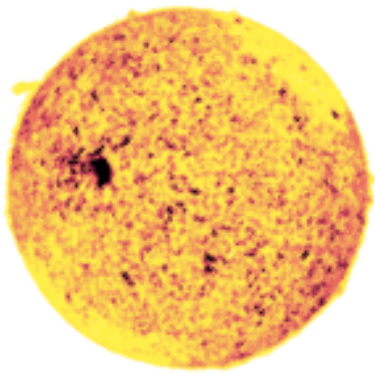
Next Step: Going Smaller and Simpler



Nuclei are made up of quarks. Quarks are fundamental ! ?

At these distances → Weak Force

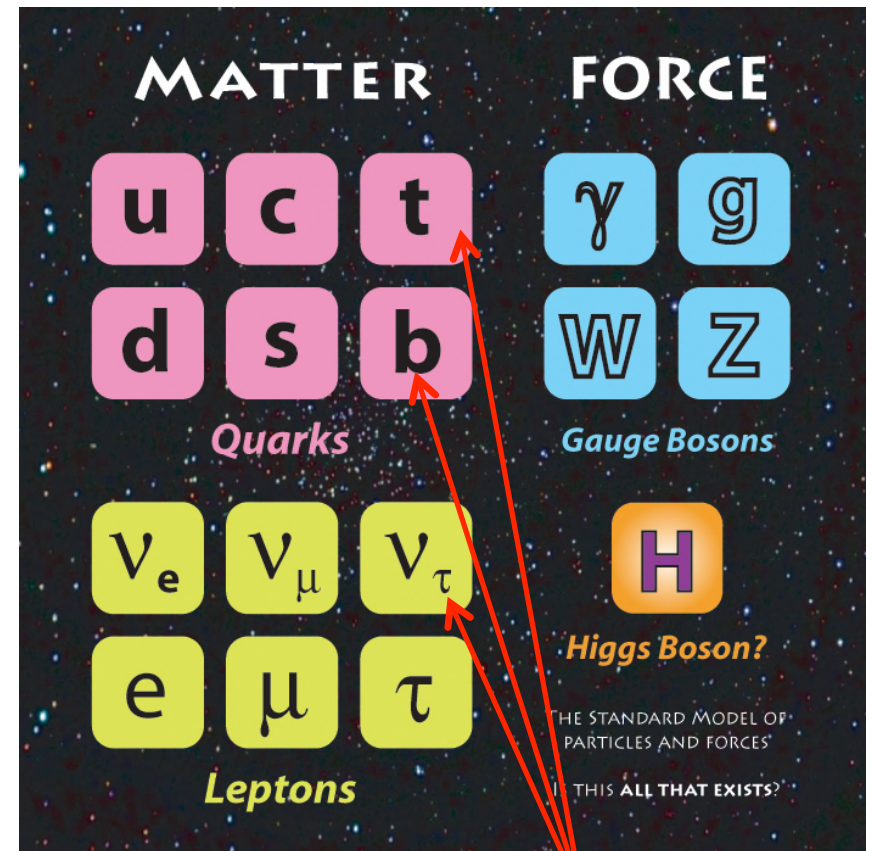
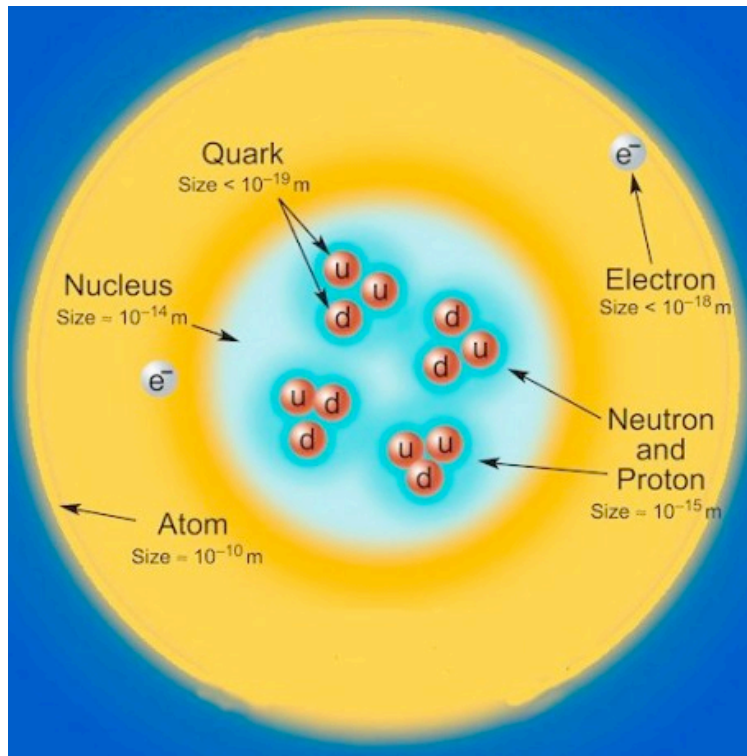
Essential for Stellar Burning



“Standard Model”: the most precise theory there is!

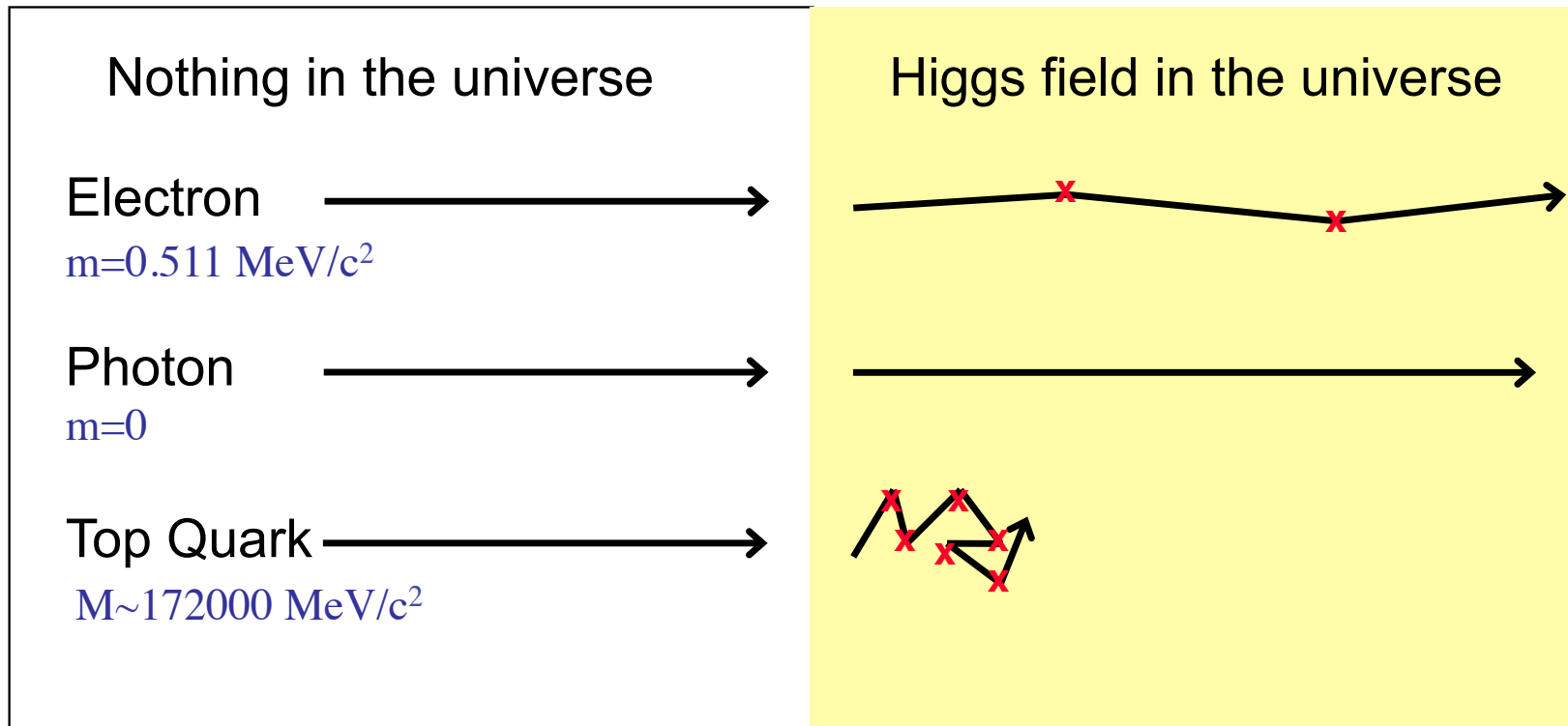


Tested in many experiments since 1960s



Discovered at Fermilab

Why Do Particles Have Mass?



Higgs field

- is present everywhere
- slows heavy particles down
 \Leftrightarrow gives them mass

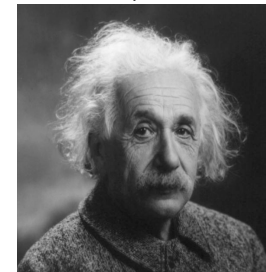
Quanta of Higgs field
= Higgs boson
= "The God Particle"

Why Need High Energy Particle Accelerators ?

High energies allow us:

- ☑ To look deeper into Nature (Energy $\propto 1/\text{size}$), (“powerful microscopes”)

To discover new particles with high(er) mass ($E = mc^2$)



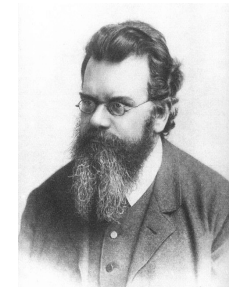
Einstein



de Broglie

- ☑ To study the early universe ($E = kT$)

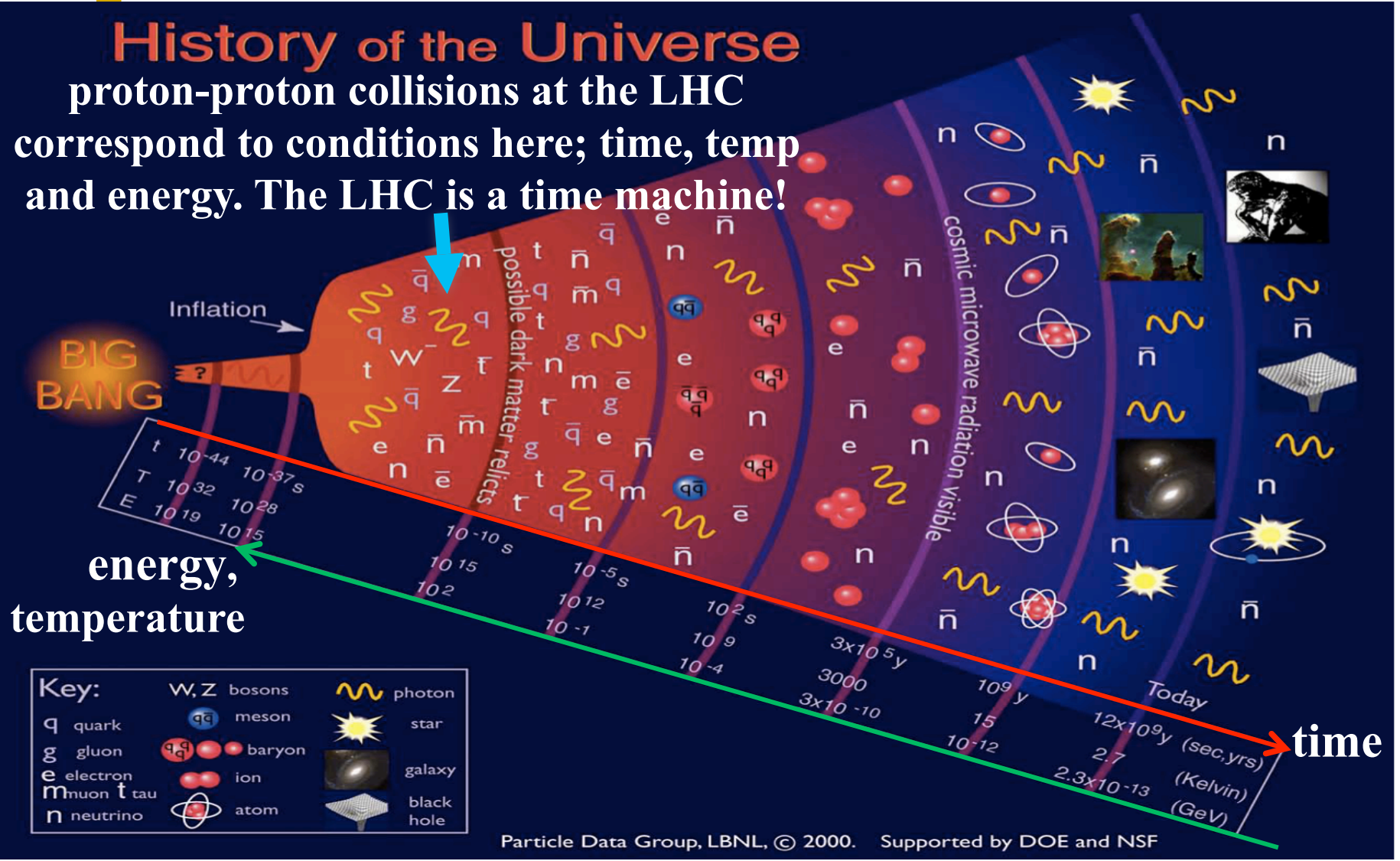
Revisit the earlier, hotter, history of our universe, searching for a new simplicity (“powerful telescopes”) by observing phenomena and particles no longer observable in our everyday experience.



Boltzmann

The History of Our Universe

History of the Universe
 proton-proton collisions at the LHC
 correspond to conditions here; time, temp
 and energy. The LHC is a time machine!



The Large Hadron Collider



LHC: the biggest, baddest atom smasher



Accelerates protons to 99.9998% of the speed of light. Smashes them 20 million times a second.

Fun Facts

- Beams store 400 MJ
→ beam dump (60 μm) creates 10 TW power
1/3rd of the entire world's instantaneous power
- The combined strands of the superconducting cable can go around the equator 6.8 times.

Lots more fun facts at:

<http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/lhc-interesting-facts.htm>

The LHC is a Big Step in Mass

- 4.5 km radius, 27 km circumference (Tevatron at Fermilab: 1 km, 6.3 km)
- operational: 2009-25?? (Tevatron: 1985-2011)
- E_{beam} : 4+4 TeV proton-proton [goal 7+7 TeV] (Tevatron: 1+1 TeV proton-anti-proton)



The gain in “mass reach” is not just the factor of 4 in proton energy. At the interesting TeV mass scale the reaction rate is a factor 10000 x greater.

World's Largest Cryogenic Plant

IT'S COLD!

16 miles of magnets and connections are kept colder than outer space, using over 100 tons of liquid helium.

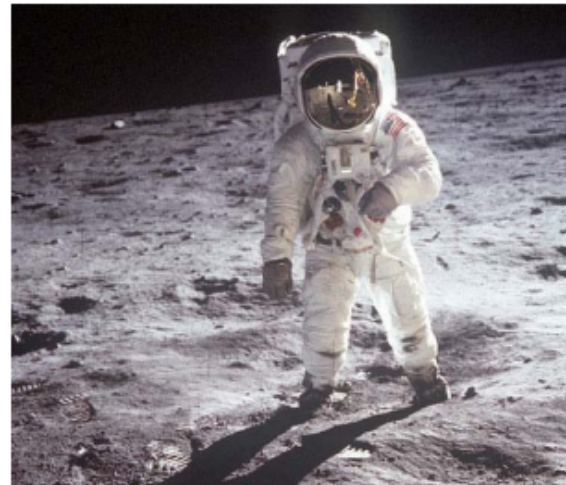
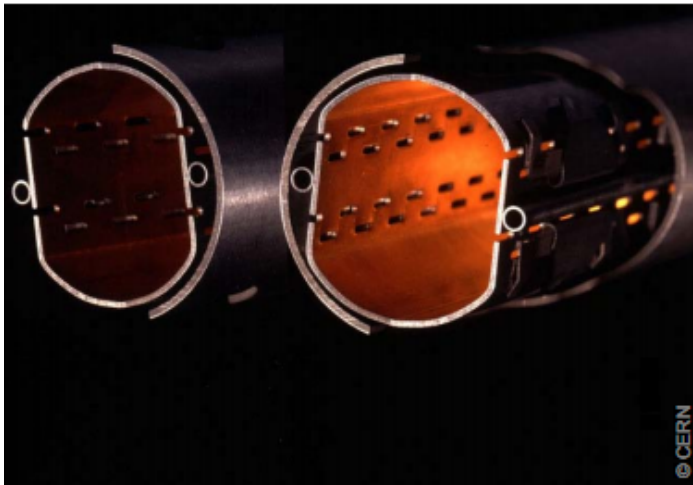


Deep space is at 2.3° above absolute zero. LHC operates at 1.8° to achieve a higher magnetic field. If normal magnets used, size would be 4x and power used would be 40x!

Extremely High Vacuum

IT'S EMPTY!

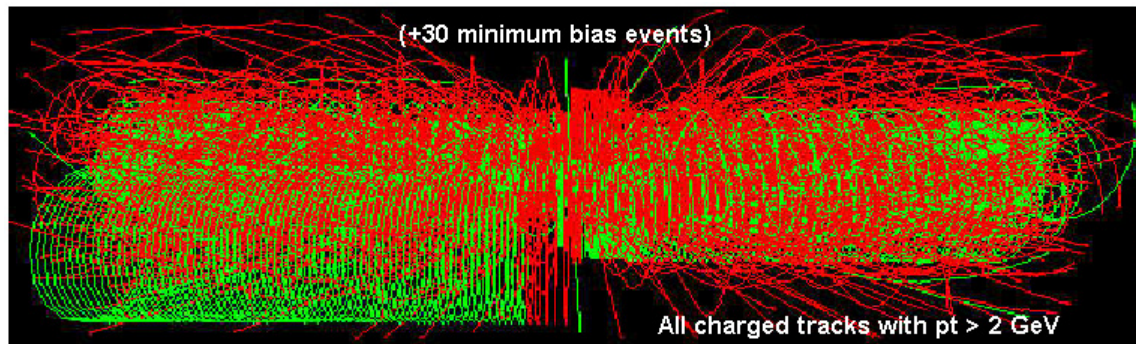
Air pressure inside the two 16-mile-long vacuum pipes is lower than on the moon.



**“Store” beams for 10 hours. Protons travel ~ 10 billion km around the LHC ring \approx round trip to Pluto !!!
 \Rightarrow need a good vacuum**

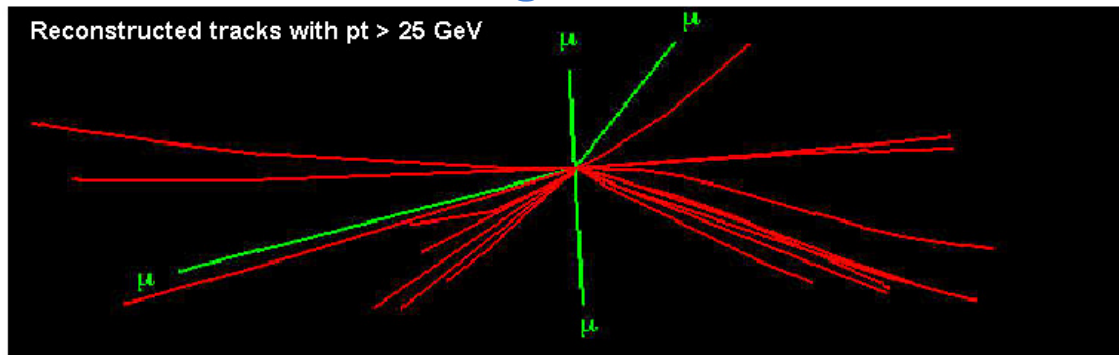
More Challenging than Needle in a Haystack ...

Starting from this event...



- 1 billion (10^9) interactions per second, 10^8 electronic channels
- 0.0002 Higgs / second

We look for this “signature”



Selectivity: 1 in 10^{13} : Like looking for 1 person in 1000 world populations



Or in layman's terms

Looking for evidence at the scene !!!

How to pick out of a crowd?
What are the backgrounds?



Ideal world

vs.



at LHC

Bring The Action All Eyes on Us

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NEWS

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Wednesday, 6 September, 2000, 22:46 GM

Scientists close in on elusive particle



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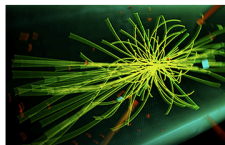
'God Particle' Found? Search for the Higgs Boson Narrows

By MICHAEL D. LEMONICK Tuesday, Dec. 13, 2011

Related



Photos: Inside the Large Hadron Collider



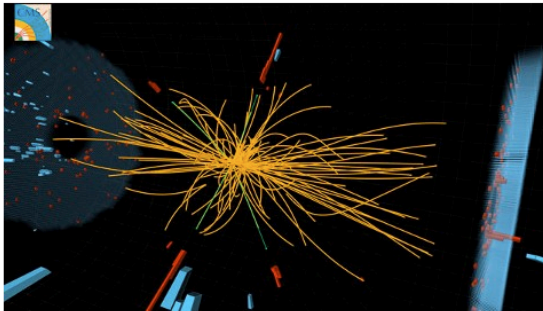
A graphic shows traces of collisions of particles at the Compact Muon Solenoid (CMS) experiment at the University of Physics exhibition of the European Organization for Nuclear Research (CERN) in Geneva on Dec. 13, 2011. Fabrice Coffini / AFP / Getty Images

Daily E-mail

Dec 13, 2011 9:57am

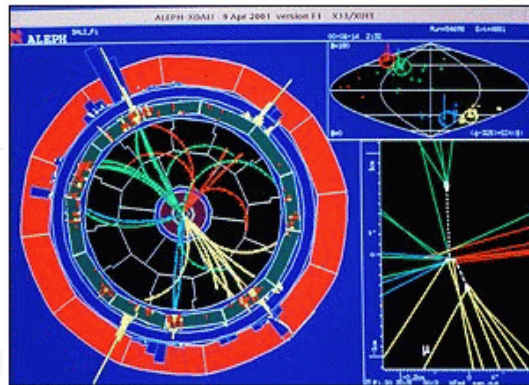
The 'God Particle': 'Tantalising Hints' of Higgs Boson Seen by CERN Physicists

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Computer readout from the search for the Higgs boson, sometimes called the "God particle." Thomas McCauley and Lucas Taylor/CMS/CERN

'God particle may not exist'



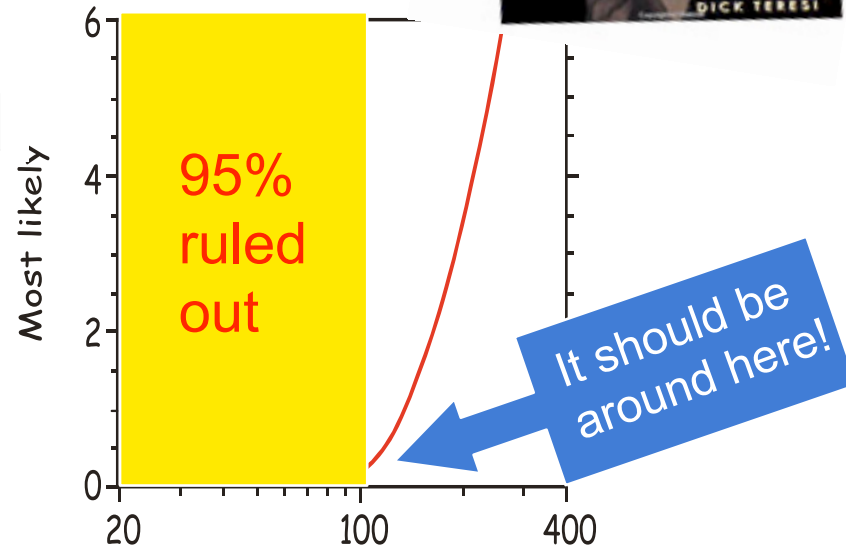
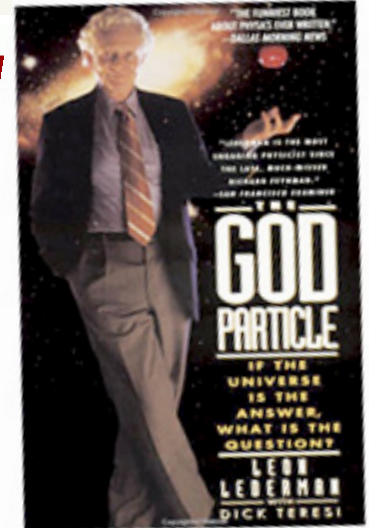
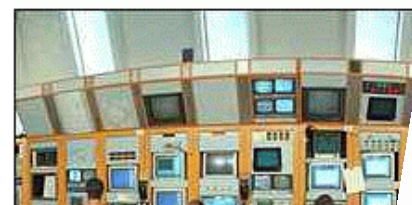
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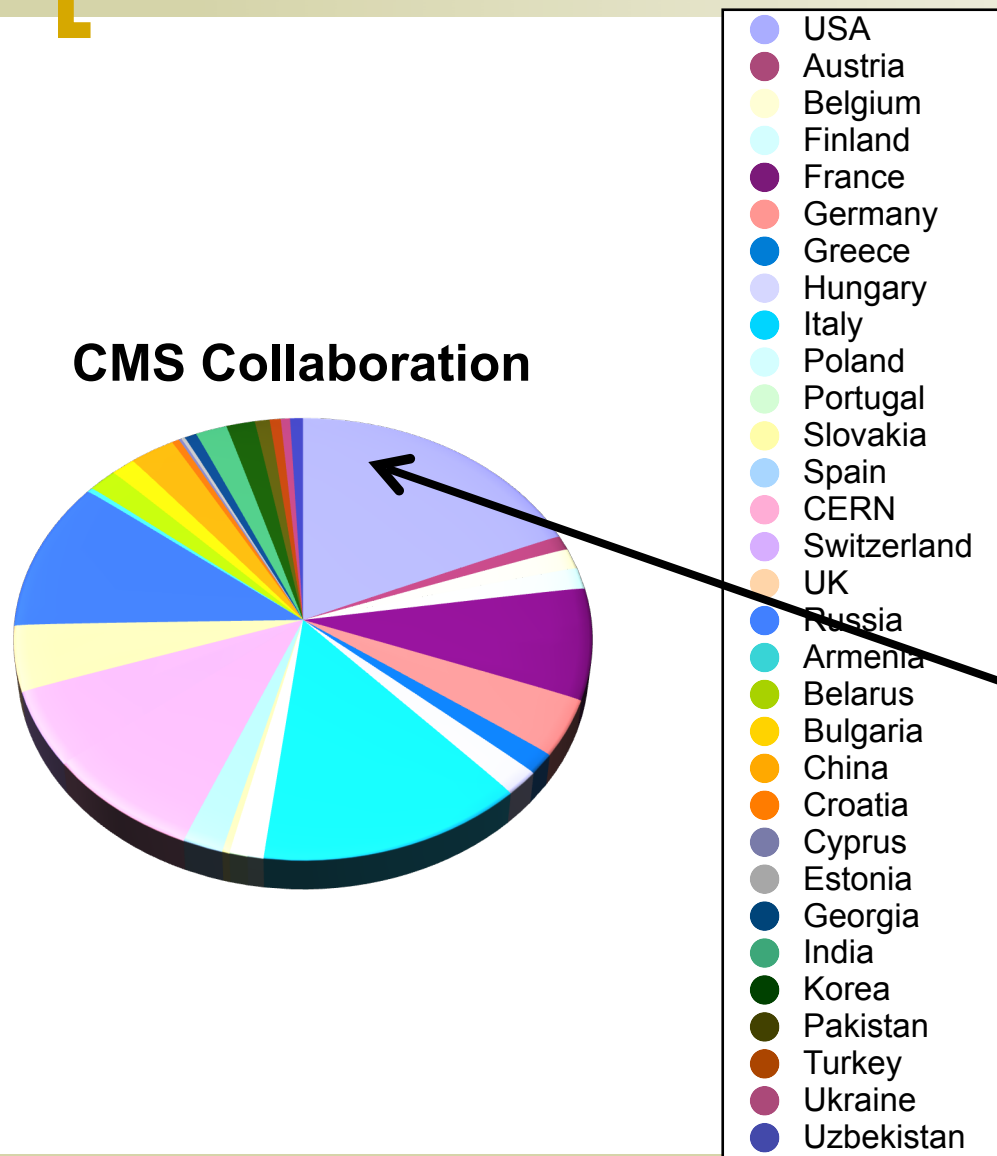
Monday, 9 April, 2001, 12:39 GMT 13:39

US team steps up search for elusive particle



Where is Higgs? Does it even exist?

The CMS Collaboration



It takes a collaboration of this size to fully address the physics of this magnitude.

The US is the largest national group in CMS – about 1/3. FNAL is the largest group in CMS and is also the host for US CMS.

The biggest & most sophisticated particle detectors

Cathedrals of science, 100 m underground !!!

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

SILICON TRACKER
Pixels (100 x 150 μm^2)
~1m² ~66M channels
Microstrips (80-180 μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

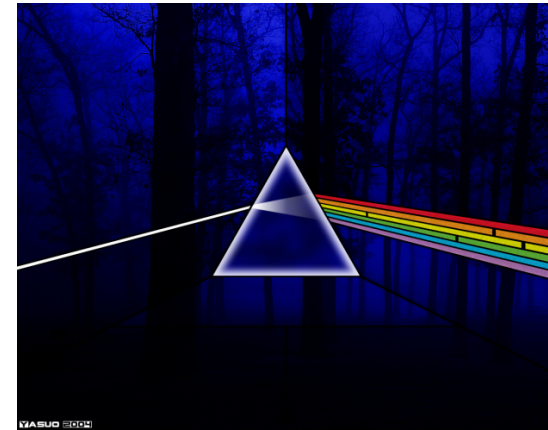
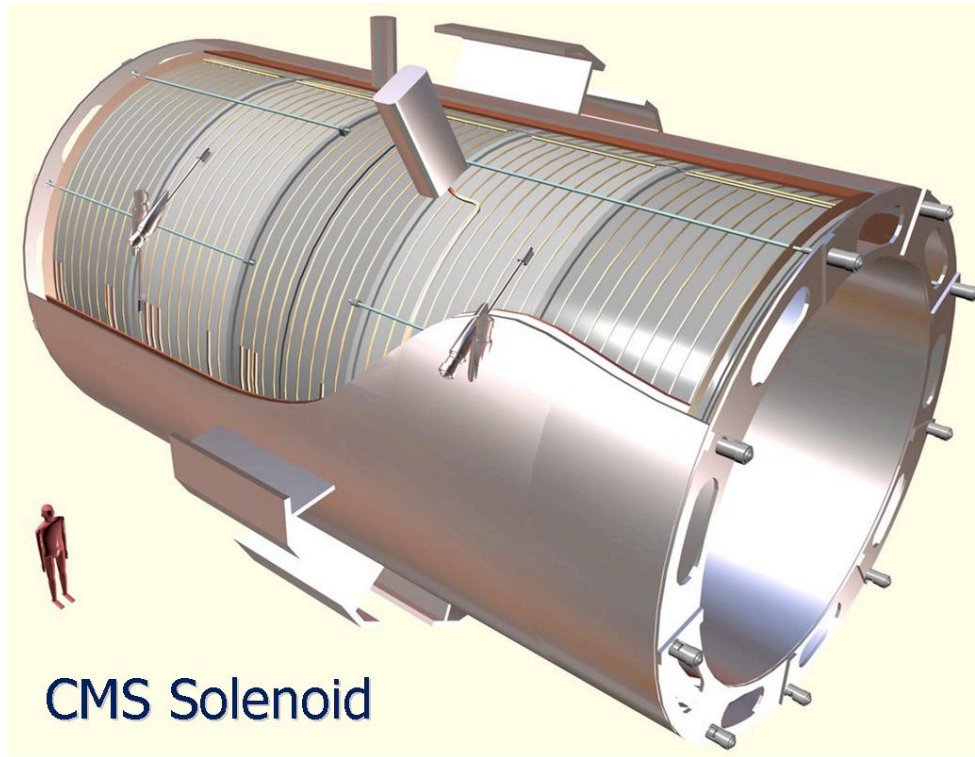
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

30% Heavier Than The Eiffel Tower



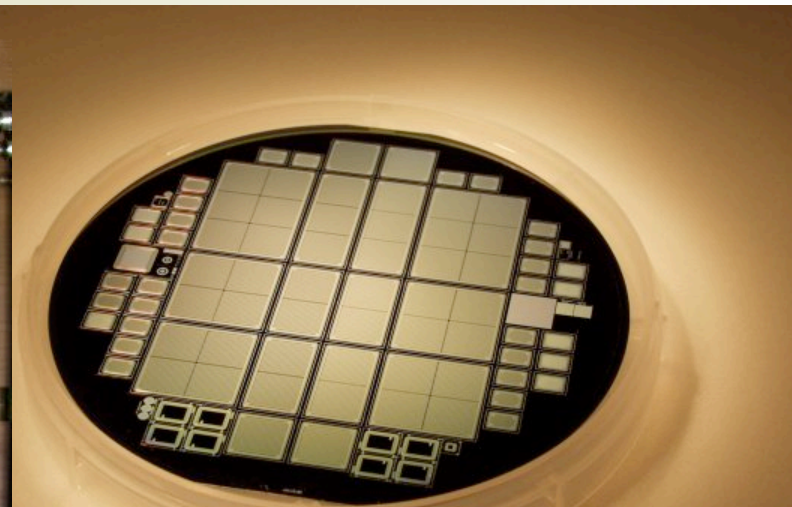
CMS Magnet: World's Largest Solenoid



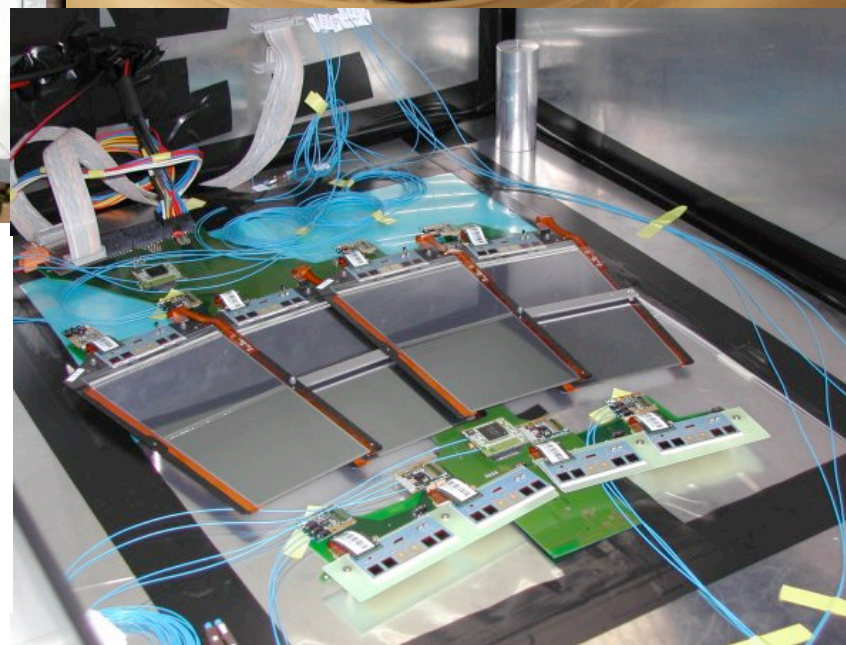
The magnet is like a prism – bending the particles with more energy by less.

The most expensive single device in CMS. 4 Tesla magnetic field.

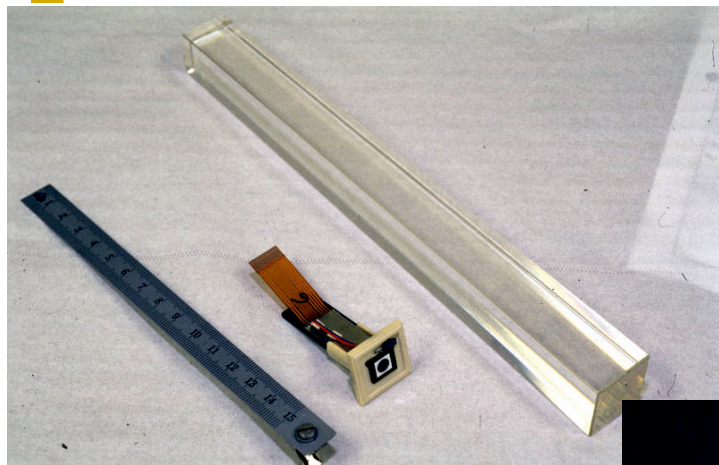
Precision Tracking



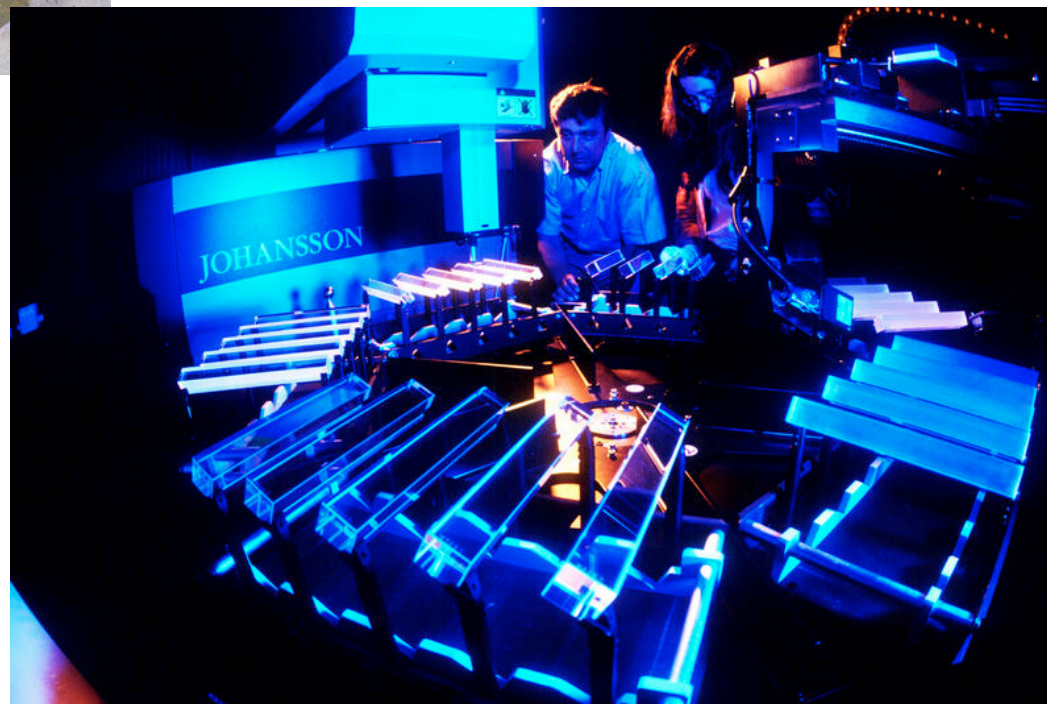
200 m² of Si with 75 million channels. A factor > 10 increase in complexity w.r.t. previous experiments. Spatial resolution of 8 μm precisely determines particle trajectories in the magnet and therefore energies.



Crystals – Energy Measurements



More than 60,000 crystals manufactured with $<1\%$ tolerances in response. Needed for precise, redundant measurement of electron energies.

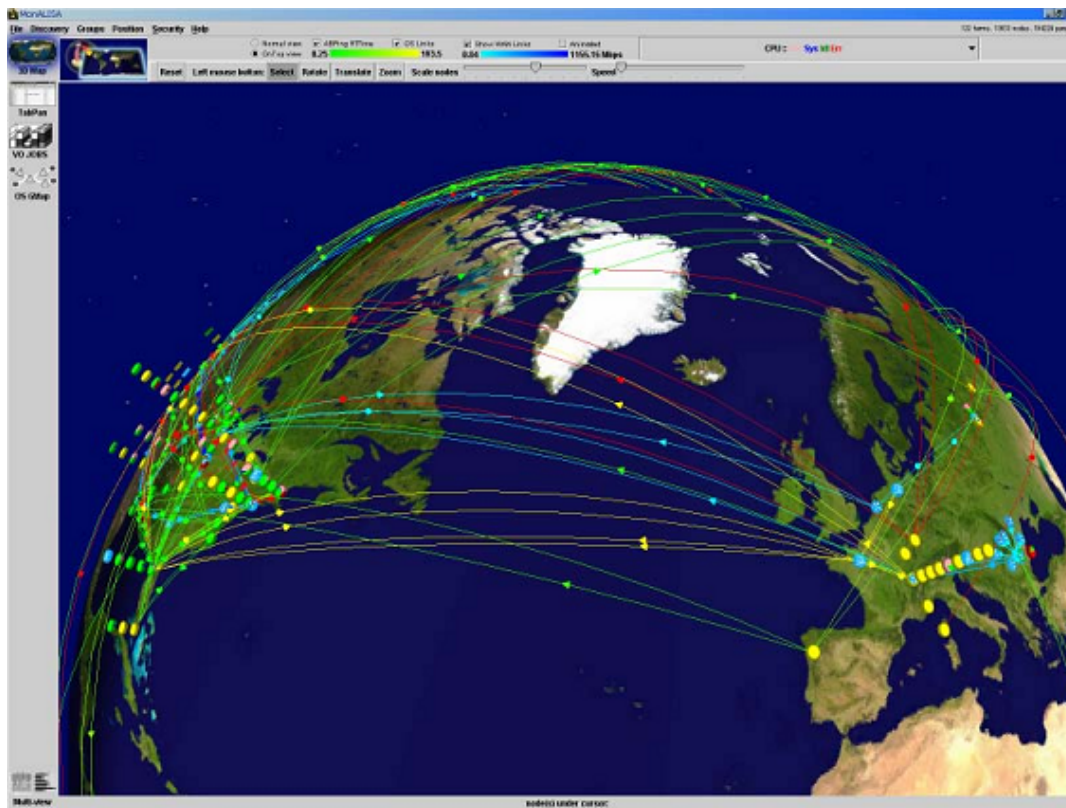


The most extensive scientific computing grid

15 petabytes (15 millions of GB) of data every year

100,000 processors at **200** computer centers in

34 countries connected with ultra-high speed data transfers



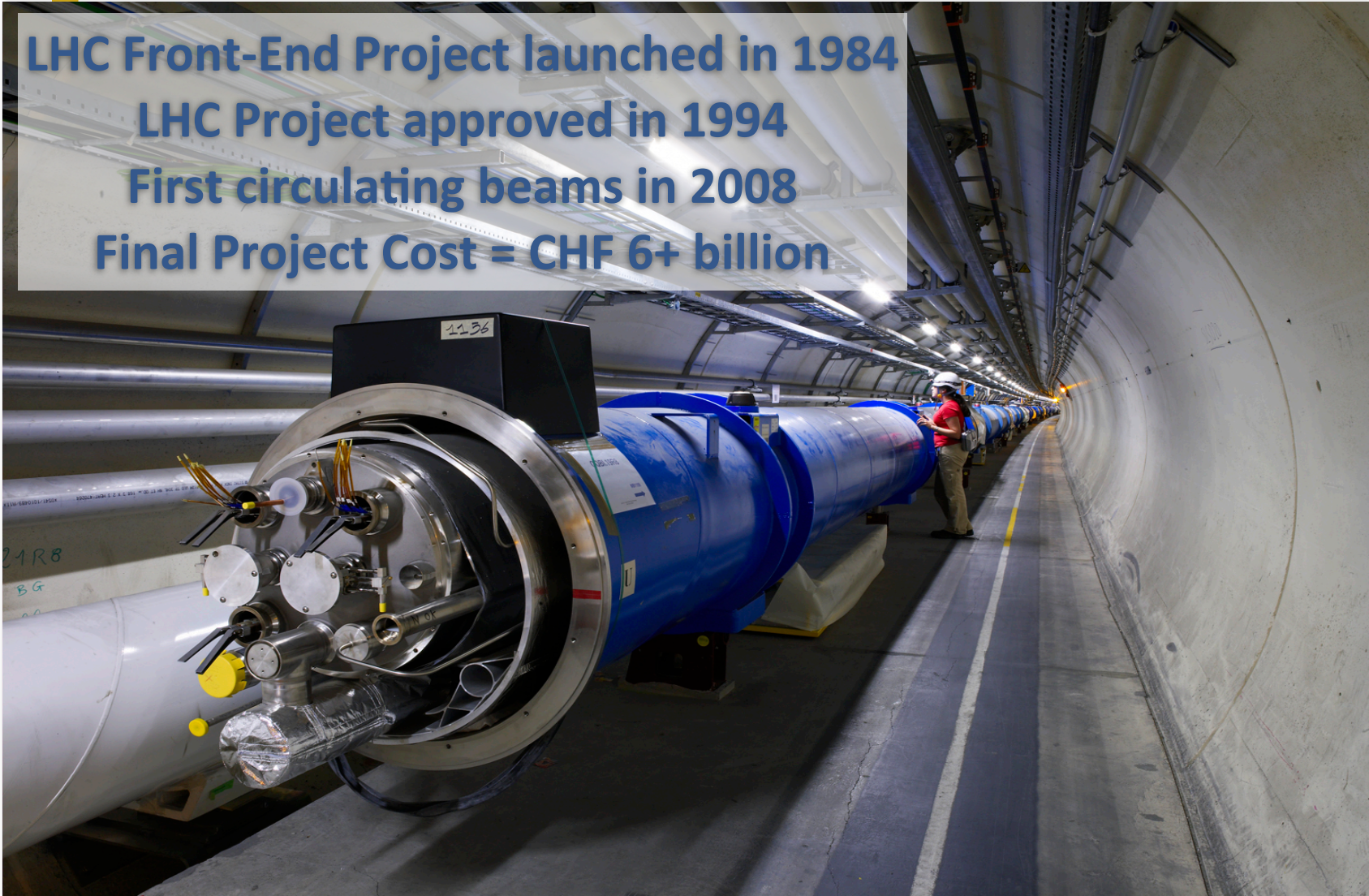
Fermilab operates the national grid for US

CMS produces 1 million DVD of data per year



Long preparation for a long voyage

LHC Front-End Project launched in 1984
LHC Project approved in 1994
First circulating beams in 2008
Final Project Cost = CHF 6+ billion

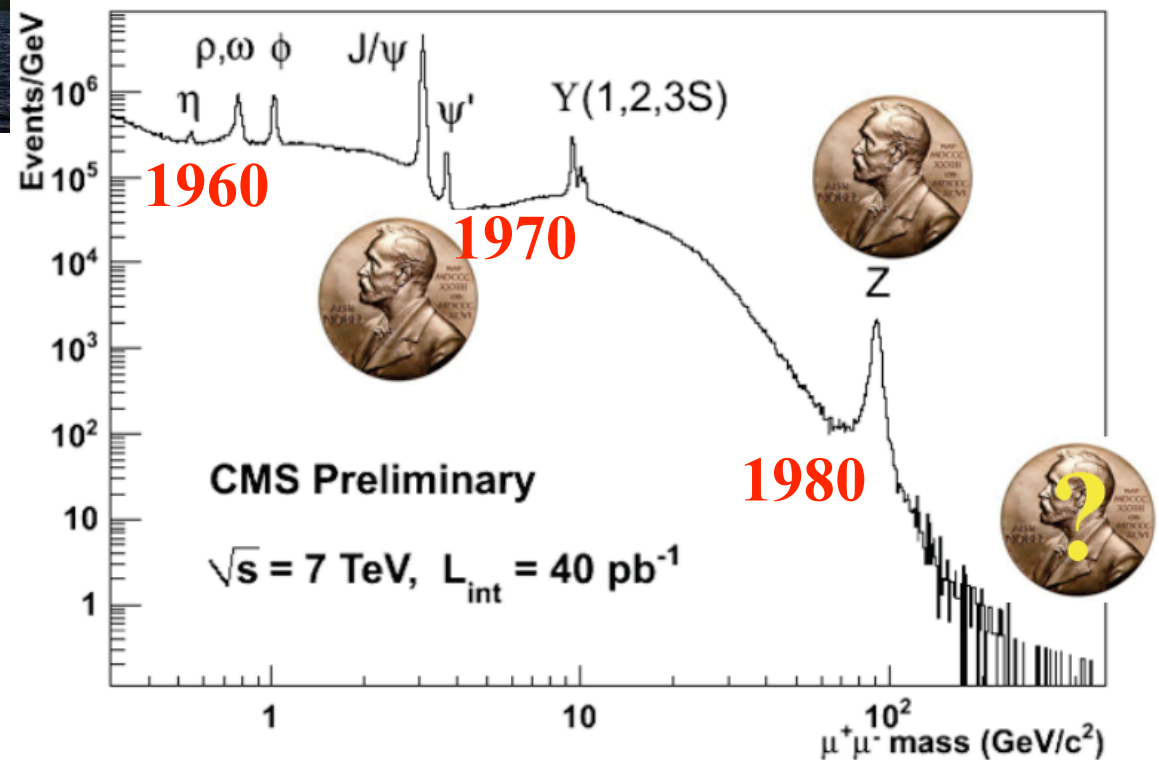


Start of the Voyage: "The Shallows"



In 2010, we measured all the particles of the Standard Model

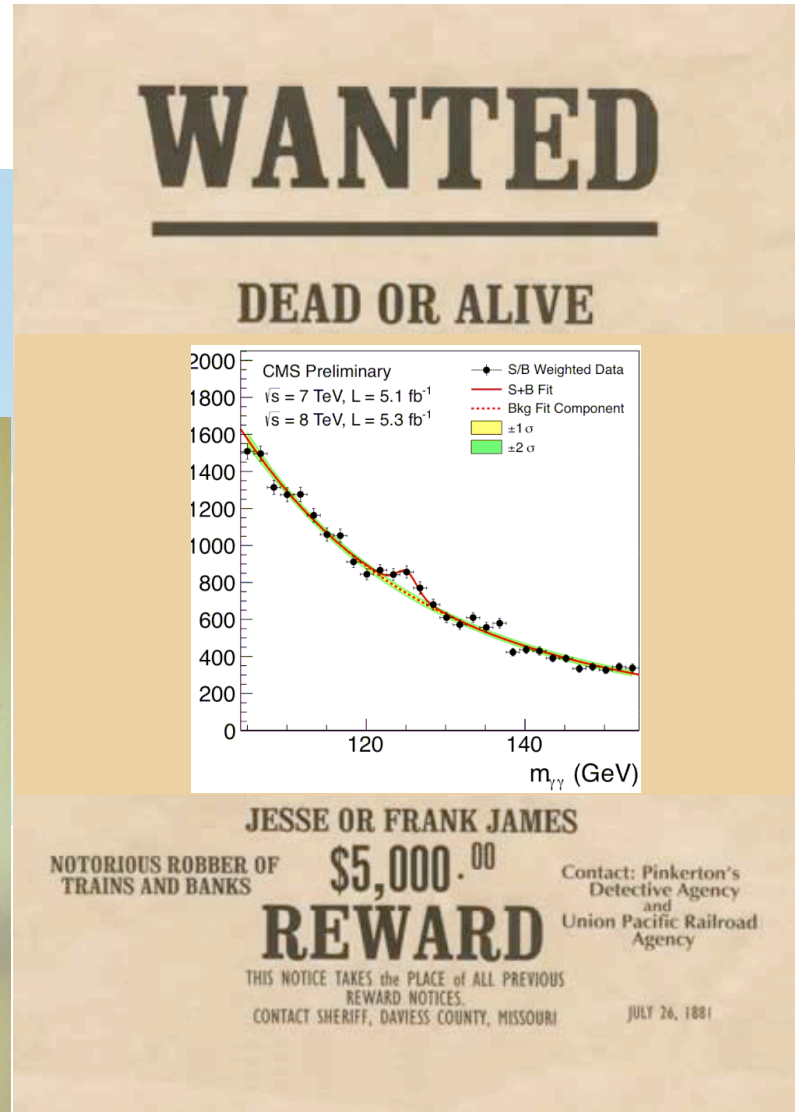
Some shown here



Into "Deep Waters"

Once past the "shallows" and on into the deeps, we set our sights on Higgs....

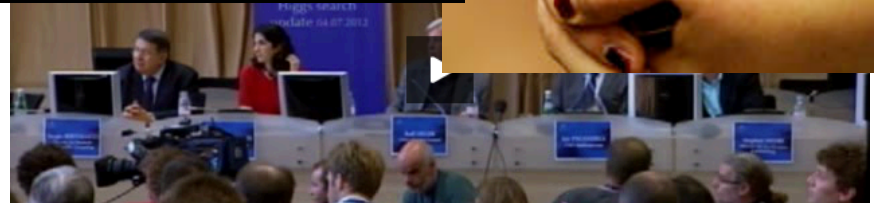
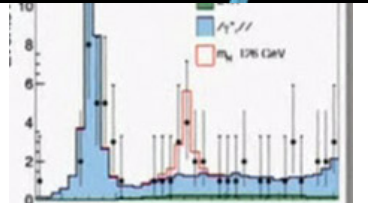
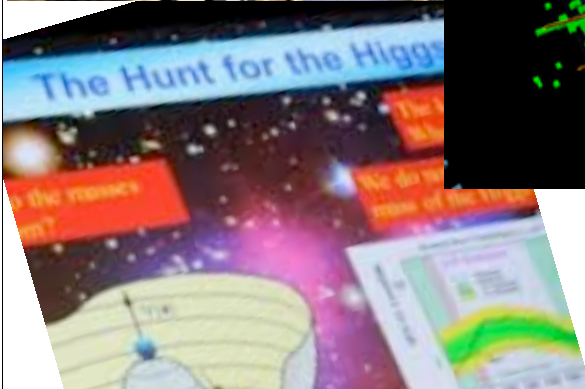
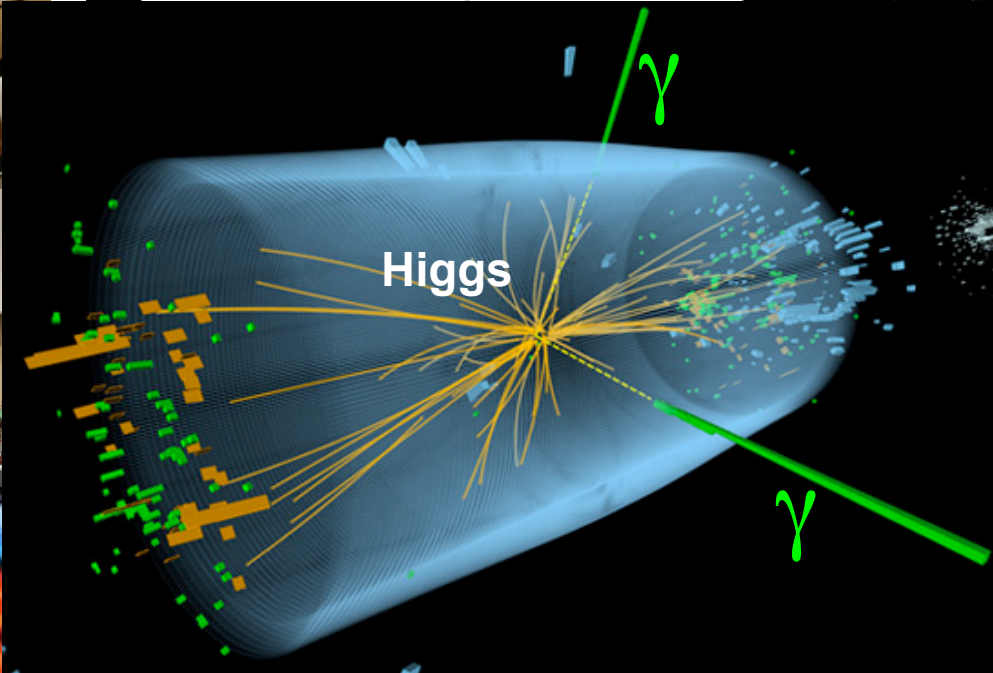
\$10 MILLION CHALLENGE



Wait over: Higgs Boson Discovered, 4th July 2012



In summary
We have observed a new boson with a mass of $125.3 \pm 0.6 \text{ GeV}$



Media Was There !

PAGE TODAY PAPER VIDEO MOST POPULAR U.S. Edition

Le Monde.fr
Le boson de Higgs découvert
99,999 % de certitude

The New York Times
Wednesday, July 4, 2012 Last Update: 4:00 AM ET

physicsworld.com
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Jul 4, 2012 37 comments
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THE WALL STREET JOURNAL.
EUROPE EDITION Wednesday, July 4, 2012 As of 7:22 PM EDT
ENVIRONMENT & SCIENCE July 4, 2012, 7:22 p.m. ET
Discovery May Help Tell Universe's Secrets
After Half-Century Search, Scientists Pin Down Higgs-Like Particle, Closing In on Explanation for Why All Objects Exist

The Washington Post
Scientists' search for Higgs boson yields subatomic particle

CNN

The Jakarta Post
Physicists say they have four boson

The Telegraph
New Particle Could Be Physics
By DENNIS OVERBYE 4 minutes ago
Higgs boson: scientists 99.999% sure 'God Particle' has been found

BBC
Higgs boson-like particle discovered claimed at LHC
COMMENTS (1665)
By Paul Rincon
Science editor, BBC News website, Geneva

HALLADA "la más sólida evidencia" de la existencia del bosón de Higgs

We have observed a new BOSON!
level 5 sigma • 04.07.2012

HIGGS BOSON

The HIGGS BOSON is the theoretical particle of the Higgs mechanism, which physicists believe

symmetry

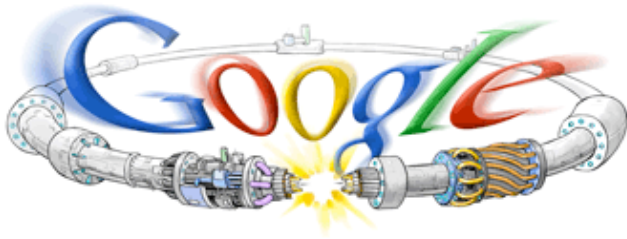
dimension of particle physics

DEALBOOK

ET QUOTES
Stock, ETFs, Fu

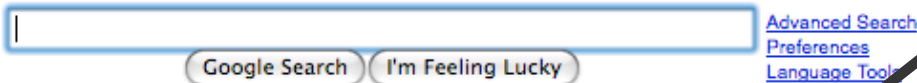
Look! Register Now

It felt like a feeding frenzy there for a while!!!



Google made a doodle of the LHC ring !

The LHC made it to the Colbert Report several times. Stephen Colbert even suggested that LHC was responsible for Obama's victory !



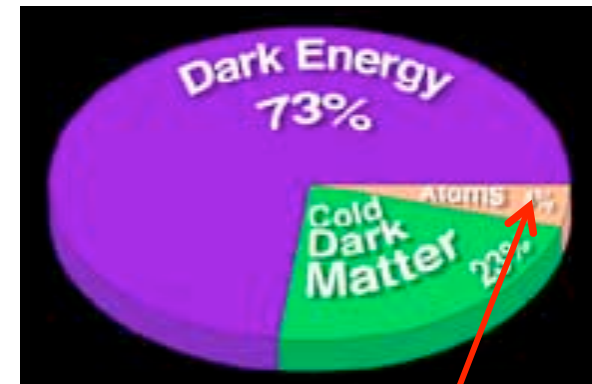
A large crowd of people & Chicago press at Fermilab to hear Higgs discovery ↓



Next Endeavor: Getting into Uncharted Seas



So far mankind's understanding is limited to only 4% of the universe !



You are here

Dark Matter is a stable, neutral relic from the earliest moments after the Big Bang – wonderful new physics to be discovered.

LHC can uncover certain kinds of dark matter ...

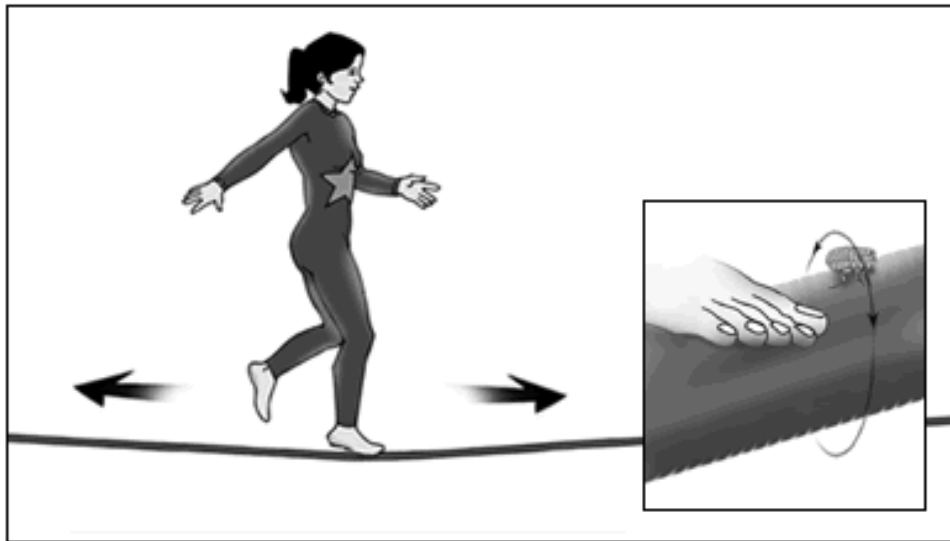


Supersymmetry is a potential extension of the Standard Model that would double the number of particles → each Standard Model particle has a partner

The lightest Supersymmetric particle (LSP) is stable and would explain Dark Matter. A LSP mass of ~ 1 TeV yields the observed relic abundance of Dark Matter particles, 23 % !

Gravity ? – Not in the Standard Model

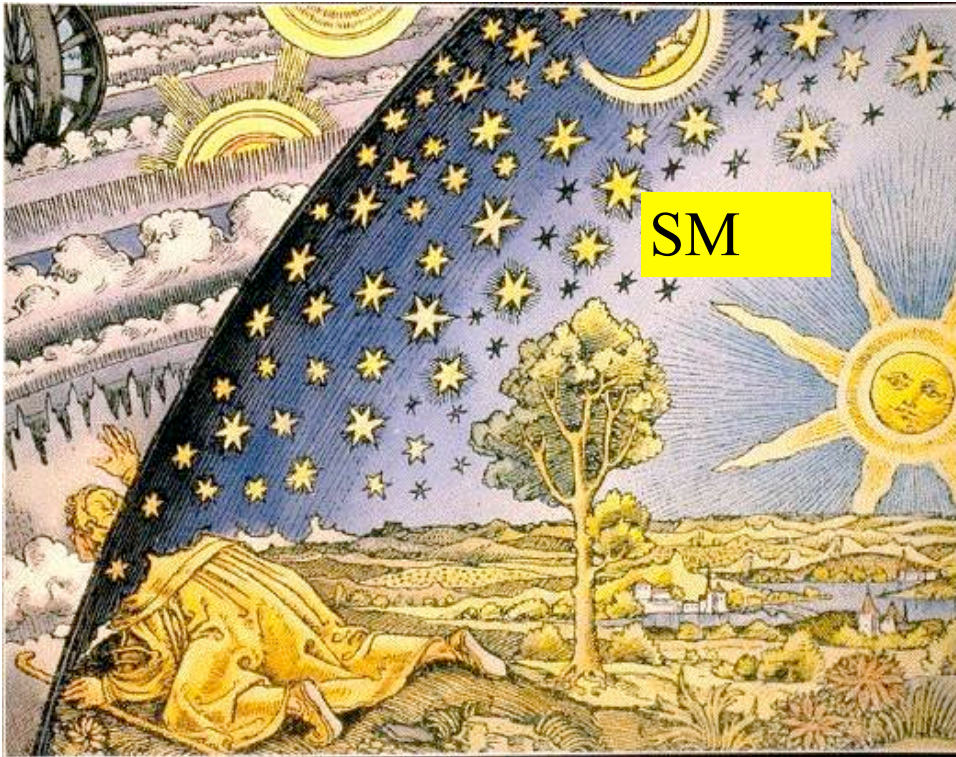
- Extra dimensions ?
- Are those dimensions observable? At the LHC we will look for extra dimensions. Perhaps we can push a particle to disappear into the unseen dimensions.
- We are presently setting limits on the mass scale of a few TeV



An aerialist on a tight wire can travel in only one dimension, forward and back. A flea on the wire finds a "rolled-up" second dimension.



Or Something We Haven't Even Thought About...



We have arrived in “terascale incognita”. The exploration of the TeV mass scale is well underway.

By the end of 2016 many possible new phenomena will have been examined decisively.

Remember:

“Nothing is too wonderful to be true if it be consistent with the laws of Nature” – Michael Faraday.

Practical applications: the World Wide Web

One day sir, you may tax it.

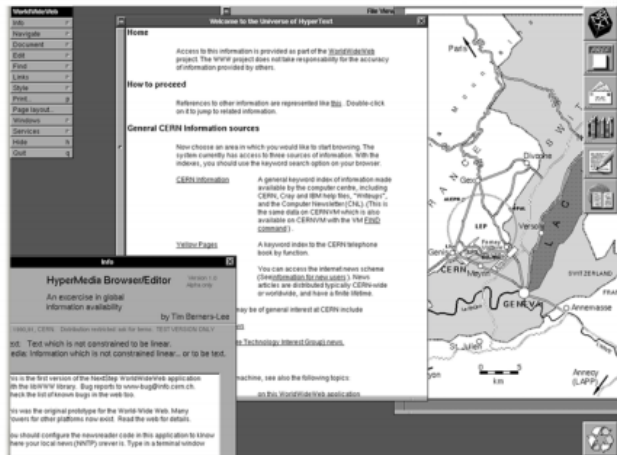
- Faraday's reply to William Gladstone, then British Chancellor of the Exchequer (minister of finance), when asked of the practical value of electricity (1850), as quoted in *The Harvest of a Quiet Eye : A Selection of Scientific Quotations* (1977), p. 56



Tim Berners-Lee's original World Wide Web browser

A screen shot taken from a NeXT computer running Tim Berners-Lee's original WorldWideWeb browser. It has taken a long time for technology to catch up with Berners-Lee's original vision. The first ever web browser was also an editor, making the web an interactive medium, the problem was that it only ran on the NeXTStep operating system. With recent phenomena like blogs and wikis, the web is beginning to develop the kind of collaborative nature that its inventor envisaged from the start.

See also a [screen shot](#) taken later, in 1993.



WWW was developed in the frame of the LHC project in 1989!

Freely given to the World!

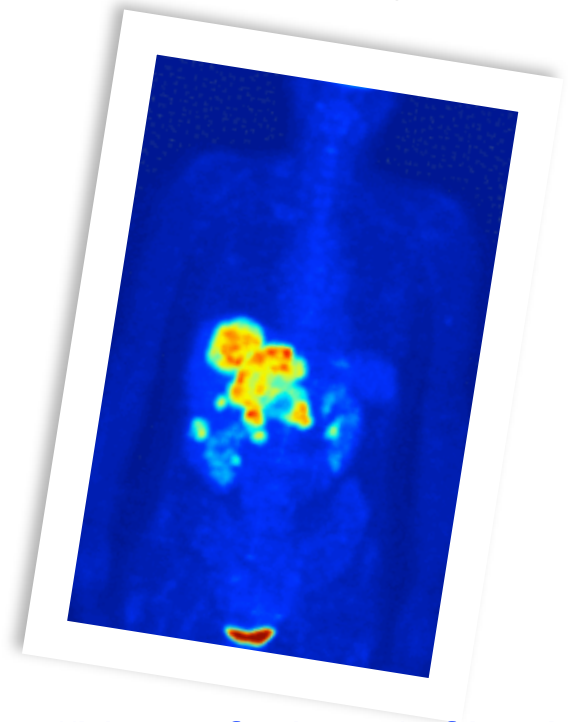


Practical applications: cancer treatment



For both detection and cure of cancers

- PET Scans
- Proton Therapy



<http://history.fnal.gov/ctf.html>

Practical applications: Cargo Scanning

Scanning trucks in < one hour without unloading them!

http://en.wikipedia.org/wiki/Cargo_scanning



Many more applications – too numerous to describe them all here

Summary

- ☑ LHC is the technological marvel of the modern era
 - Built to uncover the most fundamental mysteries of our existence

- ☑ Higgs boson was the last missing piece in the Standard Model, and arguably the most important one
 - With its discovery, accomplished the 50 year old dream
 - Voyage on to solve new mysteries: dark matter & energy

- ☑ High energy particle physics has been anchoring some of the most important technologies of our time
 - LHC has continued this tradition
 - From World Wide Web to Grid Computing

More Information

For further information

CERN: <http://www.cern.ch>

CMS: <http://cms.cern.ch>

ATLAS: <http://atlas.ch>

US LHC: <http://www.uslhc.us>

Connecting Quarks with the Cosmos: National Academy of
Science report,
<http://www.nap.edu/openbook.php?isbn=0309074061>

[The Quantum Universe: Two reports by DOE and NSF
advisory panel.](http://www.interactions.org/quantumuniverse/)
<http://www.interactions.org/quantumuniverse/>



End of talk ! Thank You.

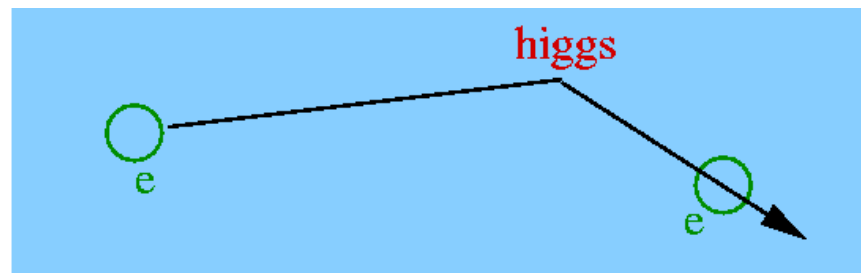
BACKUP SLIDES

The Origin of Mass: “The God Particle”

Fundamental symmetries of nature require that all elementary particles and force carriers be **massless**, but in the **real world** the elementary particles have widely differing masses → so some symmetry must be **broken**

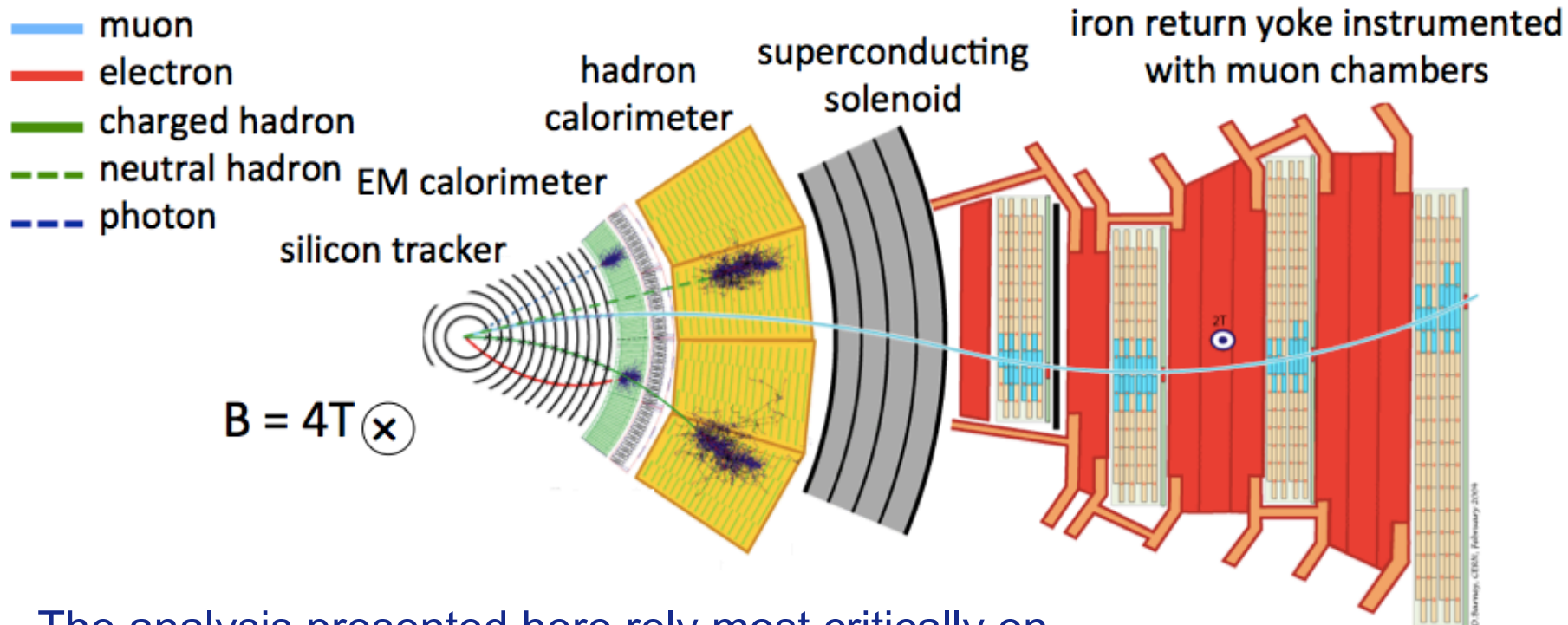
The Higgs Boson

We suspect the vacuum is permeated by a “Higgs field” that is responsible – the quantum of this field is a fundamental scalar.



To explain the neutron life time the Higgs vacuum must be 100 times denser than nuclear matter!!

CMS detector



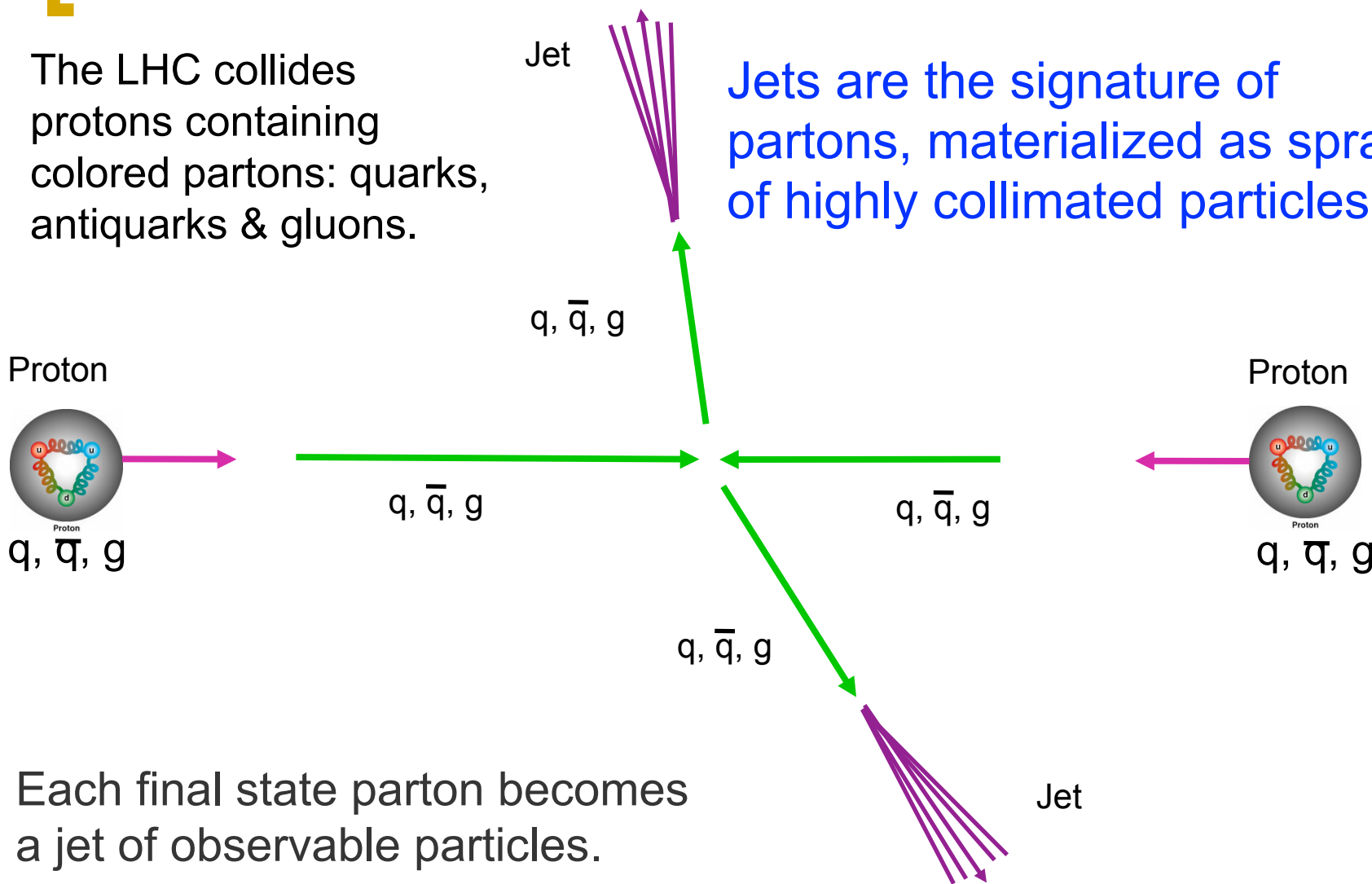
The analysis presented here rely most critically on

- **electrons**: tracks matched to clusters in EM calorimeter
- **muons**: minimum ionizing tracks, penetrate deep into muon system
- **jets / H_T** : constructed with combined tracking + calo info
- **MET**: constructed with combined tracking + calo info, hermetic detector

Particle jets

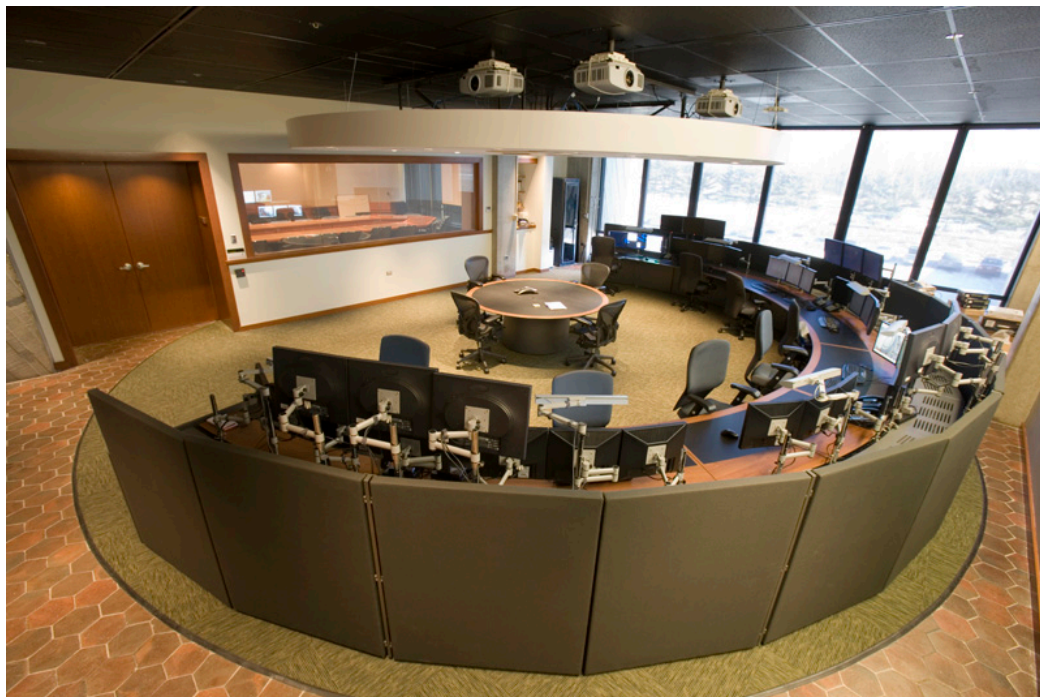
The LHC collides protons containing colored partons: quarks, antiquarks & gluons.

Jets are the signature of partons, materialized as sprays of highly collimated particles.



Each final state parton becomes a jet of observable particles.

How Do FNAL Physicists Participate?



CMS is 4500 miles away from Fermilab. Can we ‘do physics’ here? Yes indeed, all physicists are “remote”. At CERN you are 20 km away and the detector is 100m underground and inaccessible. We built the “Remote Operations Center” – and the “LHC Physics Center”.

The sun never sets on CMS. ROCs at CERN, DESY/Hamburg, FNAL.