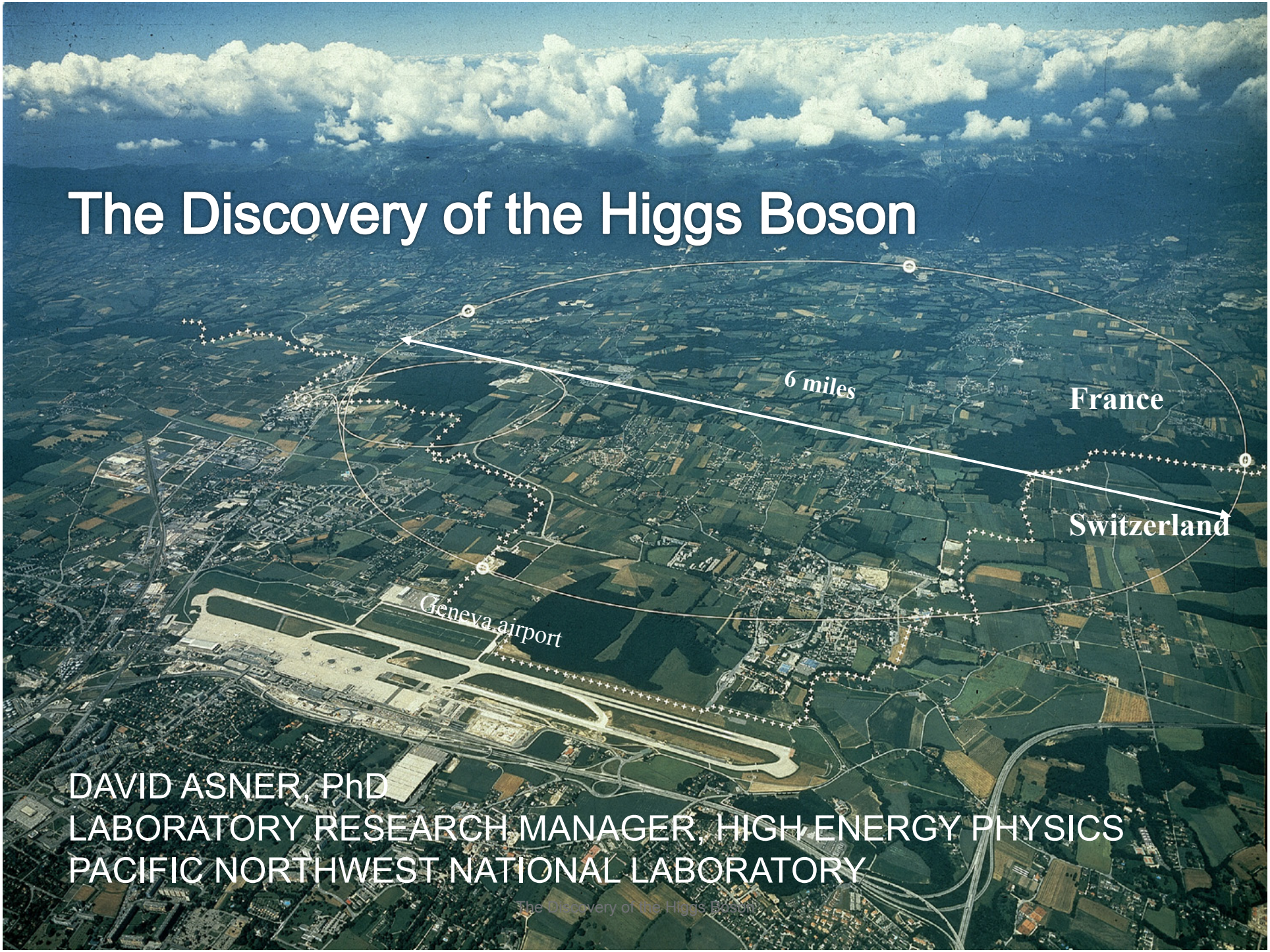
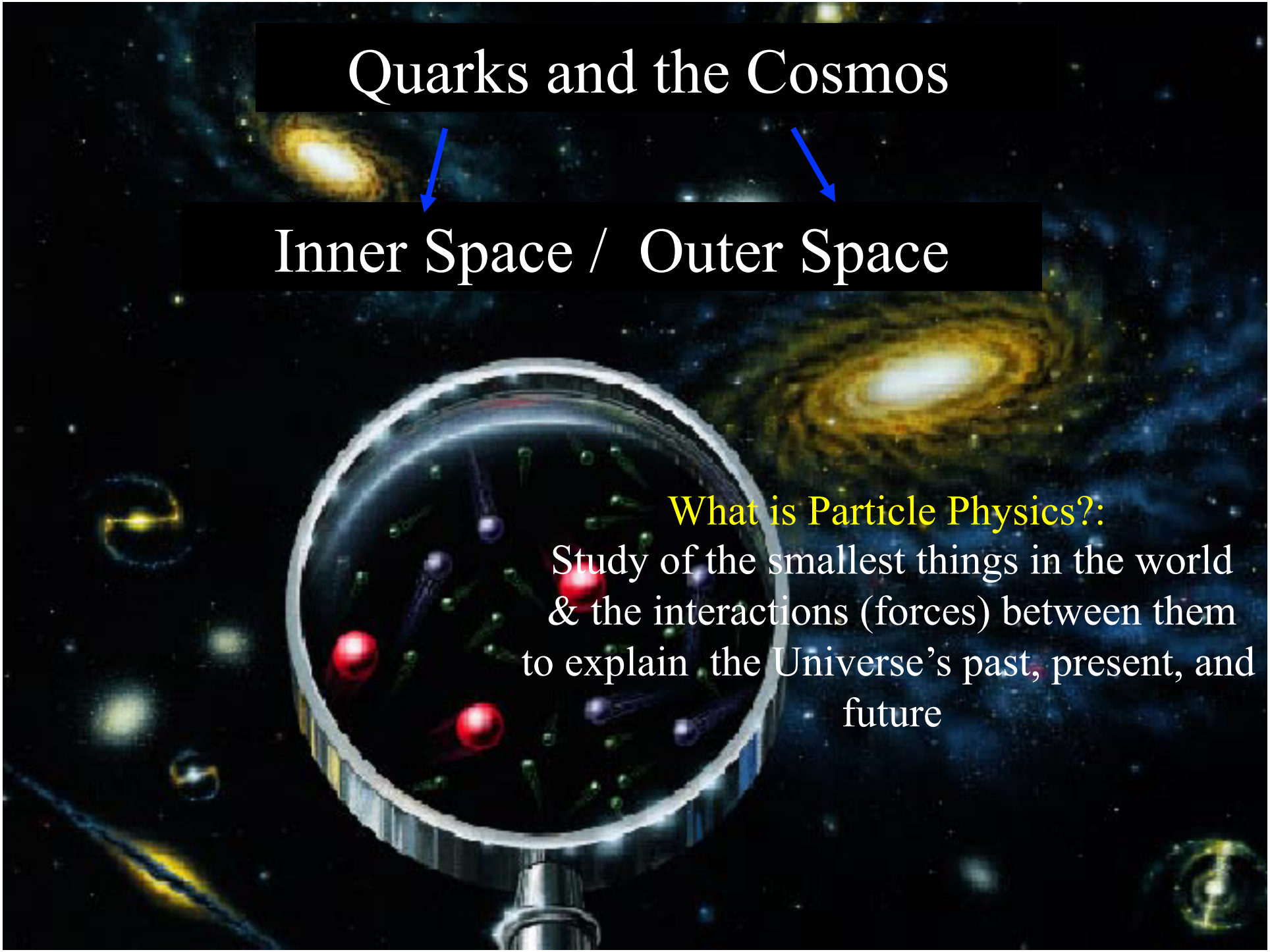
The Discovery of the Higgs Boson



DAVID ASNER, PhD
LABORATORY RESEARCH MANAGER, HIGH ENERGY PHYSICS
PACIFIC NORTHWEST NATIONAL LABORATORY

Quarks and the Cosmos

Inner Space / Outer Space



What is Particle Physics?:
Study of the smallest things in the world & the interactions (forces) between them to explain the Universe's past, present, and future

The Higgs Boson was (prior to July 4, 2012) the last remaining undiscovered particle in the Standard Model of Particle Physics

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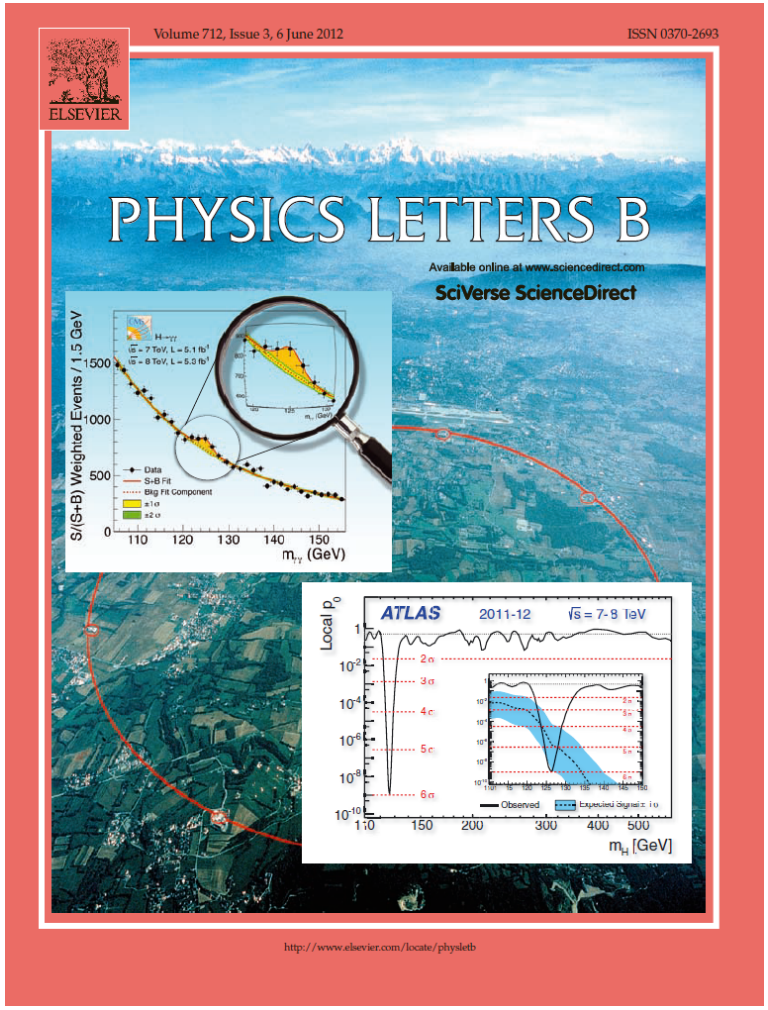
- July 4, 2012, Higgs Boson discovery announced
  - Published October 2012 in Physics Letters B
- Outline of this talk
  - The Standard Model
  - Discoveries in Particle Physics
  - Accelerators and Nobel Prizes
  - Large Hadron Collider (LHC)
  - ATLAS & CMS experiments
  - Discovery of the Higgs Boson
  - What comes next?



Peeling back the layers of Matter: The Periodic Table of Elements

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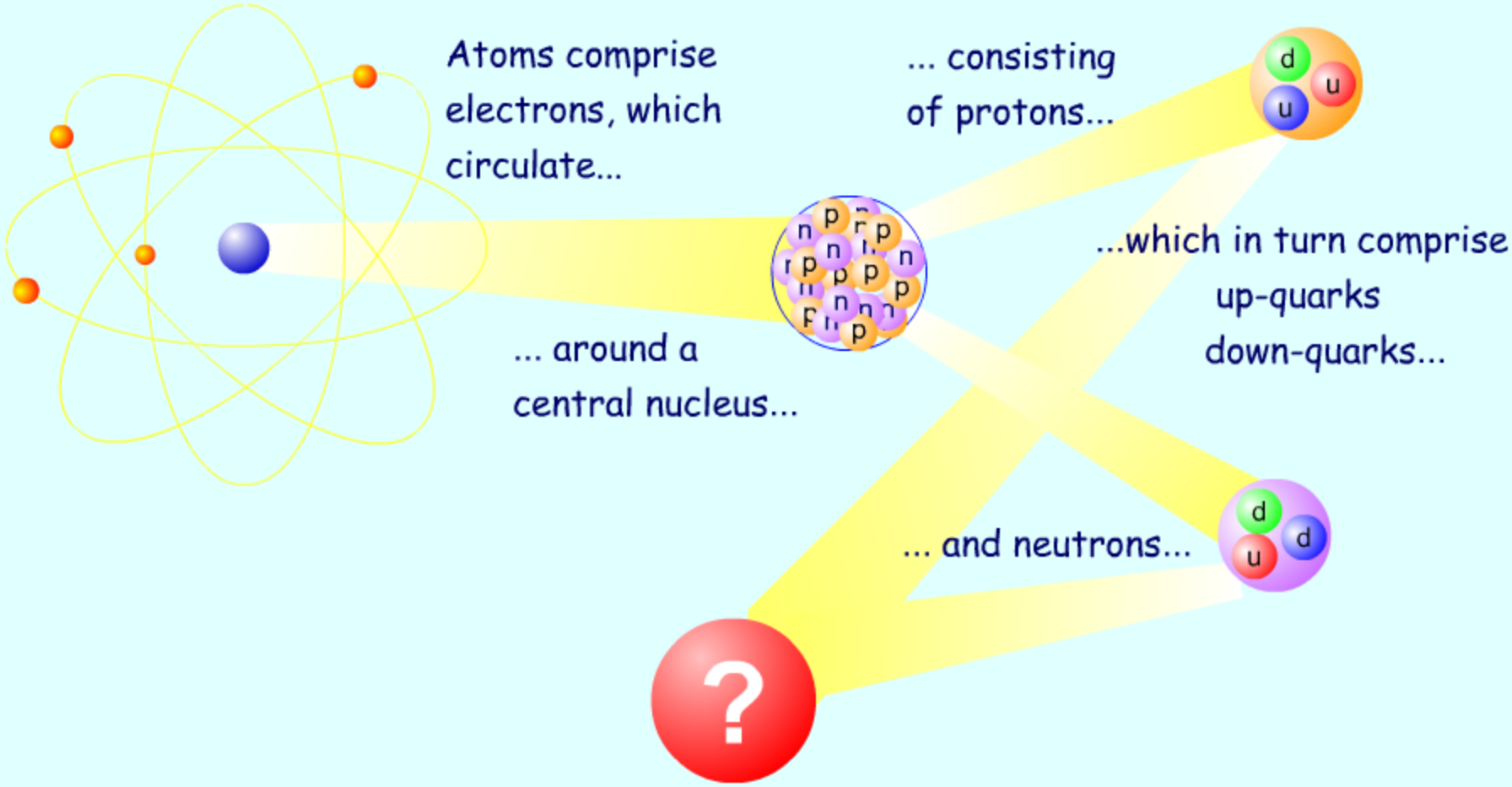
	1A	2A	3A	4A	5A	6A	7A	8			1B	2B	3B	4B	5B	6B	7B	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	L	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	A															
		L	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		A	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Inner Space: atoms, quarks & electrons



...and that is the frontier of our present understanding on the nature of matter

Animation: *Elena Symeonidou*

The size of atoms, quarks and electrons

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The size of an atom is ~0.1 nanometers

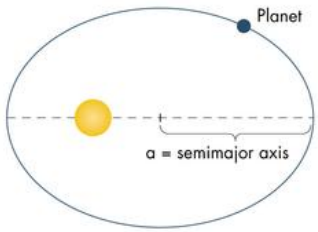
An atom compared to an apple is

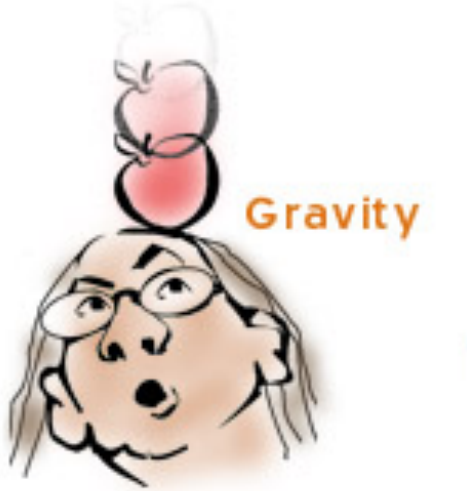
The proton compared to an atom is like a raisin in the middle of a football field

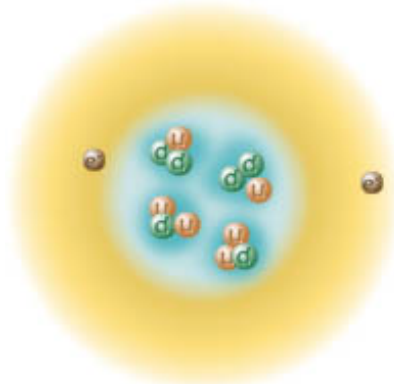
A quark has a volume less than one billionth of a proton

The detectors at the Large Hadron Collider can probe a volume one trillionth the size of a proton

Inner space: The four fundamental forces

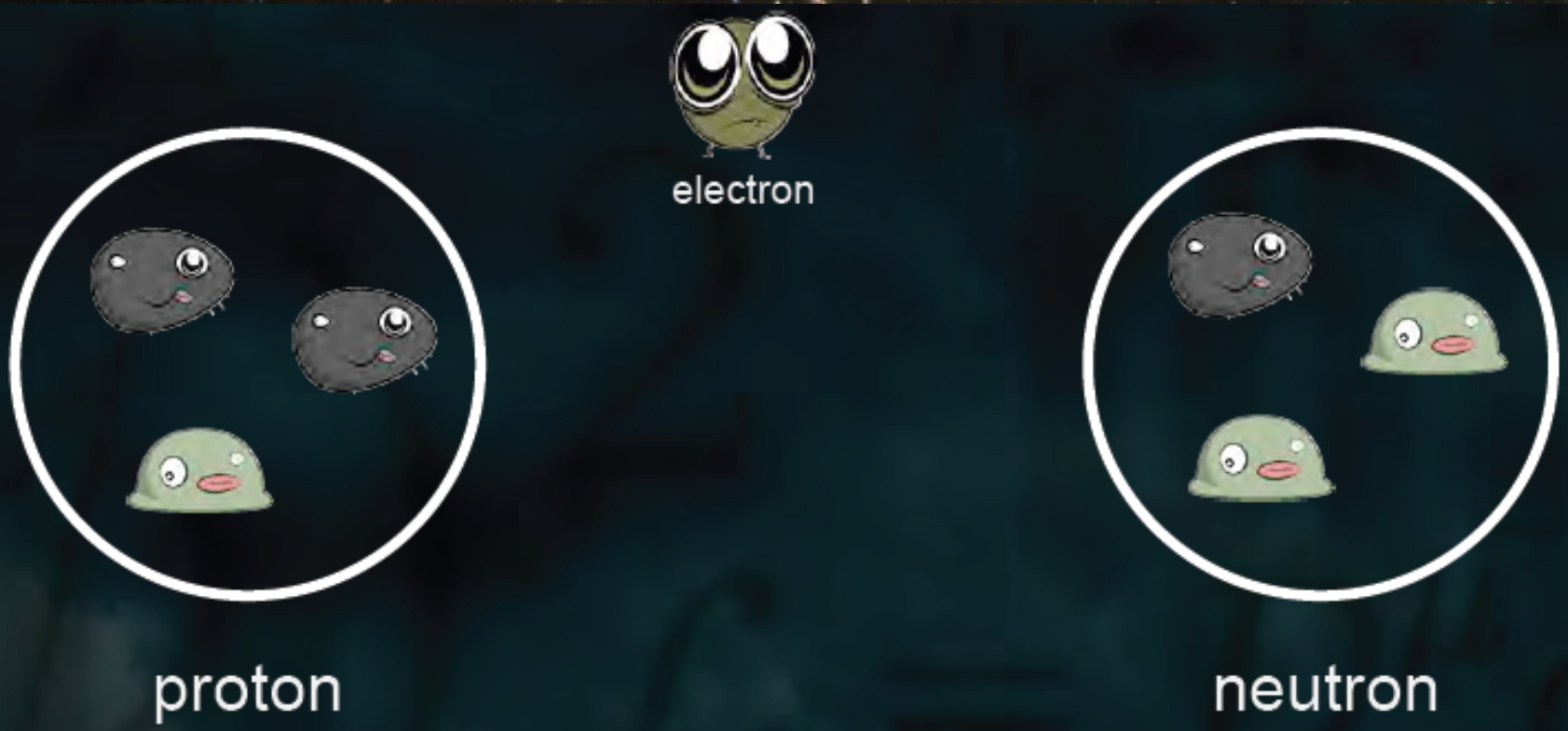






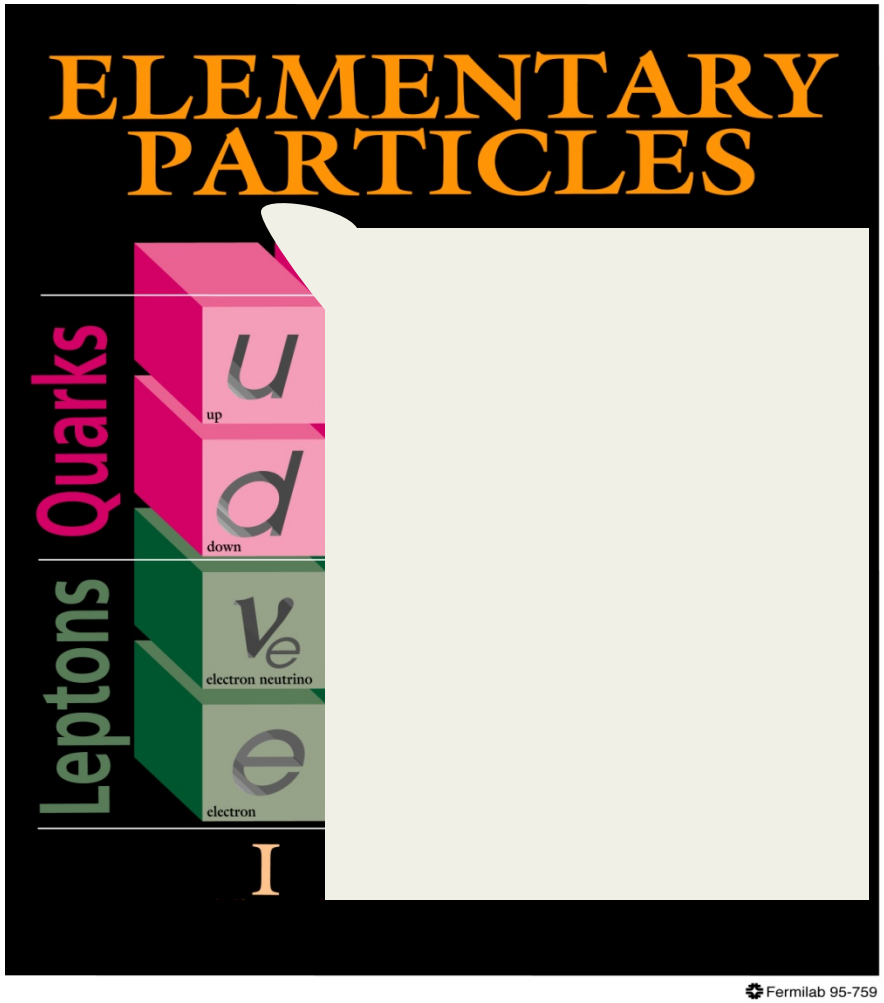
radioactivity
+ lets quarks
change identity
example: d→u

BUILDING A UNIVERSE



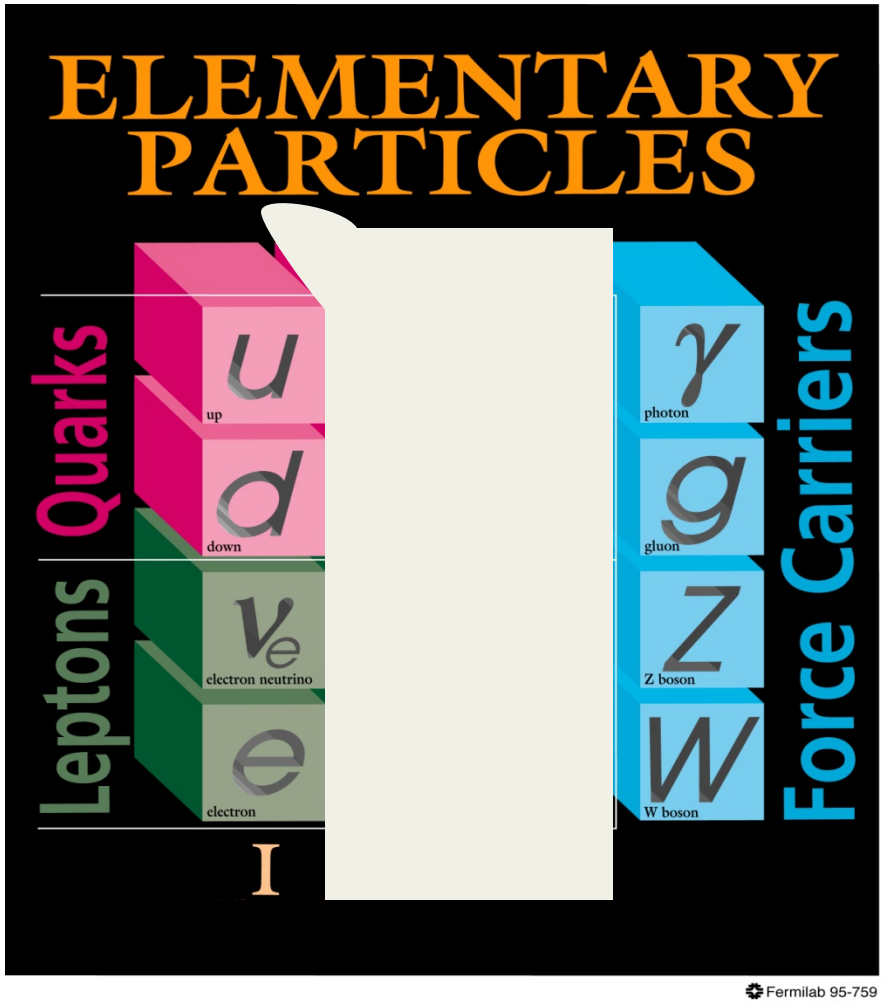
Multiply by billions and billions and billions (there are 10^{78} atoms in the universe)

The periodic table of the elementary particles



We are made of up *(u)* and down *(d)* quarks and electrons *(e)* and there are also neutrinos produced in radioactive decay

The periodic table of the elementary particles

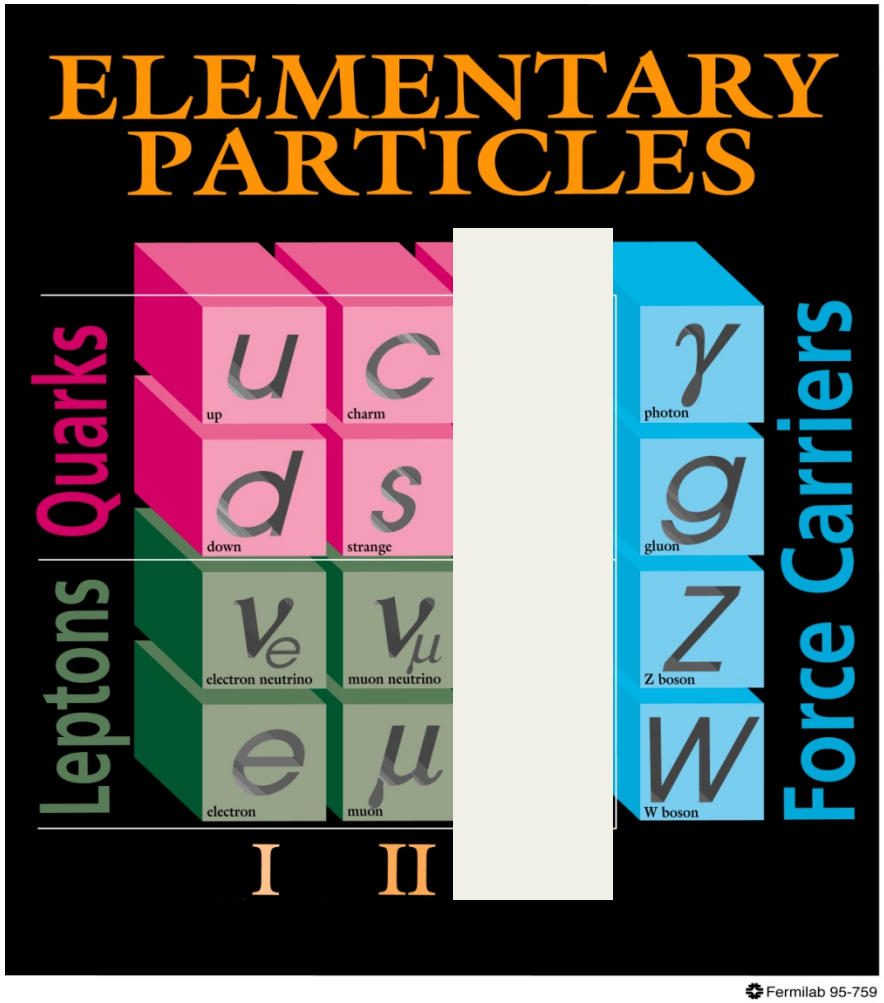


+ particles
associated with force

Photon : electromagnetic
Gluon : strong
Z and W bosons: weak

This, we thought,
was enough to make
a universe

The periodic table of the elementary particles

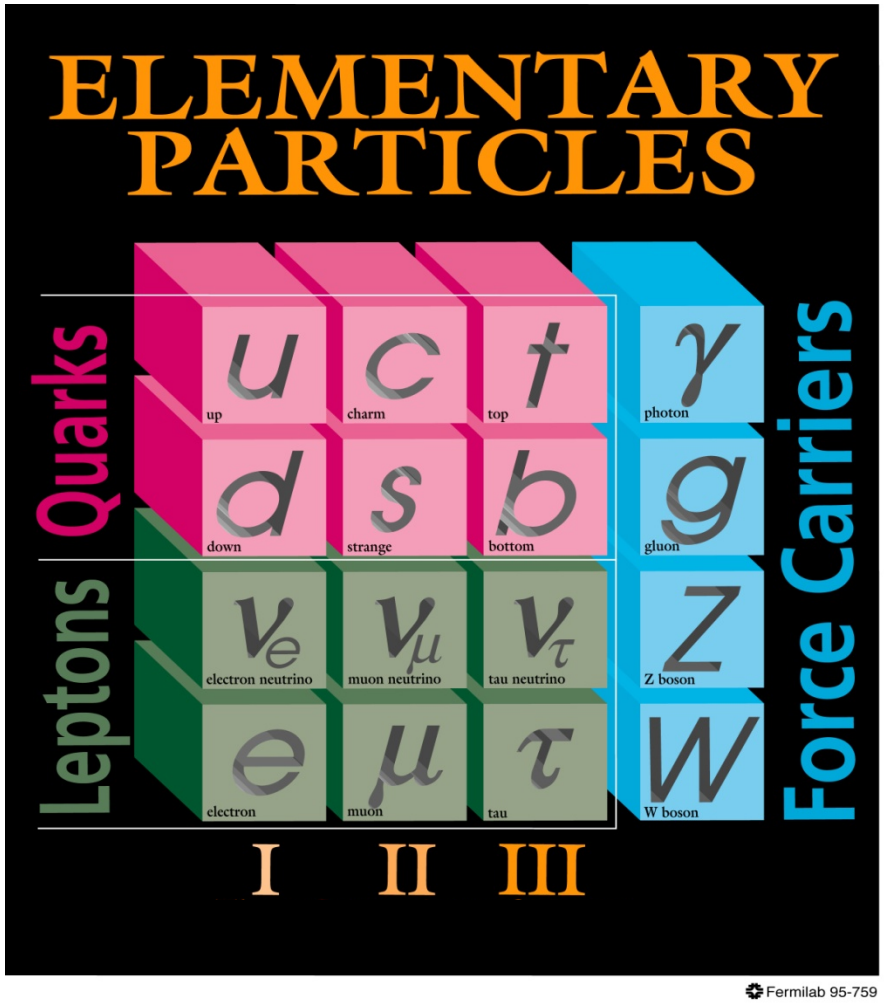


1935-1974
2nd generation of particles discovered

the first group is replicated by a second group at greater Mass

Produced in Cosmic Ray showers

The periodic table of the elementary particles

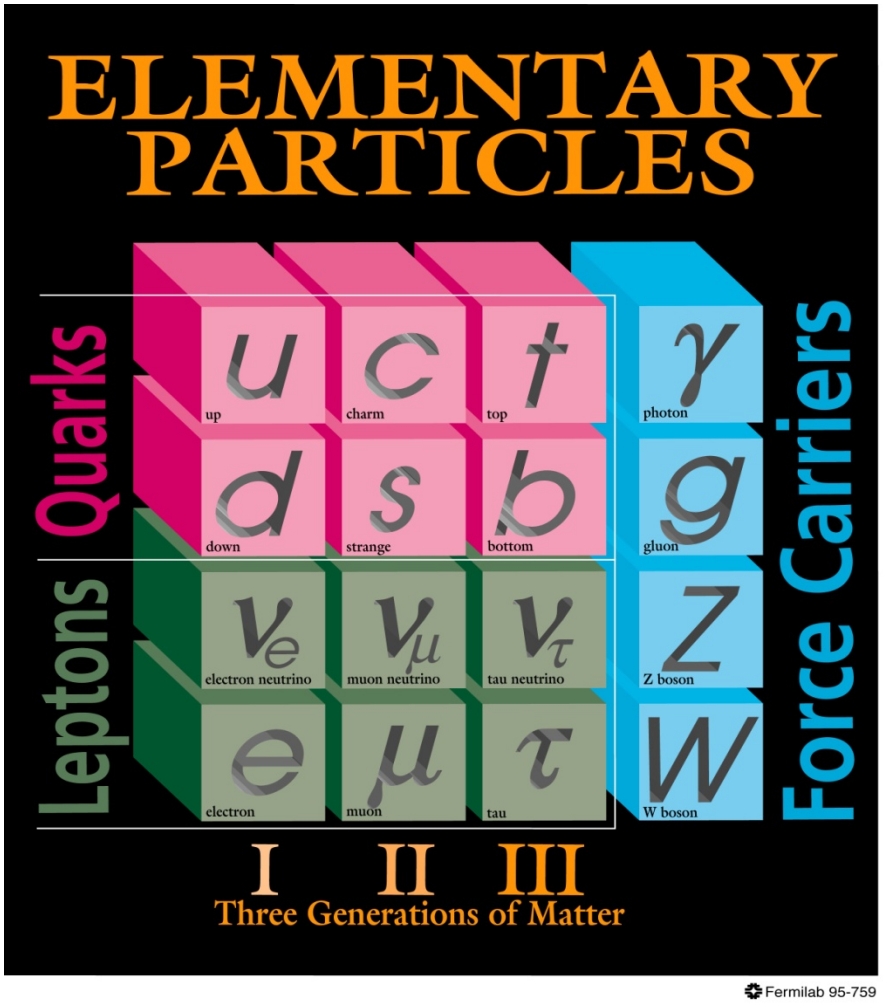


1977-2000
3rd generation of particles discovered

a third copy at still higher mass was discovered

Produced in particle accelerators

The periodic table of the elementary particles

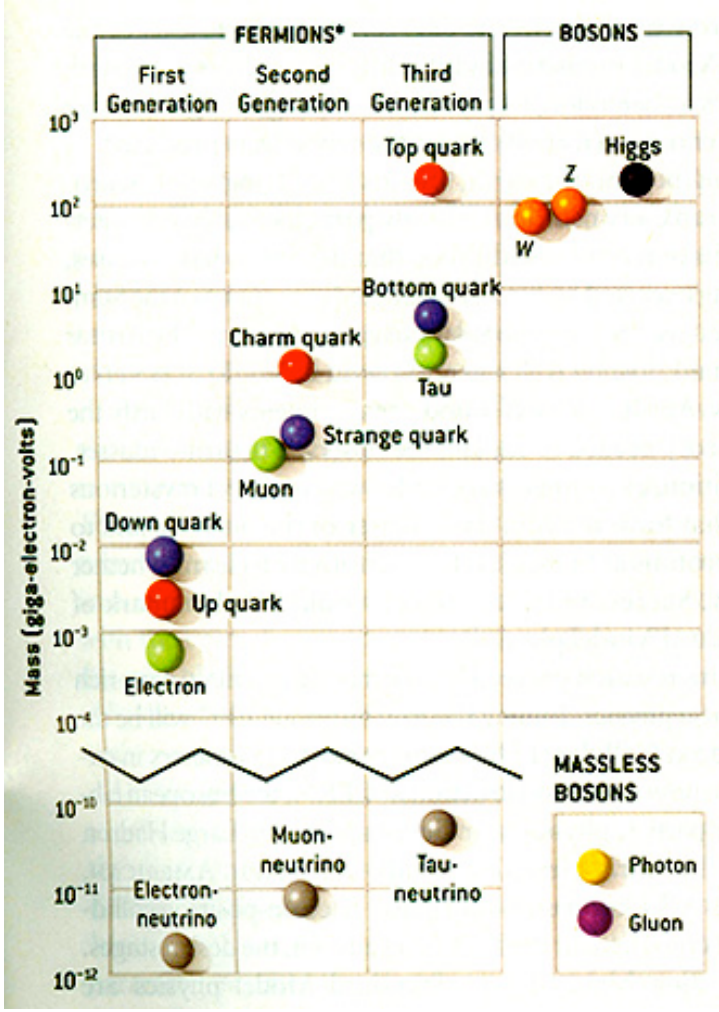


+ anti-matter (antiparticles for each quark & lepton)

- The prevailing theory (the Standard Model) is a remarkable intellectual construction
- Particle experiments confirm the theory with exquisite precision
- Several mysteries remain!

Particles have very different masses. Why?

- Why are there 3 generation of particles?
  - Ordinary matter is composed of only the first generation
- Why do they have very different masses?
  - Top quark is as heavy as a gold nucleus ~170 GeV
  - neutrinos have very tiny mass
    - < 2 eV
- We do not know the answers to these questions



Why is Mass a Problem?

- The Standard Model of Particle Physics is a quantum field theory

  Particles described by *quantum fields* defined at all points in spacetime
  - Fermion fields describe matter particles – quarks & leptons
  - Electroweak boson fields that mediate the electromagnetic and weak interactions
  - Gluon fields that mediate the strong interaction

- The Standard Model is furthermore a gauge theory

  There are degrees of freedom in the mathematical formalism that do not correspond to changes in the physical state – called *Gauge Invariance*
  - Gauge Invariance implies that the force carriers are massless

- The Higgs field was introduced to provide a Gauge Invariant way to allow the W and Z bosons to be massive
  - Mass of quarks/leptons is proportional to their interaction with the Higgs field
  - The Higgs boson is a quantum excitation of the Higgs field

Four 1964 research papers published by Robert Brout & François Englert (Belgians), two by Peter Higgs, and one by a team consisting of Americans Gerald Guralnik and Carl (Dick) Hagen and British physicist Tom Kibble.

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F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

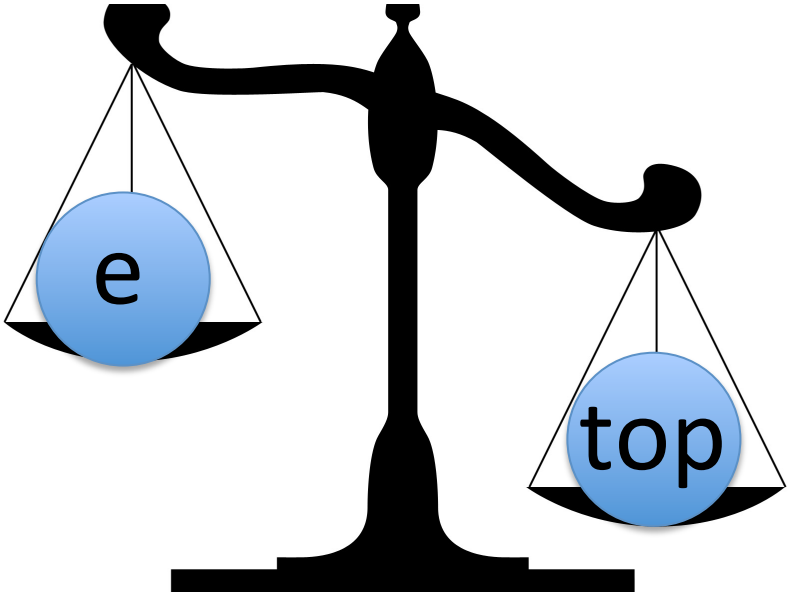
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England

What is the Higgs?

- A particle (The Higgs boson)
  - All of its properties except for its mass are predicted
  - It is a real particle which can be studied
- A field (The Higgs field)
  - When other particles (W and Z bosons, quarks and leptons too) interact with the Higgs field they become massive
  - The more a particle interacts with the Higgs field the heavier it is



The Standard Model and the Higgs Mechamism

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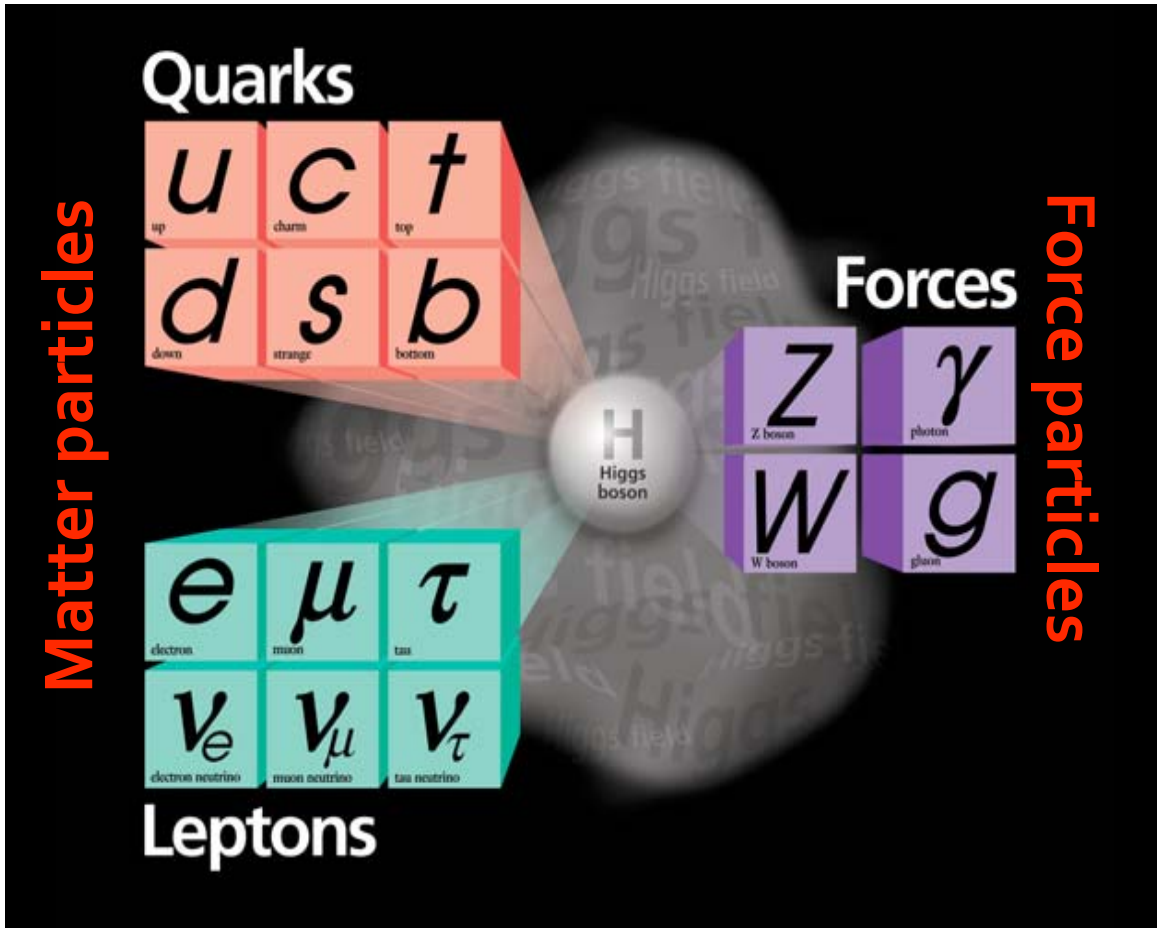
Standard Model is composed of point-like particles & force carriers.

1970's: The Higgs mechanism is used to predict the existence of the W and Z bosons with masses of 80 & 91 times that of a proton

1983-84: The W and Z bosons were discovred at CERN



Discoveries (and Nobel Prizes) made with the help of accelerators at LBL, SLAC, Brookhaven, Fermilab, CERN

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1950

The Bevatron began to operate in **1954** and the **antiproton** was discovered in **1955**.

The Nobel Prize in Physics 1959

Segrè Chamberlain

1960

The inner structure of **nucleons** (protons and neutrons) was discovered at SLAC in **1969**.

The Nobel Prize in Physics 1990

Friedman Kendall Taylor

1970

Discovery of **J/Ψ particle** (composed of charm quarks) was discovered at Brook-haven and SLAC in **1974**.

The Nobel Prize in Physics 1976

Richter Ting

1980

The **tau lepton** was discovered at SLAC in **1976**.

The Nobel Prize in Physics 1995

Perl

1990

The **W and Z particles** were discovered at the proton-antiproton collider at CERN in **1983**.

The Nobel Prize in Physics 1984

Rubbia van der Meer

2000

The first direct evidence for the **top quark** was announced at the Tevatron at Fermilab in **1995**.

more Nobel Prizes

- 1980 – (1964, BNL)
  Cronin & Fitch,
  Discovery of CP violation
- 1988 – (1962, BNL)
  Lederman, Steinberger, Schwartz
  Discovery of muon neutrino
- 2008 – (2001, SLAC, KEK)
  Nambu, Kobayashi, Maskawa
  – three quark generations & spontaneous symmetry breaking

more discoveries

- 1977 (Fermilab) – Υ particle (composed of b-quarks)
- 2000 (Fermilab) – tau neutrino
- 2012 (CERN) – Higgs Boson

Decades of Higgs Hunting

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Accelerator	type, laboratory	energy $\sqrt{s}$	years of operation
LEP-I	e^+e^- collider, CERN	91 GeV	1989 - 1994
LEP-II	e^+e^- collider, CERN	209 GeV	1995 - 2000
HERA-I	ep collider, DESY	27 + 800 GeV	1992 - 2000
HERA-II	ep collider, DESY	27 + 920 GeV	2002 - 2007
TeVatron Run I	ppbar collider, Fermilab	1.8 TeV	1987 - 1996
TeVatron Run II	ppbar collider, Fermilab	1.96 TeV	2002 - 2011
LHC, phase I	pp collider, CERN	7 TeV	2010- 2012
LHC, phase II	pp collider, CERN	14 TeV	2014- …….

LEP-II did not find Higgs (M_H> 114 GeV). Machine turned off in 2000 to make room for the Large Hadron Collider that was built in the same tunnel.

A missed opportunity

- Superconducting Super Collider (SSC)
  - To be built in Texas with 3x's the collision energy of the Large Hadron Collider
    - 40,000 GeV = 40 TeV
  - To be 54 miles in circumference
  - Cancelled in 1993
  - Would have discovered the Higgs Boson as well as any yet to be made discovery at the Large Hadron Collider

15 miles of tunnel dug near Waxahachie, Texas

After 28 years of discovery and innovation the Tevatron at Fermilab, Batavia, IL, the world's highest-energy proton-antiproton collider, shut down on Sept. 30, 2011.

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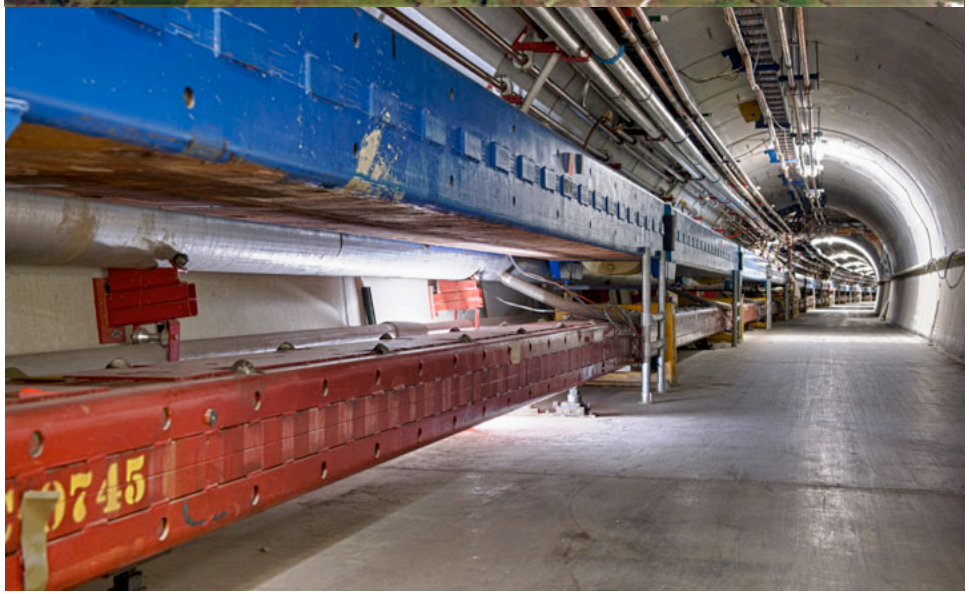
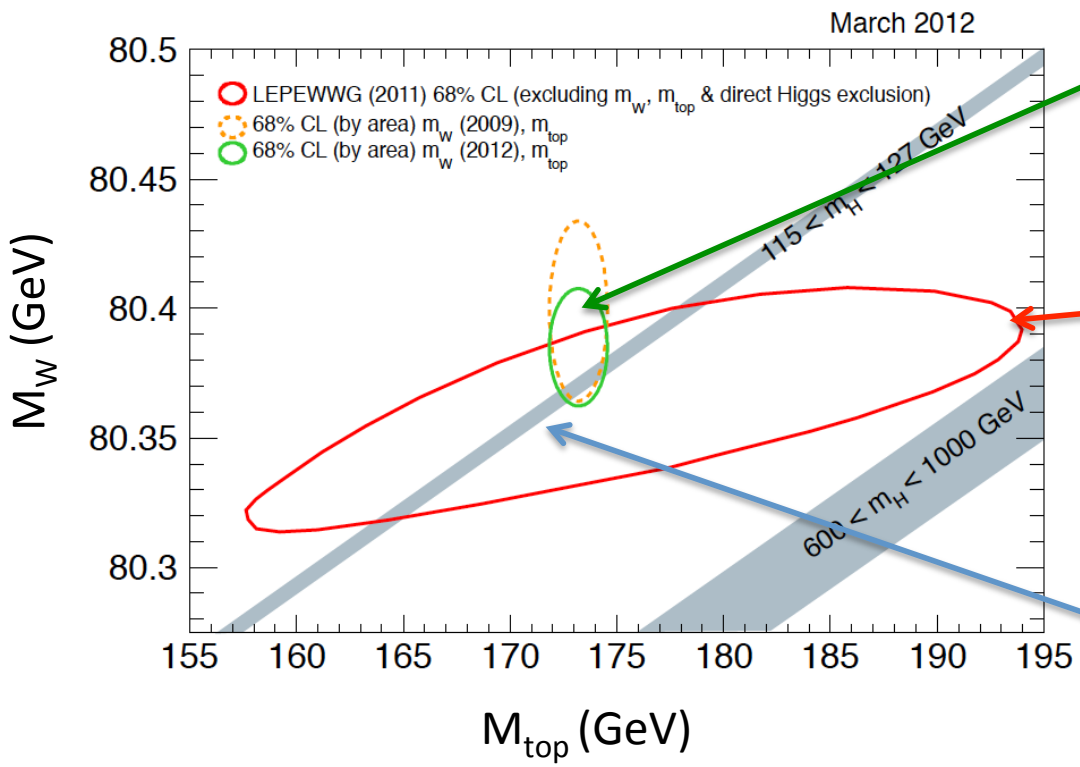
- Since 1983, the most powerful atom smasher in the US has created particle collisions recorded by the CDF and D0 experiments.
- Informed some of the most important fundamental discoveries of our time, such as
  - Discovery of the top quark
  - Most precise W mass measurement
  - Discovery of 5 baryons & B_c meson
  - B_s matter/anti-matter oscillations
- Also provided particle beams to fixed target experiments & test beam areas
- Countless achievements in detector, accelerator and computing technology



What did we know about the Higgs Boson prior to the discovery announcement July 4, 2012



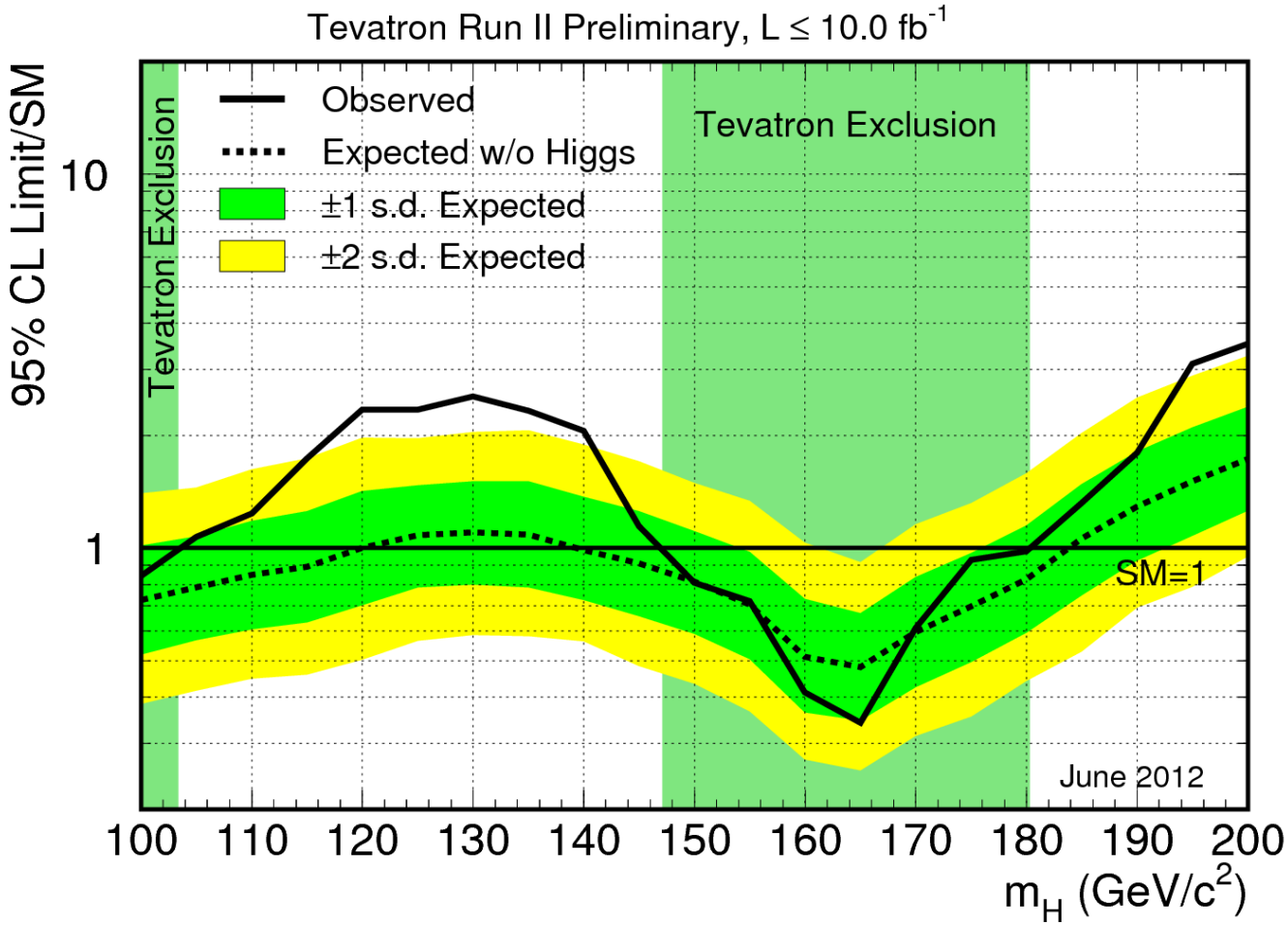
Experimental measurements from Fermilab

Inferred values of M_W and M_t from other experiments

Theory predictions

Self consistency required that the Higgs Boson not be too heavy

Tevatron Experiments excluded the Higgs from the mass regions <115 GeV & 148-180 GeV



Prior to July 4, 2012 - Combining results from Tevatron & CERN experiments leave a small mass window for the discovery of the Higgs Boson

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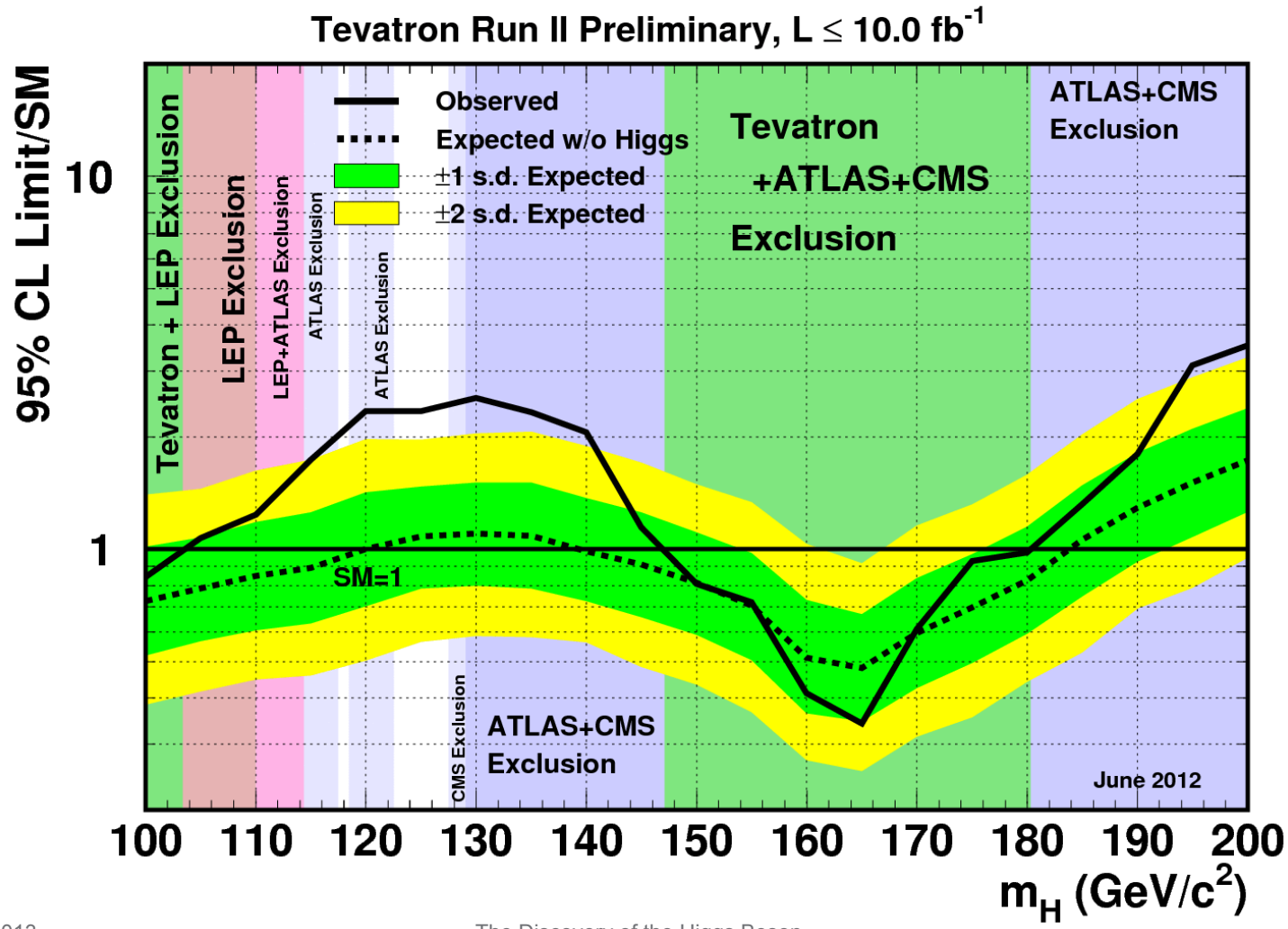

LARGE HADRON COLLIDER (LHC)

Professor Peter Higgs in the Large Hadron Collider Tunnel in 2012

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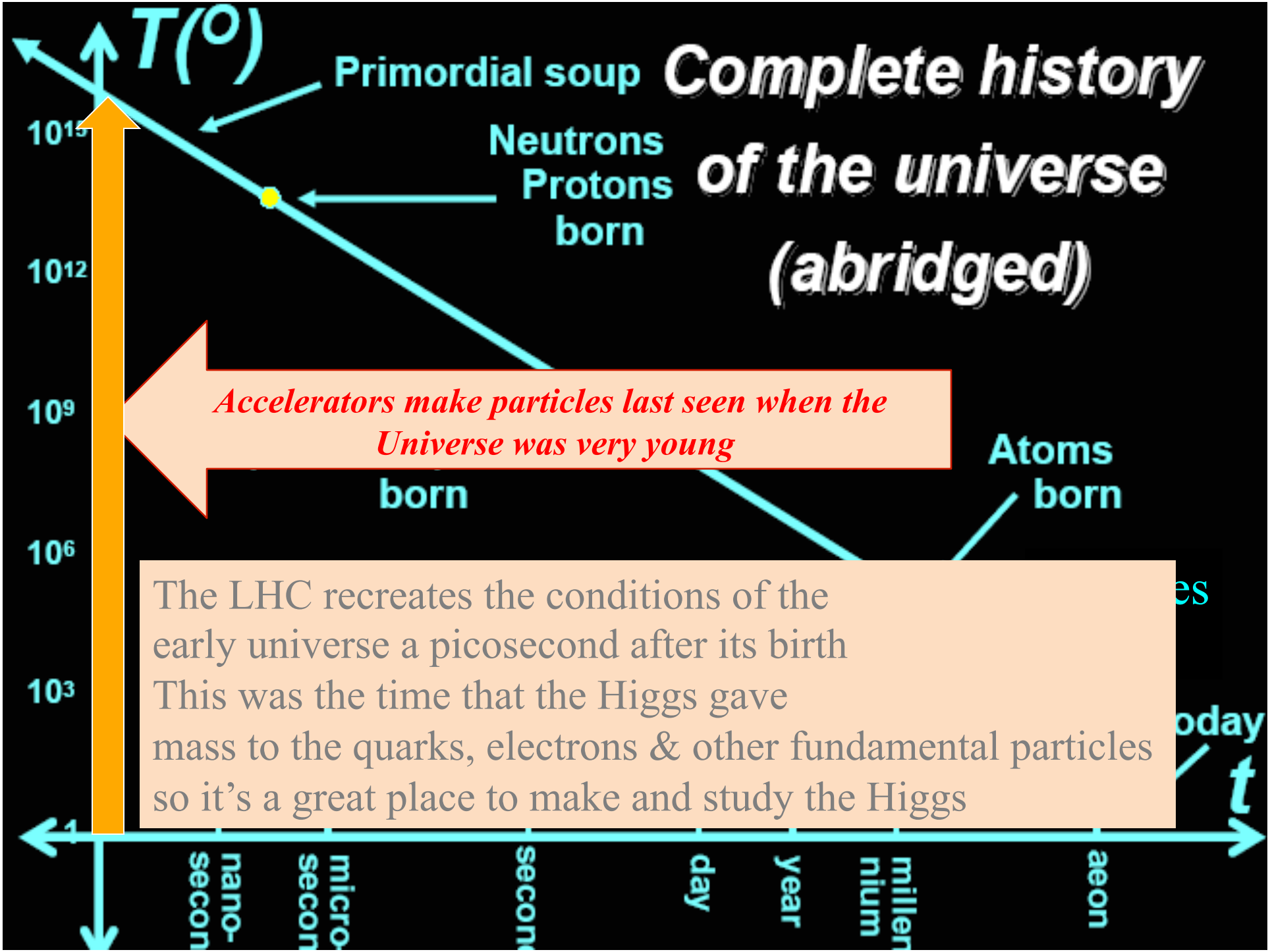


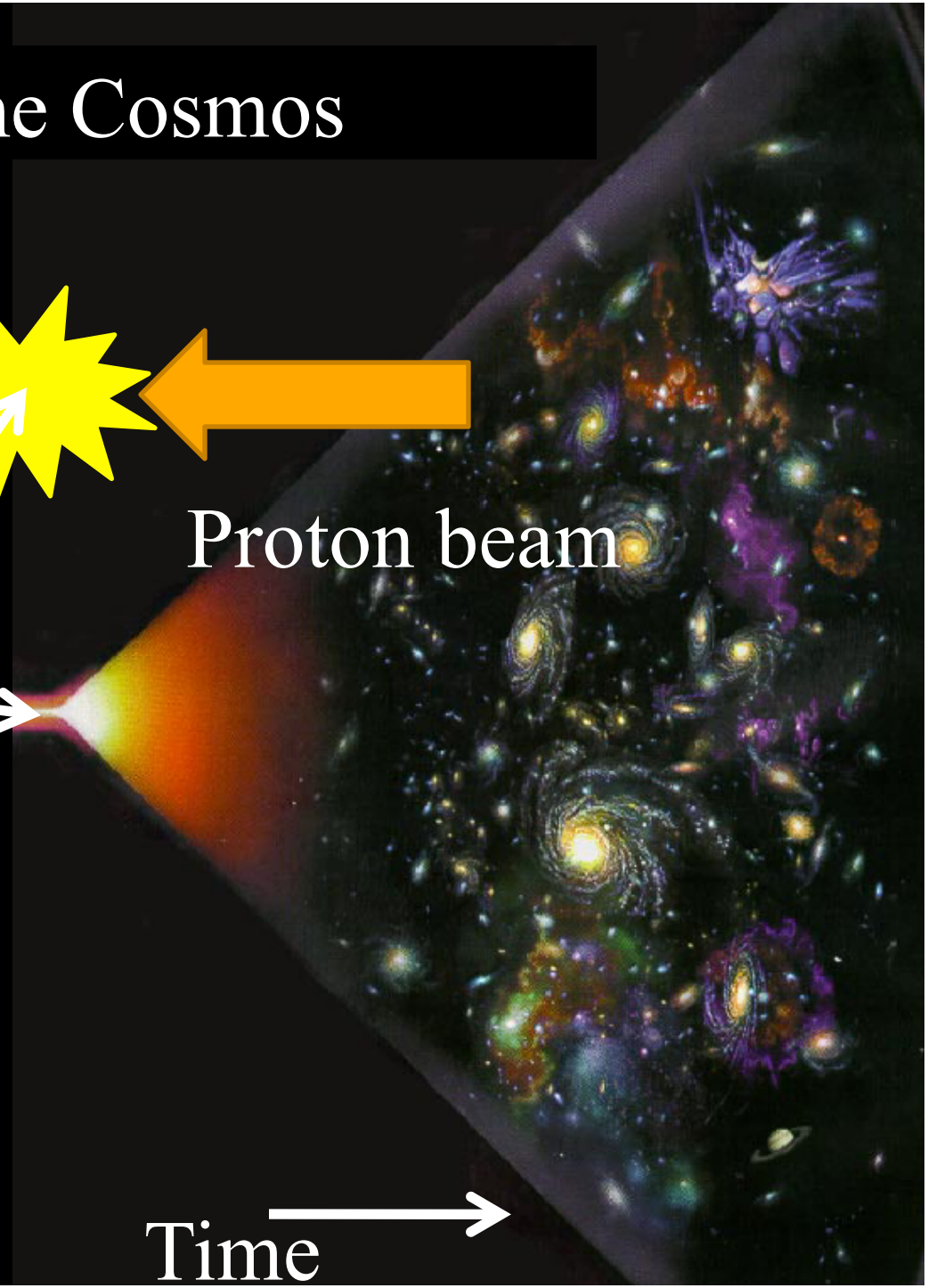
The LHC recreates the conditions of the early universe a picosecond after its birth
This was the time that the Higgs gave mass to the quarks, electrons & other fundamental particles so it's a great place to make and study the Higgs

Quarks to the Cosmos

Proton beam

Proton beam

Primordial Soup of the Universe made at the LHC



Time

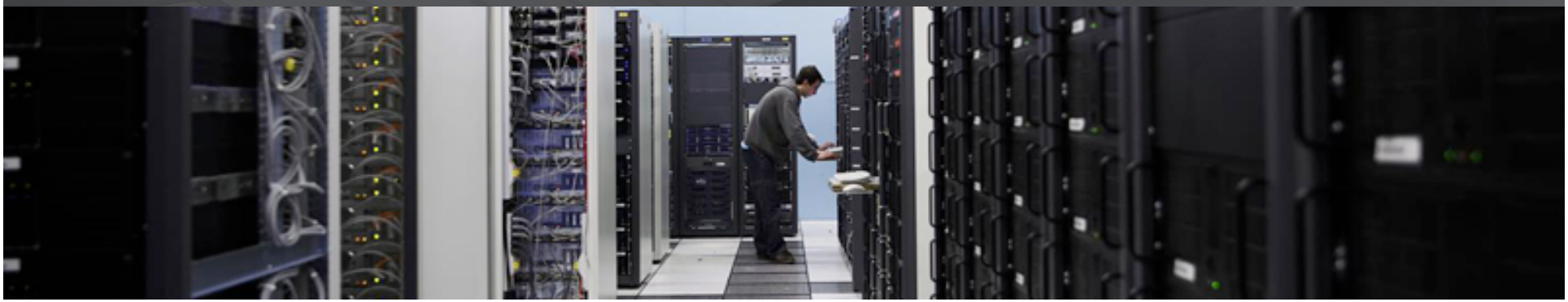
Large Hadron Collider: Facts & Figures (I)

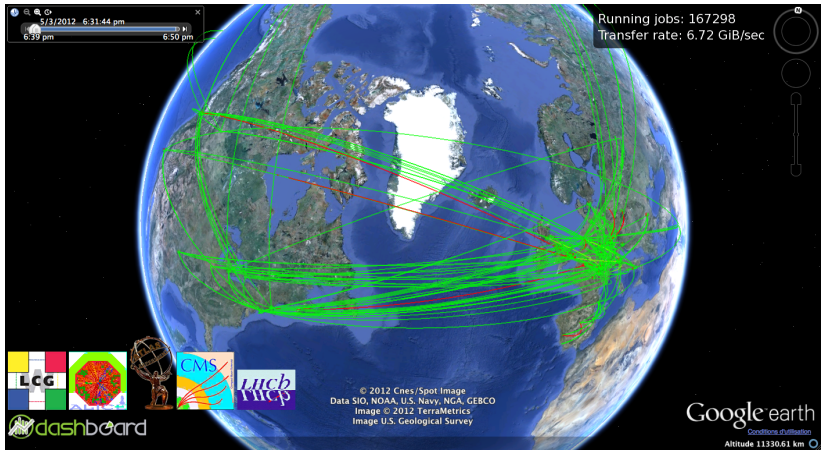
- Largest machine in the world
  - 27 km circumference, 9300 magnets
- Largest cryogenic system in the world
  - first cooled by 10k tonnes of liquid nitrogen to 80 K then cooled by 120 tonnes of liquid helium to 1.9K
- At full power, trillions of protons circulate the LHC accelerator ring 11,245 times a second, travelling at 99.9999991% the speed of light. (14 TeV collision energy)
- The emptiest space in the Solar System
  - To avoid colliding with gas molecules inside the accelerator, the beams of particles travel in an ultra-high vacuum as empty as interplanetary space. 10^{-13} atm, 10 times less than the pressure on the Moon!

Large Hadron Collider: Facts & Figures (II)

- Hottest spots in the galaxy, but colder than outer space
  - When two beams of lead ions collide, they will generate temperatures >100,000x hotter than the heart of the Sun, concentrated within a minuscule space.
  - By contrast, the 'cryogenic distribution system', which circulates superfluid helium around the accelerator ring, keeps the LHC at a temperature of -271.3°C (1.9 K) – even colder than outer space!
- The biggest and most sophisticated detectors ever built
  - Sample the results of up to 600 million proton collisions per second, physicists and engineers have built gargantuan devices that measure particles with micron precision.
  - Record only 400 interesting collisions per second
  - Sophisticated electronic trigger systems precisely measure the passage time of a particle to accuracies of a few billionths of a second and positions to a few millionths of a meter

Large Hadron Collider: Facts & Figures (III)



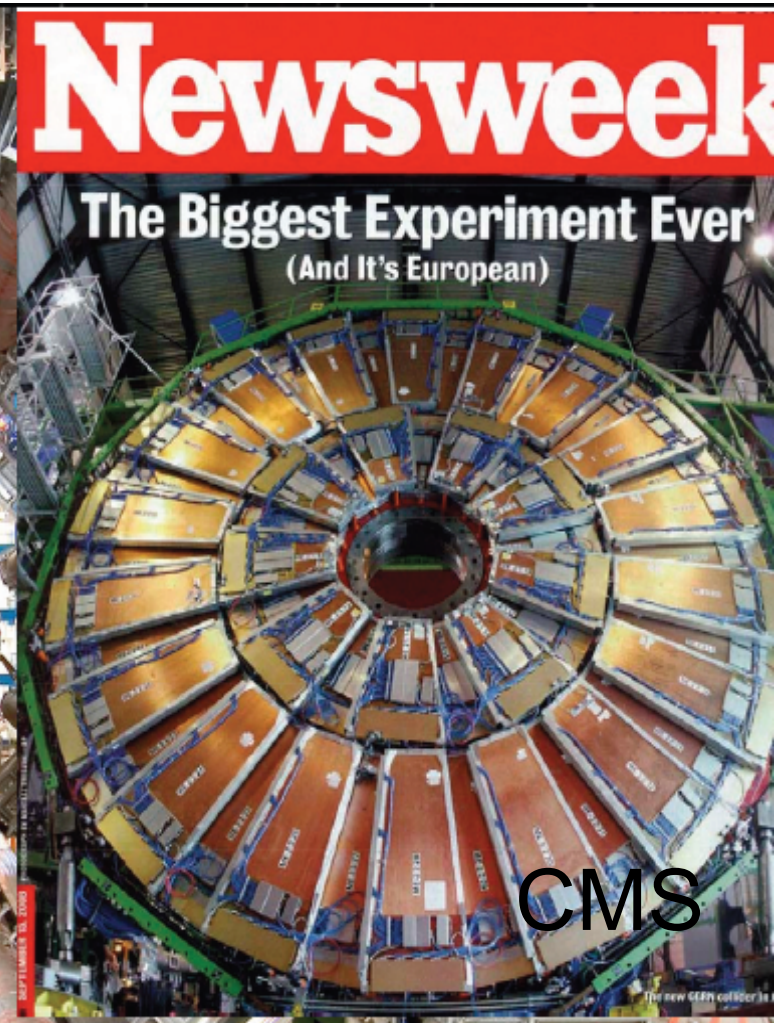


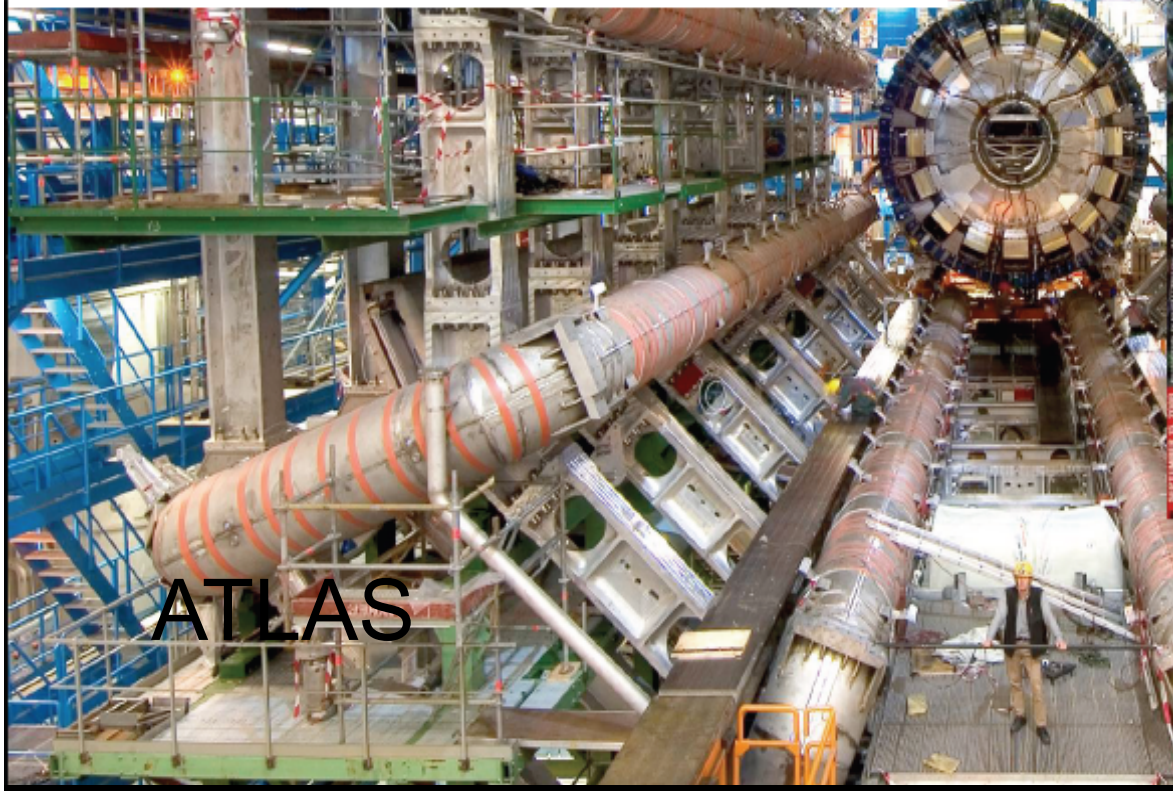
- World's most powerful computer system
  - Data recorded the experiments at the LHC will fill ~100,000 DVDs every year (15 petabytes / year)
  - A distributed computing network called "the Grid", composed of tens of thousands of computers around the world enable the thousands of scientists scattered around the globe to collaborate on the data analysis

Large Hadron Collider Requires Detectors of Unprecedented Scale

- Compact Muon Solenoid (CMS) Detector is 12,000 tons
- ATLAS Detector is 8 times the volume of CMS

Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500





CMS

ATLAS

DIGITAL CAMERAS THE SIZE OF CATHEDRALS

ATLAS Experiment

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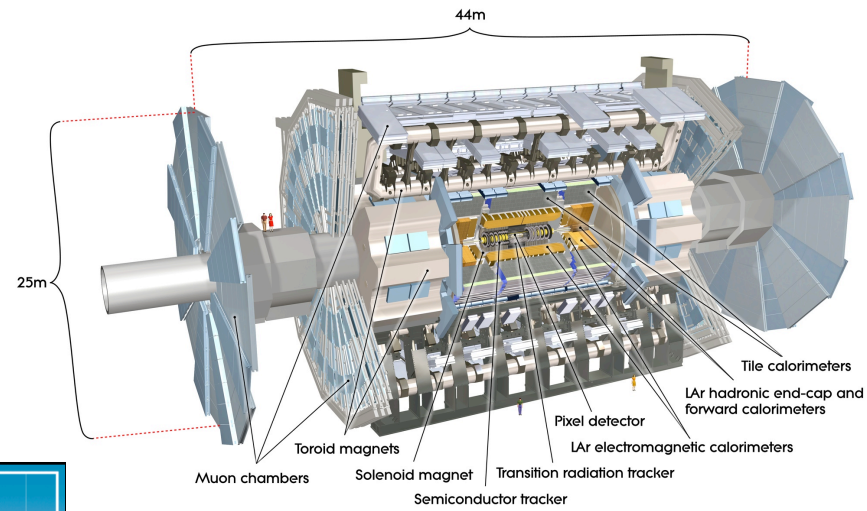
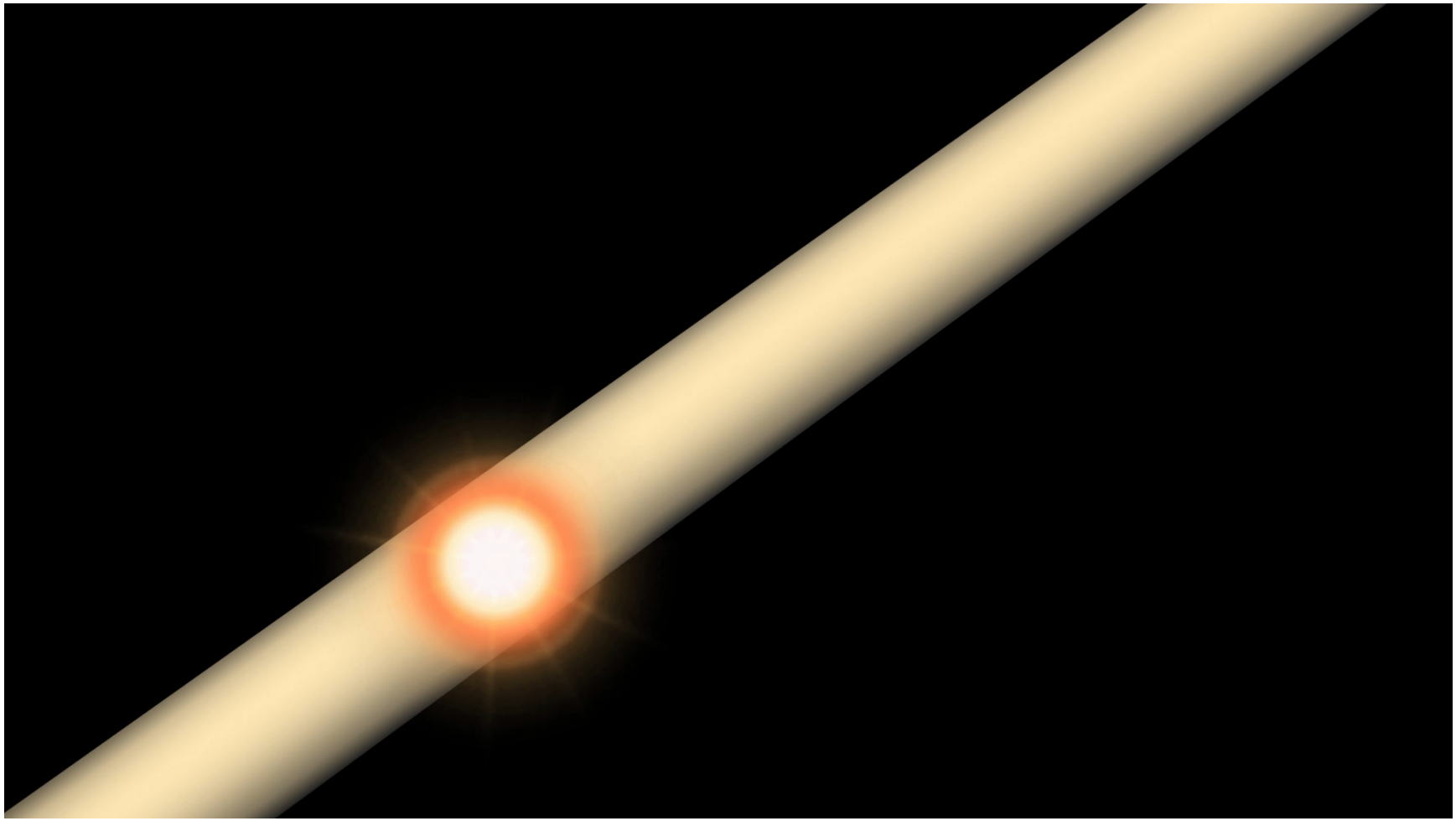
People
3000 scientists (including about 1000 graduate students) from 174 universities and labs in 38 countries



Detector Size and Weight
Diameter: 25 m
Length: 46 m
Overall weight: 7000 tonnes 3000 km of cables
ATLAS is ½ the size of Notre Dame Cathedral

Construction of the ATLAS Detector

Collision Event in ATLAS Detector



The CMS Experiment

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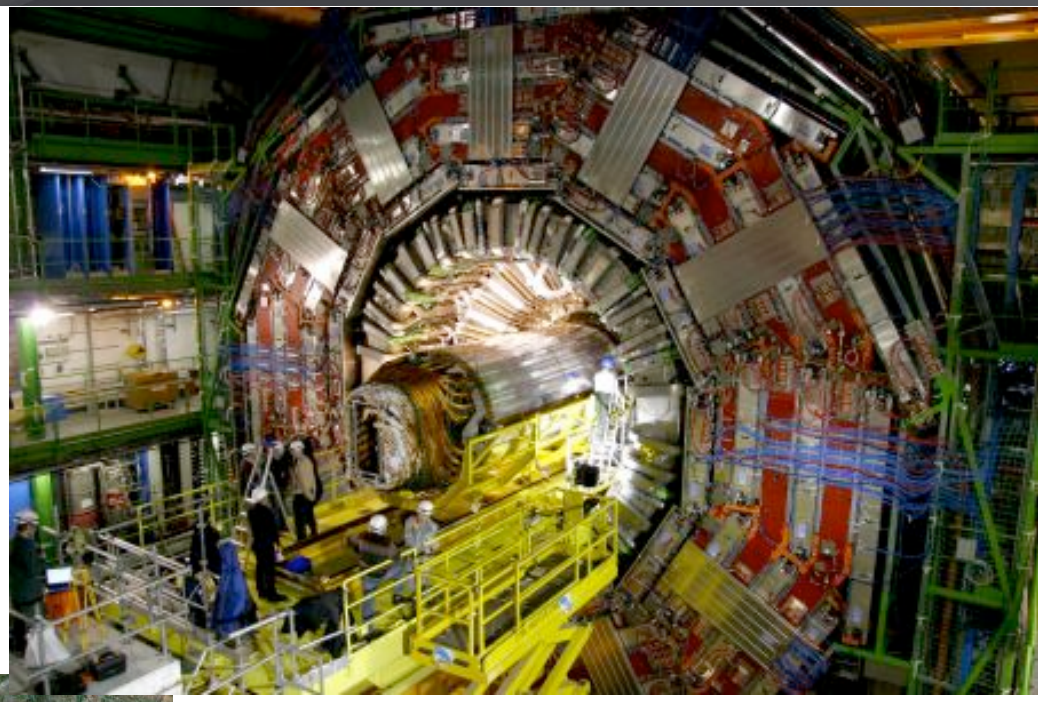
The CMS detector is situated 100 m underground at the French village of Cessy and is one of the biggest in the world, measuring 21 m in length, 15 m in diameter and weighing a total of 14,000 tonnes. It is a 5 storey-high digital camera recording hundreds of images per second of debris from LHC particle collisions



The CMS experiment is one of the largest international scientific collaborations in history, involving more than 3000 scientists, engineers, & students from 172 institutes in 40 countries.

So how do you search for a Higgs Boson?

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- Usually no Higgs Boson is made when protons collide at the LHC
  - VERY rarely a Higgs Boson is produced and then decays in 10^{-22} seconds
- ATLAS and CMS detectors were designed to be very good at measuring photons, muons and electrons
- Search for the Higgs Boson in
  - Proton + Proton (gluon fusion) → Higgs → photon photon
  - Proton + Proton (gluon fusion) → Higgs → Z Z → e+e- μ+ μ- , 4e, 4μ
- In the data presented on July 4, 2012 it is predicted that 174,000 Higgs bosons were made (now there is 3x more data)
  - 397 Higgs decayed to 2 photons
  - 20 Higgs decayed to 2 Z bosons which then decayed to 4 leptons
  - 60% of the Higgs bosons decay to b quarks

In the Standard Model the Higgs Boson decay rates depend on the Higgs Mass

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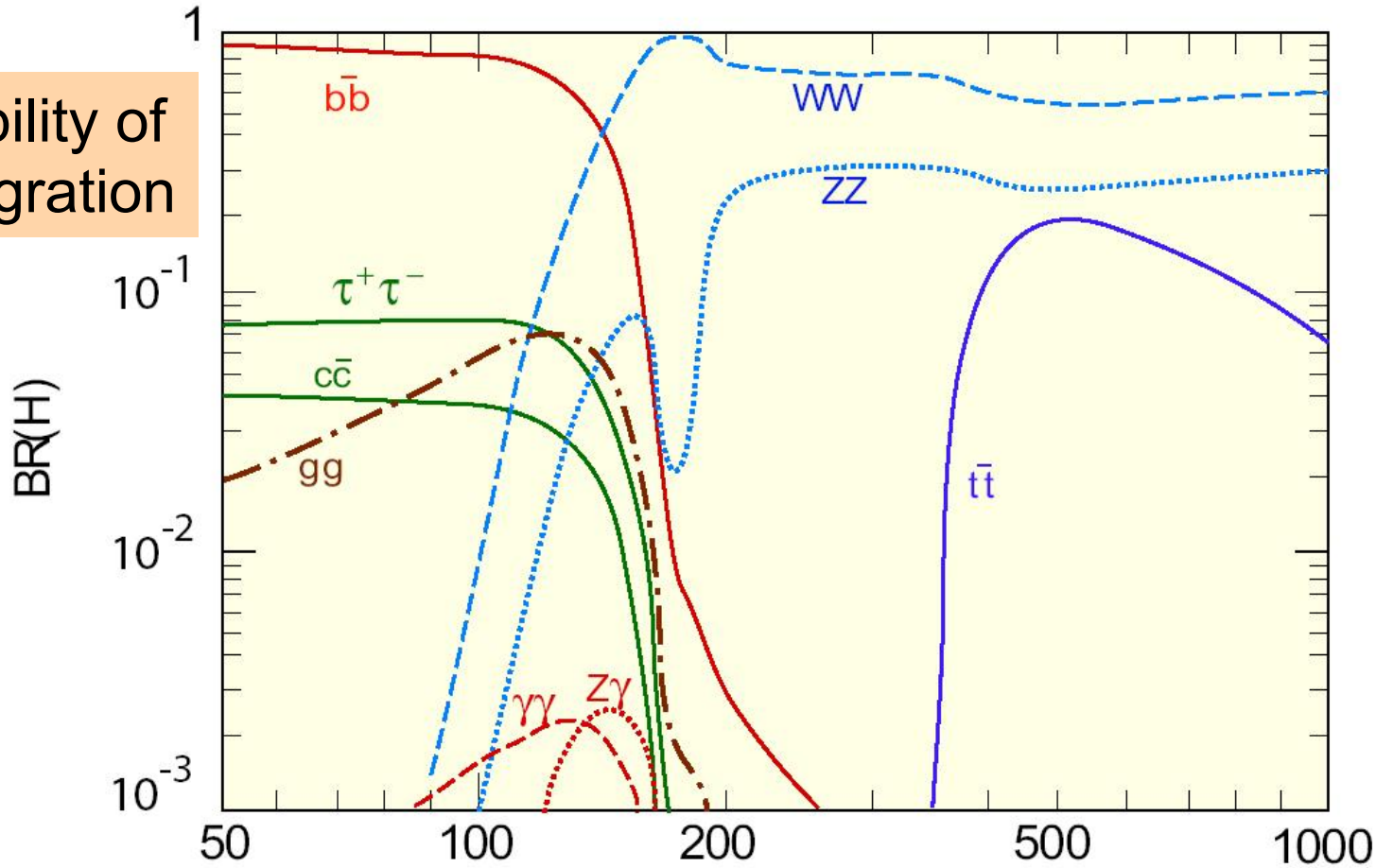
Probability of disintegration



Mass of the Higgs in Gev 1 GeV = 1 proton mass

Two photon Mass Distribution – July 4, 2012

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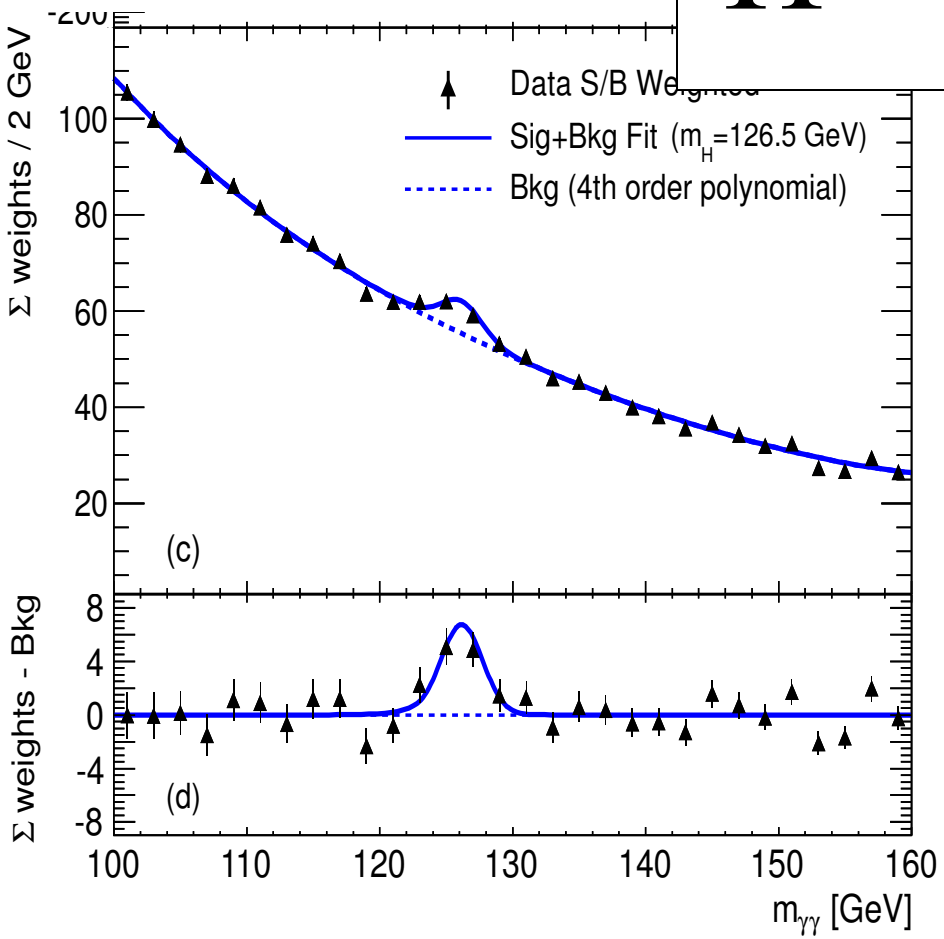
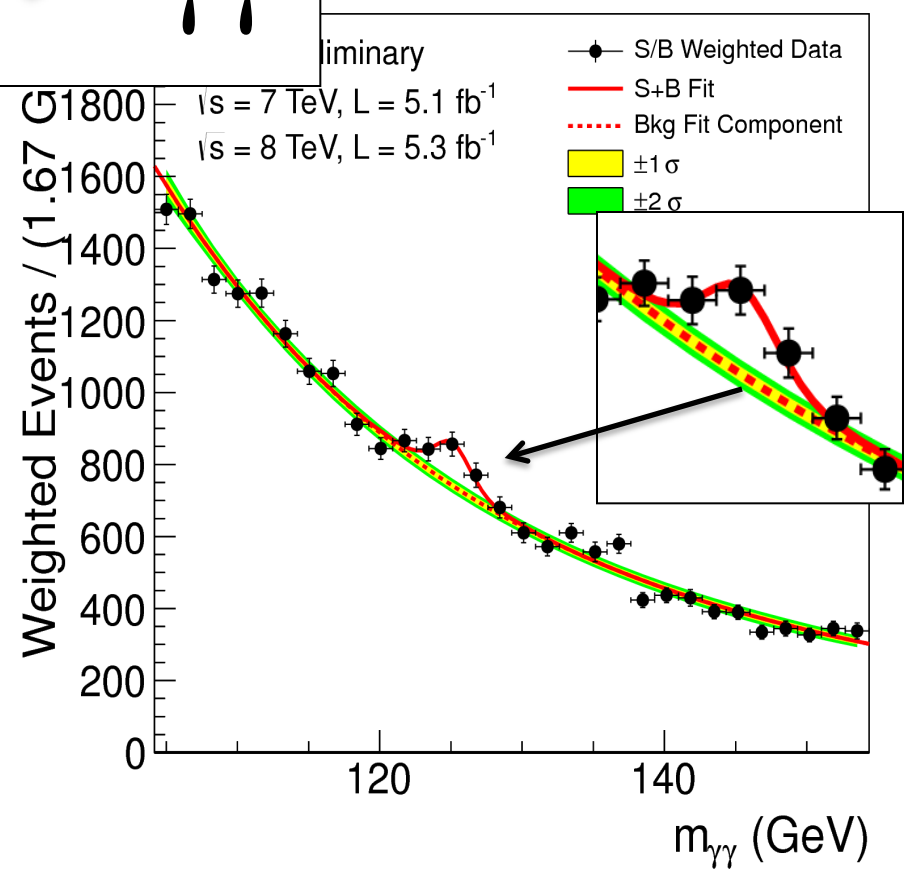
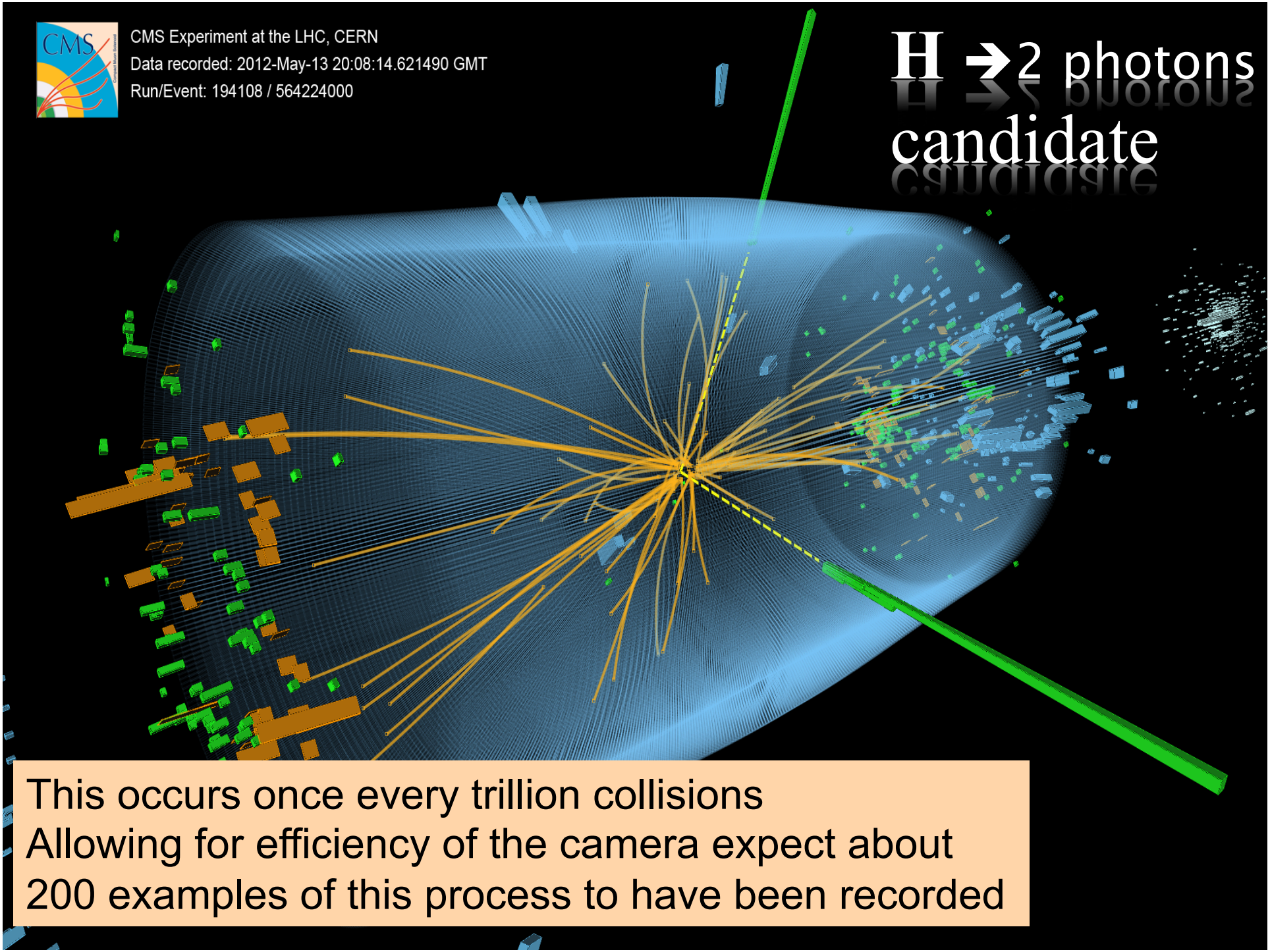
$H \rightarrow \gamma\gamma$

ATLAS



CMS





This occurs once every trillion collisions
Allowing for efficiency of the camera expect about 200 examples of this process to have been recorded

Four Lepton Mass Distribution – July 4, 2012

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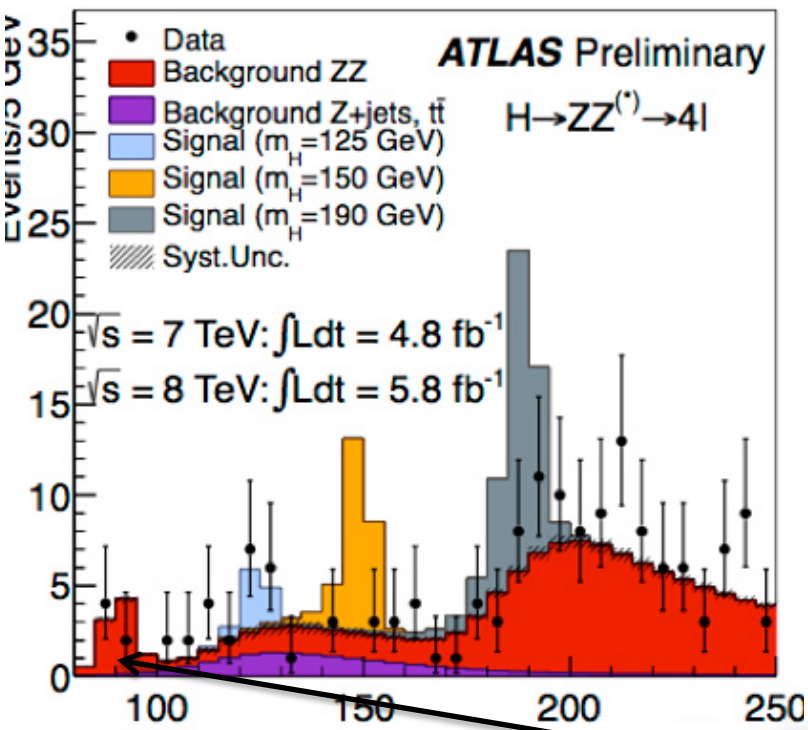
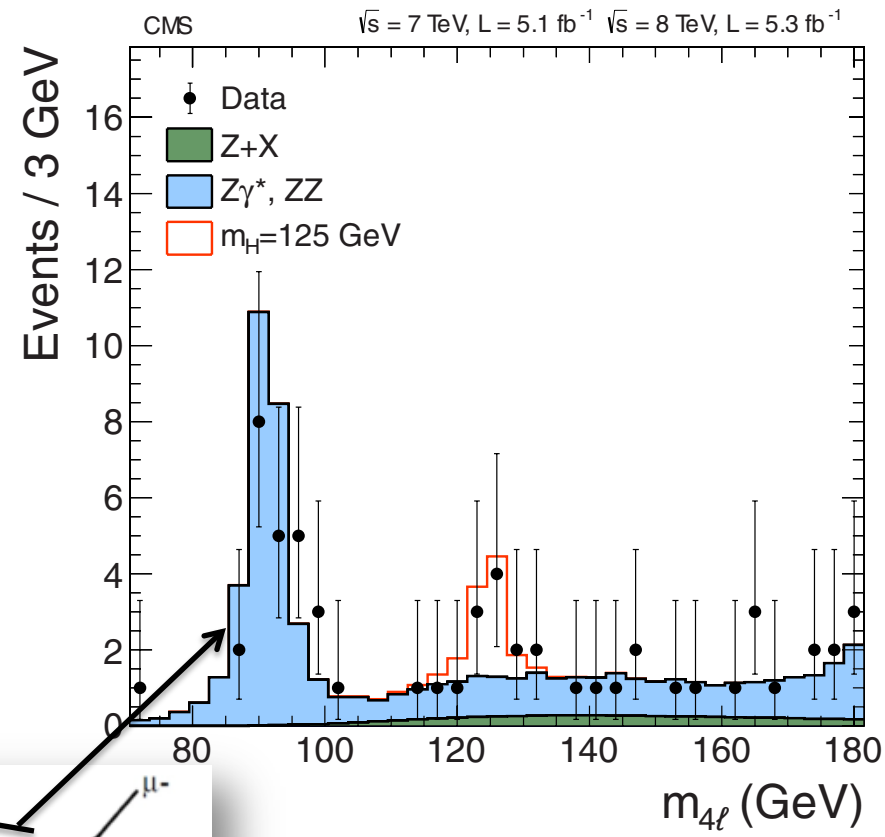
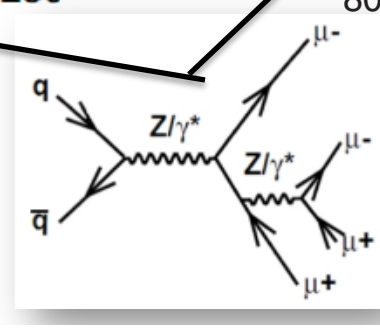
$$H \longrightarrow ZZ^* \longrightarrow 4 \text{ leptons}$$

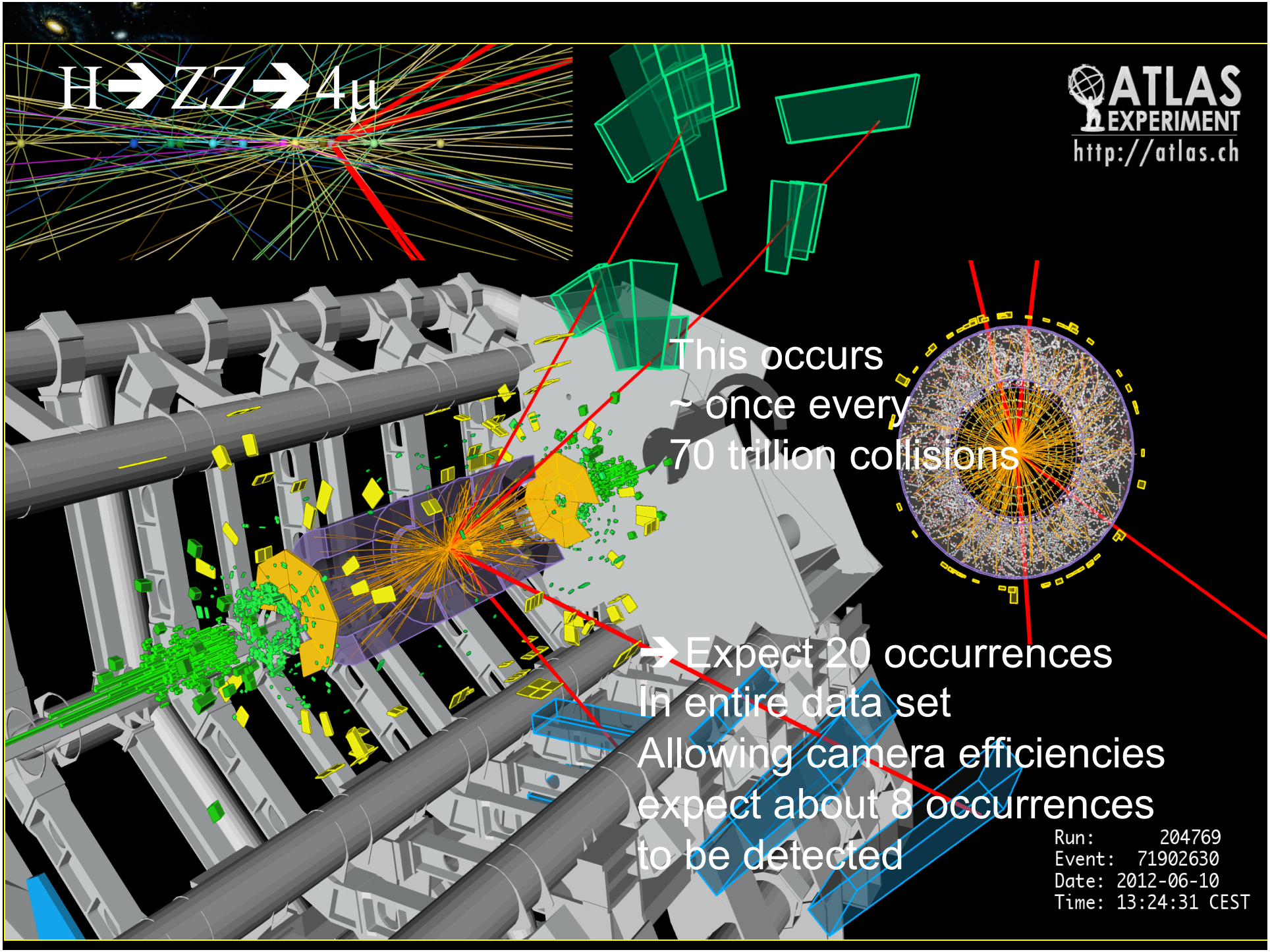
ATLAS



CMS



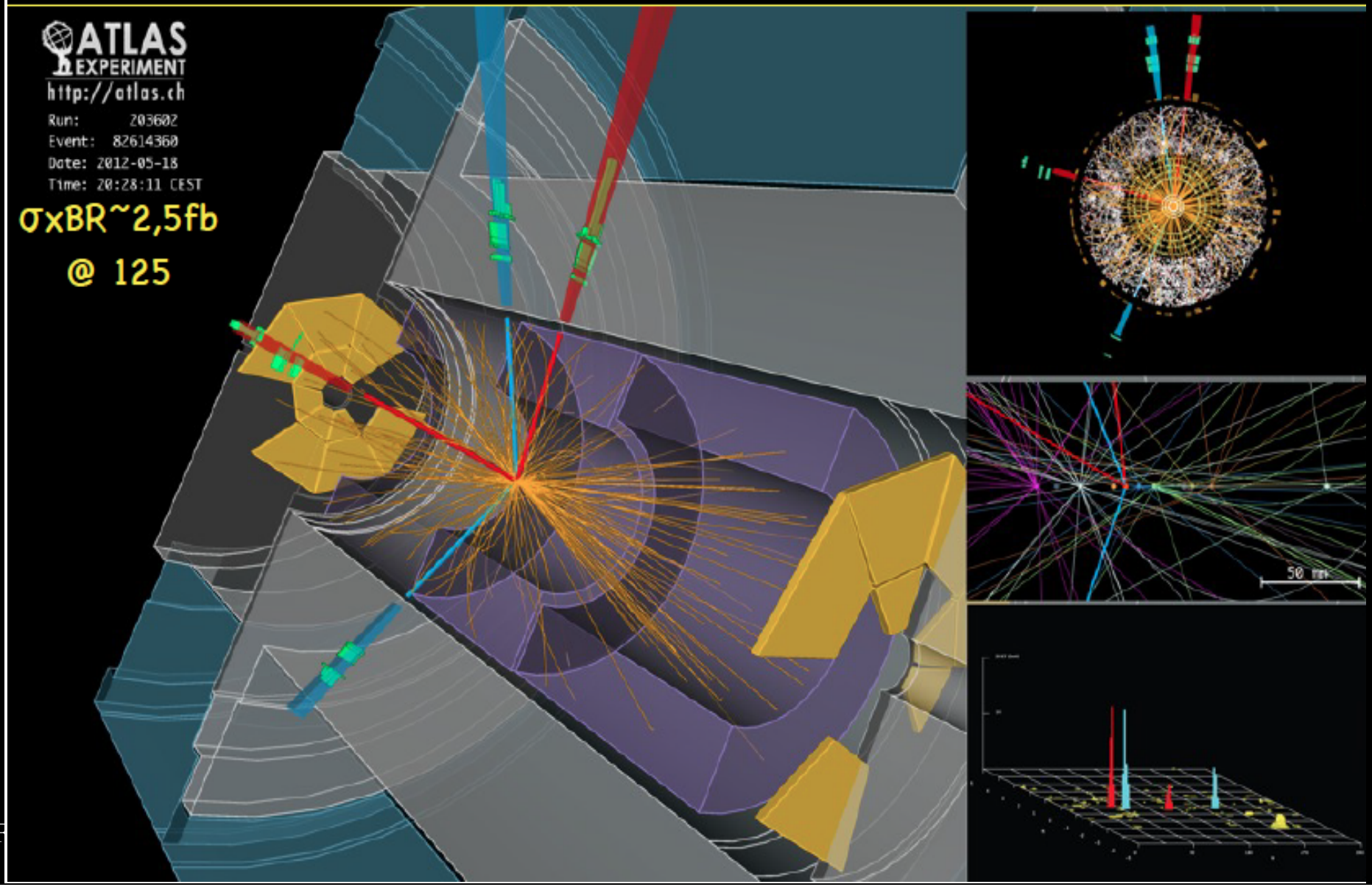



H→ZZ→4μ
ATLAS
EXPERIMENT
http://atlas.ch
This occurs
~ once every
70 trillion collisions
→Expect 20 occurrences
In entire data set
Allowing camera efficiencies
expect about 8 occurrences
to be detected
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

H→ZZ→4e

4 leptons

4e candidate with mass = 124.5 GeV



Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration[a]

[a] CERN

Abstract

Results are presented from searches for
7 and 8 TeV in the Compact Muon Solenoi
luminosities of up to 5.1 fb^{-1} at 7 TeV and
W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events i
standard deviations, at a mass near 125 GeV
a standard model Higgs boson of that mass
modes with the best mass resolution, $\gamma\gamma$ and
The decay to two photons indicates that the

ATLAS
arXiv:1207.7214

CMS
arXiv:1207.7235

Both submitted
Aug. 1 2012

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\mathrm{stat}) \pm 0.4\,(\mathrm{sys})$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

“First observations of a new particle in the search for the Standard Model Higgs boson at the LHC” – published Oct 2012

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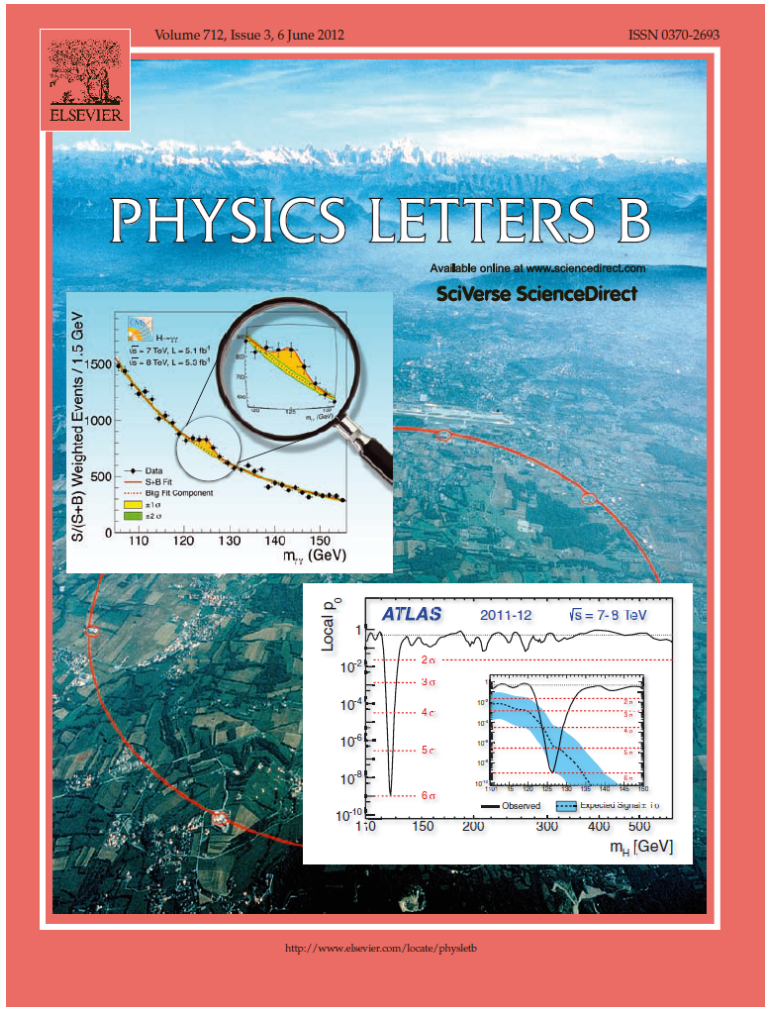

The observed particle behaves like a Standard Model Higgs Boson

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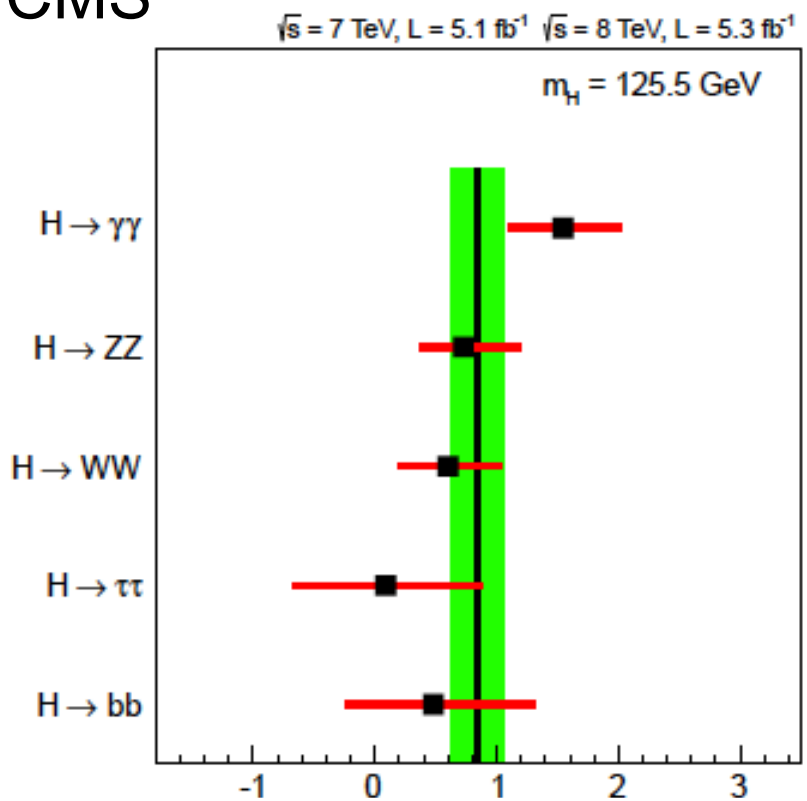
Higgs Decays as expected

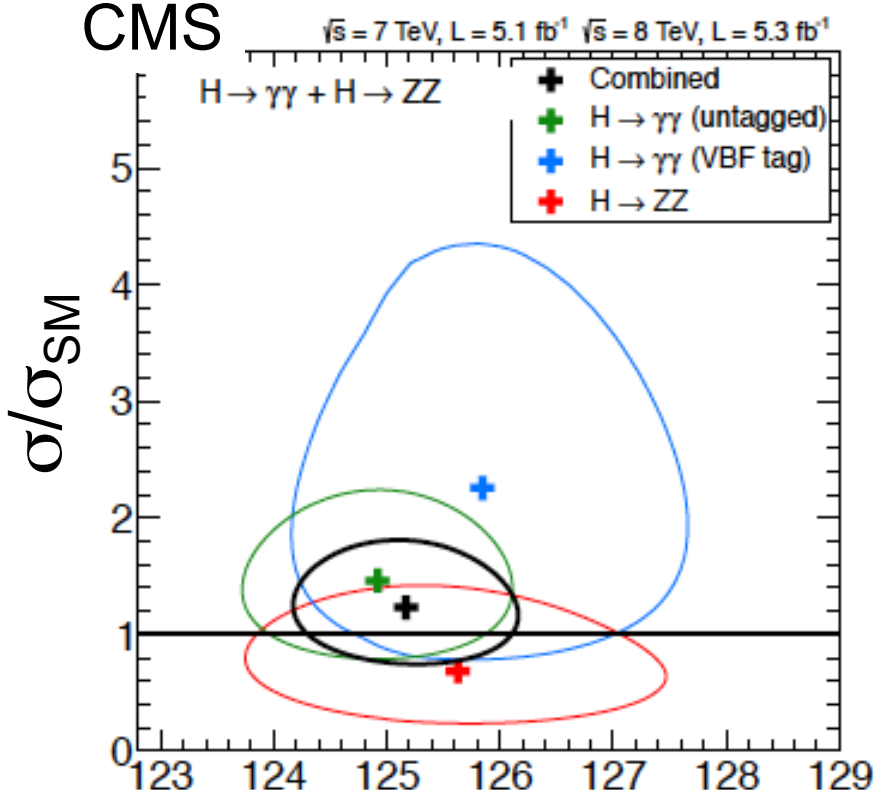
CMS



Measured rate/Predicted rate

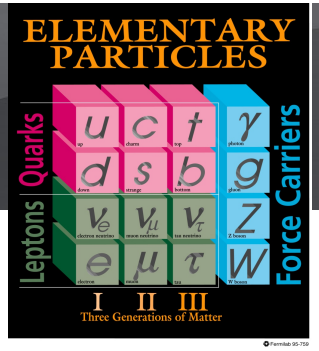
Higgs Masses extracted from different decays are consistent

CMS



M_H (GeV)

Mass Composition of the Universe



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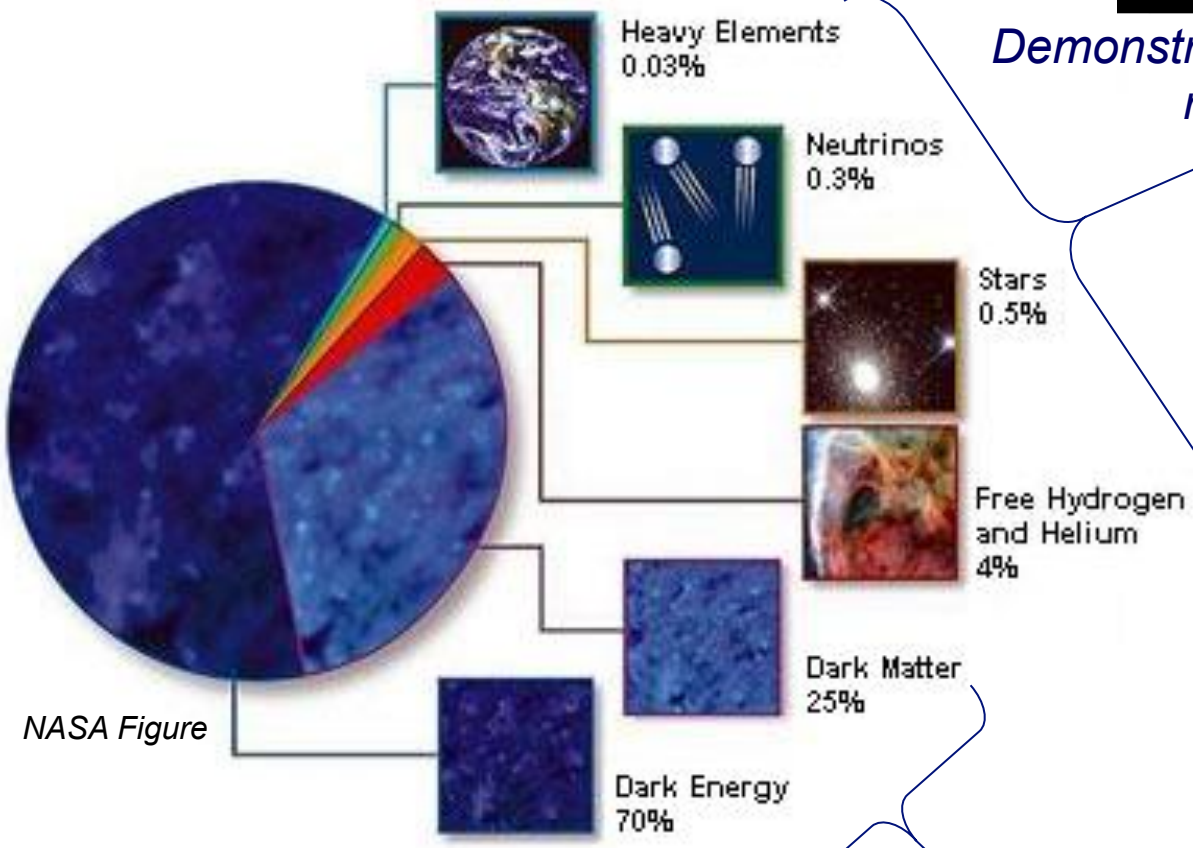

NASA Figure

Demonstrably measurable – reasonably understood

95% of the mass of the Universe is dark matter and dark energy which is NOT explained by the Higgs mechanism

Known by implication – only have speculation

Summary and Outlook

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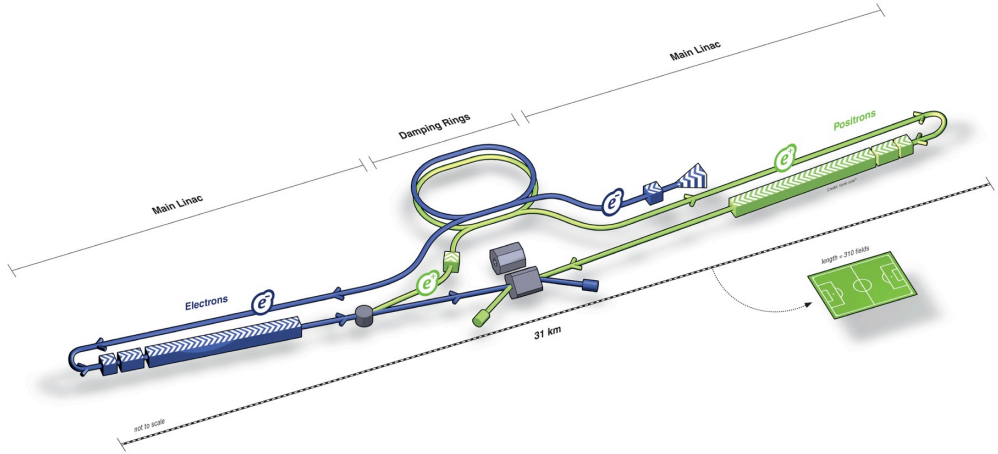
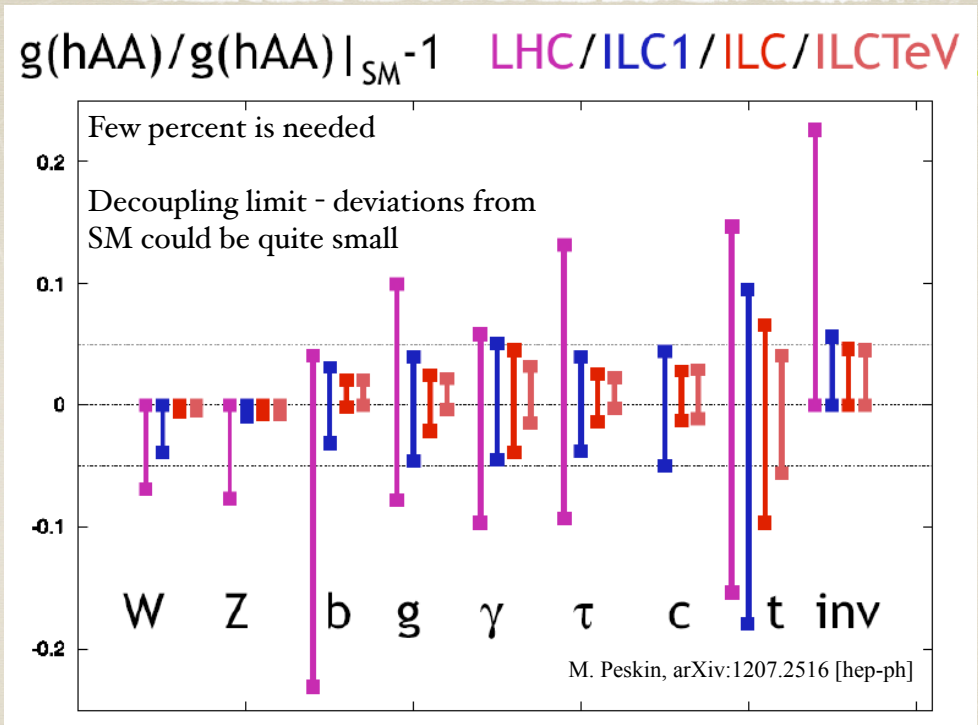
- The technical achievement of the Large Hadron Collider and the ATLAS and CMS detectors built upon decades of accelerator-based particle physics – often led by scientists and facilities in the US.
  - The US has made substantial (>$1 Billion) investment in the Large Hadron Collider and the ATLAS and CMS experiments.
- The ATLAS and CMS results provide conclusive evidence for the discovery of a new particle with mass of about 125 GeV that has many of the right properties to be the Standard Model Higgs Boson.
- Although these results are compatible with the hypothesis that the new particle is the Standard Model Higgs boson, more data are needed to assess its nature in detail.
  - Data taking at LHC will resume at end of 2014 with 14 TeV running
  - 2018 shutdown is planned to upgrade for high data rates
- Discovery of the Higgs Boson is a “big deal” and will likely result in a Nobel Prize for Peter Higgs and perhaps others

Prospects for Precision Higgs Boson studies at the International Linear Collider



- Expected to cost $10-20 Billion
- Japan interested in hosting with international partners



LHC, 300 fb^{-1}, 1 experiment
ILC1 at 250 GeV, 250 fb^{-1}
ILC at 500 GeV, 500 fb^{-1}
ILCTeV at 1000 GeV, 1000 fb^{-1}

For each decay channel, a succeeding generation measurement includes also all the previous measurements.
The symbol "inv" indicates limits on the coupling to invisible decay modes of the Higgs; the final 95% CL limit on the branching ratio is 0.3%.

Technical Design Report (machine) and Detailed Baseline Design (Detector) completed in 2013

Electron-positron colliders probe a precision probe in clean, low background environment to reveals detail of underlying physics discovered at the LHC