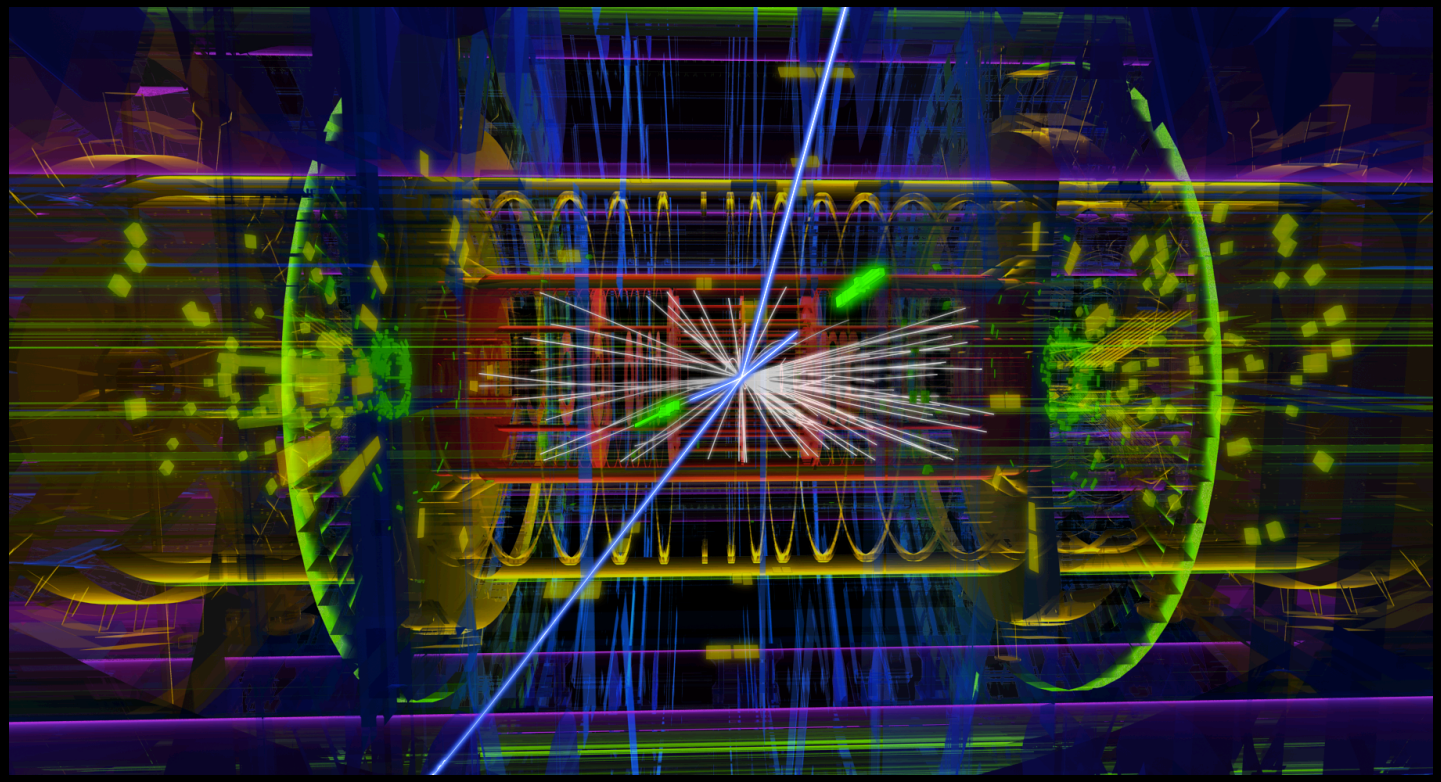
The Higgs Boson: Breakthrough of the year

The Mystery of Mass and Matter

Marcela Carena
Fermilab and U. of Chicago

The Hubble Circle Immersion, SpaceX, April 27, 2012

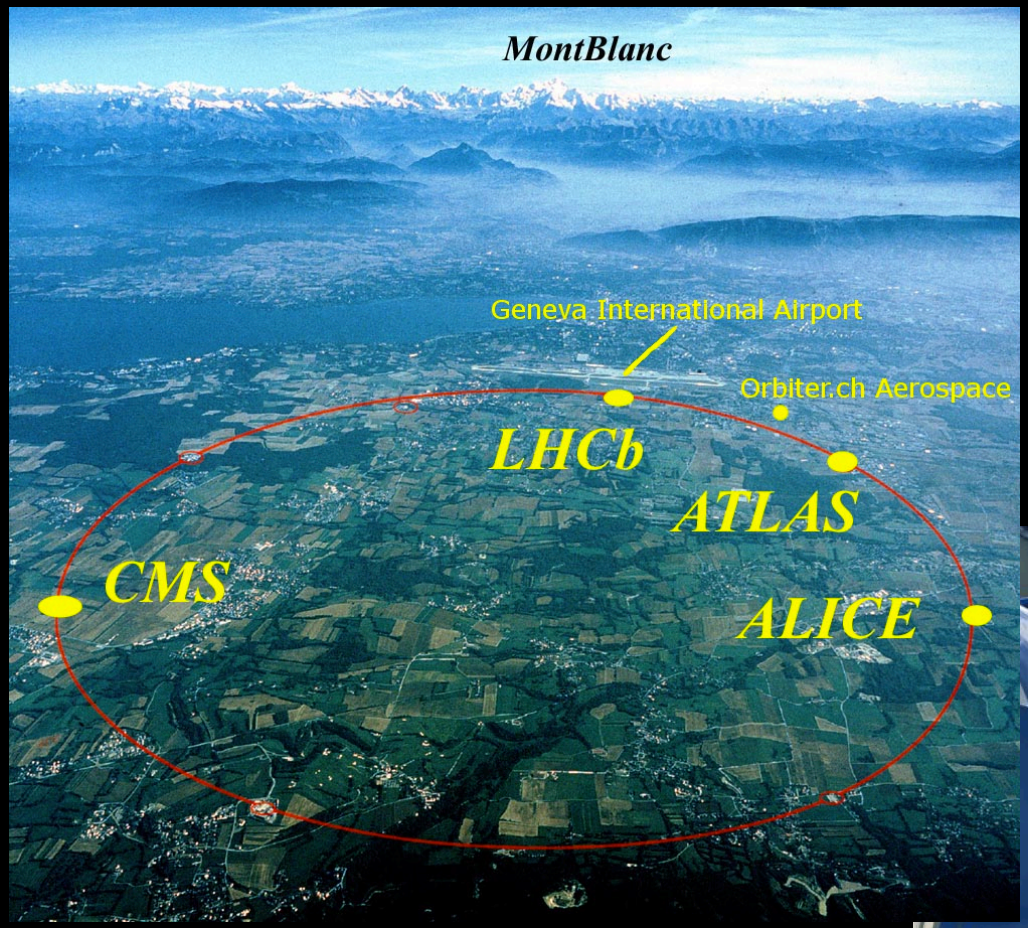
Fireworks on 4th July 2012



- Discovery of a new particle, of a type never seen before
- Confirmation of a new type of interaction among particles

A new era of particle physics and cosmology

The Large Hadron Collider (LHC) @ CERN



So much energy…

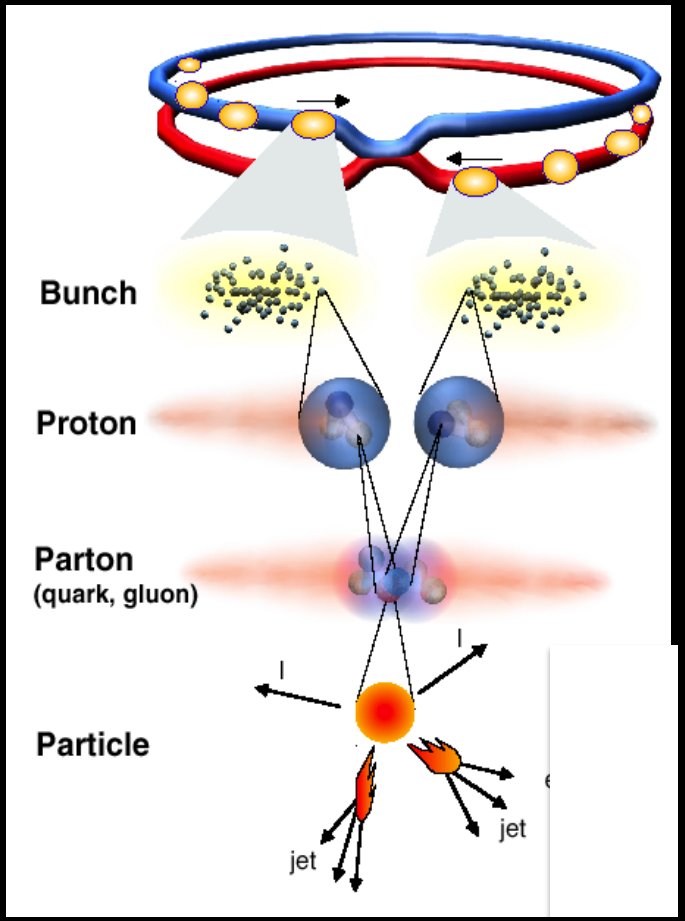
that it is like we transport ourselves to instants after the BIG BANG

A 17 mile long vacuum pipe
300 ft below ground

LHC:
why so huge and why circular ?

- Charged particles are accelerated by electric fields
- A linear accelerator would be prohibitively long
- Instead protons are sent in a circular path and they get several “kicks” with electric fields every time they come around
- Protons are bent in a circular path with magnets
- The higher the energy the harder it is to bend the protons

The size of the ring is set by the strongest magnets we can build



About a Billion proton-proton collisions per second

About 100 particles produced per collision

To look at the new particles we have powerful detectors

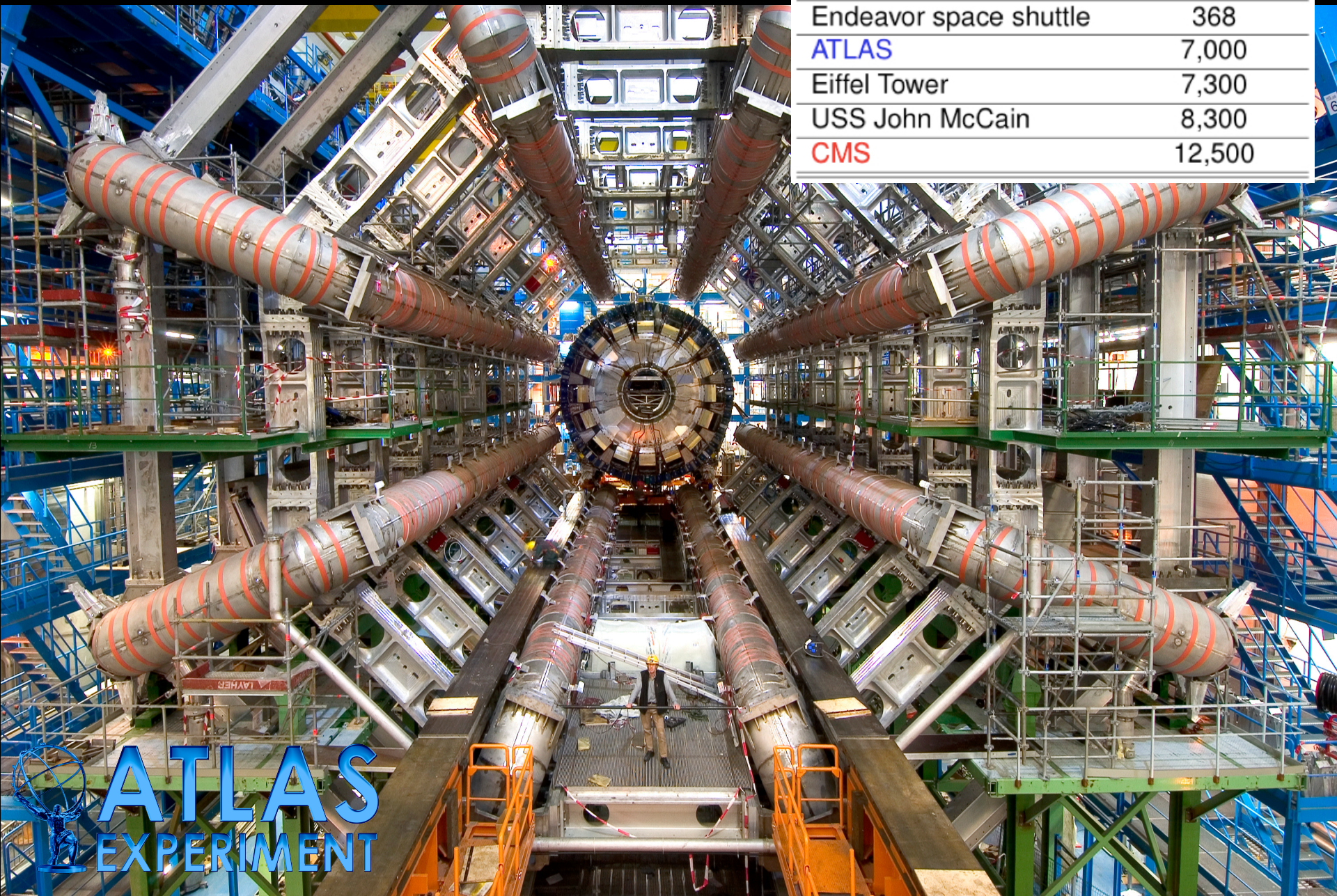
- Equivalent of a camera to take “pictures” of the collisions
- They are not ordinary cameras:

  80 Million pixels
  40 million pictures per second
  Three dimensional picture

- They are huge, complex objects with cutting-edge technology

ATLAS Detector :

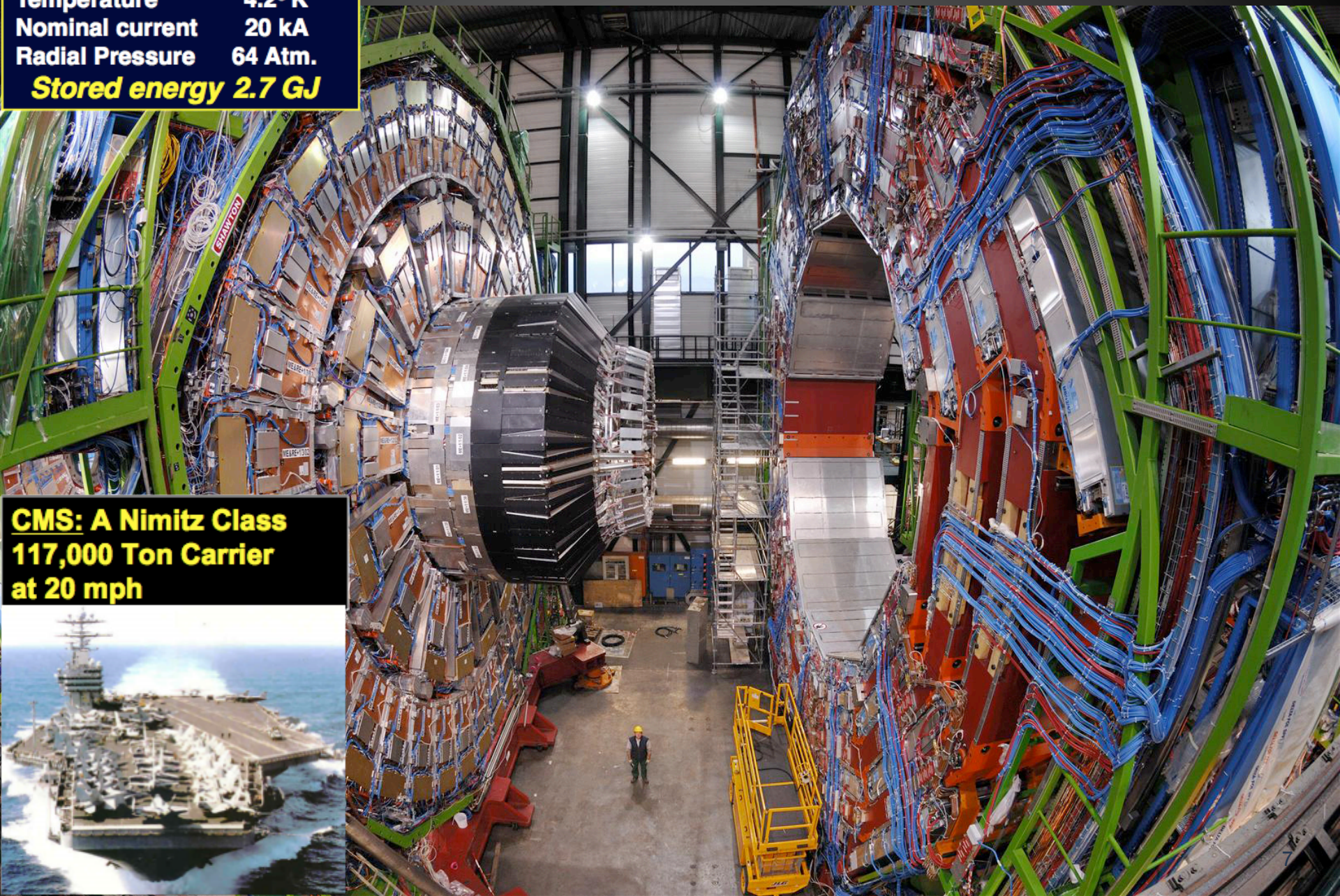
Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500



CMS Detector :

Magnetic length	12.5 m
Free bore diameter	6 m
Central B Field	3.8 Tesla
Temperature	4.2° K
Nominal current	20 kA
Radial Pressure	64 Atm.

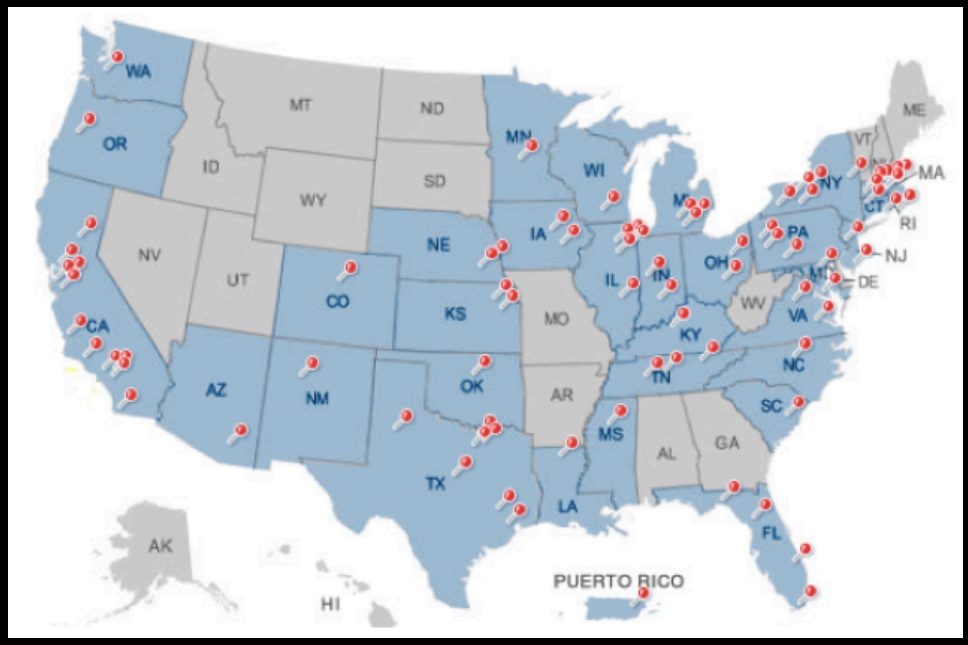
Stored energy 2.7 GJ



CMS: A Nimitz Class 117,000 Ton Carrier at 20 mph

U.S. plays a leading role in LHC discovery

- U.S. = 1/3 of CMS, the largest contingent
- U.S. = 1/5 of ATLAS
- CMS/ATLAS leadership: spokesperson, upgrade coordinator, deputy spokespersons, physics coordinators, managers, critical hands-on roles in discovery analyses, hardware, computing
- 1,700 scientists, students, engineers and technicians
- 93 universities,
  7 national labs, 32 states



July 4, 2012

"I think we have it!"

-Rolf Heuer,
CERN director general

Reactions from CERN

"I never expected this to happen in my lifetime" - Peter Higgs

The first time that the entire NYT Science section is devoted to a single story

Chasing the Higgs Boson | INTRODUCTION | PROMISED FIREBALLS | GAME OF BUMPS | STILL MISSING | OOZING INTO VIEW | OPENING THE BOX

Chasing the Higgs Boson

Large Hadron Collider near Geneva, two scientists struggled to close in on physics' particle.

OVERBYE
March 5, 2013 | 252 Comments

MEYRIN, Switzerland — Vivek Sharma missed his daughter.

sity of Sharma time away a team of dron Geneva. era flew to

Illustration by Sean McCabe/Photographs by Daniel Auf der Mauer, Toni Albir, Fabrice Coffrini, Fred Merz

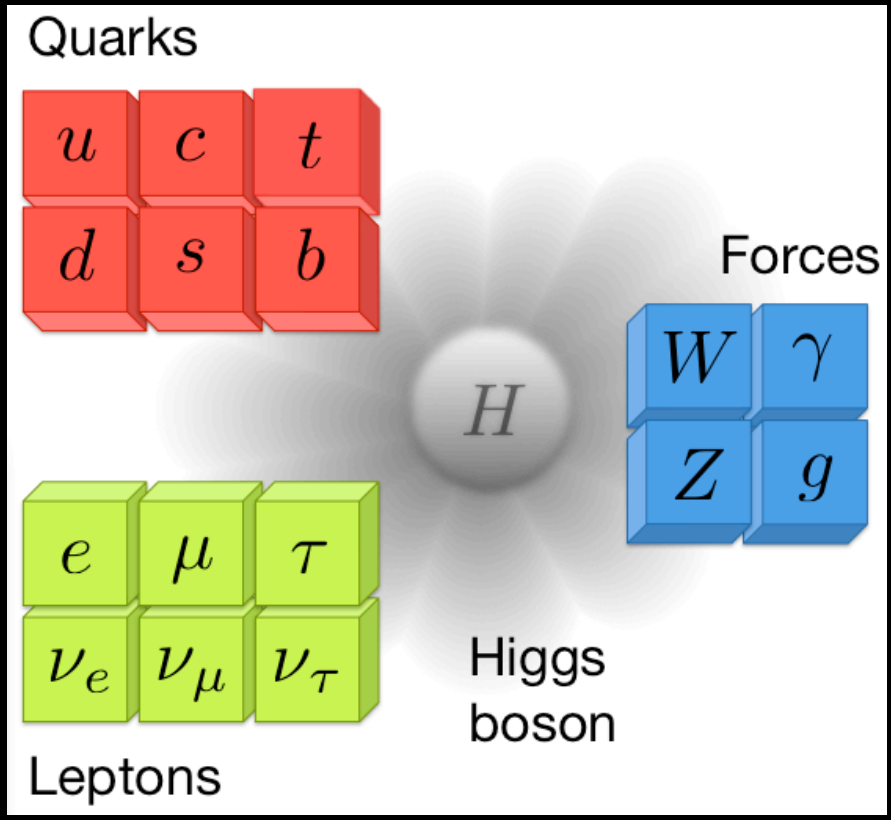
Peter Higgs, center, of the University of Edinburgh, was one of the first to propose the particle's existence. From left, physicists at CERN who helped lead the hunt for it: Sau Lan Wu, Joe Incandela, Guido Tonelli and Fabiola Gianotti.

Why is the Higgs so important ?

Sub-atomic particles of the Standard Model of Particle Physics

They have all been produced in the laboratory

They have very different masses



What causes fundamental particles to have mass?

What causes fundamental particles to have mass?

Theory of relativity:

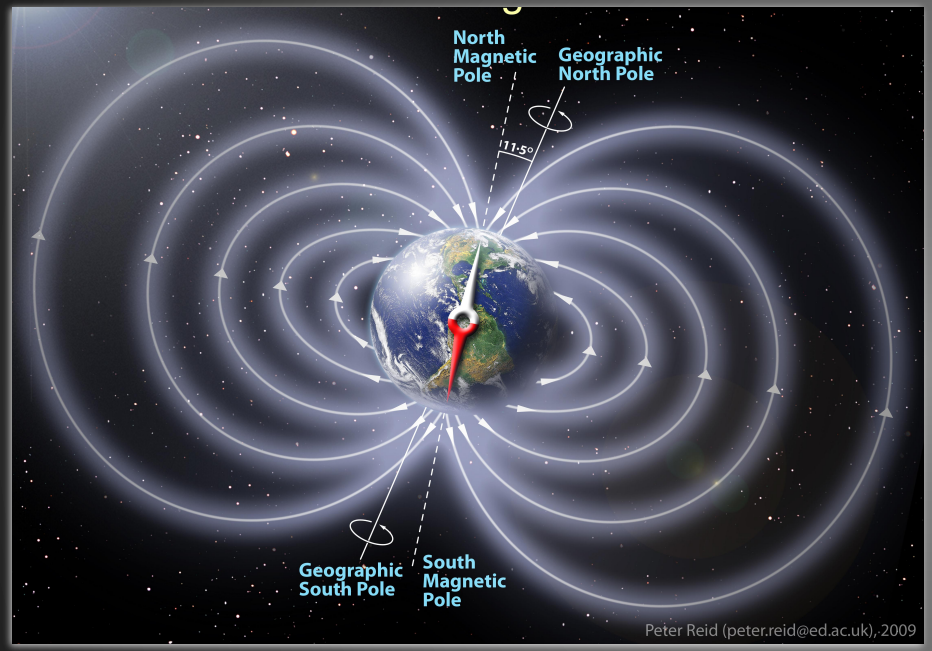
Space and time are relative and entangled: spacetime (1905)

Space and time are dynamical: mass and energy curve the spacetime (1916)

$$E=mc^2$$

A field of Energy that permeates all of the space

Invisible Force Fields



The Earth's Magnetic Field

sourced by the Earth permeates nearby space

The Higgs Field

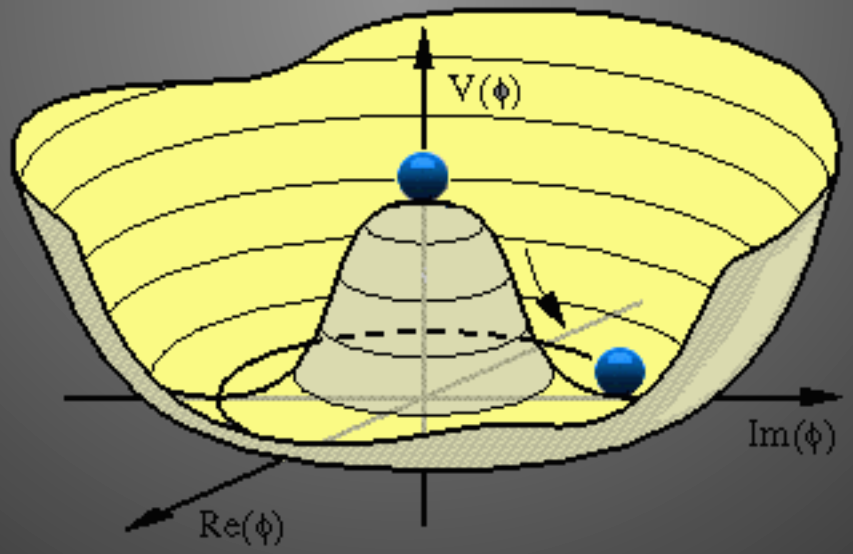
sourced by itself permeates the entire universe

What turns the Higgs field on?

The Higgs field is self-sourcing

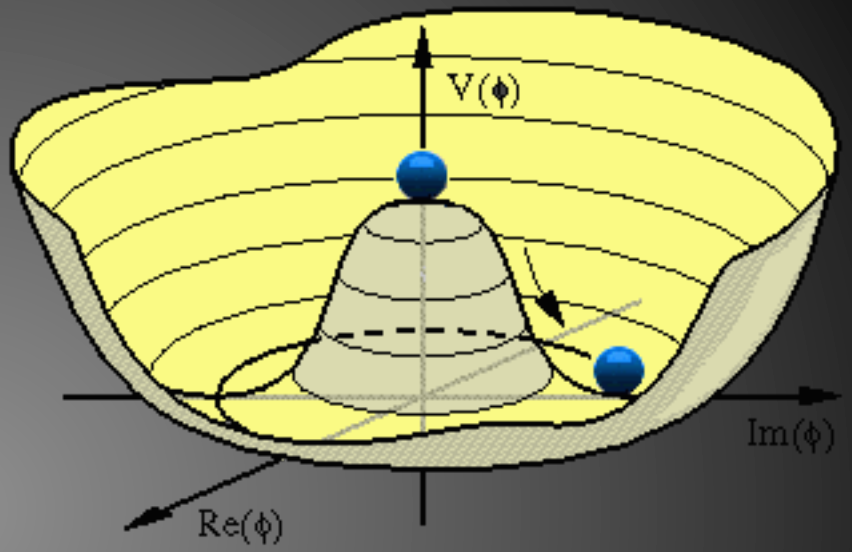
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

The Higgs potential describes the energetics of turning on the Higgs field
The global minimum defines the vacuum state



Spontaneous Symmetry Breaking

Spontaneous Symmetry Breaking

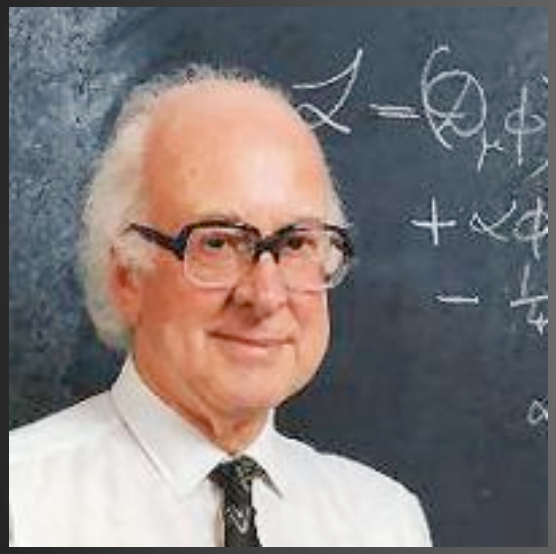


Prof. Yoichiro Nambu (U.of Chicago)
Nobel Prize in Physics 2008

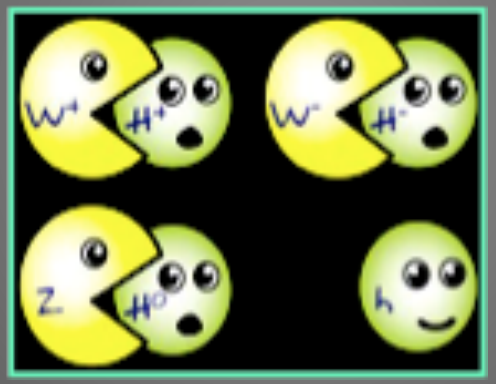
Whose plate is this ?

The Higgs Mechanism and the Higgs Boson

A fundamental scalar field with self-interactions can cause spontaneous symmetry-breaking in the vacuum without picking a preferred frame or direction, and can give gauge bosons mass



Higgs et al (1964)



Matter fields also get mass from new type of interactions with the Higgs boson

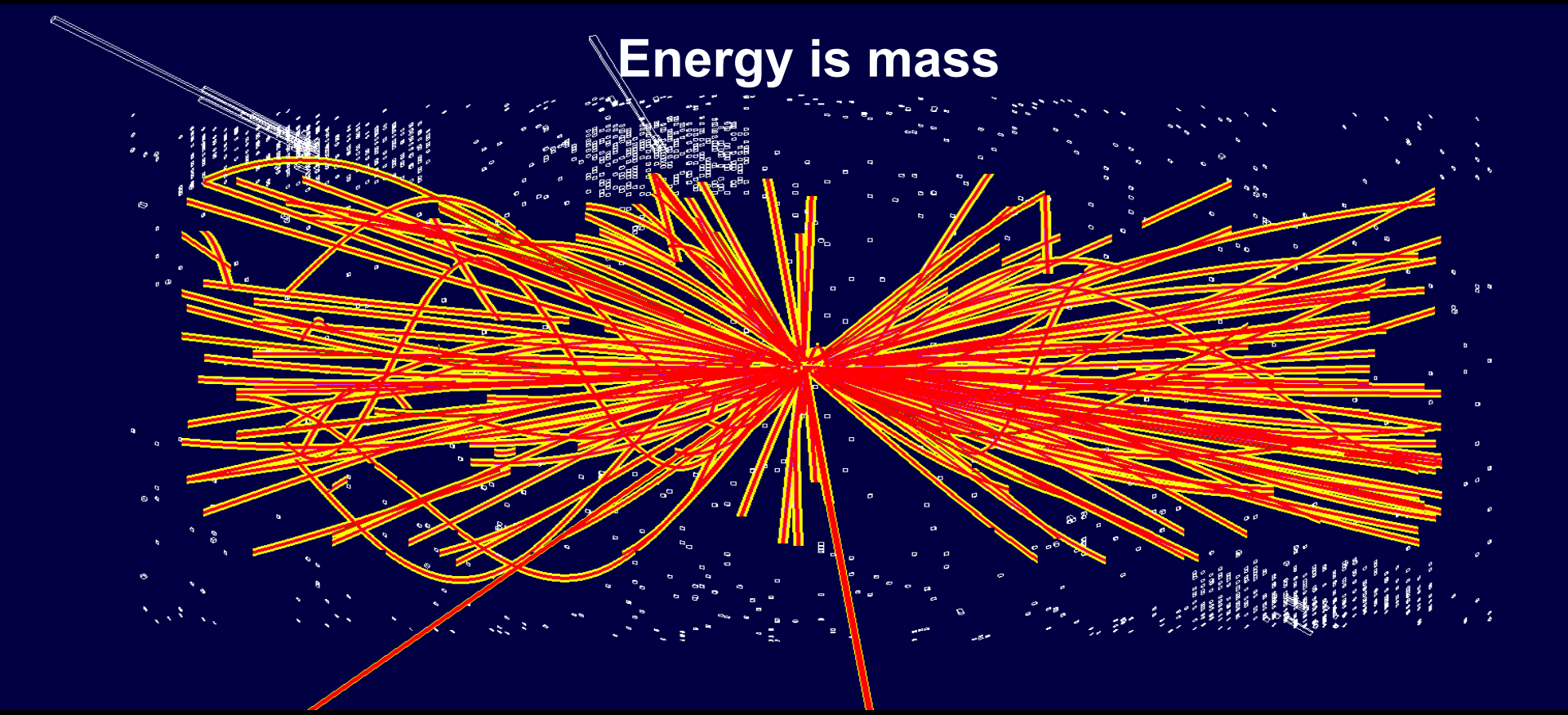
Heavier particles interact more with the Higgs

The Standard Model of Particle Physics

Weinberg-Salam (1967)

How do we search for the Higgs?

Smashing Particles at High Energy Accelerators to create it



And searching for known particles into which the Higgs transforms (decays) almost instantly

At huge Particle Accelerators,

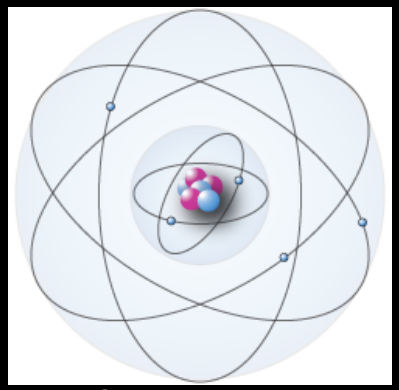
Shouldn't we expect to find particles consisting of

the initial particle constituents?

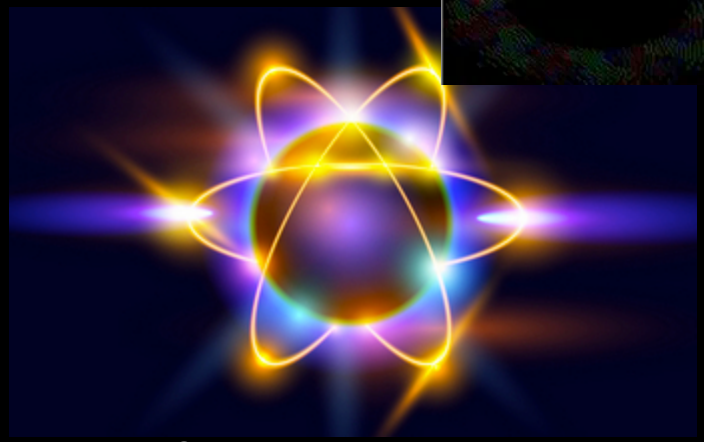
An element of chance in the microscopic world

$\Delta x \cdot \Delta p \sim h$

Werner Heisenberg



Classical
model of atoms

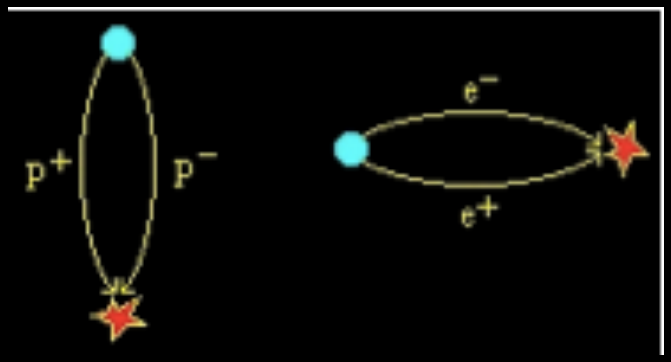


Quantum mechanical
model of atoms

Quantum Vacuum

"Nothingness" is the most exciting medium in the cosmos!

Quantum fluctuations create and annihilate "virtual particles" in the vacuum



$\Delta t \cdot \Delta E \sim h$

At huge Particle Accelerators,

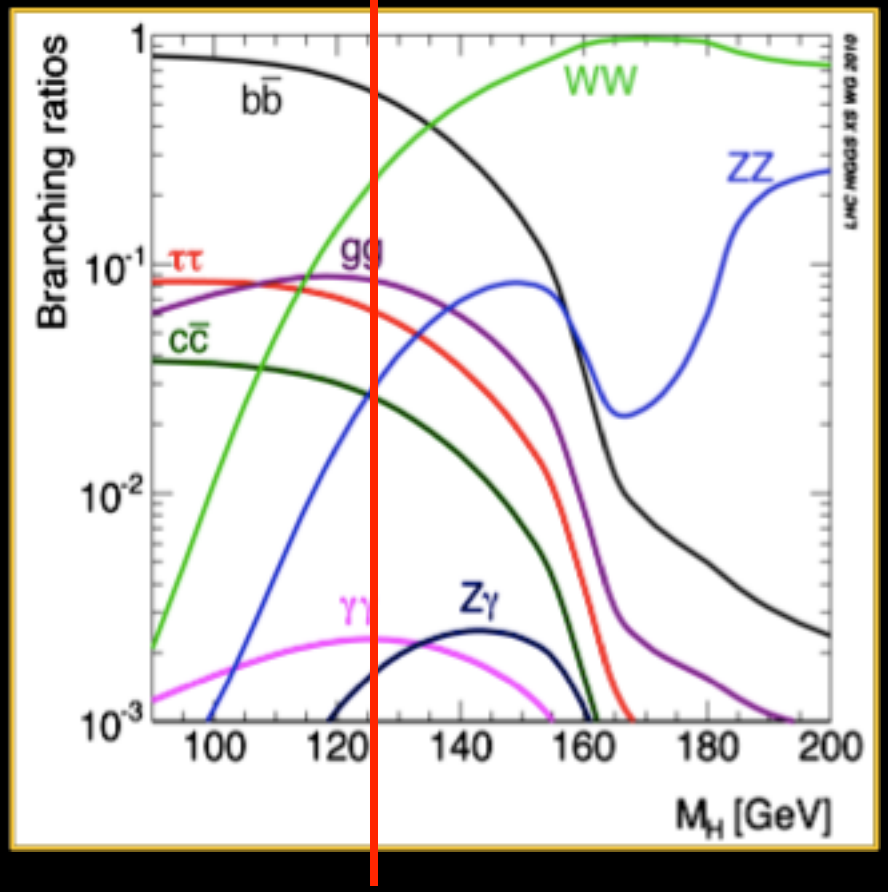
virtual particles + energy → real particles

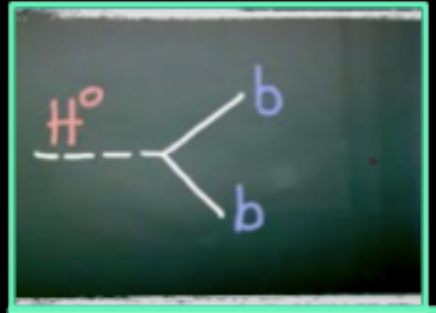
quantum vacuum — accelerator — production of new particles

Quantum Fluctuations can produce the Higgs at the LHC

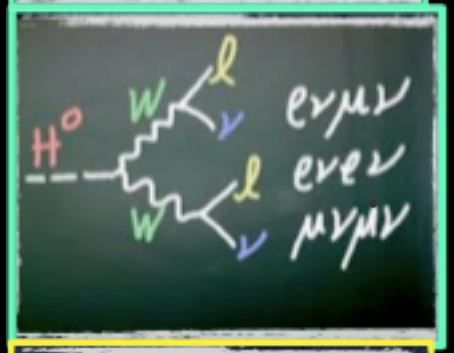
Higgs decays:

Higgs decays after about 100 yocktoseconds into various pairs of lighter particles

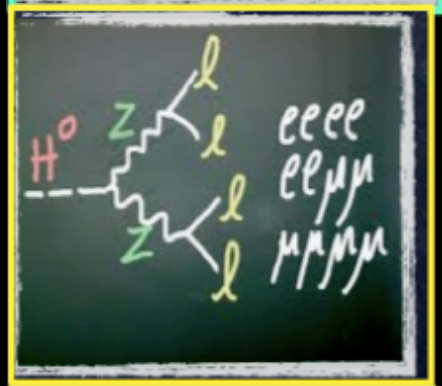




Lots of background



Neutrinos not detected

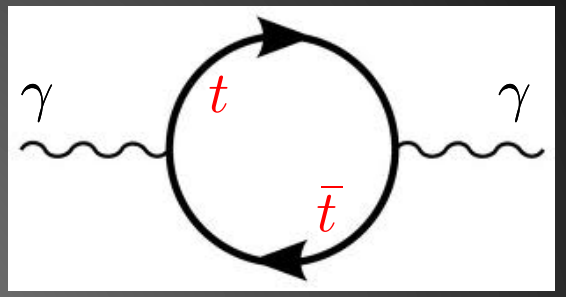


Rare but “Golden” channel

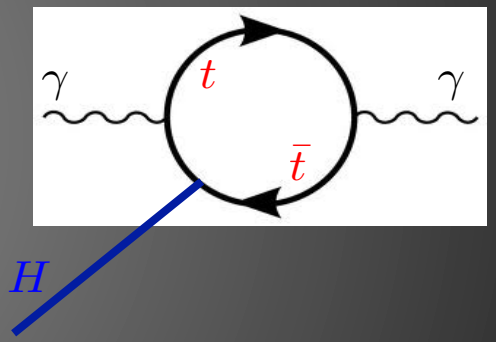
Rare but relatively clean

Virtual particles facilitate Higgs discovery

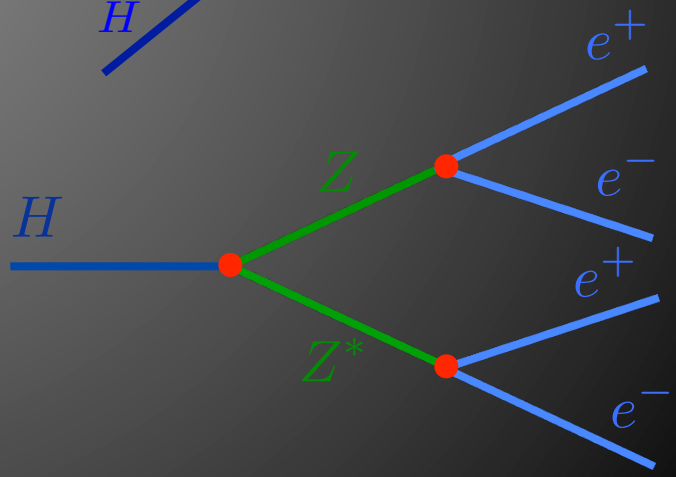
Photon propagates in Quantum Vacuum



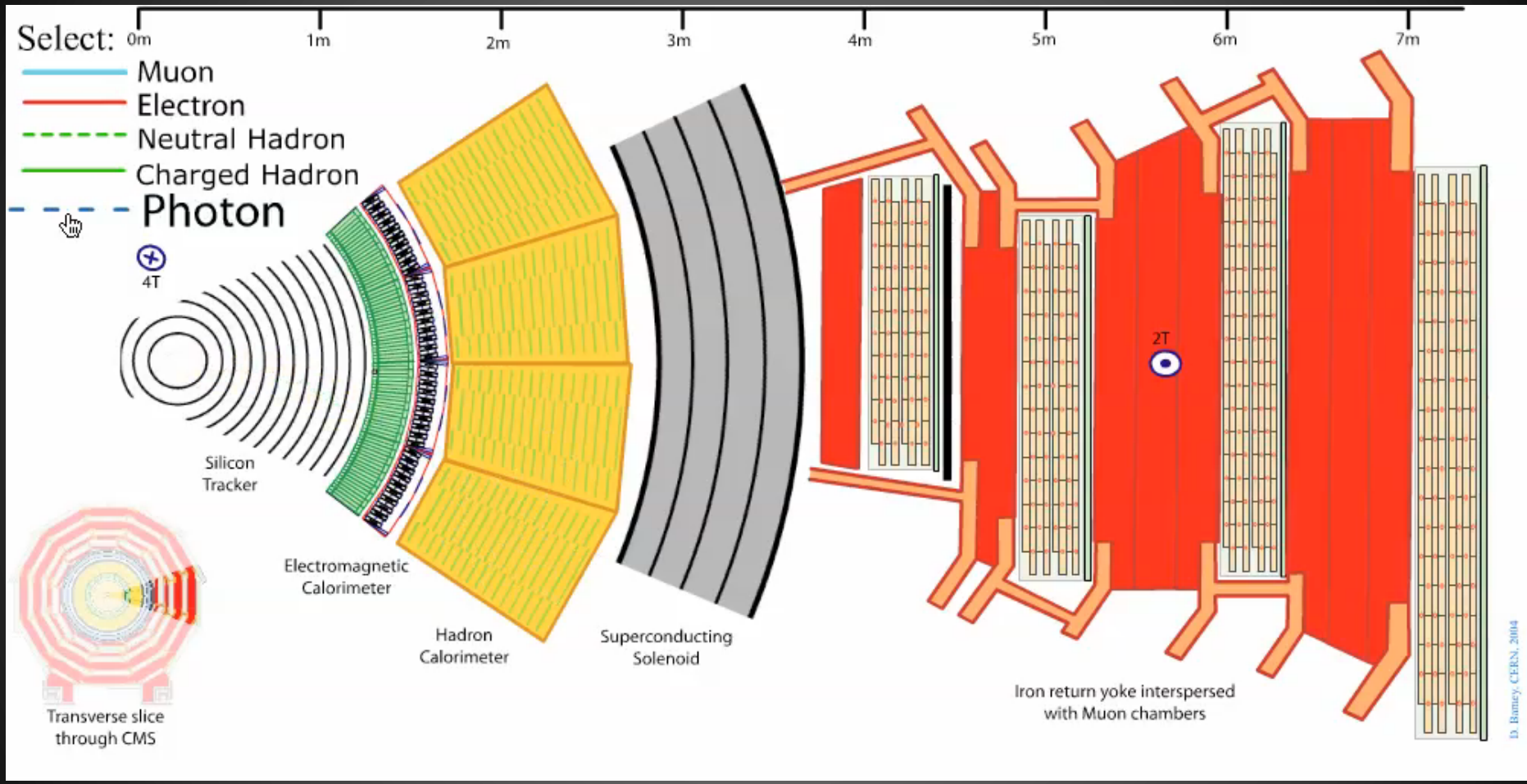
Higgs decays into 2 Photons



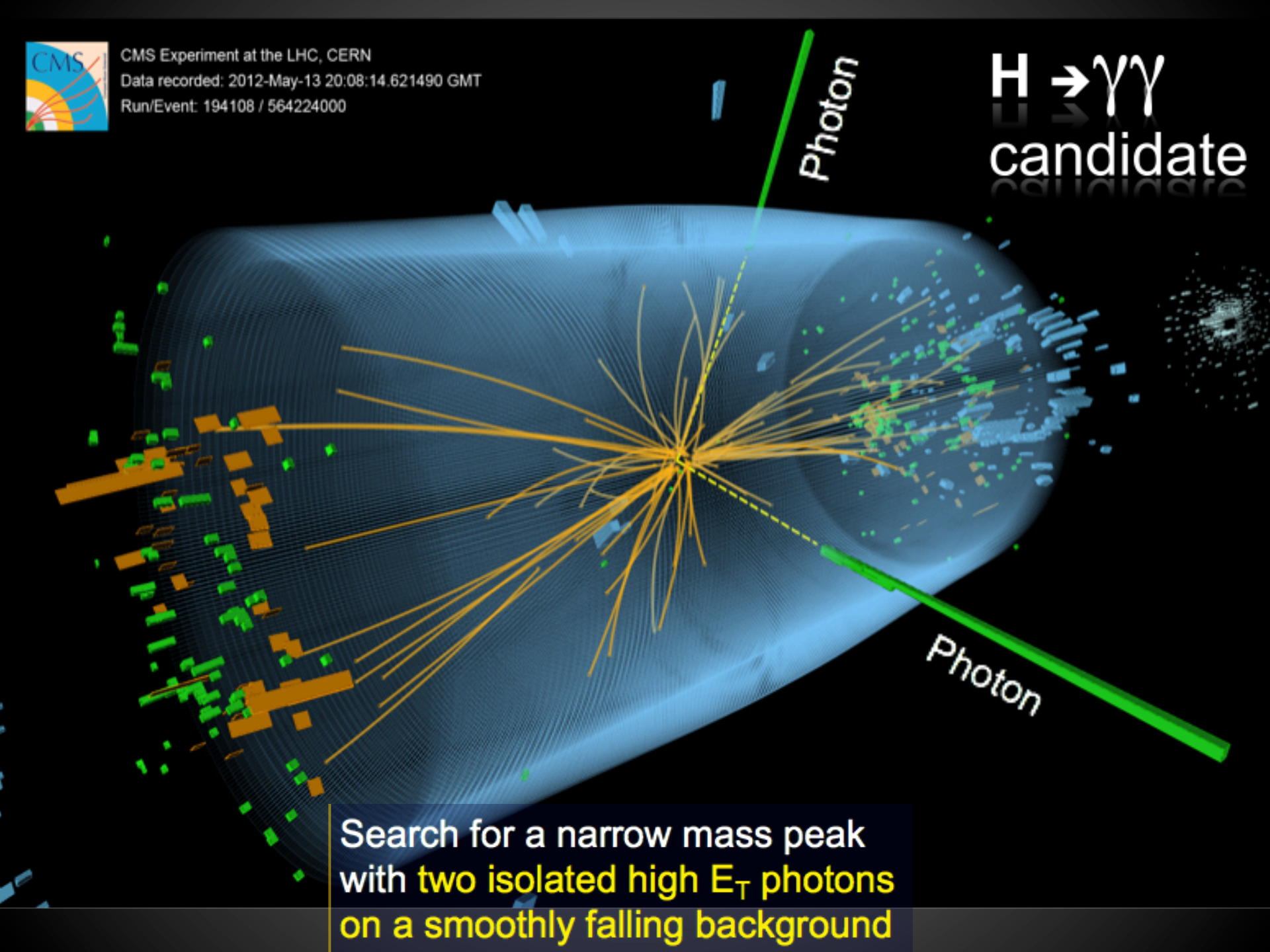
Higgs decay into 4 leptons via virtual Z bosons



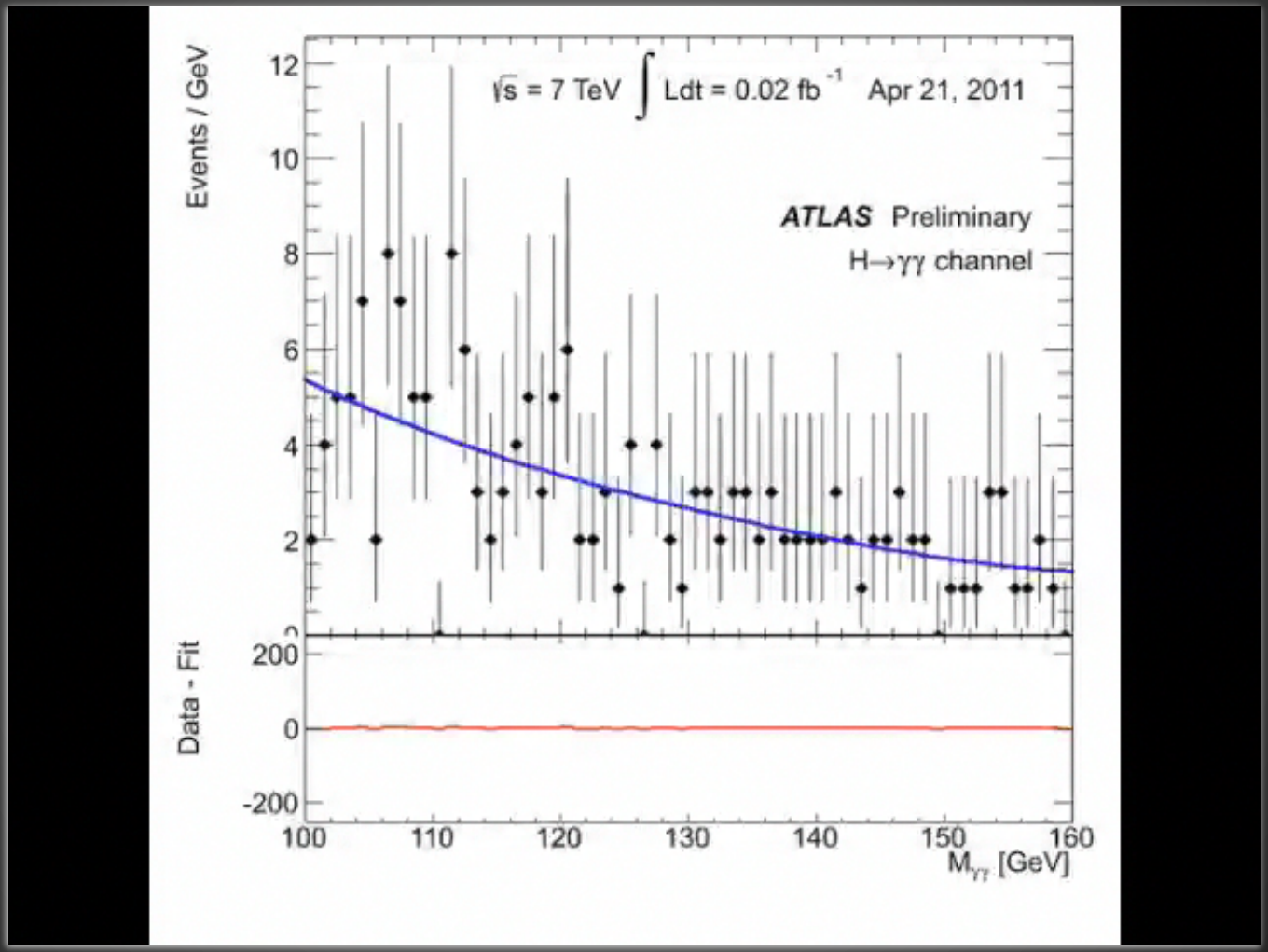
What the detectors detect



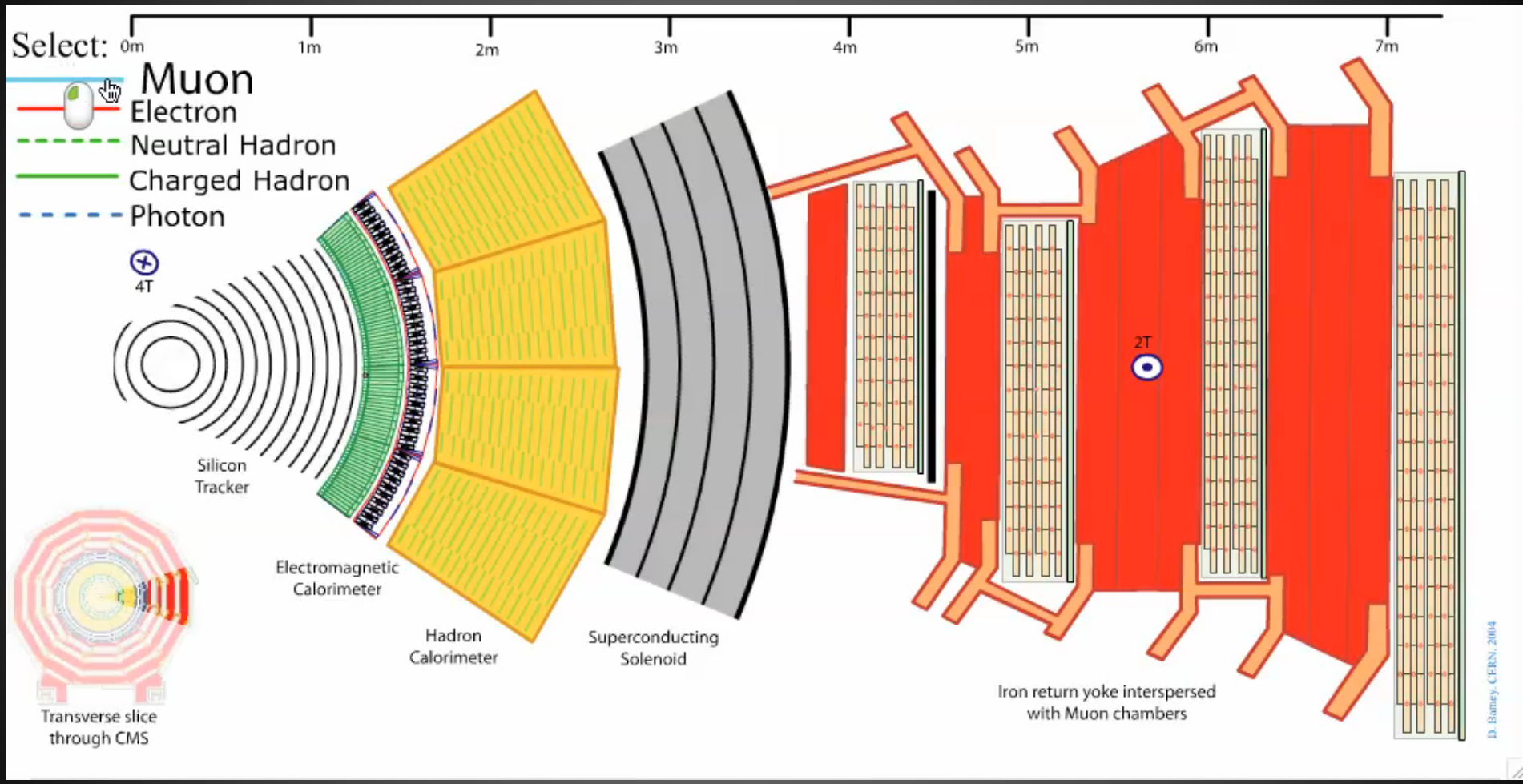
We look for the tracks that a particle leaves behind


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
Photon
H → γγ
candidate
Photon
Search for a narrow mass peak
with two isolated high E_T photons
on a smoothly falling background

The Discovery: Higgs ➔ two photons

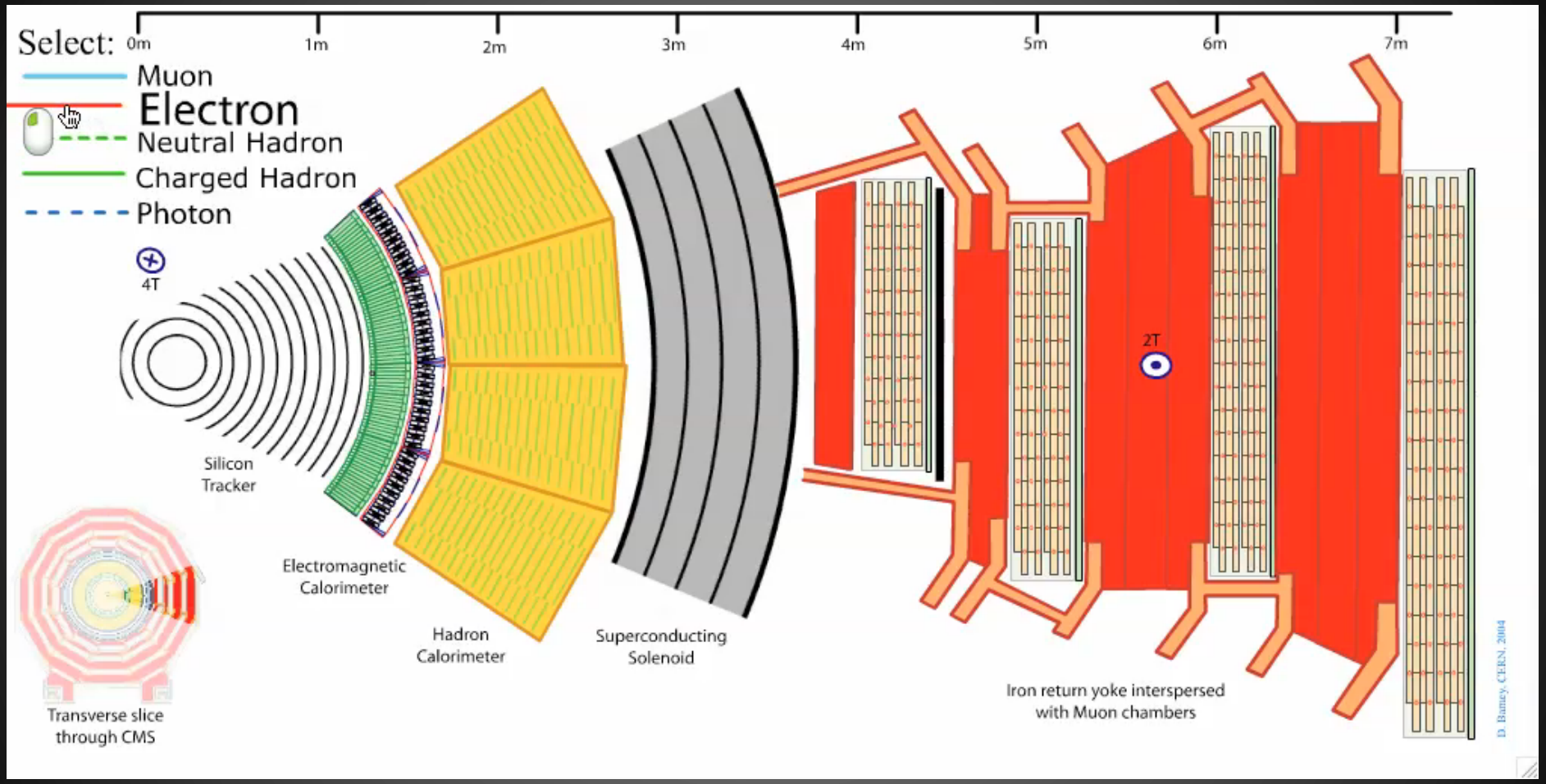


What the detectors detect



We see signals when the layers of the detector stop the particles as they fly out

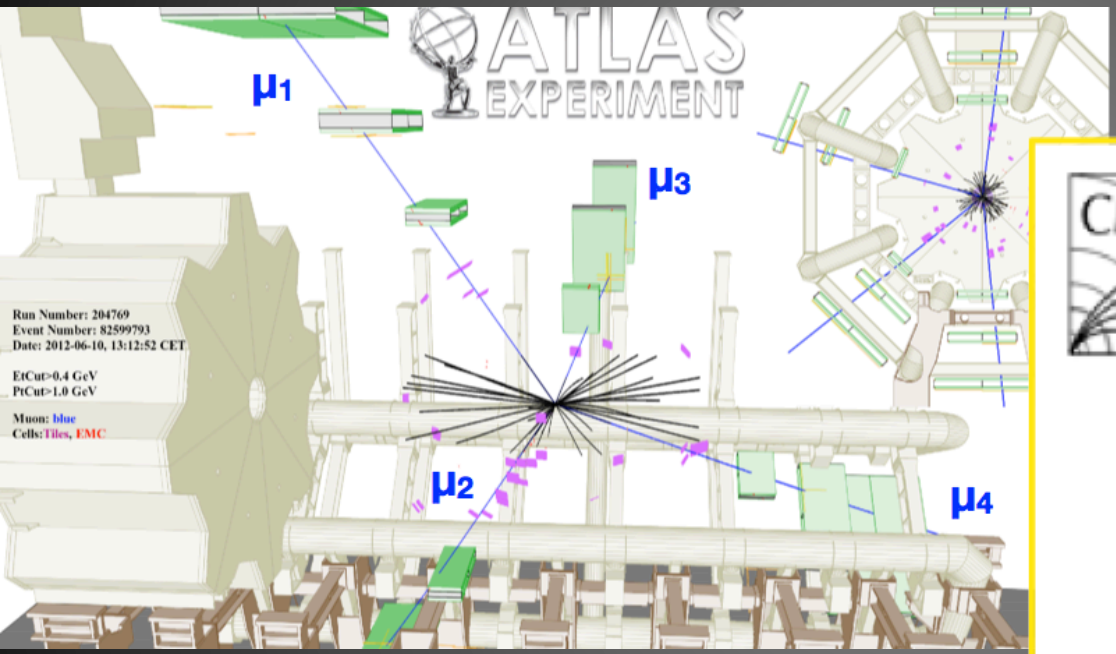
What the detectors detect

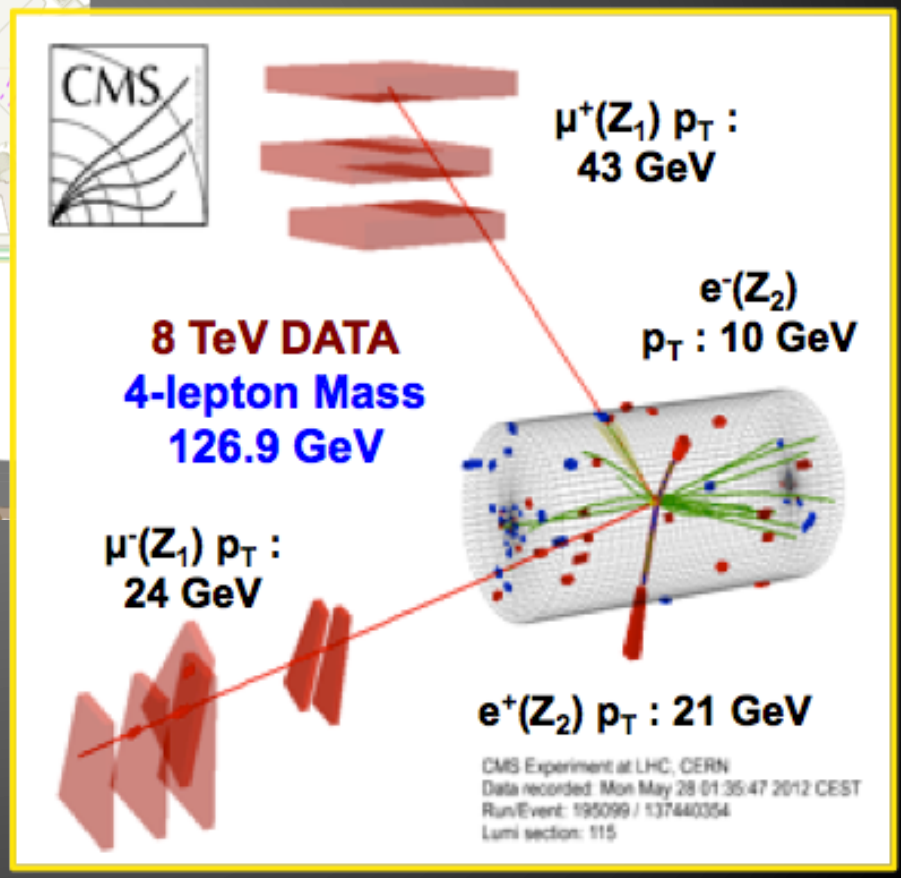


We see signals when the layers of the detector stop the particles as they fly out

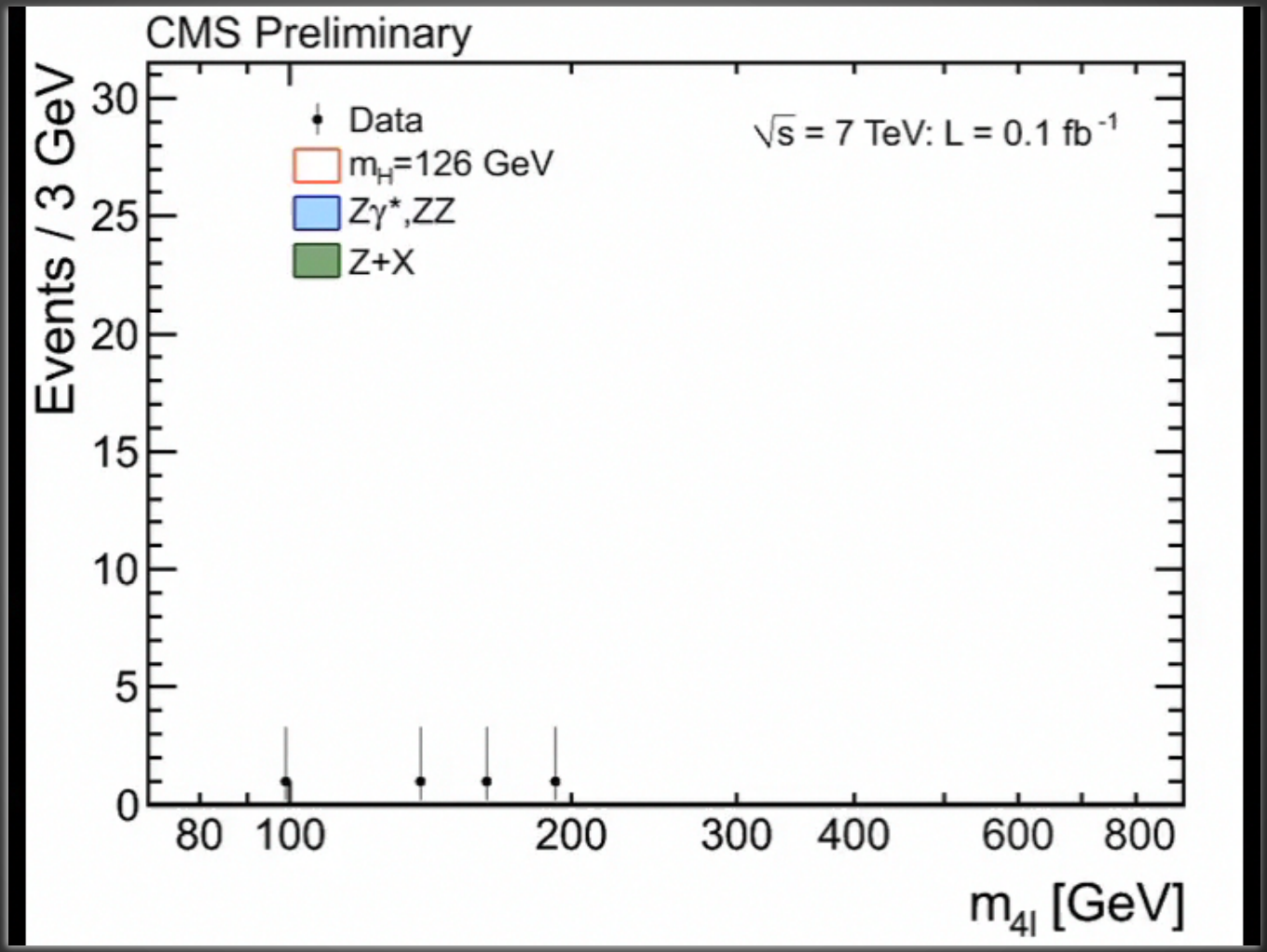
$H \rightarrow ZZ \rightarrow 4\ell$

The Golden channel



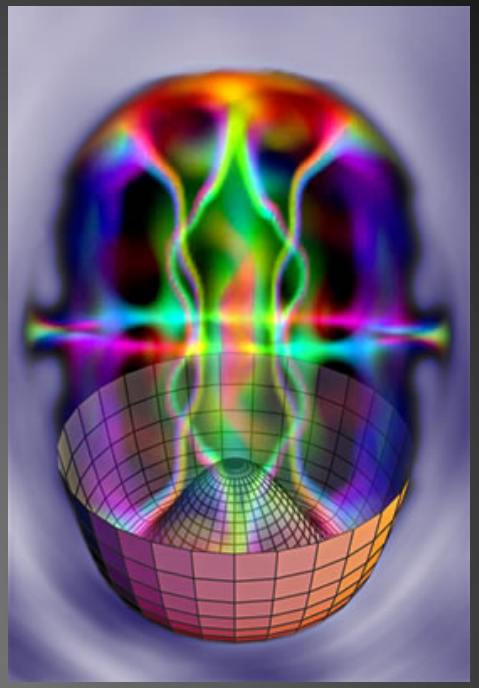


The Discovery: Higgs ➔ 4 Leptons with virtual Z bosons



Is it THE Higgs?

Are there more Higgs?



- The particle of the July 4 discovery: is it THE Higgs boson that explains the mass of fundamental particles

  ~1% of all the visible mass of the universe

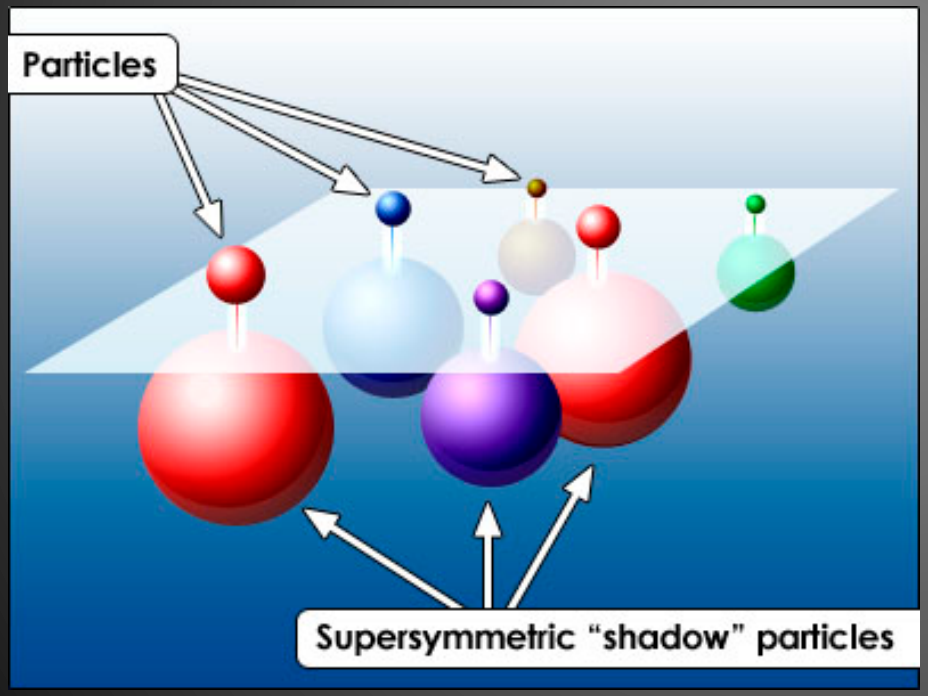
- Is it the Standard Model Higgs or just a close relative?, an impostor?

- It could have many non- Standard properties and still be “The Higgs”

The Existence of the Higgs Boson

- Creates a mathematical challenge

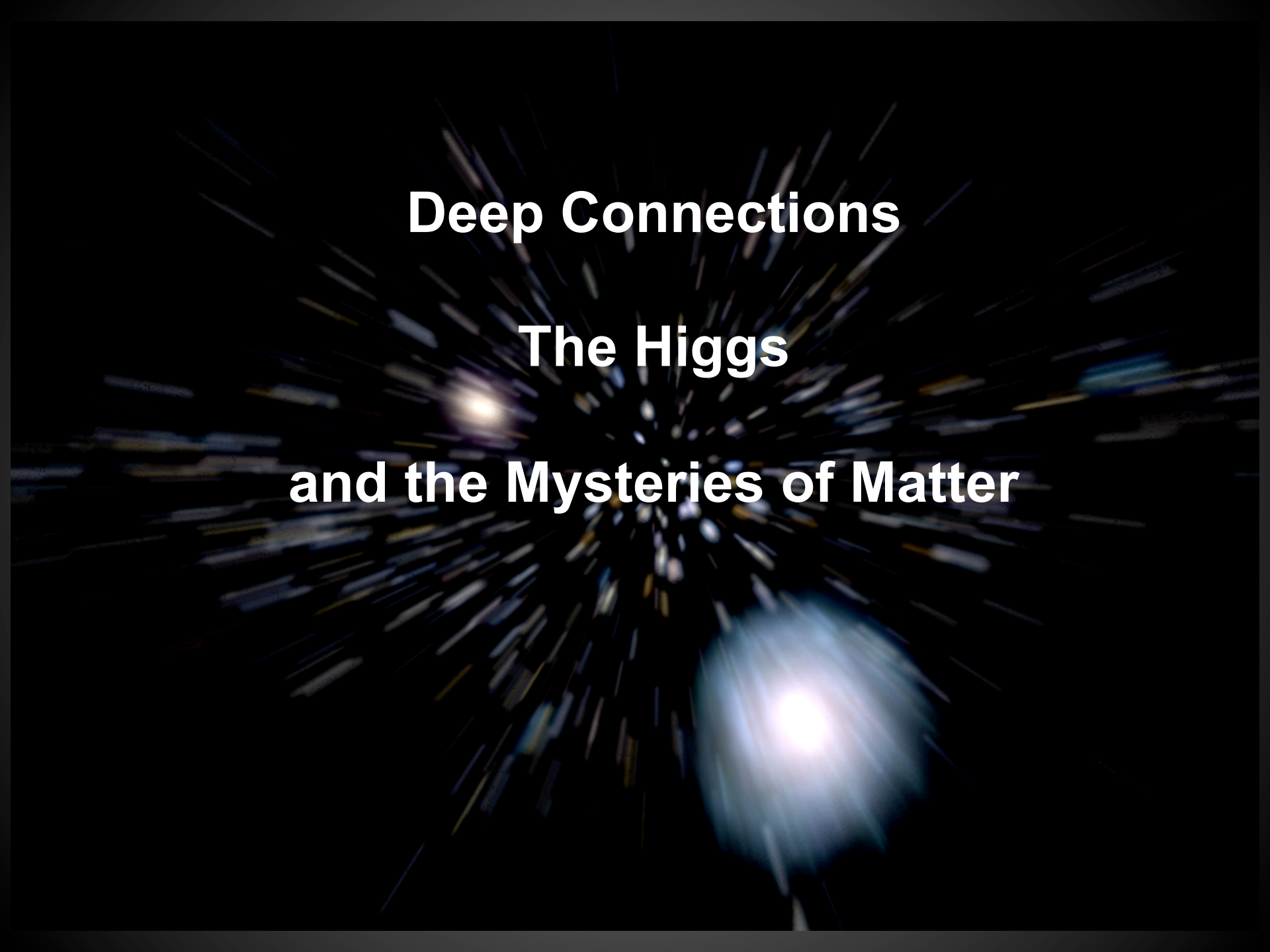
that calls for a new symmetry of nature



SUPERSYMMETRY

LHC experiments search for SUSY

No discovery, YET

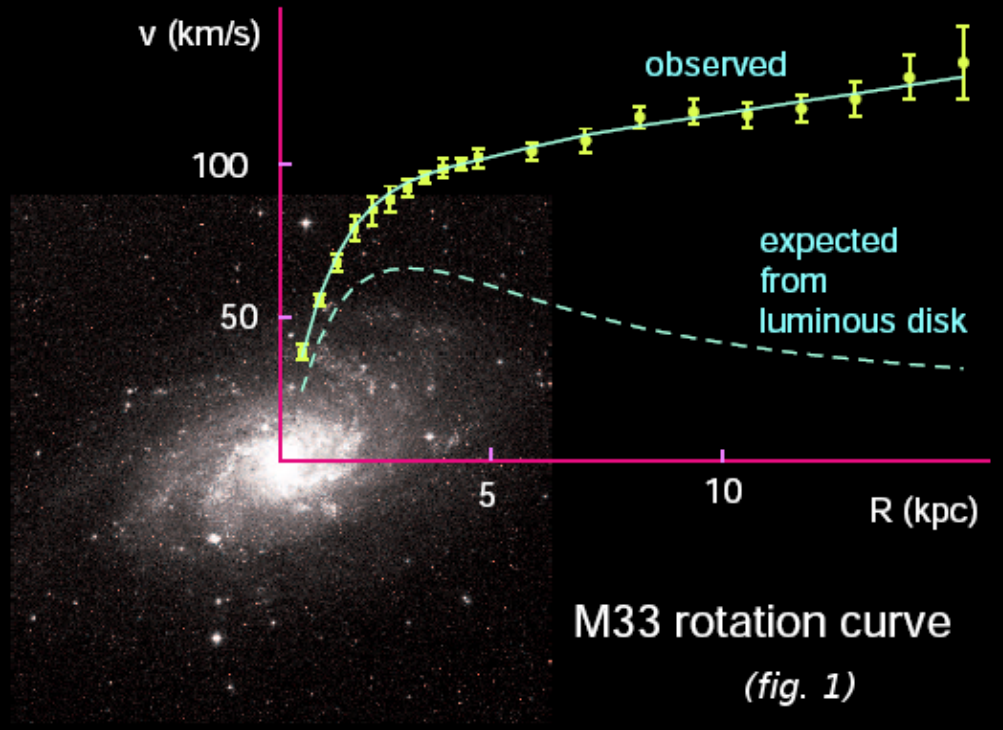

Deep Connections
The Higgs
and the Mysteries of Matter

The Dark Universe

Fritz Zwicky

Vera Rubin

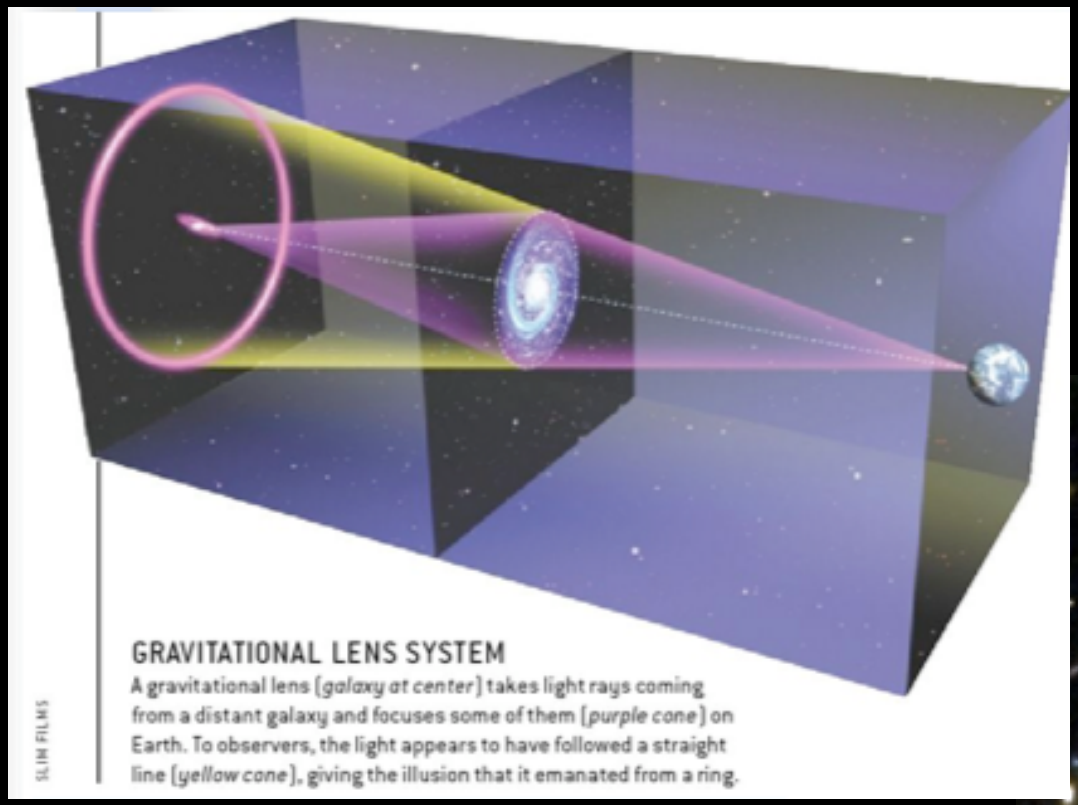
The rotational velocity of galaxies



There must be a lot of matter that we cannot see

Dark Matter ~ 85% of all the matter in the universe!

How to see Dark Matter?



Light deflection due to warping of space near massive objects: gravitational lensing

The power of the dark side

Holds the Universe Together

What is dark matter?

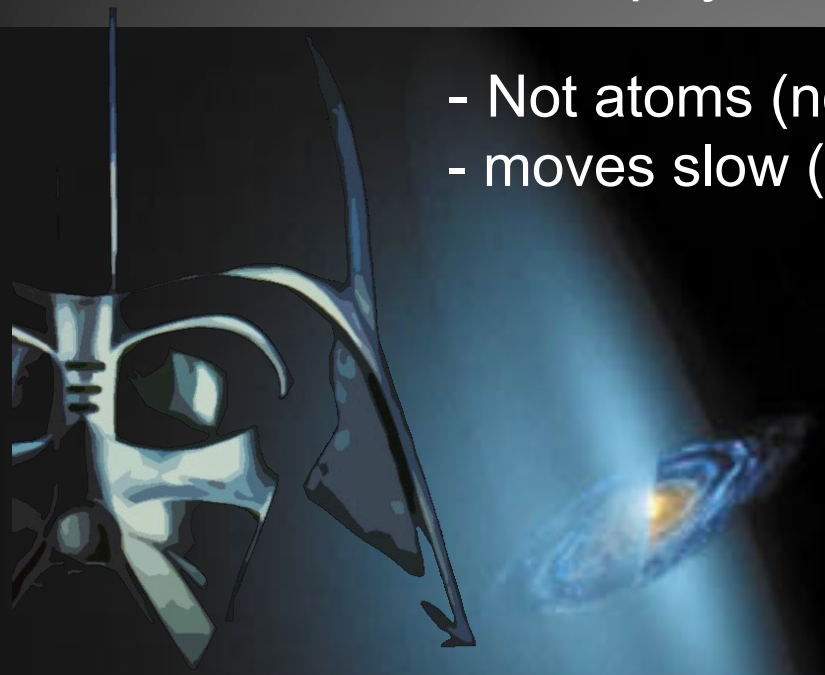
What are its properties?

Does it have substructure?

The power of the dark side

Holds the Universe Together

Astrophysics and Cosmology taught us



- Not atoms (non-baryonic)
- moves slow (cold dark matter)

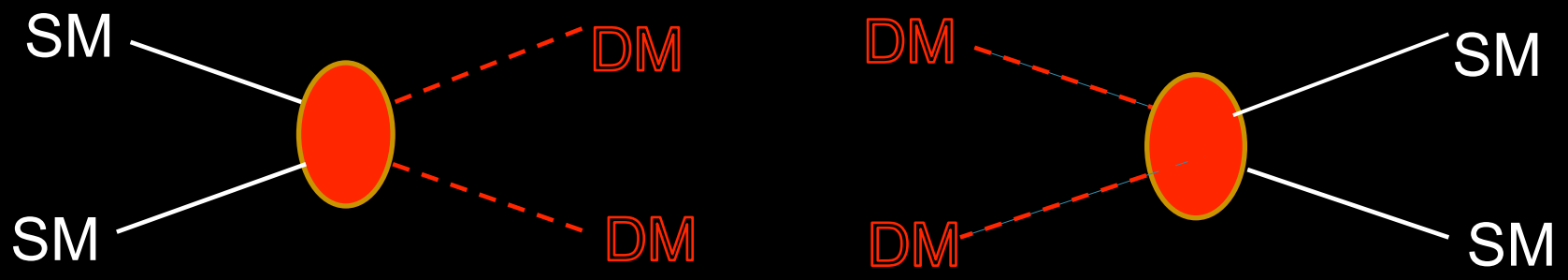
Interacts very weakly
(not charged)

→ **Gravity**

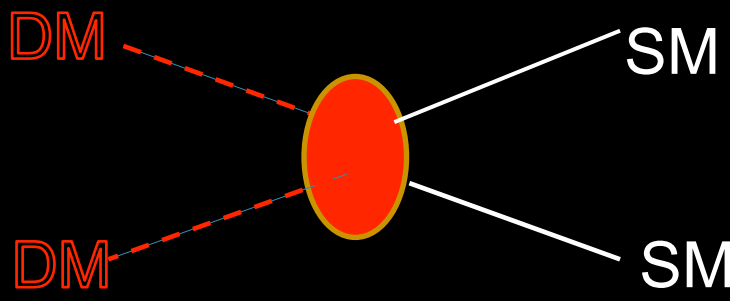
→ **Higgs-like Interactions?**

The History of the Dark Matter Abundance

- Dark matter produced in the hot early Universe can pair-wise annihilate (therm. equilibrium)



- Dark Matter density decreases as the Universe expands



- ***Finally DM annihilation stops***

The *smaller* the rate for pair annihilation,

the *larger* is the Dark Matter abundance observed today

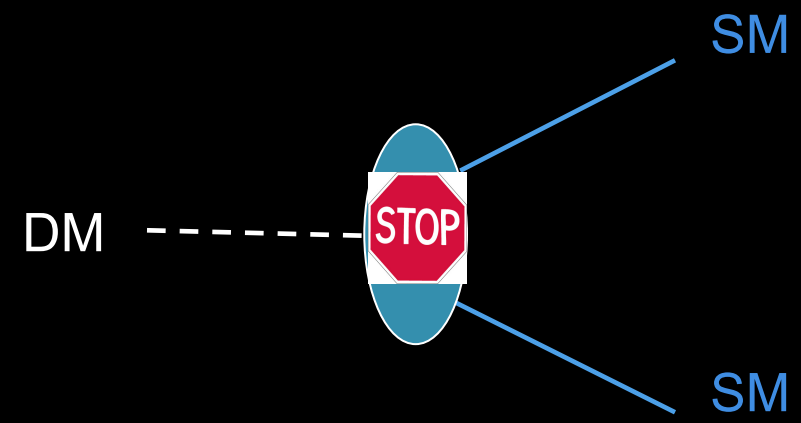
What is Dark Matter?

- DM = yet unknown, heavy, neutral elementary particle/s
- Mass estimate (model dependent) from observed dark matter abundance:

M_{DM} ~ 100 – 1000 proton masses

and fits well with a weakly interacting particle = **WIMP**

CAVEAT: To avoid decay of a WIMP to lighter visible matter, theorists invented a symmetry: "dark matter charge" such that



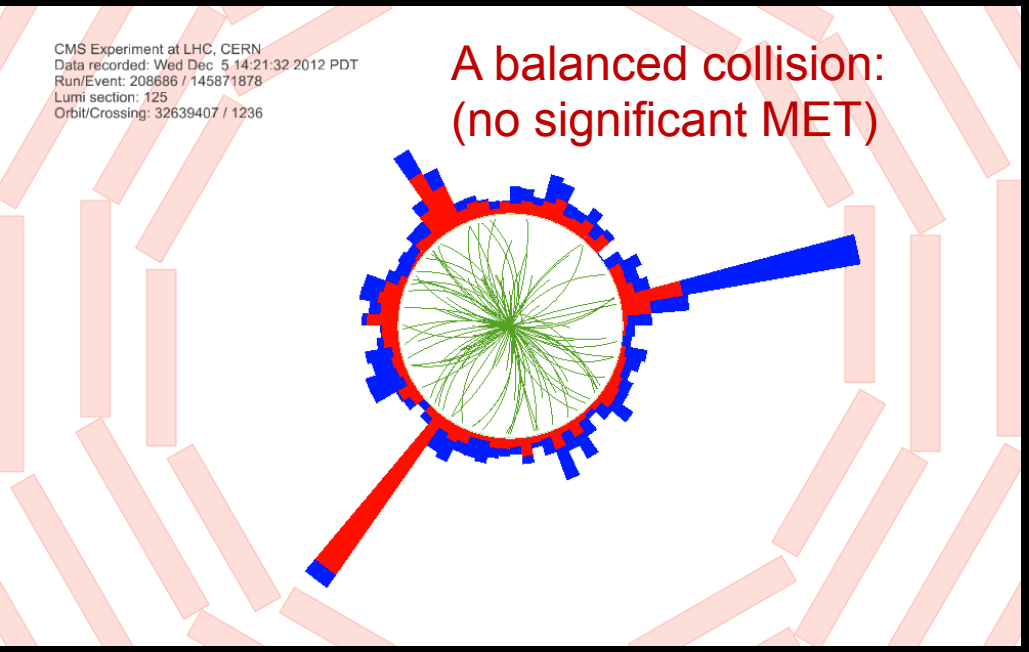
We are testing the outrageous idea

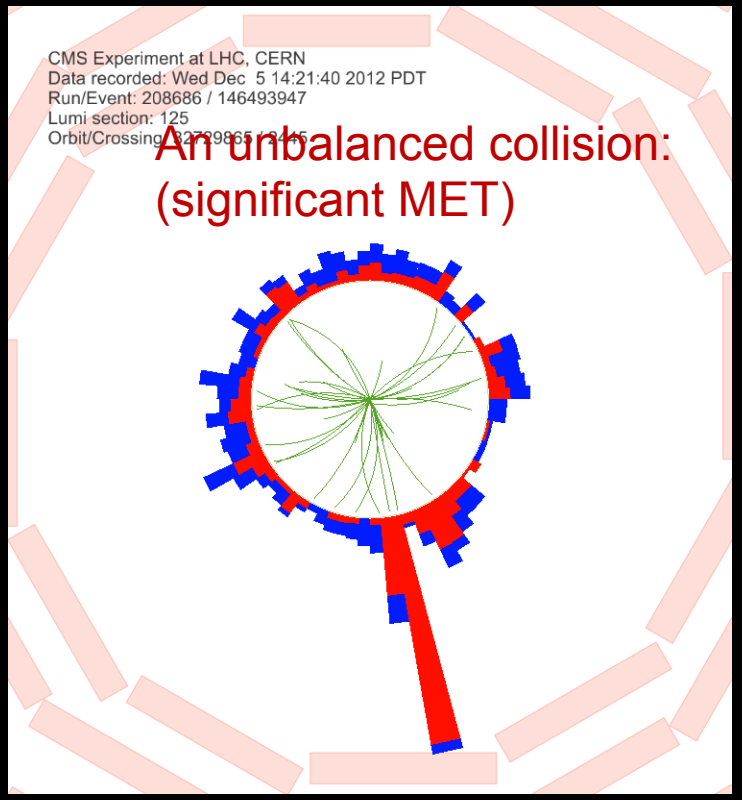
of Dark Matter using

accelerators, telescopes and specialized detectors!

A priority for Particle Physics and Cosmology

We can create Dark Matter at the LHC





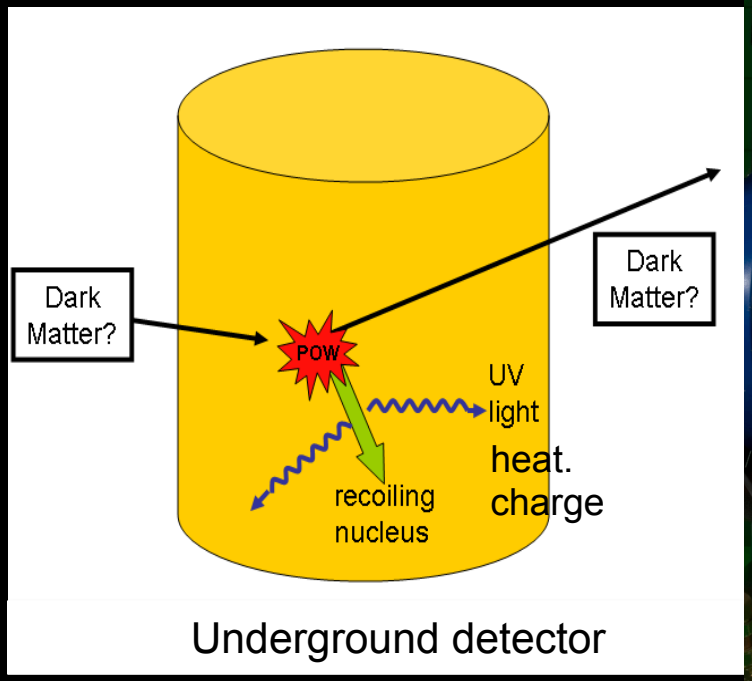
We count the energy we put in and the energy that comes out

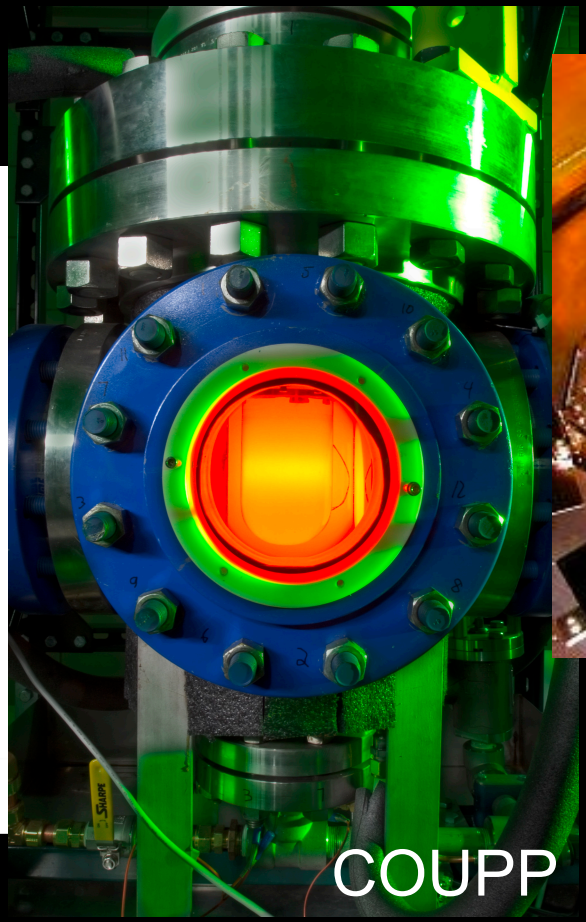
if a lot is missing we created Dark Matter

Rely on excellent understanding of detector response and standard model processes at collider

Dark Matter Search in Direct Detection Experiments

It can *collide with a single nucleus in your detector (which you observe)*

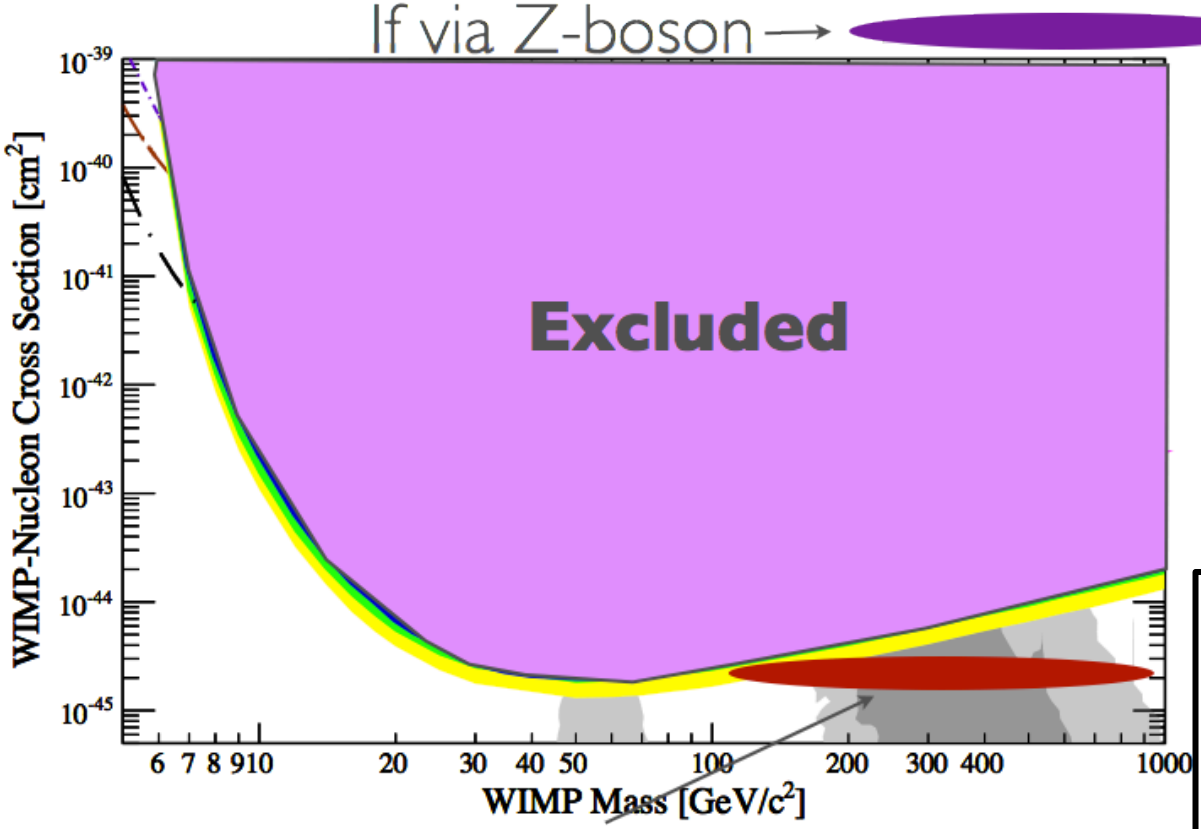


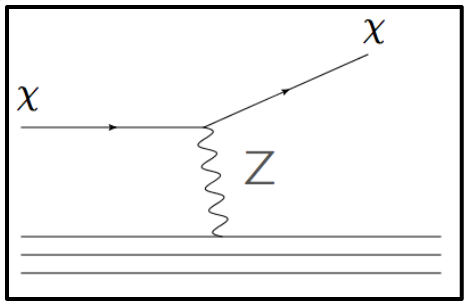


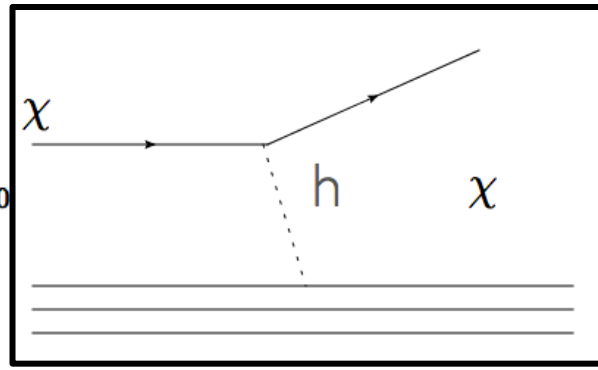
also GoGent
DAMIC
DarkSide

Leading World efforts in Chicago

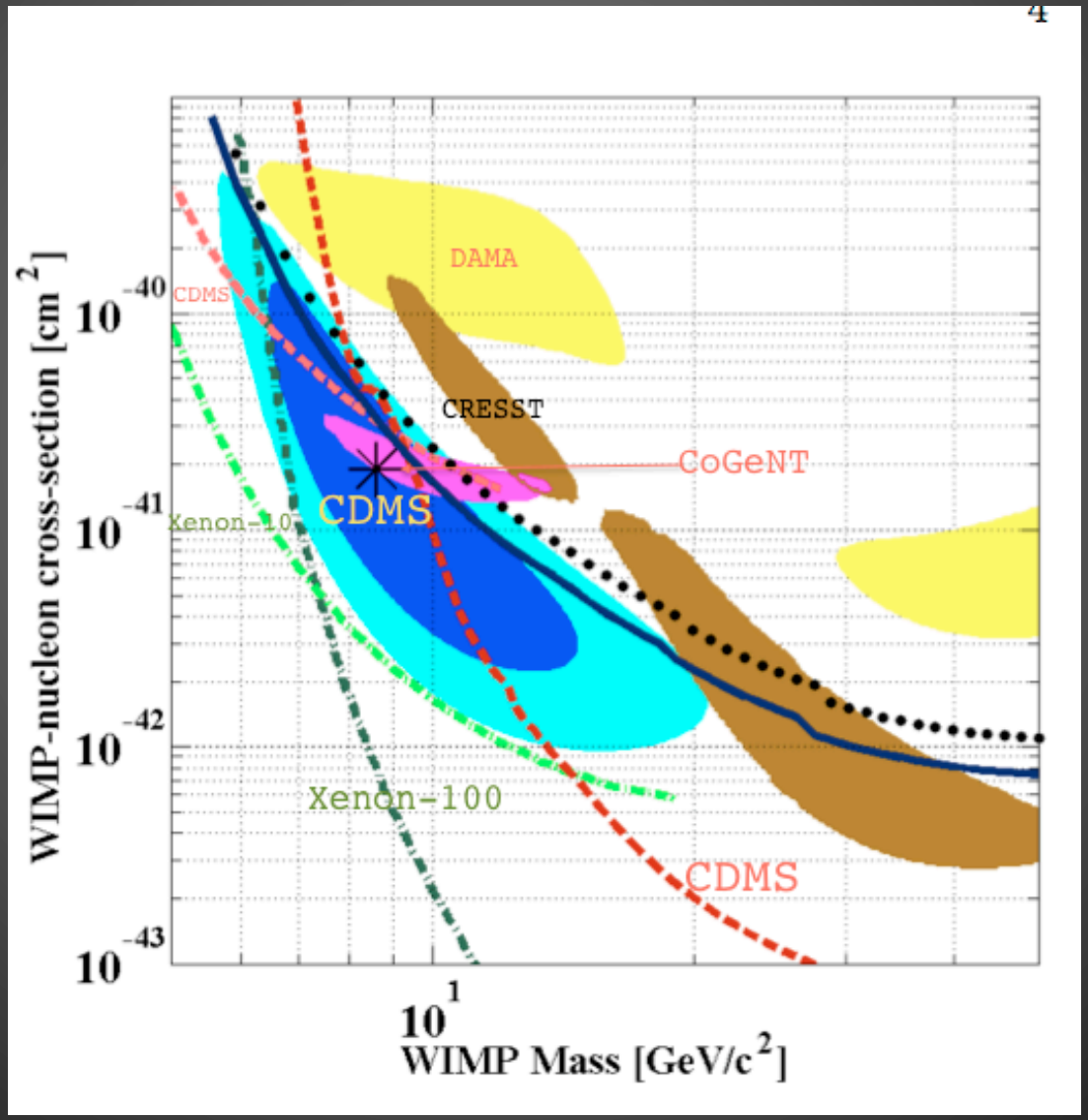
Starting to probe the Higgs Portal







There are some signals in the "excluded" region that could be Dark Matter

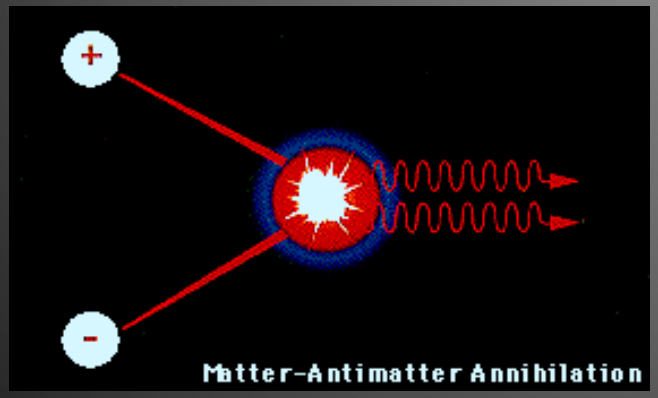


The Mystery of our Existence

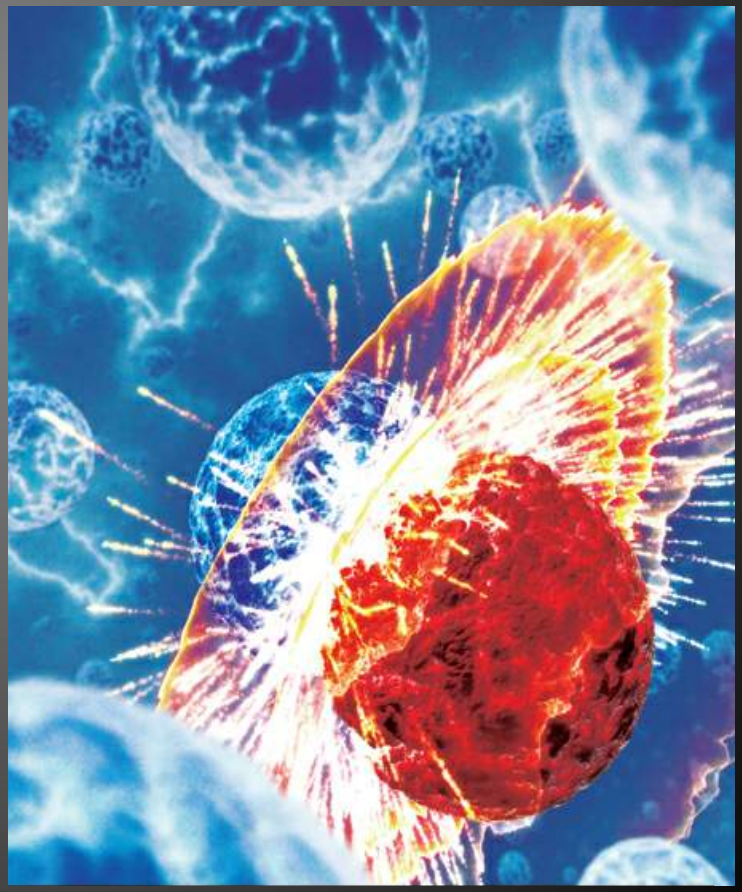
We are made of Matter but there is also Anti-Matter

Each matter particle has an anti-particle: an exact copy but…
with opposite electric charge

When matter meets anti-matter...



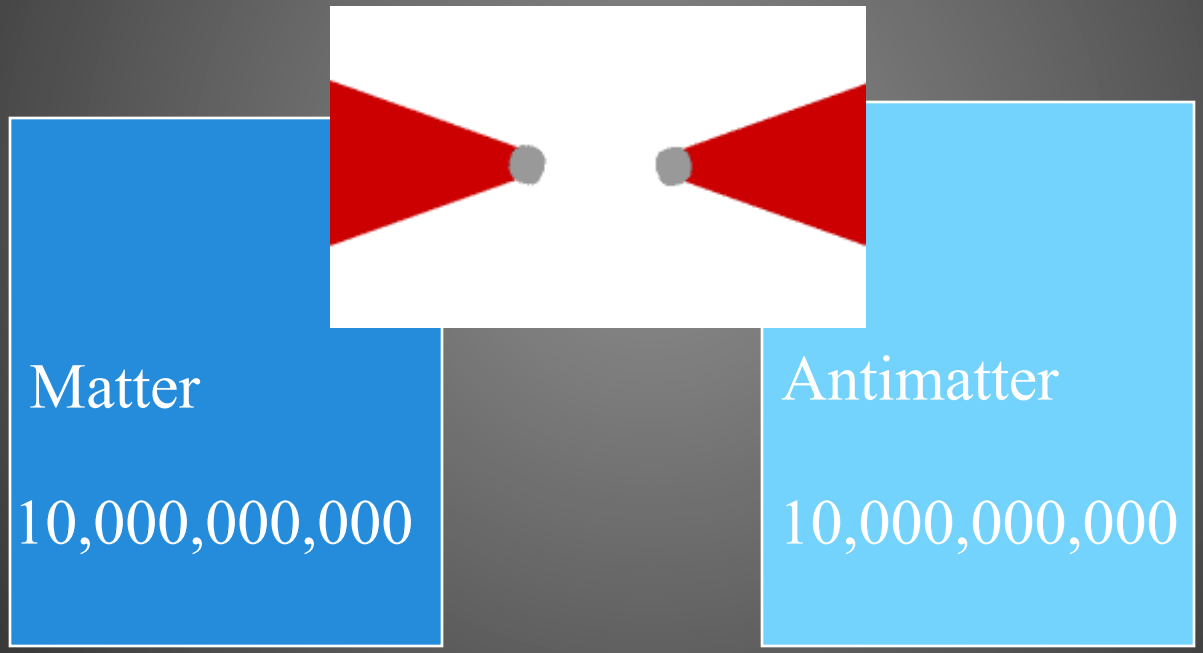
It annihilates into em radiation



At the BIG BANG :

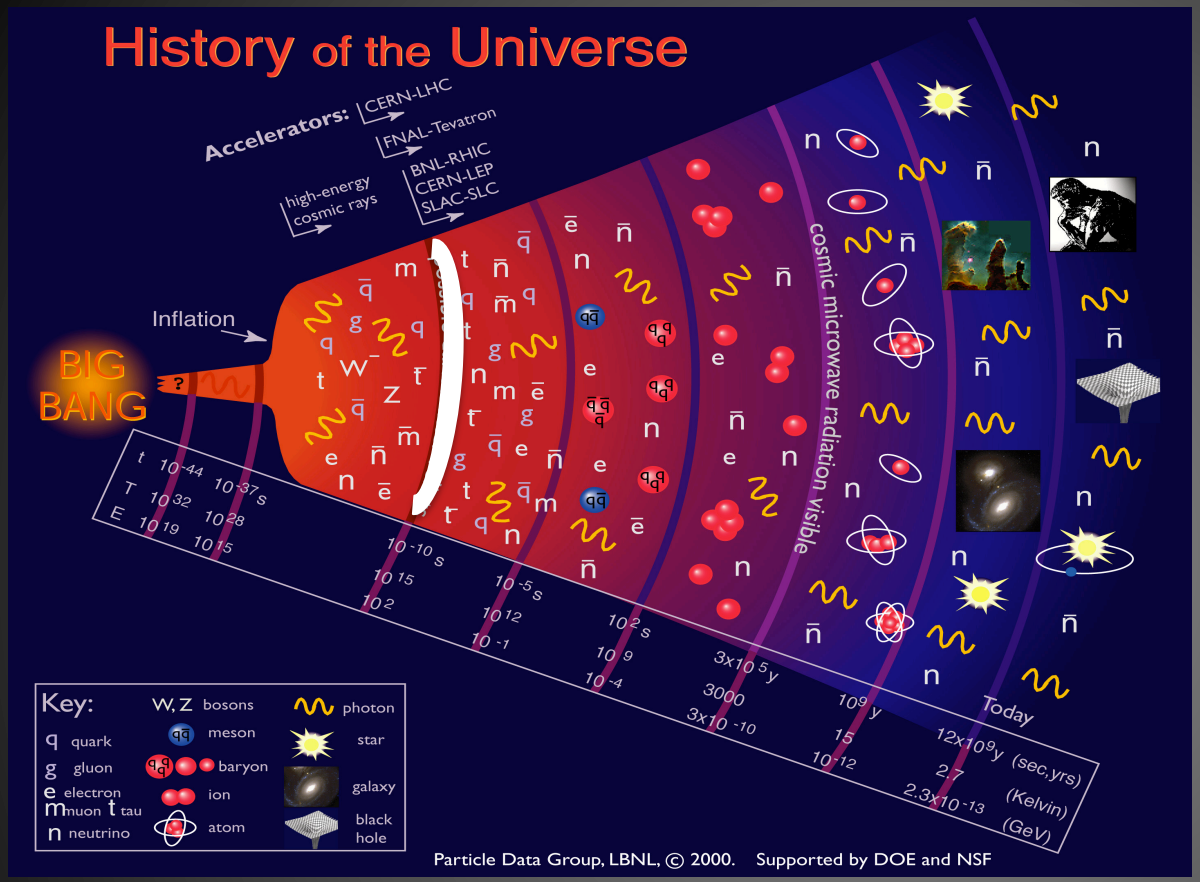
Equal amounts of Matter and Anti-matter

There was a big matter-antimatter battle…



A tiny amount of matter survived …

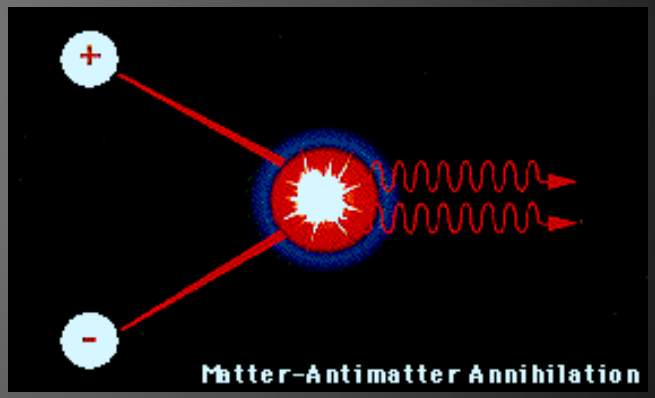
Why are we here?



At the Big Bang:

Equal amounts
of Matter and Antimatter

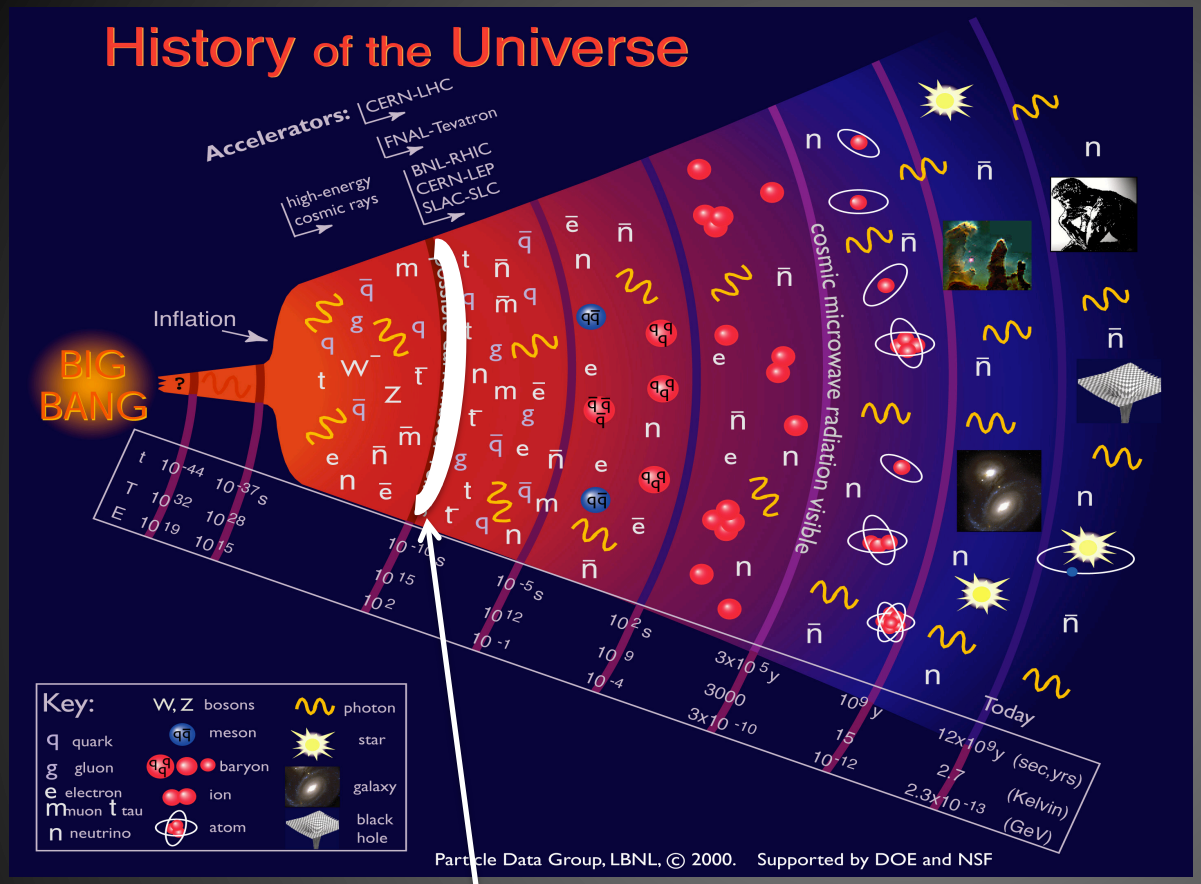
Then …



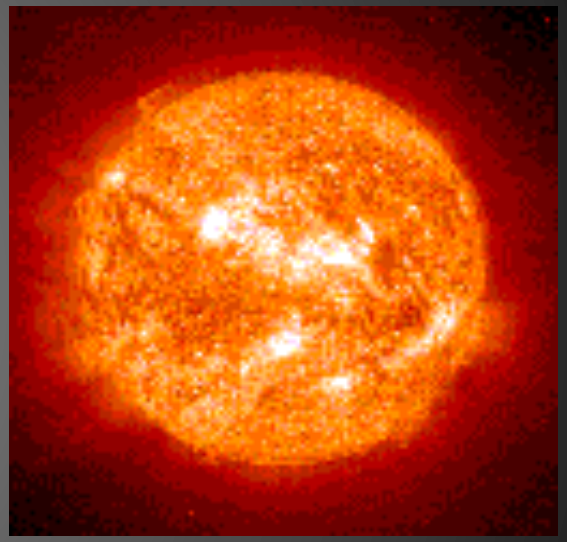
"Somehow" an imbalance occurred

- a tiny amount of matter left… that tiny part is us -

The Higgs
and the stability of our universe



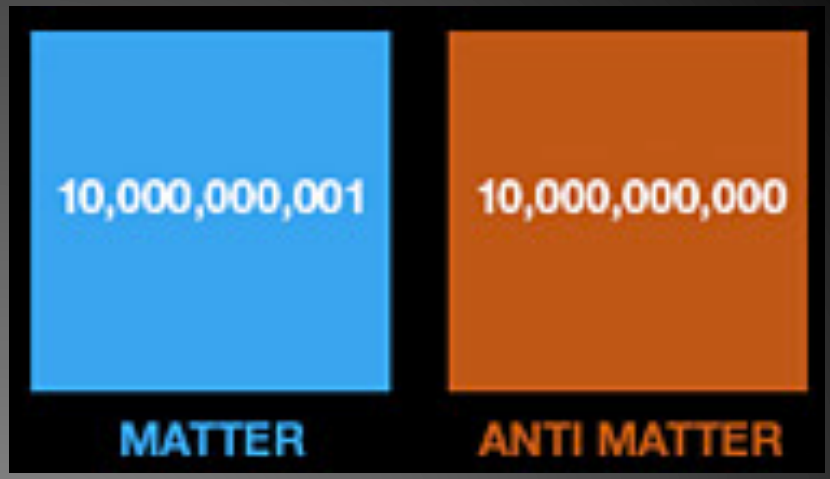
Solar Fusion



Sun still burning!

Spontaneous electroweak
Symmetry breaking

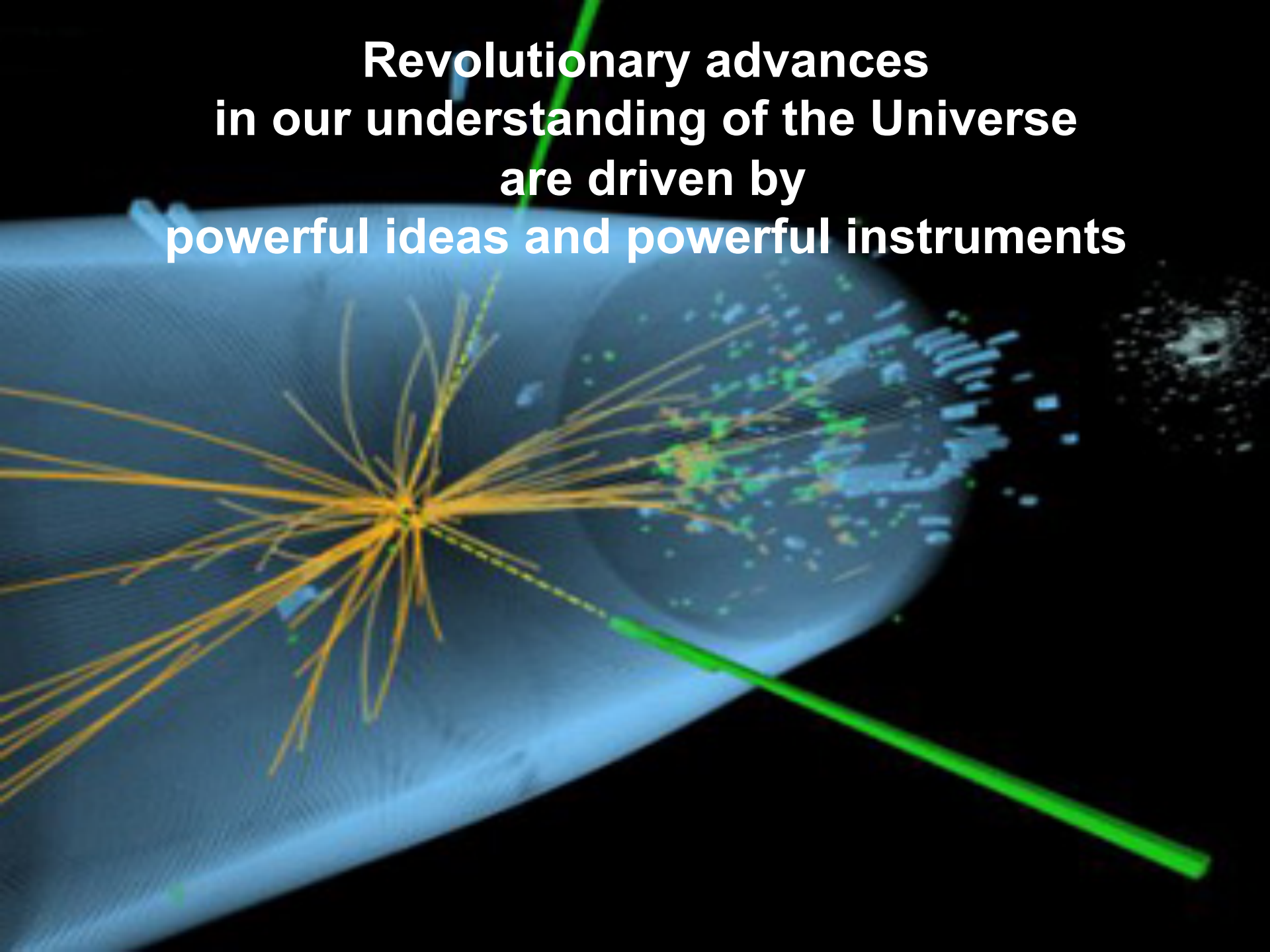
What generated the matter-antimatter imbalance?



God Mechanism ?

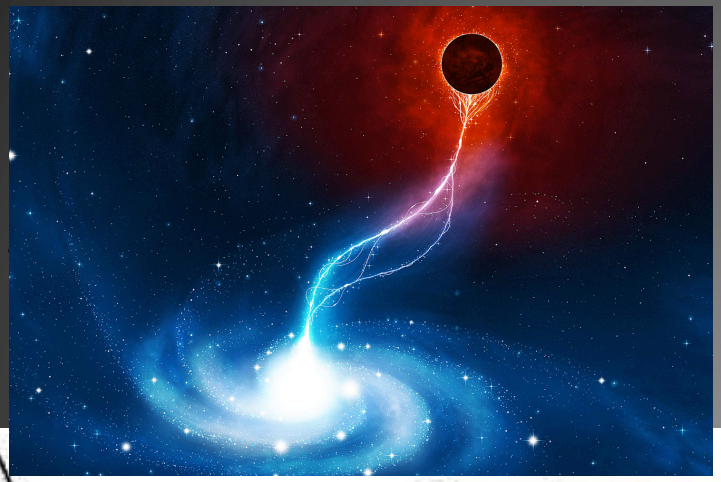
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

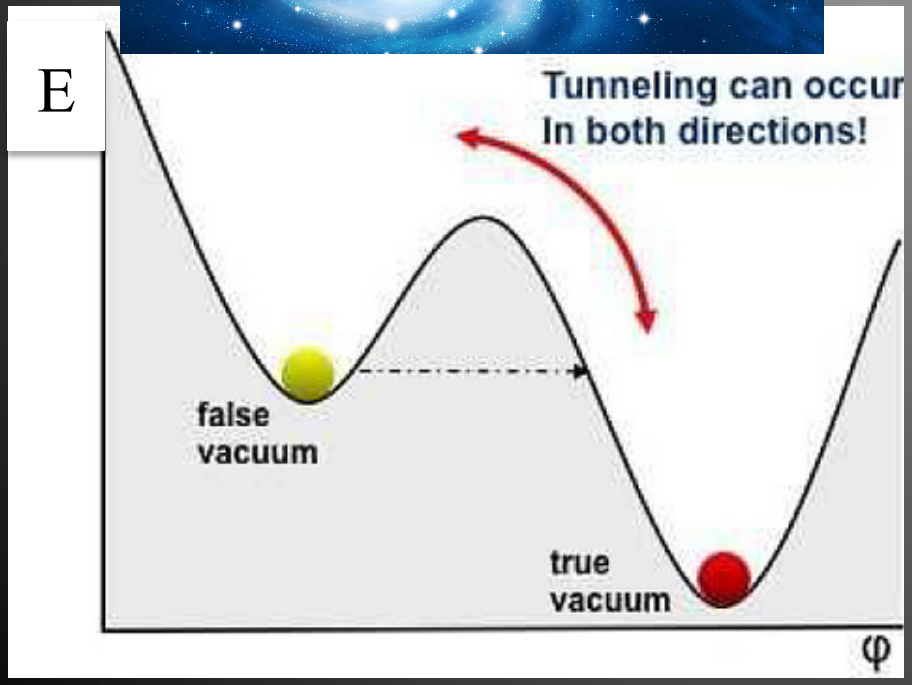
Are both Symmetry breaking mechanisms related, happening at the same time?


Revolutionary advances
in our understanding of the Universe
are driven by
powerful ideas and powerful instruments

EXTRAS

How does the measured Higgs mass fit in our modeling of the universe?



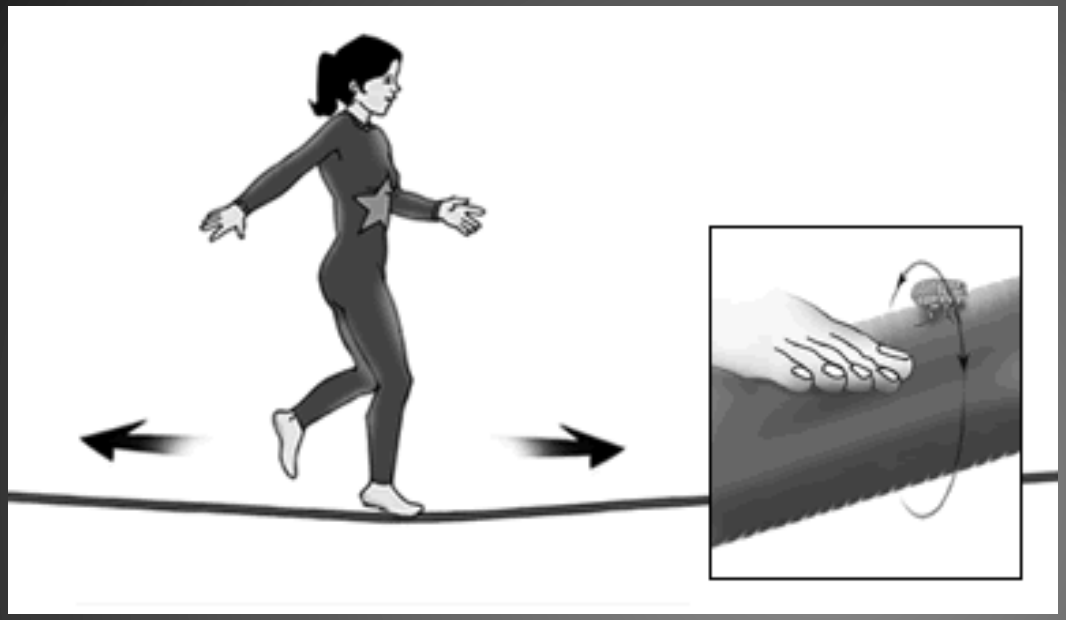


We live in a
Meta-stable vacuum

Or

A new symmetry of
nature may
stabilize the universe

Extra Dimensions of Space



- **A Higgs**
- **Dark Matter**

How would we “see” them at colliders?

- Missing Energy: copies of the graviton disappearing in ED
- New particles with masses in an ascending ladder
- Black Holes

Matter: What is it?

The Fundamental Particles and their Interactions
How do they acquire Mass?

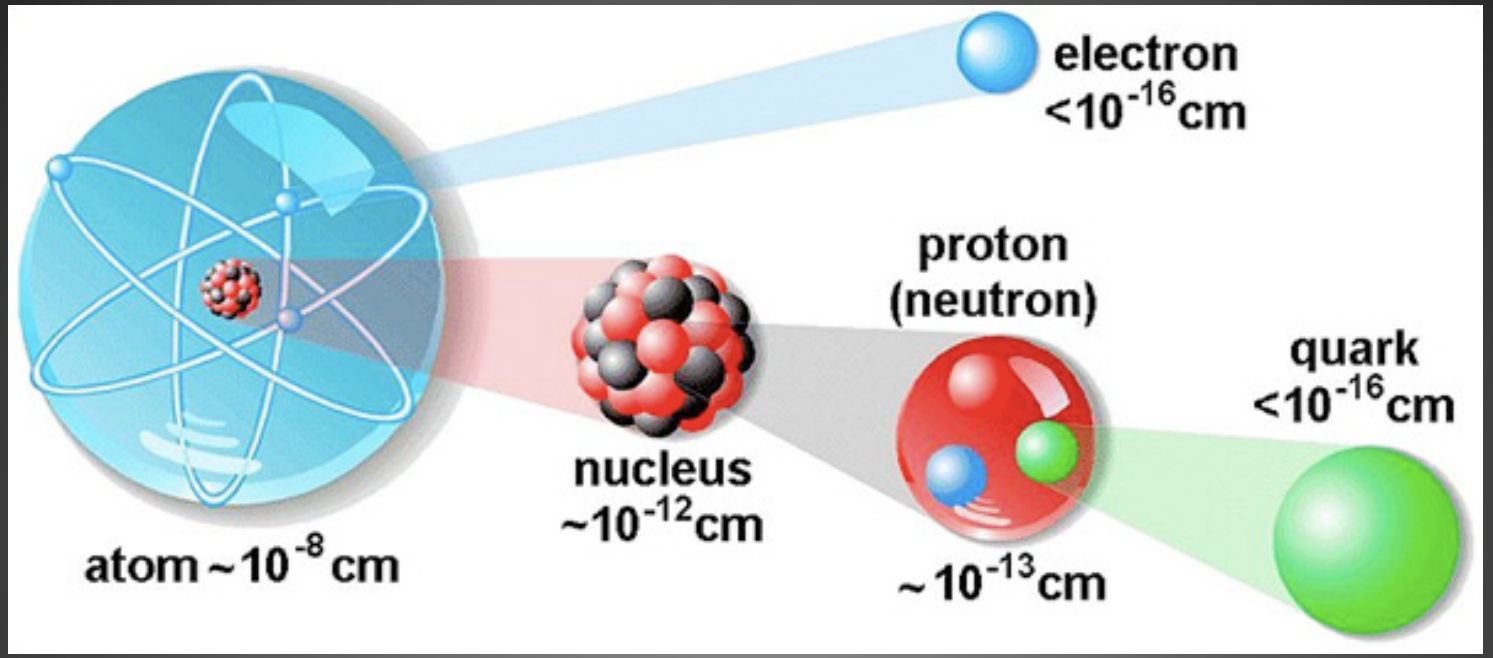
Different kinds of Matter:

Matter, Anti-Matter, Dark Matter …

The Mysteries of Matter … and the New Theories to explain them

Accelerators:
giant microscopes to study the smallest pieces of Matter

Matter: What is it?



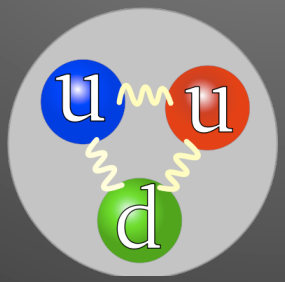
1 1/10.000 1/100.000 1/100.000.000

Electric charges

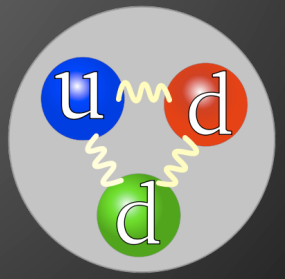
electron = -1

u-quark = 2/3

d-quark = -1/3



Proton



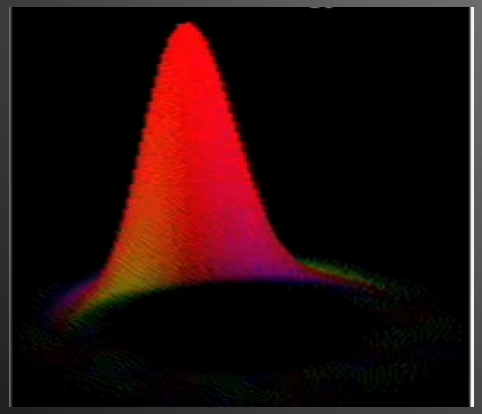
Neutron

What holds matter together?

Two forces that we experience everyday

Force	Strength	Carrier	Physical effect
Electromagnetic	.001	Photon	Light, electricity
Gravity	10^{-38}	Graviton?	Gravitation

Molecules, Rocks, Creatures are held together by the tentacles of powerful electric forces and magnetic fields inside the atoms



Atoms governed by the laws of quantum mechanics

Two forces we do not observe everyday but are essential to our life

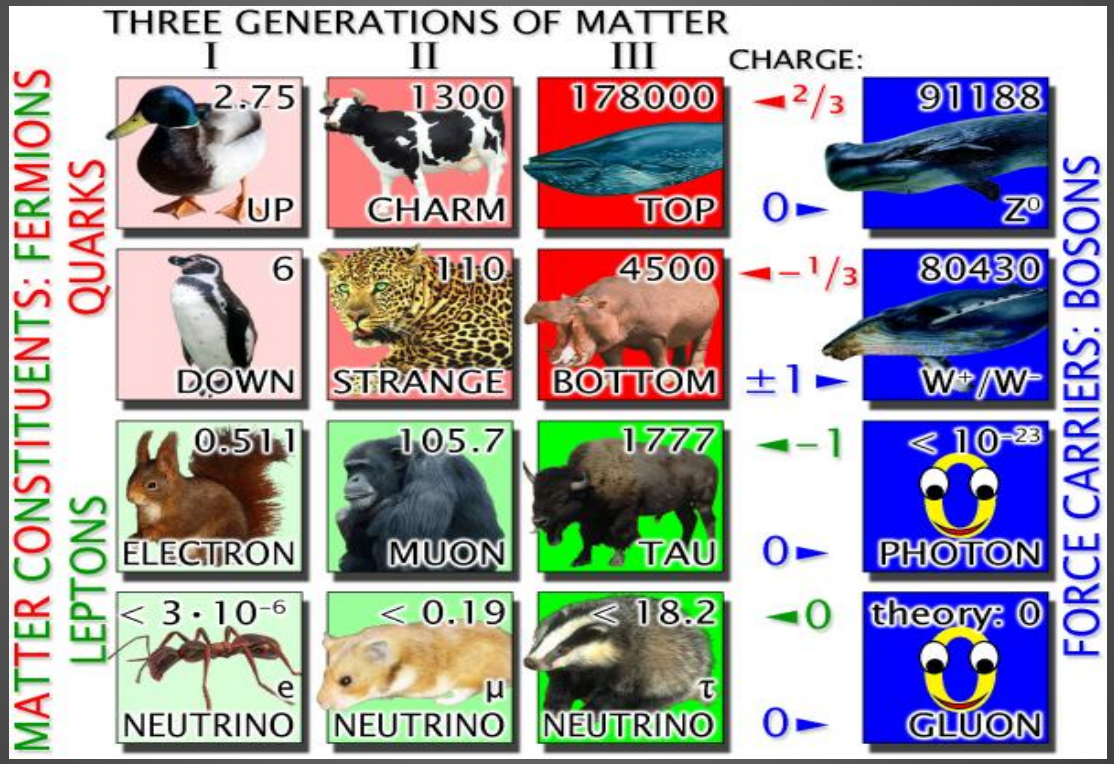
Binds together proton and neutron to form nuclei

Explains nuclear fusion in the Sun!
and ultimately, Sunlight

Force	Strength	Carrier	Physical effect
Strong nuclear	1	Gluons	Binds nuclei
Weak nuclear	.00001	Z^0, W^+, W^-	Radioactivity

The Standard Model Zoo of Sub-atomic Particles

- *Heavier copies of those which make up ordinary atoms*
- *Particles which are the mediators of sub-atomic forces*



They have all been produced in the laboratory

They have very different masses

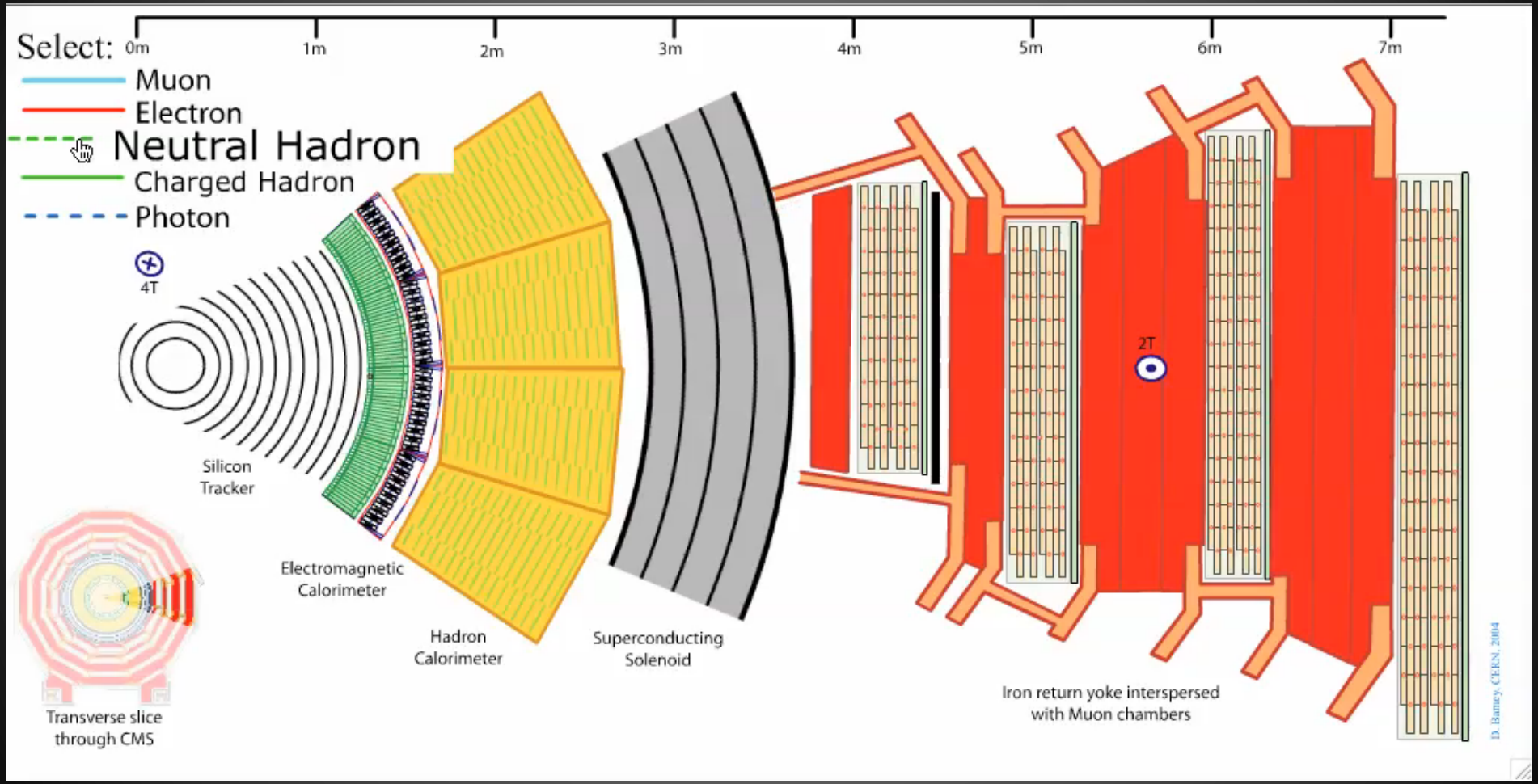
Nature does not forget

The equations governing the fundamental laws of physics contain everything possible:

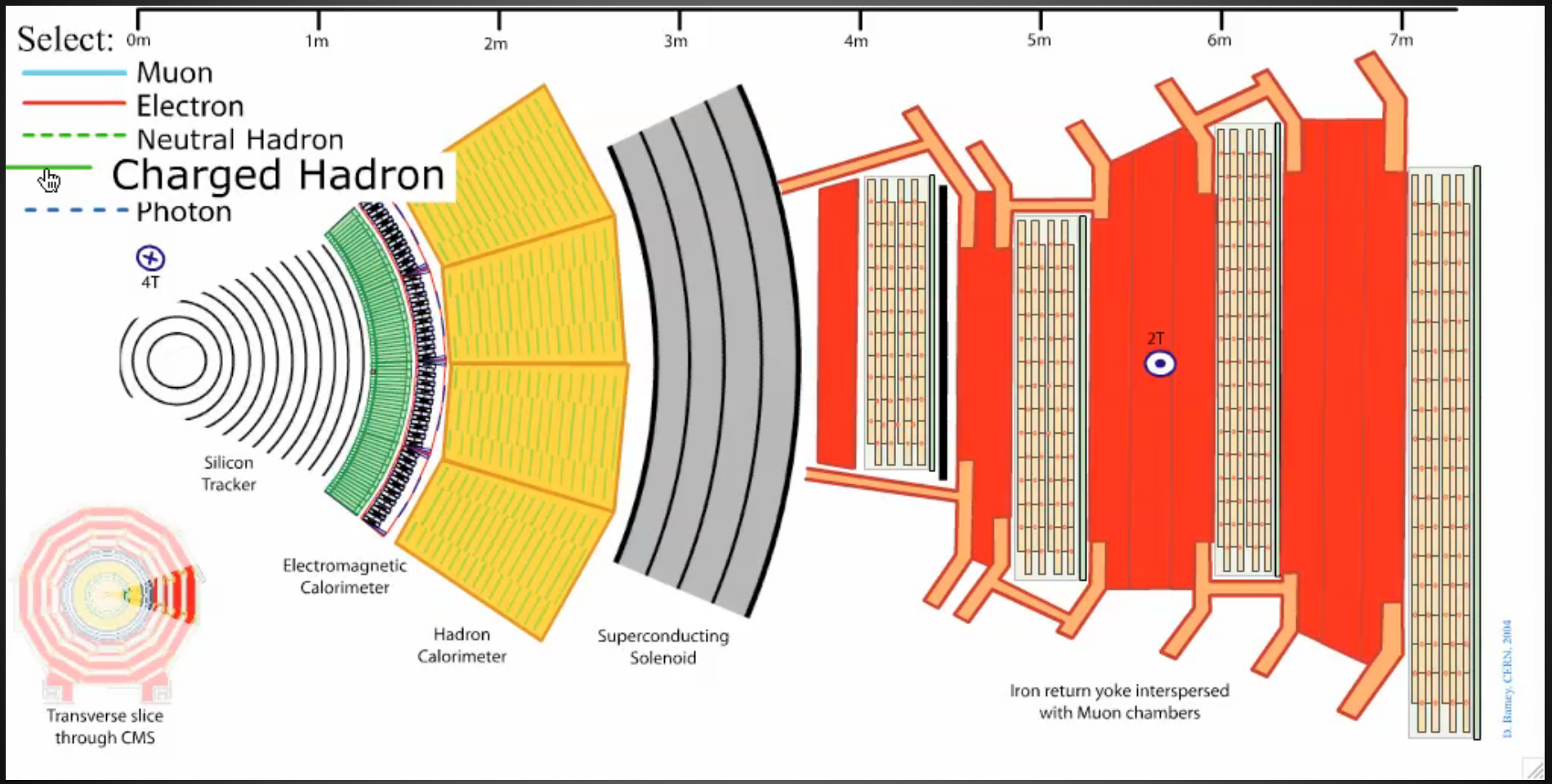
$$\mathcal{L} = \sum_{\text{particles}} \bar{\psi}\, i \not{D}\, \psi + \sum_{\text{forces}} F^2$$

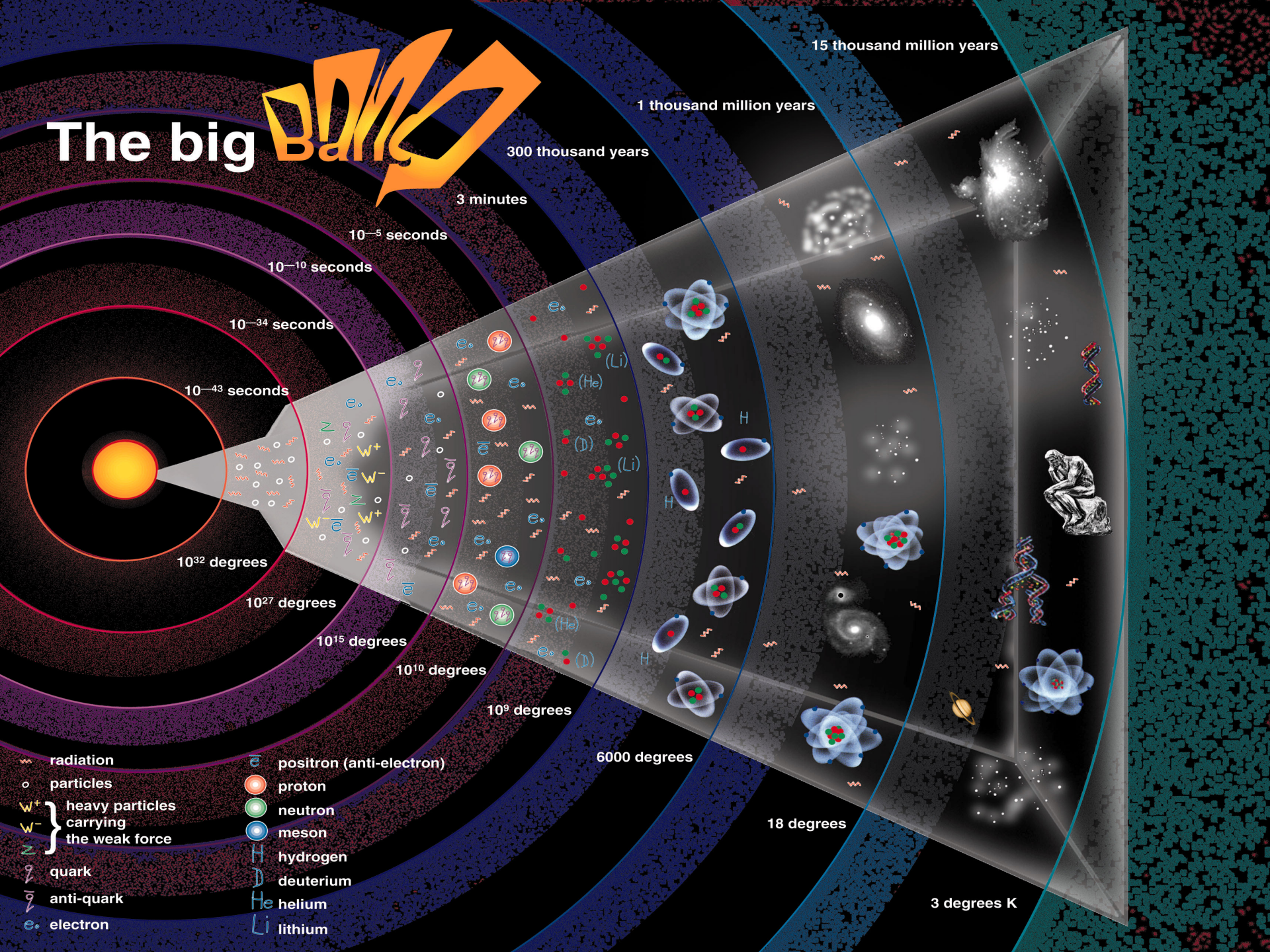
This is why we can search for particles that only existed shortly after the Big Bang using high-energy particle colliders!

What the detectors detect



What the detectors detect




The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium