

# **Intricately Searching for Simplicity**

## **An Introduction to Experimental Particle Physics**

**Nature's basic pieces and their interactions**

**Anything understood seems simple enough...**

# Reductionism

Understanding =  
Identifying fundamental constituents and  
delineating the rules of their interactions

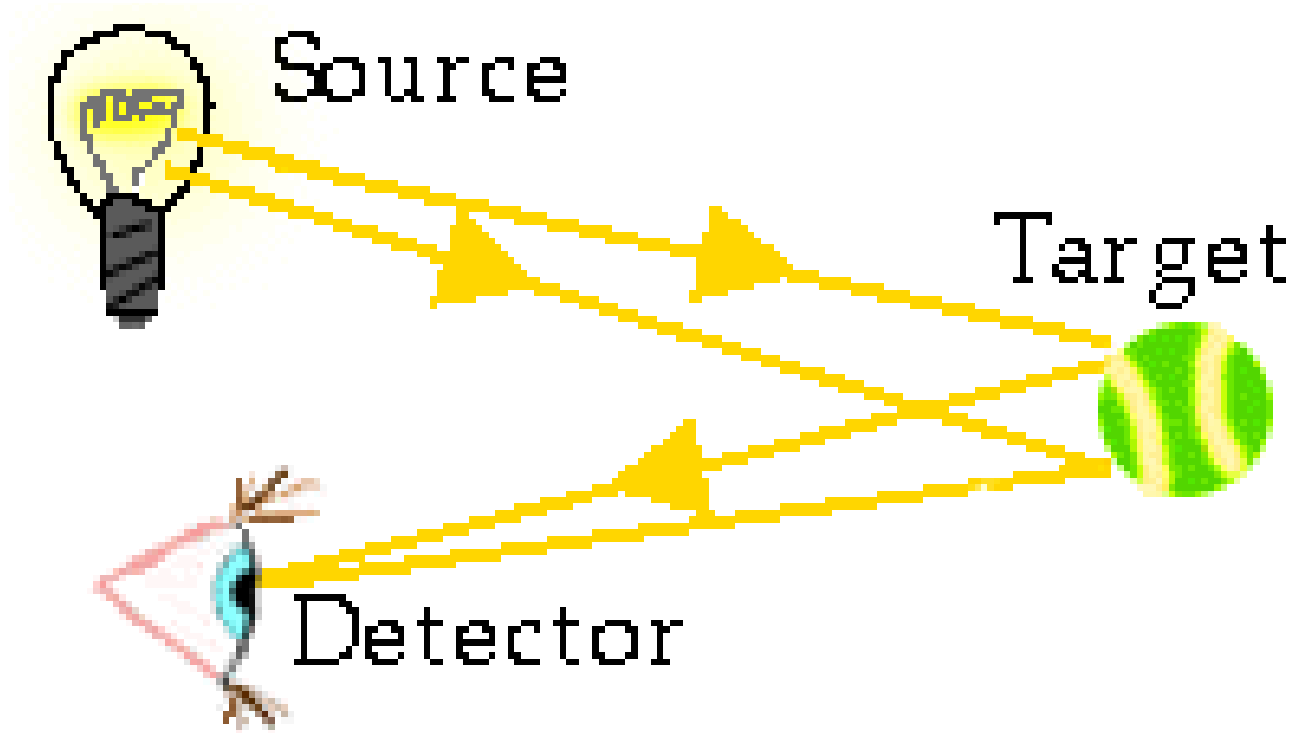
# Two Frontiers

- Energy
- Precision

# Bigger Bang $\Rightarrow$ More Muck

$$E = mc^2$$

# Seeing

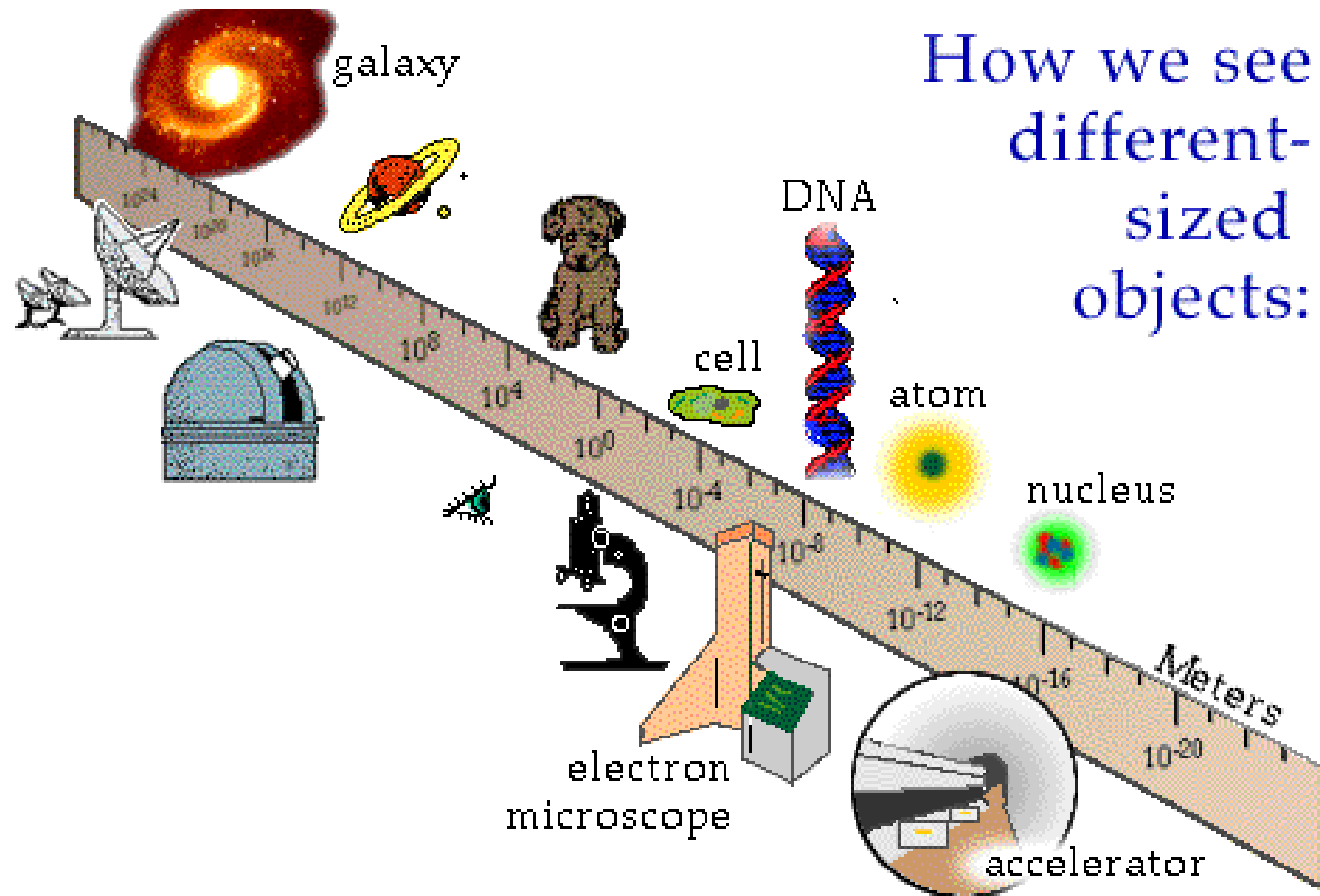


**Imaging quality limited by probe's wavelength  
and detector's sensitivity (resolution)**

# Higher Energy $\Rightarrow$ Shorter Wavelength

$$E = \frac{hc}{\lambda}$$

# The Apposite Eye and the Appropriate Wavelength



# Consequently, Accelerators

- To increase  $E = mc^2$
- To increase  $E = \frac{hc}{\lambda}$

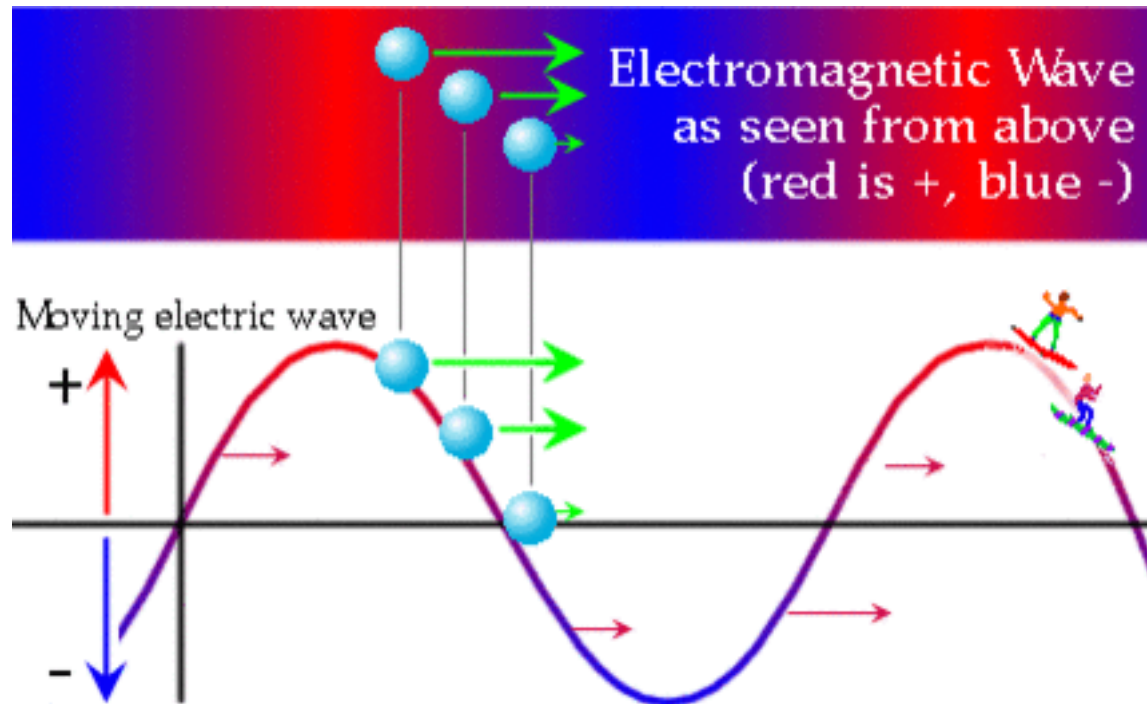
$$hc \approx 12345 \text{ eV} \cdot \text{\AA}$$

So, to “see” objects of  $10^{-20}$  m dimensions,

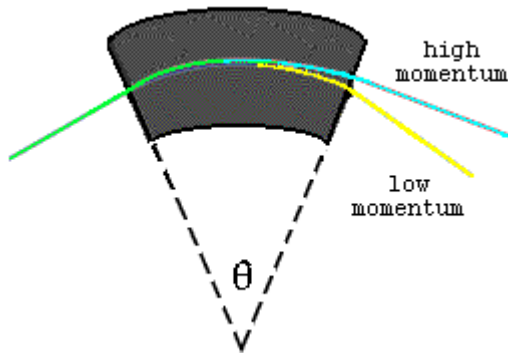
$$E \approx 10^{14} \text{ eV} = 100 \text{ TeV}$$



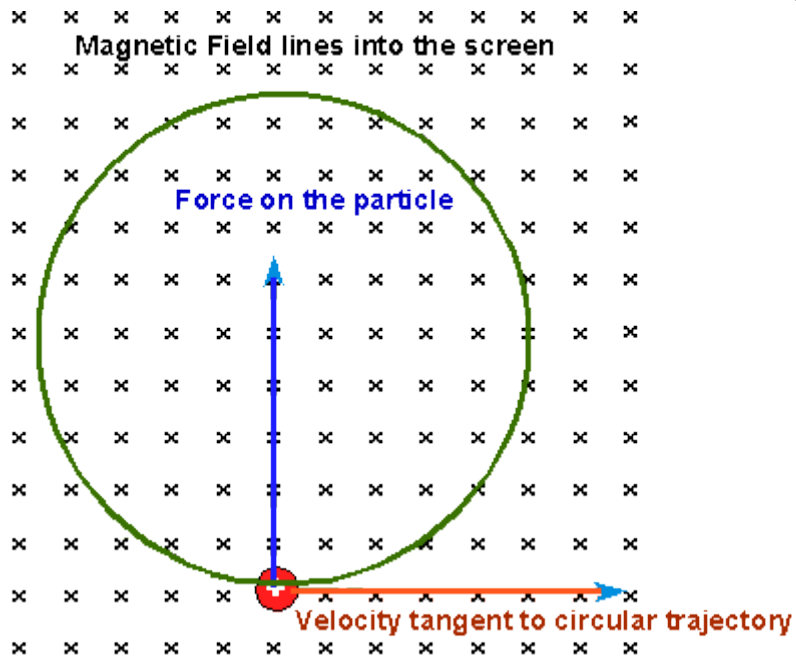
# Accelerator Physics (short course)



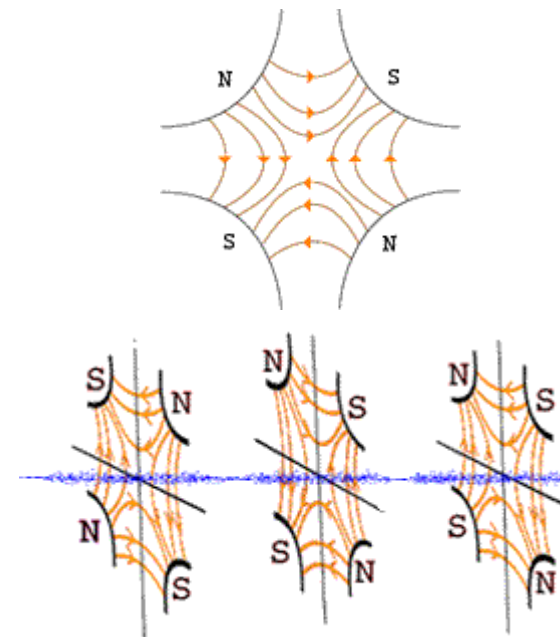
Electromagnetic waves push



## Magnets steer



turn

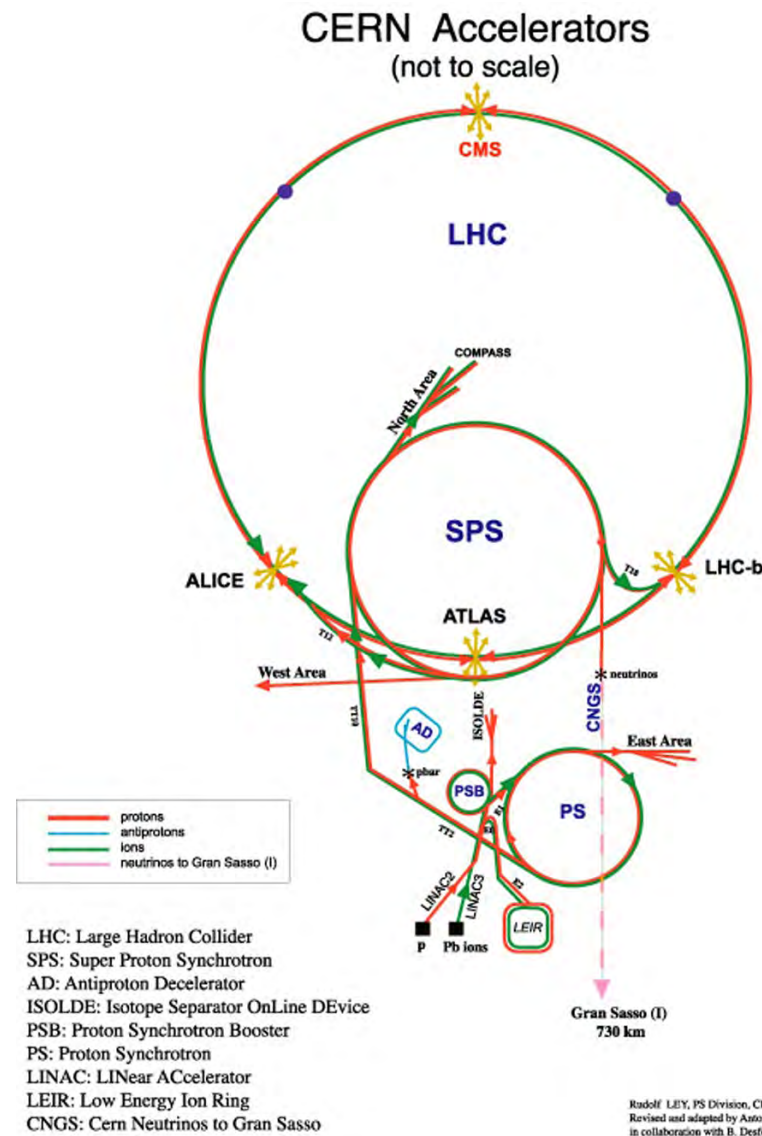


and squeeze

# CERN



# CERN Accelerator Complex



Rudolf 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. Manghji, PS Div, CERN, 23.05.01



# CERN Large Hadron Collider (LHC)



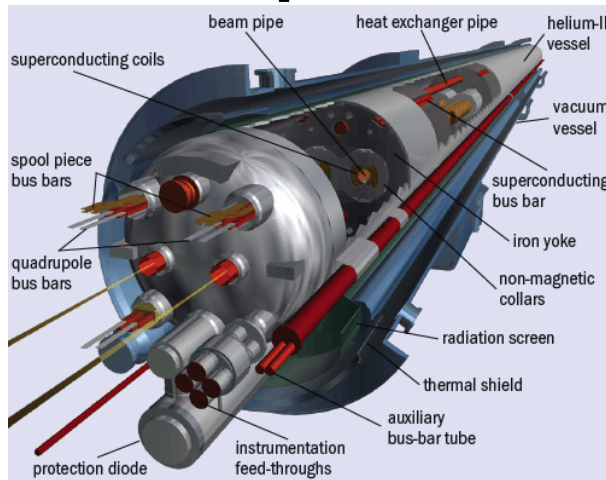
- Circumference 27 kilometers
- Revolution frequency 11.2455 kHz
- Power consumption ~120 MW

# Radio-Frequency Cavities (16)



- Accelerating field 5 MV/m
- Forward coupler power, peak 176 kW
- RF frequency 400.8 MHz

# Dipole Magnet (1232)



- Magnetic Length 14.3 m; Cold-mass weight 23800 kg
- Nominal Operating Temperature 1.9 K
- Operational Current (at 7 TeV) 11850 A
- Stored Energy per Magnet (Nom Current) 7513.9 kJ
- Operational Field (at 7 TeV) 8.3296 T
- Bending Radius 2807.456 m

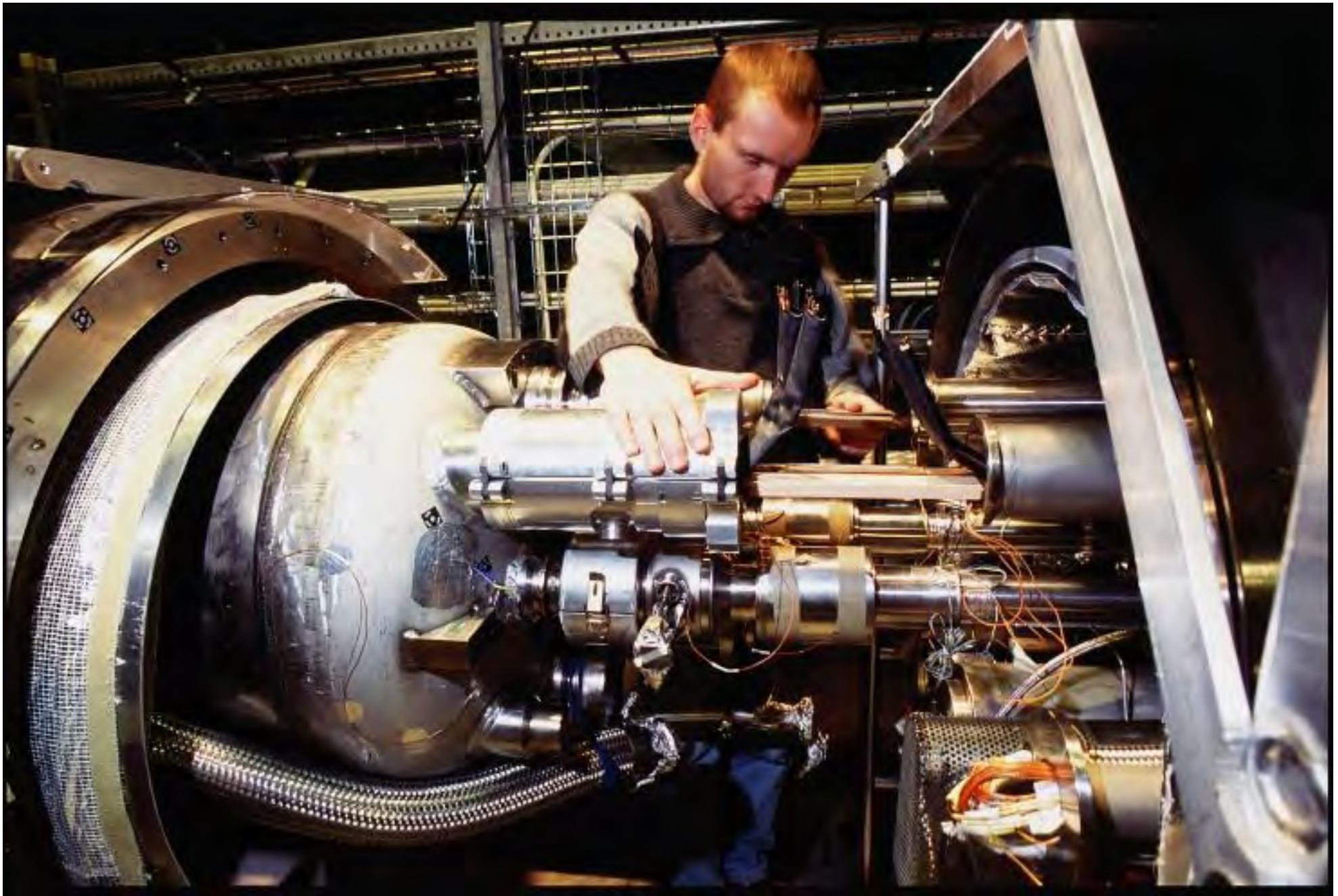


# Quadrupole Magnet (392)



- Length 3.1 m
- Weight 3600 kg
- Operating Temp 1.6 K
- Current 11870 A
- Stored Energy 394.5 kJ
- Field 3.791 T



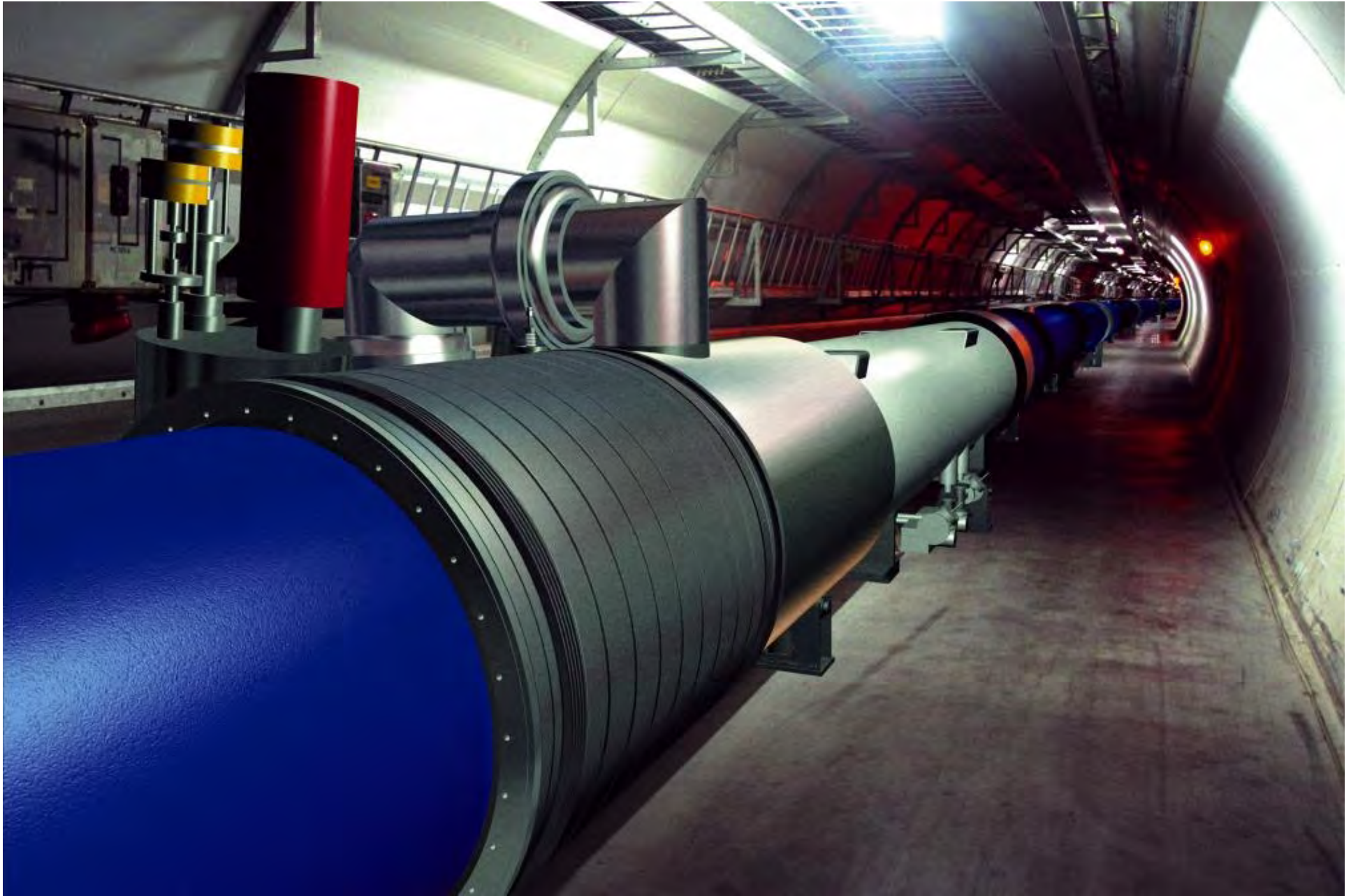


14 January 2014

Phil Rubin George Mason University

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# Then, Slam Accelerated Particles into Each Other or a Target

- Scatter for structural analyses
- Matter for production and evolution analyses

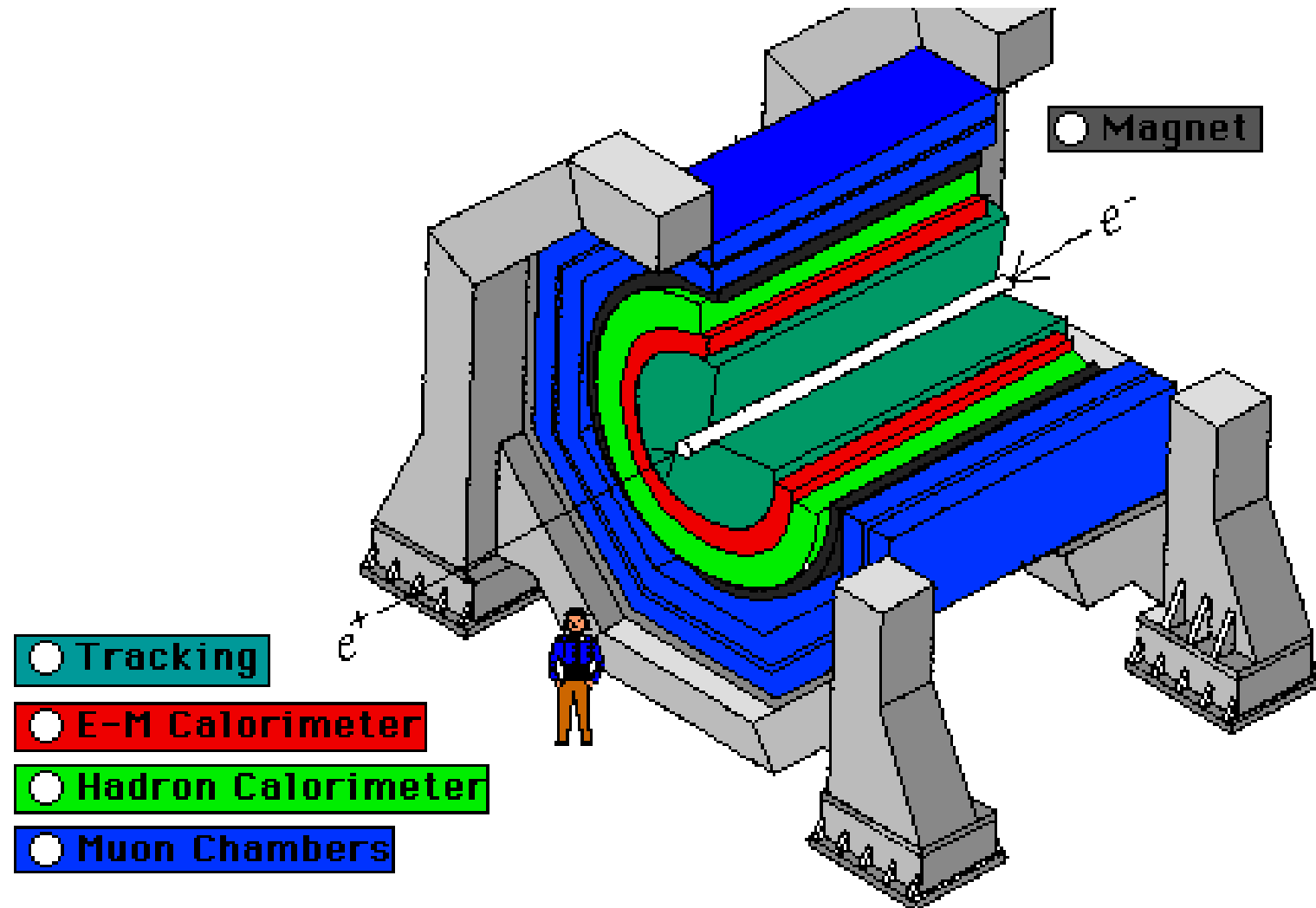
# Detectors: Seeing the Outcome

## Event Reconstruction








$$M^2 = E^2 - P^2$$

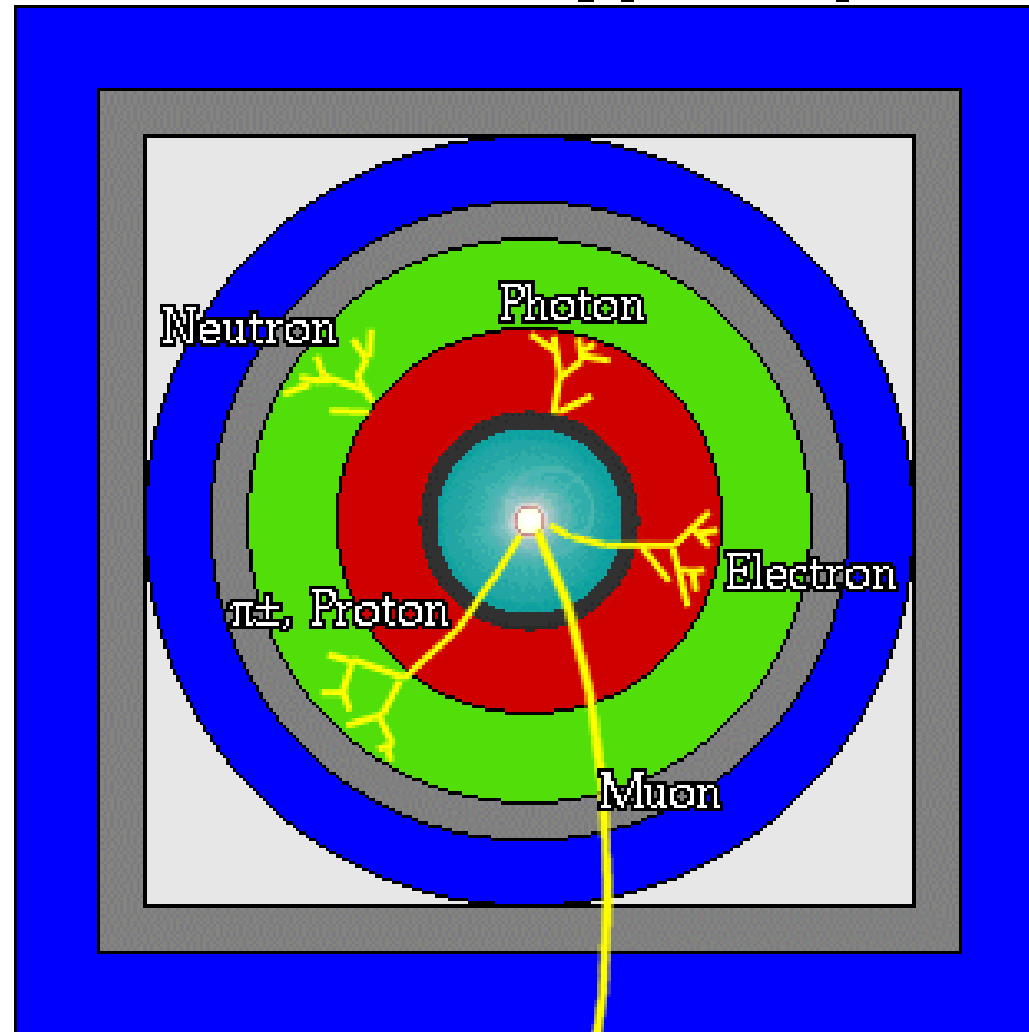
- Must determine
  - speed / momentum / energy
  - identity

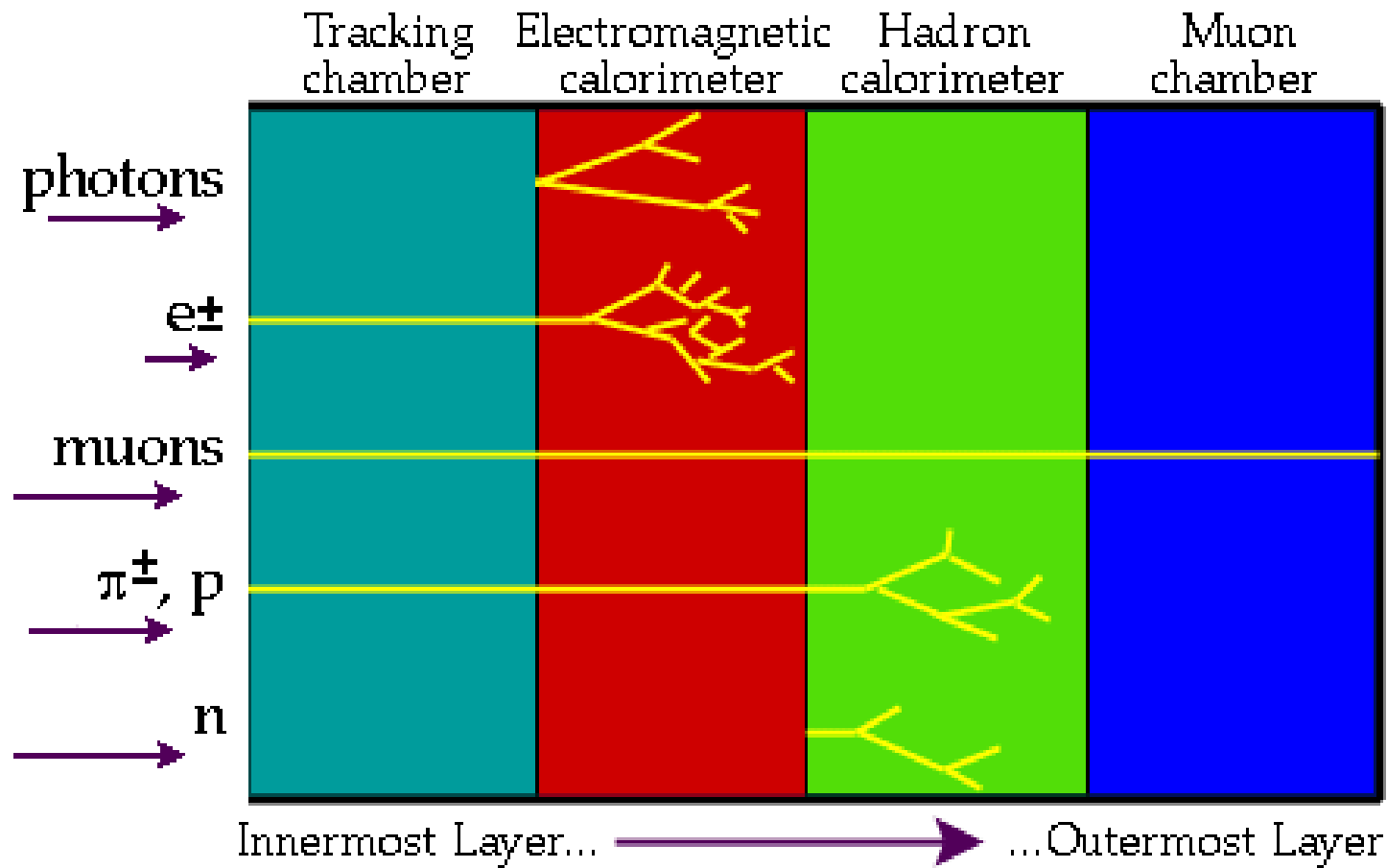
# Standard (Collider) Detector



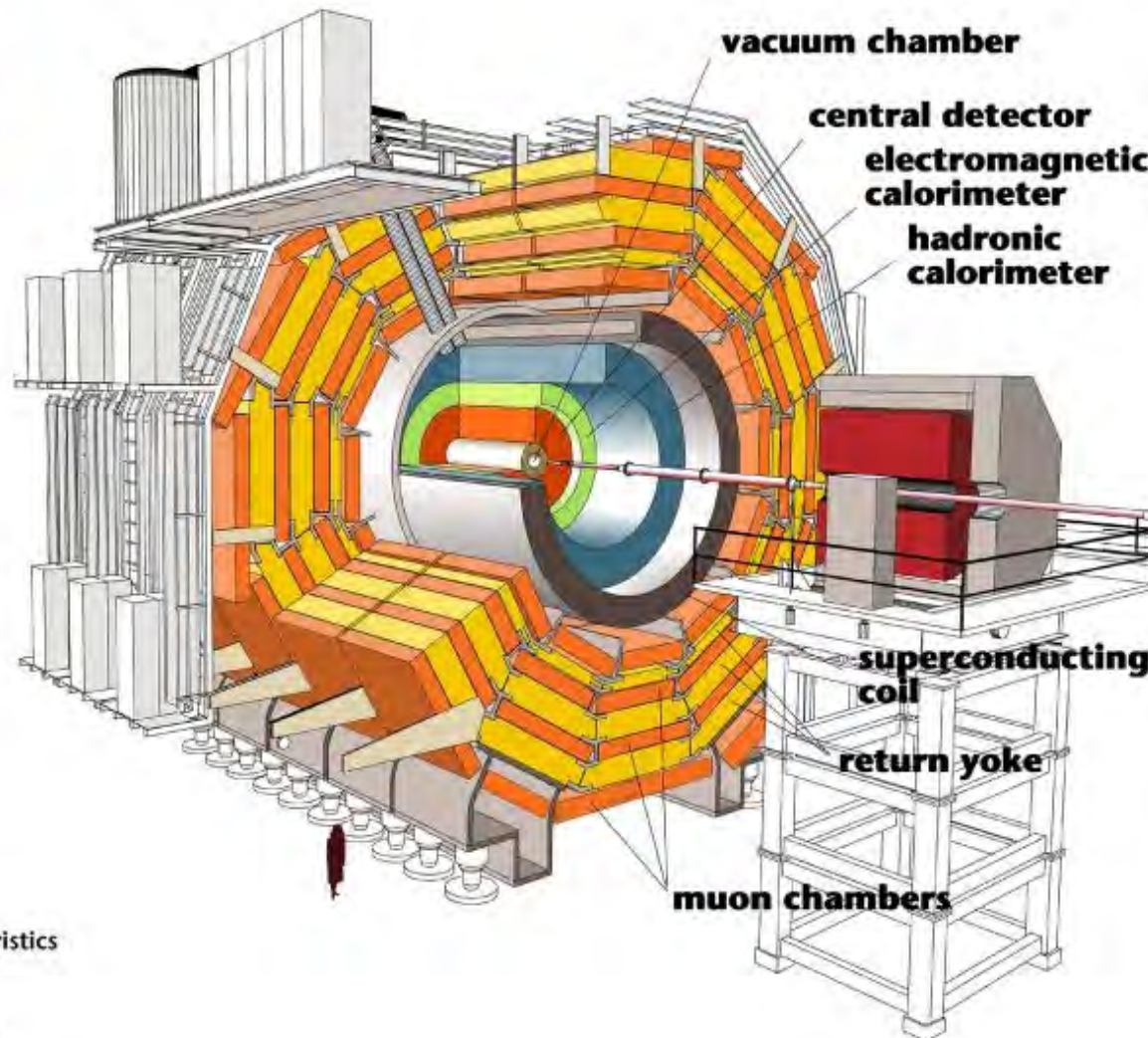
## A detector cross-section, showing particle paths

-  Beam Pipe (center)
-  Tracking Chamber
-  Magnet Coil
-  E-M Calorimeter
-  Hadron Calorimeter
-  Magnetized Iron
-  Muon Chambers





# Compact Muon Solenoid (CMS)

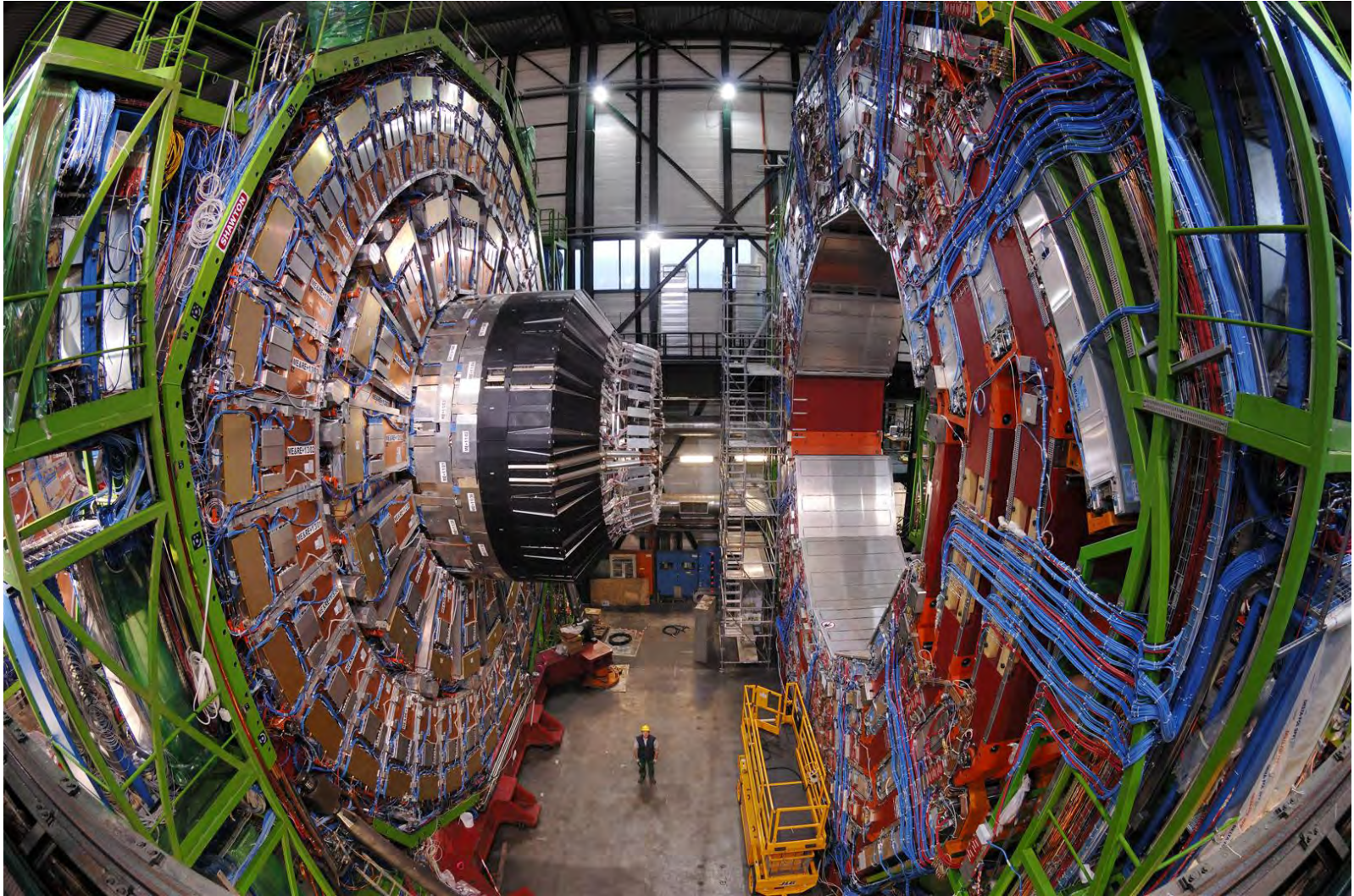


## Detector characteristics

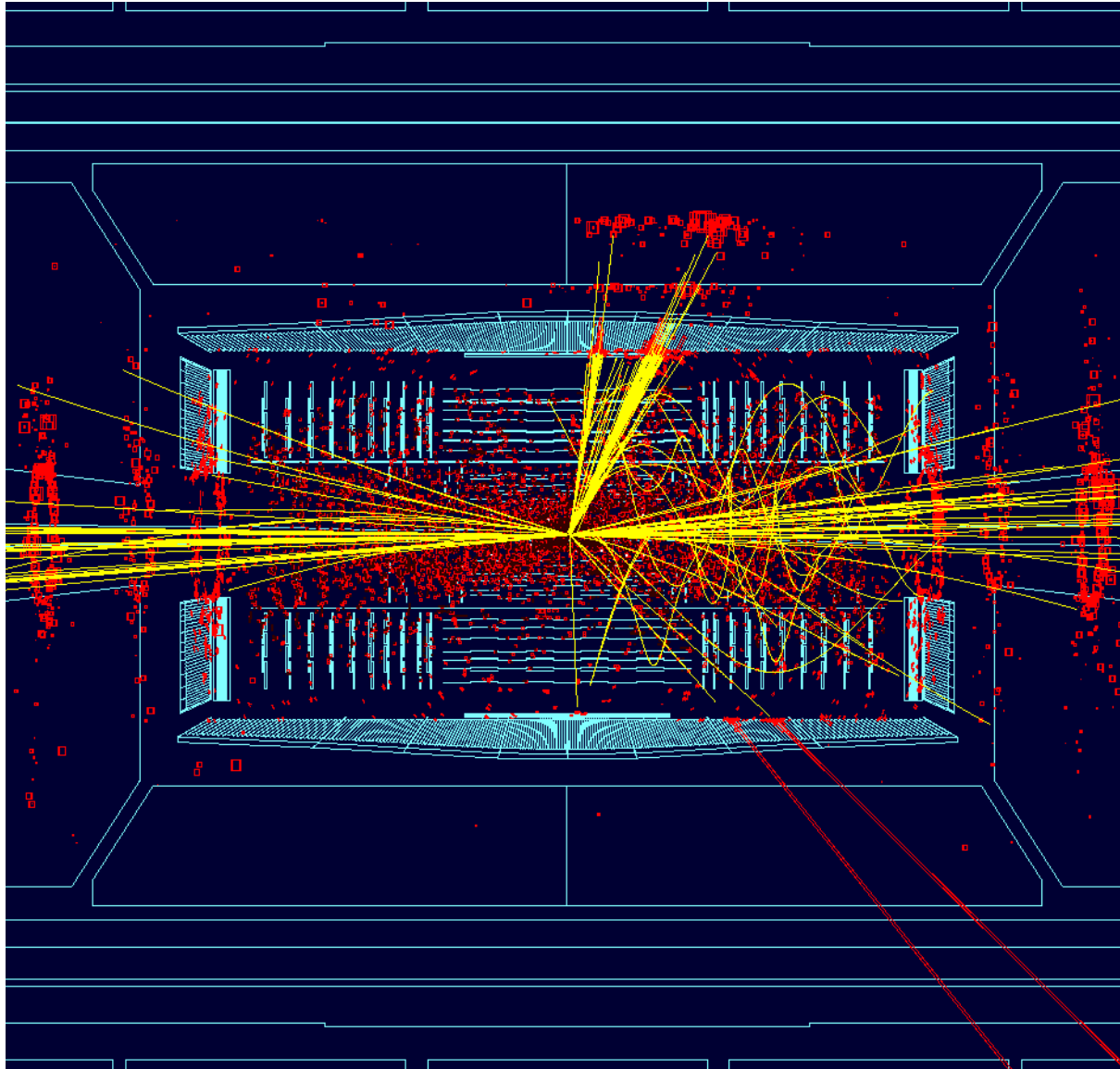
Width: 22m  
Diameter: 15m  
Weight: 14'500t



# Just Before Closing



# How an Interesting Event Appears





# The Standard Model

## Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

### FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_L$ lightest neutrino*	$(0-0.13) \times 10^{-9}$	0
e electron	0.000511	-1
$\nu_M$ middle neutrino*	$(0.009-0.13) \times 10^{-9}$	0
$\mu$ muon	0.106	-1
$\nu_H$ heaviest neutrino*	$(0.04-0.14) \times 10^{-9}$	0
$\tau$ tau	1.777	-1

\*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s  $\approx 1.05 \times 10^{-34}$  J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ) where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joule. The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

#### Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$  labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos  $\nu_L$ ,  $\nu_M$ , and  $\nu_H$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

#### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$  but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

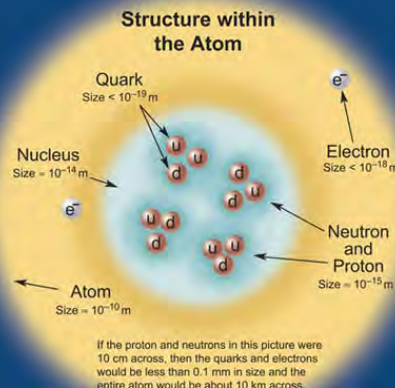
### Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating)  $W^-$  boson. This is neutron  $\beta$  (beta) decay.

An electron and positron (antilepton) colliding at high energy can annihilate to produce  $B^0$  and  $B^0$  mesons via a virtual  $Z$  boson or a virtual photon.

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
u up	0.002	2/3
d down	0.005	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	173	2/3
b bottom	4.2	-1/3



### Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass - Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-16} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 60

### Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

#### Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

#### Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

#### Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does the dark matter consist of new types of particles that interact very weakly with ordinary matter?

#### Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^-$	80.39	-1
$W^+$	80.39	+1
$Z^0$ Z boson	91.188	0

### BOSONS

force carriers  
spin = 0, 1, 2, ...

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
g gluon	0	0

#### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

#### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated - they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature mesons  $q\bar{q}$  and baryons  $qqq$ . Among the many types of baryons observed are the proton (uud), antiproton ( $\bar{u}\bar{u}\bar{d}$ ), neutron (udd), lambda  $\Lambda$  (uds), and omega  $\Omega^-$  (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  ( $u\bar{d}$ ), kaon  $K^-$  ( $s\bar{u}$ ),  $B^0$  ( $d\bar{s}$ ), and  $\eta_c$  ( $c\bar{c}$ ). Their charges are +1, -1, 0, 0 respectively.

Visit the award-winning web feature *The Particle Adventure* at **ParticleAdventure.org**

This chart has been made possible by the generous support of  
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Lawrence Berkeley National Laboratory

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# Fundamental Constituents

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# Observed Particles

## Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
<b>p</b>	proton	<b>uud</b>	1	0.938	1/2
<b><math>\bar{p}</math></b>	antiproton	<b><math>\bar{u}\bar{u}\bar{d}</math></b>	-1	0.938	1/2
<b>n</b>	neutron	<b>udd</b>	0	0.940	1/2
<b><math>\Lambda</math></b>	lambda	<b>uds</b>	0	1.116	1/2
<b><math>\Omega^-</math></b>	omega	<b>sss</b>	-1	1.672	3/2

## Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
$\pi^+$	pion	<b><math>u\bar{d}</math></b>	+1	0.140	0
<b><math>K^-</math></b>	kaon	<b><math>s\bar{u}</math></b>	-1	0.494	0
$\rho^+$	rho	<b><math>u\bar{d}</math></b>	+1	0.776	1
$B^0$	B-zero	<b><math>d\bar{b}</math></b>	0	5.279	0
$\eta_c$	eta-c	<b><math>c\bar{c}</math></b>	0	2.980	0

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Strength at {	$10^{-18}$ m	0.8	1	25
	$3 \times 10^{-17}$ m	$10^{-4}$	1	60

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# Rules (Symmetries)

- Continuous
  - Energy
  - Momentum
- Discrete
  - Charge
  - Isospin (I)
  - **Strange-ness**
  - Charm-ness
  - Bottom-ness
  - Top-ness
  - *Baryon Number (B)*
  - **Lepton Number (L/LF)**
  - Parity (P)
  - Charge Parity (C)
  - **Time Parity (T) or CP**
  - CPT

# The Nutshell

- Strong interactions create almost everything but change nothing
- Electromagnetic interactions create most of the rest and change very little (isospin)
- Weak interactions do most of the "damage"

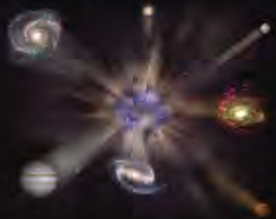


# Yet, Big Questions Remain

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# Contact

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