Elementary Particles in Nature and the Search for the Higgs Boson

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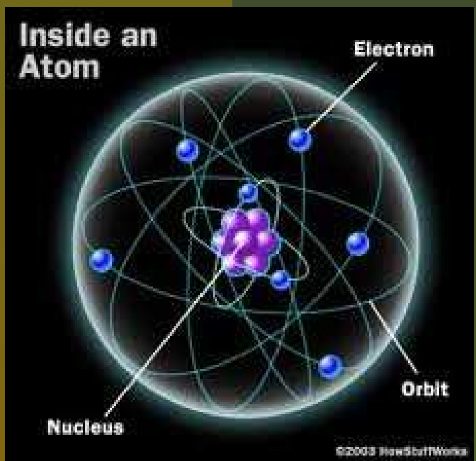
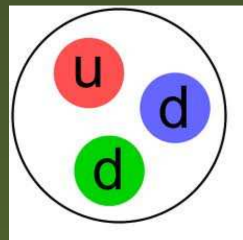
Elementary Particles

Atom 10^{-10}m (Greek: atomos = indivisible)



e + nucl (neutrons, protons) $\longrightarrow$ 

Quarks

Nucleus 10^{-14}m Nucleons 10^{-15}m

Quarks, electrons elementary particles – point-like

Standard Model of Particle Physics

$$LEPTONS: \quad e^- \quad e^+ \quad \mu^- \quad \mu^+ \quad \tau^- \quad \tau^+$$

$$\nu_e \quad \bar{\nu}_e \quad \nu_\mu \quad \bar{\nu}_\mu \quad \nu_\tau \quad \bar{\nu}_\tau$$

$$QUARKS: \quad u \quad \bar{u} \quad d \quad \bar{d} \quad s \quad \bar{s}$$

$$c \quad \bar{c} \quad b \quad \bar{b} \quad t \quad \bar{t}$$

[$e, \mu, \tau, \nu =$ electron, muon, tau, neutrino
$u, d, s, c, b, t =$ up, down, strange, charm, bottom, top quarks]

Antiparticle - same mass, opposite charge

Standard Model of Particle Physics

$LEPTONS:$	e^-	e^+	μ^-	μ^+	τ^-	τ^+
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_τ	$\bar{\nu}_\tau$
$QUARKS:$	u	$\bar{u}$	d	$\bar{d}$	s	$\bar{s}$
	c	$\bar{c}$	b	$\bar{b}$	t	$\bar{t}$
$GAUGE\ BOSONS:$	γ		$W^\pm$	Z		$g(8)$
$HIGGS\ BOSON:$	ϕ					

Antiparticle - same mass, opposite charge

PARTICLE DISCOVERIES

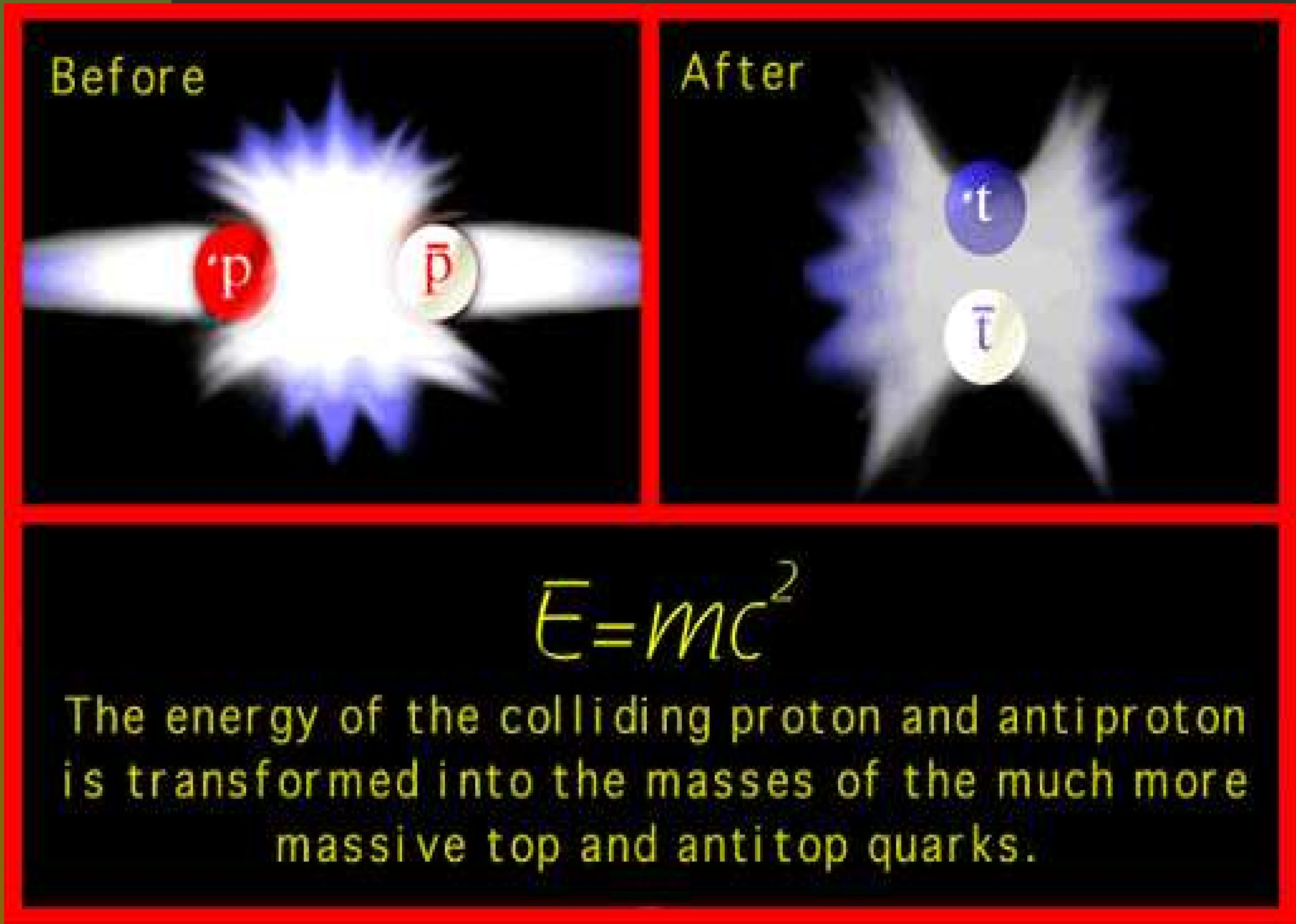
Cathode Ray Tube	Electron (1897)
Compton scattering expt	Photon (1905,1923)
Cosmic Rays	Positron (1932), Muon (1936)
Beta decay (nuclear reactors)	Electron neutrino (1956)

ACCELERATORS

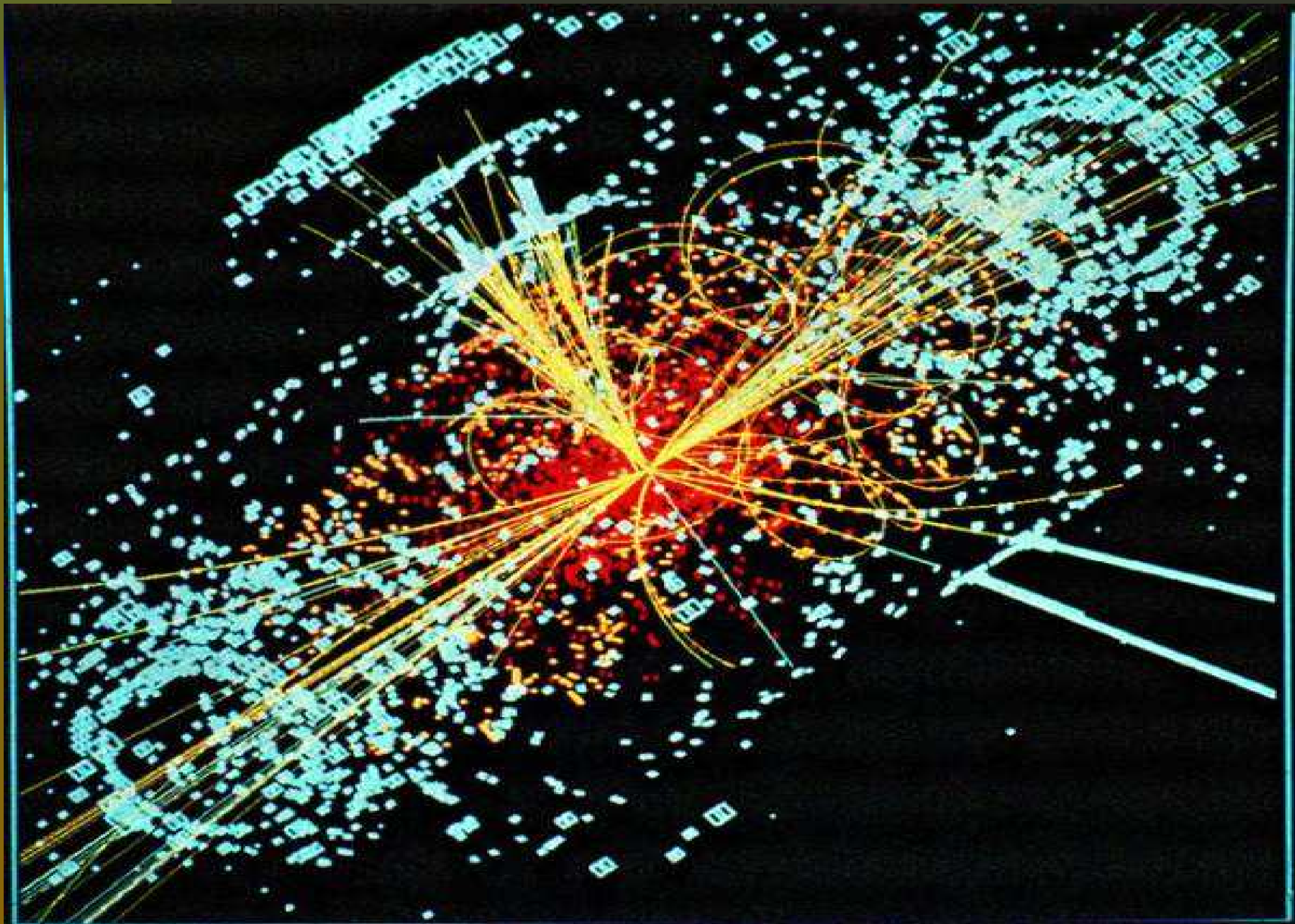
KEK	e^+e^-
CERN(LHC)	pp
BROOKHAVEN	Heavy Ion Collisions

CERN (LHC)

The LHC tunnel


Before
p
p̄
After
t
t̄
E=mc²
The energy of the colliding proton and antiproton is transformed into the masses of the much more massive top and antitop quarks.

Decaying Higgs after a p-p collision



PARTICLE DISCOVERIES

Accelerators	Muon and Tau neutrino, Tau lepton
	Up and Down quarks
	s, c, b, t quarks
	Gluons, $W^{\pm}, Z$ (1962-2000)

PARTICLE DISCOVERIES

Accelerators Muon and Tau neutrino, Tau lepton

Up and Down quarks

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Higgs particle (LHC 2012)

Why is the Higgs so important?

Why is the Higgs so important?

Need to understand how physicists describe the interactions/forces between particles and the role the Higgs plays in this.

The mathematical formulae are based on a master formula or expression called the Lagrangian.

- In the quantum theory of particle interactions, represent each particle by a field

  (photon $\rightarrow$ EM field, electron $\rightarrow$ electron field, Higgs $\rightarrow$ Higgs field)

- The Lagrangian must have some mathematical symmetry

  (Nature loves symmetry - Maxwell's equations for EM radiation in vacuum)

- Predictions must agree with experimental data

Math. symmetry of the Lagrangian

Symmmetry of the sphere, cube and cuboid

Similarly mathematical equations have symmetries – invariant under a mathematical transformation

Imply conservation of some physical quantity – energy, momentum, charge, ..

Mathematical symmetry of the Standard Model discovered from 1960-1980 by comparing theoretical conjectures with experimental data.

The mathematical symmetry of a simple Lagrangian for quarks, electrons, muons, .. interacting due to stong, weak and electromagnetic forces and without a Higgs field implies

- Particles like electrons and quarks are massless.
- W and Z (associated with weak forces) are massless (like the photon).

BUT ..

BUT experiments imply

- Electrons and quarks have mass.
- W and Z are massive (80 and 91 times the mass of a proton.)

  Weak forces effective over a range $\sim 10^{-17}$m. Beyond that very weak.

Introducing the Higgs field in the Lagrangian resolves this contradiction,

and provides a consistent mechanism (Higgs mechanism) for giving mass to particles and having a symmetric Lagrangian.

Can you avoid the Higgs mechanism?

Include a mass for electrons, quarks, ..

Include a mass for the W and Z and the weak force has a limited range. Less symmetry of Lagrangian

But calculations of high energy processes involving W and Z give physically unreasonable results.

(Very large probabalities for interactions at high energy)

The Higgs mechanism

A Higgs field ϕ in the Standard Model Lagrangian.
Fundamental particles get mass $m \propto \phi$

At early times $\phi = 0$ and all particles are massless.

Terms proportional to ϕ are 0.

The Standard Model Lagrangian then has a certain preferred mathematical symmetry.

The Higgs mechanism

Today $\phi \neq 0$ and now fundamental particles have a mass.

The mathematical symmetry of the Lagrangian is less. [Cube $\rightarrow$ cuboid]

Loss of symmetry - symmetry breaking - but no physical inconsistencies at high energies if via the Higgs mechanism.

Why ϕ change? Models exist for phase transition.

The Higgs mechanism

We believe that at early times $t < 10^{-12}$s the value of the Higgs field is 0 and fundamental particles are massless.

(Ignoring thermal mass)

Today the entire Universe is filled with a non-zero Higgs field.

Fundamental particles (q, e, W, Z,..) have mass because of their interaction with this field.

Stronger the interaction greater the mass.

The Higgs mechanism and the Higgs particle

This mechanism was proposed by Englert and Brout, Higgs, and Guralnik, Hagen and Kibble (1964).

Peter Higgs explicitly pointed out that if there was such a field there would be a corresponding particle and calculated some of its properties.

This particle is called the Higgs particle.

The discovery of the Higgs particle confirms the existence of the Higgs field and thereby confirms our understanding of why particles have mass, and how the symmetry of the Lagrangian is broken.

Some Issues

Discovering the Higgs particle

Why did it take almost 50 years to discover the Higgs particle?

1. Mass of the particle is 125 times that of the proton. So you need to collide particles at very high kinetic energy to produce the Higgs particle. (Probability of producing the Higgs increases with energy.)

At the LHC energy of the colliding particles is 8 times higher than in earlier experiments. Increased probability of producing the Higgs.

Discovering the Higgs particle

Why did it take almost 50 years to discover the Higgs particle?

2. The Higgs decays very quickly. Detect the decay products of the Higgs, not the Higgs directly.

   The same decay products are produced by other processes that do not involve the Higgs (background).

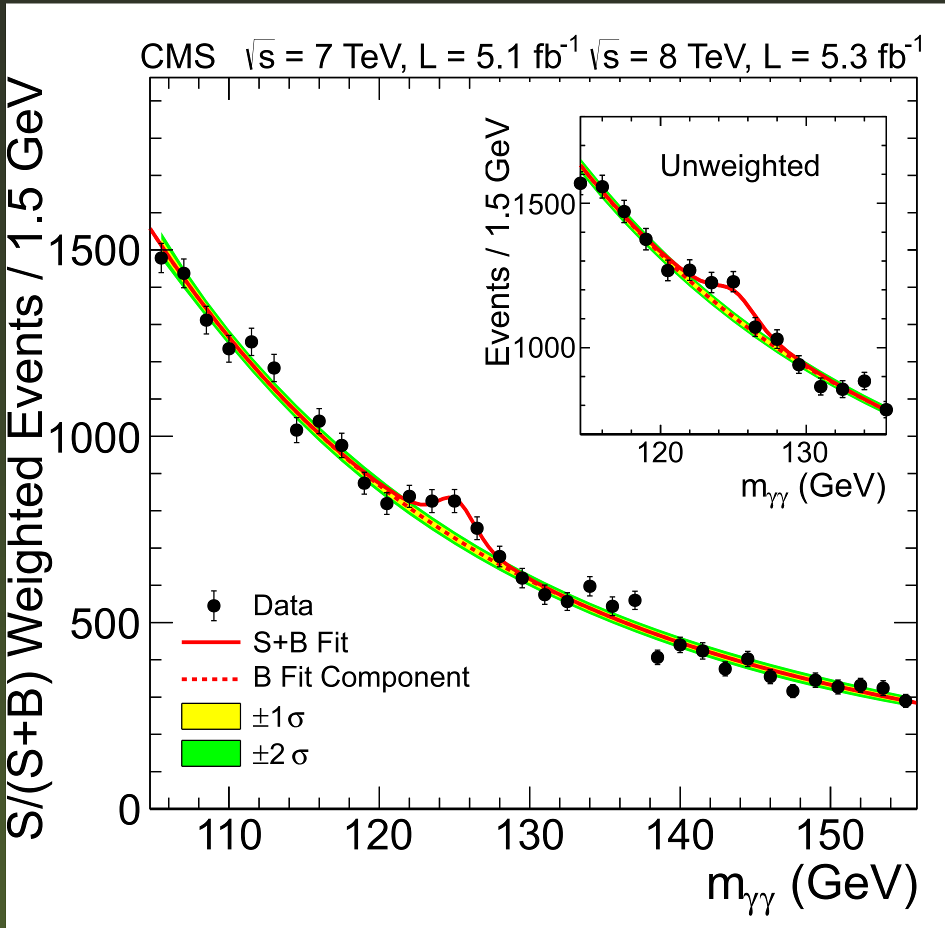
How do you discover the Higgs particle?

Higher energies

Compare what you see with what you expect from other known processes.

The excess can be attributed to the Higgs particle.

How do you discover the Higgs particle?

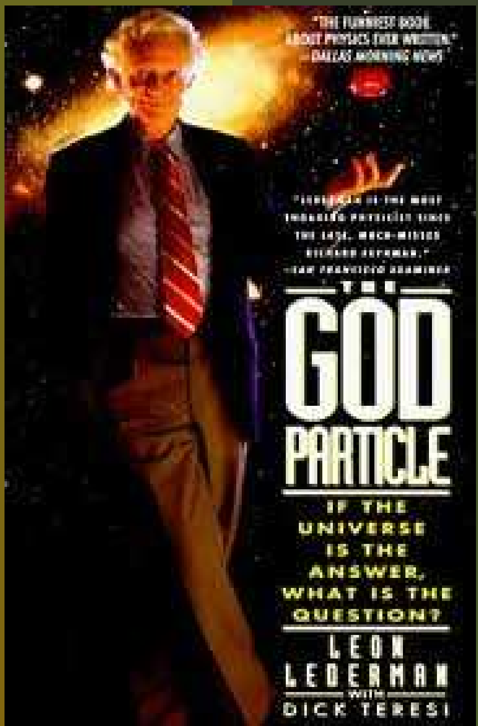


Higgs -> 2 photons. Number of photon pairs vs photon energy.
The excess can be attributed to the Higgs particle.

(Decay means transformation, Higgs elementary, not contain photons)

Why is the Higgs called the God Particle?

Title of a book by physicist Leon Lederman. The Higgs particle has nothing to do with religion or God.



India’s Role

CERN - European Organization for Nuclear Research

Involves 20 European + 3 member nations and 62 other countries.

Of these 62, 5 countries including India have Observer Status on the CERN Council (others are Turkey, Russia, USA, Japan).

India has agreed to become a member and will then have a greater say in CERN policies.

India’s Role

There are 4 different experiments (detectors) currently at LHC. India is a partner in 2 experiments

- CMS – Higgs boson and other new particles
  Panjab University, University of Delhi, SINP, BARC, TIFR
- ALICE – quark-gluon plasma
  Aligarh Muslim University, IOPB, Panjab University, University of Gauhati, University of Rajasthan, University of Jammu, IIT Bombay/Indore, Bose Institute, VECC, SINP

About 10,000 scientists and engineers; about 250 from India

LHC total cost is about 9 billion US dollars; India 60 million US dollars (Rs. 300 crores); Future

Higgs Boson

Particles are fermions or bosons – spin of particles.
Spin is mathematically similar to the angular momentum associated with spinning objects.

Quarks, electrons, ... are fermions. Spin is 1/2 (in units of the Planck constant).

Photons, W, Z, gluons have spin 1 and the Higgs has spin 0. Called bosons (integer spin).

Distribution of momenta of a gas of fermions/bosons at temperature T – Fermi and Dirac, S. N. Bose and Einstein.

Thermal (statistical) properties not relevant in the discovery of the Higgs.

What Next?

What Next?

1. Have to determine properties of the Higgs particle - spin (0 or 2), strength of its interactions with other particles

2. Is it a fundamental particle or a composite particle?

3. Understand the phase transition: $\phi = 0 \;\; \rightarrow \;\; \phi \neq 0$

Once we do that, are we done?

Is the Standard Model description the final explanation of particles and their interactions?

What Next?

NO!

The Standard Model is a theory with about 25 parameters that need to be provided as inputs.

Some theoretical issues related to the Higgs mass

In the Standard Model neutrinos are massless. Experimental evidence since 1998 that neutrinos have mass.

Most of the matter in the Universe is made up of a particle or particles that are not included in the Standard Model (dark matter).

Beyond the Standard Model

High Energy Theory $\longrightarrow$ Standard Model
(like Special Relativity $\longrightarrow$ Newtonian Physics)

SUPERSYMMETRY – Extension of the Standard Model

$$\begin{array}{ccc} \gamma\,(\mathrm{PHOTON}) & \longleftrightarrow & \tilde{\gamma}\,(\mathrm{PHOTINO}) \\ e\,(\mathrm{ELECTRON}) & \longleftrightarrow & \tilde{e}\,(\mathrm{SELECTRON}) \end{array}$$

WHY?

Resolves the theoretical issues regarding the Higgs mass

BONUS: Provides a possible candidate for dark matter

Discoveries at the LHC?

Astroparticle Physics

Astroparticle Physics

Particle Physics theories find applications in astrophysical scenarios and in the context of the Early Universe.

They allow us to test interactions of particles at very high energies (BSM).

The consequences of these high energy interactions in the early Universe influence the Universe that we see today.

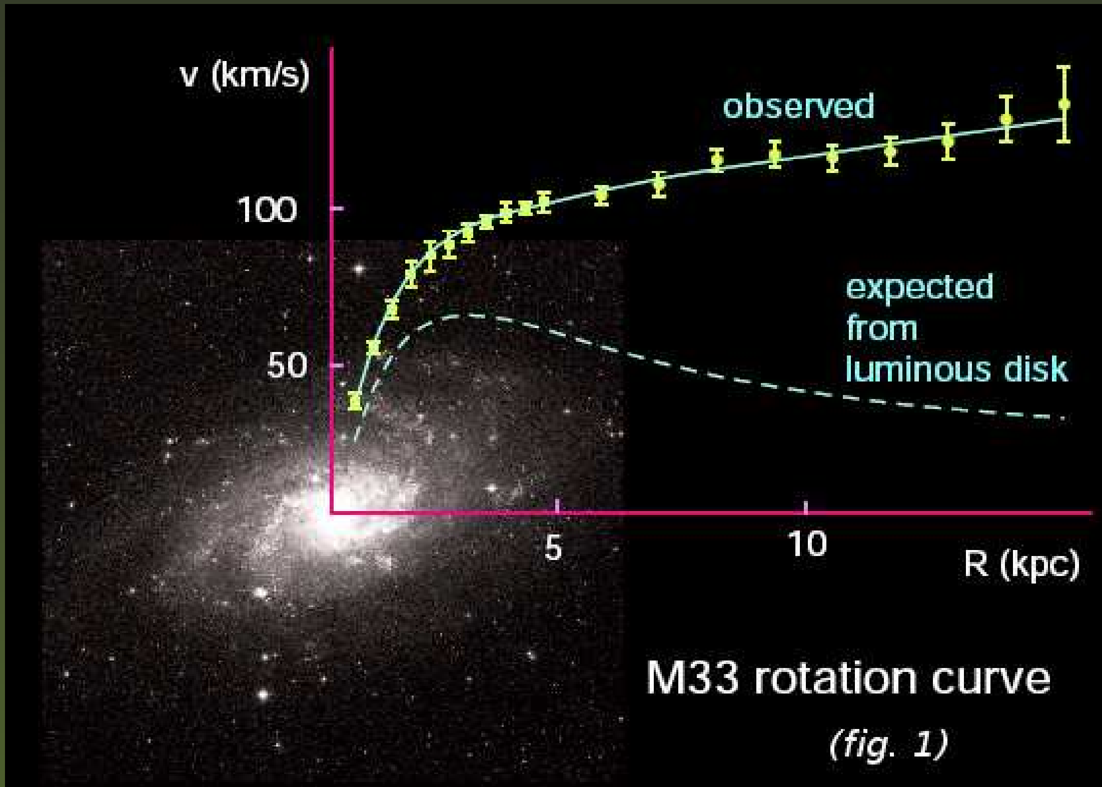
Discuss a cosmological observation related to supersymmetry.

Dark Matter

Velocity Rotation Curves of Galaxies

Expect $v \sim \frac{1}{\sqrt{r}}$, since $m\frac{v^2}{r} = G\frac{Mm}{r^2}$ and M is constant.

BUT ....


v (km/s)
observed
100
expected
from
luminous disk
50
5
10
R (kpc)
M33 rotation curve
(fig. 1)

Take $v \sim$ constant. How can this be explained?

$$m\frac{v^2}{r} = G\frac{Mm}{r^2}$$

If $M(r) = Ar$, then $v \sim$ constant.

But $M(r) = Ar \Rightarrow$ matter beyond the central luminous region which we can not see.

This matter is non-luminous (does not emit or scatter light) and is called DARK MATTER.

DARK MATTER does not emit or scatter light so it is difficult to detect.

What is it?

Consists primarily of non-Standard Model matter – supersymmetric particles

DARK MATTER does not emit or scatter light so it is difficult to detect.

What is it?

Consists primarily of non-Standard Model matter – supersymmetric particles

LHC is looking

Conclusion

- The Standard Model of Particle Physics explains what are the fundamental particles and how they interact
- The discovery of the Higgs boson, after a 50 year search, validates important aspects of the Standard Model. More data needed to establish properties of the Higgs.
- Also need to consider theories Beyond the Standard Model valid at higher energies, e.g., Supersymmetry

Conclusion

- Accelerators such as the LHC will (hopefully) discover supersymmetric particles
- Astrophysics and Cosmology (e.g., existence of dark matter) provide clues to theories Beyond the Standard Model

Particle Physics

Books

- The Cosmic Code by Heinz Pagels
- The Big and the Small, vol. I and II by G. Venkataraman

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