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CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

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The Higgs Boson

Holy Grail of Particle Physics

Linac08 Victoria BC, Canada

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LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

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Motivating Scientific Questions

1. Are there undiscovered new symmetries or laws in nature?
2. Are there extra dimensions of space? (small or large)
3. Do all the forces become one?
4. How can we solve the mystery of Dark Energy?
5. What is Dark Matter?
6. Where is all the anti-matter?
7. How to combine Q.M. & gravity?

1) and 2) motivated by new physics to stabilize Higgs mass calculation-no fine tuning 3) Hints exist & needs spontaneous symmetry breaking 4) Higgs part of discussion 5) data 6) data 7) String theory

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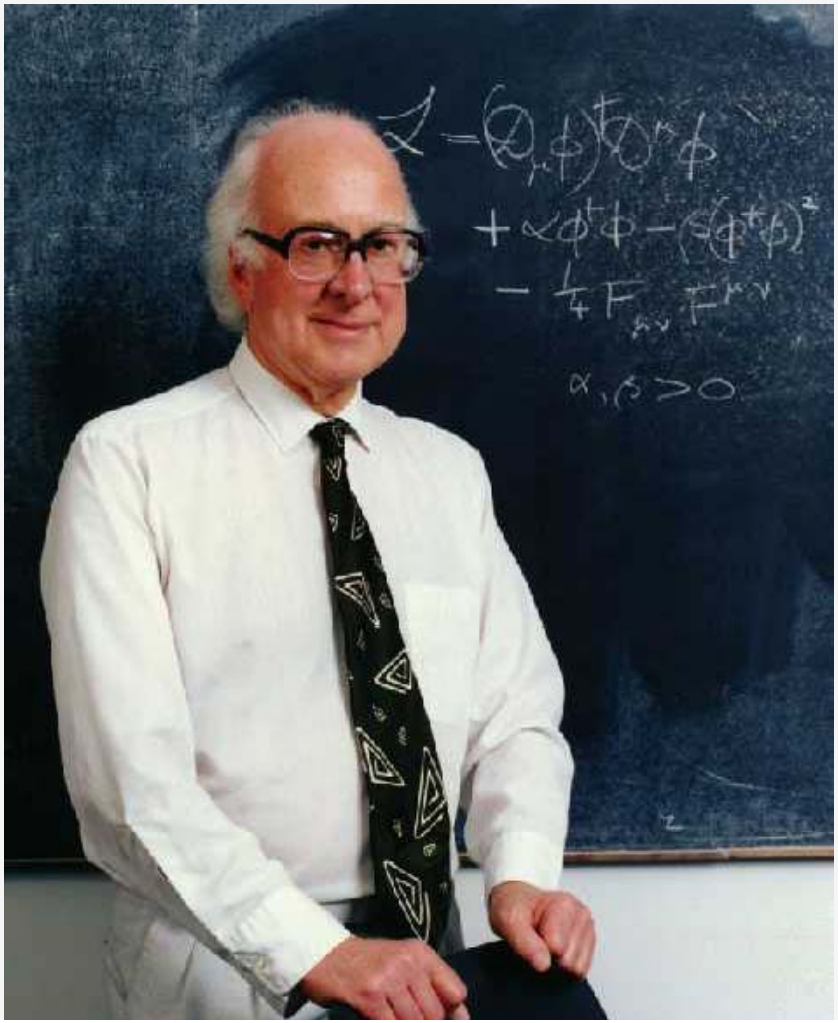
Outline

What is the Higgs Boson?
What is the Higgs Mechanism?
Why are weak interactions weak?
Connections to Nuclear Physics & Astrophysics?
Higgs at Tevatron
ILC (Higgs Factory)

Peter Higgs



Idea derived from Schrieffer (BCS) and Nambu

Higgs field a form of superconductivity in vacuum

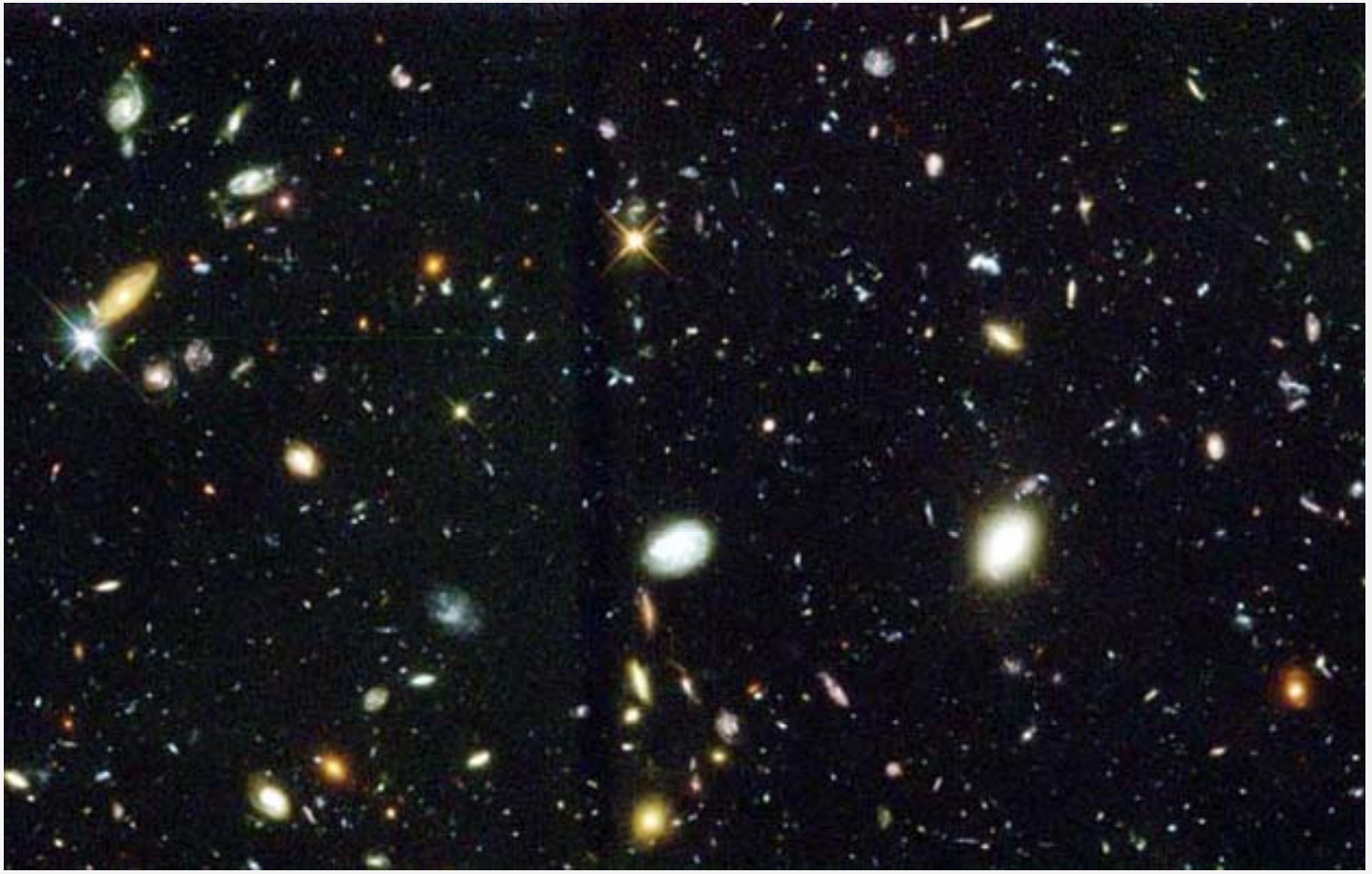
Relativistic quantum fluid filling space

Original paper rejected by PRL

"nothing new"

Waiting 44 years for particle physicists to discover his Boson

Hubble Deep Field (10 day exposure)
(12 billion years ago—we know its expanding)



Higgs Field Fills Space

Superconductivity

- Cooper pairs form a condensate which breaks EM gauge symmetry forming a superfluid
- Expels all magnetic fields from interior
  - Meissner effect
  - Interpret electromagnetic fields as short range in a superconductor
- We know ordinary metal, conductivity shields electric fields inside by arranging charges on surface until they cancel in interior
- Magnetic fields however are unimpeded by metal
- In SC…photon becomes massive and range is inversely proportional to mass

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Higgs Mechanism

- Form of superconductivity in vacuum
- Fill all space with a relativistically invariant Q. fluid
- Prevents weak force from propagating over infinite distance
- Higgs field consists of 2 neutral and 2 charged component fields (simplest case)
- When Higgs acquires a vacuum expectation value, non-zero value of field in empty space
  - The value is 246 GeV
  - 2 neutral and 1 charged mix with vector bosons (W^+,W^- & Z) giving them mass….other field is the Higgs boson
  - Weak force range is inversely proportional to mass of W and Z bosons

The Essence

Higgs field breaks the electroweak symmetry

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What is a Particle?

Disturbance in an energy field

What is a Field?

- Temperature field (scalar field)
- Higgs is a scalar field
- Defined everywhere in space
- One number at every point

- Wind field (vector field)
- Magnetic field (vector field)

Higgs Field

Neutral scalar field that fills the entire universe

Particles traveling through the universe interact with this field & become massive

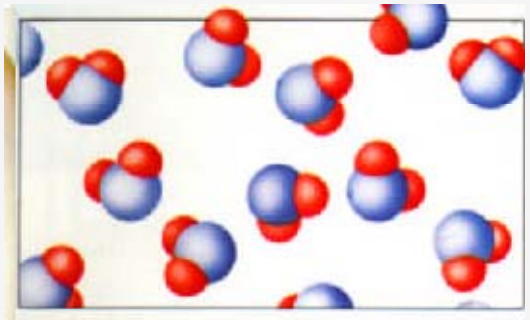
Importantly, the W and Z bosons receive mass but not the photon in the Standard Model

Symmetry in Art

M. C. Escher

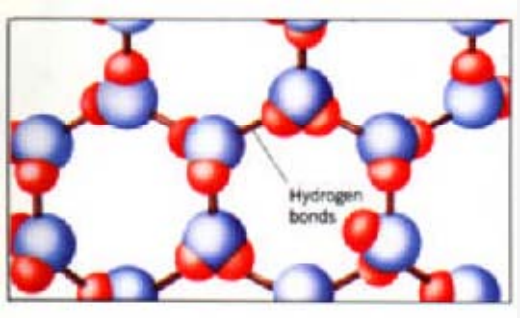
What is Spontaneous Symmetry Breaking? from Steam to Snow

Steam



Hot !
Perfect
Symmetry

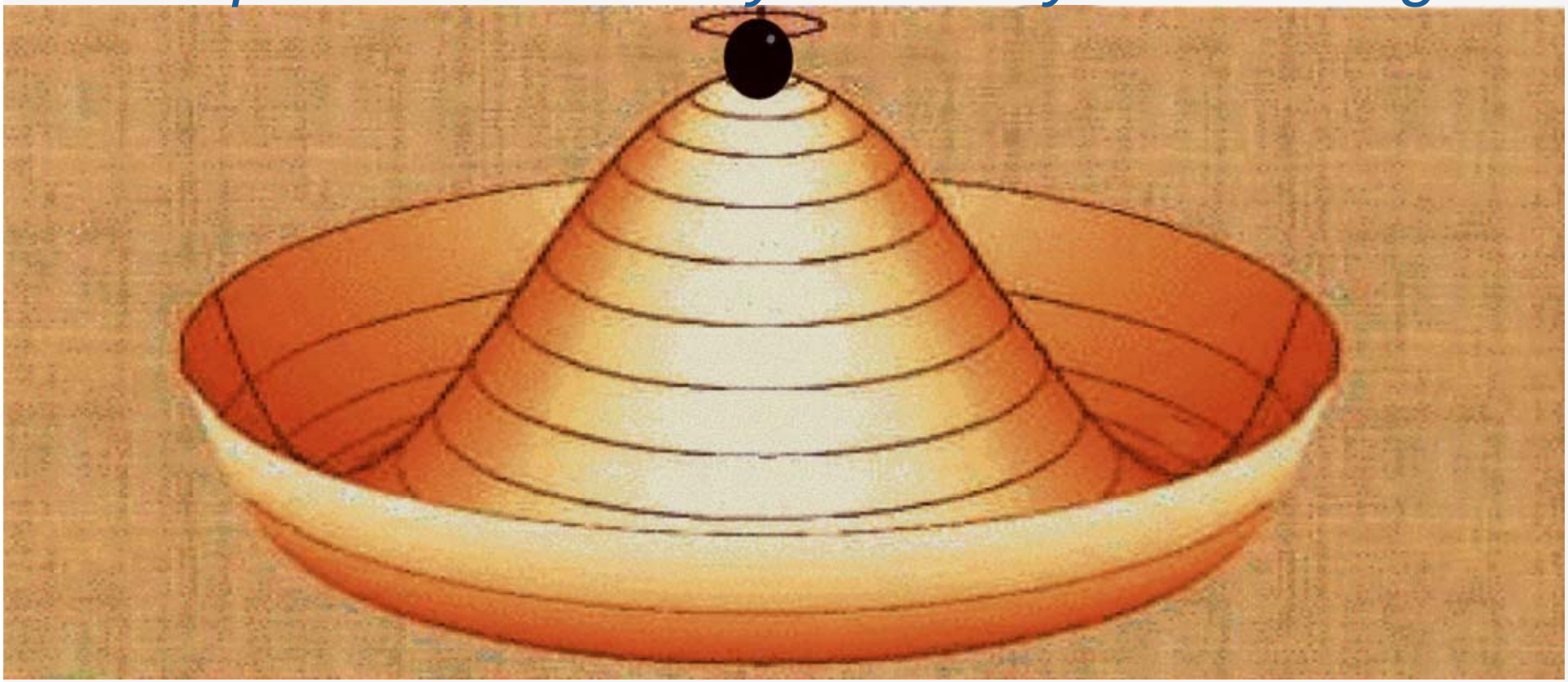
Ice



Cold !
Broken
Symmetry

Another example is iron, which below some critical temperature, becomes magnetic because the magnetic moments align. Above that temperature, spins not aligned, which is a state of greater symmetry.

Example of: spontaneous symmetry breaking



Symmetric state rolls down to ground state at critical temperature.
Picks a random direction or phase
"The massive Higgs rolls down potential breaking symmetry"

Spontaneous Symmetry Breaking(1)

- Ferromagnetism above the Curie temperature is spatially invariant and there is no magnetic field in space
- Below the Curie temperature the symmetry is spontaneously broken and there is a magnetic field created in space
- The crucial parameter is the order parameter
  - In this case magnetization goes from 0 → 1
- This is called a phase transition

Spontaneous Symmetry Breaking(2)

- In electroweak symmetry breaking there is a phase transition at the electroweak temperature
- The universe cooled below this temperature about a picosecond after the big bang
- Above this temperature, there was no Higgs field
- Below this temperature there was a Higgs field
- The electroweak symmetry breaks into electromagnetic and weak fields (same as rotational symmetry broken in ferromagnetism example)

- The W & Z (carriers of weak force) “eat” some of the Higgs field and gain mass (short range force)
- The photon (carrier of electromagnetic force) has zero mass (long range force)

Origin of Mass:

There might be something (new particle?!) in the universe that gives mass to particles

Nothing in the universe

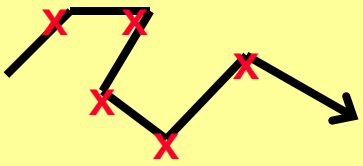
Something in the universe

Higgs Particles:

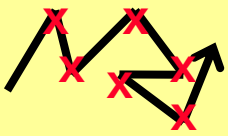
Coupling strength to Higgs is proportional to mass

Electron

Z,W Boson

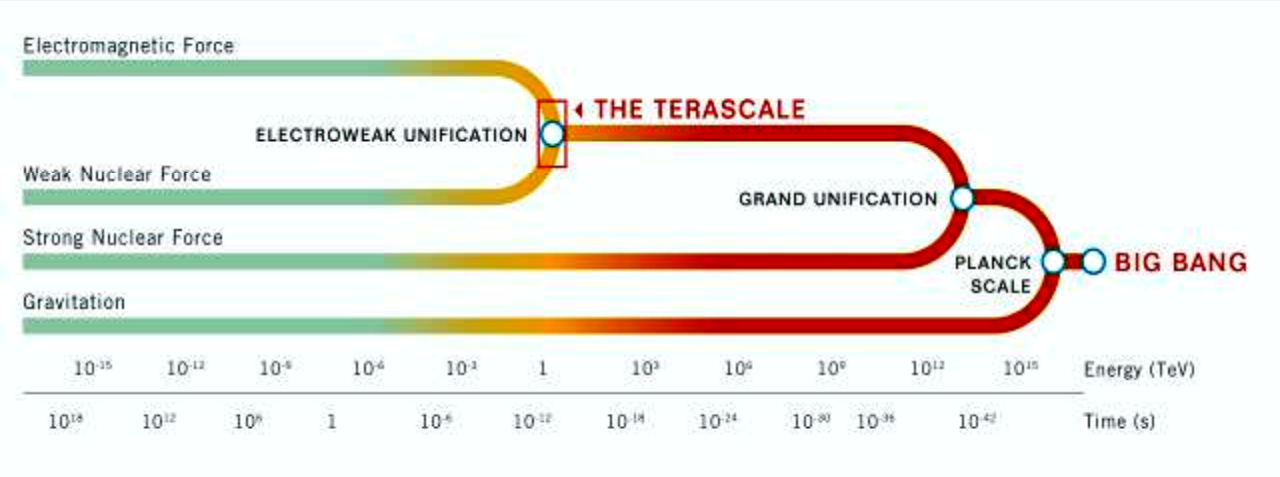


Top Quark



Unification of All Four Forces

3. Do all the forces become one?



We believe that there was just one force after the Big Bang

As the universe cooled down that single force split into the four we know today: gravity, electromagnetism, the strong and weak nuclear forces

Similar mathematical laws describe three of the forces but not gravity

At the TeV scale electromagnetism and weak forces unified

Strong interaction thought to be unified at GUT scale

Gravity unifies at Planck Scale

Why are we excited about the LHC?

The LHC will substantially increase the energy scale in particle physics, by a factor of 7. This is a big jump in historical terms, and we cannot really foresee what will happen. Exploratory machine!

But there is one really big question that we can be pretty sure will be answered at the LHC.

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Why the weak interactions are weak.

According to the Standard Model of particle physics, the weak interactions and electromagnetism are fundamentally described by the same equations of "gauge theory," and the obvious differences between them come only from "spontaneous symmetry breaking."

Somehow this determines which "gauge particles" (photons, Z bosons, W bosons) are obvious in everyday life, and which ones are hidden in the "weak interactions."

We know that this happened, because after all the weak interactions are weak, but we don't know how it happened

According to the simplest form of the Standard Model, the simplest answer involves a single new scalar field called the “Higgs field”

It measures how far one has rolled down the hat (Higgs potential), and as such was part of the inspiration for the theory of “cosmic inflation” (which involves a similar rolling of a scalar field)

If this description of symmetry breaking is right, the LHC will prove it and explain why the weak interactions are weak …

This follows from the electroweak data that we already have, which show that if the Standard Model description of symmetry breaking is correct, the Higgs mass is in a certain range (m_{higgs}~114-210 GeV).

The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

Higgs particles are spin-0 bosons.
The Higgs is neither matter nor force;
The Higgs is its own antiparticle
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Could give a handle on dark energy(scalar field)?

If discovered, the Higgs is a very powerful probe of new physics.

Mass

Inertial Mass F=ma=weight (Newton)

Gravitational Mass $F=Gmm/R^2$ (Newton)

Equivalence Principal

You cannot tell the difference between standing on the earth from accelerating in a space ship at a=g (Einstein explained)

Mass of Atom

Most of mass of atom in the nucleus

Nucleus made of protons and neutrons

Electrons are very light

1/1800 of proton mass

Mass of Proton and Neutron mostly not from constituent quarks

(this is quite strange)

Most of mass of proton not in 3 quarks (uud)

Most of mass of neutron not in 3 quarks (udd)

Mass comes from energy of quarks (Einstein)

$$m=E/c^2$$

Most of mass in luminous universe this type

But mass of quarks is critical to existence of atoms

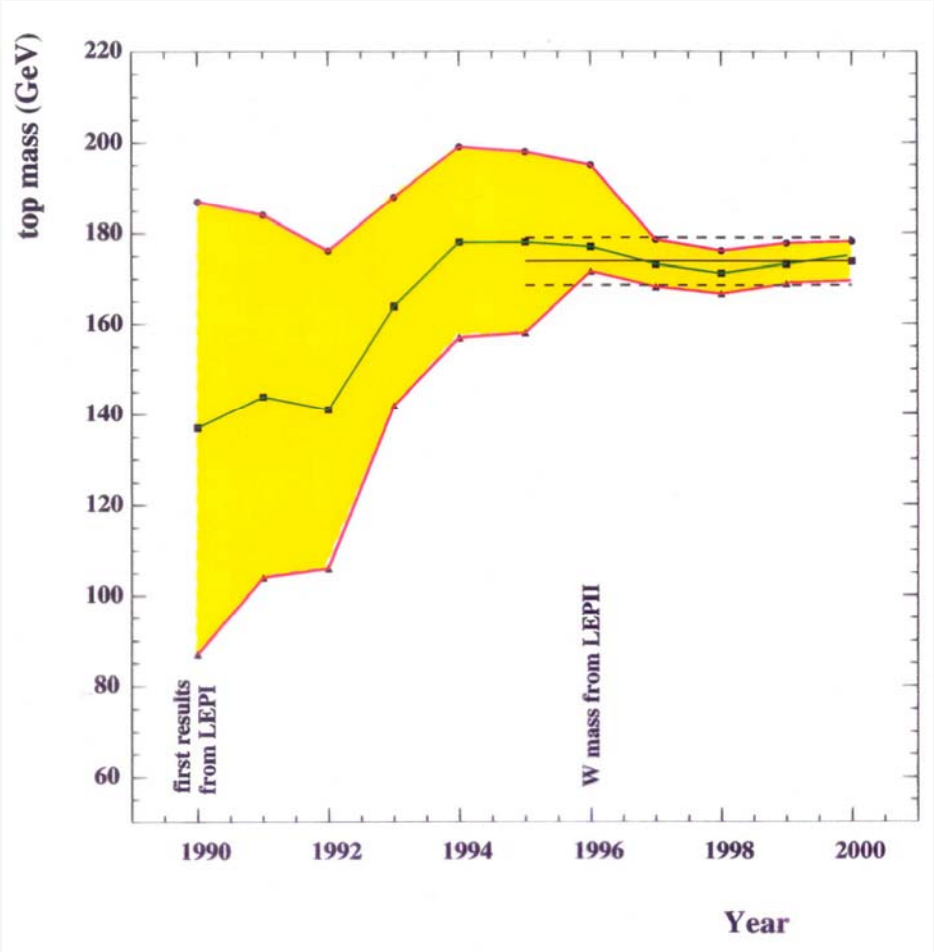
Without the Higgs

- Bohr radius (radius of electron in atom) inversely proportional to mass of electron
- If electron has no mass atom would not exist
- If the u quark mass=down quark mass, the proton would be more massive than the neutron
- Lightest nucleus would be neutral – no atoms
- The chemical elements of life would not exist

Thanks to Chris Quigg (Fermilab) for this observation

Electroweak Fits Needed TOP

LEP



Higgs last remaining particle not found needed in fit

Superconductivity and Superfluidity

Quantum gases, fermionic Alkali atoms — $T_c \sim 10^{-12}$-10^{-9} eV

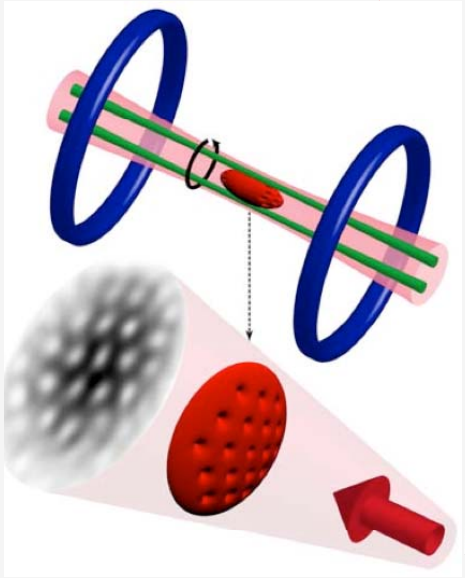
Liquid ^{3}He (2-atom Cooper pair BCS superfluid) — $T_c \sim 10^{-7}$ eV

Electrons in metals, composite materials — $T_c \sim 10^{-3}$-10^{-2} eV

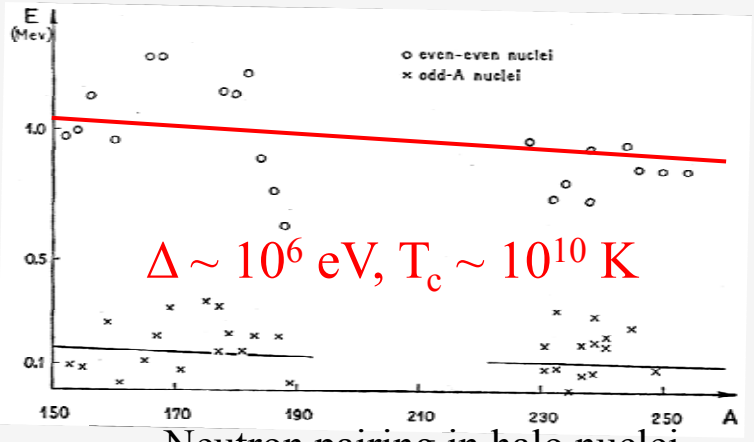
Neutron superfluidity, proton superconductivity in nuclei and neutron stars — $T_c \sim 10^{5}$-10^{6} eV

(1 eV $\sim 10^4$ K)

Superfluid vortices in **quantum gases**
Zwierlein et al. MIT (2006)

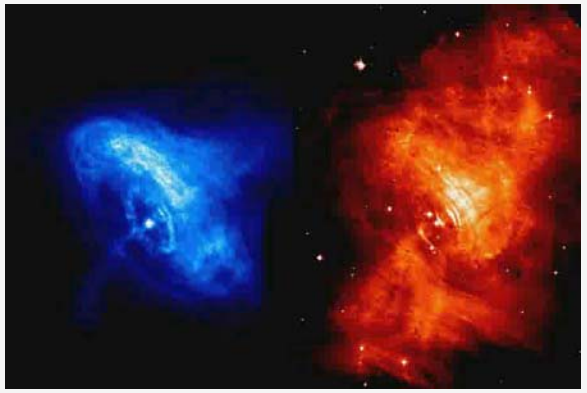


Even-even vs. odd A excitation energies



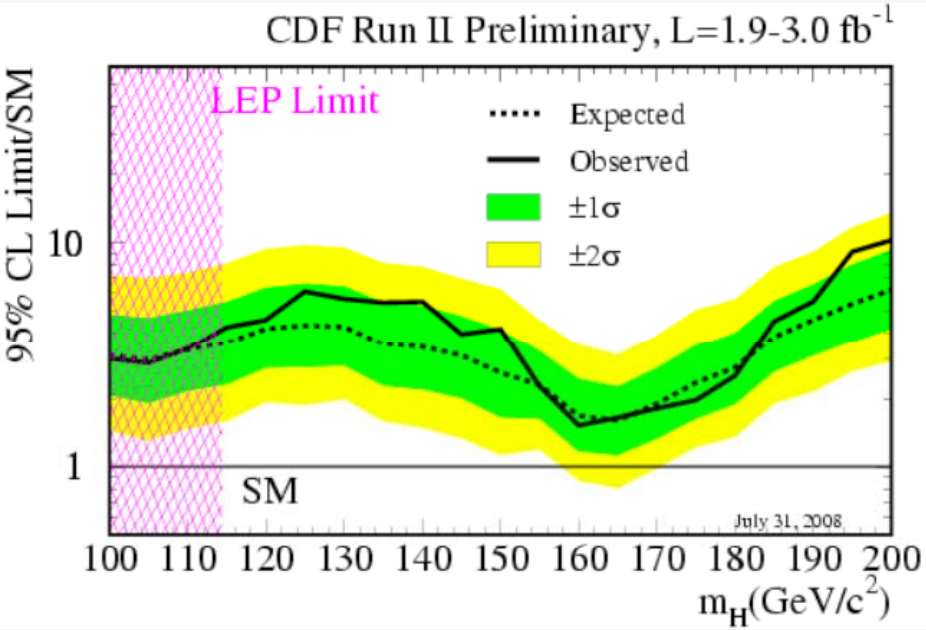
$\Delta \sim 10^6$ eV, $T_c \sim 10^{10}$ K

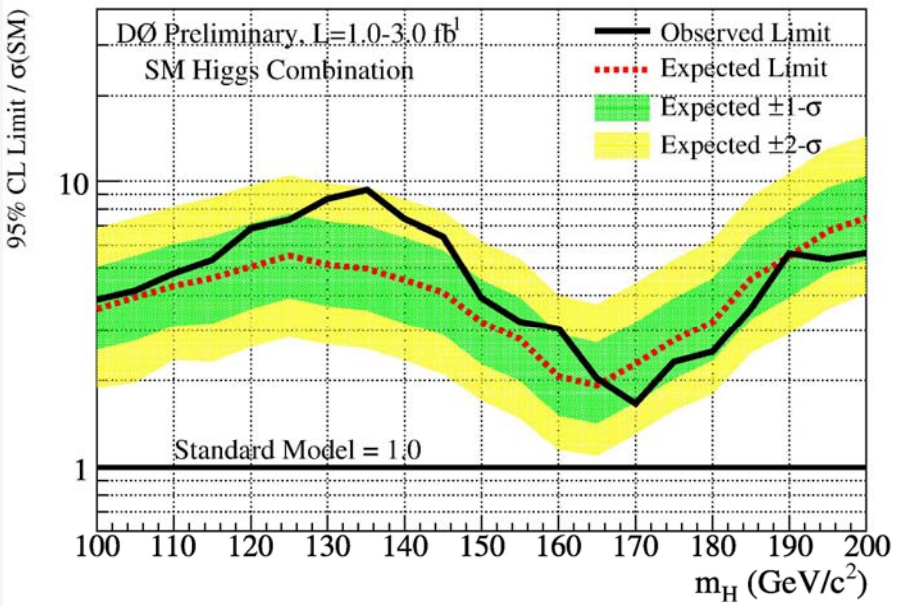
Neutron pairing in halo nuclei



Crab pulsar in X-ray and optical: Superfluidity/superconductivity impacts cooling of neutron stars

SM Higgs Combined Limits

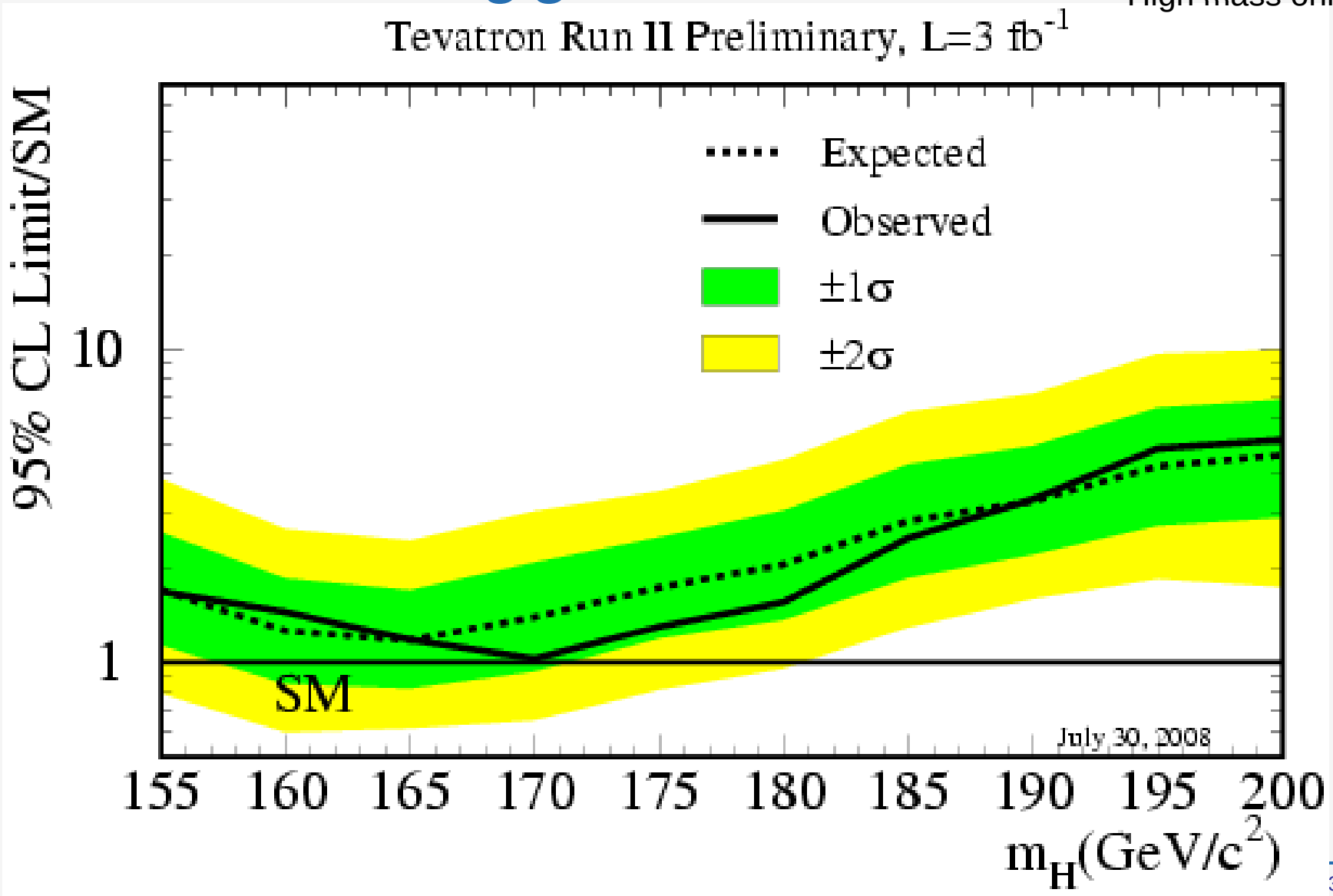




- Low mass combination difficult ~70 channels
  - Expected sensitivity of CDF/DØ combined: <3.0xSM @ 115GeV

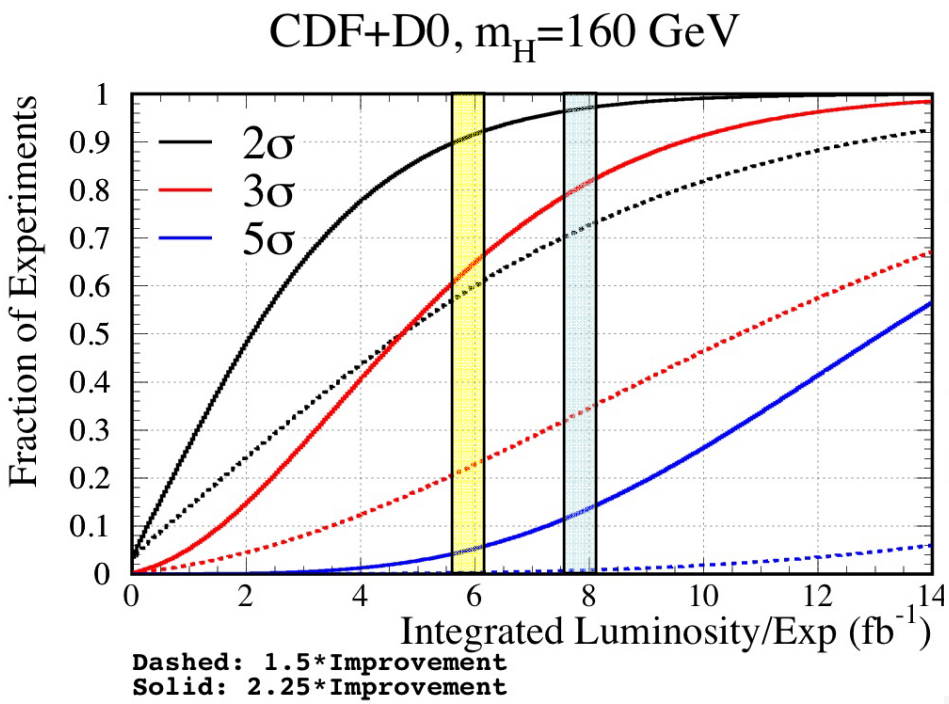
SM Higgs Combination

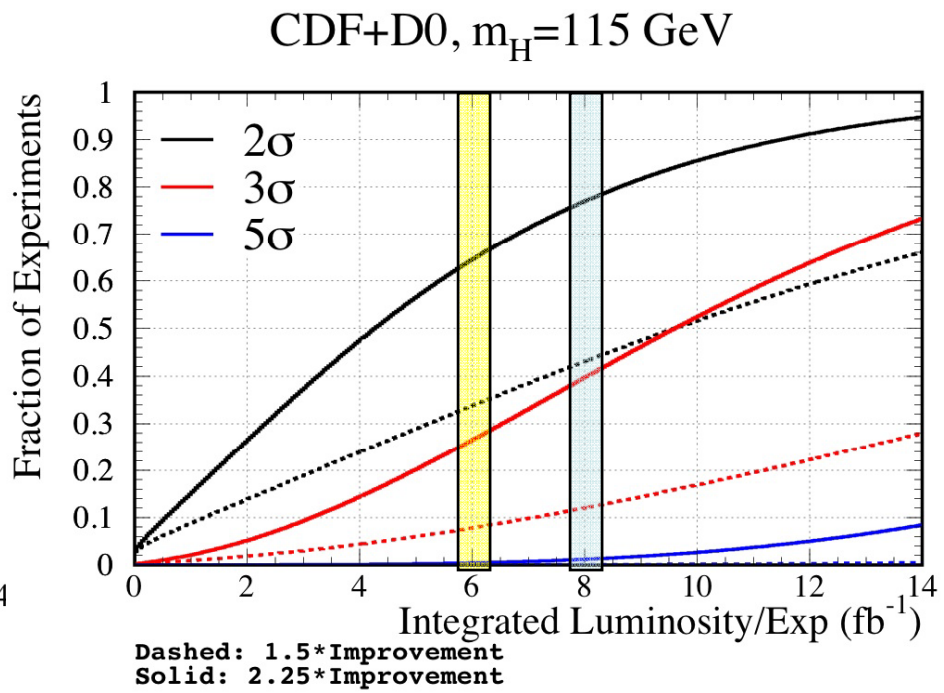
High mass only



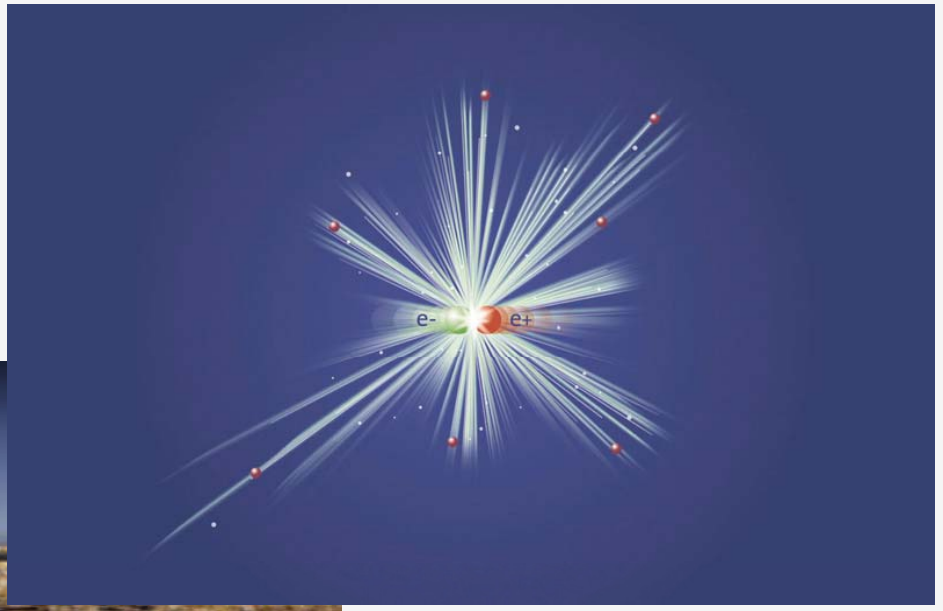
Discovery at Tevatron?

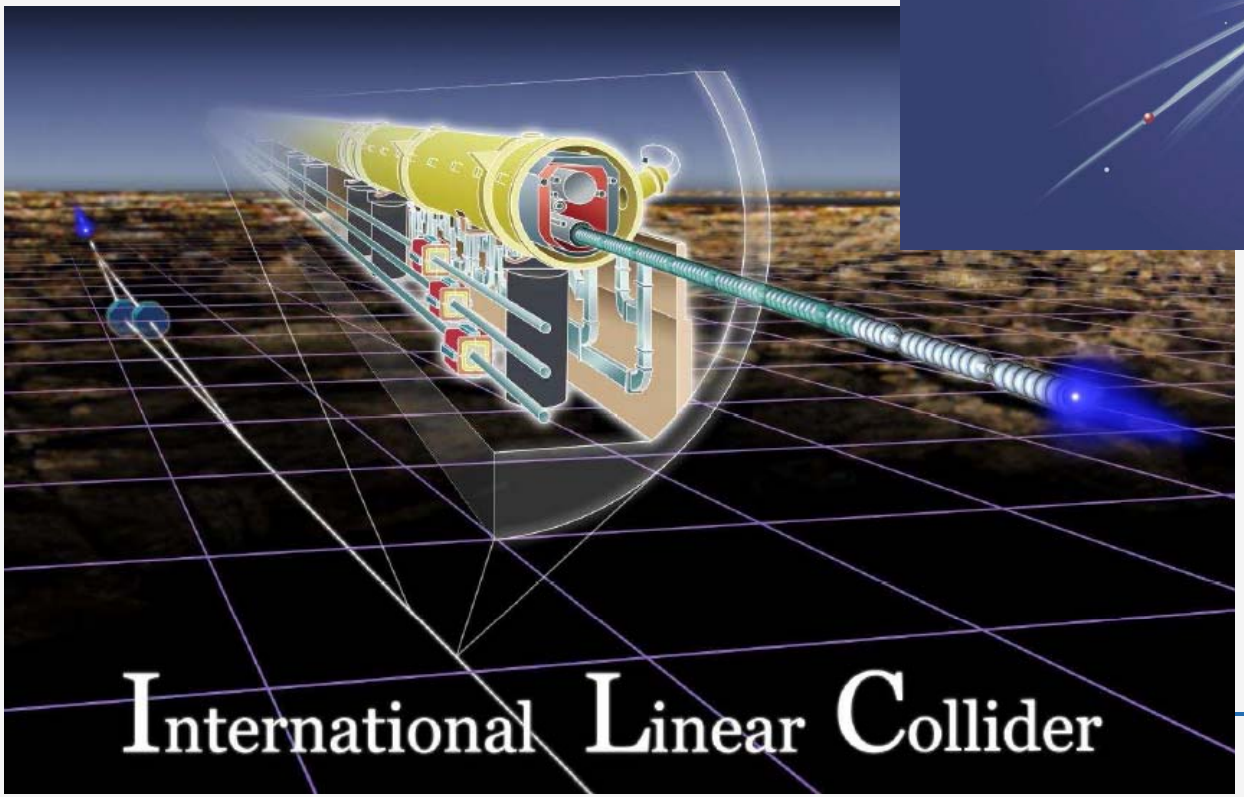
- Discovery projections: chance of 3σ or 5σ discovery



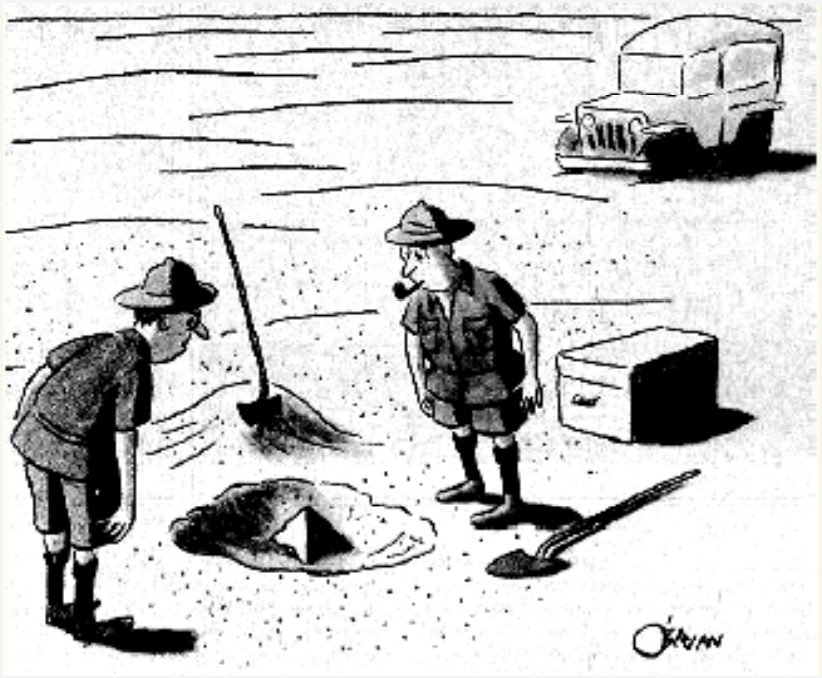


International Linear Collider





Discovery of the Century at LHC?

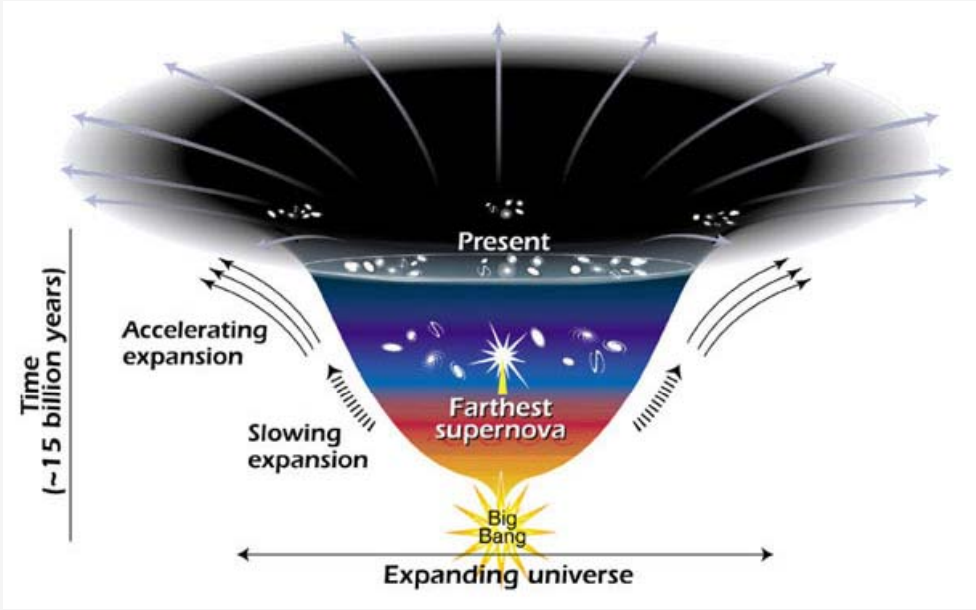


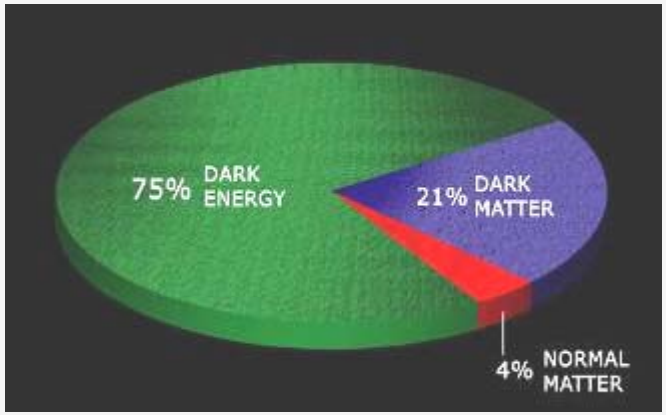
ILC will help dig down and uncover deeper picture

The Mystery of Dark energy?

Measurements by telescopes and space probes the universe is expanding at an accelerated rate.

Theorists think Dark Energy is a mysterious force responsible for pushing the galaxies apart and makes up 75% of the universe.





Luminous matter is only a tiny part of all matter!

- Are cosmological cousins of the Higgs responsible for inflation?
- Could a modification of gravity at cosmological distances, like due to extra dimensions, explain inflation?

Thanks to Marcela Carena (Fermilab)

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Conclusion

If we find the Higgs at the LHC we should move quickly to build the Higgs Factory and understand this unique scalar particle and use it as a window into new physics

Thank you

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