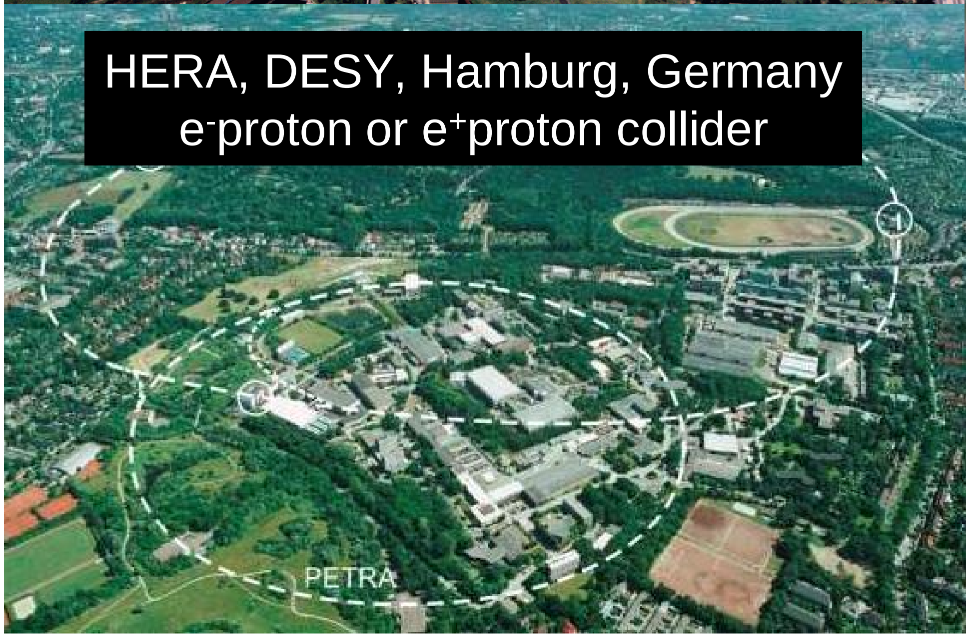
# $E = mc^2$
# Opening Windows on the World

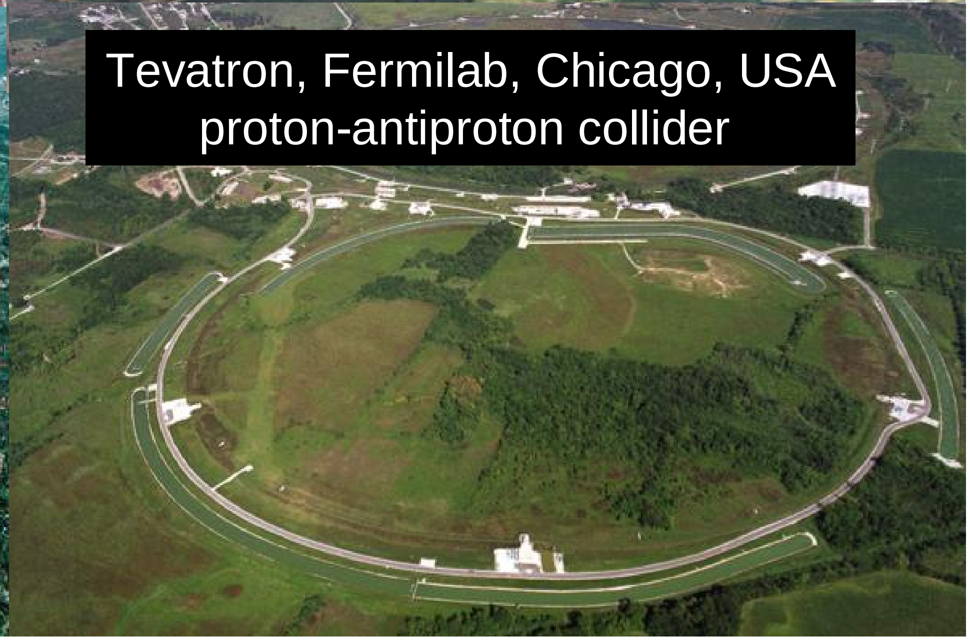
*Young-Kee Kim*
*The University of Chicago*

*Physics Department Colloquium*
*January 11, 2006*
*University of Pennsylvania*

# Accelerators (output of Accelerator Science) are powerful tools for Particle Physics!





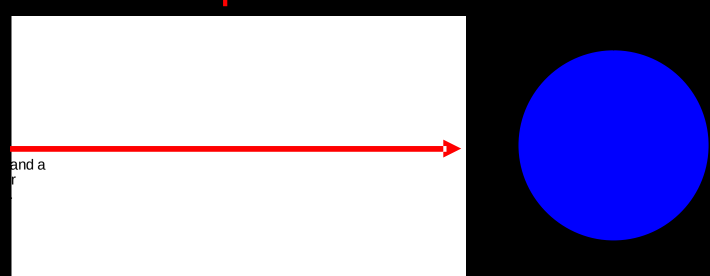



# Accelerators are Powerful Microscopes.

They make high energy particle beams
that allow us to see small things.

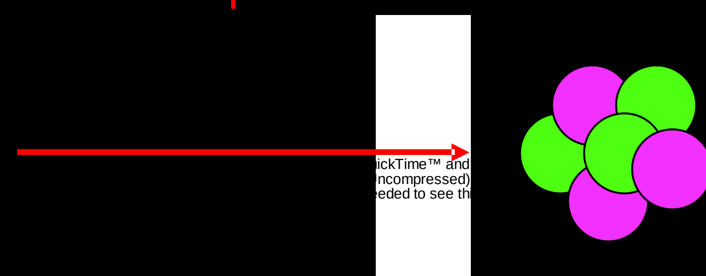
$$\lambda = \frac{h}{p}$$

beam particle



seen by
low energy beam
(poorer resolution)

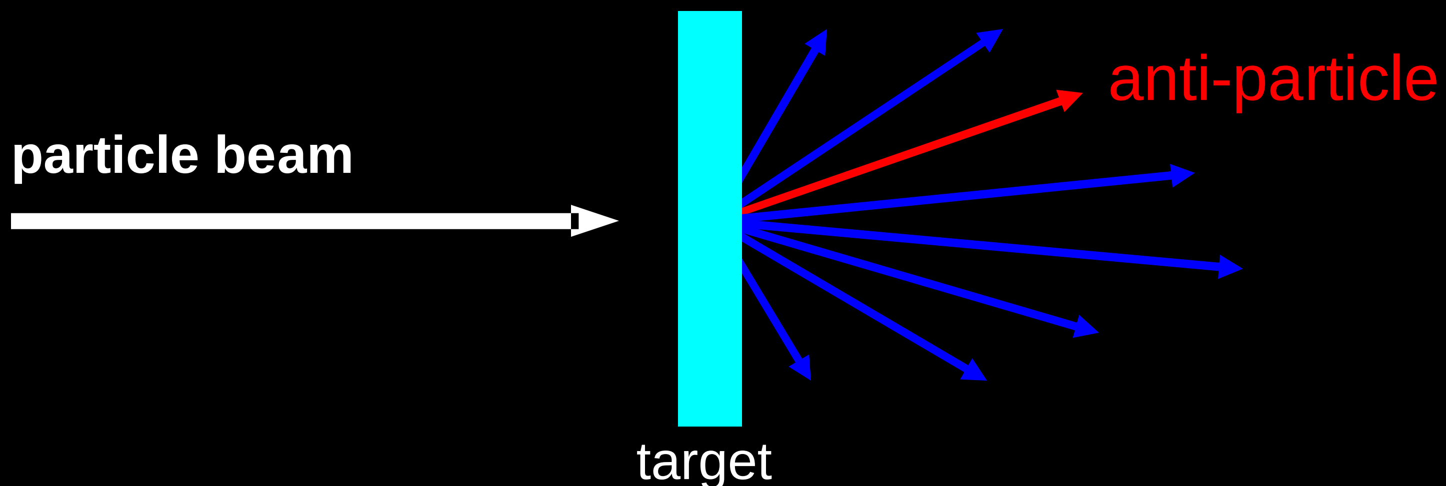
beam particle



seen by
high energy beam
(better resolution)

# Accelerators are also Time Machines

because they make particles last seen
in the earliest moments of the universe.



# Accelerators are also Time Machines

because they make particles last seen
in the earliest moments of the universe.


Particle and anti-particle annihilate.

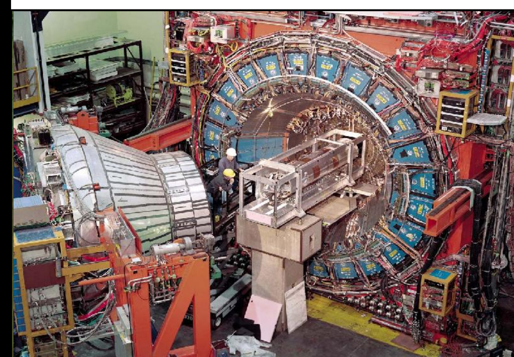
$$E = mc^2$$

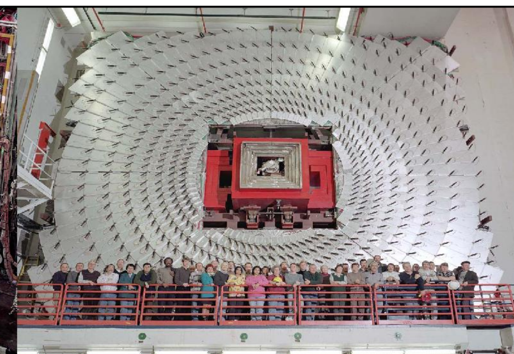
Many generations of Accelerators created
with higher and higher energy given to the beam particle

3/4 of century later


Ernest Lawrence
(1901 - 1958)

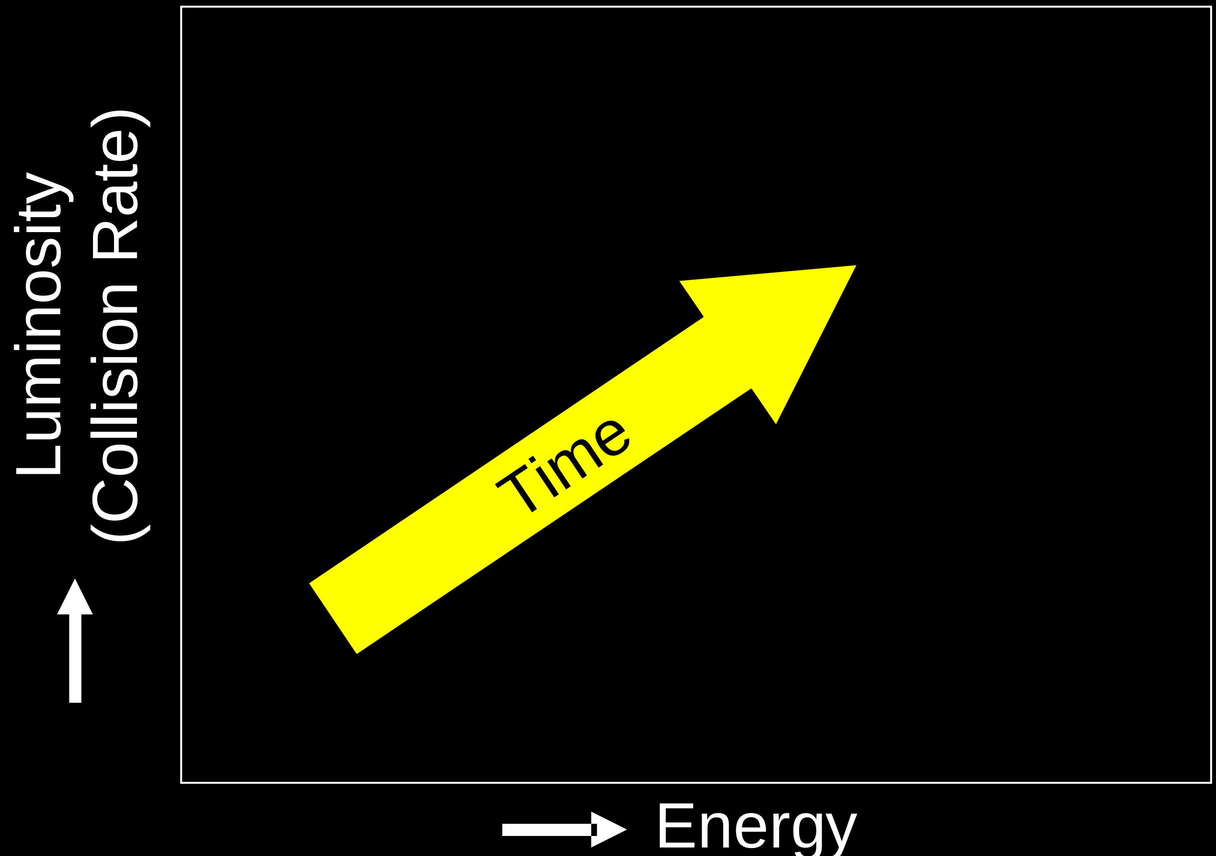

CDF ~1500 Scientists D0





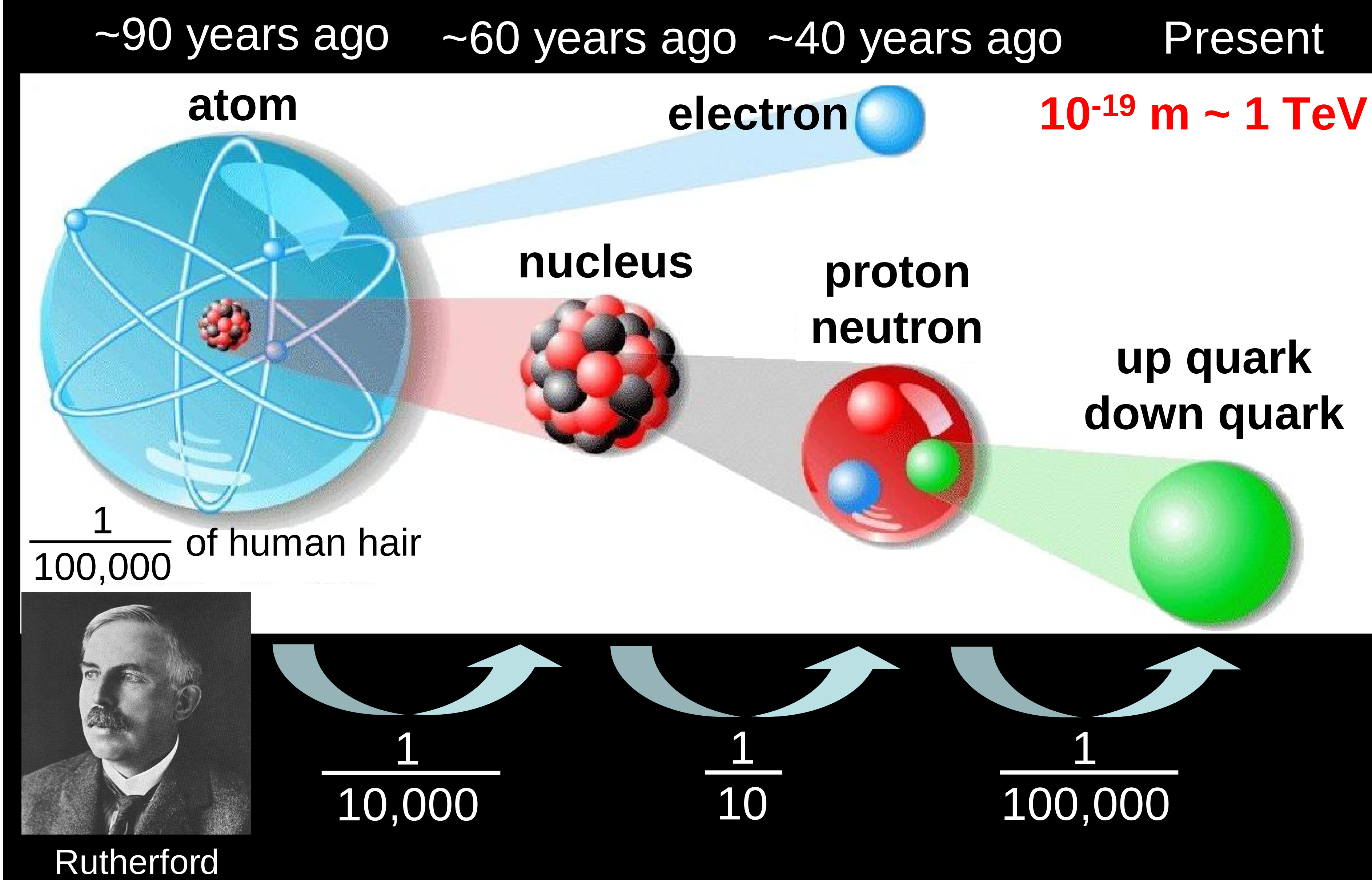
Tevatron at Fermilab
x$10^4$ bigger, x$10^6$ higher energy

With advances in accelerators, we discovered many surprises.



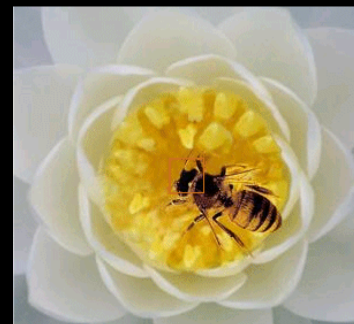

The field of Particle Physics has been tremendously successful in creating and establishing "Standard Model of Particle Physics" answering "what the universe is made of" and "how it works"

# *What is the universe made of?*

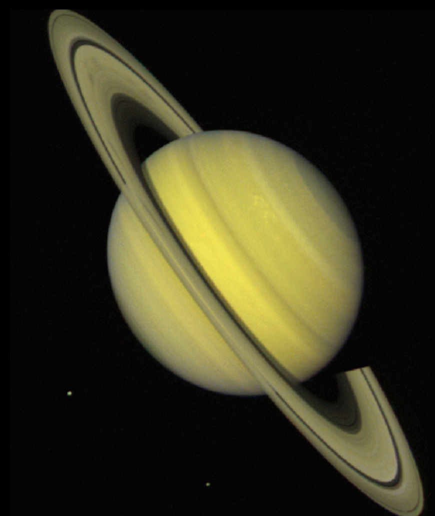


Everything is made of electrons, up quarks and down quarks.



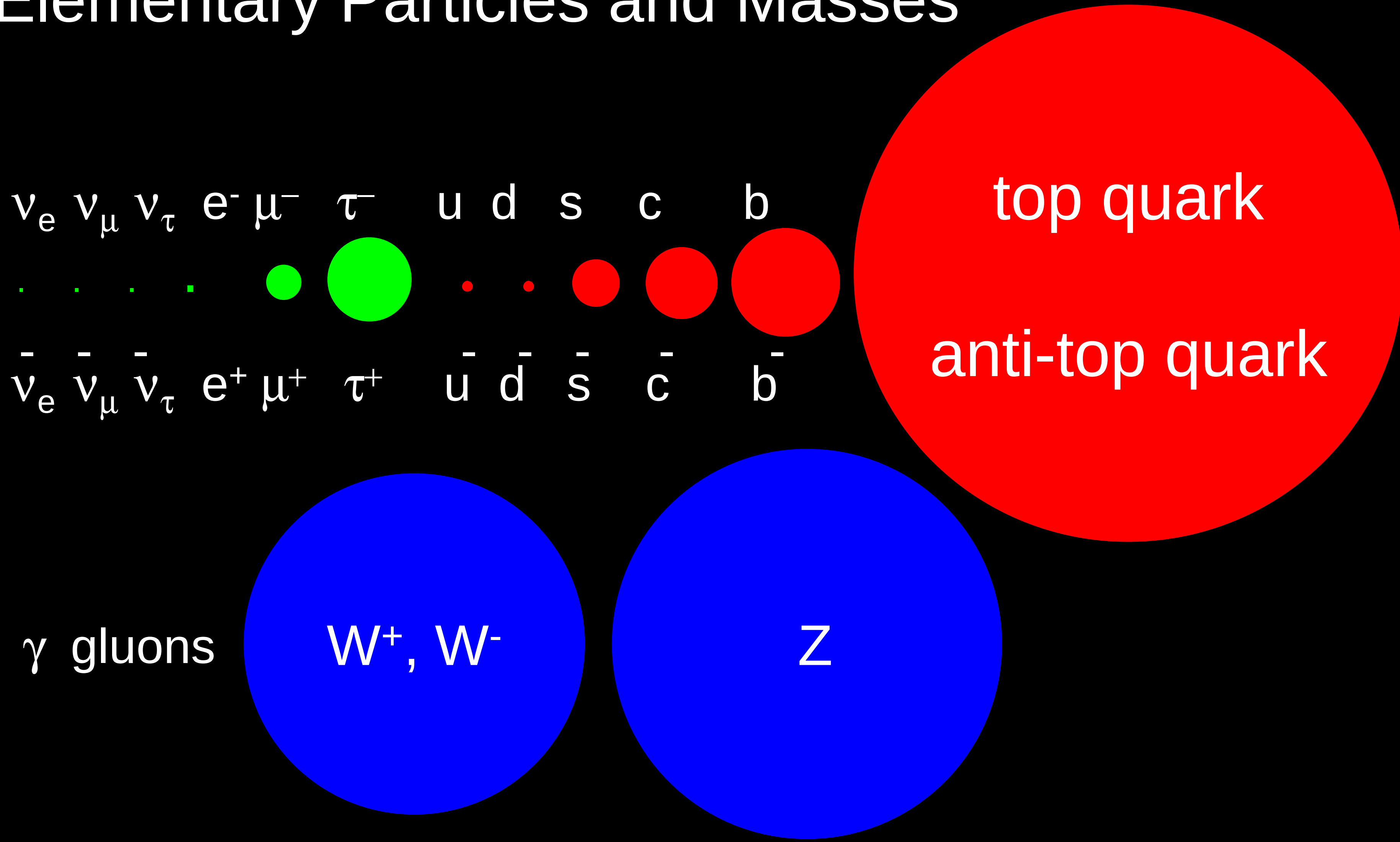







*Are they the smallest things?*

# Elementary Particles and Masses




(Mass proportional to area shown)

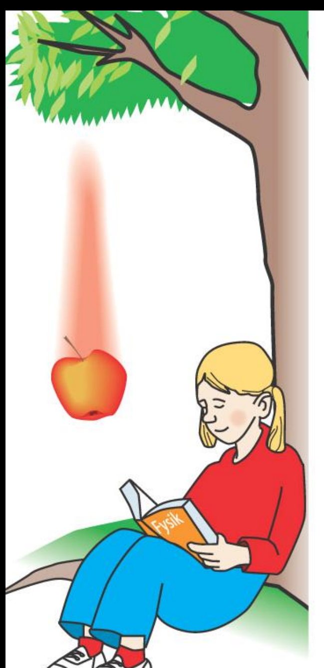
*Why are there so many? Where does mass come from?*

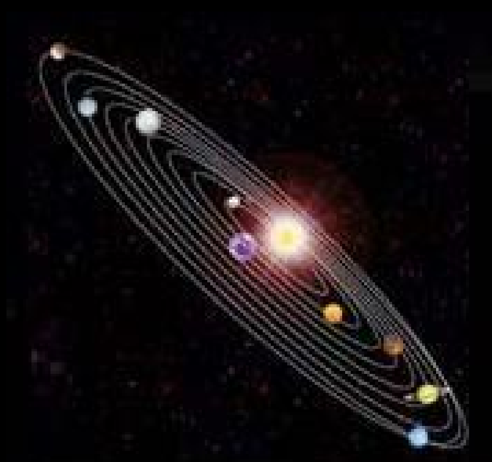
# *What holds the world together?*

## *Beginnings of Unification*

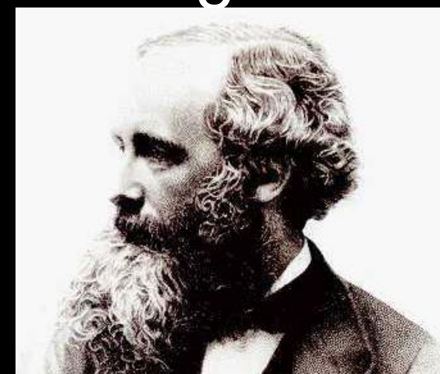
### Gravitational Force

Issac Newton
(1642 - 1727)

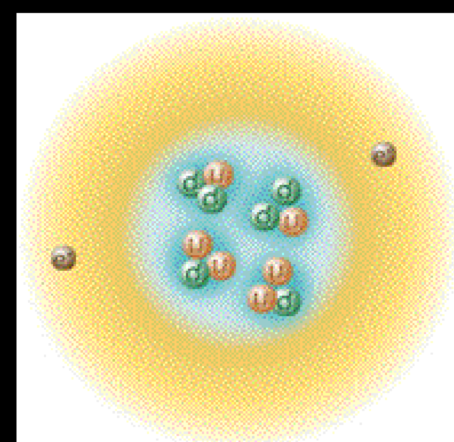


### Electromagnetic Force

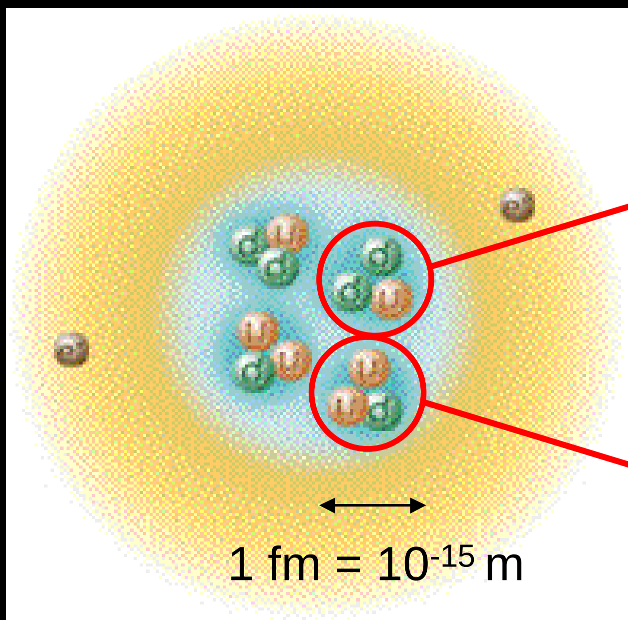


James Clerk Maxwell
(1831 - 1879)



# Unification of Gravity and Electromagnetism?

Einstein tried to unify electromagnetism and gravity but he failed.

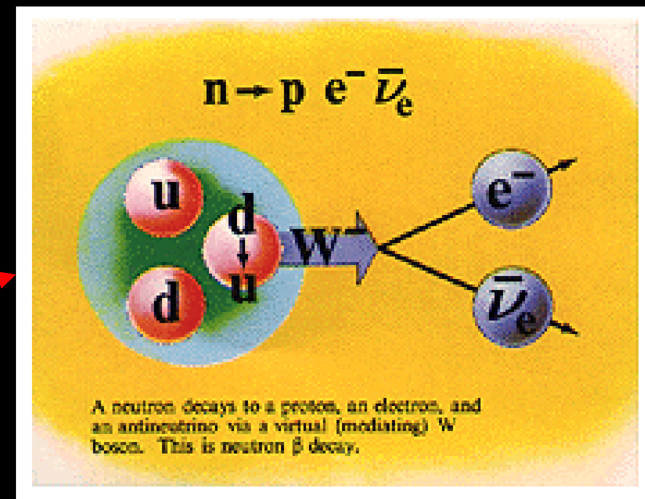



Weak Force

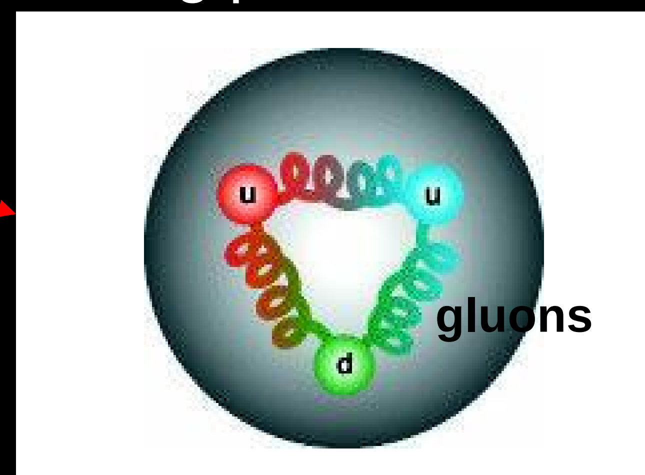
Strong Force

Enrico Fermi
(1901 - 1954)

radioactive decays




holding proton, nucleus



# Dream of Unification continues!

We believe that there is an underlying simplicity behind vast phenomena in nature.

*Do all the forces become one?*

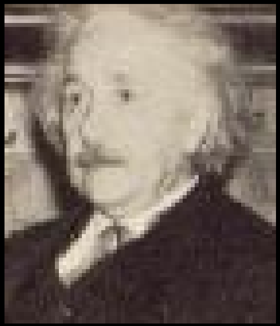
At high energy, do forces start to behave the same as if there is just one force, not several forces?

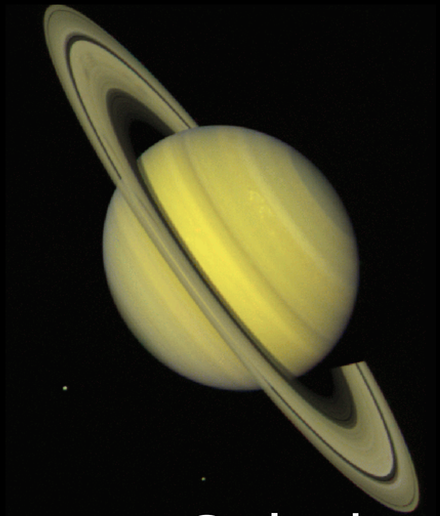
*Extra hidden dimensions in space?*

# Particle Physics & Cosmology Questions from Astrophysical Observations

~~Everything~~ is made of electrons, up quarks and down quarks.

Everything that we can see





Galaxies are held together by mass far bigger (x5) than all stars combined.

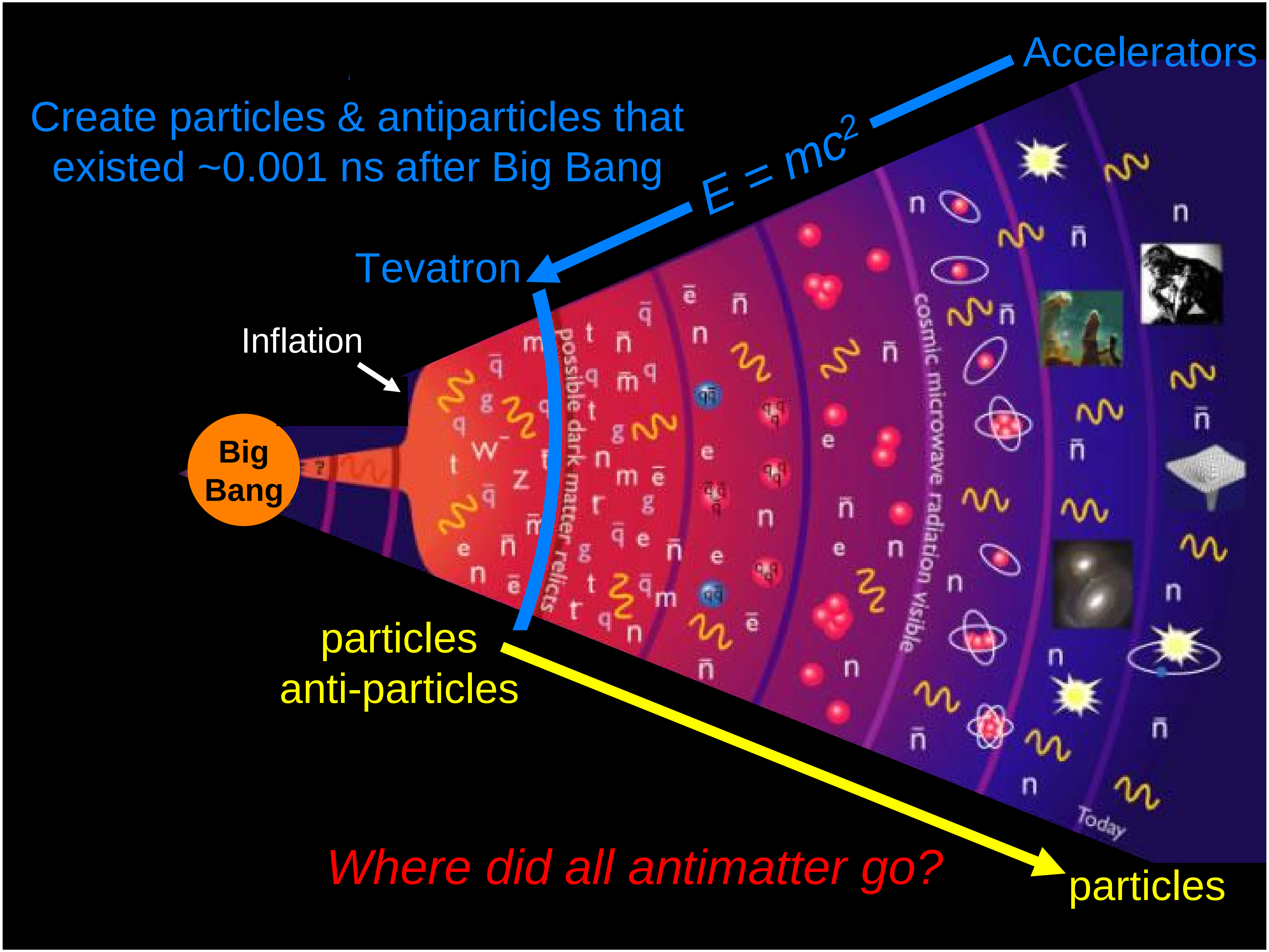
*Dark Matter - What is it?*

*Where did we come from?*

*How did we get here?*
*Where are we going?*

*Understanding our Universe!*

from Woody Alan’s Annie Hall


Create particles & antiparticles that
existed ~0.001 ns after Big Bang
Accelerators
E = mc2
Tevatron
Inflation
Big Bang
possible dark matter relicts
cosmic microwave radiation visible
Today
particles
anti-particles
Where did all antimatter go?
particles

# Matter and Anti-Matter Asymmetry (CP Violation)



Discovered CP violation in the B system.

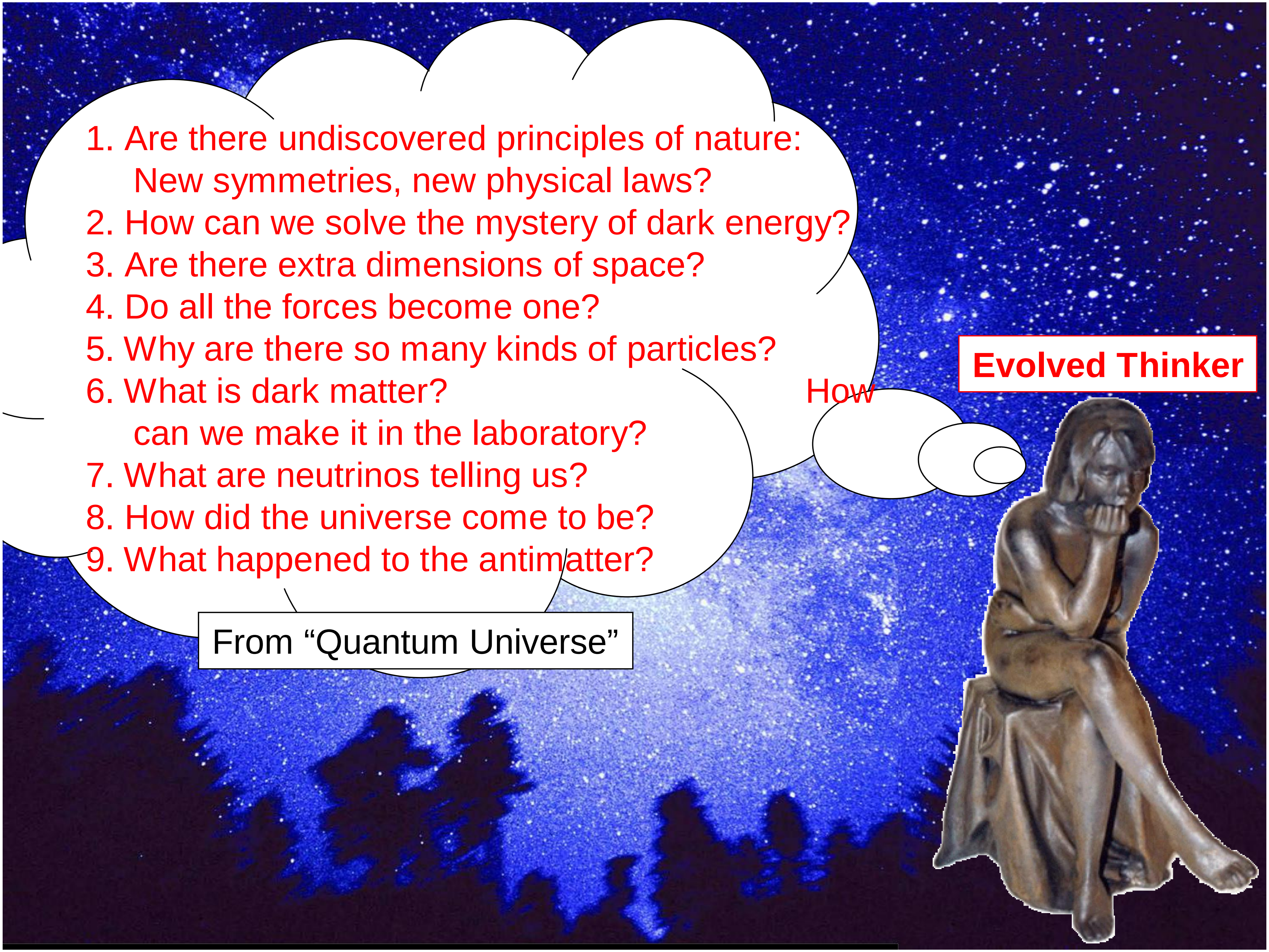
Not big enough to explain matter and anti-matter asymmetry observed in the Universe.
There must be new physics with CP violation.

Not only is the Universe expanding, it is

Accelerating!!

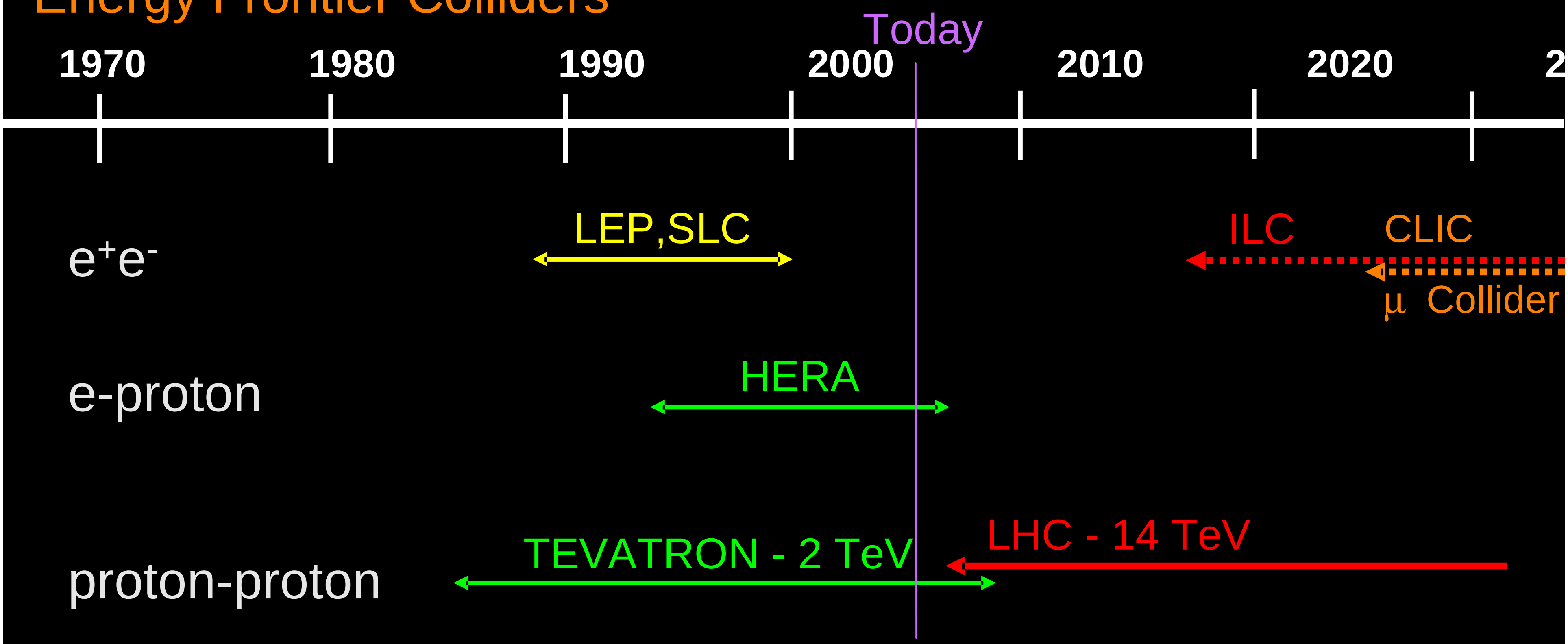
*Where does energy come from?*
*Dark Energy*


What is the world made of?
What holds the world together?
Where did we come from?
Primitive Thinker


1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?
From “Quantum Universe”
Evolved Thinker

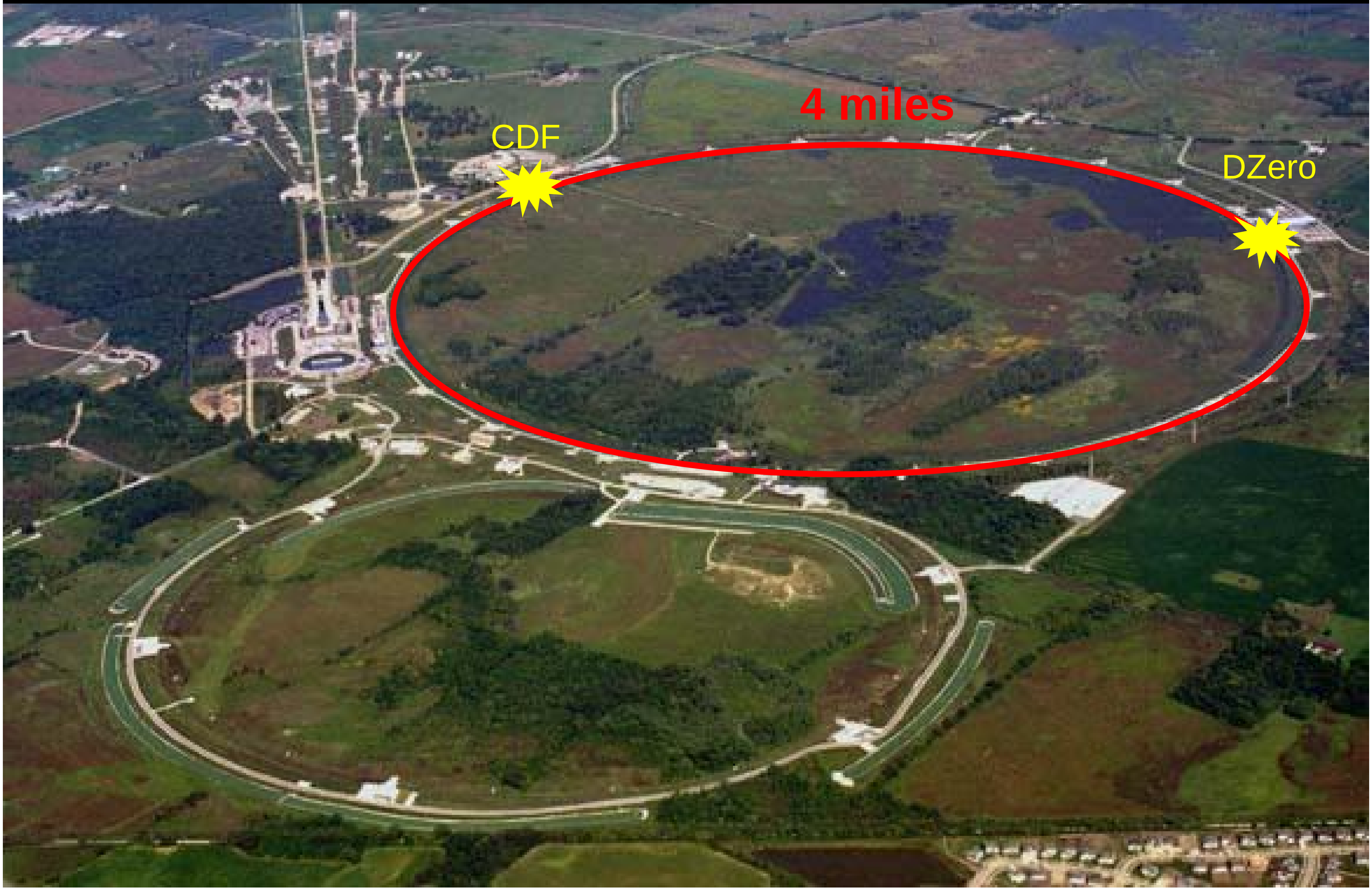
# Answering the “Exciting” Questions with Next Generation of Accelerators

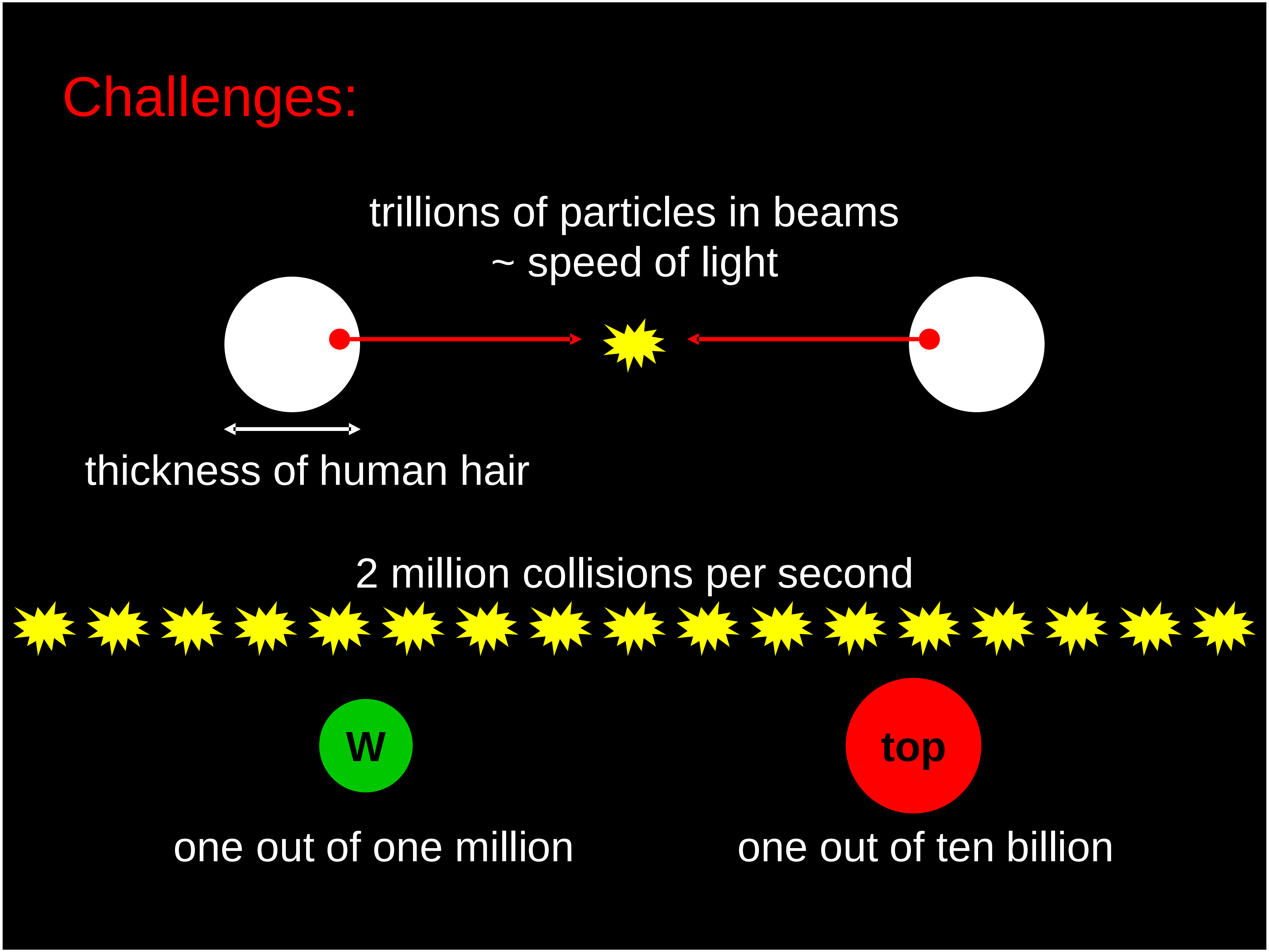
## Energy Frontier Colliders

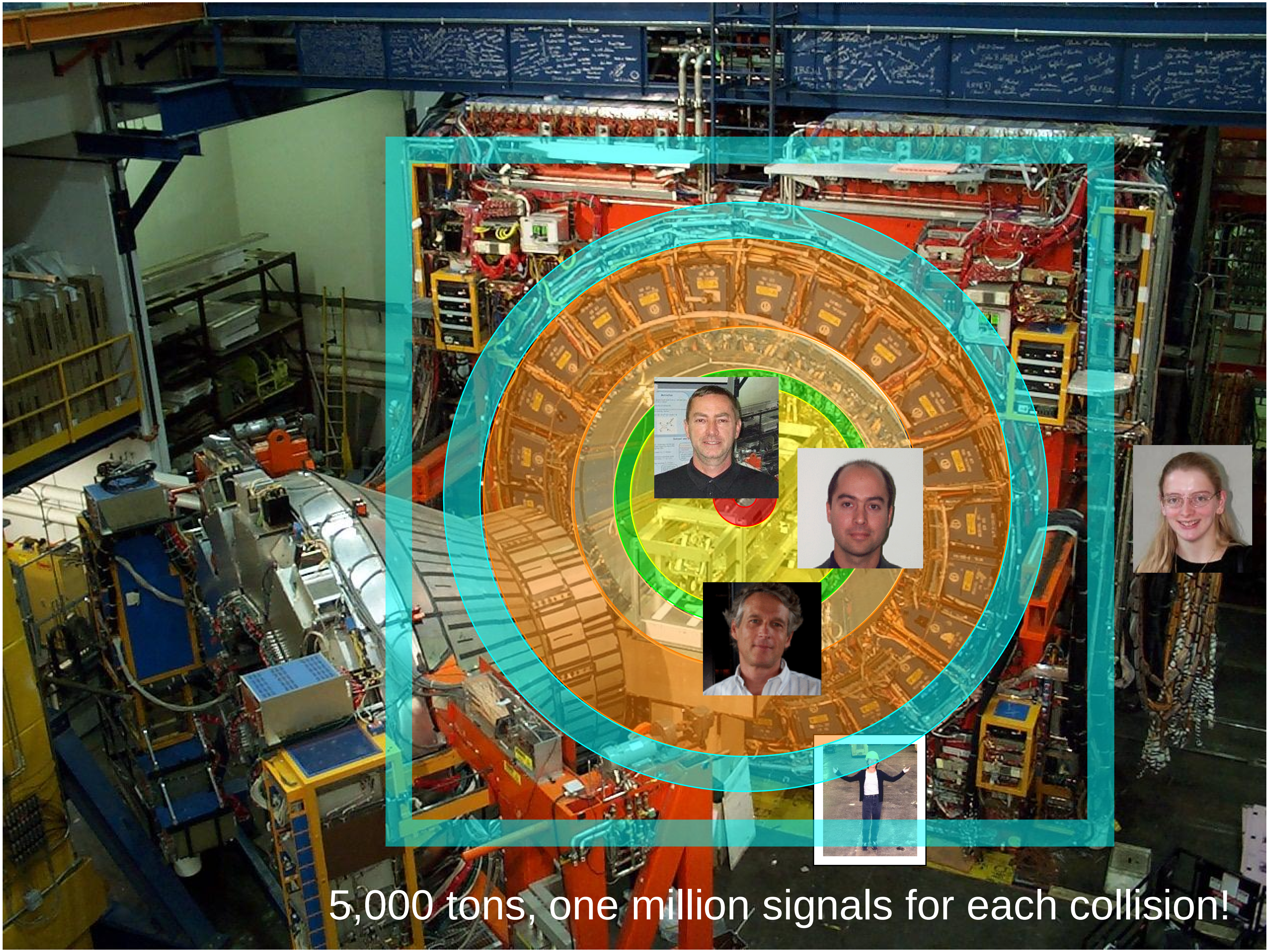



The world HEP community believes that ILC is the next accelerator to extend the discovery reach of LHC, and HEP community is working toward proposing to host this machine in US (Fermilab).

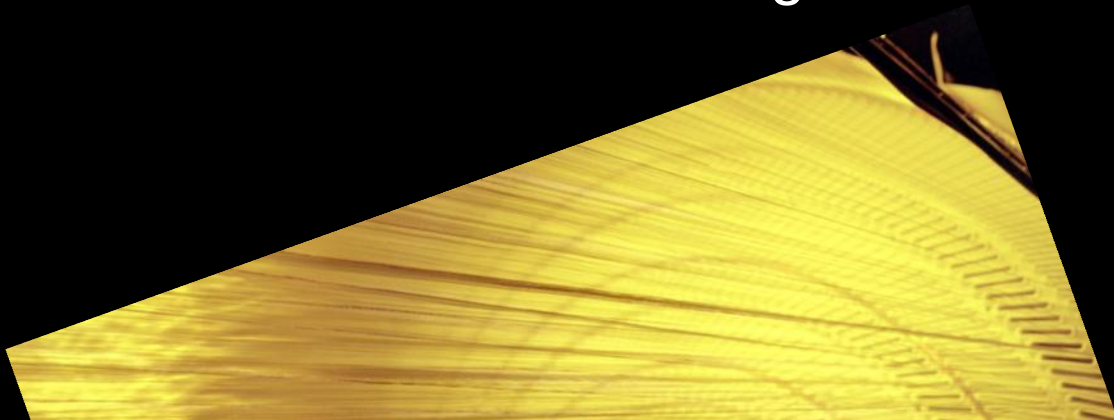
# World's Highest Energy Accelerator: Fermilab's "Tevatron"

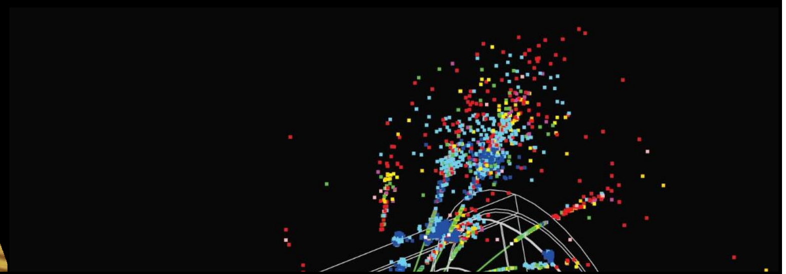



Challenges:
trillions of particles in beams
~ speed of light
thickness of human hair
2 million collisions per second
W
top
one out of one million
one out of ten billion


5,000 tons, one million signals for each collision!

30,000 high-voltage human-hair-thick Gold-plated Tungsten wires in Argon-Ethane gas





Penn instrumentation team:
a well known unique resource for HEP

Rick Van Berg

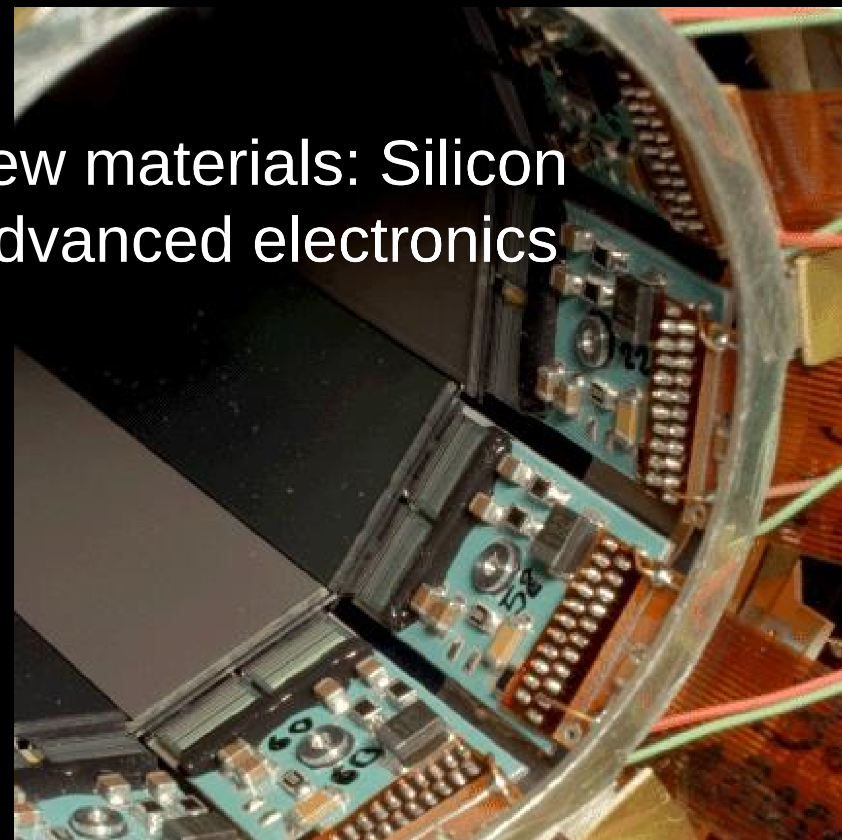
Walt Kononenko

Mitch Newcomer

# What does it take to make a discovery?

## New Silicon Detector used for Discovery of Top Quark

New materials: Silicon
Advanced electronics



For any discovery, we have to keep pushing technology,
not just in the directions we've already gone,
but with imagination to create innovative tools.

# Origin of Mass:

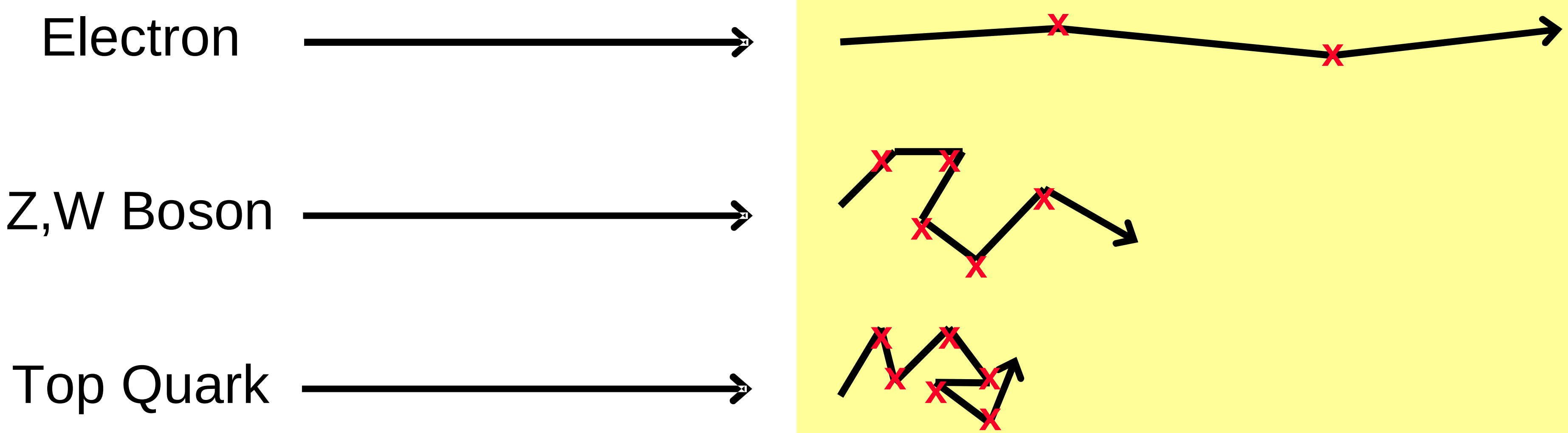
There might be something (new particle?!) in the universe

that gives mass to particles

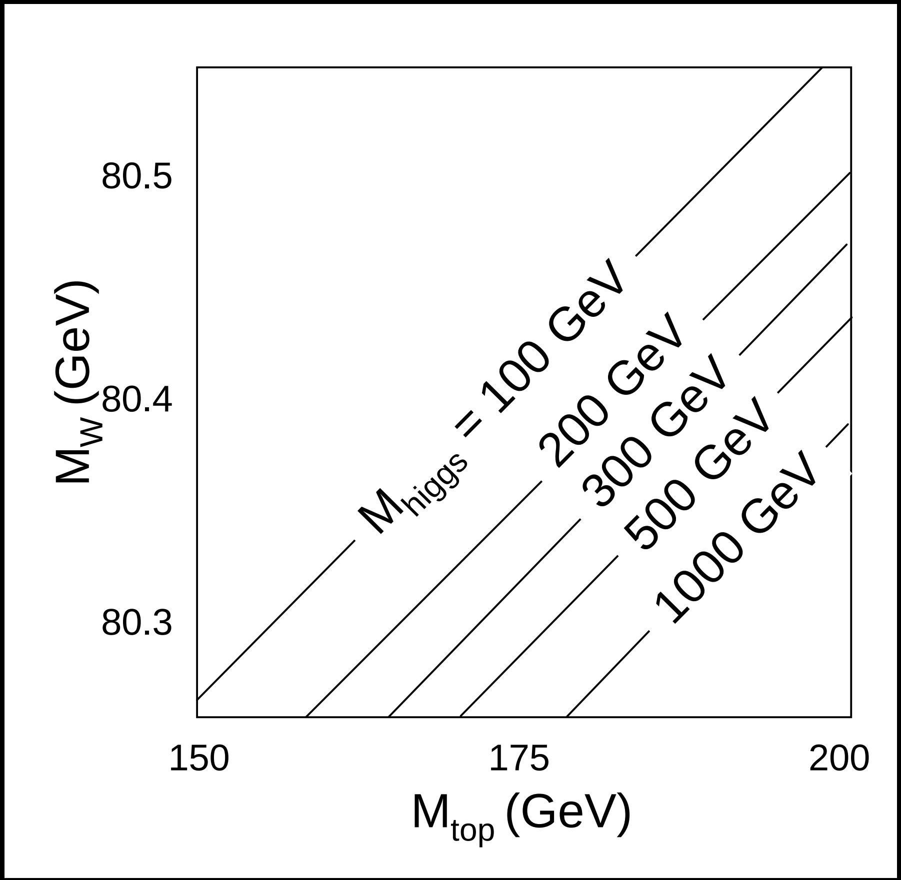
Nothing in the universe | Something in the universe

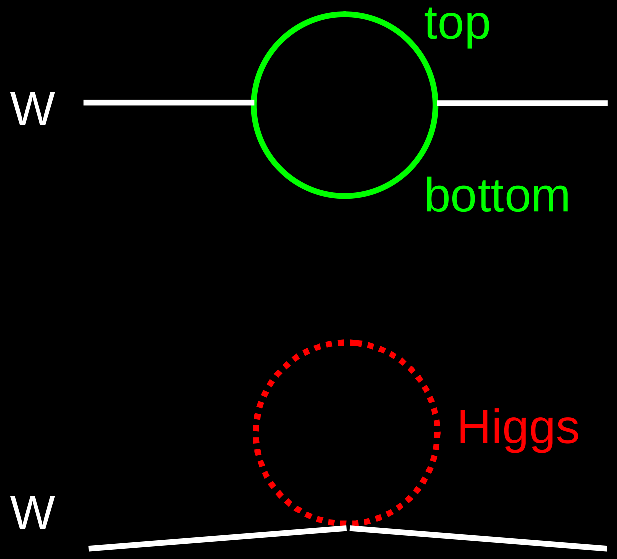
Higgs Particles:

Coupling strength to Higgs
is proportional to mass



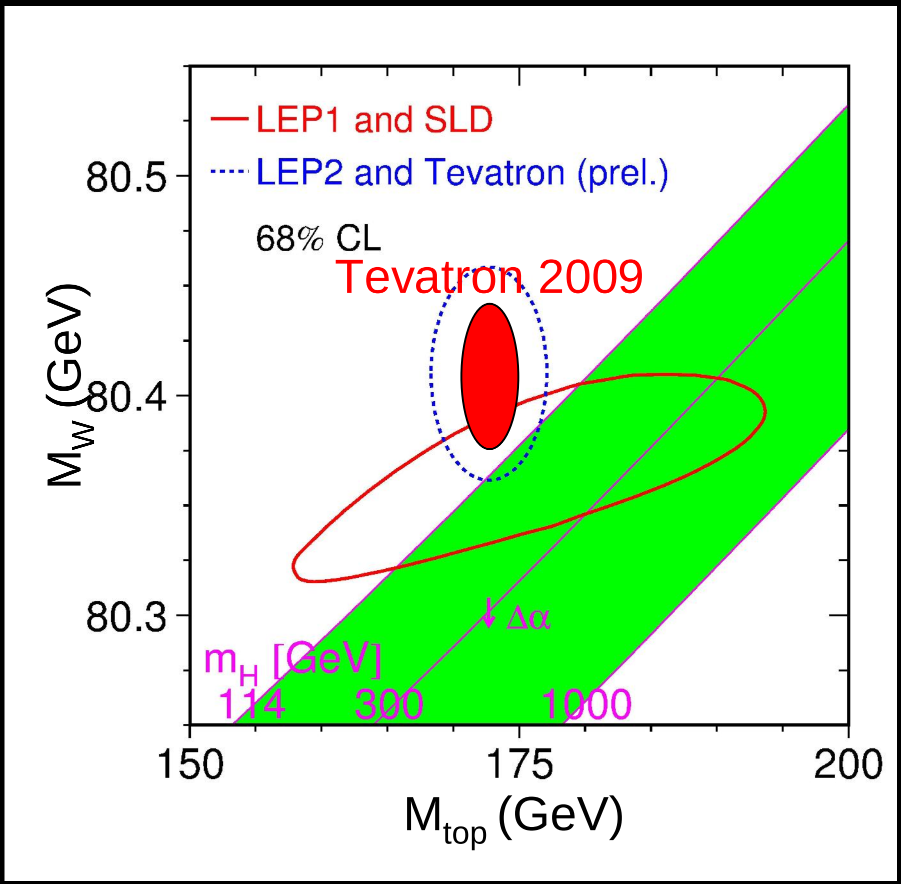
# Tevatron: Improve Higgs Mass Pred. via Quantum Corrections

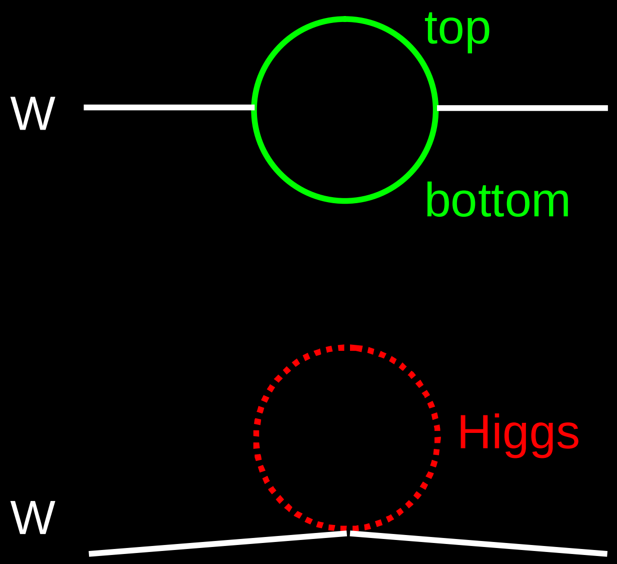



1 GeV = 1 GeV / $c^2$ ~ proton mass

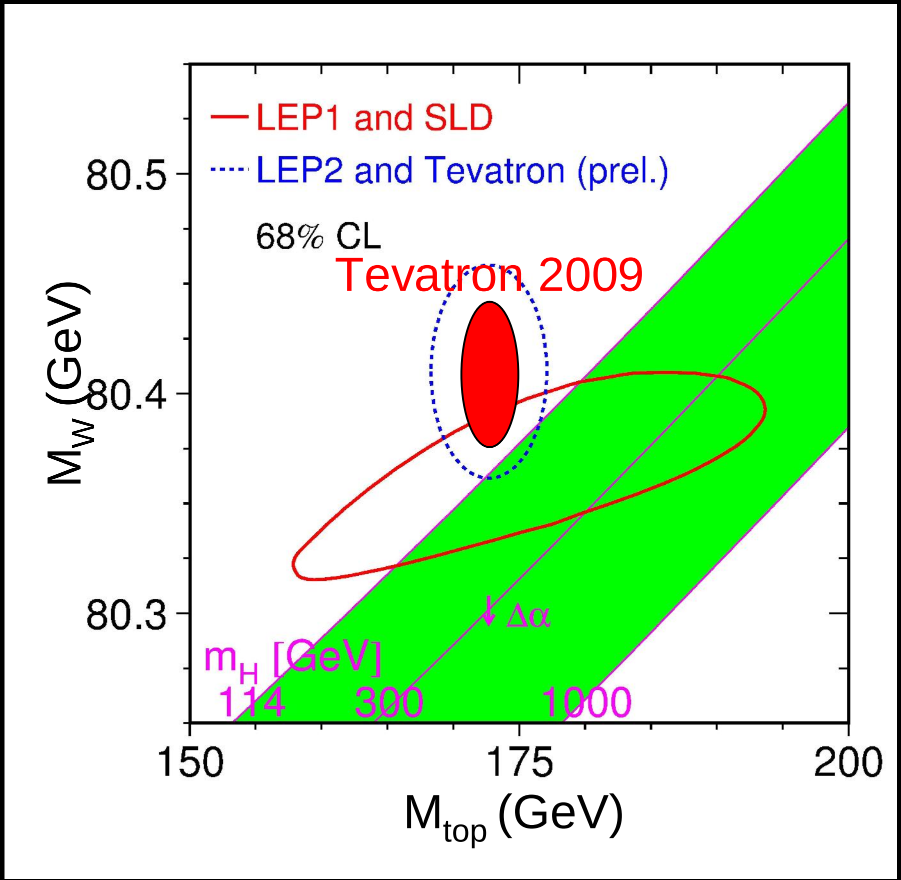
# Tevatron: Improve Higgs Mass Pred. via Quantum Corrections

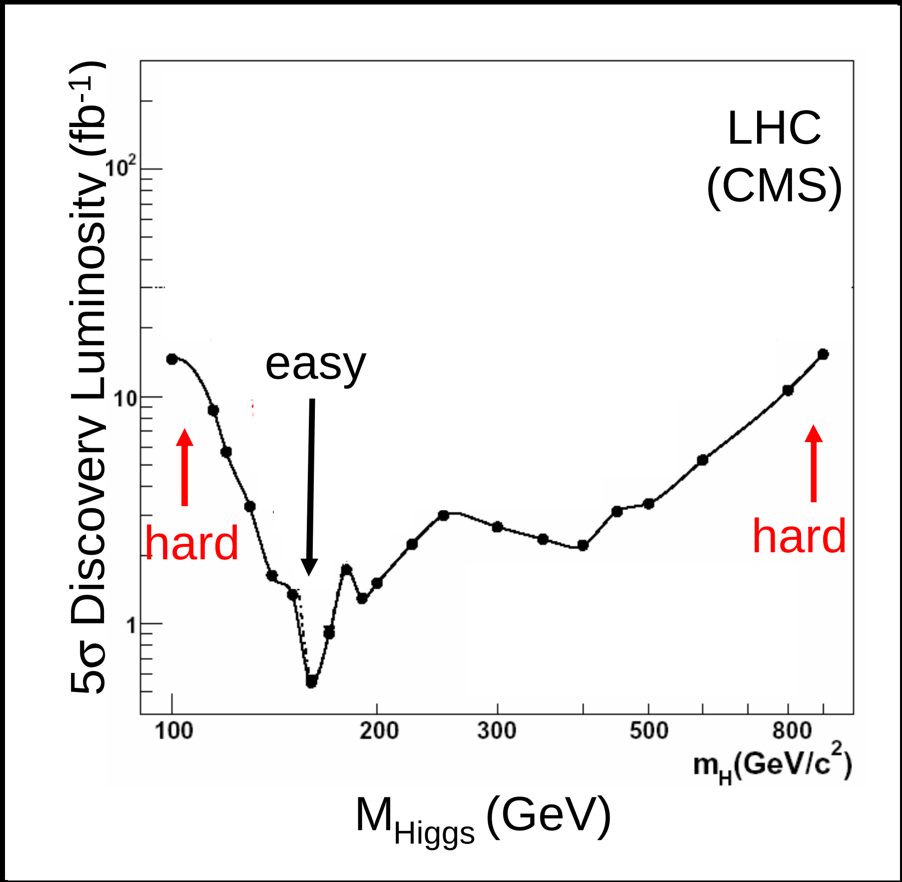



Current precision measurements favor light Higgs: < ~200 GeV at 95%CL

# Tevatron: Improve Higgs Mass Pred. via Quantum Corrections
# LHC: Designed to discover Higgs with $M_{higgs}$ = 100 ~ 800 GeV




Will the Tevatron's prediction agree with what LHC sees?

Higgs sector may be very complex. New physics models expect multiple Higgs particles.

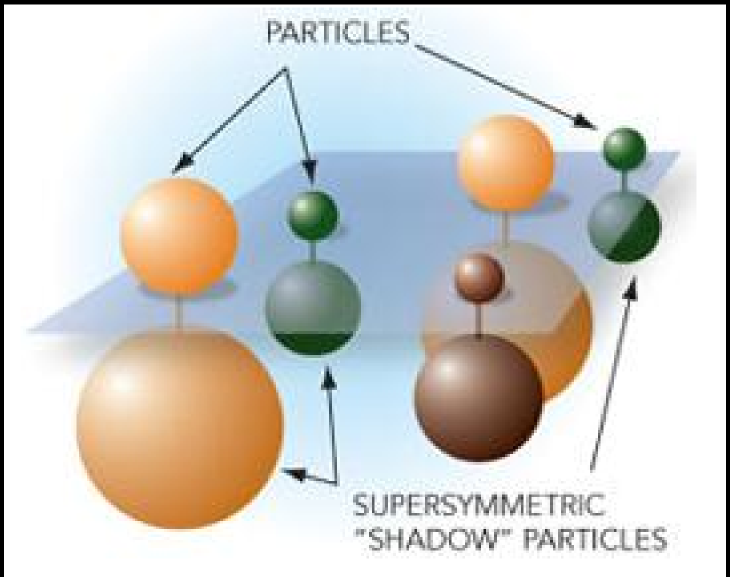
# Supersymmetric Extension of Standard Model (SUSY)

Symmetry between
fermions (matter) and bosons (forces)
"Undiscovered new symmetry"

e → e+, e-

superparticle → e (spin 1/2), $\tilde{e}$ (spin 0)

$M_e \neq M_{\tilde{e}}$




SUSY solves SM problems: divergence of Higgs mass, unification.
SUSY provides a candidate particle for Dark Matter, solution to matter-antimatter asymmetry, possible connection to Dark Energy?

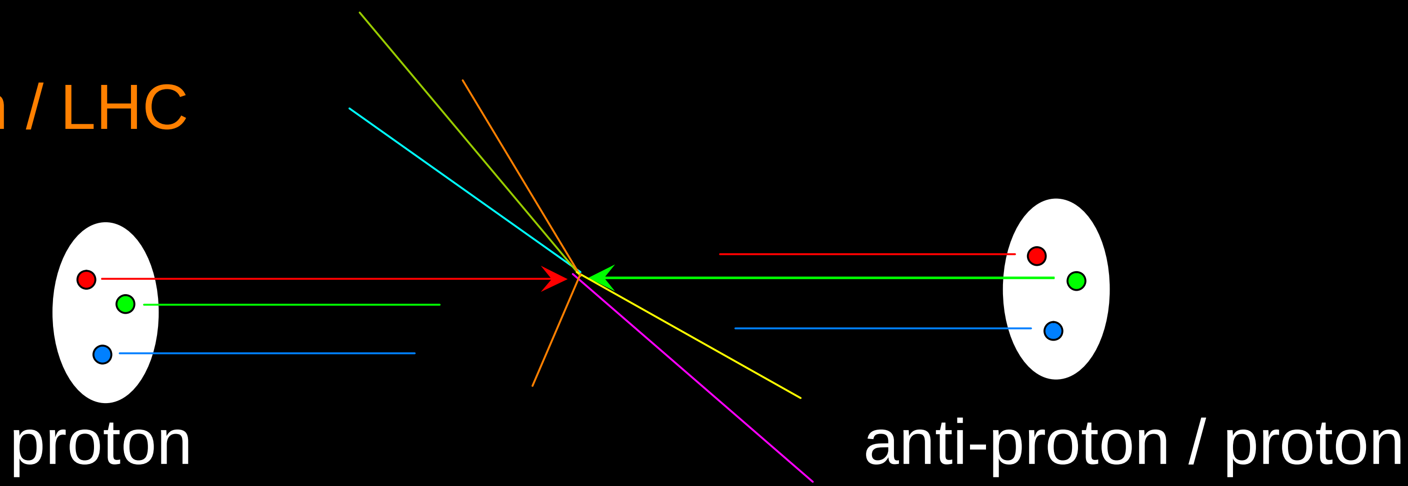
Higgs Mass: particle — super particle

LHC will be the greatest place to discover Higgs particles!

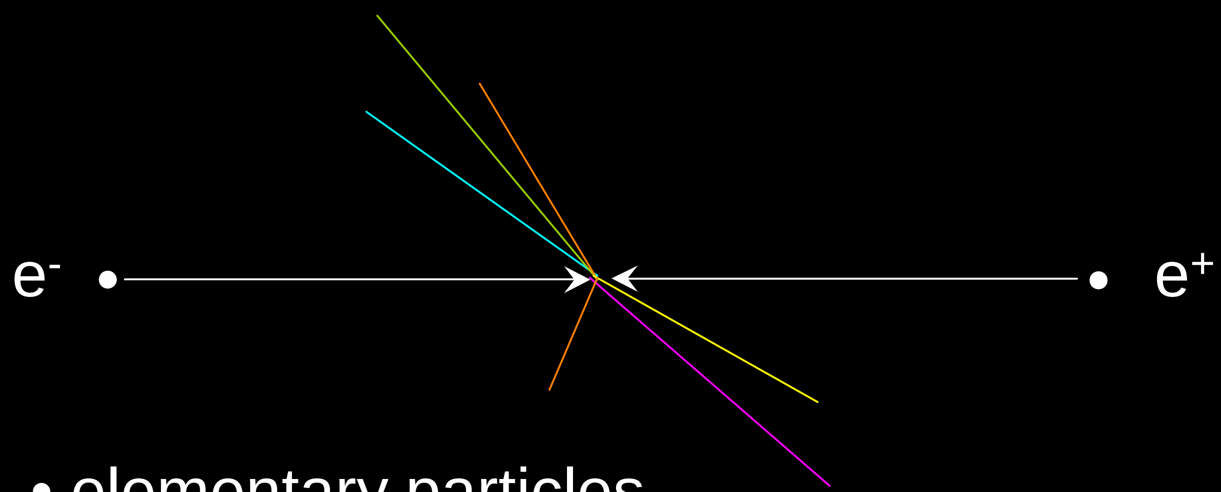
If we discover a “Higgs-like” particle,
is it alone responsible for giving mass to W, Z, fermions?

Experimenters must precisely measure
the properties of the Higgs particle
without invoking theoretical assumptions.

## Tevatron / LHC



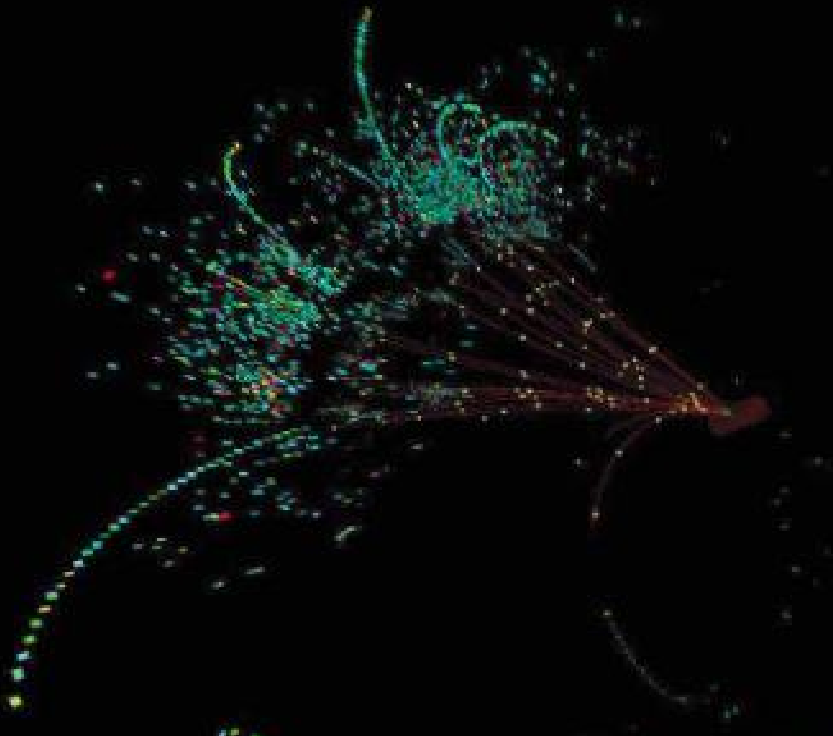

## ILC:

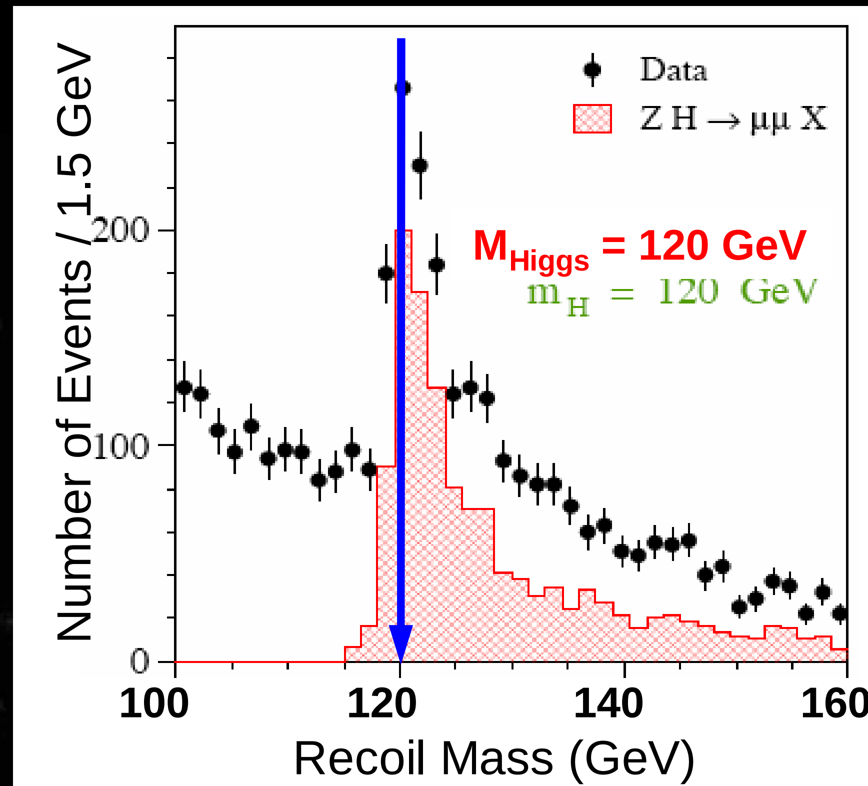



- elementary particles
- well-defined energy and angular momentum
- uses its full energy
- can capture nearly full information

# ILC can observe Higgs no matter how it decays!

ILC simulation for $e^+e^- \rightarrow Z$ + Higgs
with $Z \rightarrow 2$ b's, and Higgs $\rightarrow$ invisible






Only possible at the ILC

ILC experiments will have the unique ability to make model-independent tests of Higgs couplings to other particles. This sensitivity is sufficient to discover extra dimensions, SUSY, sources of CP violation, or other novel phenomena.

# The Higgs is Different!

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

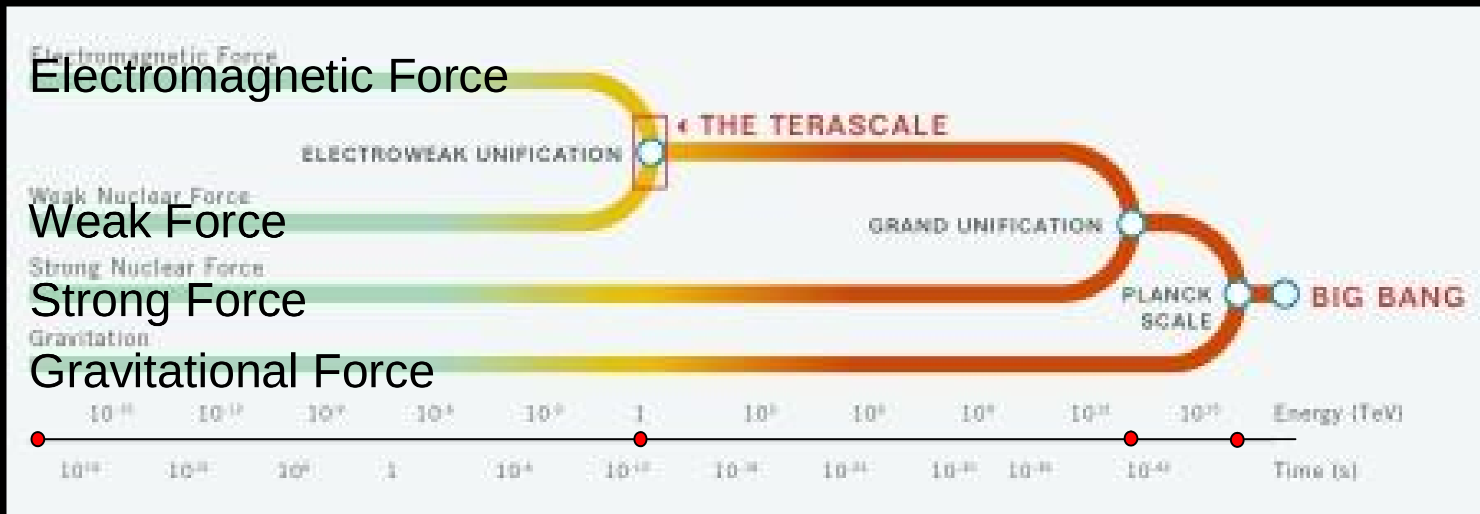
Higgs particles are spin-0 bosons.
The Higgs is neither matter nor force;
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

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.

Hadron collider(s) will discover the Higgs.
ILC will use the Higgs as a window viewing the unknown.

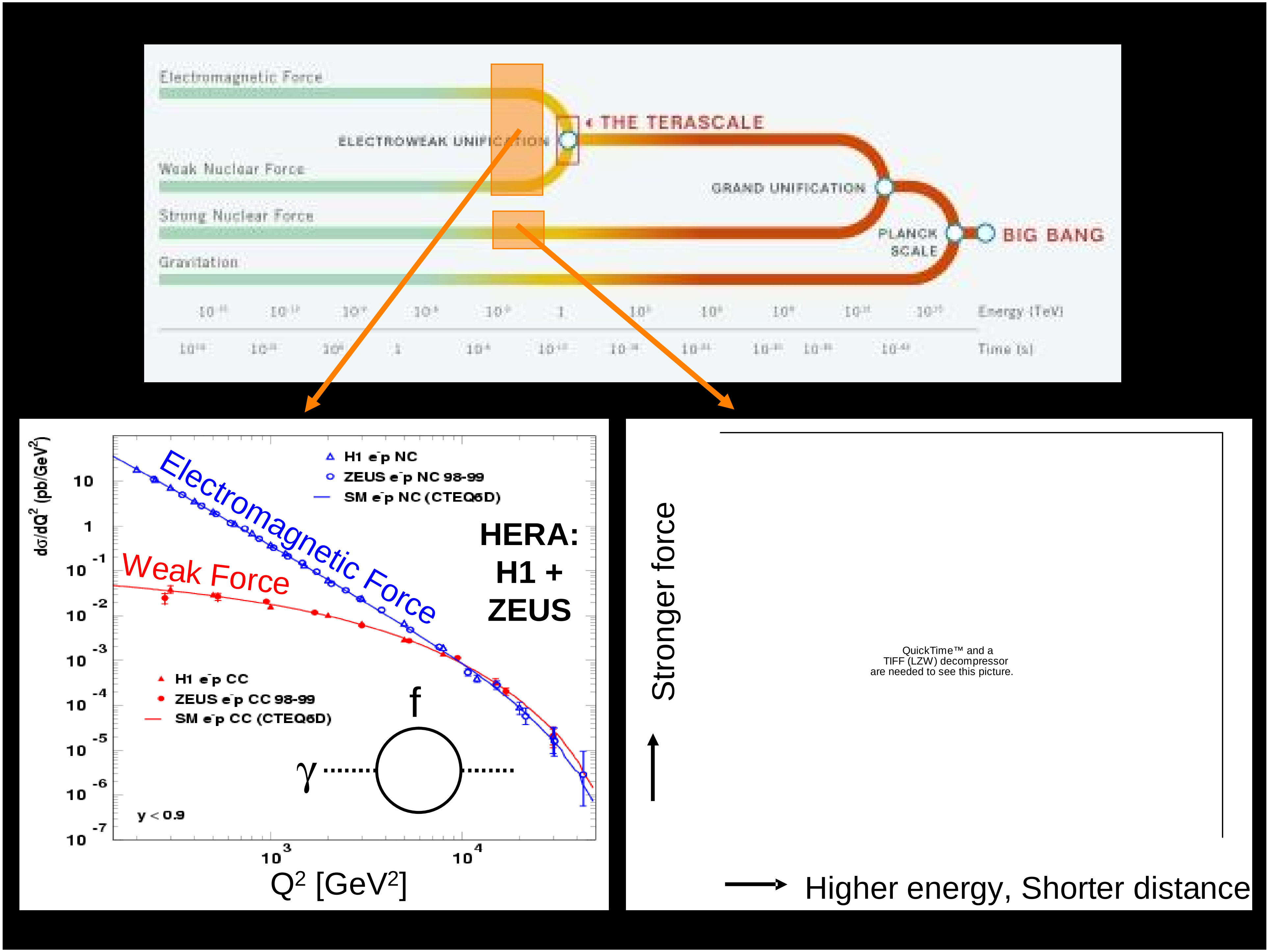
# Unification



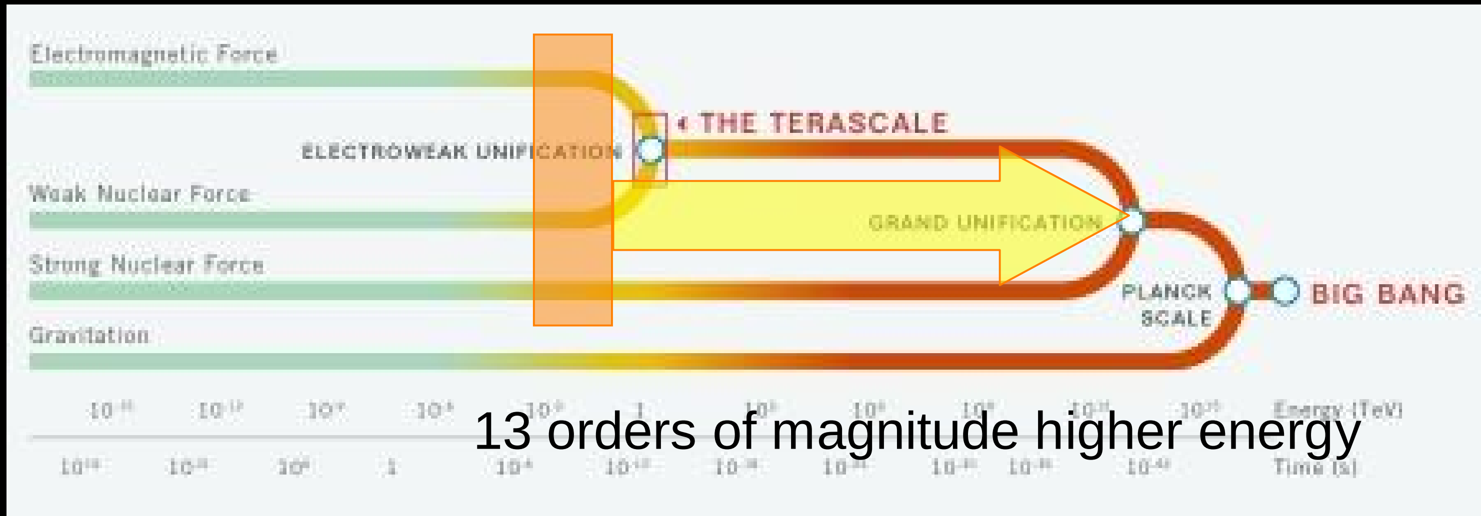

| | | | | |
|---|---|---|---|---|
| 2.3 x $10^{-13}$ GeV | 1TeV = $10^3$GeV | $10^{16}$GeV | $10^{19}$GeV | Energy |
| (2.7K) | ($10^{16}$K) | ($10^{29}$ K) | ($10^{32}$K) | Temp |
| $12\times10^9$ y | $10^{-11}$ s | $10^{-38}$ s | $10^{-41}$ s | Time |

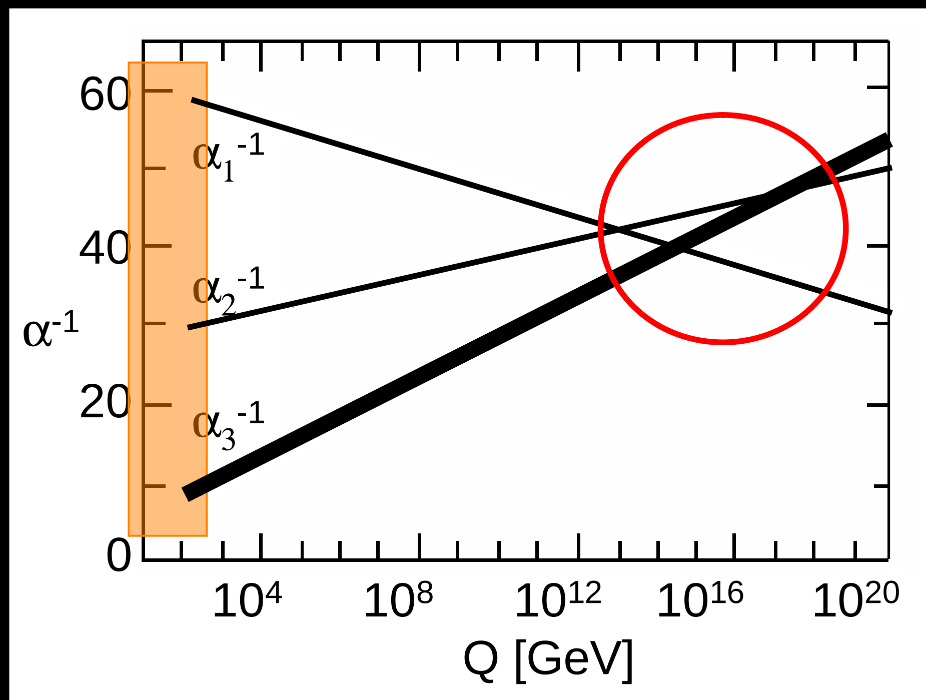
We want to believe
that there was just one force after the Big Bang.

As the universe cooled down,
the single force split into the four that we know today.

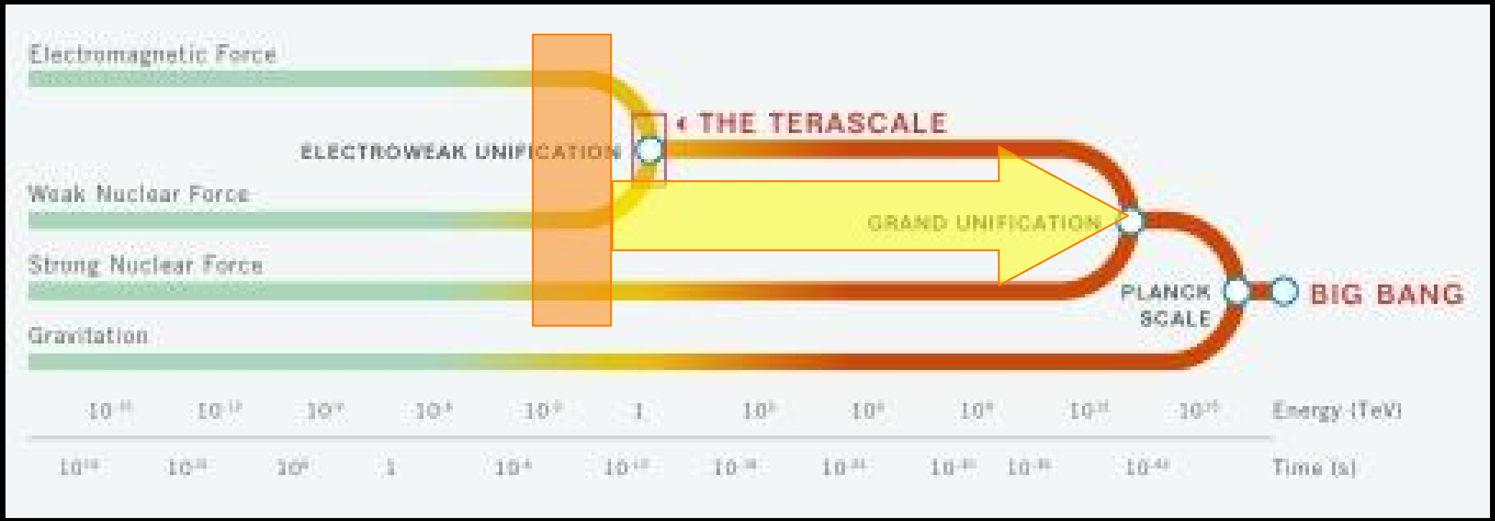


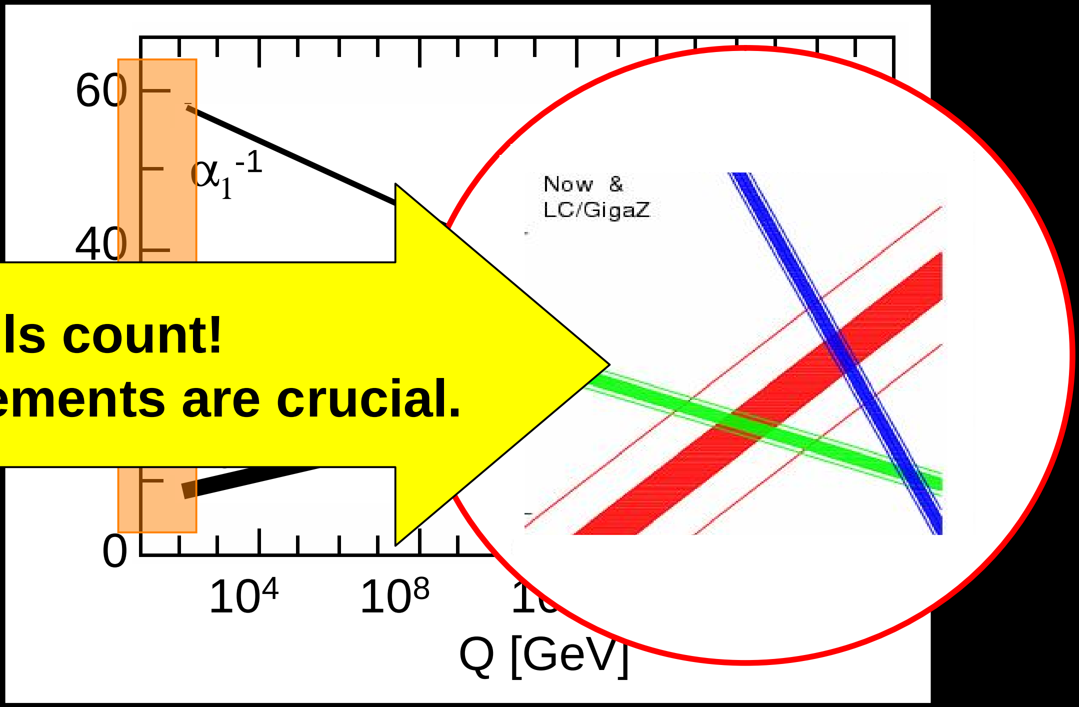
Electromagnetic Force
Weak Nuclear Force
Strong Nuclear Force
Gravitation
ELECTROWEAK UNIFICATION
THE TERASCALE
GRAND UNIFICATION
PLANCK SCALE
BIG BANG
Energy (TeV)
Time (s)
Electromagnetic Force
Weak Force
H1 e⁻p NC
ZEUS e⁻p NC 98-99
SM e⁻p NC (CTEQ6D)
HERA: H1 + ZEUS
H1 e⁻p CC
ZEUS e⁻p CC 98-99
SM e⁻p CC (CTEQ6D)
dσ/dQ² (pb/GeV²)
y < 0.9
f
γ
Q² [GeV²]
Stronger force
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Higher energy, Shorter distance



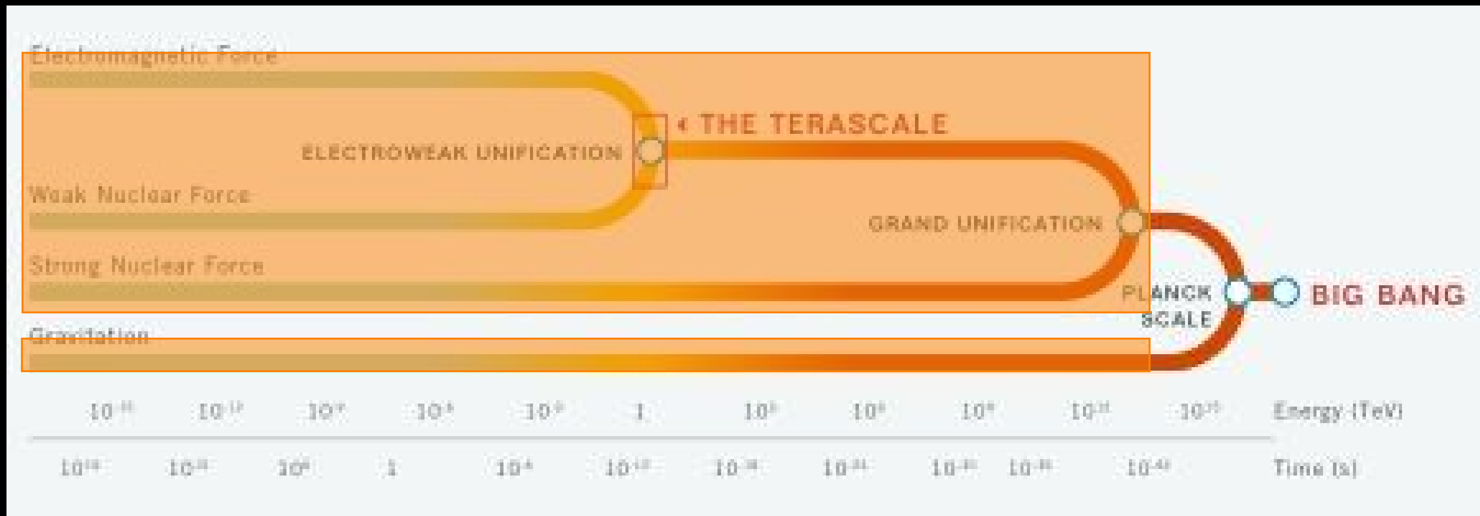




The Standard Model fails to unify the strong and electroweak forces.




**But details count!**
**Precision measurements are crucial.**




Unifying gravity to the other 3 is accomplished by String theory.

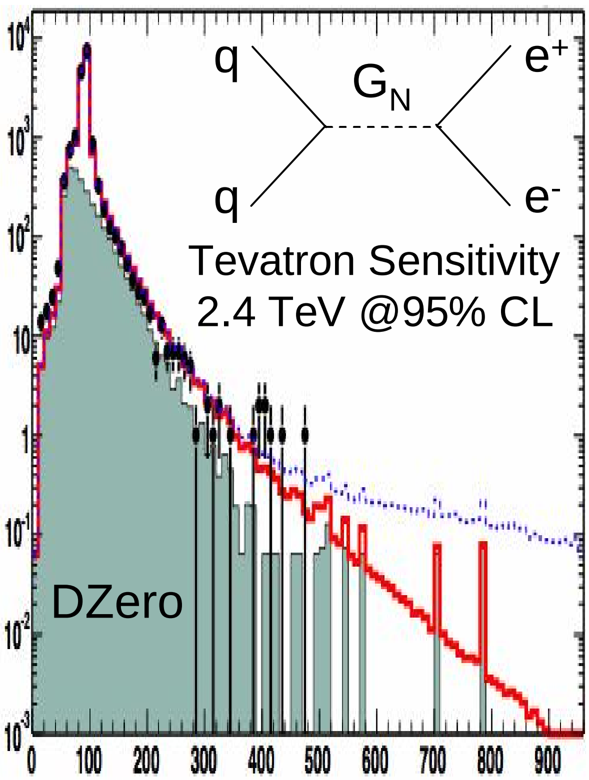
String theory predicts extra hidden dimensions in space beyond the three we sense daily.

Can we observe or feel them? too small?

Other models predict large extra dimensions: large enough to observe up to multi TeV scale.

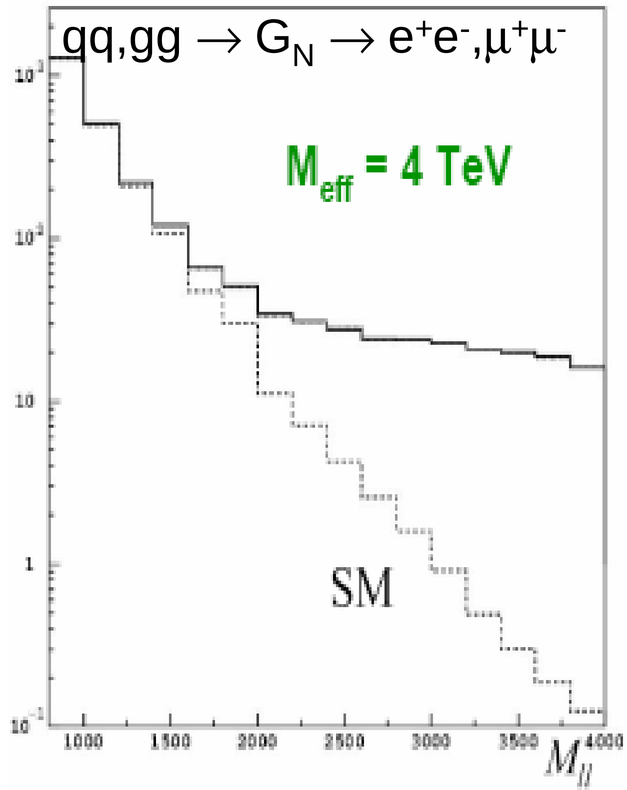
# Large Extra Dimensions of Space

## Tevatron



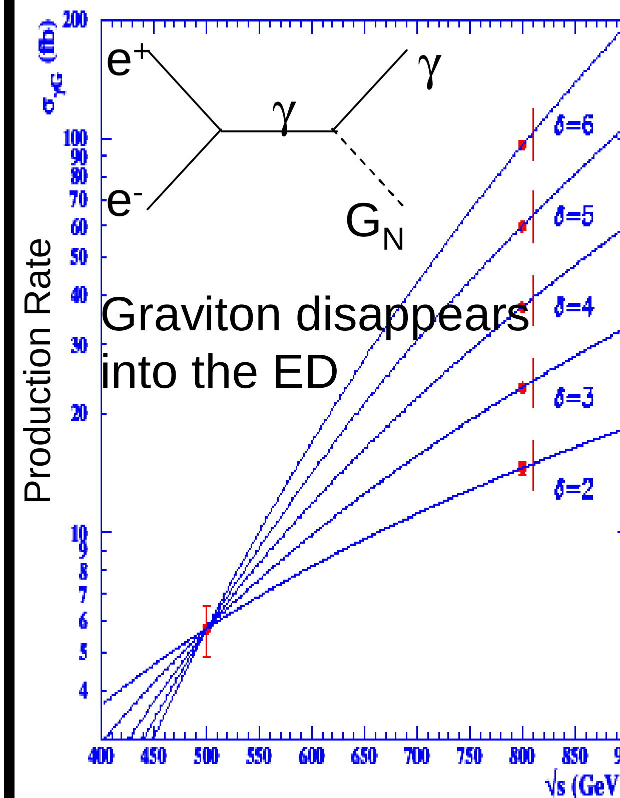

$M_{ee}$ [GeV]

## LHC




$M_{ee,\mu\mu}$ [GeV]

## ILC

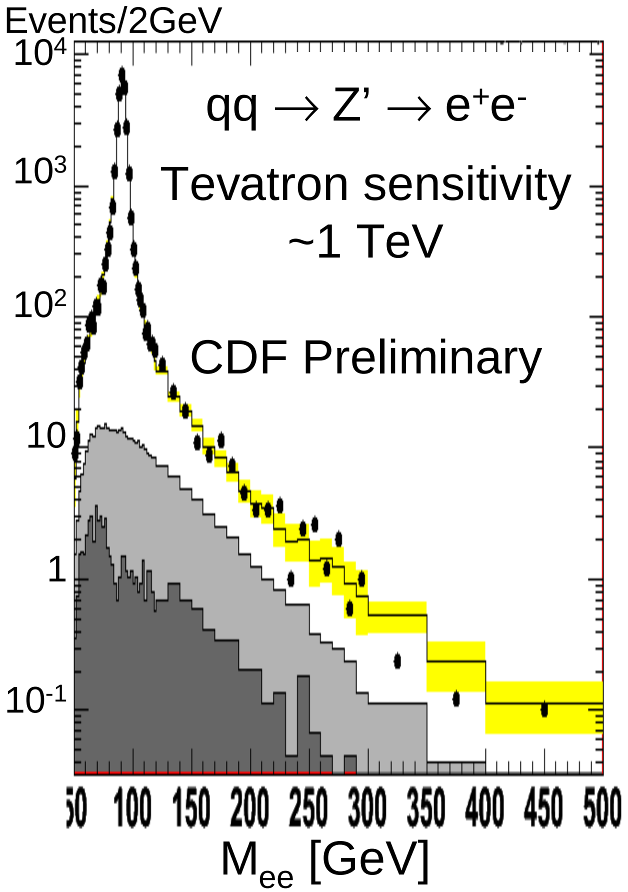



Collision Energy [GeV]

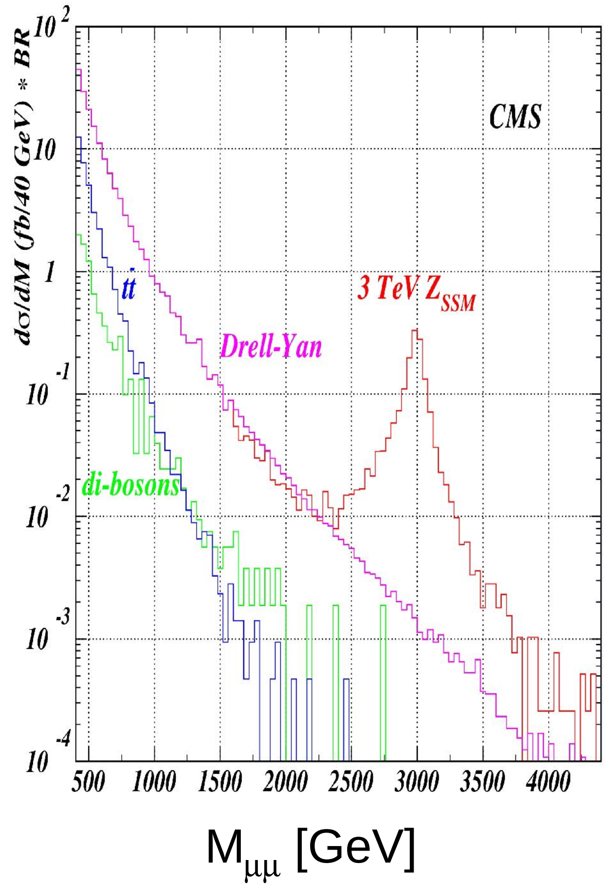
LHC can discover partner towers up to a given energy scale.
ILC can identify the size, shape and # of extra dimensions.

# New forces of nature → new gauge boson

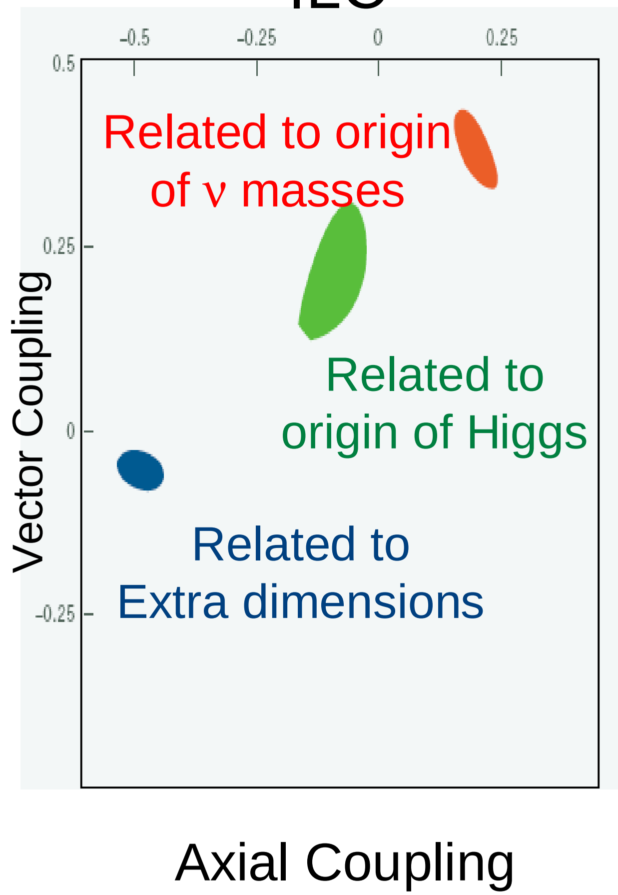
## Tevatron




## LHC




## ILC




LHC has great discovery potential for multi TeV Z'.
Using polarized $e^+$, $e^-$ beams and measuring angular distribution of leptons, ILC can measure Z' couplings to leptons, discriminate origins of the new force.

# Dark Matter in the Laboratory

A common bond between
astronomers, astrophysicists and particle physicists

Underground experiments may detect Dark Matter candidates.

Only accelerators can produce dark matter in the laboratory and understand exactly what it is.

LHC may find Dark Matter (a SUSY particle).
ILC can determine its properties with extreme detail, to compute which fraction of the total DM density of the universe it makes.

# Particles Tell Stories!

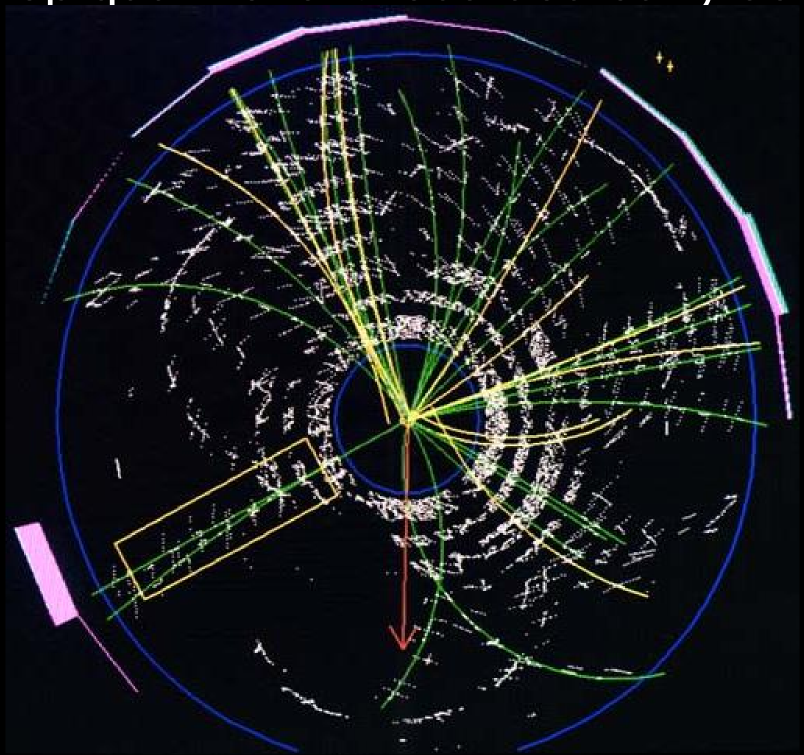
The discovery of a new particle is often the opening chapter revealing unexpected features of our universe.

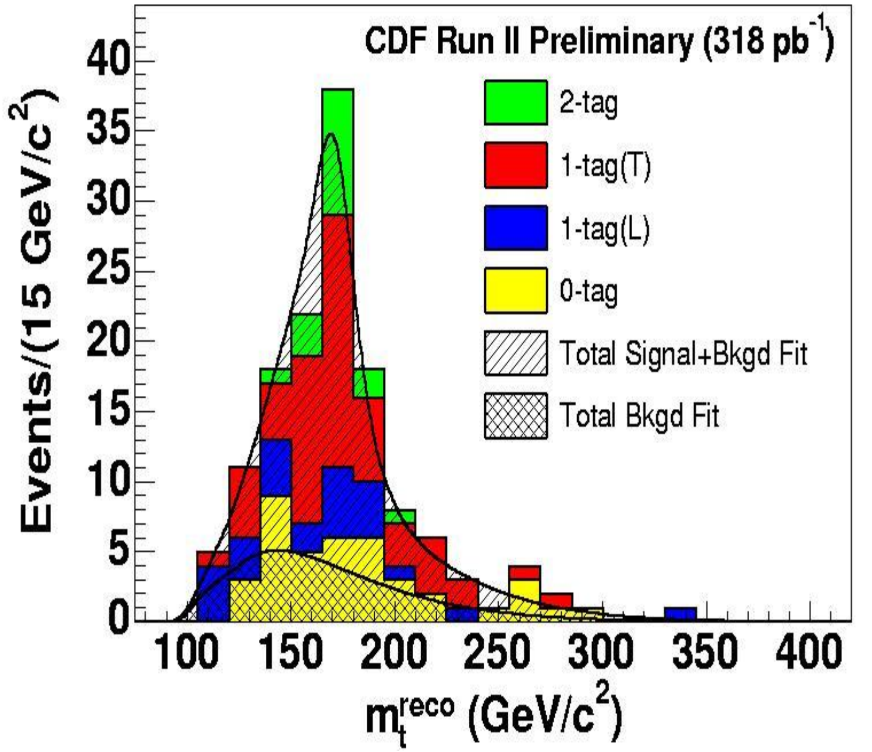
Particles are
messengers telling a profound story
about nature and laws of nature in microscopic world.

The role of physicists is
to find the particles and to listen to their stories.

# Discovering a new particle is Exciting!

Top quark event recorded early 90's






**$M_{top}^{world}$ = 172.7 ± 2.9 GeV**

We are listening to the story that top quarks are telling us: Story is consistent with our understanding of the standard model so far. But why is the mass so large? We are now searching for a story we have not heard before.

# Discovering “laws of nature” is even more Exciting!!

We are hoping in the next ~5 years LHC will discover Higgs.
ILC will allow us to listen very carefully to Higgs. This will open windows for discovering new laws of nature.

This saga continues….
There might be supersymmetric partners, dark matter, another force carrier, large extra dimensions, ……
for other new laws of nature.

## Whatever is out there,
## this is our best opportunity to find it’s story!