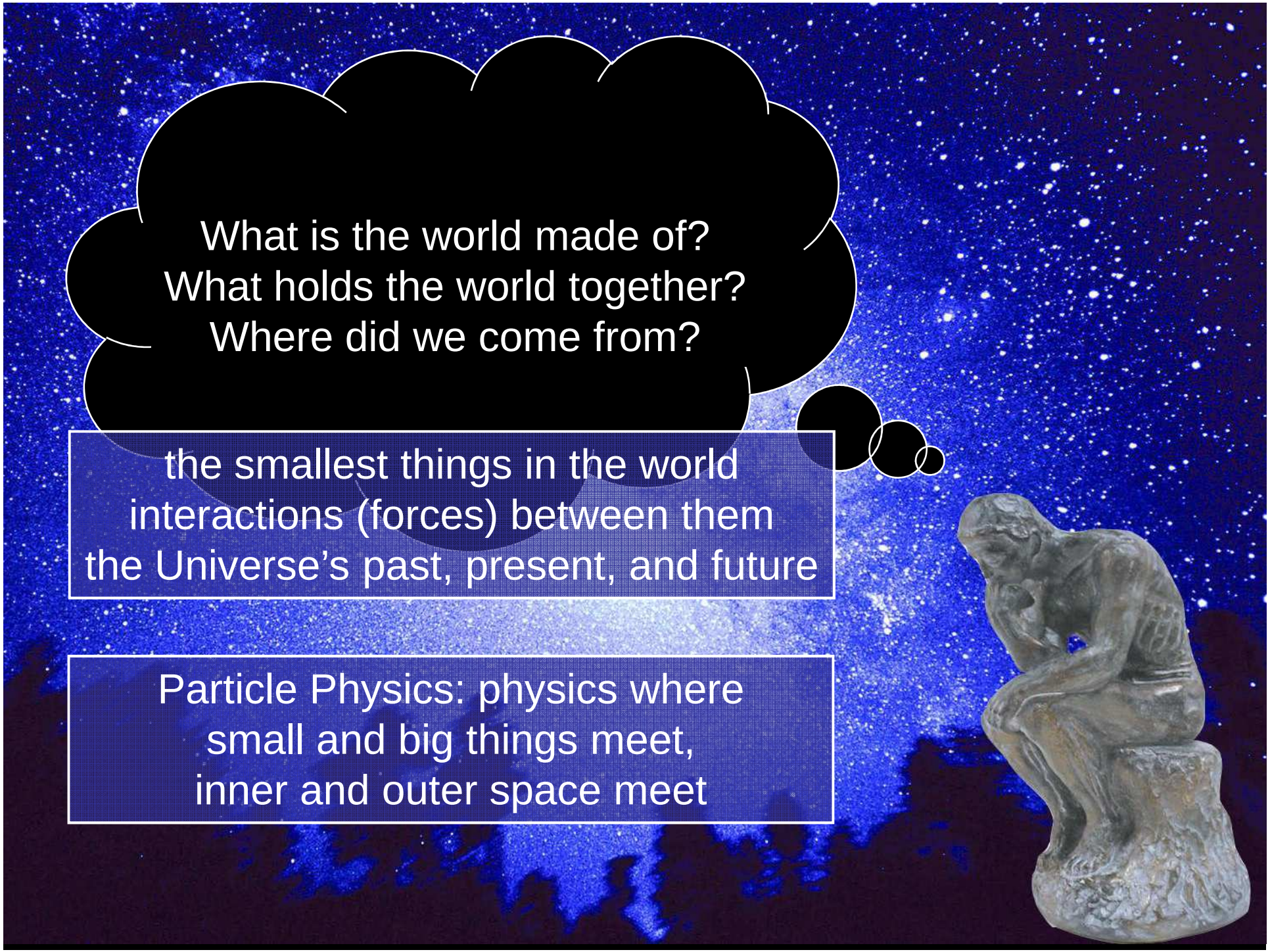
# $E = mc^2$

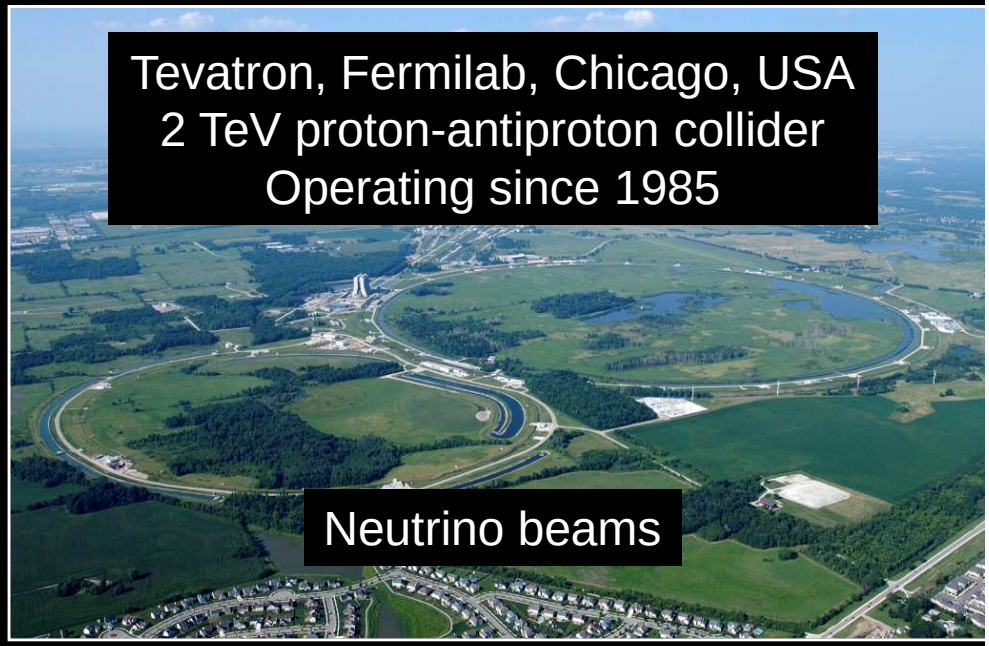
## Opening Windows on the World

*Young-Kee Kim*
*Fermilab and the University of Chicago*

*Physics Department Colloquium*
*University of Virginia*
*September 4, 2009*


What is the world made of?
What holds the world together?
Where did we come from?
the smallest things in the world
interactions (forces) between them
the Universe's past, present, and future
Particle Physics: physics where
small and big things meet,
inner and outer space meet

# Accelerators are powerful tools for Particle Physics!

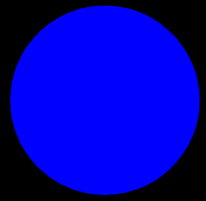




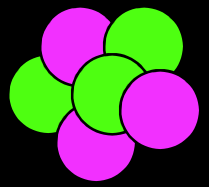
# Accelerators are Powerful Microscopes.

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

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



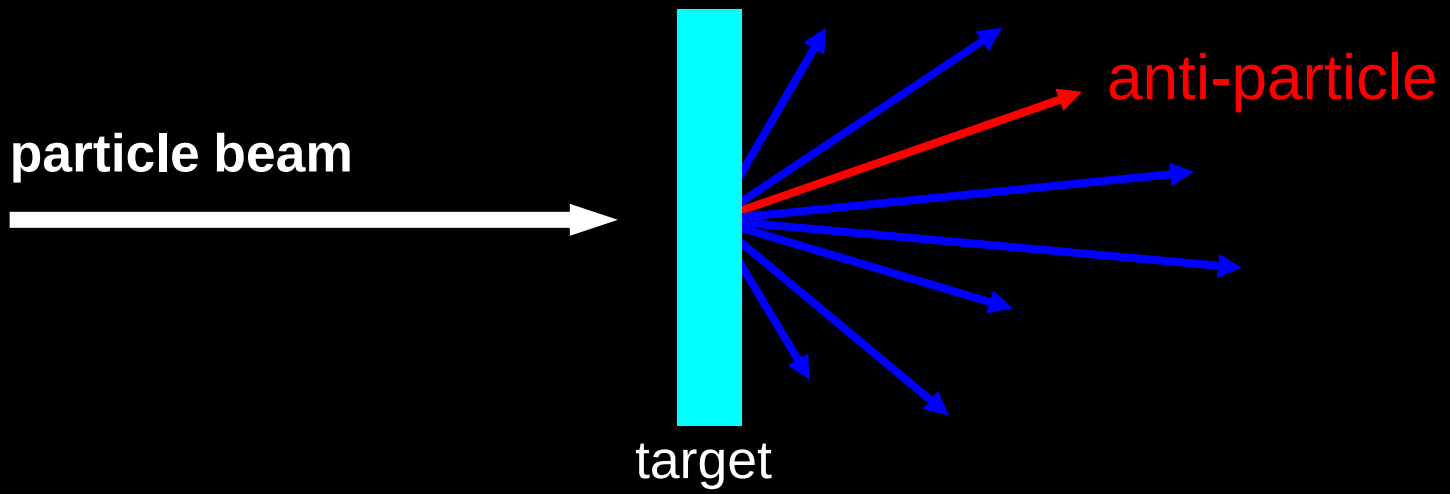
seen by
low energy beam
(poorer resolution)



seen by
high energy beam
(better resolution)

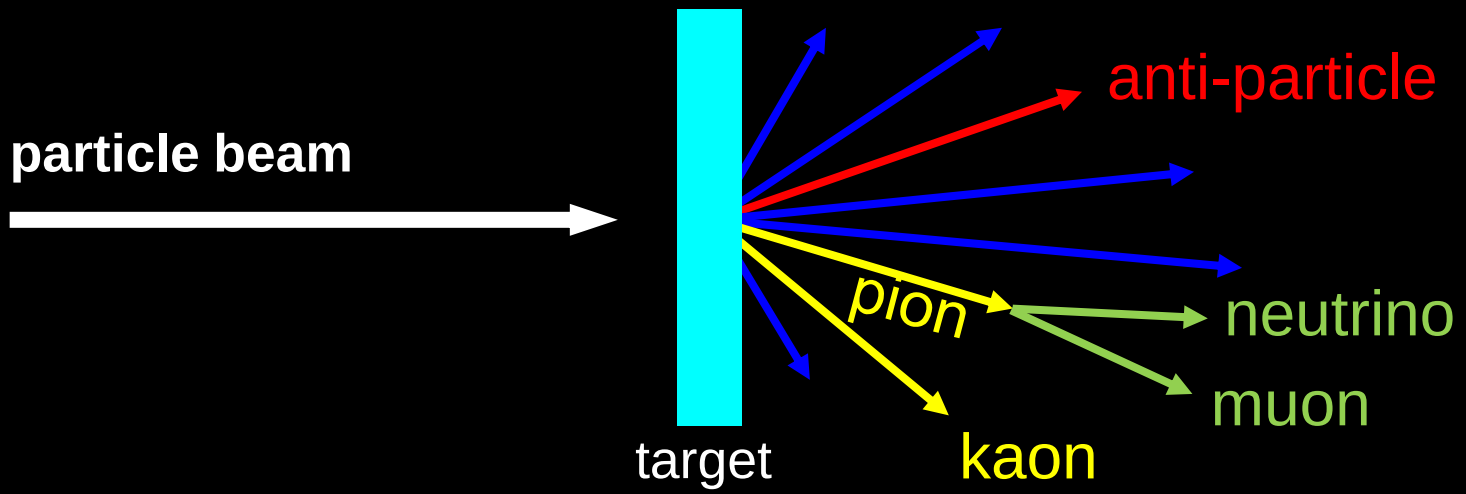
# Accelerators are also Time Machines

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.



# Accelerators are also Time Machines

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

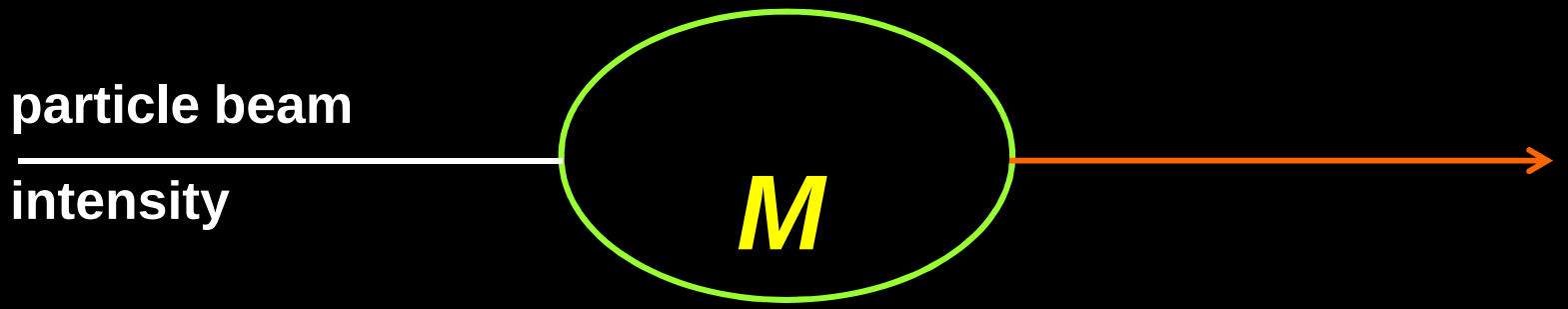

Particle and anti-particle annihilate.

$$E = mc^2$$

# Accelerators are also Time Machines

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

$$E = Mc^2$$



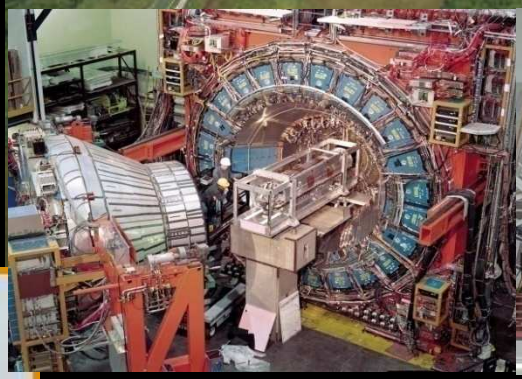

$$m_\nu \longleftrightarrow M_N$$

Many generations of Accelerators created
with higher and higher energy and intensity beams


Ernest Lawrence
(1901 - 1958)

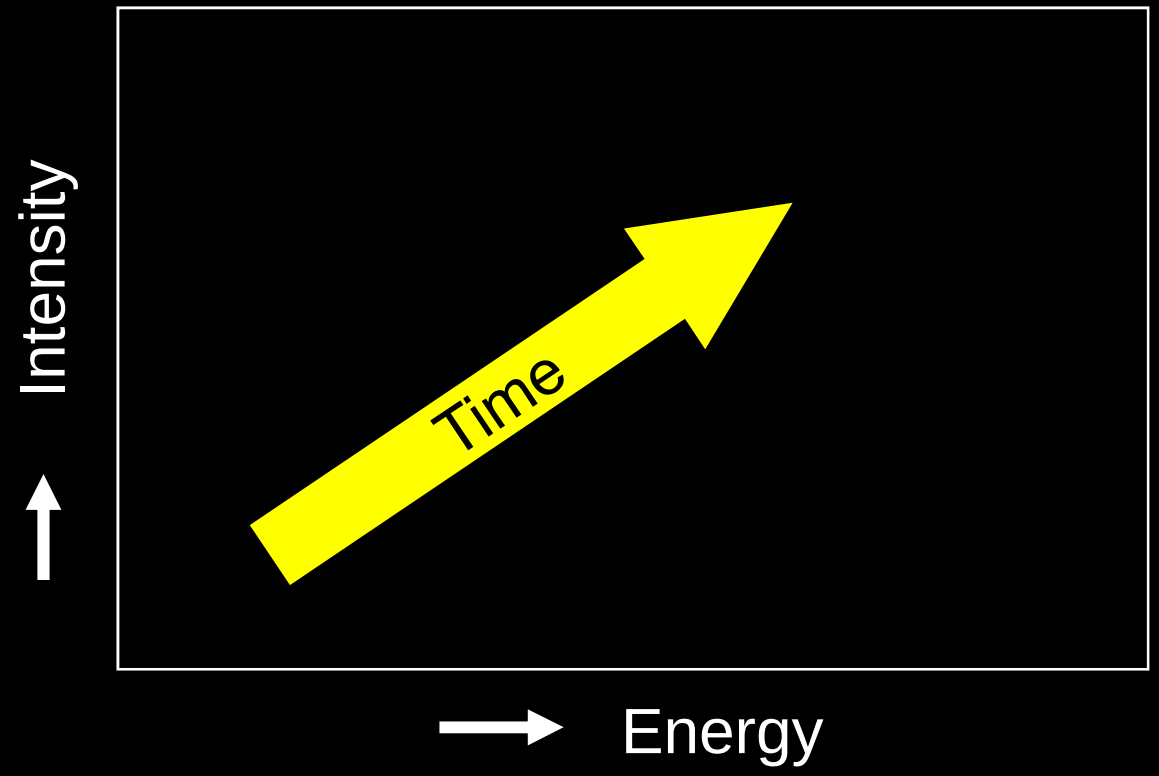
Today (Fermilab)

~2000 Scientists
Fermilab experiments using accelerators
> 2 publications every week
~2 Ph.D.s every week



Tevatron: x$10^4$ bigger, x$10^6$ higher energy
Intense neutrino beams

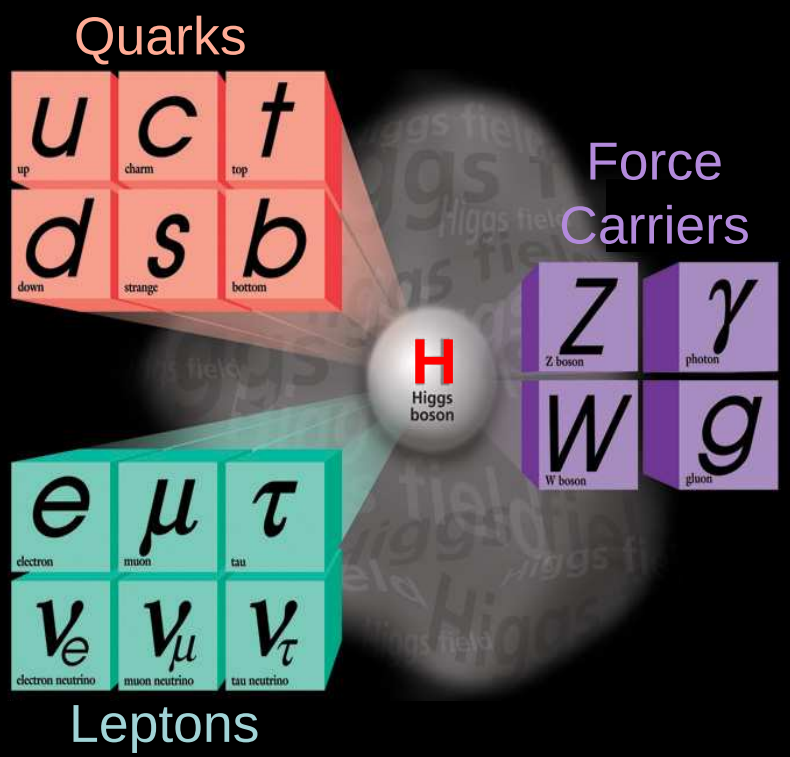
With advances in accelerators, we discovered many surprises.




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”

# Scientific Drivers

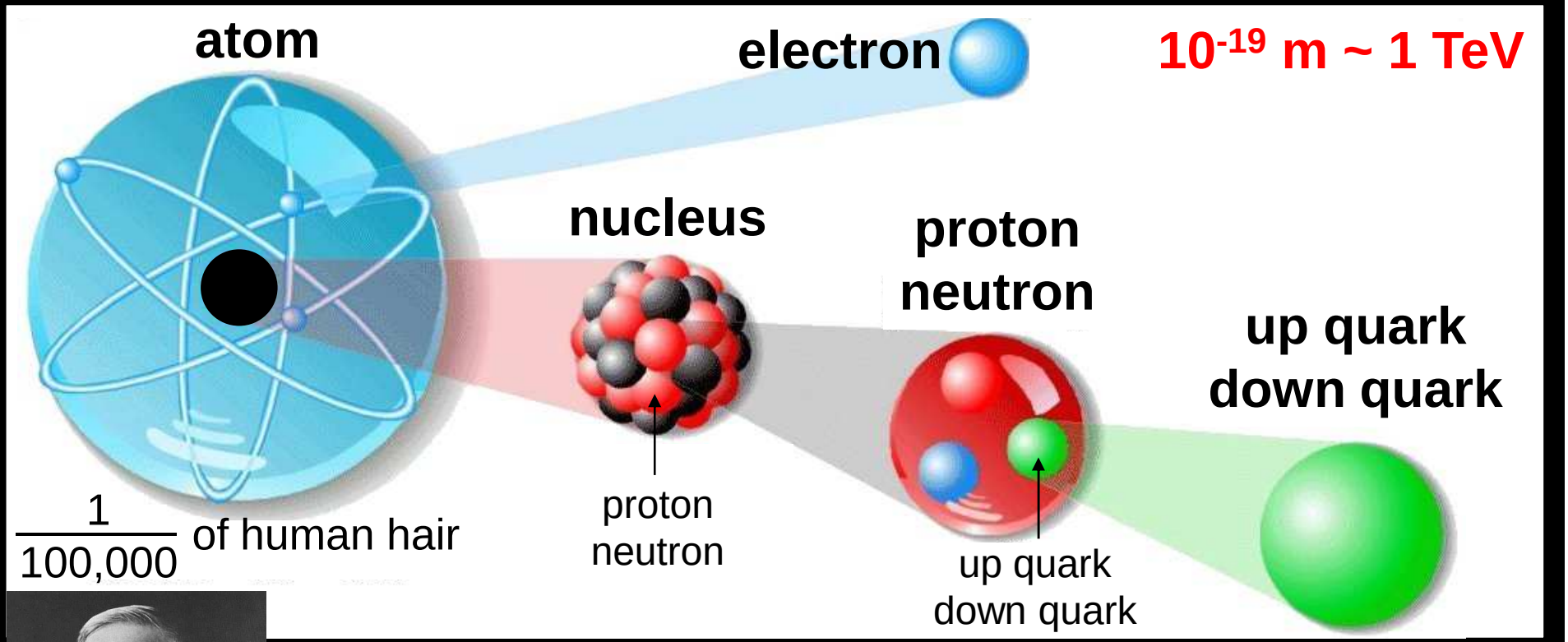
- Present theory (Standard Model) is a remarkable intellectual construction
- Every particle experiment ever done (except neutrino expt.s) fits in the framework
- But huge questions remain unanswered.
- New physics is required to answer
  - e.g. Supersymmetric extension of SM, extra dimensions, ….

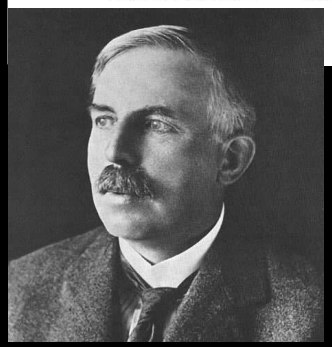



**H** (Higgs) yet to be discovered

# *What is the universe made of?*

~90 years ago ~60 years ago ~40 years ago Present



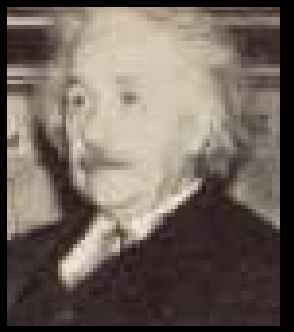
Rutherford

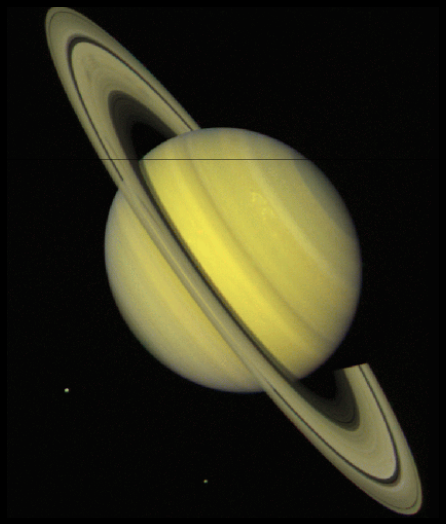
1/10,000 1/10 1/100,000

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



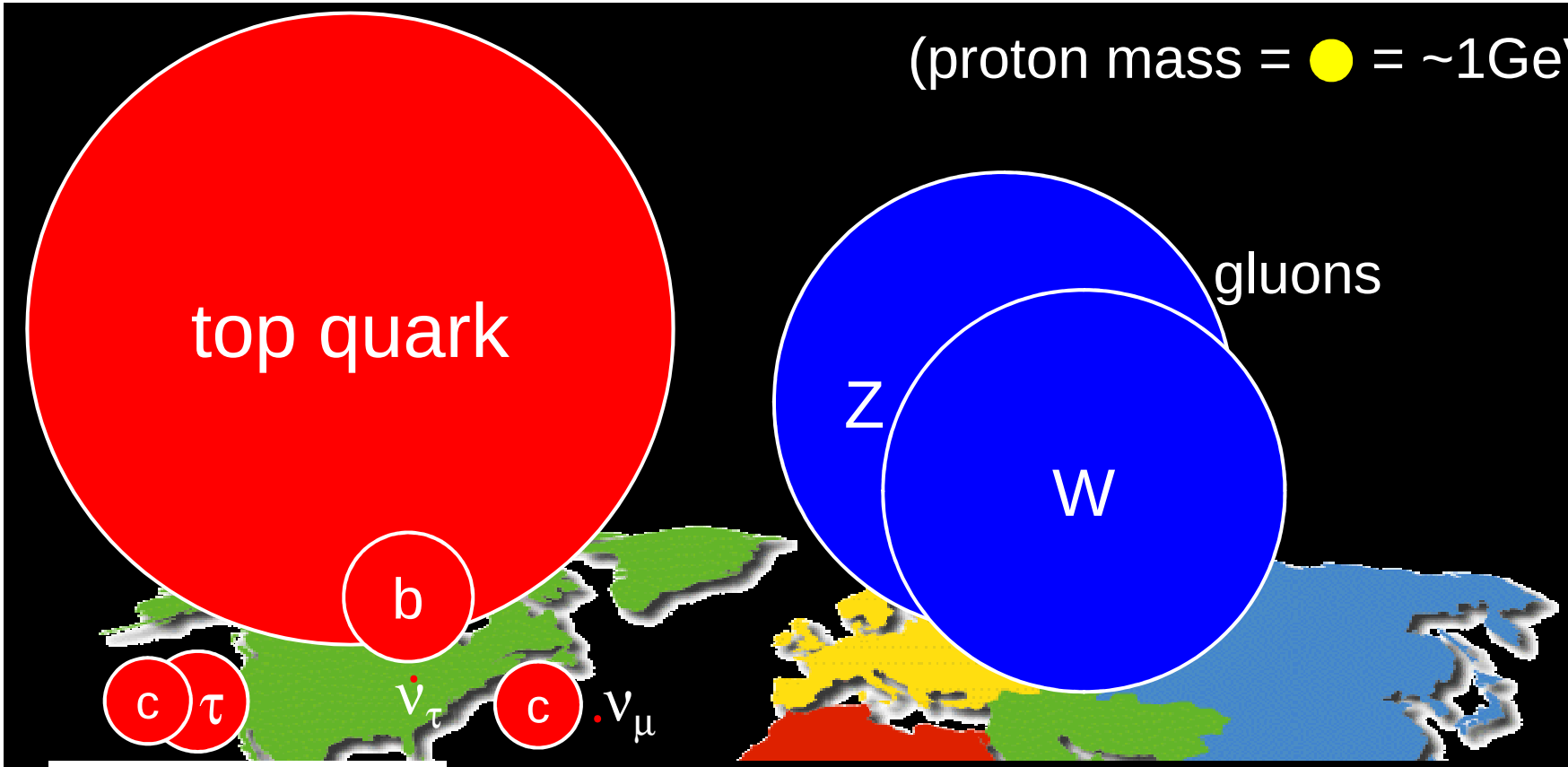







*Are they the smallest things?*

(proton mass = ● = ~1GeV/$c^2$ )




| | Fermions | | |
|---|---|---|---|
| Quarks | u up | c charm | t top |
| | d down | s strange | b bottom |
| Leptons | $\nu_e$ electron neutrino | $\nu_\mu$ muon neutrino | $\nu_\tau$ tau neutrino |
| | e electron | μ muon | τ tau |

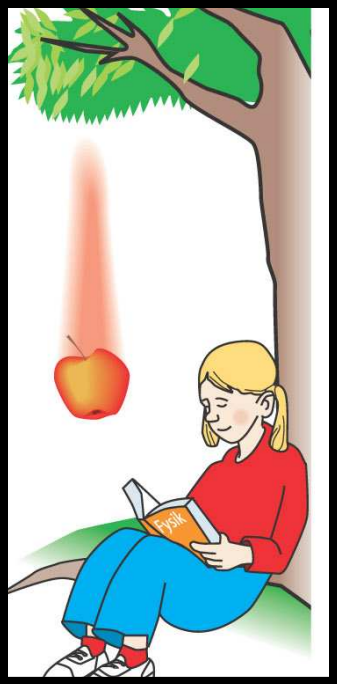
*Why so many elementary particles?*
*Why 3 families?*
*Where does mass come from? Higgs?*
*Origin of neutrino mass?*
*Would charged leptons oscillate?*
*Did they all come from ONE?*

# *What holds the world together?*

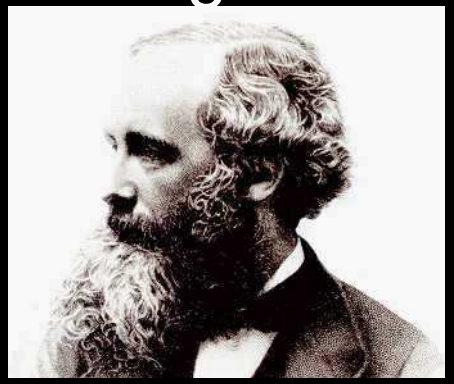
## *Beginnings of Unification*

### Gravitational Force

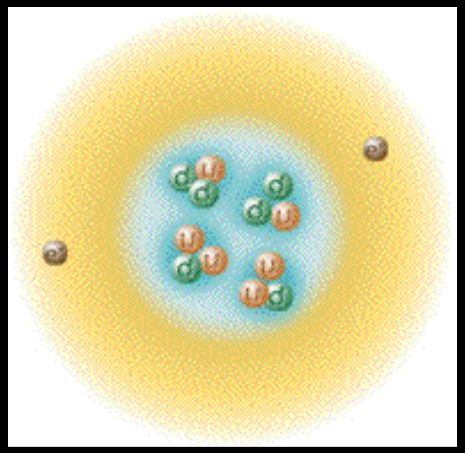
Issac Newton
(1642 - 1727)



### Electromagnetic Force



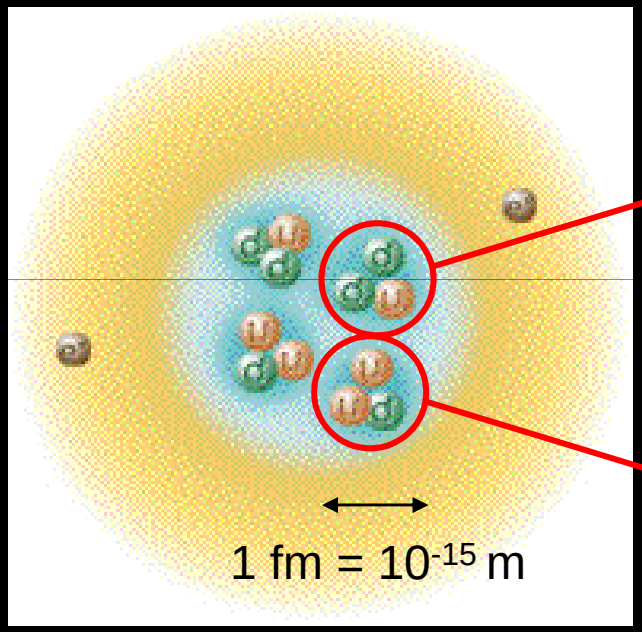
James Clerk Maxwell
(1831 - 1879)



# Unification of Gravity and Electromagnetism?

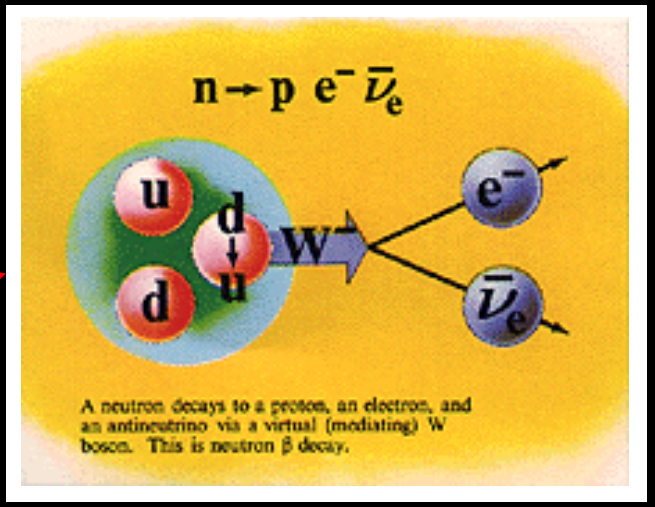
Einstein tried to unify electromagnetism and gravity but he failed.

Enrico Fermi
(1901 - 1954)



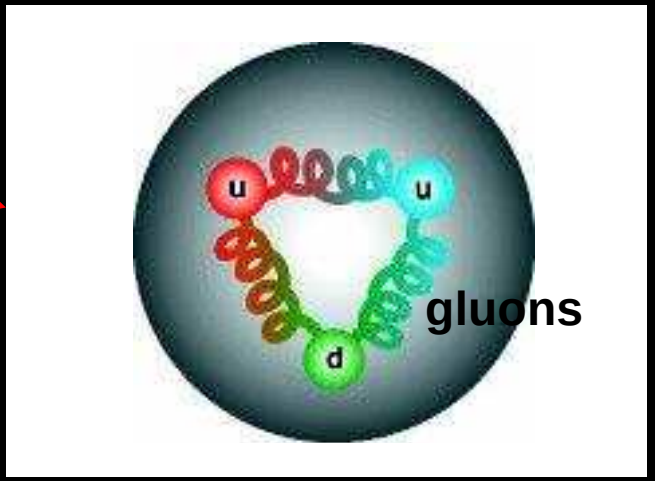

Weak Force

radioactive decays




Strong Force

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?*

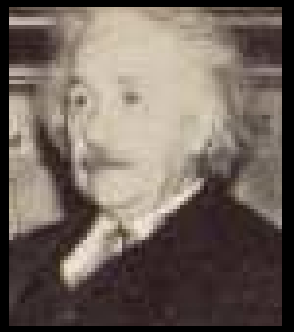
# Particle Physics & Cosmology Questions from Astrophysical Observations

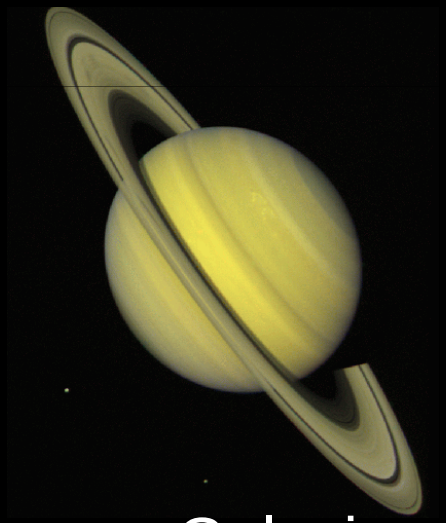
~~Everything~~ is made of electrons, up quarks and down quarks.

Everything that we can see







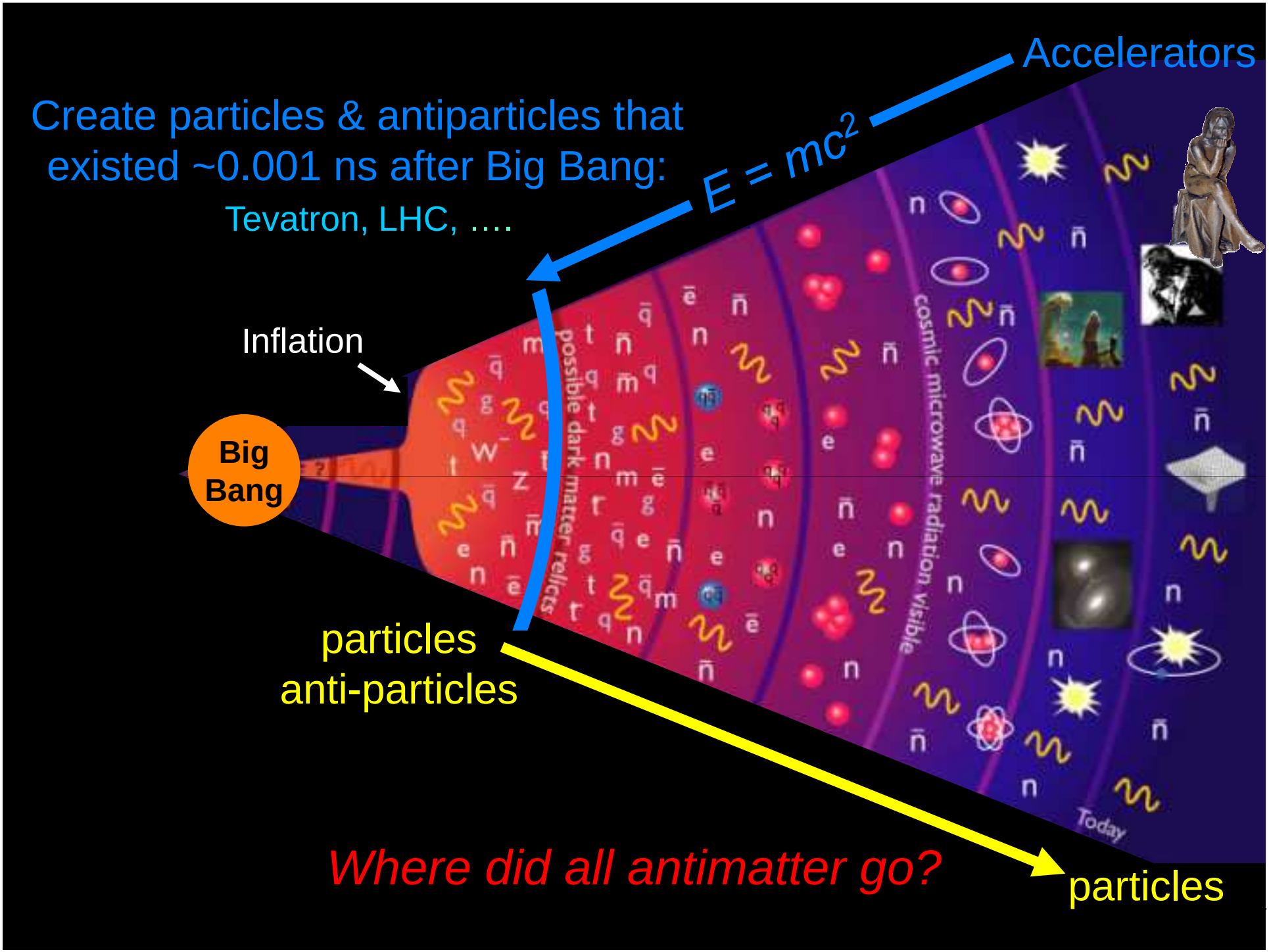

Galaxies are held together by mass far bigger (x5) than all stars combined.

*Dark Matter - What is it?*

*Where did we come from?*

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

*Understanding our Universe!*


Accelerators
Create particles & antiparticles that existed ~0.001 ns after Big Bang:
Tevatron, LHC, ….
$E = mc^2$
Inflation
Big Bang
possible dark matter relics
cosmic microwave radiation visible
Today
particles
anti-particles
Where did all antimatter go?
particles

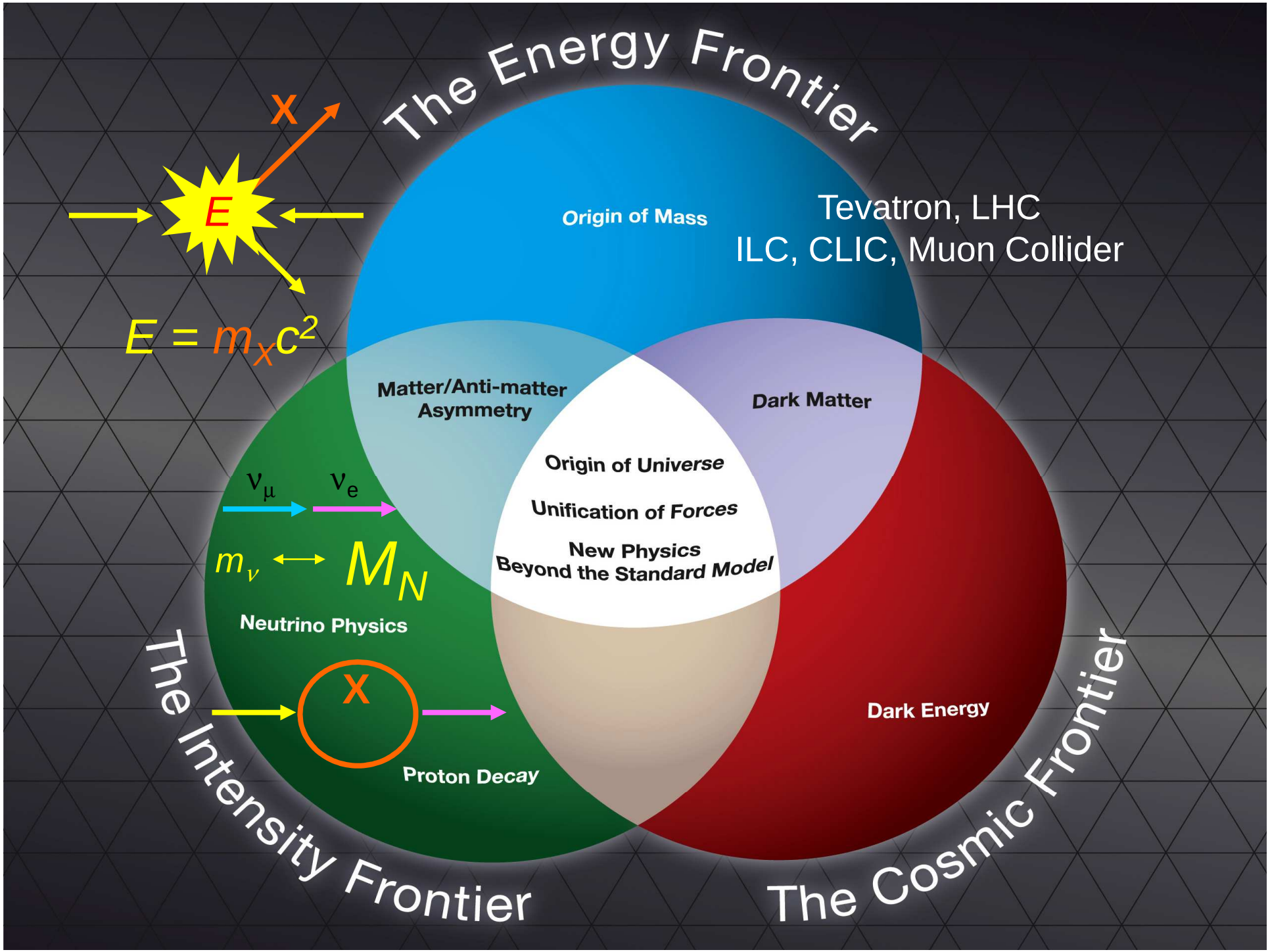
Not only is the Universe expanding, it is

# Accelerating!!

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

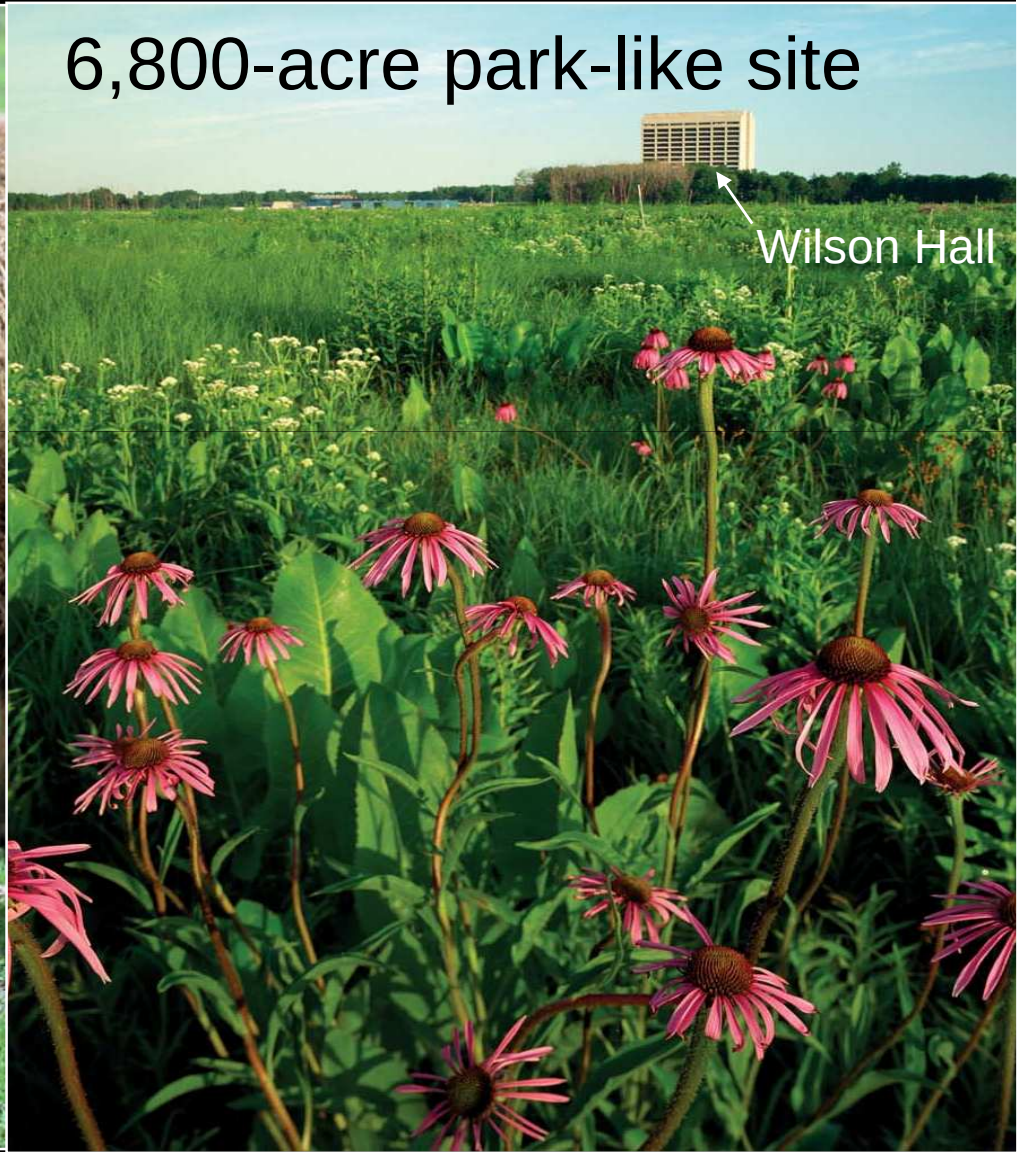

What is the world made of?
What holds the world together?
Where did we come from?
Primitive Thinker

1. What is the origin of mass for fundamental particles?
2. Why are there so many kinds of particles?
3. Do all the forces become one?
4. Are there extra dimensions of space?
5. What are neutrinos telling us?
6. What happened to the antimatter?
7. What is dark matter?
8. How can we solve the mystery of dark energy?
9. How did the universe come to be?
10. Are there undiscovered principles of nature:
    new symmetries, new physical laws?


The Energy Frontier
X
E
$E = m_X c^2$
Origin of Mass
Tevatron, LHC
ILC, CLIC, Muon Collider
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
$\nu_\mu$
$\nu_e$
$m_\nu \leftrightarrow M_N$
Neutrino Physics
X
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

# Particle Physics in the World

A herd of American bison, symbolizing Fermillab's presence on the frontiers of particle physics and the connection to its prairie origins.



# 2008 Nobel Prize in Physics

Nambu (Univ. of Chicago)
Kobayashi (KEK) – Maskawa (Kyoto Univ.)

for “Mechanism of Symmetry Breaking”


“Broken Symmetry”

# The Energy Frontier: “Tevatron”
# The Intensity Frontier: Neutrino Beams

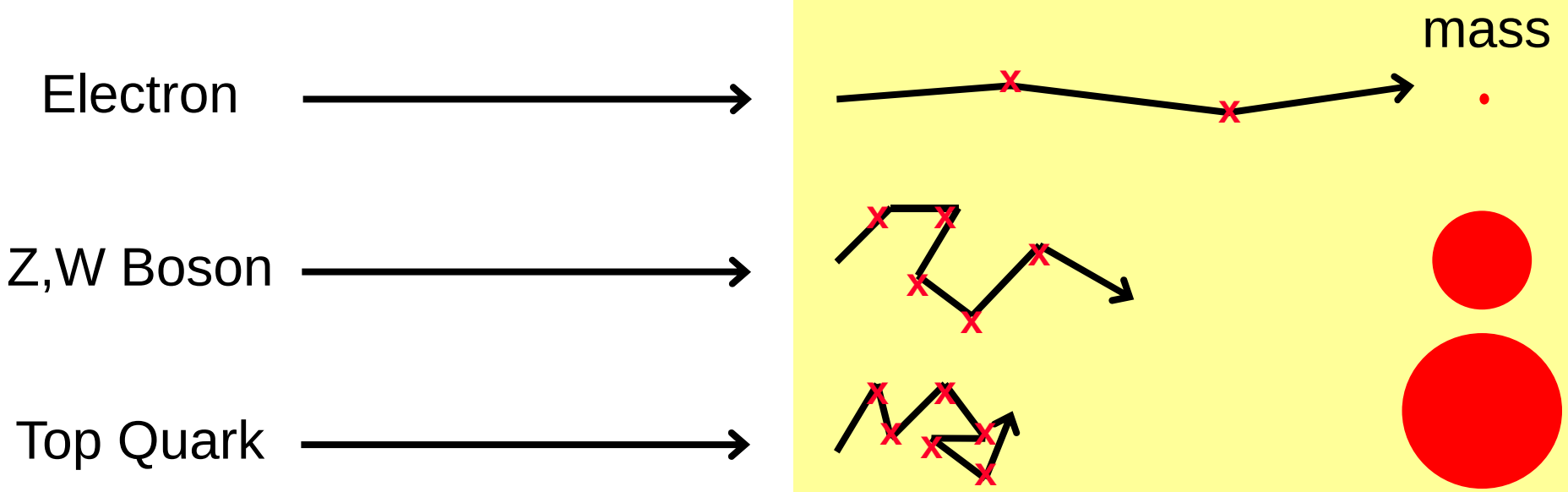
# Origin of Mass:

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

Nothing in the universe

Something in the universe

Higgs Particles:



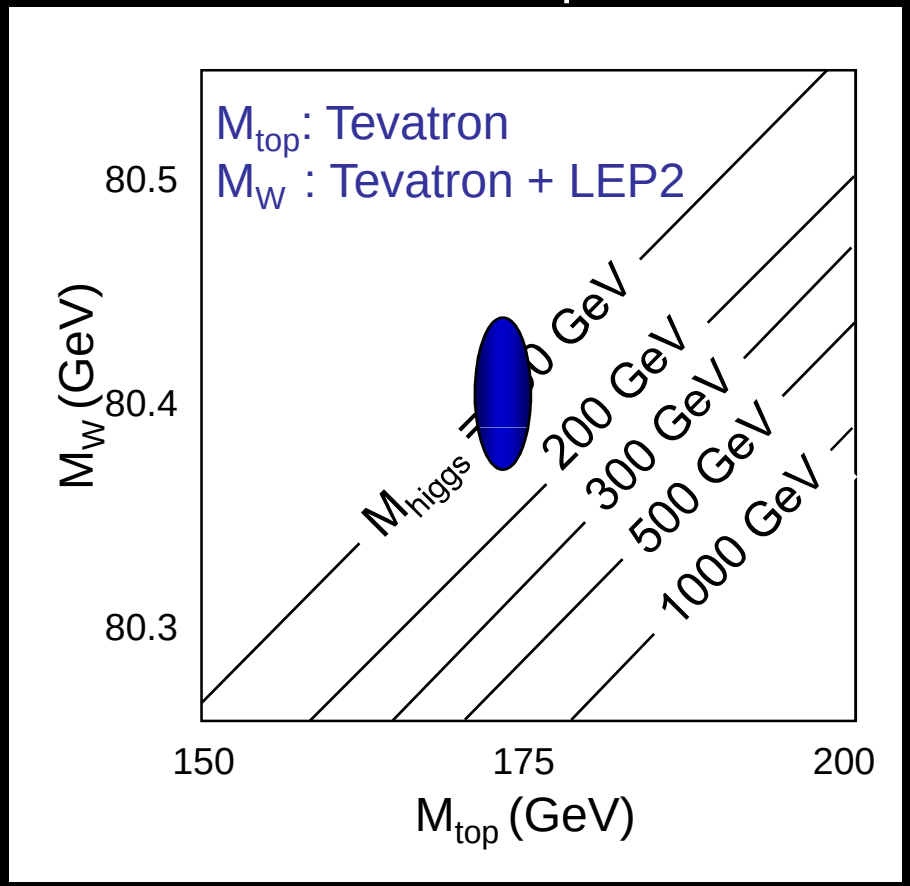

Mass

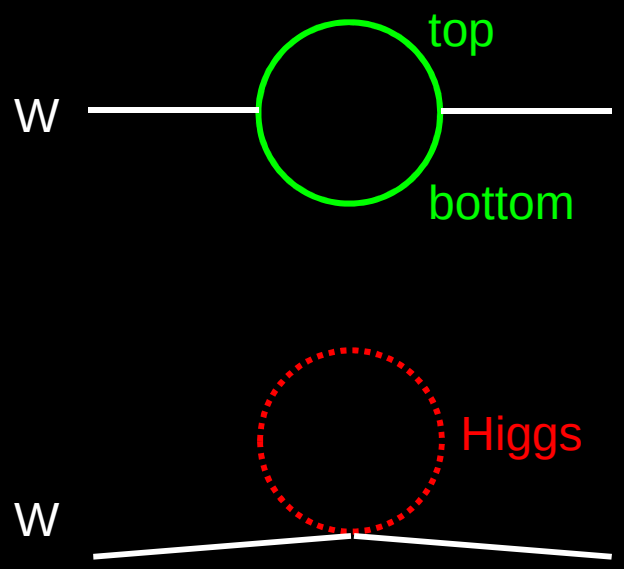
∞

coupling strength to Higgs

# Tevatron: Improve Higgs Mass Pred. via Quantum Corrections

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



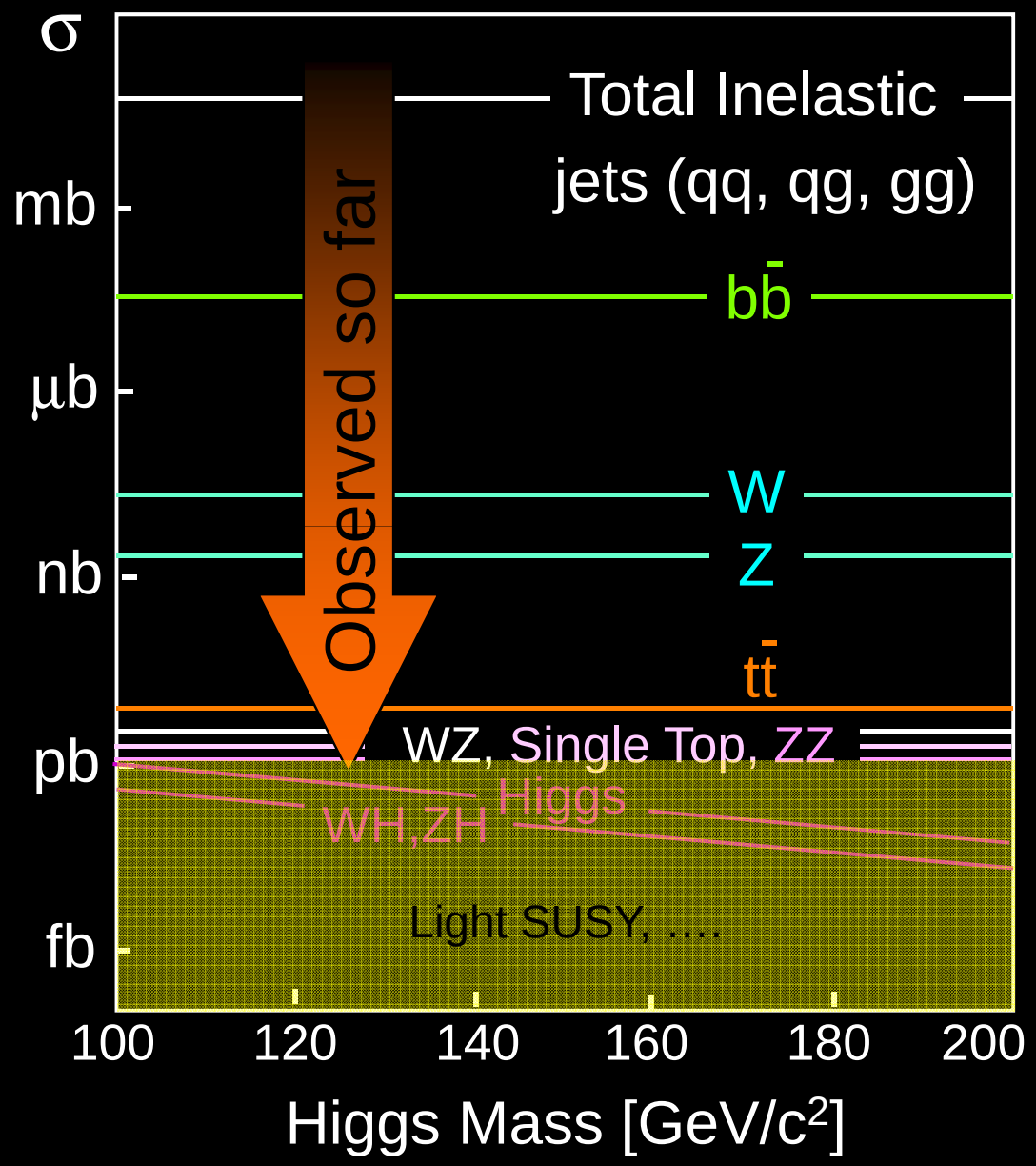




$M_W$ and $M_{top}$ measurements favor light Higgs < ~180 GeV

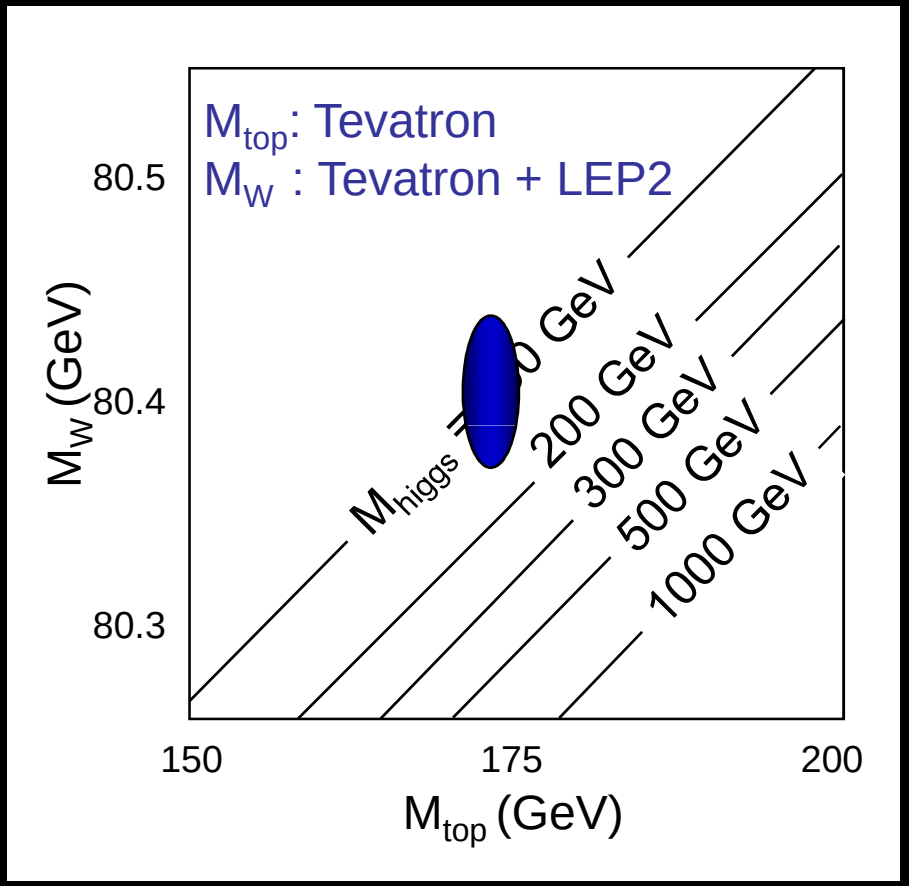
LEP2 direct searches – excluded Higgs < 114 GeV at 95% CL

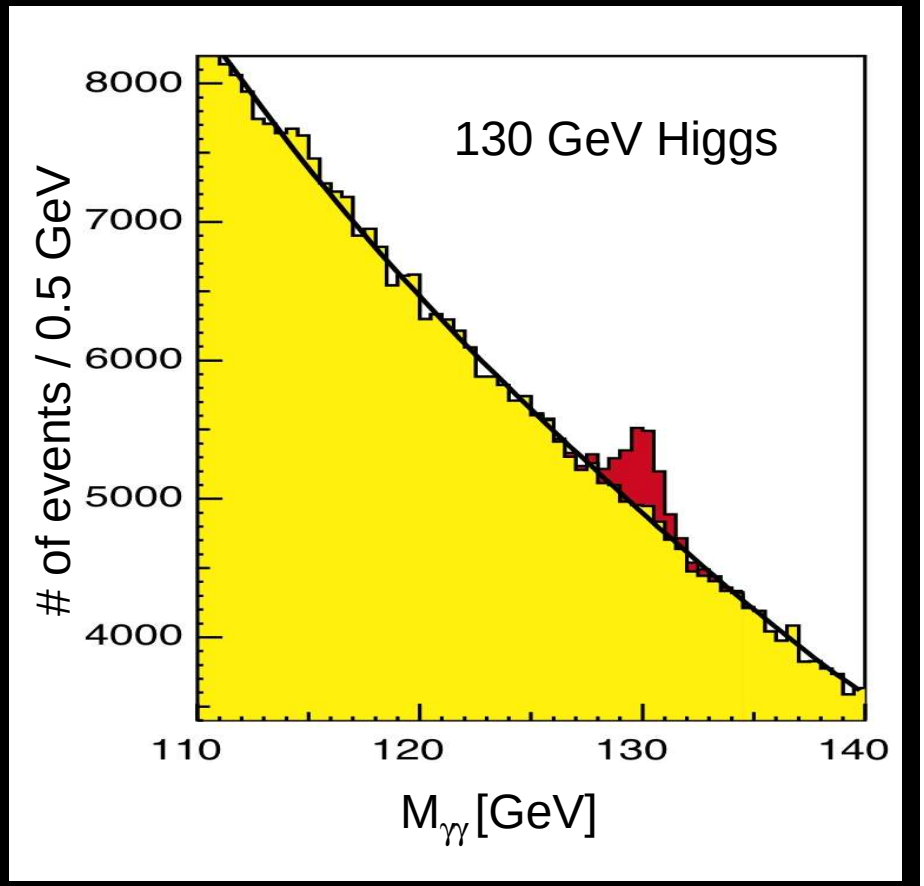
Favored Higgs mass range (114 – 180 GeV) is great for the Tevatron!

# Physics at the Tevatron

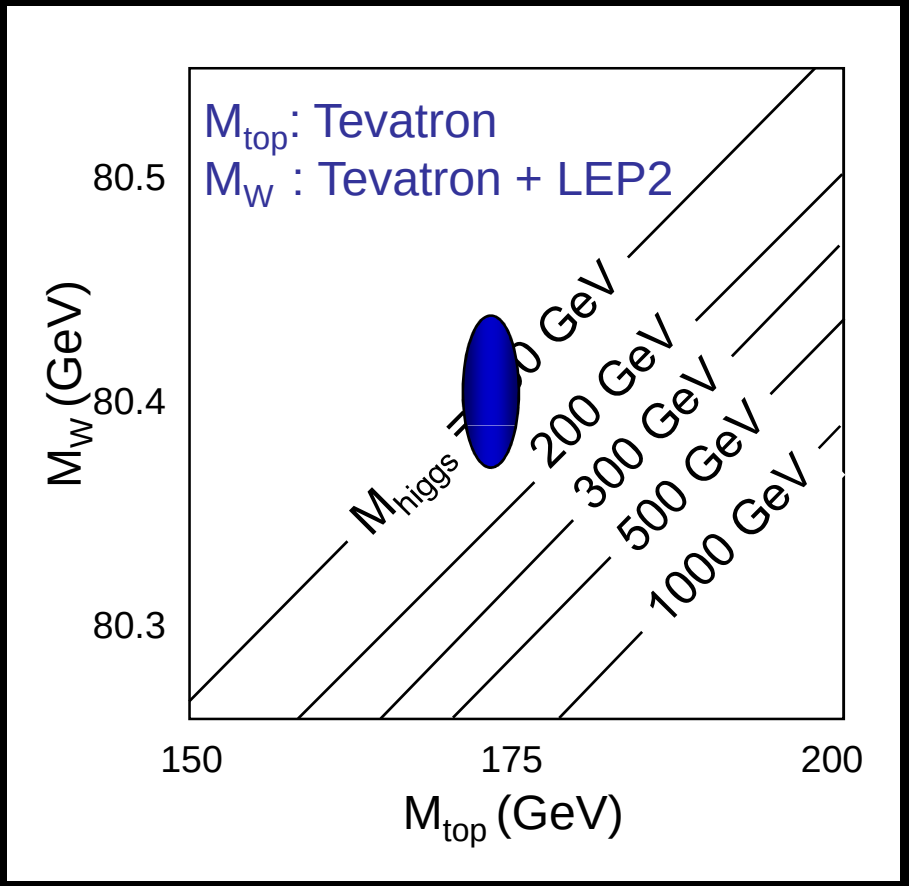


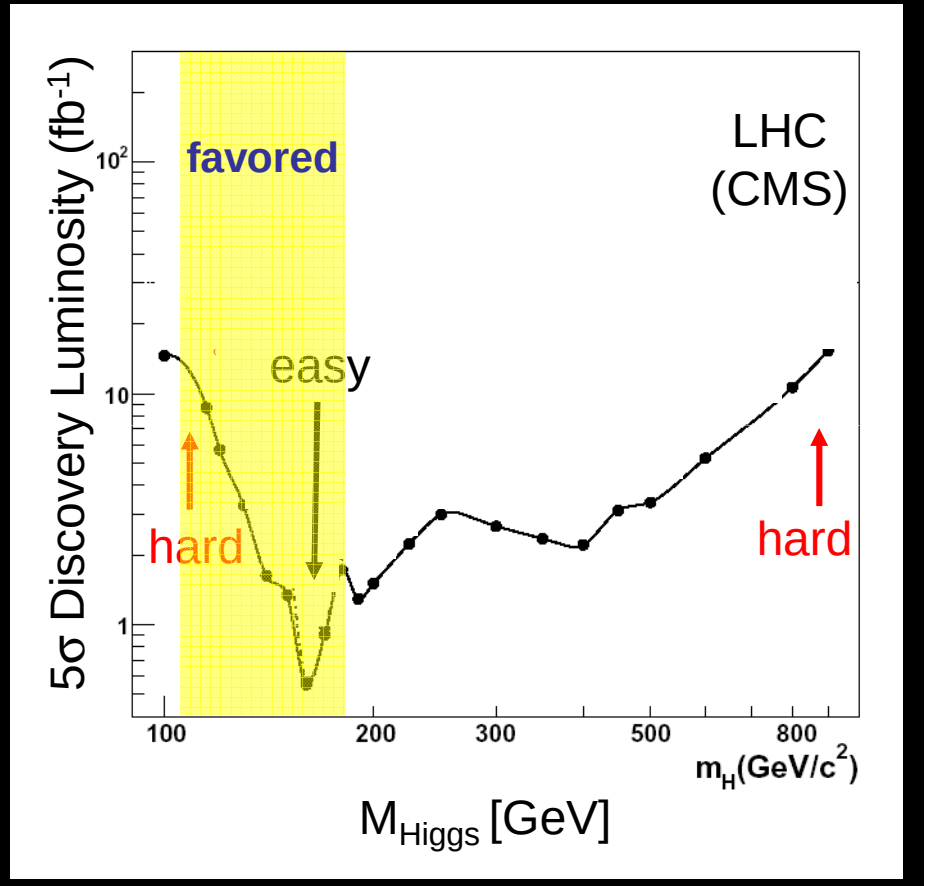
# Tevatron: Improve Higgs Mass Pred. via Quantum Corrections
# LHC: Designed to discover Higgs with $M_{higgs}$ = 100 ~ 800 GeV



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




Tevatron: favors < ~180 GeV, excludes 160-170 GeV, continues to improve
Will Tevatron's Higgs prediction agree with what LHC sees?

# Fermilab and LHC


US CMS Host Lab; the only US CMS Lab

CMS Tier-1 Computing Center
LHC Physics Center
Support US CMS Community

**To Fermilab**

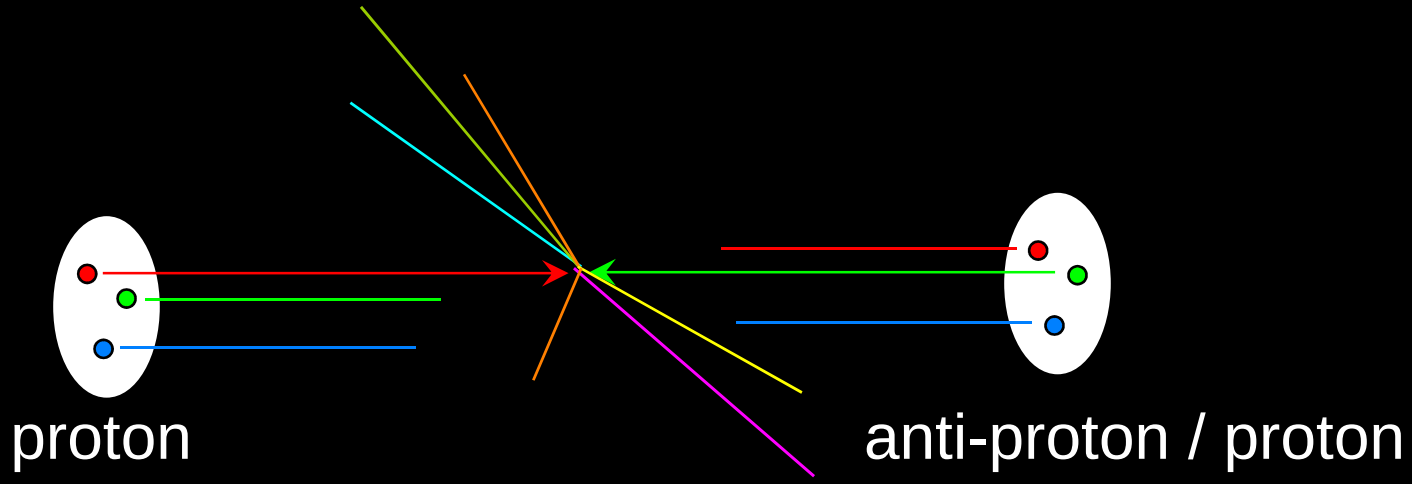
Remote Operation Center:
Detector Commissioning and Monitoring
Accelerator Monitoring
CERN Night = FNAL Day

To make being at Fermilab as productive as being at CERN.
Requires critical mass (~100 Fermilab + University Scientists at Fermilab).

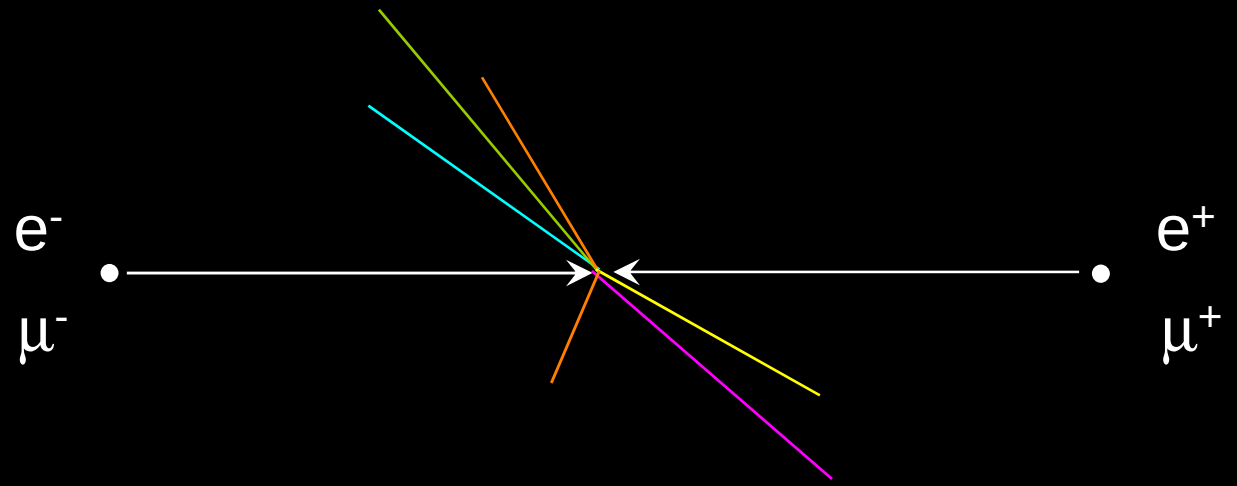
If we discover a “Higgs-like” particle,
is it alone responsible for giving mass to W, Z, fermions?

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

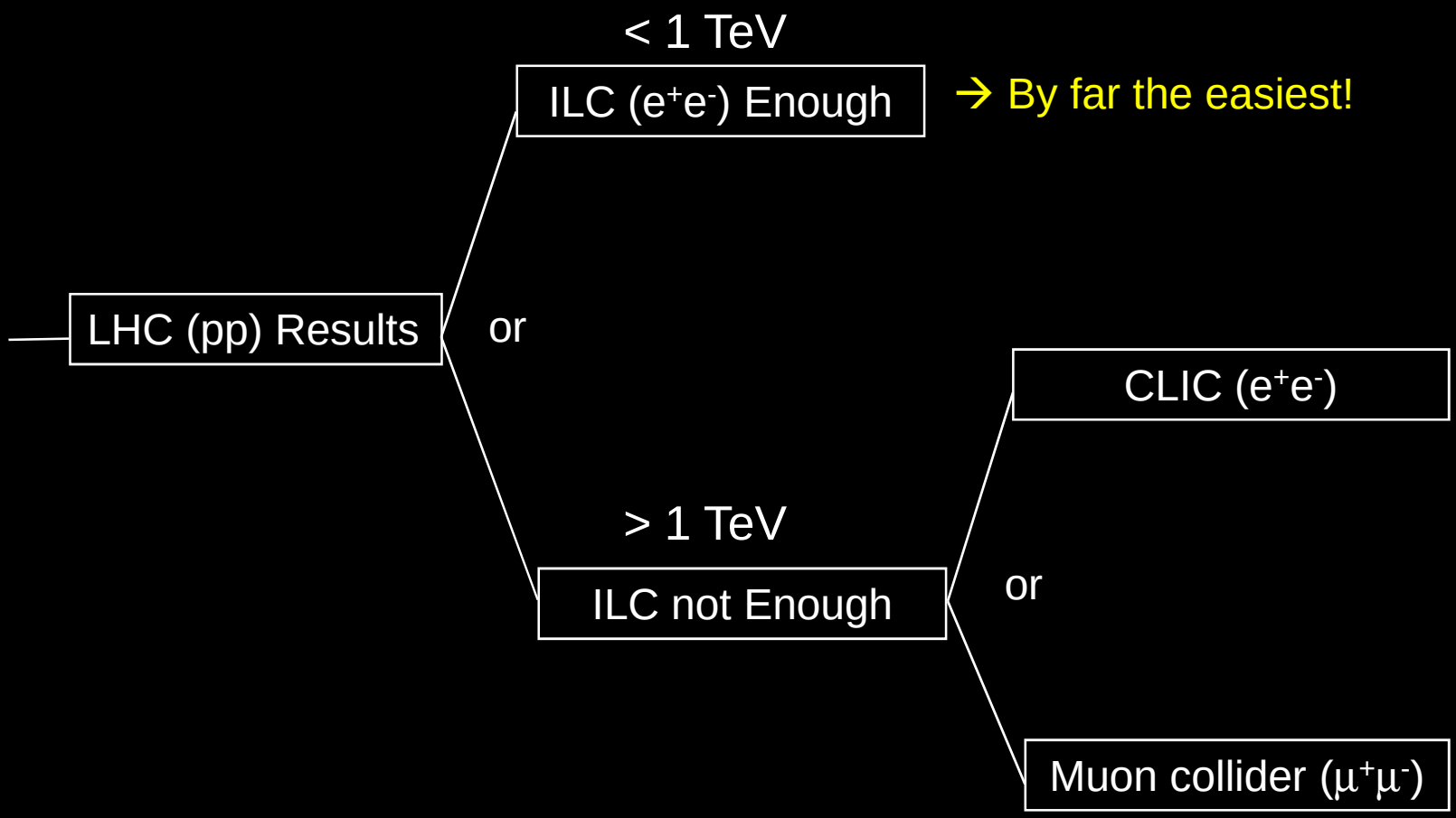
## Hadron Collider (Tevatron / LHC):

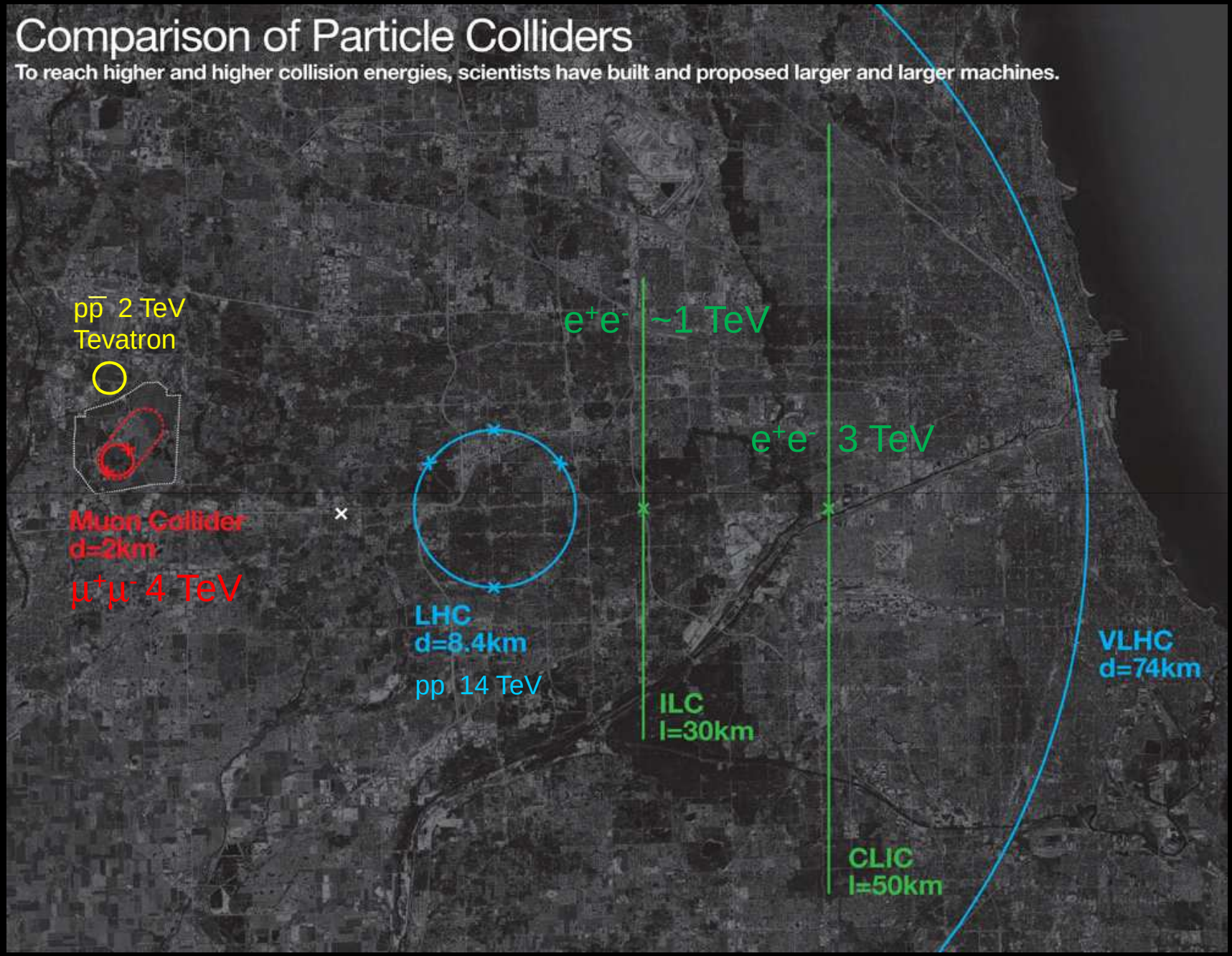



## Lepton Collider (ILC, CLIC, Muon Collider):



# Lepton colliders beyond LHC




Comparison of Particle Colliders
To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.
p$\bar{p}$ 2 TeV
Tevatron
Muon Collider
d=2km
$\mu^+\mu^-$ 4 TeV
LHC
d=8.4km
pp 14 TeV
$e^+e^-$ ~1 TeV
ILC
l=30km
$e^+e^-$ 3 TeV
CLIC
l=50km
VLHC
d=74km

# 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.
Dark Energy – Scalar Field
Could give a handle on dark energy(scalar field)?

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

# Probing Dark Energy

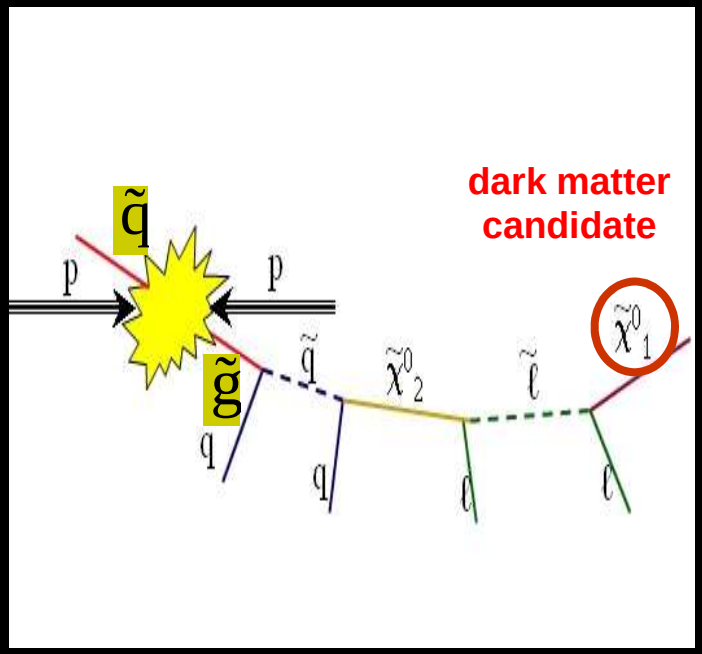
1. SDSS (Sloan Digital Sky Survey)
   - 2.5 m telescope in New Mexico
   - Power spectrum of galaxies constrain dark energy density parameter
   - Ranks as the facility with the highest impact in astronomy for the 3rd year in a row.

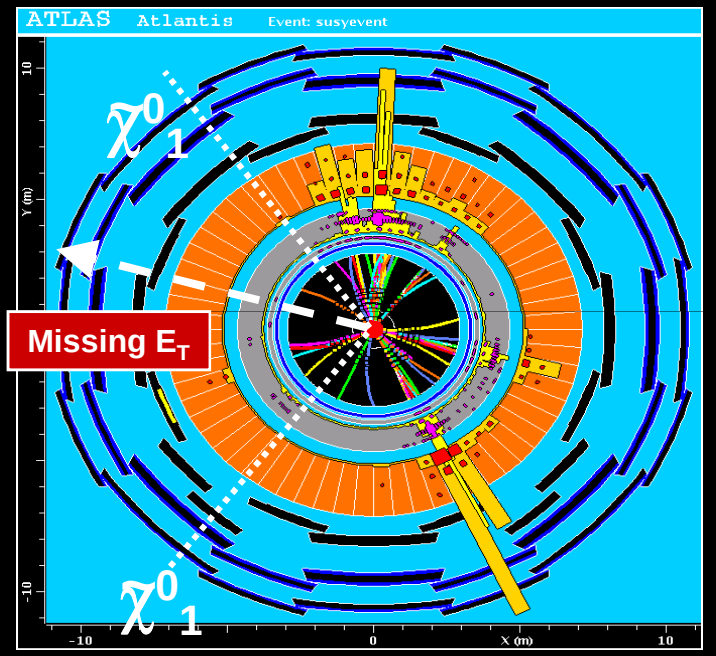
2. DES (Dark Energy Survey)
   - 4 m telescope in Chile (Construction)
   - Operation: 2011 – 2016

3. JDEM (Joint Dark Energy Mission)
   - Space telescope (Proposed)
   - Fermilab's goal: run Science Ops. Center.

# Interplay: Energy Frontier ⟷ Intensity Frontier

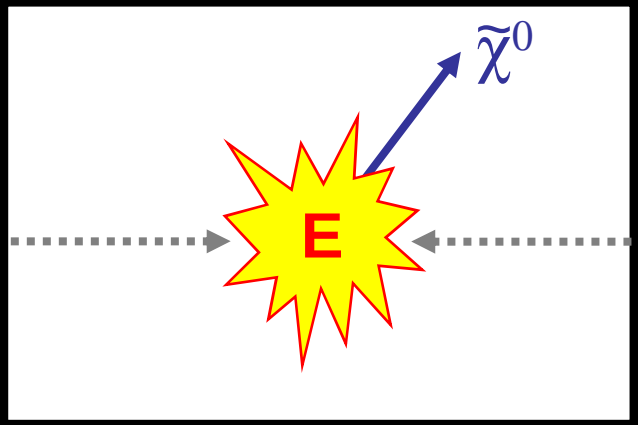
LHC discovers strongly coupled SUSY

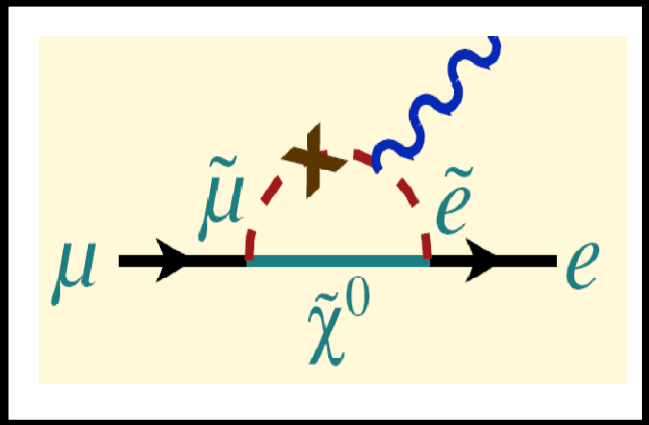



A host of new particles: fit roughly some masses,
make assumption on couplings

# Interplay: Energy Frontier ⟷ Intensity Frontier



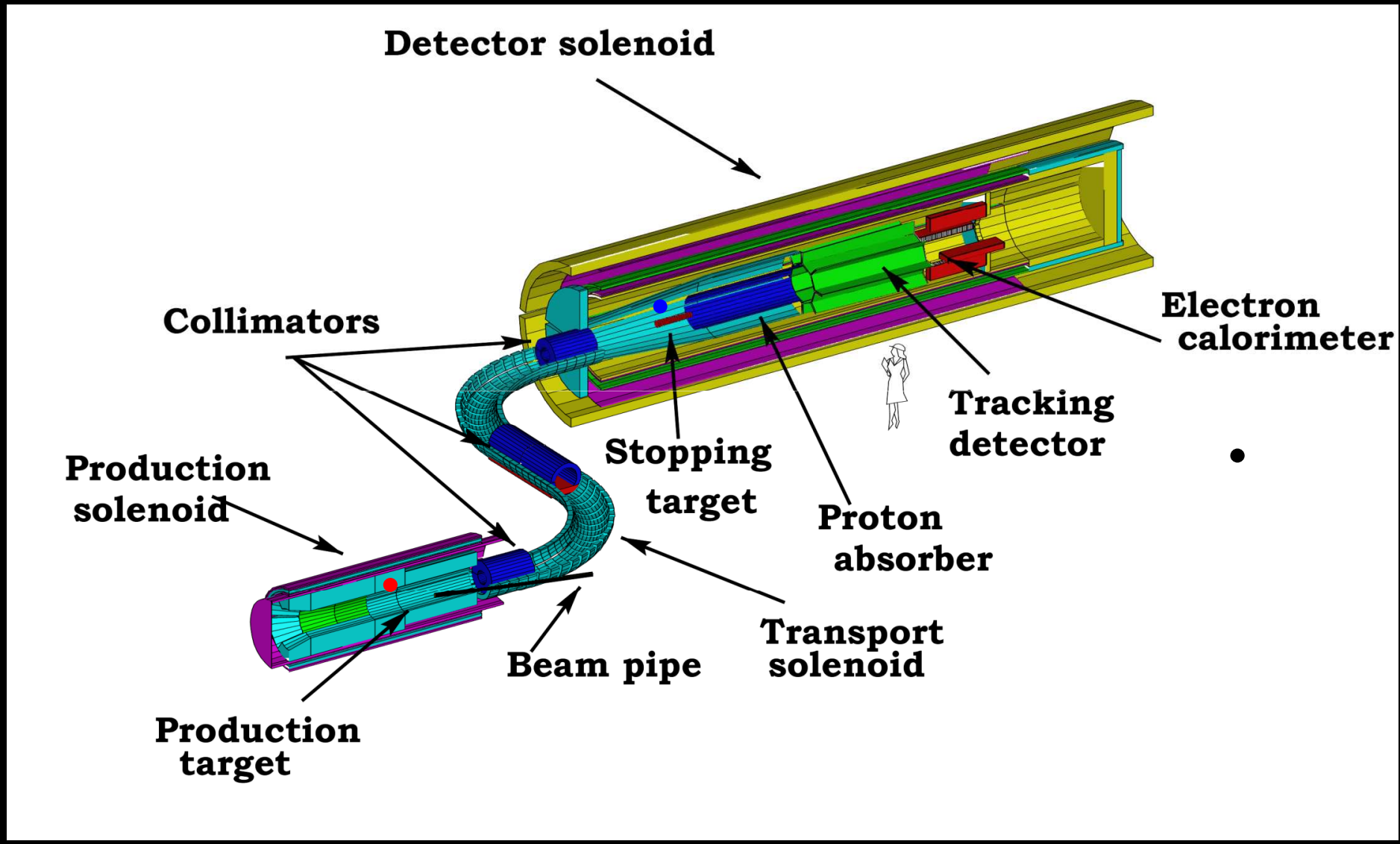




The Intensity Frontier can probe new physics at a scale >> TeV.

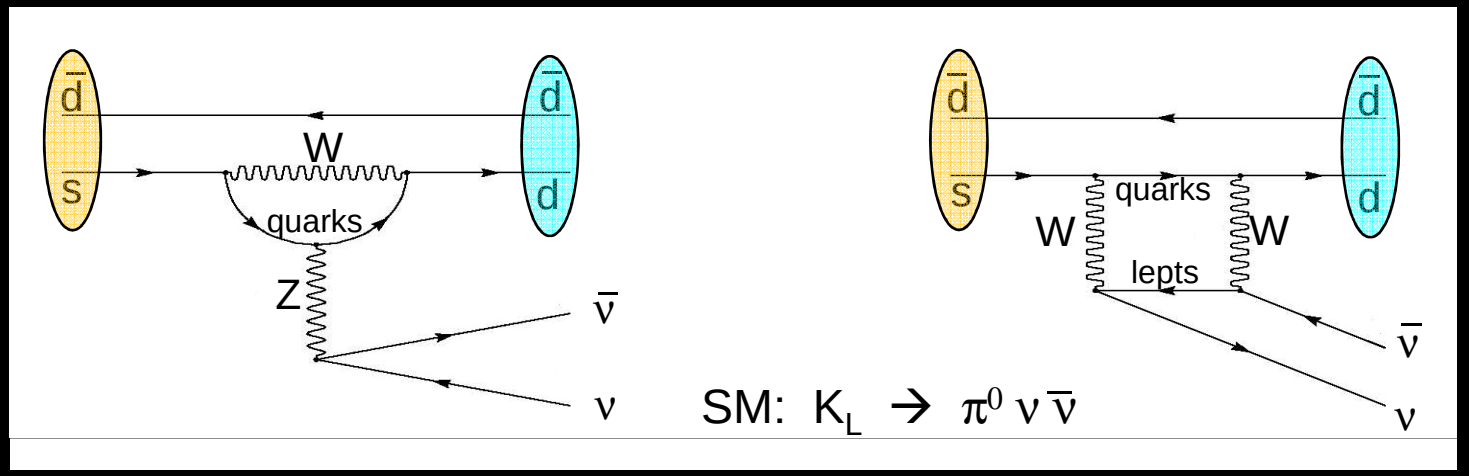
Muon to electron conversion: μN → eN

Neutrinos change from one kind to another.
Do charged leptons do, too?

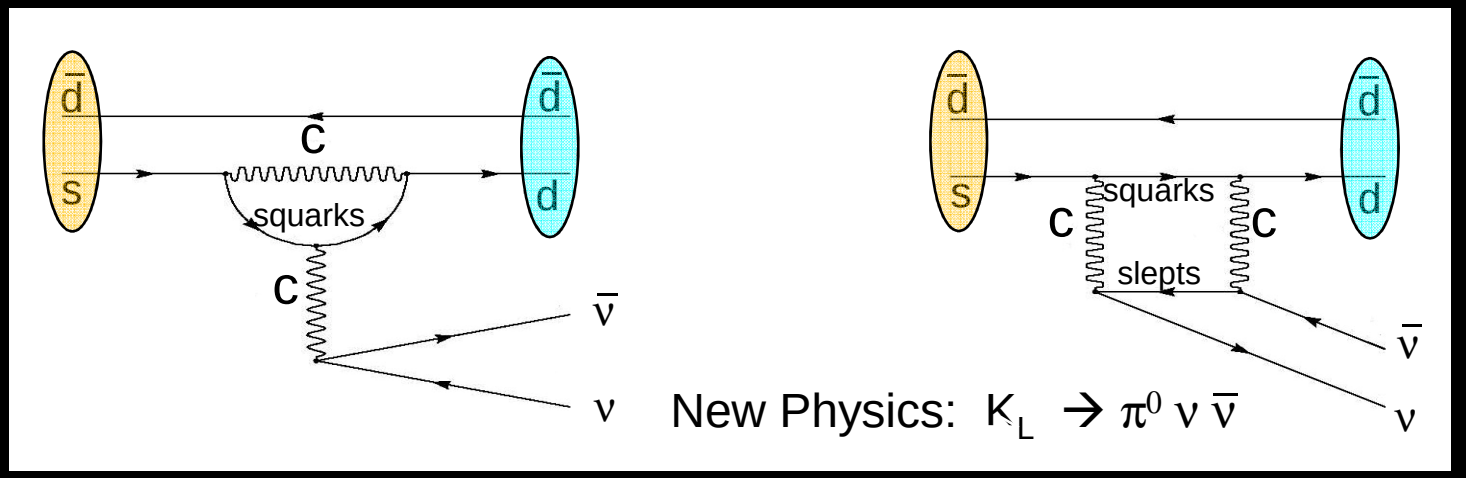
# Mu2e Experiment: μ to e Conversion (μN → eN)



# Large effects in kaon decay rates

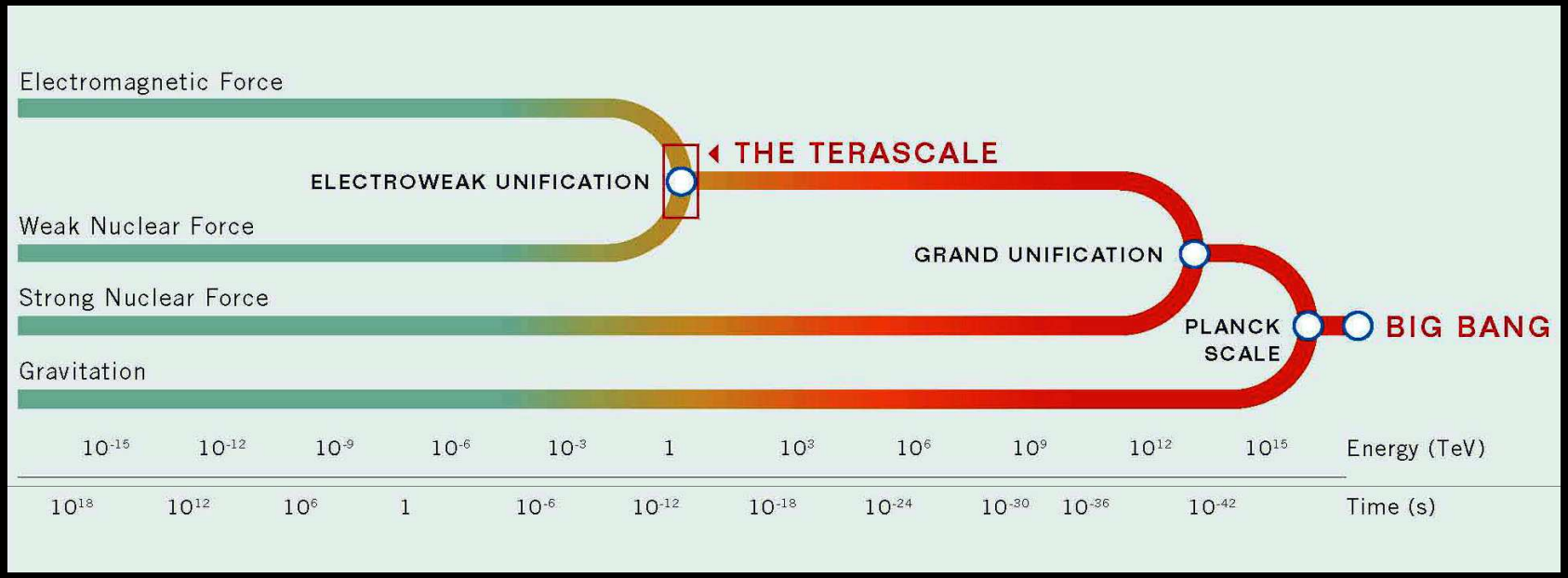



SM: $K_L \rightarrow \pi^0 \nu \bar{\nu}$



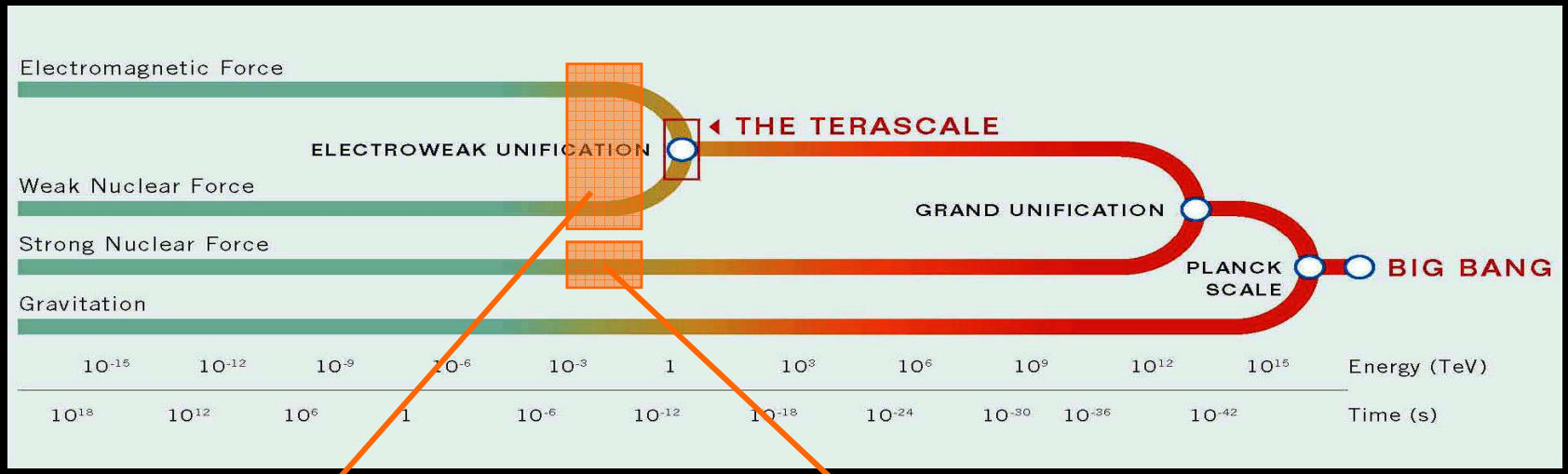

New Physics: $K_L \rightarrow \pi^0 \nu \bar{\nu}$

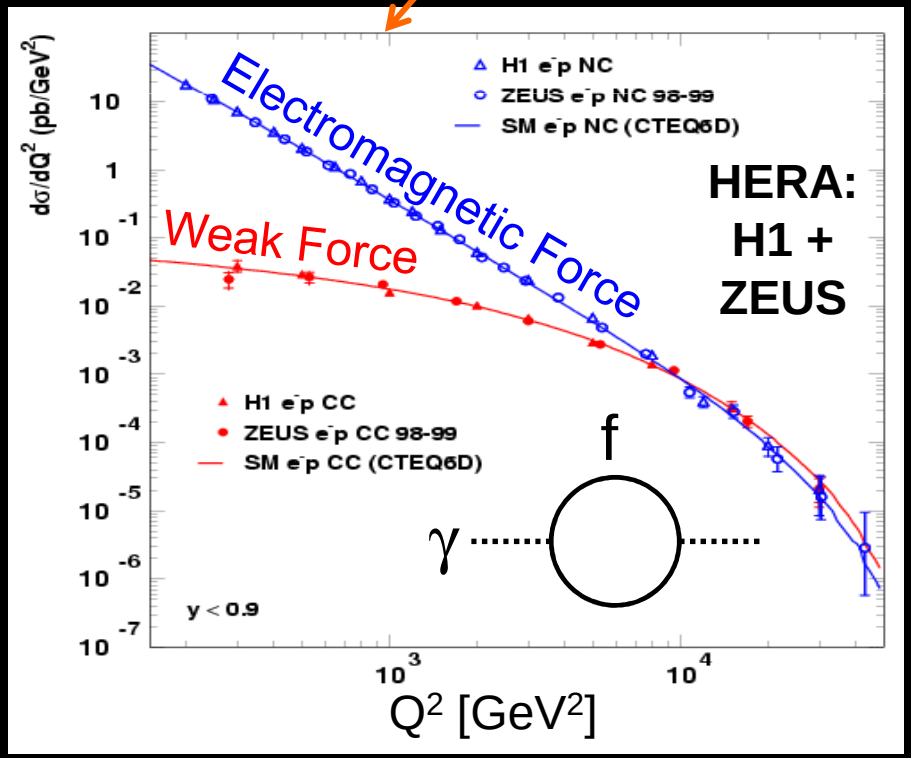
# Unification

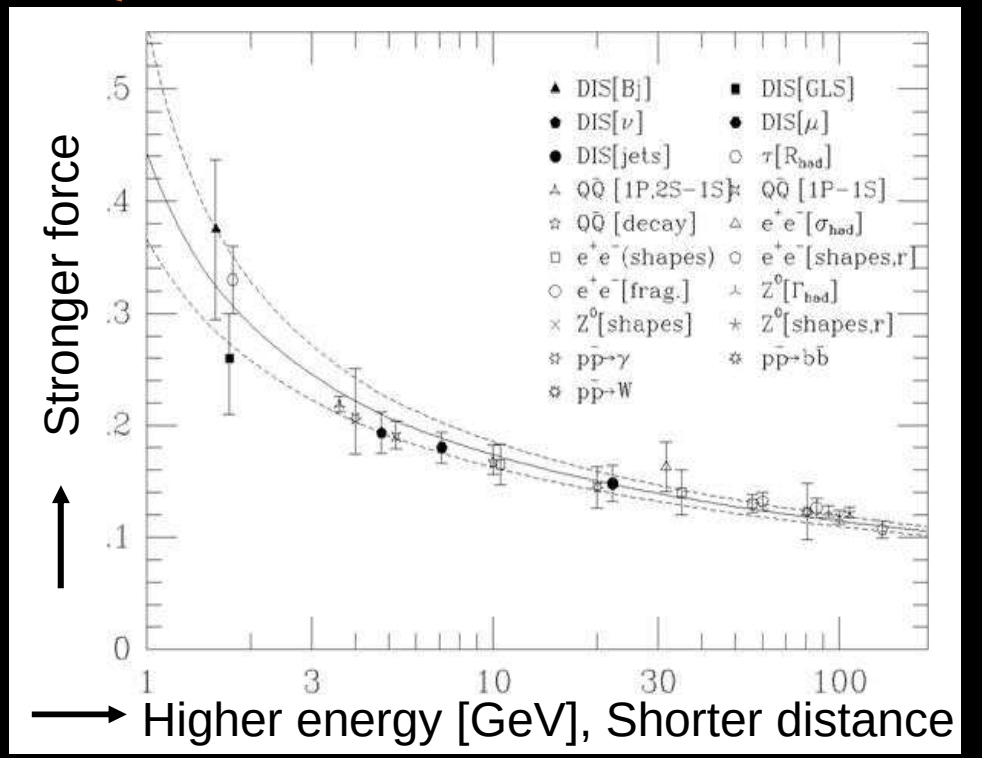


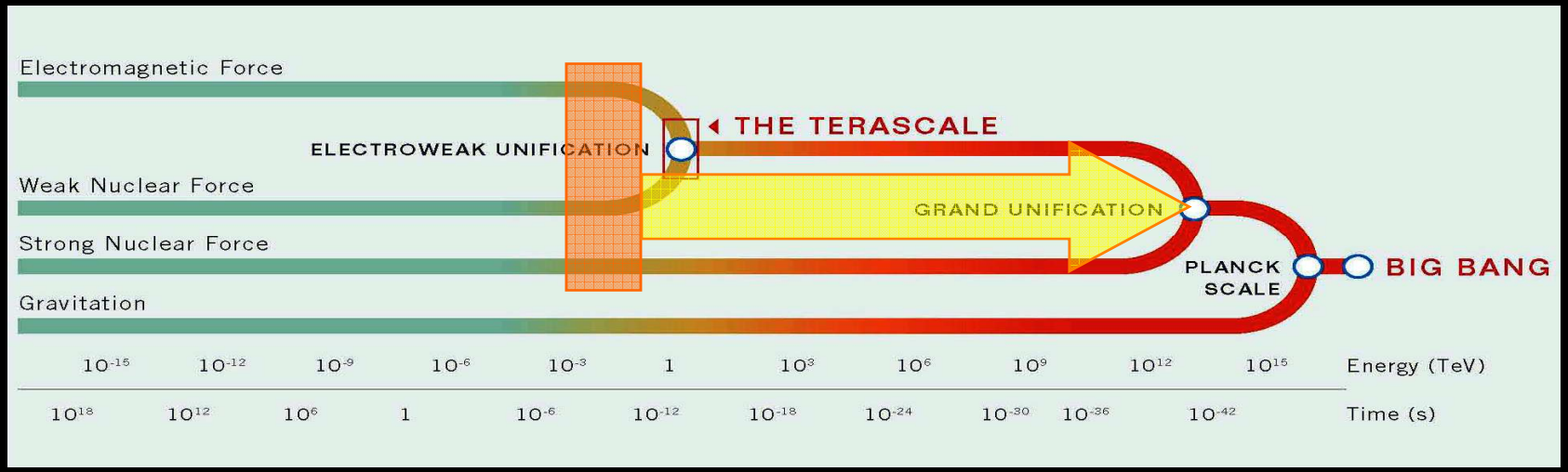

We want to believe
that there was just one force after the Big Bang.

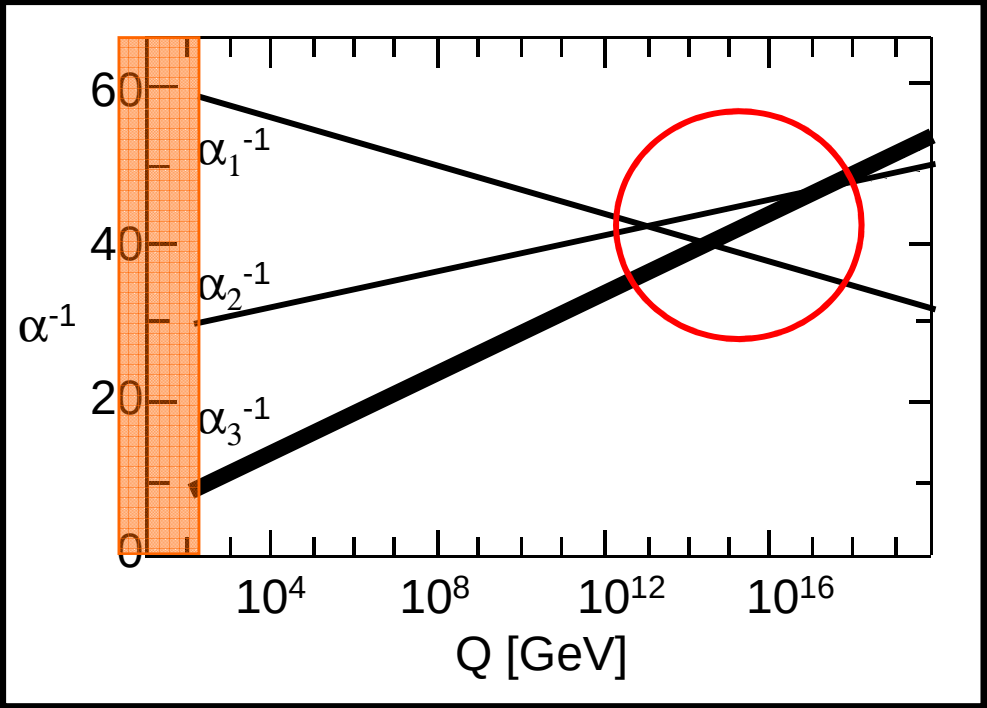
As the universe cooled down,
the single force split into the four that we know today.


Electromagnetic Force
Weak Nuclear Force
Strong Nuclear Force
Gravitation
ELECTROWEAK UNIFICATION
THE TERASCALE
GRAND UNIFICATION
PLANCK SCALE
BIG BANG
Energy (TeV)
Time (s)

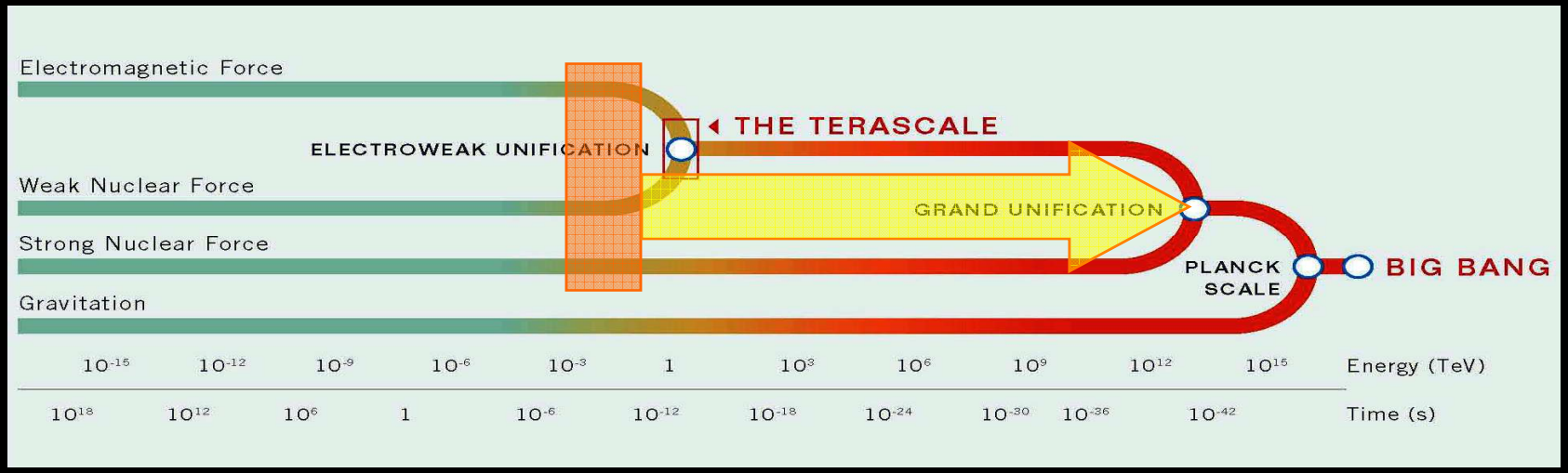

H1 e⁻p NC
ZEUS e⁻p NC 98-99
SM e⁻p NC (CTEQ6D)
Electromagnetic Force
Weak Force
HERA: H1 + ZEUS
H1 e⁻p CC
ZEUS e⁻p CC 98-99
SM e⁻p CC (CTEQ6D)
f
γ
y < 0.9
dσ/dQ² (pb/GeV²)
Q² [GeV²]

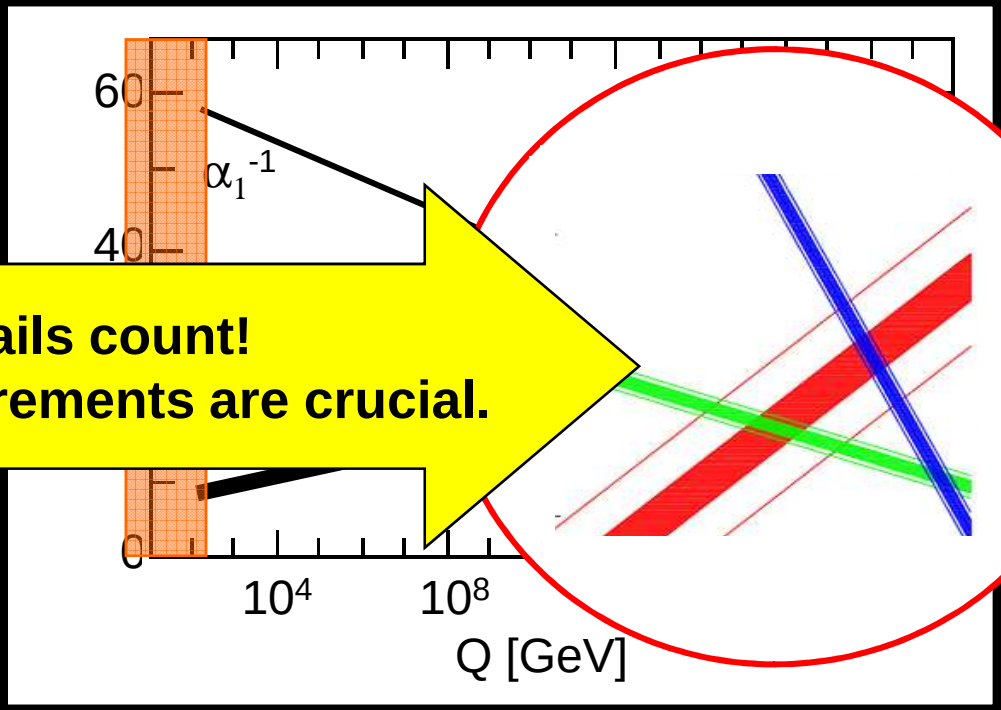

Stronger force
Higher energy [GeV], Shorter distance



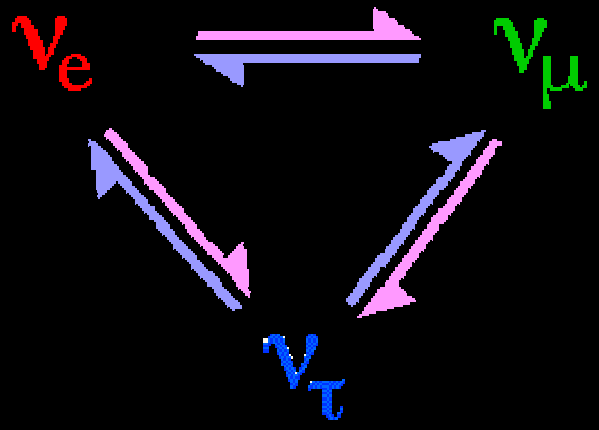

The Standard Model fails to unify the strong and electroweak forces.




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

# Neutrinos:



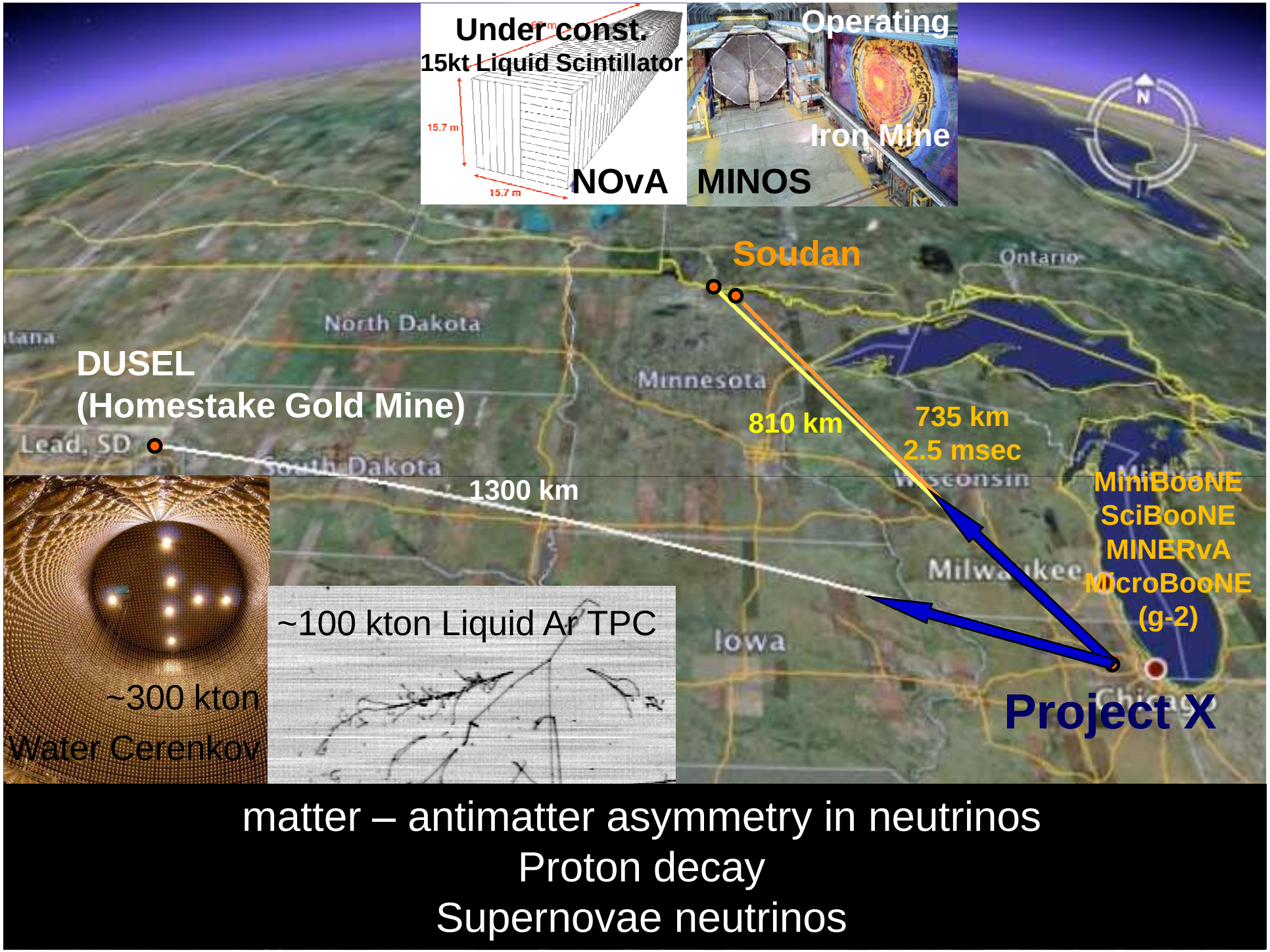

The enigmatic neutrinos are among the most abundant of the tiny particles that make up our universe.
To understand the universe, must understand neutrinos.

Behavior is so different from other particles.

## Opening a “new” window:

Unification, Matter-Antimatter Asymmetry

$$m_\nu M = (m_{quark})^2$$




matter – antimatter asymmetry in neutrinos

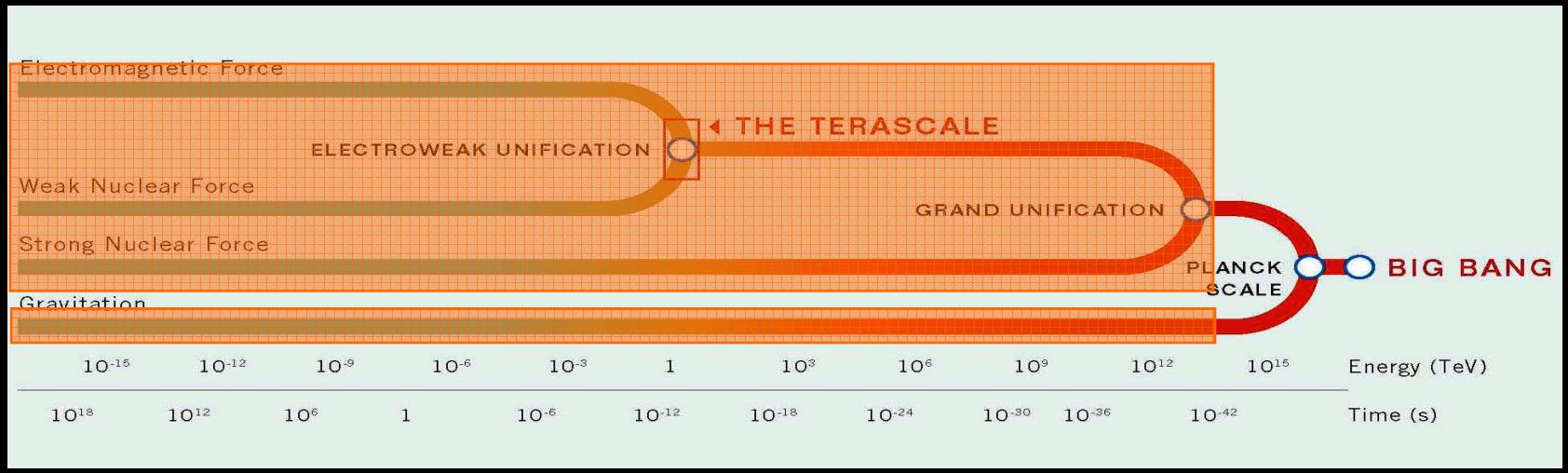
Proton decay

Supernovae neutrinos

# Project X (Proposed)

National Project with International Collaboration


- Fantastic machine at intensity frontier for ν, μ, kaon beams
- Would develop technologies to position US to host a global facility at the energy frontier (ILC and muon collider)




Unifying gravity to the other 3 forces

→ extra hidden dimensions in space beyond the 3 we sense daily.

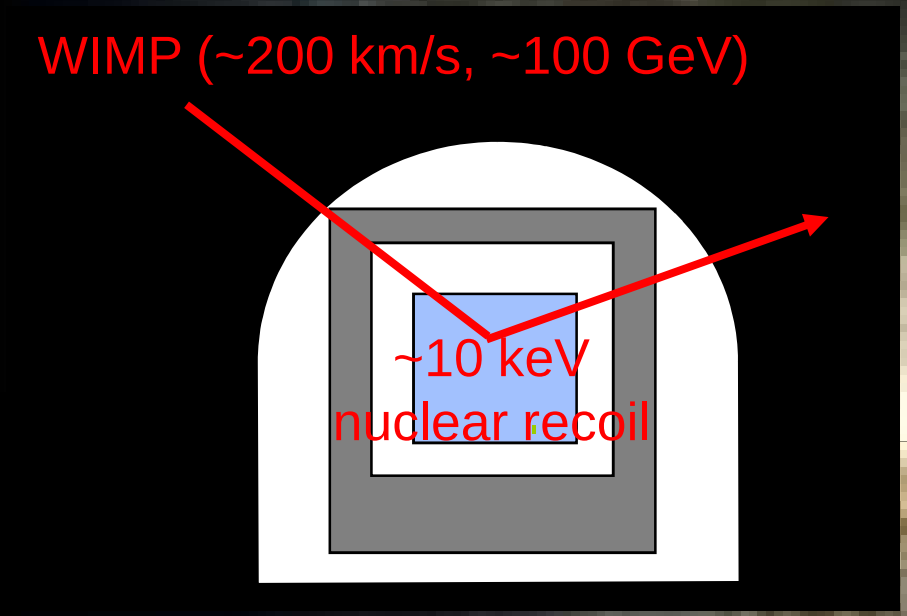
Too small to observe?

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

LHC may discover extra dimensions.
A lepton collider can identify size, shape, # of extra dimensions.

# Dark Matter

Underground experiments may detect Dark Matter candidates.




Cosmic Frontier

# Dark Matter Searches – Underground Detectors

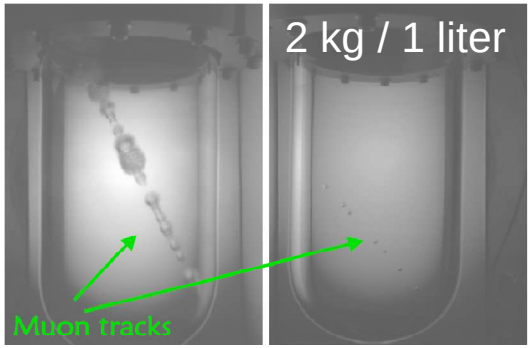

## CDMS

Low temp. Ge / Si crystals


**World's Best Limits**

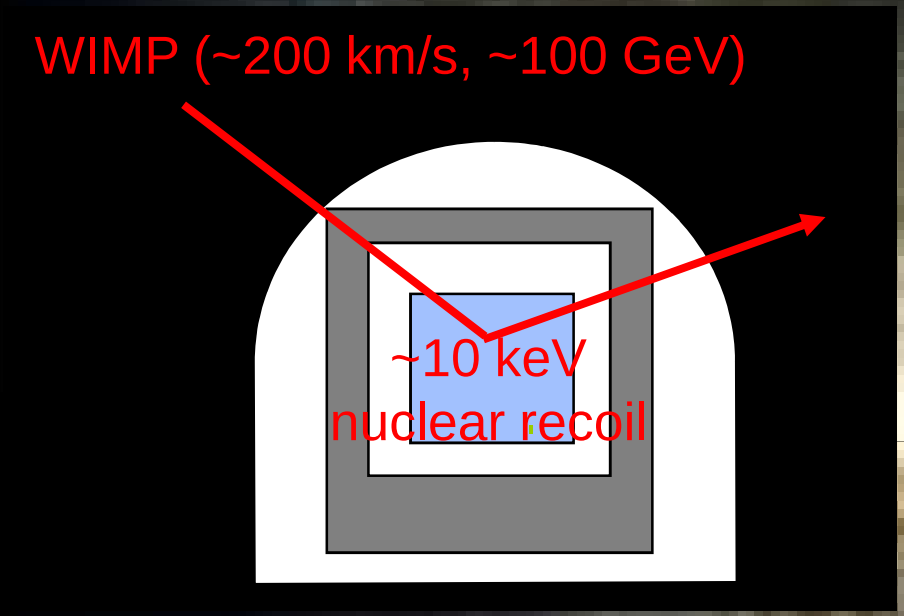
## COUPP

Room temp. $CF_3I$ Bubble Chamber



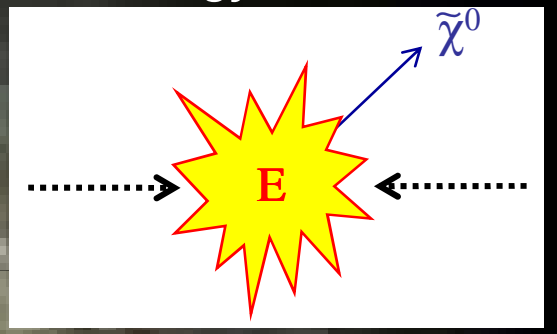
# Dark Matter

Underground experiments may detect Dark Matter candidates.

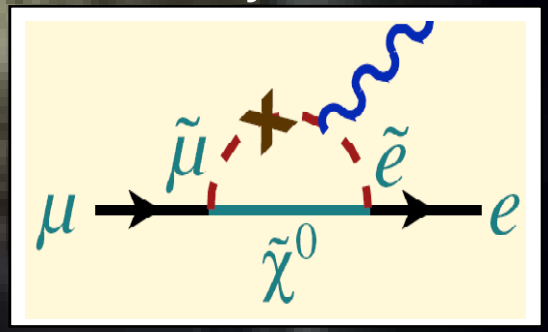



Cosmic Frontier

Energy Frontier




Intensity Frontier




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

# Particles Tell Stories!

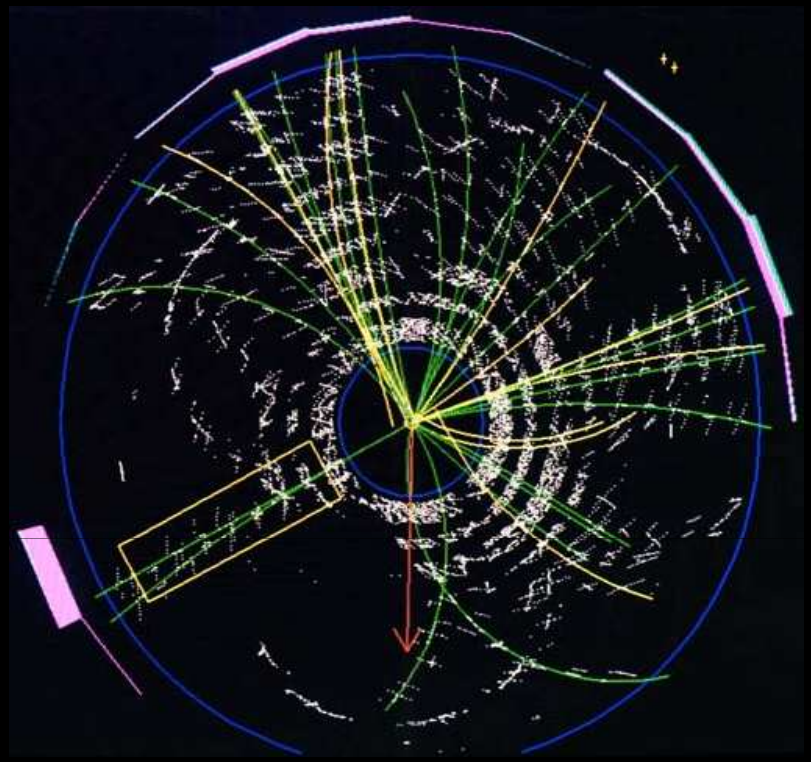
The discovery of a new particle is often the opening chapter revealing unexpected features of our universe.

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



We have been listening to the story that top quarks are telling us:
The top mass told us about the Higgs mass.
Story is consistent with our understanding of the standard model
We keep searching for a story we have not heard before.

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

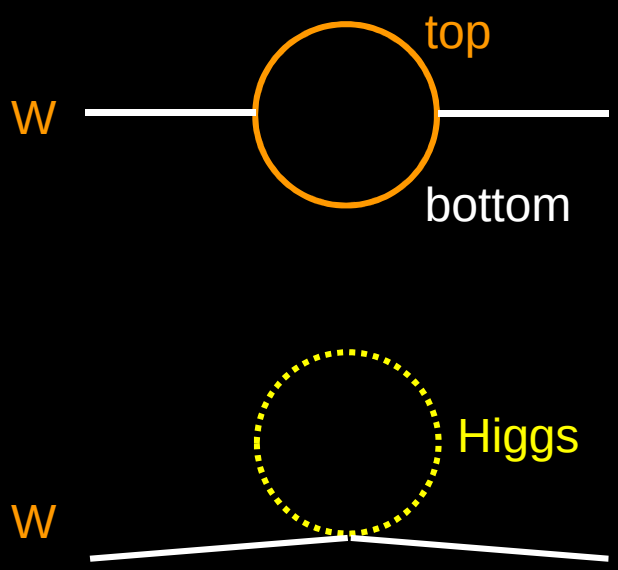
Hope in the next ~5 years we will discover Higgs
and listen very carefully to Higgs.
What are neutrinos telling us?
What are muons telling us?
What are kaons telling us?
This will open windows for discovering new laws of nature.

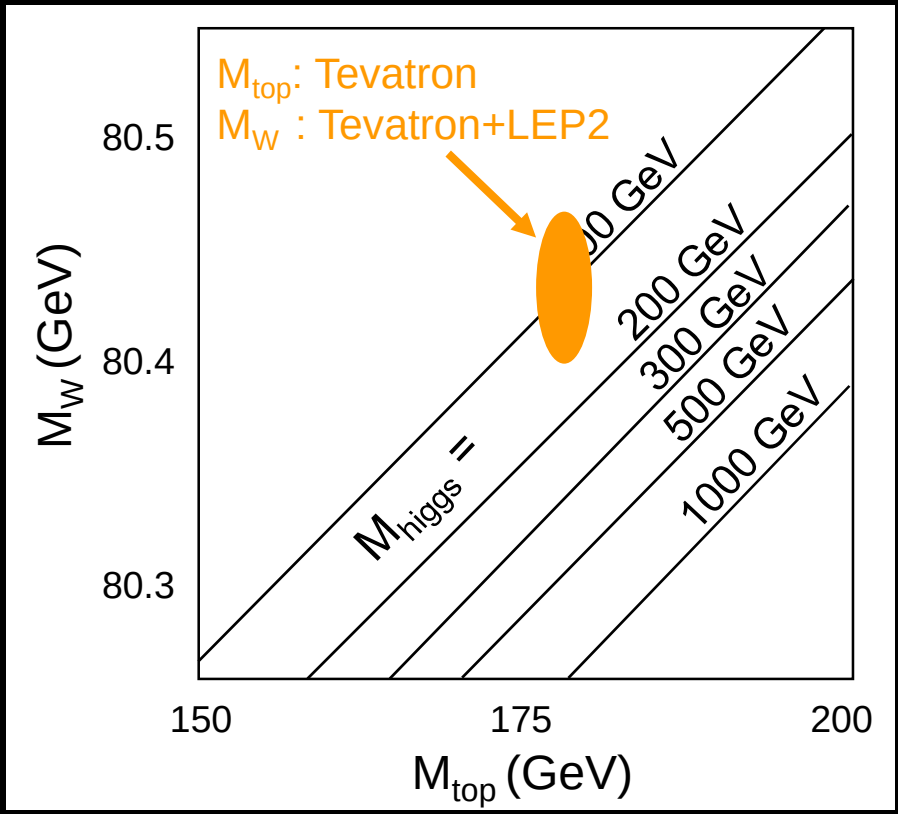
This saga continues….
There might be supersymmetric partners, dark matter,
another force carrier, large extra dimensions, ……
for other new laws of nature.

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

END

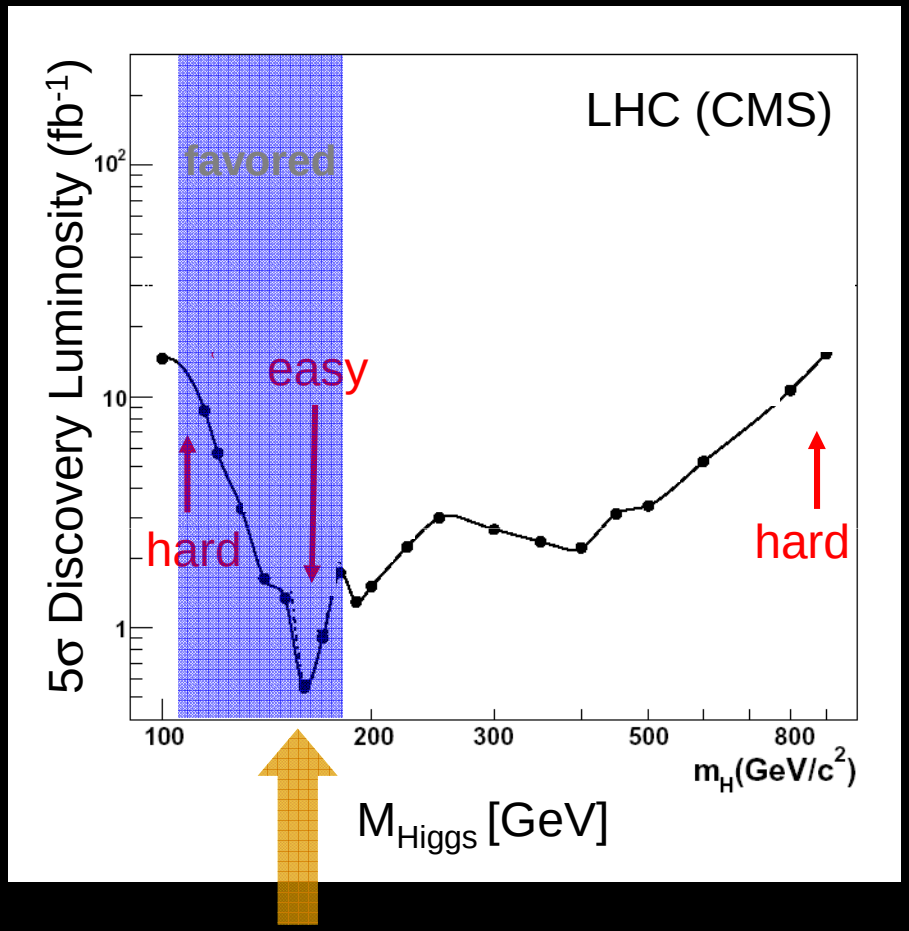
# The Tevatron Predicts Higgs Mass via Quantum Corrections



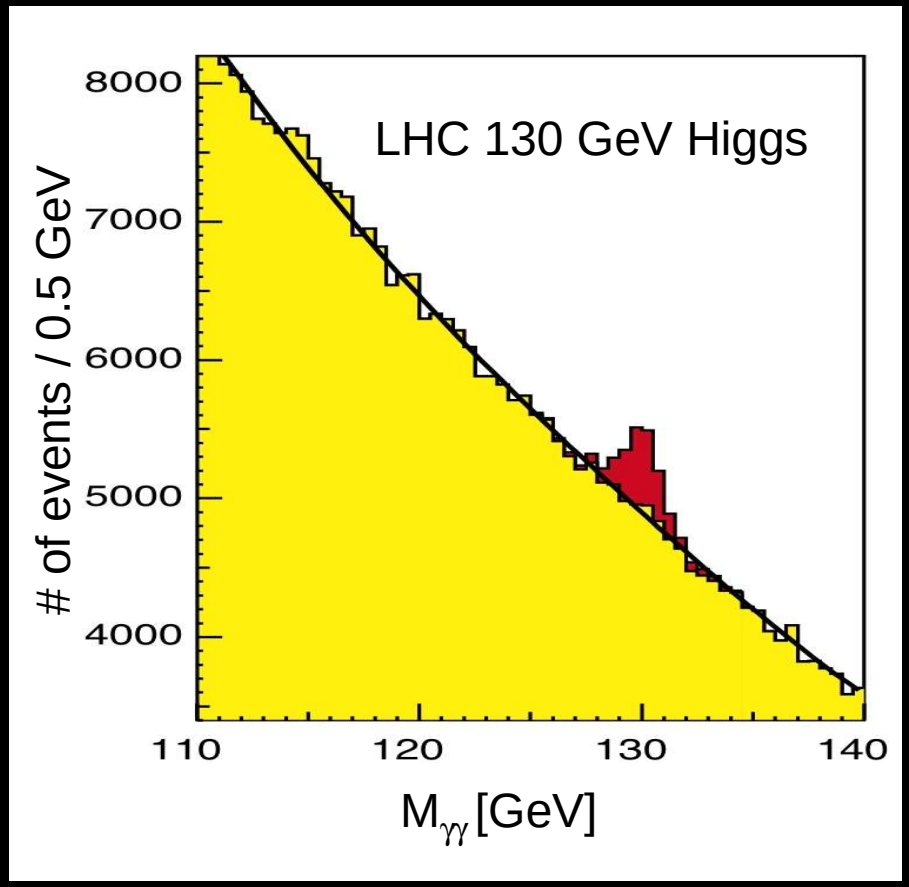




Favors Higgs mass range (114 – 180 GeV) at 95% CL.
In this range, Tevatron has good potential.

# Higgs at LHC and Tevatron




160 – 170 GeV
Excluded by Tevatron (3-4 $fb^{-1}$)



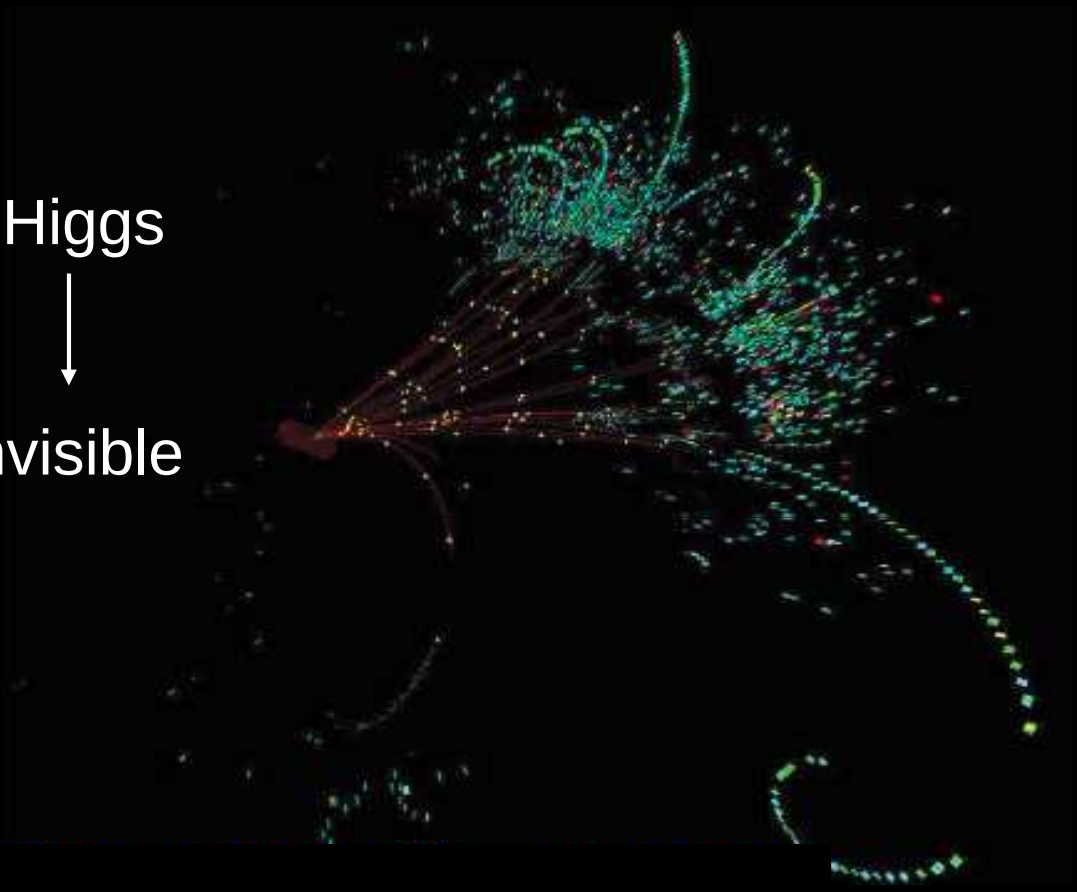

Low Mass Higgs
(LHC: H → γγ, ττ) vs. (Tevatron: H → bb)

# ILC can observe Higgs no matter how it decays!

$e^+e^- \rightarrow Z + \text{Higgs}$

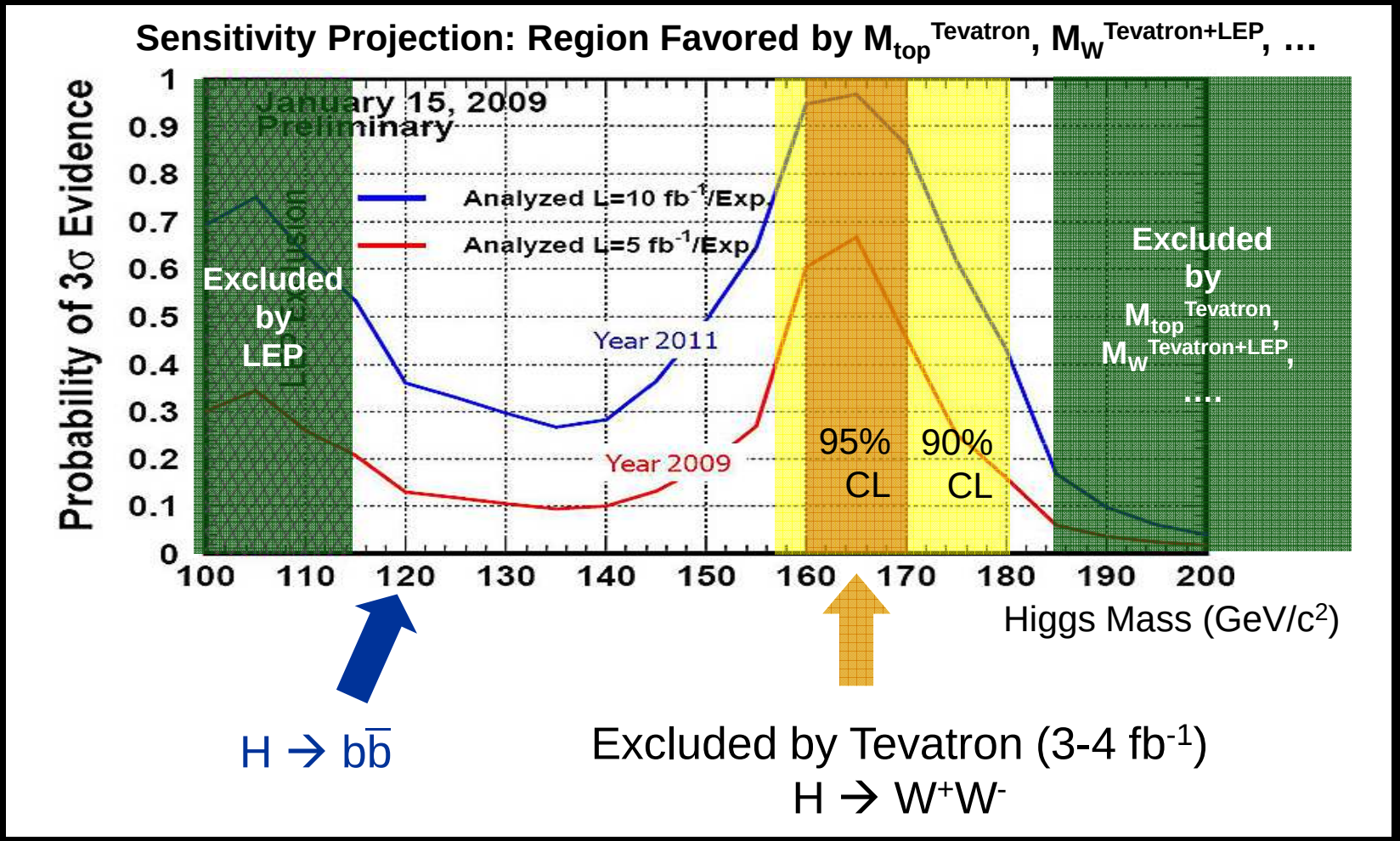
Z → 2 b's

Higgs → invisible



Unique ability for model-independent tests of Higgs couplings to other particles

# Tevatron Sensitivity on Standard Model Higgs




Update the results with 5 fb$^{-1}$ data soon

# Interplay: LHC ⟷ Intensity Frontier