



## Today

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- Announcements:
  - HW#10 is due April 9 at 8:00 am.
  - The Spring Break Story Winner is ..
- What is matter? What is mass?



## Standard Model

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- The fundamental theory of nature's constituents and their interaction is called the Standard Model
- The theory includes:
  - Strong interactions due to the color charges of quarks and gluons.
  - A combined theory of weak (weak charge) and electromagnetic interaction (charge), known as electroweak theory.
- The theory does not include the effects of gravity. Gravity is tiny compared to the other forces and can be neglected in describing atoms.



## What is matter

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- Matter is the collection of objects made of baryons and leptons.
- Objects have quantum numbers that describe their nature

Electron:

Charge, lepton number, baryon number, etc.

Electrons also have mass. What is mass?



## Four Fundamental Forces

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<u>Force</u>	<u>Particles</u>	<u>Strength</u>	<u>Range</u>	<u>Mediator</u>
Gravity	All	$6E-39$	Infinite	Graviton
Weak	All	$1E-5$	$1E-17$ m	$W^{\pm}, Z^0$
Electro- magnetic	Charged Particles	$1/137$	Infinite	Photon
Strong	Hadrons (protons and neutrons)	1	$1E-15$ m	Gluon

# Standard Model Particles

Charge

$+2/3 \rightarrow$

$-1/3 \rightarrow$

Anti-particles have the opposite charge.

matter particles

	1st gen.	2nd gen.	3rd gen.
Q U A R K	<i>u</i> <i>up</i>	<i>c</i> <i>charm</i>	<i>t</i> <i>top</i>
	<i>d</i> <i>down</i>	<i>s</i> <i>strange</i>	<i>b</i> <i>bottom</i>
L E P T O N	<i><math>\nu_e</math></i> <i>e neutrino</i>	<i><math>\nu_\mu</math></i> <i><math>\mu</math> neutrino</i>	<i><math>\nu_\tau</math></i> <i><math>\tau</math> neutrino</i>
	<i>e</i> <i>electron</i>	<i><math>\mu</math></i> <i>muon</i>	<i><math>\tau</math></i> <i>tau</i>

guage particles

<p>Strong Force</p> <i>g</i> <i>Gluon</i>
<p>Electro-Magnetic Force</p> <i><math>\gamma</math></i> <i>photon</i>
<p>Weak Force</p> <i>W<sup>+</sup></i> <i>W<sup>-</sup></i> <i>Z</i> <i>W bosons</i> <i>Z boson</i>

scalar particle(s)

<i>H</i> <i>Higgs</i> $\dots$
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# Quantum Numbers (1)

The row gives the principle quantum number.

- $n = 1$
- $n = 2$
- $n = 3$
- $n = 4$
- $n = 5$
- $n = 6$
- $n = 7$

1 1.01 <b>H</b> Hydrogen																	2 4.003 <b>He</b> Helium
3 6.94 <b>Li</b> Lithium	4 9.01 <b>Be</b> Beryllium											5 10.81 <b>B</b> Boron	6 12.01 <b>C</b> Carbon	7 14.01 <b>N</b> Nitrogen	8 15.999 <b>O</b> Oxygen	9 18.998 <b>F</b> Fluorine	10 20.18 <b>Ne</b> Neon
11 22.99 <b>Na</b> Sodium	12 24.31 <b>Mg</b> Magnesium											13 26.98 <b>Al</b> Aluminum	14 28.09 <b>Si</b> Silicon	15 30.97 <b>P</b> Phosphorus	16 32.06 <b>S</b> Sulfur	17 35.45 <b>Cl</b> Chlorine	18 39.96 <b>Ar</b> Argon
19 39.10 <b>K</b> Potassium	20 40.08 <b>Ca</b> Calcium	21 44.96 <b>Sc</b> Scandium	22 47.90 <b>Ti</b> Titanium	23 50.94 <b>V</b> Vanadium	24 51.996 <b>Cr</b> Chromium	25 54.94 <b>Mn</b> Manganese	26 55.85 <b>Fe</b> Iron	27 58.93 <b>Co</b> Cobalt	28 58.70 <b>Ni</b> Nickel	29 63.55 <b>Cu</b> Copper	30 65.37 <b>Zn</b> Zinc	31 69.72 <b>Ga</b> Gallium	32 72.59 <b>Ge</b> Germanium	33 74.92 <b>As</b> Arsenic	34 78.96 <b>Se</b> Selenium	35 79.90 <b>Br</b> Bromine	36 83.80 <b>Kr</b> Krypton
37 85.47 <b>Rb</b> Rubidium	38 87.62 <b>Sr</b> Strontium	39 88.91 <b>Y</b> Yttrium	40 91.22 <b>Zr</b> Zirconium	41 92.91 <b>Nb</b> Niobium	42 95.94 <b>Mo</b> Molybdenum	43 (98) <b>Tc</b> Technetium	44 101.07 <b>Ru</b> Ruthenium	45 102.91 <b>Rh</b> Rhodium	46 106.40 <b>Pd</b> Palladium	47 107.87 <b>Ag</b> Silver	48 112.41 <b>Cd</b> Cadmium	49 114.82 <b>In</b> Indium	50 118.69 <b>Sn</b> Tin	51 121.75 <b>Sb</b> Antimony	52 127.60 <b>Te</b> Tellurium	53 126.90 <b>I</b> Iodine	54 131.30 <b>Xe</b> Xenon
55 132.91 <b>Cs</b> Cesium	56 137.33 <b>Ba</b> Barium	57 138.91 <b>La</b> Lanthanum	72 178.49 <b>Hf</b> Hafnium	73 180.95 <b>Ta</b> Tantalum	74 183.85 <b>W</b> Tungsten	75 186.21 <b>Re</b> Rhenium	76 190.20 <b>Os</b> Osmium	77 192.22 <b>Ir</b> Iridium	78 195.09 <b>Pt</b> Platinum	79 196.97 <b>Au</b> Gold	80 200.59 <b>Hg</b> Mercury	81 204.37 <b>Tl</b> Thallium	82 207.19 <b>Pb</b> Lead	83 208.98 <b>Bi</b> Bismuth	84 (209) <b>Po</b> Polonium	85 (210) <b>At</b> Astatine	86 (222) <b>Rn</b> Radon
87 (223) <b>Fr</b> Francium	88 226.03 <b>Ra</b> Radium	89 227.03 <b>Ac</b> Actinium	104 (261) <b>Rf</b> Rutherfordium	105 (262) <b>Db</b> Dubnium	106 (266) <b>Sg</b> Seaborgium	107 (262) <b>Bh</b> Bohrium	108 (265) <b>Hs</b> Hassium	109 (266) <b>Mt</b> Meitnerium	110 (271) <b>Ds</b> Darmstadtium	111 (272) <b>Rg</b> Roentgenium	(277)	(284)	(289)	(290)	(292)	(294)	118 (294)

Lanthanides	58 140.12 <b>Ce</b> Cerium	59 140.91 <b>Pr</b> Praseodymium	60 144.24 <b>Nd</b> Neodymium	61 (145) <b>Pm</b> Promethium	62 150.40 <b>Sm</b> Samarium	63 151.96 <b>Eu</b> Europium	64 157.25 <b>Gd</b> Gadolinium	65 158.93 <b>Tb</b> Terbium	66 162.50 <b>Dy</b> Dysprosium	67 164.93 <b>Ho</b> Holmium	68 167.26 <b>Er</b> Erbium	69 168.93 <b>Tm</b> Thulium	70 173.04 <b>Yb</b> Ytterbium	71 174.97 <b>Lu</b> Lutetium
Actinides	90 232.04 <b>Th</b> Thorium	91 231.04 <b>Pa</b> Protactinium	92 238.03 <b>U</b> Uranium	93 237.05 <b>Np</b> Neptunium	94 (244) <b>Pu</b> Plutonium	95 (243) <b>Am</b> Americium	96 (247) <b>Cm</b> Curium	97 (247) <b>Bk</b> Berkelium	98 (251) <b>Cf</b> Californium	99 (252) <b>Es</b> Einsteinium	100 (257) <b>Fm</b> Fermium	101 (260) <b>Md</b> Mendelevium	102 (269) <b>No</b> Nobelium	103 (262) <b>Lr</b> Lawrencium

- The structure of the periodic table arises from the underlying quantum numbers.



## Quantum Numbers (2)

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- Names like top, charm, strange, color, etc. do not mean the same things they do in everyday life. They are just identifiers.
- These names represent a set of quantum numbers that explain the number and types of particles that we observe.
- Chemistry, nuclear science, and particle physics all use different sets of quantum numbers, although they are all based on related ideas.



## Rules for particle interactions

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Example:  $e^- + \bar{e}^+ \rightarrow u + \bar{u}$  ALLOWED

$n \rightarrow p^+ + e^-$  NOTALLOWED (lepton number)

$n \rightarrow p^+ + e^- + \bar{\nu}$  ALLOWED

Conserved: Electric charge, lepton number ( $e = +1$ ,  $\bar{e} = -1$ ), color charge, baryon number (could also count quarks: quarks  $+1/3$ , antiquarks  $-1/3$ ), energy, momentum, and angular momentum.

$$n + p^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

$$\pi^- \rightarrow e^- + \bar{\nu}$$

The standard model explains how particles interact and transform.





## What is mass

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- Most mass in matter comes from energy:  
 $E=mc^2$
- The mass of the quarks that make up a proton is only a few percent of the mass. Most of the mass is in gluons (the carriers of the force).

## What is mass? The interaction with a field

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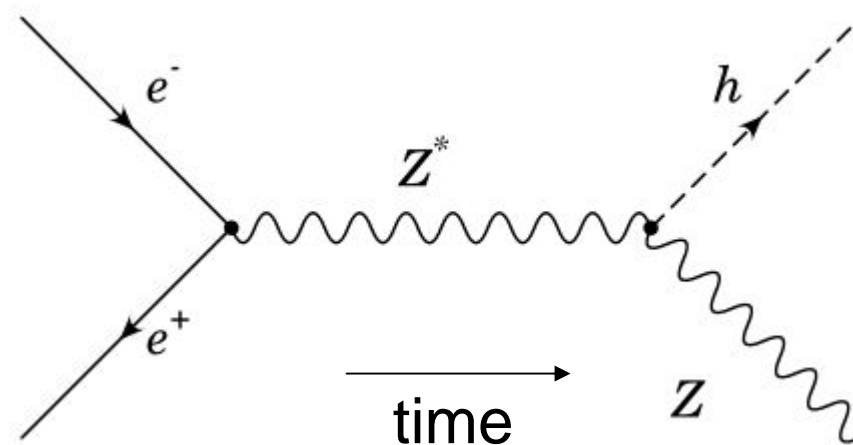
Space is filled with a (scalar) particle called the Higgs boson. The more a particle interacts with the Higgs field, the greater its mass is.



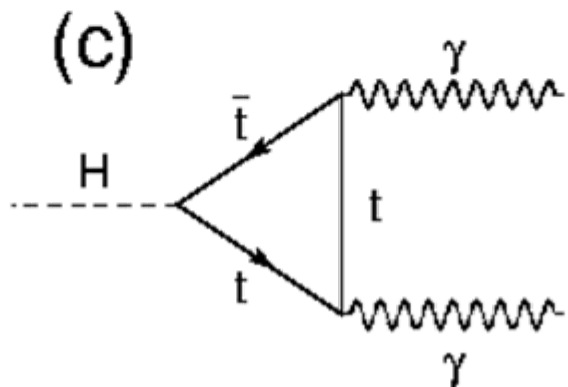
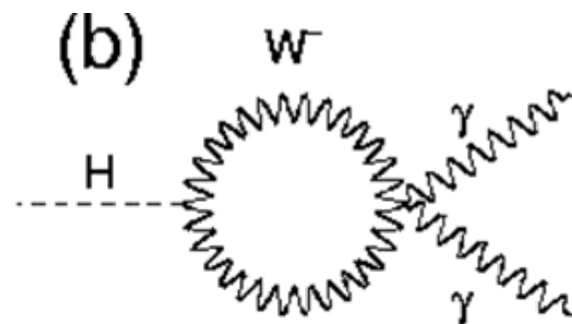
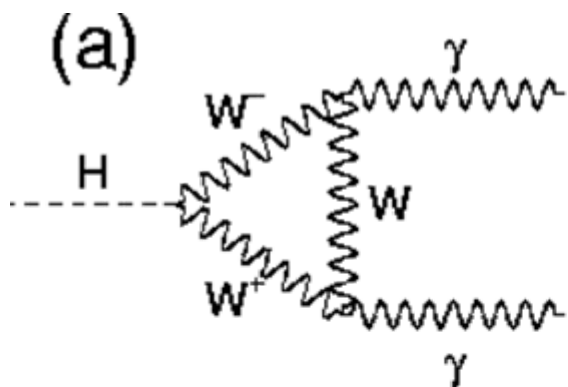
# Higgs Particle

- The Higgs is the most famous undiscovered particle. A new collider called the Large Hadron Collider may find it.
- The world community is spending 10 billion \$ to find this.

Here is how to produce one:



# How the Higgs will decay and be detected



time



## Problems with the Standard Model

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- Why so many particles?
- Are there more particles we don't know about yet?
- What is charge? Why does it come in fixed units?  
Same for lepton number and baryon number...
- Why is the standard model so complicated?
- Why 4 forces?
- How is gravity related to the other forces?
- In general the standard model does not answer the WHY question. Everyone agrees it is not a complete theory.



## What comes next?

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- There are attempts to extend the standard model to include gravity; these are called supersymmetric theories.
- These say that all fermions (which make up matter) and bosons (that transmit forces) have a corresponding partner boson (to go with our standard fermions) and fermion (to go with our standard bosons).
- Supersymmetric theories predict a whole set of new particles called s-particles, e.g. selectron, sneutrino, photino, Wino, and so on
- A new accelerator (Large Hadron Collider at CERN [Europe]) may be able to produce some of these particles in the next two years.

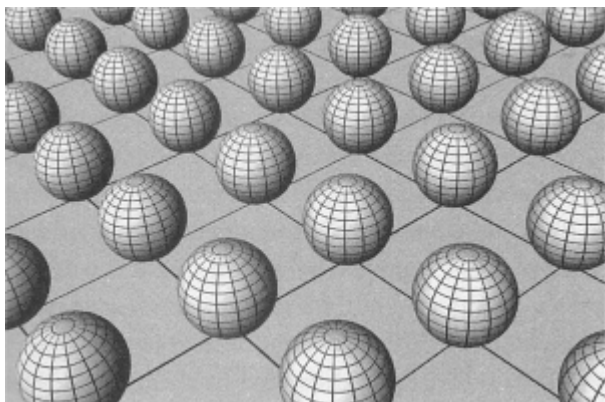


## Superstring Theory

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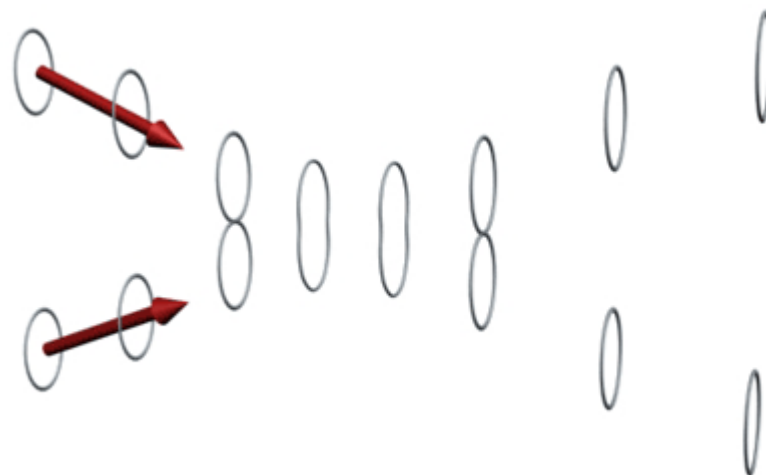
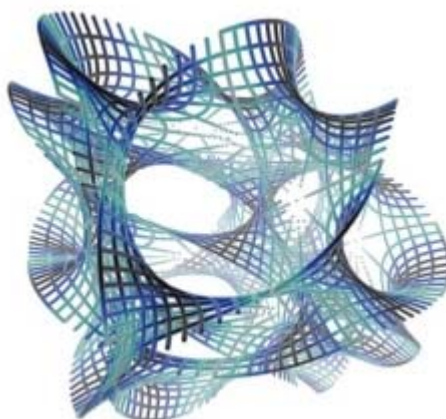
- One of the promising new theories is string theory. It says that the fundamental building blocks of nature are tiny ( $10^{-35}$  m) strings.
- The particles we observe in nature are different ways for strings to vibrate.
- String theory is not accepted because so far it has not devised an experiment that could test it.
- String theories require at least 10 dimensions.
- Gravity is weak because the graviton exists mostly in another dimension, but there is a slight overlap with us

# String Theory Pictures



Extra Dimensions

What one of the dimensions might look like (Calabi-Yau space)



## Interaction of Strings:

The finite size ( $10^{-35}$  m) overcomes many of the problems with the interaction of point particles.





## More energy – smaller wavelength

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- It is a quirk of nature that, the smaller a particle is, the greater is the energy need to see it.
- To study a particle you have to have sufficient concentrated energy to create it.
- This has fueled the construction of particle accelerators, then colliders, which have continuously increased in size.



## Scale of Energy (per Particle)

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- Chemistry Experiment  $\sim 0.1\text{-}5\text{ eV}$
- First Cyclotron (USA)  $8\text{E}4\text{ eV}$
- National Superconducting Cyclotron Laboratory (USA)  
 $1.4\text{E}8\text{ eV}$
- Super Proton Synchrotron (Europe)  $4\text{E}11\text{ eV}$
- Relativistic Heavy Ion Collider (USA)  $1\text{E}11\text{ eV}$
- Tevatron (USA)  $1\text{E}12\text{ eV}$
- Large Hadron Collider (Europe)  $7\text{E}12\text{ eV}$
- [Superconducting Super Collider (USA)]  $2\text{E}13\text{ eV}$

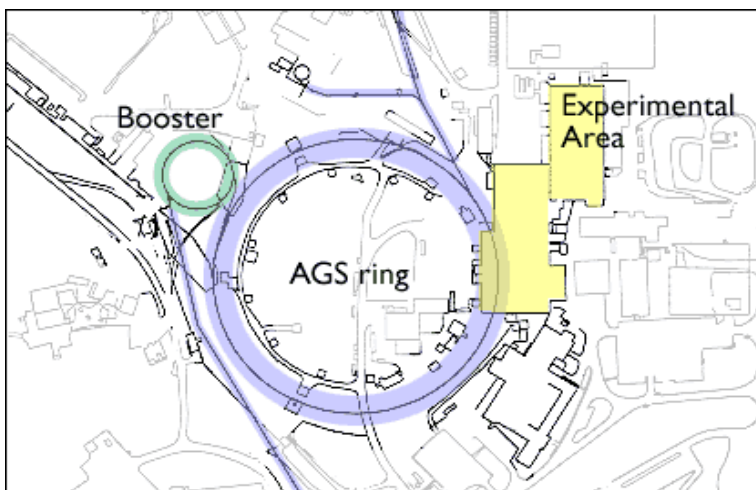
# Relativistic Heavy-Ion Collider



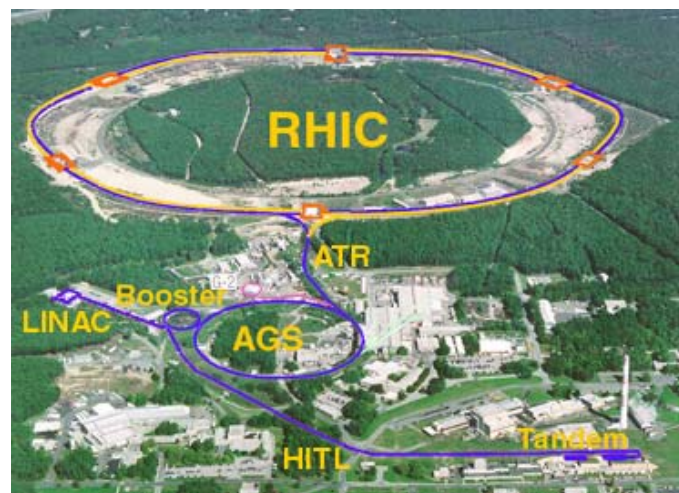
Long Island (New York)



RHIC from space!

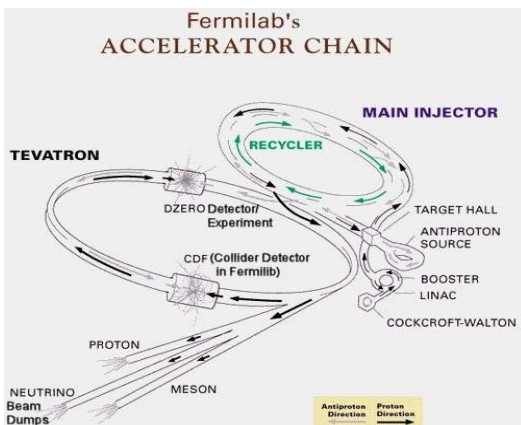


The Alternating Gradient Synchrotron complex



Goal: Create a plasma of quarks and gluons

# Tevatron – Fermilab (Illinois)



Goal: Produce the top quark

# Tevatron - Fermi National Laboratory (Illinois)

Goal: Produce the top quark



Drift Tube Linac

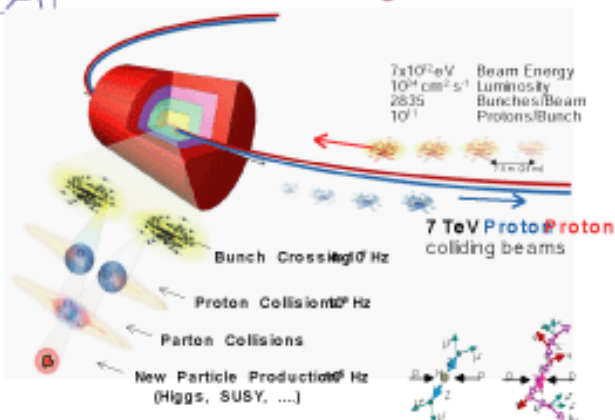
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# Large Hadron Collider – CERN (Europe)



## Collisions at the Large Hadron Collider



Introduction to CERN

David Barney, CERN



## CERN in numbers

- Financed by 20 European countries
  - Special contributions also from other countries:
    - USA, Canada, China, Japan, Russia, etc.
- 1000 CHF (650 M€) budget to cover operation + new accelerators
- 2,200 staff (and diminishing)
- 6,000 users (researchers) from all over the world
  - broad visitor and fellowship program



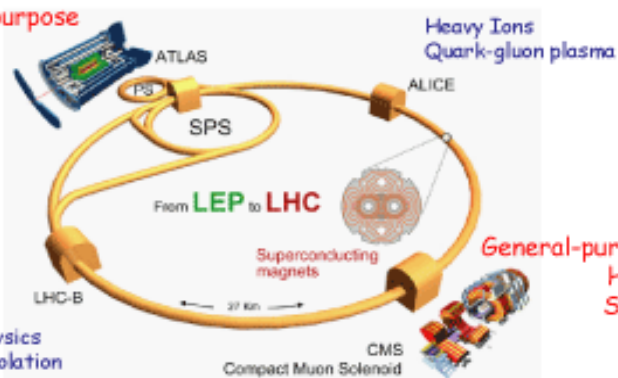
May 2004

Greene Jarp



## LHC Detectors

General-purpose  
Higgs  
SUSY  
??

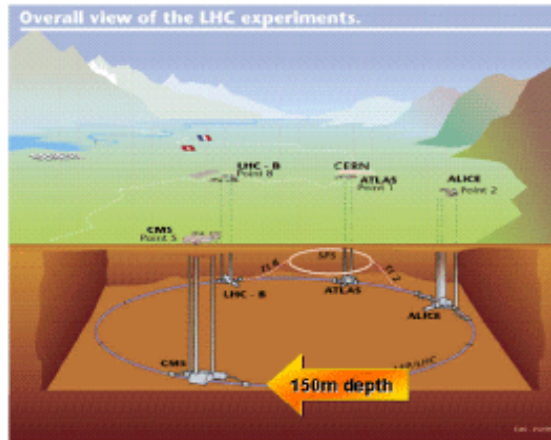


Introduction to CERN

David Barney, CERN

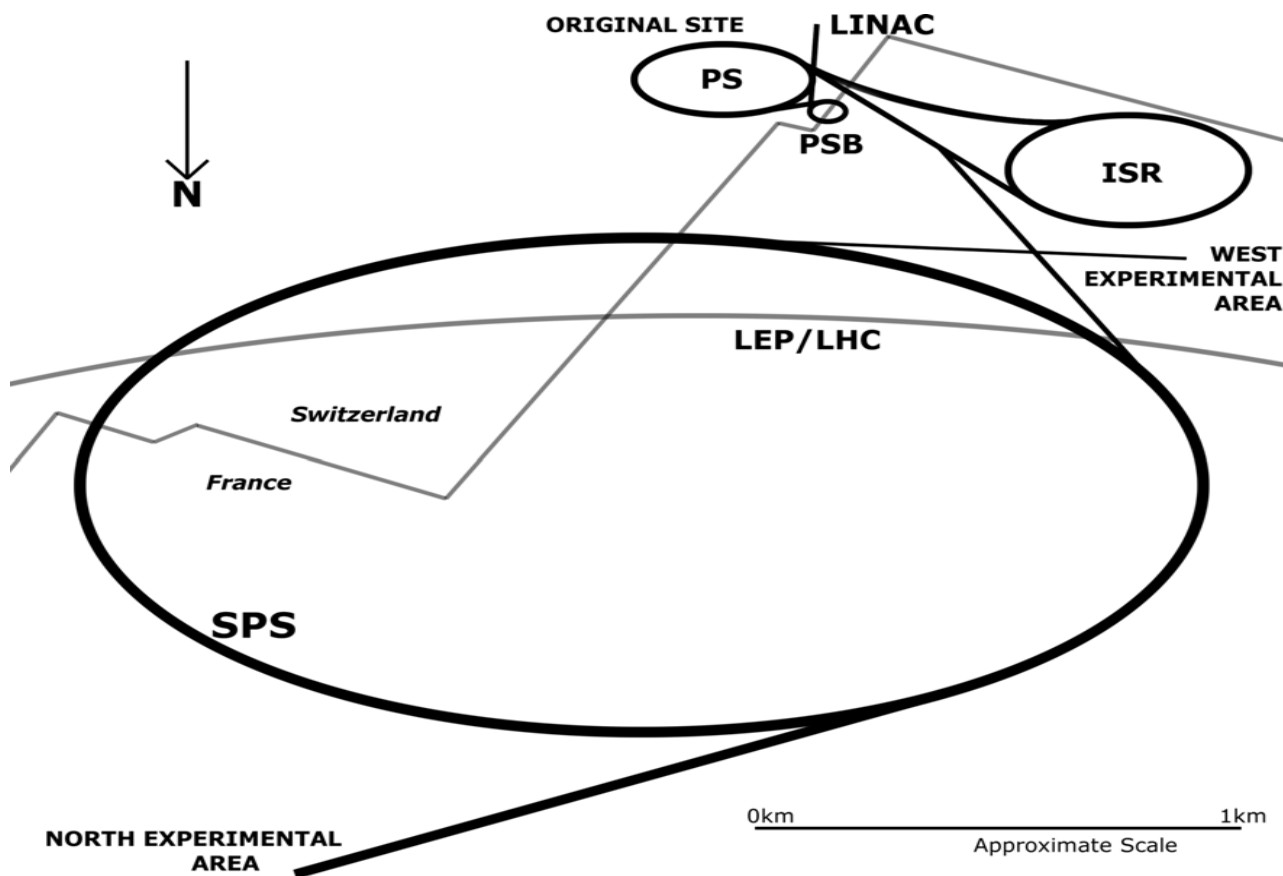


## Accelerators and detectors in underground tunnels and caverns



Lec

# CERN Beam Gymnastics (2)





## Cost

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- It is worth noting that these experiments are very expensive. The cost of a single particle:
  - Burning one carbon atom tiny, almost free
  - Gold small, almost free
  - Radioactive isotope ( $^{64}\text{Fe}$ ) ~\$0.001
  - Superheavy nucleus ( $^{272}\text{Rg}$ ) ~\$200,000
  - Higgs particle \$0.1-1 billion
- How much are you/we willing to pay for a greater understanding of the universe?