



Today

- 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

- 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

- 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

<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.

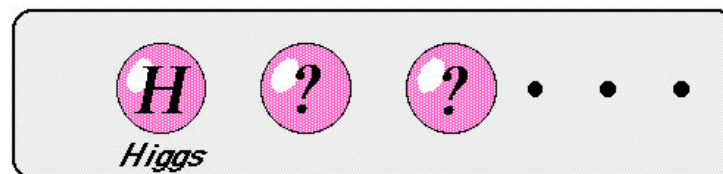
matter particles

	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	ν_e <i>e neutrino</i>	ν_μ μ <i>neutrino</i>	ν_τ τ <i>neutrino</i>
	<i>e</i> <i>electron</i>	μ <i>muon</i>	τ <i>tau</i>

guage particles

<p>Strong Force</p> <i>g</i> <i>Gluon</i>
<p>Electro-Magnetic Force</p> γ <i>photon</i>
<p>Weak Force</p> W^+ W^- <i>Z</i> <i>W bosons</i> <i>Z boson</i>

scalar particle(s)





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 H Hydrogen																	2 4.003 He Helium
3 6.94 Li Lithium	4 9.01 Be Beryllium											5 10.81 B Boron	6 12.01 C Carbon	7 14.01 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.18 Ne Neon
11 22.99 Na Sodium	12 24.31 Mg Magnesium											13 26.98 Al Aluminum	14 28.09 Si Silicon	15 30.97 P Phosphorus	16 32.06 S Sulfur	17 35.45 Cl Chlorine	18 39.96 Ar Argon
19 39.10 K Potassium	20 40.08 Ca Calcium	21 44.96 Sc Scandium	22 47.90 Ti Titanium	23 50.94 V Vanadium	24 51.996 Cr Chromium	25 54.94 Mn Manganese	26 55.85 Fe Iron	27 58.93 Co Cobalt	28 58.70 Ni Nickel	29 63.55 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.92 As Arsenic	34 78.96 Se Selenium	35 79.90 Br Bromine	36 83.80 Kr Krypton
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.91 Y Yttrium	40 91.22 Zr Zirconium	41 92.91 Nb Niobium	42 95.94 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.40 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.30 Xe Xenon
55 132.91 Cs Cesium	56 137.33 Ba Barium	57 138.91 La Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.21 Re Rhenium	76 190.20 Os Osmium	77 192.22 Ir Iridium	78 195.09 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon
87 (223) Fr Francium	88 226.03 Ra Radium	89 227.03 Ac Actinium	104 (261) Rf Rutherfordium	105 (262) Db Dubnium	106 (266) Sg Seaborgium	107 (262) Bh Bohrium	108 (265) Hs Hassium	109 (266) Mt Meitnerium	110 (271) Ds Darmstadtium	111 (272) Rg Roentgenium	(277)	(284)	(288)	(290)	(292)	(294)	118 (294)

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

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



Quantum Numbers (2)

- 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

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.

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

The standard model explains how particles interact and transform.



What is mass

- 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

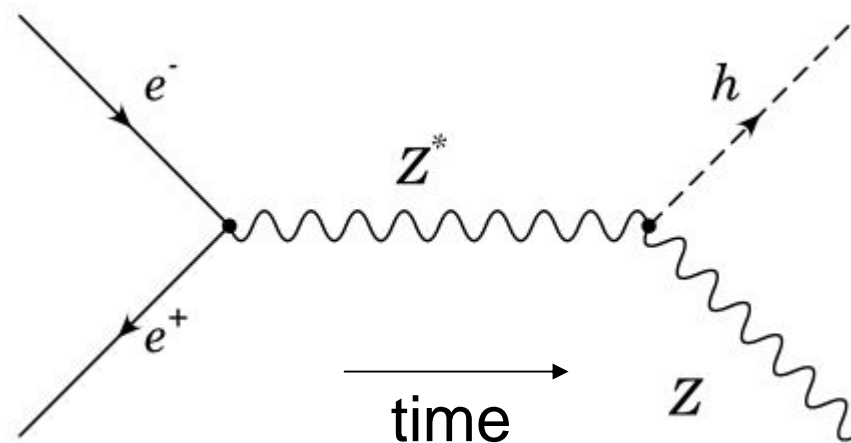
Space is filled with a (scalar) particle called the Higgs boson. The more a particle interacts with the Higgs field, the greater its mass is.



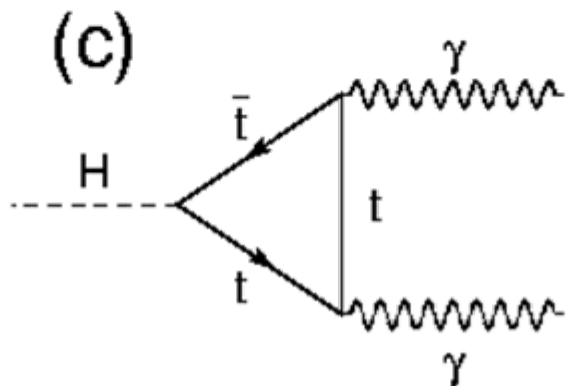
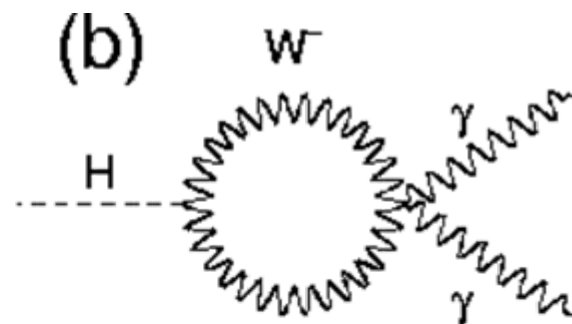
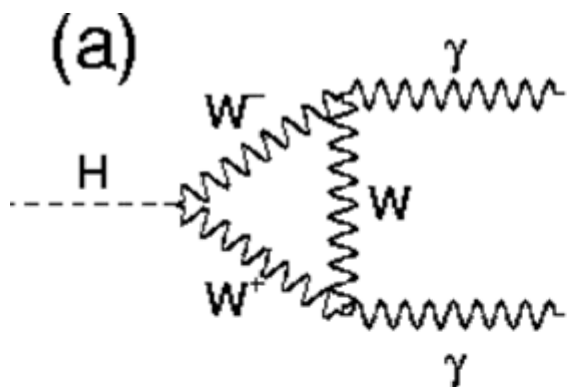
Higgs Particle

- 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

- 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?

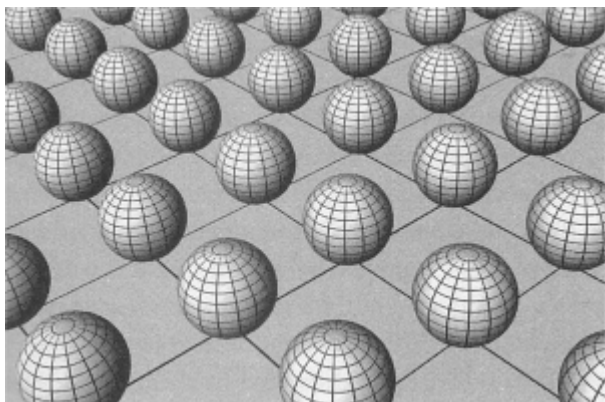
- There are attempts to extend the standard model to include gravity; these are called supersymmetric theories.
- These say that all fermions (which make up matter) and bosons (that transmit forces) have a corresponding partner boson (to go with our standard fermions) and fermion (to go with our standard 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

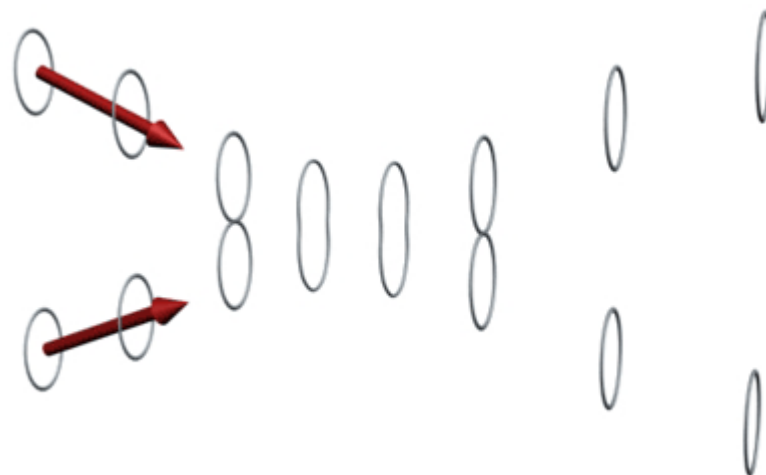
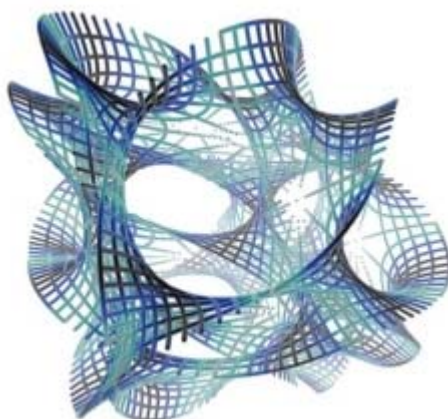
- One of the promising new theories is string theory. It says that the fundamental building blocks of nature are tiny (10^{-35} m) strings.
- The particles we observe in nature are different ways for strings to vibrate.
- String theory is not accepted because so far it has not devised an experiment that 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

- 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)

- 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)] $2\text{E}13\text{ eV}$

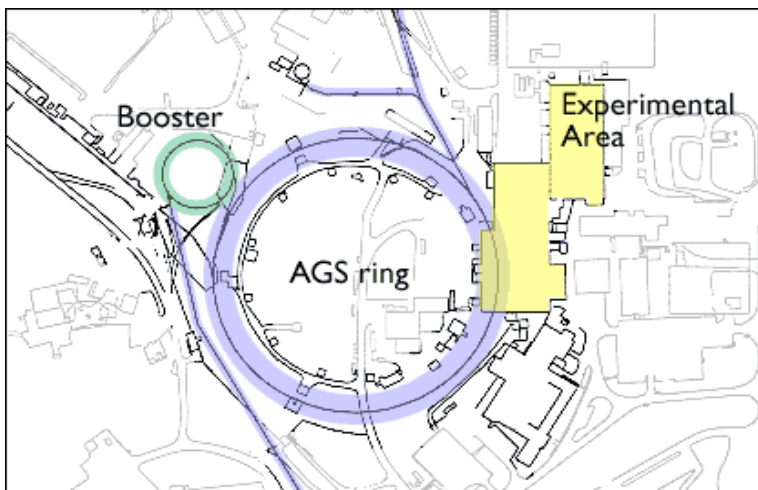
Relativistic Heavy-Ion Collider



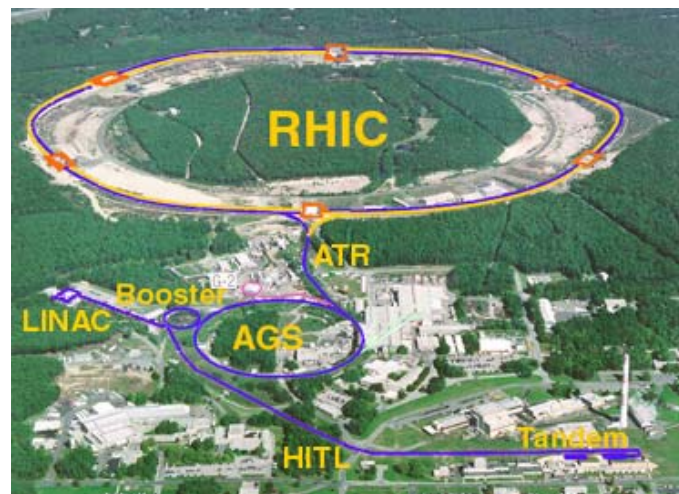
Long Island (New York)



RHIC from space!

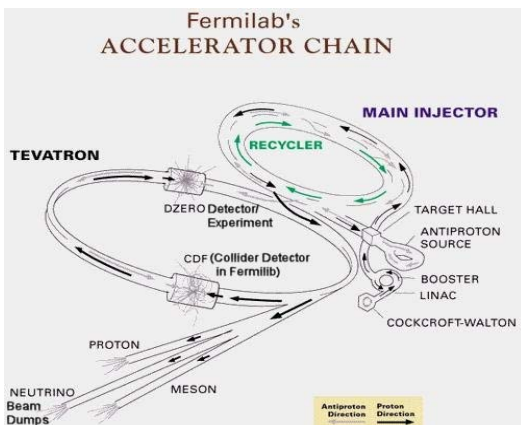


The Alternating Gradient Synchrotron complex



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

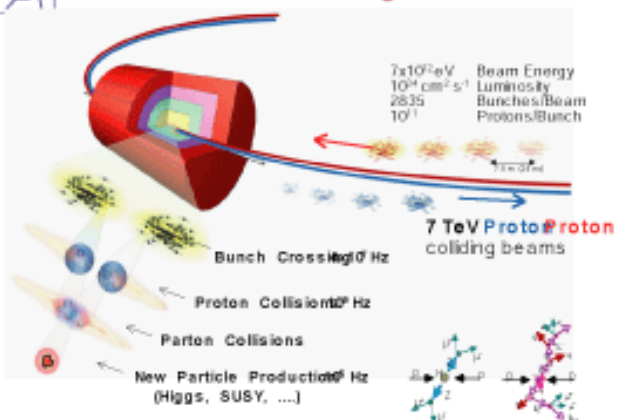
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Large Hadron Collider – CERN (Europe)



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



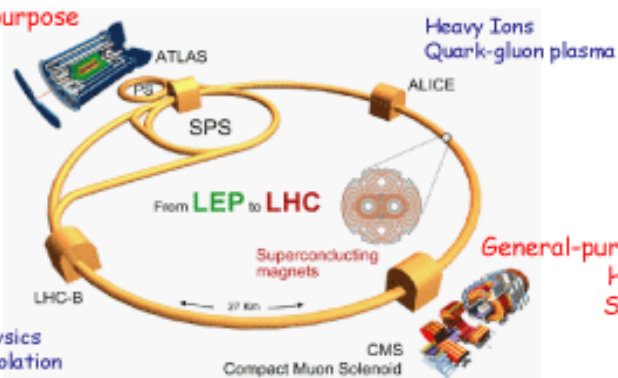
May 2004

Greene Jarp



LHC Detectors

General-purpose
Higgs
SUSY
??



General-purpose
Higgs
SUSY
??

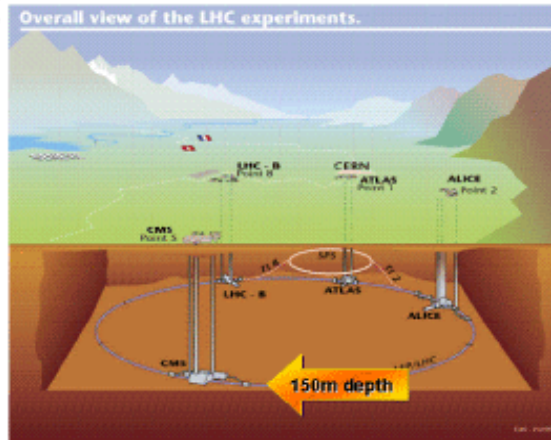
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Introduction to CERN

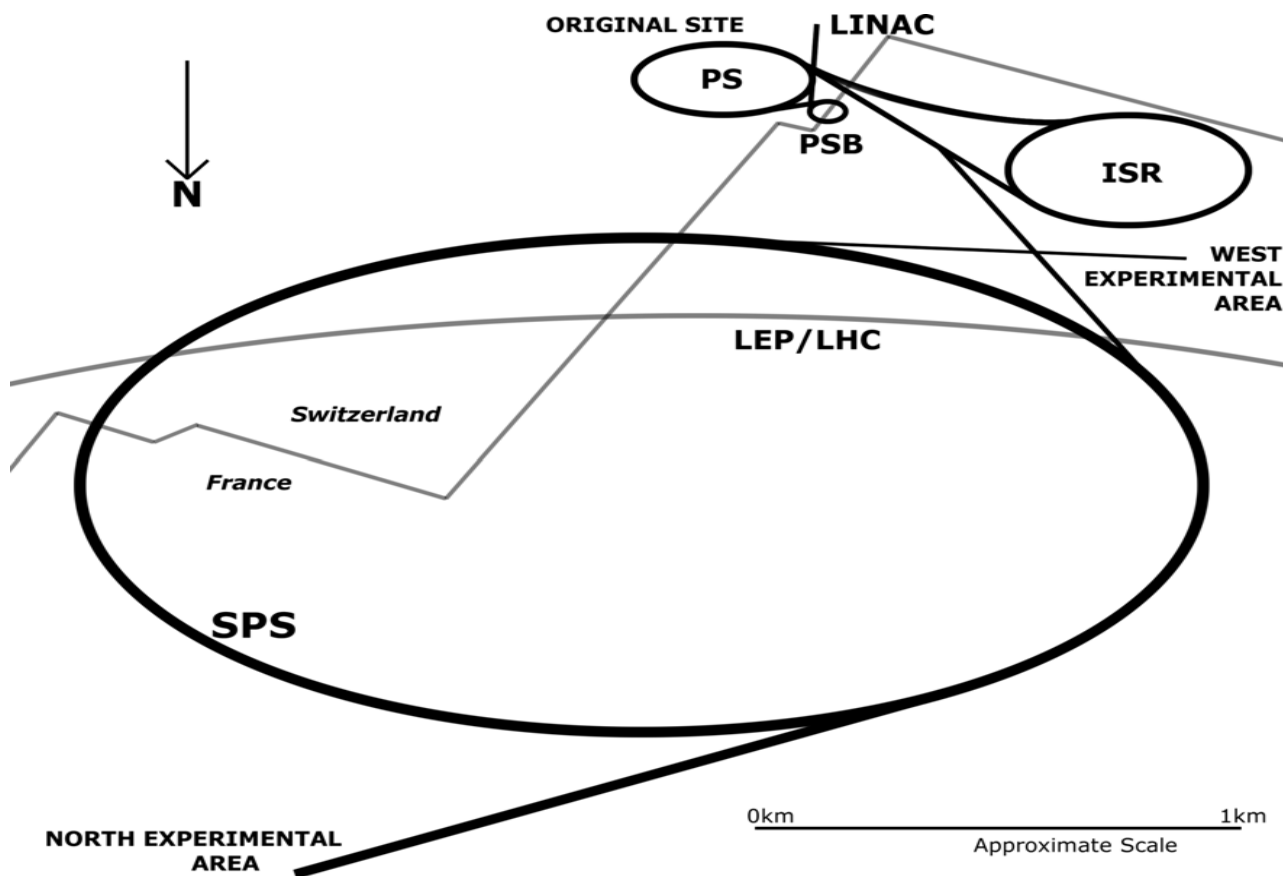
David Barney, CERN



Accelerators and detectors in underground tunnels and caverns



CERN Beam Gymnastics (2)





Cost

- 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}Fe) ~\$0.001
 - Superheavy nucleus (^{272}Rg) ~\$200,000
 - Higgs particle \$0.1-1 billion
- How much are you/we willing to pay for a greater understanding of the universe?