The Large Hadron Collider (LHC)
and
College Physics

C.-P. Yuan 袁簡鵬

Michigan State University

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Univ. of Science and Technology of China

LHC, located at CREN, Geneva, started operating in 2008.

It is the highest energy hadron collider currently existing in the world.

The connection between Cosmology and Particle Physics

- Today’s Universe

  ``Dark’’ Universe

- Early Universe

  Deduced from the

  Standard Model of Cosmology

- Elementary Particle Physics

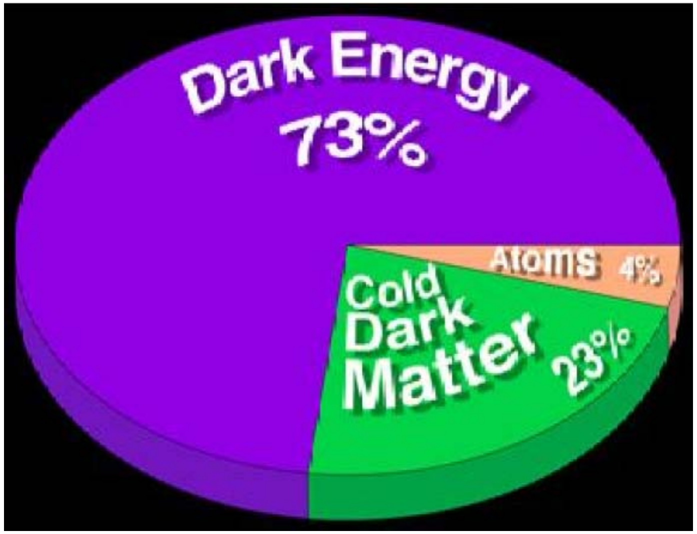
  Needed to describe the early universe.

“Dark” Universe

Recent astrophysics data told us that
our Universe is made of :

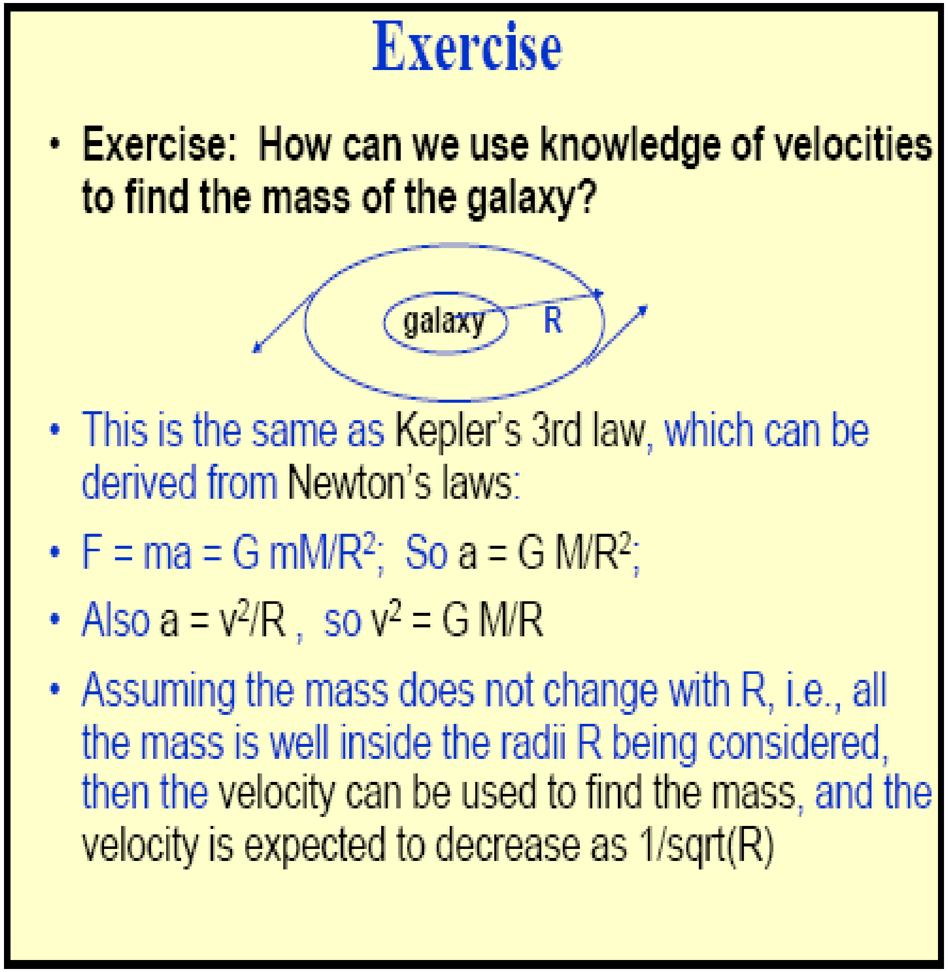
- starts and galaxies (ordinary matter) 0.5%
- Rest of ordinary matter 4.5%
- Dark matter (not ordinary matter) 25%
- Dark Energy (filling up empty space) 70%

The “sky”
is made mostly by
something other than
ordinary matter.



What is Dark Matter?

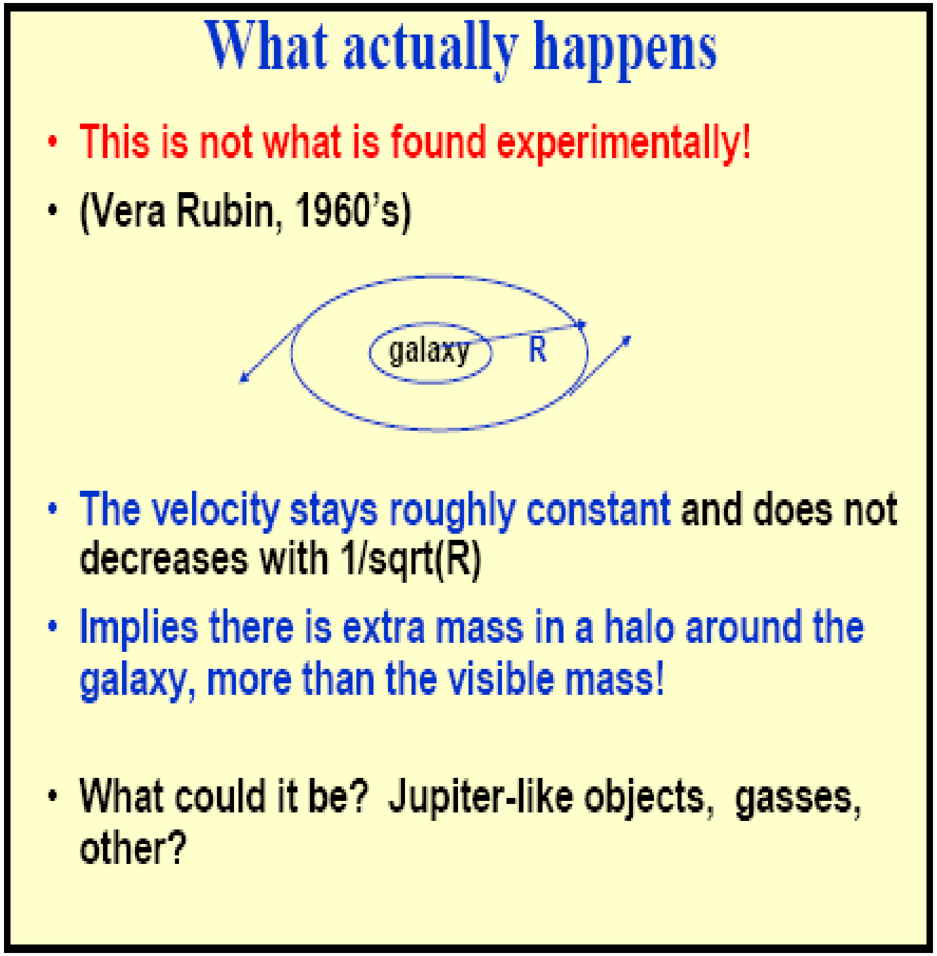
Evidence of Dark Matter



Exercise

- Exercise: How can we use knowledge of velocities to find the mass of the galaxy?

- This is the same as Kepler's 3rd law, which can be derived from Newton's laws:
- $F = ma = G\,mM/R^2$; So $a = G\,M/R^2$;
- Also $a = v^2/R$, so $v^2 = G\,M/R$
- Assuming the mass does not change with R, i.e., all the mass is well inside the radii R being considered, then the velocity can be used to find the mass, and the velocity is expected to decrease as 1/sqrt(R)

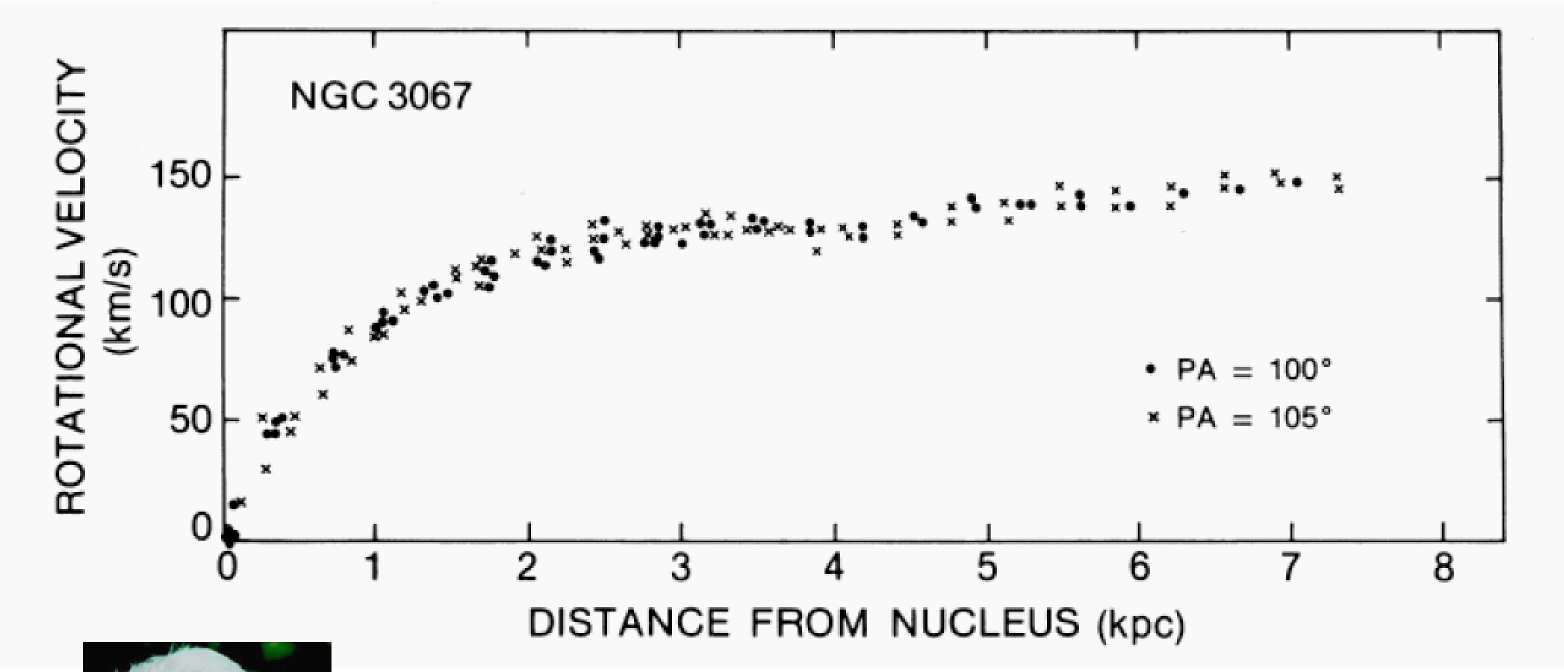


What actually happens

- This is not what is found experimentally!
- (Vera Rubin, 1960's)

- The velocity stays roughly constant and does not decreases with 1/sqrt(R)
- Implies there is extra mass in a halo around the galaxy, more than the visible mass!
- What could it be? Jupiter-like objects, gasses, other?

but for the outlying stars in galaxies, one finds:

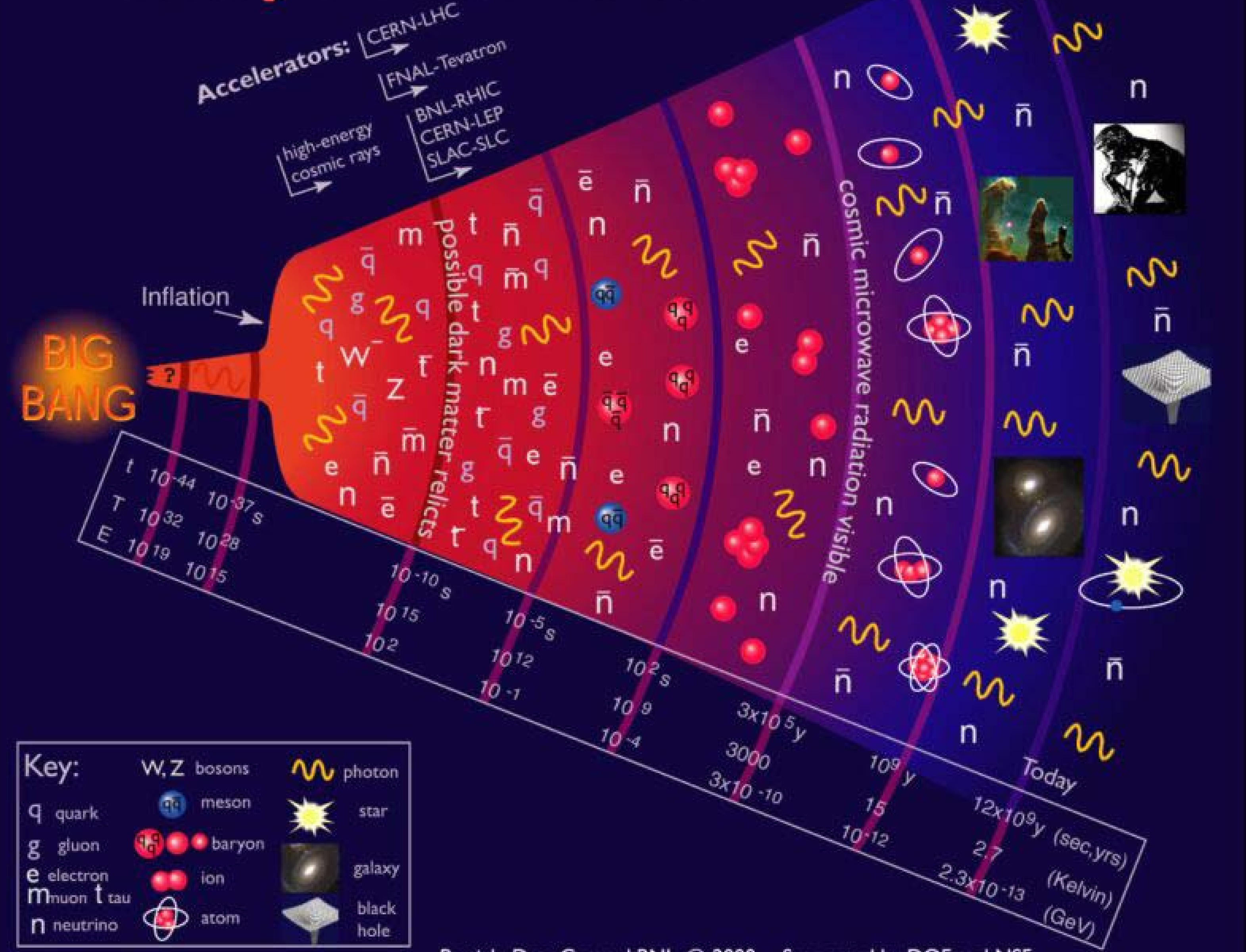


Vera Rubin

Rubin, Thonnard, Ford

"Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio M/L greater than 100."

History of the Universe

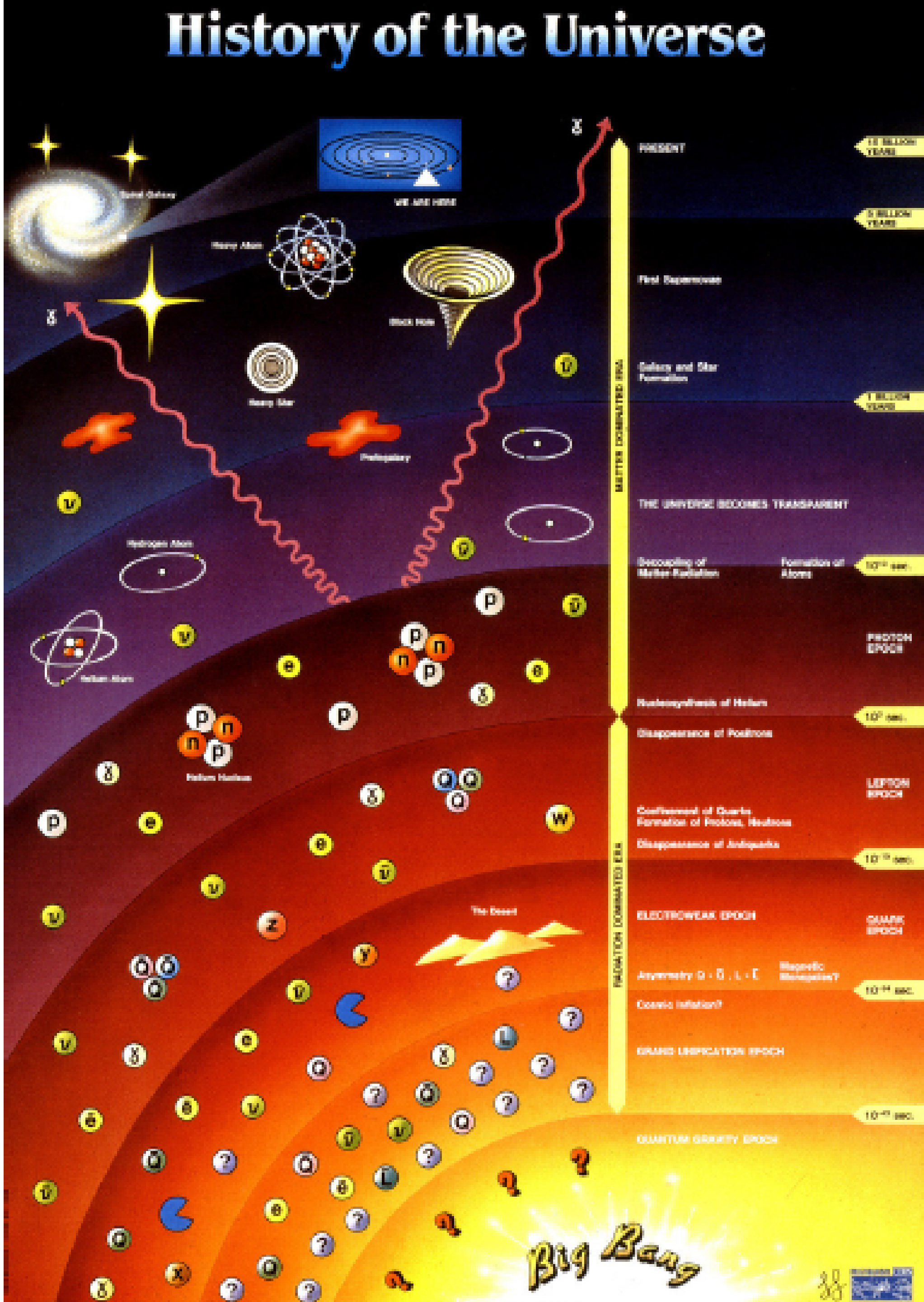


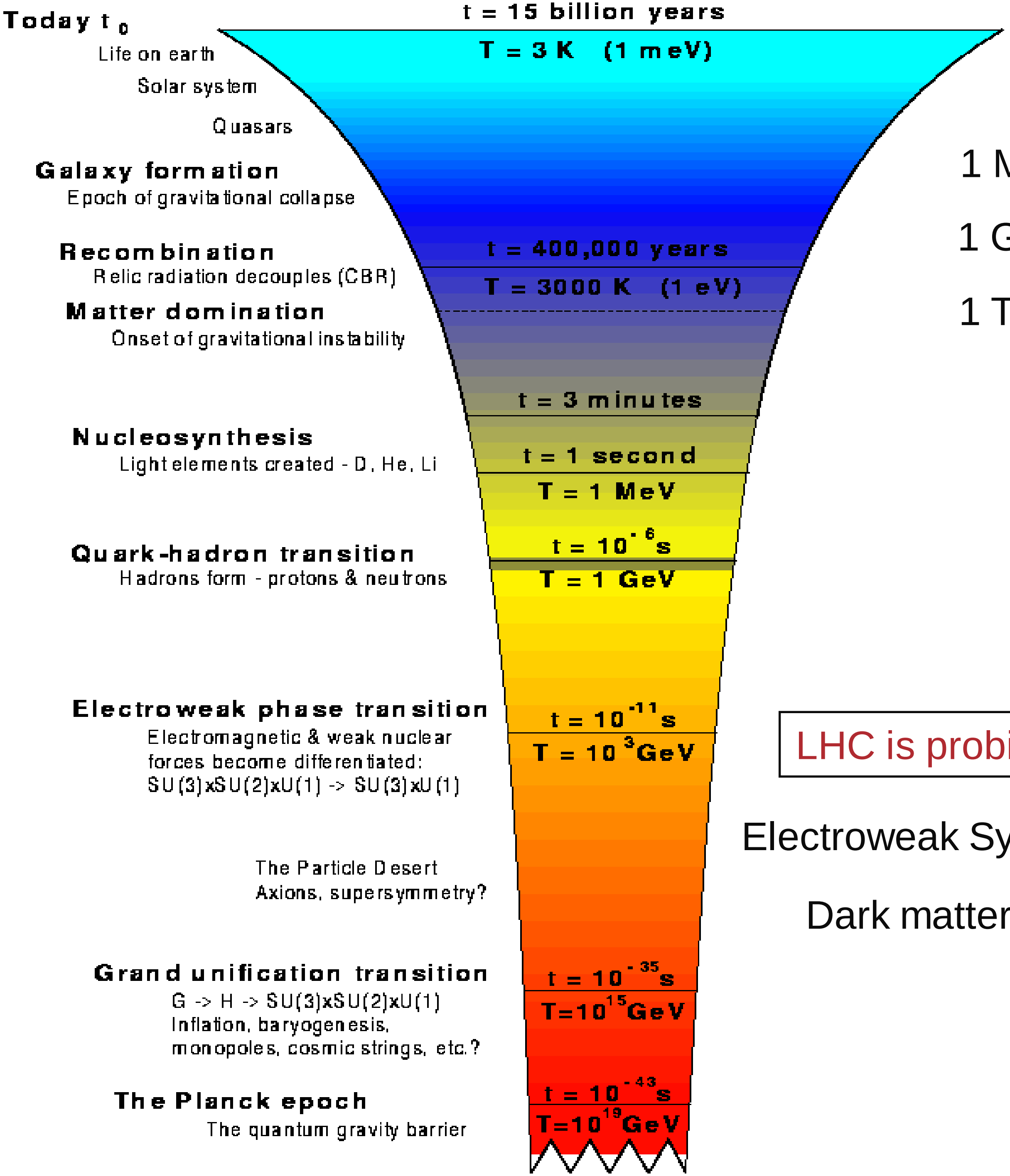
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

LHC recreates conditions of early universe

- Investigate matter-antimatter assymetry of universe
- Understand the origin of mass
- Might find dark matter

Particle Physics
|
Astrophysics





Today t_0

t = 15 billion years

T = 3 K (1 meV)

Life on earth

Solar system

Quasars

Galaxy formation

Epoch of gravitational collapse

Recombination

Relic radiation decouples (CBR)

t = 400,000 years

T = 3000 K (1 eV)

Matter domination

Onset of gravitational instability

t = 3 minutes

Nucleosynthesis

Light elements created - D, He, Li

t = 1 second

T = 1 MeV

Quark-hadron transition

Hadrons form - protons & neutrons

$t = 10^{-6}$ s

T = 1 GeV

Electroweak phase transition

Electromagnetic & weak nuclear forces become differentiated: SU(3)xSU(2)xU(1) -> SU(3)xU(1)

$t = 10^{-11}$ s

$T = 10^{3}$ GeV

The Particle Desert

Axions, supersymmetry?

Grand unification transition

G -> H -> SU(3)xSU(2)xU(1)

Inflation, baryogenesis, monopoles, cosmic strings, etc.?

$t = 10^{-35}$ s

$T = 10^{15}$ GeV

The Planck epoch

The quantum gravity barrier

$t = 10^{-43}$ s

$T = 10^{19}$ GeV

1 MeV = 10^{6} eV

1 GeV = 10^{9} eV

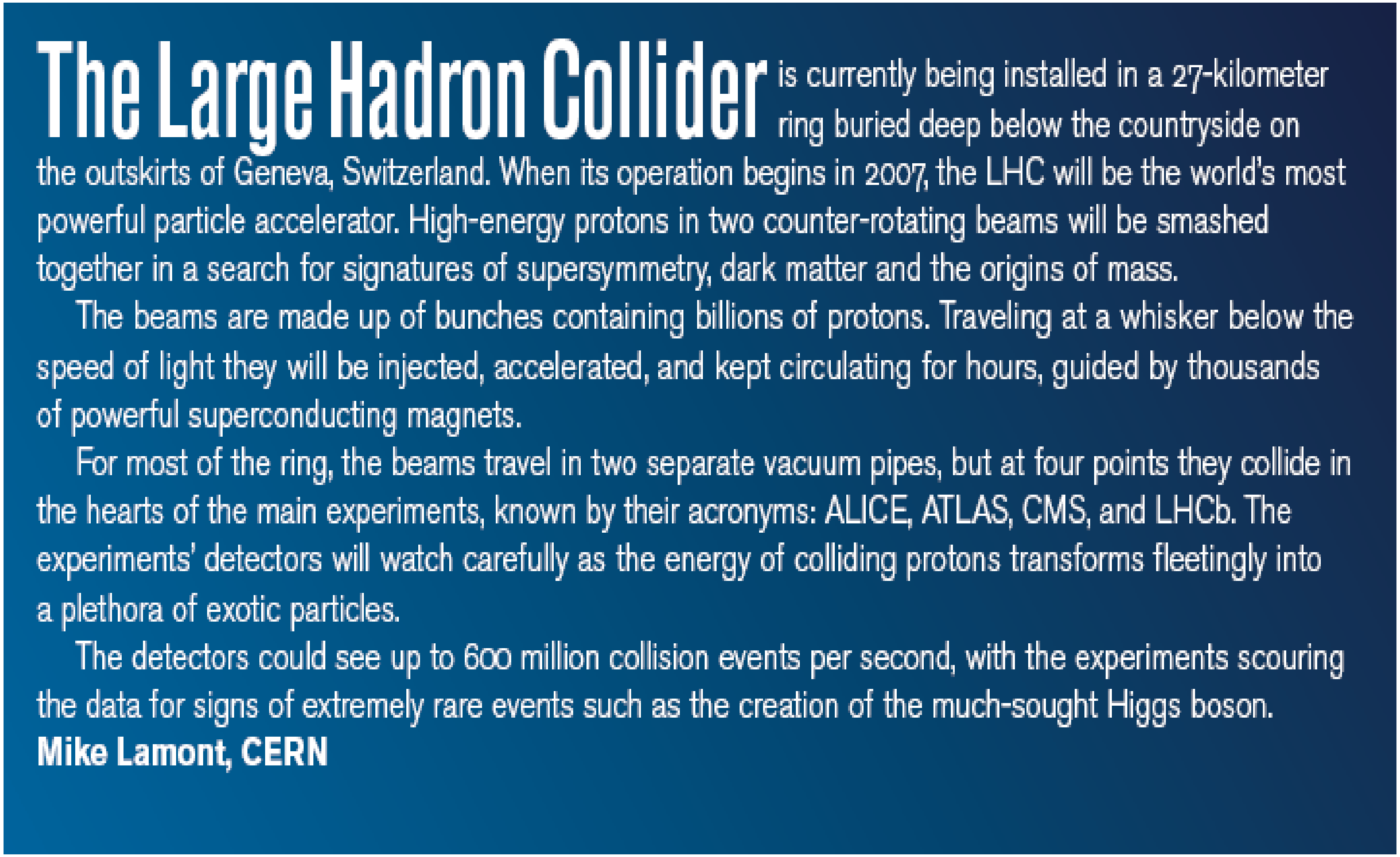
1 TeV = 10^{12} eV

LHC is probing TeV region

Electroweak Symmetry Breaking

Dark matter candidate

CERN LHC



The Large Hadron Collider is currently being installed in a 27-kilometer ring buried deep below the countryside on the outskirts of Geneva, Switzerland. When its operation begins in 2007, the LHC will be the world's most powerful particle accelerator. High-energy protons in two counter-rotating beams will be smashed together in a search for signatures of supersymmetry, dark matter and the origins of mass.

The beams are made up of bunches containing billions of protons. Traveling at a whisker below the speed of light they will be injected, accelerated, and kept circulating for hours, guided by thousands of powerful superconducting magnets.

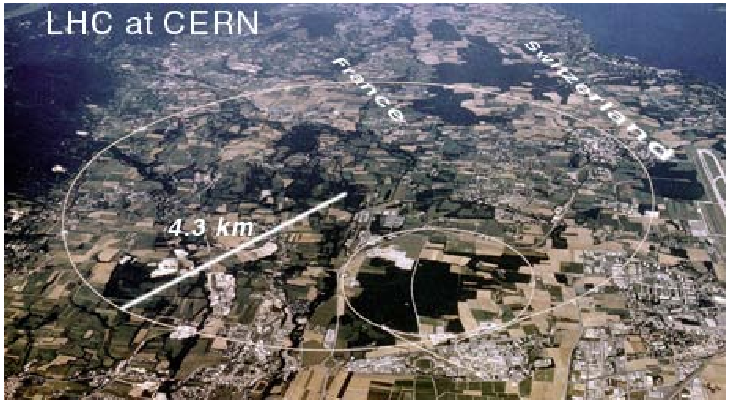
For most of the ring, the beams travel in two separate vacuum pipes, but at four points they collide in the hearts of the main experiments, known by their acronyms: ALICE, ATLAS, CMS, and LHCb. The experiments' detectors will watch carefully as the energy of colliding protons transforms fleetingly into a plethora of exotic particles.

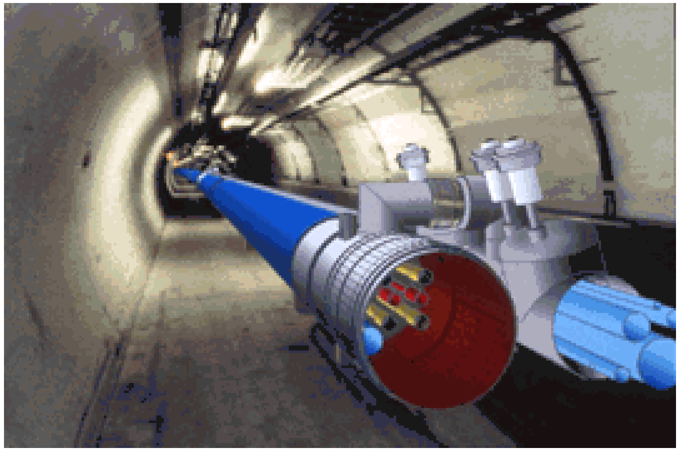
The detectors could see up to 600 million collision events per second, with the experiments scouring the data for signs of extremely rare events such as the creation of the much-sought Higgs boson.

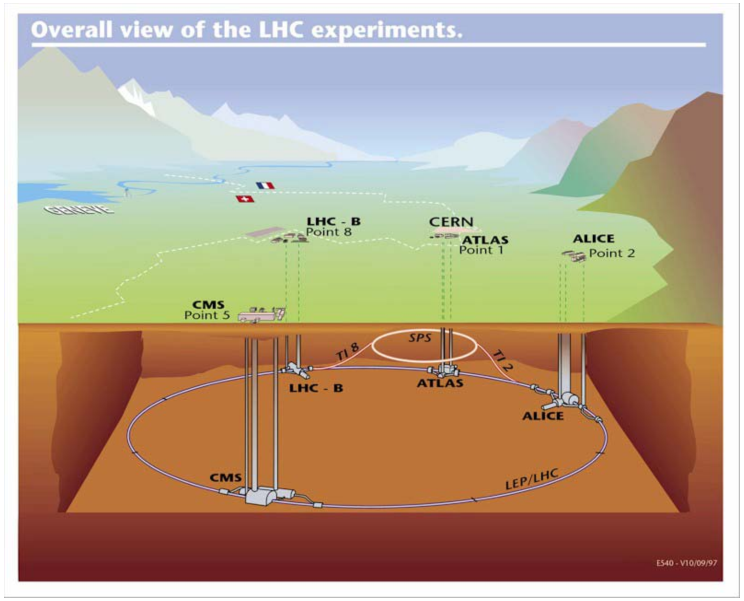
Mike Lamont, CERN

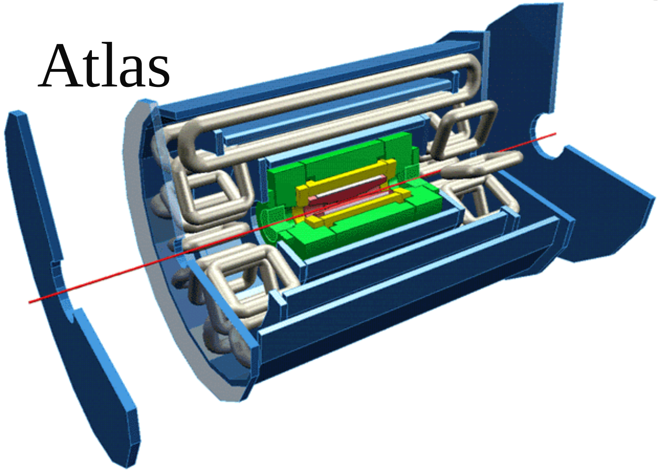
- The Large Hadron Collider (LHC) was built in a circular tunnel 27 km in circumference. The tunnel is buried around 50 to 175 m underground. It straddles the Swiss and French borders on the outskirts of Geneva.

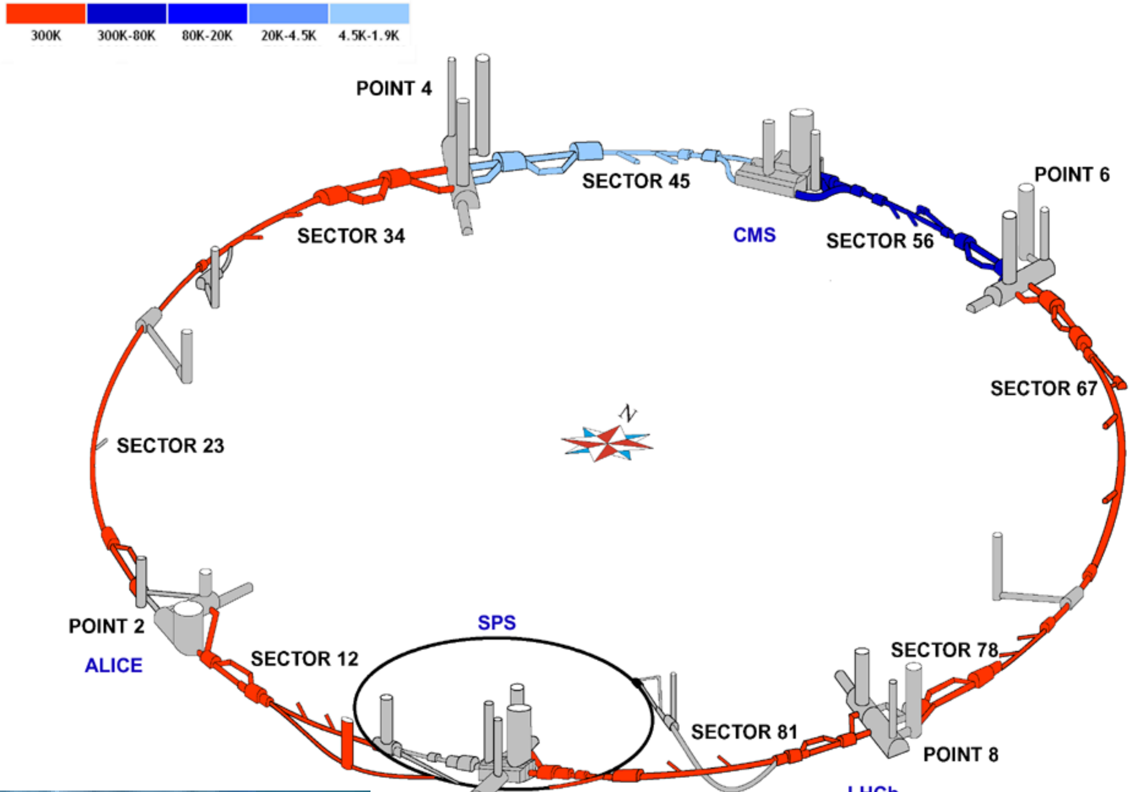
The CERN Large Hadron Collider (LHC)











The Large Hadron Collider (LHC) is a 27km long circular accelerator built at CERN, near Geneva Switzerland.

The beam was successfully tested on September 10, 2008. It will produce data in 2009.

Each Collider Beam at LHC

- Each proton beam at full intensity will consist of 2808 bunches per beam moving in a circular tunnel 27 km in circumference.

- Each bunch contains 1.15×10^{11} protons.

- Each proton beam is few cm. long with transverse dimensions of the order 1 mm, but at the collision point of LHC it is 16 microns (when fully squeezed).

- The particles in the LHC are ultra-relativistic and move at 0.999999991 the speed of light (7 TeV).

- Total beam energy at top energy, nominal beam, 362 MJ

(2808 bunches * $1.15*10^{11}$ protons @ 7 TeV each. =
$2808*1.15*10^{11}*7*10^{12}*1.602*10^{-19}$ Joules = 362 MJ per beam)

- The energy content of TNT is 4.68 MJ/kg, thus it is equivalent to

362/4.68 = 77.4 kg of TNT

Each Collider Beam at LHC

- The distance from one bunch to the next is 7.5 m. Since it takes light 25 nanoseconds (or 25 ns) to travel 7.5 m, and the protons are practically moving at the speed of light, head-on meetings between bunches at every collision point occur every 25 ns, or 40 million times per second.

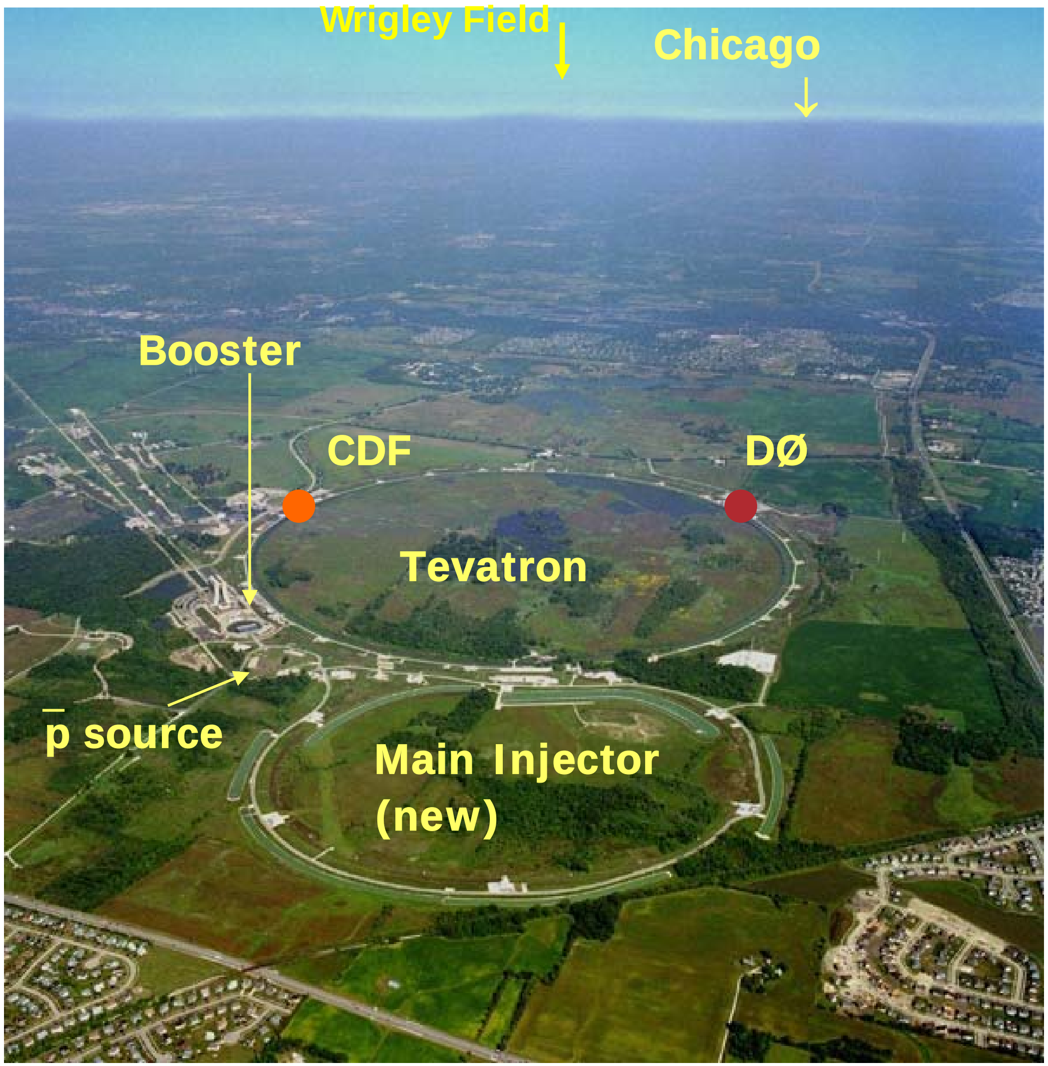
- The bunch spacing in the LHC is 25 ns., however, there are bigger gaps (e.g. to allow dump kickers the time to get up etc.). Because of the gaps we get

  an average crossing rate = number of bunches * revolution

  frequency = 2808 * (3*10^8)/(27*10^3 m) = 31.6 MHz.

- 31.6 MHz times 19 events per crossing at nominal luminosity gives us 600 million inelastic events per second.

Fermilab Tevatron Collider



- Collide protons and anti-protons at CDF and D0
- Total energy is

  1.96×10^{12} eV
- Circumference is 6.28 km
- Top quark was discovered here in 1995
- Tau neutrino was discovered here in 2000

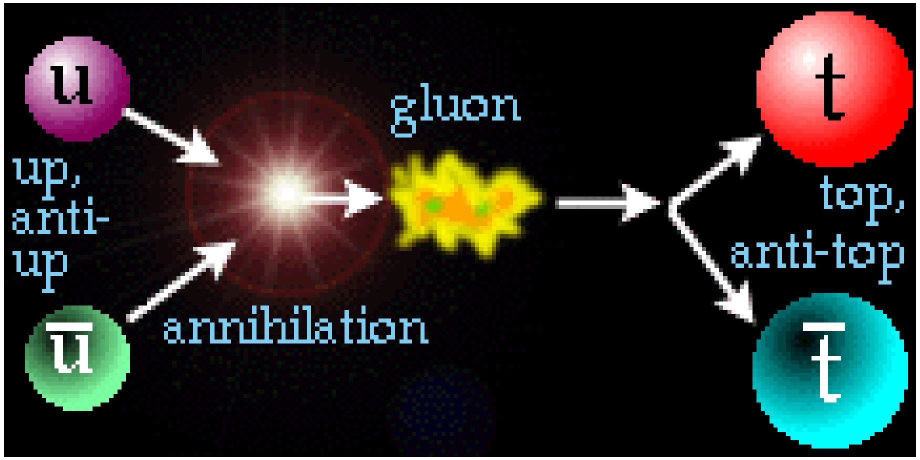
Tevatron

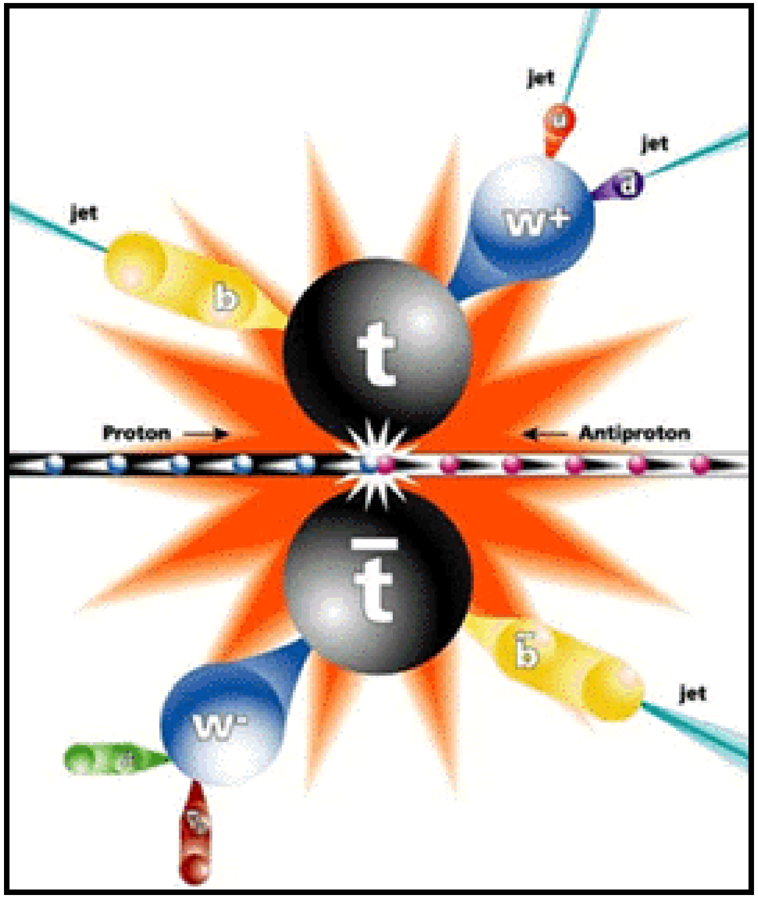
- Tevatron (proton/anti-proton)

  980 GeV beam energy - 36 bunches of 2.3×10^{11} protons gives an energy per beam around 1.3 MJ

- LHC beam power = 280 x Tevatron!

Top Quark and Anti-Top Quark Pair Production at Hadron Collider



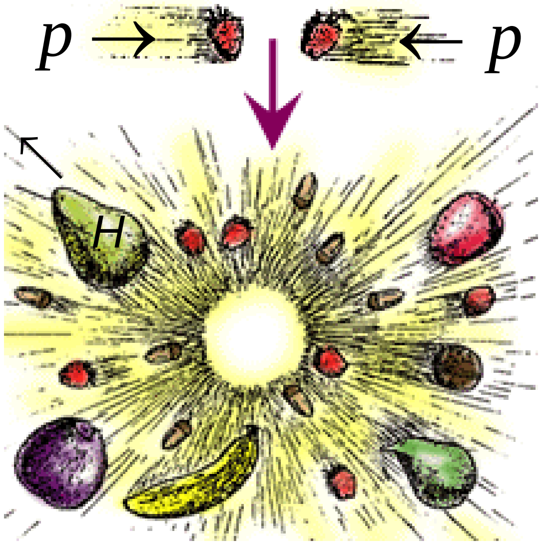


Discovered in 1995 at Fermilab

$$m_t = 172.5 \pm 2.3 \text{ GeV}$$

Find the Higgs Boson

The CERN Large Hadron Collider (LHC) will collide protons on protons at energy of 14 trillion electron Volts (14 TeV)



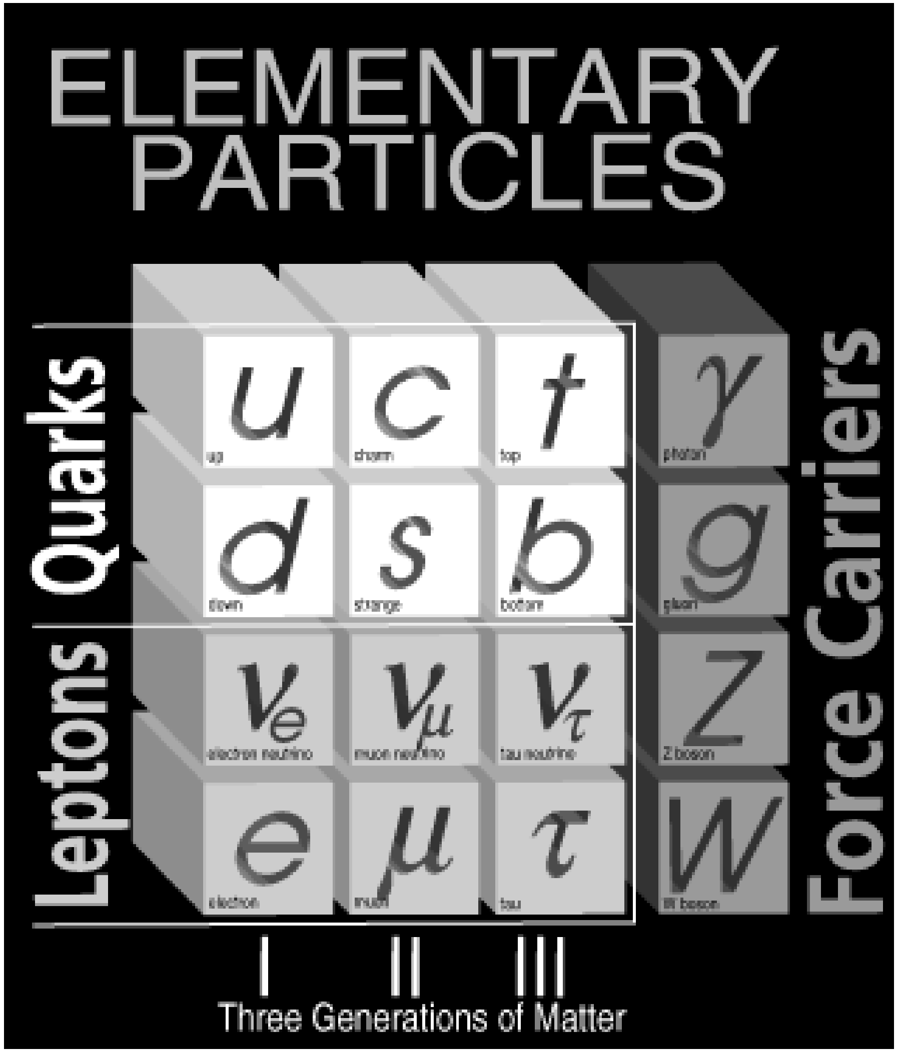
With such high energy it is hoped to produce the Higgs boson via

$$E = M c^2$$

The Traditional Opening Pitch

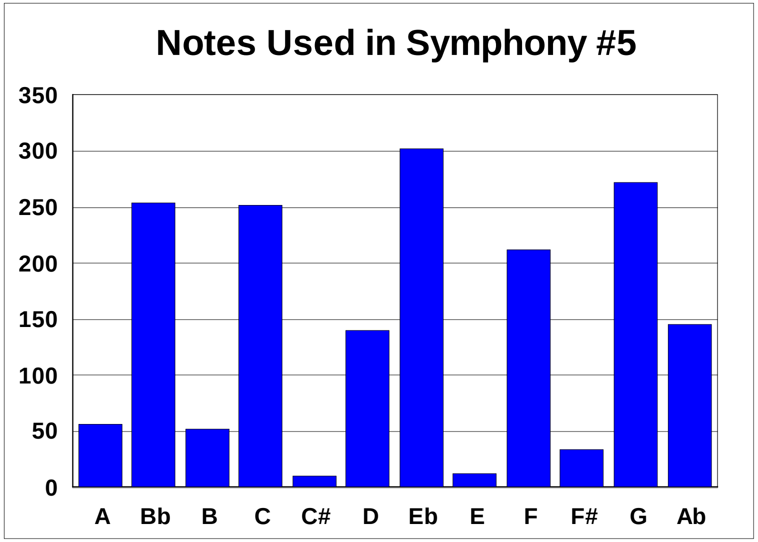
- Practically every High Energy Physics (HEP) talk starts with this slide.

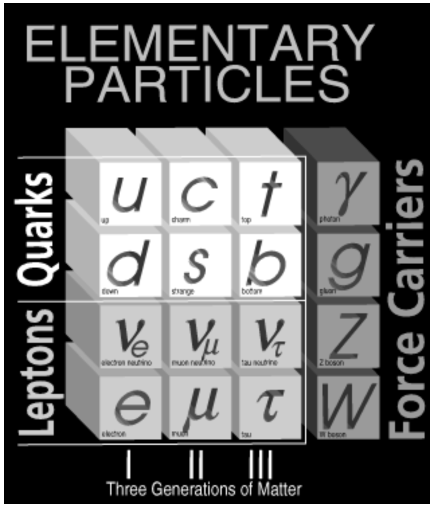
- This isn't the way I want to start this talk.



Comparing Two Figures

A histogram of the notes used in Beethoven's 5th Symphony, first movement.





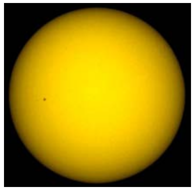
- Both plots focus on the constituents of a thing, rather than their interactions.
- While there is meaning in both plots, it can be hard to see.
  - A plot of a composition by A. Schoenberg would look different.

I'd like to come at this from a different direction.

Outline

- A 19th Century Puzzle & the 21st Century Puzzle that Emerges from It
- How One Builds a Large Hadron Collider (LHC)
- Detection of Particles
- The ATLAS and CMS Experiments
- The Structure of the Proton
- The Higgs Mechanism & Electroweak Symmetry Breaking
- When This is All Going To Happen
- Conclusions

The Older Age of the Earth Controversy



All science is either physics or stamp collecting.
Ernest Rutherford

- The “Helios”
  - e.g. Hermann von Helmholtz, Simon Newcomb
  - (Incorrectly) argued that there was no way the sun could shine longer than 10-20 million years
    - *The earth can be no older than the sun*
- The “Geos”
  - e.g. Charles Darwin, George Darwin
  - (Correctly) argued that features on the earth indicated that it was older than several hundred million years
    - *The earth must be at least as old as any feature on it*

From relative abundance of radioactive isotopes (U-235 and U-238), the earth is about 4.6 billion years old.

Where Helmholtz Went Wrong: The Age of The Sun

- Helmholtz et al. related the gravitational potential energy of the sun to its luminosity (dE/dt)
  - This gives ~10-15 million years

$$t \approx \frac{GM_\odot^2}{R_\odot}\frac{1}{L_\odot}$$

- We know today that the energy source of the sun isn't gravity: it's nuclear fusion
  - Has ~1000x as much energy as gravity

$$4p \rightarrow {}^4\mathrm{He} + 2e + 2\nu$$

This doesn't solve the problem.

Adding another energy source doesn't make the sun burn longer. It makes the sun burn *brighter*.

(Tossing a stick of dynamite in your fireplace doesn't make it burn longer, does it?)

The Sun and the LHC

- The sun is powered by the reaction $4p \rightarrow {}^4\mathrm{He} + 2e + 2\nu$
- This requires two protons to turn into two neutrons
  - It's the weak interaction – carried by the W boson - that does this
  - The strength of this interaction is suppressed by a factor $(E/M_W)^4$
    - *For the sun, this is ~10^{-32}*
    - *This throttles the nuclear fusion so the sun can last for billions of years*

We understand now how the sun can shine for billions of years – its because the W boson is heavy. (mass of a bromine atom) A 5% change in W mass corresponds to a factor of 2 in the sun's lifetime.

But this opens up a new question – why is the W so heavy?

This is what the LHC is trying to find out.

How does Standard Model predict … ?

- In Quantum Mechanics

Schrodinger Equation:

$$i\frac{\partial\Psi}{\partial t} = H\Psi$$

1. Figure out what H is.
2. Insert H in S.E.
3. Calculate Predictions

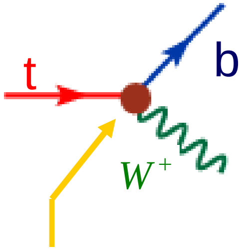
- In Relativistic Quantum Field Theory

SM gives the Interaction Lagrangian $\mathcal{L}$

$\mathcal{L}$

⇩

Feynman Rules
Feynman Diagrams }



Vertex; coupling

⇩

S-Matrix Elements

⇩

Predictions

Local Gauge Invariance – Part I

- In quantum mechanics, the probability density is the square of the wavefunction: $P(x) = |\Psi|^2$
  - If I change Ψ to $-\Psi$, anything I can observe remains unchanged

- $P(x) = |\Psi|^2$ can be perhaps better written as $P(x) = \Psi\Psi^*$
  - If I change Ψ to $\Psi e^{i\phi}$ anything I can observe still remains unchanged.
  - The above example was a special case ($\phi = \pi$)

- If I can't actually observe ϕ, how do I know that it's the same everywhere?
  - I should allow ϕ to be a function, $\phi(\mathbf{x},t)$.
  - This looks harmless, but is actually an extremely powerful constraint on the kinds of theories one can write down.

Local Gauge Invariance – Part II

- The trouble comes about because the Schrödinger equation (and its descendents) involves derivatives, and a derivative of a product has extra terms.

$$\frac{d}{dx}uv = u\frac{dv}{dx} + v\frac{du}{dx}$$

- At the end of the day, I can’t have any leftover ϕ’s – they all have to cancel. (They are, by construction, supposed to be unobservable)

- If I want to write down the Hamiltonian that describes two electrically charged particles, I need to add one new piece to get rid of the ϕ’s: a massless photon.

A Good Theory is Predictive…or at least Retrodictive

- This is a theoretical tour-de-force: starting with Coulomb's Law, and making it relativistically and quantum mechanically sound, and out pops:
  - Magnetism
  - Classical electromagnetic waves
  - A quantum mechanical photon of zero mass
- Experimentally, the photon is massless ($< 10^{-22} m_e$)
  - 10^{-22} = ratio of the radius of my head to the radius of the galaxy

Quantum Electrodynamics (QED)

The gauge boson that mediates the
electromagnetic interaction is
the massless photon.

Elementary Particle Physics

To answer

What are the Elementary Constituents of Matter?

What are the forces that control their behaviour at the most basic level?

People have long asked,

“ What is the world made of? ”
and
“ What holds it together? ”

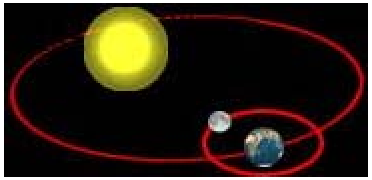
Elementary Particle Physics
or
High Energy Physics

Studying Fundamental Interactions (Forces)
in Nature

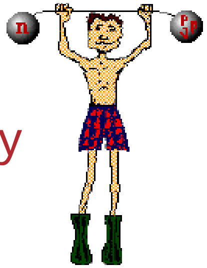
Interactions (Four forces in Nature)

1 Gravity

Newton



3 Weak Interaction



Beta (radioactive) decay

Sun is shining

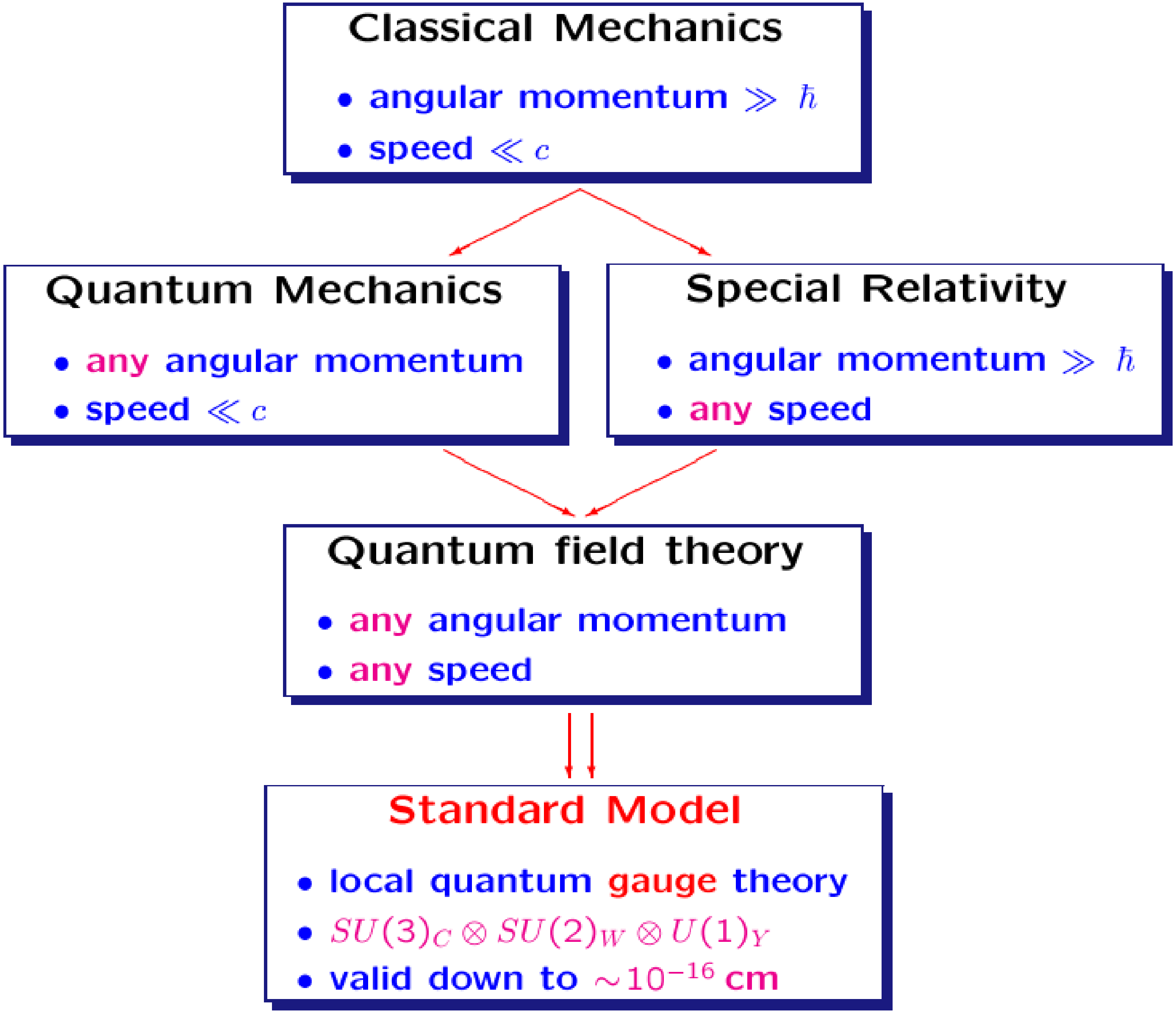
2 Electromagnetism

Faraday

4 Strong Interaction

Hold nuclei together

Shape of the Standard Model



Classical Mechanics

- angular momentum $\gg \hbar$
- speed $\ll c$

Quantum Mechanics

- any angular momentum
- speed $\ll c$

Special Relativity

- angular momentum $\gg \hbar$
- any speed

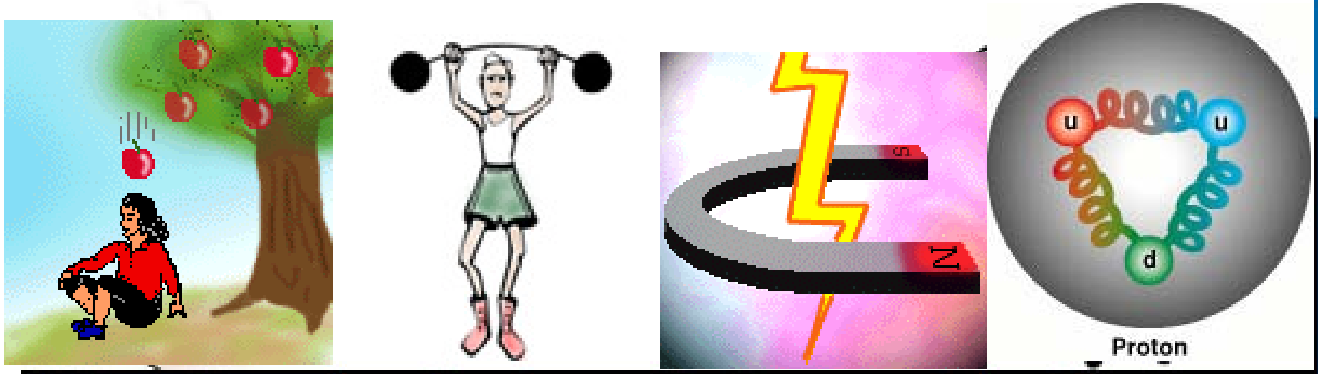
Quantum field theory

- any angular momentum
- any speed

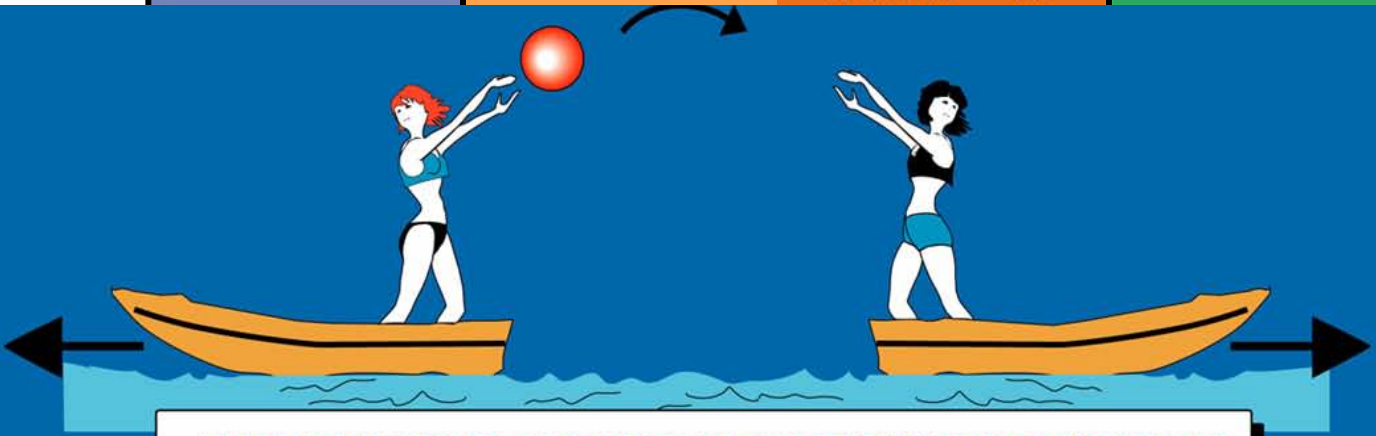
Standard Model

- local quantum gauge theory
- $SU(3)_C \otimes SU(2)_W \otimes U(1)_Y$
- valid down to $\sim 10^{-16}$ cm

The forces in Nature



	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons



THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

Let’s Do It Again

- A Hamiltonian that describe electrically charged particles also gives you:
  - a massless photon ☺

- A Hamiltonian that describes particles with color charge (quarks) also gives you:
  - a massless gluon (actually 8 massless gluons) ☺

- A Hamiltonian that describes particles with weak charge also gives you:
  - massless W^+, W^- and Z^0 bosons
  - Experimentally, they are heavy: 80 and 91 GeV/c^2 ☹

$$1\ GeV/c^2 = 10^9\ eV/c^2 \sim mass\ of\ proton$$

Why this doesn’t work out for the weak force – i.e. why the W’s and Z’s are massive – is what the LHC is trying to find out.

Nobody Wants A One Trick Pony

- One goal: understand what's going on with "electroweak symmetry breaking"
  - e.g. why are the W and Z heavy when the photon is massless
- Another goal: probe the structure of matter at the smallest possible distance scale
  - Small λ (=h/p) means high energy (Heisenberg uncertainty principle)
- Third goal: search for new heavy particles
  - This also means large energy ($E=mc^2$)
- Fourth goal: produce the largest number of previously discovered particles (top & bottom quarks, W's, Z's …) for precision studies

"What is the LHC for?" is a little like "What is the Hubble Space Telescope for?" – the answer depends on whom you ask.

A multi-billion dollar instrument really needs to be able to do more than one thing.

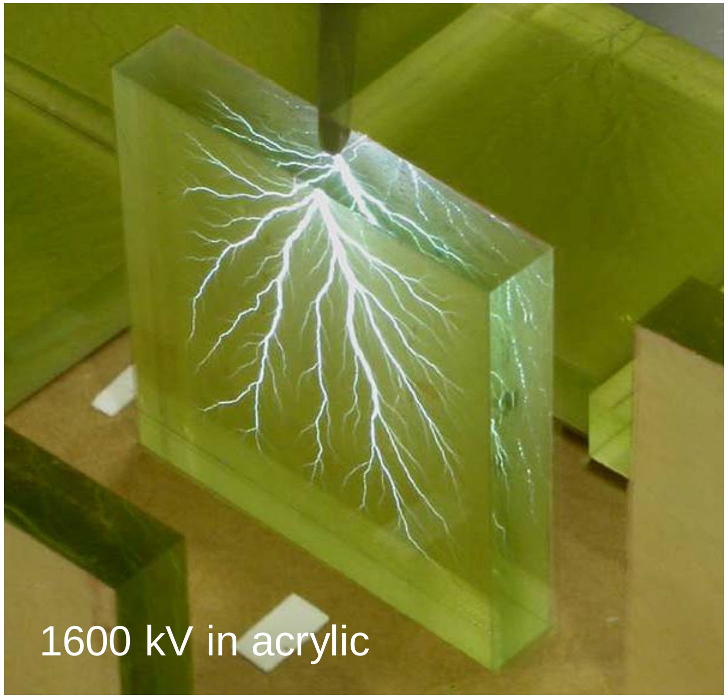
All of these require the highest energy we can achieve.

Getting a Beam of 7 TeV Protons

$$(1\ TeV = 10^{12}\ eV)$$

- In principle, this is simple: put 7 trillion volts of potential on a proton and …
- This may not be the safest course of action – here is what less than one four-millionth of this potential can do:

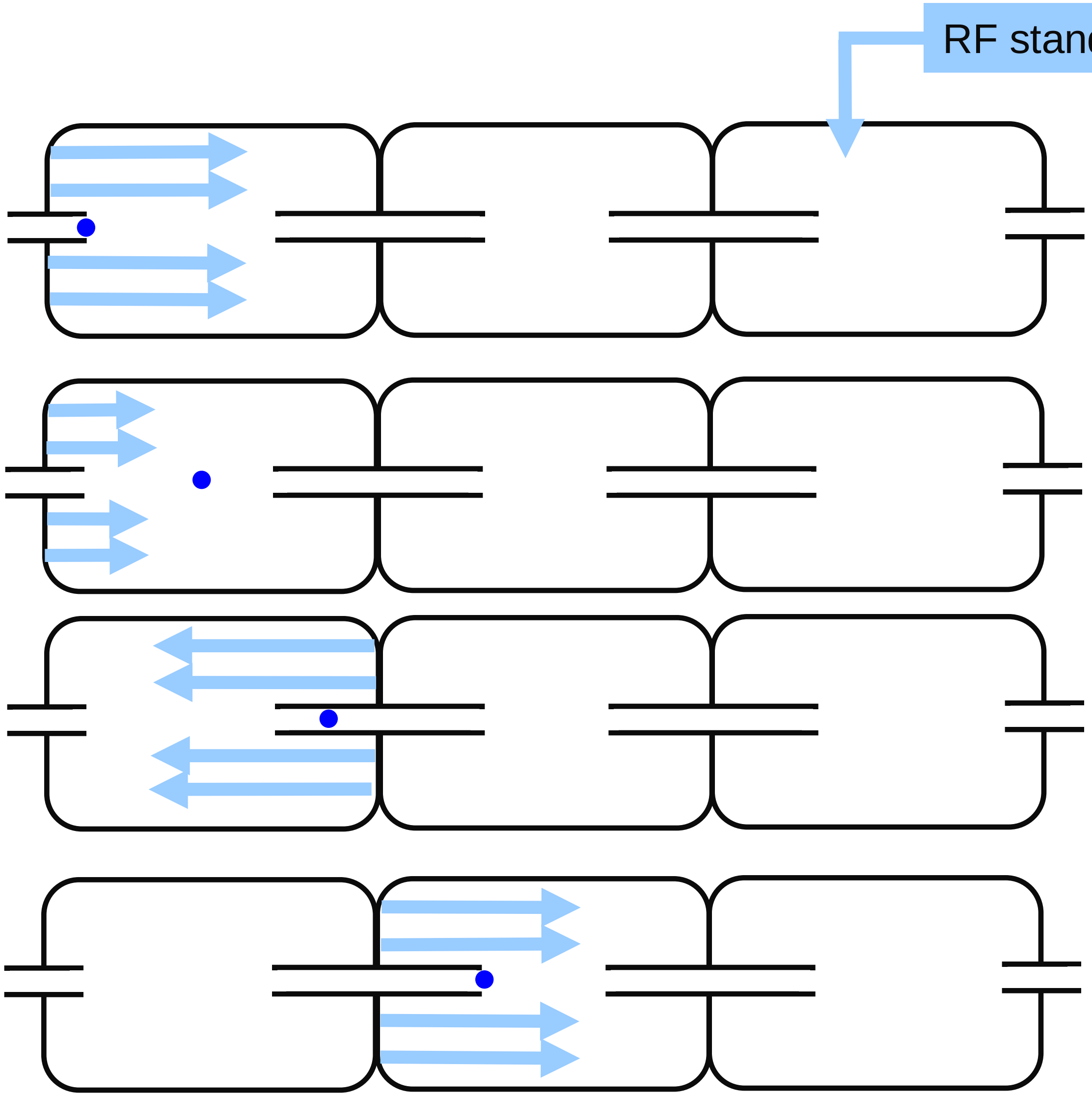
500 kV in air



1600 kV in acrylic

Even in vacuum this won't work – the electric fields necessary would rip the atoms apart.

How To Build a Linear Accelerator



RF standing wave inside these cavities

Proton enters cavity. Electric field accelerates it to the right.

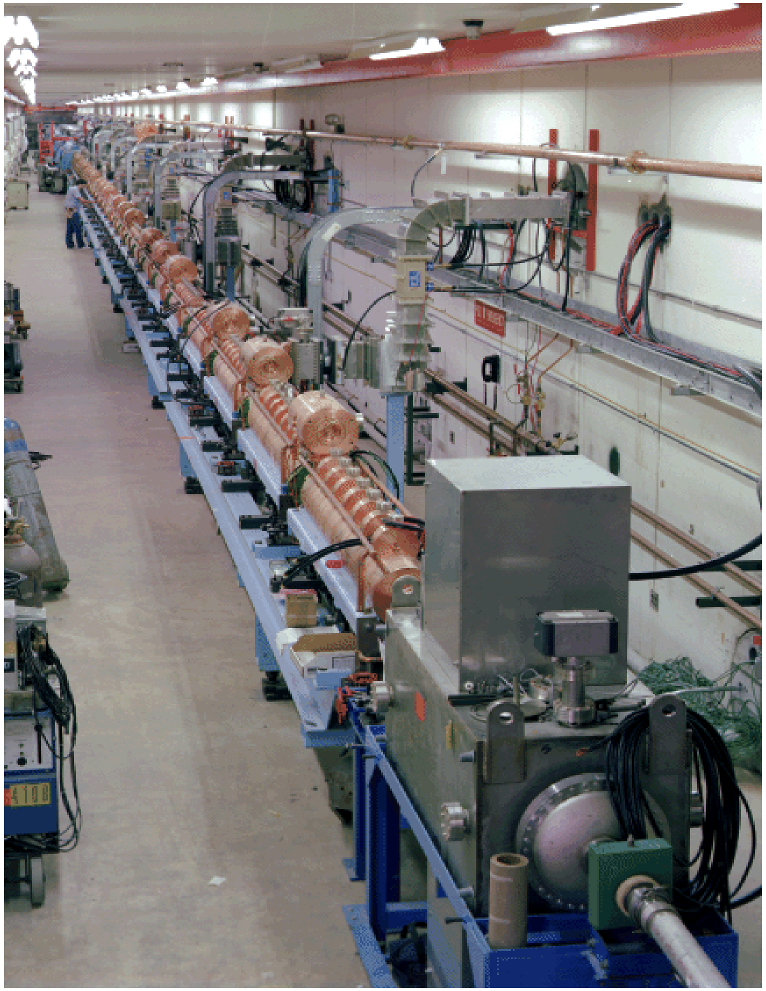
Proton continues. Electric field decreases.

Electric field reverses sign. Proton enters a field free region and feels no force.

Proton enters the next cavity. Electric field accelerates it to the right.

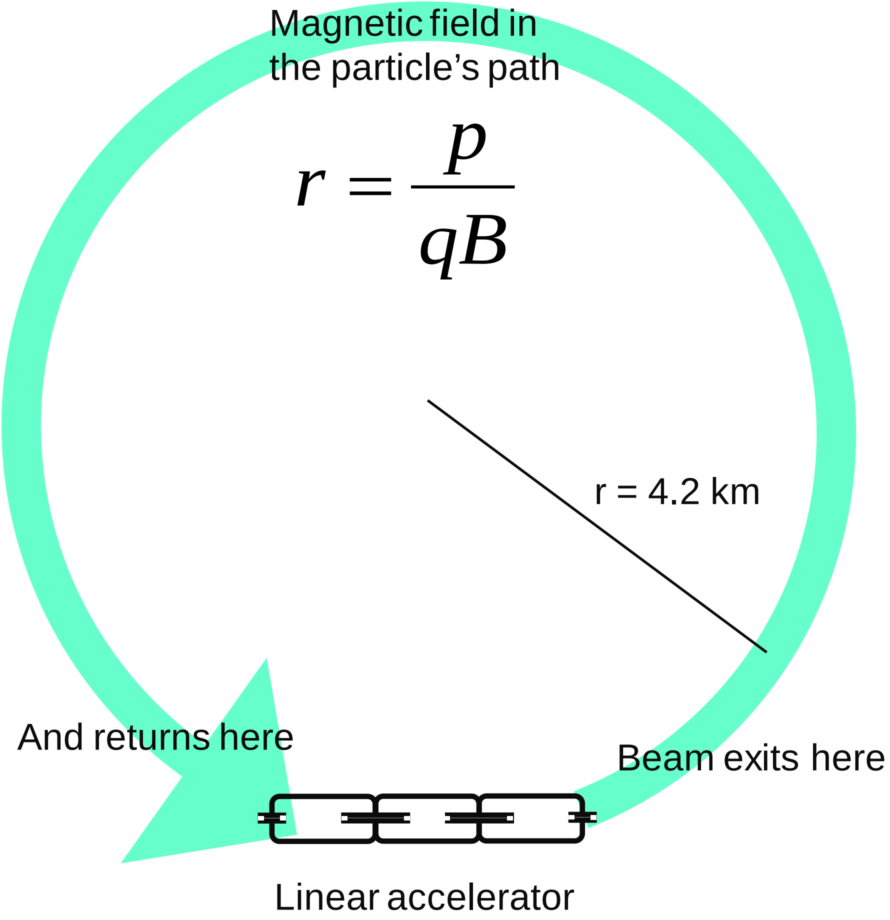
Linear Acceleration

- In principle, our problem is solved: simply build a long enough linear accelerator
- This isn’t too practical. Using state of the art cavities, reaching the LHC energy of 7 TeV on 7 TeV means
  - It would be 150 miles long
  - It would cost $75 billion USD



A portion of Fermilab’s linear accelerator

Recycling: The Proton Synchrotron



Magnetic field in the particle's path

$$r = \frac{p}{qB}$$

r = 4.2 km

And returns here

Beam exits here

Linear accelerator

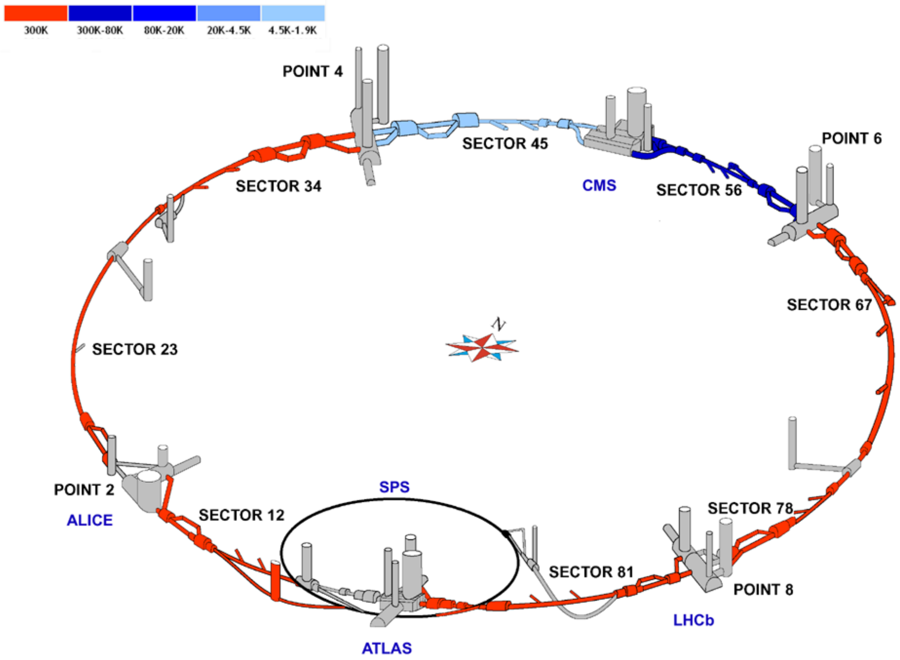
- Accelerating structures are reused ~20 million times during each fill of the LHC
- The cost of such a machine is ~an order of magnitude cheaper than an equivalent linear accelerator
- The energy that can be reached is limited by the strength of the magnetic field in the arcs

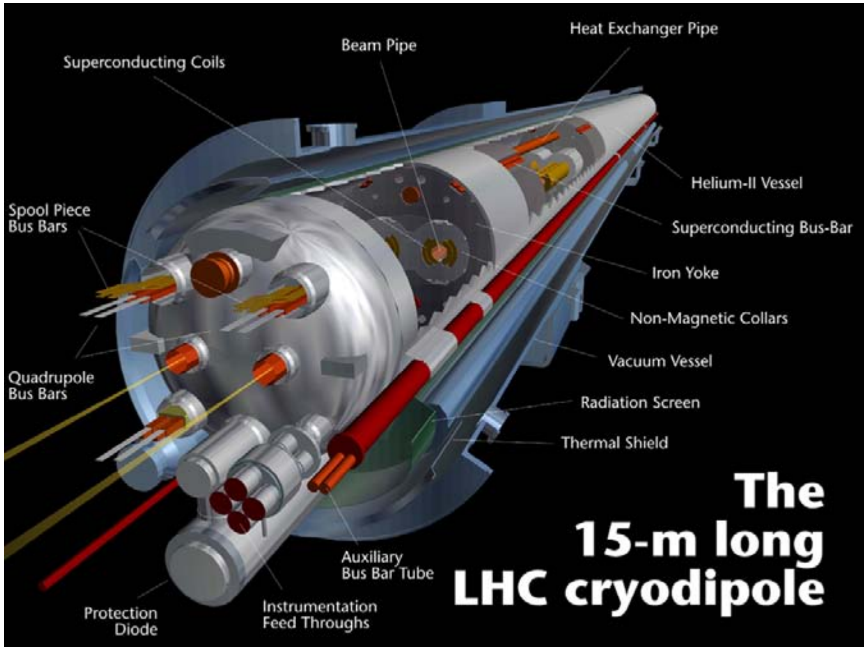
High energy physicists usually set $c=h/2\pi=1$.

A Less Cartoonish View

The Large Hadron Collider is a 26km long circular accelerator built at CERN, near Geneva Switzerland.

The magnetic field is created by 1232 dipole magnets (plus hundreds of focusing and correction magnets) arranged in a ring in the tunnel.

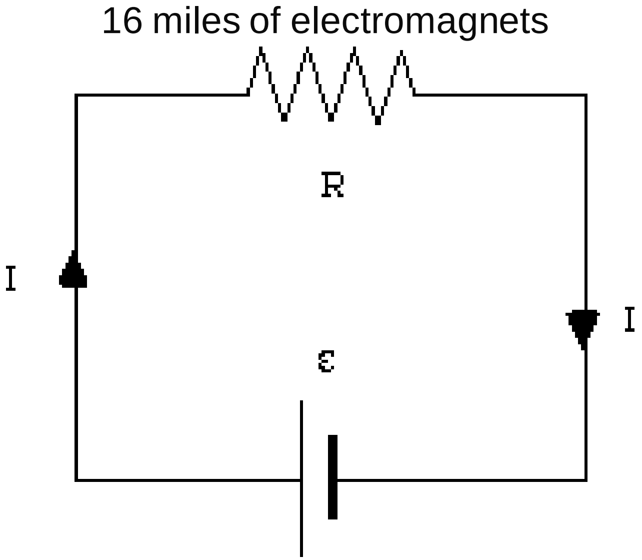




Our Next Problem - Resistance

- To generate the field we want, we need to carry about 12000 Amperes.
- NFPA code says one needs a “wire” that has a diameter of about 14” to safely carry this current.
  - This is 000…000 (32 zeros) gauge “wire”
    - *In practice one would use a shaped piece of copper.*
    - *It’s probably impossible to control the shape of the current flow accurately enough*
- Resistance is only 0.02 Ω
  - This means Joule heating is 3 megawatts

Need to go to superconducting magnets.



LHC Circuit Diagram

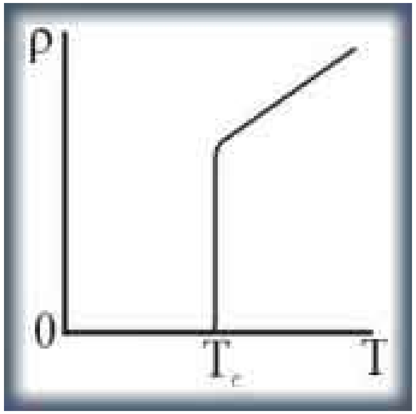
$$E = IR$$

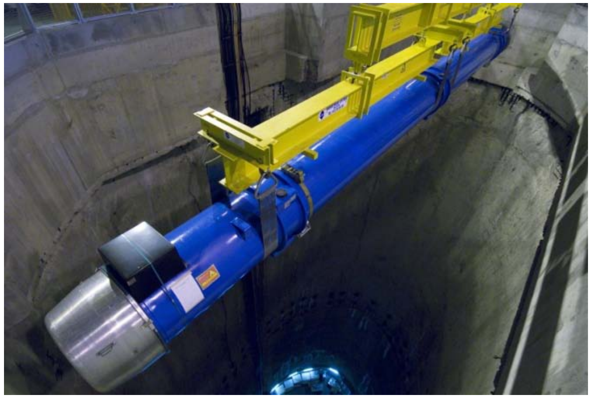
$$P = EI$$

$$P = I^2 R$$

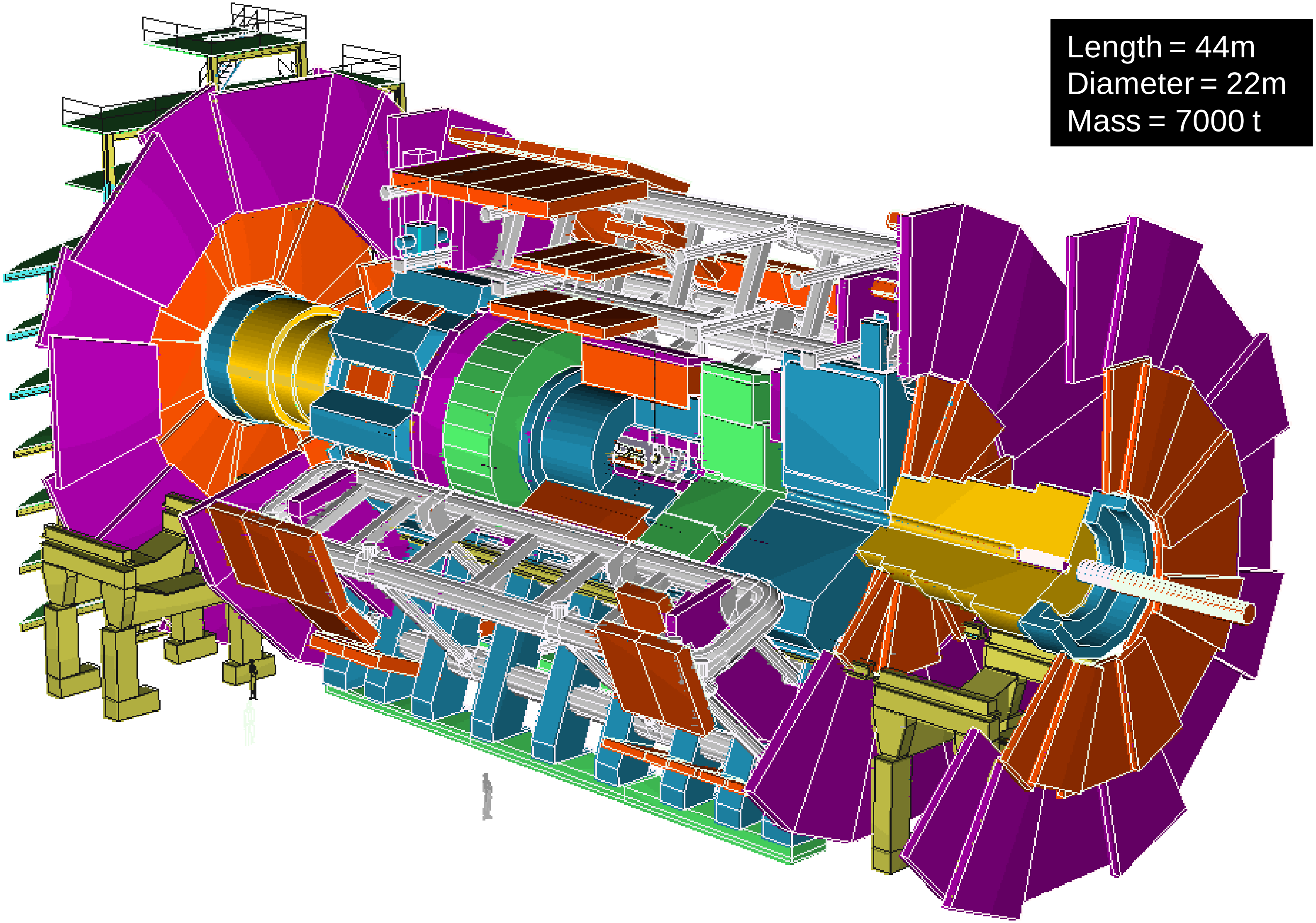
Using Superconducting Magnets

- Zero resistance – a good thing!
- Field is limited to ~9 Tesla
- They have to be kept cold: around 1.9K





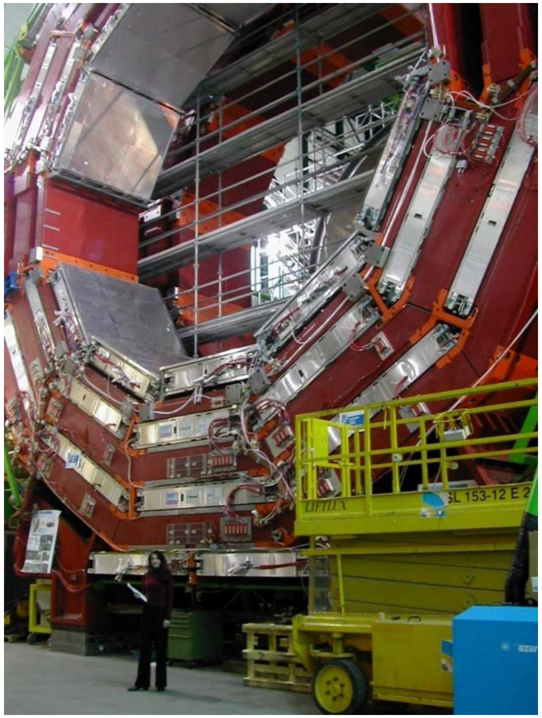
ATLAS = A Toroidal LHC ApparatuS

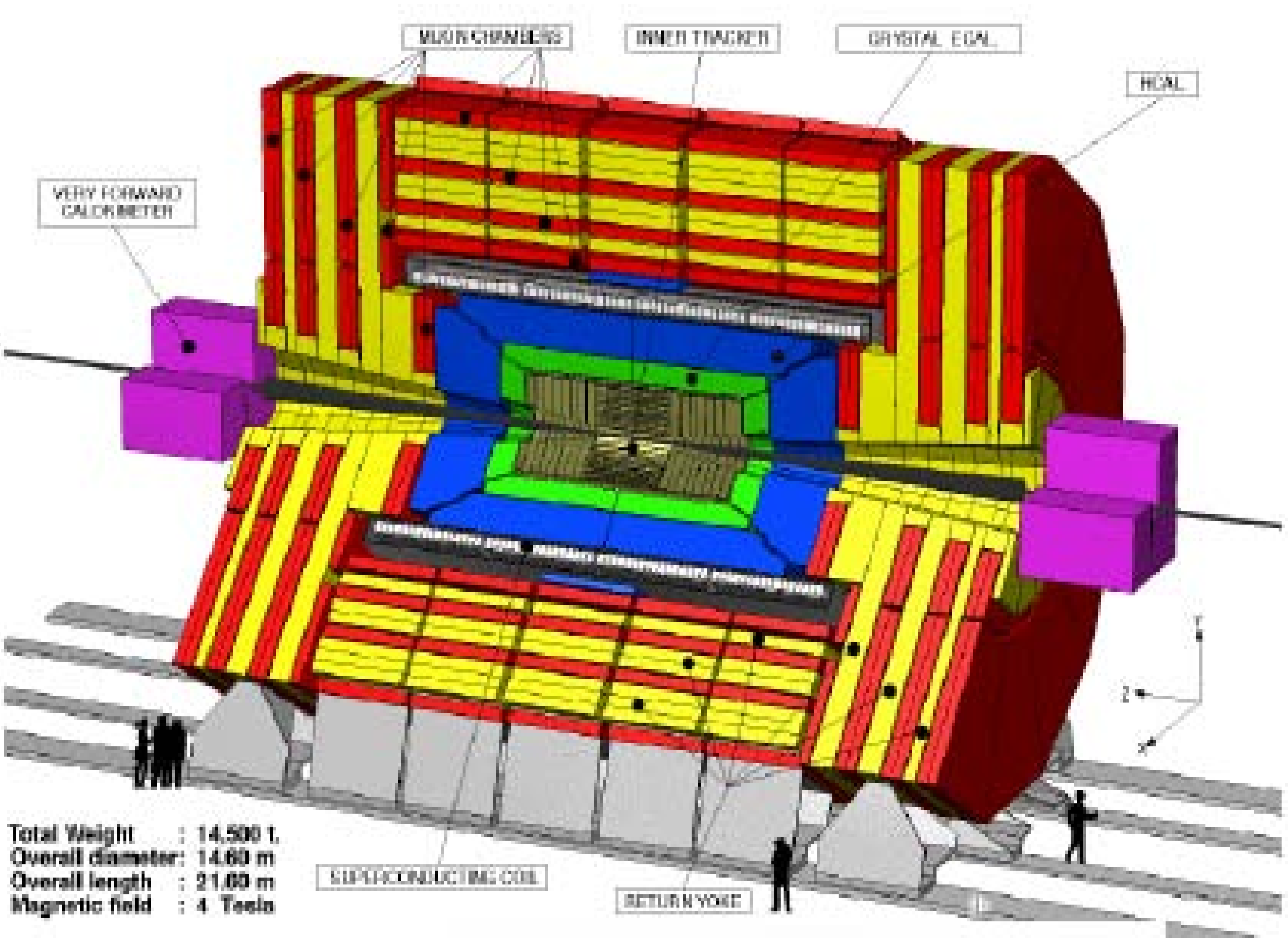


Length = 44m
Diameter = 22m
Mass = 7000 t

CMS

The compact Muon Solenoid Experiment

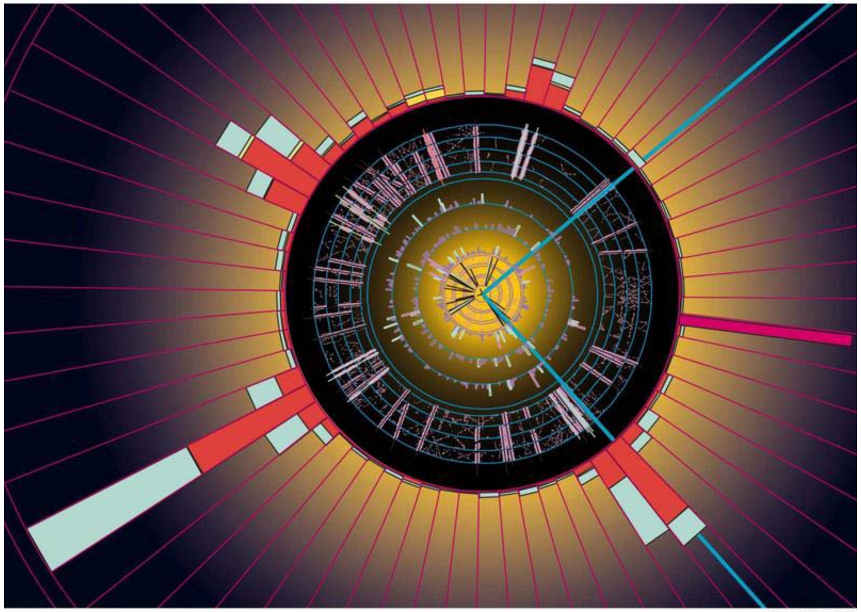




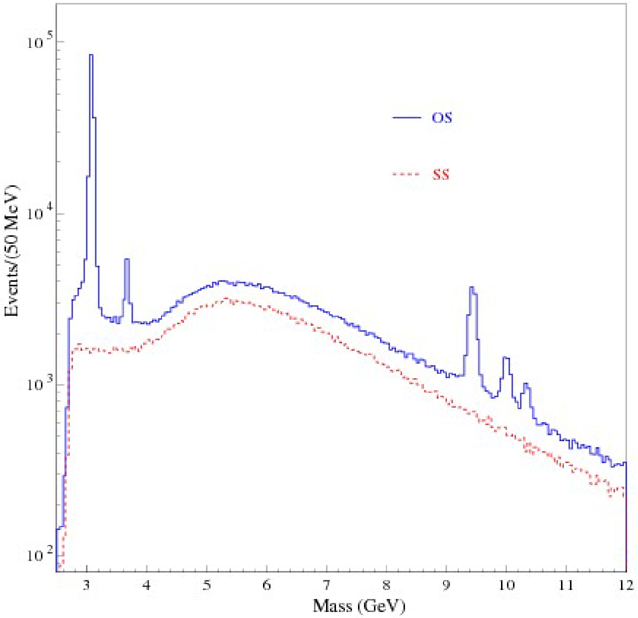
Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Understanding a Collision

- Most particles we are interested in decay in a very short time:
  - Around 10^{-24} s
  - We don't detect them – we can only detect their decay products



Fermilab #97-1889D

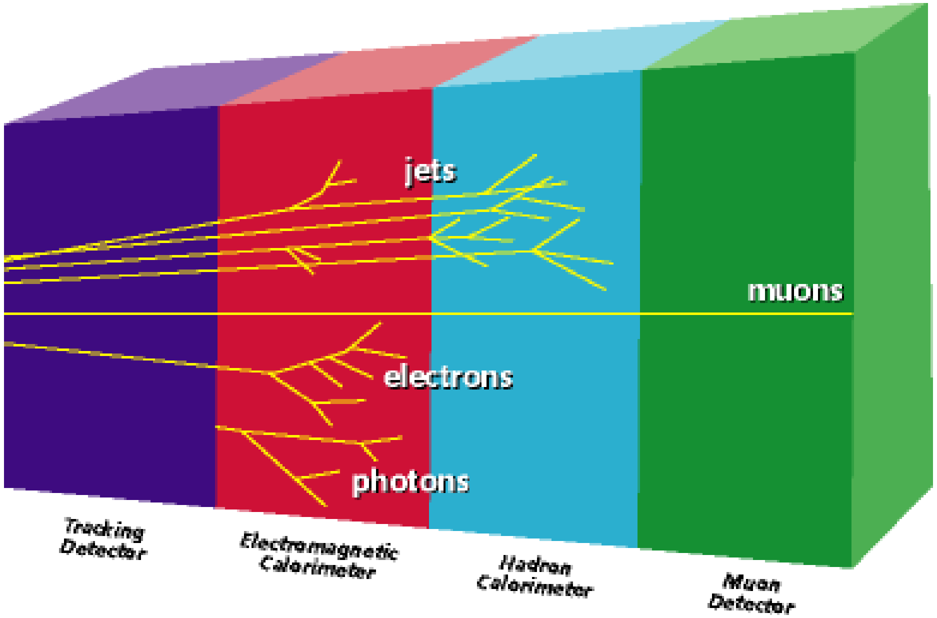


A common trick is to combine the particles you detect assuming they are the daughters in a decay chain, and plot the invariant mass of the combination.

A bump means you've correctly reconstructed the parent.

J/Ψ (charm quark) was discovered, in a similar way, by Sam Ting in 1974.

How It Works



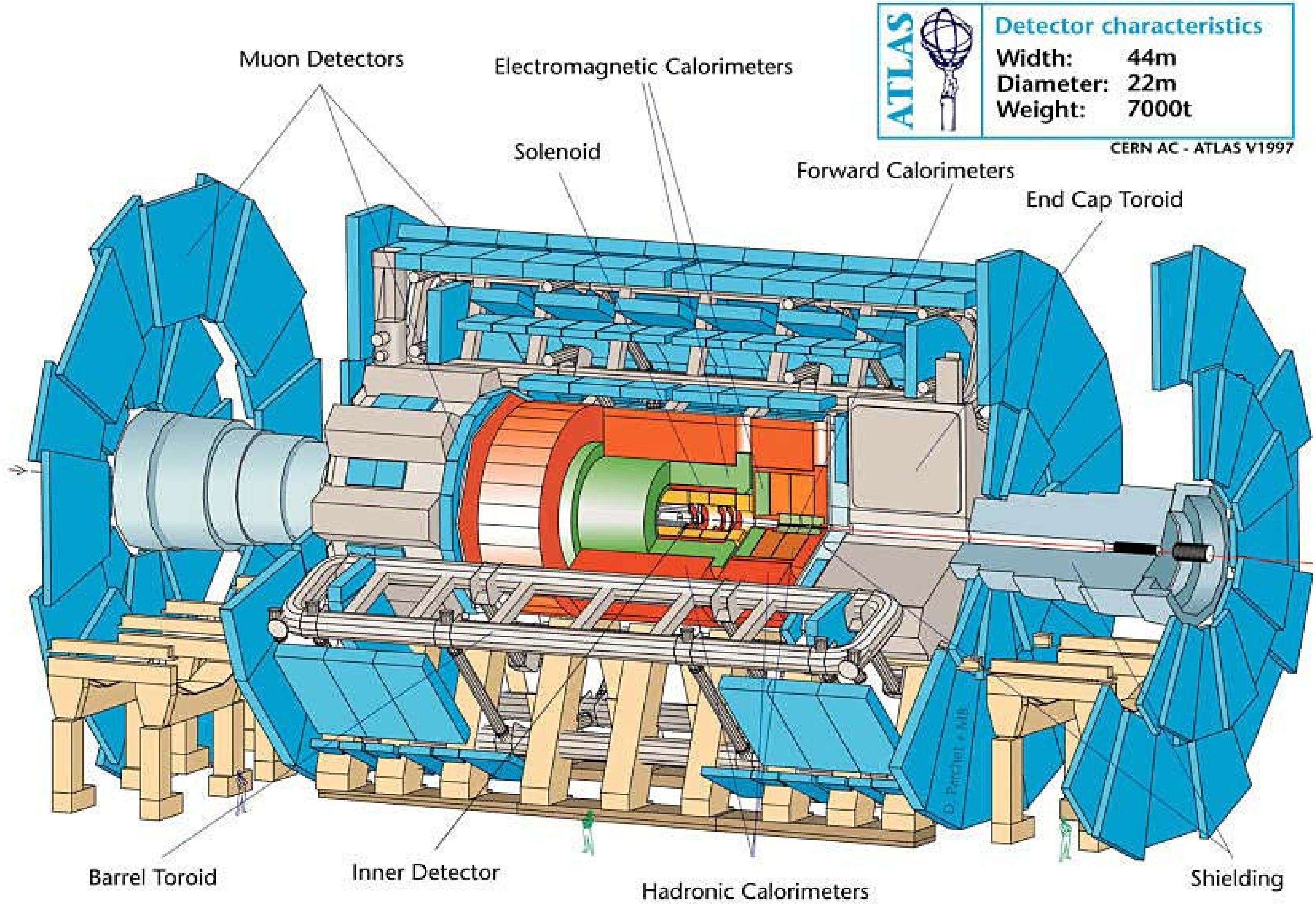
Different particles propagate differently through different parts of the detector; this enables us to identify them.

- Particles curve in a central magnetic field
  - Measures their momentum

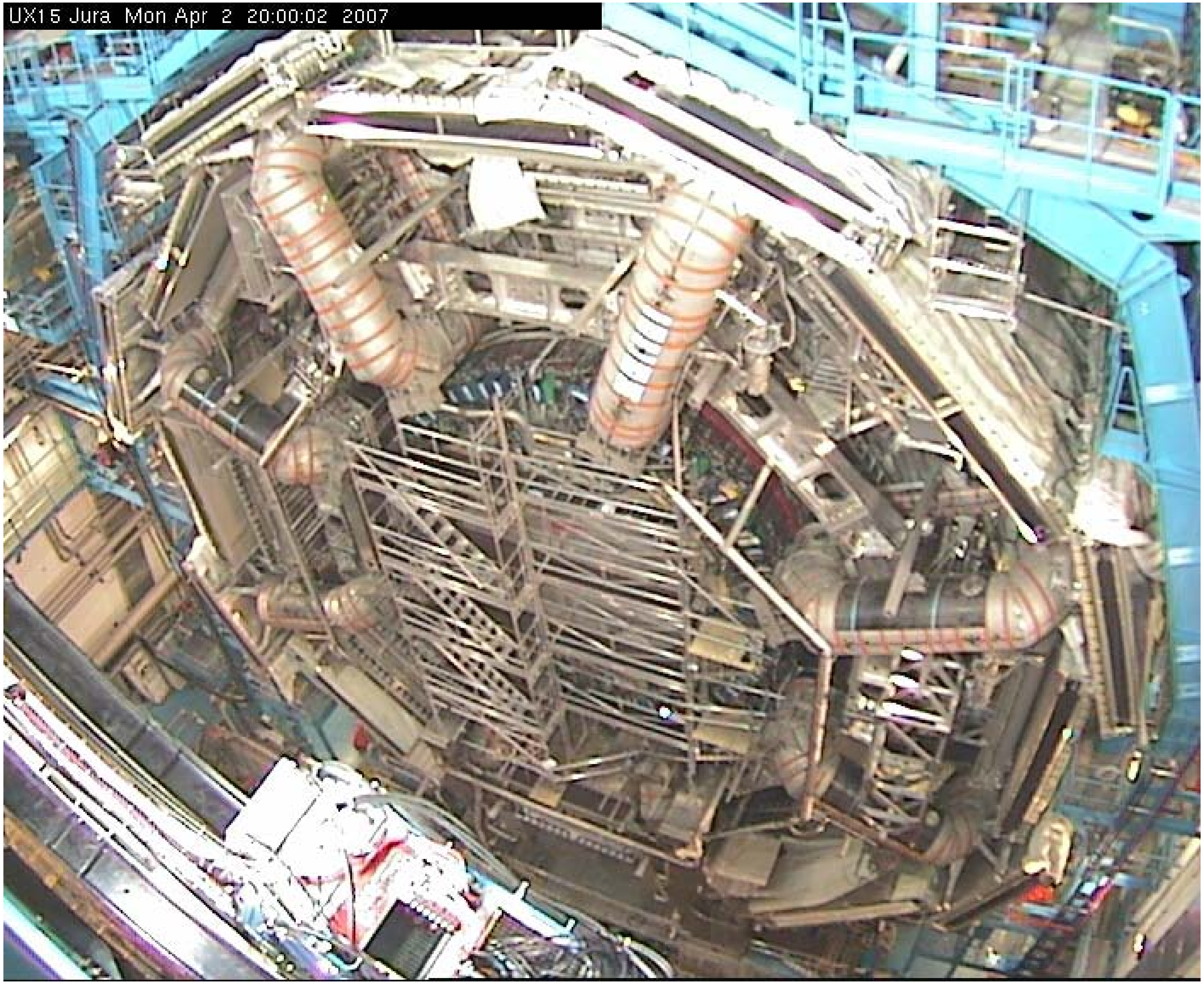
$$\boxed{r = \frac{p}{qB}}$$

- Particles then stop in the calorimeters
  - Measures their energy
- Except muons, which penetrate and have their momenta measured a second time.

ATLAS Revisited



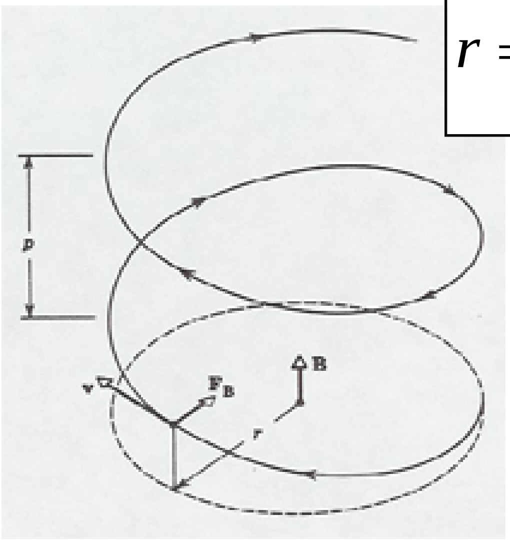
What ATLAS Looks Like Today



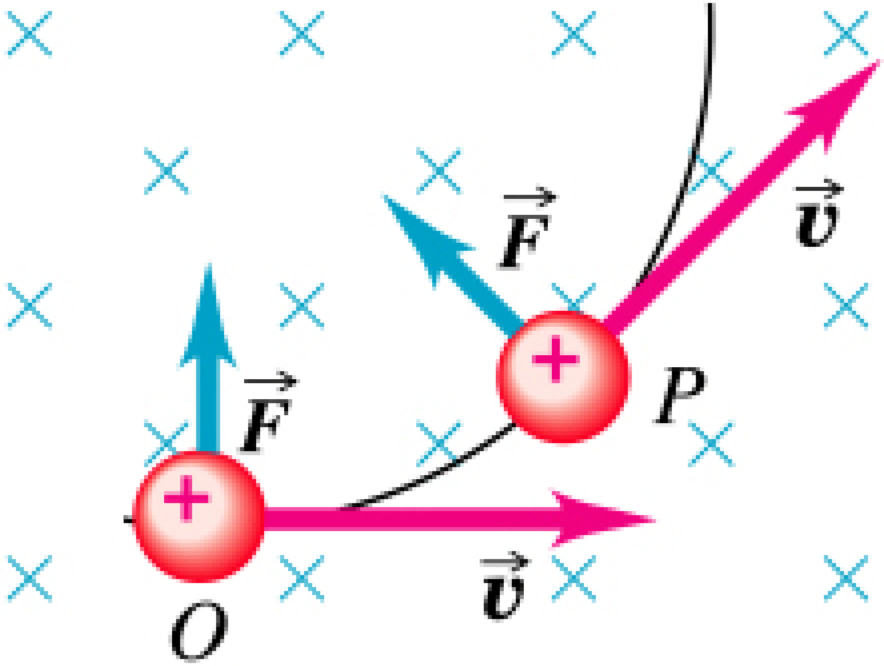
Why is ATLAS so big?

Motion of a Particle in a Magnetic Field

Charged particles in a uniform magnetic field $\vec{B} = B_0\hat{z}$ move in helices:



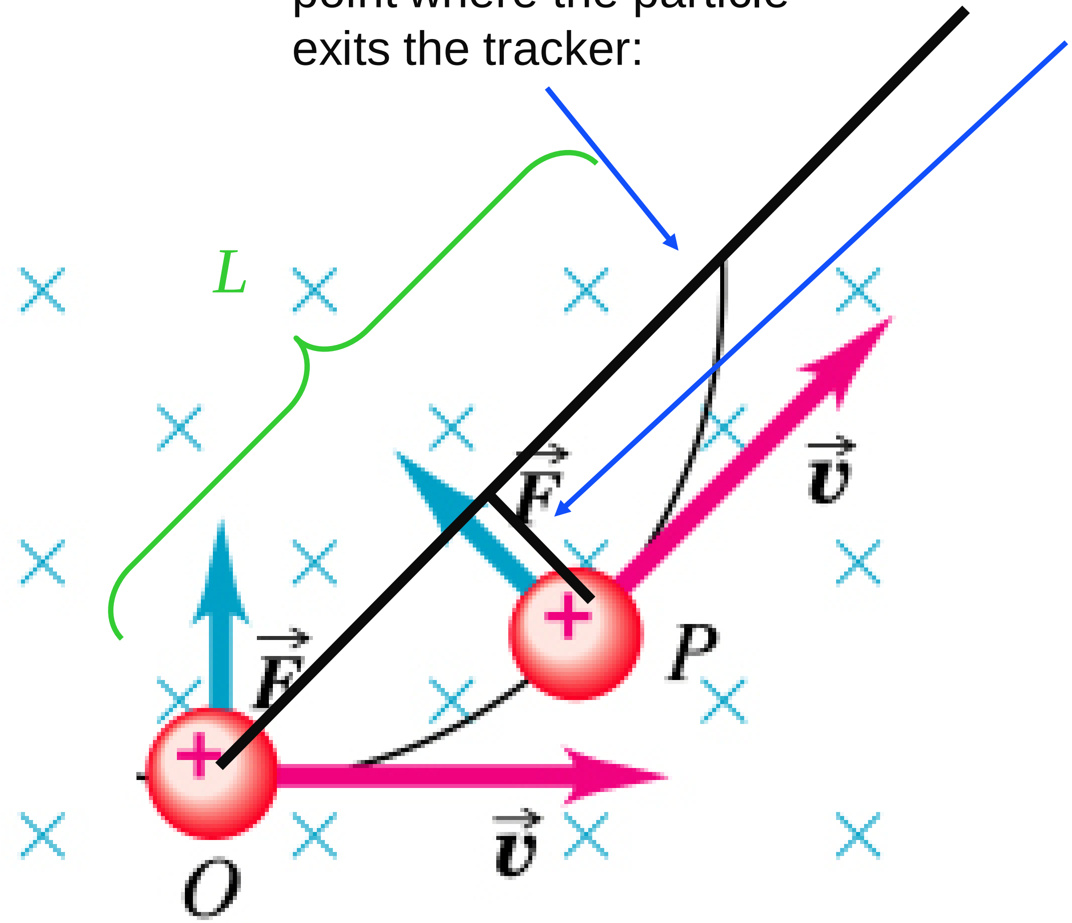
$$\boxed{r = \frac{p}{qB}}$$



It’s convenient to work in the transverse plane (i.e. the plane normal to the B direction)

In this plane, the helices project to circles.

Tracking measures 1/p



The sagitta (“arrow”) s is the distance of maximum deflection from a straight line track:

$$s = \frac{qBL^2}{8\,p_T}$$

or

$$p_T = \frac{qBL^2}{8s}$$

(Transverse momentum, relative to the beam axis.)

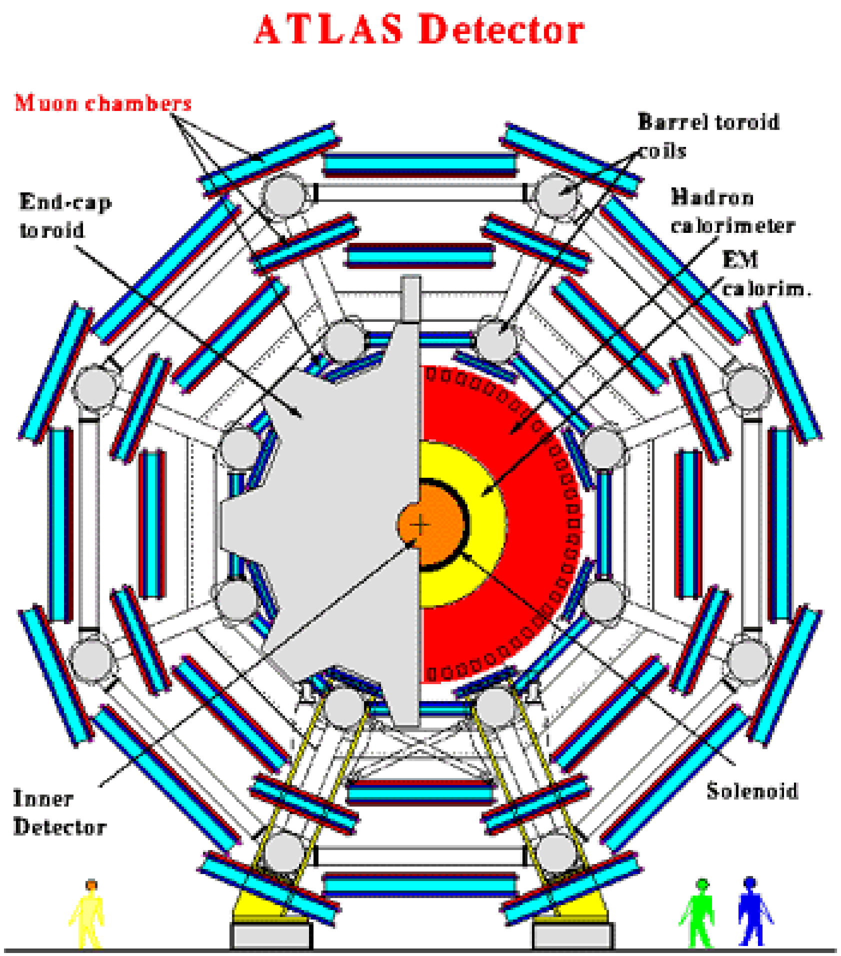
Why is ATLAS so big?

- The tracking power goes as BL^2
- The stored energy in the magnetic field goes as $(B^2)(L^3)$
- The cost goes roughly as (stored energy)^n

For a fixed cost,
performance goes as $\sqrt{L}$

Conclusion: Build ATLAS as big as you possibly can

The ATLAS Muon Spectrometer



Beam’s eye view: d= 22m

Pictures from Jim Shank, Boston University

- We would like to measure a 1 TeV muon momentum to about 10%.
  - Implies a sagitta resolution of about 100 µm.
- Thermal expansion is enough to cause problems.

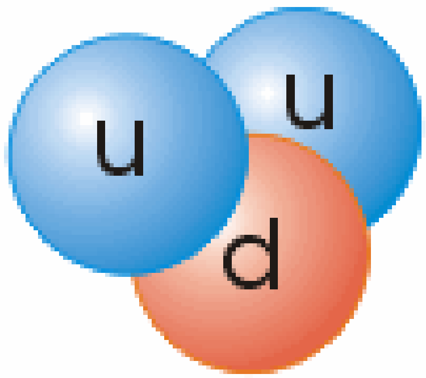
$$\frac{\Delta x}{x} = \alpha \Delta T$$

$$\Delta T = \frac{\Delta x}{\alpha x} \approx 0.2K$$

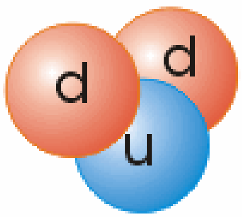
- Instead of keeping the detector in position, we let it flex:
  - It’s easier to continually measure where the pieces are than to keep it perfectly rigid.

An Early Modern, Popular and Wrong View of the Proton

The Proton



The Neutron



- The proton consists of two up (or *u*) quarks and one down (or *d*) quark.
    - A u-quark has charge +2/3
    - A d-quark has charge –1/3
- The neutron consists of just the opposite: two d’s and a u
    - Hence it has charge 0
- The u and d quarks weigh the same, about 1/3 the proton mass
    - That explains the fact that m(n) = m(p) to about 0.1%
- Every hadron in the Particle Zoo has its own quark composition

So what’s missing from this picture?

Energy is Stored in Fields

Thunder is good, thunder is impressive; but it is lightning that does the work.
(Mark Twain)

- We know energy is stored in electric & magnetic fields
  - Energy density ~ $E^2 + B^2$
  - The picture to the left shows what happens when the energy stored in the earth's electric field is released
- Energy is also stored in the gluon field in a proton
  - There is an analogous $E^2 + B^2$ that one can write down
  - There's nothing unusual about the idea of energy stored there
    - *What's unusual is the amount:*

	Energy stored in the field
Atom	10^{-8}
Nucleus	1%
Proton	99%

$E = M c^2$ Mass is a form of energy.

Interactions Generate Mass

- Quarks themselves only contribute a very small part, about 1.3%, of the proton (uud) mass:

- 99.7% of proton mass originates from the interactions among the 3 quarks inside proton. (Mass is a form of kinetic and potential energy.)

Nambu (Nobel Prize 2008)

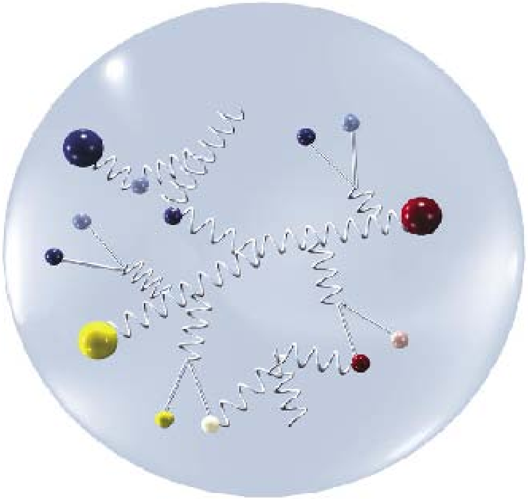
- These energies are converted into the mass of the proton as described by Einstein's equation that relates

Energy (E) to Mass (M) by

$$E = M c^2$$

C is the speed of light = 3×10^8 meters per second.

The Modern Proton



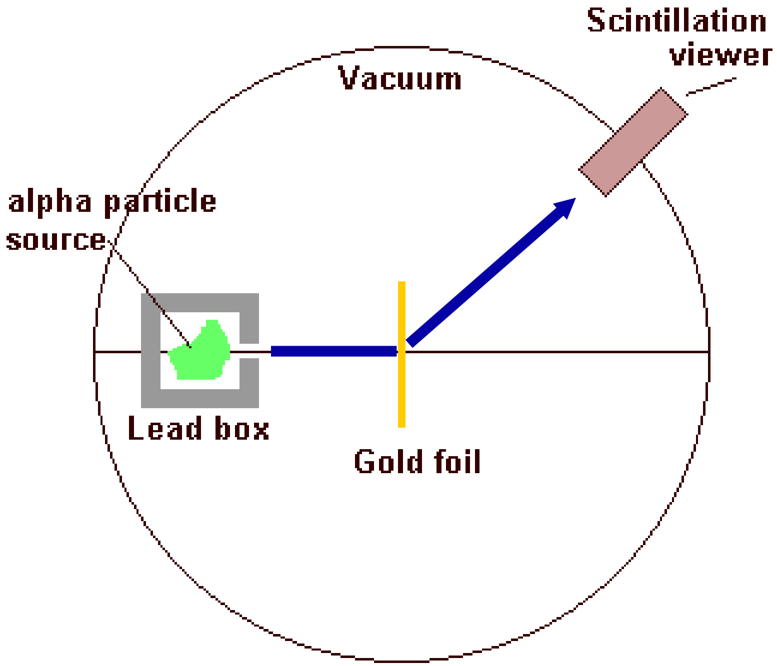
The Proton

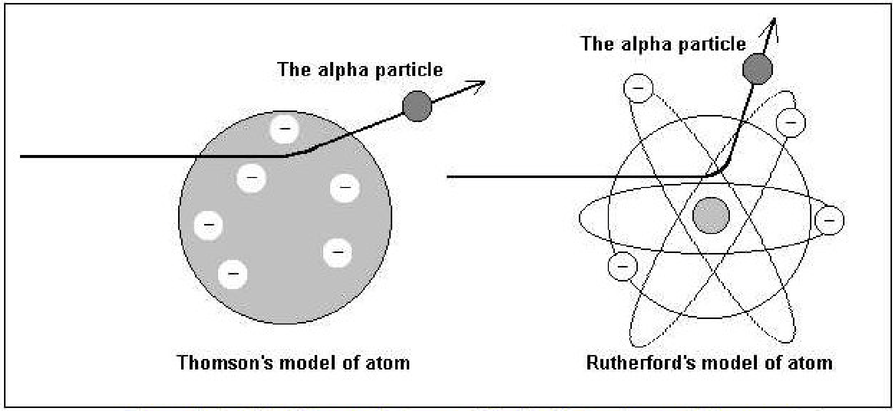
Mostly a very dynamic self-interacting field of gluons, with three quarks embedded.

Like plums in a pudding.

- 99% of the proton's mass/energy is due to this self-generating gluon field
- The two u-quarks and single d-quark
  - 1. Act as boundary conditions on the field (a more accurate view than generators of the field)
  - 2. Determine the electromagnetic properties of the proton
    - *Gluons are electrically neutral, so they can't affect electromagnetic properties*
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Has nothing to do with the quarks

The “Rutherford Experiment” of Geiger and Marsden





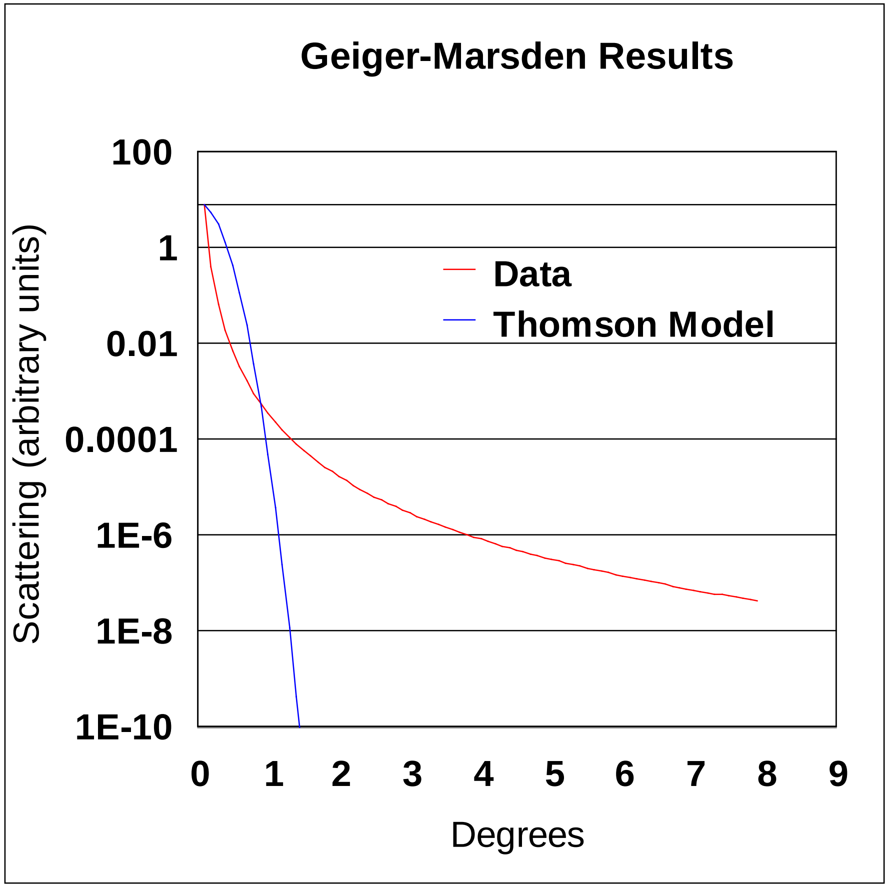
The models of the Thomson's atom and Rurtherford's atom; and the expected aberrations of alpha particle in both cases.

α particle scatters from source, off the gold atom target, and is detected by a detector that can be swept over a range of angles

(n.b.) α particles were the most energetic probes available at the time

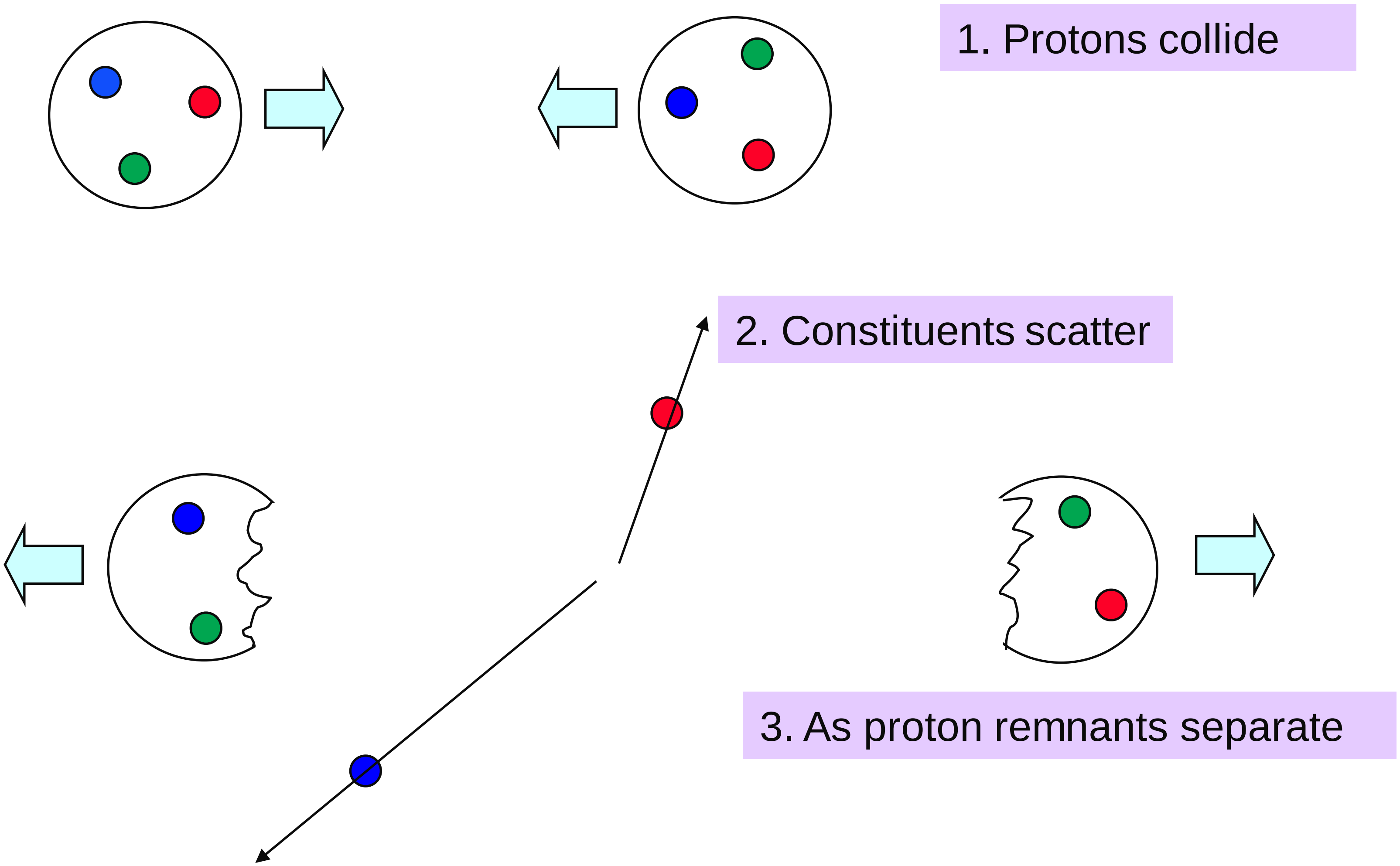
The electric field the α experiences gets weaker and weaker as the α enters the Thomson atom, but gets stronger and stronger as it enters the Rutherford atom and nears the nucleus.

Results of the Experiment



- At angles as low as 3^o, the data show a million times as many scatters as predicted by the Thomson model
  - Textbooks often point out that the data disagreed with theory, but they seldom state how bad the disagreement was
- There is an excess of events with a large angle scatter
  - This is a universal signature for substructure
  - It means your probe has penetrated deep into the target and bounced off something hard and heavy
- An excess of large angle scatters is the same as an excess of large transverse momentum scatters

Proton Collisions: The Ideal World



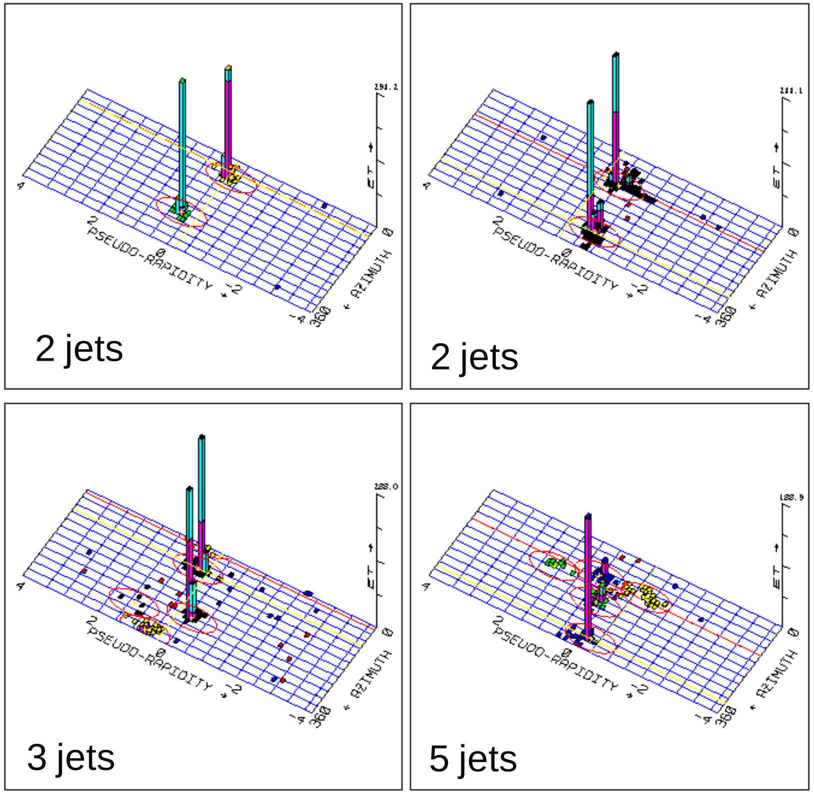
1. Protons collide

2. Constituents scatter

3. As proton remnants separate

What Really Happens

You don’t see the constituent scatter. You see a **jet**: a “blast” of particles, all going in roughly the same direction.



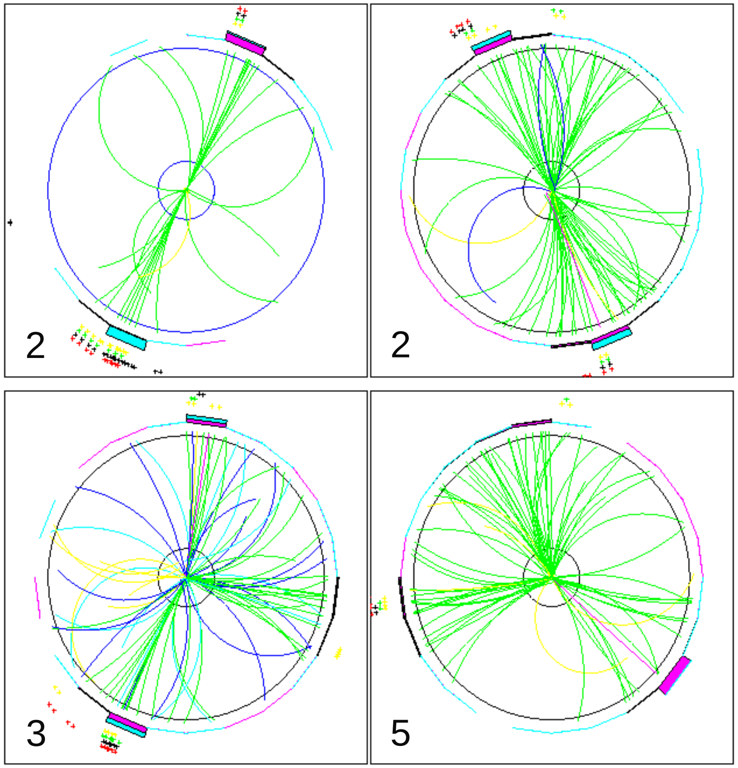
2 jets

2 jets

3 jets

5 jets

Calorimeter View



2

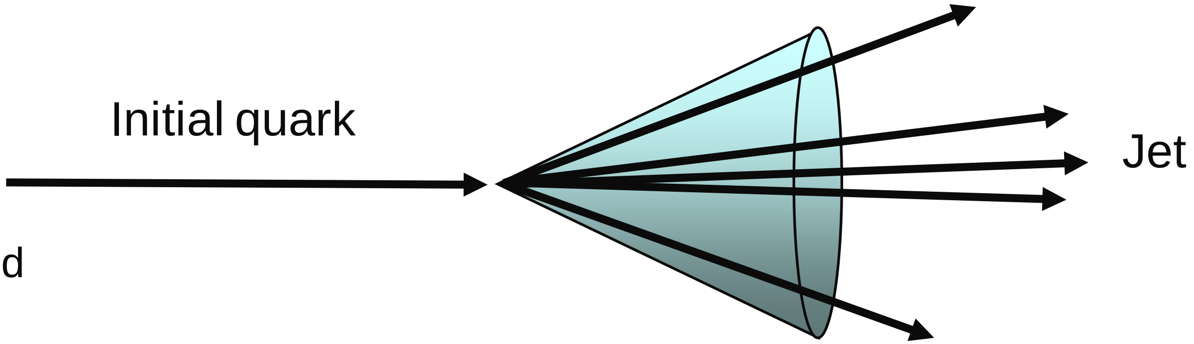
2

3

5

Same Events, Tracking View

Jets



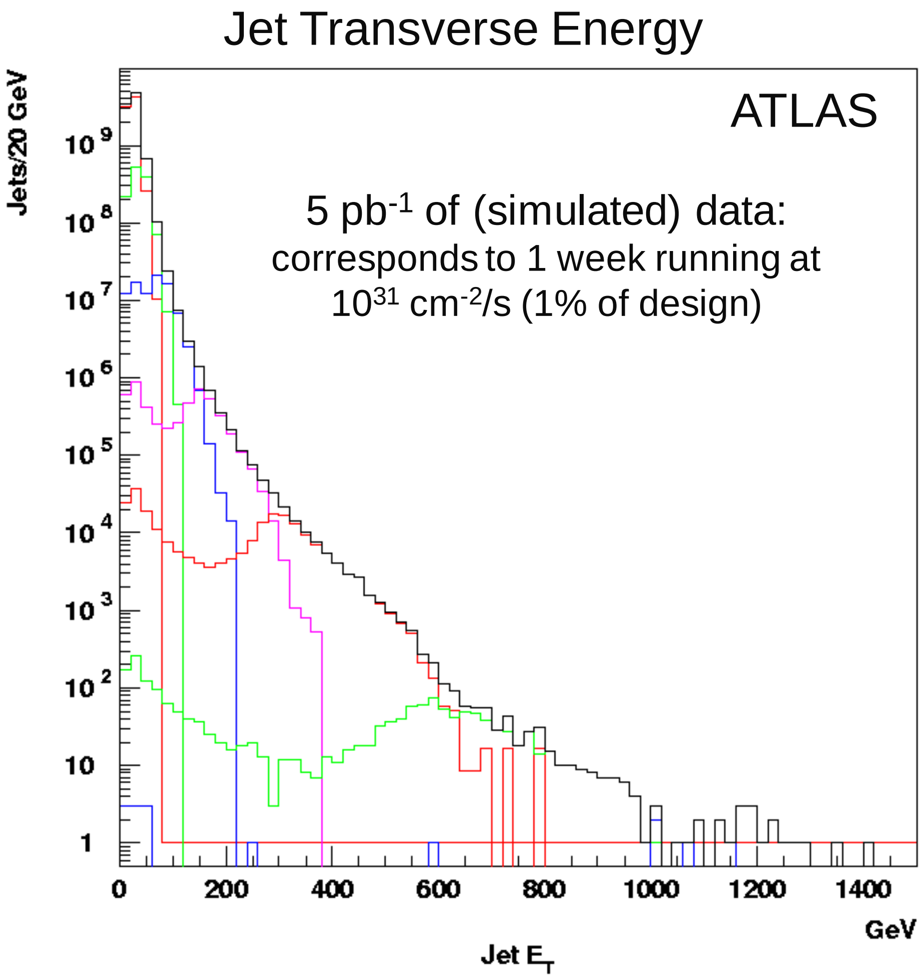
- The force between two colored objects (e.g. quarks) is ~independent of distance
  - Therefore the potential energy grows (~linearly) with distance
  - When it gets big enough, it pops a quark-antiquark pair out of the vacuum
  - These quarks and antiquarks ultimately end up as a collection of hadrons

- At this moment, we can't calculate how often a jet's final state is, e.g. ten π's, three K's and a Λ.

- Fortunately, **it doesn't matter**.
  - We're interested in the quark or gluon that produced the jet.
  - Summing over all the details of the jet's composition and evolution is A Good Thing.
    - *Two jets of the same energy can look quite different; this lets us treat them the same*

What makes the measurement possible & useful is the conservation of energy & momentum.

Jets after "One Week"

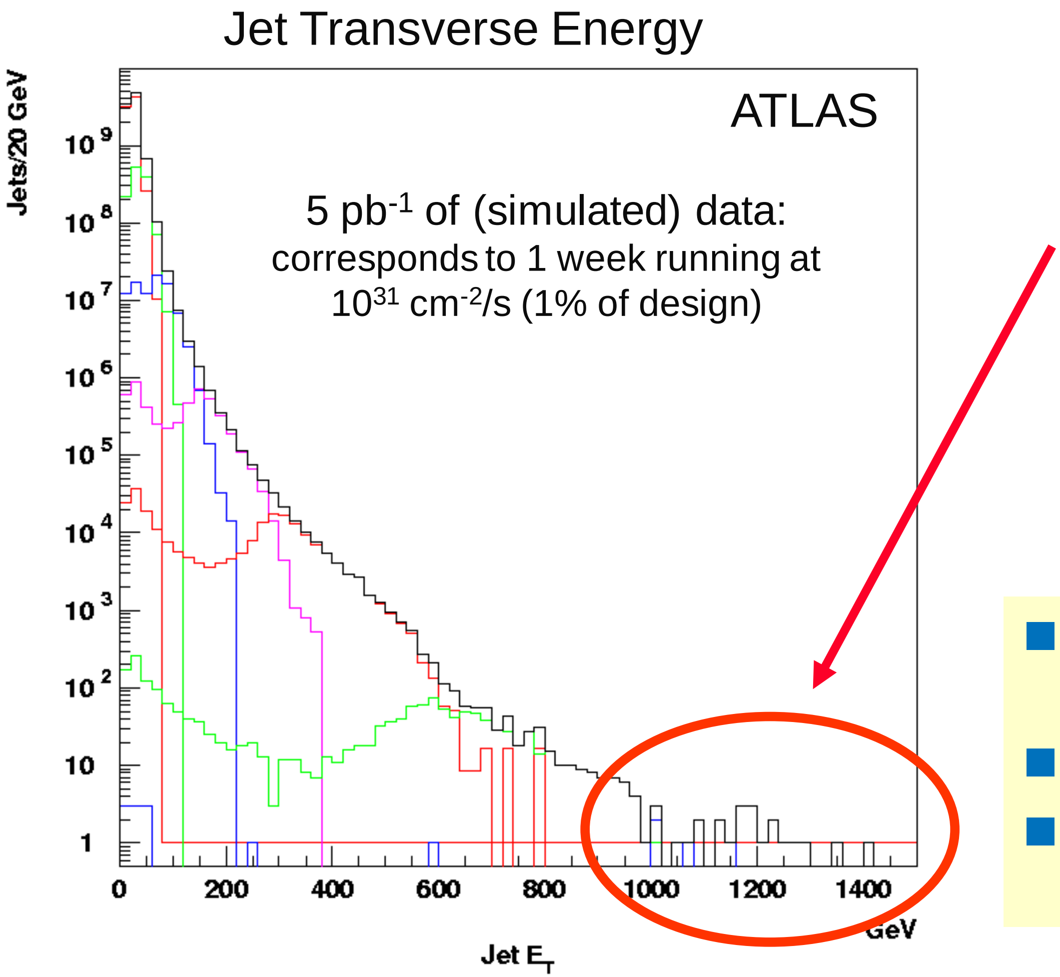

Jet Transverse Energy

ATLAS

5 pb^{-1} of (simulated) data:
corresponds to 1 week running at
10^{31} cm^{-2}/s (1% of design)

This is in units of transverse momentum. Remember, large angle = large p_T

Jets after “One Week”



Jet Transverse Energy

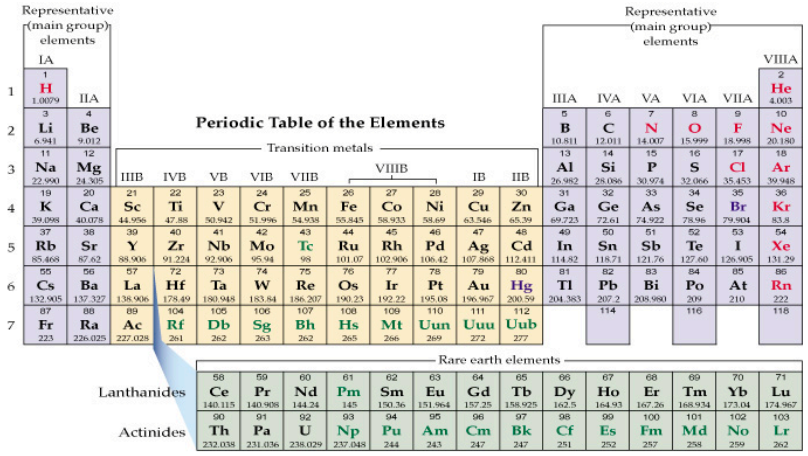
ATLAS

5 pb^{-1} of (simulated) data:
corresponds to 1 week running at
10^{31} cm^{-2}/s (1% of design)

New physics (e.g. quark substructure) shows up here.

- Number of events we expect to see: ~**12**
- If new physics: ~**50**
- Number we have seen to date worldwide: **0**

Compositeness & The Periodic Table(s)



Representative (main group) elements

Periodic Table of the Elements

Transition metals

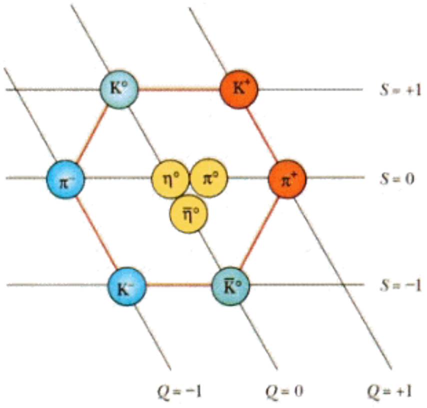
	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 H 1.0079																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.066	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.8
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc 98	44 Ru 101.07	45 Rh 102.906	46 Pd 106.42	47 Ag 107.868	48 Cd 112.411	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.905	54 Xe 131.29
6	55 Cs 132.905	56 Ba 137.327	57 La 138.906	72 Hf 178.49	73 Ta 180.948	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.967	80 Hg 200.59	81 Tl 204.383	82 Pb 207.2	83 Bi 208.980	84 Po 209	85 At 210	86 Rn 222
7	87 Fr 223	88 Ra 226.025	89 Ac 227.028	104 Rf 261	105 Db 262	106 Sg 263	107 Bh 262	108 Hs 265	109 Mt 266	110 Uun 269	111 Uuu 272	112 Uub 277		114		116		118

Rare earth elements

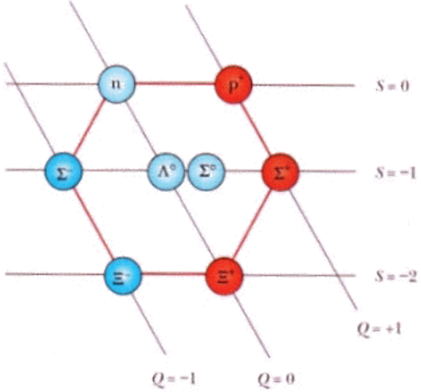
Lanthanides	58 Ce 140.115	59 Pr 140.908	60 Nd 144.24	61 Pm 145	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.925	66 Dy 162.5	67 Ho 164.93	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.967
Actinides	90 Th 232.038	91 Pa 231.036	92 U 238.029	93 Np 237.048	94 Pu 244	95 Am 243	96 Cm 247	97 Bk 247	98 Cf 251	99 Es 252	100 Fm 257	101 Md 258	102 No 259	103 Lr 262

Arises because atoms have substructure:
electrons

Arises because hadrons have substructure:
quarks



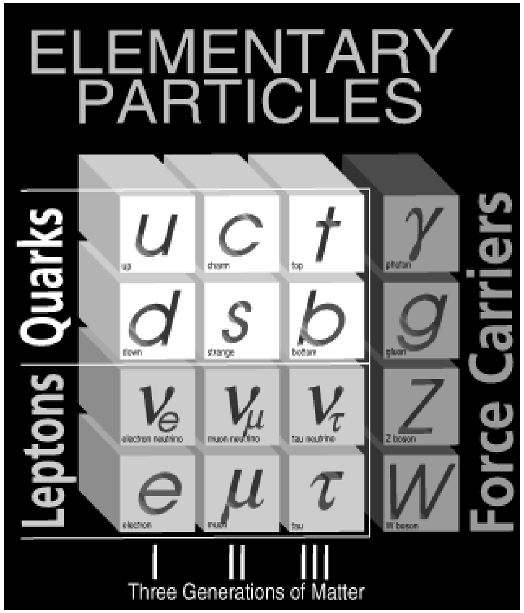
The 9 lightest spin-0 particles



The 8 lightest spin-1/2 particles

Quark model

Variations on a Theme?

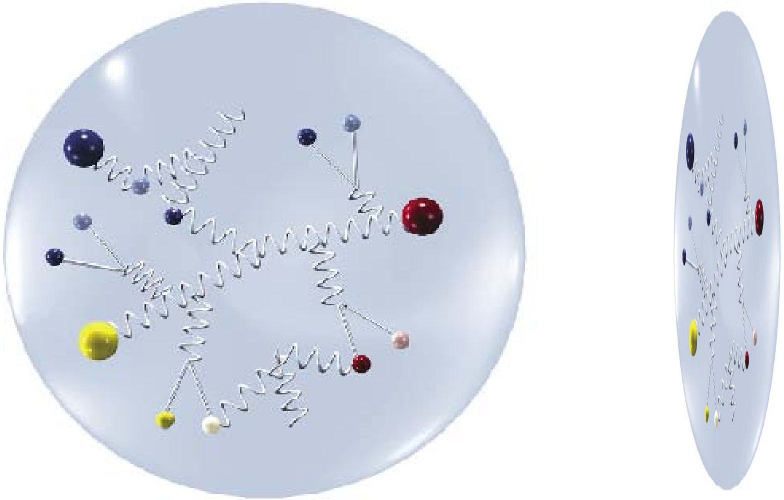


Does this arise because quarks have substructure?

- A good question – and one that the LHC would address
- Sensitivity is comparable to where we found “the next layer down” in the past.
  - Atoms: nuclei (10^5:1)
  - Nuclei: nucleons (few:1)
  - Quarks ($>10^4$:1) will become ($\sim10^5$:1)
- There are some subtleties: if this is substructure, its nature is different than past examples.

The Structure of the Proton

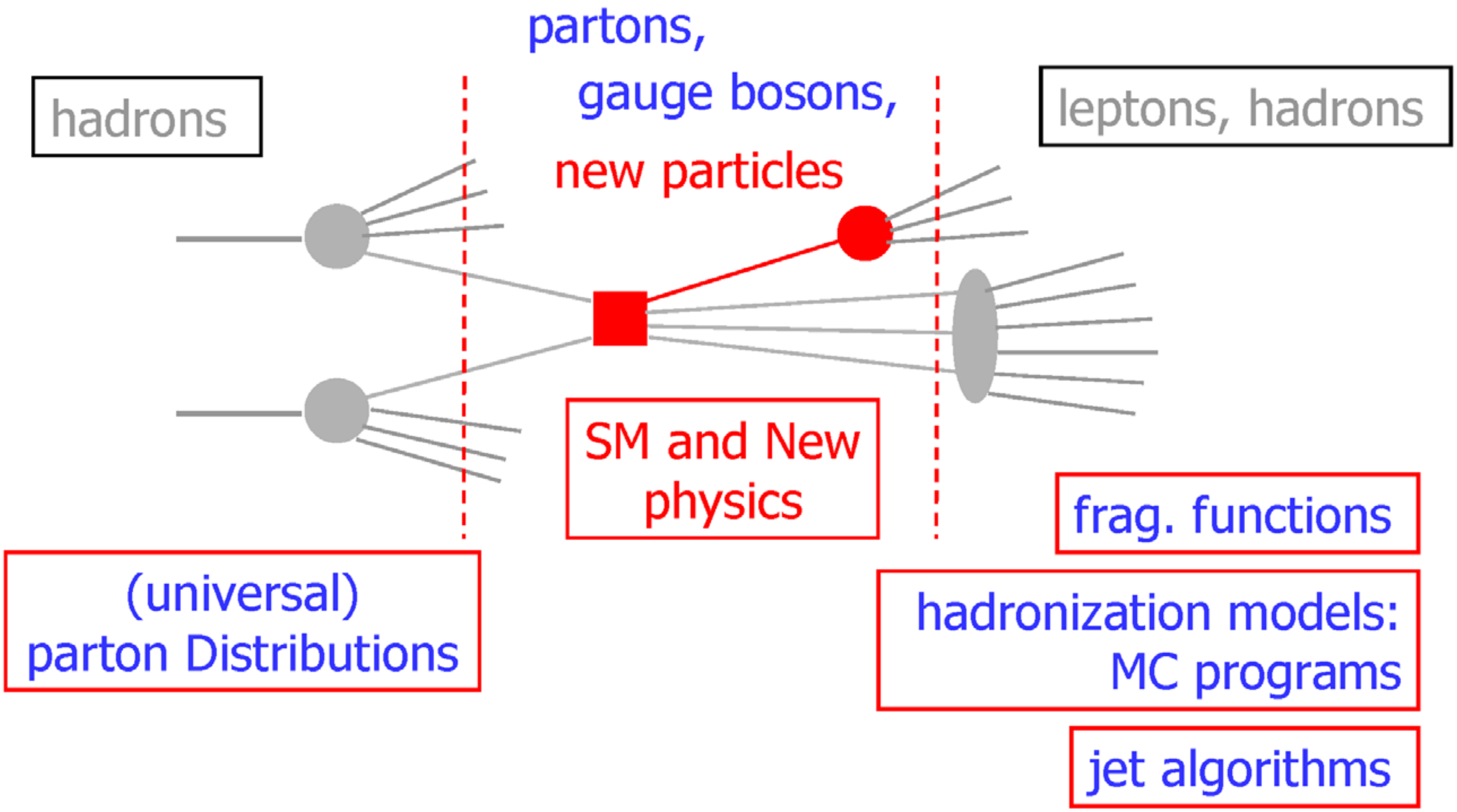
Even if there is no new physics, the same kinds of measurements can be used to probe the structure of the proton.



Because the proton is traveling so close to the speed of light, it’s internal clocks are slowed down by a factor of 7500 (in the lab frame) – essentially freezing it. We look at what is essentially a 2-d snapshot of the proton.

CTEQ

Hadron Collider Physics



partons,

gauge bosons,

new particles

hadrons

leptons, hadrons

SM and New physics

(universal) parton Distributions

frag. functions

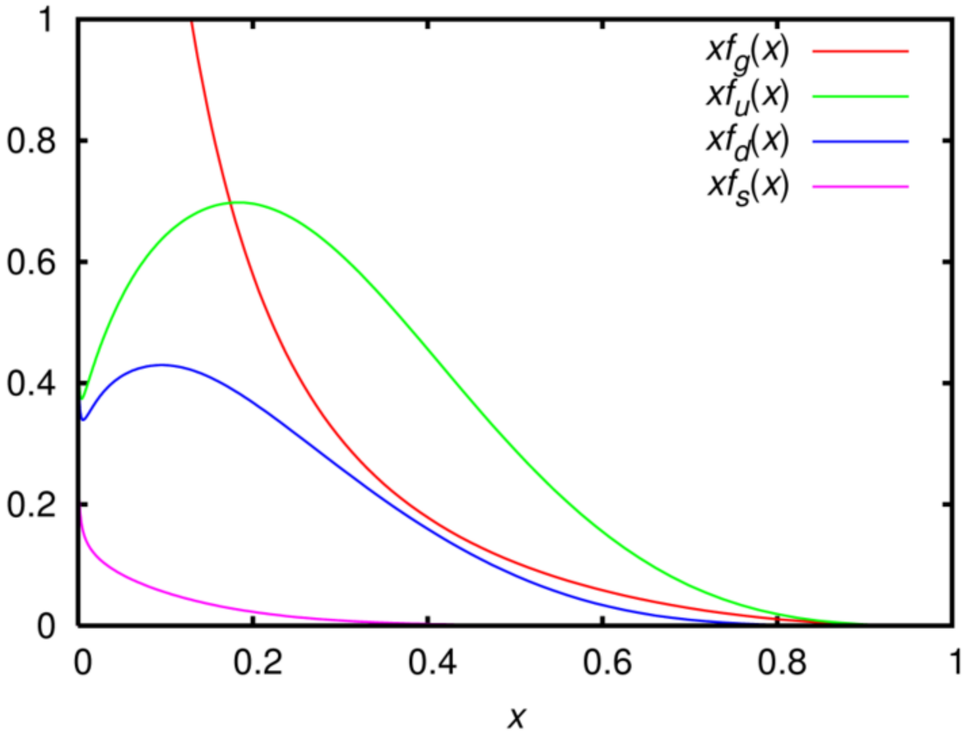
hadronization models: MC programs

jet algorithms

Parton Densities inside Proton

Parton Distribution Function (PDF)

- What looks to be an inelastic collision protons is actually an elastic collision partons: quarks and gluons.
- In an elastic collision, measuring the momenta of the final state particles completely specifies the momenta of the initial state particles.
- Different final states probe different combinations of initial partons.
  - This allows us to separate out the contributions of gluons and quarks.
  - Different experiments also probe different combinations.



- It's useful to notate this in terms of x:
  - $x = p$(parton)/p(proton)
  - The fraction of the proton's momentum that this parton carries
- This is actually the Fourier transform of the position distributions.
  - Calculationally, leaving it this way is best.

The Standard Model of Particle Physics

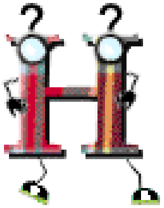
- Gauge Symmetry (Gravity is not included)

$$\underbrace{SU(3)_{\text{Color}}}_{\text{QCD}} \otimes \underbrace{SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}}_{\text{WEAK} \oplus \text{QED}}$$

(Strong Interaction)

(Unification of
Weak and Electromagnetic)

Spontaneously Broken
(Higgs Mechanism)



$$U(1)_{\text{E.M.}}$$

QED
(Electromagnetic Interaction)

The Standard Model of Particle Physics

- Matter fields (make up all visible matter in the universe)
  - Fermions (Spin 1/2)

Lepton

(No Strong Interaction)

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \qquad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \qquad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$$

$$e^-_R \qquad \mu^-_R \qquad \tau^-_R$$

Quarks

(q)

$$\underbrace{\begin{matrix} \begin{pmatrix}u\\ d\end{pmatrix}_L & \begin{pmatrix}u\\ d\end{pmatrix}_L & \begin{pmatrix}u\\ d\end{pmatrix}_L & \begin{pmatrix}c\\ s\end{pmatrix}_L & \begin{pmatrix}c\\ s\end{pmatrix}_L & \begin{pmatrix}c\\ s\end{pmatrix}_L & \begin{pmatrix}t\\ b\end{pmatrix}_L & \begin{pmatrix}t\\ b\end{pmatrix}_L & \begin{pmatrix}t\\ b\end{pmatrix}_L \\ u_R & u_R & u_R & c_R & c_R & c_R & t_R & t_R & t_R \\ d_R & d_R & d_R & s_R & s_R & s_R & b_R & b_R & b_R \end{matrix}}_{\textbf{3 families}}$$

  - Scalar (Spin 0)

Higgs Boson (Not yet found!)

(From Higgs Mechanism —— Spontaneous Symmetry Breaking)

The Standard Model of Particle Physics

- Interactions (mediated by interchanging Gauge Bosons, spin-1 force carrier)

1) Electromagnetic Interaction (QED)

   Photon (massless)

2) Strong Interaction (QCD)

   Gluon (massless) (1979)

3) Weak Interaction

   W^+, W^- and Z Gauge Bosons (1983)

(massive $M_W = 80.42 \text{ GeV}$
$M_Z = 91.187 \text{ GeV}$ $1 \text{ GeV} = 10^9 \text{ eV}$)

In SM, the Mass of W-boson, either $W^\pm$ or Z , arises from the Higgs Mechanism

(Without it, Gauge Bosons have to be massless from gauge principle.)

Higgs Mechanism in the SM

Two outstanding mysteries in the Electroweak theory :

- The cause of Electroweak Symmetry Breaking

  (M_W = 80 GeV, M_Z = 91 GeV)

- The origin of Flavor Symmetry Breaking

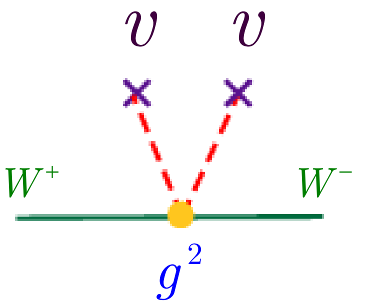
  (Quarks and Leptons have diverse masses.)

Both Symmetry Breaking are accommodated by including a fundamental weak doublet of scalar (Higgs) boson:

$$\Phi = \begin{pmatrix} \dfrac{v + H + i\,\phi^0}{\sqrt{2}} \\ i\,\phi^- \end{pmatrix}$$

- To generate M_W and M_Z

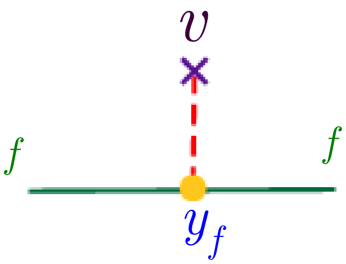
$$L_\Phi = \left(D_\mu \Phi \right)^+ \left(D^\mu \Phi \right) - \lambda \left(\Phi^+ \Phi - \frac{v^2}{2} \right)^2$$



$$\Rightarrow \quad M_W = \frac{1}{2} g v$$

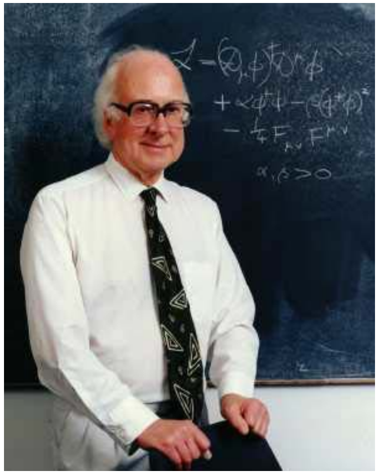
- To generate m_f

$$y_f \bar{F}_L \Phi f_R + \cdots$$



$$\Rightarrow \quad m_f = y_f \frac{v}{\sqrt{2}}$$

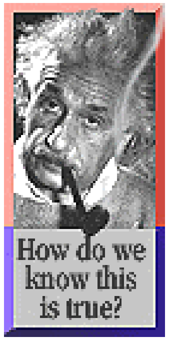
The Higgs Boson



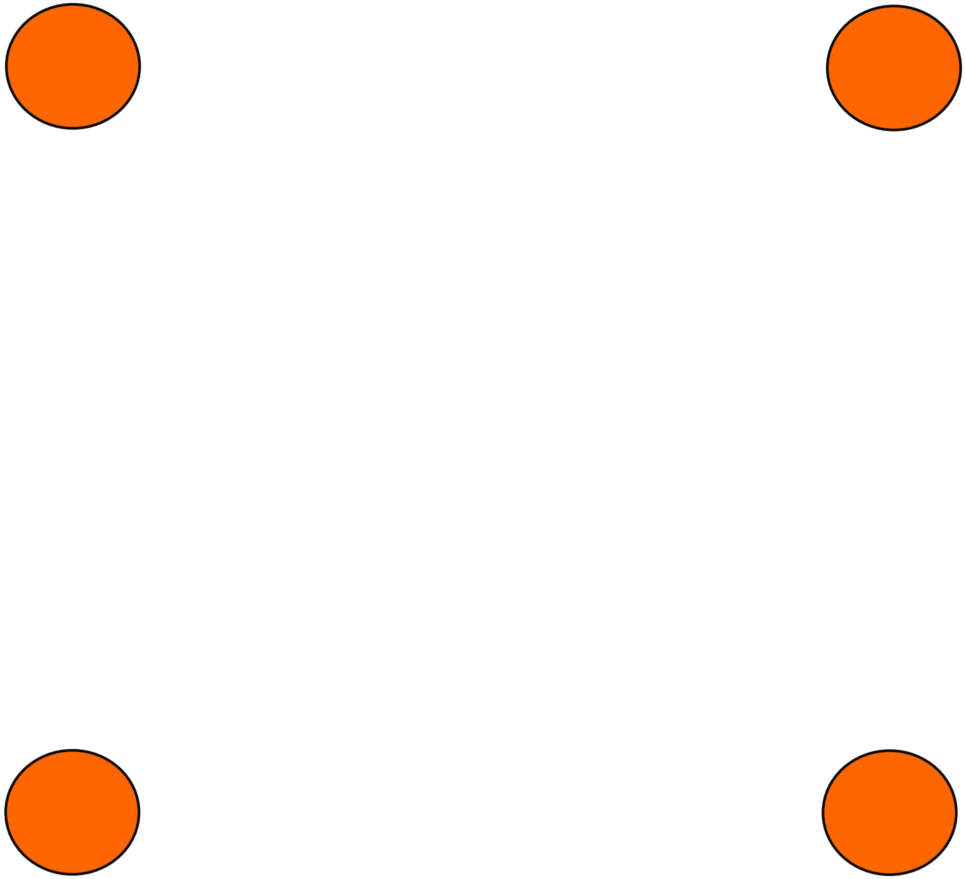
In the “Standard Model” the origin of mass is addressed using a mechanism named after the British physicist Peter Higgs.

This predicts a new particle: the Higgs boson.

What is the Higgs boson?
In 1993, the then UK Science Minister, William Waldegrave, issued a challenge to physicists to answer the questions 'What is the Higgs boson, and why do we want to find it?' on one side of a single sheet of paper. This cartoon is based on David Millar’s winning entry.

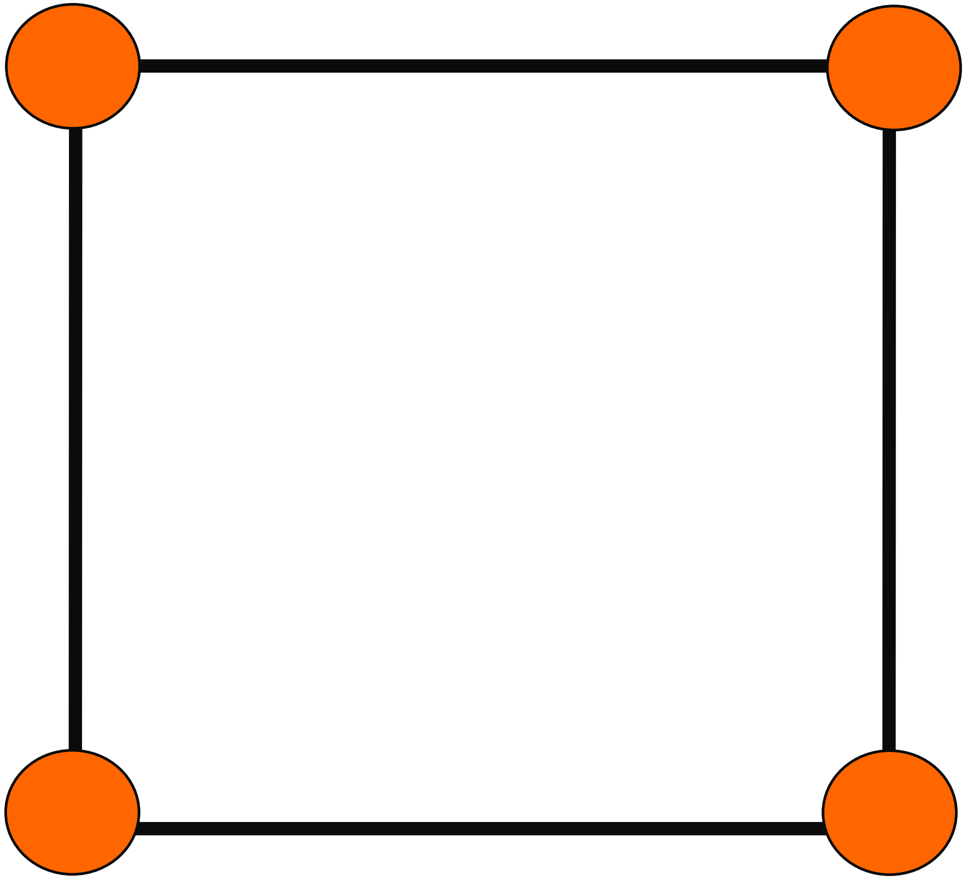


Spontaneous Symmetry Breaking



What is the least amount of railroad track needed to connect these 4 cities?

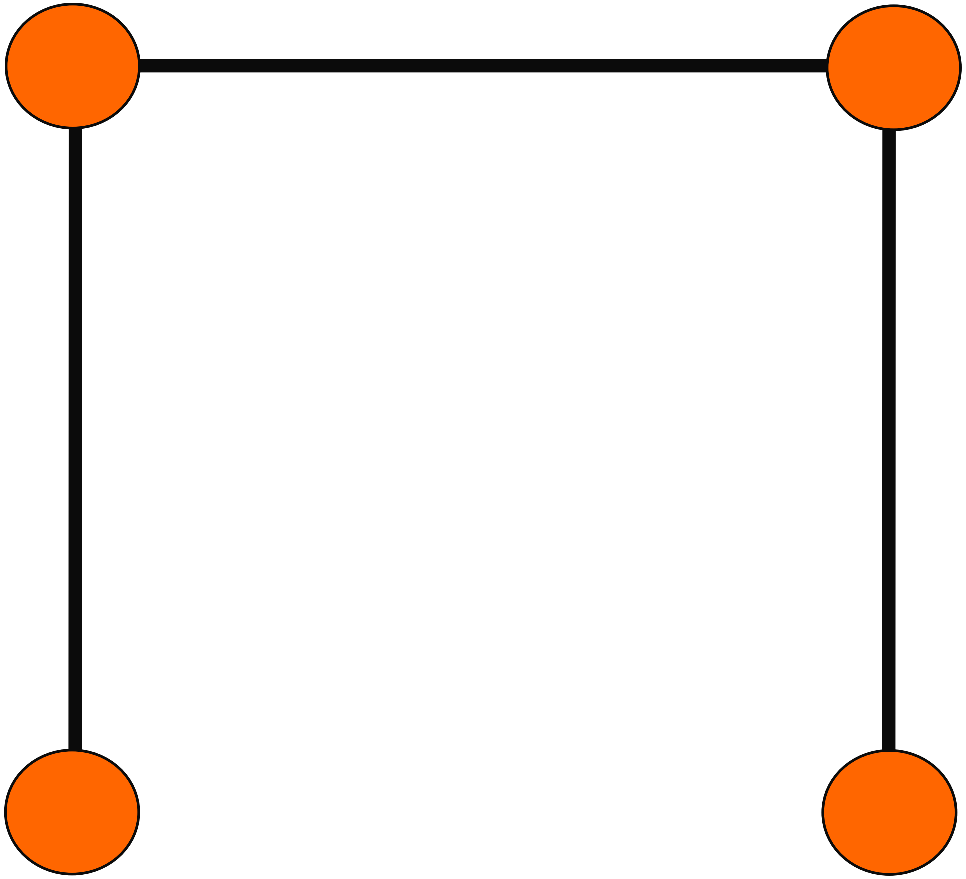
One Option



I can connect them this way at a cost of 4 units.

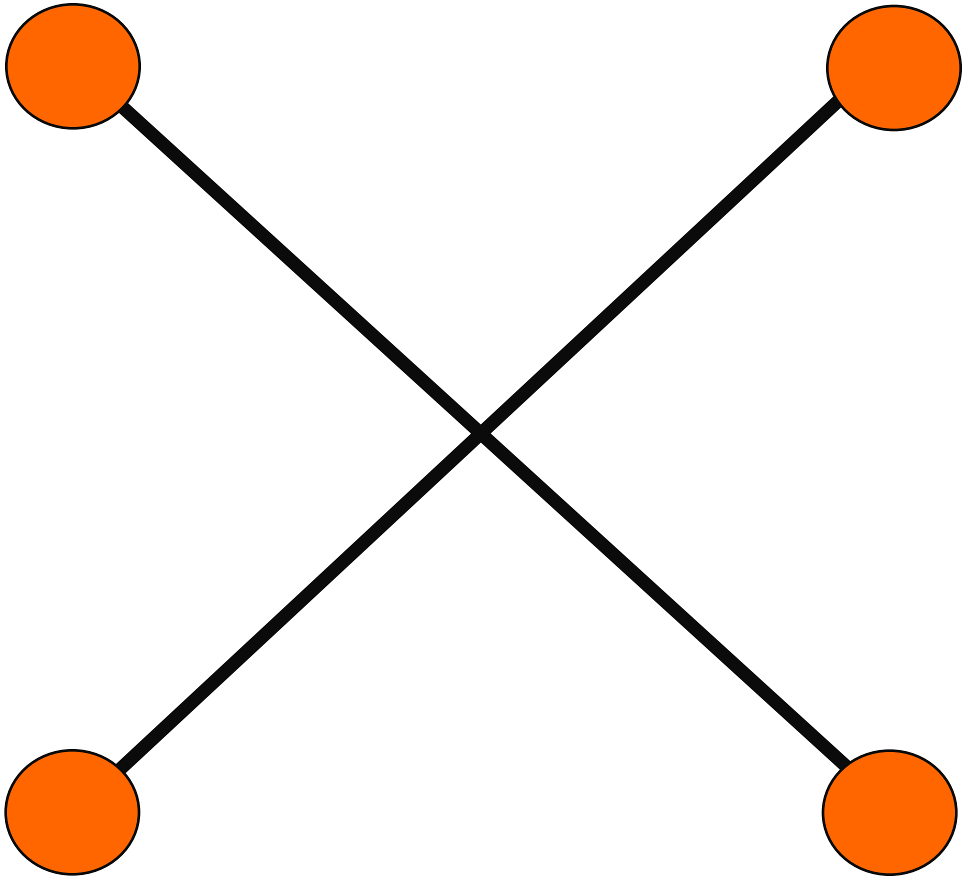
(length of side = 1 unit)

Option Two



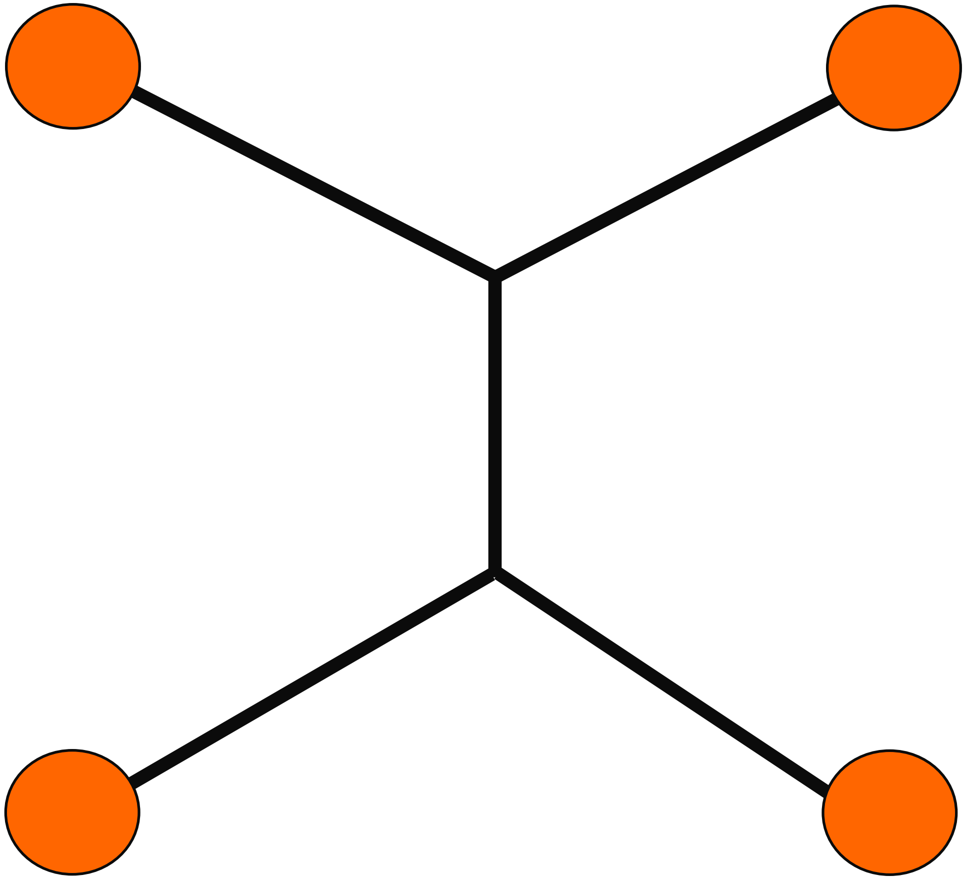
I can connect them this way at a cost of only 3 units.

The Solution that Looks Optimal, But Really Isn't



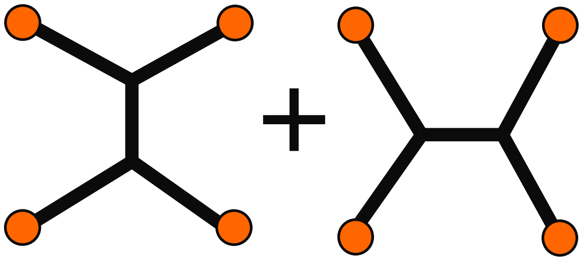
This requires only $2\sqrt{2}$

The Real Optimal Solution



This requires $1+\sqrt{3}$

Note that the symmetry of the solution is lower than the symmetry of the problem: this is the definition of *Spontaneous Symmetry Breaking*.

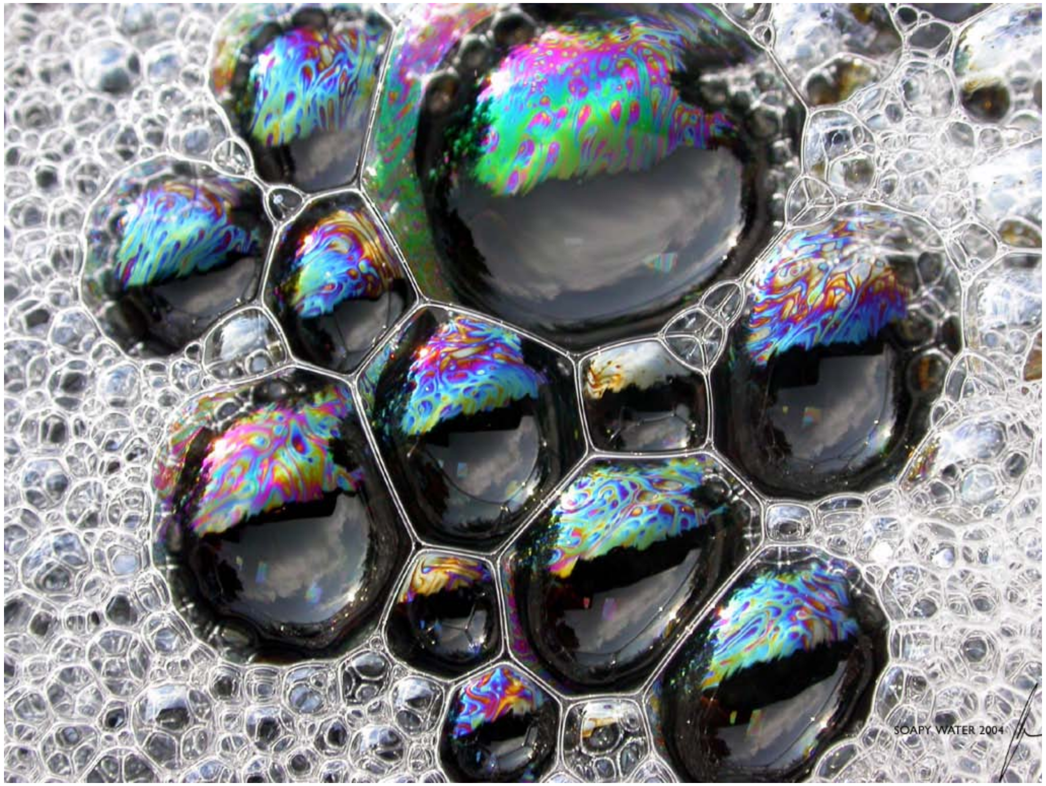


n.b. The sum of the solutions has the same symmetry as the problem.

A Pointless Aside

One might have guessed at the answer by looking at soap bubbles, which try to minimize their surface area.

But that's not important right now…



Another Example of Spontaneous Symmetry Breaking

Ferromagnetism: the Hamiltonian is fully spatially symmetric, but the ground state has a non-zero magnetization pointing in some direction.

The Higgs Mechanism

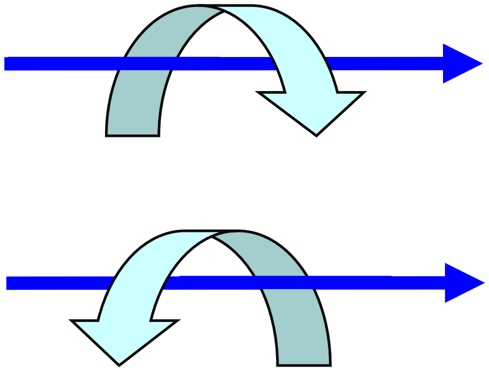
in the Standard Model of Particle Physics

- Write down a theory of massless weak bosons
  - The only thing wrong with this theory is that it doesn't describe the world in which we live
- Add a new doublet of spin-0 particles:
  - This adds *four* new degrees of freedom (the doublet + their antiparticles)

$$\begin{pmatrix} \varphi^{+} \\ \varphi^{0} \end{pmatrix} \begin{pmatrix} \varphi^{-} \\ \varphi^{*0} \end{pmatrix}$$

- Write down the interactions between the new doublet and itself, and the new doublet and the weak bosons in just the right way to
  - Spontaneously break the symmetry: i.e. the Higgs field develops a non-zero vacuum expectation value
    - *Like the magnetization in a ferromagnet*
  - Allow something really cute to happen

The Really Cute Thing



$m = \pm 1$ “transverse”

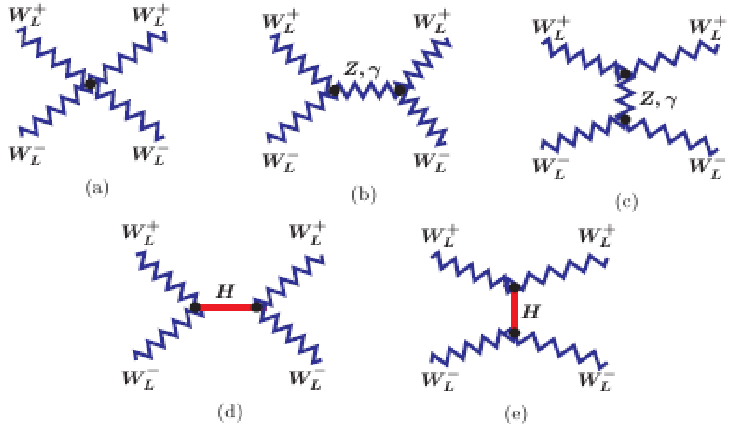
- The massless w^+ and ϕ^+ mix.
  - You get one particle with *three* spin states
    - *Massive particles have three spin states*
  - The W has acquired a mass

$m = 0$ “longitudinal”

- The same thing happens for the w^- and ϕ^-
- In the neutral case, the same thing happens for one neutral combination, and it becomes the massive Z^0.
- The other neutral combination doesn’t couple to the Higgs, and it gives the massless photon.
- That leaves one degree of freedom left, and because of the non zero v.e.v. of the Higgs field, produces a massive Higgs.

How Cute Is It?

- There's very little choice involved in how you write down this theory.
  - There's one free parameter which determines the Higgs boson mass
  - There's one sign which determines if the symmetry breaks or not.

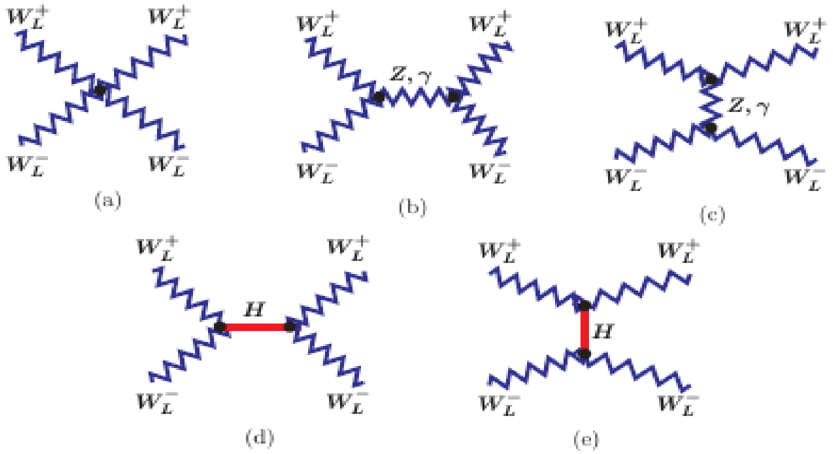


- Longitudinal polarization: $\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$
- E-Cancellations in $W_L^+ W_L^-$ Scattering:

- The theory leaves the Standard Model mostly untouched
  - It adds a new Higgs boson – **which we can look for**
  - It adds a new piece to the WW → WW cross-section
    - *This interferes destructively with the piece that was already there and restores unitarity*

- In this model, the v.e.v. of the Higgs field ***is*** the Fermi constant
  - The sun shines for billions of years because of the Higgs mechanism and the spontaneously broken electroweak symmetry

Review: Unitarity of 4d Standard Model



(a) (b) (c)
(d) (e)

- Longitudinal polarization: $\epsilon_L^\mu(k) = \dfrac{k^\mu}{m_w} + \mathcal{O}\left(\dfrac{m_w}{E}\right)$
- E-Cancellations in $W_L^+ W_L^-$ Scattering:

Graphs	$g^2 \frac{E^4}{m_w^4}$	$g^2 \frac{E^2}{m_w^2}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$	$+2 - 6\cos\theta$
(b)	$-4\cos\theta$	$-\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	0	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum	**0**	**0**

- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow$ $E < \sqrt{4\pi}\, v \simeq 0.9$ TeV

The "No Lose Theorem" at the LHC

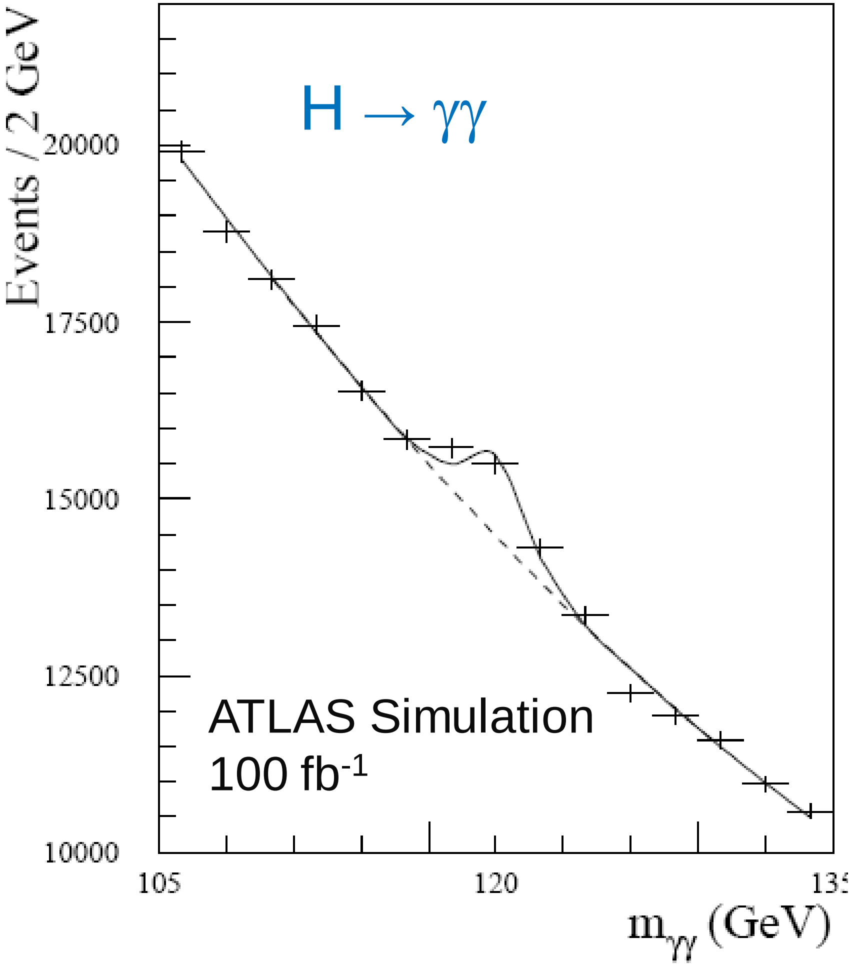
Either we find Higgs Boson, or
we must find new physics signature.

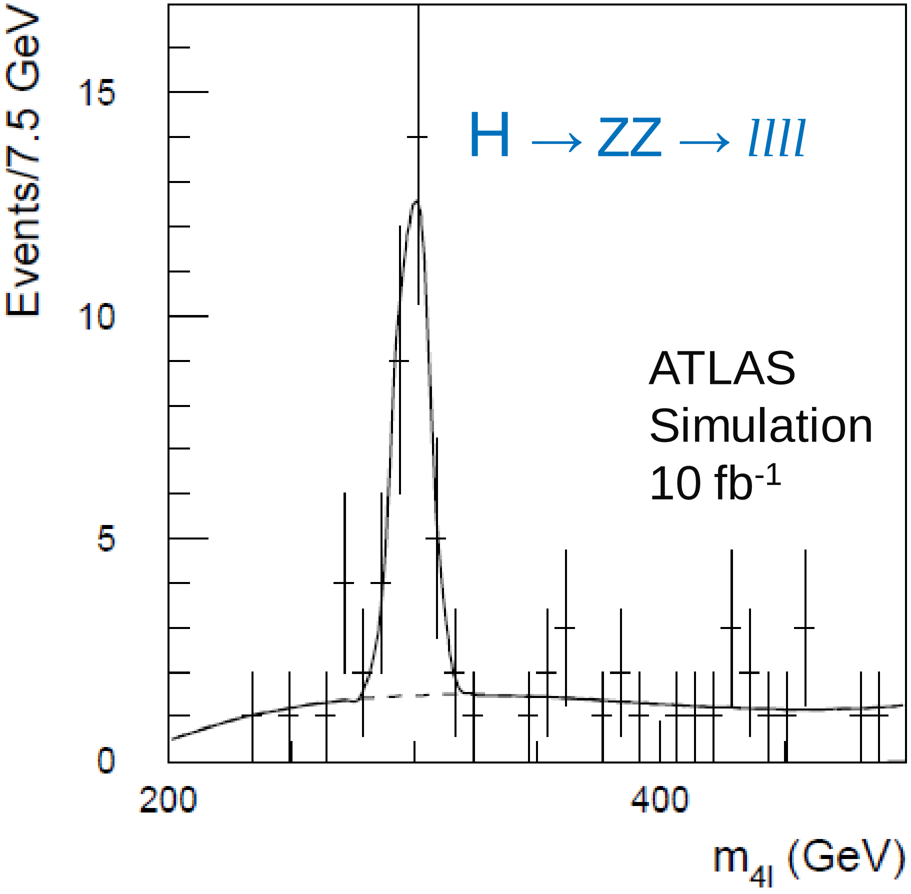
- Imagine you could elastically scatter beams of W bosons:
  WW → WW
- We can calculate this, and at high enough energies
  "the cross-section violates unitarity"
  - A fancy way of saying the probability of a scatter exceeds 1: nonsense
  - The troublesome piece is (once again) the longitudinal spin state
- "High enough" means about 1 TeV
  - A 14 TeV proton-proton accelerator is just energetic enough to give you enough 1 TeV parton-parton collisions to study this

The Standard Model is a low-energy effective theory. The LHC gives us the opportunity to probe it where it breaks down. Something new must happen.

Searching for the Higgs Boson

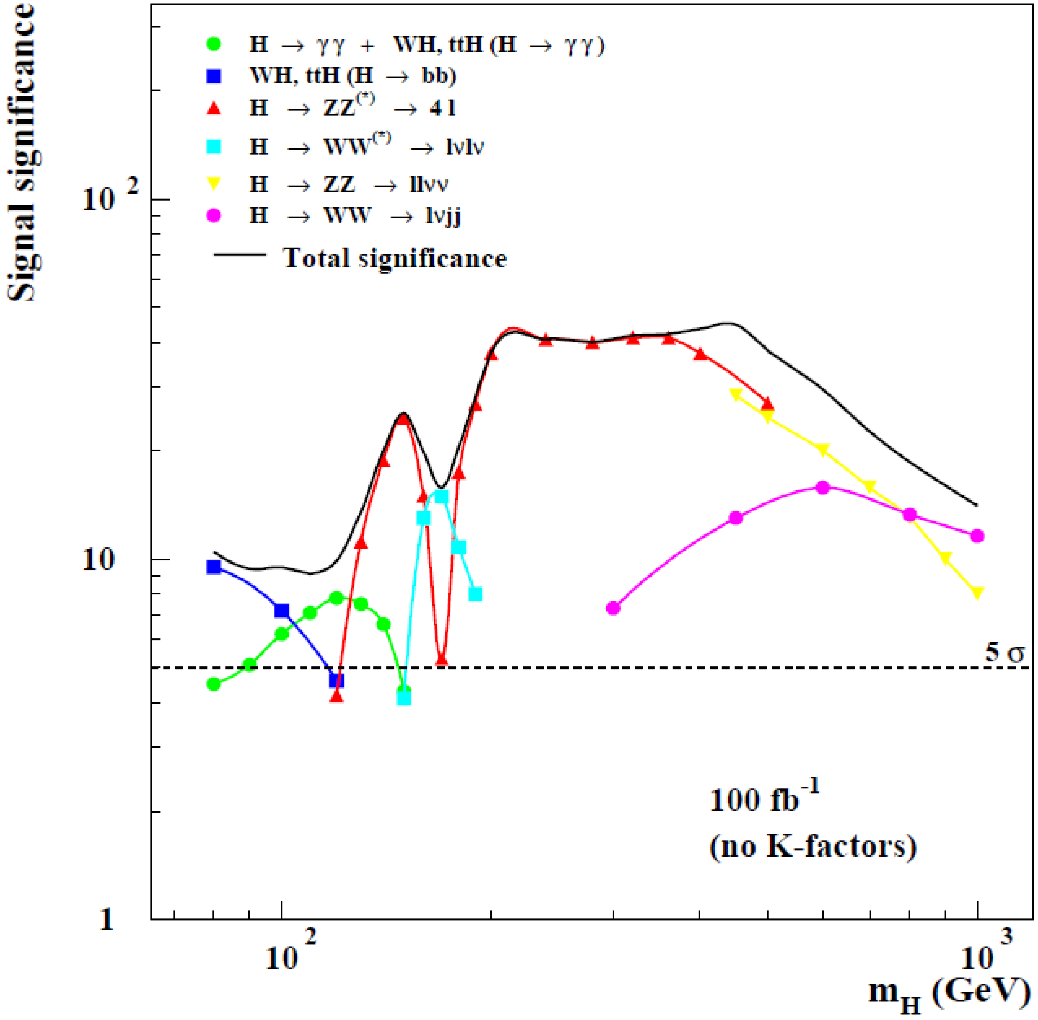
Because the theory is so constrained, we have very solid predictions on where to look and what to look for.





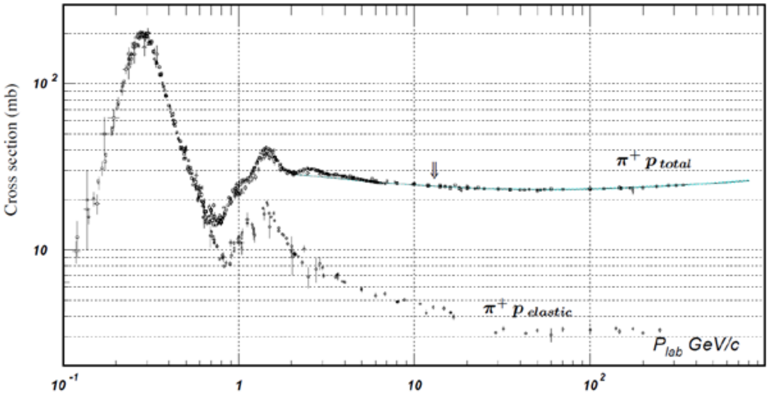
Combining All Channels

- If there is a Higgs boson, ATLAS will find it with a few years' data, no matter what its mass is
- For most of the mass range, we will see the Higgs in multiple channels
  - We can start probing its couplings: it looks like a Higgs, but does it act like a Higgs?
  - Detailed measurements will take a future linear collider.
- The other experiment, CMS, has comparable sensitivity



Two Alternatives (New Physics models)

- Multiple Higgses
  - I didn't have to stop with one Higgs doublet – I could have added two
  - This provides four more degrees of freedom: (e.g., Supersymmetry)
    - *Manifests as five massive Higgs bosons:* h^0, H^0, A^0, H^+, H^-
      - Usually some are harder to see, and some are easier
  - You don't have to stop there either…
- New Strong Dynamics
  - Maybe the WW → WW cross-section blowing up is telling us something:
    - *The* $\pi + p \to \pi + p$ *cross-section also blew up: it was because of a resonance: the* Δ.
    - *Maybe there are resonances among the W's and Z's which explicitly break the symmetry. (e.g., Technicolor)*



Many models: ATLAS data will help discriminate among them.

Apologies

- I didn’t cover even a tenth of the LHC physics program
  - Precision measurements
  - Top Quark Physics
    - *Orders of magnitude more events than at the Tevatron*
  - Search for new particles
    - *Can we produce the particles that make up the dark matter in the universe?*
  - Search for extra dimensions
    - *Why is gravity so much weaker than other forces?*
    - *Are there mini-Black Holes?*
  - B Physics and the matter-antimatter asymmetry
    - *Why is the universe made out of matter?*
  - Heavy Ions
    - *What exactly has RHIC produced?*

When this is all going to happen

The first beams of the Large Hadron Collider (LHC) **were circulated successfully on 10th September 2008**.

Unfortunately on 19th September a fault developed on a small number of superconducting magnets. The repair will required a long technical intervention which overlaps with the planned winter shutdown.

The LHC beam will, therefore, not see beam again before spring 2009.

Summary

- Electroweak Symmetry Breaking is puzzling
  - Why is the weak force so weak? (i.e. why does the sun so old?)
- The Large Hadron Collider is in a very good position to shed light on this
  - The “no lose theorem” means *something* has to happen. Maybe it’s a Higgs, maybe it’s not.
- Any experiment that can do this can also answer a number of other questions
  - For example, addressing the structure of the proton
  - Identify dark matter
  - And the dozens I didn’t cover
- Even in an enterprise this advanced, there is a lot of college level physics that matters.

Thanks for inviting me!

Backup Slides

WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP)

The WMAP mission reveals conditions as they existed in the early universe by measuring the properties of the cosmic microwave background radiation over the full sky. This microwave radiation was released approximately 380,000 years after the birth of the universe.

WMAP creates a picture of the microwave radiation using temperature difference measured from opposite directions (anisotropy). The content of this image tells us much about the fundamental structure of the universe.

Cosmic Microwave Background

- *WMAP satellite result*

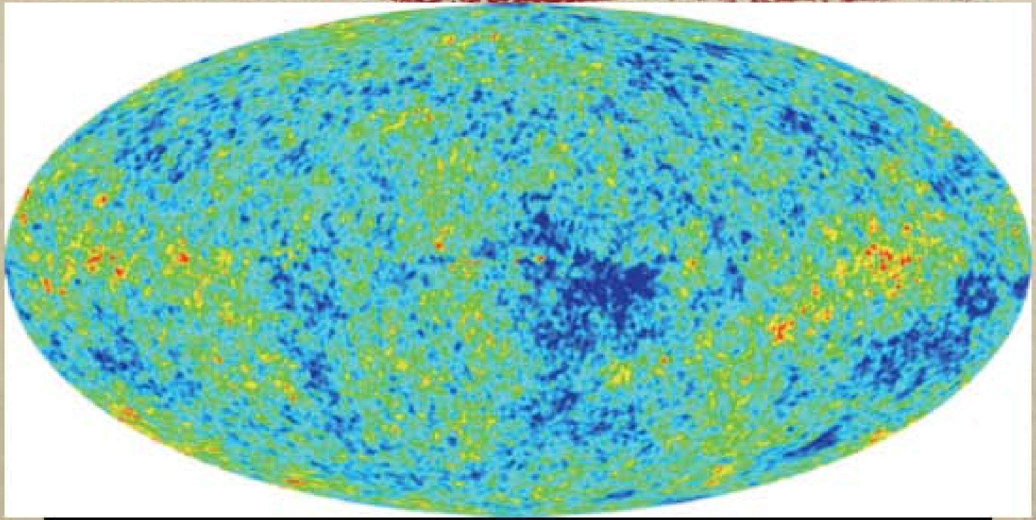
  $h=0.71\pm0.04$

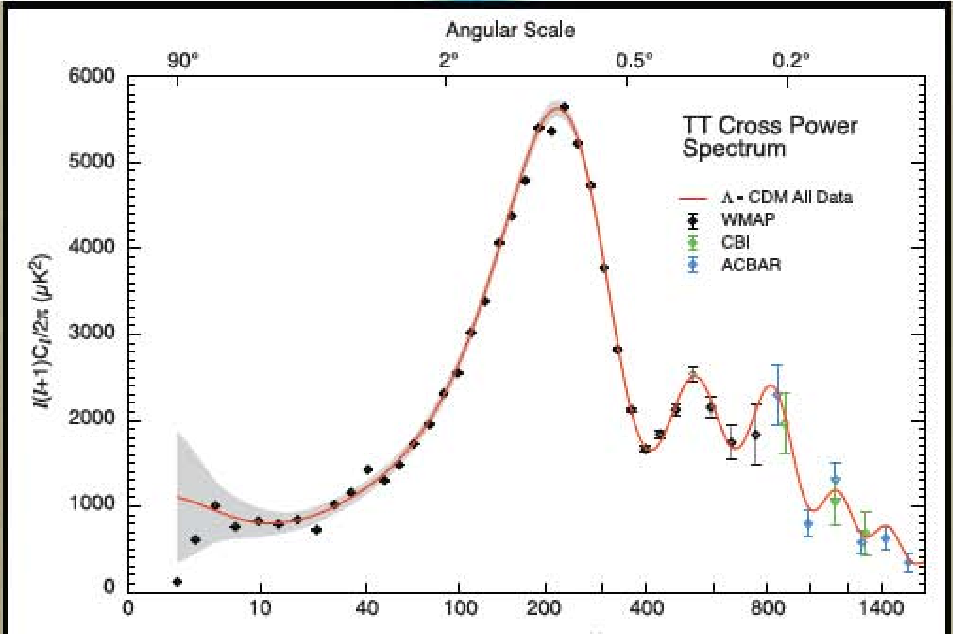
  $\Omega_M h^2=0.135\pm0.009$

  $\Omega_b h^2=0.0224\pm0.0009$

  $\Omega_{tot}=1.02\pm0.02$

- $>12\sigma$ *signal for exotic dark matter*





Collision rate

- The total proton-proton cross section at 7 TeV is approximately 110 mbarns. This total can be broken down in contributions from:

  - inelastic (= 60 mbarn)
  - single diffractive (= 12 mbarn)
  - elastic (= 40 mbarn)

- The cross section from elastic scattering of the protons and diffractive events will not be seen by the detectors as it is only the inelastic scatterings that give rise to particles at sufficient high angles with respect to the beam axis.

- By definition,

  Event rate = Luminosity * Cross section

Searching for Particles

- Event rates are governed by
  - Cross section $\sigma(E)[\mathrm{cm}^2]$ –physics
  - Luminosity $[\mathrm{cm}^{-2}\mathrm{s}^{-1}] = N_1N_2f / A$
    - *N_1N_2= particles/bunch*
    - *f = crossing frequency*
    - *A = area of beam at collision*
    - *$N_{events} = \sigma \int L dt$*
    - *Acceptance and efficiency of detectors*
- Higher energy: threshold, statistics
- Higher luminosity: statistics

With 10^{34} Luminosity (m^{-2} s^{-1})

Luminosity Equation:

$$L = \frac{f\,E}{\varepsilon_n}\,\frac{n_b N_p^2}{\beta^*}$$

- Quantities we cannot easily change:
  - *f*: revolution frequency of the LHC
    - ***set by radius and c***
  - *E*: beam energy
    - ***set by physics goals***
  - ε_n: beam emittance at injection
    - ***set by getting the beam into the LHC***

- Quantities we can easily change
  - n_b: number of bunches
    - ***Factor of 3 lower initially***
  - β^* : strength of final focus
    - ***Factor of ~2 possible***
  - N_p: protons per bunch
    - ***Can be as small as we want***
    - ***Initially, can be within a factor of ~2 of design***

A high rate of collisions requires small bunch size, many protons per bunch, and many bunch crossings per unit time. These properties, which depend on the design of the collider, can be combined into a single useful parameter, luminosity.

LHC Beam Stored Energy in Perspective

Luminosity Equation:

$$\boxed{L = \frac{fE}{\varepsilon_n}\frac{n_b N_p^2}{\beta^*}}$$

USS New Jersey (BB-62)
16”/50 guns firing

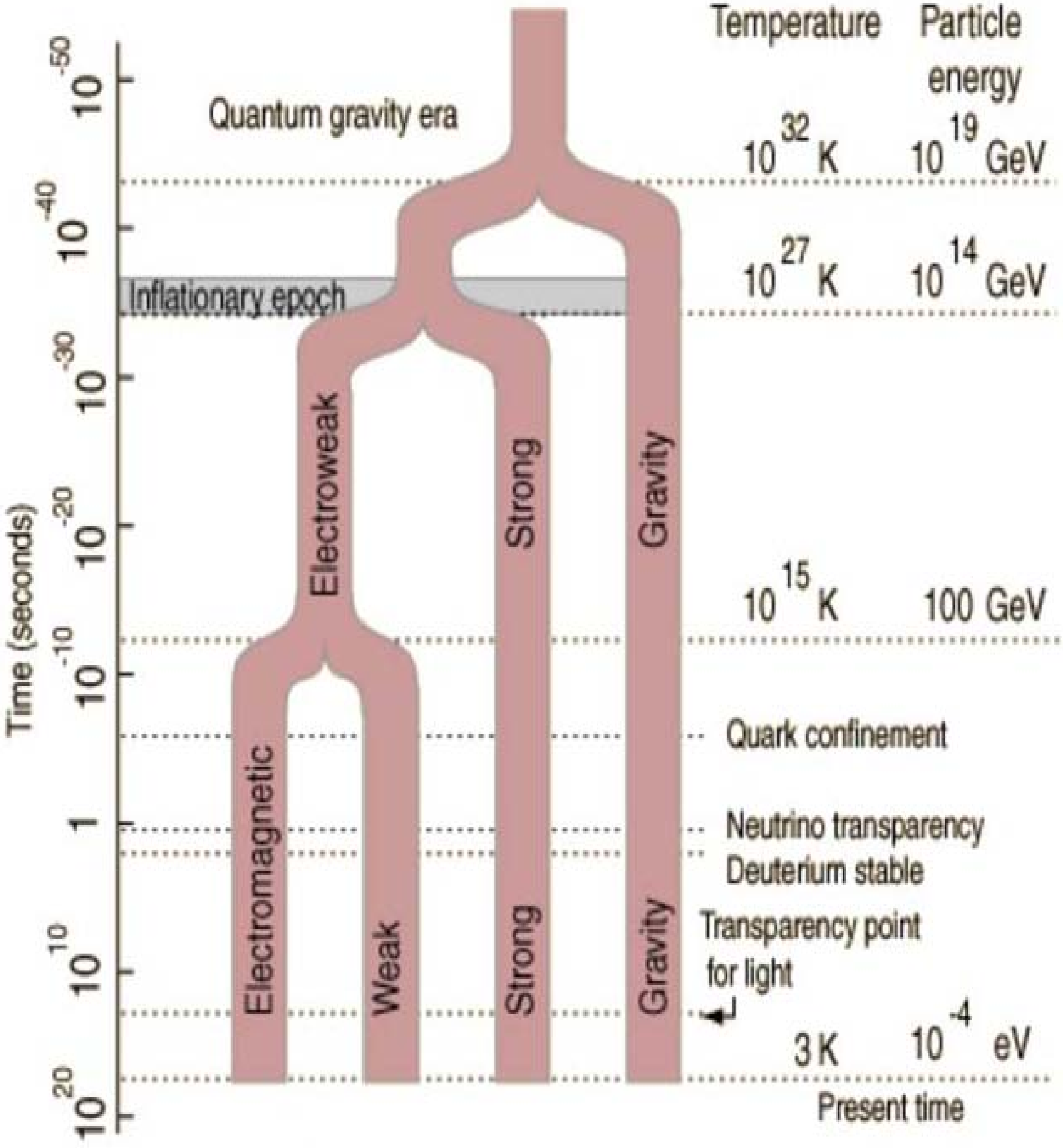
- Luminosity goes as the *square* of the stored energy.
- LHC stored energy at design ~700 MJ
  - Power if that energy is deposited in a single orbit: ~10 TW (world energy production is ~13 TW)
  - Battleship gun kinetic energy ~300 MJ
- It’s best to increase the luminosity with care

1 GeV = 10^9 eV

1 TeV = 10^{12} eV

LHC is probing TeV region

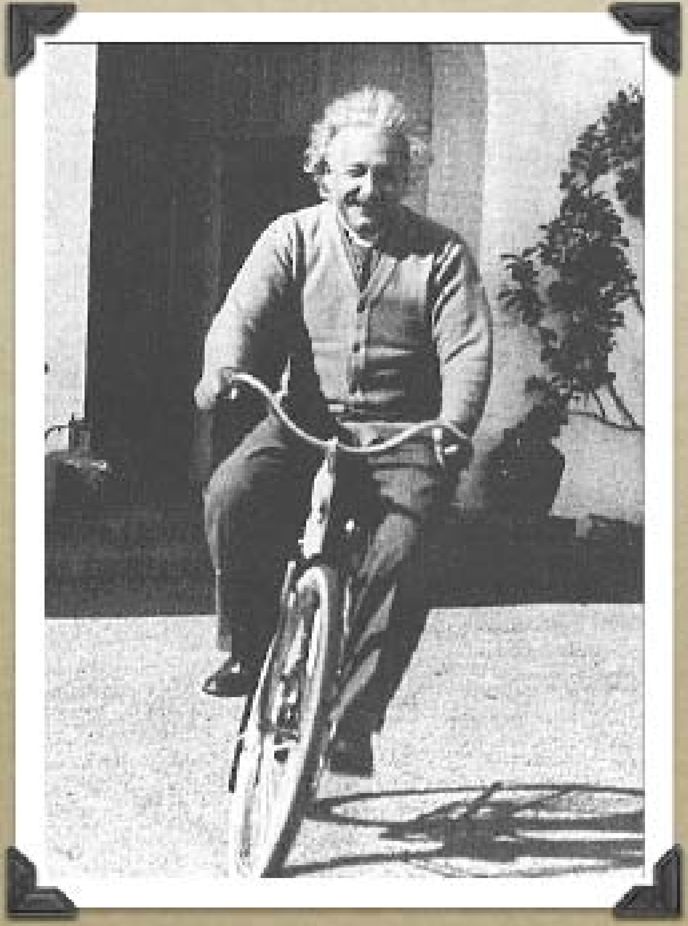
It is about
0.00000000001 second
after Big Bang,
or,
about 14 billion years ago.



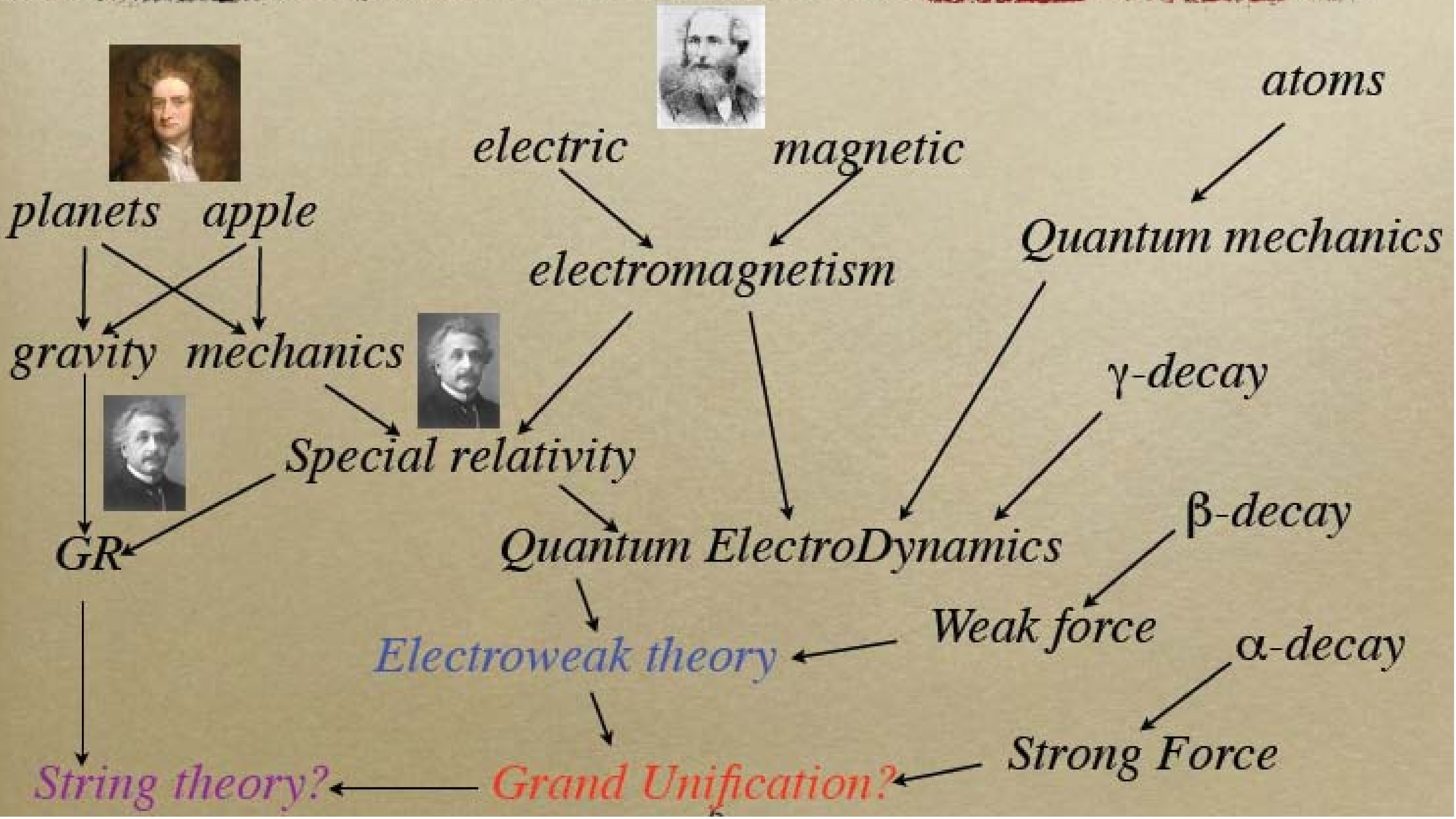
Early universe chronology

Einstein's Dream

- *Is there an underlying simplicity behind vast phenomena in Nature?*
- *Einstein dreamed to come up with a unified description*
- *But he failed to unify electromagnetism and gravity (GR)*



History of Unification



atoms

electric magnetic

planets apple

Quantum mechanics

electromagnetism

gravity mechanics

γ-decay

Special relativity

β-decay

GR

Quantum ElectroDynamics

Weak force

α-decay

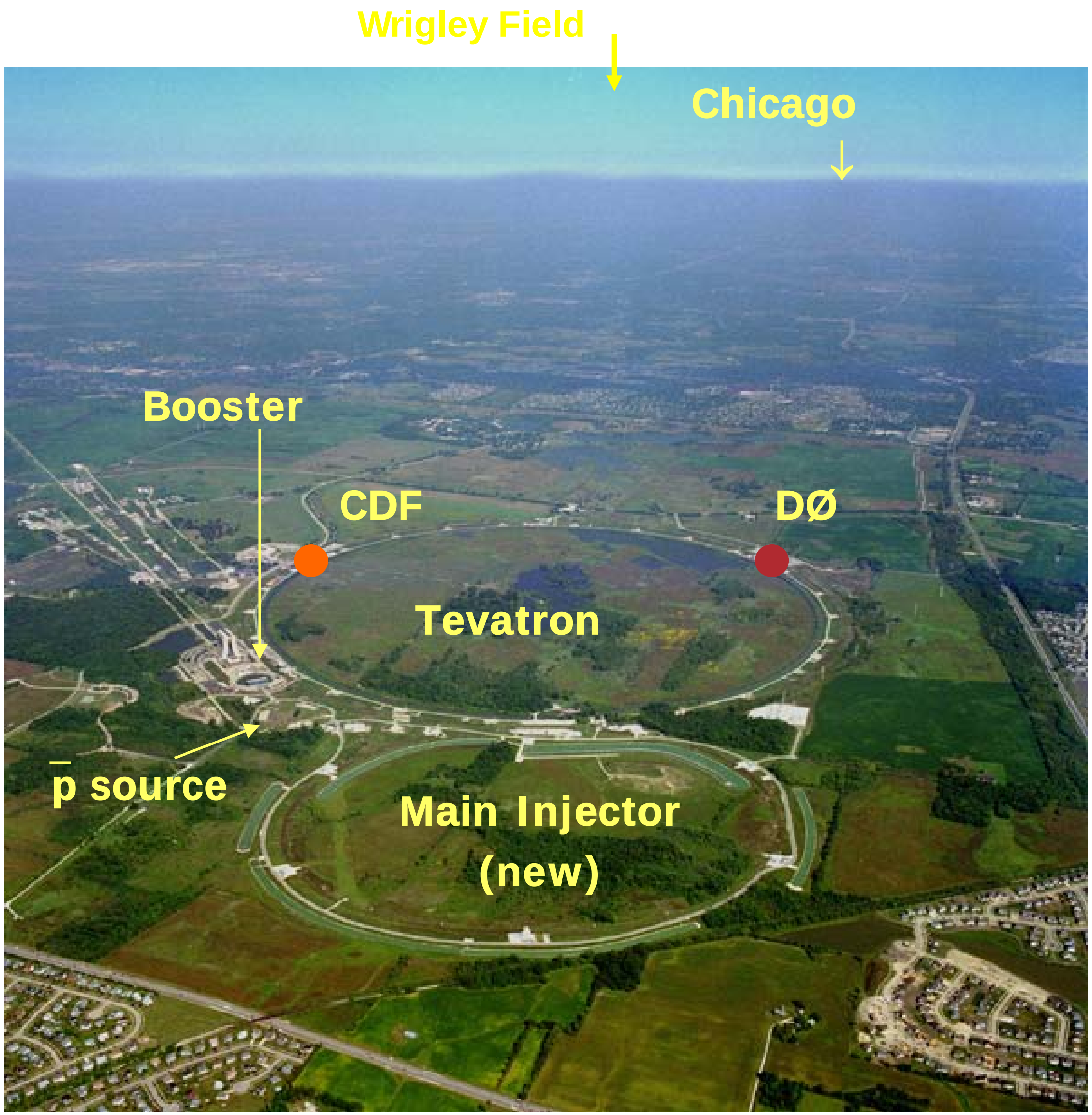
Electroweak theory

Strong Force

String theory? ← Grand Unification?

Tevatron

Fermilab, USA



- Collide protons and anti-protons at CDF and D0
- Center of mass energy is 1.96 TeV
- 36 x 36 bunches, in circumference 6.28km
- 396 ns between crossings
- About 5 inelastic scatterings per crossing