The Large Hadron Collider
and
College Physics

C.-P. Yuan 袁簡鵬

Michigan State University

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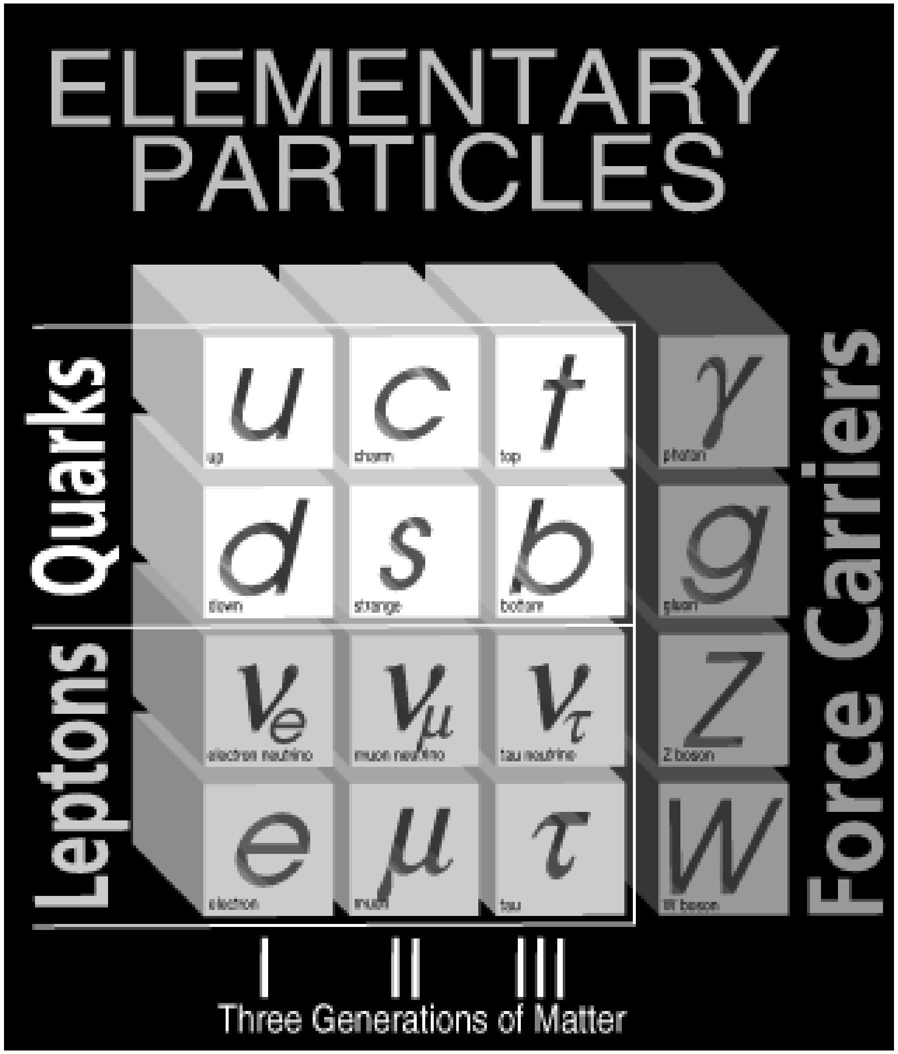
LHC, located at CREN, Geneva, will operate in 2008.

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

The Traditional Opening Pitch

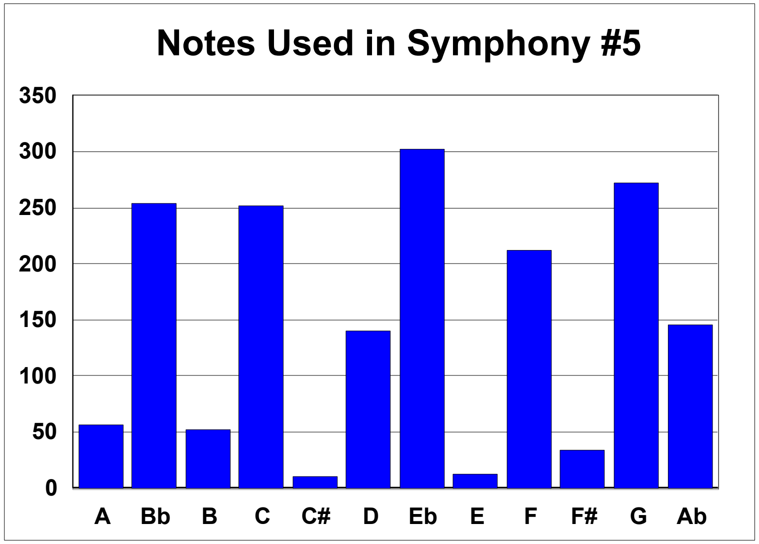
- Practically every High Energy Physics (HEP) talk starts with this slide.

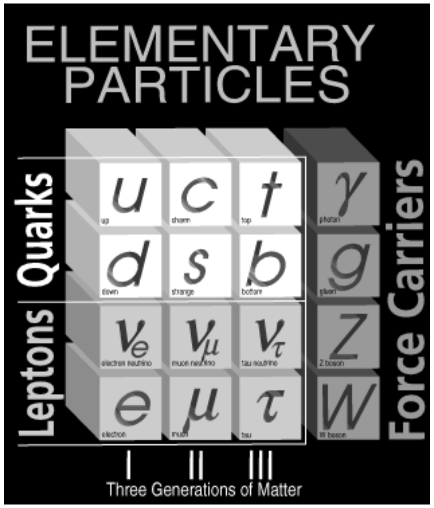
- This isn't the way I want to start this talk.



Comparing Two Figures

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





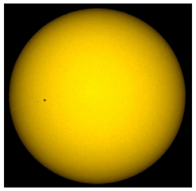
- Both plots focus on the constituents of a thing, rather than their interactions.
- While there is meaning in both plots, it can be hard to see.
  - A plot of a composition by A. Schoenberg would look different.

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

Outline

- A 19^{th} Century Puzzle & the 21^{st} 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 $4p \to {}^4\mathrm{He} + 2e + 2\nu$
- 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

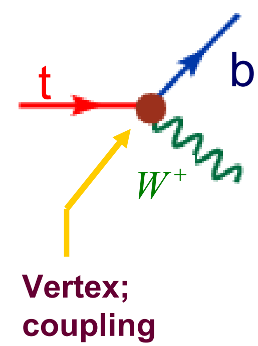
- In Relativistic Quantum Field Theory

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

$$\mathcal{L}$$

$$\Downarrow$$

Feynman Rules
Feynman Diagrams



$$\Downarrow$$

S-Matrix Elements

$$\Downarrow$$

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

$$\boxed{\text{Quantum Electrodynamics (QED)}}$$

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

People have long asked,

“ What is the world made of? ”

and

“ What holds it together? ”

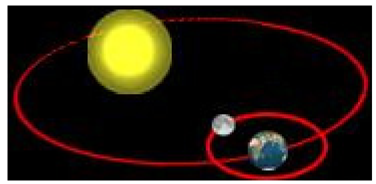
Elementary Particle Physics
or
High Energy Physics

Studying Fundamental Interactions (Forces) in Nature

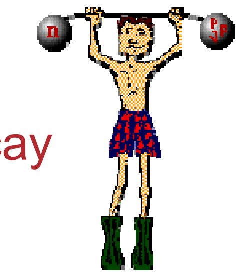
Interactions *(Four forces in Nature)*

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

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.

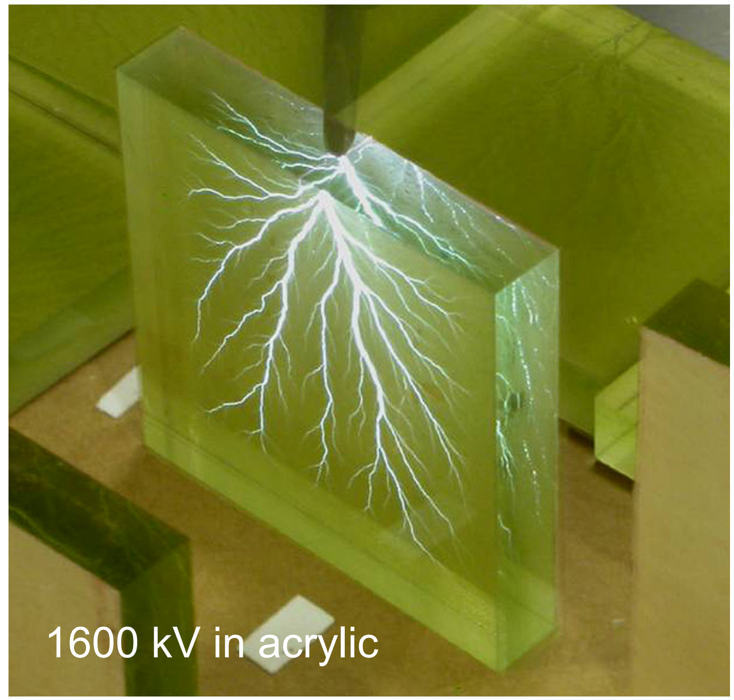
A multi-billion dollar instrument really needs to be able to do more than one thing.

All of these require the highest energy we can achieve.

Getting a Beam of 7 TeV Protons

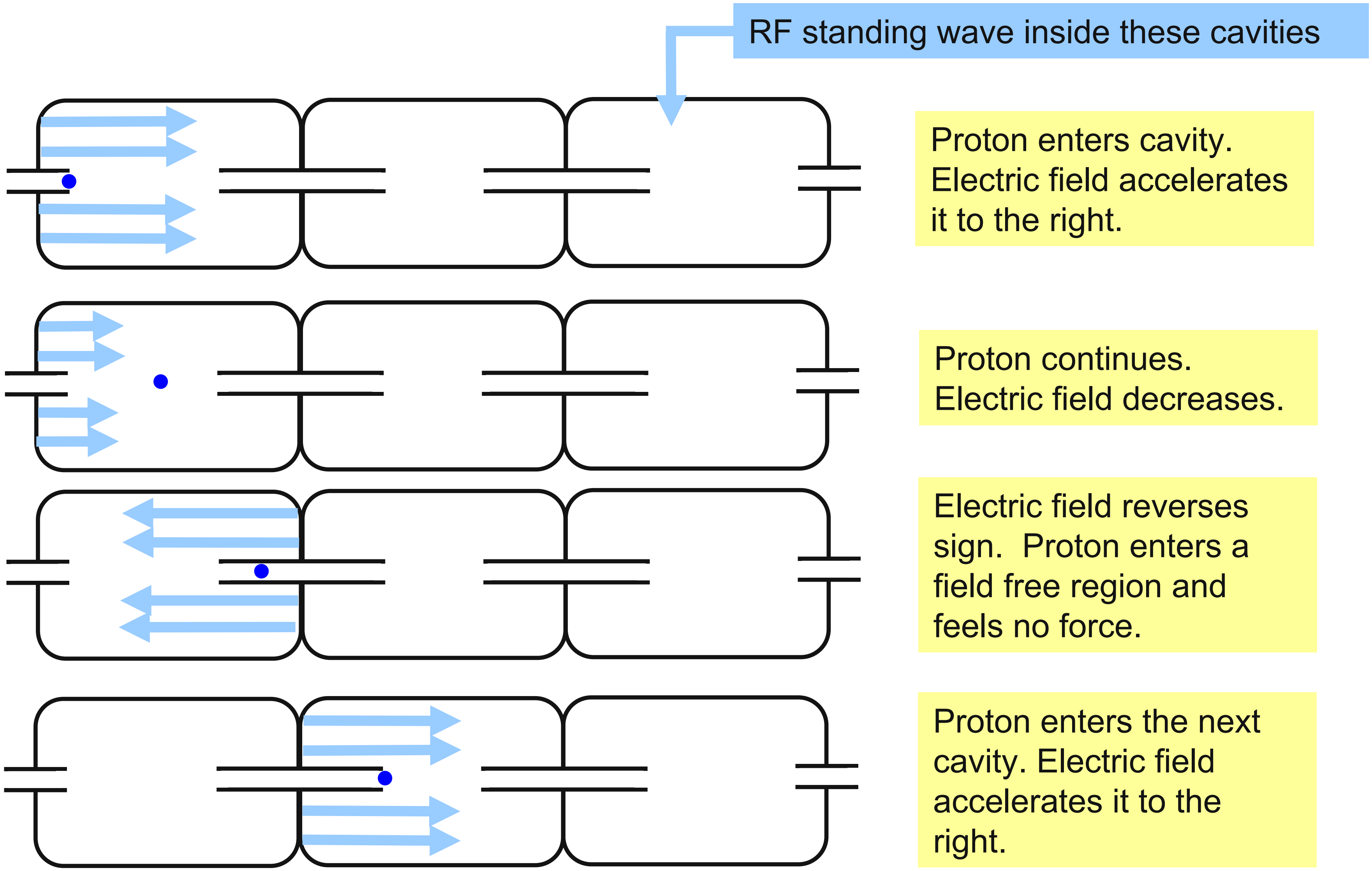
$$(1\ TeV = 10^{12}\ eV)$$

- 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:



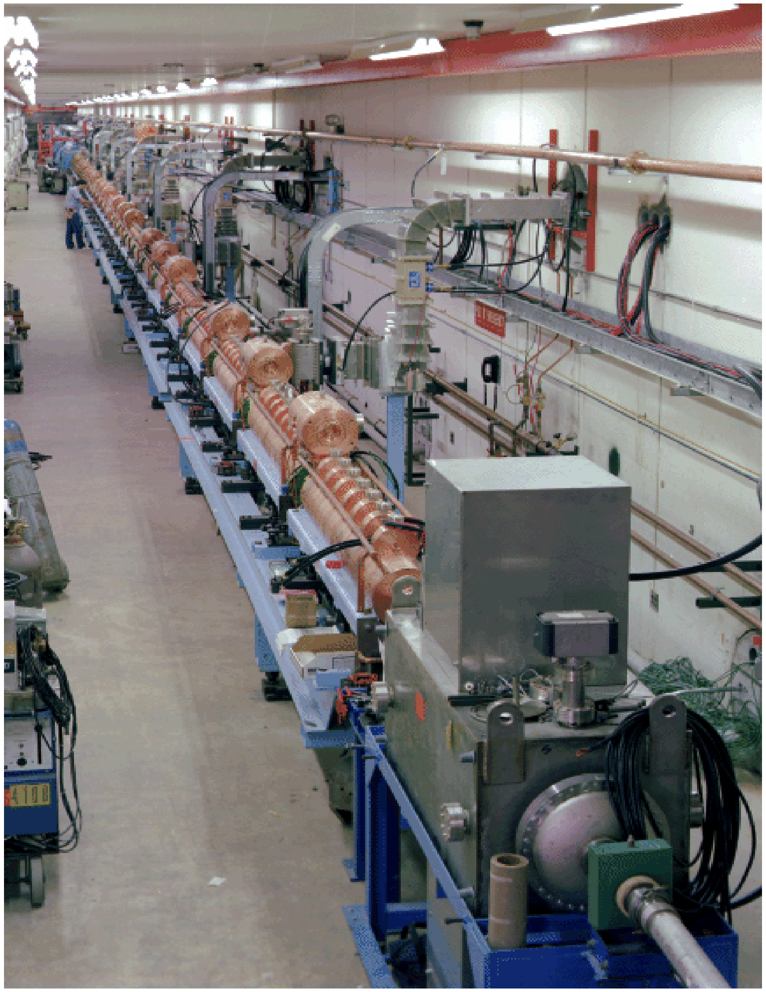
Even in vacuum this won't work – the electric fields necessary would rip the atoms apart.

How To Build a Linear Accelerator



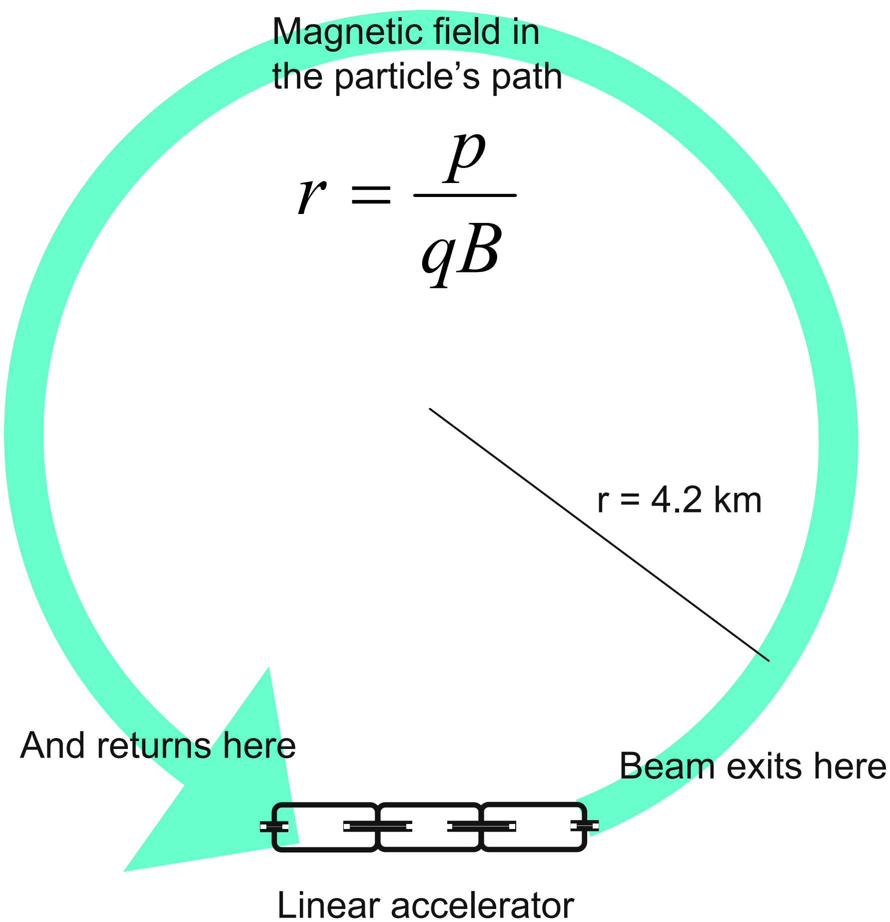
Linear Acceleration

- 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

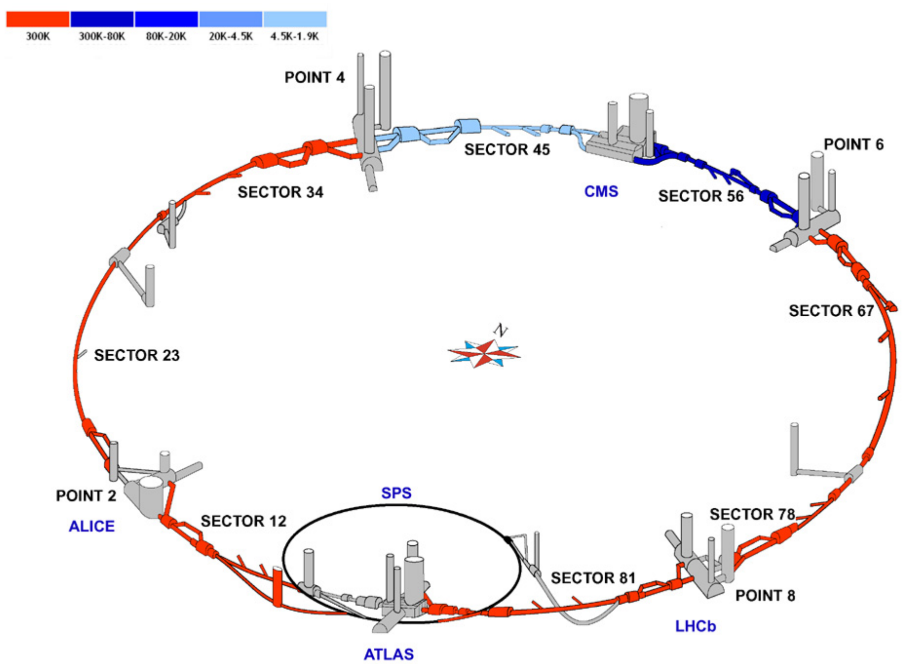
Recycling: The Proton Synchrotron



- 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

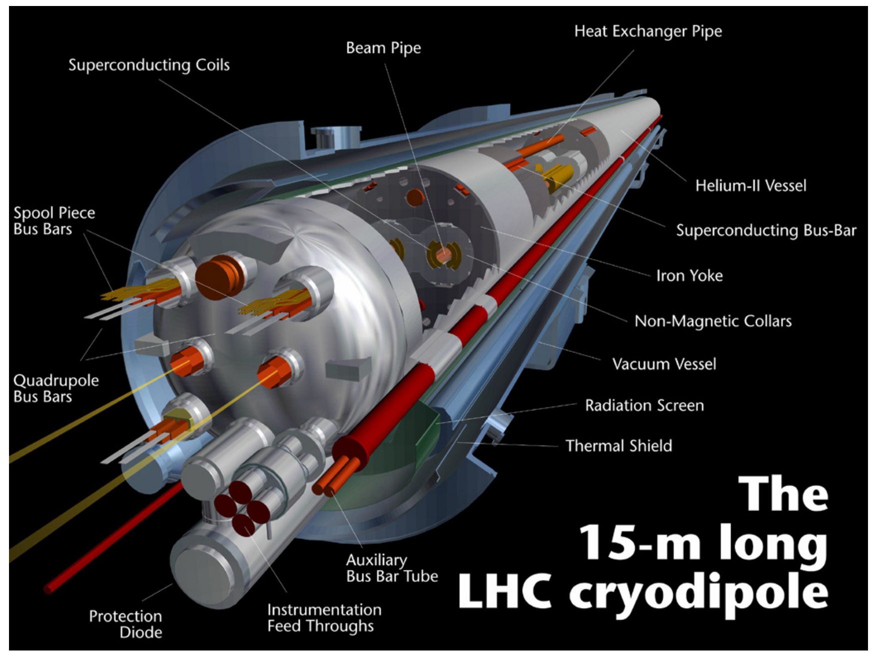
$\boxed{\text{High energy physicists usually set } c=h/2\pi=1.}$

A Less Cartoonish View



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

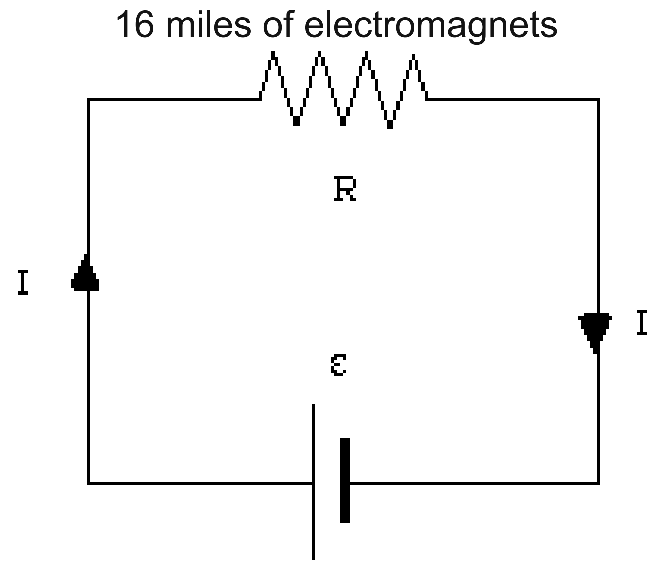
The magnetic field is created by 1232 dipole magnets (plus hundreds of focusing and correction magnets) arranged in a ring in the tunnel.



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

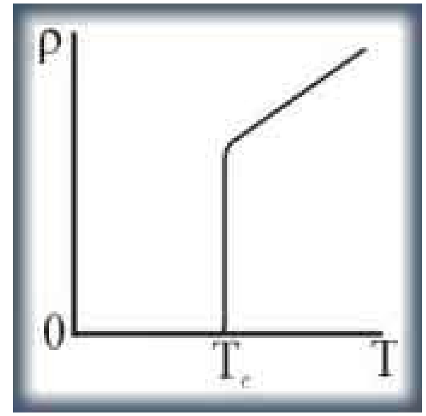
$$E = IR$$

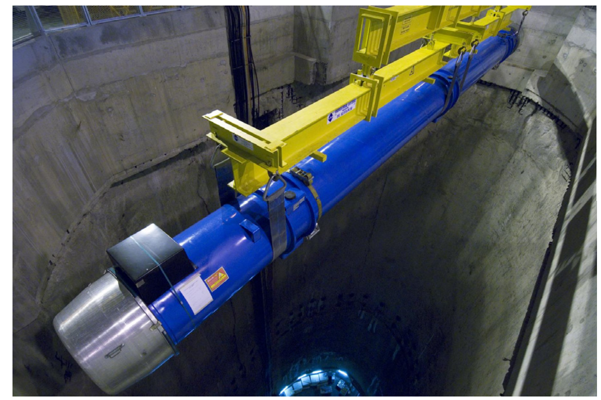
$$P = EI$$

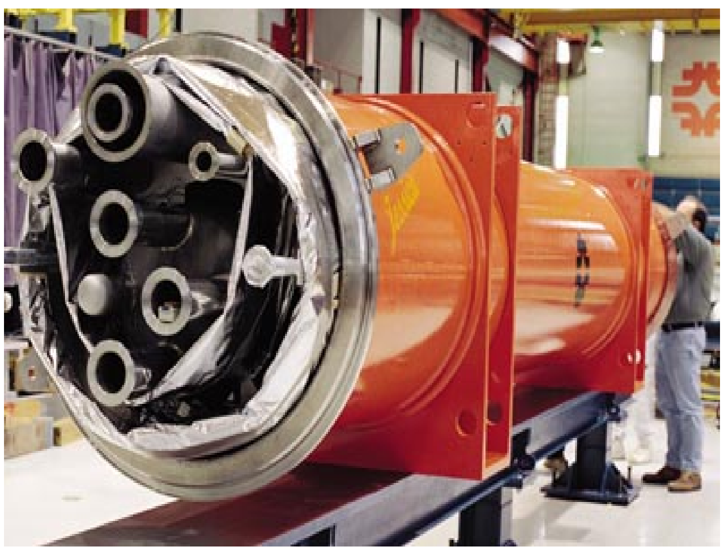
$$P = I^2 R$$

Using Superconducting Magnets

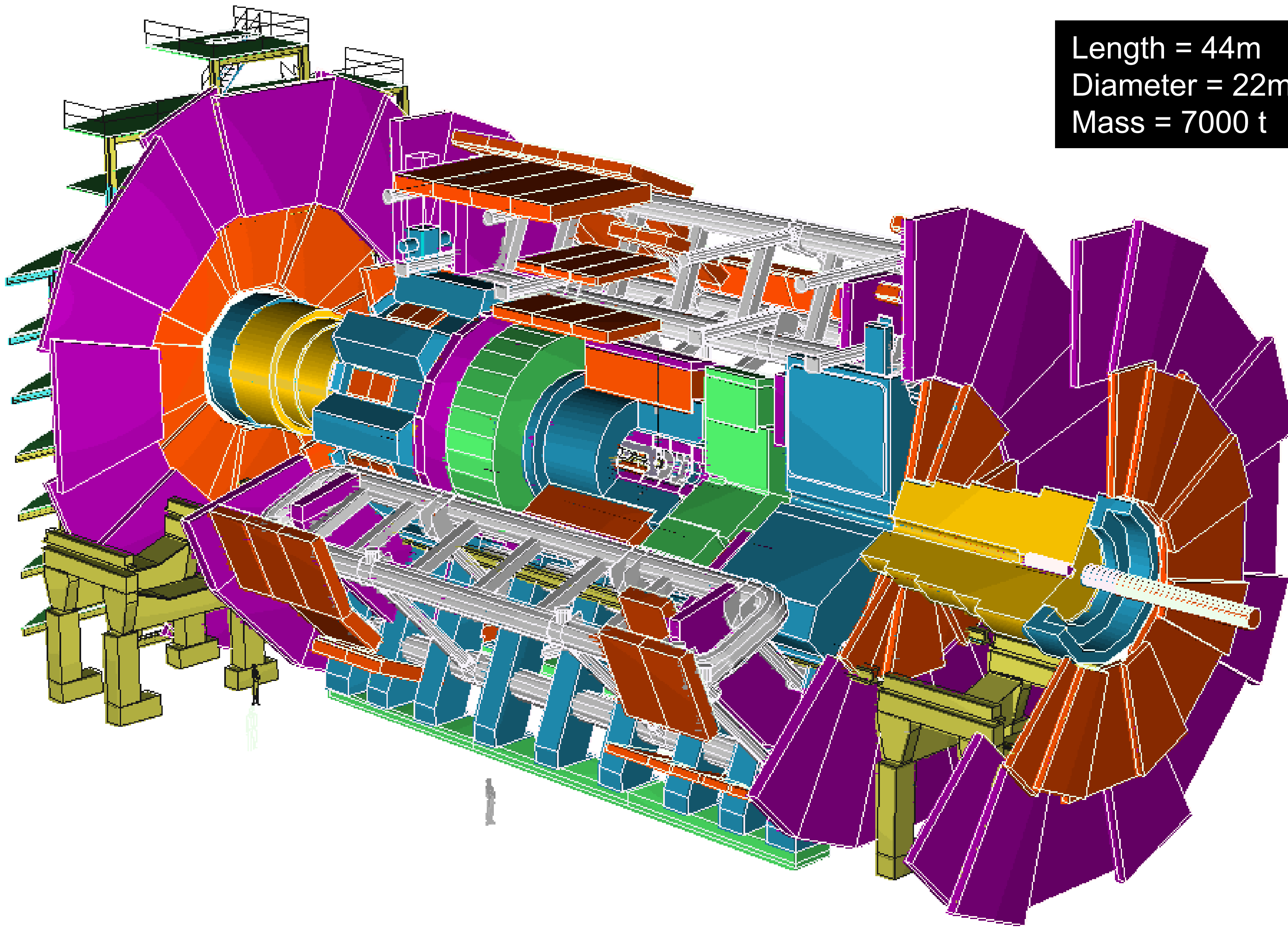
- Zero resistance – a good thing!
- Field is limited to ~9 Tesla
- They have to be kept cold: around 1.9K



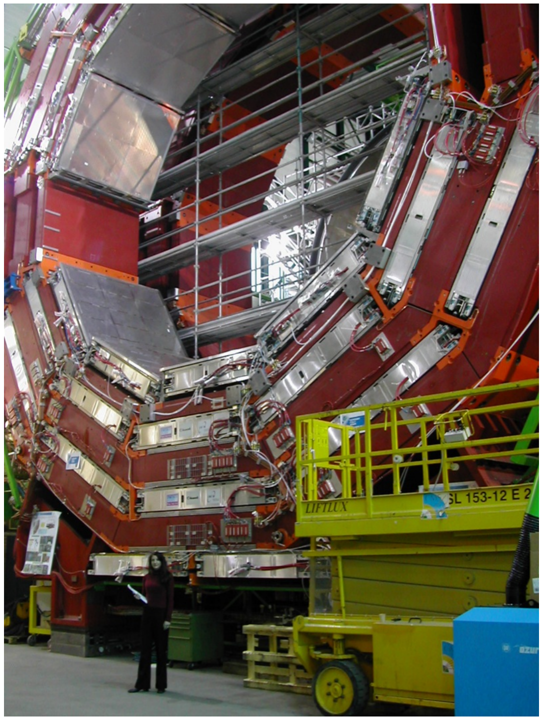




ATLAS = A Toroidal LHC ApparatuS

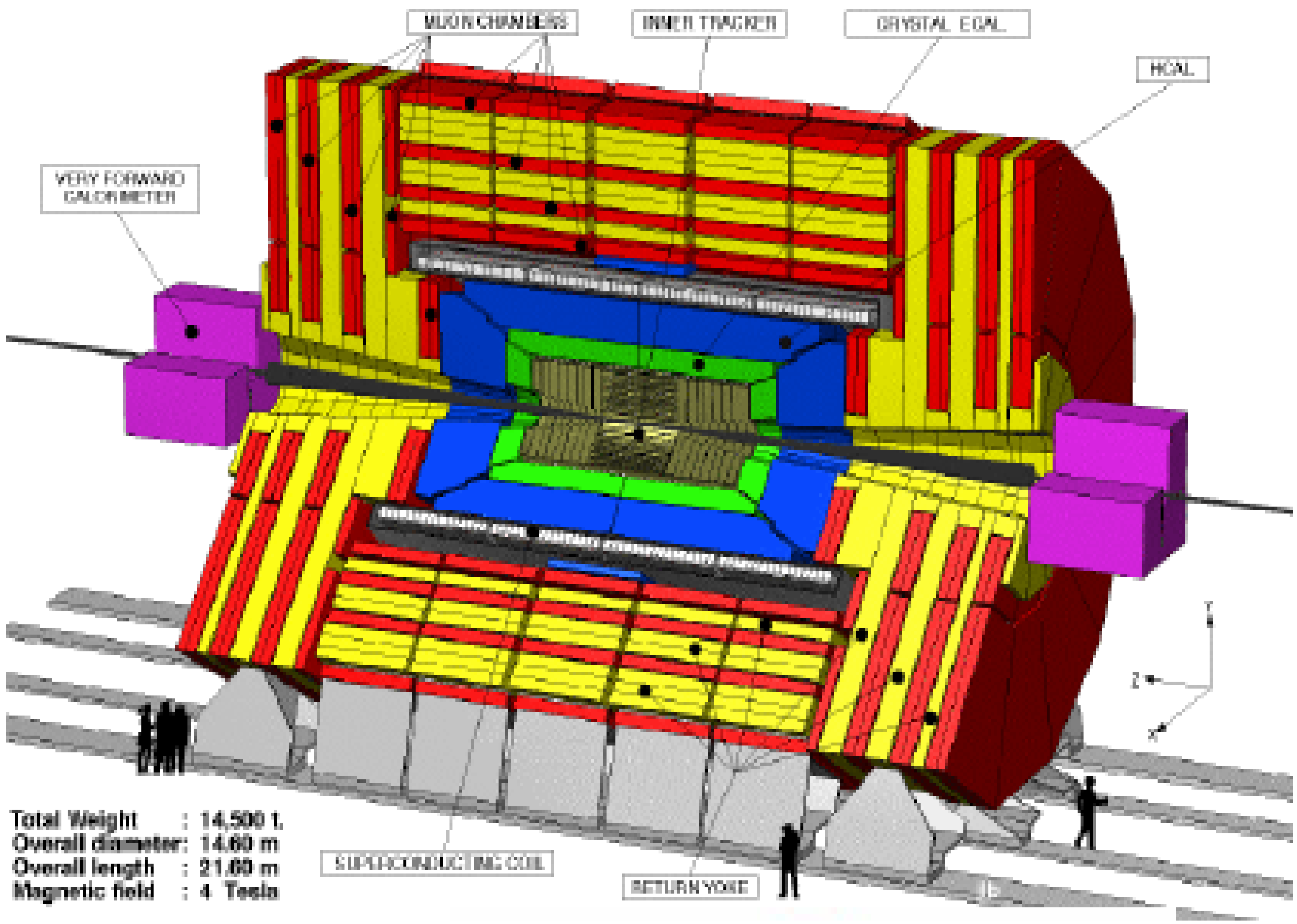


Length = 44m
Diameter = 22m
Mass = 7000 t



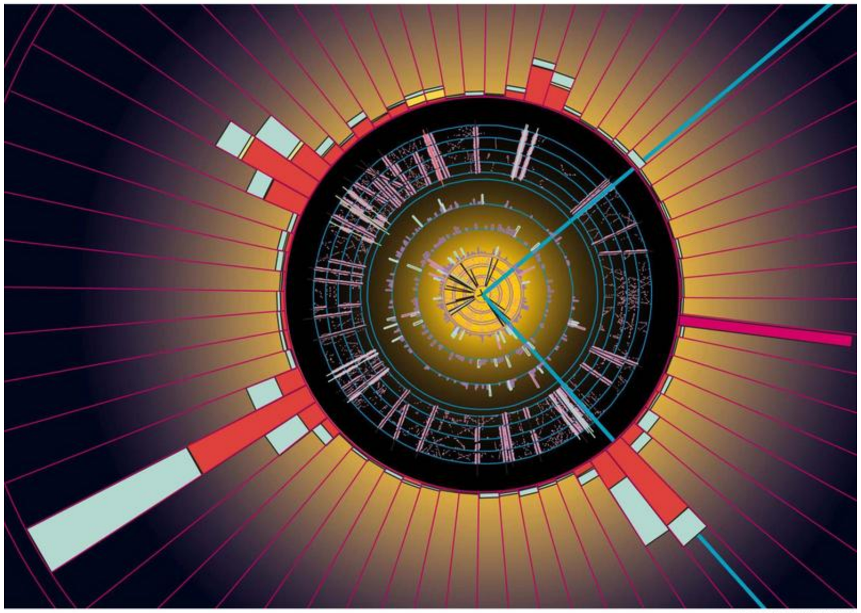
CMS

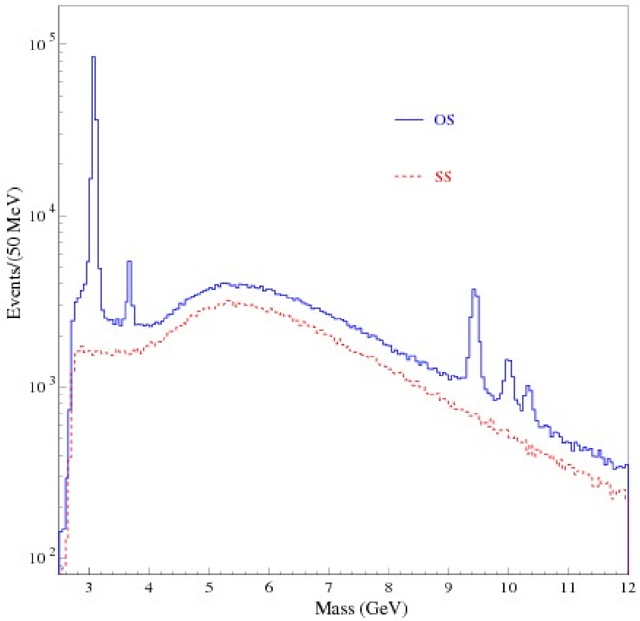
The compact Muon Solenoid Experiment



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



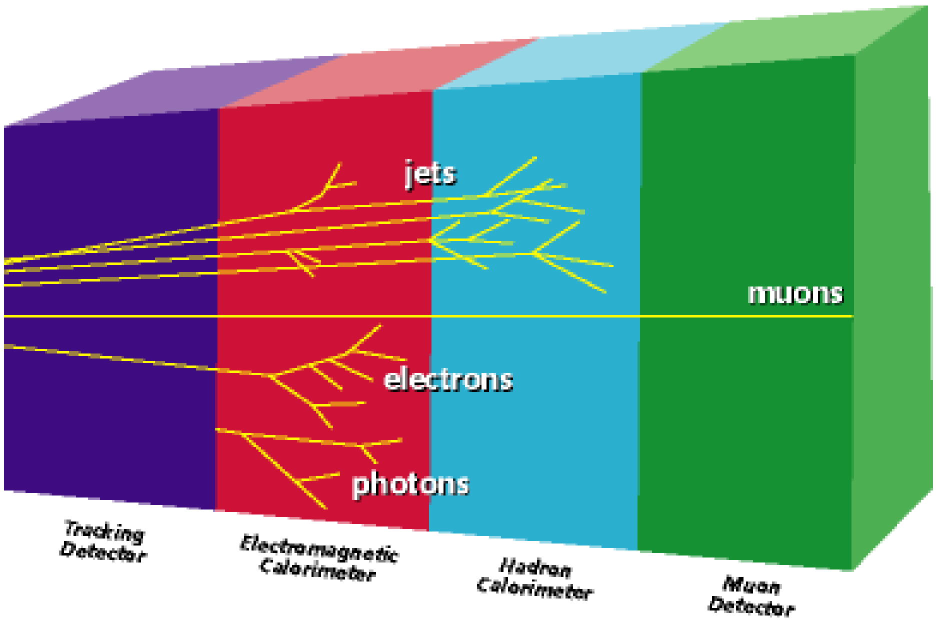


A common trick is to combine the particles you detect assuming they are the daughters in a decay chain, and plot the invariant mass of the combination.

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



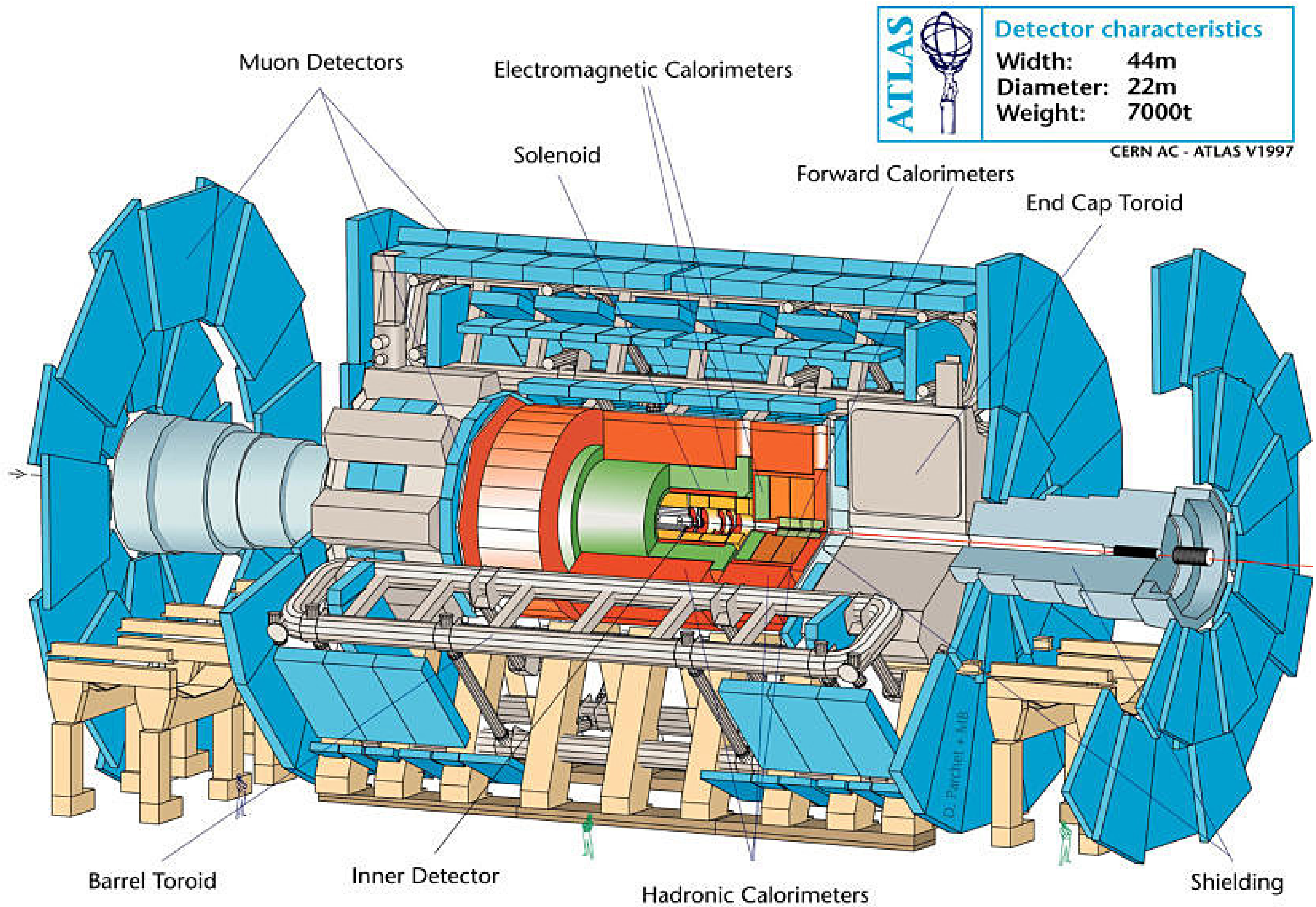
Different particles propagate differently through different parts of the detector; this enables us to identify them.

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

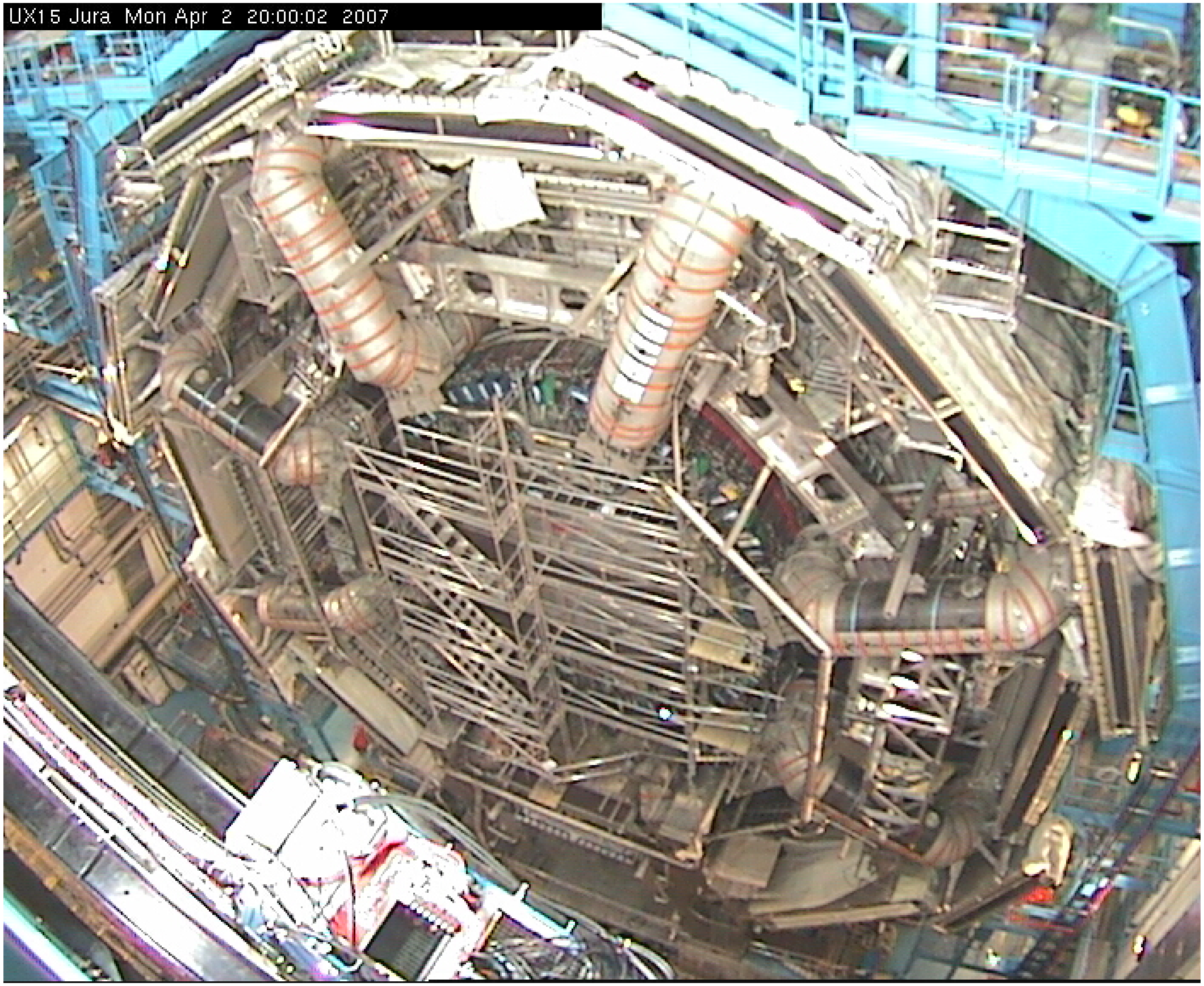
$$\boxed{r = \frac{p}{qB}}$$

- 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

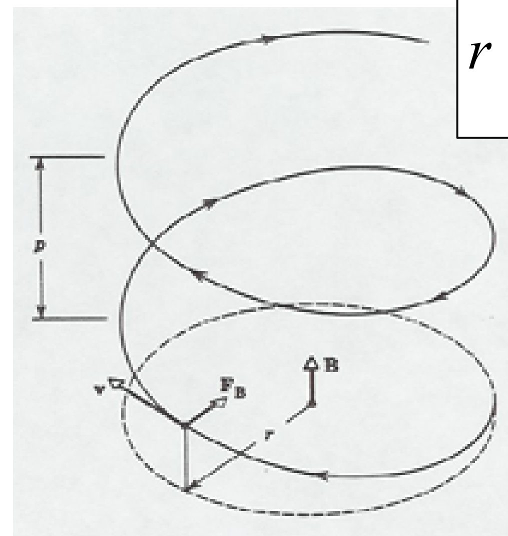


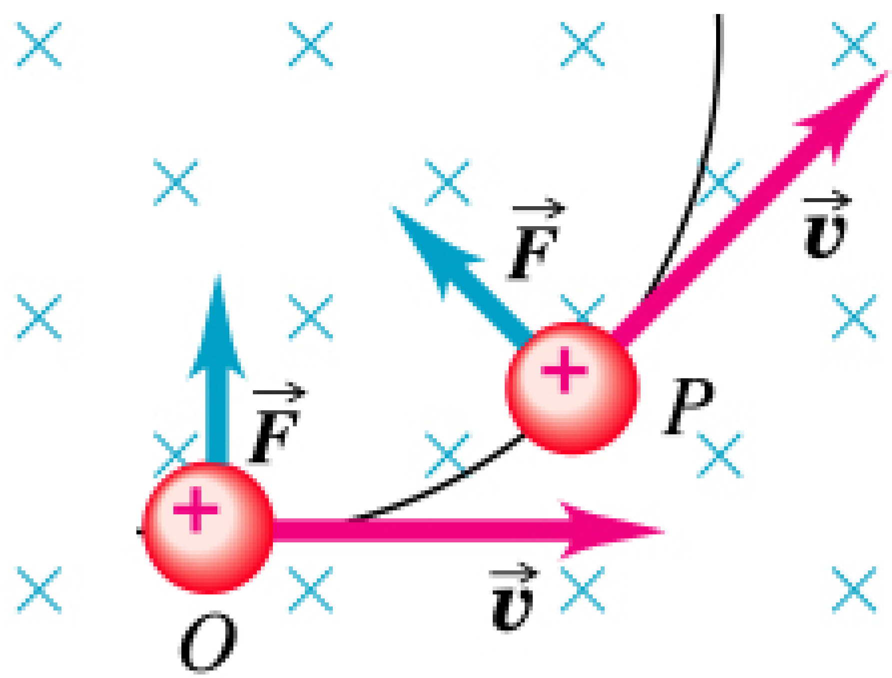
Why is ATLAS so big?

Motion of a Particle in a Magnetic Field

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

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

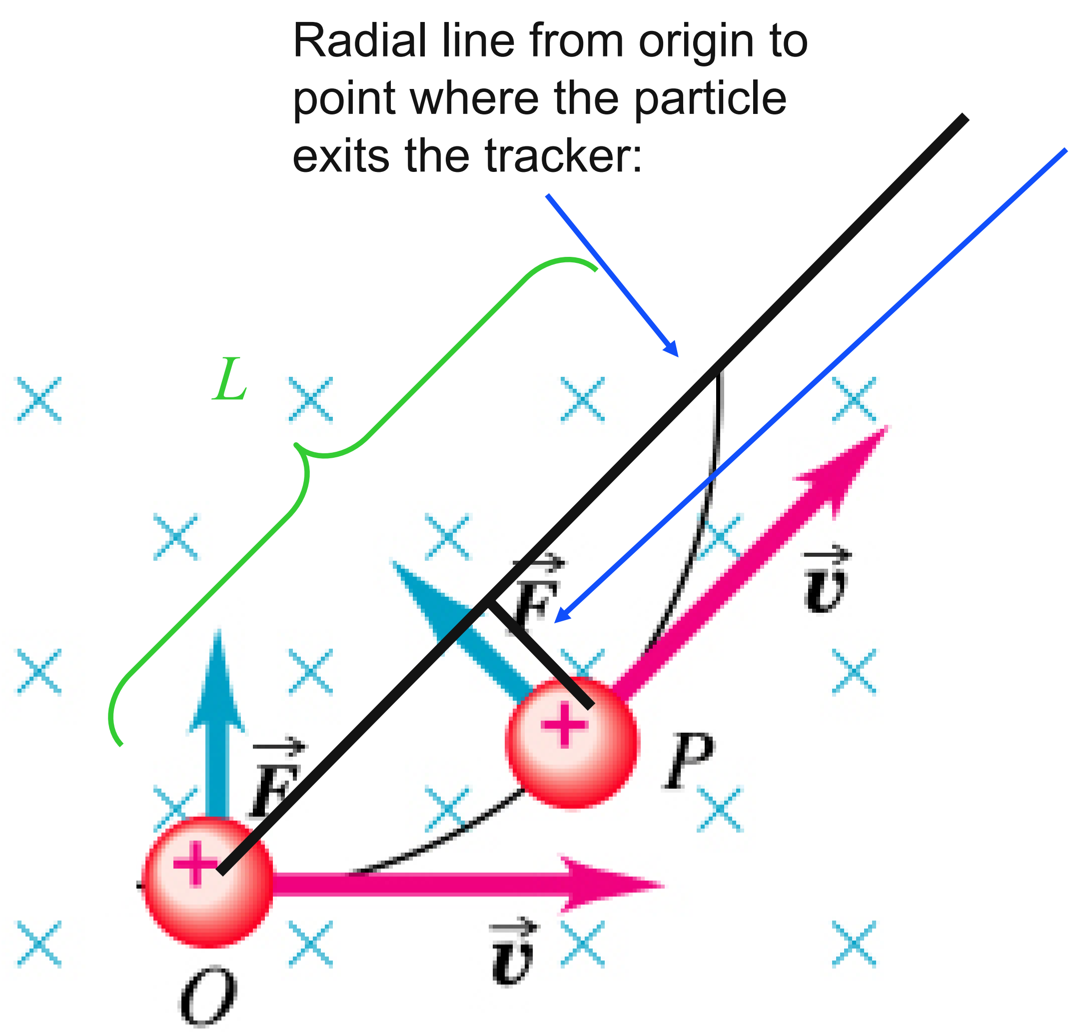




It's convenient to work in the transverse plane (i.e. the plane normal to the B direction)

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:

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

or

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

(Transverse momentum, relative to the beam axis.)

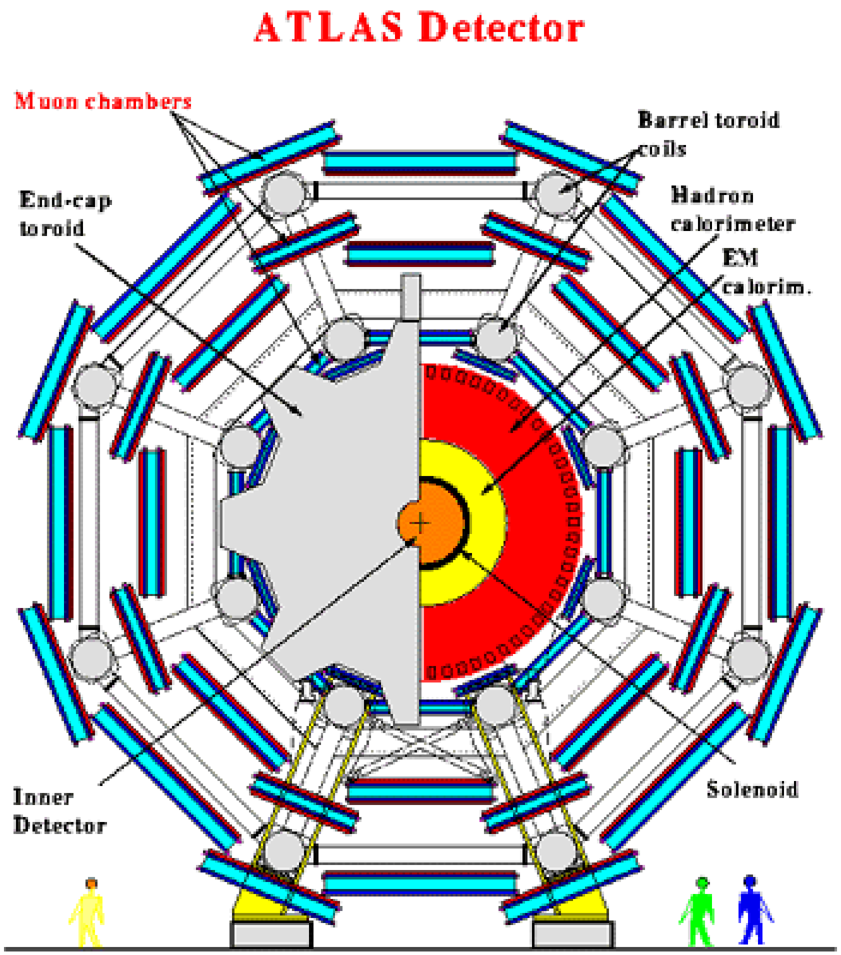
Why is ATLAS so big?

- 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

- 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.

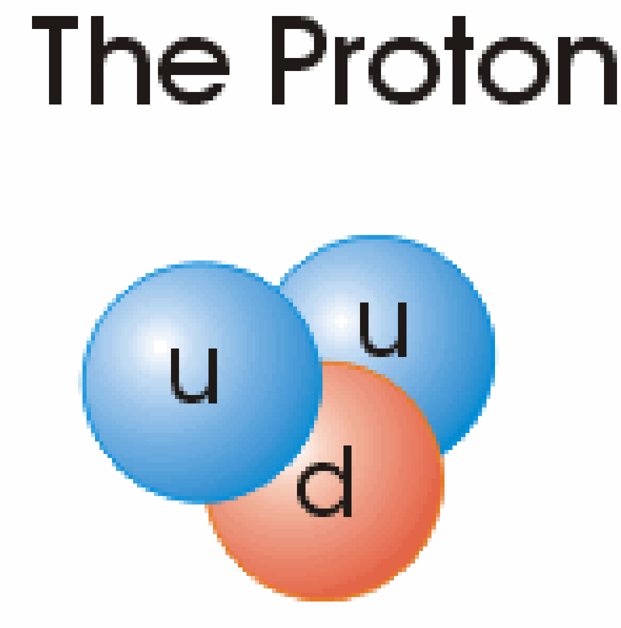
$$\frac{\Delta x}{x} = \alpha \Delta T$$

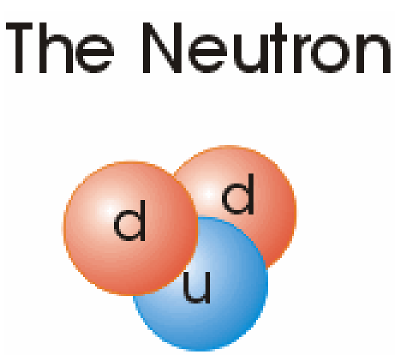
$$\Delta T = \frac{\Delta x}{\alpha x} \approx 0.2K$$

- 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.

Pictures from Jim Shank, Boston University

An Early Modern, Popular and Wrong View of the Proton





- 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.

The Modern Proton

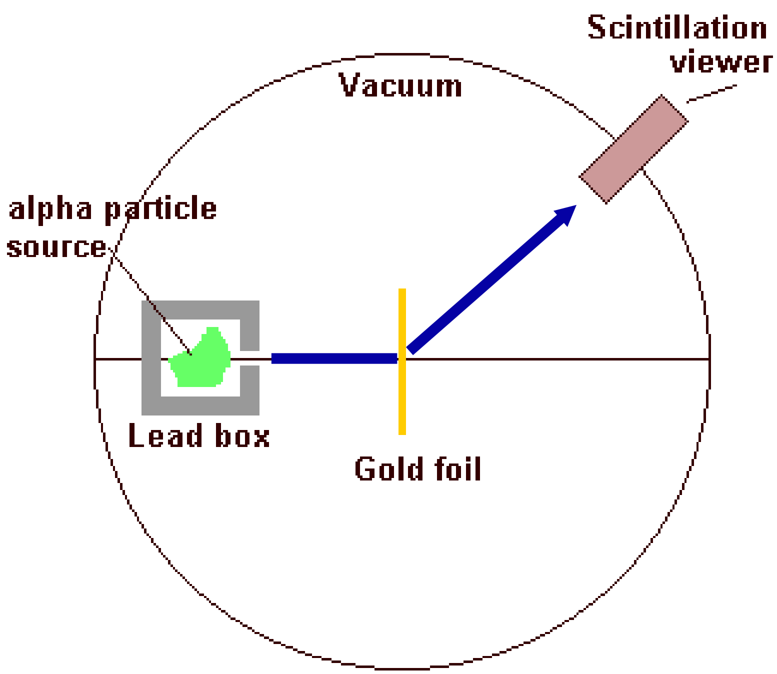
The Proton

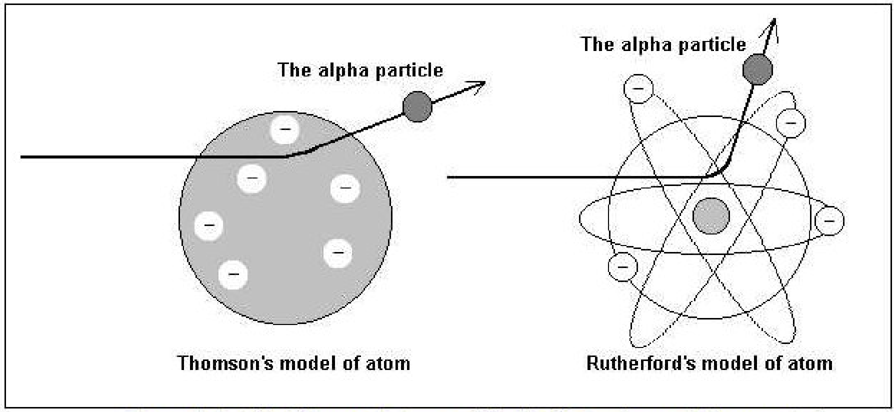
Mostly a very dynamic self-interacting field of gluons, with three quarks embedded.

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





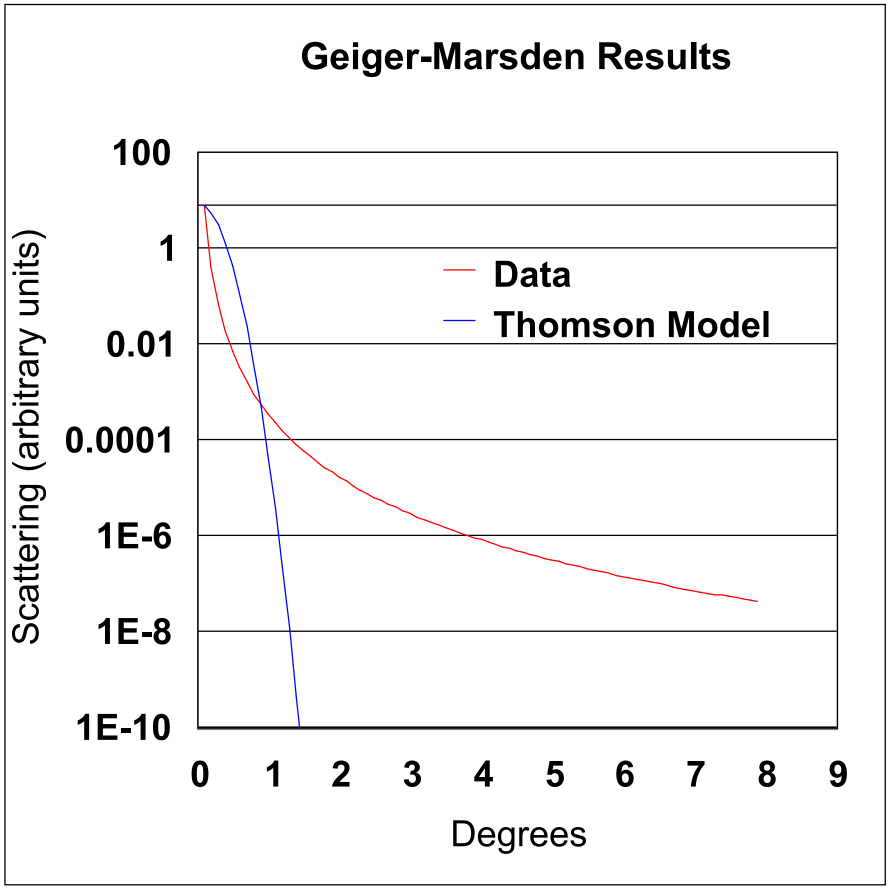
The models of the Thomson's atom and Rurtherford's atom; and the expected aberrations of alpha particle in both cases.

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

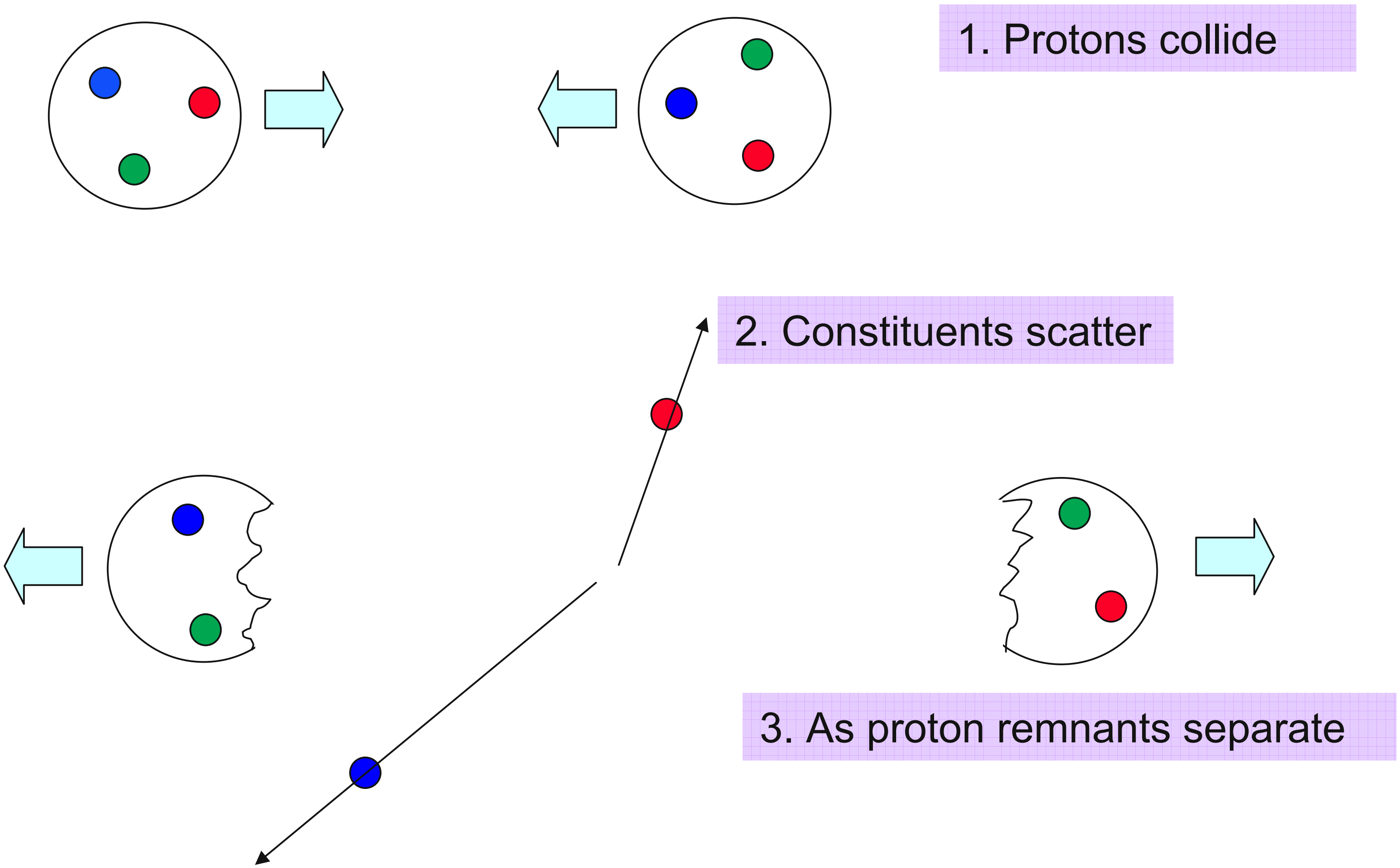
The electric field the α experiences gets weaker and weaker as the α enters the Thomson atom, but gets stronger and stronger as it enters the Rutherford atom and nears the nucleus.

Results of the Experiment



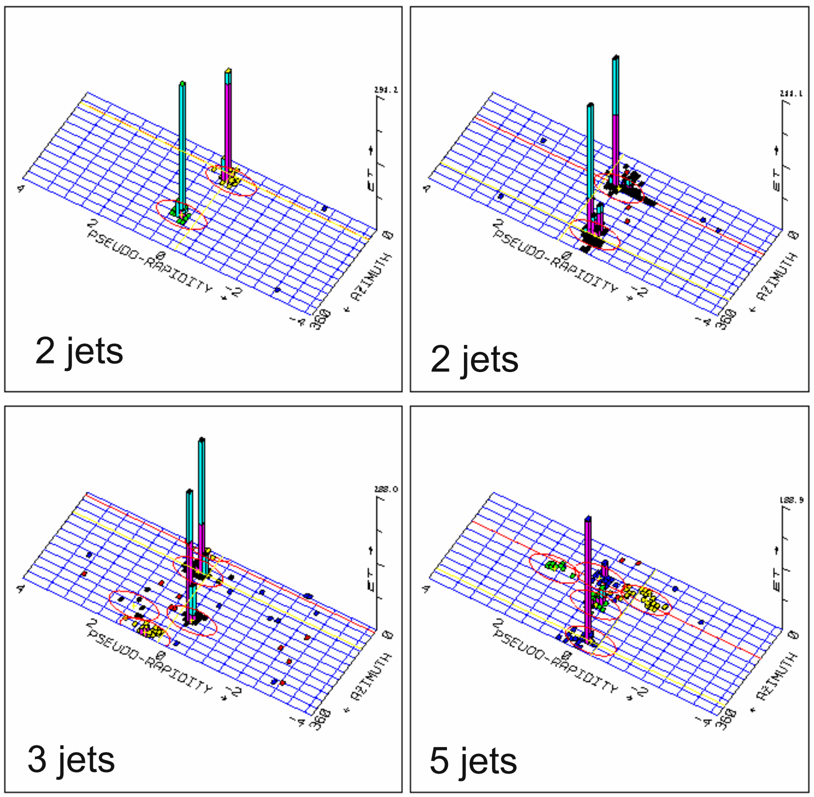
- At angles as low as 3^{o}, the data show a million times as many scatters as predicted by the Thomson model
  - Textbooks often point out that the data disagreed with theory, but they seldom state how bad the disagreement was
- There is an excess of events with a large angle scatter
  - This is a universal 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

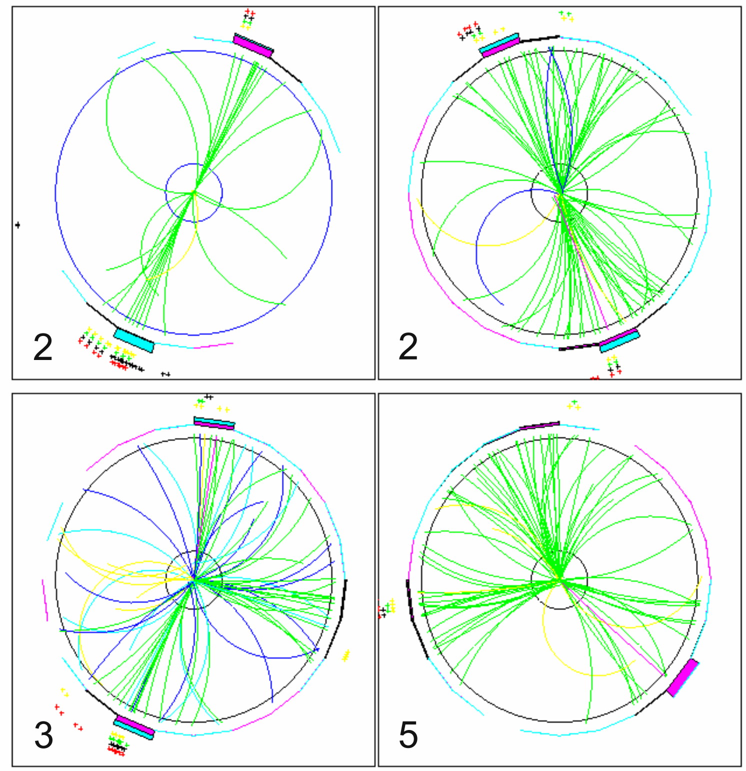


What Really Happens

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

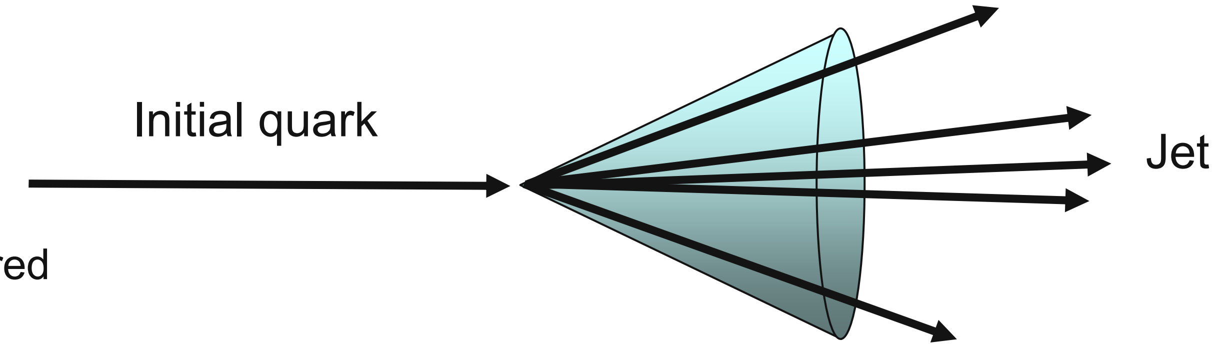


Calorimeter View



Same Events, Tracking View

Jets

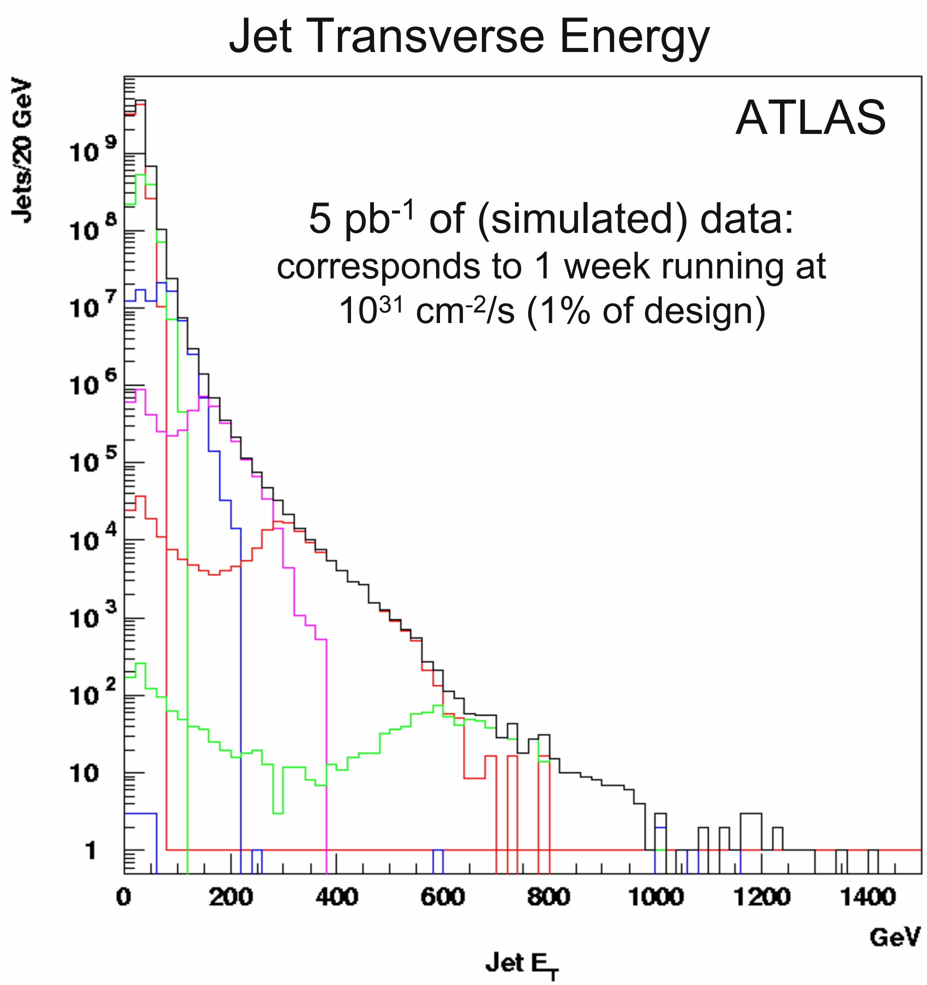


- The force between two colored objects (e.g. quarks) is ~independent of distance
  - Therefore the potential energy grows (~linearly) with distance
  - When it gets big enough, it pops a quark-antiquark pair out of the vacuum
  - These quarks and antiquarks ultimately end up as a collection of hadrons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

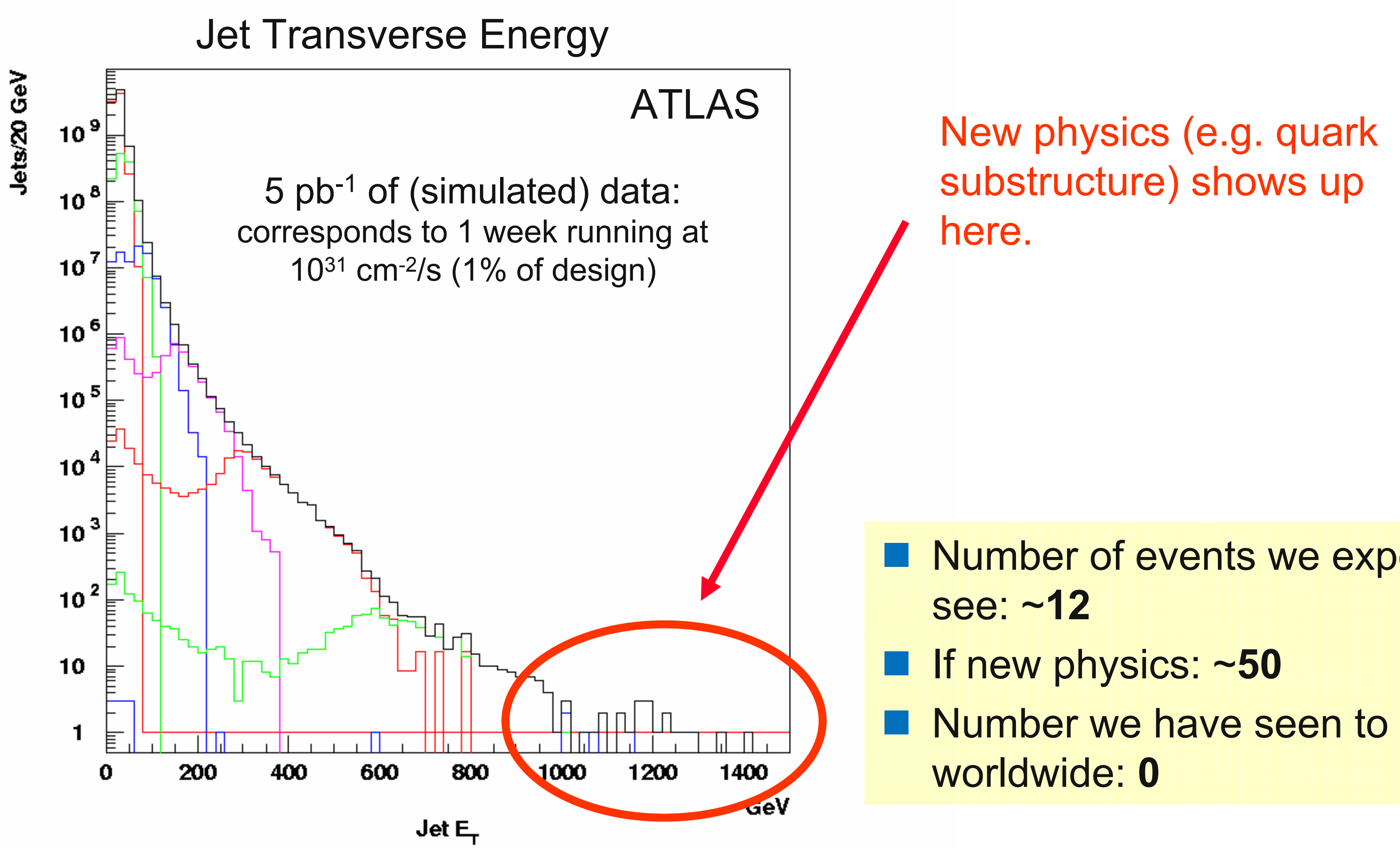
What makes the measurement possible & useful is the conservation of energy & momentum.

Jets after "One Week"



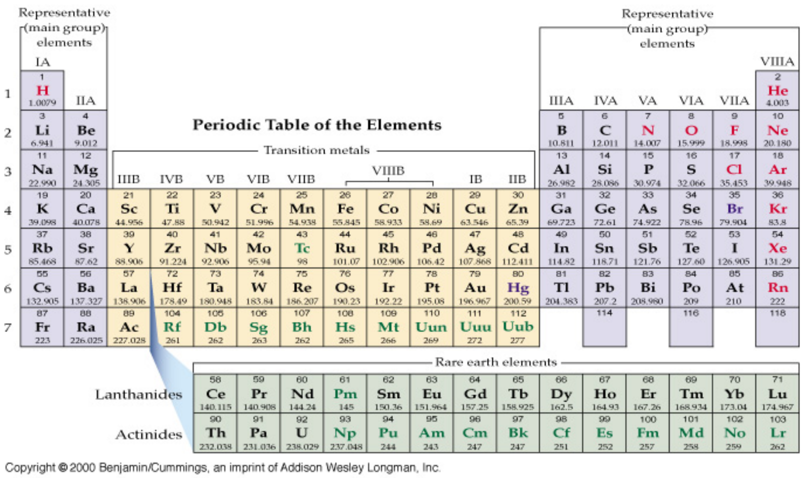
This is in units of transverse momentum. Remember, large angle = large p_T

Jets after "One Week"



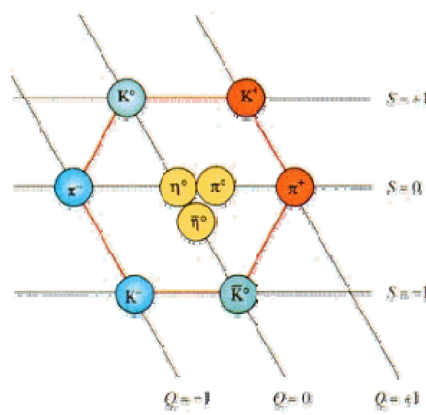
- Number of events we expect to see: **~12**
- If new physics: **~50**
- Number we have seen to date worldwide: **0**

Compositeness & The Periodic Table(s)

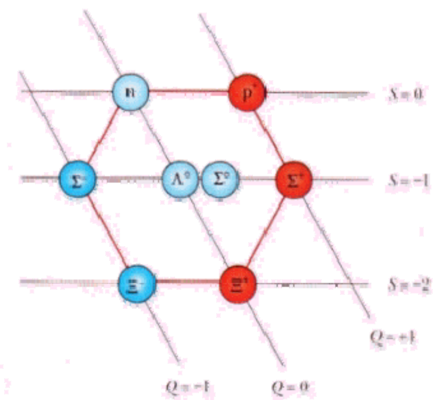


Arises because atoms have substructure: **electrons**

Arises because hadrons have substructure: **quarks**



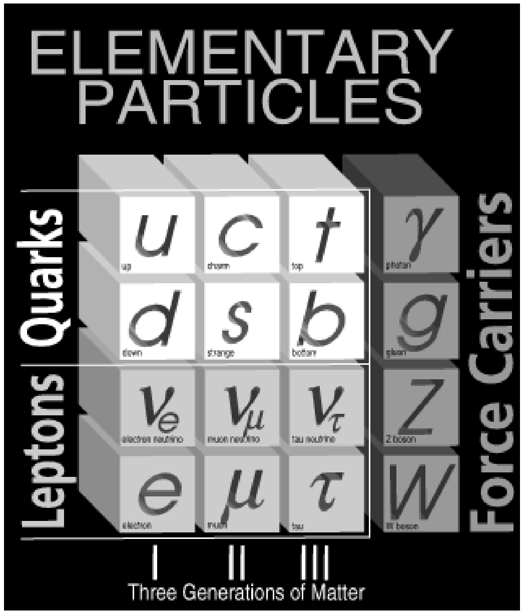
The 9 lightest spin-0 particles



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 (~10^5:1)
- There are some subtleties: if this is substructure, its nature is different than past examples.

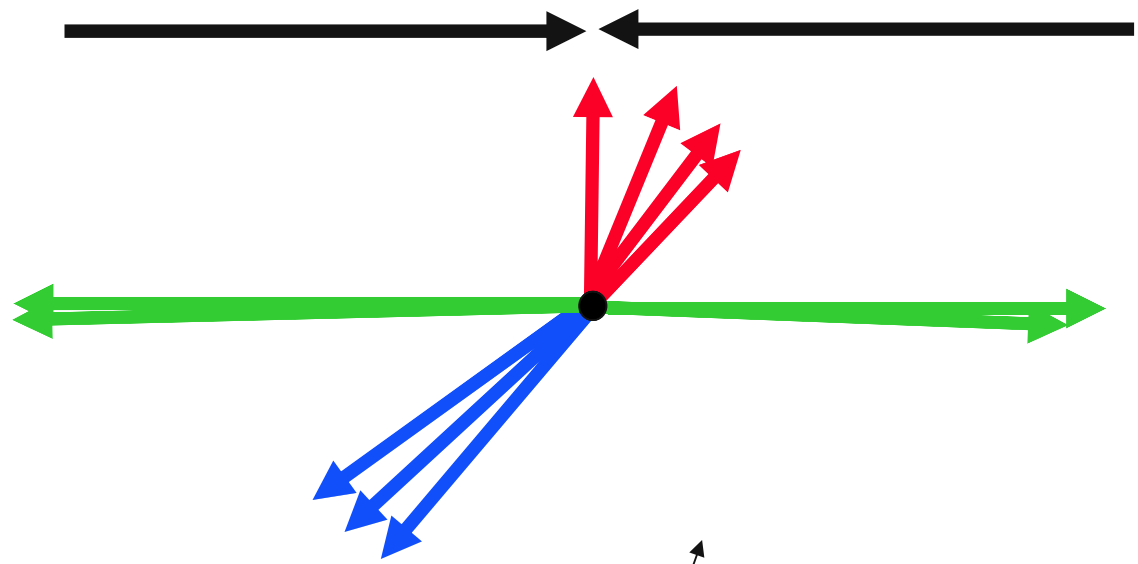
The Structure of the Proton

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.

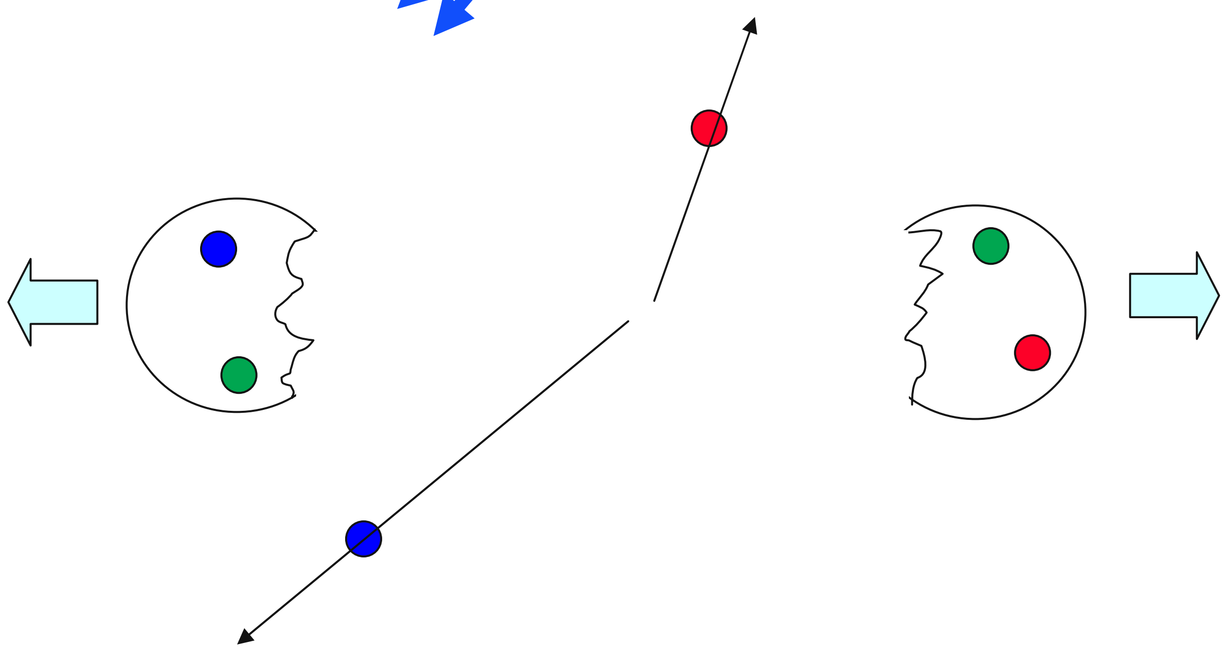
The Collision

What appears to be a highly ***inelastic*** process: two protons produce two jets of other particles…
(plus two remnants that go down the beam pipe)



… is actually the ***elastic*** scattering of two constituents (i.e., partons) of the protons.

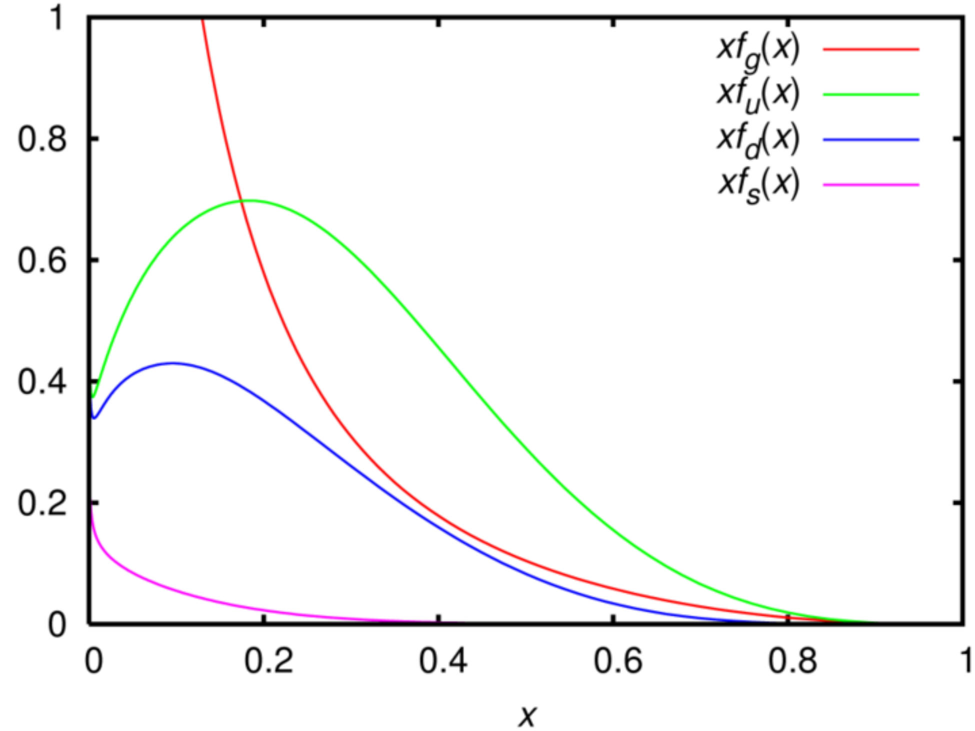
Parton model



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:
  - $x = p(\text{parton})/p(\text{proton})$
  - 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.

Quantum Chromodynamics, QCD

Credit Where Credit Is Due

(at Michigan State University)

CTEQ PDF

The plot on the last slide took an incredible amount of effort by literally hundreds of physicists to make.

One of the giants in the field is MSU’s own Wu-Ki Tung.

After Wu-Ki retired, his former student Hong-Liang Lai is carrying on this important task.

The Standard Model of Particle Physics

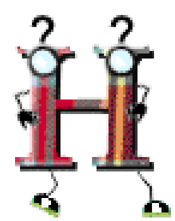
- Gauge Symmetry (Gravity is not included)

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

(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)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \; u_R \; u_R \qquad c_R \; c_R \; c_R \qquad t_R \; t_R \; t_R$$

$$d_R \; d_R \; d_R \qquad s_R \; s_R \; s_R \qquad b_R \; b_R \; b_R$$

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)

$$\left(\text{massive} \quad \begin{aligned} M_W &= 80.42 \text{ GeV} \\ M_Z &= 91.187 \text{ GeV} \end{aligned} \qquad 1 \text{ GeV} = 10^9 \text{ eV} \right)$$

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

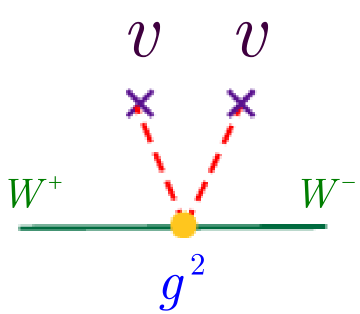
  (Quarks and Leptons have diverse masses.)

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

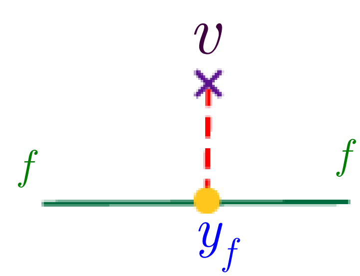
$$L_\Phi = \left(D_\mu \Phi\right)^+ \left(D^\mu \Phi\right) - \lambda \left(\Phi^+\Phi - \frac{v^2}{2}\right)^2$$



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

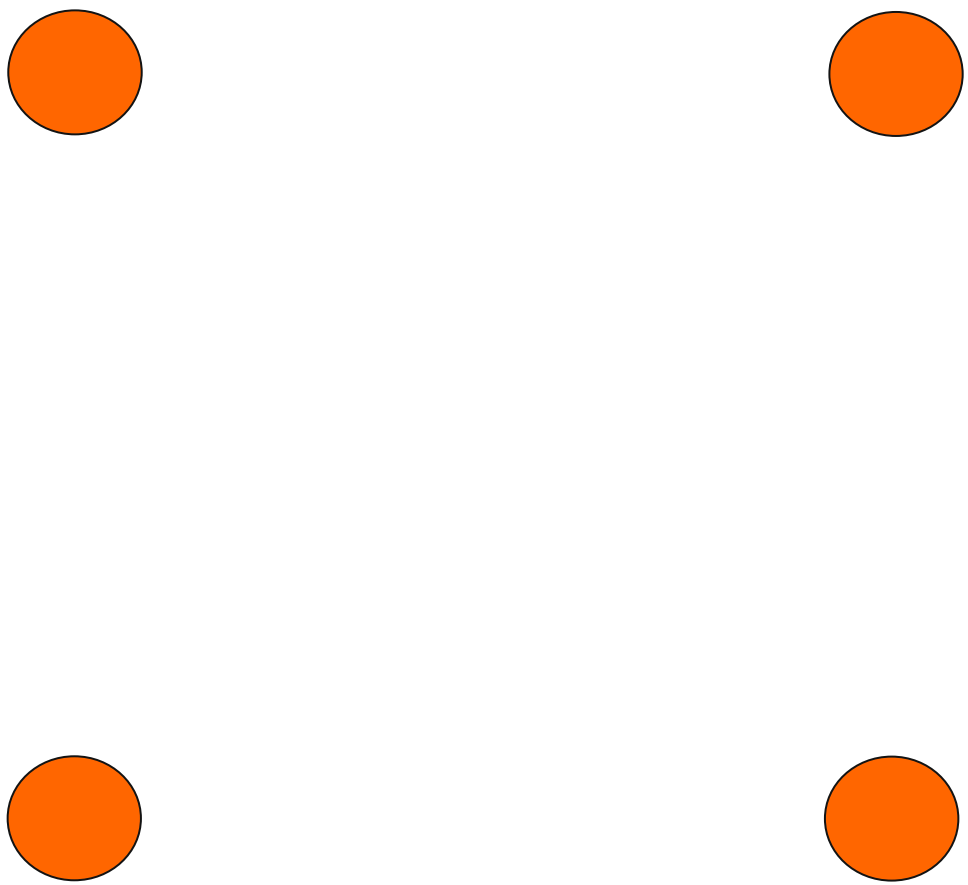
- To generate m_f

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



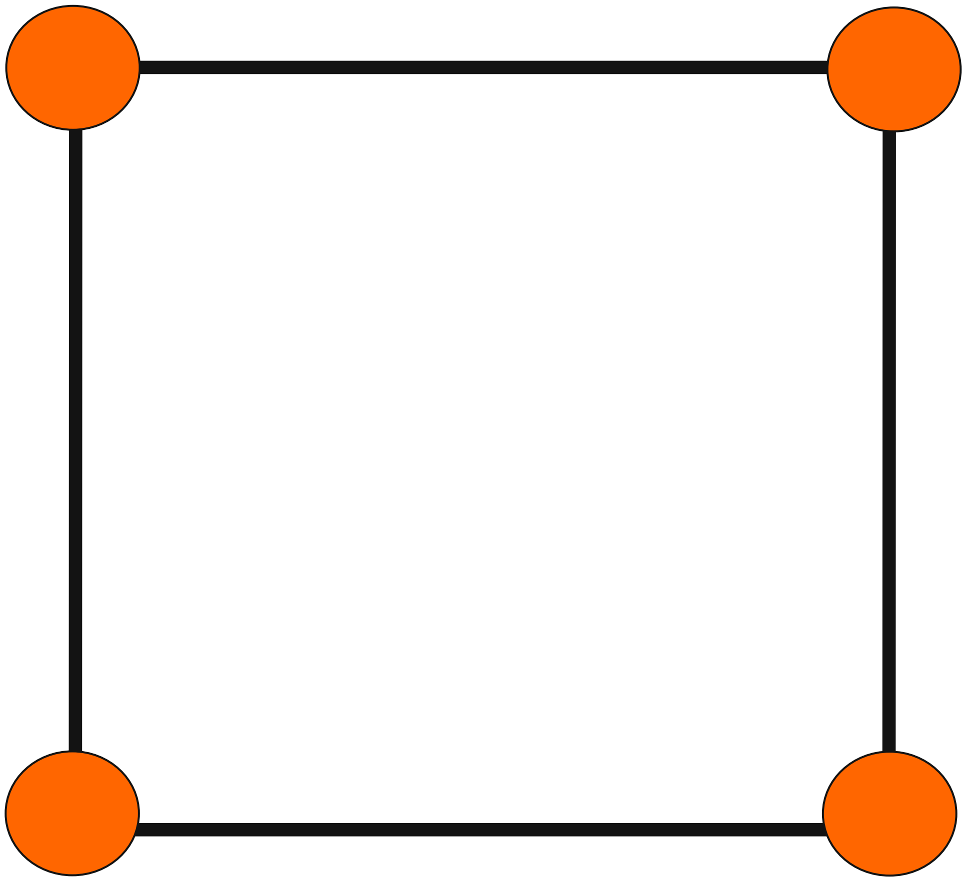
$$\Rightarrow \quad m_f = y_f \frac{v}{\sqrt{2}}$$

Spontaneous Symmetry Breaking



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

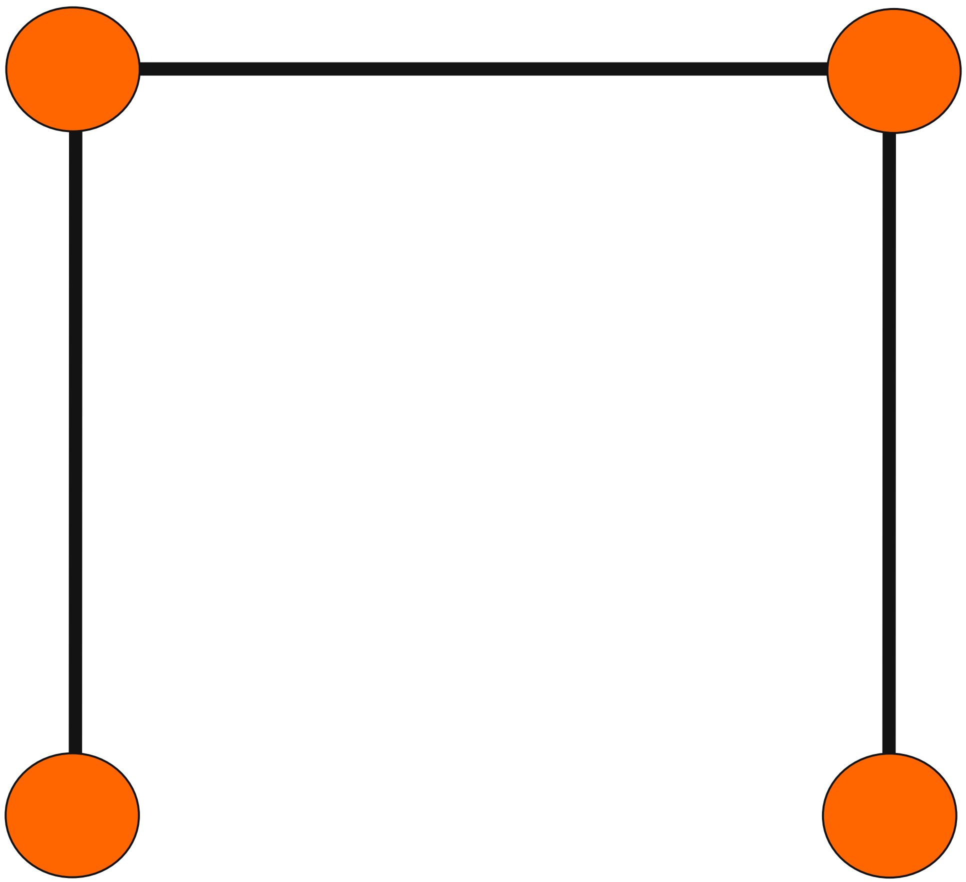
One Option



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

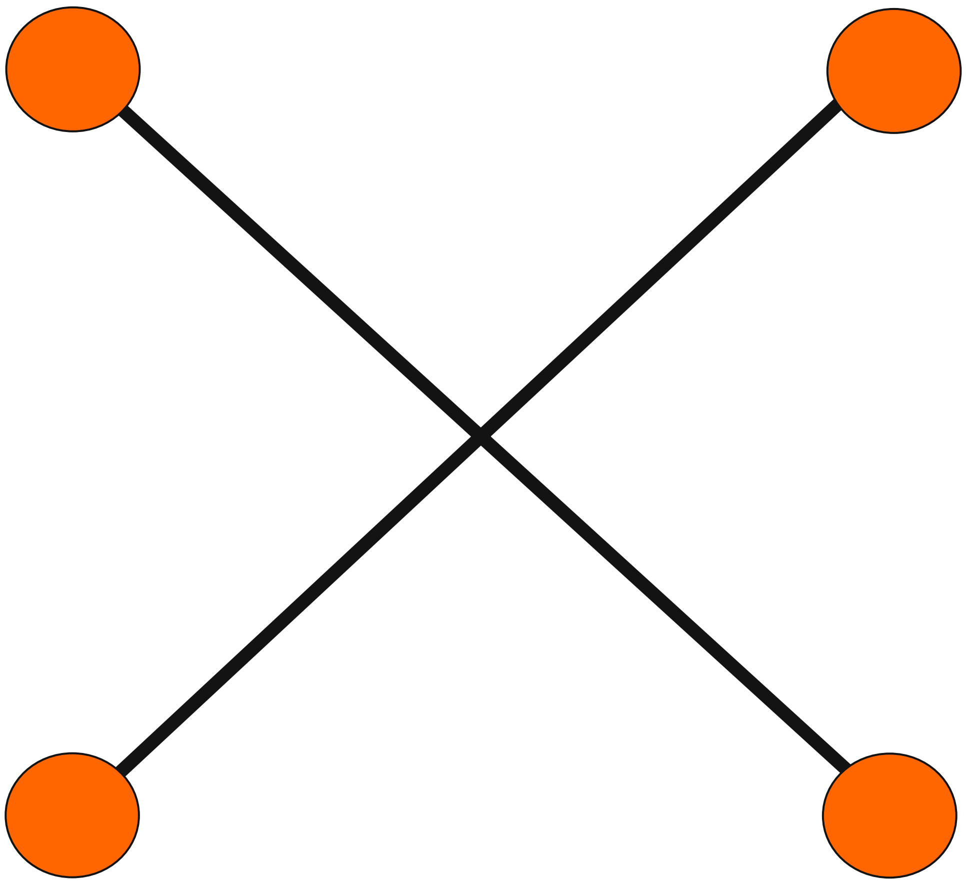
(length of side = 1 unit)

Option Two



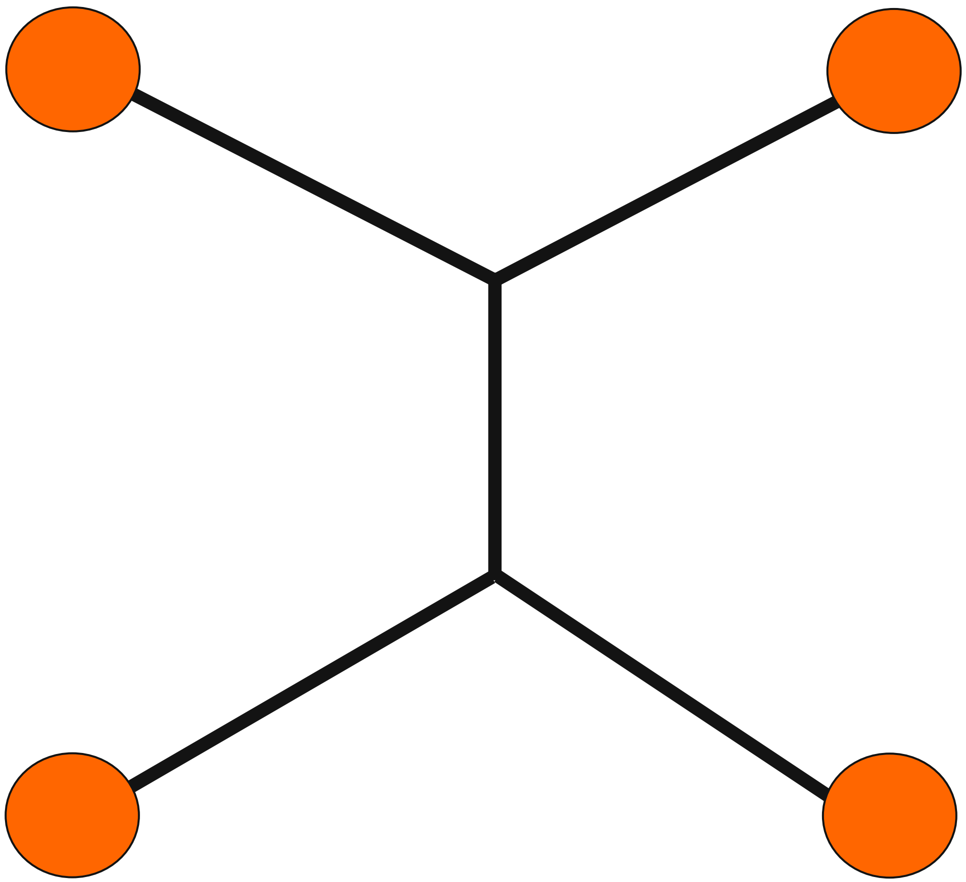
I can connect them this way at a cost of only 3 units.

The Solution that Looks Optimal, But Really Isn't



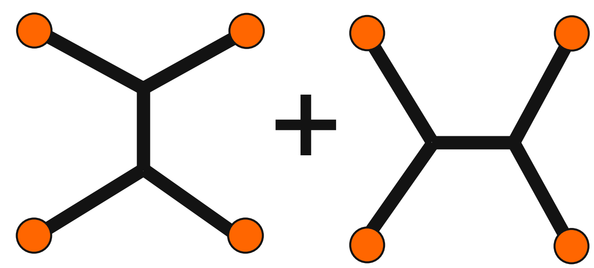
This requires only $2\sqrt{2}$

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

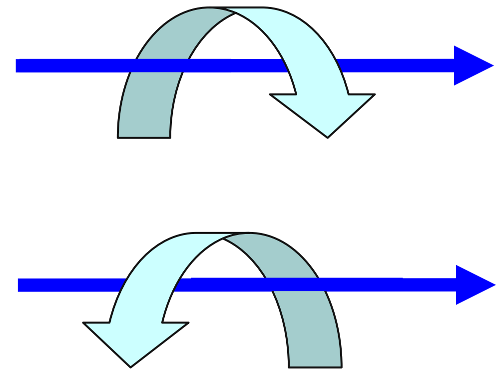
- Write down a theory of massless weak bosons
  - The only thing wrong with this theory is that it doesn't describe the world in which we live
- Add a new doublet of spin-0 particles:
  - This adds *four* new degrees of freedom (the doublet + their antiparticles)

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

- 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

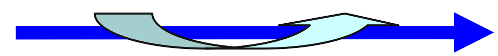
The Really Cute Thing

- 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



$m = \pm 1$ “transverse”

- The same thing happens for the w^- and ϕ^-

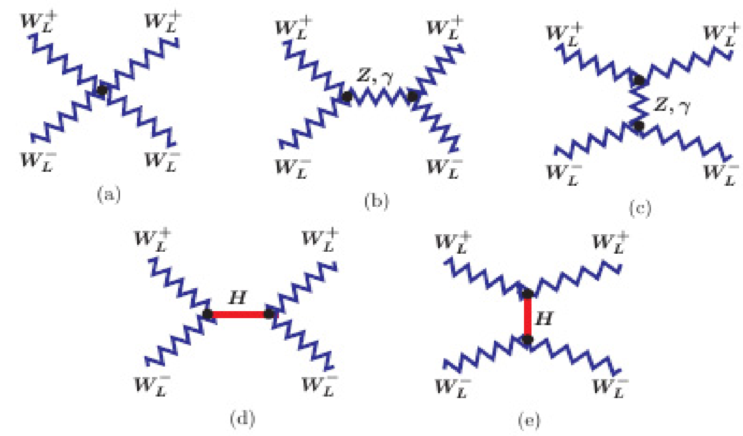


$m = 0$ “longitudinal”

- 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

The "No Lose Theorem" at the LHC

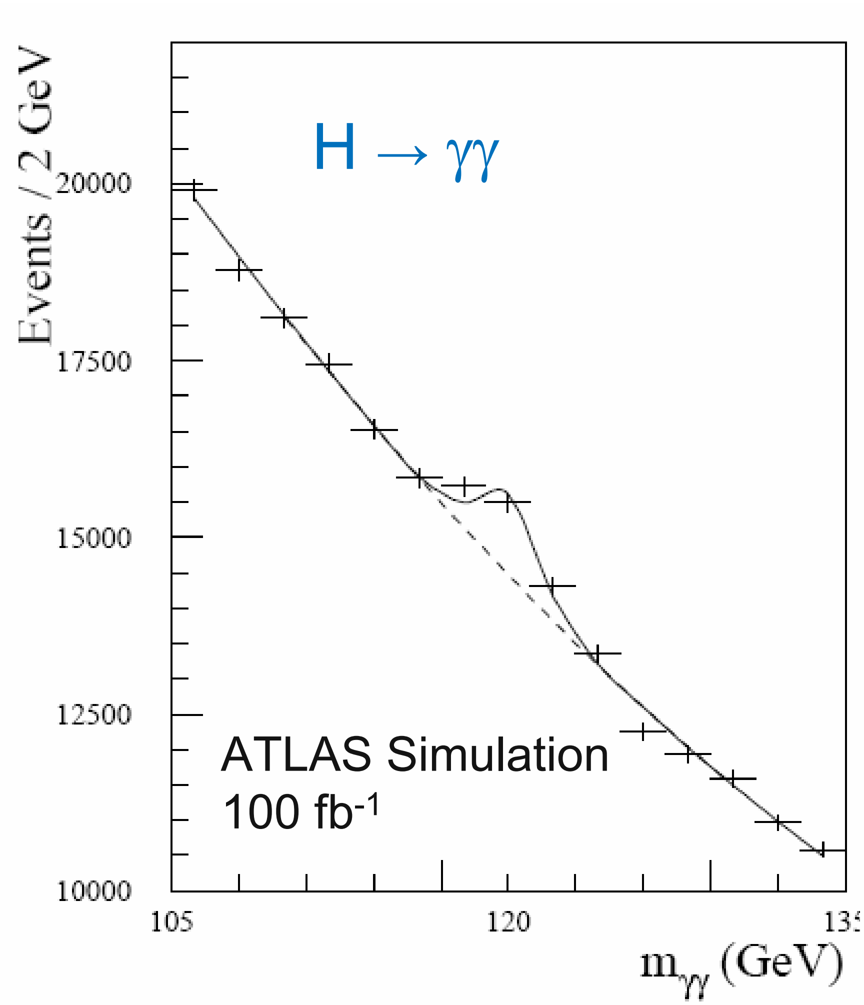
Either we find Higgs Boson, or
we must find new physics signature.

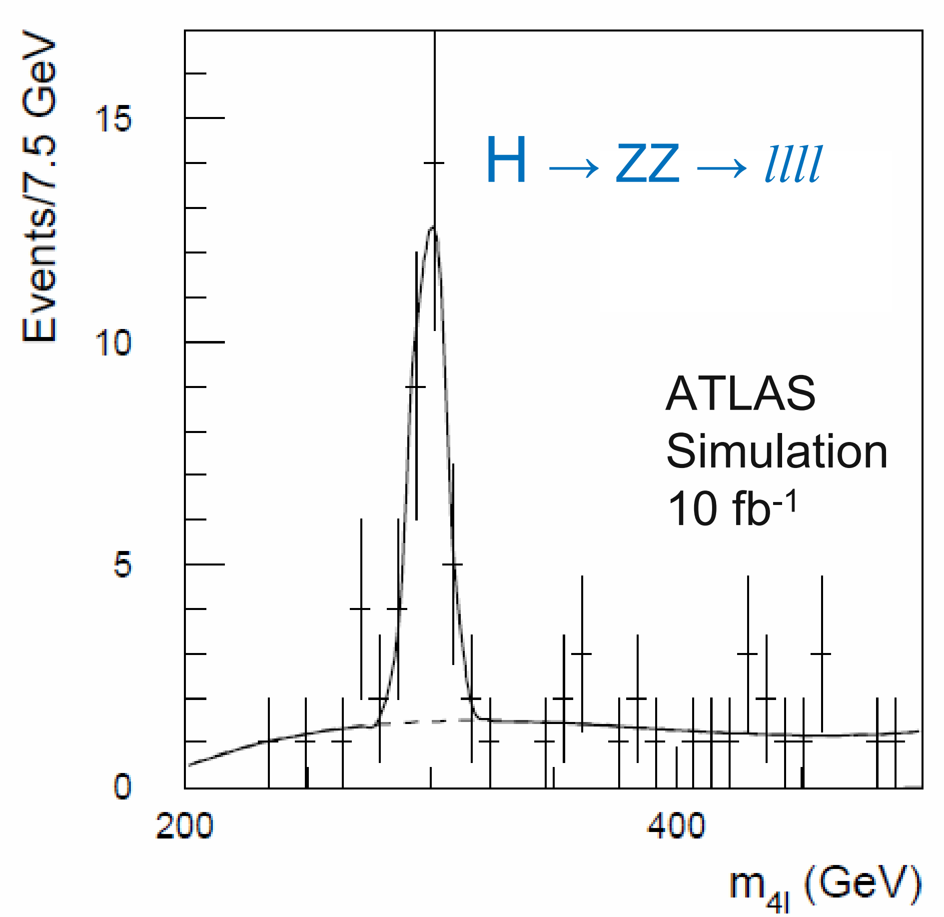
- Imagine you could elastically scatter beams of W bosons:
  $WW \rightarrow WW$
- We can calculate this, and at high enough energies
  "the cross-section violates unitarity"
  - A fancy way of saying the probability of a scatter exceeds 1: nonsense
  - The troublesome piece is (once again) the longitudinal 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.



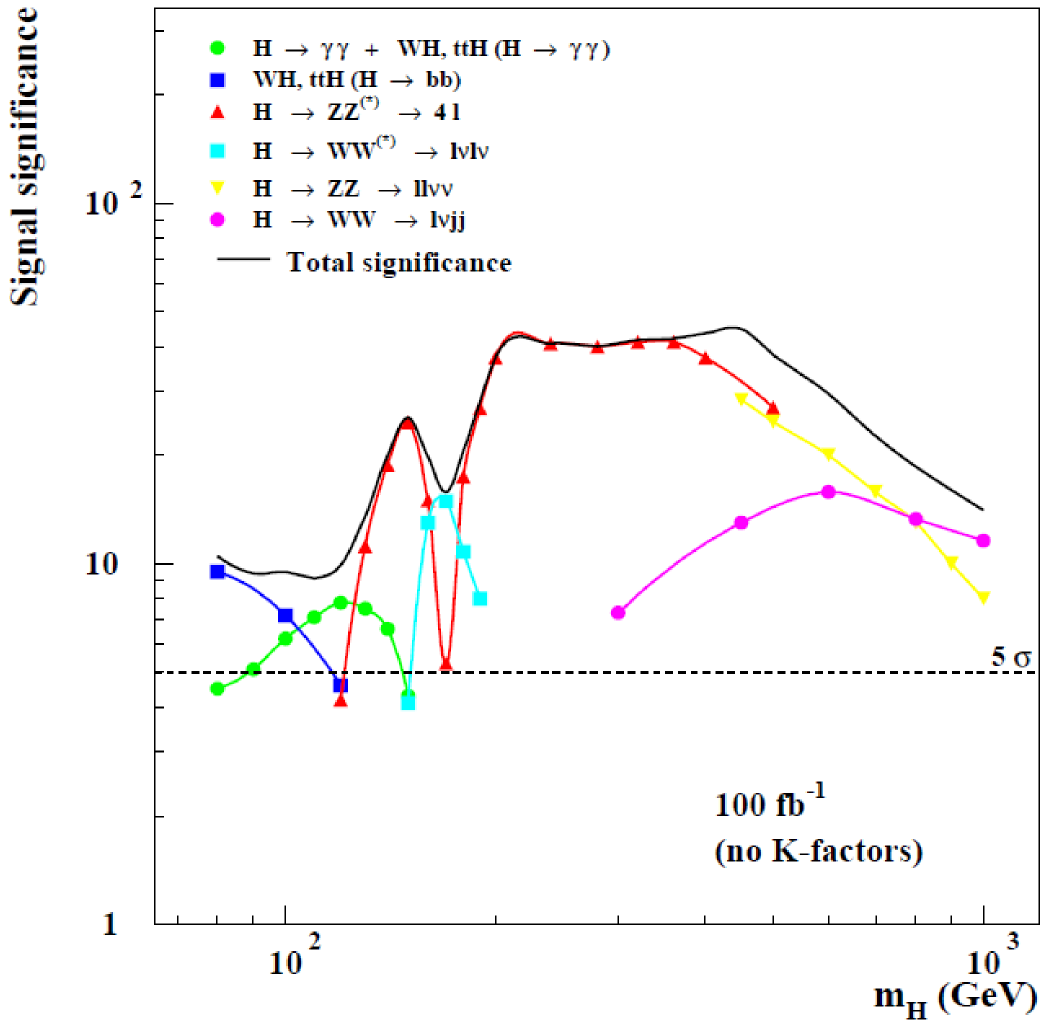


Combining All Channels

- 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.

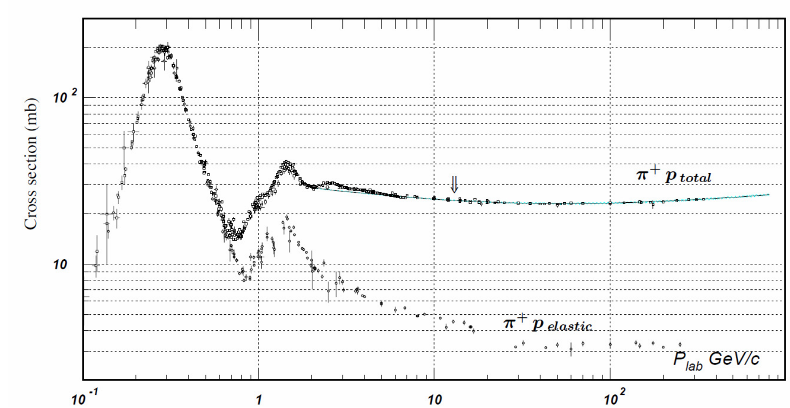
- The other experiment, CMS, has comparable sensitivity



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:
    - *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 $\pi + p \rightarrow \pi + p$ 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*



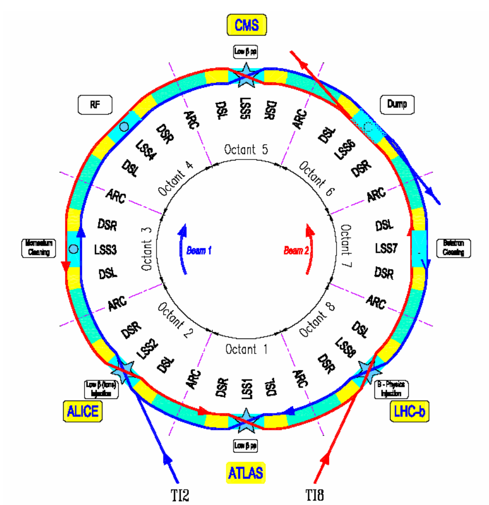
Many models: ATLAS data will help discriminate among them.

So, When Is This Going To Happen?

The latest schedule shows the LHC ready for beam around May 26th in 2008.

Beam will be injected into sectors as soon as they are cold.

	Pressure test	Cool-down		Powering tests	
Sector 12	wk. 49 (2007)	wk. 07 (2008)	wk. 12 (2008)	wk. 13 (2008)	wk. 25 (2008)
Sector 23	*Done*	wk. 06 (2008)	wk. 11 (2008)	wk. 12 (2008)	wk. 23 (2008)
Sector 34	*Done*	wk. 10 (2008)	wk. 15 (2008)	wk. 16 (2008)	wk. 24 (2008)
1 Sector 45	*Done*	*Started*	wk. 48 (2007)	wk. 49 (2007)	wk. 03 (2008)
2		wk. 14 (2008)	wk. 17 (2008)	wk. 18 (2008)	wk. 25 (2008)
Sector 56	*Done*	wk. 49 (2007)	wk. 07 (2008)	wk. 09 (2008)	wk. 19 (2008)
Sector 67	*Done*	wk. 05 (2008)	wk. 11 (2008)	wk. 12(2008)	wk. 20 (2008)
1 Sector 78	*Done*	*Done*	*Done*	*Done*	*Done*
2	*Done*	wk. 04 (2008)	wk. 10 (2008)	wk. 11 (2008)	wk. 22 (2008)
Sector 81	*Done*	wk. 51 (2007)	wk. 09 (2008)	wk. 10 (2008)	wk. 22 (2008)



It takes almost two months to cool down one sector.

My Take on The Schedule

- If we only have the same old problems (i.e. no new ones) there will beam in July
  - Each surprise adds two months to that date
- We will turn on with very low luminosity and this will grow slowly as we learn to handle the stored energy
  - Luminosity grows as the square of stored energy
- After maybe a year, the luminosity will shoot up like a rocket
  - Luminosity grows as the square of stored energy

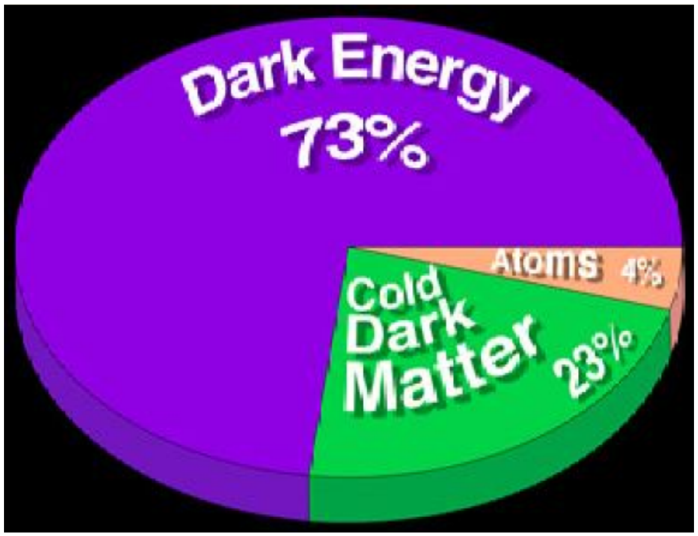
Apologies

- 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?*

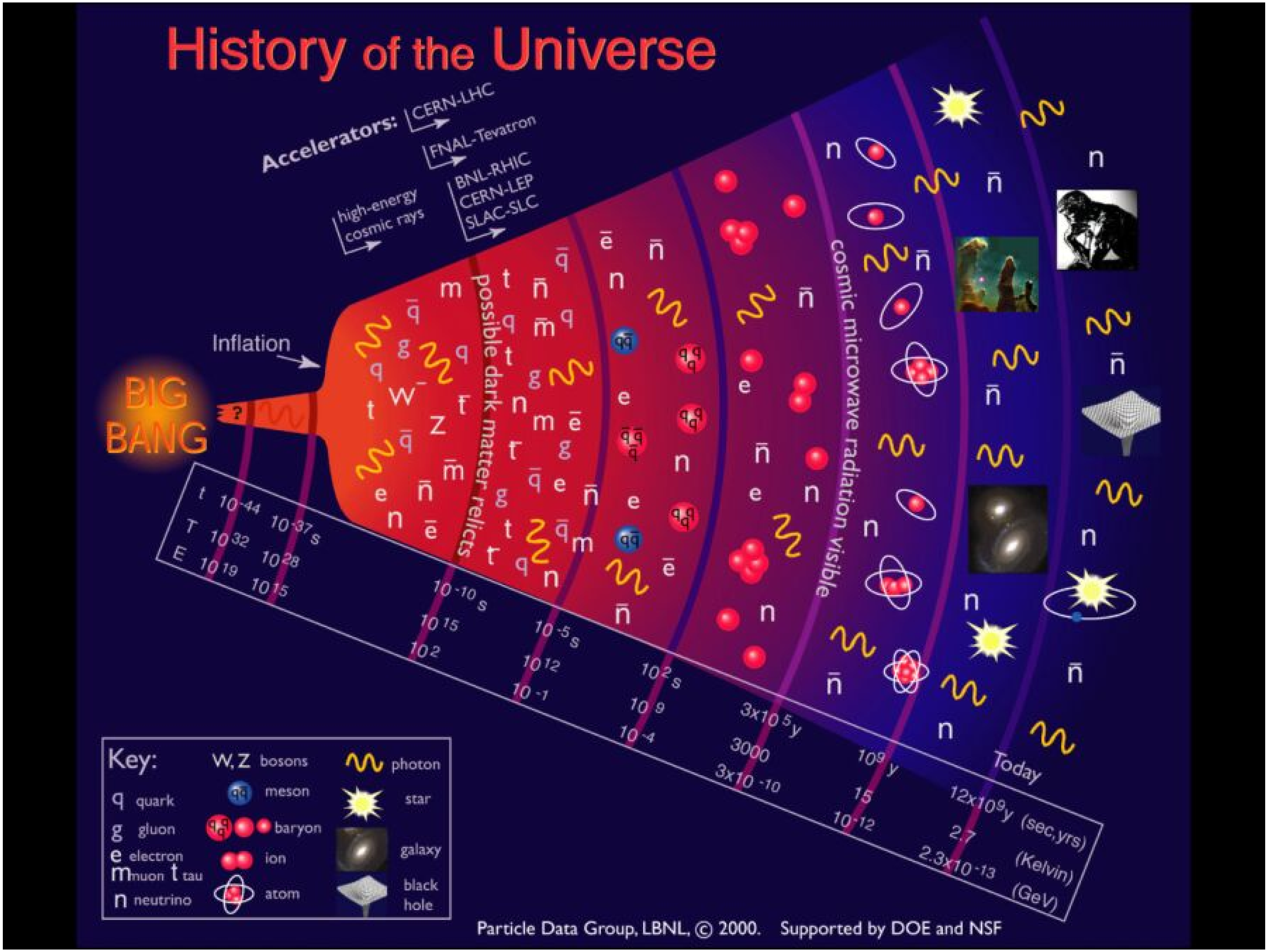
Dark Universe

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

- starts and galaxies (ordinary matter) 0.5%
- Rest of ordinary matter 3.5%
- Dark matter (not ordinary matter) 23%
- Dark Energy (filling up empty space) 73%



Standard Model can not be the final theory for describing the Interaction of electromagnetism, weak and strong forces.


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
3×10^{5} y
3000
3×10^{-10}
10^{9} y
15
10^{-12}
Today
12×10^{9} y (sec,yrs)
2.7 (Kelvin)
2.3×10^{-13} (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Summary

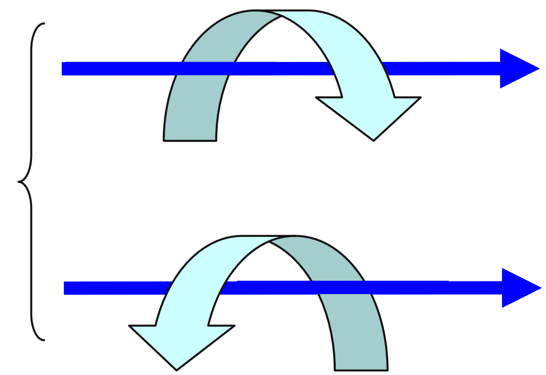
- Electroweak Symmetry Breaking is puzzling
  – Why is the weak force so weak? (i.e. why does the sun so old)
- The Large Hadron Collider is in a very good position to shed light on this
  – The "no lose theorem" means *something* has to happen. Maybe it's a Higgs, maybe it's not.
- Any experiment that can do this can also answer a number of other questions
  – For example, addressing the structure of the proton
  – 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!

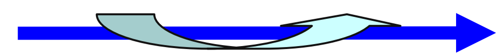
Backup Slides

Massless?

- A massive spin-1 particle has three spin states (m = 1,0,-1)
- A massless spin-1 particle has only two.
  - Hand-wavy argument: Massless particles move at the speed of light; you can't boost to a frame where the spin points in another direction.
- To cancel all the ϕ's, I need just the two m = ± 1 states ("degrees of freedom")
  - Adding the third state overdoes it and messes up the cancellations
  - The photon that I add must be massless



$m = \pm 1$ "transverse"

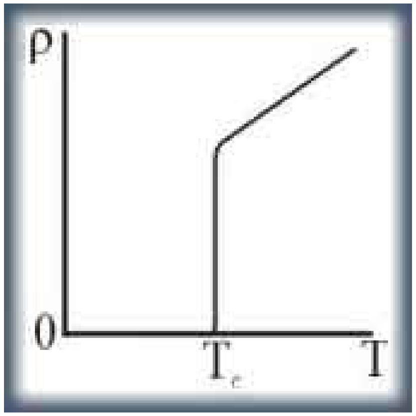


$m = 0$ "longitudinal"

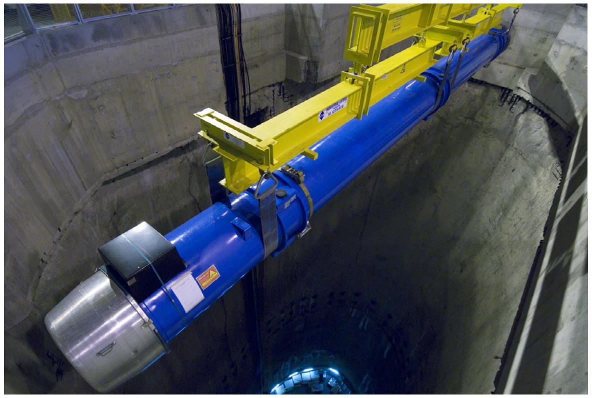
Aside: this has to be just about the most confusing convention adopted since we decided that the current flows opposite to the direction of electron flow.

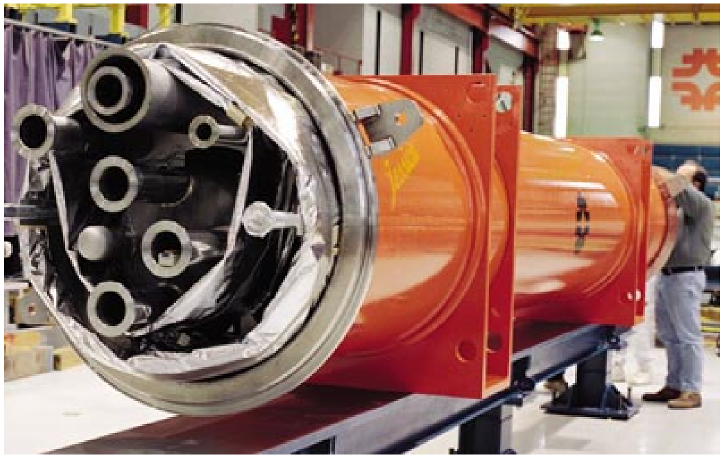
We're stuck with it now.

Using Superconducting Magnets

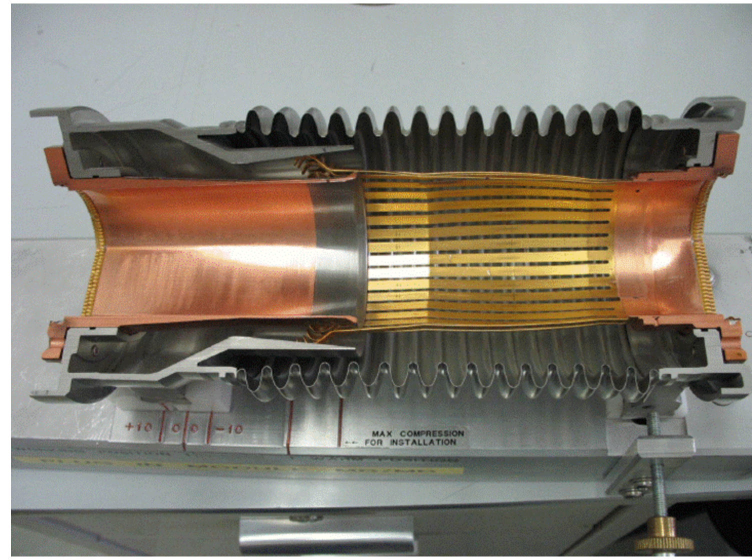


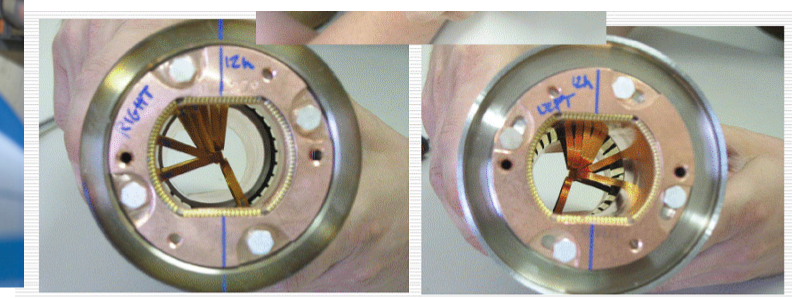
- Zero resistance – a good thing!
- Field is limited to ~9 Tesla (see next slide)
- They have to be kept cold: around 1.9K
  - Carnot efficiency of pumping out any heat that's leaked in is 1.9K/300K < 1%.
  - This is less than 15W per magnet for superconducting magnets to "win"





Thermal Expansion and the LHC

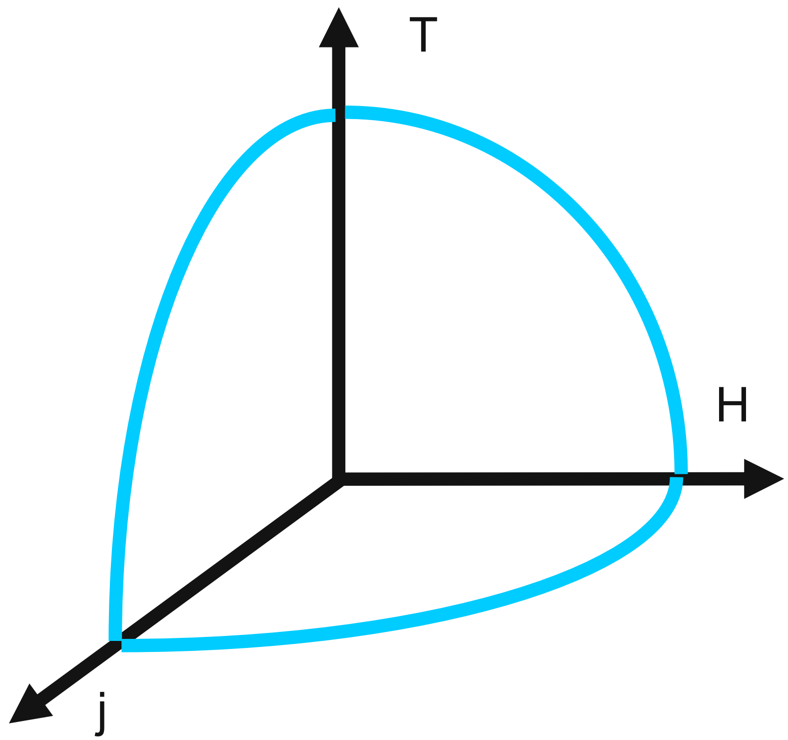




$$\frac{\Delta x}{x} = \alpha \Delta T$$ means that the LHC should shrink ~50 feet in radius when cooled down.

The tunnel is only about 10 feet wide.

Superconductivity Facts

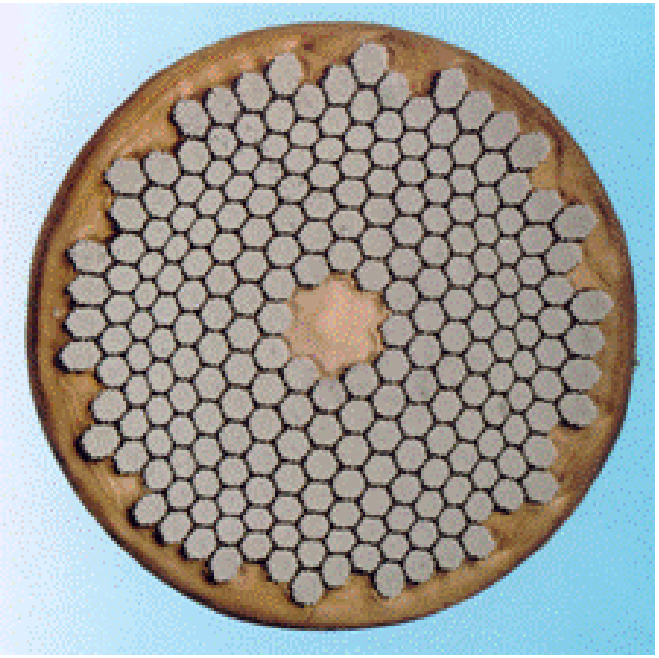


Phase diagram for a superconductor

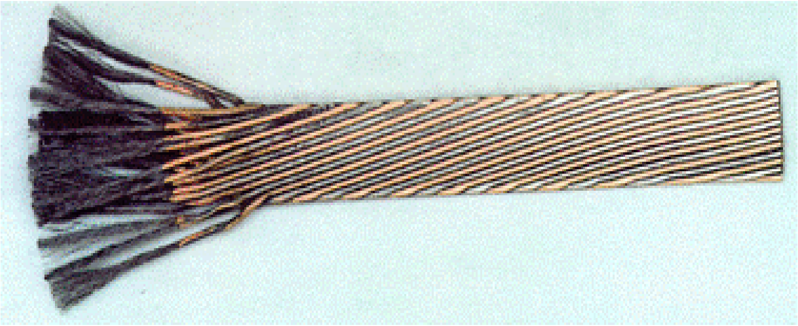
Think “critical surface” instead of “critical temperature”

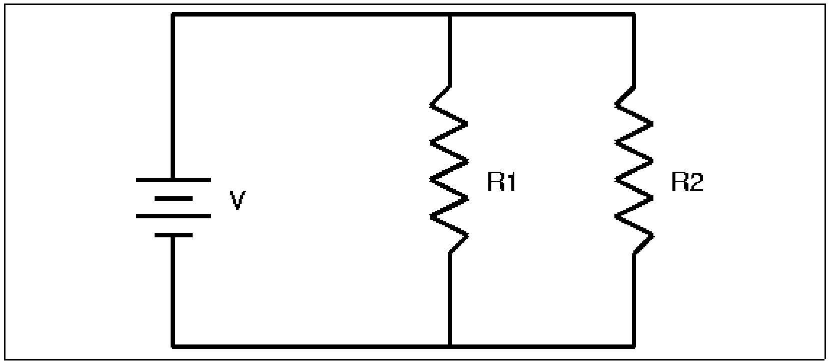
- Superconductivity can be destroyed by:
  - Shaking apart the Cooper pairs (exceeding T_c)
  - Pulling apart the Cooper pairs (exceeding H_c or j_c)
- Because we want to run at high fields/high currents we want a cold magnet
  - T = 1.9K
  - T_c for Ni-Ti is 17.9K
- At 1.9K the small sample limit is ~9T
  - LHC magnets operate at 8.36T

Superconducting "Wire"



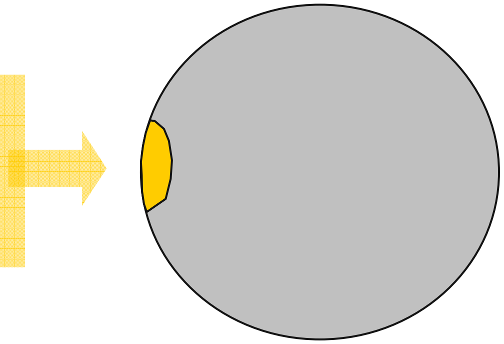
- Nb-Ti has great superconducting properties
  - High T_c, H_c and j_c.
- It has the mechanical consistency of toothpaste.
- It's surrounded by a thin (~ 10% of the radius) copper jacket
  - Provides mechanical strength
  - Carries most (~80%) of the current when the magnet is warm
    - *Copper area is 20% of the area of the cable, but copper's resistivity is 40x smaller.*



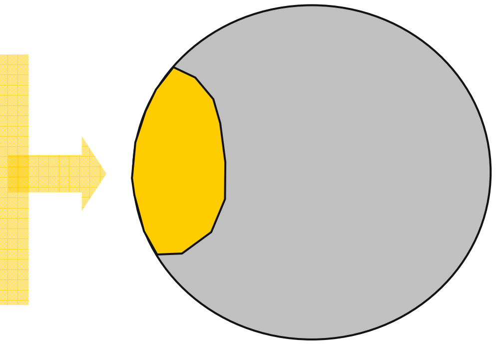


What NOT to Do With Your Magnet

Suppose a small region in your superconducting cable goes normal.



Current will flow around the resistive spot, driving it past j_c; the spot grows

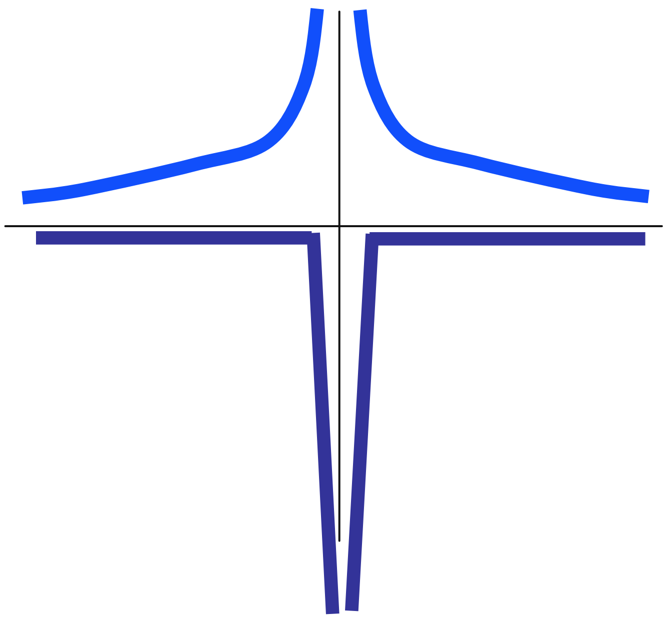


Eventually, the entire cross-section goes normal, and now you have a resistive wire. All the heat is dissipated in that spot.

Stored energy in magnets = 10 GJ, same as a 747 at top speed.)

A magnet undergoing a controlled quench.

The Complication

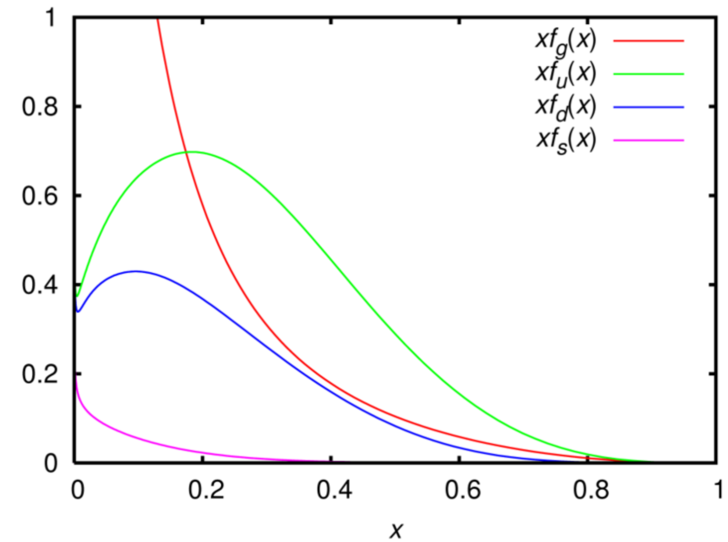


- Light quarks are…well, light.
  - Masses of a few MeV
- Any subcomponents would be heavy
  - At least 1000 times heavier
    - *Otherwise, we would have already discovered them*
- Therefore, they would have to be bound very, very deeply. (binding energy ~ their mass)

A δ-function potential has only one bound state – so the "particle periodic table" can't be due to them being simply different configurations of the same components. Something new and interesting has to happen.

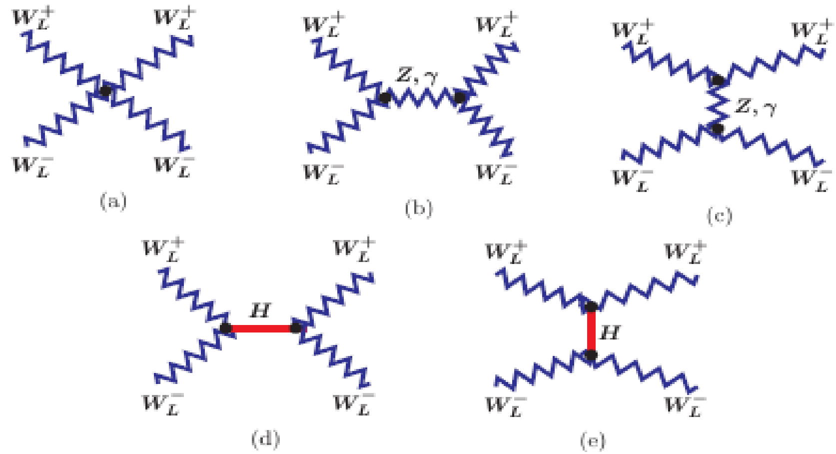
Three Subtleties

(Quantum Chromodynamics, QCD)



- These densities are not quite universal
  - They depend on the wavelength of your probe of the proton.
- A large fraction of the proton's momentum is carried by gluons at low x
  - There is a halo around the proton of large wavelength gluons (and quark-antiquark pairs)
    - *This sounds a lot like a particle physicist's description of a pion cloud*
  - It's a little paradoxical – one needs the highest energy (i.e. shortest wavelength) to probe this large wavelength halo
- Rarely, one gets two partons to collide in each proton
  - Two experiments (AFS, at CERN & CDF, at Fermilab) were able to conclude that the parton densities were not independent, but little else.
  - The LHC will have more than five orders of magnitude more events of this kind.

▶ Review: Unitarity of 4d Standard Model



▶ 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	$\mathbf{0}$	$\mathbf{0}$

▶ $\mathcal{O}(E^0) \Rightarrow$ 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

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 $\sigma(E)[cm^2]$ –physics
  - Luminosity $[cm^{-2}s^{-1}] = N_1 N_2 f / A$
    - *$N_1 N_2$= 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.

Two Months?

- Liquid Nitrogen can only get you to ~80K
  - Even that presents difficulty: there are serious safety issues with putting that much LN2 into a confined space
    - *This is important science. Not so important it's worth killing someone over.*
- Between 80K and 4K, you have to use gaseous helium
  - Helium has almost no heat capacity
    - *It's a monatomic gas*
    - *C_V is 60% that of N_2 for the same volume*
- The real problem isn't "monatomic". It's "gas".
  - Not much material to carry away the heat.

The nuns always told me patience was a virtue.

LHC Beam Stored Energy in Perspective

Luminosity Equation:

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

- 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