The Large Hadron Collider's First Year: Recent Results from ATLAS

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-or-

Life at the Zeptoscale

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Outline

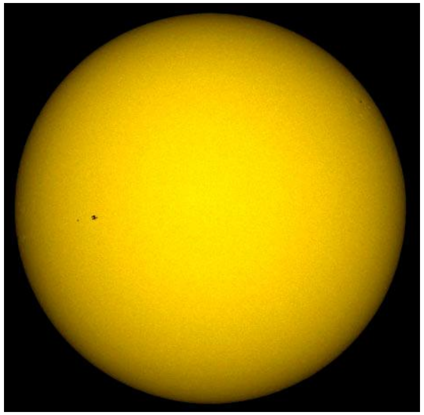
- A 19^{th} Century Puzzle & the 21^{st} Century Puzzle that Emerges from It
- How One Builds a Large Hadron Collider
- How One Breaks a Large Hadron Collider
- Detection of Particles
- The ATLAS Experiment
- Jets and the search for Quark Substructure
- Jets in Heavy Ion Collisions
- The Higgs Mechanism & Electroweak Symmetry Breaking
- Conclusions

Age of the Earth Controversies

In 2011:

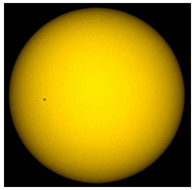
vs

In 1860:



vs

The Older Age of the Earth Controversy



- 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

All science is either physics or stamp collecting.
Ernest Rutherford

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

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

- 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 $\sim 10^{-32}$
    - 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.

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.

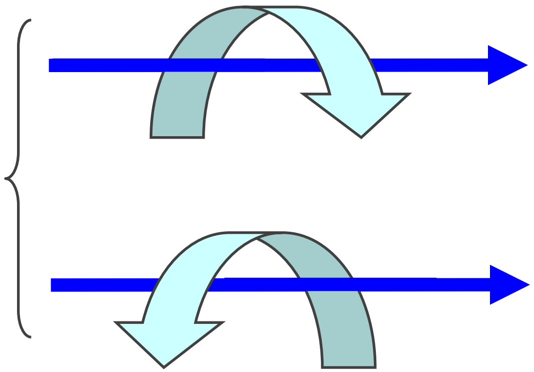
$$\frac{d}{dx}uv = u\frac{dv}{dx} + v\frac{du}{dx}$$

- 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.

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 $m = \pm 1$ states ("degrees of freedom")
  - Adding the third state overdoes it and messes up the cancellations
  - The photon that I add must be massless



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.

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} = concentration of ten molecules of ethanol in a glass of water
    - Roughly the composition of "Lite" Beer
  - 10^{-22} = ratio of the radius of my head to the radius of the galaxy
  - 10^{-22} = probability Lindsay Lohan won't do anything shameless and stupid in the next 12 months

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 ☹

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
- 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

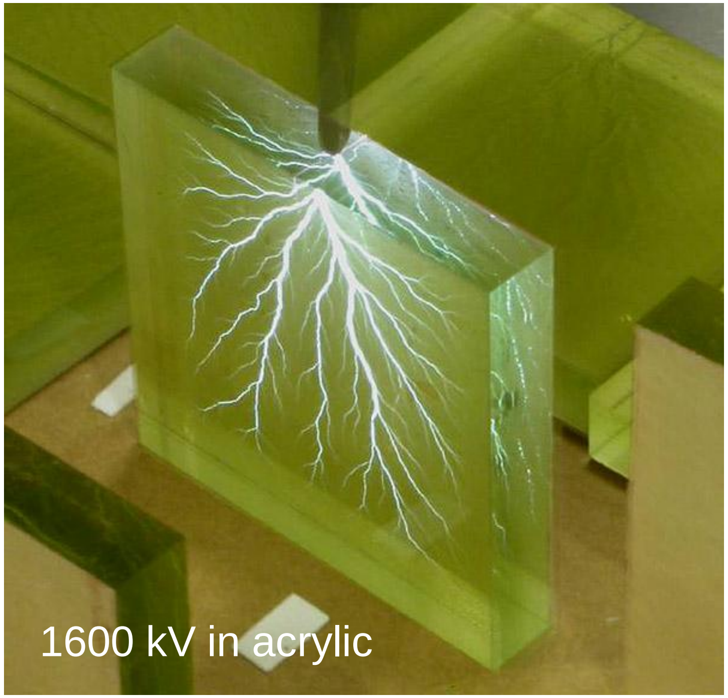
"What is the LHC for?" is a little like "What is the Hubble Space Telescope for?" – the answer depends on who you ask.

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

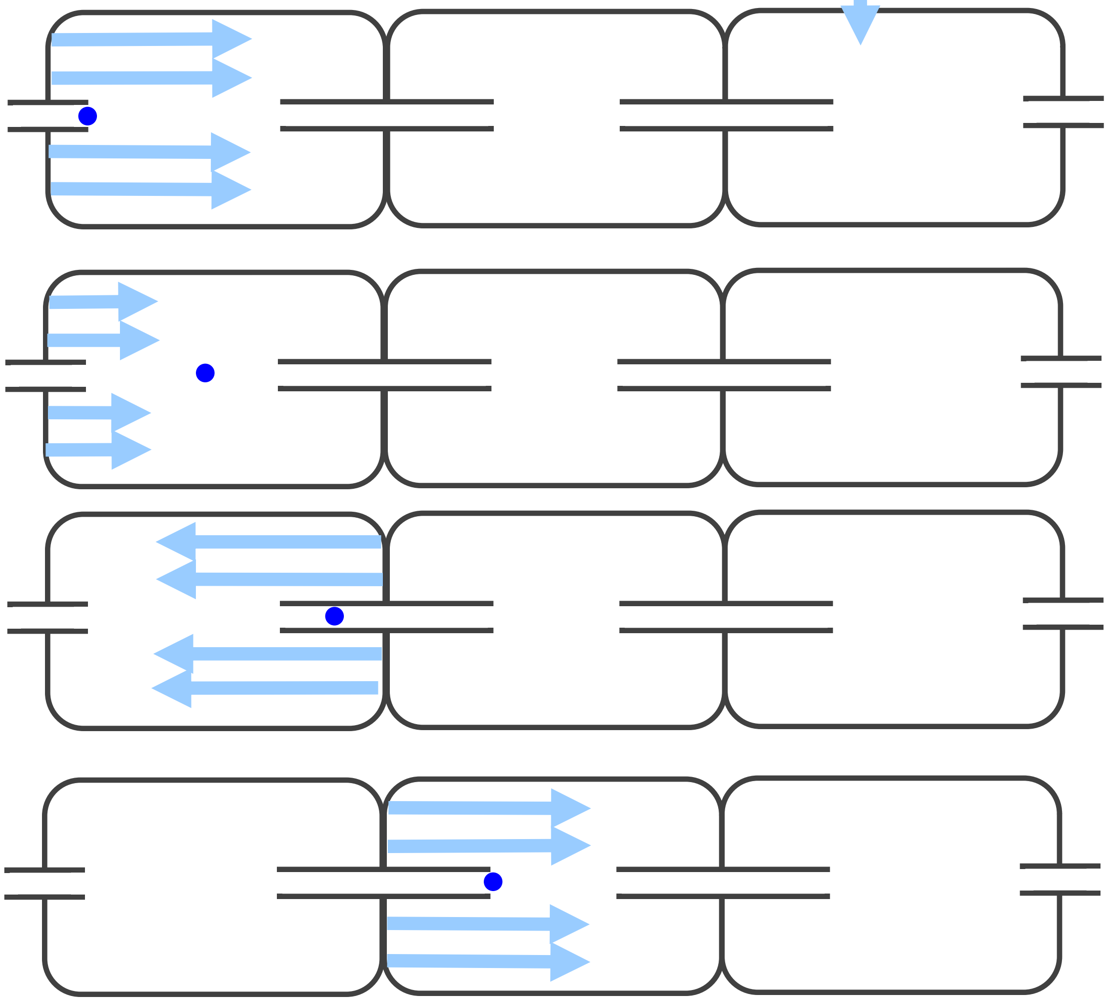
- In principle, this is simple: put 7 trillion volts of potential on a proton and let 'er rip…
- This may not be the safest course of action – here is what less than one four-millionth of this potential can do:



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

How To Build a Linear Accelerator

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.

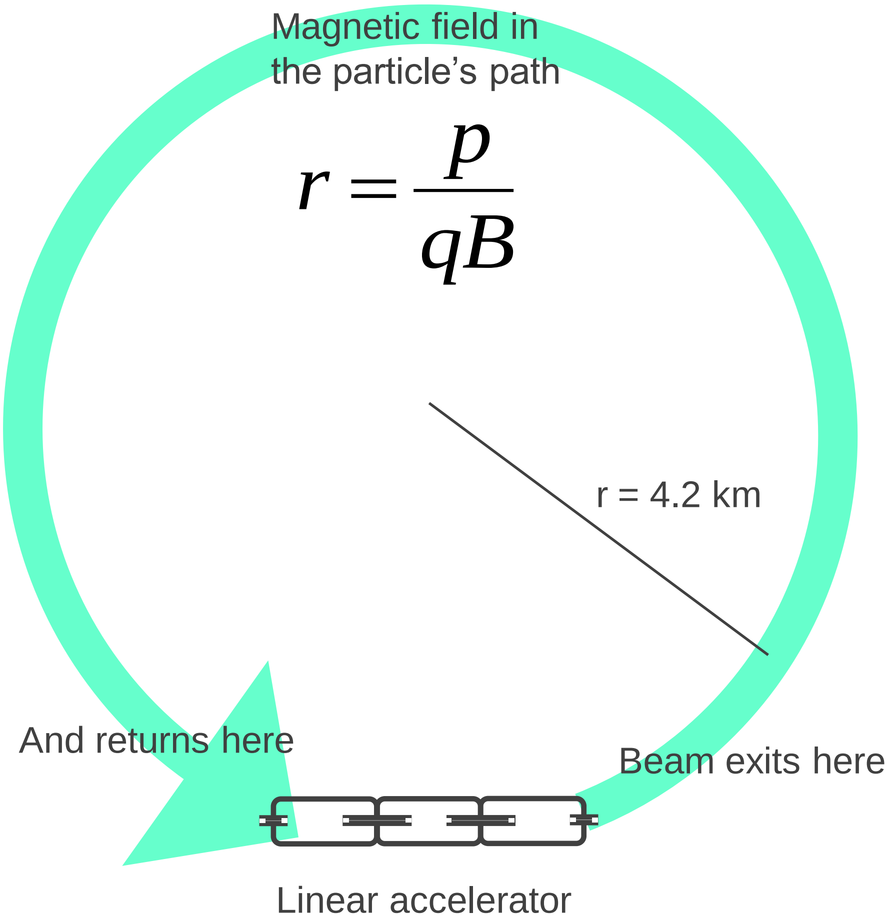
Proton enters the next cavity. Electric field accelerates it to the right.

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

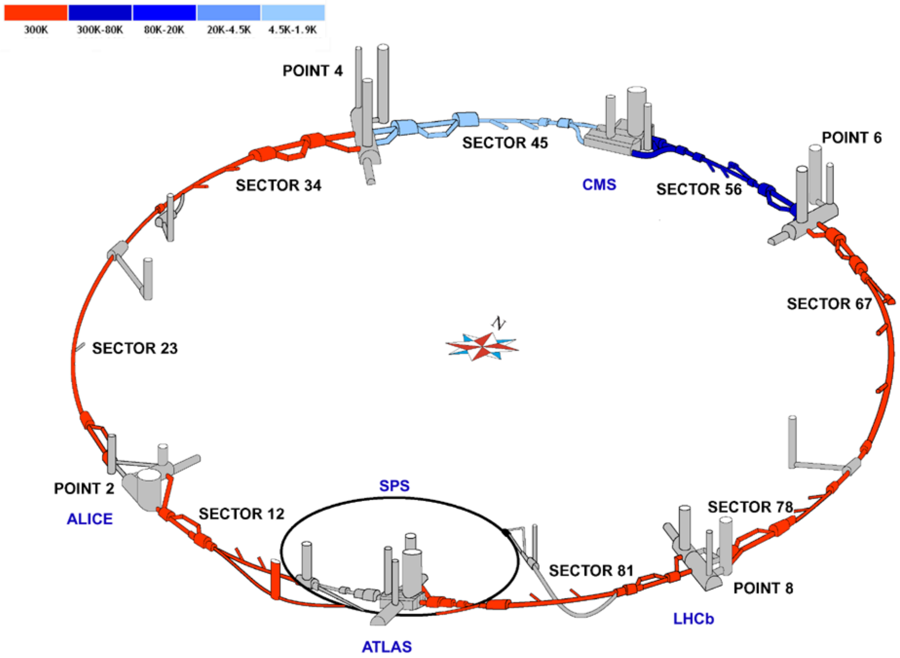
A portion of Fermilab's linear accelerator

Recycling: The Proton Synchrotron



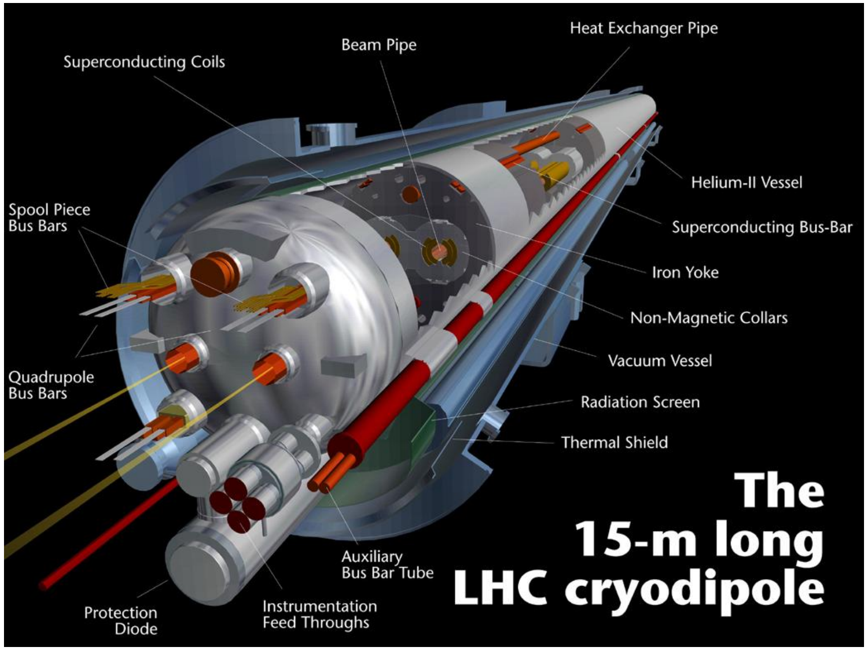
- Accelerating structures are reused ~20 million times during each fill of the LHC
- The cost of such a machine is ~an order of magnitude cheaper than an equivalent linear accelerator
- The energy that can be reached is limited by the strength of the magnetic field in the arcs

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 thousands of focusing and correction magnets) arranged in a ring in the tunnel.



Our Next Problem - Resistance

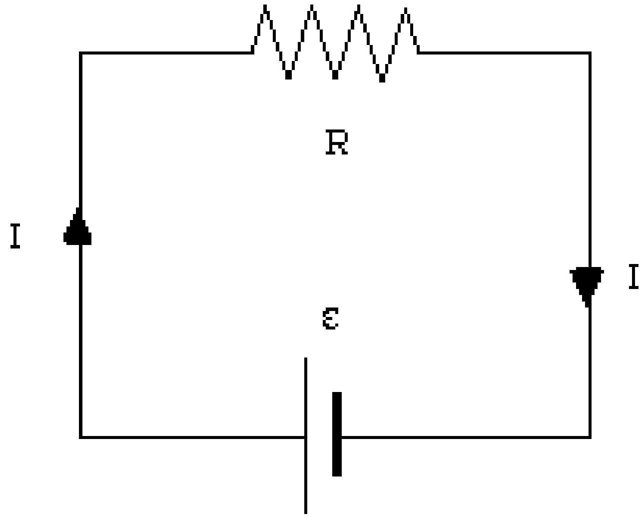
- To generate the field we want, we need to carry about 12000 Amperes.

- NFPA code says one needs a “wire” that has a diameter of about 35 cm 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.

16 miles of electromagnets



LHC Circuit Diagram

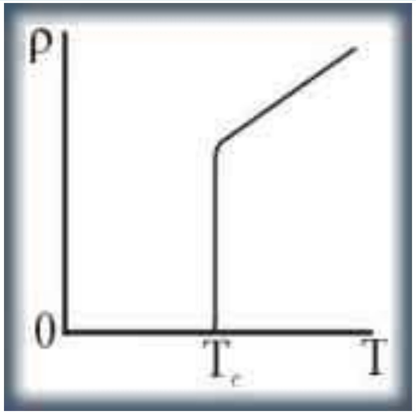
$$E = IR$$

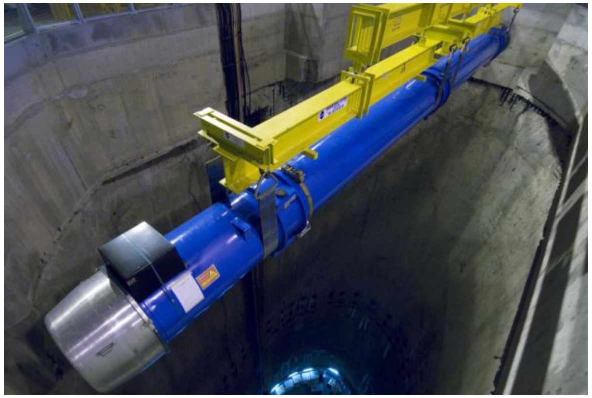
$$P = EI$$

$$P = I^2 R$$

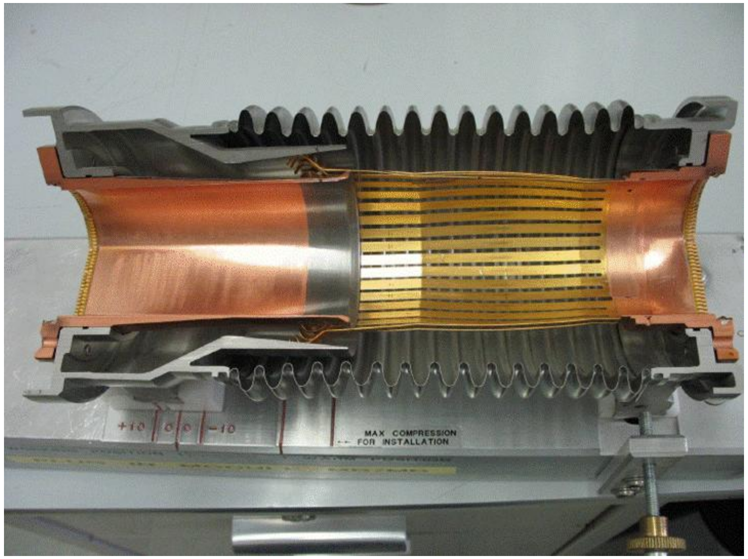
Using Superconducting Magnets

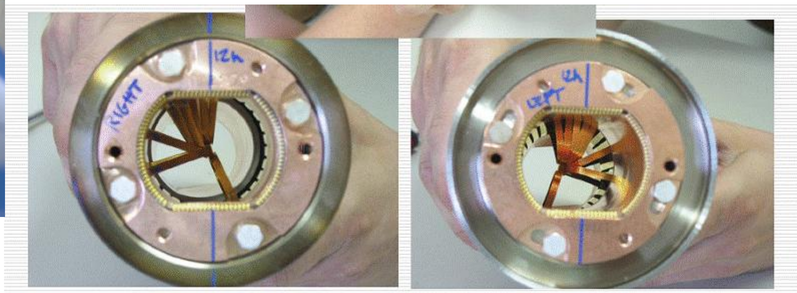
- Zero resistance – a good thing!
- Field is limited to ~9 Tesla (see next slide)
- They have to be kept cold: around 1.9K
  - Carnot efficiency of pumping out any heat that's leaked in is 1.9K/300K < 1%.
  - This is less than 15W per magnet for superconducting magnets to "win"





Thermal Expansion and the LHC

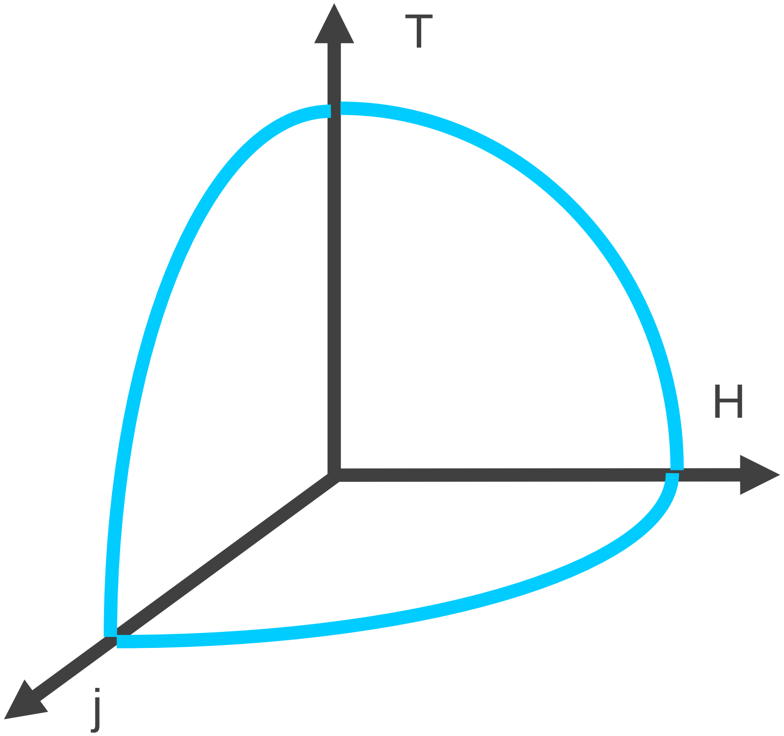




$\frac{\Delta x}{x} = \alpha \Delta T$ means that the LHC should shrink ~15 m in radius when cooled down.

The tunnel is only about 3 meters wide.

Superconductivity Facts

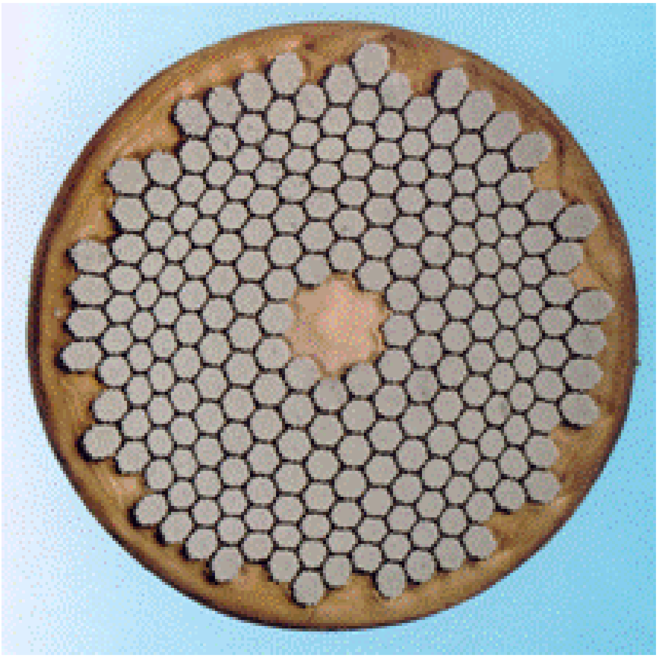


Phase diagram for a superconductor

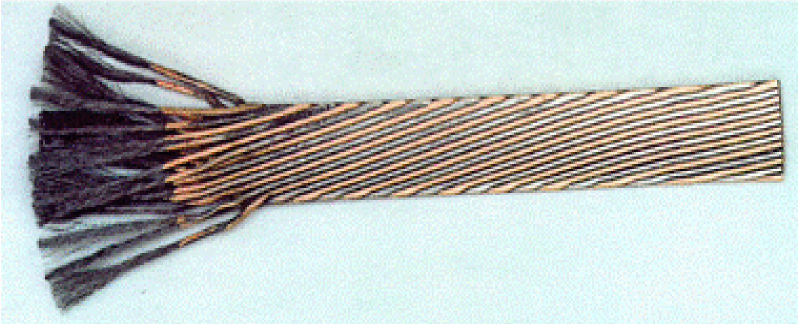
- Superconductivity can be destroyed by:
  - Shaking apart the Cooper pairs (exceeding T_c)
  - Pulling apart the Cooper pairs (exceeding H_c or j_c)
- Because we want to run at high fields/high currents we want a cold magnet
  - T = 1.9K
  - T_c for Ni-Ti is 17.9K
- At 1.9K the small sample limit is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

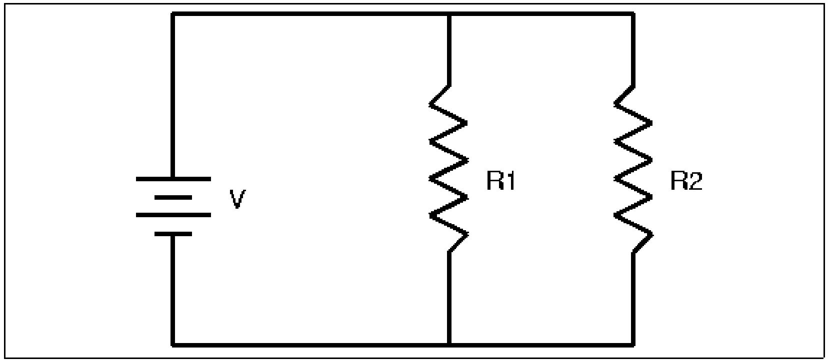
Think "critical surface" instead of "critical temperature"

Superconducting "Wire"



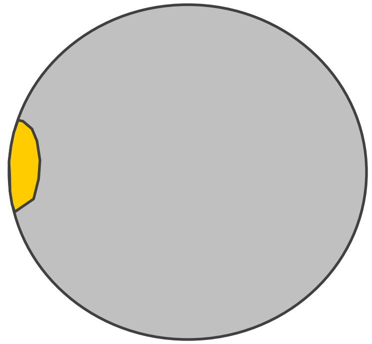
- Nb-Ti has great superconducting properties
  - High T_c, H_c and j_c.
- It has the mechanical consistency of toothpaste.
- It's surrounded by a thin (~ 10% of the radius) copper jacket
  - Provides mechanical strength
  - Carries most (~80%) of the current when the magnet is warm
    - Copper area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



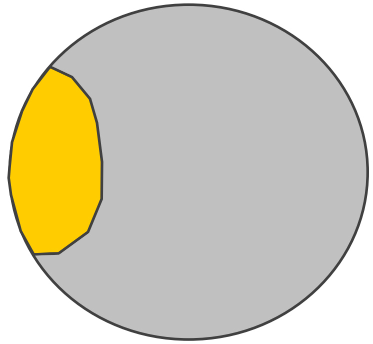


What NOT to Do With Your Magnet

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.

Timeline

- March 2008 – CERN announces the LHC will start with 5 TeV per beam rather than 7 TeV. This avoids a lengthy magnet retaining process.

- 10 September 2008 – amidst much media hoopla, beams are circulated at 450 GeV (injection energy). At this time, 7 of the 8 sectors are “qualified for 10 TeV collisions”, meaning they operate properly at 11 TeV equivalent current.

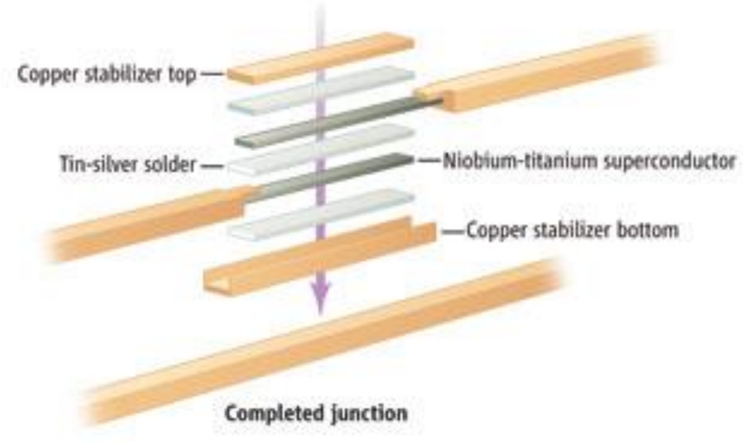
- 18 September 2008 – a transformer near Point 5 fails. EDF says it will take a couple of days to find and install a replacement. Two sectors start to warm. Decided to return to qualifying the last sector, 3-4, in parallel.

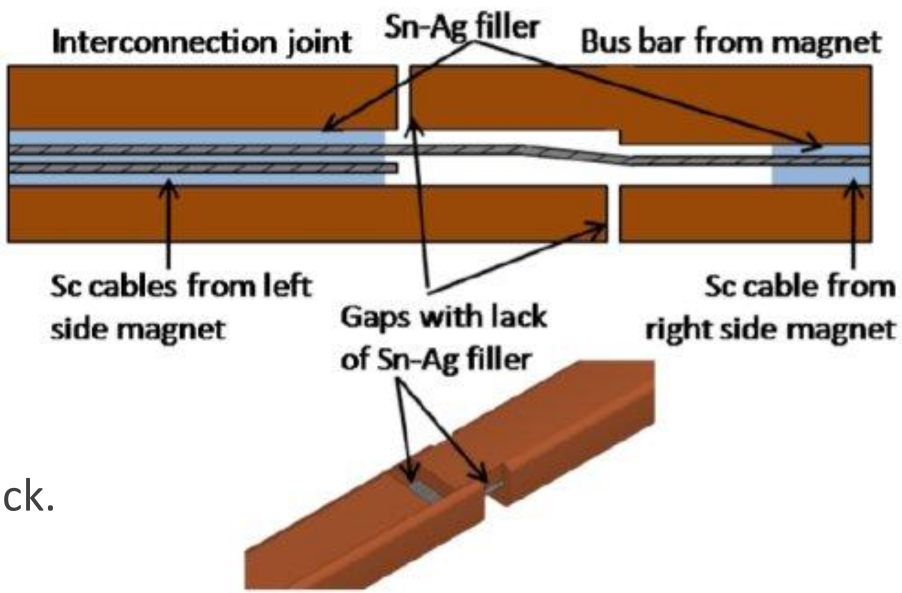
- 19 September 2008 – during one of these tests, a magnet quench led to an electrical arc, which in turn led to a catastrophic loss of helium, which made a great big mess.

In More Detail

- One interconnect had a resistance of 220 nΩ. At 9000 A, that means that we were injecting 18W of heat ($P=I^2R$) into the liquid helium.
- This was not occurring in the magnet coils, so the quench protection system did not immediately notice this.
- The helium boiled.
- The resistance increased to about 1 mΩ. The quench protection system engages. About the same time, an electrical arc develops, puncturing the helium enclosure.
- 6 tons of helium boil, and expand through the tunnel at 10 m/s.

p = mv: this is the same momentum as a truck.





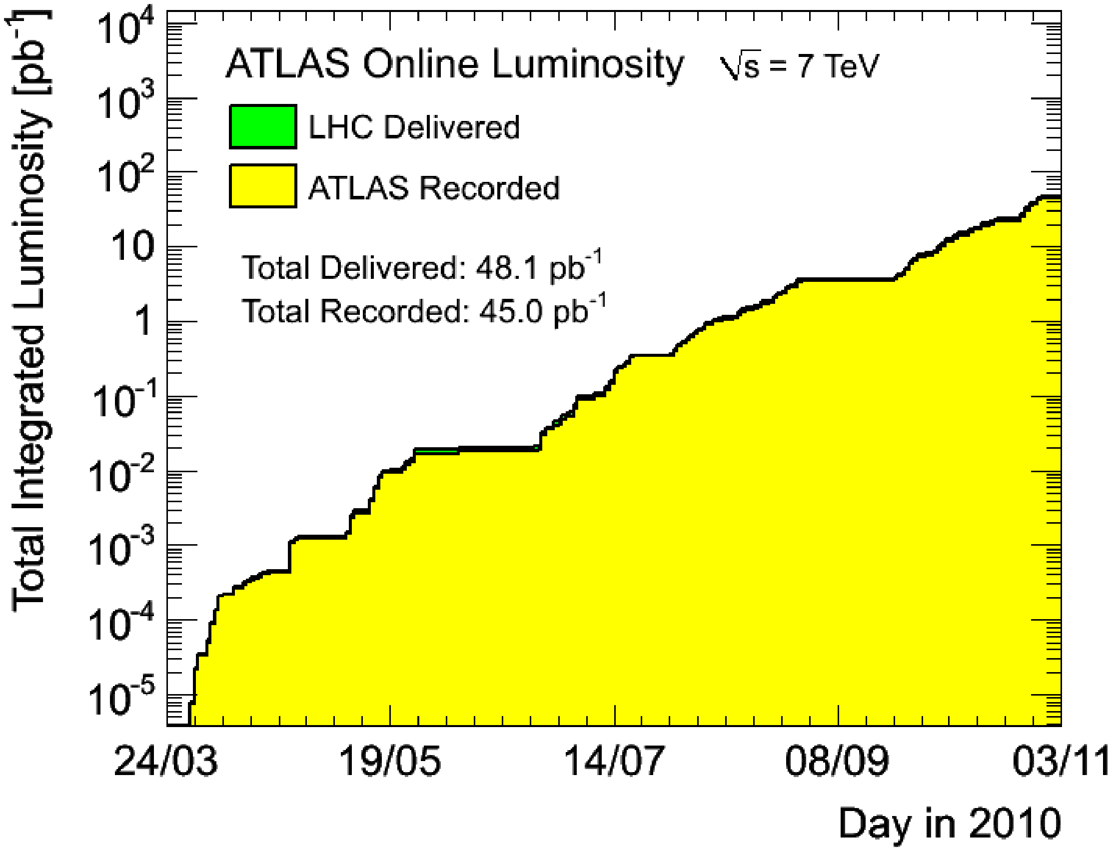
Aftermath

- A one-year delay
  - 53 magnets had to be removed and repaired or replaced
  - Quench protection system redesigned and replaced
  - Additional vents were added to most of the dipoles
- Beam energy lowered to 3.5 TeV per beam
  - This is 4x safer ($P=I^2R$)
  - This also allows for a lower dump resistance and faster dump – reduced risk.
  - However, the physics reach is less (by 5-10), but still far beyond what we had before.

2010 LHC Performance

Peak luminosity in ATLAS
L ~ 2.1 x 10^{32} cm^{-2} s^{-1}

Luminosity detectors calibrated with van der Meer scans. Luminosity known today to 11% (error dominated by knowledge of beam currents)



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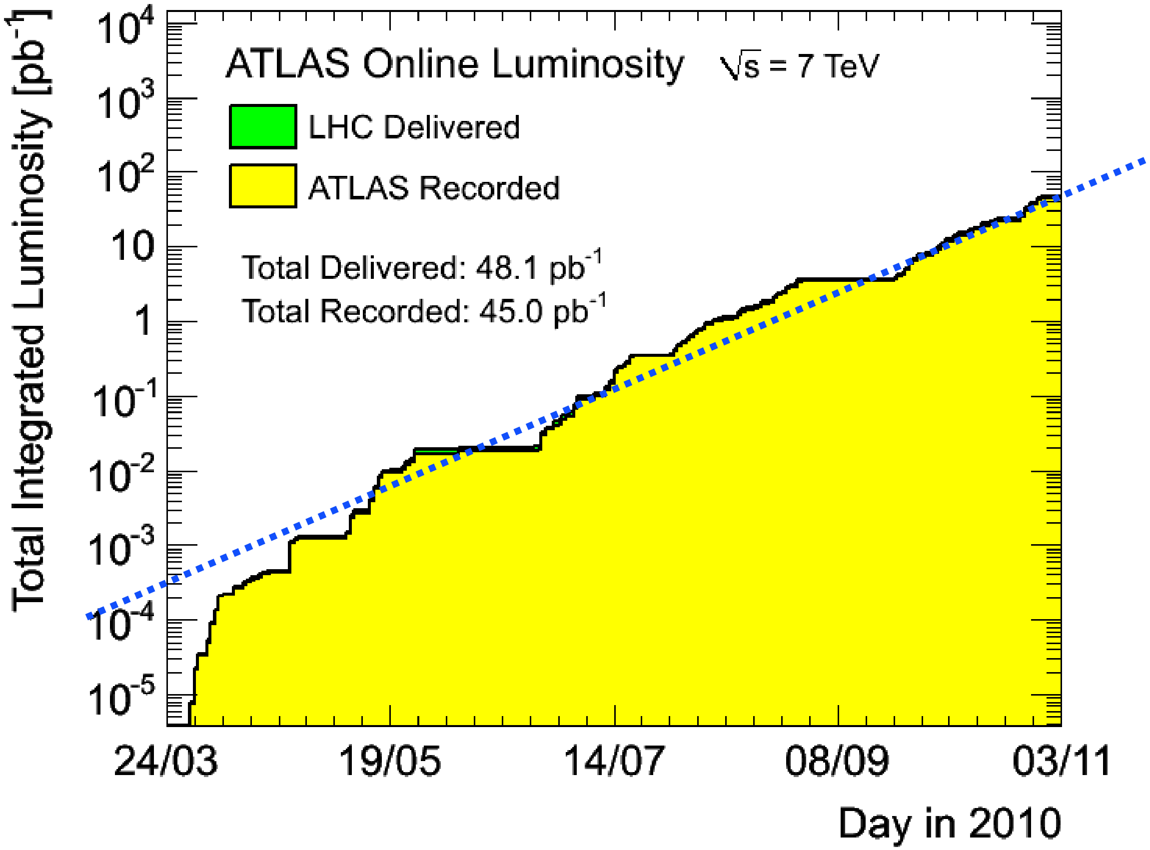
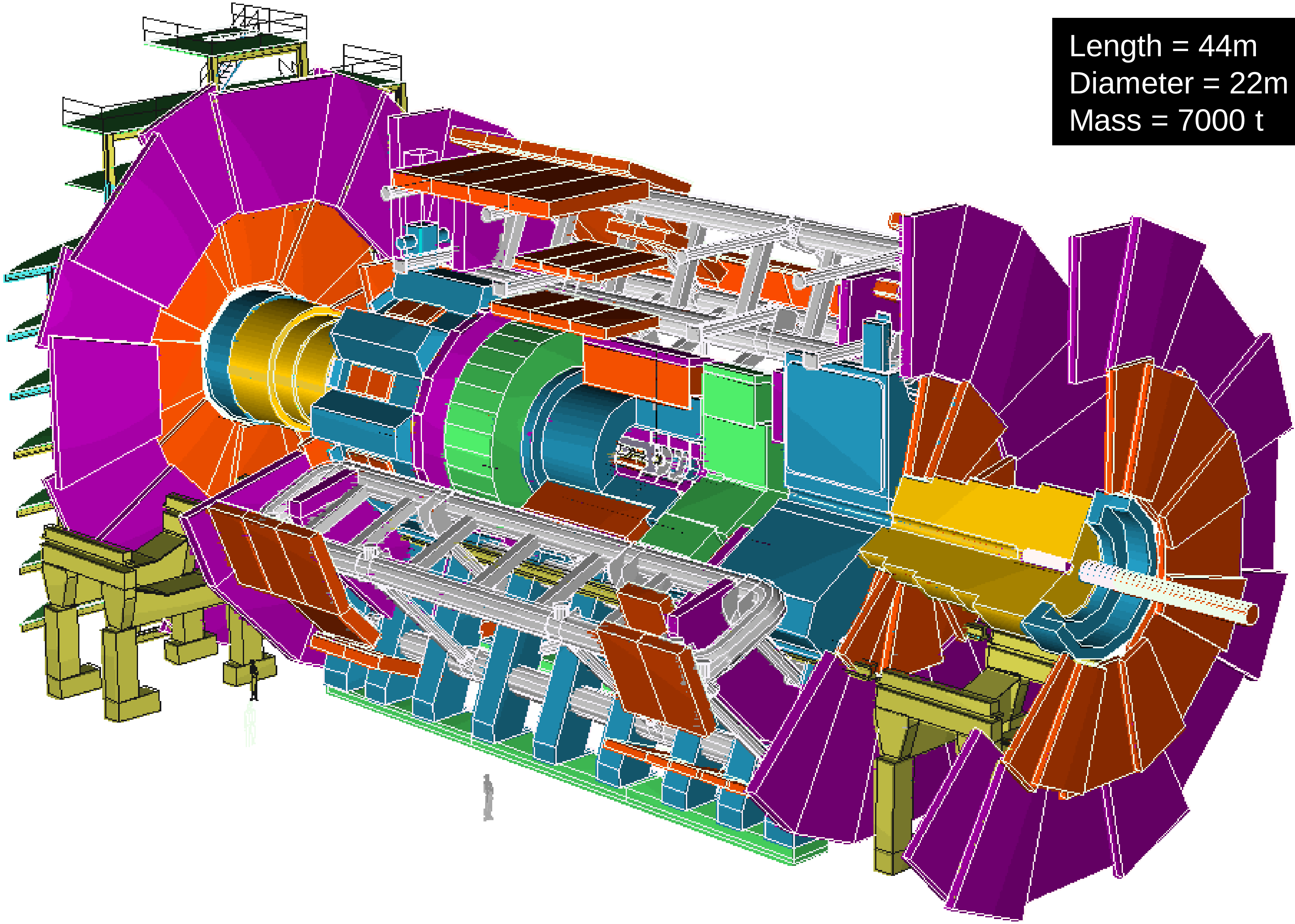


- The doubling time for integrated luminosity (collisions delivered) was <2 weeks.
  - By the end of the 1st year the LHC delivered 0.05% of the expected total data at 2% of the expected ultimate luminosity
  - Caution has dictated a slow start, compensated by the rapid growth in delivered beam.

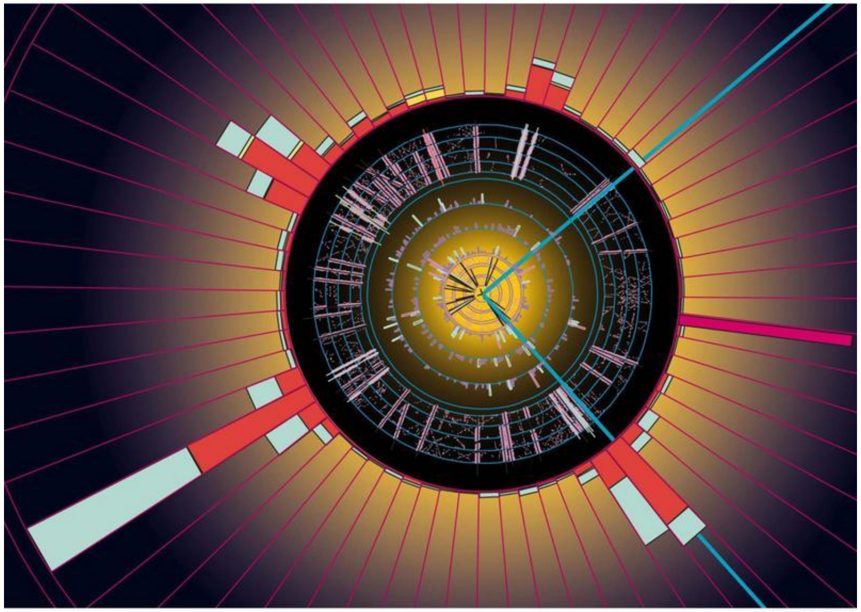
ATLAS = A Toroidal LHC ApparatuS



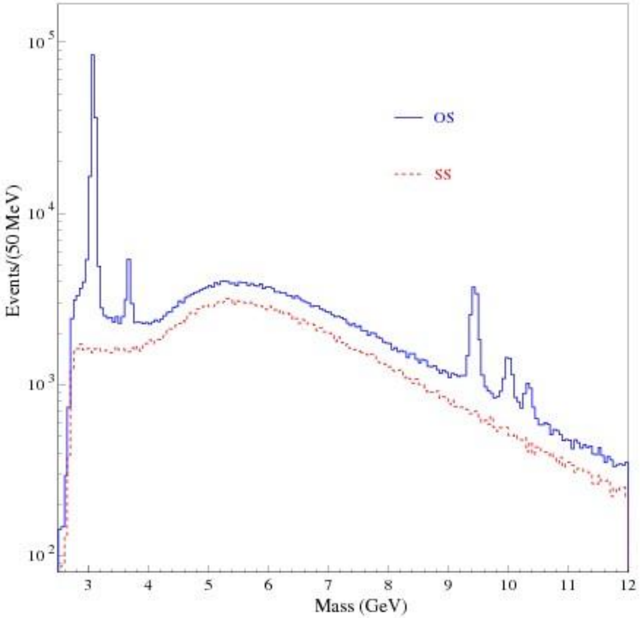
Length = 44m
Diameter = 22m
Mass = 7000 t

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



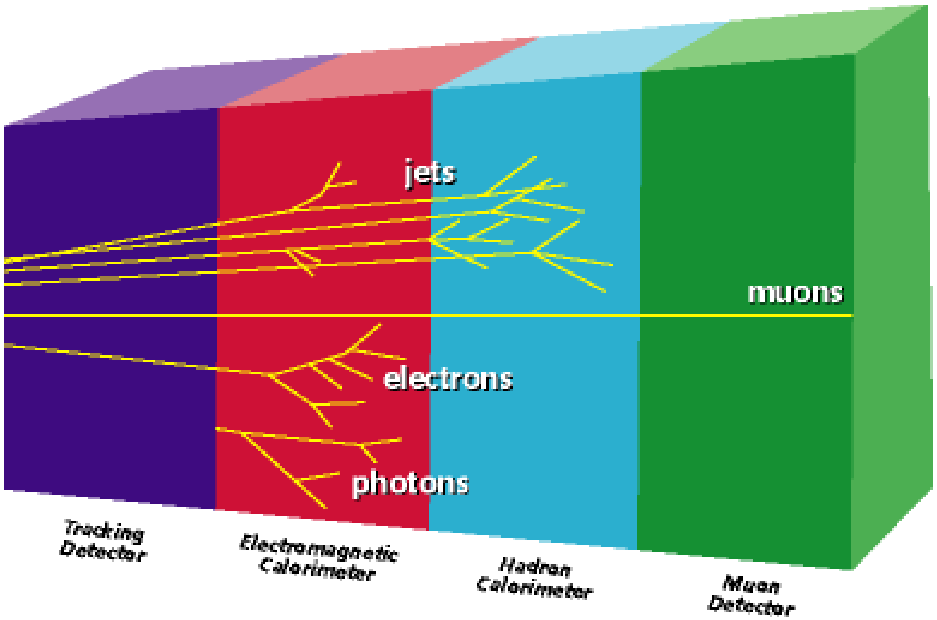
Fermilab #97-1889D



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.

How It Works



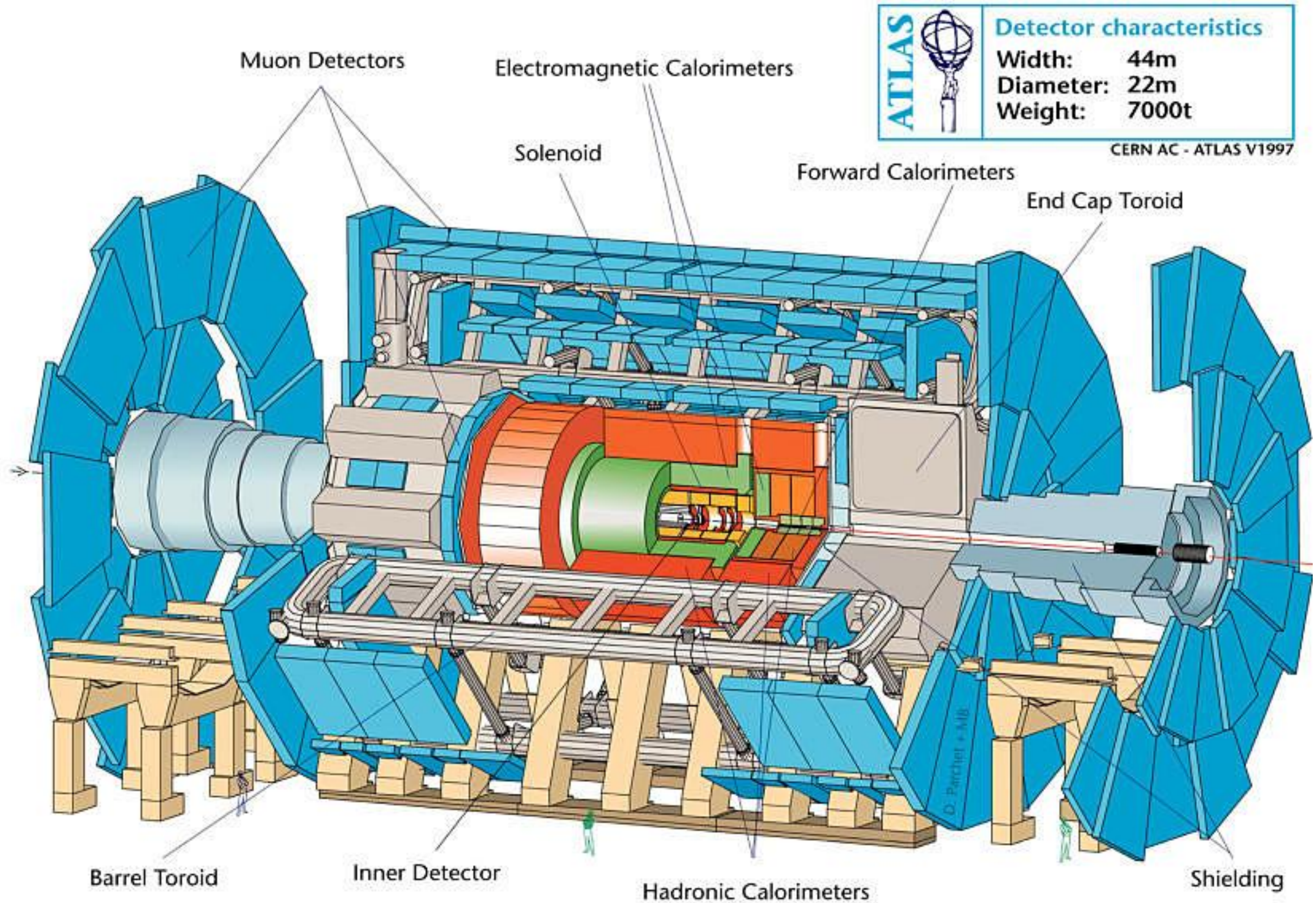
Different particles propagate differently through different parts of the detector; this enables us to identify them.

- 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.

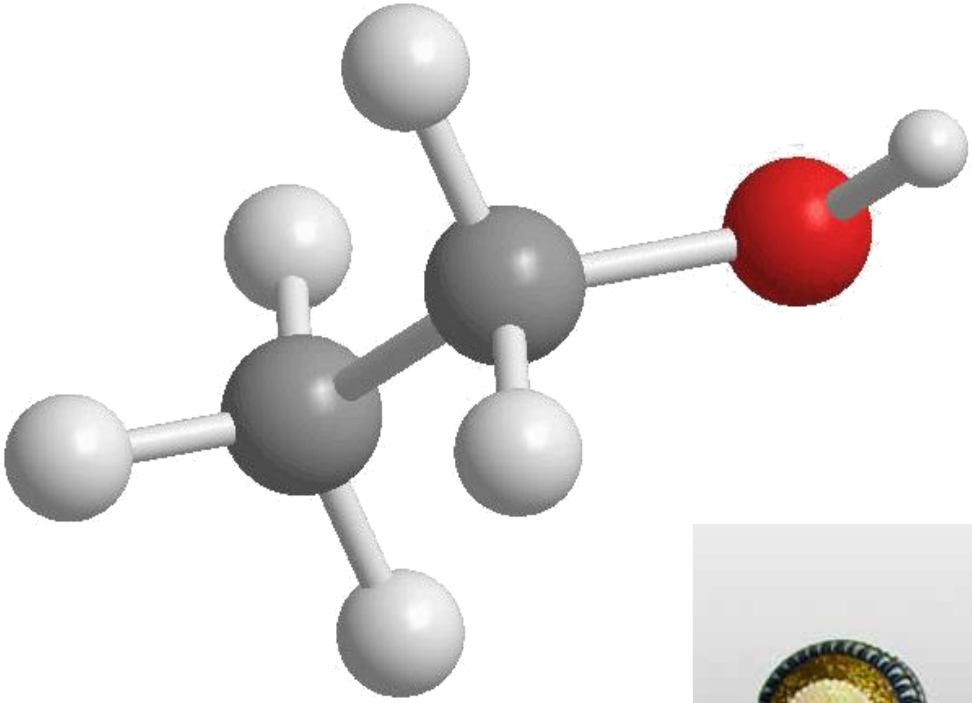
ATLAS Revisited



The Most Important Component

3100 collaborators in 176 institutions in 38 countries.

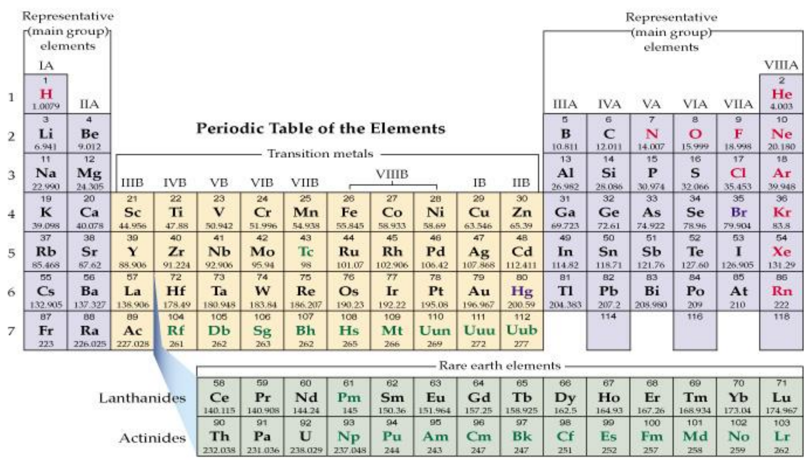
Which Is The Better Picture of Matter?



Indivisible particles, with different properties resulting from different arrangements?

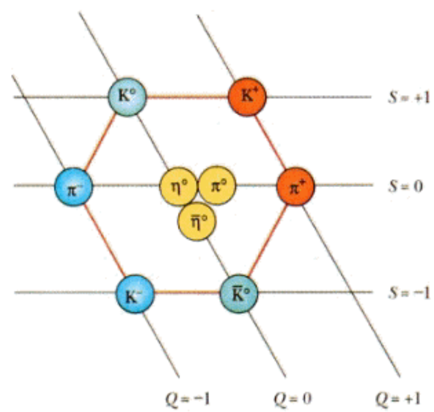
Or layers upon layers of substructure?

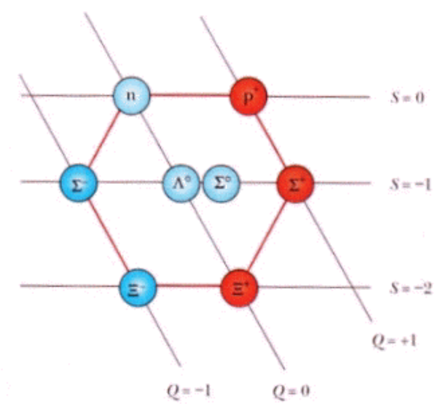
Compositeness & The Periodic Table(s)



Arises because atoms have substructure:
electrons

Arises because hadrons have substructure:
quarks

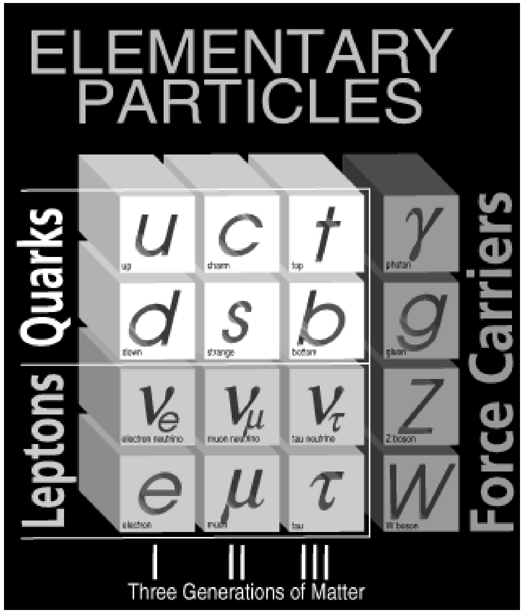




The 9 lightest spin-0 particles

The 8 lightest spin-1/2 particles

Variations on a Theme?

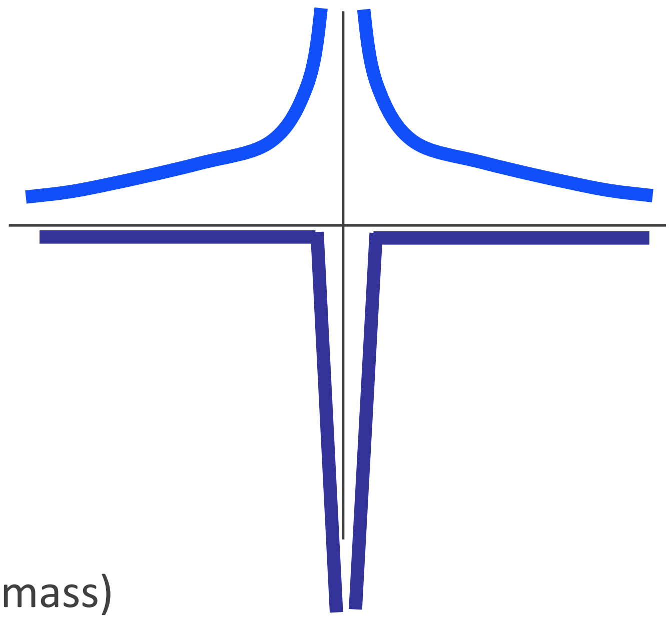


Does this arise because quarks have substructure?

- A good question – and one that the LHC addresses
- 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 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.

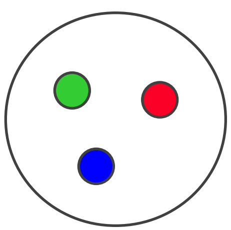
I'm an experimenter. This isn't my problem.

What IS My Problem:

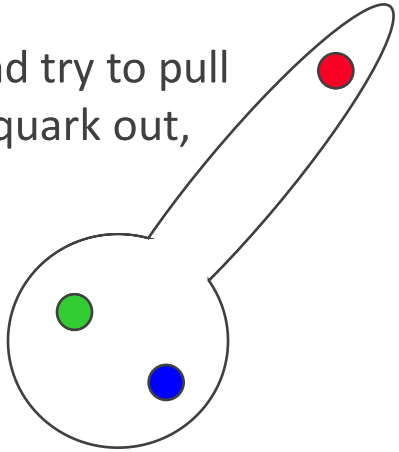
We Can't Pluck A Quark Out of A Proton

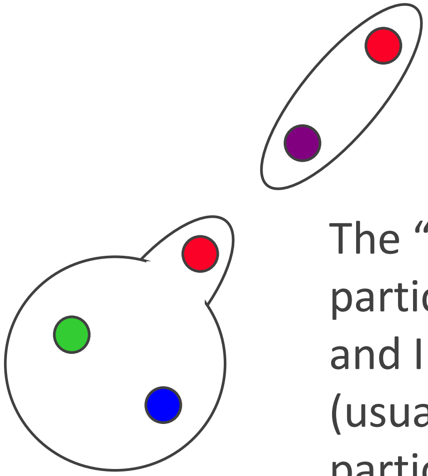
A good analogy is a magnet: if I try to break off the north pole of a magnet, I fail and end up with two smaller magnets.

If I take a proton,



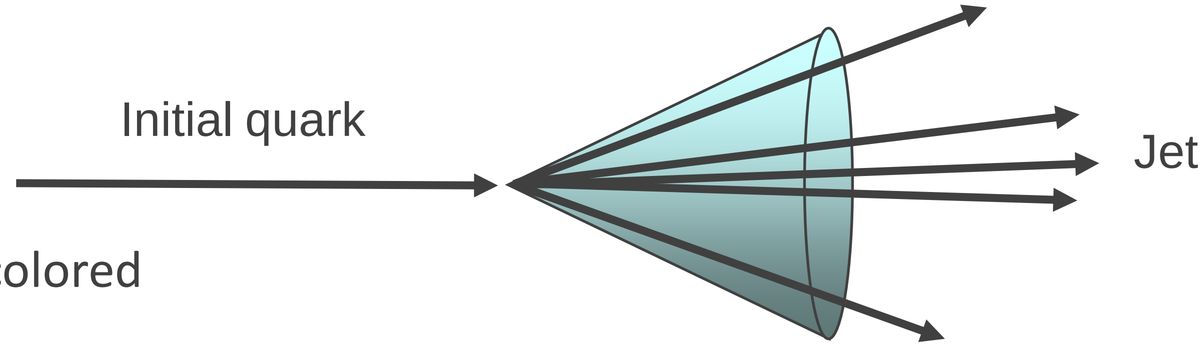
and try to pull a quark out,





The "string" holding the particle together breaks, and I produce more (usually many more) particles.

Jets



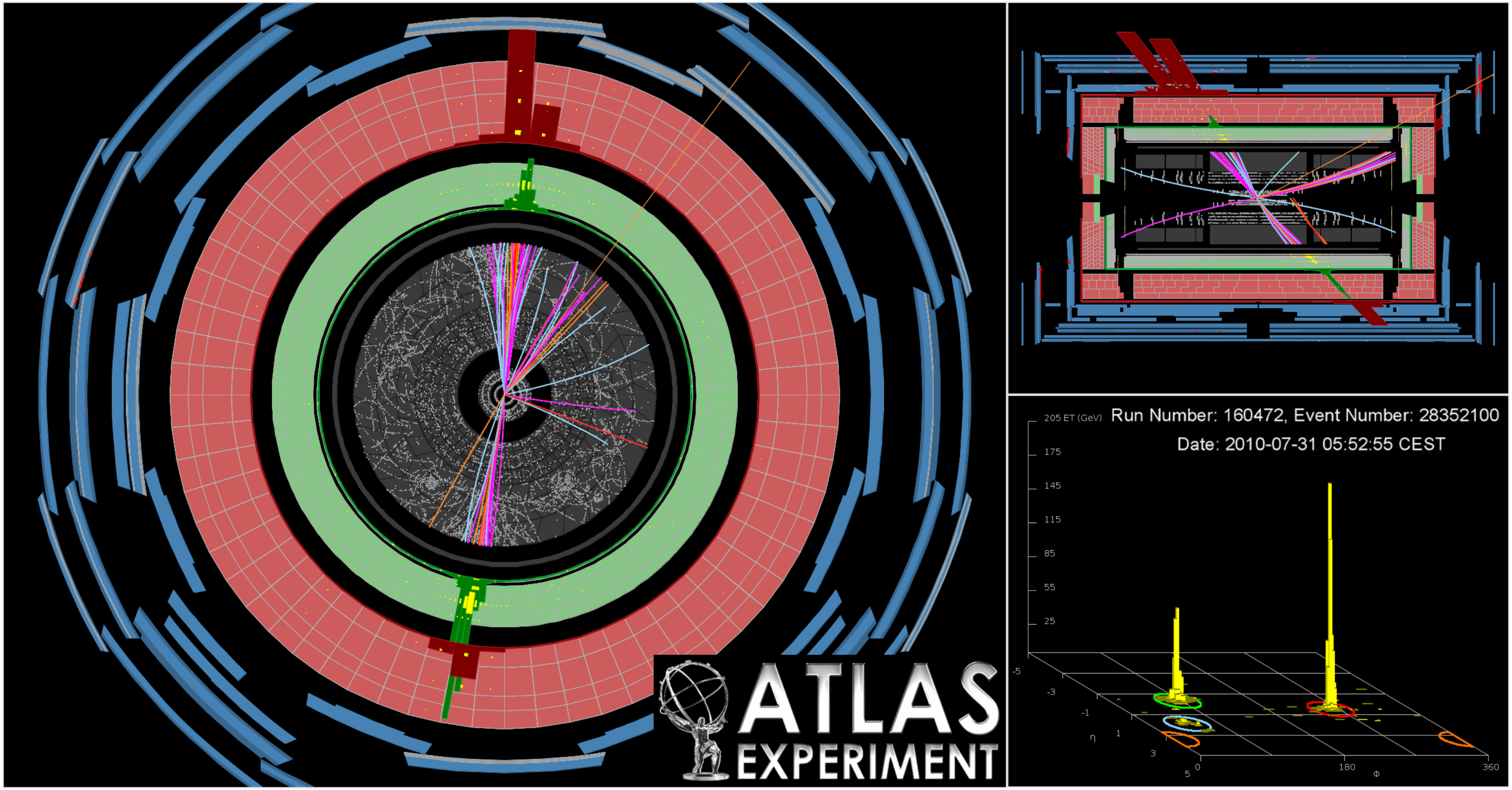
- The force between two colored objects (e.g. quarks) is ~independent of distance
  - Therefore the potential energy grows (~linearly) with distance
  - When it gets big enough, it pops a quark-antiquark pair out of the vacuum
  - These quarks and antiquarks ultimately end up as a collection of hadrons

- 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

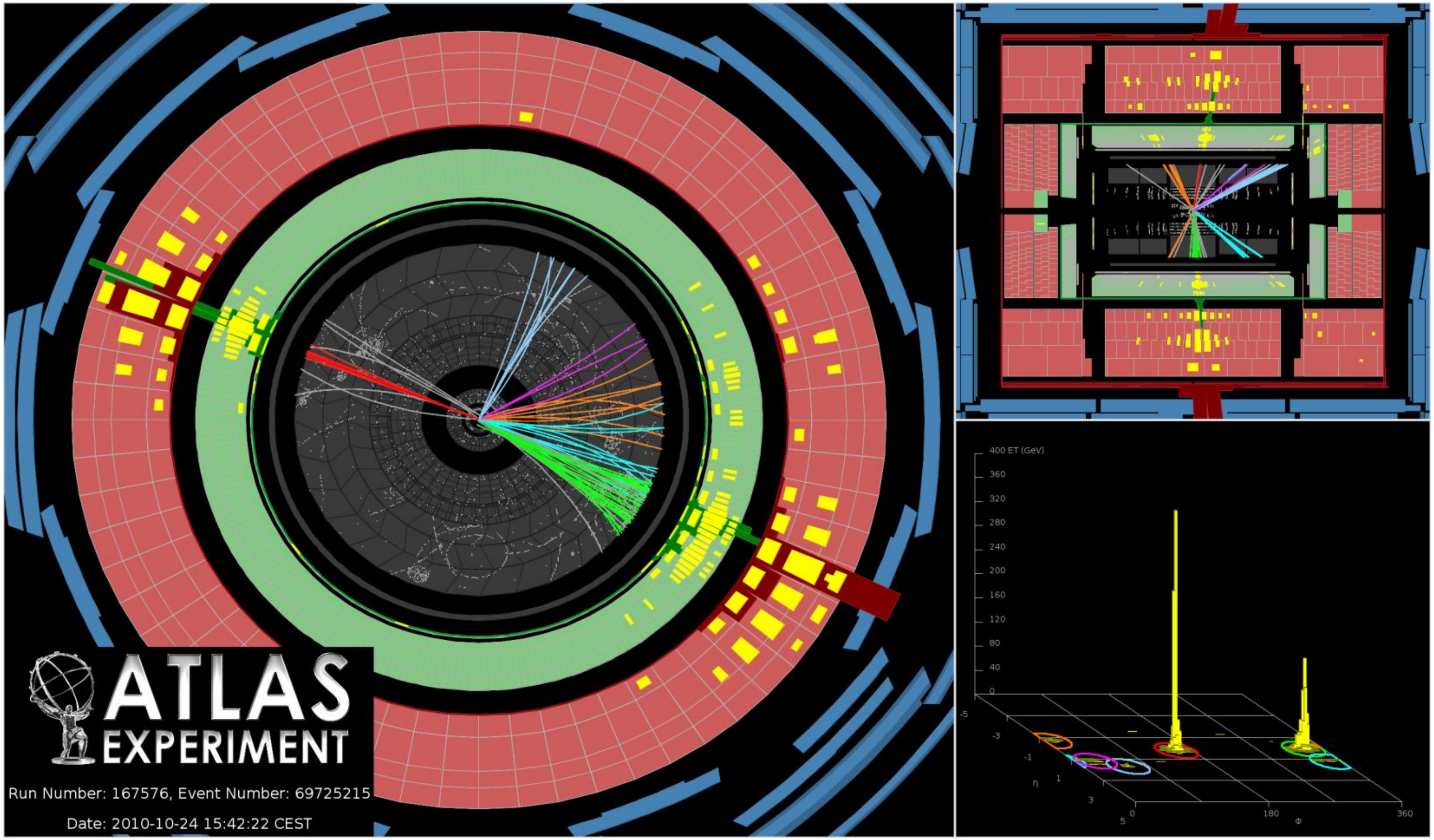
What makes the measurement possible & useful is the conservation of energy & momentum.

Jets

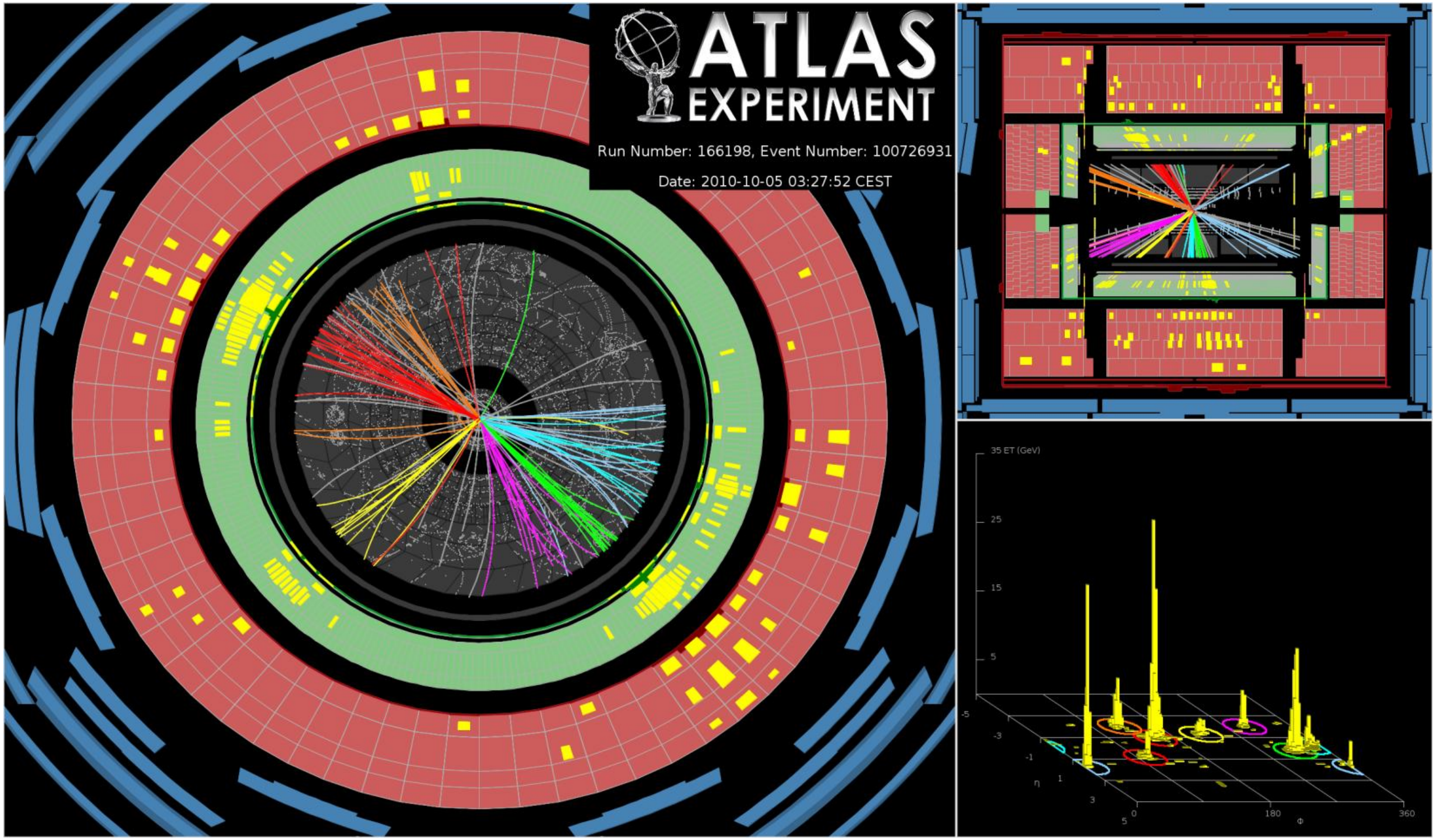


ATLAS
EXPERIMENT
Run Number: 160472, Event Number: 28352100
Date: 2010-07-31 05:52:55 CEST
205 ET (GeV)
175
145
115
85
55
25
-5
-3
-1
1
3
5
η
0
180
360
Φ

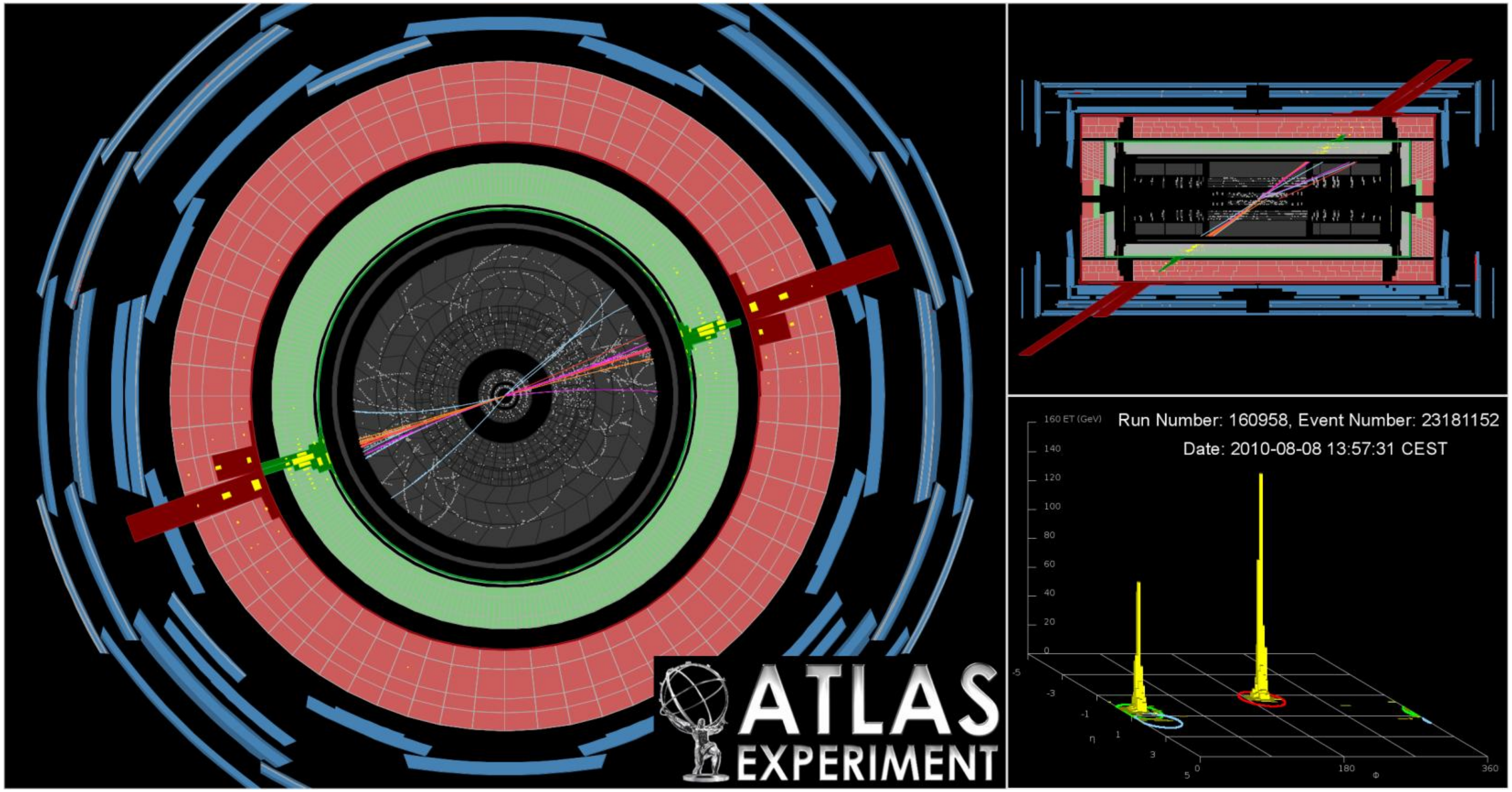
More Jets


ATLAS
EXPERIMENT
Run Number: 167576, Event Number: 69725215
Date: 2010-10-24 15:42:22 CEST
400 ET (GeV)
360
320
280
240
200
160
120
80
40
0
η
Φ
180
360

An Event With Many Jets

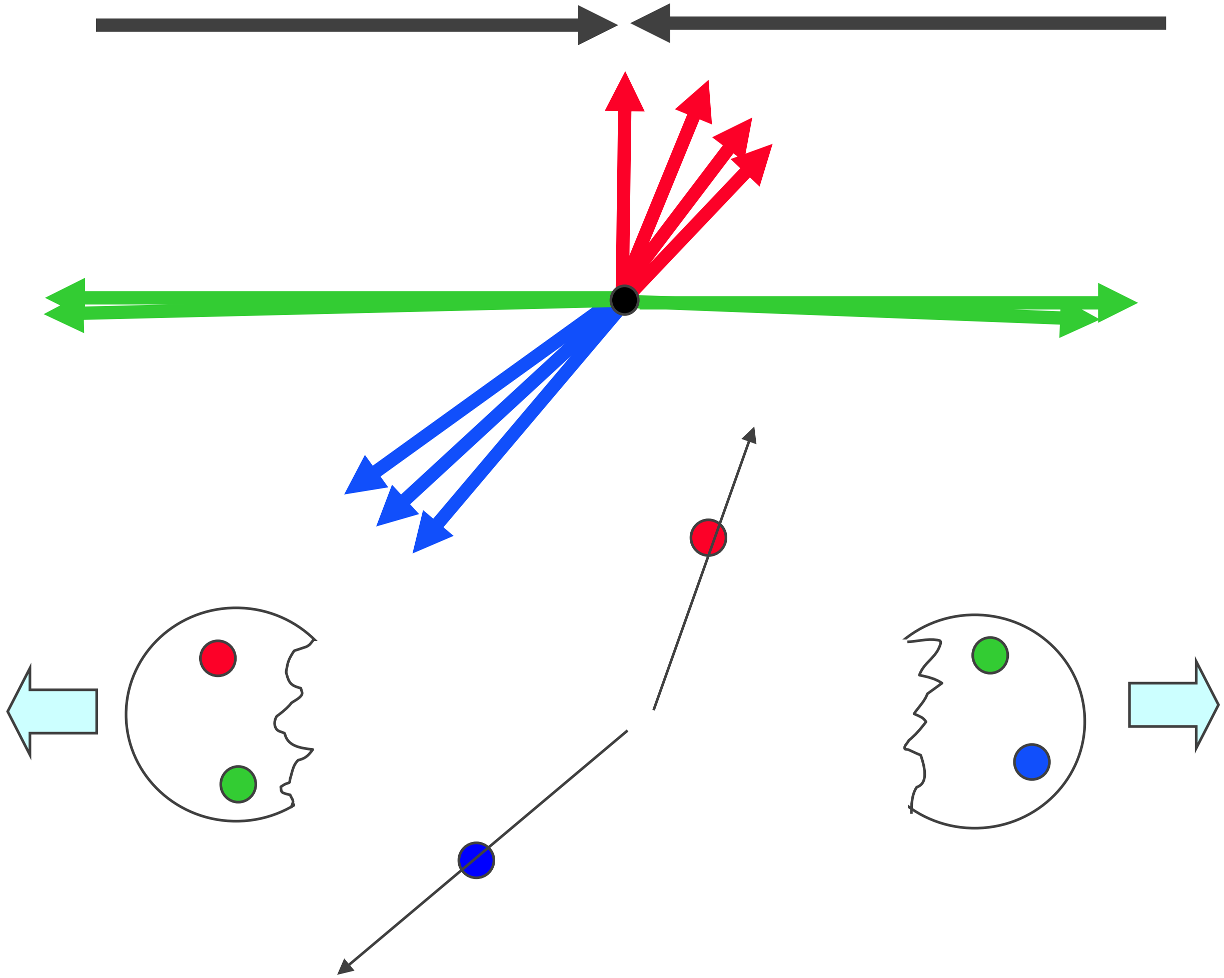


And an Event With Only Two



The Utility of Jets

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)

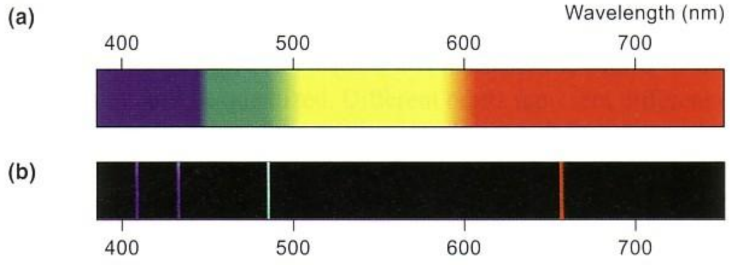


… is actually the ***elastic*** scattering of two constituents of the protons.

Jets are the best window we have into what the quarks are doing. Things that look very complicated when discussing individual particles simplify when talking about jets.

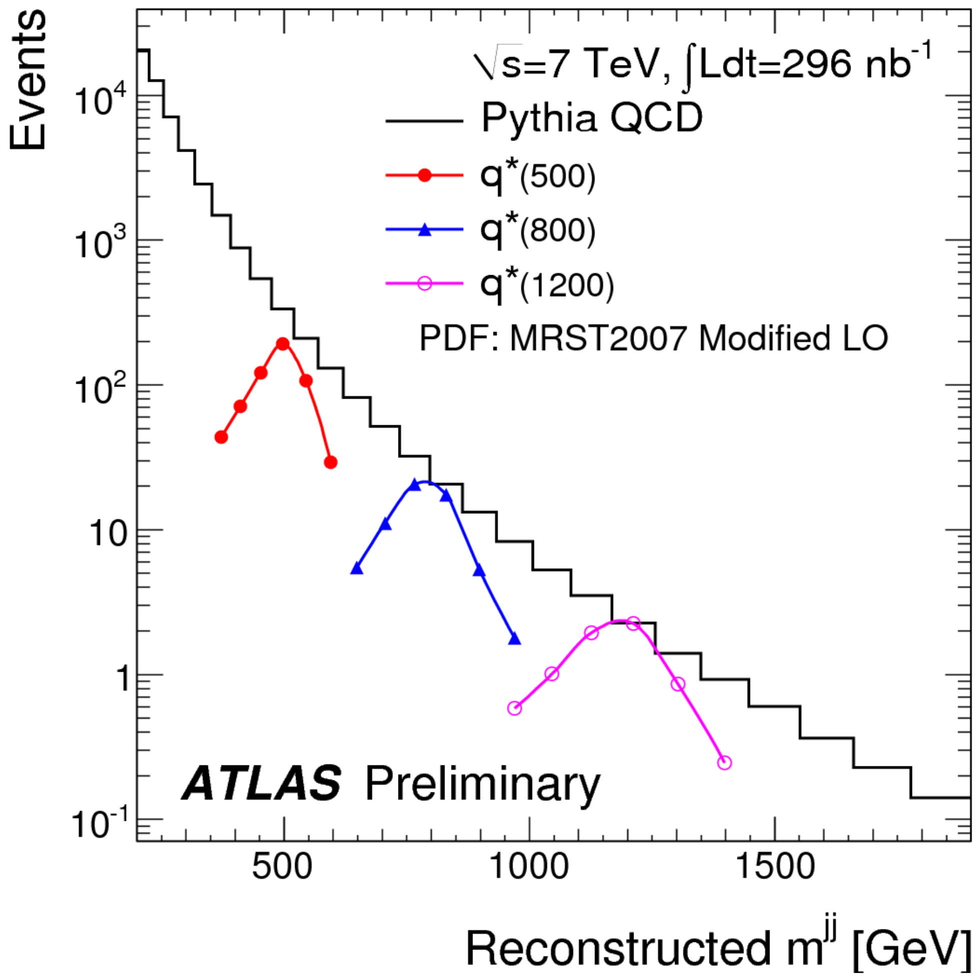
Energy Levels: Drawing a Parallel between Atoms and Quarks

- Put a lot of energy into an atom
- The atom transitions to an excited state
- The atom emits a photon and returns to its ground state
- We see a line spectrum



- Put a lot of energy into a quark
- The quark transitions to an excited state
  - Only if such a state exists of course!
- The excited quark (q*) emits a gluon (jet) and returns to its ground state.
- What would we see?

What We Might See



Lines in atomic spectra correspond to bumps in the jet-jet mass plot

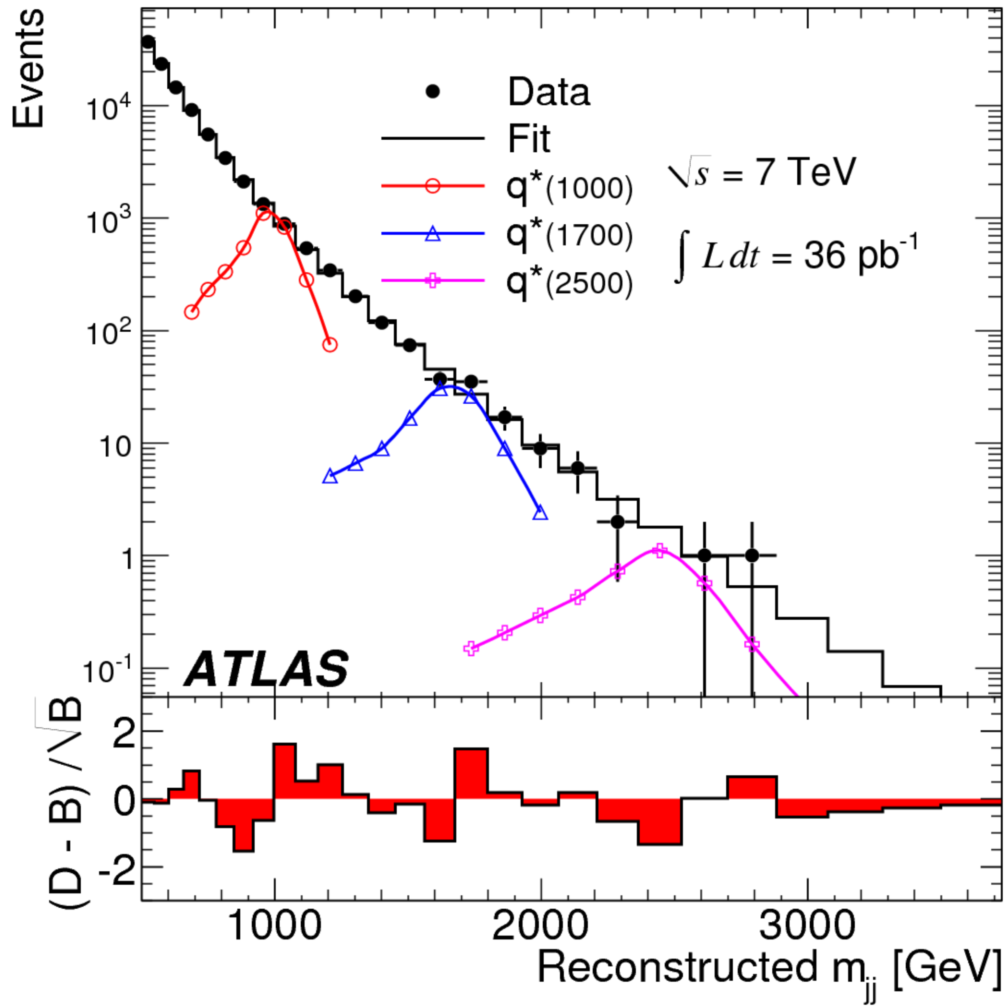
- One jet is the emitted gluon
- The other is the recoil quark
- (With atoms, the recoil is small)

The experimental question is whether this distribution is smooth or whether it has bumps

The background (black) is huge – it's like trying to measure atomic spectra at noon outside rather than in a dark room.

What Do The Data Look Like?

- The data are perfectly smooth. **No sign of bumps or energy levels.**
- We can set a limit on excited quarks – if they exist, they must be heavier than 2.15 TeV
  - The expected limit is 2.07 TeV
- The University of Toronto made major contributions to this analysis

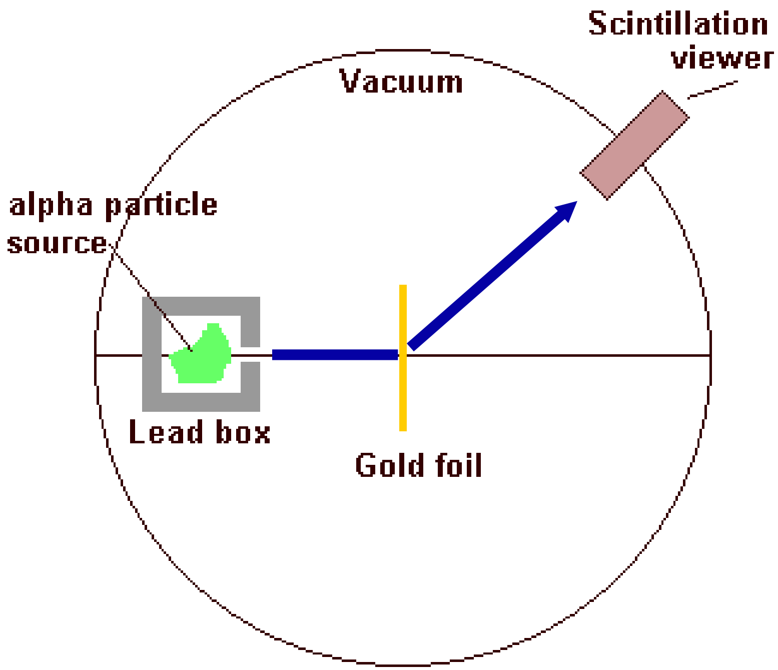


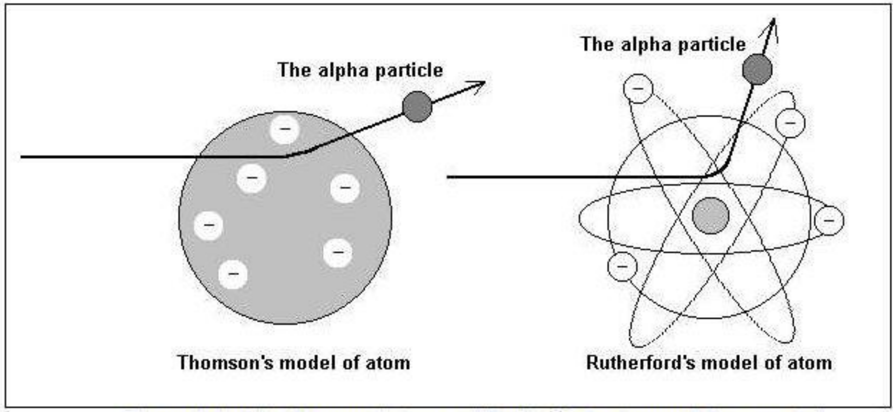
From Data to Paper

- The previous best limit was 0.89 TeV (CDF, 2009)
  - 20 years after the Tevatron start
- We had enough data for an expected limit beyond that on Monday, July 19th.
  - 111 days after first high-energy collisions
- On Friday, July 23rd, we showed the first results beyond the Tevatron at the ICHEP conference.
- On August 13th, that paper was submitted to PRL.

- Two lessons:
- Higher energy is a **huge** advantage
- Large collaborations are not necessarily slow.

The “Rutherford Experiment” (of Geiger and Marsden)





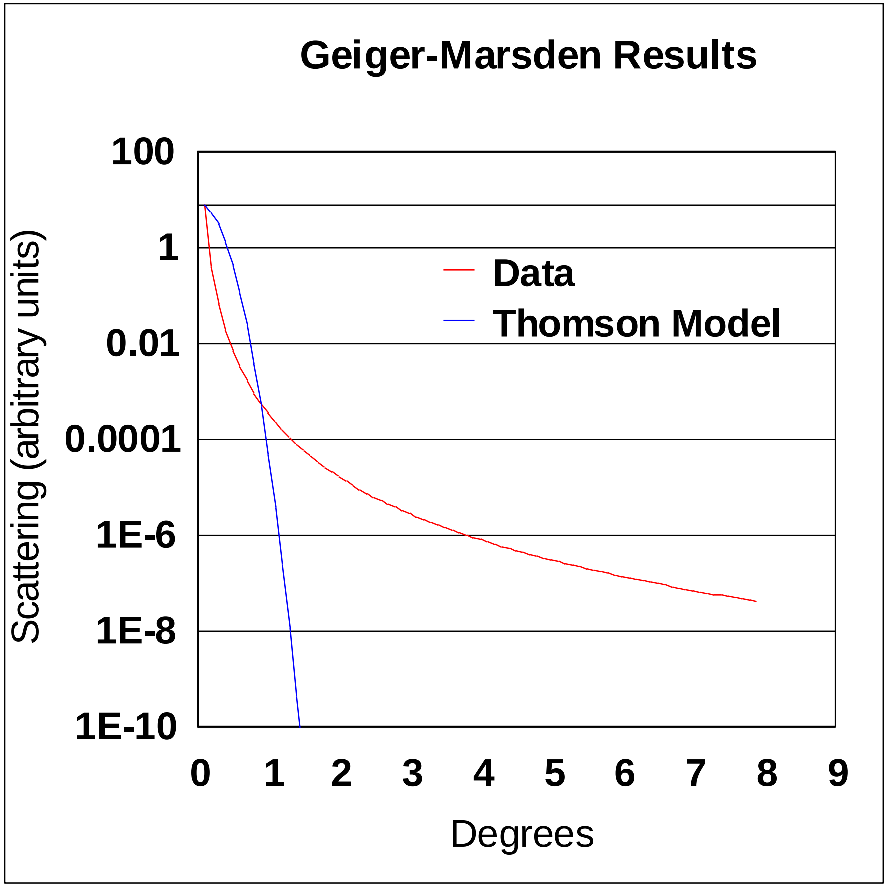
The models of the Thomson's atom and Rurtherford's atom; and the expected aberrations of alpha particle in both cases.

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

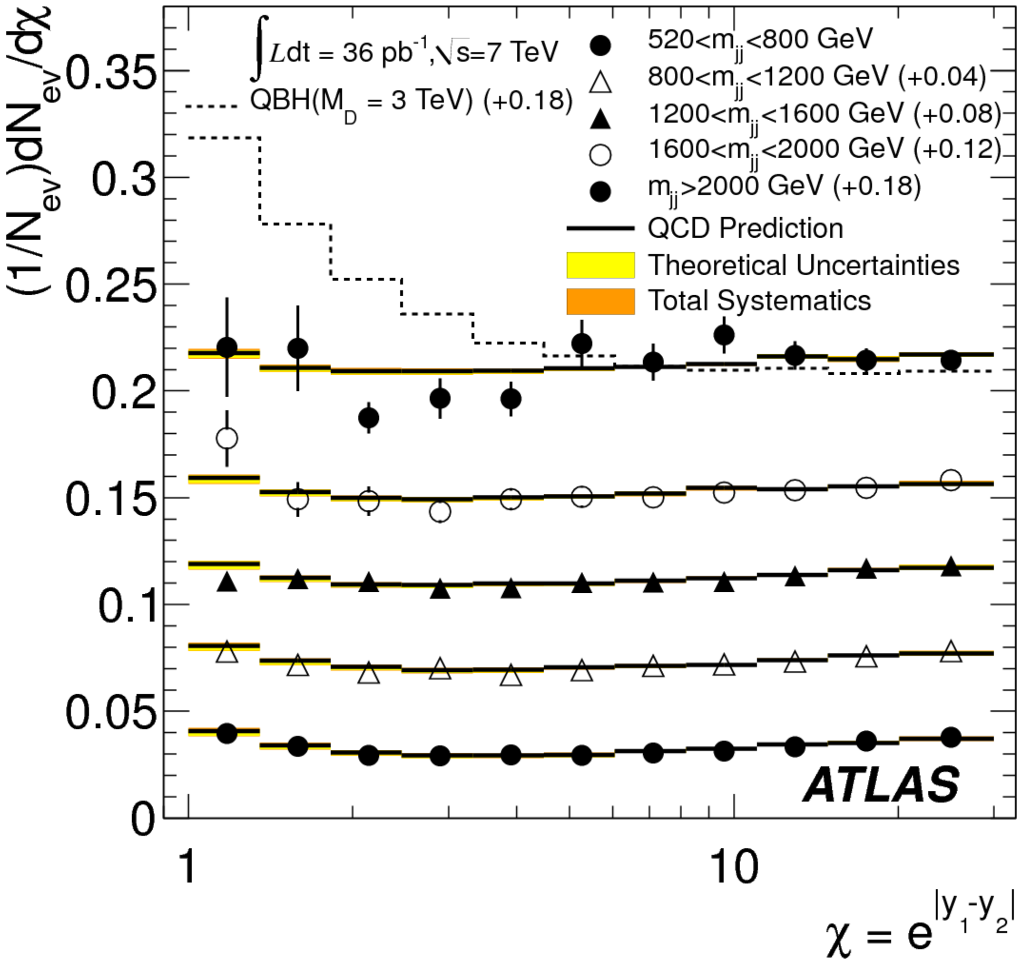


- At angles as low as 3°, the data show a million times as many scatters as predicted by the Thomson model
  - Textbooks often point out that the data disagreed with theory, but they seldom state how bad the disagreement was
- There is an excess of events with a large angle scatter
  - This is a universal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

ATLAS Scattering Data

- Quark substructure would appear as an shape like that shown by the dashed line.
- No substructure would appear (almost) flat.
- The data are consistent with being flat.
- From that, we can extract a limit: there is no quark substructure at a scale of Λ < 9.5 TeV
  - A length scale of approximately 22 zeptometers. (22 x 10^{-21} meters)
  - The expected limit is 5.7 TeV
    - Since we are sensitive to $1/\Lambda^2$, these numbers are closer than they look.

Plotted with a change of variables so we don't have to deal with exponentials.



Another measurement with a large UT contribution.

Relative Sizes in Context

If an atom were the size of the earth,

A nucleus would be the size of the CN Tower.

(A big, skinny nucleus, like ^{238}U)

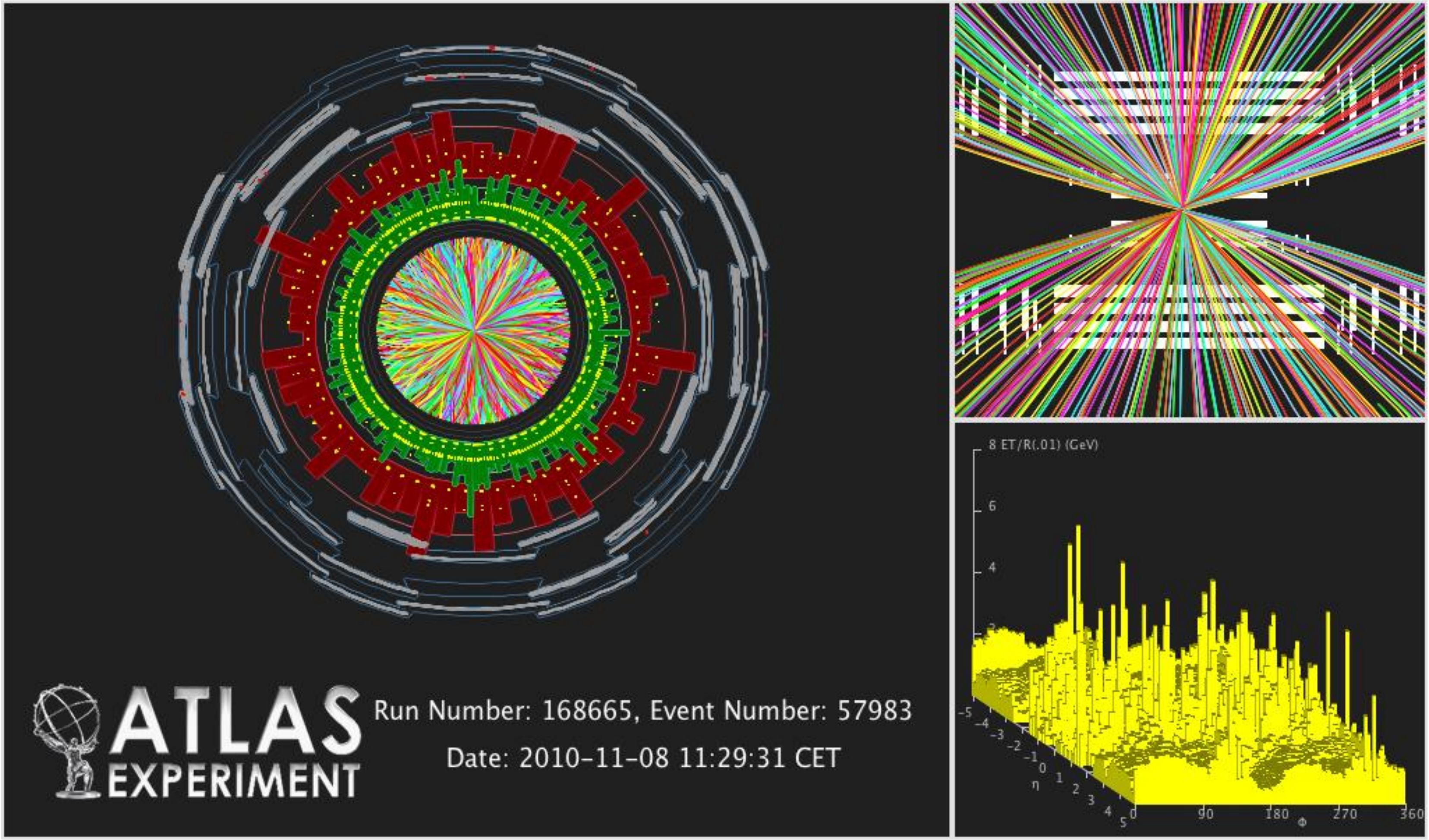
Relative Sizes in Context

From past experiments, we learned that quarks had to be smaller than a grape

Today we know that quarks are smaller than a pea.

Ultimately, we expect the LHC will reach the sensitivity of a single sprinkle on a Pop-Tart

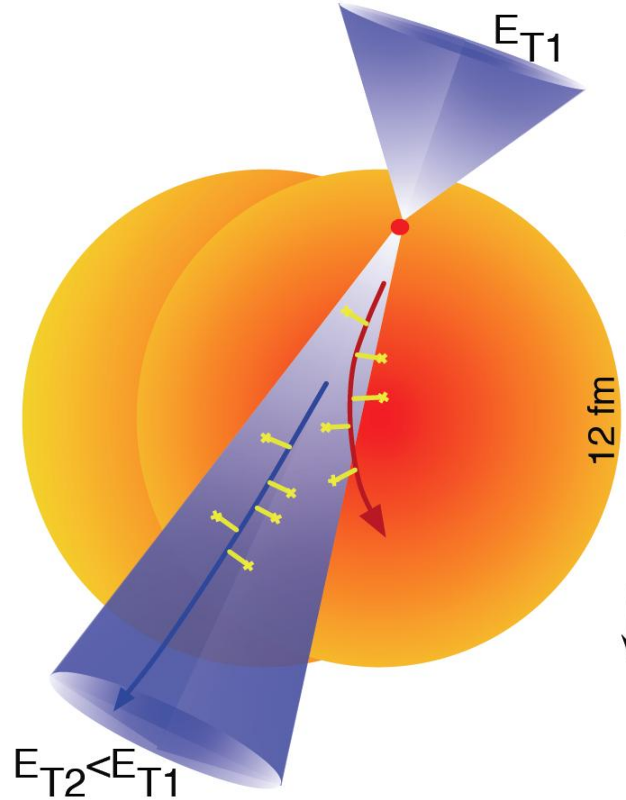
Heavy Ion Collisions

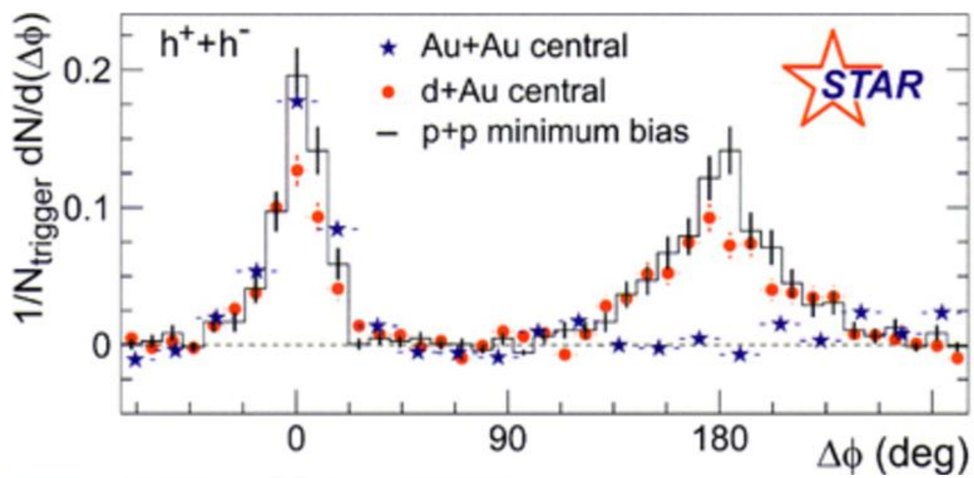


The LHC runs for one month per year colliding Pb^{82+} ions instead of protons, at an energy of 574 TeV (2.76 TeV per nucleon).

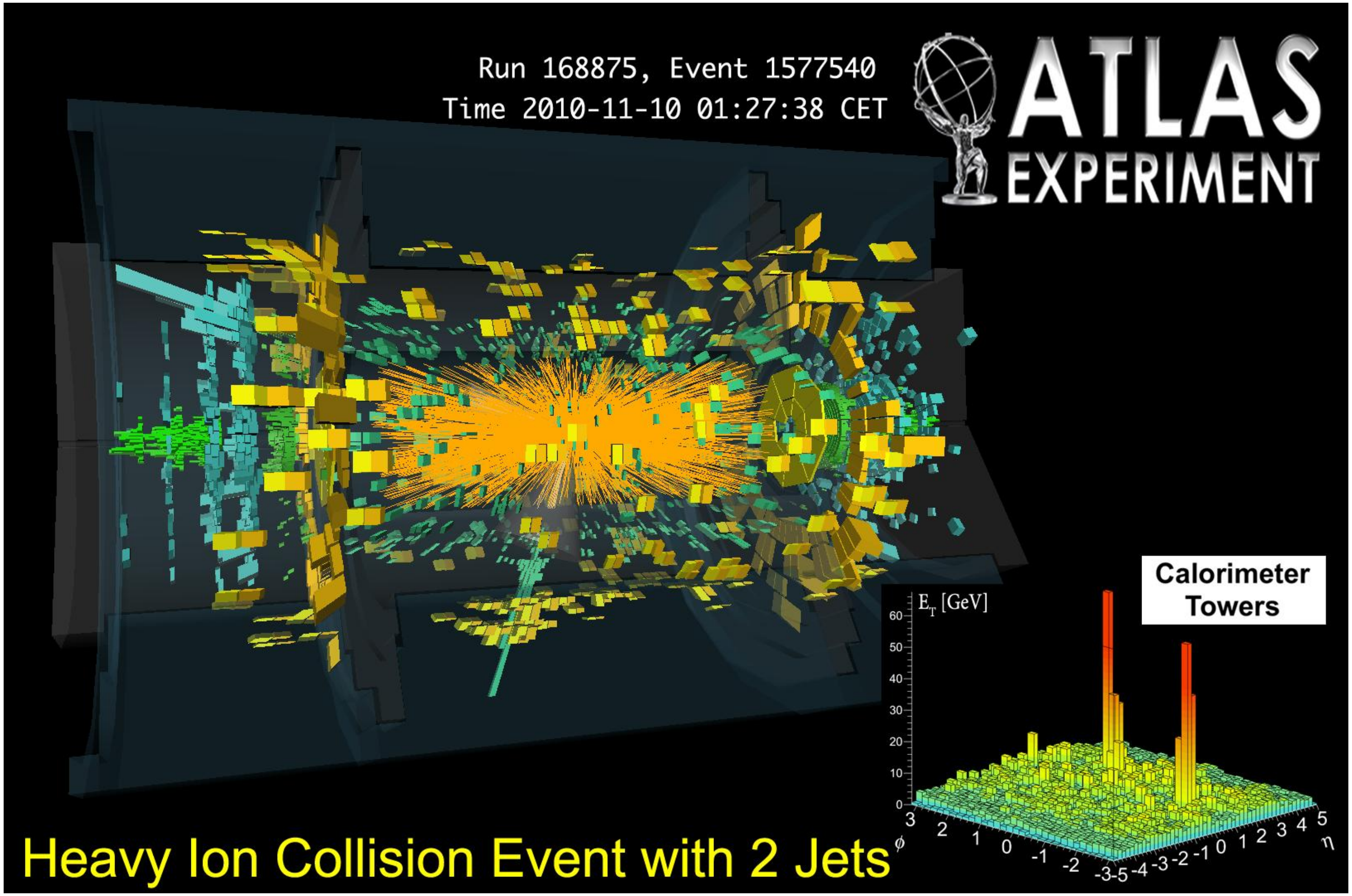
"Jet Quenching"

- When partons scatter, they have nearly equal energies (conservation of momentum)
- When they do so in the right geometry, one traverses the medium and the other does not.
- The partons form jets, and the difference in energy is related to the energy loss in the medium.
- The energy loss depends on the heat capacity, which depends on the number of degrees of freedom
  - Large for a Quark-Gluon Plasma
  - Small for cold nuclear matter

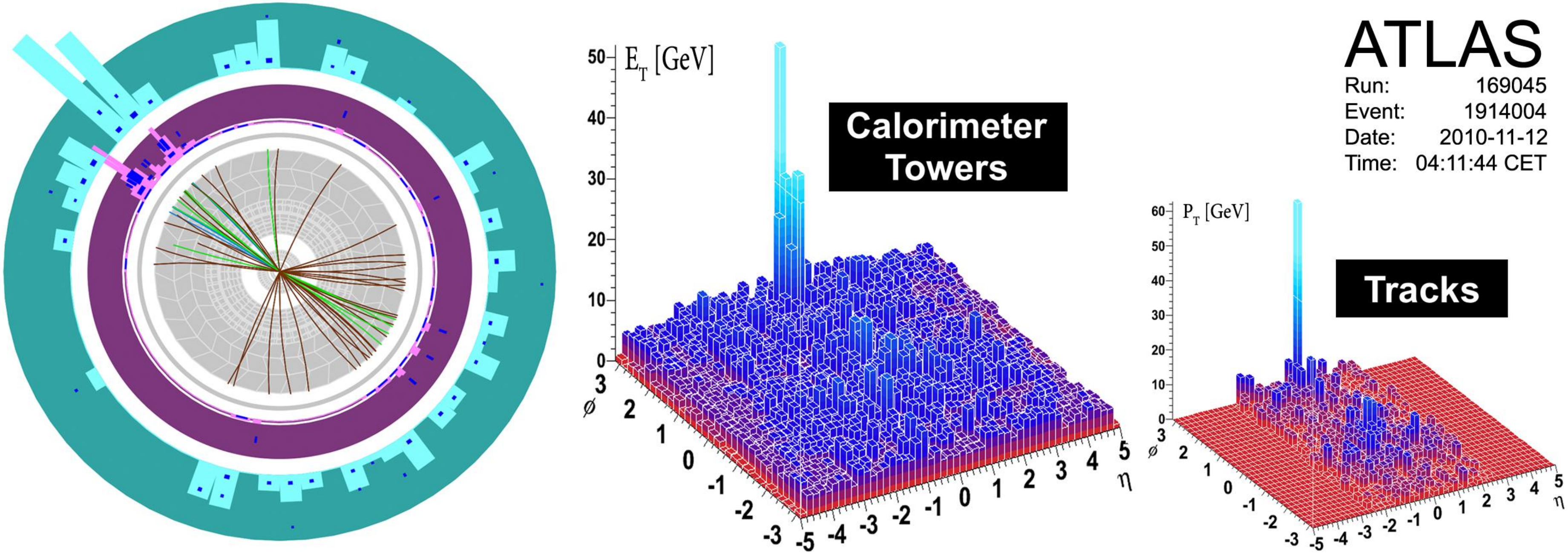




We See Ordinary Dijet Events



And Very Asymmetric Events

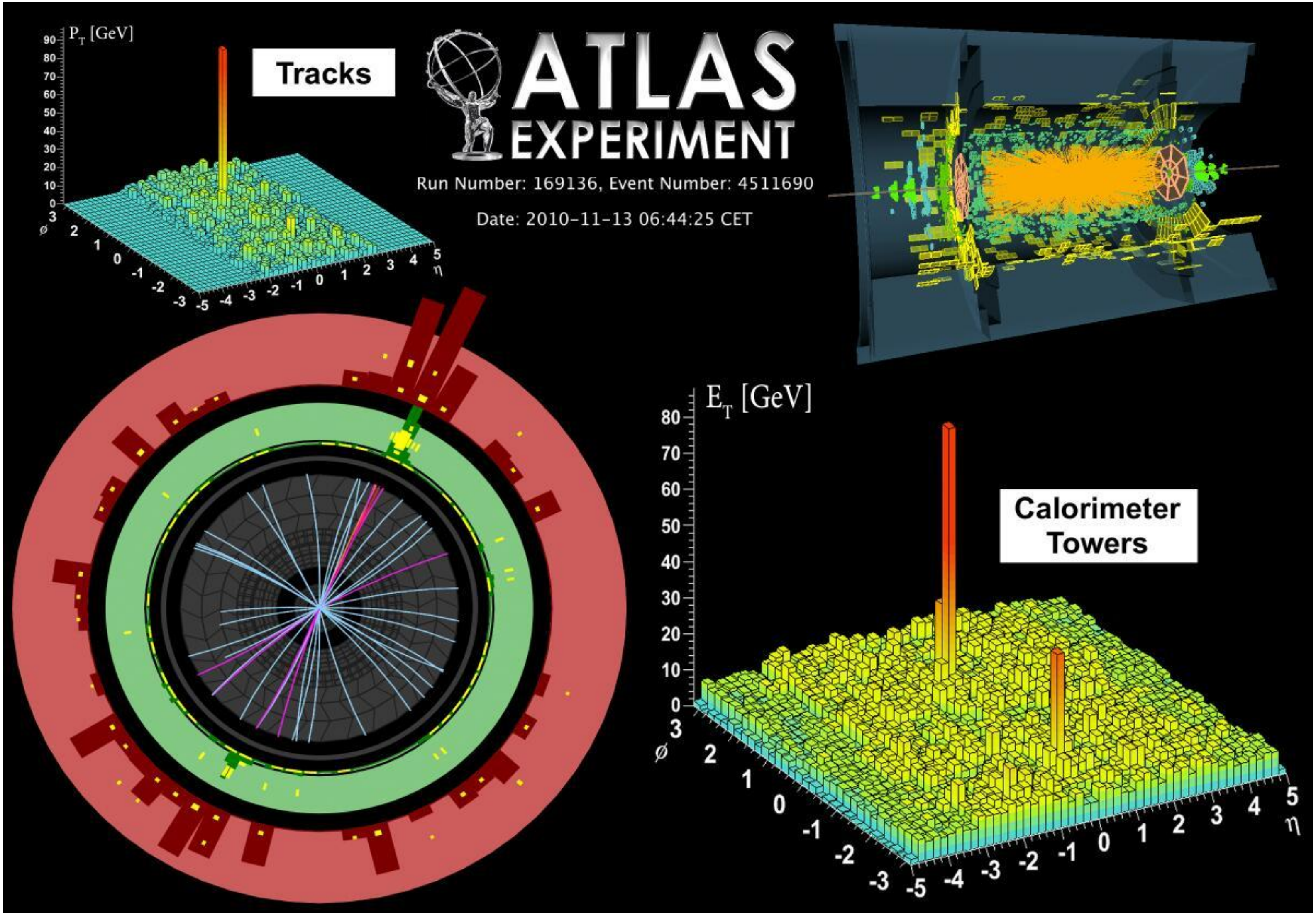


- One jet looks normal
- The other seems to be spread out over such a large area that it is difficult to see above the underlying event.

A STAR-like signal

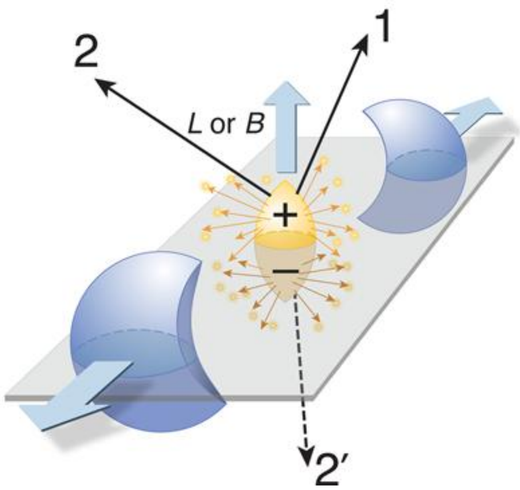
- We noticed this on-line.
- This is a typical event. I think it was the third one that we scanned.

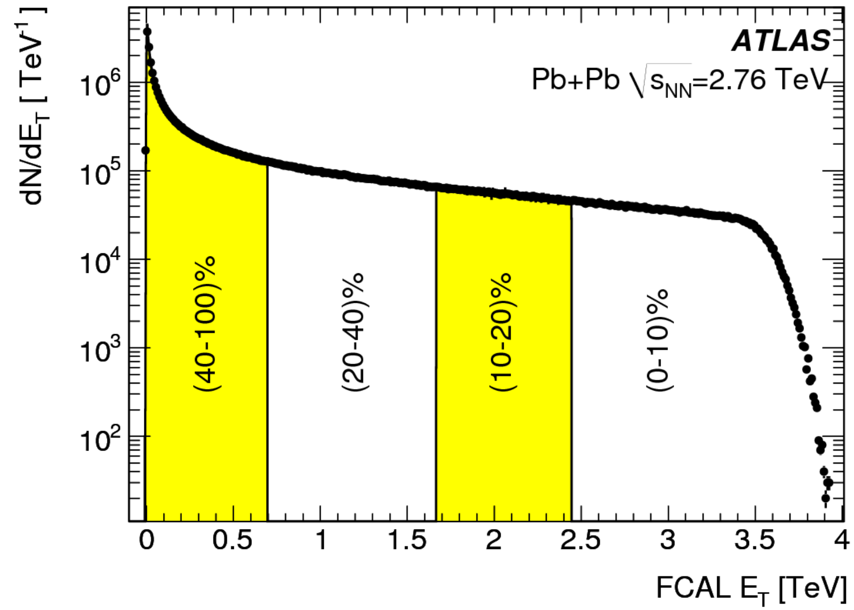
This Is Far From Unique

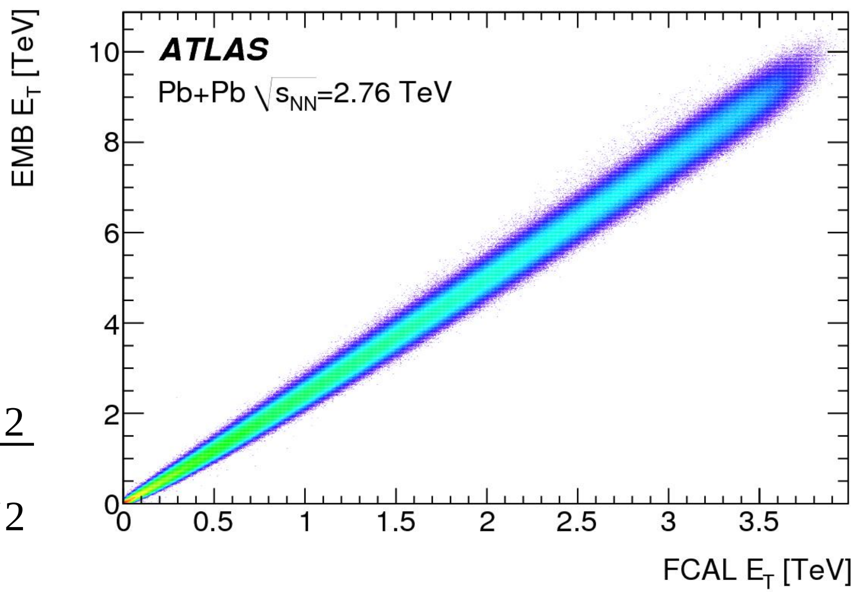


The Next Step

- How does this effect depend on global event parameters?
- The simplest one is “centrality”
  - Related to the impact parameter of the colliding lead ions.
  - We use energy in the forward part of the detector as a proxy for this



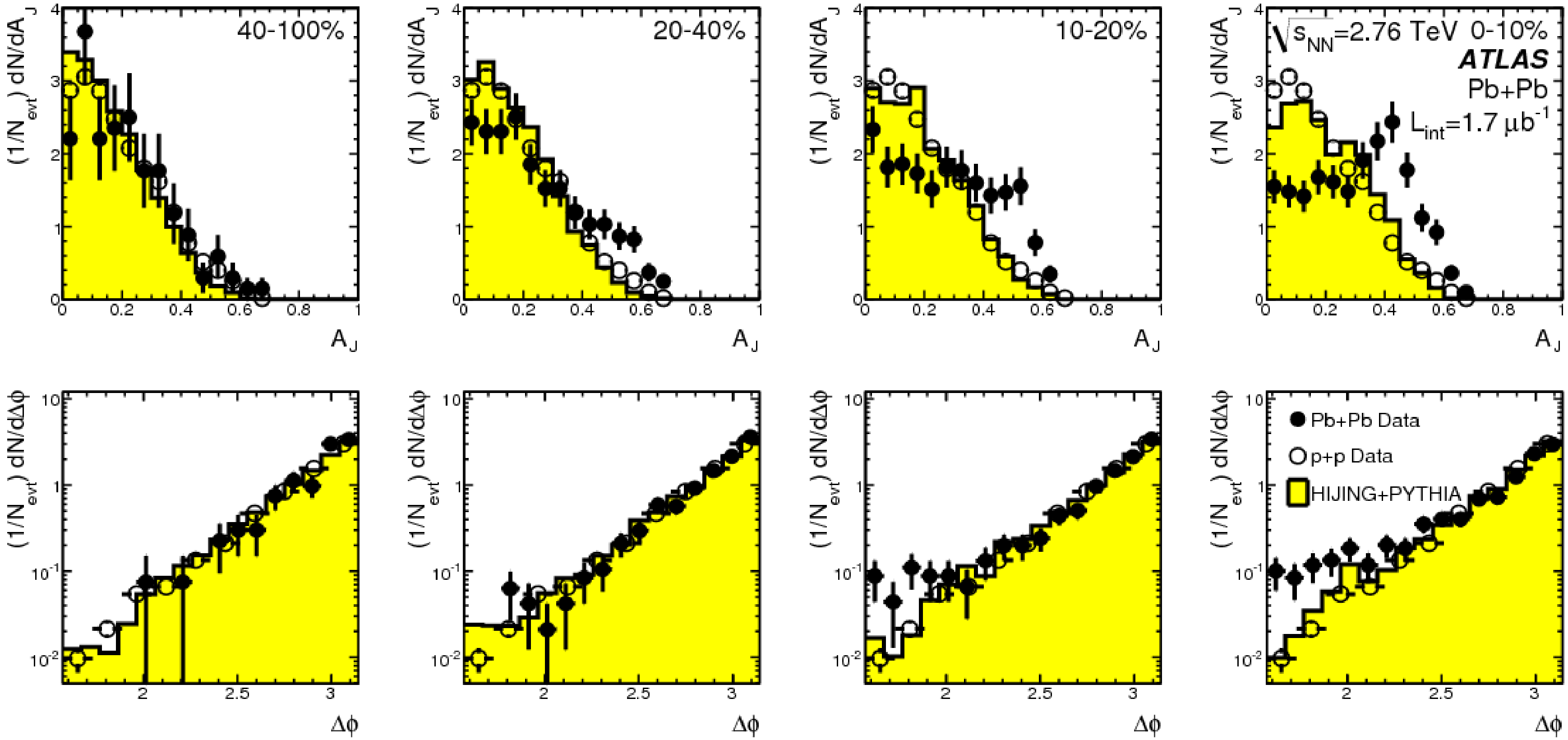




- We also quantify the effect: $$A = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

Results

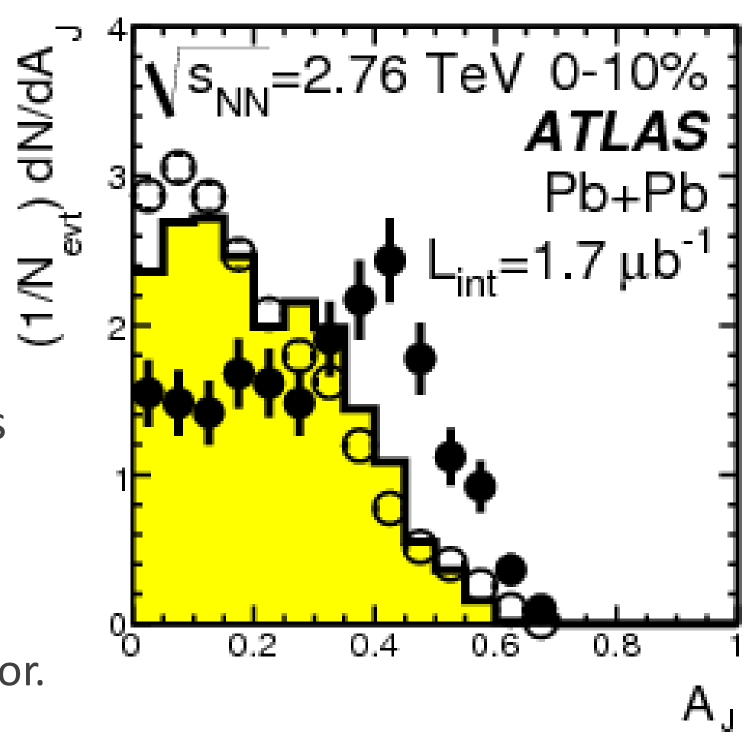
Asymmetry Increases With Centrality



Jets Are Still Predominantly Back-to-Back

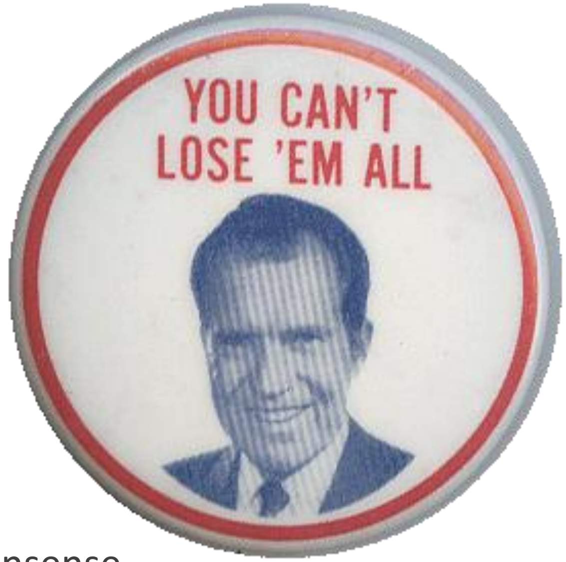
Interpretation

- The paper focuses on the observation, not an interpretation.
  - This was intentional.
- If one interprets this as energy loss in the medium, the degree is substantial: a few 10's of GeV/12 fm
- This is a huge effect – much more than expected from ordinary nuclear matter.
- Talking about temperature is always dicey if we are not in equilibrium, but this would correspond to a cooling rate of about 10^{37} K/s



The world's hottest substance is its best refrigerator.

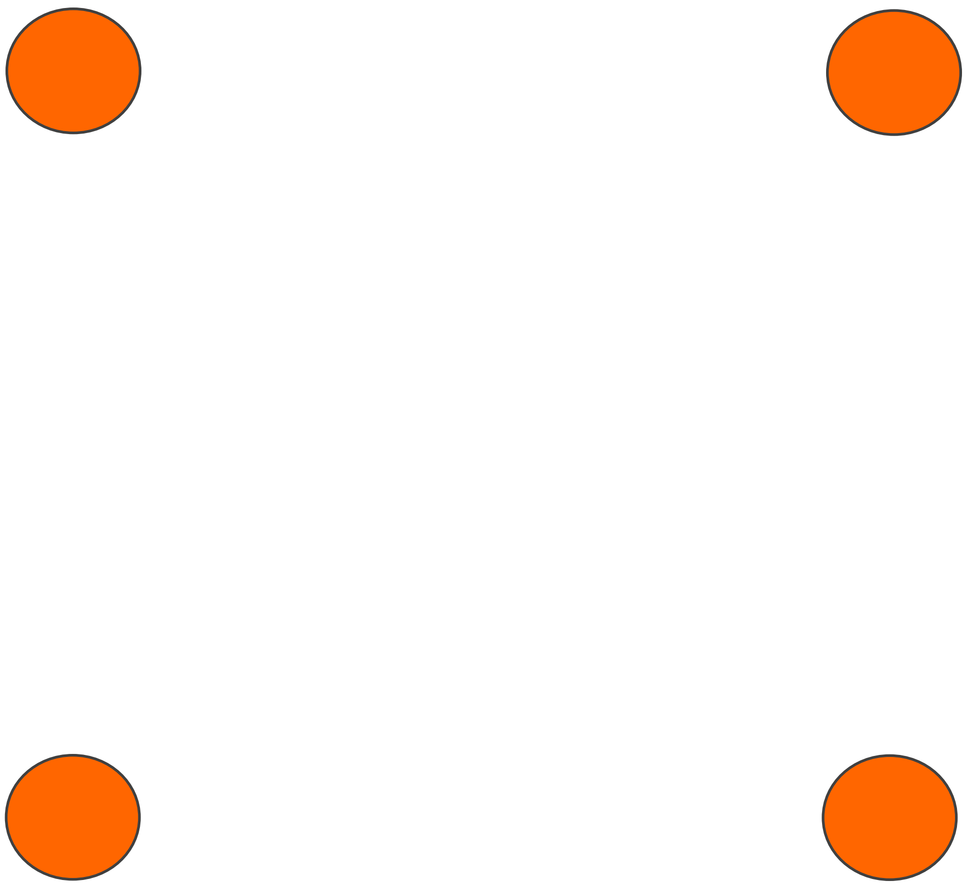
The “No Lose Theorem”



- 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.

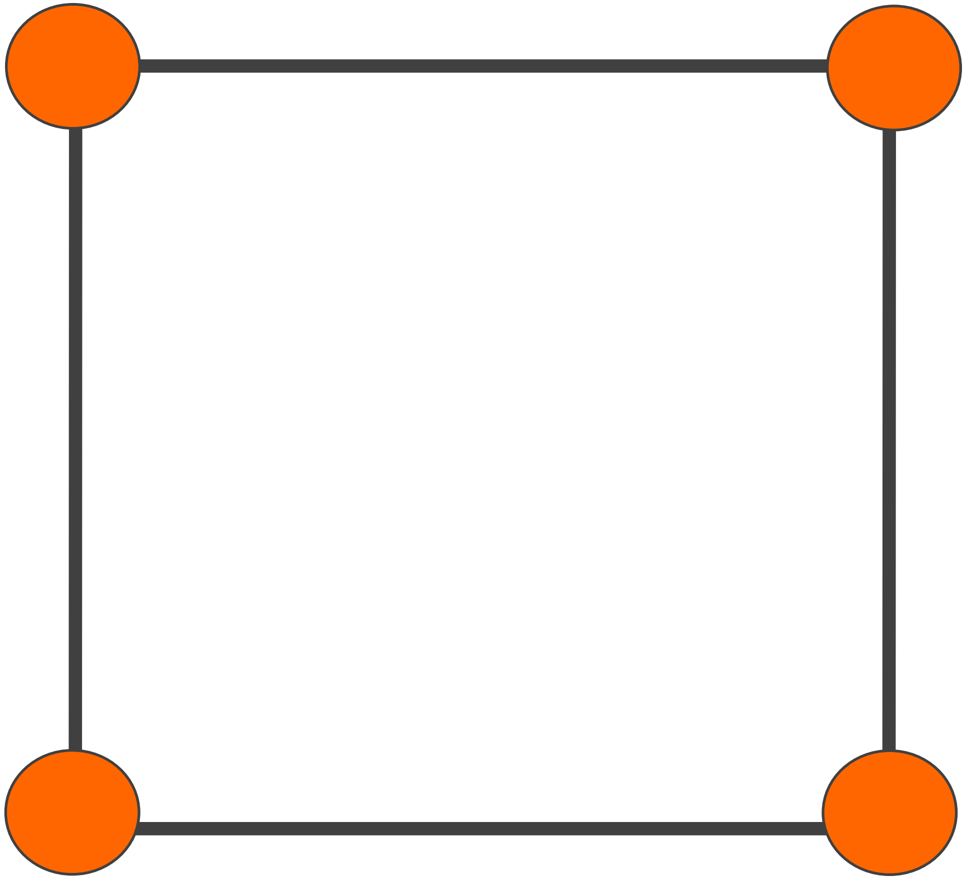
The Standard Model is a low-energy effective theory. The LHC gives us the opportunity to probe it where it breaks down. Something new must happen.

Spontaneous Symmetry Breaking



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

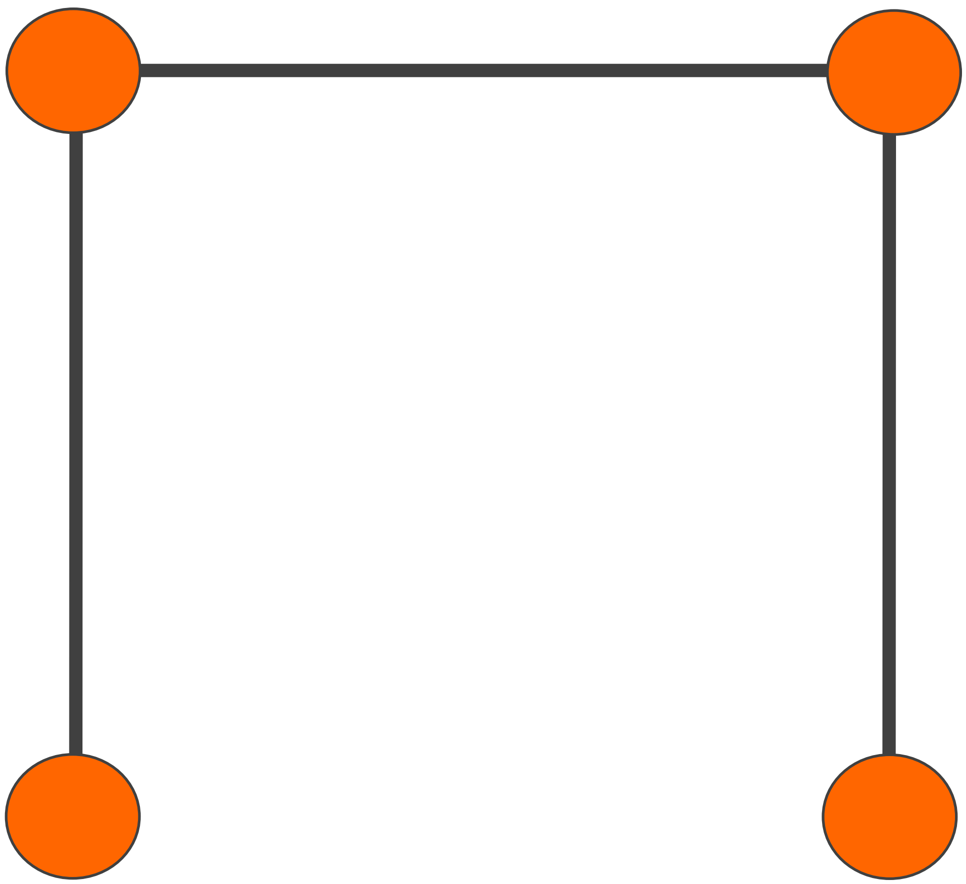
One Option



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

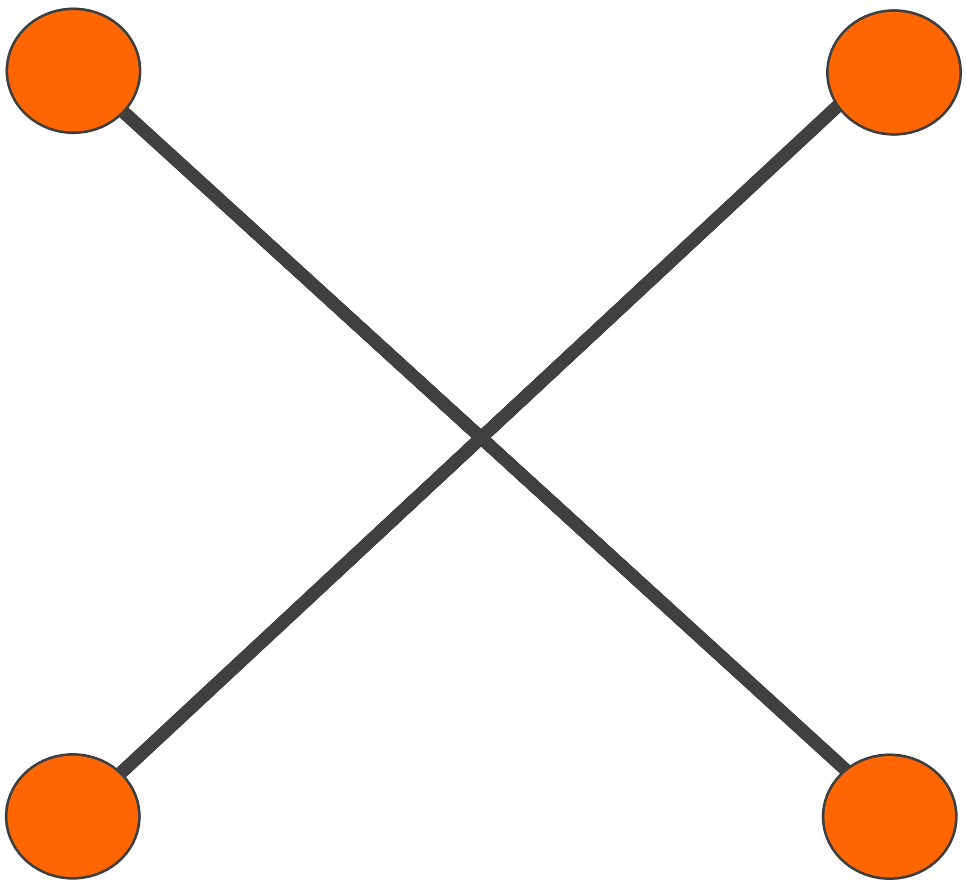
(length of side = 1 unit)

Option Two



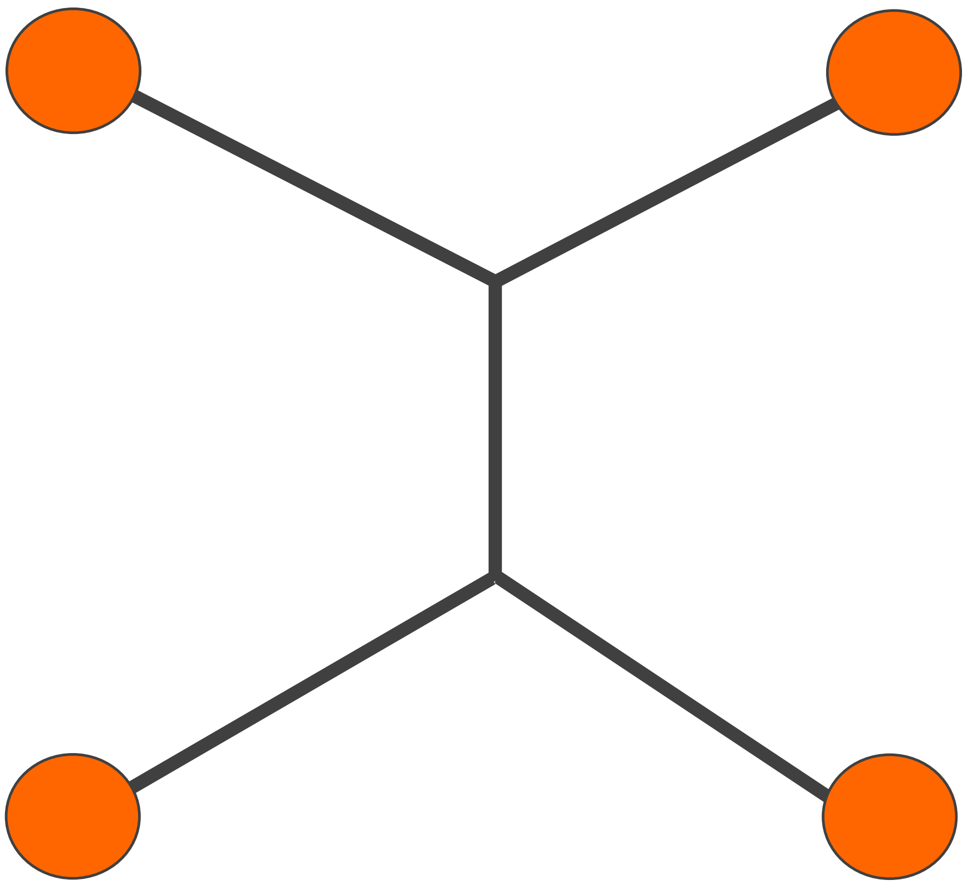
I can connect them this way at a cost of only 3 units.

The Solution that Looks Optimal, But Really Isn't



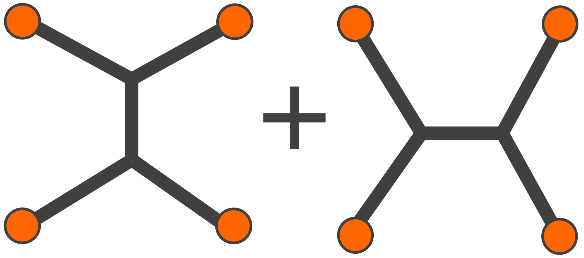
This requires only $2\sqrt{2}$

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.

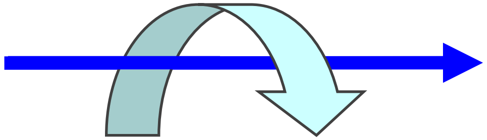
The Higgs Mechanism

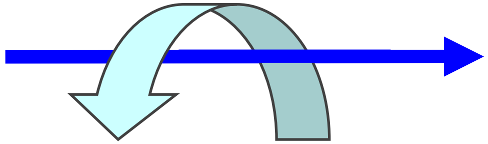
- Write down a theory of massless weak bosons
  - The only thing wrong with this theory is that it doesn't describe the world in which we live
- Add a new doublet of spin-0 particles:
  - This adds *four* new degrees of freedom (the doublet + their antiparticles)

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

- 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
- 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?

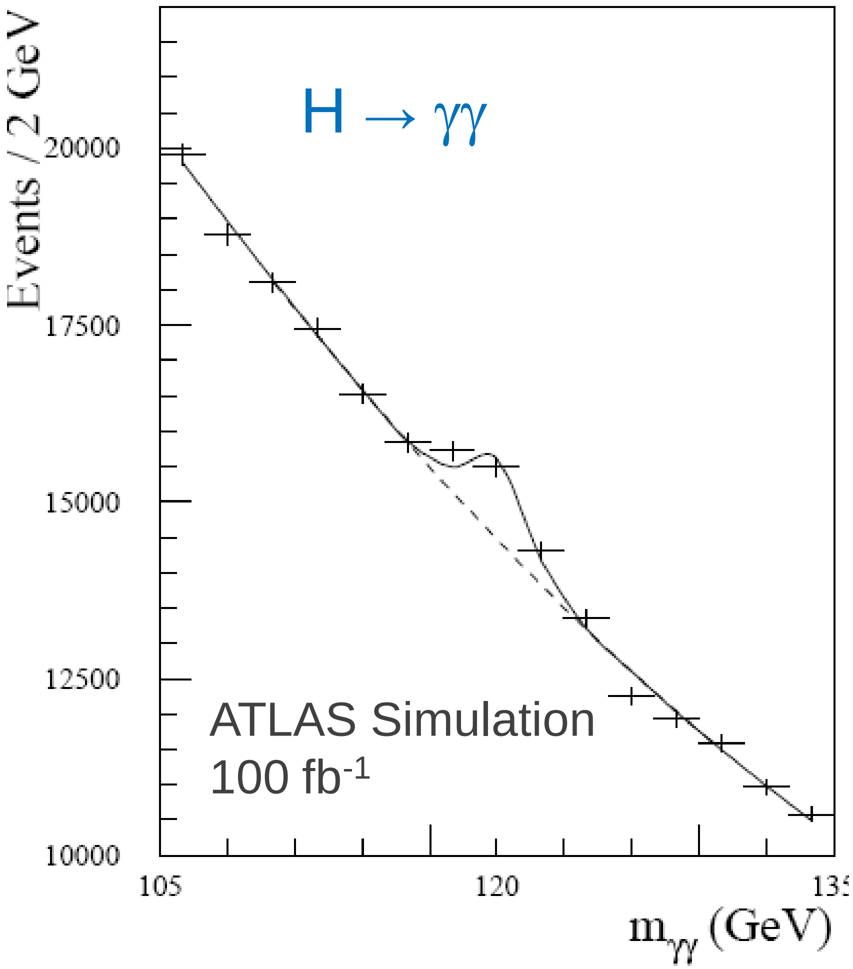
- There's very little choice involved in how you write down this theory.
  - There's one free parameter which determines the Higgs boson mass
  - There's one sign which determines if the symmetry breaks or not.

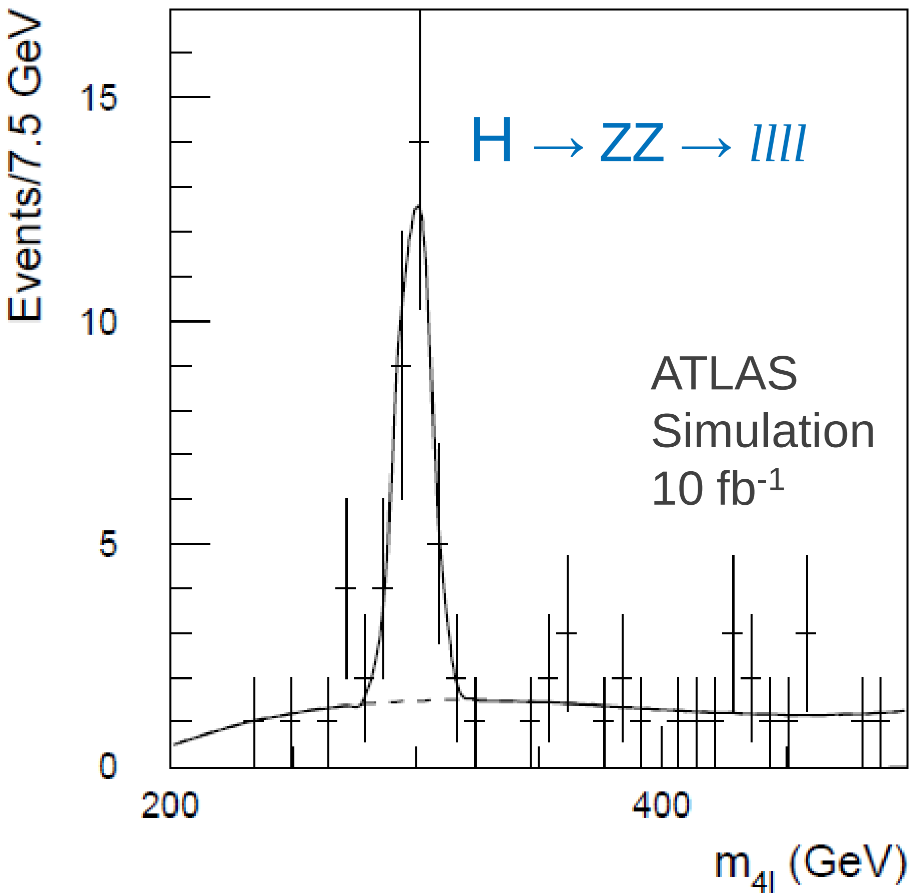
- The theory leaves the Standard Model mostly untouched
  - It adds a new Higgs boson – **which we can look for**
  - It adds a new piece to the WW → WW cross-section
    - This interferes destructively with the piece that was already there and restores unitarity

- 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

Searching for the Higgs Boson

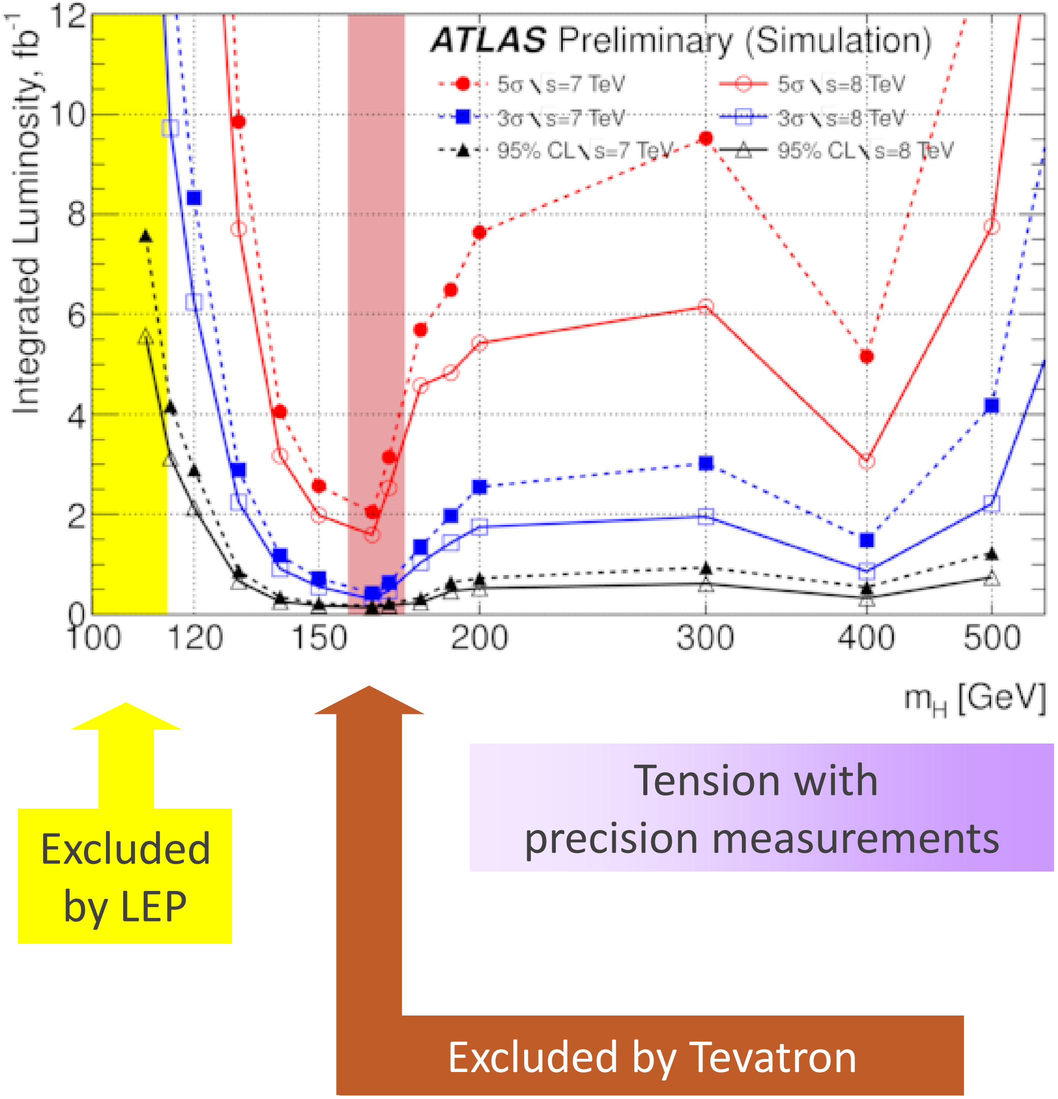
Because the theory is so constrained, we have very solid predictions on where to look and what to look for.





Combining All Channels

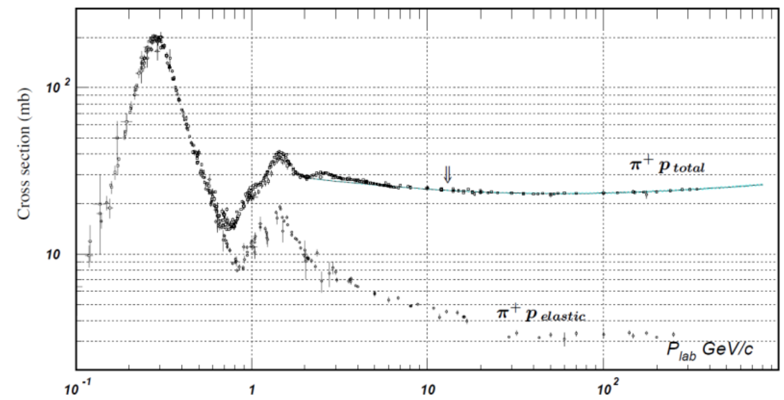
- The next two years will be very exciting in terms of the Higgs search:
  - 2011: 1-2 fb^{-1} at 7 TeV
  - 2012: a few fb^{-1} at 7 or 8 TeV
- For much of the mass range, we will see the Higgs in multiple channels
  - We can start probing its couplings: it looks like a Higgs, but does it act like a Higgs?



Two Alternatives

- 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.

Apologies

- I didn't cover even a tenth of the ATLAS 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?

ATLAS has 27 published results, 12 drafts in review by the collaboration and 21 in the pipeline so far. We also have 100 preliminary results that can be shown at conferences.

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 investigate a number of other questions
  - For example, are quarks fundamental or are they composite?
- It was a rough start, but the LHC is now starting to produce results beyond what had been achieved before…and this year promises to be even better.

Thanks for inviting me!