Thinking scientifically

Cornell University

Peter Wittich
Laboratory for Elementary Particle Physics

Science’s lessons: Tools for being a smart citizen in modern world

- Buzzwords: “Innovation economy,” “Information society”
  - Being technically literate is a key to success in today’s economy
- Science is a place where school can teach some of the tools to allow our children to succeed
- For instance
  - Physical Science (esp. physics) teaches a familiarity with numbers
  - Experimental science teaches about measurement and tools
- Both are crucial tools for living life in the modern age
  - How do I do my taxes?
  - How do I use a computer?
  - What do poll results mean?
  - Perpetual motion?
    - Scams, lies, tricks, and claims

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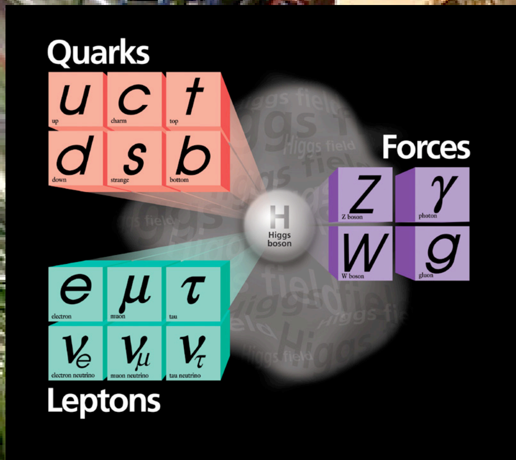
Elementary-Particle Physics

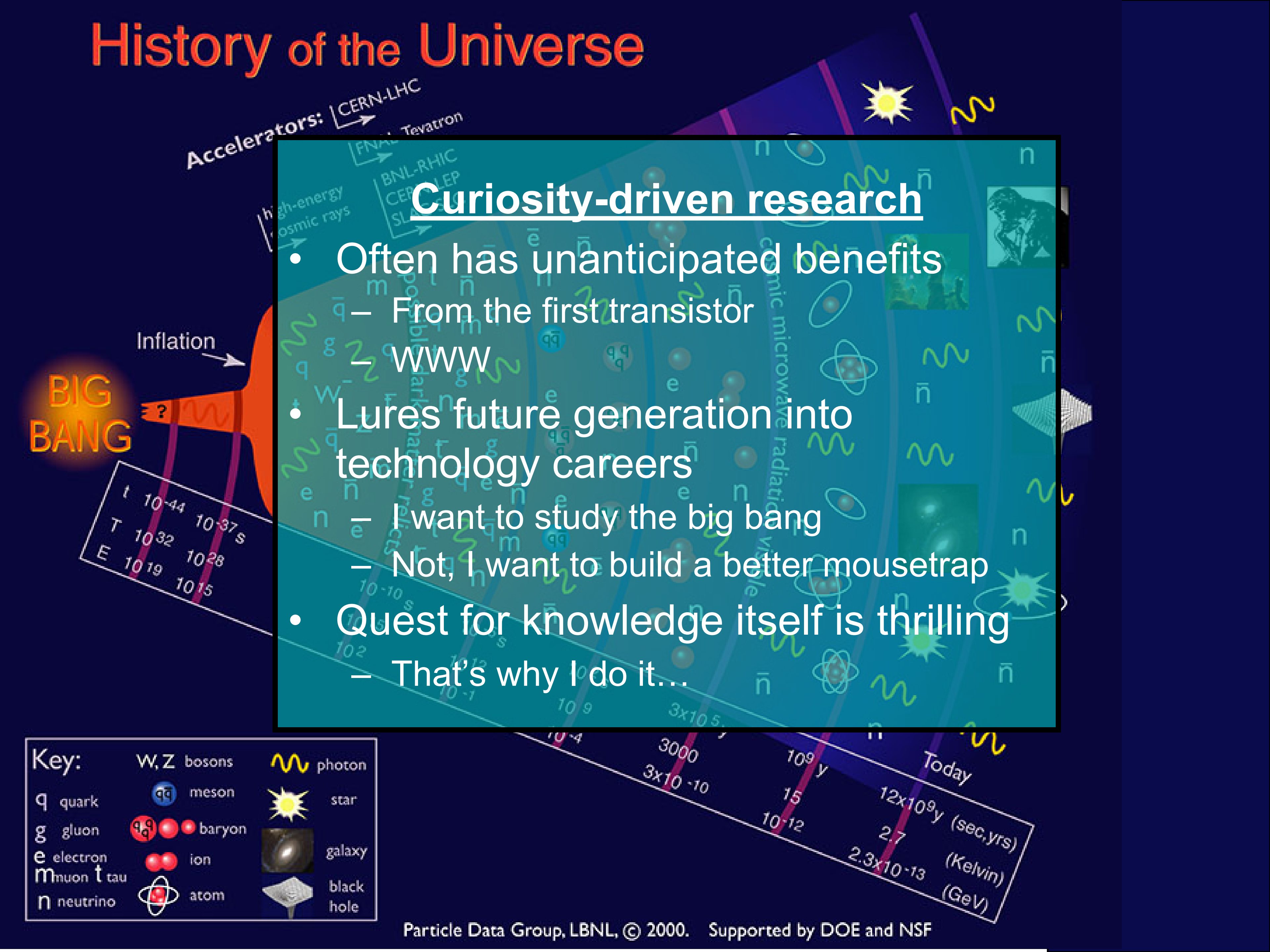
My Science - Particle Physics



- CMS experiment at CERN
  - Particle collider
- We try to understand the smallest building blocks of nature
- We ask questions often asked by your students (maybe not in these words!)
  - What is space and time?
  - Are there more than three space-like dimensions?
  - What gives particles mass?
  - Where is the antimatter?
- Some of the most fundamental questions in science today.

Curiosity-driven research

- Often has unanticipated benefits
  - From the first transistor
  - WWW
- Lures future generation into technology careers
  - I want to study the big bang
  - Not, I want to build a better mousetrap
- Quest for knowledge itself is thrilling
  - That's why I do it…



Goals of scientific endeavor: natural laws

- A process of discovery
- Natural laws are predictive
- A way of thinking that fits in anyone's toolset
  - Same skills can be turned on many problems
- Science as a process

Science teaches more than just the subject matter

Thinking scientifically: the scientific method

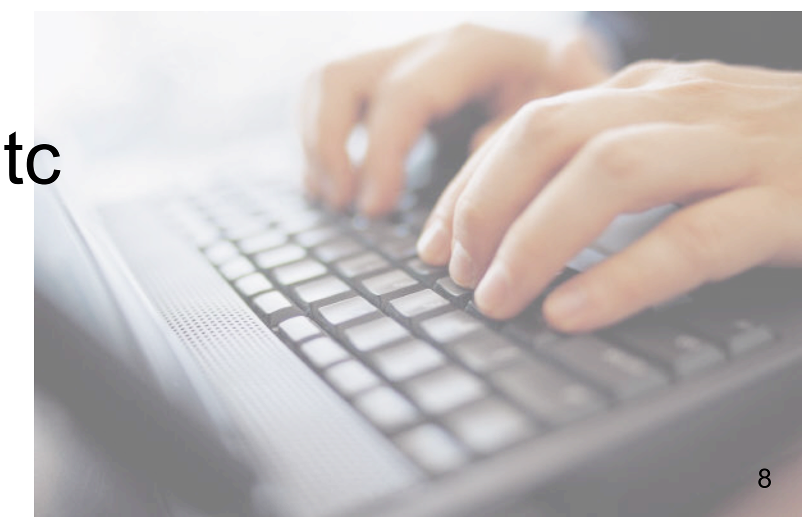
- scientific method - *noun*
  - a method of procedure that has characterized natural science since the 17th century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses.
- Key phrases:
  - Systematic observation
  - Formulation of hypothesis
  - Testing of hypothesis
  - Modification of hypothesis

What's a good hypothesis?

- Can we tell if the theory is wrong?
  - A scientific theory has to be testable by making predictions
  - Those tests have to be able to disprove the theory, i.e., falsify it.
  - If two theories make all the same predictions, they are the same
    - Occam's razor
    - No real reason to choose one or another
- Falsifiability not necessarily in a particular experiment but in any conceivable experiment
  - Challenge to both the people who think up the hypotheses

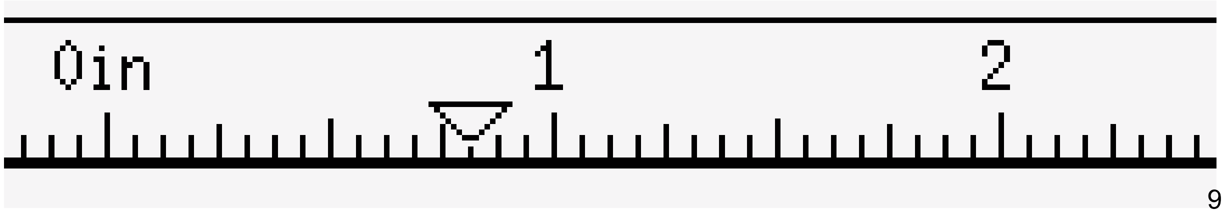
Errors, Uncertainty, and Bias

- Humans (and our machines) are fallible
  - We know this in everyday life -- I’m *sure* I turned off the stove
- Our machines are fallible too
  - Blue Screen of Death
- How does this affect my experiment?
  - Central question in science
- Margin of uncertainty, errors, etc



Experimental design

- When we design our experiment, we have to estimate how well it can do
- Can the experiment tell if the theory is right?
  - No measurement is 100% accurate
    - Experimental Uncertainty
  - For instance, on a ruler, can't tell more than the smallest division
- Sometimes this limits if an experiment can even test a theory



Subtle Bias

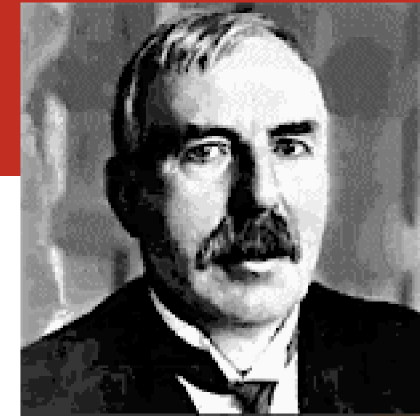
- Unconsciously manipulate the data to fit your expectation
  - We have beliefs and are invested in the status quo
  - Maybe you formulated the hypothesis that's being disproven
  - Maybe it made you famous
- We have techniques to try to get rid of bias
  - For example, blind, double-blind techniques
  - Hide the data from the researcher to prevent her from fooling herself

(Unfortunately, there are other cases)

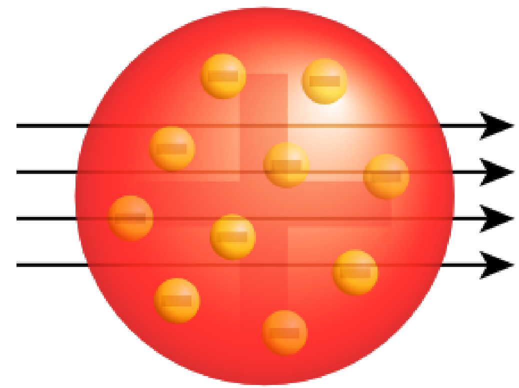
- South Korean cloning case
- Physics faked data

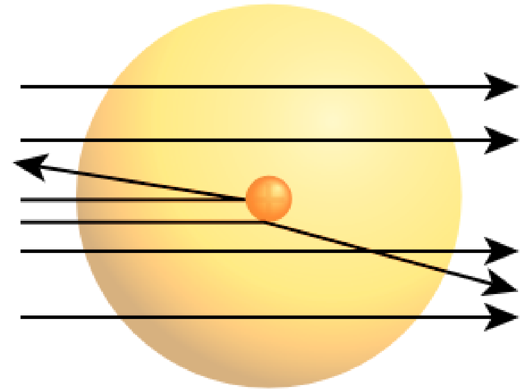
- Almost none of the tools will prevent us from catching someone who actively cheats

Sometimes, being wrong is best



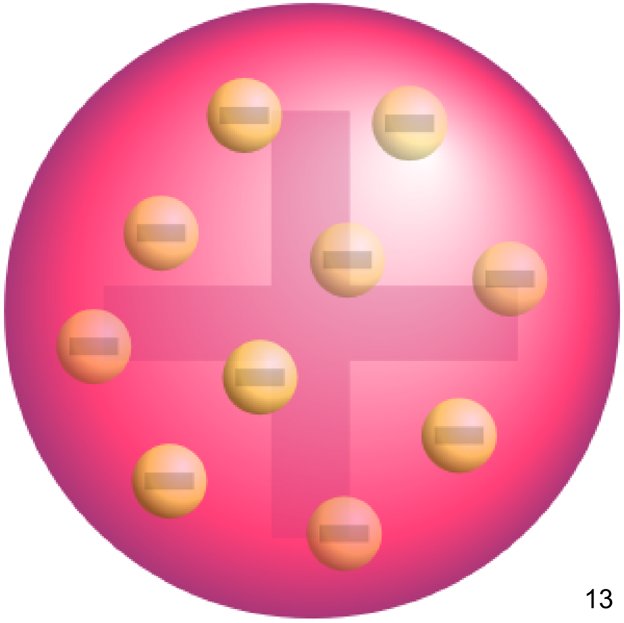
- Rutherford's experiment: radical rethinking of nature of the atom
  - Also known as:
    - Geiger-Marsden experiment
    - Gold foil experiment
- Goal: test nature of the atom
- Let's go through it one step at a time

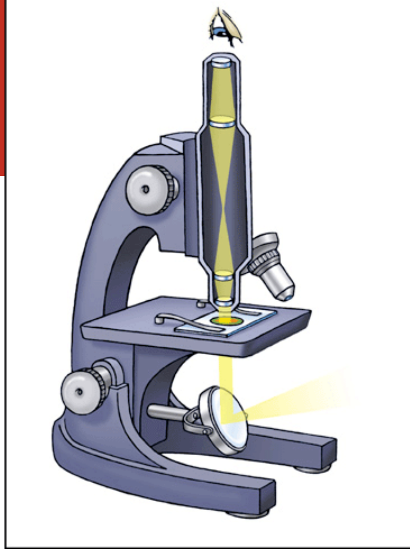




Background

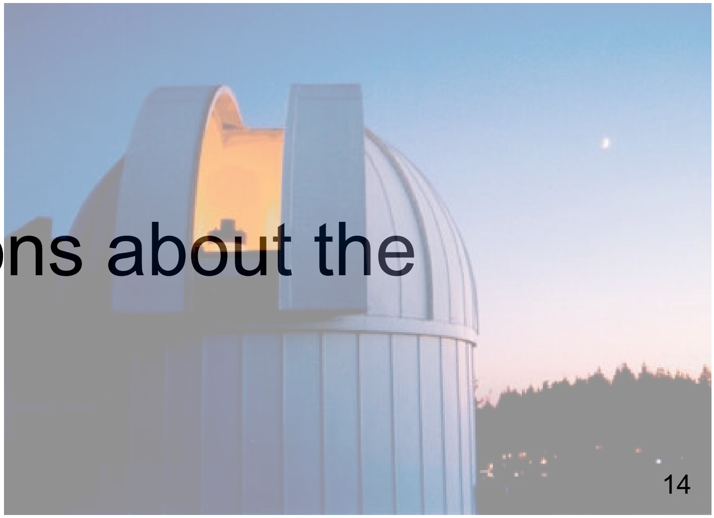
- In 1897, JJ Thomson discovered the negatively charged particle called electron
- Constituent of the (neutral) atom
  - atom must have something positively charged to offset
- Theory: blob of positive charge where electrons are embedded
  - This is our **hypothesis**
- Rutherford experiment: test it!
- But: how do you test it?
  - Can't use a ruler: too small
  - *Indirect* measurement



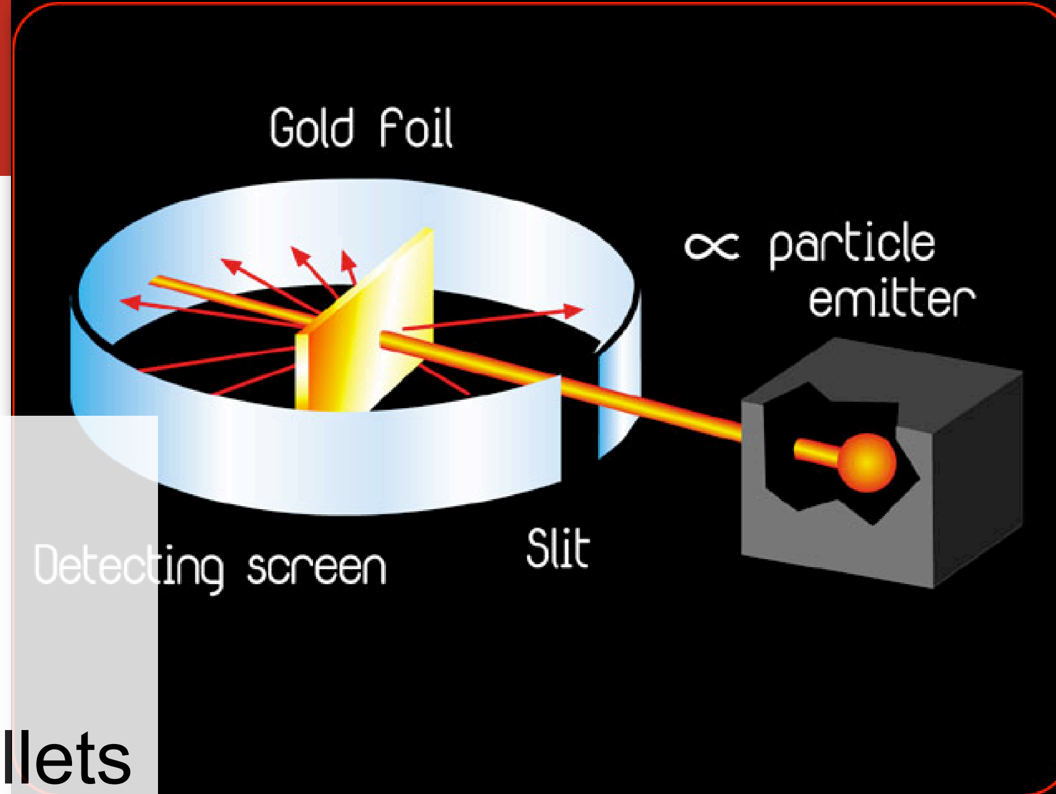


Indirect Measurement

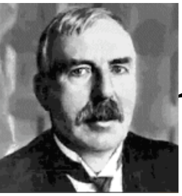
- In everyday life, we learn about things by holding them and looking at them with our eyes
- What if they are too small?
- We need *indirect measurements* to tell us
- Some tools are familiar:
  - microscopes, telescopes
- Others, less so
- All of them let you draw conclusions about the object that you are measuring



Rutherford experiment



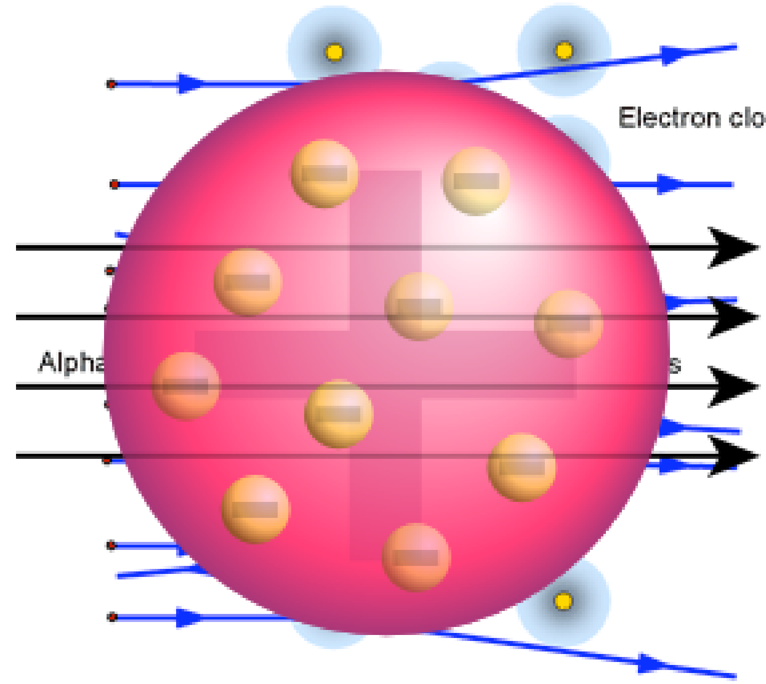
- measure properties of atoms indirectly
- thin gold foil: target
- alpha particles: little bullets
- shoot “bullets” at target and see what happens
- see how bullets deflect to draw conclusions about target
  - that is, alpha path deflection tells us about atomic structure
- Expectation: most of them go right through the foil, just deflected a little bit by the diffuse charge



"It was almost as incredible as if you fired a fifteen-inch shell at a piece of tissue paper and it came back and hit you..."

Experimental Results

- Most of the data was just as expected: alphas "bullets" went straight through
- Some, however, were deflected right back!
- Model was wrong: most of the charge was spread in small area, the nucleus



Hypothesis is wrong!

- No “plum pudding”
  - positive charge focused in small area in center of nucleus
  - Early hint to revolution: Quantum Mechanics
    - Transistor, computer, www...

New theories must always be able to accommodate all the old data, too

  - Clearly it needs to change
  - Don’t throw it all out
    - Model correctly predicted much of the results
    - Our new theory needs to still work for everything that lead us to suggest it in the first place

Classroom activity: Modeling Rutherford's Experiment

- Hidden flat shape to model atom
  - Three shapes: triangle, circle, rectangle
- Marbles to model alpha particles
  - Roll marbles against the hidden object
- Observe the deflected paths
  - What can they tell us about the shapes?
- Draw conclusions

Hypothesis

Systematic Observation

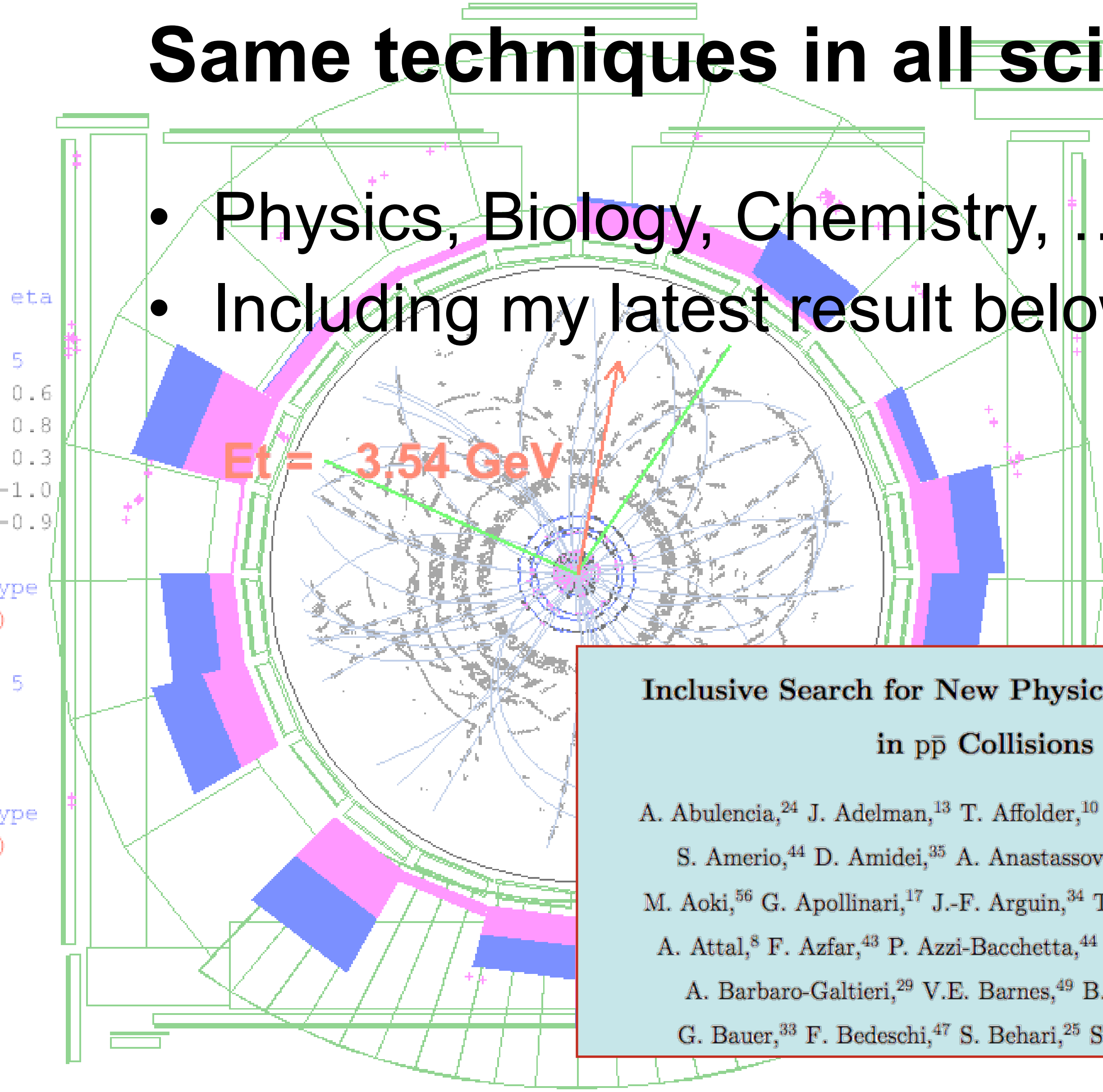
Test Hypothesis

We've done an experiment

- All the steps of our scientific method
- We learned that in science we have to
  - Formulate a hypothesis
  - Design an experiment to test it
  - Compare our data to the hypothesis
  - Rinse and repeat as necessary
- These are the steps of all measurements

Same techniques in all sciences

- Physics, Biology, Chemistry, …
- Including my latest result below!

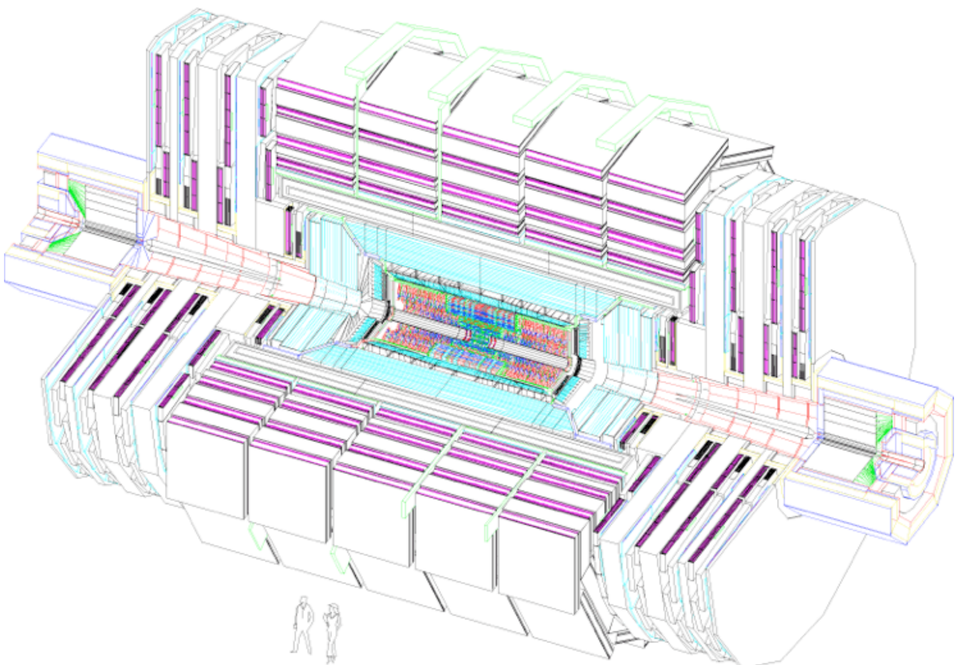


Inclusive Search for New Physics with Like-Sign Dilepton Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

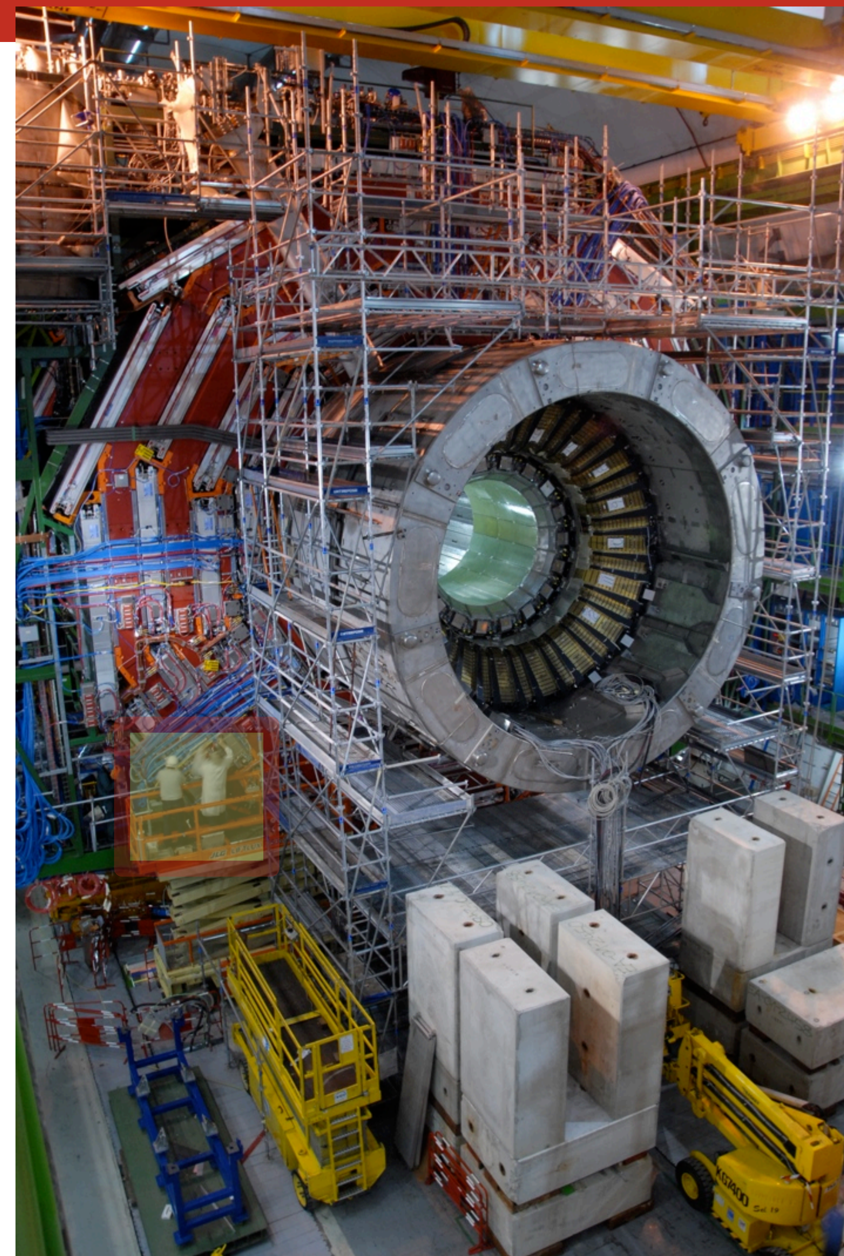
A. Abulencia,[24] J. Adelman,[13] T. Affolder,[10] T. Akimoto,[56] M.G. Albrow,[17] D. Ambrose,[17] S. Amerio,[44] D. Amidei,[35] A. Anastassov,[53] K. Anikeev,[17] A. Annovi,[19] J. Antos,[14] M. Aoki,[56] G. Apollinari,[17] J.-F. Arguin,[34] T. Arisawa,[58] A. Artikov,[15] W. Ashmanskas,[17] A. Attal,[8] F. Azfar,[43] P. Azzi-Bacchetta,[44] P. Azzurri,[47] N. Bacchetta,[44] W. Badgett,[17] A. Barbaro-Galtieri,[29] V.E. Barnes,[49] B.A. Barnett,[25] S. Baroiant,[7] V. Bartsch,[31] G. Bauer,[33] F. Bedeschi,[47] S. Behari,[25] S. Belforte,[55] G. Bellettini,[47] J. Bellinger,[60]

Modern Rutherford experiment

- My research: modern Rutherford's experiment
- Everything is indirect

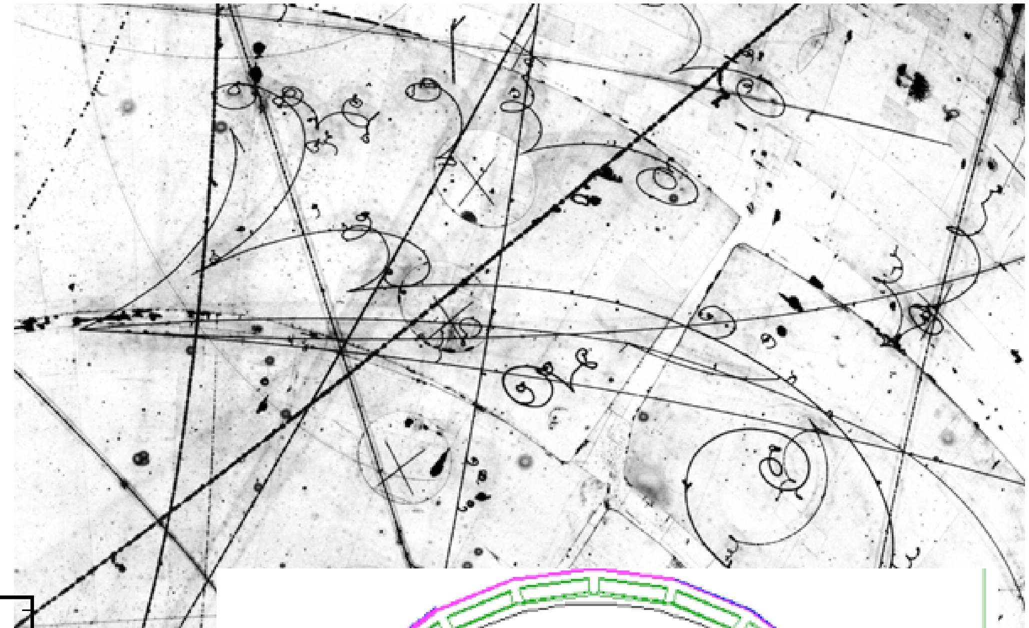


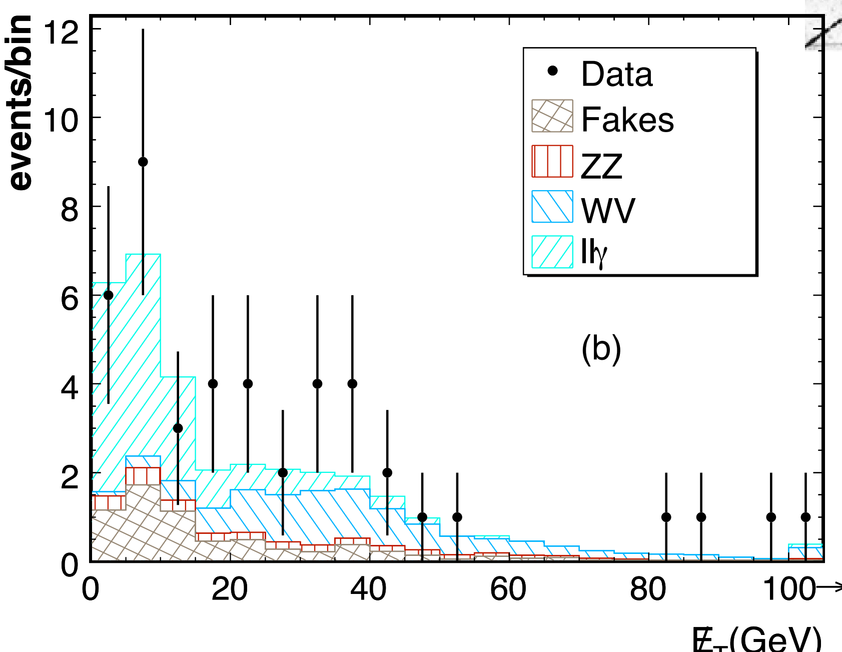
Compact Muon Solenoid

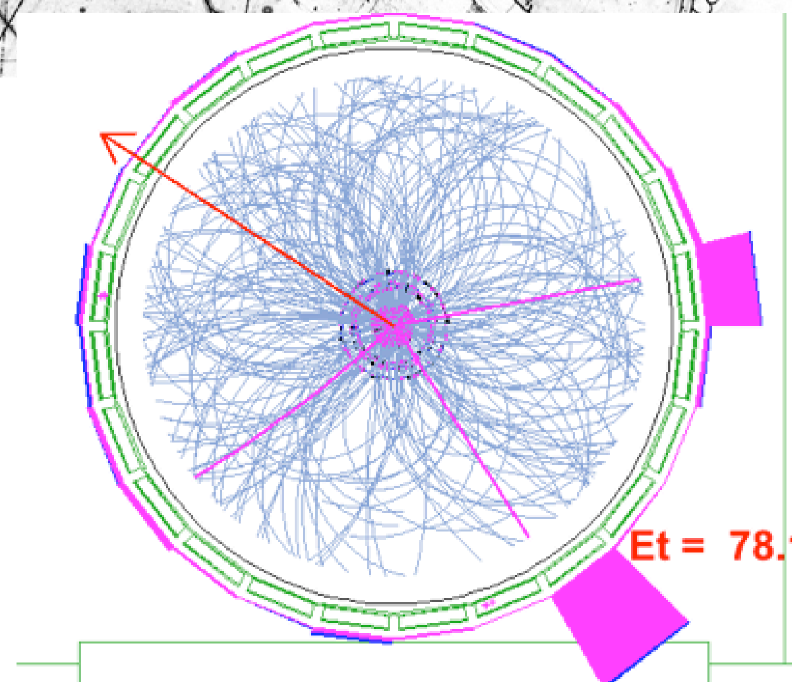


Equivalent of marks of tracks

- We count and look at many marble rolls at once
  - (40 million a second for years!)

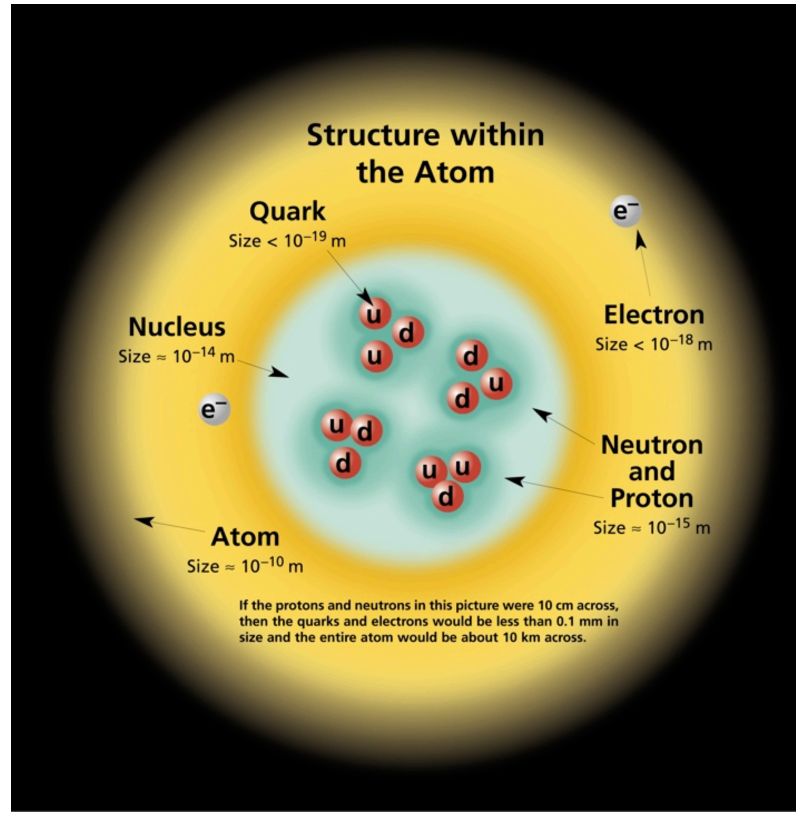






Pushing sizes to next level

- Smaller and smaller scales, more of nature's mysteries
- now two more layers of onion unveiled - we think we are close!



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

In conclusion

- Thinking scientifically is a process that is useful for scientists and non-scientists alike
- Ability to tackle problems with this toolset is among the keys to success in our innovation economy
  - Gathering Storm, Support from Tech Industry
- You are the front-lines and I hope we can support you in bringing more kids to us to do science!

Reproducibility, Peer Review, Publication

- A result that can't be duplicated will not be believed
  - When you discover something cool, others will do it to
- Science thrives on peer review
  - Ask your colleagues to check your results
- Publish your results
  - Currency of science is sharing your results with others
  - Science is by nature international and crosses many boundaries
- CERN as first pan-European institution after WW2

Backup slides

Scientific method in detail

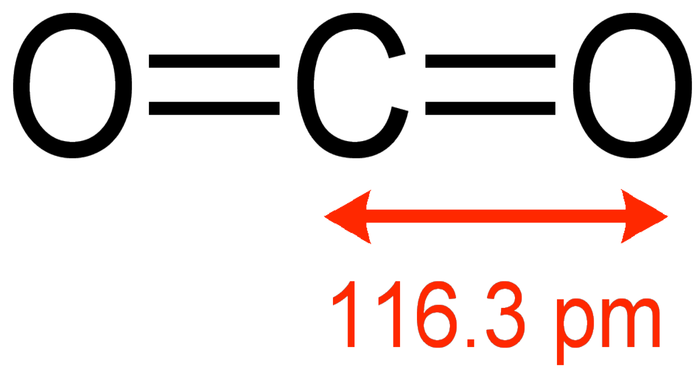
- Define the question
- Gather information and resources
- Form hypothesis
- Perform experiment and collect data
- Analyze data
- Interpret data and draw conclusions that serve as a starting point for new hypotheses
- Publish results

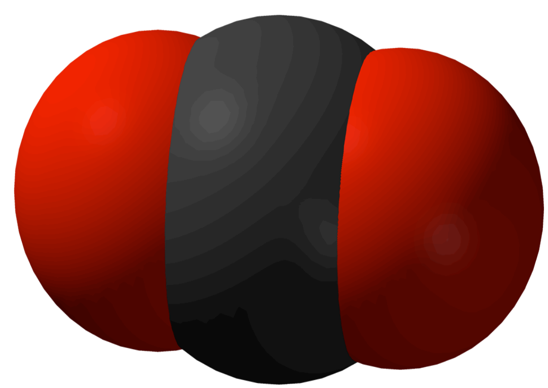
Let's do an experiment right now!

- Let's look at the melting of CO2 as if we were exploring the science of phase transitions
  - Transitions btw states of matter (solid, liquid, gaseous)
- This exercise will allow us to view many important parts of the scientific process on a small scale

Dry Ice Properties

- Solid form of CO_2 - carbon dioxide
- CO_2 exists in plant cycles (photosynthesis), in the body (carried in blood), produced in industrial processes
  - (burning - Global warming!)





Phase transitions: heat a solid

- What happens when you heat a solid?
- Basis for our understanding: H_2O
  - Ice turns to water when heated past 0°C (32°F)
- Hypothesis:

  All solids turn to liquid when they melt
- Experiment: observe melting in H_2O and in CO_2 (dry ice)

  ✓Observe
  ✓Formulate a hypothesis

Hypothesis is wrong!

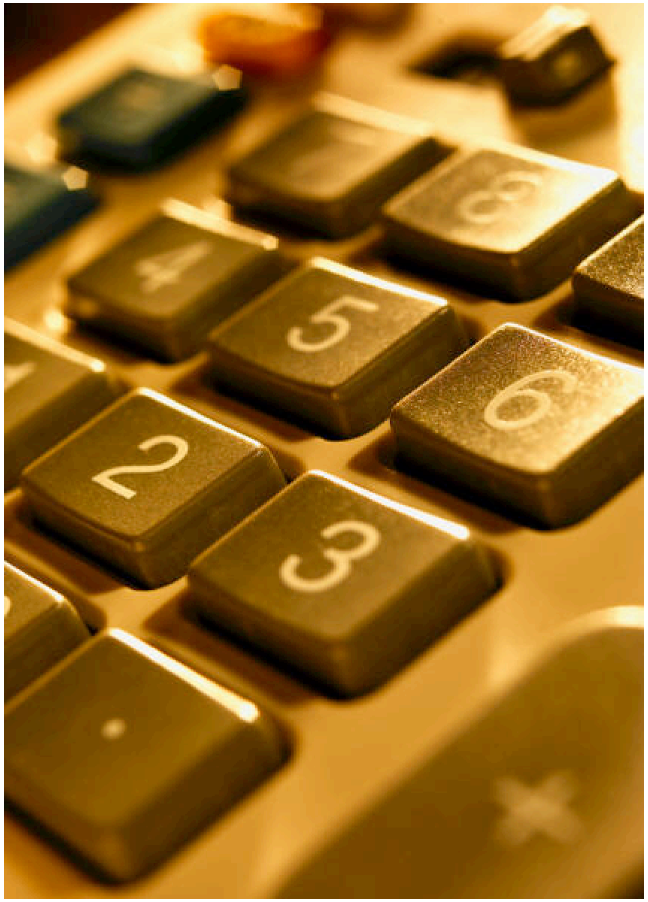
- Our dry ice did not turn into a liquid!
  - No melting: sublimation (direct transformation from solid to gaseous state.)
- What happens to our hypothesis?
  - Clearly it needs to change
  - Don't throw it all out

New theories must always be able to accommodate all the old data, too

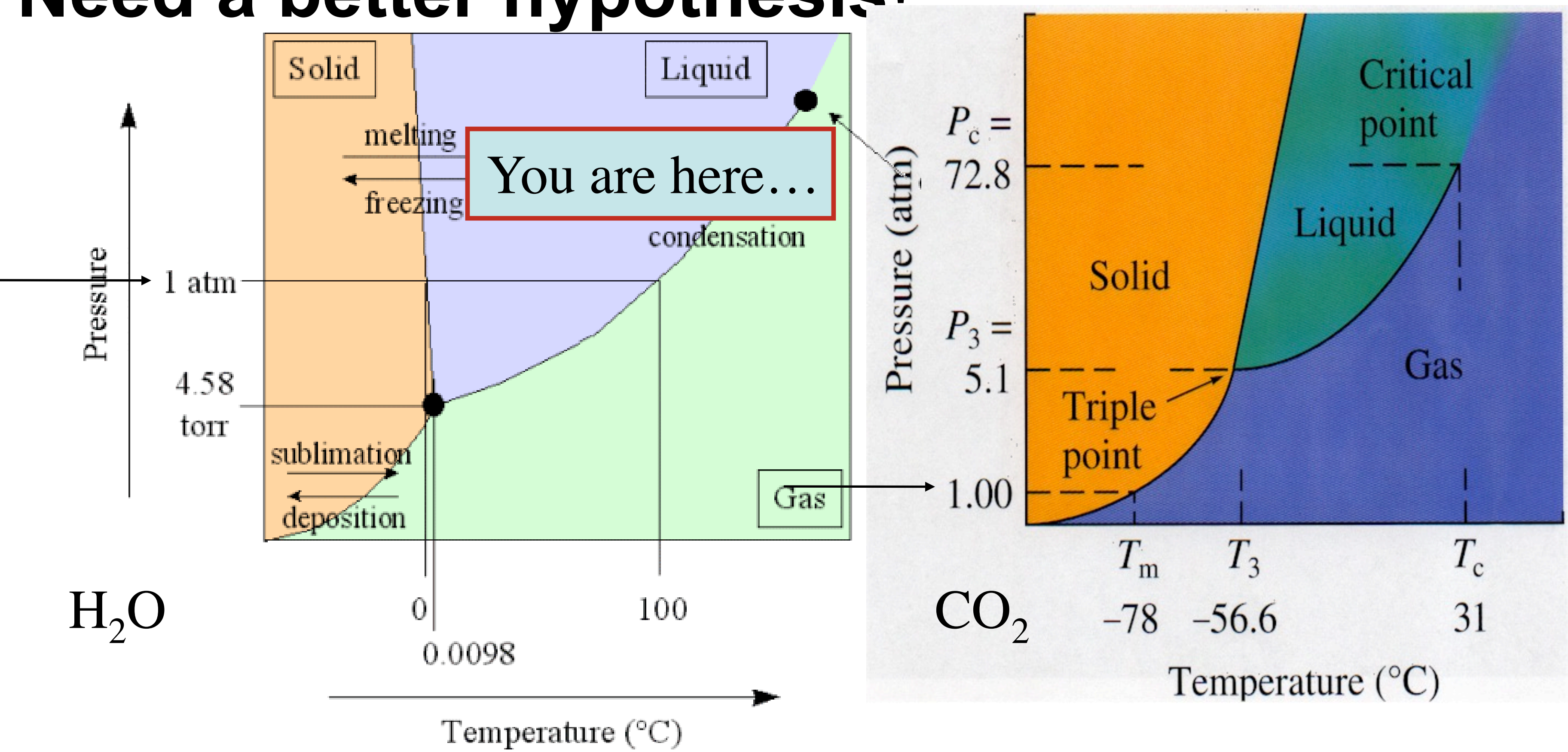
    - Our new theory needs to still work for everything that lead us to suggest it in the first place

Evaluate the data: No liquid CO_2!

- Our experiment finds that dry ice changes from solid to gas directly
  - Sublimation
- Our theory has been disproven
  - Prediction was made
  - We took some data
  - We compared data to prediction and found disagreement
- What now?
  - Refine our prediction
  - Our new theory better still work for H_2O



Need a better hypothesis!



- We realize that we to adapt our hypothesis
  - Add an additional variable, the pressure
- At 1 atm, CO_2 goes straight from the solid phase to the gas phase
  - Water does not!