Science: The Good, the Bad, and the Ugly

Eric Prebys
Professor, Dept. of Physics and Astronomy
Director, Crocker Nuclear Laboratory

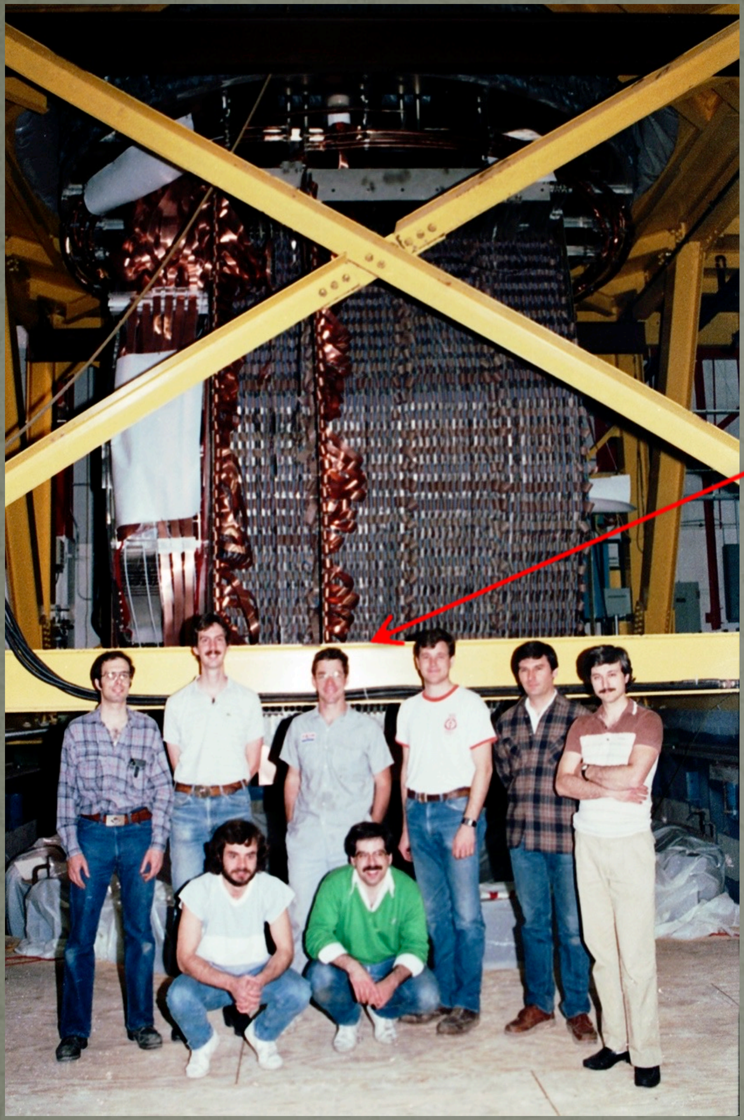
My Background

- 1984: BS in Engineering Physics, University of Arizona
  - Got a job in an HEP group after being fired from a gas station.
- 1984-1990: Grad Student, University of Rochester
  - PhD topic: Direct Photon Production in Hadronic Interactions
- 1990-1992: CERN Fellow, CERN
  - Studied e+e- reactions on the OPAL Experiment at LEP
- 1992-2001: Postdoc and Assistant Professor, Princeton U.
  - GEM Experiment at the Superconducting Super Collider
  - Belle CP Violation Experiment at KEK, Japan
  - Nonlinear QED in E-144 Experiment at SLAC
- 2001-2017: Scientist, Fermilab
  - MiniBooNE short baseline neutrino oscillation experiment
  - Proton Source Department Head
  - Director of LHC Accelerator Research Program (LARP)
  - Mu2e rare muon conversion experiment
  - Created Lee Teng Internship and ran it for 10 years
- 2017-present, Professor, UC Davis
  - Mu2e
  - Director, Crocker Nuclear Laboratory (cyclotron)

Experimental HEP

Accelerator Physics and HEP

Nuclear Physics
Medical Physics



Fermilab E-706 Rochester Group
~1987

“Buck’s River Road Exxon”

Me

Kwan Lai, the guy that hired me

Then

Recent

Why I'm Teaching This Course

- I've always been interested in outreach.
- I've always been frustrated with the level of ignorance about (and sometimes hostility toward) science.
- Studying bad science is often a good way to help understand good science.
  - I would not recommend this in other fields, e.g. brain surgery.
- Like many in science, I take public money, so I feel I have a responsibility to advise others of questionable results reported in the popular media, or even in scientific journals
  - i.e. give your opinion whether they want it or not

Goals of this Course

- Give students an understanding of what is and isn't science.
- Gain a basic understanding of errors and significance!
  - Misunderstanding the significance of results is one of the biggest problems in the media and the public
- Learn some of the warning signs of bad science.
  - Good science turning bad
  - Good science that's incorrectly reported.
  - Deliberate fraud
- Learn some ways to improve your understanding
  - Accept that you can be fooled.

Lectures

- 9/24: Introduction and Goals
- 10/1 The Good: Enlightened by Light
- 10/8: Lies, Damned Lies, and Statistics
- 10/15: Energy: No Such Thing as a Free Lunch
- 10/22: Bad Medicine
- 10/29: Criminally Bad Forensic Science
- 11/5: “Science” or Just Racism?
- 11/12: Satanic Panic and other Dangerously Bad Science
- 11/19: Spooky Bad Paranormal Studies
- 11/26: The Media and Science: Friends or Foes?
- 12/3: Science and Politics are a Dangerous Mixture

Grading

- This course will be graded Pass/Fail
  - I don't feel obligated to fail anyone, but..
- It's an interactive course, so attendance is mandatory
  - No more than two unexcused absences to pass!
- In lieu of a midterm, you will write a short paper going into depth on one example of a erroneous scientific result.
- The in class final will present a number of experimental scenarios, and you'll be asked to identify potential sources of bias in the protocols and/or suggest improvements.
- Grading
  - Class participation: 40%
  - Midterm paper: 30%
  - Final: 30%

Scope of The Course

- For the most part, we're going to restrict ourselves to things that bear some resemblance to "good" science.
  - In many cases, things that were taken very seriously by the scientific community.
- Except for the occasional comic relief, we'll steer clear of truly crazy stuff
  - Flat Earth
  - Moon Landing Hoax
  - Hollow Earth
  - Velikovsky

Definitions…

- The Good:
  - Make observations and measurements
  - Develop a model to explain these with the fewest possible variables and assumptions (must also be consistent with all existing data).
  - Investigate the predictions and consequences of this model.
- The Bad We'll spend most of our time on this
  - Like good science in principle, but lack of rigor and/or bias (intentional or unintentional) lead to erroneous conclusions.
  - Whether accidental or intentional, it can have grave consequences.
- The Ugly
  - Propose theories or claim experimental results which cannot possibly be reconciled with significant body of real world data.
  - Can be the product of profound ignorance or deliberate fraud.
  - Aka "Crackpot Science", "Voodoo Science", etc

How Scientific Discovery Works

- Broadly speaking, science advances in two ways:
  - Experiment driven:
    - A completely unexpected and surprising observation is made.
    - A new theory or theoretical modification must be proposed to explain it
    - Examples:
      - Superconductivity
      - Parity and charge-parity violation
      - Mossbauer Effect
    - The new theory then becomes the input for…
  - Theory driven:
    - A theory is proposed that is consistent with current empirical observations
    - Additional experiments are carried out to either confirm or refute the additional predictions of the the theory.
    - Examples:
      - Failed
        - Ether wind (Michelson-Morley Experiment)
        - Cold fusion (MUCH more about this in a few lectures)
      - Successful:
        - Discovery of Neptune
        - Antimatter
        - Several quarks
        - W, Z, and Higgs particles

Science: Myth vs. Reality

- Myth

- Independent
- Maverick
- Makes lots of important discoveries in career
- Results come quickly

- Reality

- Systematic and meticulous
- Often work in large groups
- Results take time!!
- One significant discover y = Nobel Prize!

Society loves this… … but benefits from this

Science vs. Technology

- It's very important to make a distinction between "science" and "technology"
  - "Science" is how we learn the fundamental rules of nature
  - "Technology" is the application of these rules.
- Science and technology are closely intertwined, but they are still distinct.
  - New science enables new technology
  - New technology gives us the tools to push the boundaries of science.
- Although we live in a time of amazing technological advances, fundamental scientific advances are still few and far between.

Incorrect Results in Science

- There have been cases of intentional fraud in science
  - Piltdown Man
  - Andrew Wakefield linking vaccines to autism (we're still suffering from this)
  - Jaques Benveniste's seeming confirmation of homeopathy ("water with memory") was probably fraud by an overzealous lab tech.

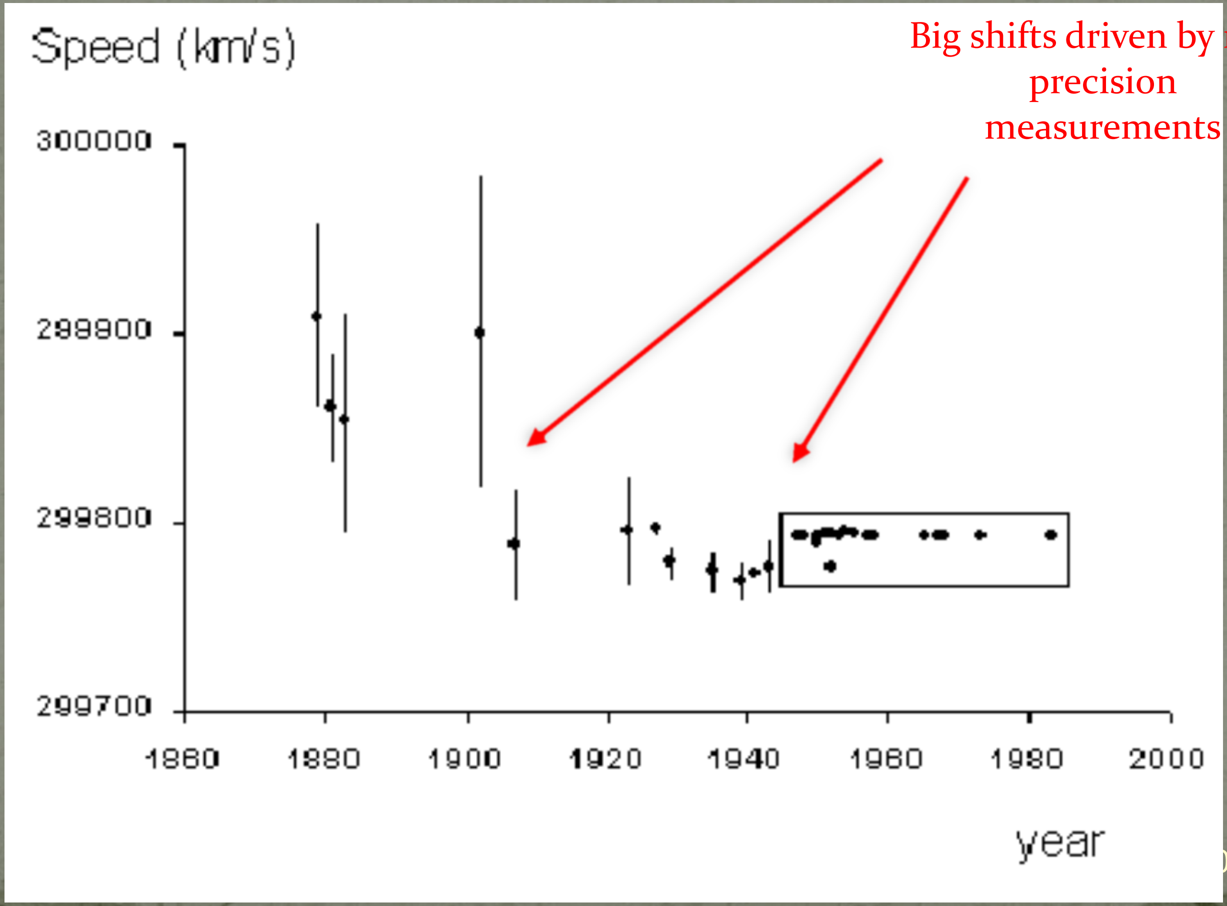
  but these are fairly rare (and usually involve things that are potentially profitable!)
- On the other hand, there have been many cases of inaccurate results in science, based on some combination of sloppy analysis, experimental bias, wishful thinking, and occasionally willful self-deception.
  - or at least that's how it starts (e.g. Cold Fusion)
- Procedural remedies to mitigate these problems were fairly long in coming
  - For example, blind analyses were not standard in many fields of physics until the mid to late 1990s.

The Importance of Blinding

- Even with the best intentions, people are susceptible to biases.
- Knowing what "answer" we're looking for might subtly affect the sort of things we look for in quality control and cross checks.
- For example, if the model predicts a certain number of events in a signal region:
  - If I see fewer than that, I might be inclined to search for *inefficiencies* in my detector or analysis cuts.
  - If I see more than that, I might be more inclined to search for *backgrounds* or other false positives.
  - In reality, I could have both of these things and preferentially searching for one or the other could bias my result.
- Blinding procedures in physics started to become common in the mid-1990s and have now become expected.
  - There would be little confidence in a discovery today that didn't come from a blind analysis.

Evidence of Bias

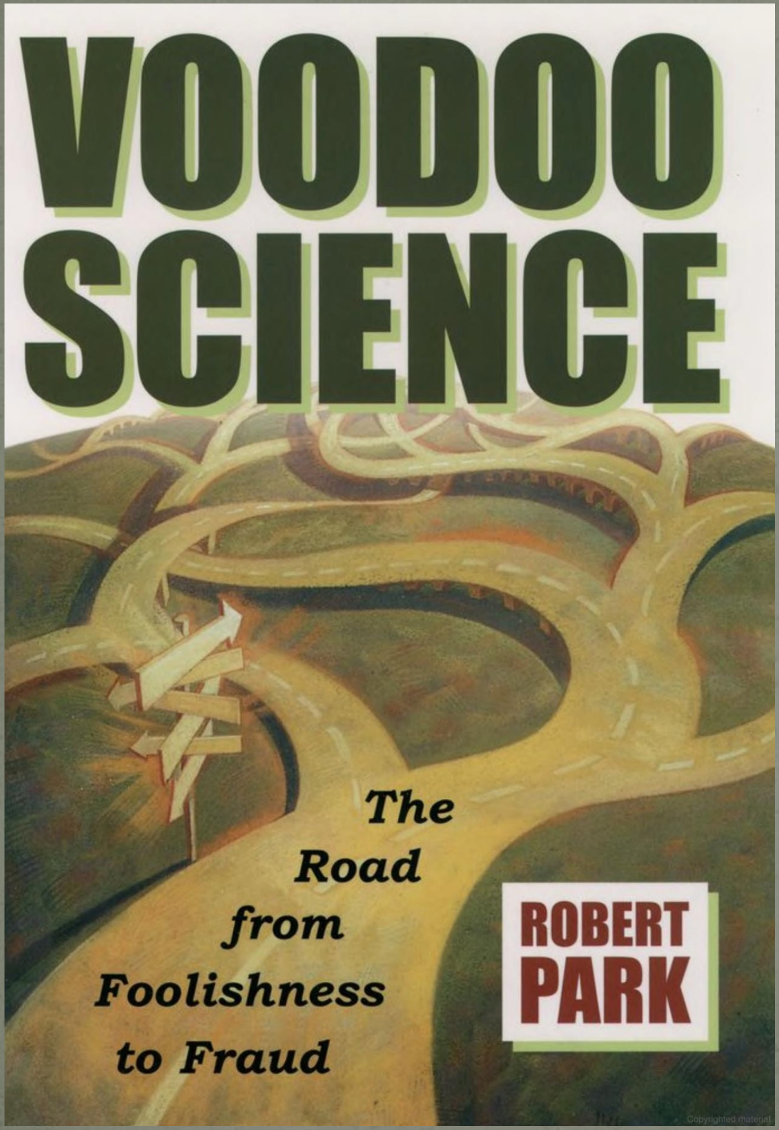
- Without blinding, results have a habit of tracking either predictions or previous results.
- Example: speed of light



What does Double Blind Mean?

- In experiments involving people, you have the possibility of bias both on the part of the researcher AND the subject.
- For example, in a drug trail:
  - The patient should not know whether they are getting the drug or the placebo.
  - The person evaluating the effect of the drug should also not know.
  - The information as to who got the drug and who got the placebo should only be released after the evaluation of the effects has been made.
- Sometimes this is much harder than others.

Course Text



- Bob Park was a University of Maryland Professor to covered science and science policy in Washington DC for the APS for many years.
- He published a weekly newsletter, which many of us were addicted to in the early days of the internet. It included the famous disclaimer
  - "These are not necessarily the views of the APS, but they should be."
- This book is a fantastic resource for understanding what is and isn't science.
- It's also short, which I like in a book.

Bob's Seven Indicators of Voodoo Science

1. The discoverer pitches the claim directly to the media.
2. The discoverer says that a powerful establishment is trying to suppress his or her work.

We'll see these again and again

3. The scientific effect involved is always at the very limit of detection.
4. Evidence for a discovery is anecdotal.
5. The discoverer says a belief is credible because it has endured for centuries.
6. The discoverer has worked in isolation.
7. The discoverer must propose new laws of nature to explain an observation.

I'll add an 8th:

8. Discovery relies on "special skills" on the part of the observer, which brings us to…

Example: N-Rays

- In 1903, French scientist René Blondot claimed that some type of ray emanating from an X-ray tube or other sources caused slight changes in brightness in a spark gap or flame.
  - The changes were very slight. You had to be "trained" to see them.
  - He called these rays "N-Rays" after the University of Nancy, where he worked.
- In the next few years *over 300 papers by 120 scientists* confirmed the existence of N-rays and measured diffraction and scattering spectra off of different materials.
- In 1904, American physicist Ron Wood visited Blondot's lab. He surreptitiously removed the scattering target, but Blondot continued to "see" the diffraction spectrum.
- The whole thing had been completely imaginary!

Other Good Texts…

- Martin Gardner, "Fads and Fallacies in the Name of Science"
  - Similar to Park's Book, with more in-depth coverage of a limited number of topics.
- Stephen J. Gould, "The Mismeasure of Man"
  - History of bad science in support of racism
- Richard Harris, "Rigor Mortis: How Sloppy Science Creates Worthless Cures, Crushes Hope, and Wastes Billions"
  - A disturbing book about some of the serious issues in medical research
- Ray Hyman, "The Illusive Quarry: A Scientific Appraisal of Psychical Research
  - An analysis of some of the sincere - but deeply flawed - paranormal research that went in the the late 20th century

Defense of "fringe" science

- It's important to distinguish "crackpot science" from" fringe science"
- "Fringe science" is science that involves measurements or theories which are extremely difficult to reconcile with the prevailing theoretical framework but *are nevertheless not yet ruled out experimentally.*
  - Fringe science is not only legitimate but vital.
- Many accepted theories were once "fringe"
  - Plate tectonics
  - Theory of relativity
  - Quantum mechanics
  - Expanding universe
- Some examples of current fringe experiments include
  - Search for tachyons
  - Gravitational mass of antimatter
- Unfortunately, unless care is taken, fringe science can easily become crackpot science…

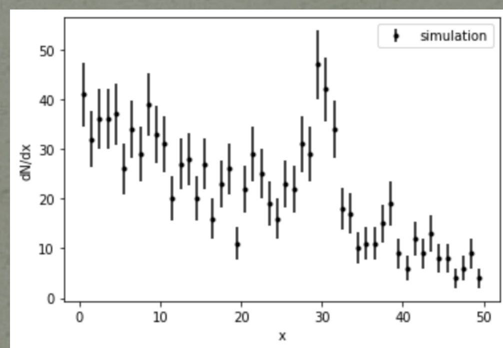
Some Things to Remember

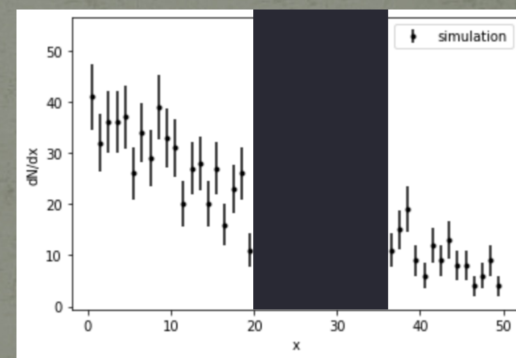
- The media love a story and are generally terrible at covering science.
  - ALWAYS read the original source.
  - More often that not, it bears little relation to the news story.
- Be on the lookout for "weasel words"
  - e.g. "The data suggest" = "We needed to publish something even though we can't draw a solid conclusion".
- The plural of "anecdote" is not "evidence"
  - Personal experience make good news stories, but there are of little value in determining causality.
- Look for consistency
  - Example:
    - One study of powerlines found a weak correlation with leukemia and no correlation with brain tumors.
    - Another found a weak correlation with brain tumors and no correlation with leukemia
    - In fact, this weakened the statistical significance of BOTH, but it was reported as "data suggest powerlines cause leukemia AND brain tumors".

Backup Slides

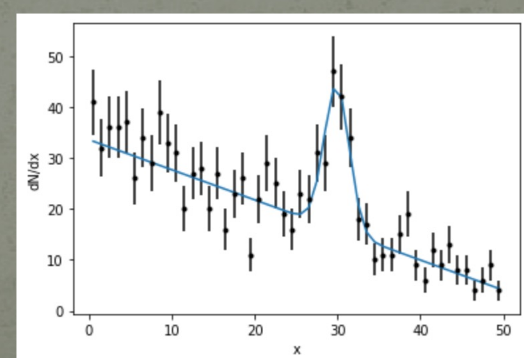
Blinding Techniques

- It takes a lot of confidence to do a blind analysis!
- You need to somehow gain confidence in your measurements without looking in the signal region
- Sometimes it's pretty easy.
- To use our example from lecture, if I'm looking for a resonance on top of a spectrum, I simply exclude the region of the resonance and use the other events to estimate the background.



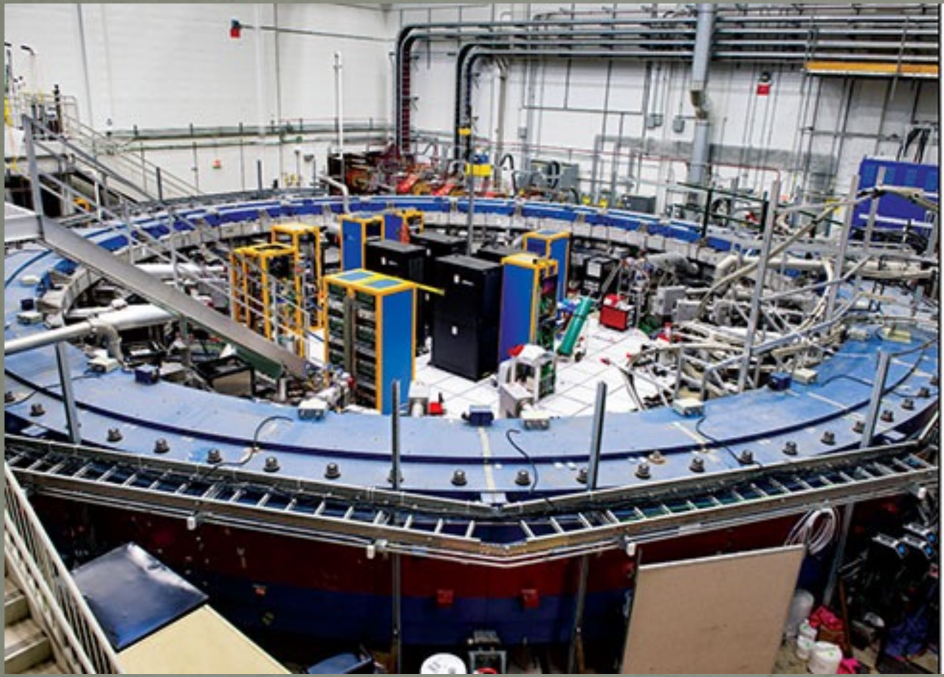


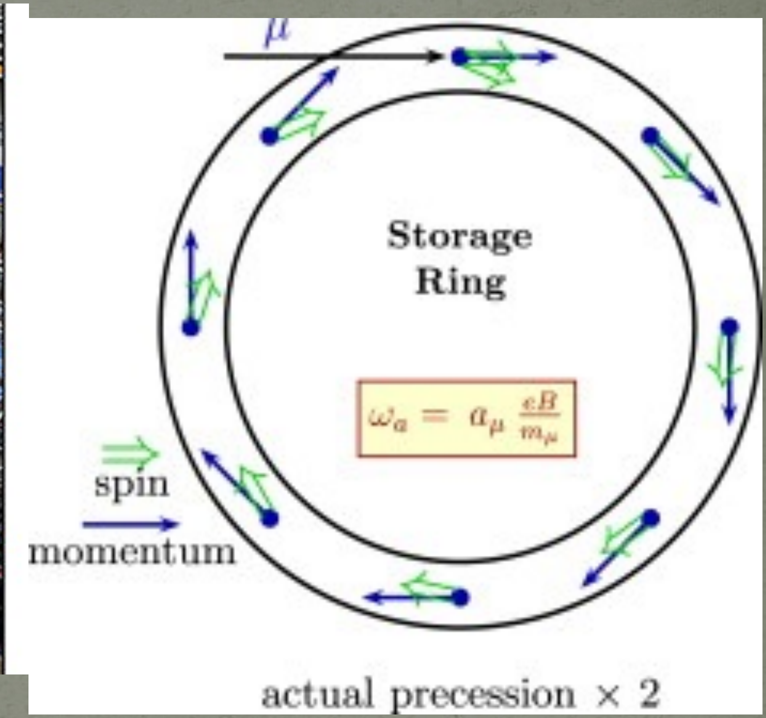
- Once I'm confident in my understanding of my backgrounds and efficiencies, I "open the box" (often with great ceremony) and do the final fit.
- Then publish the result *no matter what it is*!



Another Easy Example: Muon g-2*

- The "g-2" experiment at Fermilab looks for new physics by precisely measuring the precession of muons in a magnetic field.

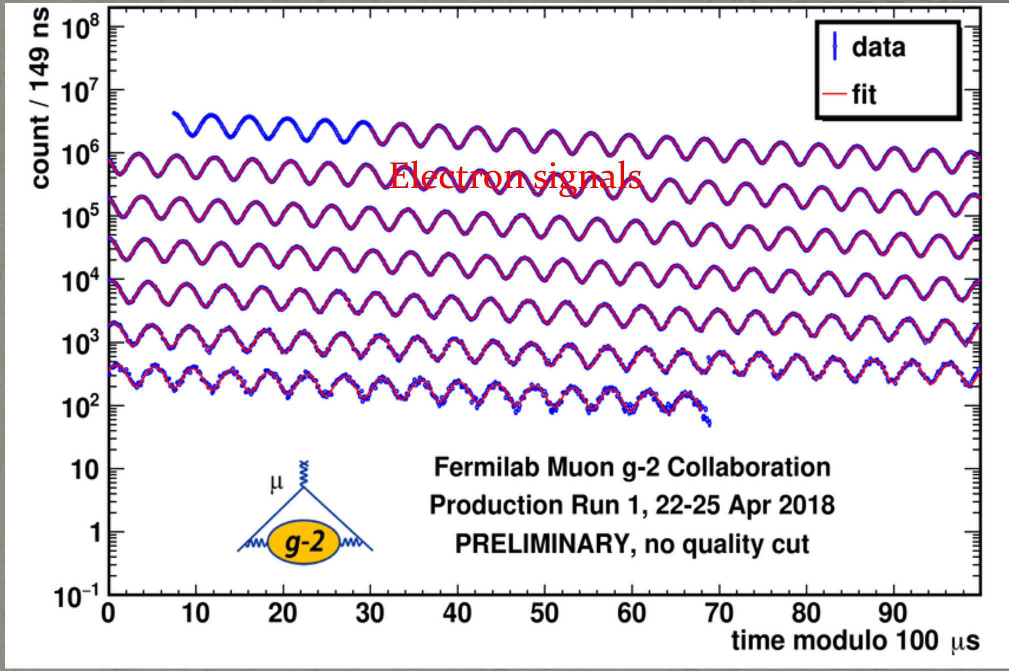




*the blinding is easy. The experiment's hard as hell!

The result

- To first order (g=2), the precession frequency is ” and as the revolution frequencies
- Higher order corrections cause a “beating” that directly measures the difference (g-0)
  - The muons are highly polarized along their direction of motion when they enter the ring
  - As they decay to an electron and a neutrino, the electron is preferentially along the direction of spin.
  - The frequency of this plot is a direct measure of the anomalous moment.



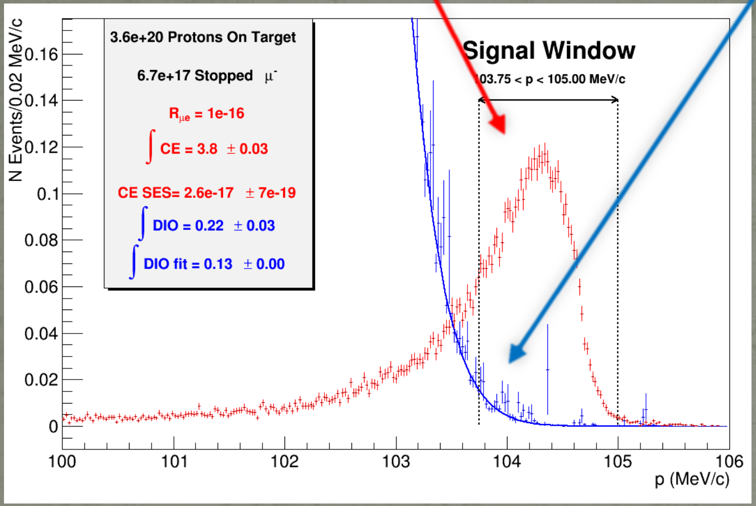
- How did they blind it?
  - The entire analysis was done using an arbitrary time unit.
  - The conversion factor to μs was kept “secret”, and not revealed until they had performed all quality control checks and were confident in their results.

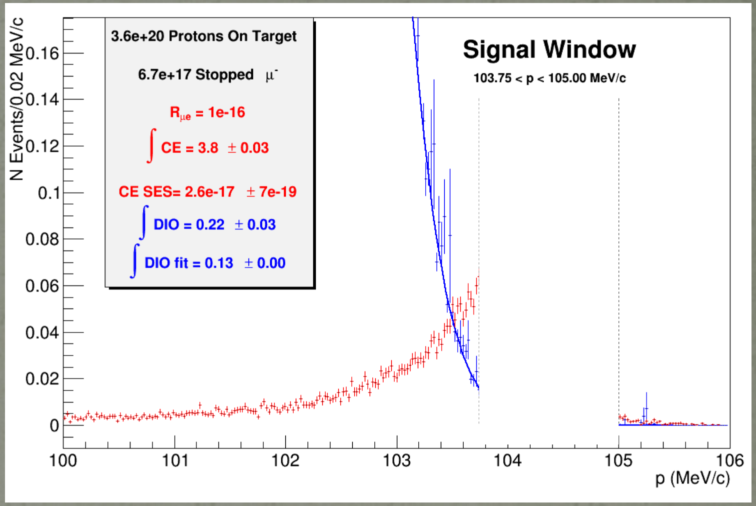
Sometimes it's Harder

- In the Mu2e Experiment at Fermilab, the signal region is at the end of the background spectrum.

Statistically enhanced signal region. We want to be able to claim a signal with just a few

Can we really gain confidence in this background region by just looking at one side?





- Also, once you've opened the box, how do you deal with additional data?
- Determining the blinding procedures for an experiment are one of the most important parts of the analysis.