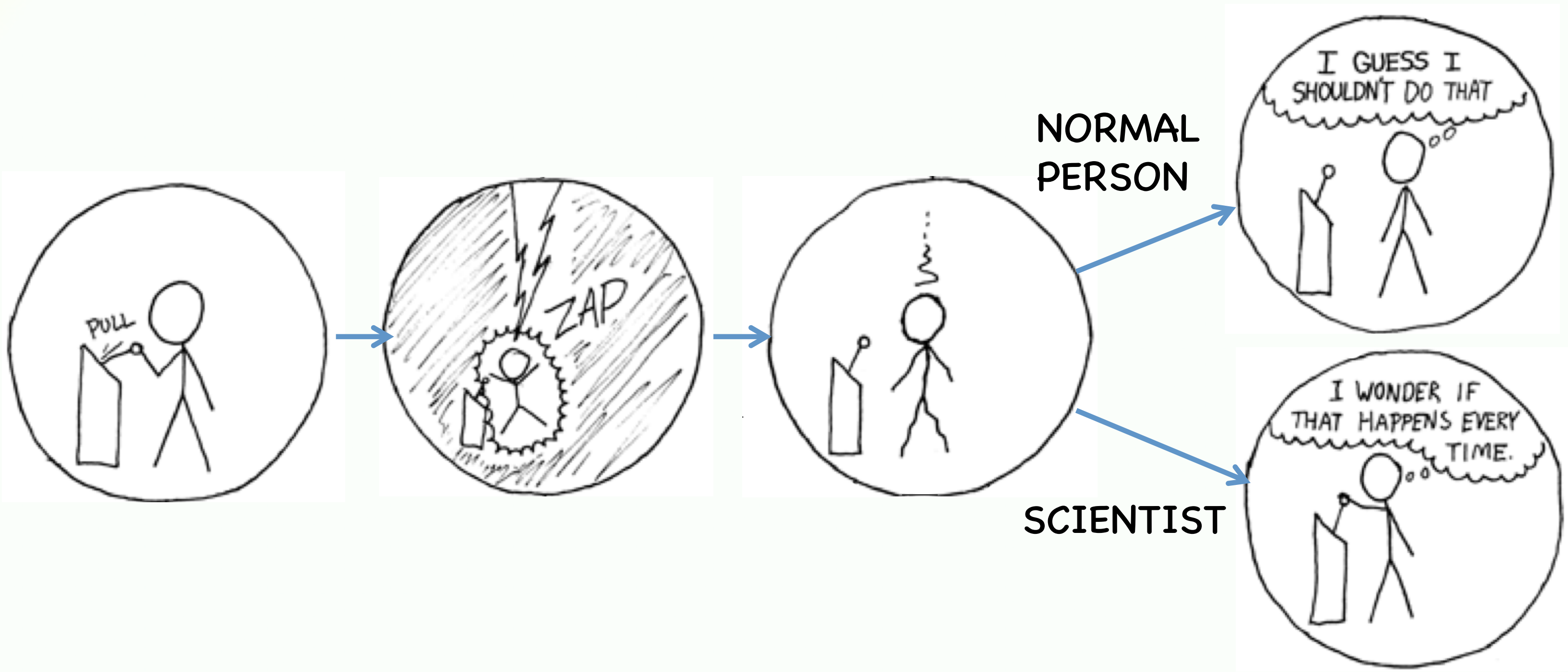
The Difference



Advanced Physics Lab

Introduction

PHY 327/424

- Welcome, Goals, People, Safety 9:10
- How to succeed in the APL 10:10
- Analysis and Uncertainty 11:10

What is the Point of the Advanced Lab?

To help you learn all physics not taught in other courses.

What is the Point of the Advanced Lab?

- How to measure and model physical systems, and communicate that knowledge.
  - Physics is an experimental science that tries to describe, understand, and predict the behaviour of physical systems.
  - Our goal is to help you better understand the methods and myriad challenges of making such measurements and judging whether relevant physical theories are consistent with your data.

What is learned in the Advanced Lab?

- Instrumentation and methods
  - Oscilloscopes, electronic meters, interferometers, lasers, lock-ins, vacuum, high voltages, cryogenics, spectrometers, X-rays, …
- Physics
  - Classical, Quantum, Mechanics, Optics, Electromagnetism, Nonlinear, Nuclear, Particle, Condensed matter, biophysics, …
- Modelling
- Problem solving
- Analysis
  - Nonlinear fitting with x & y error bars, uncertainty, interpretation, …
- Breadth & Design
  - work on own (mostly)
  - design, decide, measure, analyse, communicate , …
- Communication
  - oral, written
  - informal, formal
  - …
- That science is messy
- …

What is learned in the Advanced Lab?

- Impossible to teach every physics topic or experimental method or other skills that you might need in your career
- We want you to develop your capacity to cope with new situations.

How does the course work?

- **Read the Course Outline!**
- If you don't read and understand the outline, you will likely do less well.
- Ignorance is no excuse.
  - e.g. Don't assume we'll remind you about deadlines; they are in the outline and online.
  - If you don't understand something – ask.

Dates and Deadlines

- In outline and at http://www.physics.utoronto.ca/~phy326/dates.htm
    - Experiment Preference Sheets due 4pm today
    - Start experiments in next lab period
    - Data analysis assignment due 25/26 Sept
    - …
- Let Coordinator know immediately if you notice any issues with the dates.
- Late penalties will be applied unless arrangements made in advance, or you are ill or have other valid excuse.
    - Contact relevant professor ASAP.
- Shelves and slots in MP251 may be used to hand in and return assignments, lab books, formals, ….

Preference Form

Tells us

- who you are
  - e.g. whiteboard name
- how to contact you
- when you will be in the lab
  - and if you would like to switch sections
- which experiments you would like to do
  - Experiments must be with different profs

Due by 4pm today

(or hand in this morning)

Grading Scheme (PHY327/424)

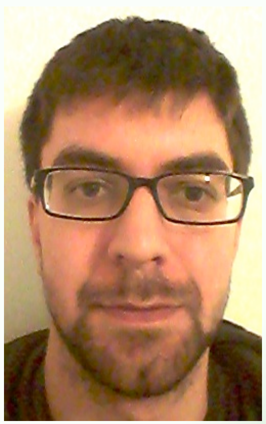
• Data Analysis Project	4 %
• 3 experiments @ 20% each	60 %
• Formal Report and Peer Review	18 %
• Oral exam	18 %


People


http://www.physics.utoronto.ca/~phy326/people.htm









Robert Ivars Smidrovskis

March 22, 1958 - August 14, 2017

This semester, especially the beginning, is going be rocky without Rob.
Some experiments will not work.

IF YOU NEED HELP

- **Look** for (in order) Demo, Professor, Technologist.
- Profs and Demos are only around for about half the lab period, but if you can't find someone, **call** them.
- **Ask** Lab Coordinator.
- Outside regular lab periods, you can still call, but we are less likely to be available.

BUT …

- No one in the lab understands all the experiments.
- If you ask a Professor or Demonstrator a question, the most common answer will be something like
  - "I don't know, let's sit down and see if we can figure it out."

Academic Integrity

Office of Academic Integrity : http://www.artsci.utoronto.ca/osai

Honesty, trust, fairness, respect, and responsibility

- Ignorance is no excuse.
  - All students are expected to be familiar with the University's rules
- The primary product of academia is knowledge, so plagiarism and lying are cardinal sins.
- Always fully attribute and acknowledge!
  - don't forget to acknowledge help in notebook
- Read guidelines, talk to Coordinator if unsure.

Plagiarism in Writing

- Never use sources without attribution.
  - e.g. Improperly copying just one sentence from our write-up into your Formal Report is sufficient for you to face serious sanctions from the Office of the Dean.
- It is better to lose a few marks because of poor writing instead of plagiarising and risking severe punishment.
- Students are caught and punished for plagiarising in the Advanced Lab.

Hazards

- compressed gases
- cutting edges
- cryogenic fluids
- dust
- fire
- flammable liquids
- heat
- heavy metals
- heavy objects
- high voltage
- intense sound
- lasers
- low voltage
- magnetic fields
- radioactivity
- slip and trip
- toxic chemicals
- ultraviolet light
- vacuum
- x-rays
- ...

Safety

- Everyone's responsibility. Staff do their utmost to ensure a safe learning environment, but in the end **it is your skin** (and your colleague's).
- Always assess, consider, and mitigate any potential risks.
- Physics Health and Safety website
  - http://www.physics.utoronto.ca/physics-at-uoft/services/health-and-safety
- All safety related incidents, including close calls, must be reported to lab staff.

Safety Equipment

- You must use safety equipment provided
  - laser glasses, safety goggles, face-shields
  - gloves, ear-protectors, dust masks
  - …
- Sandals are not safe and are not allowed.

- If you think you are missing safety equipment, ask any of the lab staff.

Fire

- Immediately notify lab staff if you smell any burning odour or see smoke.
- In case of fire: leave room, close door, pull alarm, exit building.
- If the fire alarm sounds, you **must** immediately exit the building. Do not use the elevator.
  - Notify the Lab Coordinator at the beginning of the course if you have mobility issues that might prevent you from using the stairs.
  - DO NOT RE-ENTER until authorized by Fire or Police Personnel.

Ionizing Radiation

- Any student using an X-ray machine must wear a radiation dosimeter available from Technologist in MP 250.
- Radioactive sources must be signed out from the Technologist.
- Radioactive sources must never be left unsupervised, and must be returned whenever you leave the lab.

Final safety comments

- Most common unexpected risk is slipping in a puddle from leak or spill.
  - usually water, sometimes oil or particulates
- Don't leave a mess!
- Food and drink are not allowed in the laboratory.
  - May eat or drink in MP251, but clean up.
- No question about safety is silly! Ask if you are unsure about anything.

Emergencies

For immediate medical, fire, or police response,

CALL 911,

then call Campus Police at 416-978-2222.

If in doubt, call.

- Note, from phone in MP251 (or any university phone) call 9-911, then 82222
  - This is McLennan Physics, North wing, 60 St. George Street, room numbers on doors.

Handouts

Questions?

The Way of the Physicist

- Physicists
  - construct mathematical / functional model of a physical system
  - solve the model analytically or computationally
  - make physical measurements of the system
  - compare the measurements with the expectations
  - communicate results with others
  - improve model, calculation, experiment; iterate

How TO SUCCEED IN THE ADVANCED LAB

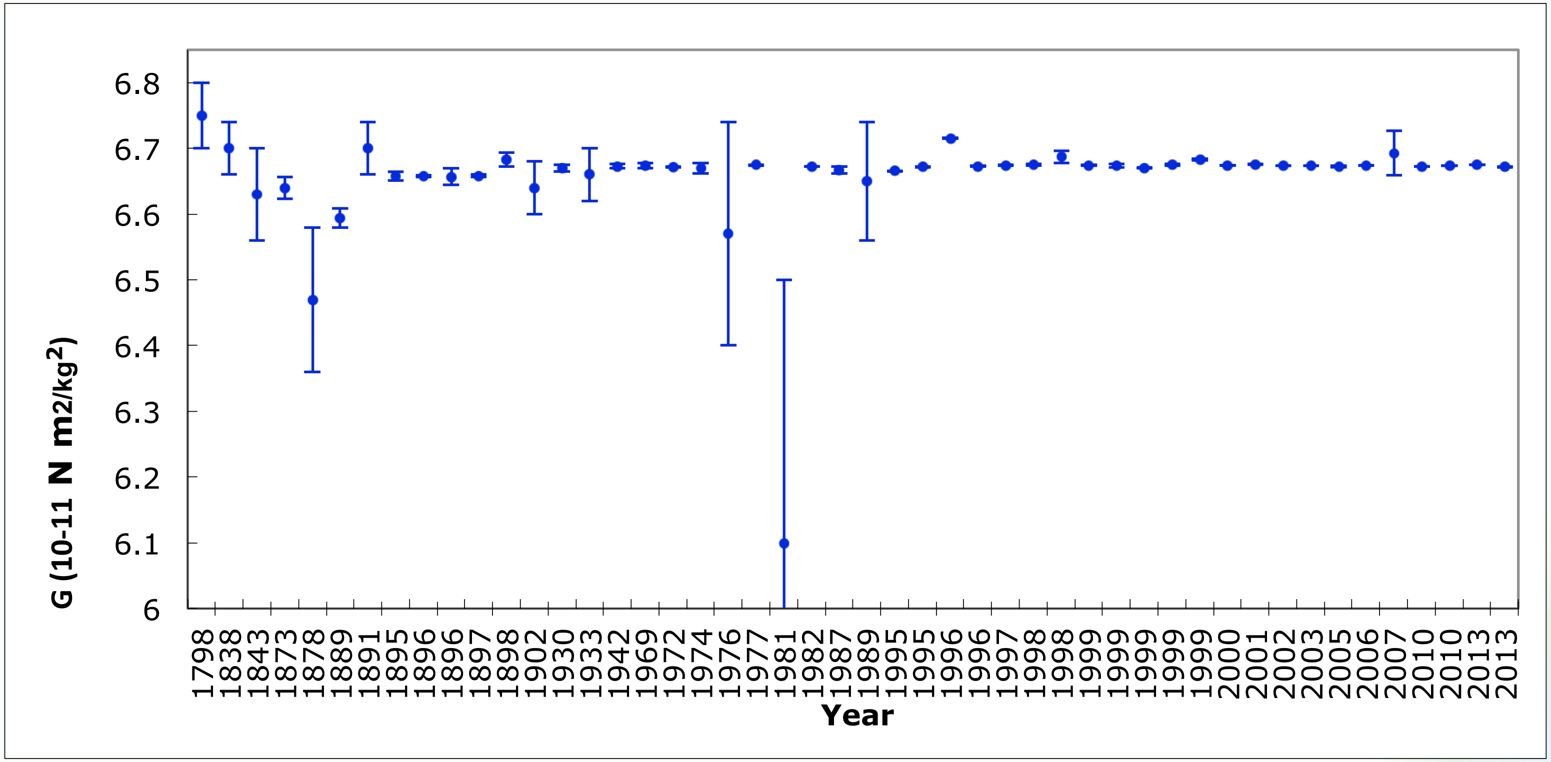
Reminder

The goal of the lab is to improve your ability to measure and model physical systems, and to communicate that knowledge.

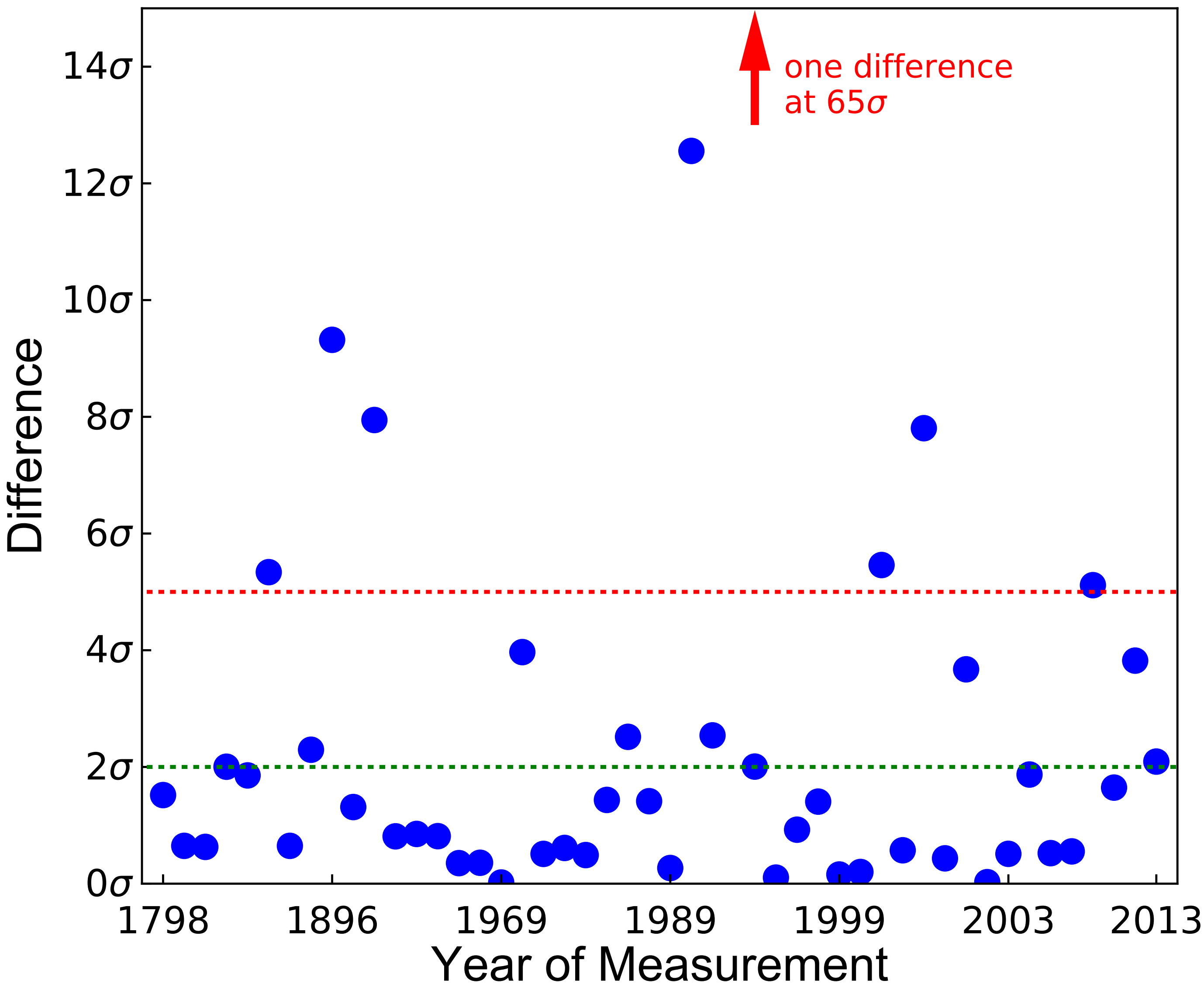
Experiments are tough

- What was the first fundamental constant measured in the lab?
- What is the worst measured fundamental constant?

Newton's Gravitational Constant: G_N



$(G_N - G_{CODATA})/\sigma$



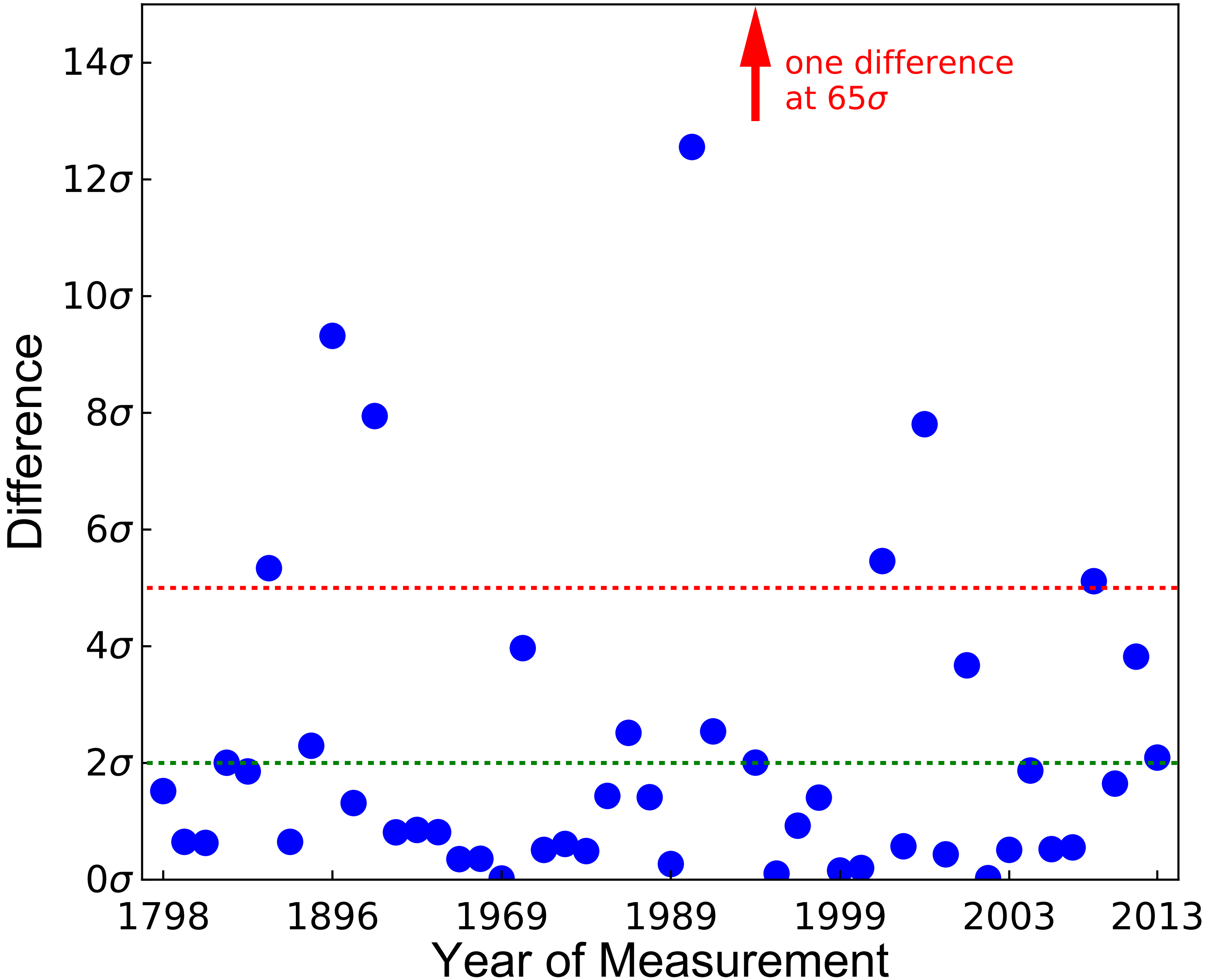
Chi-squared

- Sum of distance-squared between data and curve, measured in units of the uncertainty.
- Consider n independent random variables x_i, distributed as Gaussian densities with theoretical means μ_i and standard deviations σ_i, respectively.

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{x_i - \mu_i}{\sigma_i} \right)^2$$

- The mean value of the χ^2 is approximately the number of degrees of freedom, e.g. the number of bins less the number of fit parameters.

$(G_N - G_{CODATA})/\sigma$



χ^2/dof since

1798 is 138

(cdf=0)

1992 is 293

(cdf=0)

1995 is 13

(cdf=10^{-26})

(Un)Skills

Unskills

- Fear
  - of getting it wrong
  - of equipment
- Frustration
  - Not getting it right the first (or second or …) time

Convert fear to mindfulness

Skills

- Playing
  - with equipment
- Persistence
  - not giving up
- Problem solving
- Judgement
  - are you finished?
- Focus

What is the Point?

- What is my goal?
- What am I trying to accomplish
  - in this course?
  - in this experiment?
  - today?
  - by making this measurement?
  - by doing this instead of that?

Idealized Experiment Progress

3 weeks to complete each experiment.

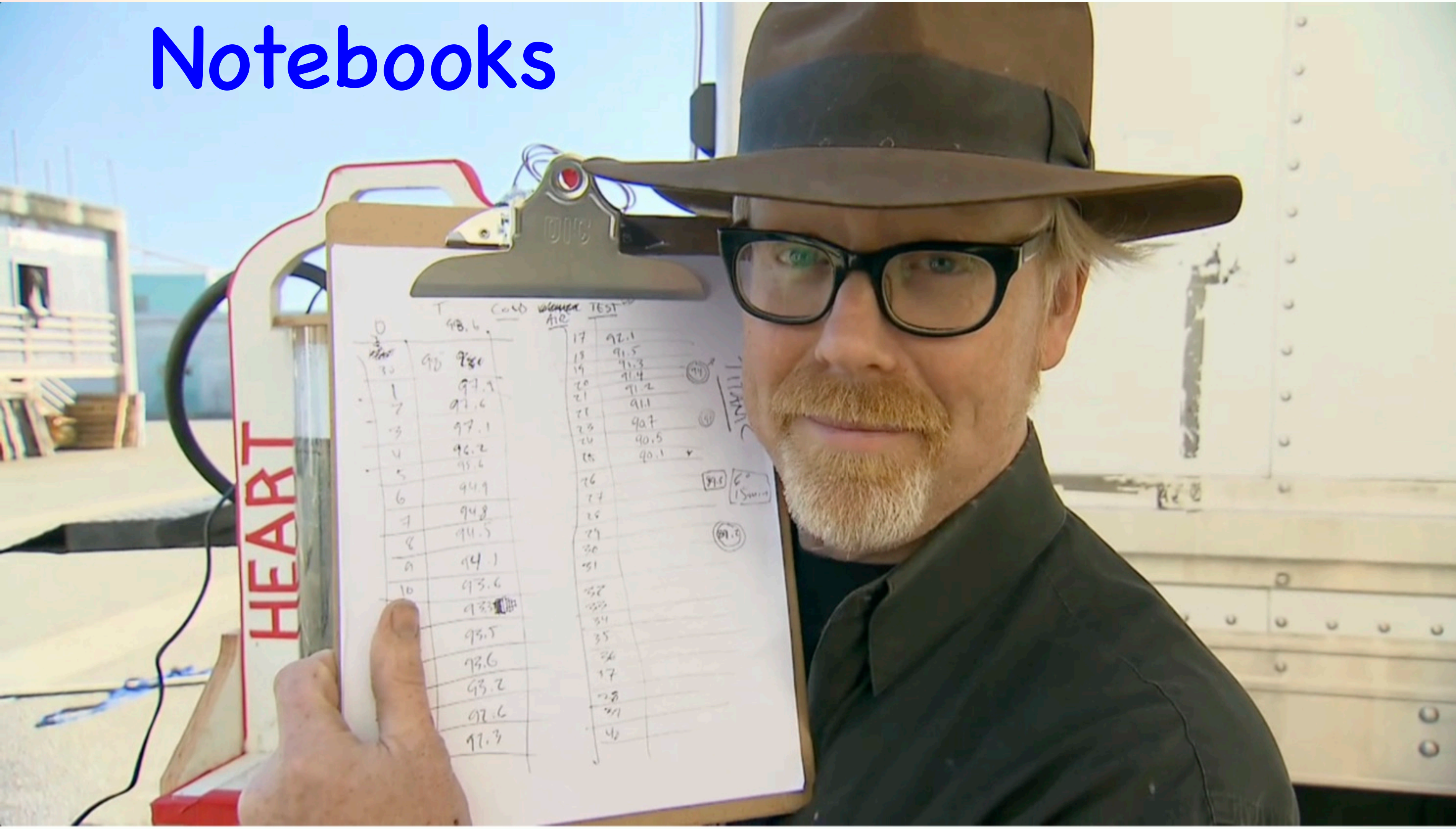
- Week 1: Become familiar with physics and apparatus, make plenty of notes and sketches, and attempt some preliminary measurements.
- Week 2: Complete at least one data-taking run and gone through all the analysis steps at least once.
- Week 3: Have some good data with well-understood uncertainties, and most analysis and conclusions well documented.

Typical Experiment Mark

- Experiment - 75%
  - Attendance 10% (2% per meeting with prof)
  - Progress Check 5%
  - Physics Understanding 10%
    Goals, underlying physics, anomaly identification, …
  - Experimental Skill 40%
    e.g. Ability to make the experiment work, response to problems and issues, quality of data, analysis and uncertainties.
  - Innovation 10%
    New measurements, ideas, methods, …
- Communications - 25%
  - Final Summary Abstract 7%
  - Notebook Quality 10%
    Clarity, completeness, organization, …
  - Interview Presentation 8%

Most important is doing the best job possible under the circumstances.

Notebooks



"Remember kids, the only difference between screwing around and science, is writing it down."

Adam Savage, Mythbusters, Episode 190 "Titanic Survival", Discovery Channel, 7 October 2012.

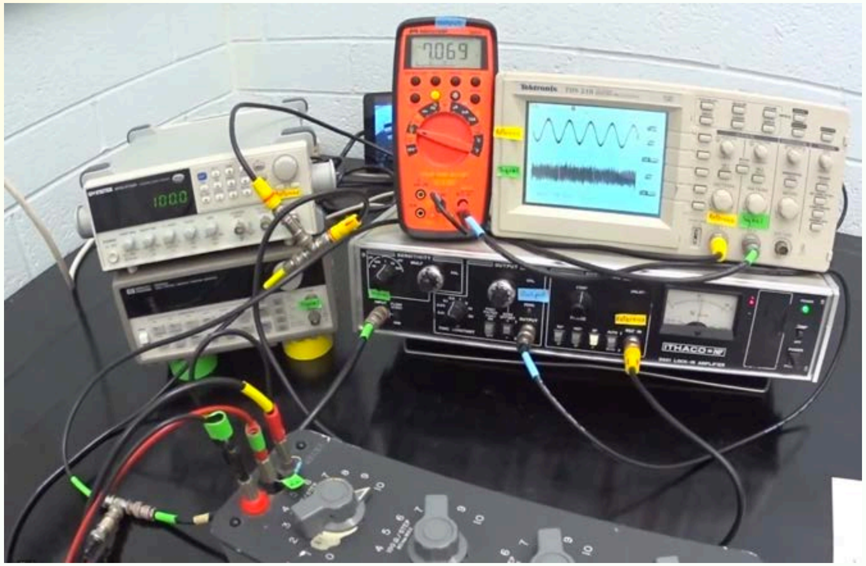
How a Prof reads a lab notebook

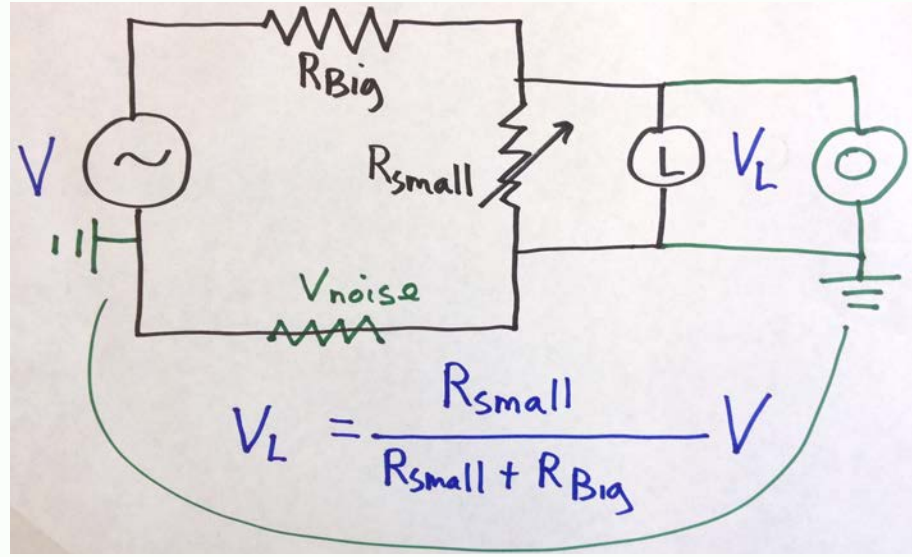
- We don't read every word.
  - But we will be unhappy if we look for some information and cannot find it.
  - Completeness first, legibility second
- Start with the Summary/Abstract
  - Your chance to guide us.
  - What is the point?
  - Where to go?
- We love forward/backward cross-references.
- Can't get good marks for work that we don't know about or can't understand.

You need two lab notebooks

- You won't get first notebook back before second experiment starts.
- You may reuse lab notebooks from previous courses,
  - number all pages from beginning of notebook, not beginning of experiment.
  - dates at the top of each page; note time frequently.
- Notebooks are journals, not formal reports!
- Notebooks are journals, not formal reports!!
  - record what happens when it happens, not later
  - We don't want a beautiful fiction.

Photos document, diagrams model





- Write down all settings
  - often unreadable in photo.
  - makes you think about why they exist.

How to understand equipment

- Check for safety warnings and issues

1) Play with it.
   - When I do this, that happens.
   - Try to understand what it is supposed to do, i.e. model its function.
2) Read the manual.
3) Repeat (1).

Problem solving

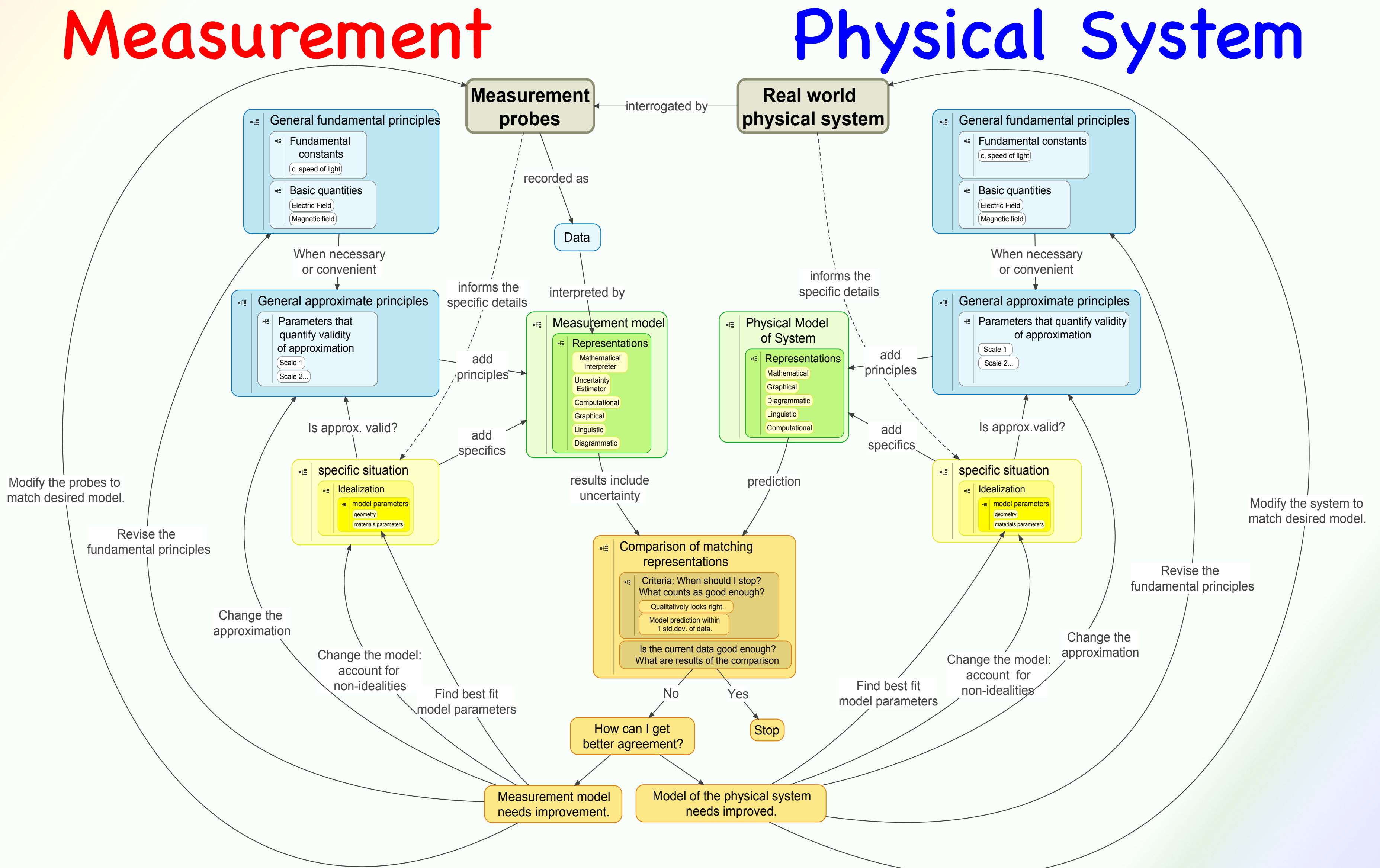
1) Restart
   - Turn equipment off and on, restart program, reboot computer, retake data, …
2) Read the manual.
3) Model, then compare to reality.
4) Calibrate
   - Measure something you know.
5) Break down problem into components
   - Test each component separately.
     - But life is not always linear: sometimes components work fine alone, but not together.
6) Iterate

Professor Skills

Why professors are usually better than students at making experiments work.

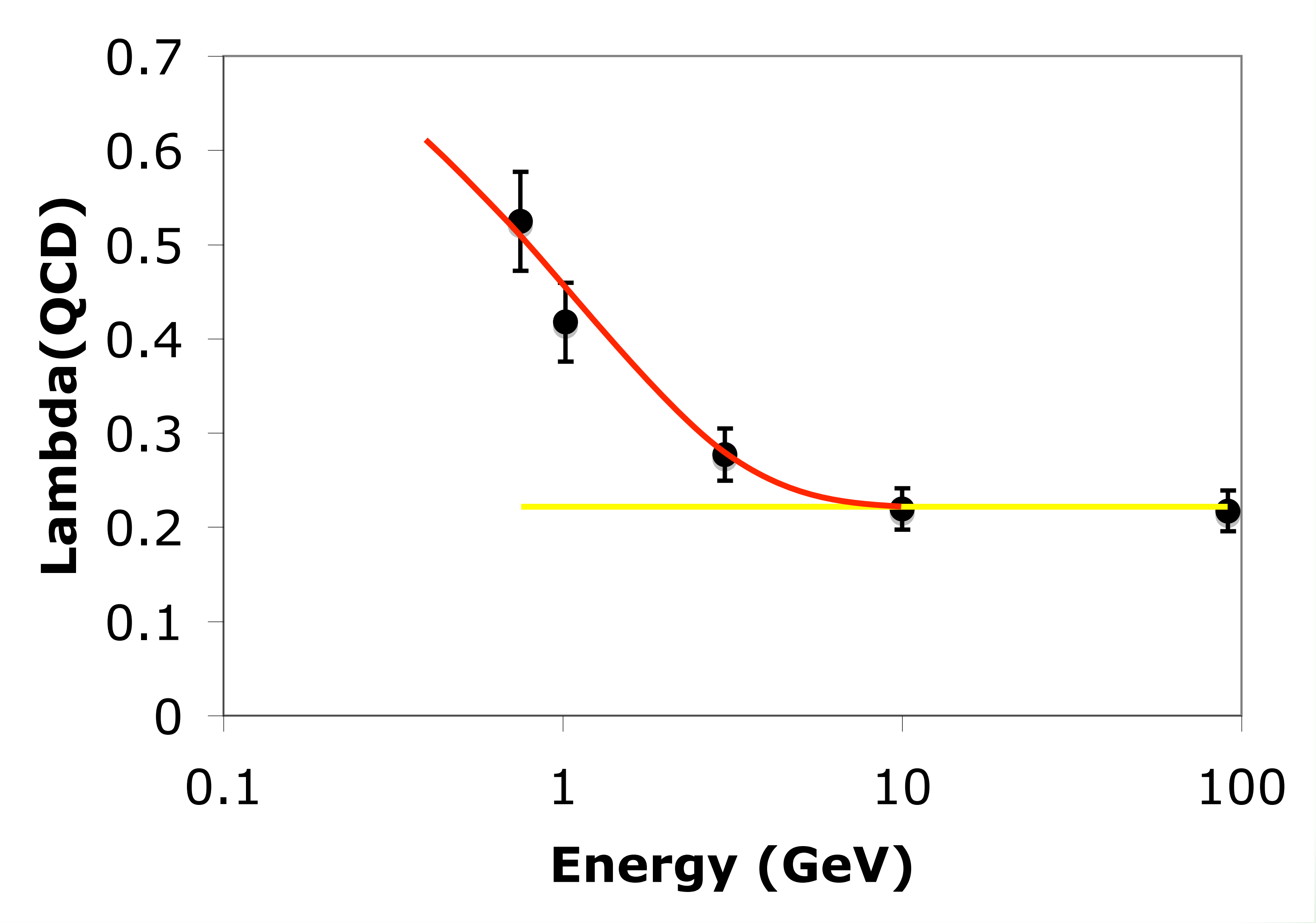
1) Less fear and frustration
2) Experience
   - Familiarity
     - with instruments, failure modes
3) Modelling
   - drives actions and measurements
4) Keep track of the point.

Models

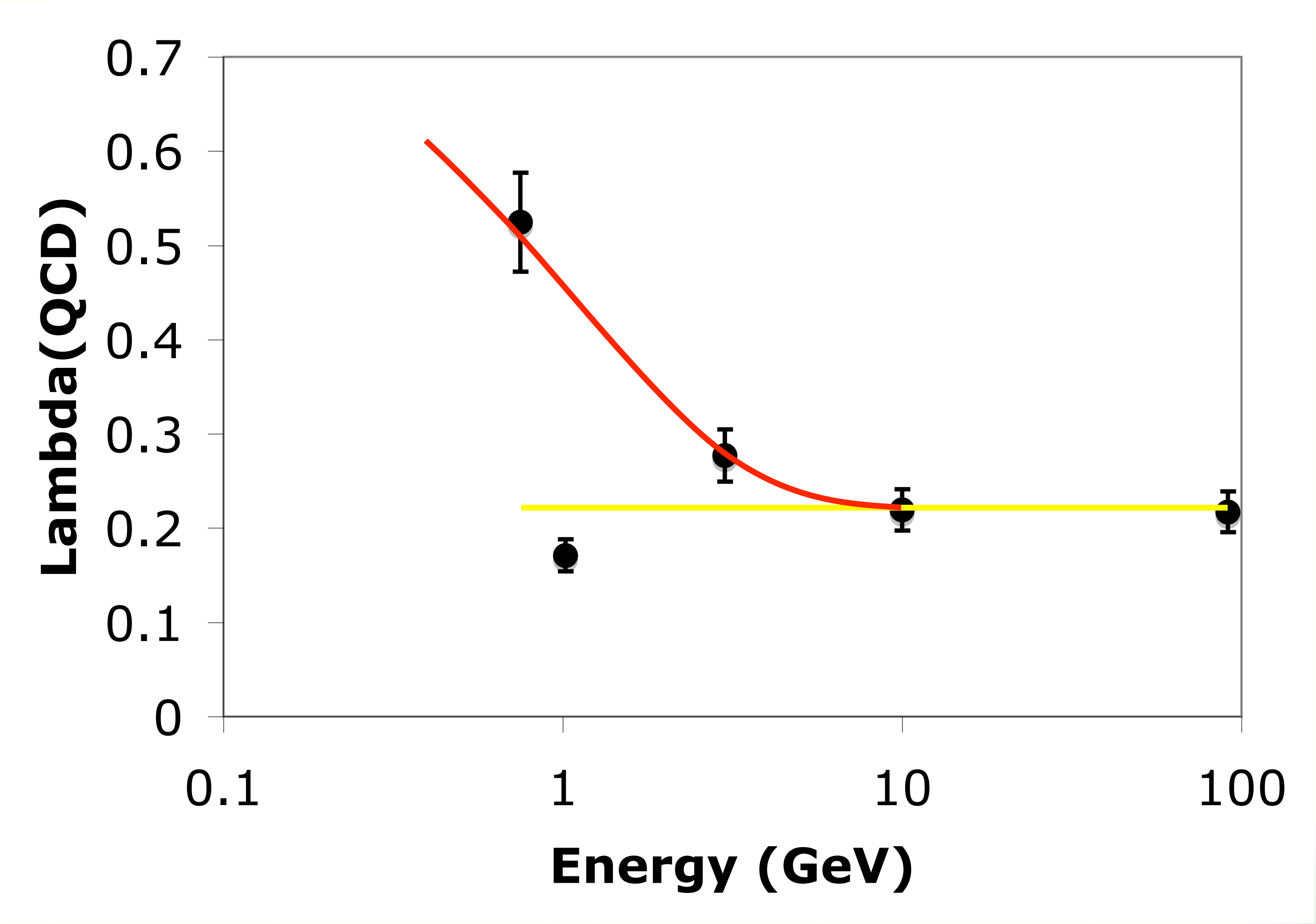


Measurement
Physical System
Measurement probes
interrogated by
Real world physical system
recorded as
Data
interpreted by
General fundamental principles
Fundamental constants
c, speed of light
Basic quantities
Electric Field
Magnetic field
When necessary or convenient
General approximate principles
Parameters that quantify validity of approximation
Scale 1
Scale 2...
informs the specific details
add principles
add specifics
Is approx. valid?
specific situation
Idealization
model parameters
geometry
materials parameters
Measurement model
Representations
Mathematical Interpreter
Uncertainty Estimator
Computational
Graphical
Linguistic
Diagrammatic
results include uncertainty
General fundamental principles
Fundamental constants
c, speed of light
Basic quantities
Electric Field
Magnetic field
When necessary or convenient
General approximate principles
Parameters that quantify validity of approximation
Scale 1
Scale 2...
informs the specific details
Physical Model of System
Representations
Mathematical
Graphical
Diagrammatic
Linguistic
Computational
add principles
add specifics
Is approx.valid?
specific situation
Idealization
model parameters
geometry
materials parameters
prediction
Comparison of matching representations
Criteria: When should I stop? What counts as good enough?
Qualitatively looks right.
Model prediction within 1 std.dev. of data.
Is the current data good enough? What are results of the comparison
No
Yes
How can I get better agreement?
Stop
Measurement model needs improvement.
Model of the physical system needs improved.
Modify the probes to match desired model.
Revise the fundamental principles
Change the approximation
Change the model: account for non-idealities
Find best fit model parameters
Modify the system to match desired model.
Revise the fundamental principles
Change the approximation
Change the model: account for non-idealities
Find best fit model parameters

Where should you spend your time?



Where should you spend your time?



Flag Anomalies

That's weird, …

- If there is some aspect of your analysis (or experiment) that doesn't make sense, say so in your lab notebook!
- Even if you don't have time or the tools to investigate further, you want to be the one that points out issues, not the professor.

APL Mistakes

Experiments

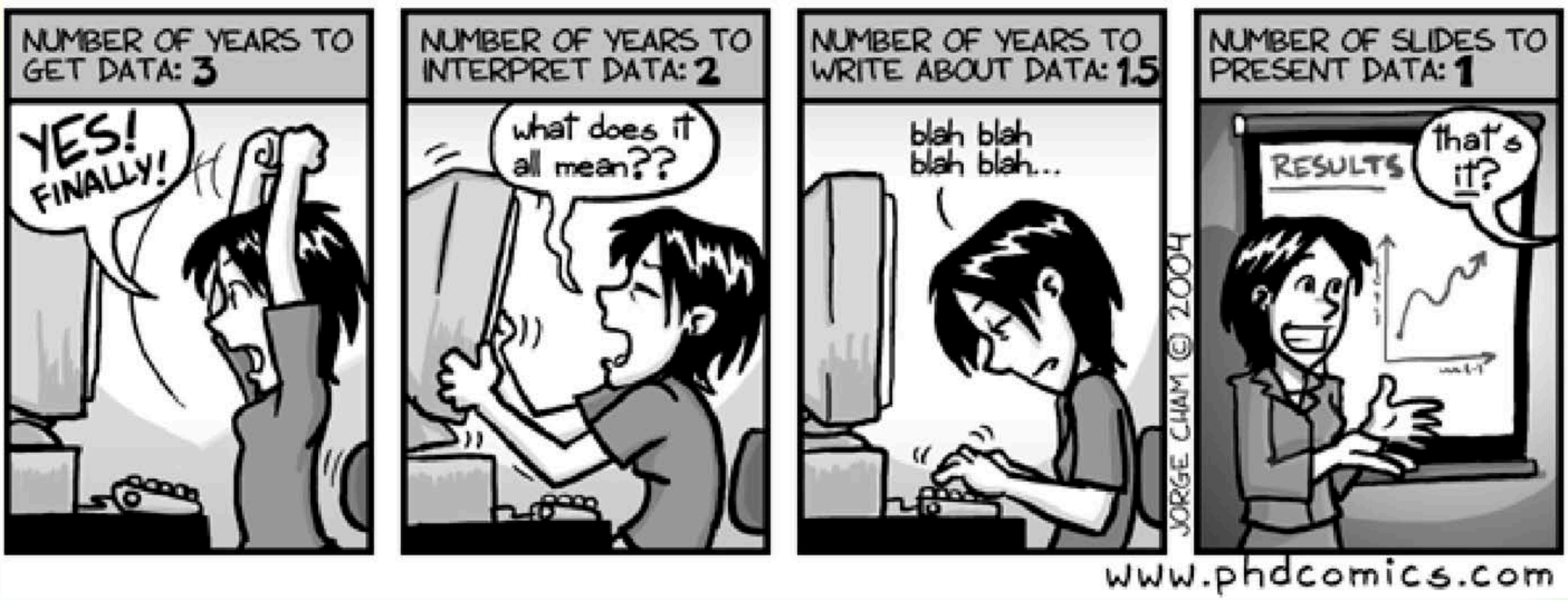
- **Not showing up**
- Not talking regularly to Profs & Demos
- Trying to understand everything before taking data.
- Taking data without understanding anything.
- Not analyzing data as you go.
  - You can't understand your data without taking some data
  - It is better to have less data that is well understood rather than lots of data poorly analyzed.

Formal Report

- Skipping peer review
  - "only worth 1.1% of final grade"
  - but also typically lose several % because of poor report.

Questions?

DATA: BY THE NUMBERS



http://www.phdcomics.com/comics.php?f=462,

Data and Uncertainty

- Natural science is fundamentally inductive, not deductive.
- Data is used to modify our beliefs in
  - whether hypotheses are true
  - the likely values of parameters
- Uncertainties parameterize the likelihood that two measurements will agree.
  - not the probability distribution of the true value
- Uncertainties are defined by convention.
  - If everyone uses the same reasonable convention, we can compare results.

Normal Convention

- "$x \pm \sigma$" means
  - if other measurements of the same parameter are made, "$x_i \pm \sigma_i$", we expect

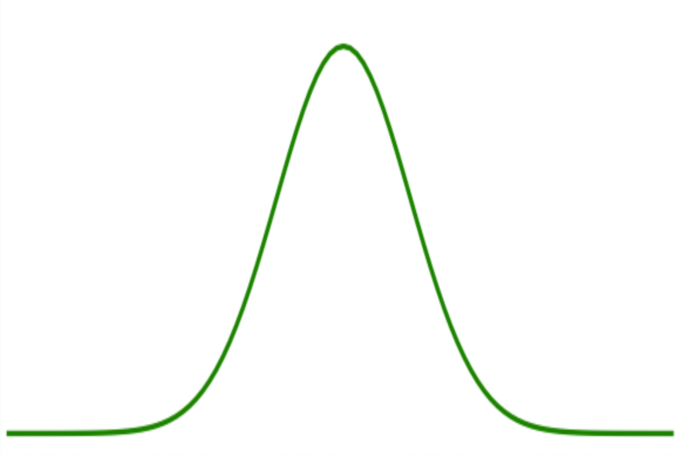
$$|x - x_i| < \sqrt{\sigma^2 + \sigma_i^2}$$

- 68.3% of the time.

Normal (Gaussian) Distributions

$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Mean μ, RMS width σ



- Limit of Binomial distribution for many trials with mean not near zero; for large counting statistics, $\mu=\sigma^2=N$.
- The Central Limit Theorem says (almost?) everything averages out to a Gaussian.
  - Careful! Long tails are common, see http://rsos.royalsocietypublishing.org/content/4/1/160600
- Many resolution functions approximately Gaussian.
- Only distribution many physicists really know.

Systematic Uncertainties

A correlated (rather than random) error that is NOT simply reduced by taking more data.

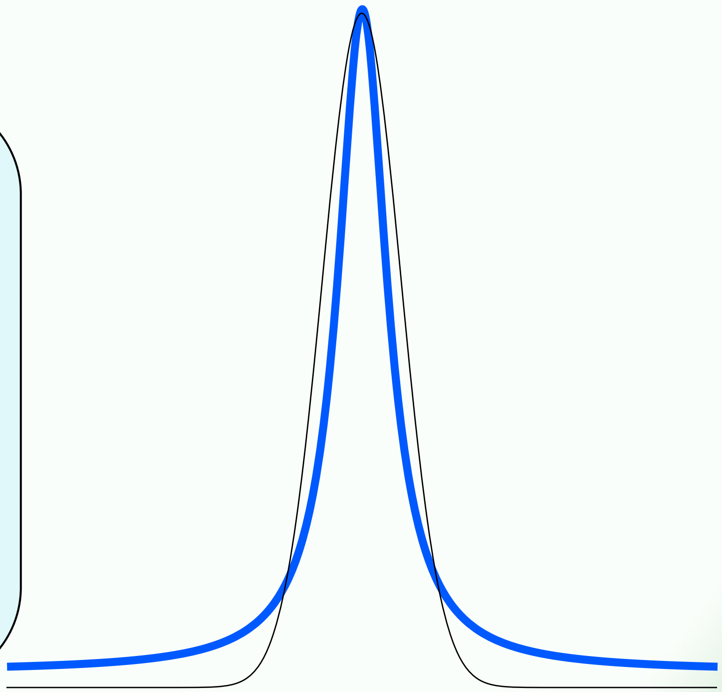
Often due to inaccurate measurement model

- Mis-calibration, e.g. Thermocouple ref temp
- Uncertain inputs, e.g. COMP: Pure Pb?
- Theory dependence, e.g. Thick or thin LENS?
- Instrumental, e.g. ground loops
- Backgrounds, noise, inefficiencies, …

Cauchy / Lorentzian / Breit-Wigner Distribution

$$P(x) = \frac{1}{\pi\sigma\left[1+\left(\frac{x-\mu}{\sigma}\right)^2\right]}$$

Mean μ, FWHM width σ



- Average value, standard deviation are undefined, and all higher moments are undefined.
- Natural shape of spectroscopic lines, i.e. it is the fourier transform of and exponential decay.

Experimental Paranoia

Assume that the universe is conspiring to spoil your experiment.

e.g. Don't assume equipment is calibrated, that it is the same as the last time you used it,* there are no typos, there is no noise, …

If you do make such assumptions, clearly state them in your notebook.

* Remember, two APL sections this semester

Fitting

- "Fitting" data means adjusting the variable parameters in the physics (mathematical) model so that it best agrees with the data.
- A metric is used to measure agreement between the model and the data. A fit minimizes the value of the metric.
- Most usual metric is χ^2.

Software

- Matlab, Octave, Sage…
- Maple, Mathematica, Reduce, …
- Excel (for preliminary analysis)
- Faraday, DataStudio, Kaleidagraph, …
- **Python**, C, C++, …
- …

We don't care what you use, but we do care that you understand what you do.

But, **if in doubt, use Python**, since that is best supported for UofT UG Physics.

Weighted Least Squares

- Minimize
$$\chi^2 = \sum_{i=1}^{n} \left(\frac{y_i - f(x_i; \mathbf{p})}{\sigma_i} \right)^2$$
- Ordinary/linear least squares for equal uncertainties, minimizes
$$\chi^2 = \frac{1}{\sigma^2} \sum_{i=1}^{n} \left(y_i - f(x_i; \mathbf{p}) \right)^2$$
- Never, ever, use Ordinary Least Squares if the uncertainties are not equal!
- Fit should give best values for parameters, their uncertainties, and χ^2 and CDF (cumulative distribution function) for the fit.

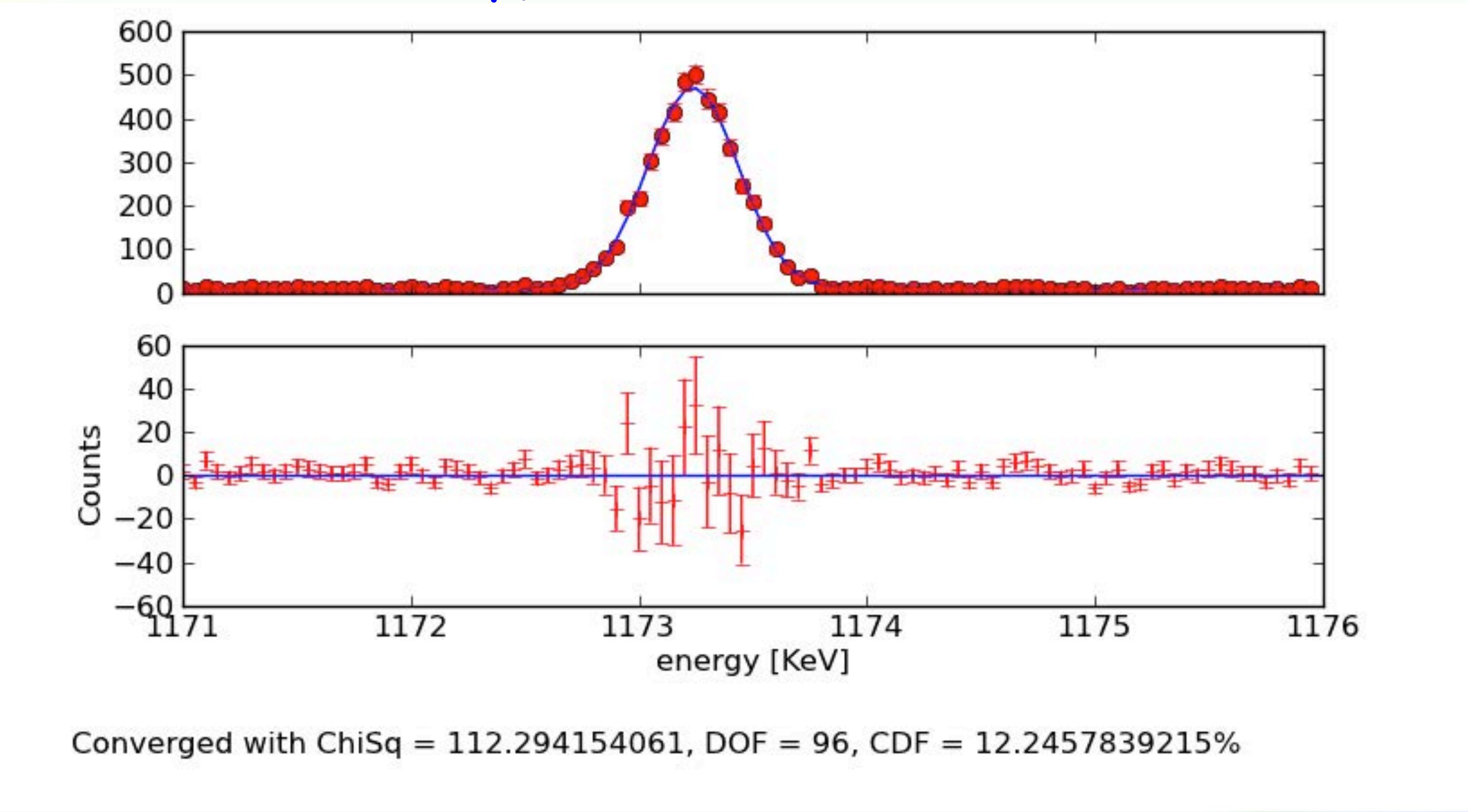
Python for the Advanced Lab

http://www.physics.utoronto.ca/~phy326/python/

- Python Code Repository
- curve_fit_to_data.py or
  - simple_curve_fit_to_data.py
  - extended_curve_fit_to_data.py
- odr_fit_to_data.py
  - for errors in x and y
- If you don't base your analysis on these examples, please be sure that you know what you are doing.

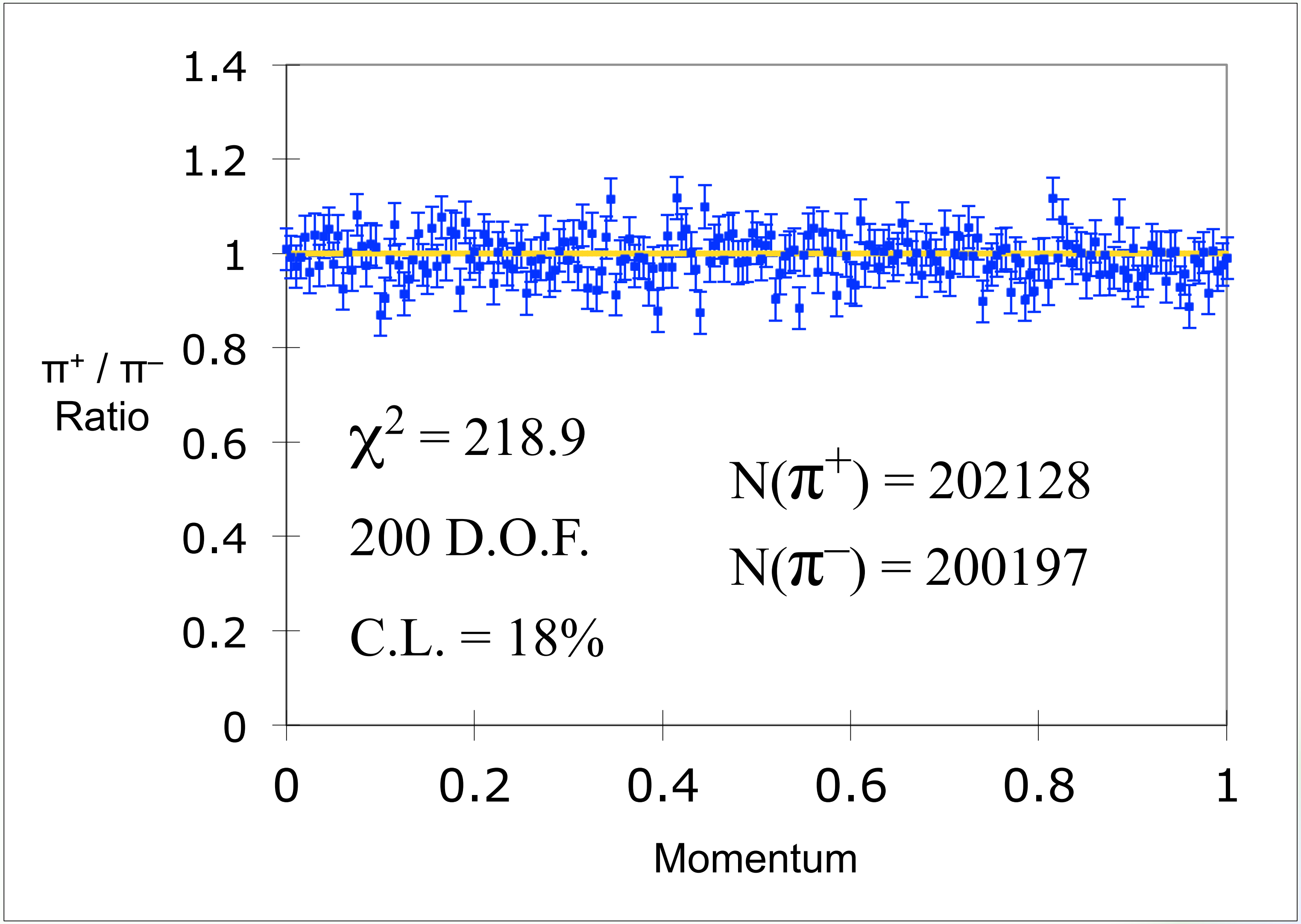
Example

http://www.physics.utoronto.ca/~phy326/python/curve_fit_to_data.py



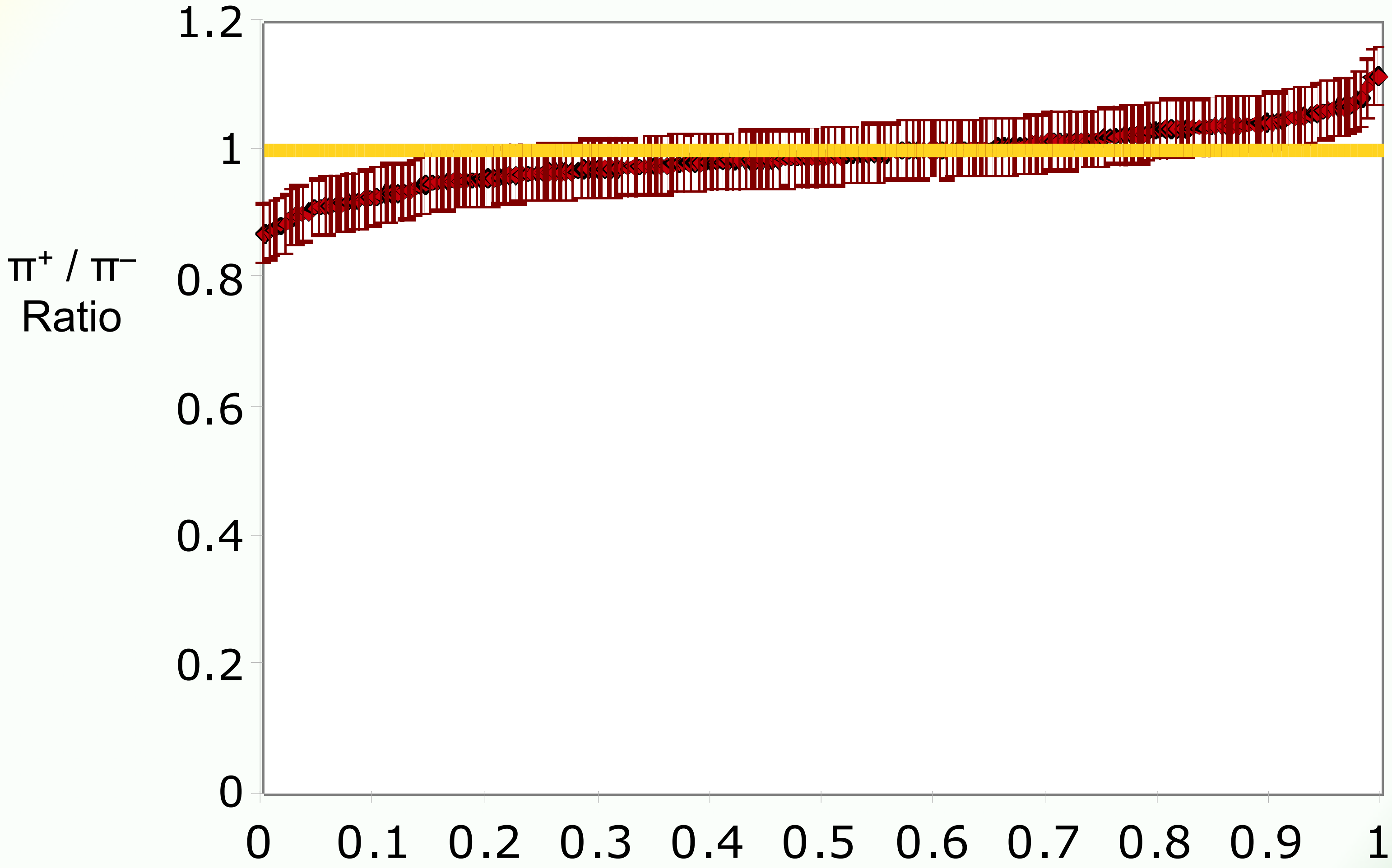
χ^2 does not tell you everything

- $p\bar{p} \rightarrow \pi^+\pi^0\pi^-$ Charge Conjugation Test



What about this data?

- Do (red) data and (yellow)model agree?



Correlated Errors

- e.g. common calibration uncertainty.

Minimize

$$\chi^2 = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(y_i - f\left(x_i;\mathbf{p}\right)\right)\left(y_j - f\left(x_j;\mathbf{p}\right)\right)\mathbf{V}_{ij}^{-1}$$

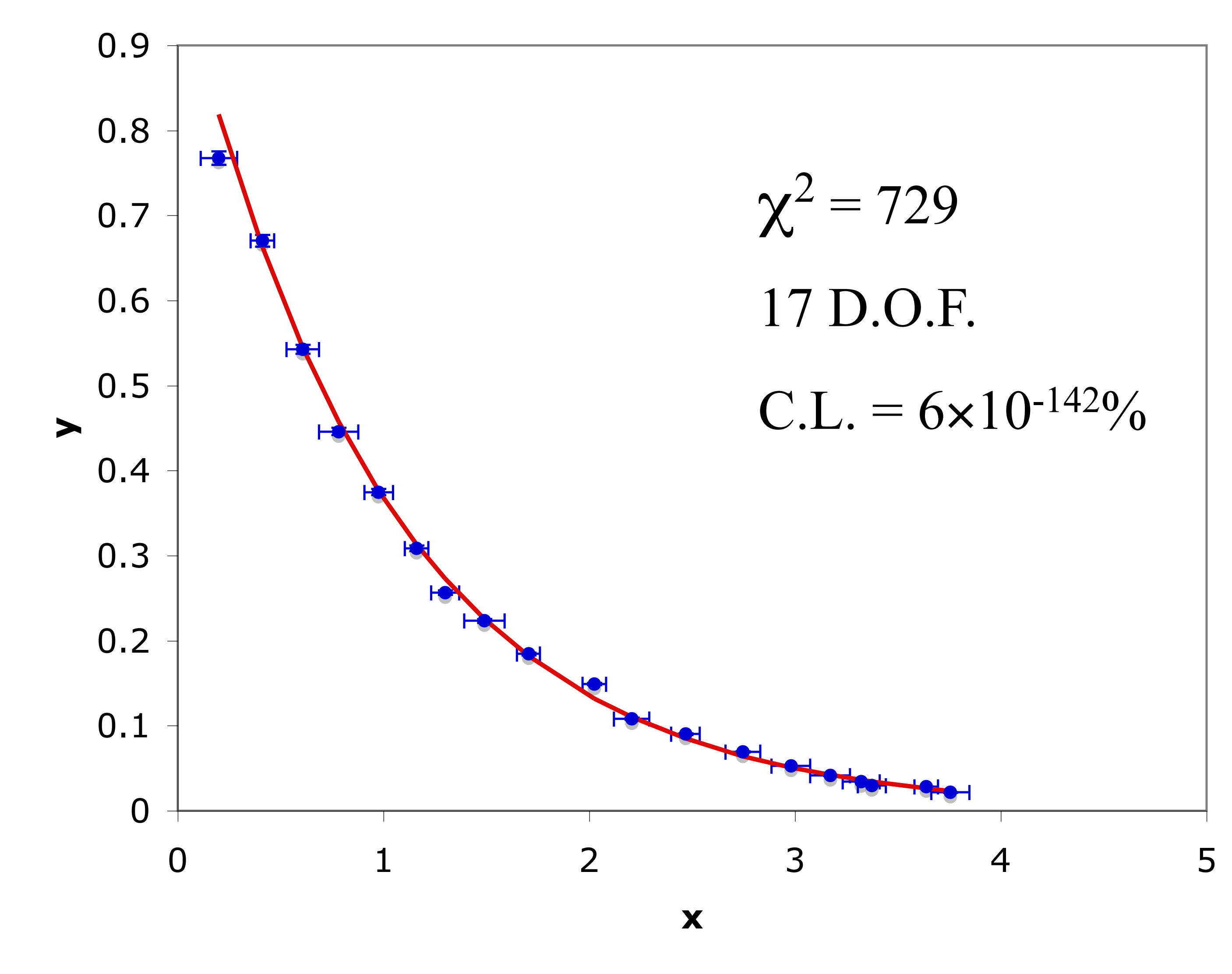
Covariance matrix

$$\mathbf{V} = \left\langle\left(y_i - \mu\right)\left(y_j - \mu\right)\right\rangle$$

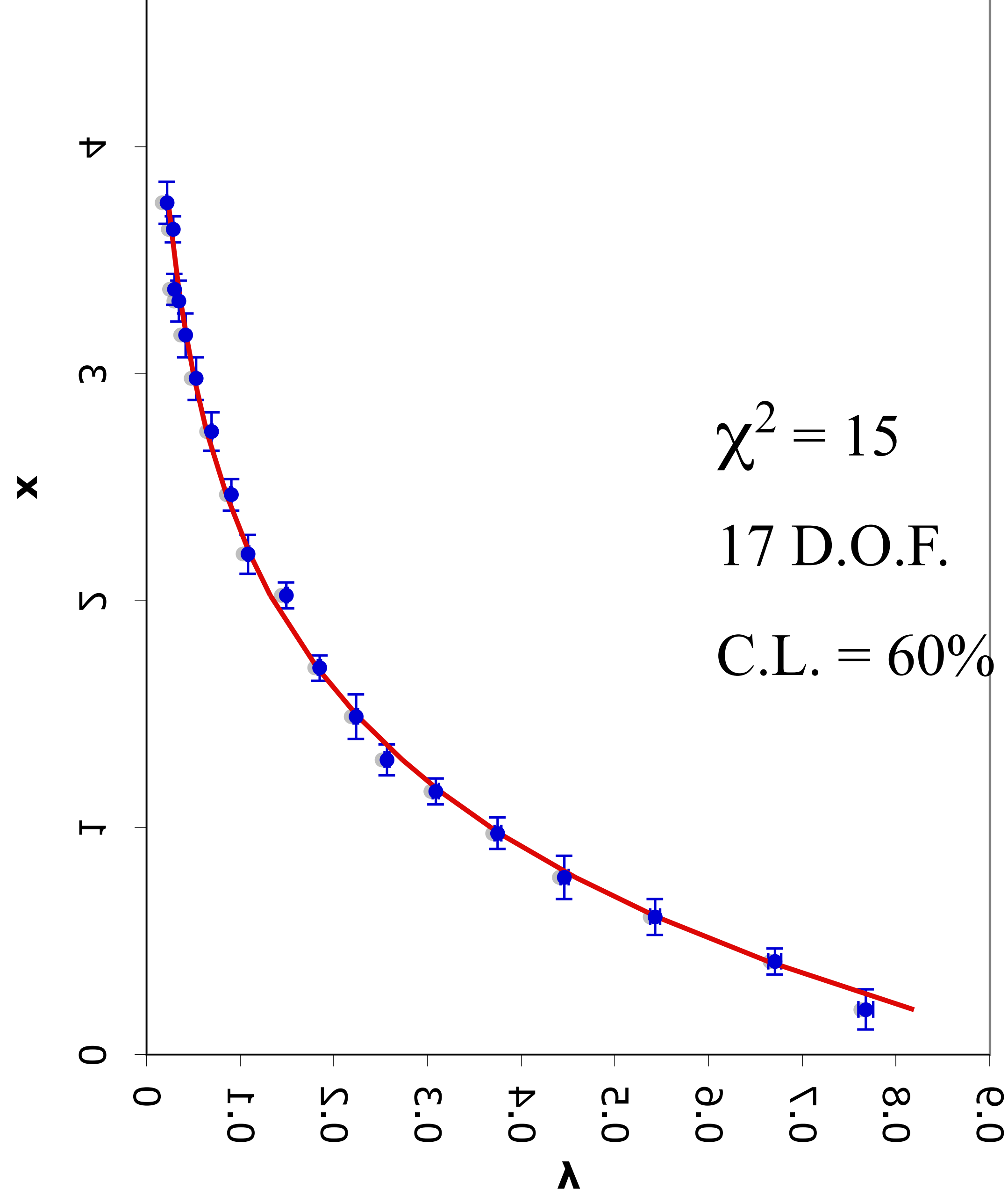
$$= \delta_{ij}\sigma^2$$ if y_i uncorrelated

$$= \delta_{ij}\sigma^2 + b^2$$ common uncertainty b

What about this data?



What about this data?



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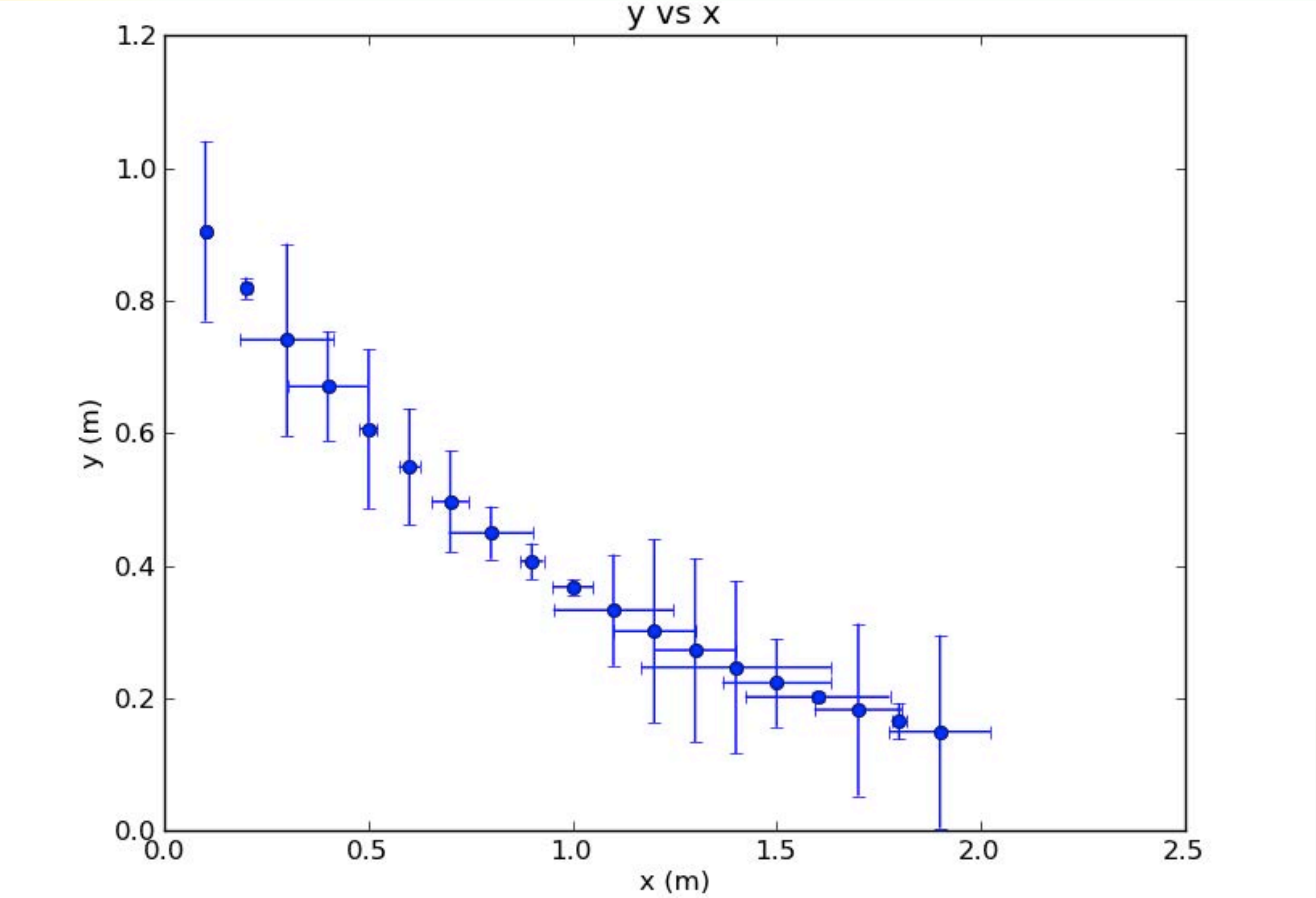
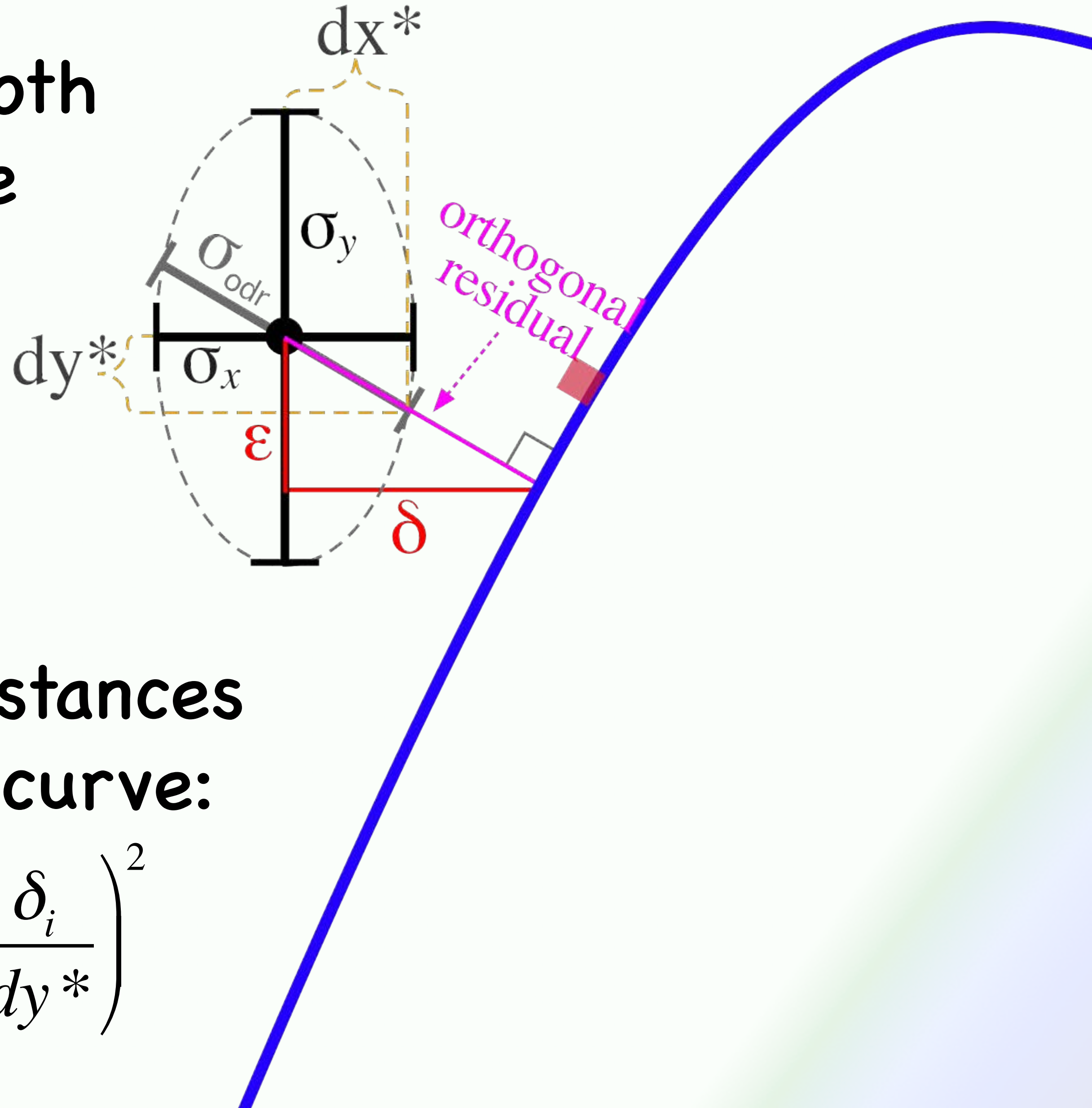


Orthogonal Distance Regression

- Good when both σ_x and σ_y are significant

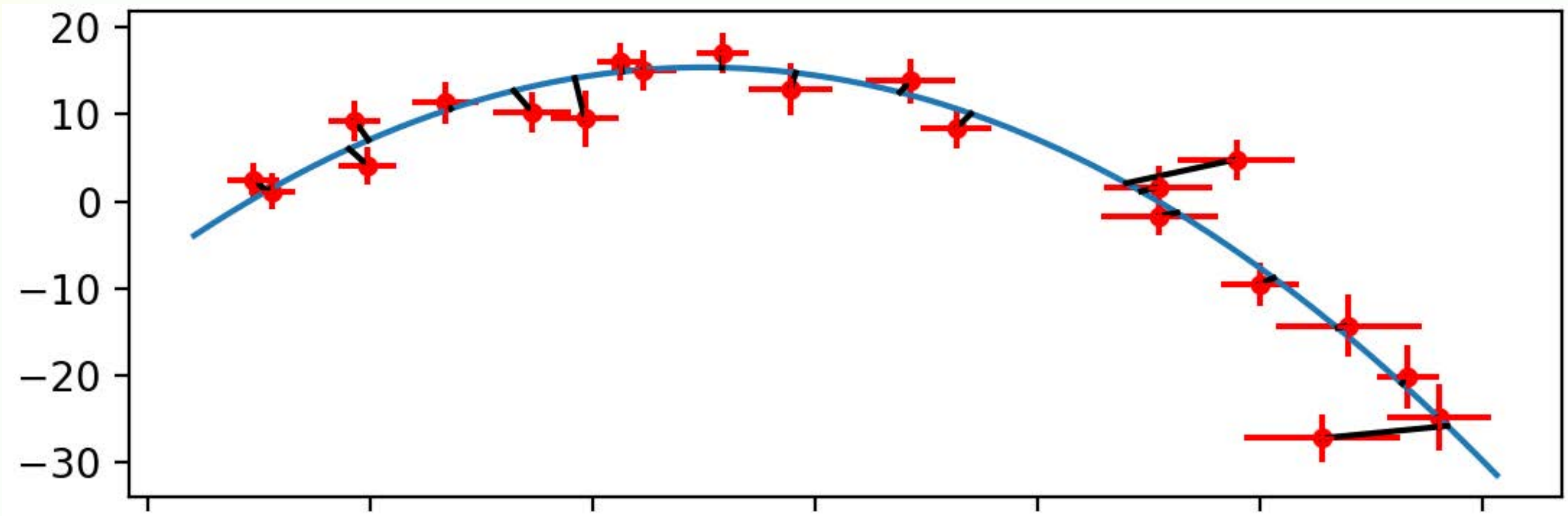


- Minimizes orthogonal distances from data to curve:

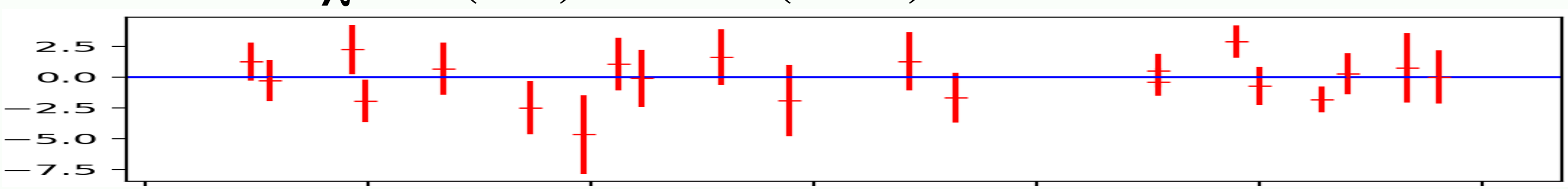
$$\sum_{i=1}^{n}\left(\frac{\varepsilon_i}{dy^*}\right)^2+\left(\frac{\delta_i}{dy^*}\right)^2$$

ODR Example

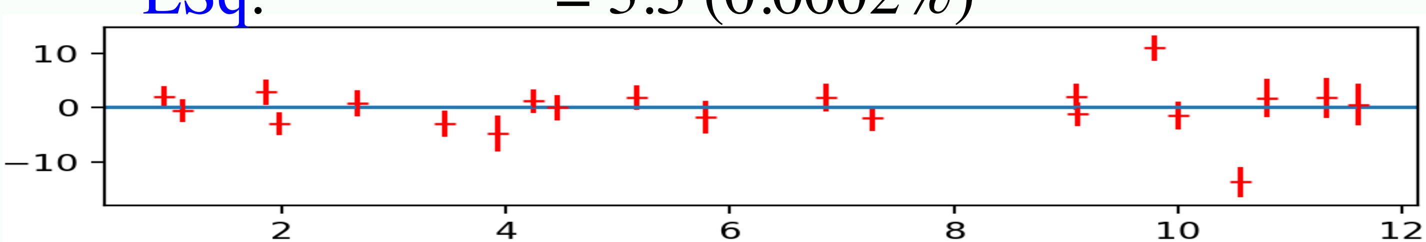
(parabola_xy_errors.txt)



ODR: χ^2/df (cdf) = 0.96 (51%)

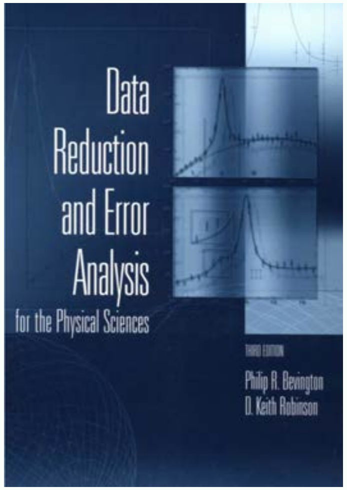


LSq: = 3.3 (0.0002%)



Data analysis in the Advanced Lab

References



- P.R.Bevington and D.K.Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, 3rd Ed., (McGraw-Hill 2002).
- I.G. Hughes and T.P.A. Hase, Measurements and their Uncertainties: A Practical Guide to Modern Error Analysis (Oxford 2010)
- Lectures on course website by Bailey, Krieger, Thywissen, Harrison

Data Analysis Assignment

- Required of all first-time APL students
- Ensures students have skills needed for APL data analysis.
  - nonlinear fitting
  - uncertainties in both *x* and *y*
  - careful thought and communication about analysis and uncertainty.

Questions?

Reminders

- Return Experiment Preference Sheet by 4pm today.
- Read the course outline.
- Have Fun!