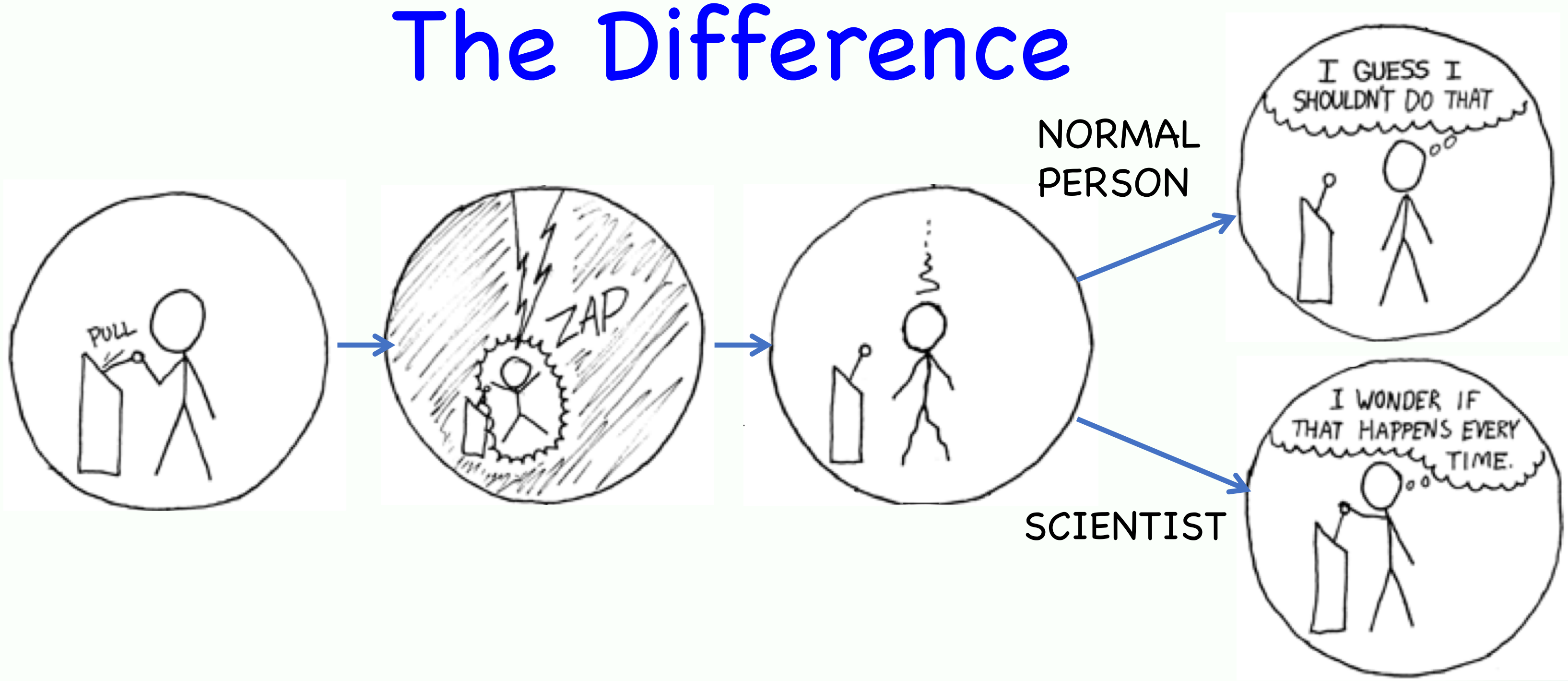
Please pick up handouts from desk by door

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

These slides will be available online later today.

Welcome to the Advanced Physics Lab!

- Physics is the science that tries to describe, understand, and predict the behaviour of physical systems.
- Our goal is to help you learn the methods and understand the myriad challenges of making careful observations and accurate measurement of such systems, judging their consistency with theoretical models, and communicating this work.
- Doing the right thing more than getting the "right" answer. A "perfect experiment" is an oxymoron.
- Not showing up (enough) is the number one reason for a student not doing well in this course.

What is the Point of the Advanced Lab?

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

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 and learn new skills and knowledge.

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.
  - Information often posted outside MP251, but **don't assume we'll remind you about deadlines; they are in the outline and online.**
  - If you don't understand something – ask.

Grading Scheme (PHY424)

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

Grading Scheme (PHY327)

• Data Analysis Project	4 %
• 3 experiments @ 20% each	57 %
• Design Reflection	3 %
• Formal Report and Peer Review	18 %
• Oral exam	18 %

Dates and Deadlines

- In outline and at http://www.physics.utoronto.ca/apl/dates.htm
  - Experiment Preference Sheets due 4pm today
  - Start experiments in next lab period
  - Data analysis assignment due 23 September.
  - …
- 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 Sheet

Tells us

- who you are
  - name you would like used (e.g. on whiteboard)
- how to contact you
- when you will be in the lab
- which experiments you would like to do
  - Experiments must be with different profs
  - You can always later ask for different experiment

Due by 4pm today

(or hand in this morning)

Advanced Physics Lab **Contact & Schedule** University of Toronto Fall 2019

This form must be returned to the Lab Coordinator, David Bailey, in MP 251A by 4:00 pm on 6 September
(If Prof. Bailey is not there, place on shelf with his name in MP251 by the whiteboard.)

Contact

Student Name:____________________ **Name (e.g. first) for whiteboard:** __________

Student Number:____________________ **Course you are registered in:**__________

Official UofT Email:____________________**@mail.utoronto.ca**

Alternate Contact (Optional) e.g. gmail /phone:____________________

Schedule

Please put tick-marks (✓) in the cells to indicate the times you will most likely be in the lab (including the normal Tuesday and Friday time slots), **and Xs (✖) to show the times when you have conflicts** (e.g. with lectures in another course). It helps if you indicate all currently known regular conflicts, even those outside the regular lab periods, in case we want to arrange a meeting.

Timetable

	Mon	Tue	Wed	Thu	Fri
9 – 10					
10 – 11					
11 – 12					
12 – 13					
13 – 14					
14 – 15					
15 – 16					

Any preferred partner(s) for (at most) one experiment: ____________________

Any other information you think we should know, comments, or special requests: ____________________

Return this form to the Lab Coordinator in MP 251A by 4:00 pm on 6 September. (If the Coordinator is not there, place on shelf with their name in MP251 by the whiteboard.) If you do not return the form, we will randomly assign you a free experiment. Changes may be possible later, depending on experiment availability.

List of experiments available:

Code	Prof	Experiment Name
AFM	DW	Atomic Force Microscope
ASL	PK	Aperiodic Structures (under development)
BRI	DW	Brillouin scattering
CC	PS	Cloud Chamber
C3D	DW	Conductivity in less than three dimensions
COMP	PK	Measurement of the Compton total cross section
ESR	PK	Electron spin resonance
FAR	PS	Faraday Waves
FE	JW	Ferroelectrics
FTS	DW	Fourier transform spectroscopy
FVF	PS	Fractal Viscous Fingering
GE	PK	Gamma ray spectroscopy with a germanium detector
GRAN	PS	Granular Patterns (under development)
HALL	JW	Semiconductor resistance, band gap, and Hall effect
HEL	JT	Helicons in metals
HENE	DW	The helium-neon laser
HEP	PS	High energy physics
HTCM†	JW	High temperature superconductors (Make)
HTCK	JW	High temperature superconductors (Kit)
KNOT	PS	Knots and topological transformations in vibrating chains
LAUE	PS	Laue back reflection of X-Rays
LENS	DW	Lenses
LPP	JT	Linear Pulse Propagation and Dispersion
LTC	JW	Magnetization & transition temperatures of superconductors
MASS	DW	Mass spectrometer
MOS	PK	Mossbauer effect
MUON	PK	Muon lifetime (under development)
NEEL	PK	Phase change in chromium at the Neel temperature
NMR	PK	Nuclear magnetic resonance
PXR	PS	Powder method of X-ray analysis
OPT	JT	Optical Tweezers
QIE†	JT	Quantum Interference and Entanglement
RAM	DW	Raman effect
RB	JT	Optical pumping of rubidium
RES	PK	Electrical resistivity at low temperatures
SOL	DW	Solitons
SONO	PK	Sonoluminescence
SQM	PK	SQUID magnetometer
UFF	JT	Ultrafast Fibre Laser (under development)
XRF	PS	X-ray fluorescence
SPEC	DB	Special Projects

† These experiments are usually done together by two students; some other experiments may also be done in pairs if the lab enrolment is large enough to make it necessary.

Professors are:

DB = David Bailey
PK = Peter Kreiger
PS = Pekka Sinervo
JT = Joseph Thywissen
JW = John Wei
DW = Debra Wunch

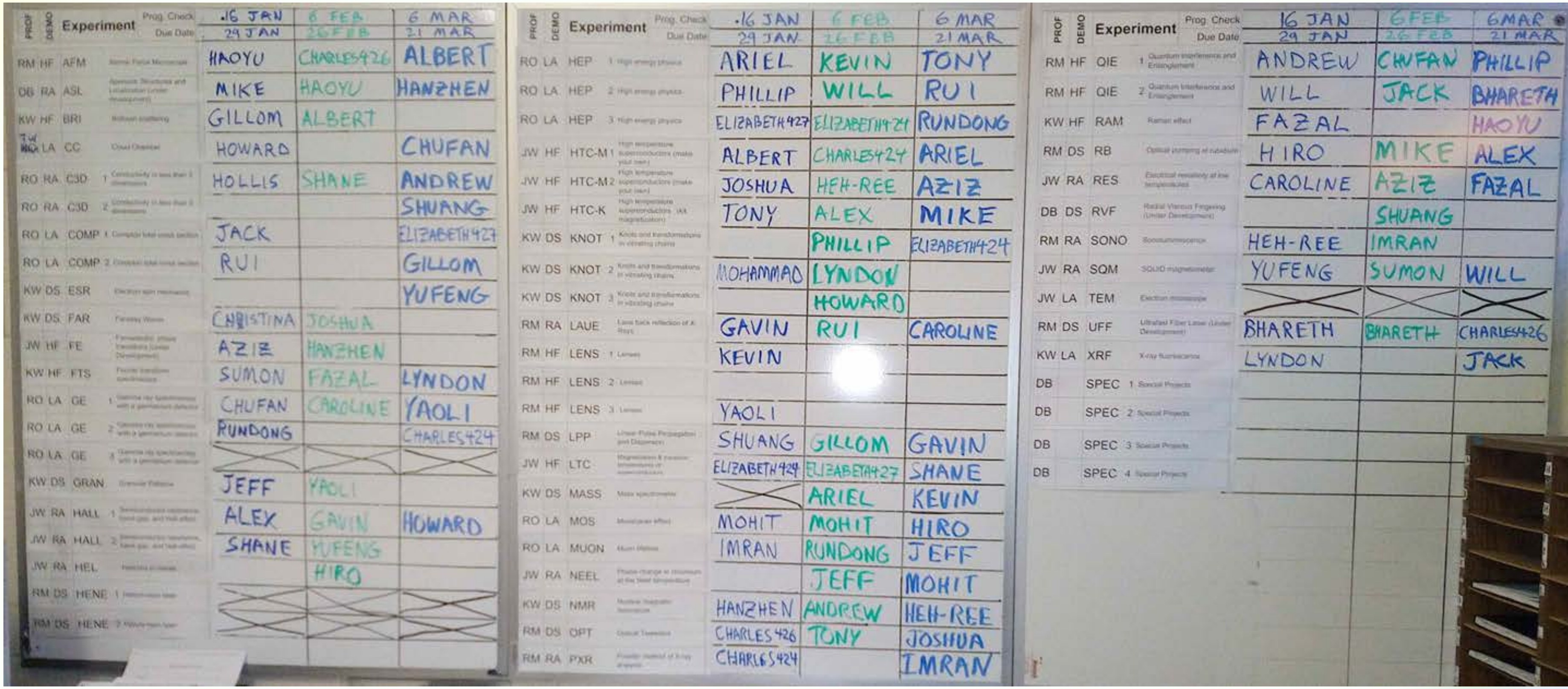
List in order of preference

at least 25 of the experiments you would like to do. If you are taking this course for the first time, your rankings should include experiments for each professor. List the codes only and list your most preferred experiments first:

1)____ 2)____ 3)____ 4)____
5)____ 6)____ 7)____ 8)____
9)____ 10)____ 11)____ 12)____
13)____ 14)____ 15)____ 16)____
17)____ 18)____ 19)____ 20)____
21)____ 22)____ 23)____ 24)____
25)____ 26)____ 27)____ 28)____
29)____ 30)____ 31)____ 32)____

Students in PHY 327 and 424 should keep in mind that they must do experiments with 3 different professors, so be sure to list a mix of experiments.

Whiteboard
in MP251



Attendance Sheet

Complete top and place in red binder in MP251, and sign in whenever in the lab.

By far our best predictor of student success in the Advanced Lab is whether we are seeing you regularly.

- You can skip lectures and still do well in a lecture course.
- You can pull an all-nighter to finish a problem set, but not an experiment.
- You cannot skip lab periods and do well in the Advanced Lab course. Experiments take time!

Attendance Record Sheet

First Name: ____________ Course #:________ Last Two Digits of a Student Number:______

Initial	Date	Time	Initial	Date	Time
1.			26.		
2.			27.		
3.			28.		
4.			29.		
5.			30.		
6.			31.		
7.			32.		
8.			33.		
9.			34.		
10.			35.		
11.			36.		
12.			37.		
13.			38.		
14.			39.		
15.			40.		
16.			41.		
17.			42.		
18.			43.		
19.			44.		
20.			45.		
21.			46.		
22.			47.		
23.			48.		
24.			49.		
25.			50.		

People



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










IF YOU NEED HELP

- **Look** for (in order) Demo, Professor, Technologist.
- Profs and Demos are not around the whole 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."

Questions?

- We'll talk more about how to succeed in the Advanced Lab in hours 2 & 3.
- But now need to talk about academic integrity and safety.

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
    - TAs, Profs, Techs, other students. …
- Read guidelines, talk to Coordinator if unsure.

Plagiarism in Writing

- Never use sources without attribution.
  - e.g. Improperly copying just one sentence into your Formal Report is (in principle) 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.

Do not plagiarise Experiment Manuals for Formal Report !!!!!!

- Do not copy text except as properly attributed quotations !
- Attribute any figures used !!
- Do not plagiaphrase !!!
  - Reordering phrases, switching a few words, or using synonyms is not sufficient.
  - When paraphrasing, acknowledge the source somehow in the sentence/paragraph.

Questions?

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.

Hazards

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

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.

Ionizing Radiation

- Any student using an X-ray machine must wear a radiation dosimeter available from Technologist in MP 234.
- 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.

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.

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.

Questions
?

Don't forget to take handouts.

The Way of the Physicist

Physicists

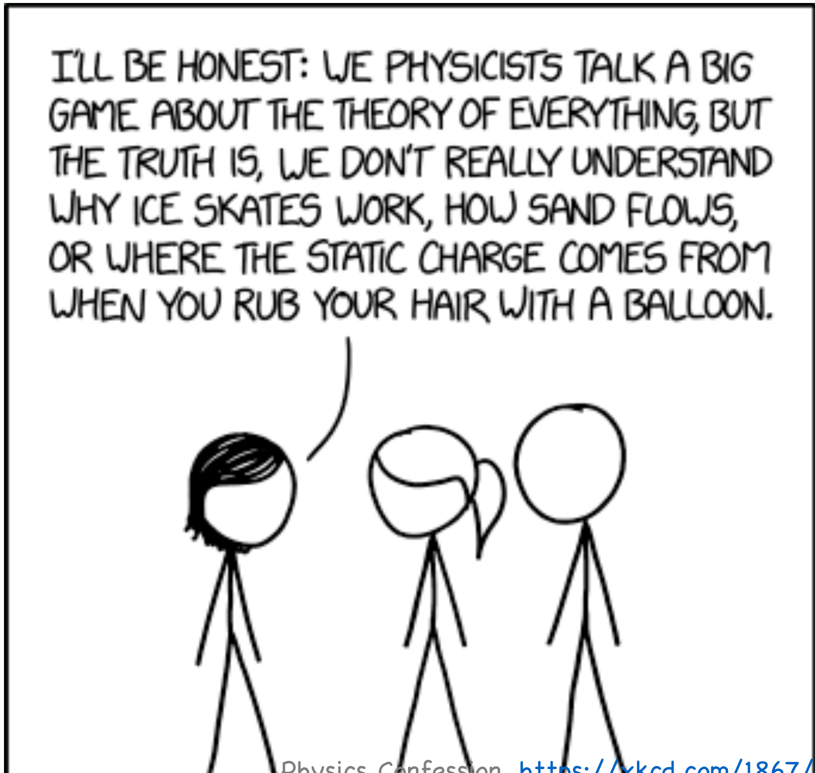
- construct mathematical model of a physical system
- solve the model analytically or computationally

Lecture Courses

- measure the system
- compare measurements with expectations
- communicate results with others

APL

- improve model, calculation, experiment; iterate



Physics Confession, https://xkcd.com/1867/ by Randall Munroe (CC BY-NC 2.5).

How TO SUCCEED IN THE ADVANCED LAB

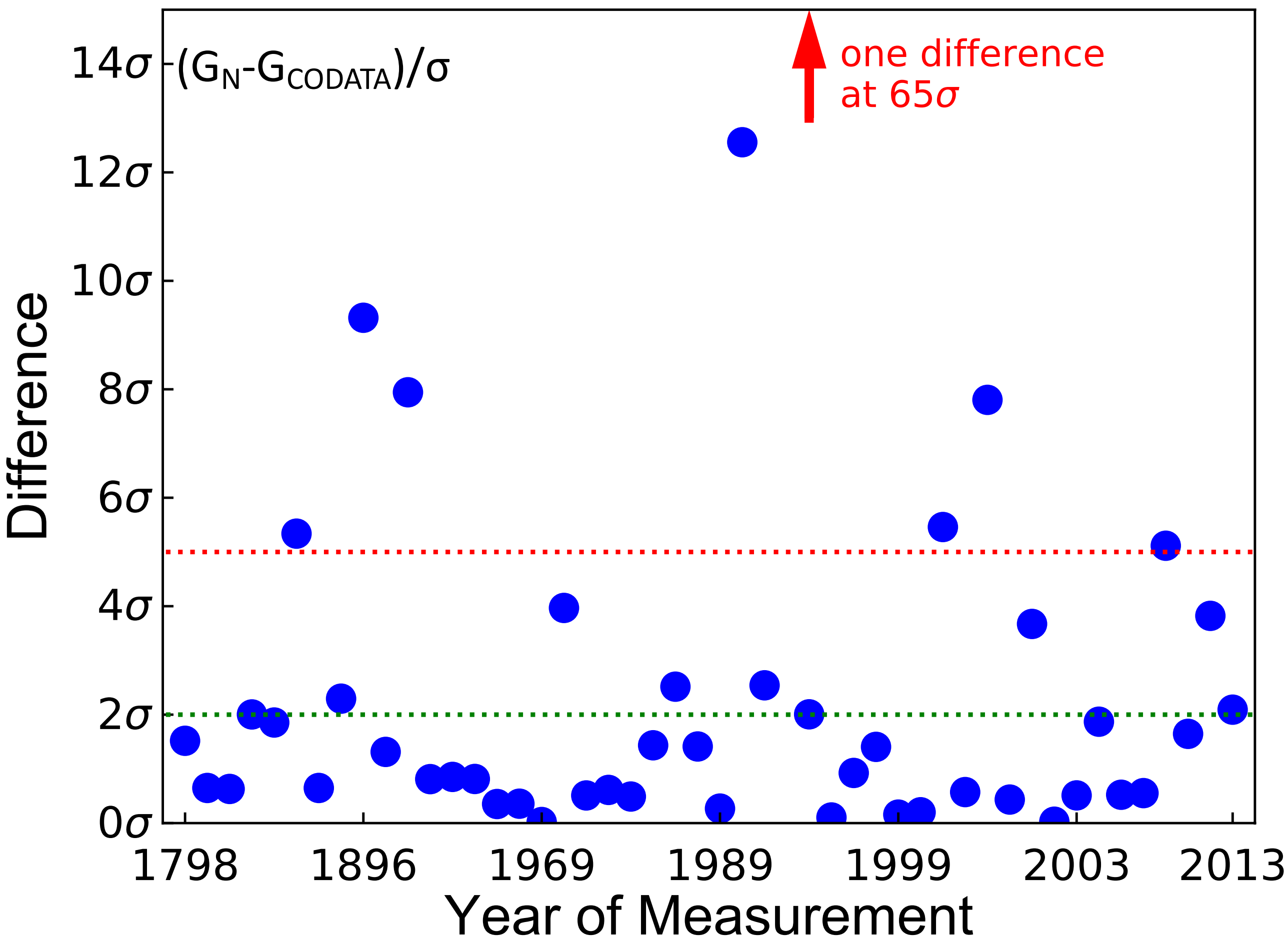
Reminder: The goal of the lab is to improve your ability to measure and model physical systems and to communicate that knowledge.

What matters is trying to do the best job possible under the circumstances, while understanding and documenting what you are doing.

Experiments are tough

- What was the 1st fundamental constant measured in a lab?
- What is the worst measured fundamental constant?

Newton's Gravitational Constant: G_N



χ^2/df since

1798 is 138
(cdf=0)

1992 is 293
(cdf=0)

1995 is 13
(cdf=10^{-26})

David Bailey, "*Why outliers are good for science*", Significance Magazine, February 2018

(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
- Judgment
  - 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.

How science is done

As proposed

Actual (successful) research

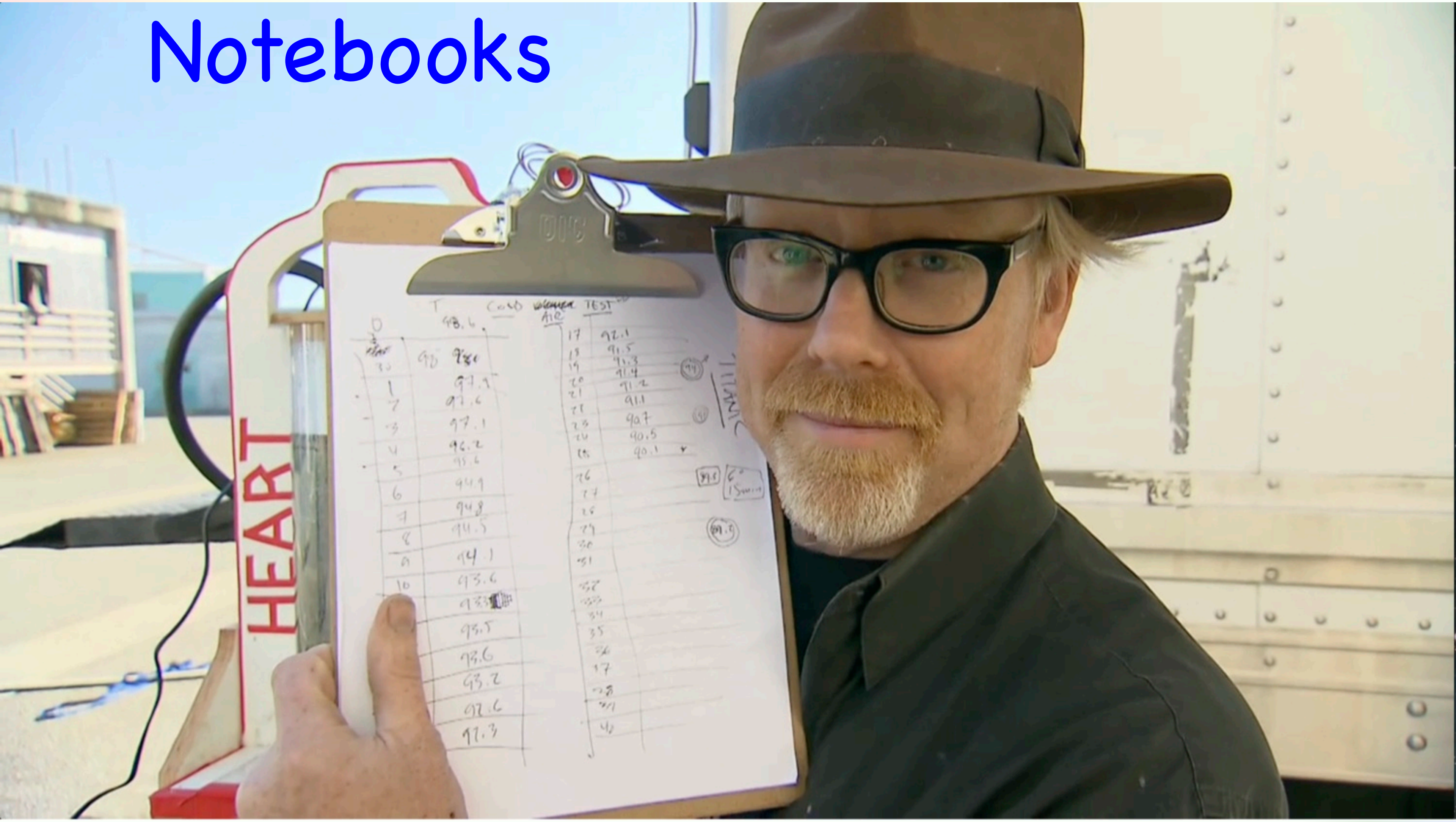
As described in published journal article

A Typical Experiment Rubric

• Attendance (~2% per meeting with prof)	10%
• Effort (~6 productive hours/week in lab)	20%
• Experimental skill ~ Achieve basic goals ~ Problem solving & making experiment work ~ Data quantity/quality	20%
• Analysis of data/uncertainty	9%
• Understanding of physics and methods ~ based on interview, notebook, and in-lab discussions	6%
• Progress check*	5%
• Notebook quality* ~ Page numbers, dates, times, diagrams/sketches, settings ~ Readability (legibility, organization, cross-references, …) ~ Completeness	14%
• Final summary/abstract*	6%
• Interview clarity*	3%

*At least 25% communications (& note that you can't get credit for good work that we don't know about or can't understand.)

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.

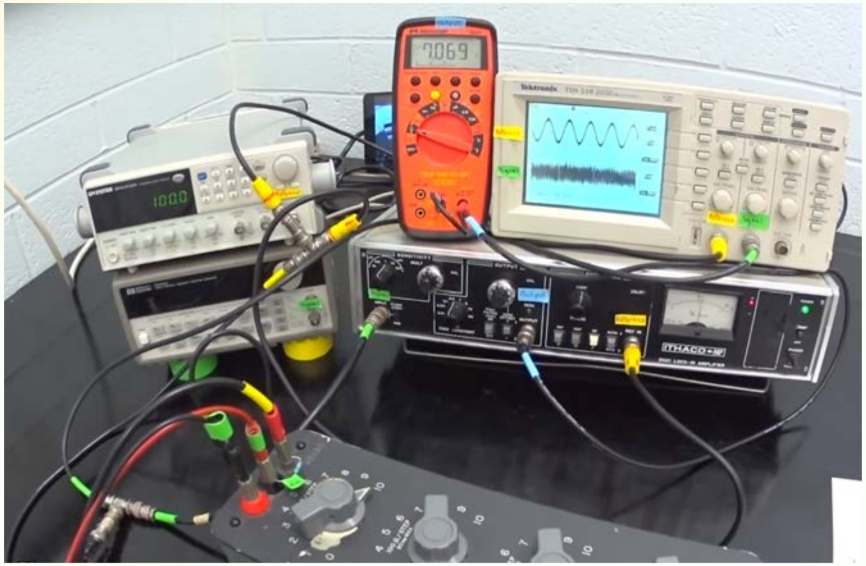
How a Prof reads a lab notebook

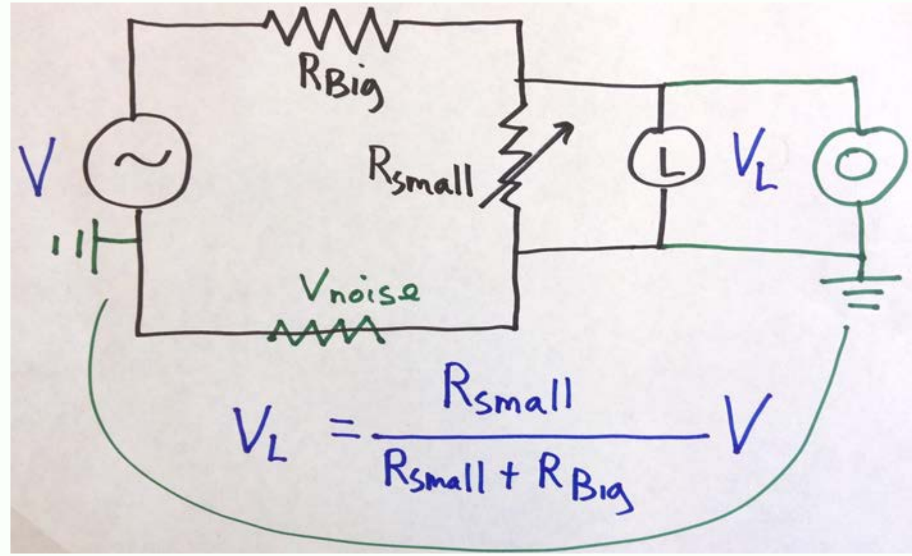
- We don't read every word.
  - But we will be unhappy if we look for some information and cannot find it.
  - Completeness first, legibility second
- We start with the Summary/Abstract
  - Your chance to guide us.
  - What is the point?
  - What was accomplished?
  - Where to find stuff?
- We love forward/backward 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.
- May reuse lab-books from previous courses
  - number all pages from beginning of notebook, not beginning of experiment.
  - date at top of each page; note time frequently.
- Notebooks are journals, not formal reports!
- Notebooks are journals!!
  - **record what happens when it happens, not later**
  - We don't want a beautiful fiction.
    - Unlike a formal report or scientific paper where the messy details and missteps may be omitted.

Photos document, diagrams model





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

Note: In interviews and oral exams we may ask what a piece of equipment does and how to use it, and sometimes how it works.

Questions?

How get started

1) Read the experiment write-up.
   – But don't trust it to be always accurate or up-to-date.
2) Check for safety warnings and issues.
3) Identify equipment
   – sketch apparatus and connections
   – note knobs and settings
4) Play with it.
   – "When I do this, that happens."
   – Try to understand what it does, i.e. model its function.
5) If necessary, check the instrument manual
   – We have manuals for most(?) instruments.
6) If needed, repeat (4).
7) Ask TA, Prof, or another student for help

Measurement Models are as Important as Physics Models

e.g. ESR (Electron Magnetic Moment)

Physics Model

- QED: $\mu_e(1 + a_e)\frac{e}{m}\vec{S}$

Fourteen thousand Feynman diagrams later

$$a_e \times 10^{12} = 1159652181.643$$
$$\pm 0.025 \text{ (8}^{\text{th}}\text{ order QED)}$$
$$\pm 0.023 \text{ (10}^{\text{th}}\text{ order QED)}$$
$$\pm 0.016 \text{ (weak/hadronic)}$$
$$\pm 0.763 \; (\alpha_{Rb10})$$

Measurement Model

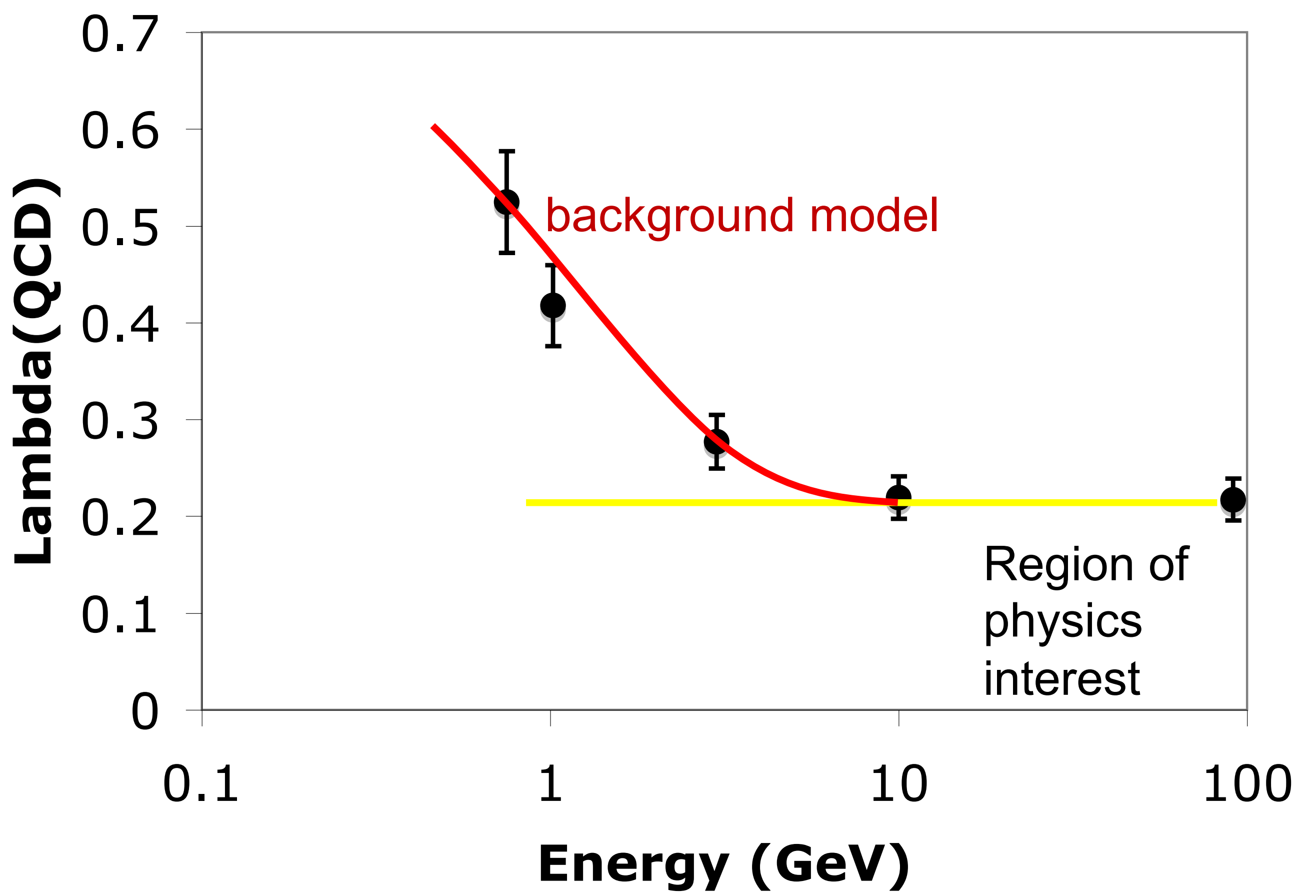
- dipole in uniform magnetic field
  - DC electromagnet
  - AC coils
  - gaussmeter
- microwaves
  - Gunn diode
  - Resonant Cavity
  - waveguides
  - magic T
  - modes
  - absorption
- electrical measurement
  - oscilloscope, multimeter
- electrons in matter
  - how free are they?
- experimenter makes many decisions
- …

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

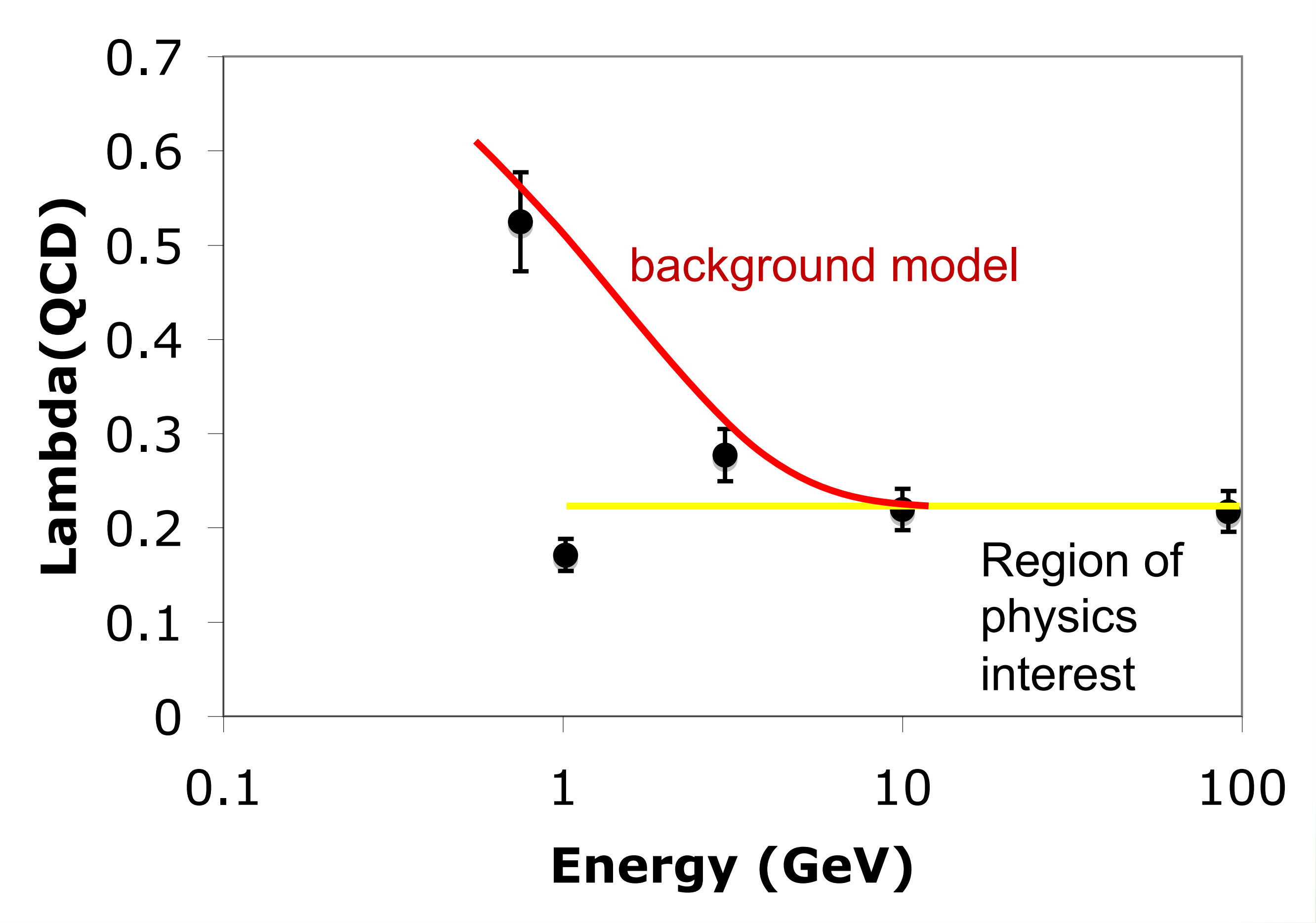
Try to be efficient*

Where should you take more data?



* But "if you are not wasting some time, you are wasting time"; "the perfect is the enemy of the good"

Where should you spend your time here?



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
  - Better to have less data that is well understood rather than lots of data poorly analyzed.

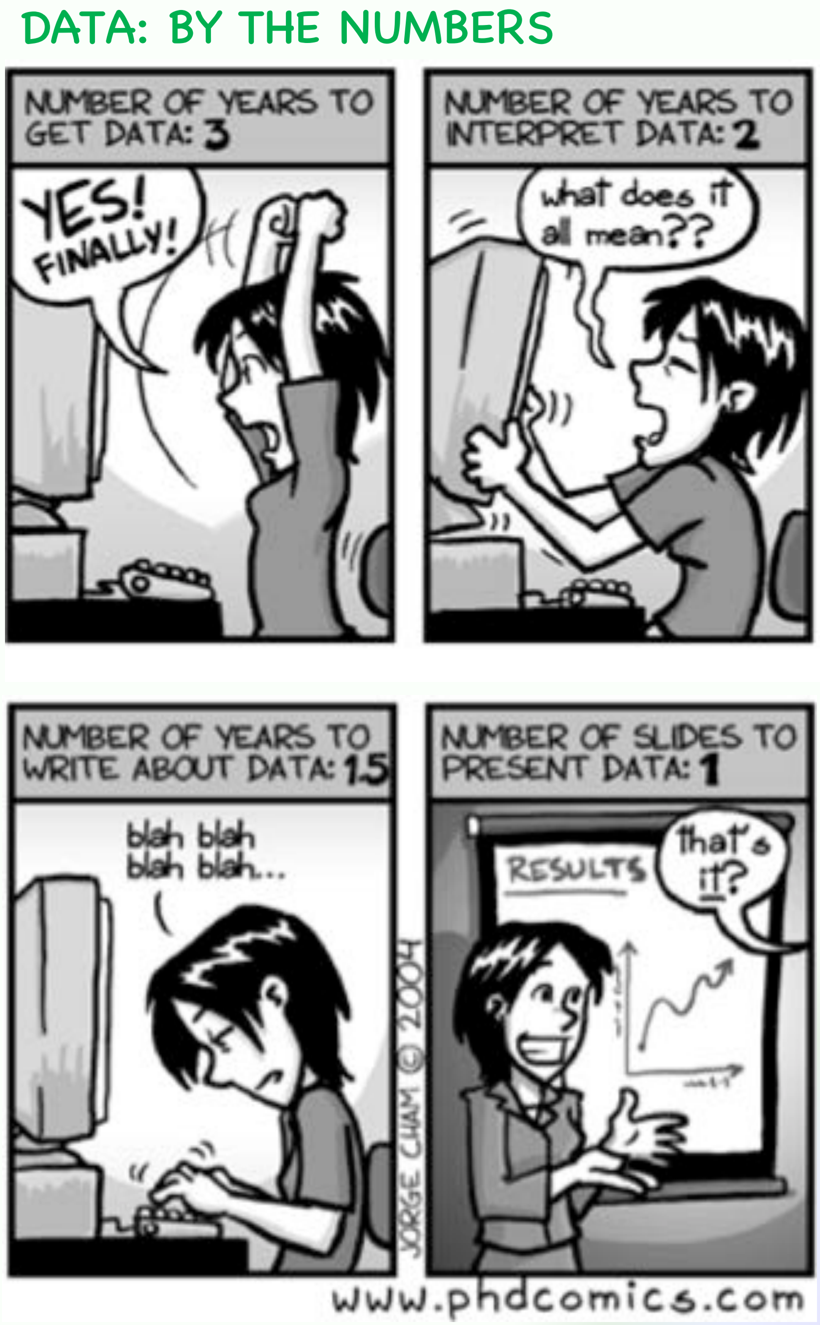
Formal Report

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

You Can Do It!

- You have all completed at least 2 years of university level physics.
- All these labs have something interesting that you can figure out and learn from.
- Try to have fun!
- Often things go wrong or something breaks or changes
  - That is part of experimental physics (and scientific research in general).
  - Just document EVERYTHING in your notebook, try your best to fix things, and seek help when appropriate.
- If you do these things, show up regularly and put in your best effort, you will be well on your way towards a good grade in this course!

Questions ?



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 in our models
- Uncertainties parameterize the likelihood that two measurements will agree.
  - not the probability distribution for 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

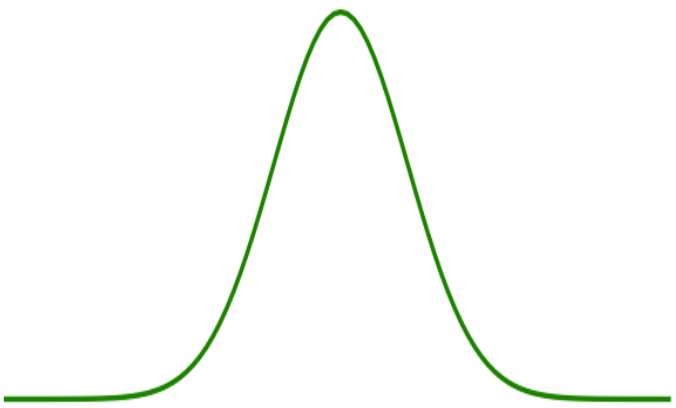
$$|x - x_i| < \sqrt{\sigma^2 + \sigma_i^2}$$

- 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.
- The Central Limit Theorem says (almost?) everything averages out to a Gaussian.
- Many resolution functions approximately Gaussian.

Normal Assumption

- Often works pretty well for "statistical uncertainties", i.e. those uncertainties that automatically get smaller as you take more data.
  - e.g. $\sigma_{stat} = \sigma_{STD}/N^{1/2}$

- But understanding the systematics is what takes forever … (literally)

Systematic Uncertainties

Correlated (rather than random) errors that are NOT simply reduced by taking more data.

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, …

Causes long uncertainty tails!

http://rsos.royalsocietypublishing.org/content/4/1/160600

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.**

Analysing Data

e.g. for Data Analysis assignment

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 common 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 the language we support.

Weighted Least Squares

- Minimize

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{y_i - f\left(x_i; \mathbf{p}\right)}{\sigma_i} \right)^2$$

- Ordinary/linear least squares assumes equal uncertainties and hence minimizes

$$\chi^2 = \frac{1}{\sigma^2} \sum_{i=1}^{n} \left(y_i - f\left(x_i; \mathbf{p}\right)\right)^2$$

- **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.

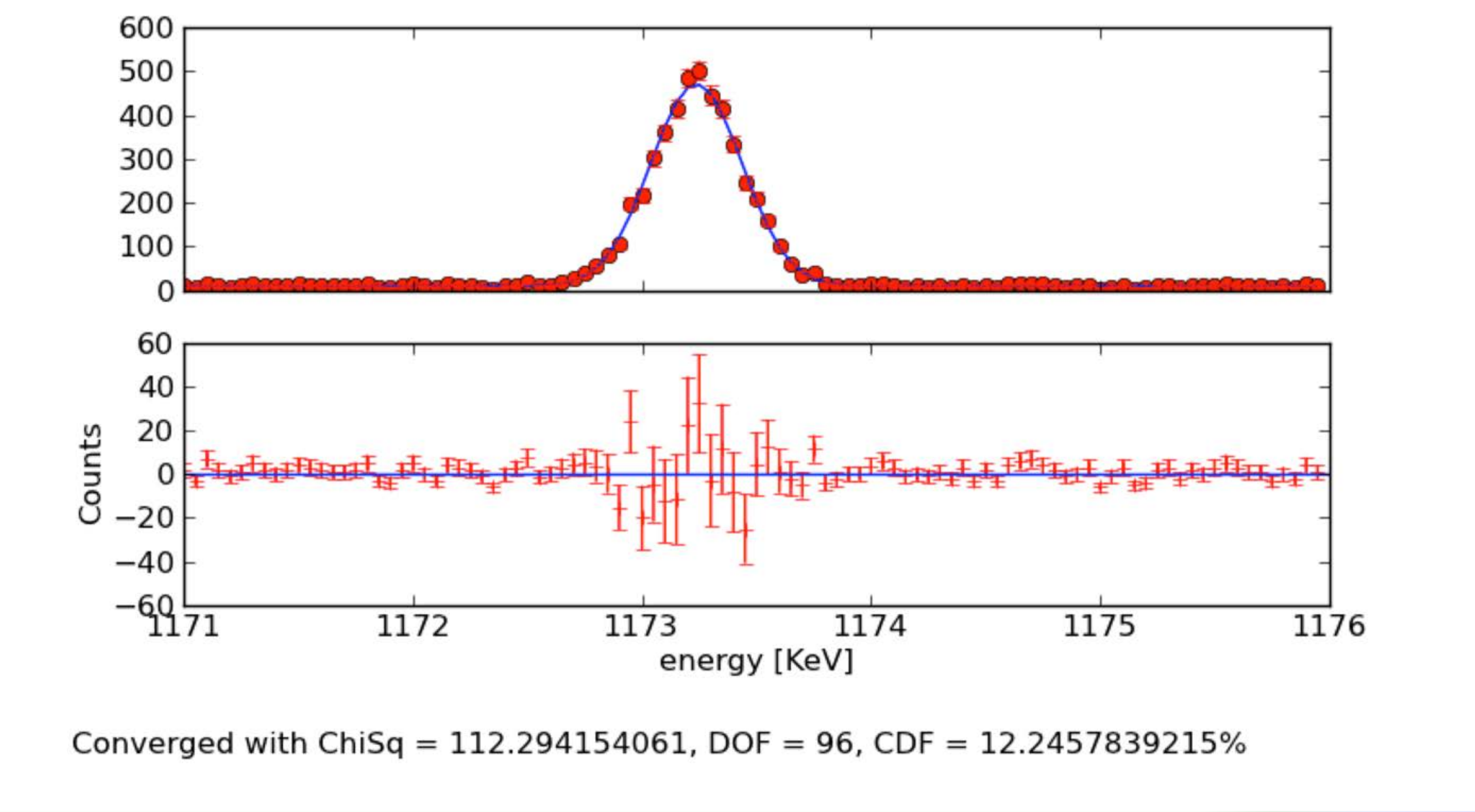
Python for the Advanced Lab

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

- curve_fit_to_data.py or
  - simple_curve_fit_to_data.py
  - extended_curve_fit_to_data.py
- odr_fit_to_data.py or
  - for errors in x and y
- odr_fit_extended.py (new)
  - calibration or systematic errors
  - non-Gaussian uncertainties
- If you don't base your analysis on these, please be sure you know what you are doing.

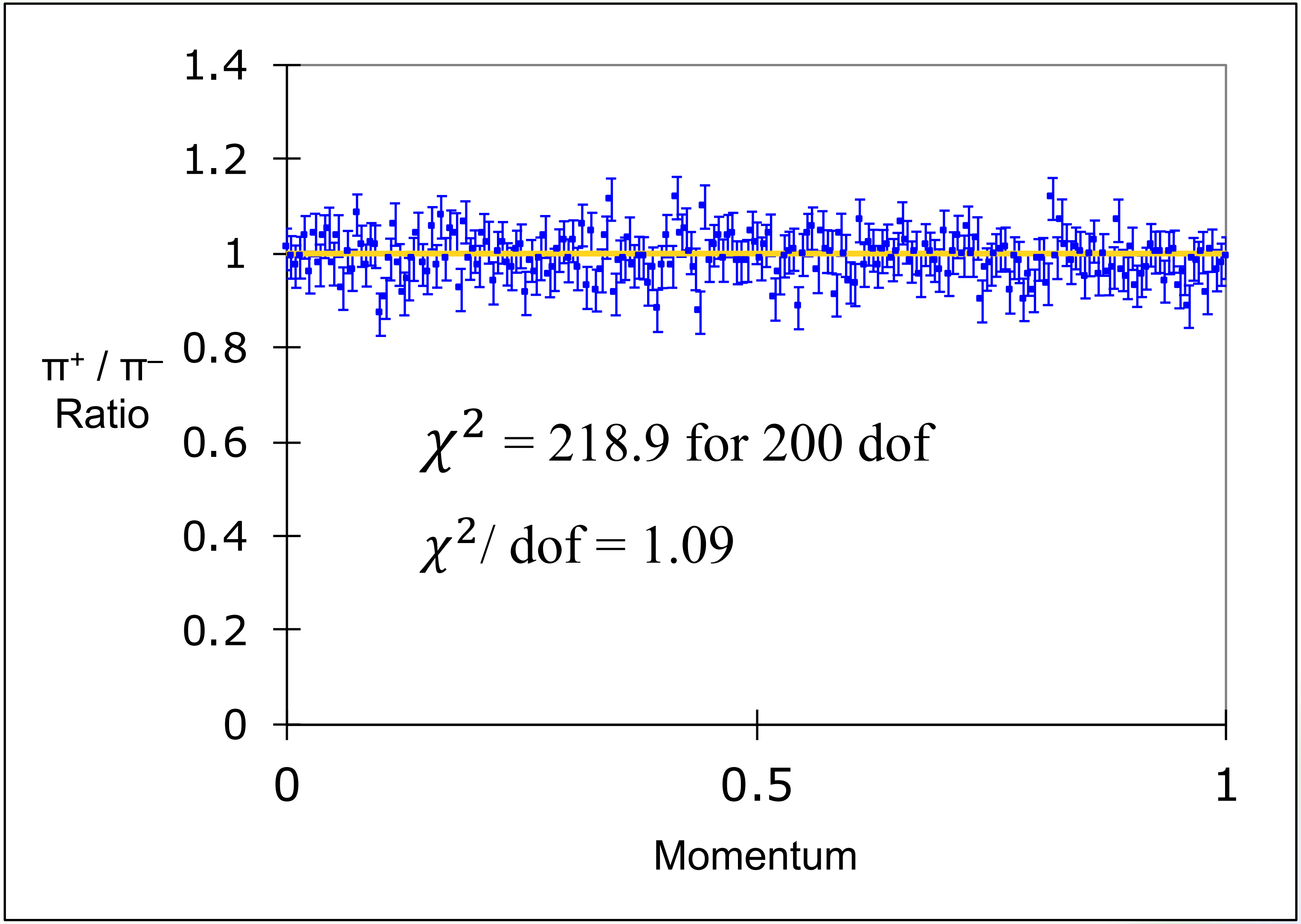
Example

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



χ^2/dof is insufficient

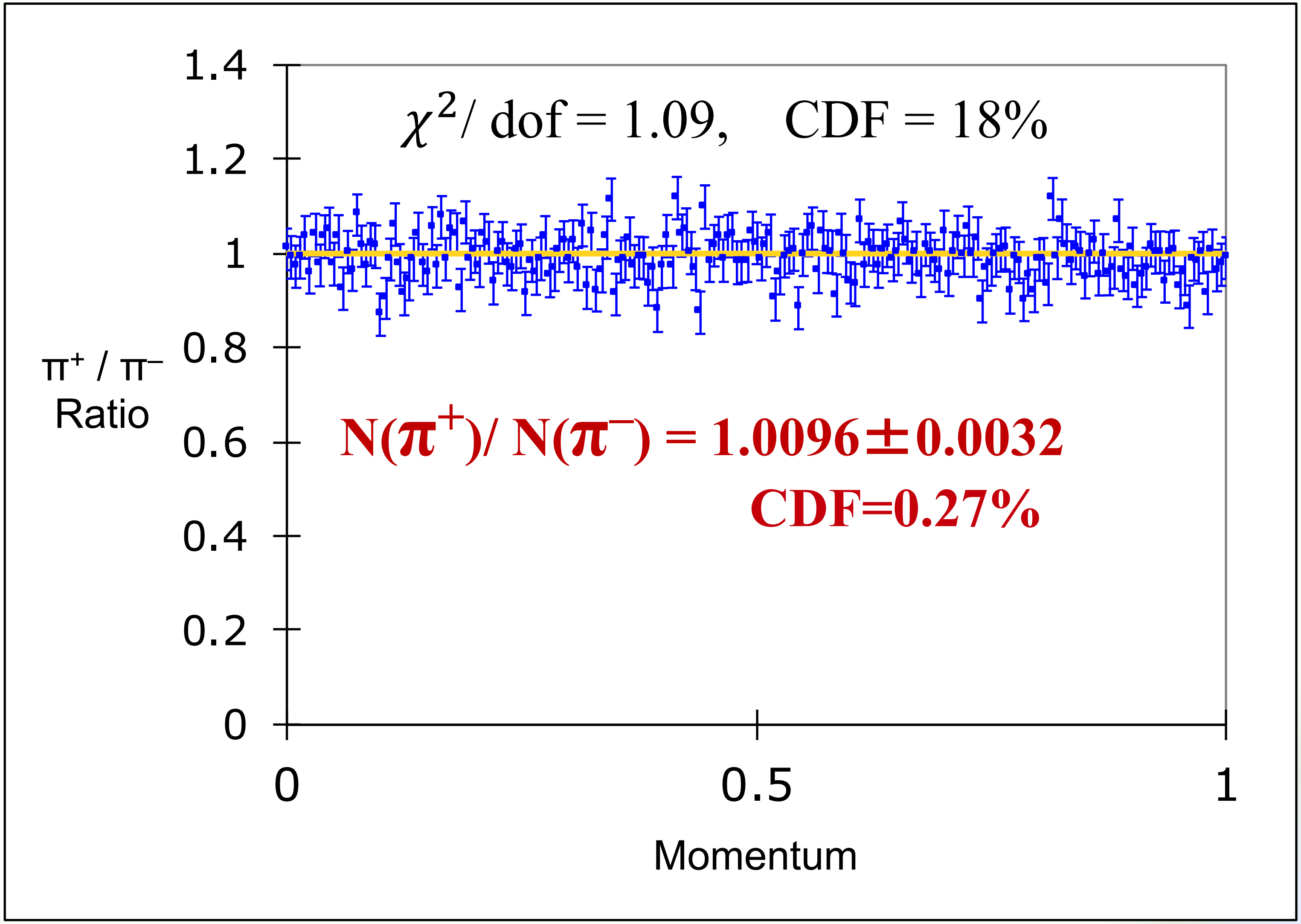
χ^2/ DoF	DoF	CDF
1.09	200	18%
1.09	800	4%
1.09	3200	0.02%
1.7	200	0.0000002%
1.7	20	3%
1.7	8	9%

χ^2/dof near 1 does not always mean it is a good fit.

χ^2/dof away from 1 does not always mean it is a bad fit.

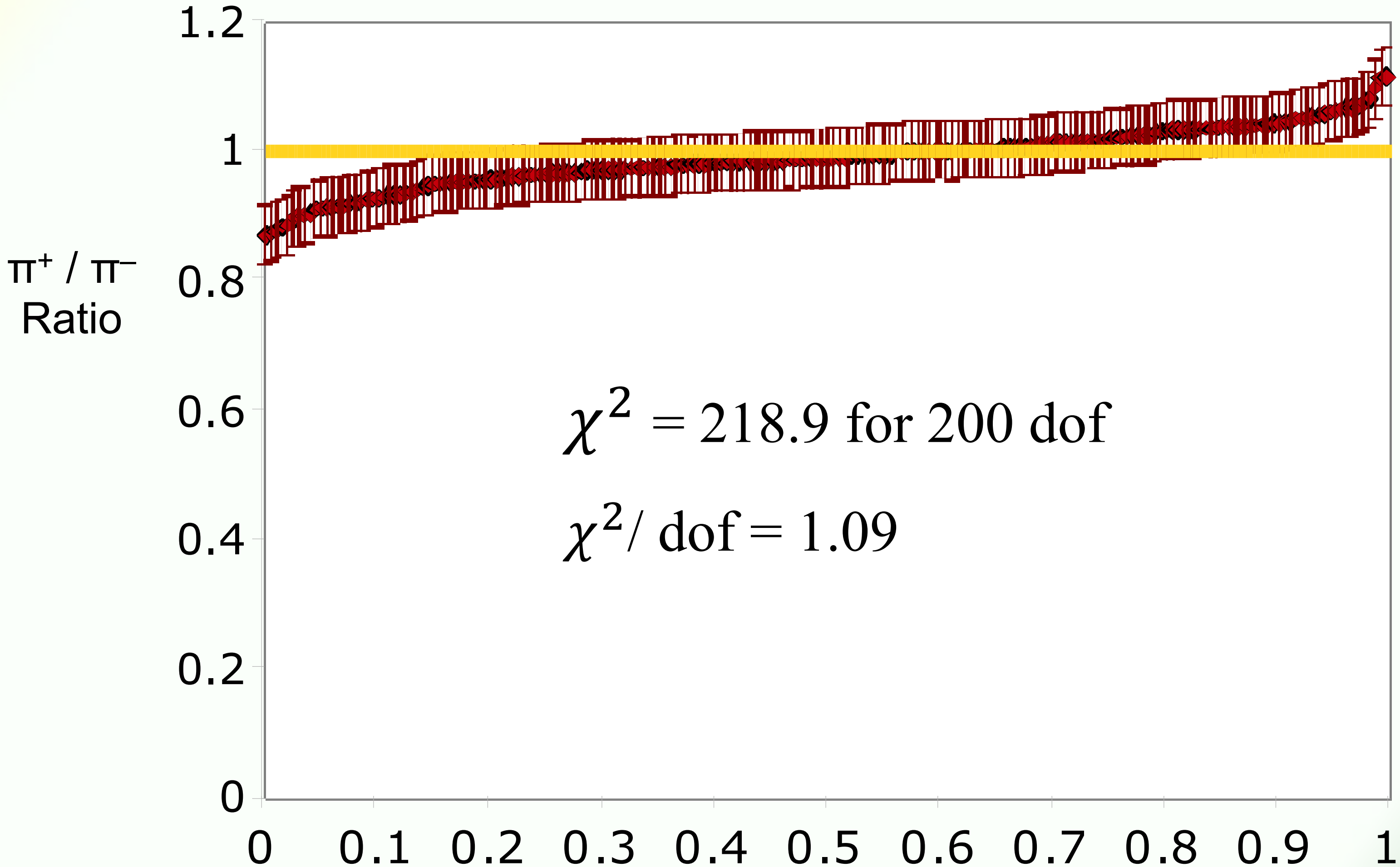
χ^2 does not tell you everything

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



Is this a good fit?

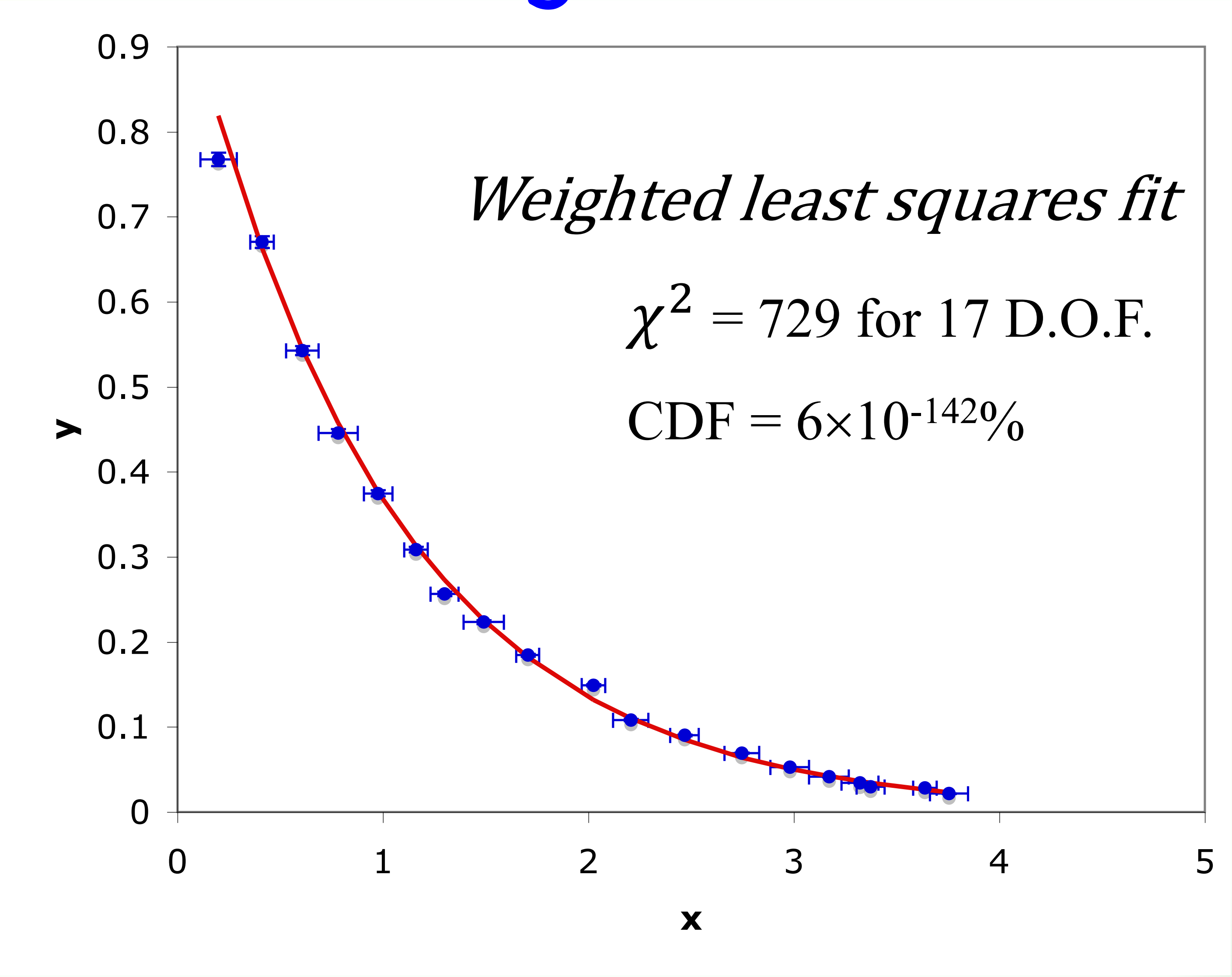
- i.e. Do (red) data and (yellow) model agree?



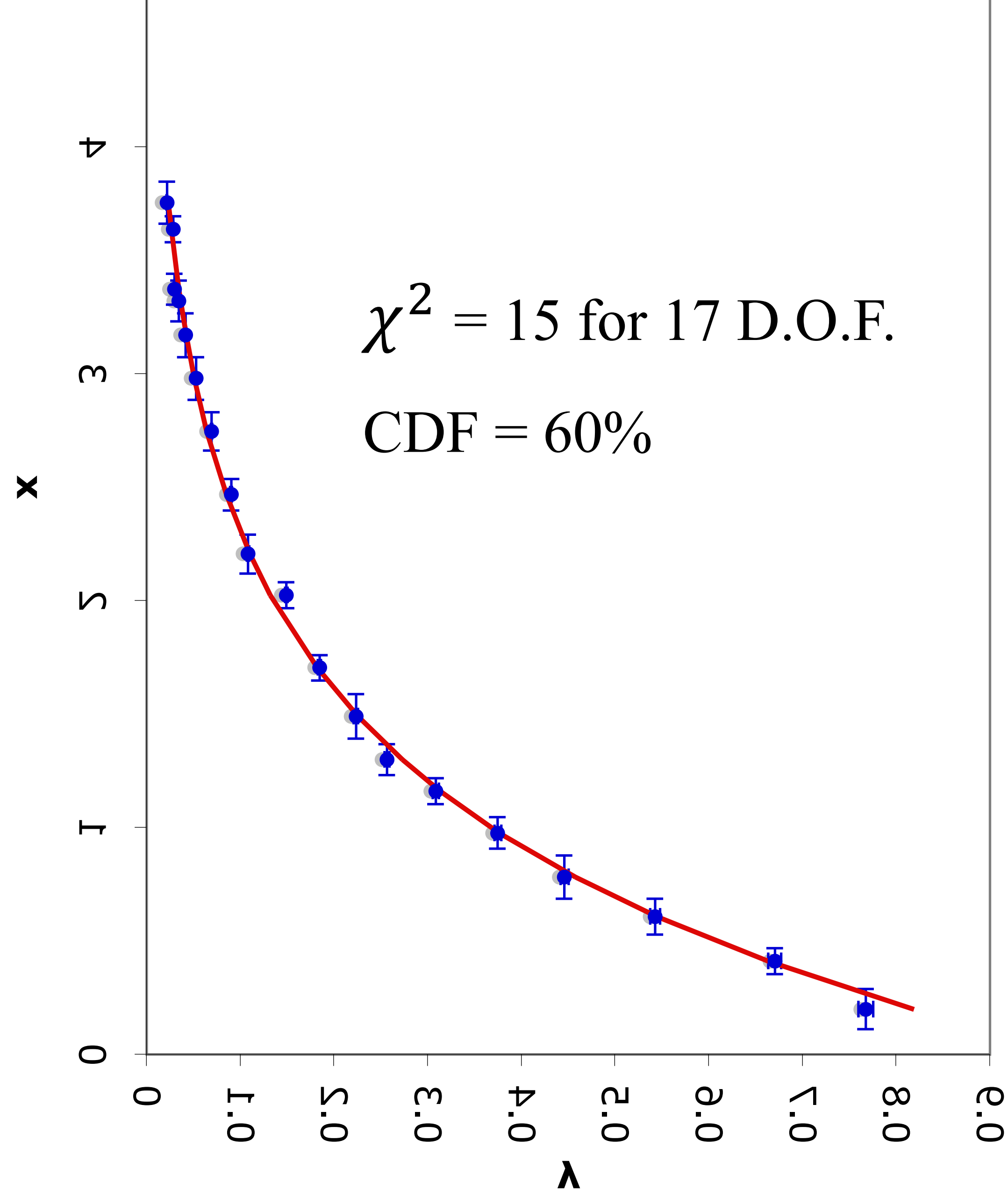
$\chi^2 = 218.9$ for 200 dof

$\chi^2/\text{dof} = 1.09$

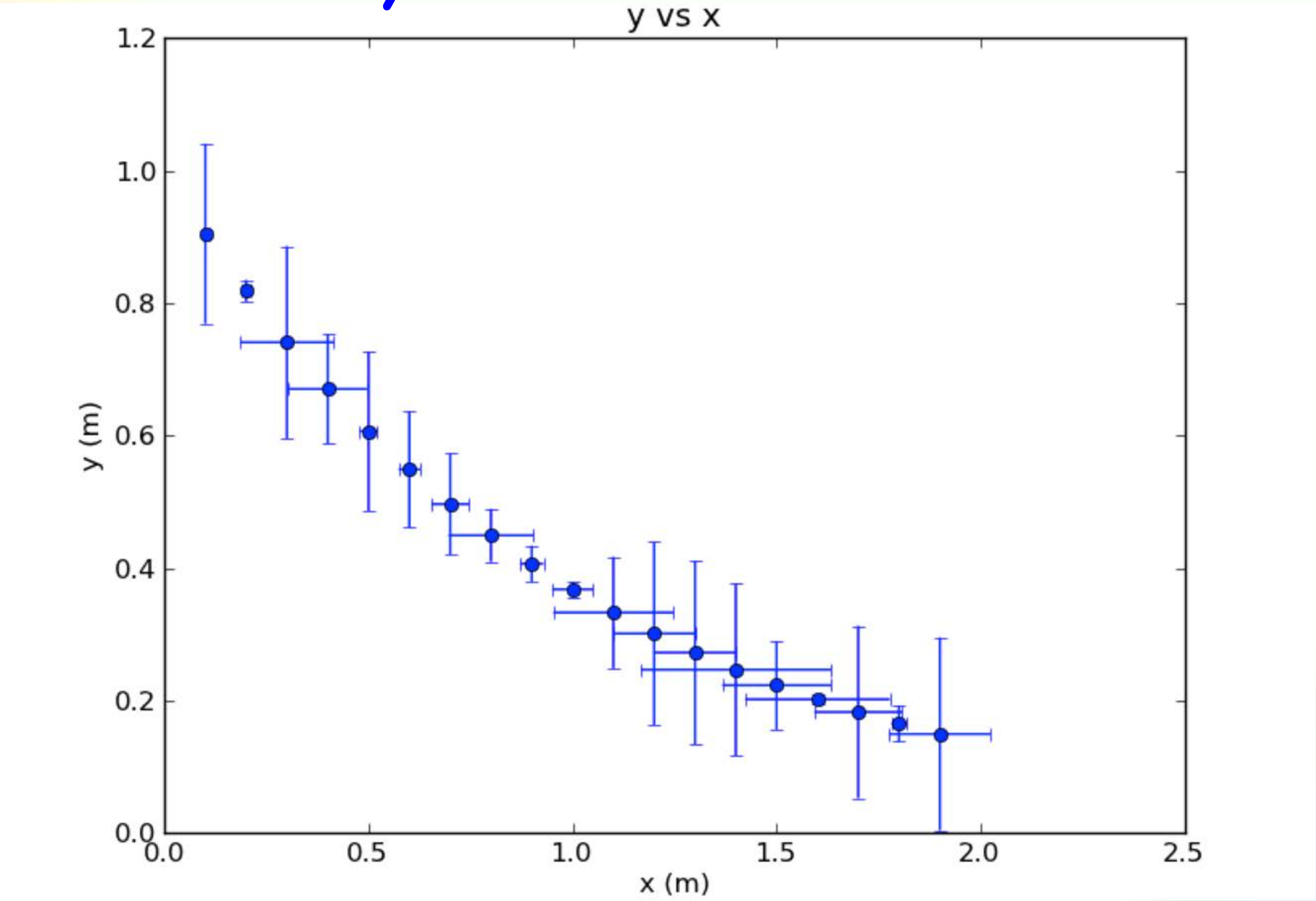
Is this a good fit?



What about this data?

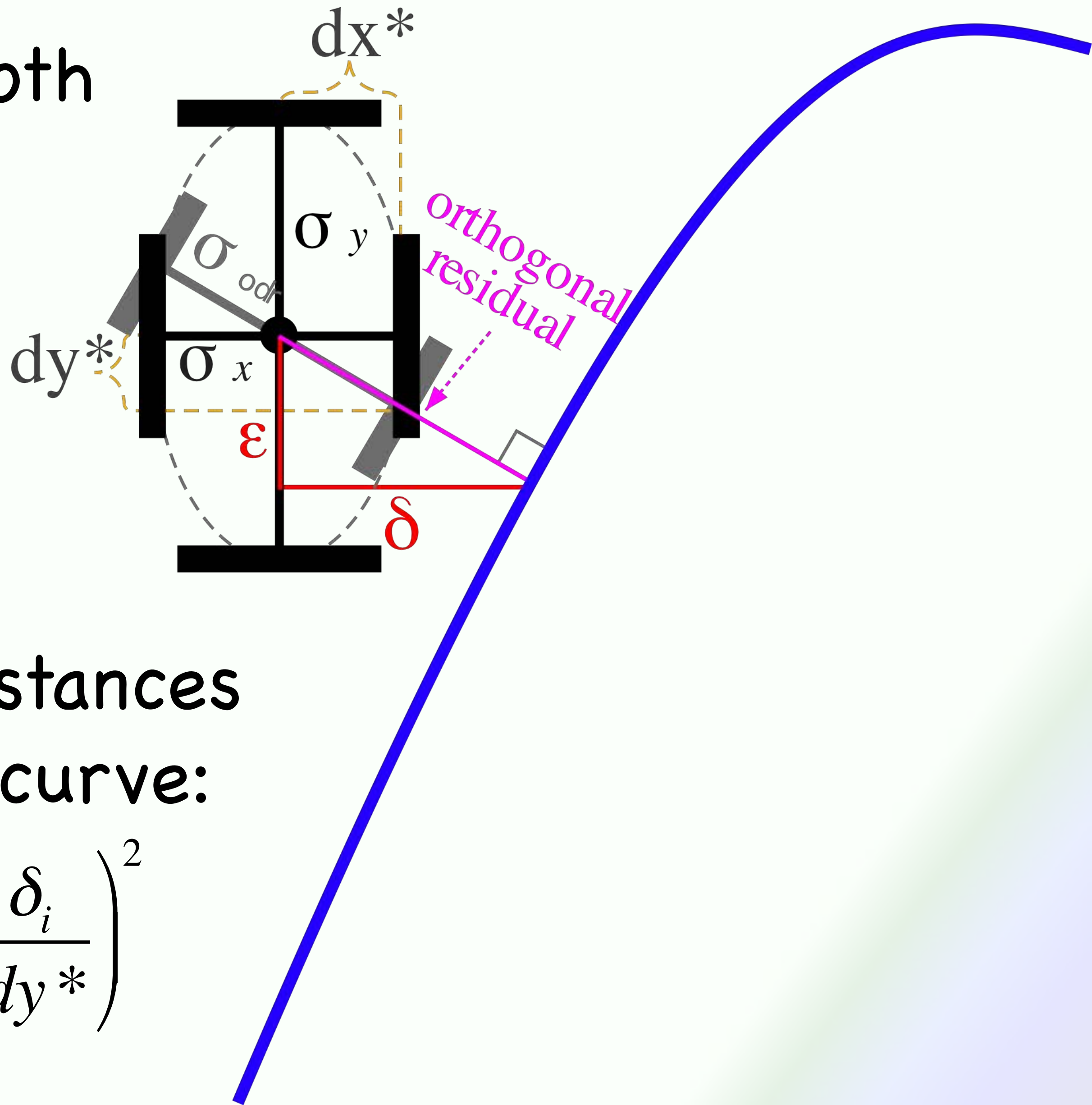


How do you fit this data?



Orthogonal Distance Regression

- Good when both σ_x and σ_y are significant

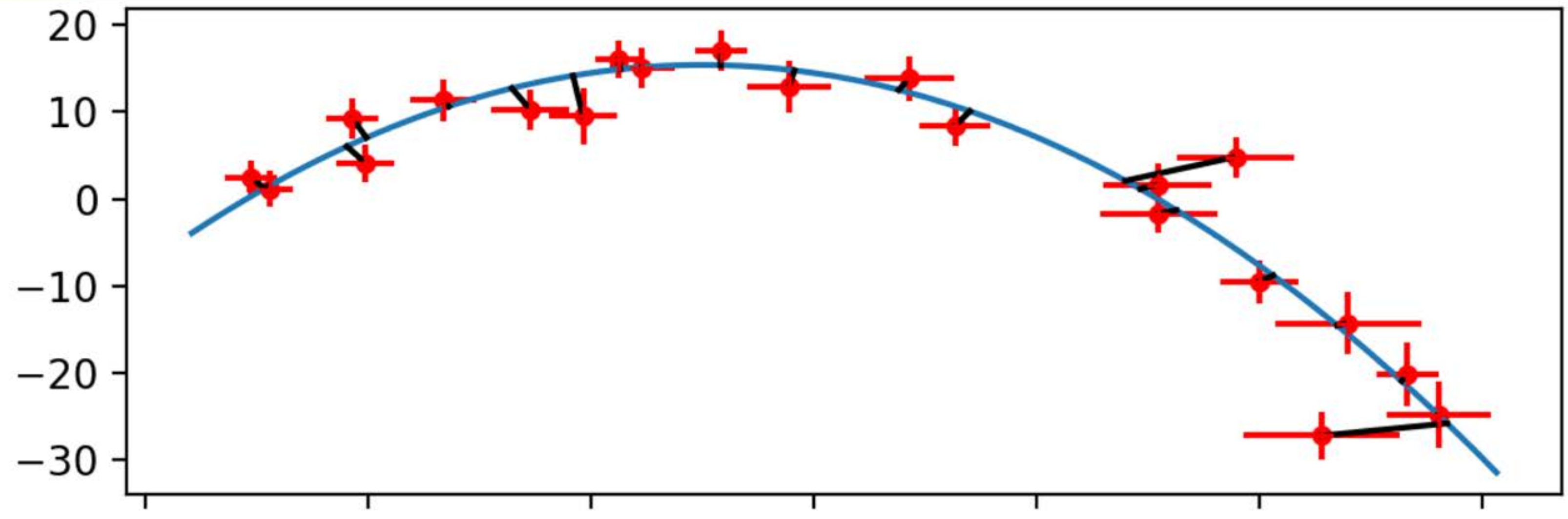


- Minimizes orthogonal distances from data to curve:

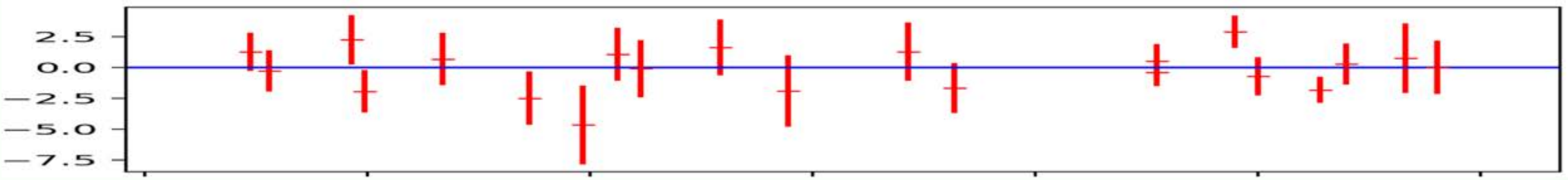
$$\sum_{i=1}^{n}\left(\frac{\varepsilon_i}{dy^*}\right)^2+\left(\frac{\delta_i}{dy^*}\right)^2$$

ODR Example

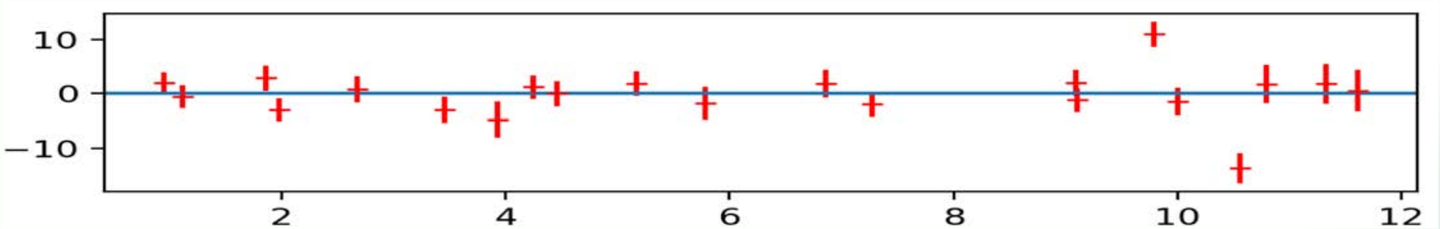
(parabola_xy_errors.txt)



ODR: $\chi^2/\text{df} = 0.96$; CDF = 51%

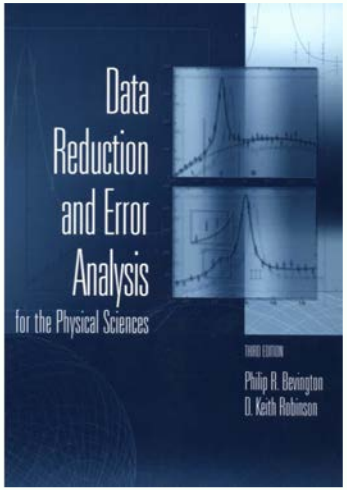


LSq: = 3.3; CDF = 0.0002%



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

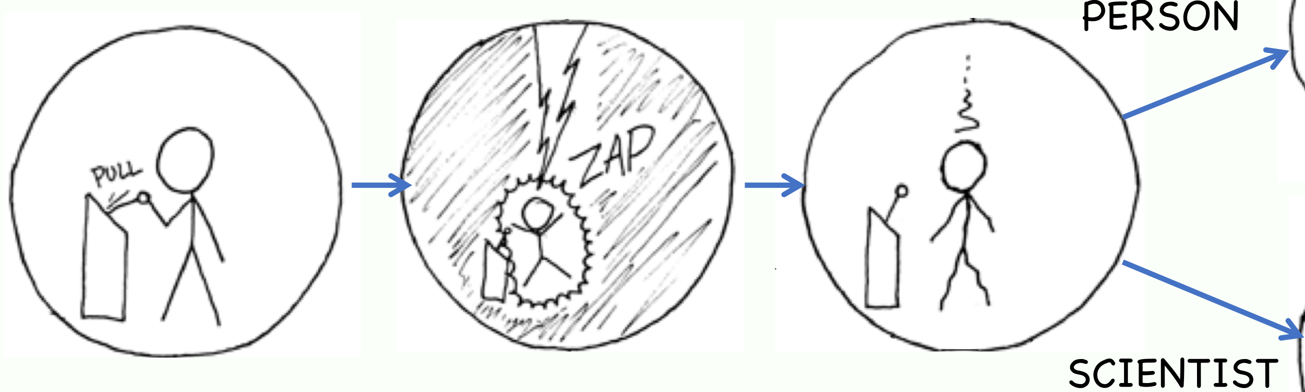
Data Analysis Assignment

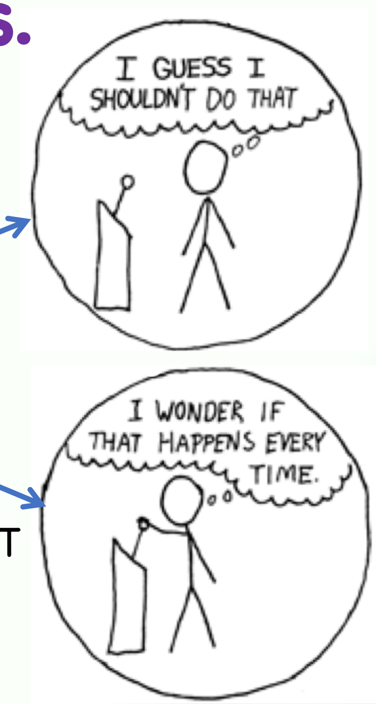
- Required of all first-time APL students
- Ensures students have skills needed for APL data analysis.
  - nonlinear fitting
  - uncertainties in both x and y
  - careful thought and communication about analysis and uncertainty.

Questions?

Reminders

- **Return Preference Sheet by 4pm today.**
  - **Your experiment will be posted on course website by Monday noon.**
- **Read the course outline.**
  - **Talk to me if you have questions.**
- **Have Fun!**





The Difference, https://xkcd.com/242/, by Randall Munroe (CC BY-NC 2.5), rearranged