Physics 3306

Provides an introduction to a wide variety of topics in classical (pre-quantum) physics as a bridge to prepare students for subsequent upper-level courses in physics. The topics covered include thermodynamics, fluid mechanics, mechanical waves, optics, radiation, electromagnetic phenomena, atoms, and laboratory techniques. Prerequisites: C- or better in PHYS 1106; and in PHYS 1304 or PHYS 1308.

Saptaparna Bhattacharya

January 22nd, 2025

Who am I?

- I joined Southern Methodist University as an Assistant Professor in the fall of 2024
- I am building my new group and recruiting a postdoc and students
- I work on the **ATLAS** experiment
- My experiment is at CERN
- My research interests lie in multiboson physics, polarization measurements and effective field theories
- I am also interested in studying event generators on GPUs and contributing to ATLAS upgrades

Are we all here?
Lets do an attendance check
Also, do our computers work?

Are people getting my emails from canvas?

Structure of a laboratory notebook

jupyter 01_Time_Mass_Length_Measurements Last Checkpoint: 2 months ago

File Edit View Run Kernel Settings Help Trusted

Markdown JupyterLab Python 3 (ipykernel)

Write your name, section, and today's date in the cell below:

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Name -
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Synopsis

1. To learn:

- Instruments to measure time, mass and length,
- Physics in instruments beyond hand tools.

2. To do:

- Use the provided hand tools to measure time, mass (weight) and length,
- Research tools that measure nano meter or mass of atoms.

Purpose of this lab:

- Physics, which studies matter, energy and the interactions among them, is a science based on observations, measurements and modeling, in the language of mathematics.
- The ability to select and utilize the right instruments to conduct a measurement is essential in research and engineering. Above this is the understanding of the physics that empowers the instruments. This understanding leads to invention of new instruments which is the vanguard in advancing cutting-edge work.

Measurement in mechanics:

The basic measurements are for time, mass and length.

Installing and running jupyter-notebooks

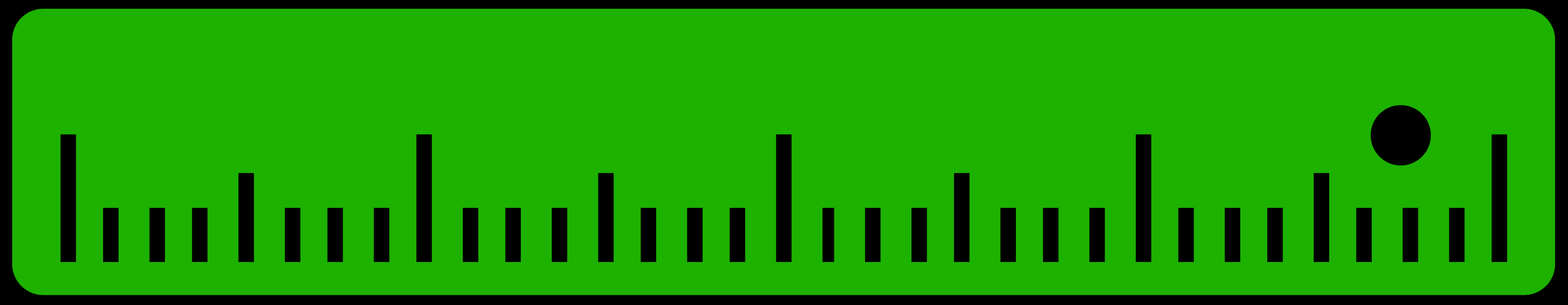
- What is a jupyter-notebook:
  - “The **Jupyter Notebook interface** is a Web-based application for authoring documents that combine live-code with narrative text, equations and visualizations.”
- What kind of computers are we using?
- For installation of jupyter-notebooks:
  - Various methods here: https://docs.jupyter.org/en/latest/install.html
- We want to install the classic notebook:
  - https://docs.jupyter.org/en/latest/install/notebook-classic.html

Structure of the lab - I

- Some labs, specially an introductory lab, where we are measuring lengths, studying an oscilloscope and building simple circuits can be done individually
- Some of the more complicated experiments will be done in groups of 2 (or exceptionally 3)
- Error analysis and lab notebook submission, including jupyter-notebooks will be done individually
  - Each of you must record your work on your own!
  - This means doing an error analysis of your measurement
  - The questions in the jupyter-notebooks are sometimes open ended, so let them reflect your originality!

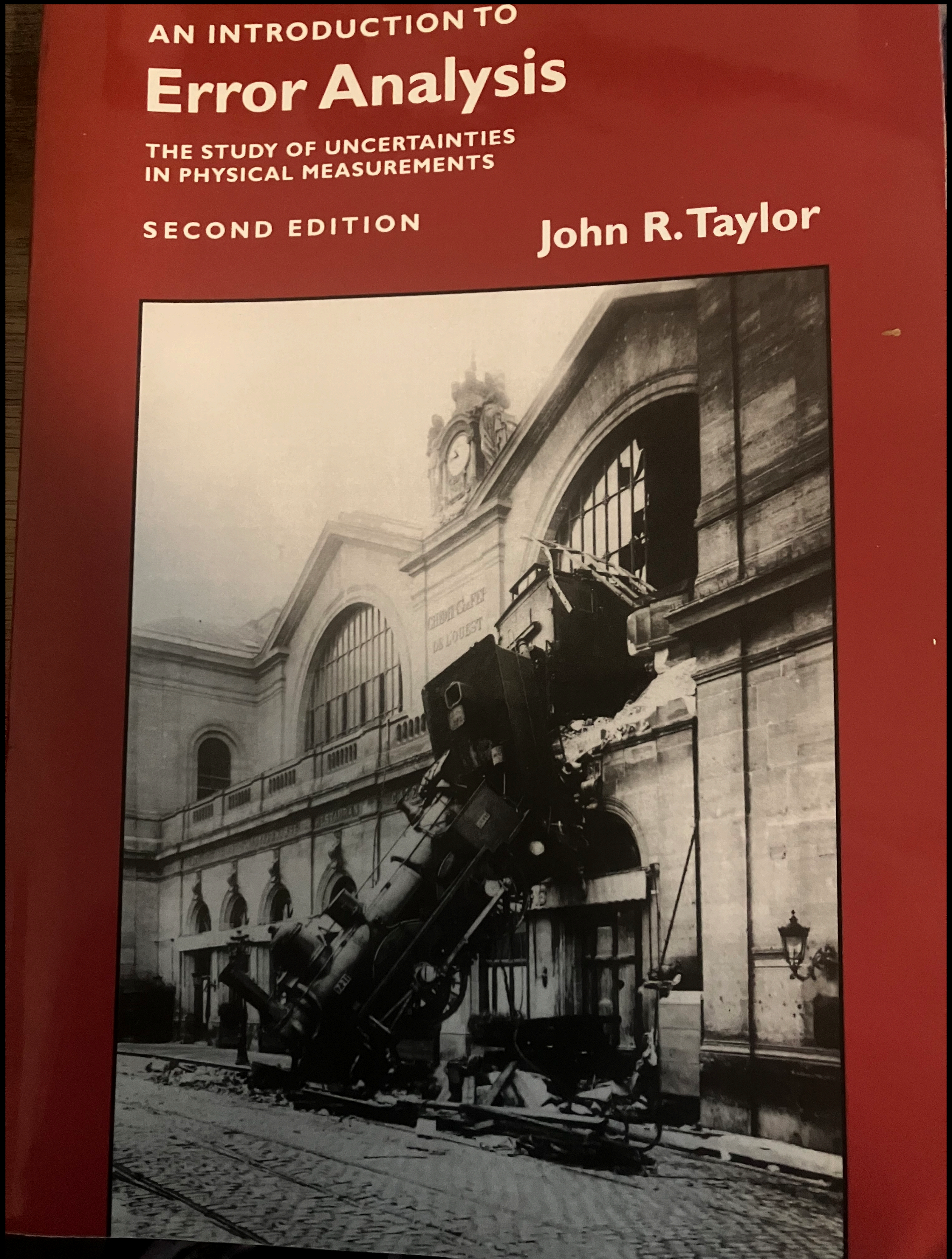
Structure of the lab - II

- Any measurement, whether it is a measurement with a ruler or measurement with a measuring scale, is always accompanied with an error!
- Error analysis "is the study and evaluation of these uncertainties"
- It serves two main functions:
  - Allows us to estimate uncertainty
  - Reduce them when necessary



Reference

Considered a classic!



What happens when measurements are done improperly?

Story 1: On September 23, 1999 NASA lost the $125 million Mars Climate Orbiter spacecraft after a 286-day journey to Mars. Miscalculations due to the use of English units instead of metric units apparently sent the craft slowly off course -- 60 miles in all. Thrusters used to help point the spacecraft had, over the course of months, been fired incorrectly because data used to control the wheels were calculated in incorrect units. Lockheed Martin, which was performing the calculations, was sending thruster data in English units (pounds) to NASA, while NASA's navigation team was expecting metric units (Newtons).

https://spacemath.gsfc.nasa.gov/weekly/6Page53.pdf

What happens when measurements are done improperly?

Story 3: On 23 July 1983, Air Canada Flight 143 ran completely out of fuel about halfway through its flight from Montreal to Edmonton. Fuel loading was miscalculated through misunderstanding of the recently adopted metric system. For the trip, the pilot calculated a fuel requirement of 22,300 kilograms. There were 7,682 liters already in the tanks.

https://spacemath.gsfc.nasa.gov/weekly/6Page53.pdf

What happens when a proper error analysis is not done…

https://keninstitute.com/the-worst-engineering-disasters-due-to-mechanical-errors/

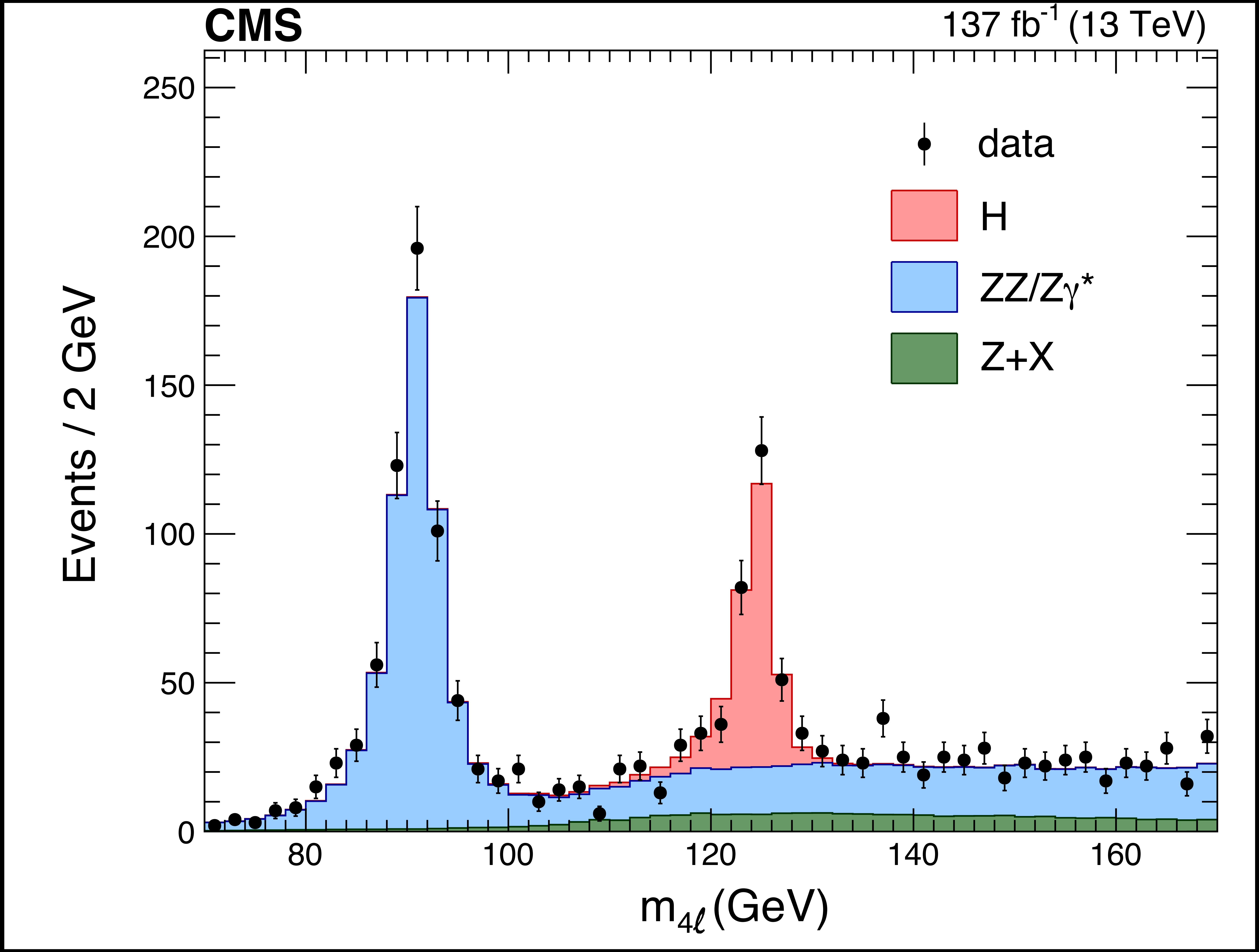
• Space Shuttle Challenger Disaster (1986)

The Space Shuttle Challenger exploded 73 seconds after lift-off, resulting in the deaths of all seven crew members. The disaster was traced back to the failure of an O-ring seal in one of the shuttle's solid rocket boosters, which was exacerbated by cold weather conditions.

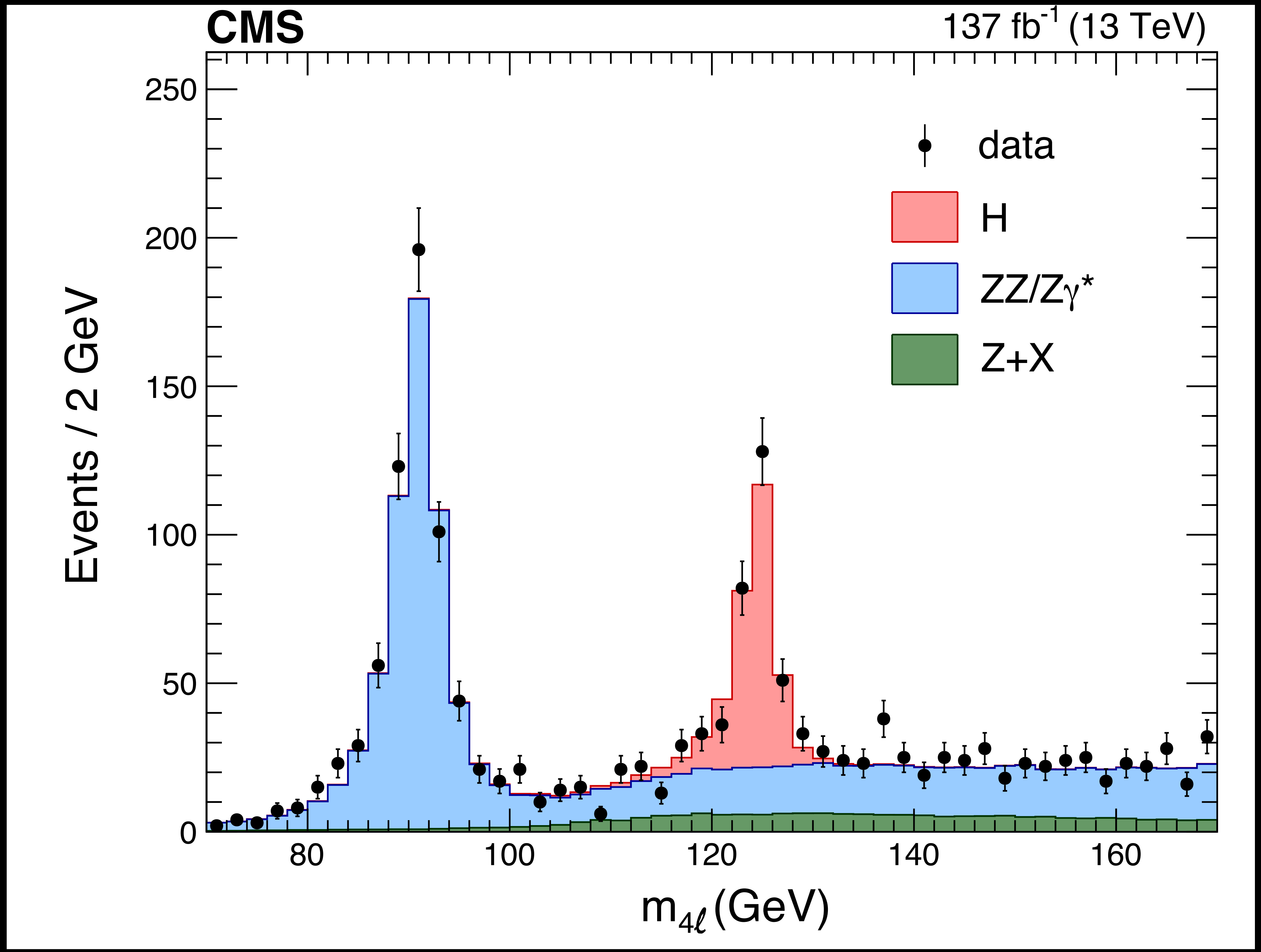
The cause of this Engineering Disaster was the failure of the primary and secondary redundant O-ring seals in a joint in the shuttle's right solid rocket booster (SRB). The record-low temperatures on the morning of the launch had stiffened the rubber O-rings, reducing their ability to seal the joints. Shortly after liftoff, the seals were breached, and hot pressurized gas from within the SRB leaked through the joint and burned through the aft attachment strut connecting it to the external propellant tank (ET), then into the tank itself. Both SRBs detached from the now-destroyed ET and continued to fly uncontrollably until the range safety officer destroyed them.

Let’s look at an experimental example

Signal in red peaks out!
This is a great example of a graph!

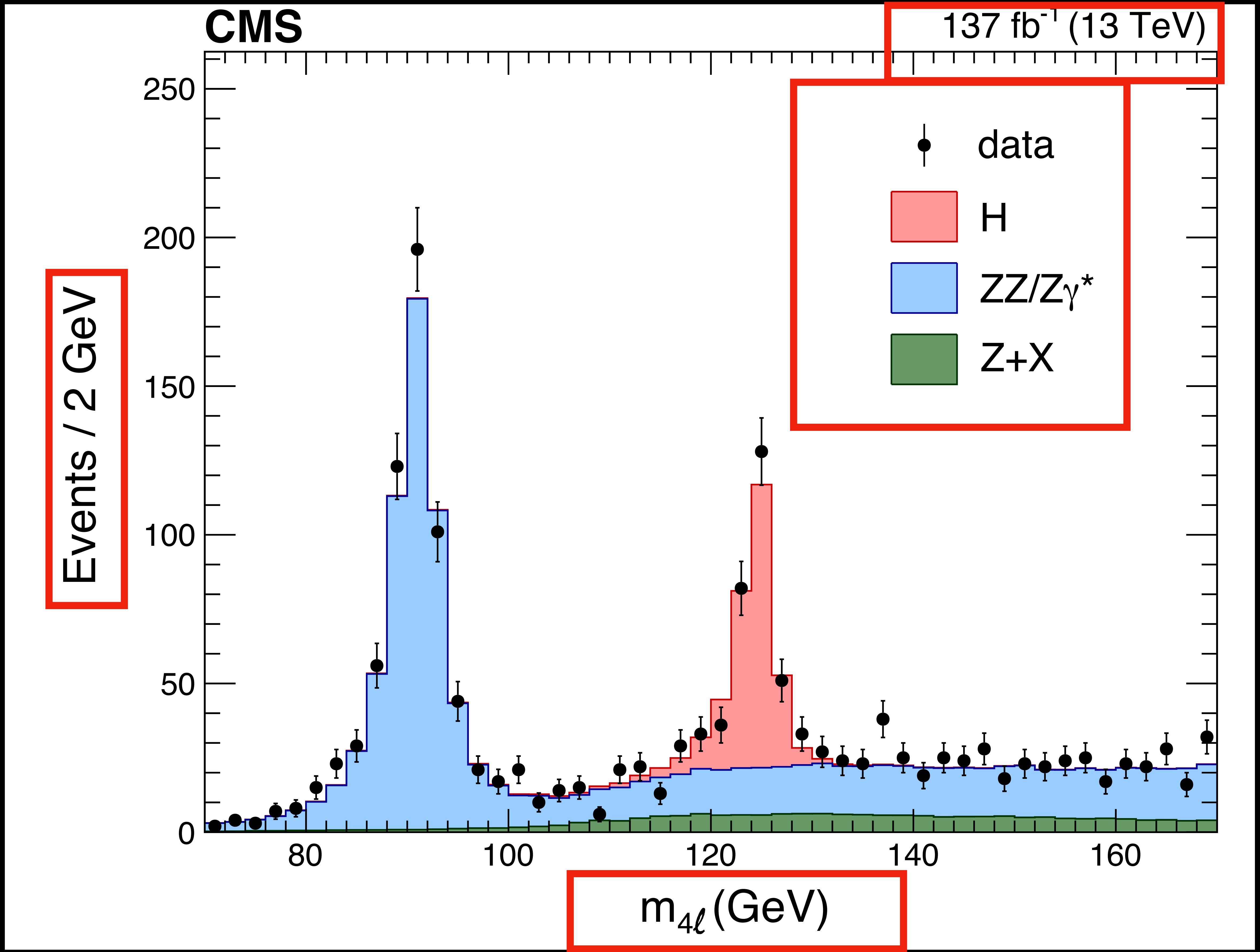


Let’s take a quick detour: what makes a good graph?



- What do you notice?

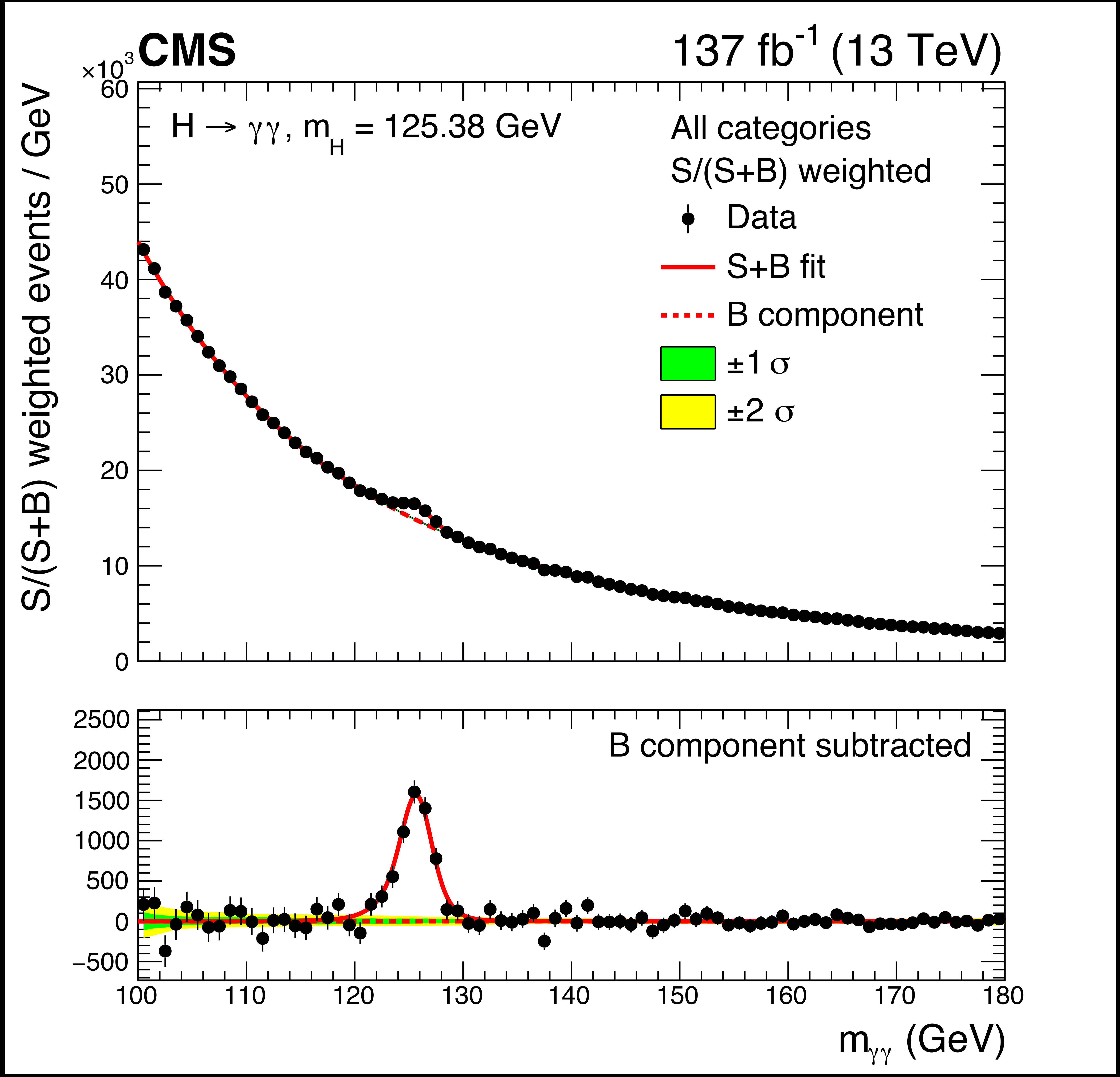
Let's take a quick detour: what makes a good graph?



- What do you notice?
  - What kind of graph is this?
  - Clear axis labels!
  - Legends clearly marked
  - Data-taking conditions clear
  - Placement of x-axis ticks adjusted to the variable being plotted
  - Can you read the location of the read peak?

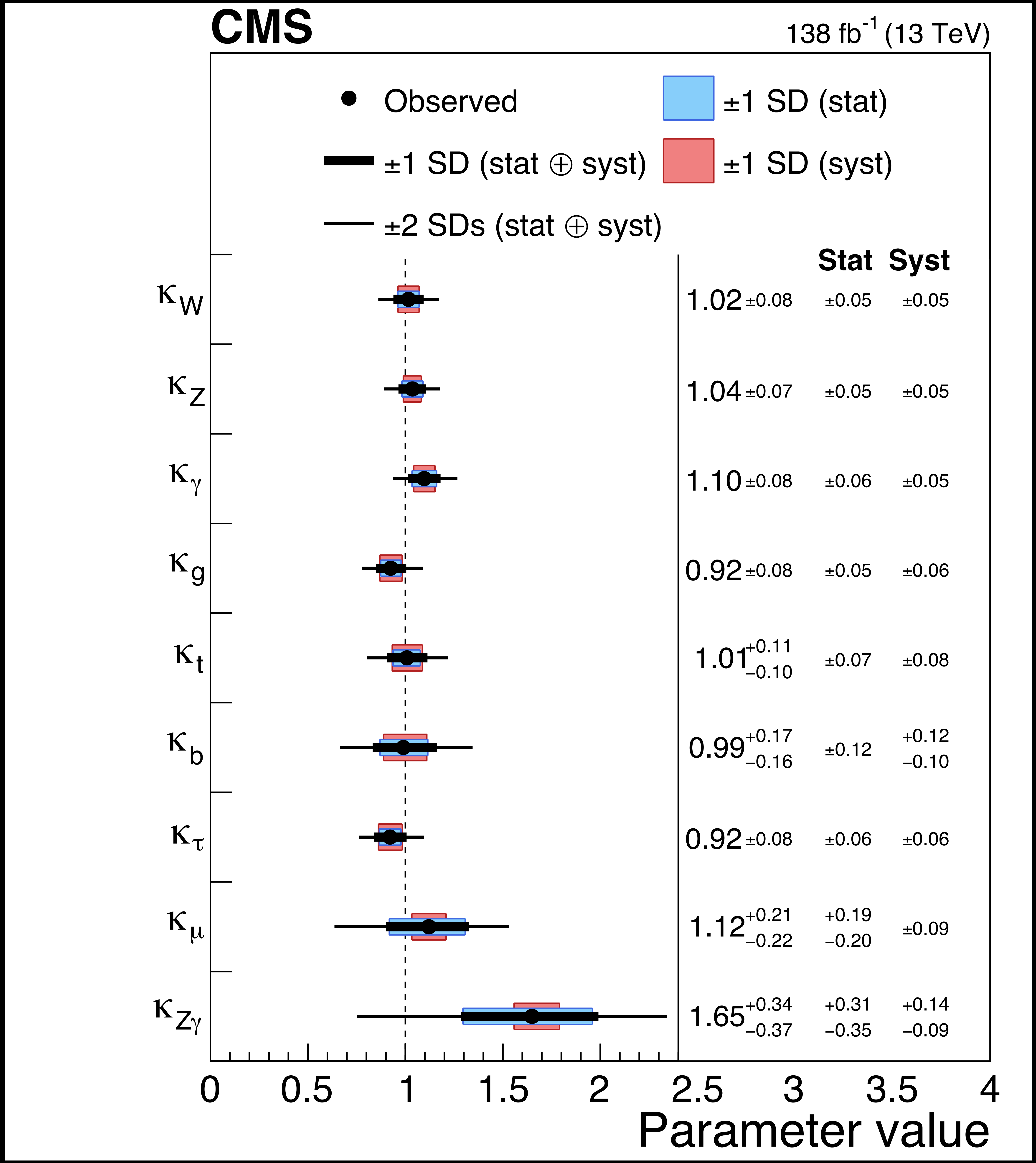
Let’s look at an experimental example

Signal unearthed in huge backgrounds



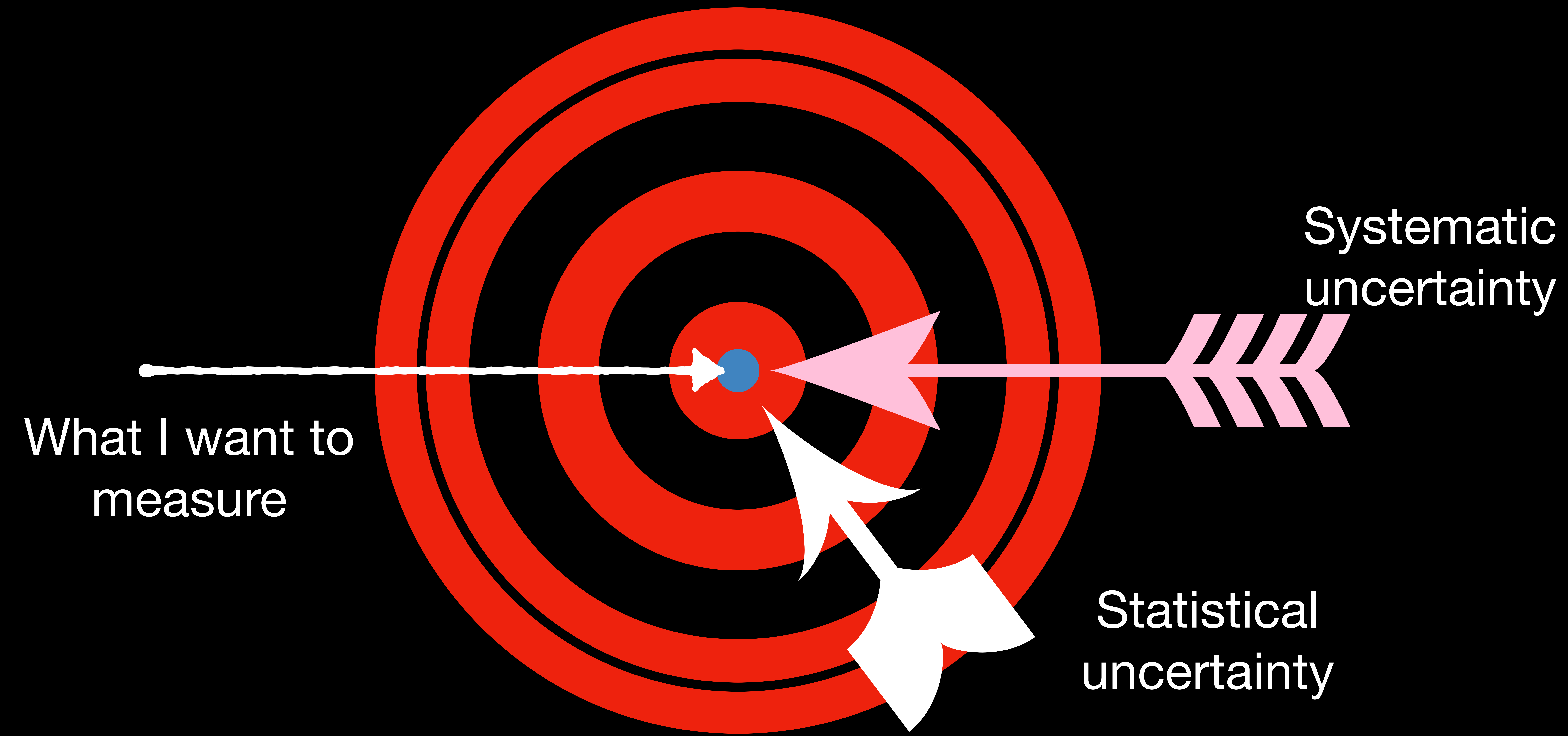
- On July 4th, 2012
  - Two experiments announced that they had observed a *new* particle!
- Theorists Peter Higgs and Francois Englert awarded Nobel prize in 2013!

Let’s look at an experimental example

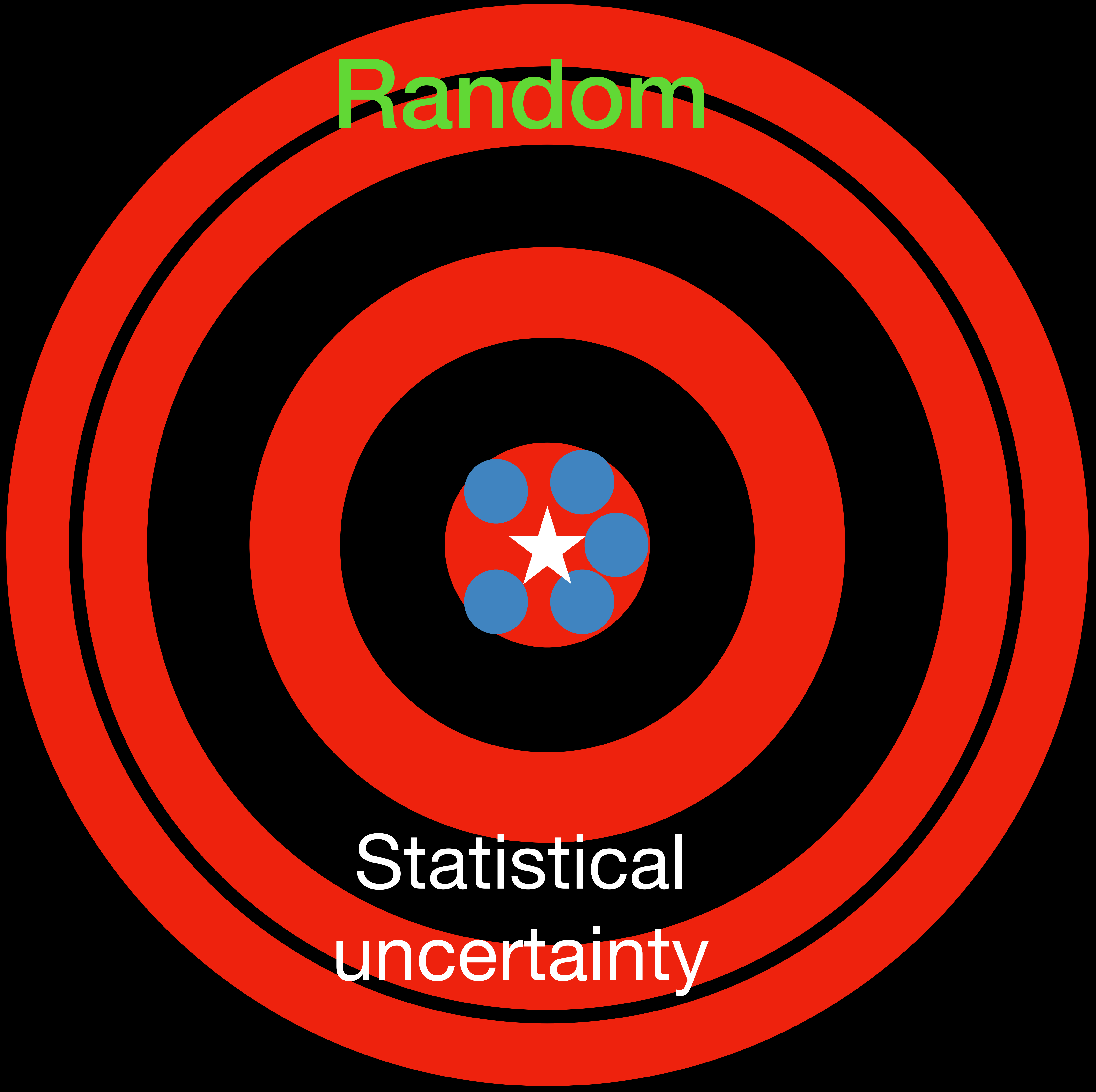


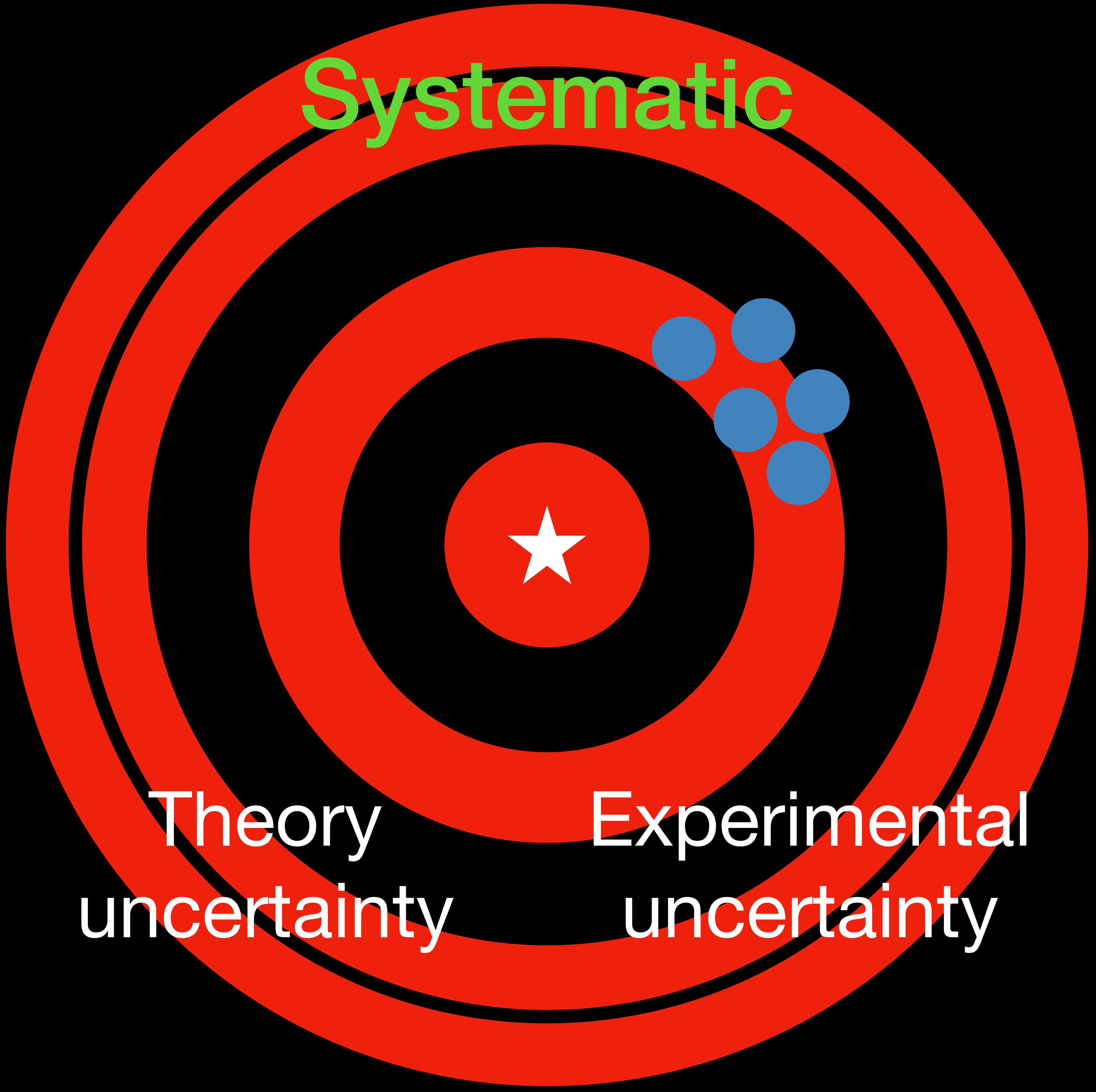
Notice anything interesting?

Experimental Measurements



Types of uncertainties

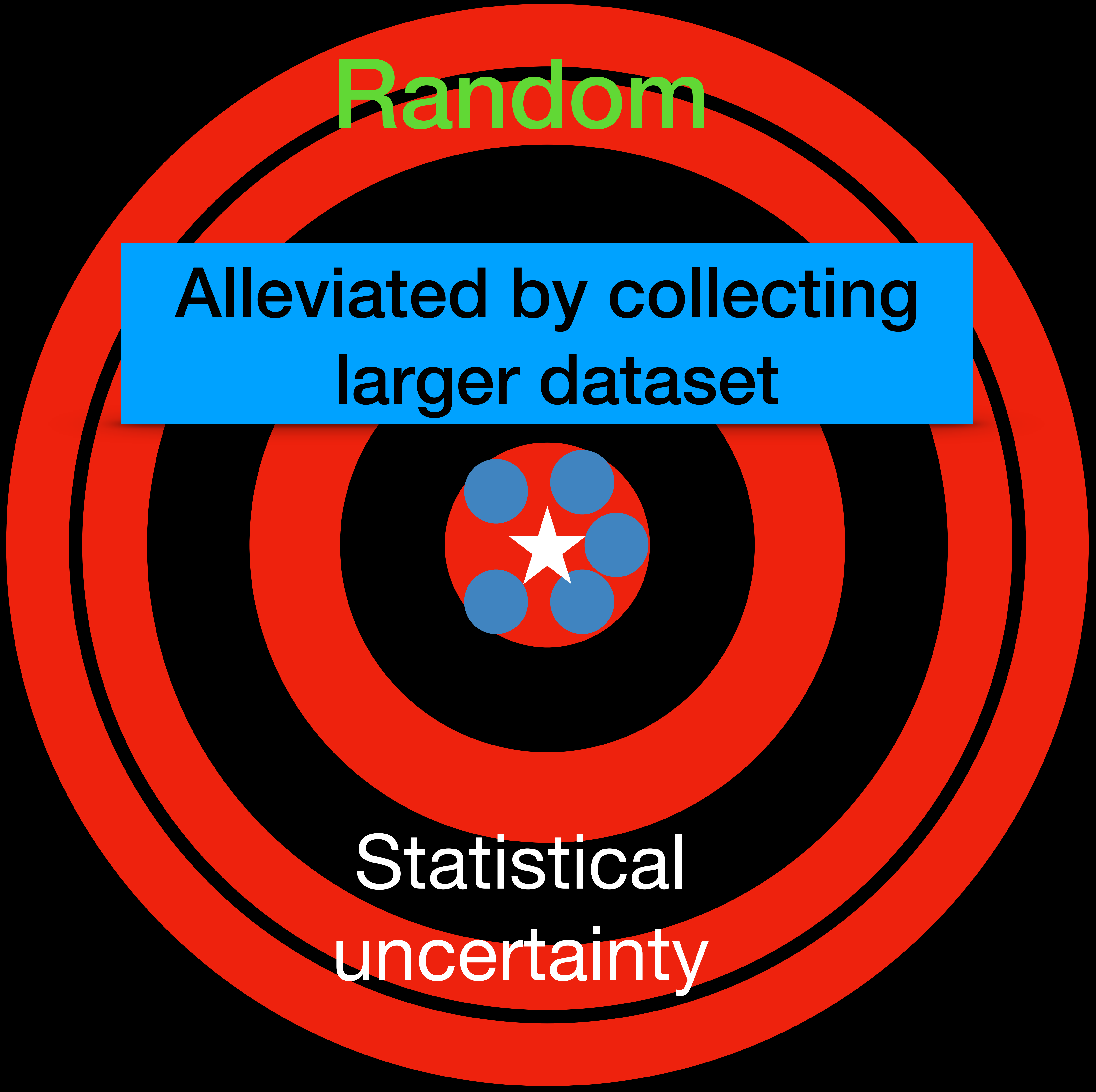


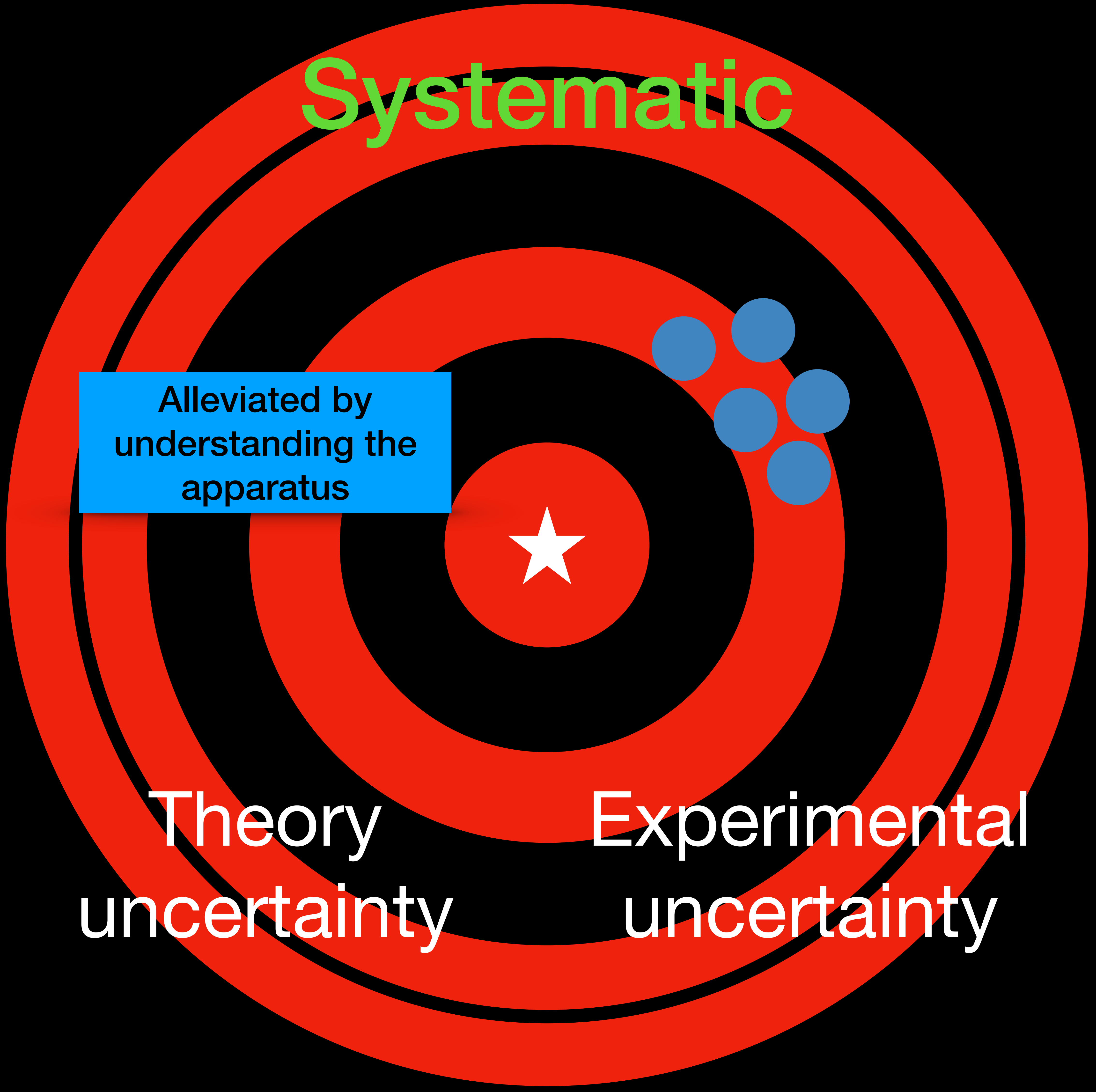


Sources of systematic uncertainty

- Can you name some sources of systematic uncertainty?
- Think of any measurement
  - Measuring length or
  - Measuring mass

Types of uncertainties



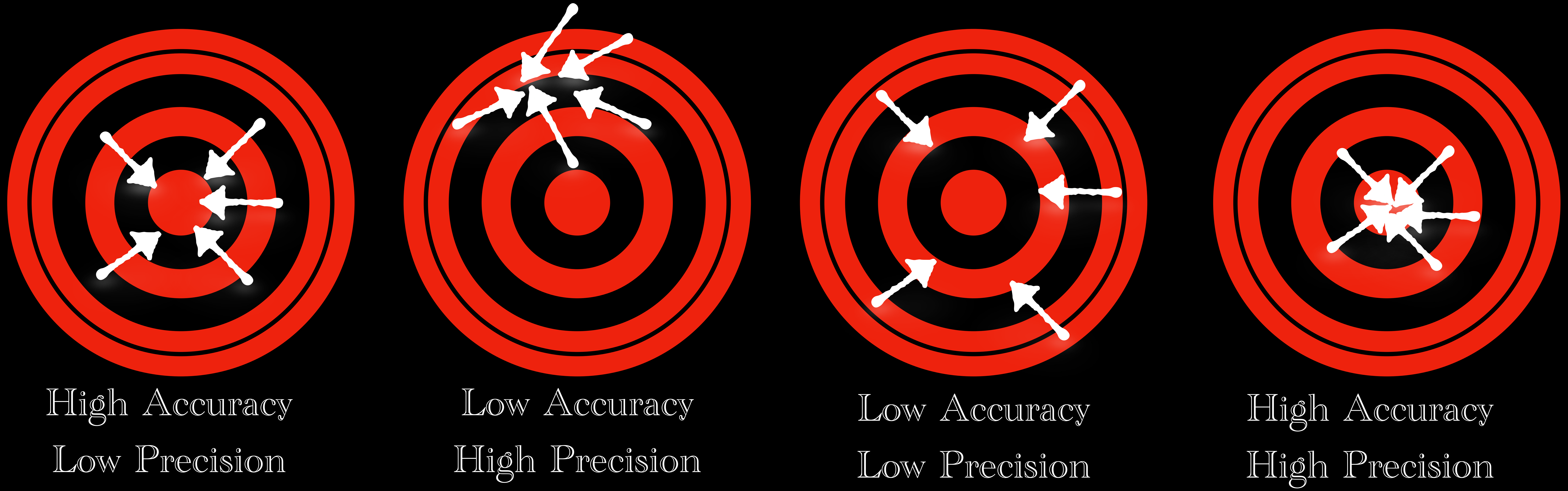


Types of uncertainties

- Which is the bigger problem?
  - Random (statistical uncertainty) or systematic uncertainty

Precision and accuracy

- Terms often used interchangeably in English!
- Not in this lab though!



Reducing statistical uncertainties

- How would you reduce random or statistical uncertainties?

Reducing statistical uncertainties

- Take many measurements and compute an average!
- Say, we are measuring length (ℓ), take many measurements ($\ell_1, \ell_2, \ell_3, \ell_4, \ell_5 \cdots$)
- Take average:
- $$\bar{\ell} = \frac{1}{N}\sum_{j=1}^{N} \ell_j$$
- This is the best estimate of the true measurement

The standard deviation

- The standard deviation (SD) or σ_ℓ is a measure of the average uncertainty of the individual measurements ℓ_i:
  - $$\sigma_\ell = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}(\ell_j - \bar{\ell})^2}$$
  - Say we have 3 measurements (2.9, 3.0, 3.1 cm), average is 3.0 cms and the Standard deviation is: 0.1 cm
  - The standard deviation associated with a measurement stabilizes after several measurements are taken
  - When the value stabilizes, we know that the measurement is more reliable

The standard deviation of the mean

- The standard deviation of the mean (SDOM) can be written as:
  - $\sigma_{\bar{\ell}} = \frac{\sigma_\ell}{\sqrt{N}}$, where N is the number of measurements
  - With more measurements, the value of $\sigma_{\bar{\ell}}$ decreases, measurement becomes more precise
  - How much does $\sigma_{\bar{\ell}}$ decrease if N goes from 2 to 4? 1 to 100?

Propagation of uncertainties

- I am measuring the density, which is a function of mass m and volume V and is given by:
  - $\rho(m, V) = m/V$
  - For a functional dependence of one measured quantity x, $f(x)$ with an uncertainty Δx in x, the uncertainty in $f(x)$ can be computed as:
    - $\Delta f_x = |f(x + \Delta x) - f(x)|$
  - For multiple variables, as is the case here, we add the uncertainties in quadrature:
    - $\Delta\rho = \sqrt{(\Delta\rho_m)^2 + (\Delta\rho_v)^2} \equiv \sqrt{|\rho(m + \Delta m, V) - \rho(m, V)|^2 + |\rho(m, V + \Delta V) - \rho(m, V)|^2}$

Significant figures - I

- Significant figures
  - "the digits in a measured number that are considered reliable and contribute to the accuracy of the measurement"
  - If you tell me that the value of a quantity is 4.9, is it 4.99999999….?
  - There are some rules regarding significant figures (http://www.astro.yale.edu/astro120/SigFig.pdf)

Significant figures - II

What is a "significant figure"?

The number of significant figures in a result is simply the number of figures that are known with some degree of reliability. The number 13.2 is said to have 3 significant figures. The number 13.20 is said to have 4 significant figures.

Rules for deciding the number of significant figures in a measured quantity:

(1) All nonzero digits are significant:

1.234 g has 4 significant figures,
1.2 g has 2 significant figures.

(2) Zeroes between nonzero digits are significant:

1002 kg has 4 significant figures,
3.07 mL has 3 significant figures.

(3) Zeroes to the left of the first nonzero digits are not significant; such zeroes merely indicate the position of the decimal point:

0.001^o C has only 1 significant figure,
0.012 g has 2 significant figures.

(4) Zeroes to the right of a decimal point in a number are significant:

0.023 mL has 2 significant figures,
0.200 g has 3 significant figures.

(5) When a number ends in zeroes that are not to the right of a decimal point, the zeroes are not necessarily significant:

190 miles may be 2 or 3 significant figures, 50,600 calories may be 3, 4, or 5 significant figures. The potential ambiguity in the last rule can be avoided by the use of standard exponential, or "scientific," notation. For example, depending on whether 3, 4, or 5 significant figures is correct, we could write 50,6000 calories as:

5.06×10^4 calories (3 significant figures)
5.060×10^4 calories (4 significant figures), or
5.0600×10^4 calories (5 significant figures).

Resources - I

- All of the materials (including these slides) will be uploaded on canvas
- I am maintaining documentation for this course here: https://www.physics.smu.edu/saptaparnab/

Resources - II

- I am also making checklist for each day

3306 physics laboratories, Spring 2025
Prof. Saptaparna Bhattacharya
https://www.physics.smu.edu/saptaparnab
Intro lab: Resources and first-week checklist

Resources

- Weekly worksheet with mandatory and graded pre-lab submissions and information for your required preparation, experiment introductions, uncertainty analysis summary and labs: https://www.physics.smu.edu/saptaparnab/intro-uncertainty-analysis/

Your learning outcomes today

Keep asking your instructor until you have thoroughly understood each of those terms and concepts, and until you are familiar to use the necessary software. The following labs will require that you have fully understood those topics (your checklist):

- ☐ Precision vs. accuracy in the context of measurements
- ☐ Random/statistical uncertainties vs. systematic uncertainties
- ☐ Standard deviation of a measurement and how to calculate it
- ☐ Standard deviation of the mean and how to calculate it
- ☐ Uncertainty propagation in multiple variables
- ☐ Significant figures (Uncertainties are always quoted to one significant figure)

Additionally you will need to know how to

- ☐ work with jupyter-notebooks

Make use of your instructor's office hours and ask them about your graded worksheet/report or about your preparation for the following week's experiment.