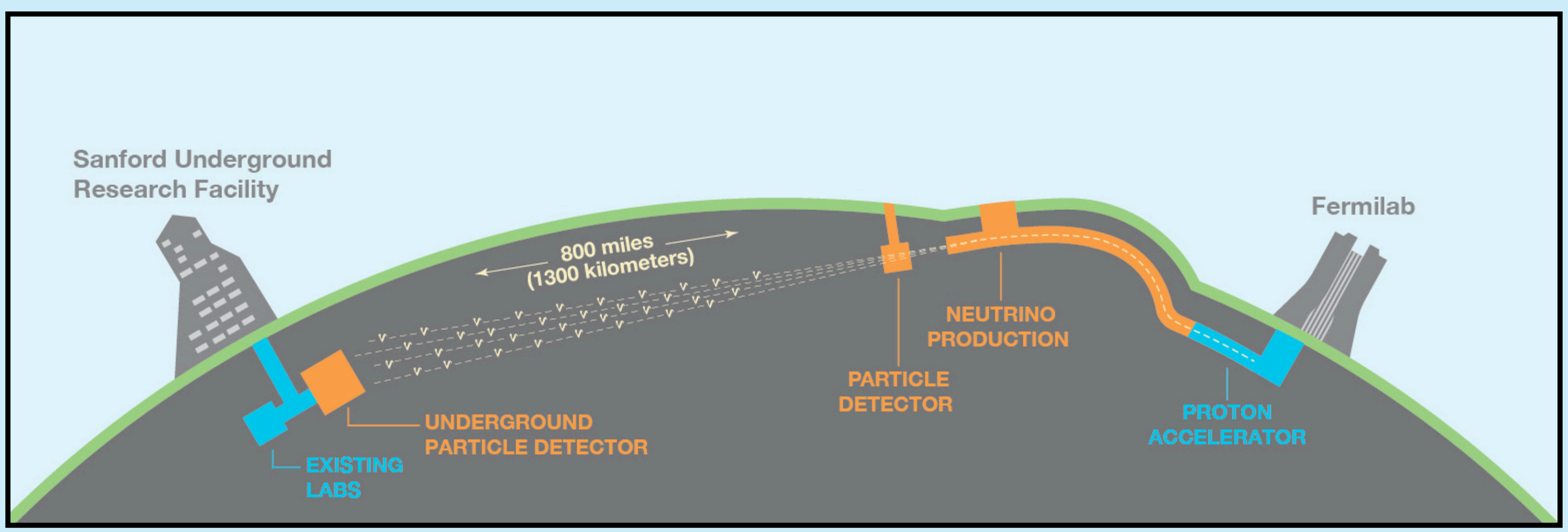
So you want to measure a cross section…

Anne Norrick, Fermilab

DUNE Interactions School

June 14, 2021



Fermilab

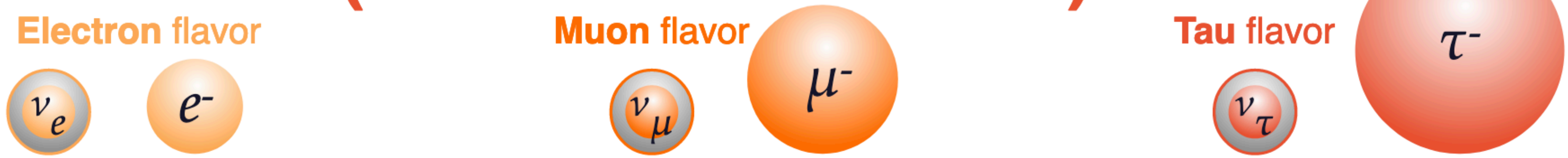
DUNE

Neutrino Interaction School 2021

Quick refresher from last week

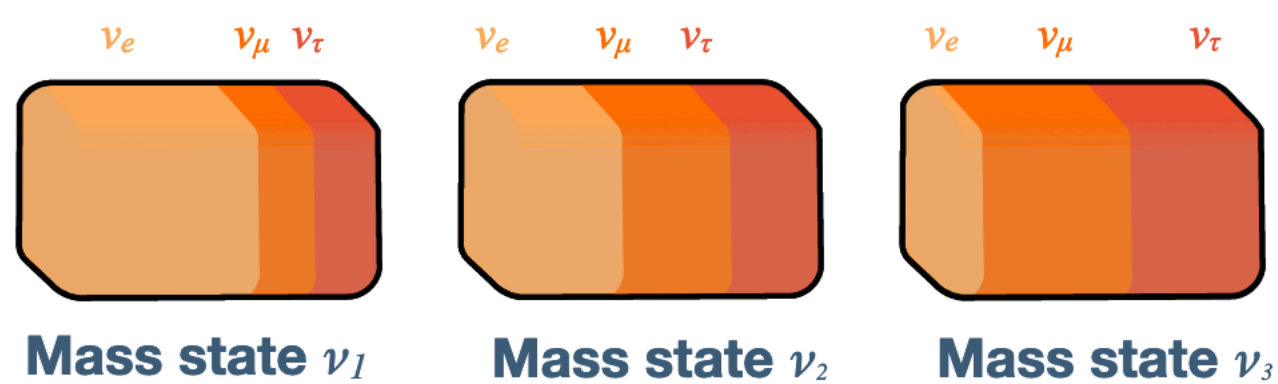
Neutrinos (Three different ones)

Electron flavor | **Muon flavor** | **Tau flavor**



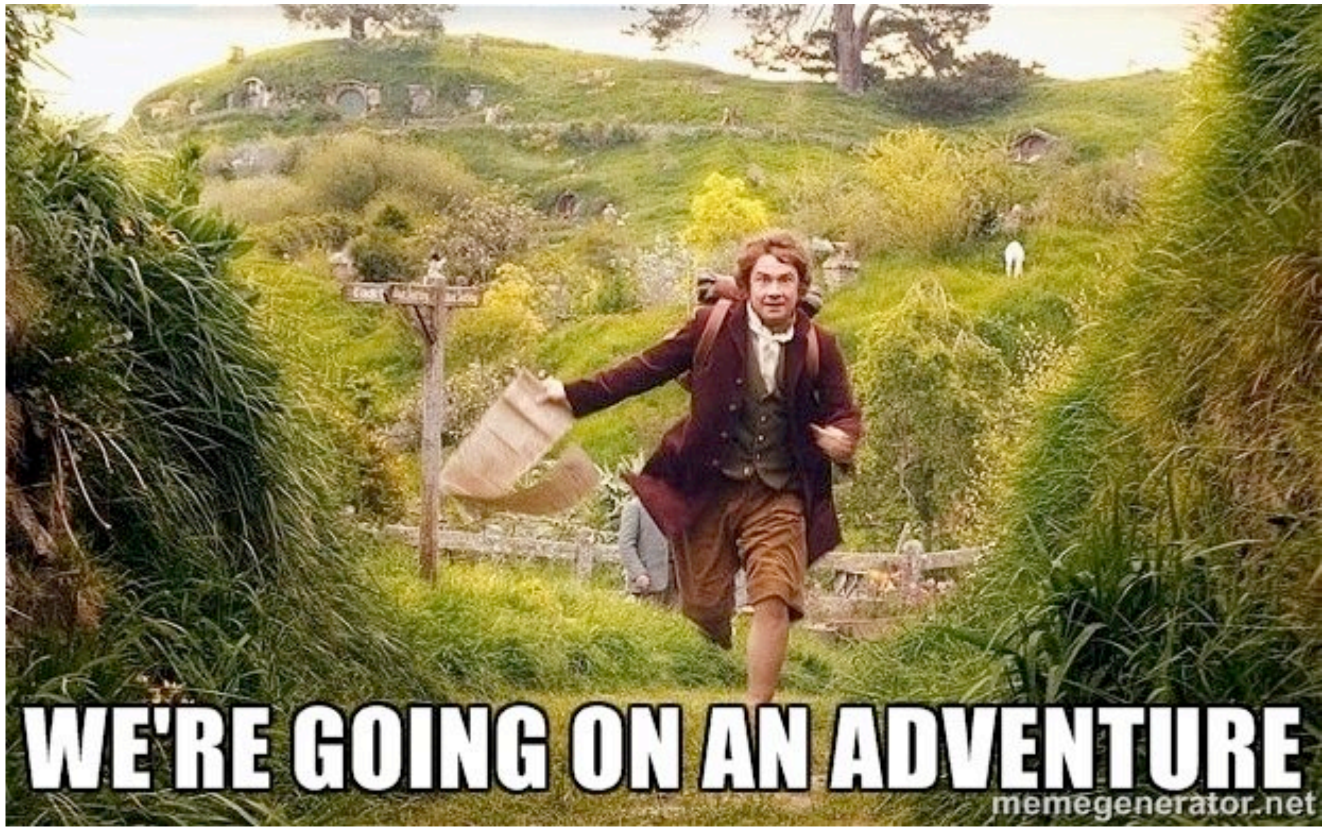
$m_e =$ 511 keV $m_\mu =$ 106 MeV $m_\tau =$ 1.8 GeV

- **No electric charge**
- **Leptons** (fermions, spin 1/2). Always **left-handed** (antineutrinos always right-handed)
- ~~Massless (in the Standard Model)~~
- Interact via **weak interaction** only… which conserves **lepton flavor**
- **Oscillate** between flavors over time…
- … and therefore have **mass** (massless particles don't see time)
- The three mass states are a **mix** (quantum superposition) of flavor states



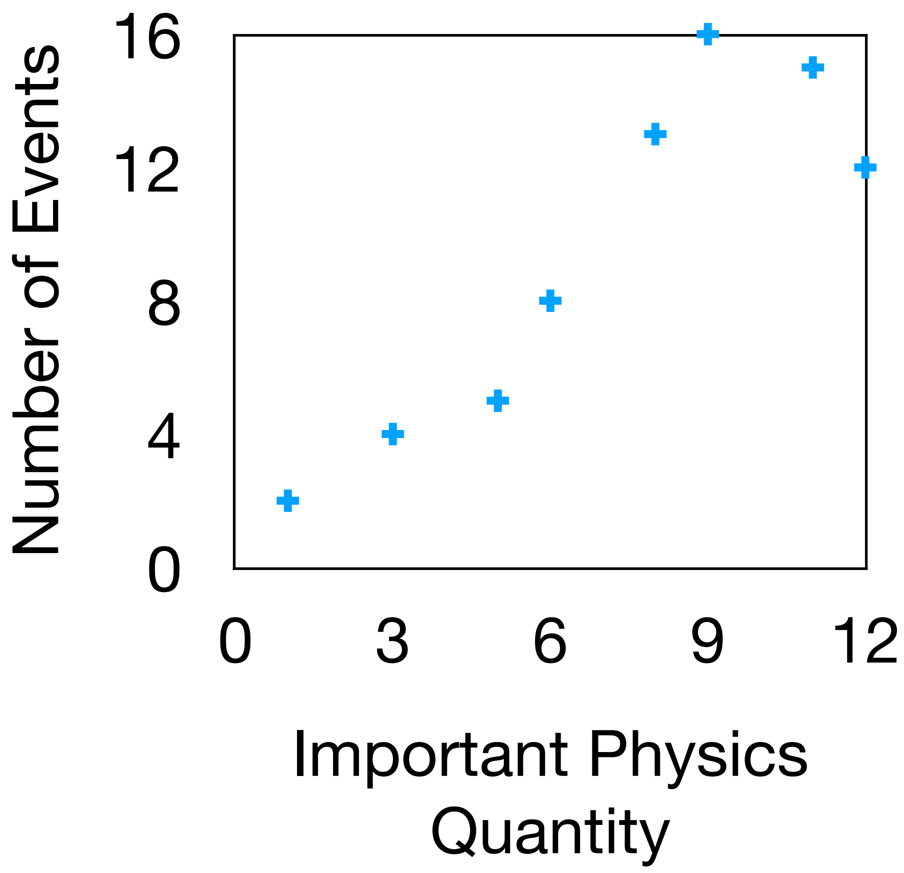
The plan for this talk

- I'm going to walk through the process of measuring a cross section.
- There is no way to cover all of the ins and outs of cross section measurements in one talk, so I'm going to give you the basics.
- If you have questions, please write into the chat. If the question requires a longer discussion, I might direct you to office hours instead.

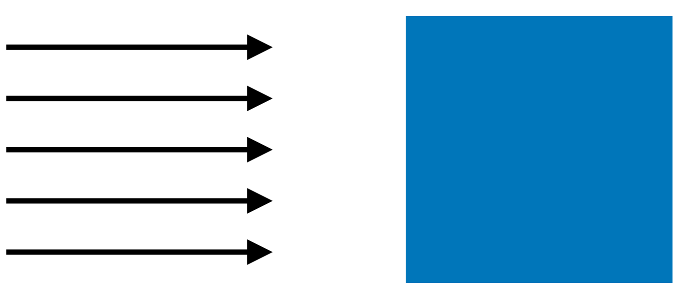


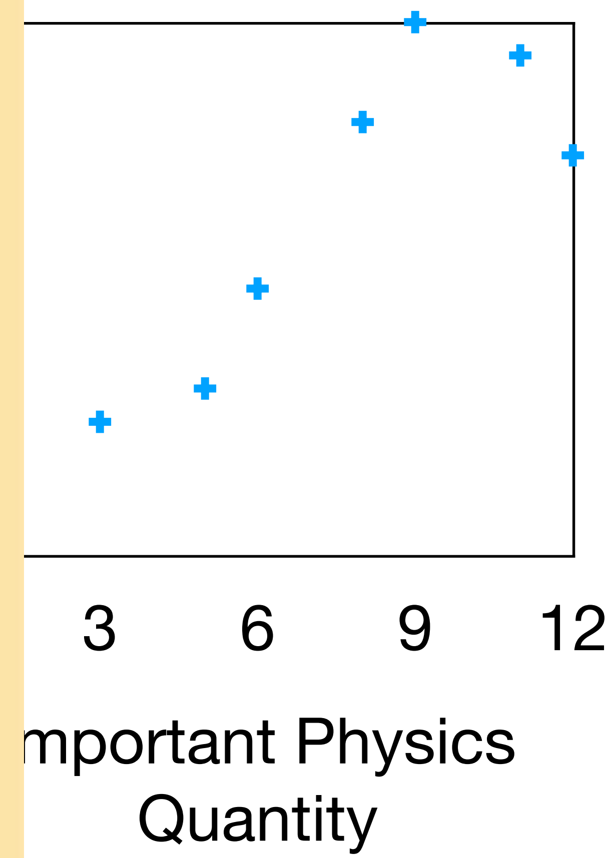
Adventure time!

What is a Cross Section?



What is a Cross Section?





What is a Cross Section?

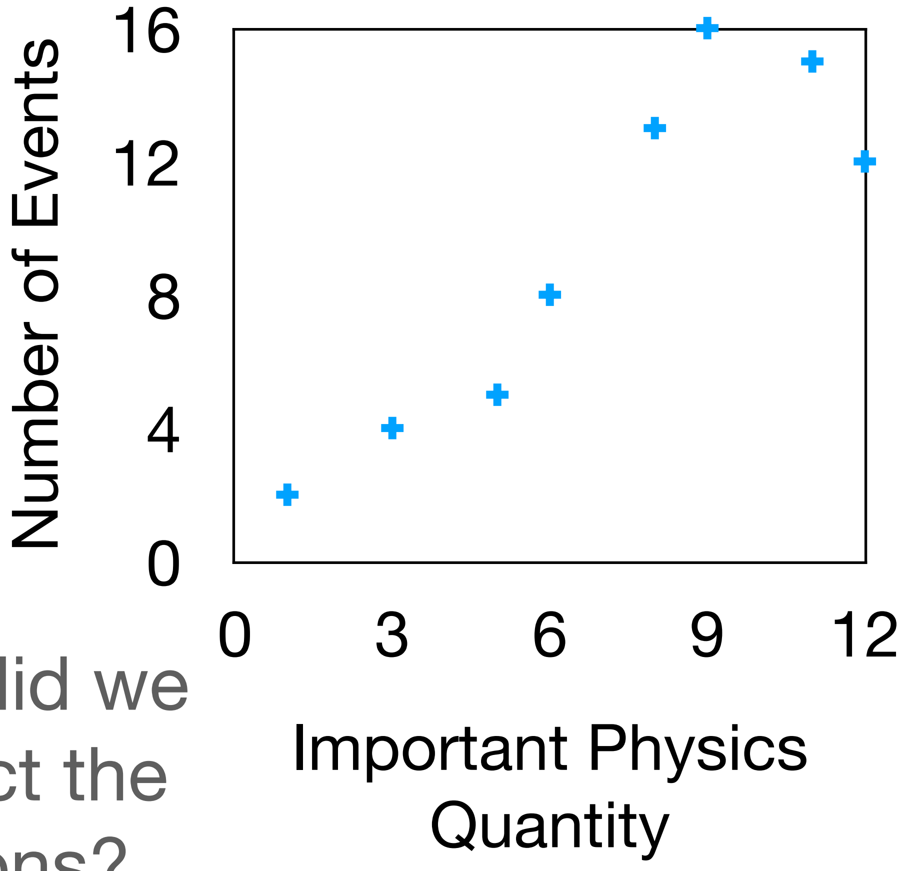
How many neutrinos did they send?

How efficient were we at finding the neutrinos?

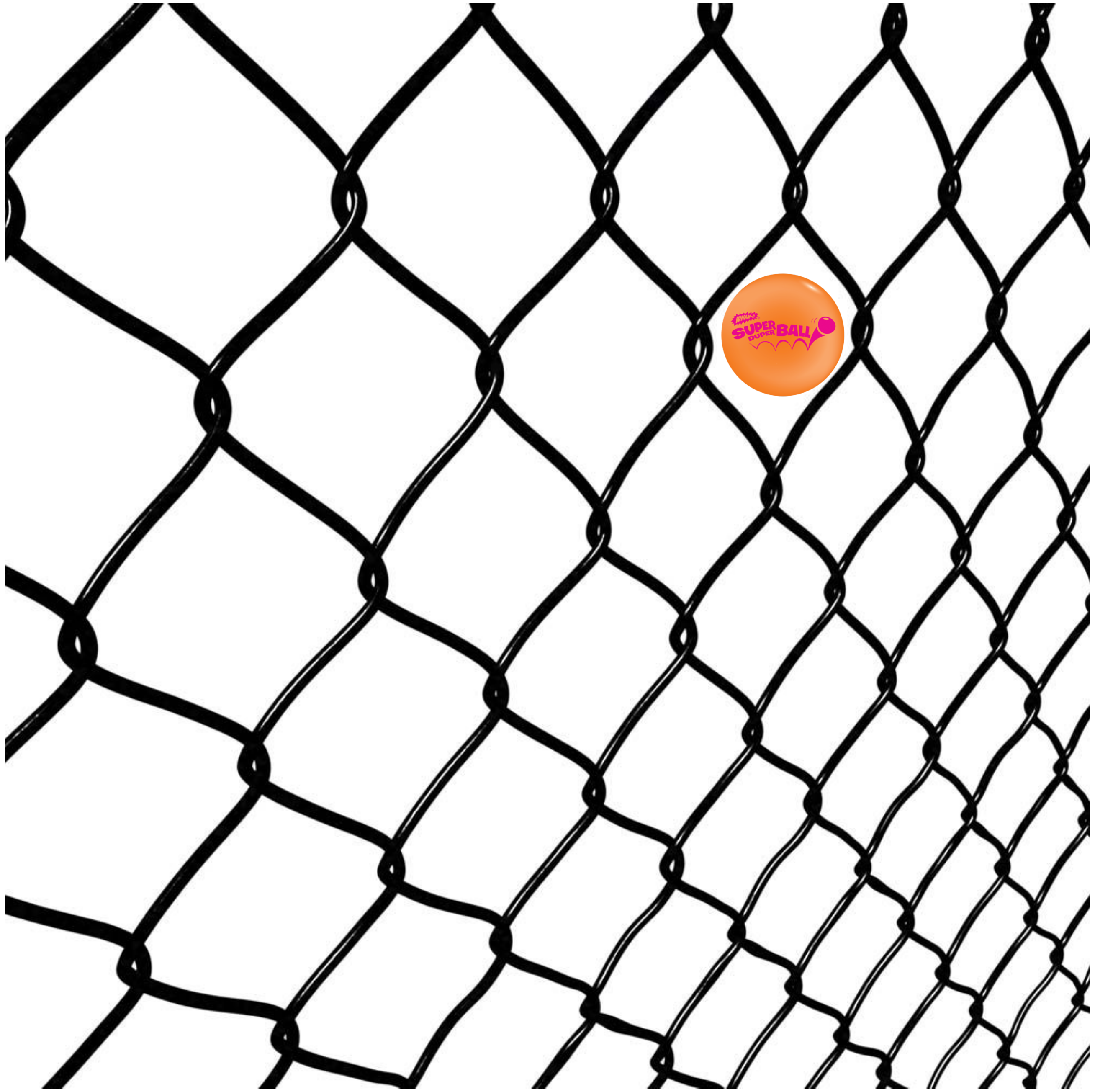
What was the neutrino energy spectrum?

How much “stuff” is in our detector?

How well did we reconstruct the interactions?



What are Cross Sections?



What are Cross Sections?

Reminder… we need to have an interaction to "see" a neutrino

How to “See” a Neutrino

What you won’t see

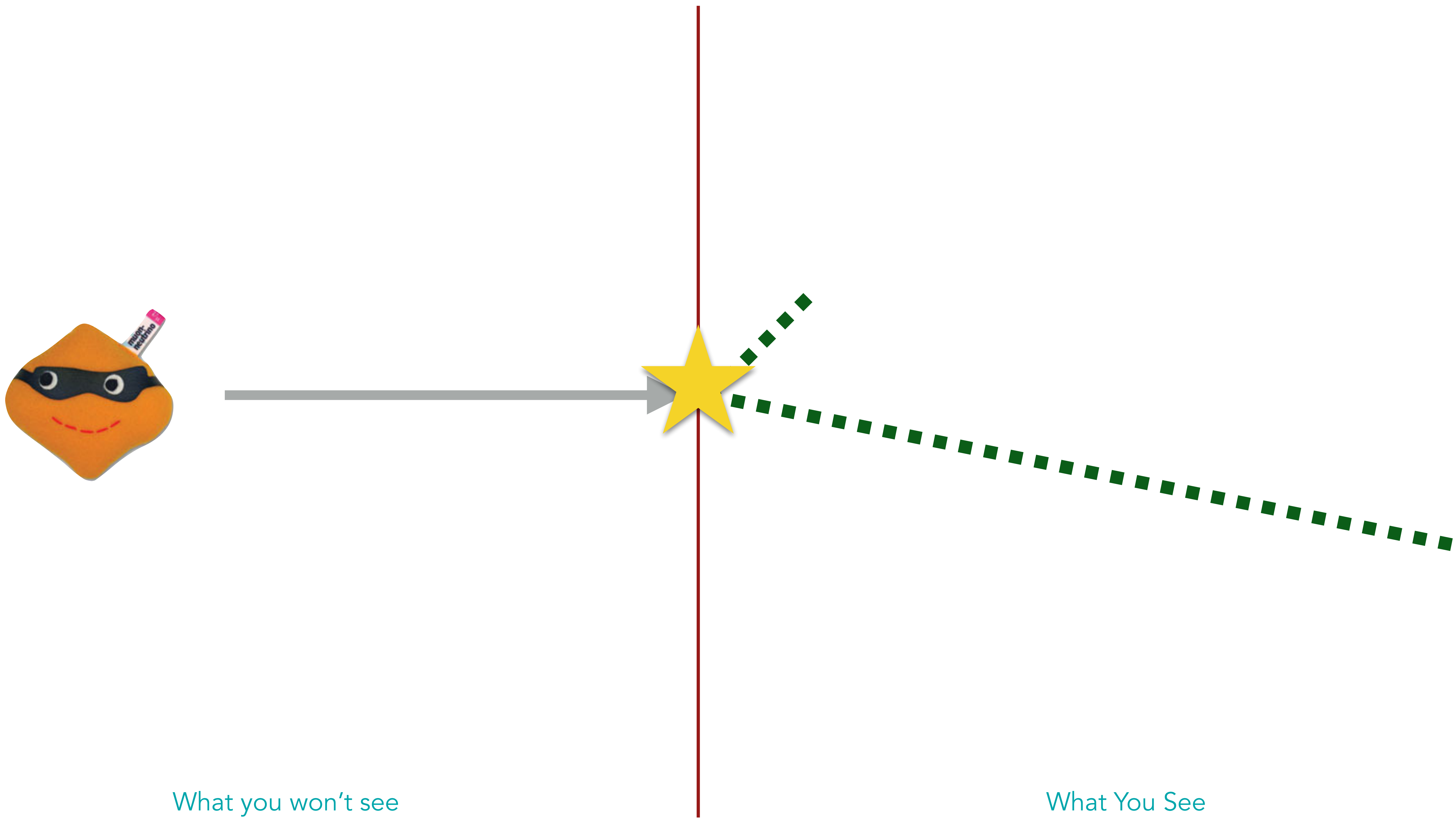
What You See

How to "See" a Neutrino

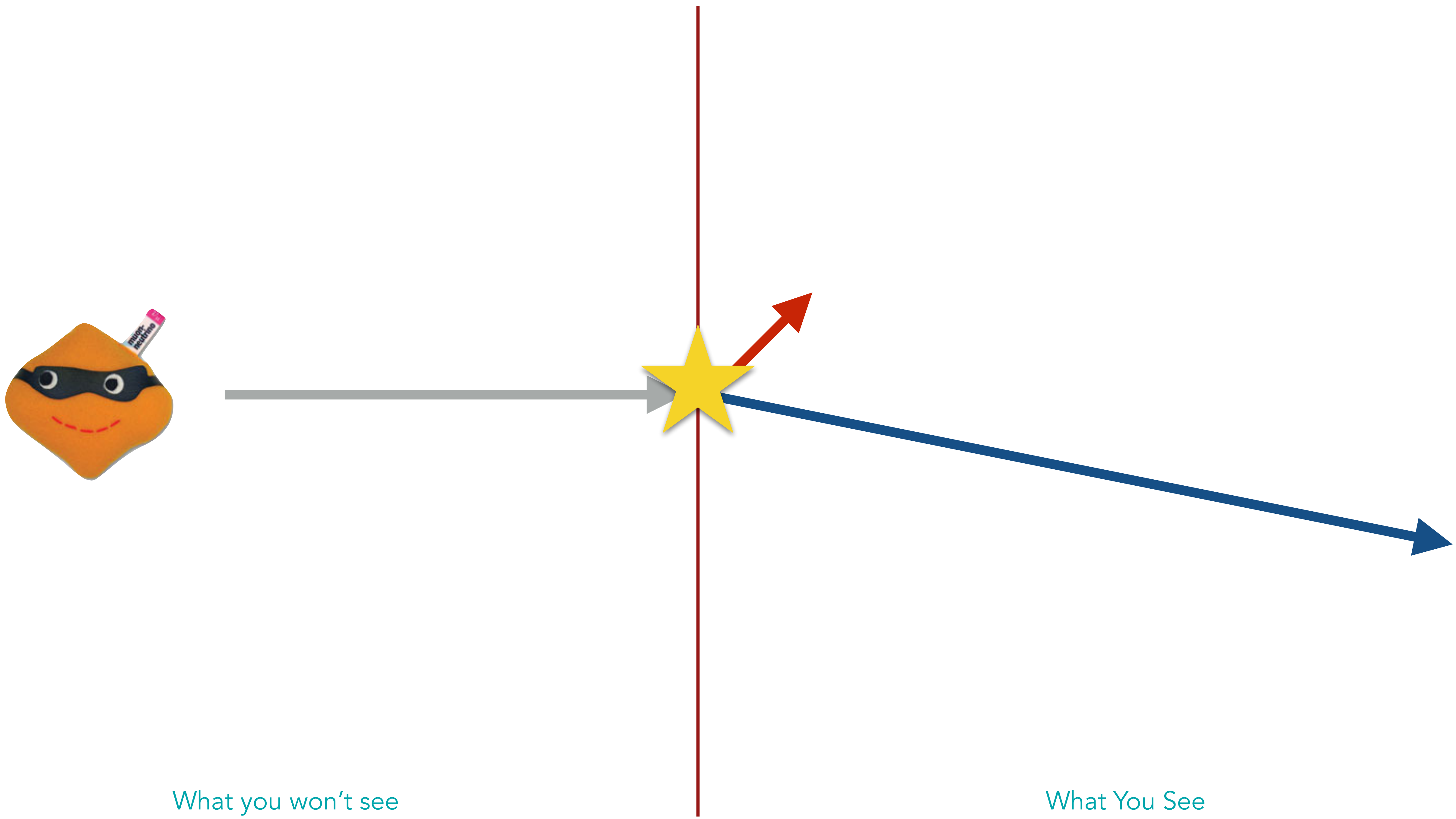
What you won't see

What You See

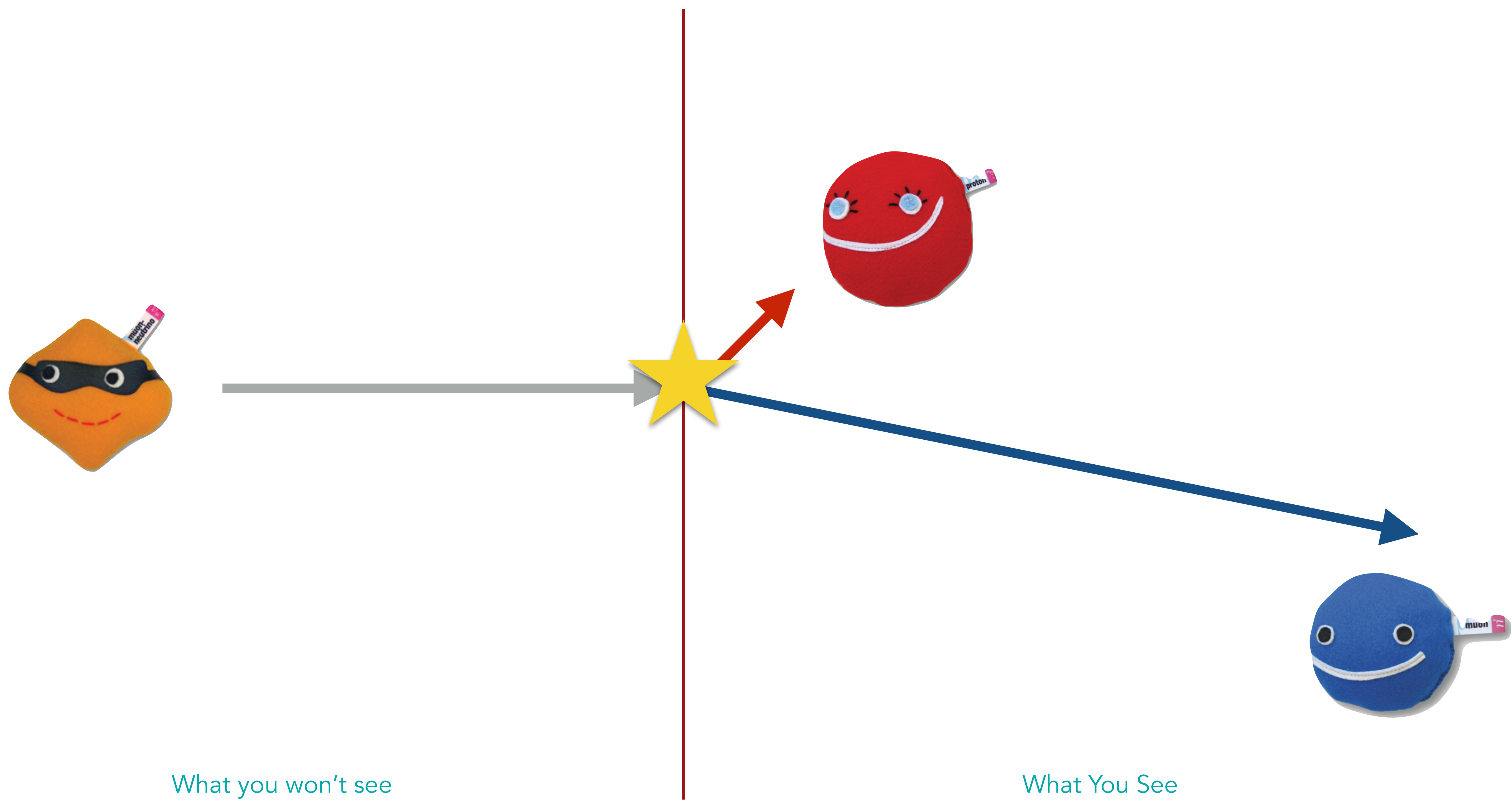
How to "See" a Neutrino



How to "See" a Neutrino



How to "See" a Neutrino

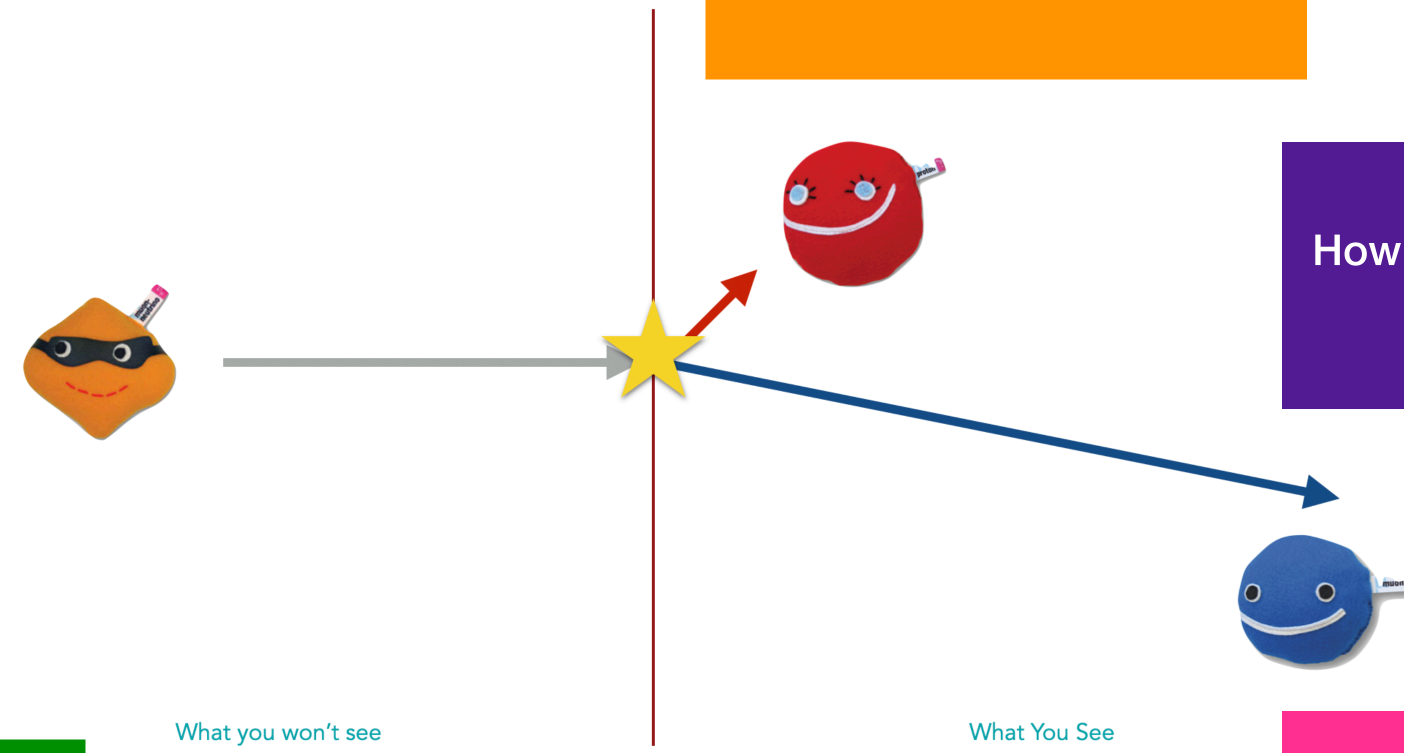


Sidetrack!

Dealing with a detector

What are the angles of each particle?

How do we know this is a proton?



How much energy does the proton have?

How do we know this is a muon?

What am I missing?

How much energy does the muon have?

Is it a muon or an anti-muon?

This isn’t a talk about detectors.. but…

- It’s important to understand how your detector works!
- Figure out what your detector can do well and what it can’t
    - It’s great to get creative, and to look for every opportunity to do cool physics with your detector, but it is important to recognize the limits.
    - For instance, if you don’t have charge separation, don’t try to do an analysis that relies heavily on knowing the charge of a particle!
- We’re going to talk about the DUNE Near Detectors in the mini-talks, each have their own benefits and drawbacks for specific types of measurements.

Calibration

- It is important to understand how well your detector matches reality.
- e.g. How accurate is your ruler?
  - We can deal with slightly inaccurate rulers, but it helps to know by how much!
- Normally achieved through the use of a standard input

Reconstruction

This deserves it's own talk…

- Even once we have calibrated signals from the detector, we still need to figure out what they mean!
- Historically, humans looked at bubble chamber images and reconstructed particles by hand.
- Large stats-> need for reconstruction algorithms!
- But what are we actually able to reconstruct and, thus, measure?

Reconstruction

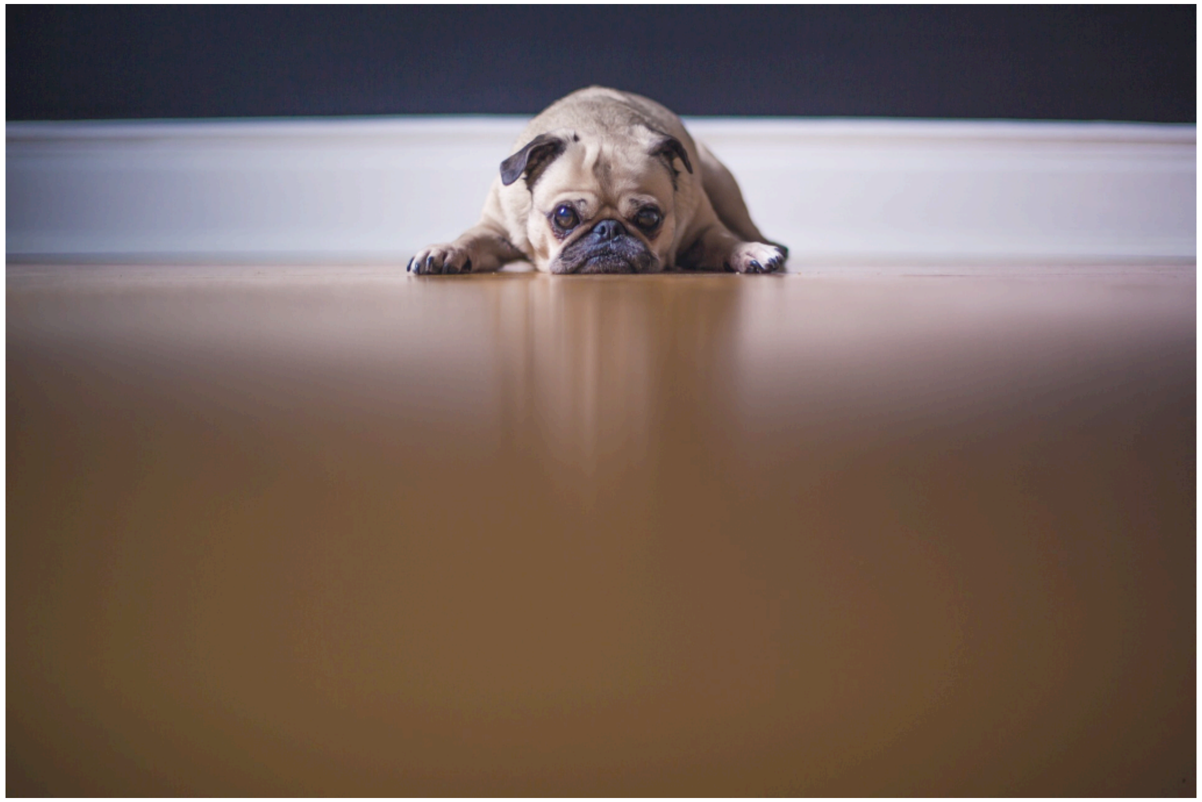
This deserves it’s own talk…

- E… till n…
- H… re…
- L…
- B… ure?

Energy Deposits

Angles

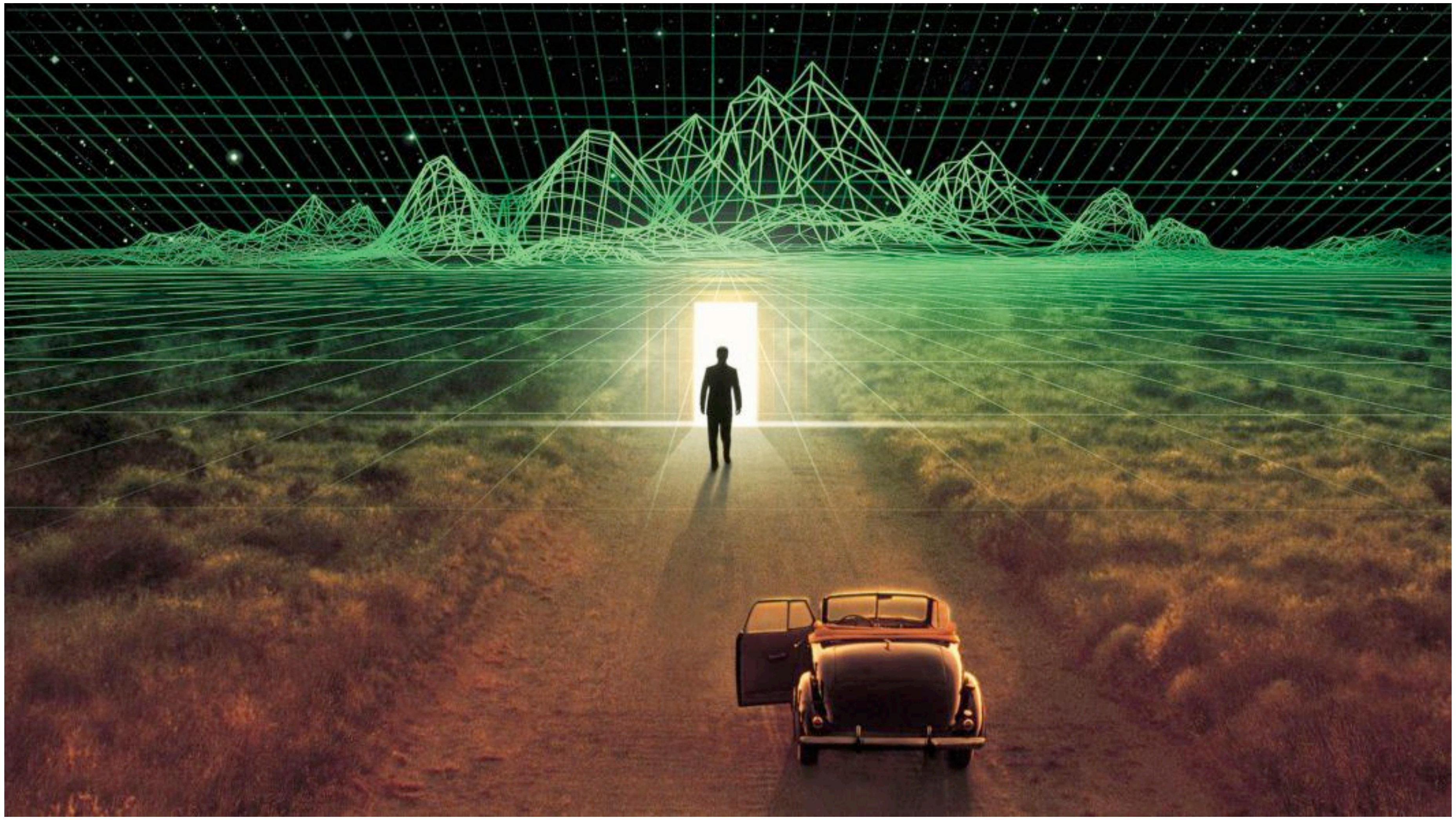
But wait!!!



Waiting is hard………….

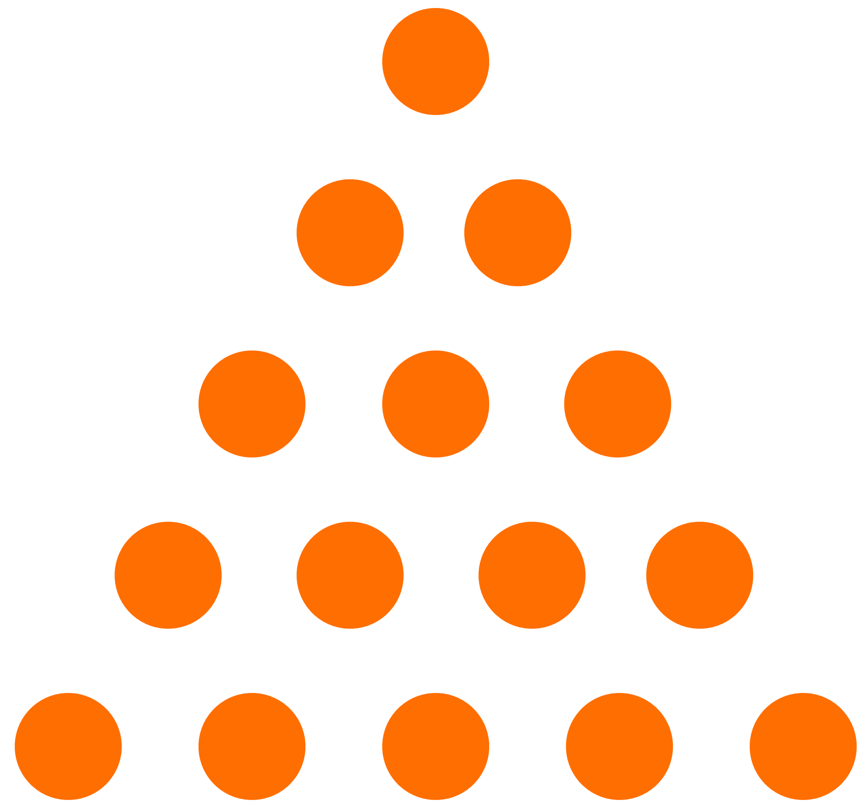
- We are not going to see neutrinos in DUNE for ***years***!
- What are we supposed to do in the meantime?
- Also, how do we even know what we should expect to see??

The Realm of Simulation

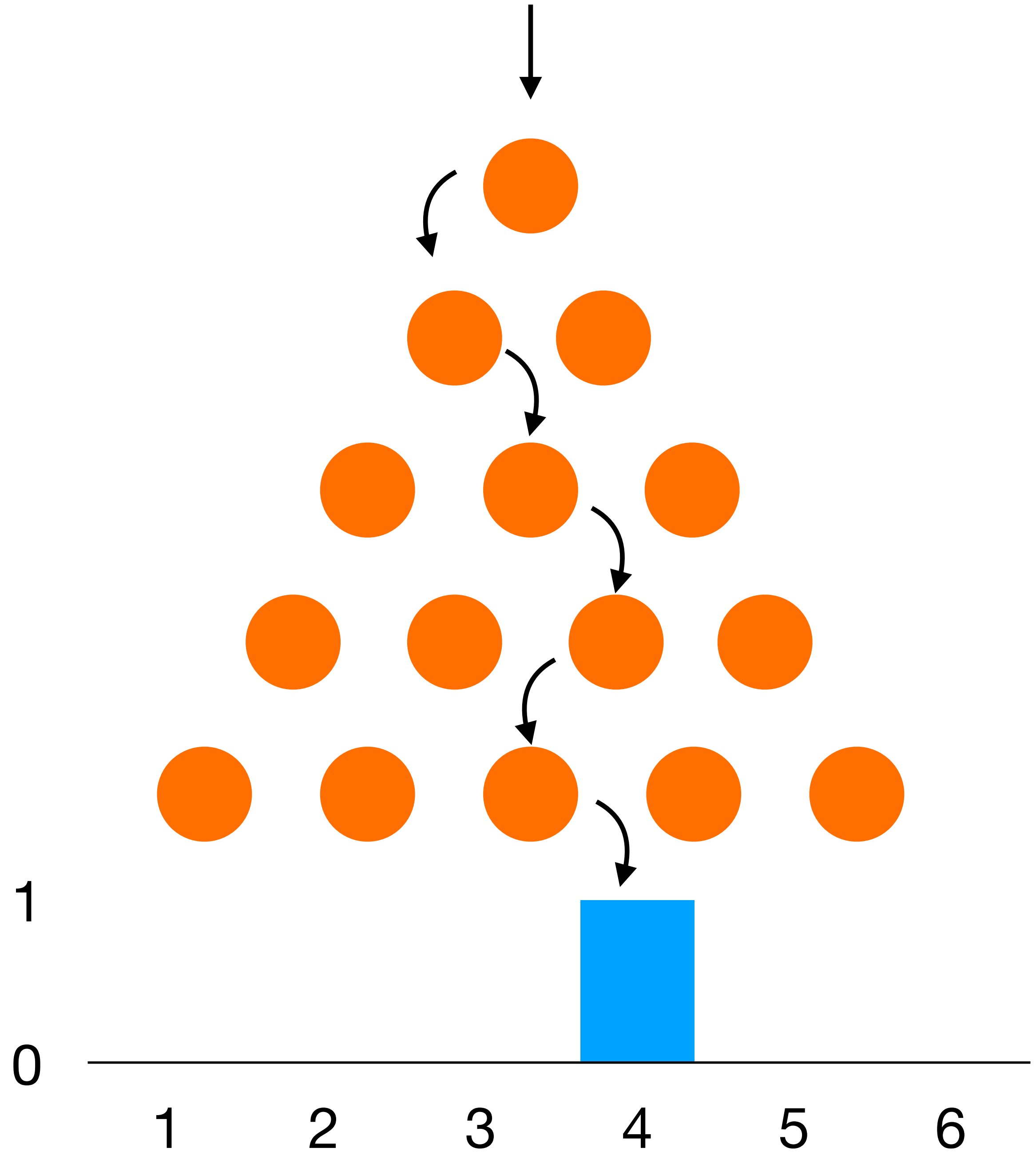


- Simulations show us our best guess at what things will look like in our experiment.
- And they do it through a lot of random number generation…

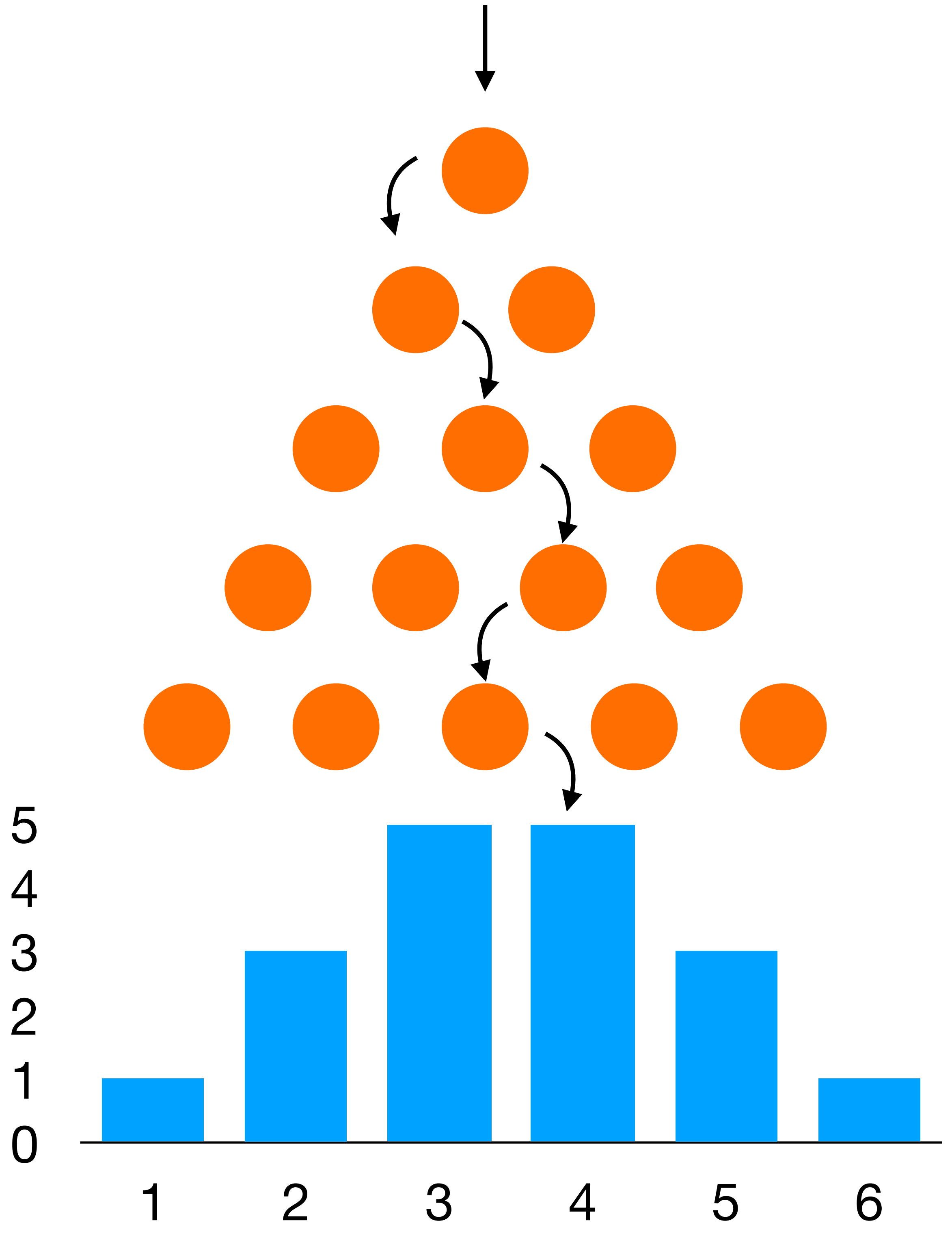
Easy example: Plinko



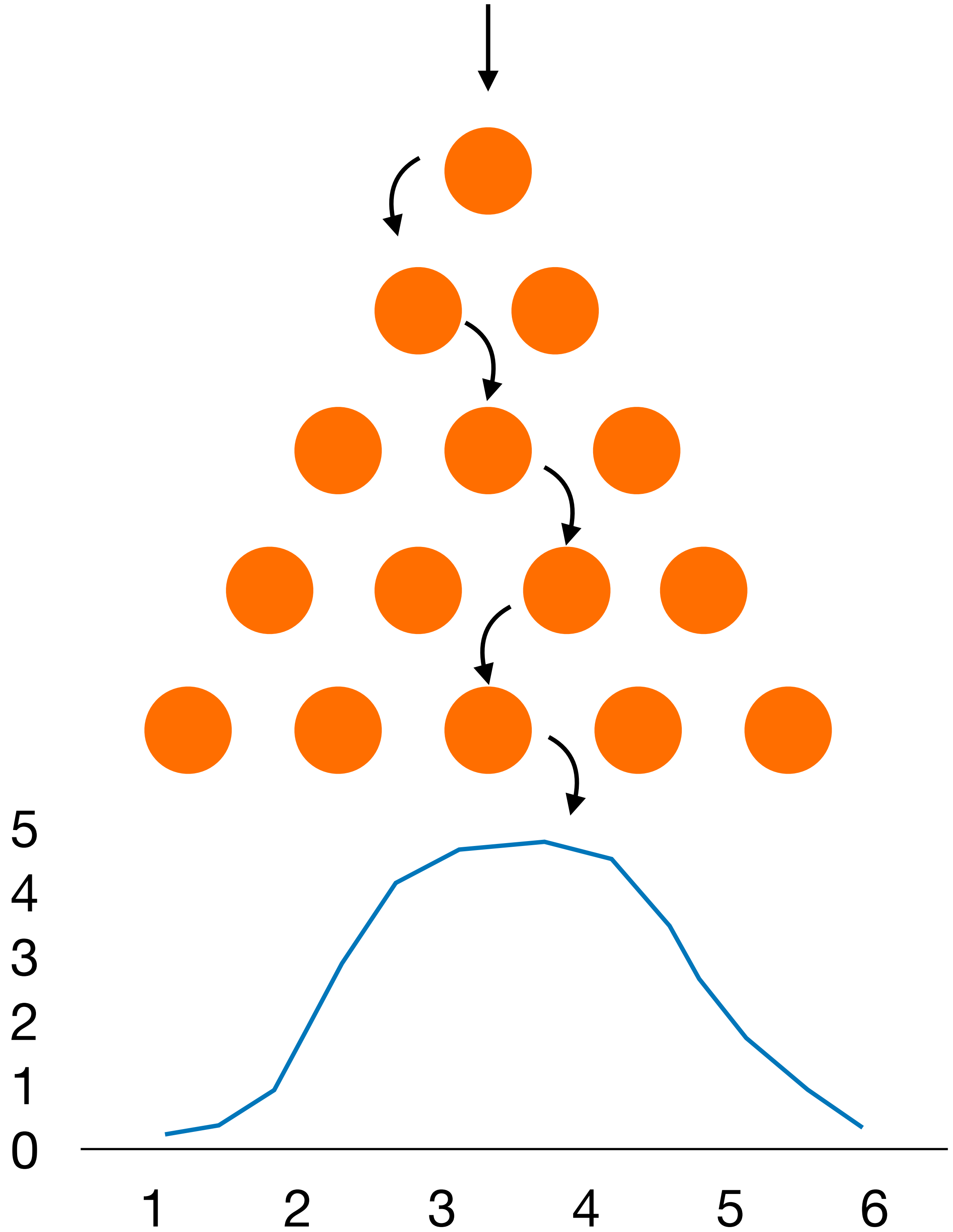
Easy example: Plinko



Easy example: Plinko

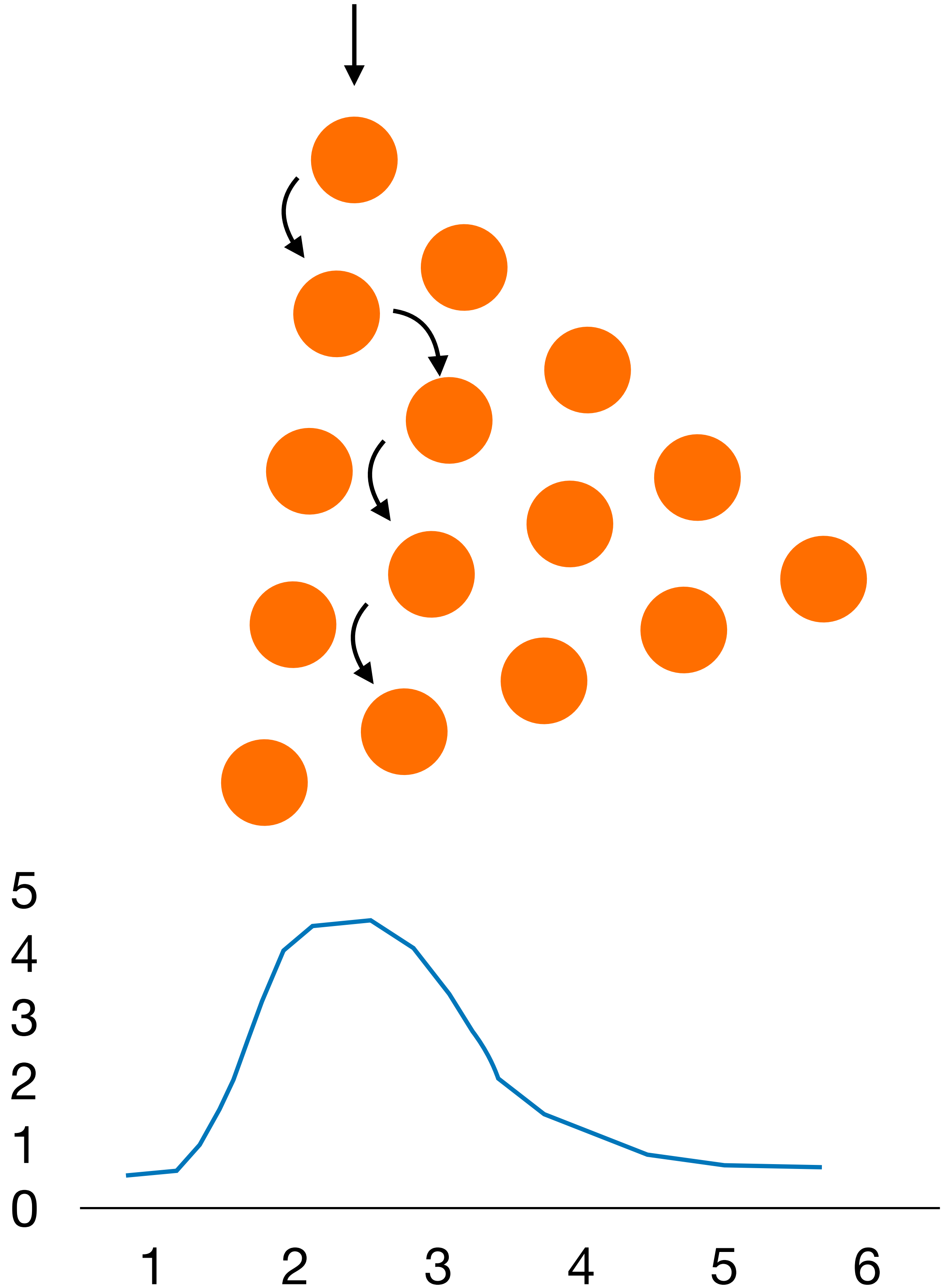


Easy example: Plinko



Easy example: Plinko

What if the plinko wasn't level?



Easy example: Plinko

What if the plinko wasn't level?

Exercise for the reader!

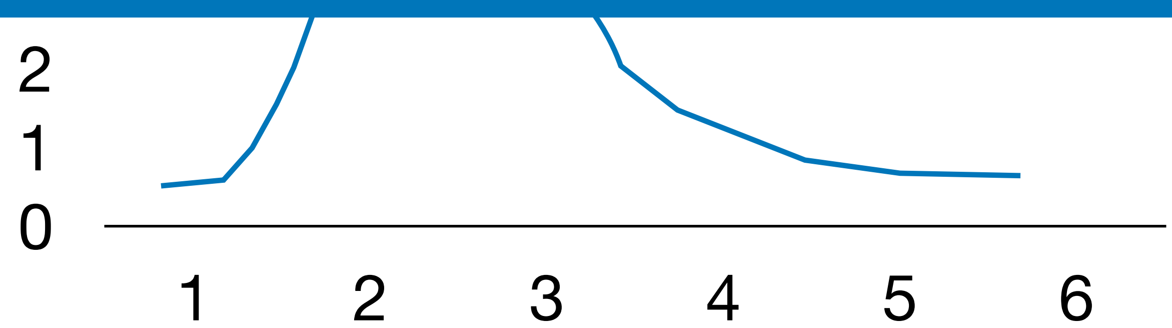
If you're new to Monte Carlos (or coding!), try to code Plinko.

Pick your favorite language.

Learn how to use a random number generator.

Write a loop for your number of levels you want in your game.

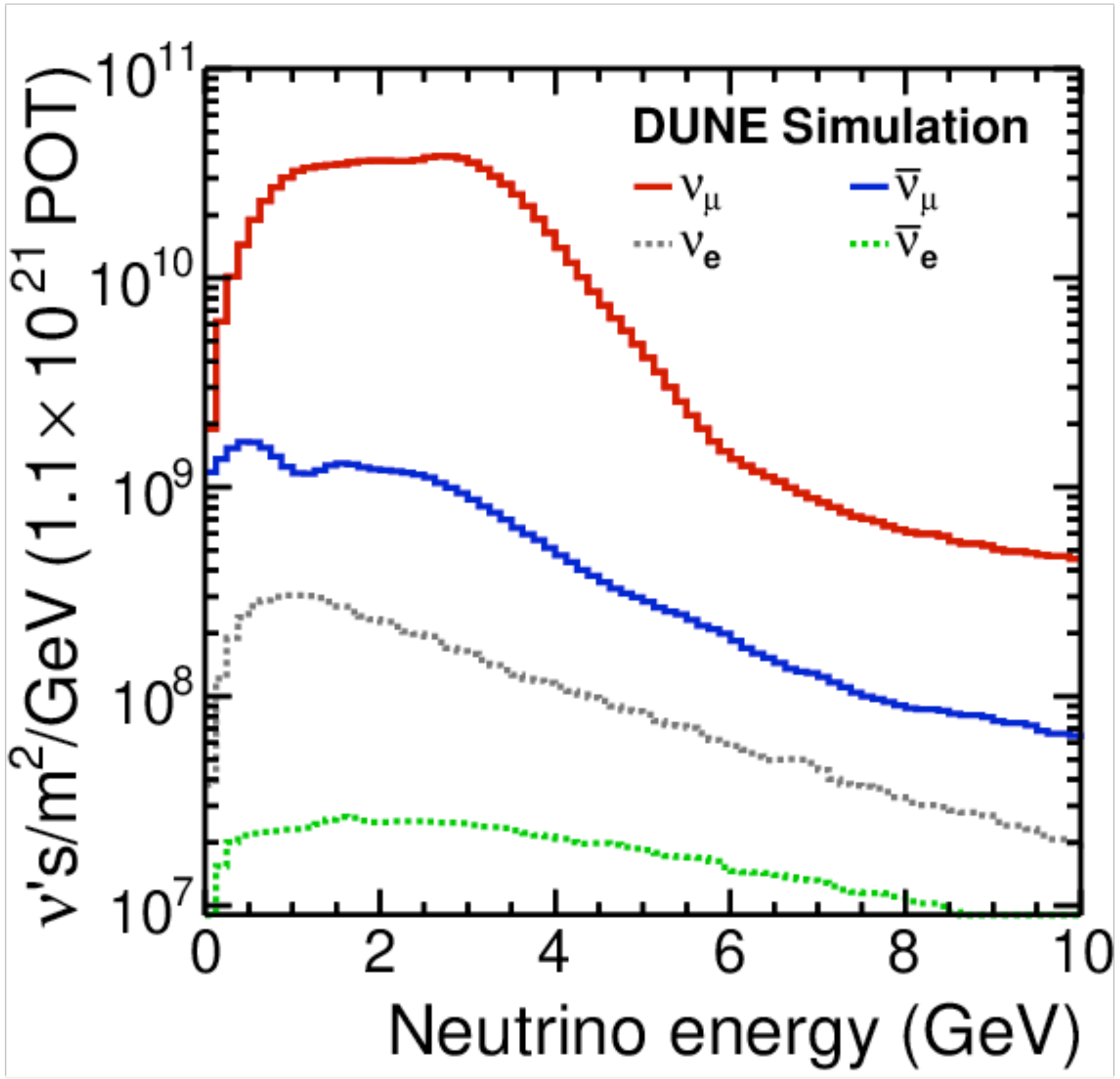
Do you get a Gaussian?



Neutrino Interaction Plinko

Neutrino Interaction Plinko

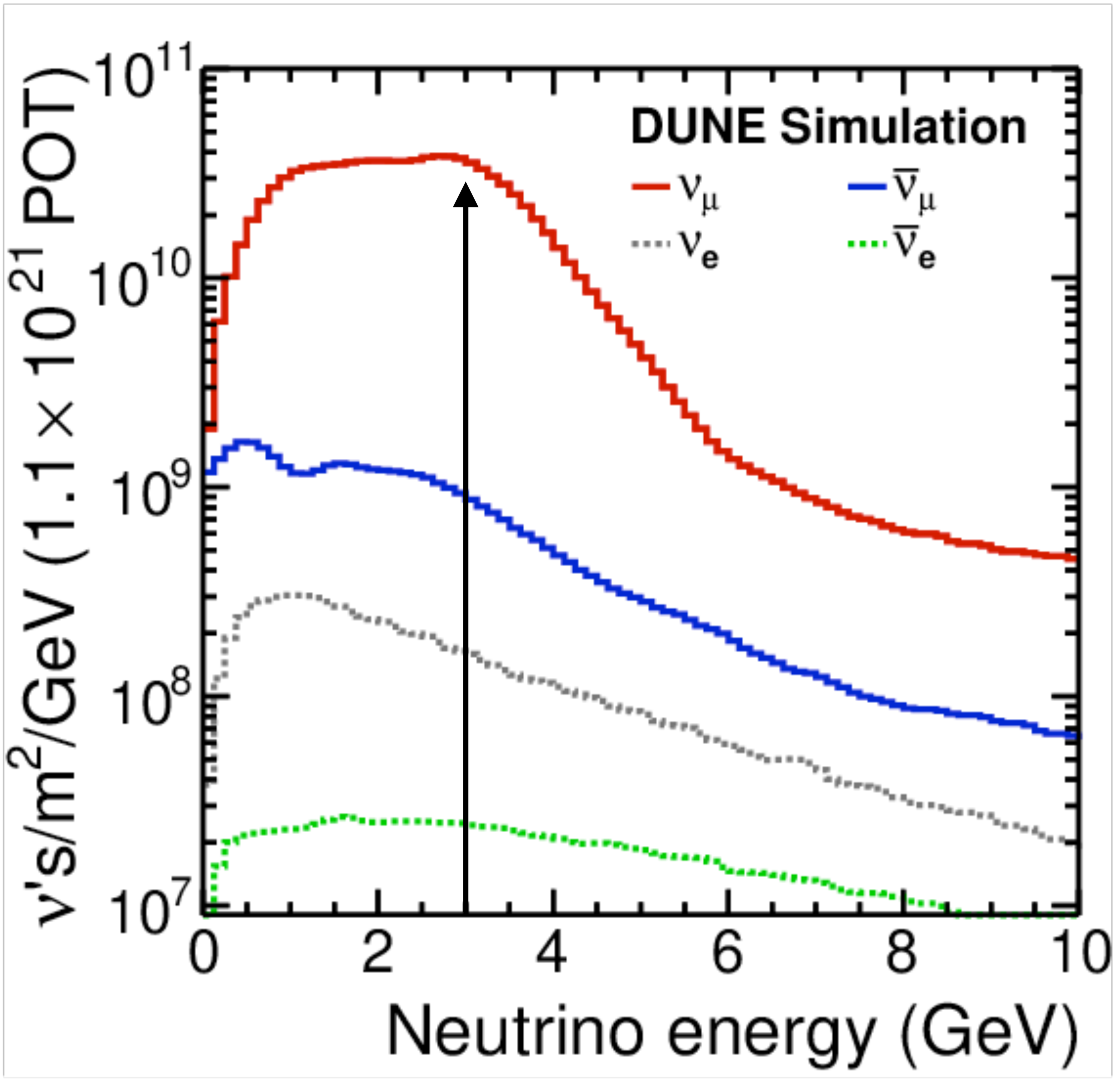
Pick a neutrino energy



Neutrino Interaction Plinko

Pick a neutrino energy

3 GeV

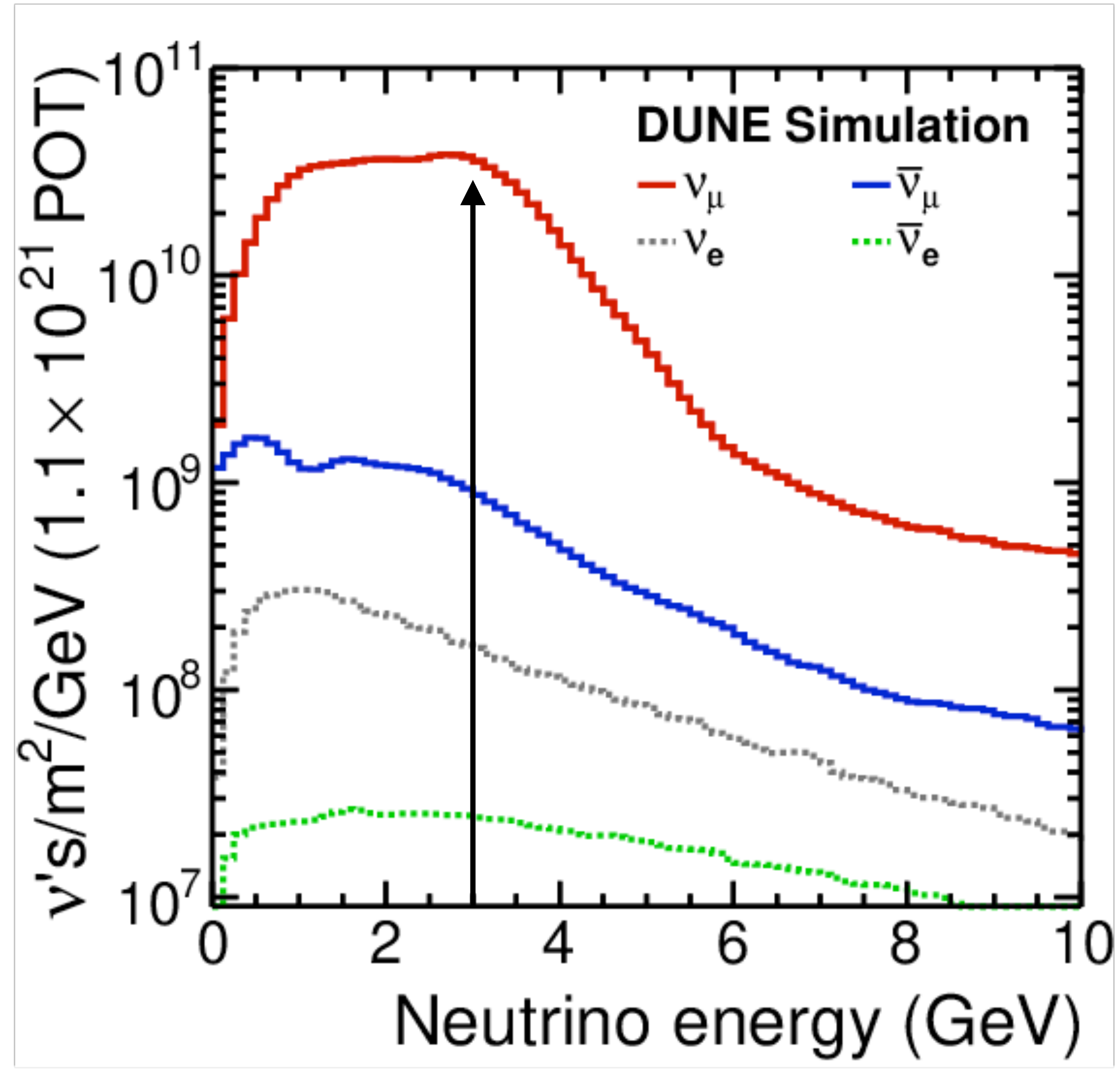


Neutrino Interaction Plinko

Pick a neutrino energy

Pick a neutrino flavor

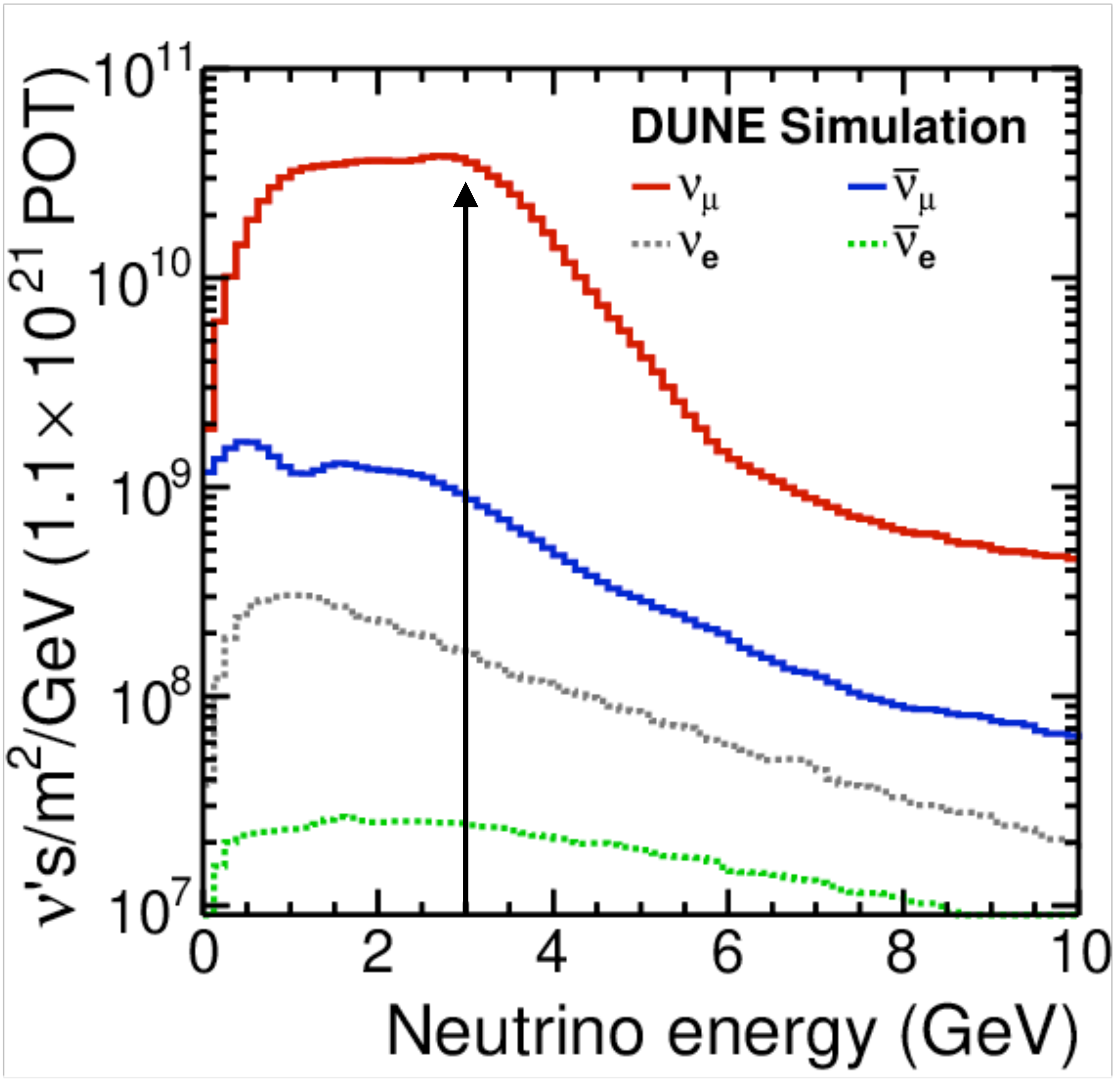
3 GeV



Neutrino Interaction Plinko

Pick a neutrino energy — 3 GeV

Pick a neutrino flavor — Muon Neutrino

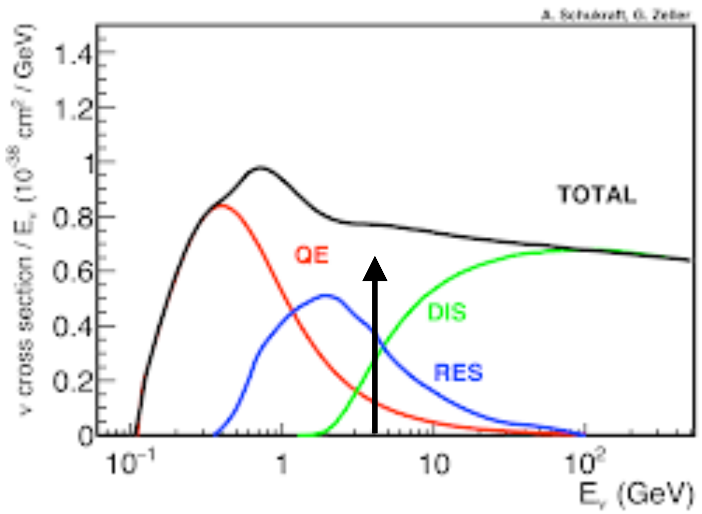


Neutrino Interaction Plinko

Pick a neutrino energy — **3 GeV**

Pick a neutrino flavor — **Muon Neutrino**

Pick an interaction type

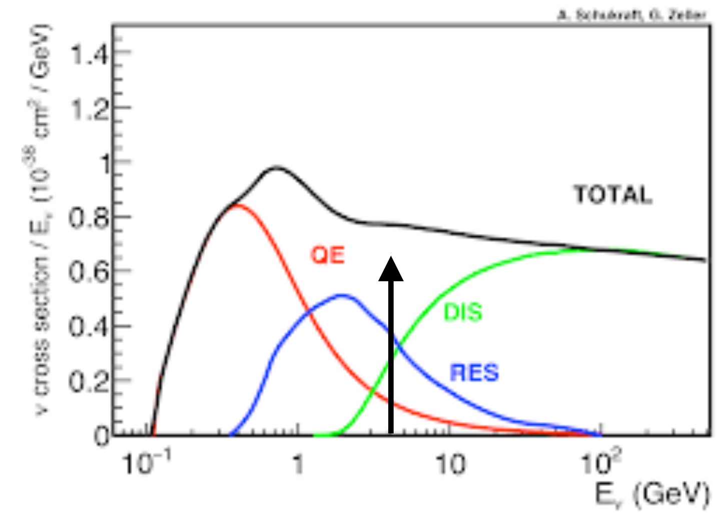


Neutrino Interaction Plinko

Pick a neutrino energy — 3 GeV

Pick a neutrino flavor — Muon Neutrino

Pick an interaction type — Single Pion Resonance



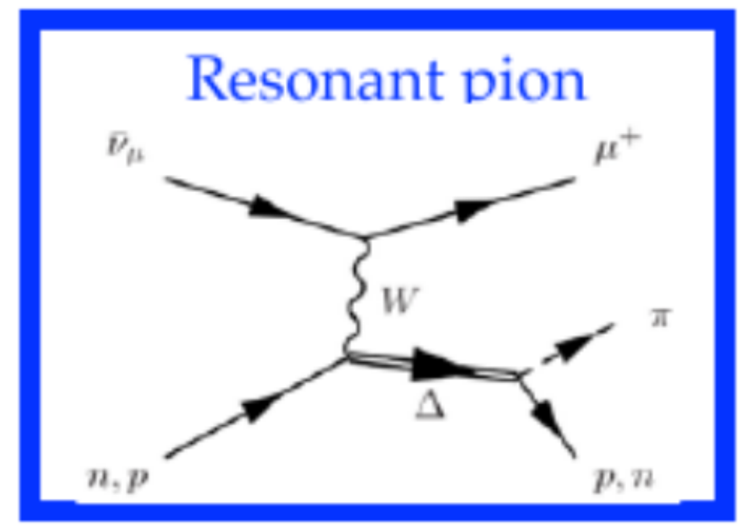
Neutrino Interaction Plinko

Pick a neutrino energy — 3 GeV

Pick a neutrino flavor — Muon Neutrino

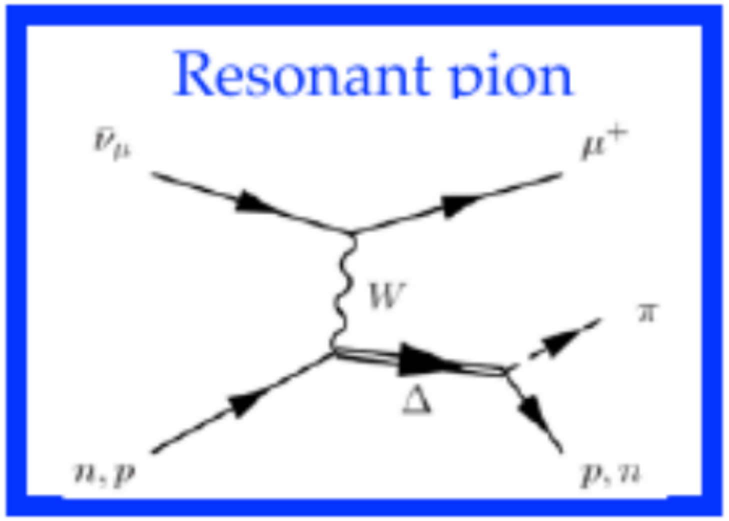
Pick an interaction type — Charged Current Single Pion Resonance

What are the particles created?



Neutrino Interaction Plinko

Pick a neutrino energy	3 GeV
Pick a neutrino flavor	Muon Neutrino
Pick an interaction type	Charged Current Single Pion Resonance
What are the particles created?	Muon, Delta++, decays into a single pion, proton



Neutrino Interaction Plinko

Pick a neutrino energy	3 GeV
Pick a neutrino flavor	Muon Neutrino
Pick an interaction type	Charged Current Single Pion Resonance
What are the particles created?	Muon, Delta++, decays into a single pion
What are the particles kinematics?	

Neutrino Interaction Plinko

Pick a neutrino energy	3 GeV
Pick a neutrino flavor	Muon Neutrino
Pick an interaction type	Charged Current Single Pion Resonance
What are the particles created?	Muon, Delta++, decays into a single pion
What are the particles kinematics?	1 GeV Muon, 30 deg angle 2 GeV, -20 deg angle

Neutrino Interaction Plinko

Pick a neutrino energy	3 GeV
Pick a neutrino flavor	Muon Neutrino
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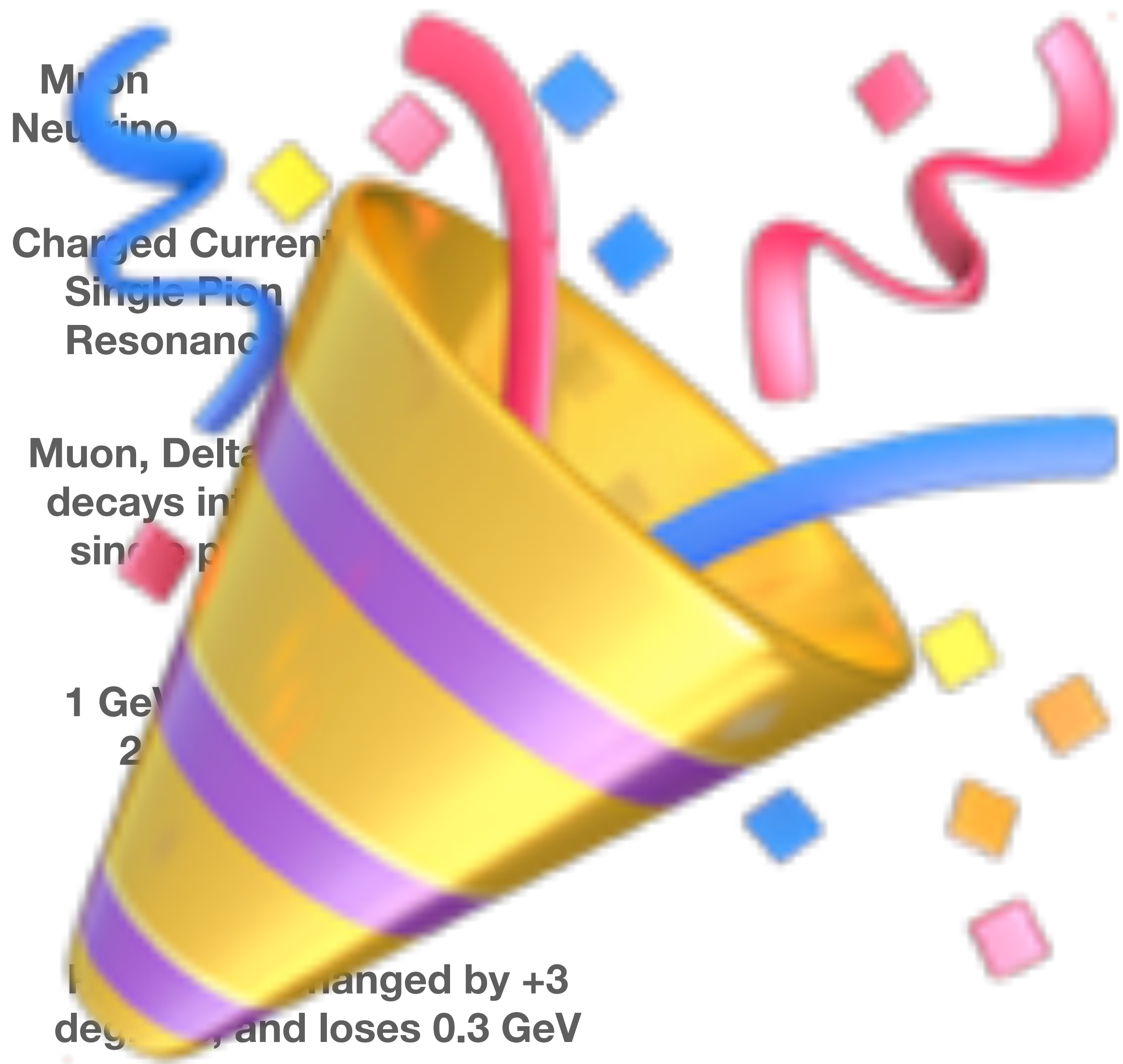
What are the particles created?	Muon, Delta++, decays into a single pion
What are the particles kinematics?	1 GeV Muon, 30 deg angle 2 GeV, -20 deg angle
What happens as the particles exit the nucleus?	

Neutrino Interaction Plinko

Pick a neutrino energy	3 GeV
Pick a neutrino flavor	Muon Neutrino
Pick an interaction type	Charged Current Single Pion Resonance
What are the particles created?	Muon, Delta++, decays into a single pion
What are the particles kinematics?	1 GeV Muon, 30 deg angle 2 GeV, -20 deg angle
What happens as the particles exit the nucleus?	Pion angle changed by +3 degrees, and loses 0.3 GeV

Neutrino Interaction Plinko

Pick a neutrino energy	3 GeV
Pick a neutrino flavor	M on Neu rino
Pick an interaction type	Charged Curren Single Pion Resonanc
What are the particles created?	Muon, Delt decays in sin p
What are the particles kinematics?	1 Ge 2
What happens as the particles exit the nucleus?	anged by +3 deg and loses 0.3 GeV



Neutrino Interaction Plinko

This whole endeavor is fraught with dragons.

Note the dragon where the MC is used!

We are building in our assumptions.

It is important to understand your MC and the limitations of the MC.

The MC is often listed as “Truth” in files. In fact, **it is not the truth. It is** our *best guess*.

Ok! Finally! Cross Sections!!

Total Cross Section

of Scattering Centers

$$N = \Phi T \sigma$$

Number of Interactions

Flux

Cross Section!

Differential Cross Section

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

- j represents the reconstructed bin
- Alpha represents the true bin
- x is the quantity you want to measure your cross section with respect to.

Cross Section Formula

Cross Section
in bin alpha

Unfolding
Matrix

Selected
Events

Subtract
Backgrounds

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{E_\alpha (\Phi T)(\Delta x)}$$

Efficiency in
bin alpha

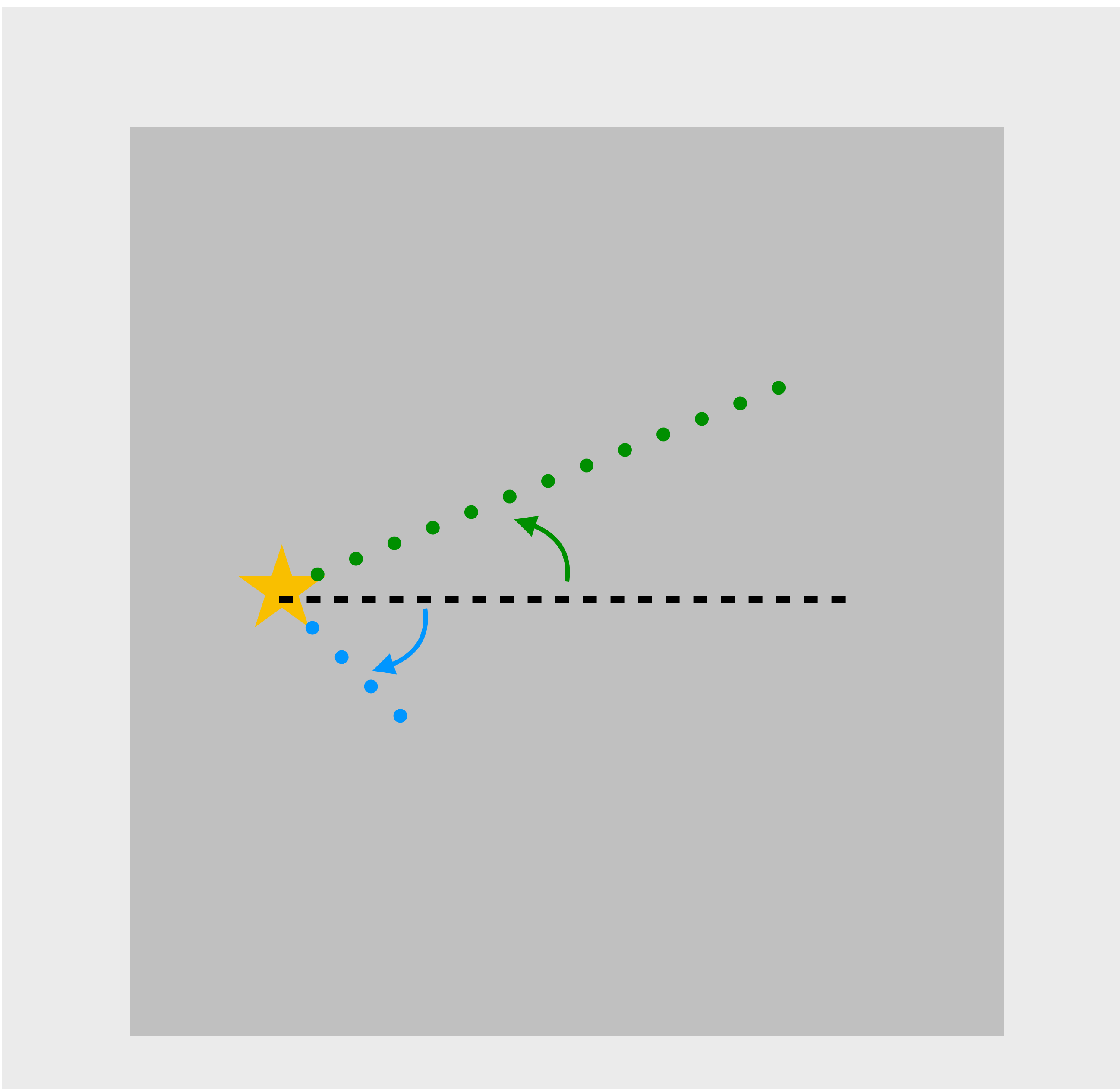
Flux times
the number
of scattering
centers

Bin Width
Normalize

- j represents the reconstructed bin
- Alpha represents the true bin
- x is the quantity you want to measure your cross section with respect to.

Event Selection

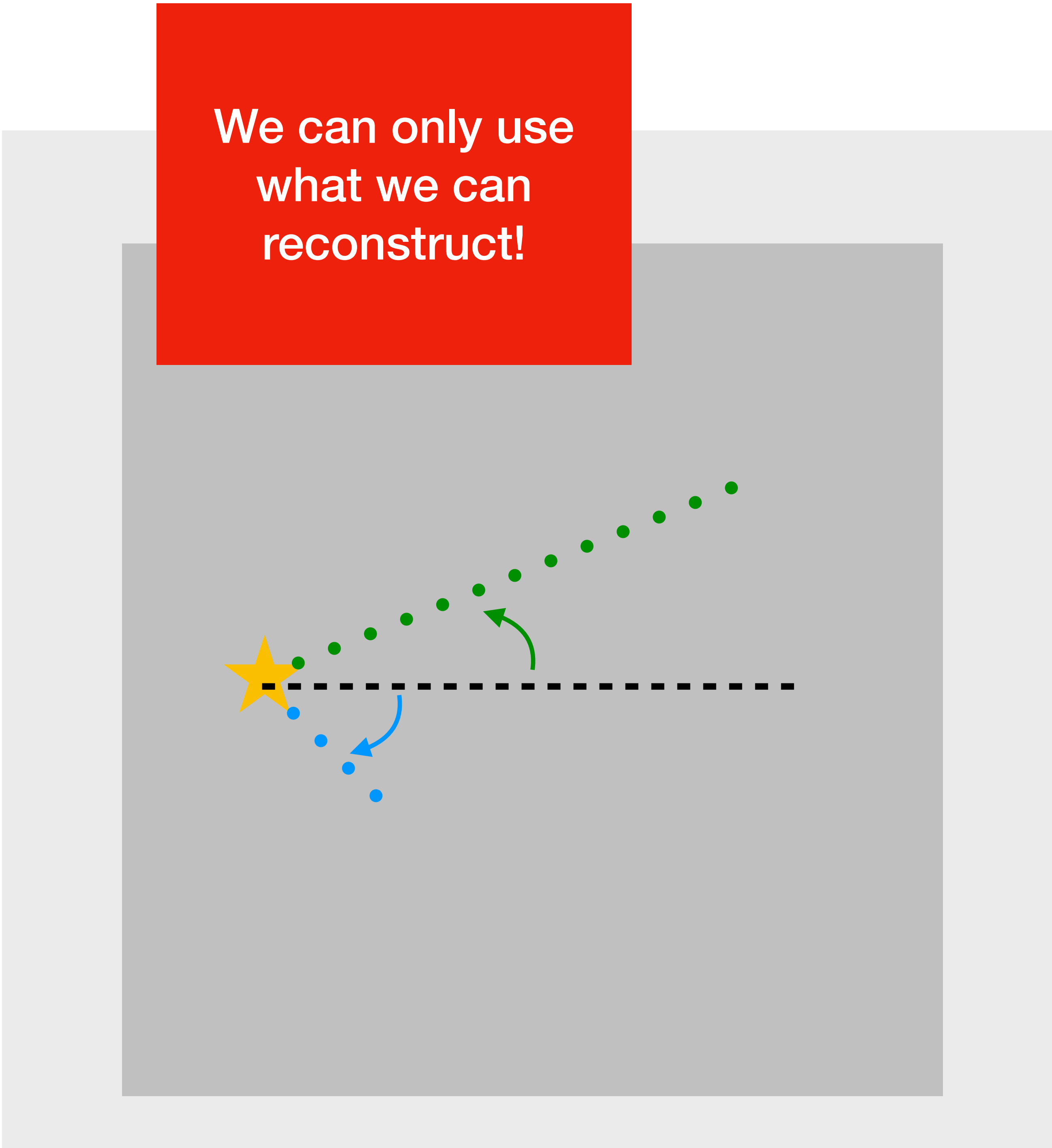
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$



- What do our ideal events look like? (Example)
  - Starts inside the detector
  - Ends inside the detector
  - Reconstructed with the particles we care about
  - Has kinematic properties we care about

Event Selection

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$



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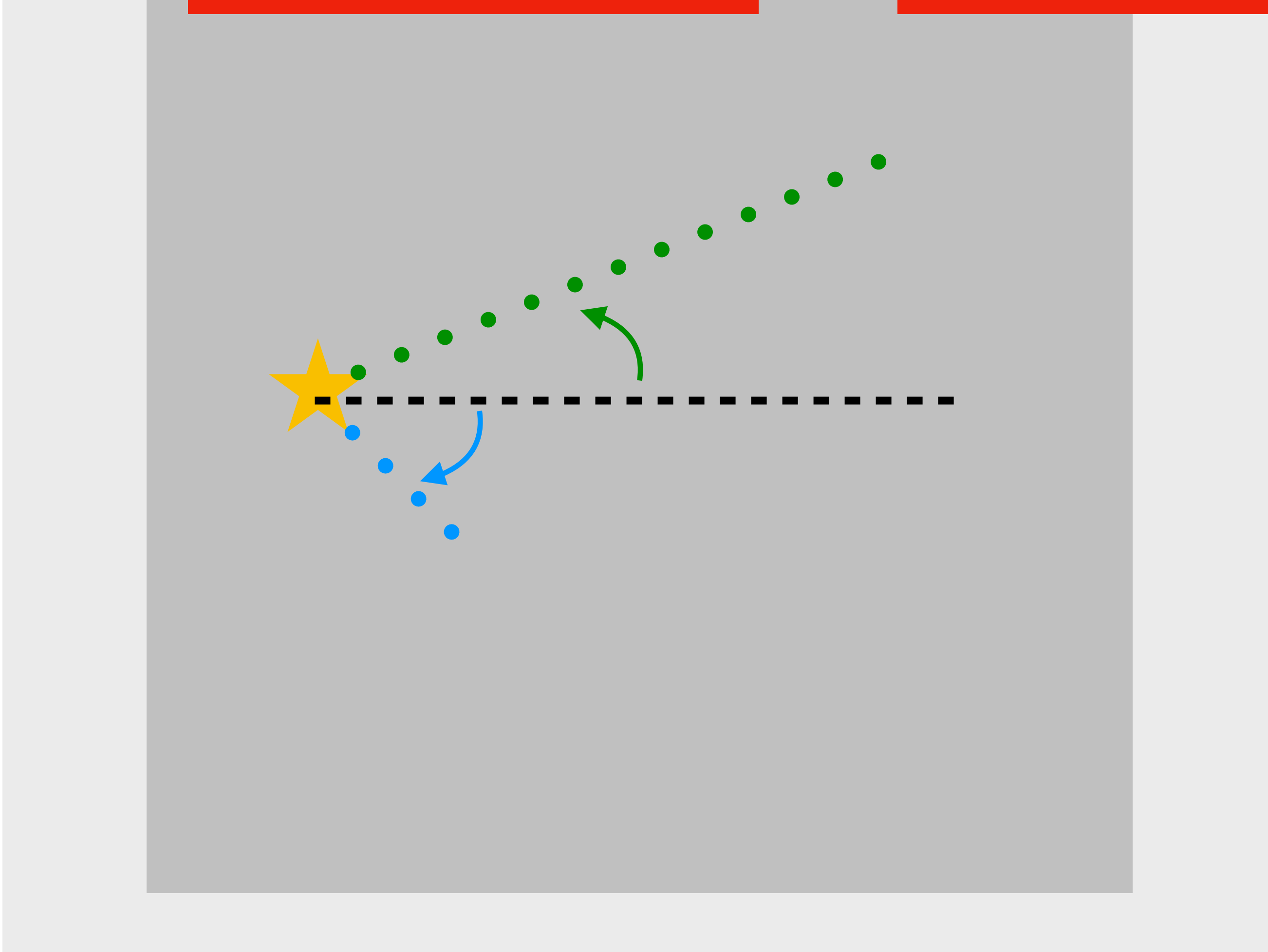
Event Selection

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

We can only use what we can reconstruct!

Make selections based on what your detector can see!



hat do our ideal events ok like? (Example)

- Starts inside the detector
- Ends inside the detector
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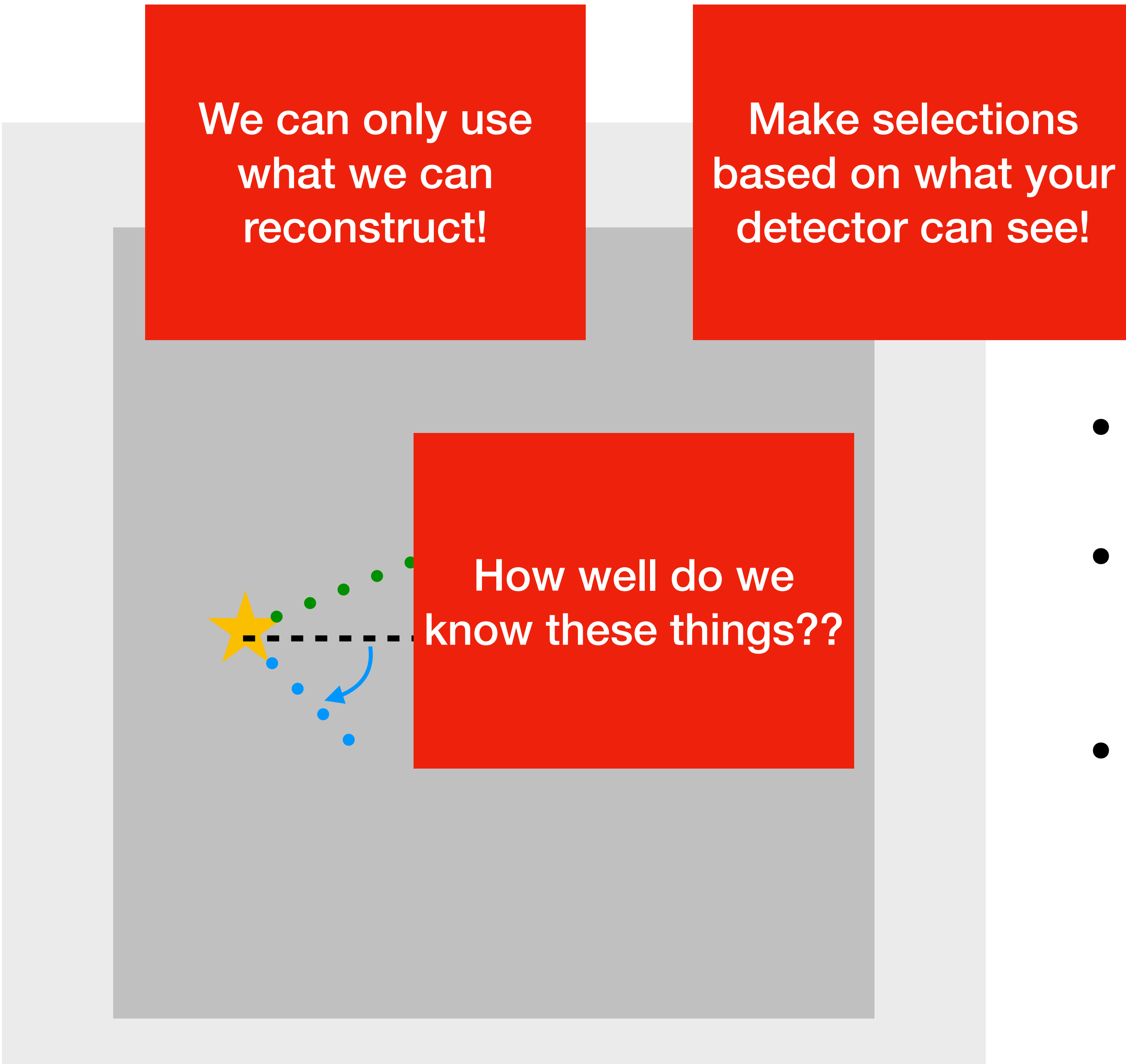
Event Selection

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(\boxed{N_{data,j}} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$



hat do our ideal events ok like? (Example)

Starts inside the detector

- Ends inside the detector
- Reconstructed with the particles we care about
- Has kinematic properties we care about

Event Selection

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

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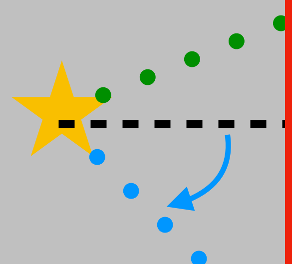


/hat do our ideal events
ok like? (Example)

Starts inside the detector

- Ends inside the detector
- Reconstructed with the particles we care about
- Has kinematic properties we care about

Event Selection

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

- How would you tell an alien how to find the sheep in this picture?
  - Number of legs?
  - Fur Color?
  - Ear shape?
  - Hoof type?
  - Nose color?

Event Selection

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

- It's a balancing act
    - Need enough sheep
    - But you don't want too many goats
- If you're going after a rare process with lots of background, we often use a figure of merit such as

$$\frac{s}{\sqrt{s+b}}$$

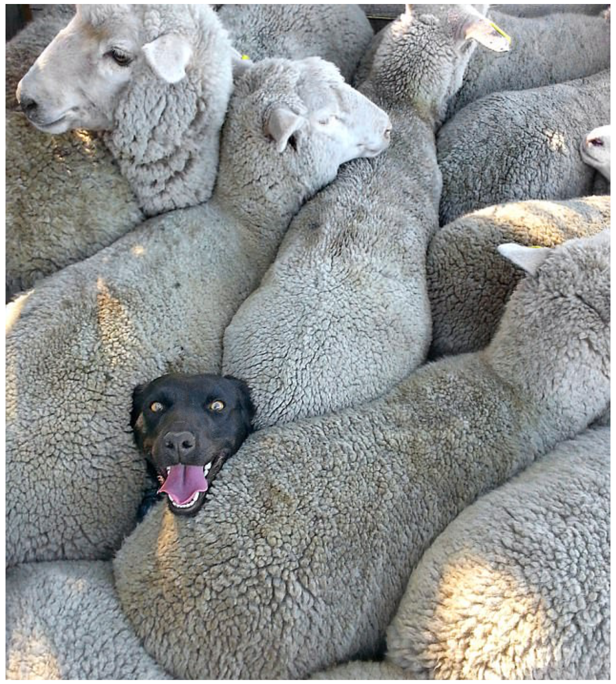
- Taking into account the systematic errors you'll get based on different cuts can also help define your event selection.

Backgrounds!

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - \boxed{N^{bkgd}_{data,j}})}{E_\alpha(\Phi T)(\Delta x)}$$

Signal

Signal + Bkgd

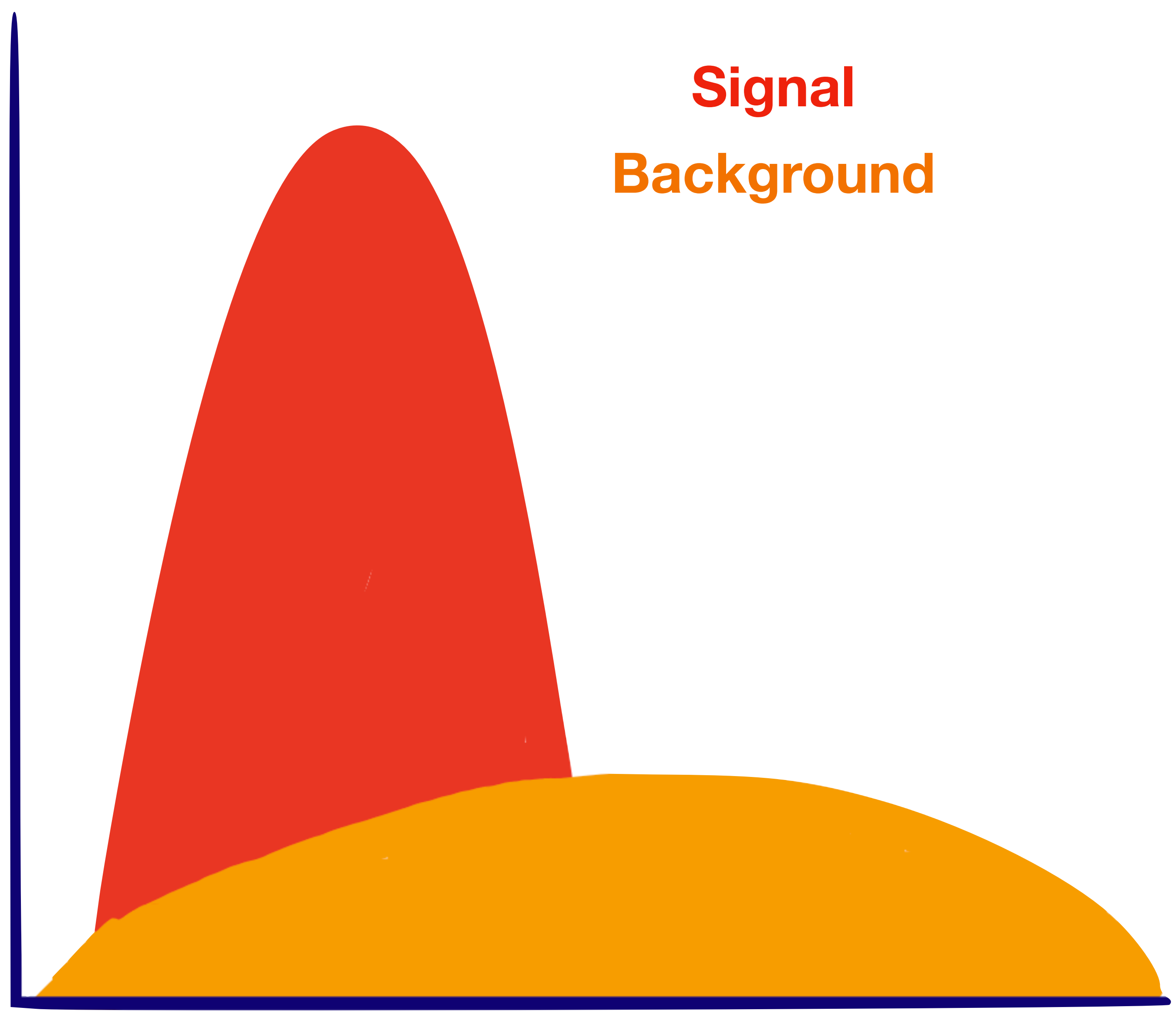


- There are always going to be some events in your distribution that aren't truly your signal.
- Subtracting off your background is a place where we rely on our **Monte Carlo**, so we often use a data-driven tuning in your background region.
    - Simplest version: Look in a background-rich region and tune the MC to the data in that region.
- The methods you use for your background subtraction depends a lot on what your sample looks like.

Backgrounds!

Sideband Fitting

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

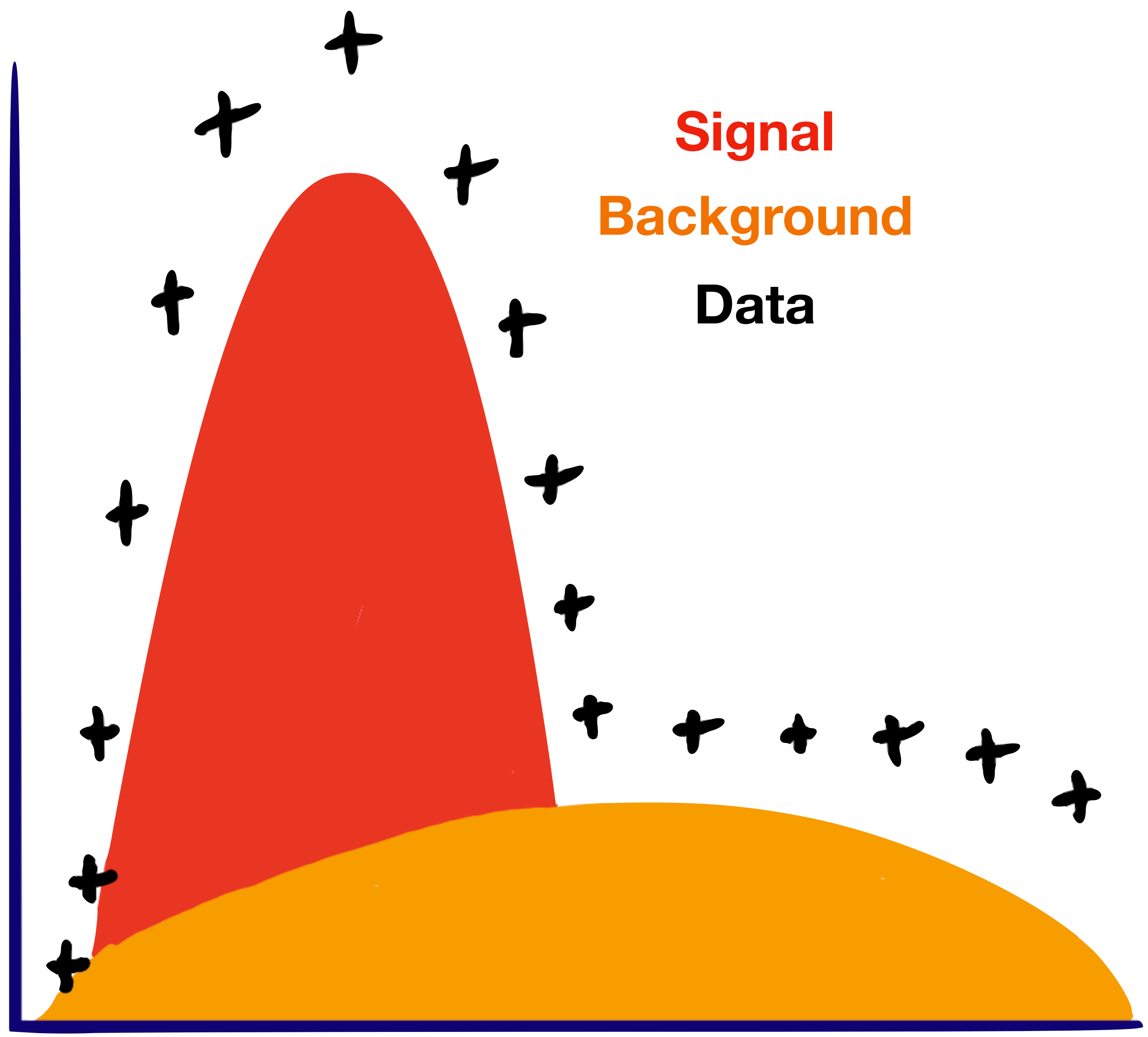


- Start with the model prediction

Backgrounds!

Sideband Fitting

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - \boxed{N_{data,j}^{bkgd}})}{E_\alpha(\Phi T)(\Delta x)}$$

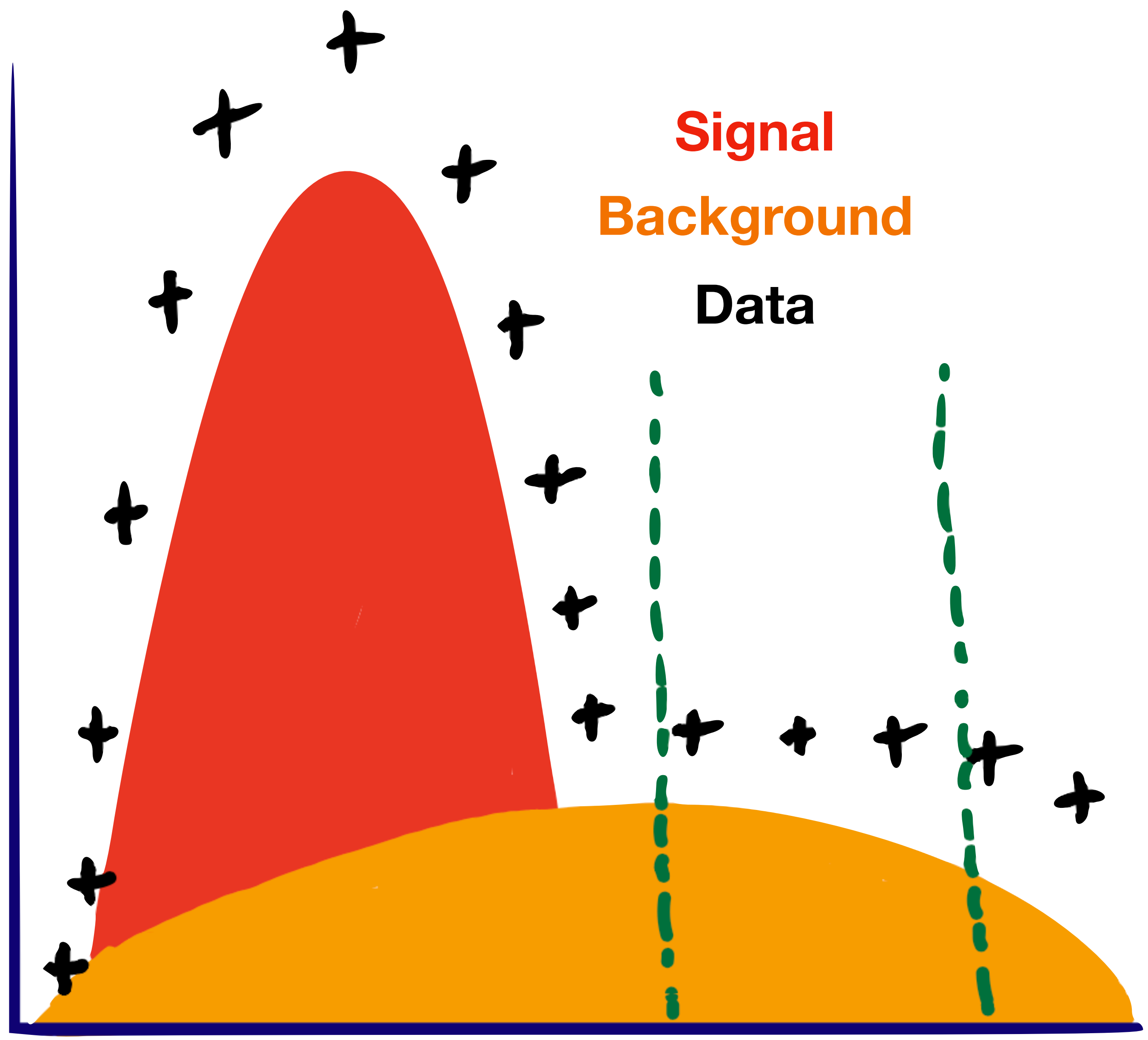


- Start with the model prediction
- How does your data compare?

Backgrounds!

Sideband Fitting

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - \boxed{N^{bkgd}_{data,j}}}{E_\alpha(\Phi T)(\Delta x)}$$

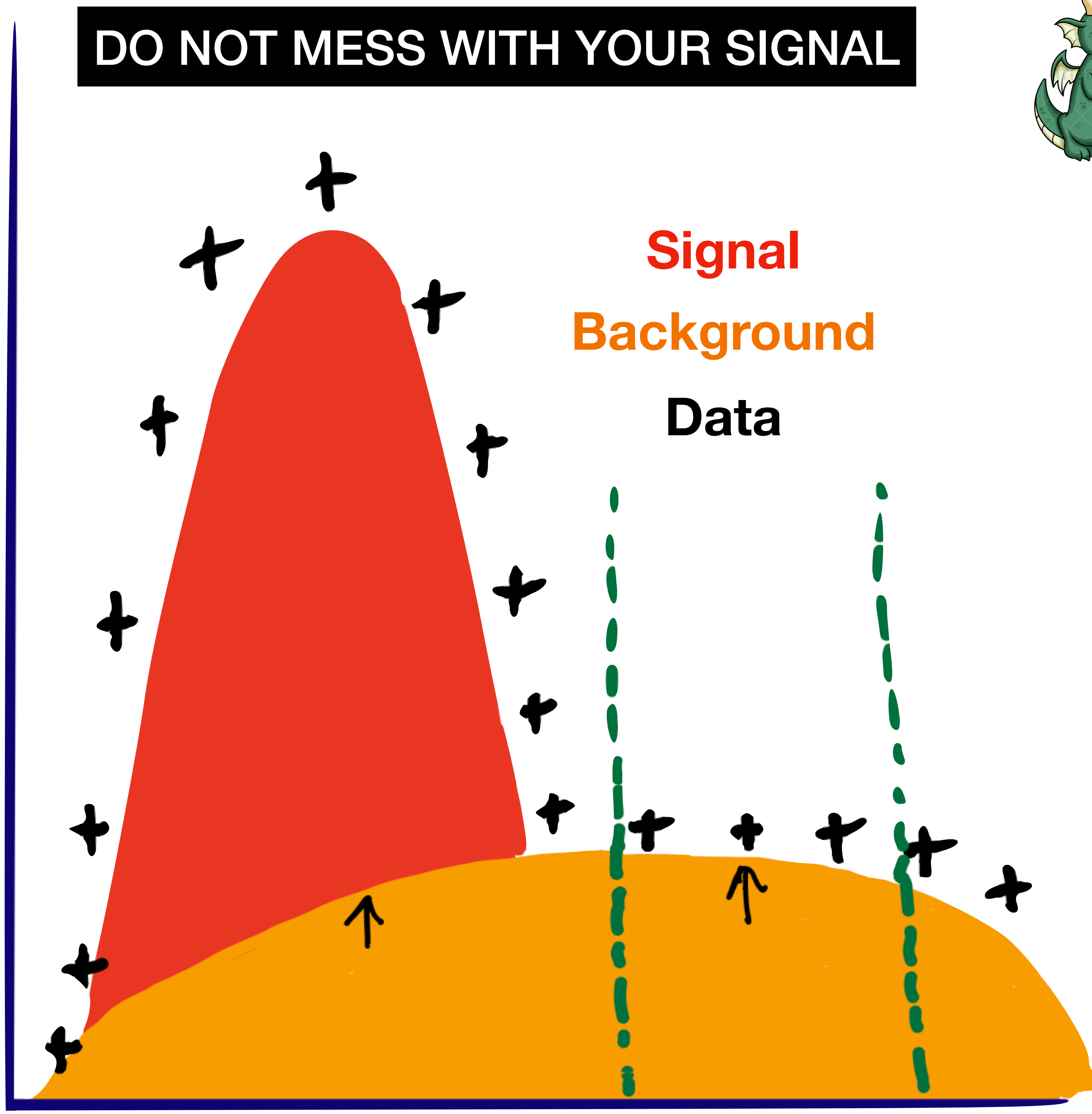


- Start with the model prediction
- How does your data compare?
- Look in a region where you expect little to no signal

Backgrounds!

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

Sideband Fitting



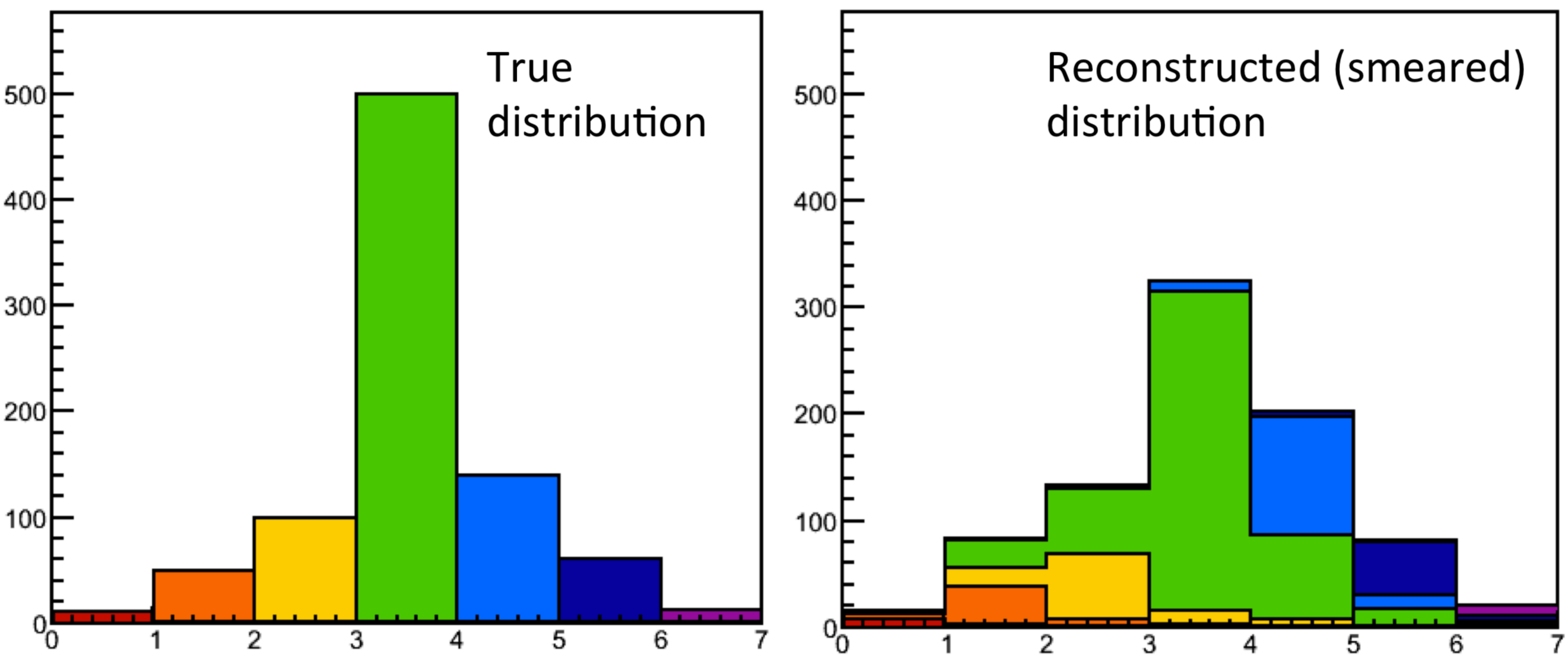
- Start with the model prediction
- How does your data compare?
- Look in a region where you expect little to no signal
- Fit the MC to the data in the sideband region, apply across the board.

Unfolding

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

- Since we can't actually reconstruct events perfectly, we sometimes end up with events in the wrong bin:

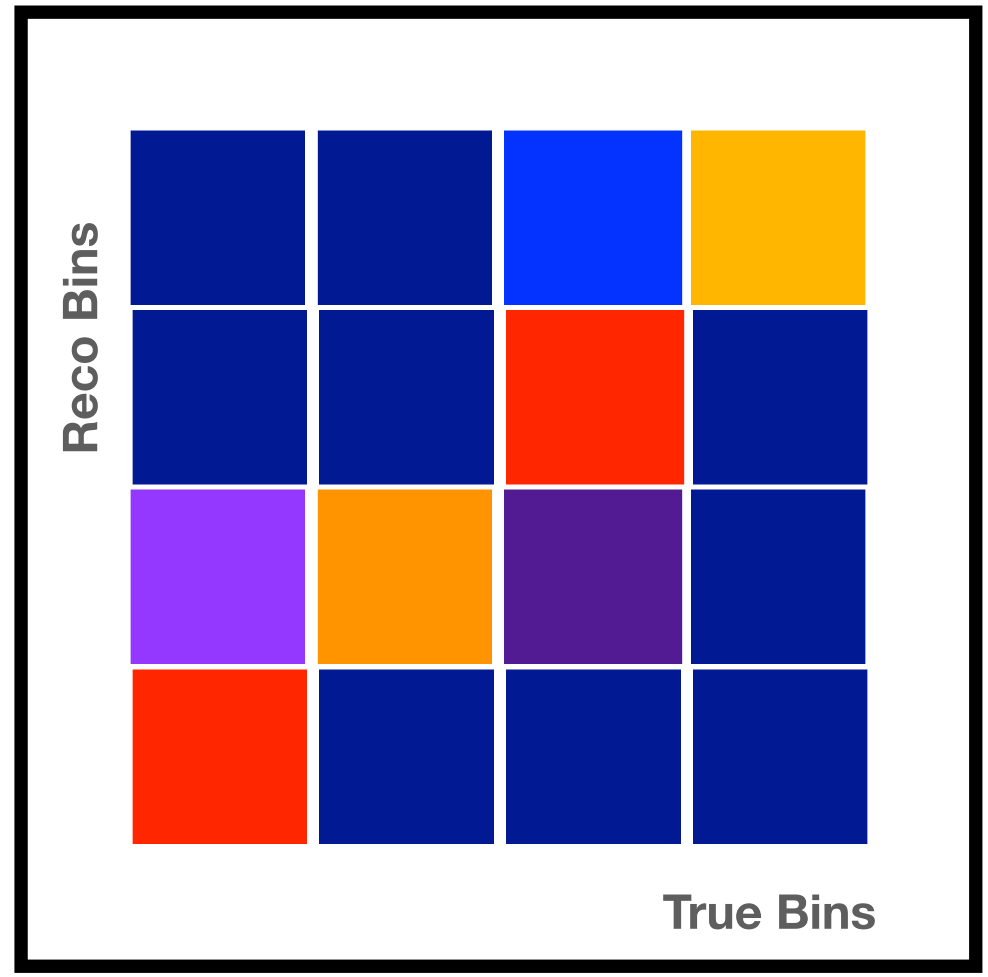
Thanks Cheryl for this perfect graphic



Unfolding

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

- Nominally, you could just take the migration matrix and invert it…. But it generally isn't that simple….
- Unfolding techniques are numerous, controversial, the subject of another talk…
- This is another spot where your MC is really important. Be careful!



Unfolding

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha(\Phi T)(\Delta x)}$$

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Anne’s soapbox. There are more and less useful times and ways to unfold your analysis.

The most important thing is to know what you are doing, and to fully explain what you are doing.

Efficiency

$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_{\alpha}(\Phi T)(\Delta x)}$$

- No matter what we do, our selection cuts aren't going to be able to find all of the events.
- Why not?
  - Detector acceptance
  - Reconstruction Efficiency
- Relies on your MC, so be careful!
- If you run your unfolding and efficiency correction on your MC distribution should return your generator distribution (a good test to run!).

$$E_{\alpha} = \frac{N_{\alpha\, signal,\, reconstructed}}{N_{\alpha\, signal}}$$

Efficiency

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{\boxed{E_\alpha}(\Phi T)(\Delta x)}$$

Start with an event

Should I have selected this event according to the MC?

Yes → Did I select this event using my reconstruction?

- Yes → Goes in Numerator and Denominator
- No → Goes only in the denominator

No →

Efficiency

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha (\Phi T)(\Delta x)}$$

Start with an event

↓

Should I have selected this event according to the MC?

- Yes → Did I select this event using my reconstruction?
  - Yes → Goes in Numerator and Denominator
  - No → Goes only in the denominator
- No →

Number of Scattering Centers

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha \boxed{(\Phi T)} (\Delta x)}$$

- We divide by the number of places that the neutrino could interact.
- What is a scattering center?
    - Depends on the measurement you're trying to make! If the interaction only takes place on a whole nucleus, then you would count the number of nuclei. If the interaction only takes place on protons, then count the number of protons!

The Flux

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{E_\alpha \boxed{\Phi T} (\Delta x)}$$

It might be a quagmire….
but maybe it's a quagmire with some boardwalks

- The way we understand and calculate the flux should definitely be the subject of another talk.
- Integrated Flux cross sections: anything that isn't with respect to neutrino energy.
- Techniques include:
  - Using a process with a well defined cross section (low hadronic energy cross sections, or neutrino-electron scattering)
  - Use detectors that monitor the muons created in the beam line
  - Use hadron production measurements to constrain your flux.
- This again is a land that can rely heavily on Monte Carlo! Be careful!!!

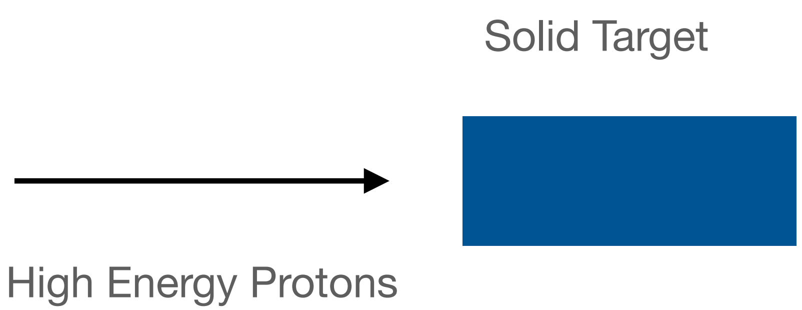
The Flux

$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{E_{\alpha}\boxed{(\Phi T)}(\Delta x)}$$

High Energy Protons

The Flux

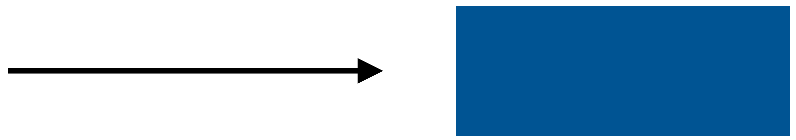
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha \boxed{(\Phi T)} (\Delta x)}$$



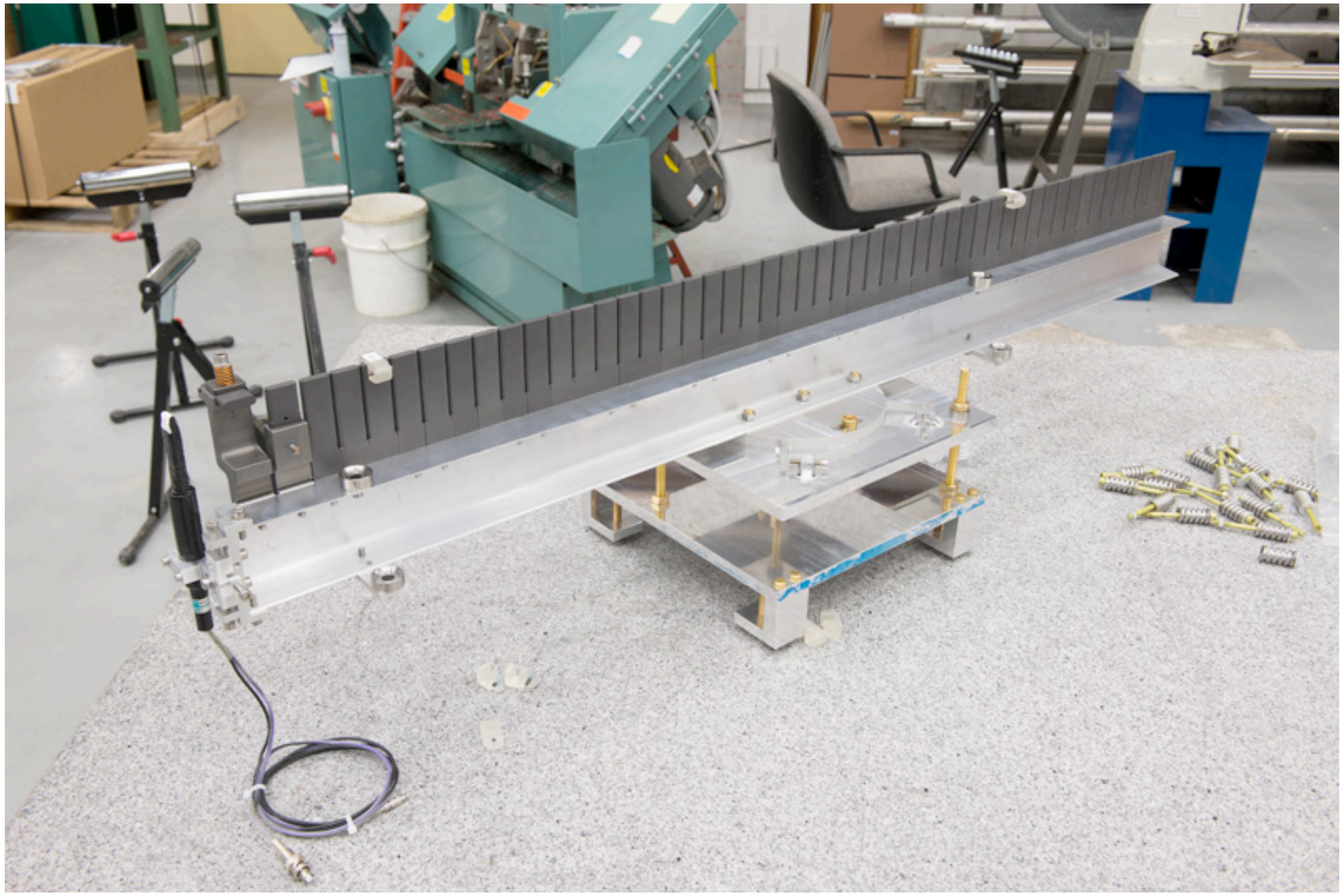
The Flux

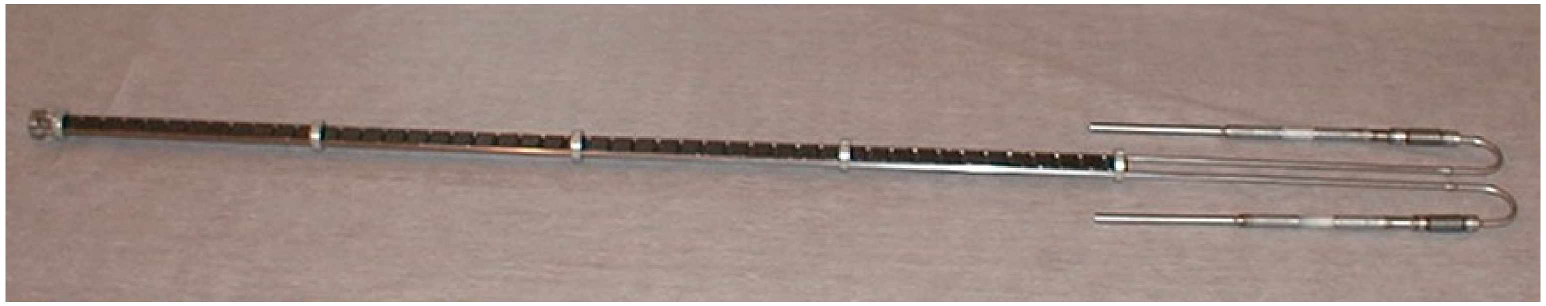
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{E_\alpha \boxed{(\Phi T)} (\Delta x)}$$

Solid Target



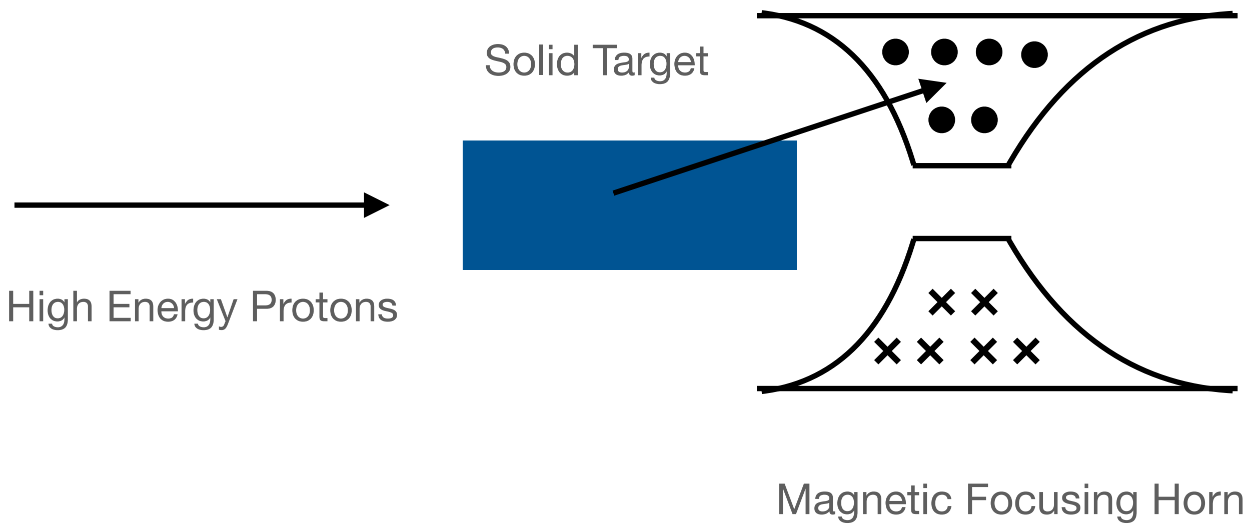
High Energy Protons





The Flux

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha (\Phi T)(\Delta x)}$$



The Flux

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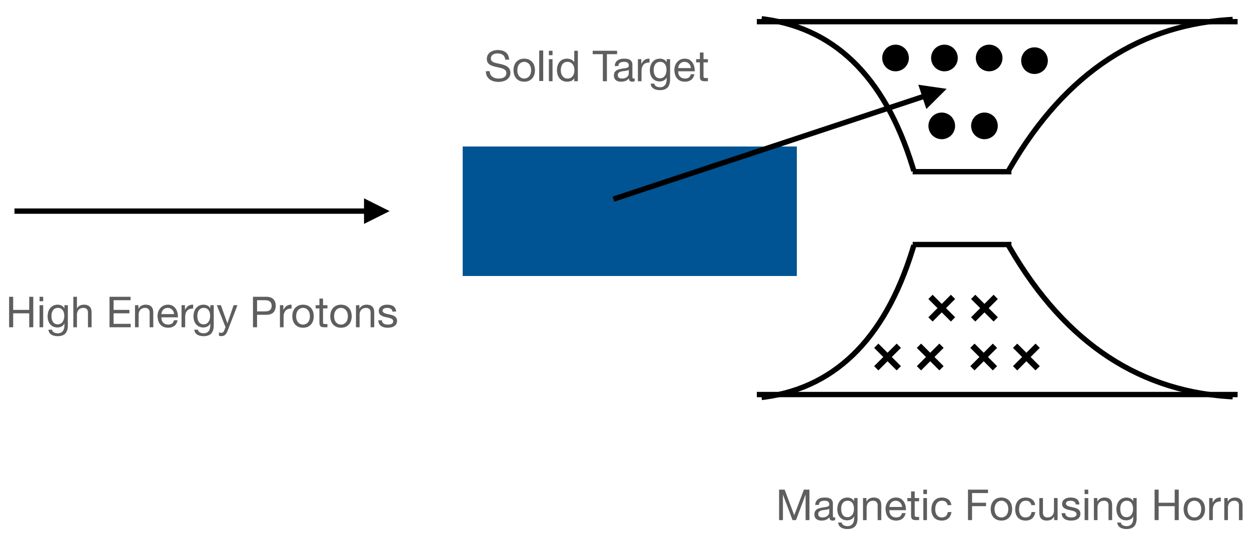

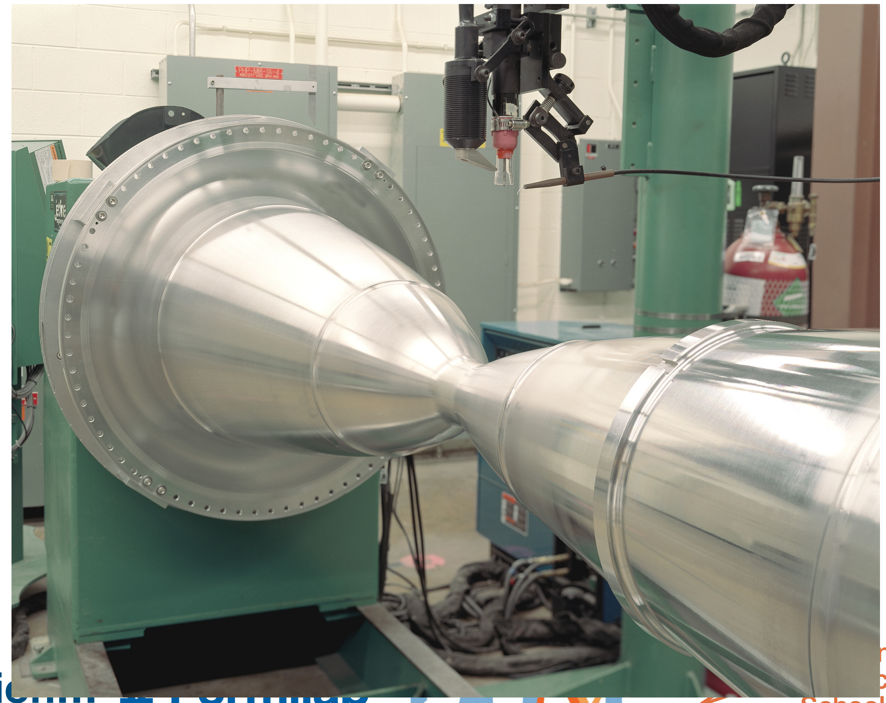

The Flux

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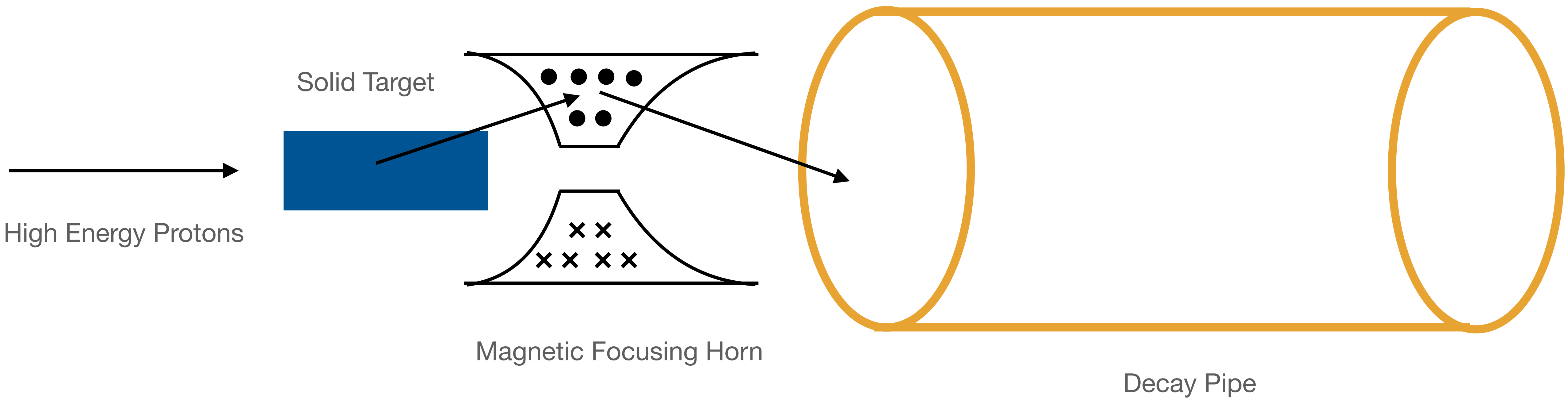

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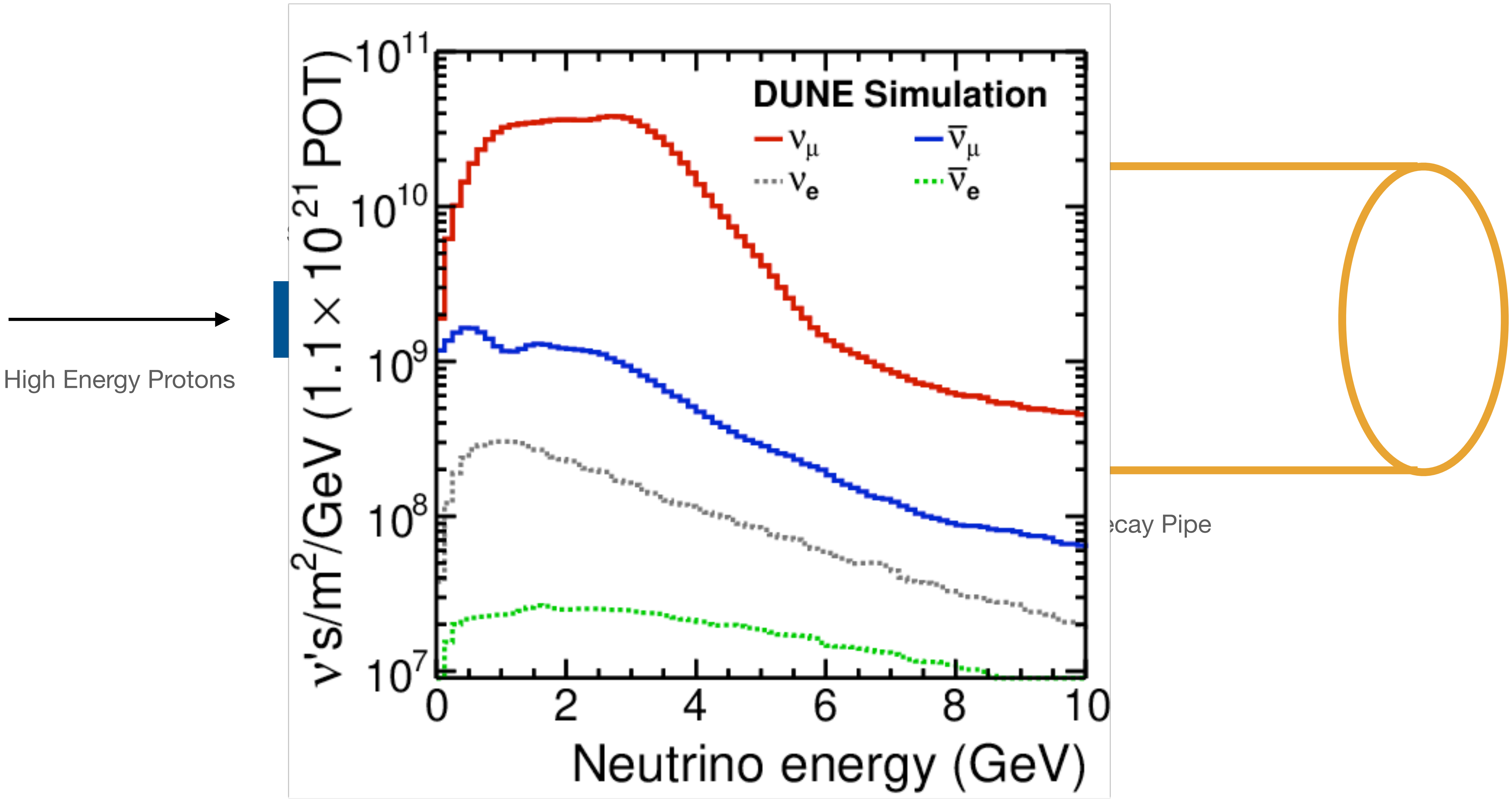


The Flux

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha \boxed{(\Phi T)} (\Delta x)}$$

Techniques for constraining the flux…

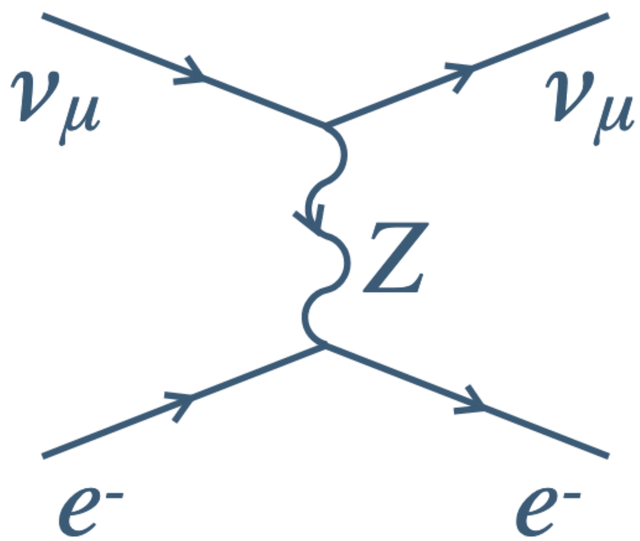
- Using Hadron Production Data
  - Make measurements of the particles produced in the target in a different setting.
  - Normally a whole separate experiment!
- Beamline Monitoring
  - Add in extra components that monitor the muons or hadrons that are leftover in the beam.
  - Done during the running of the experiment.

The Flux

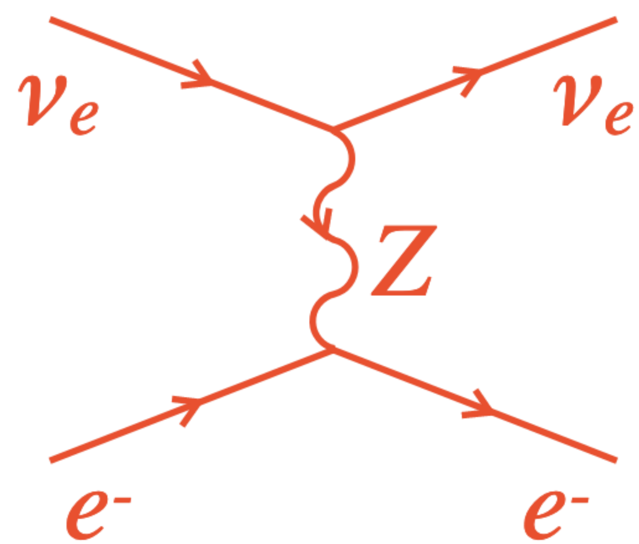
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha \boxed{\Phi T}(\Delta x)}$$

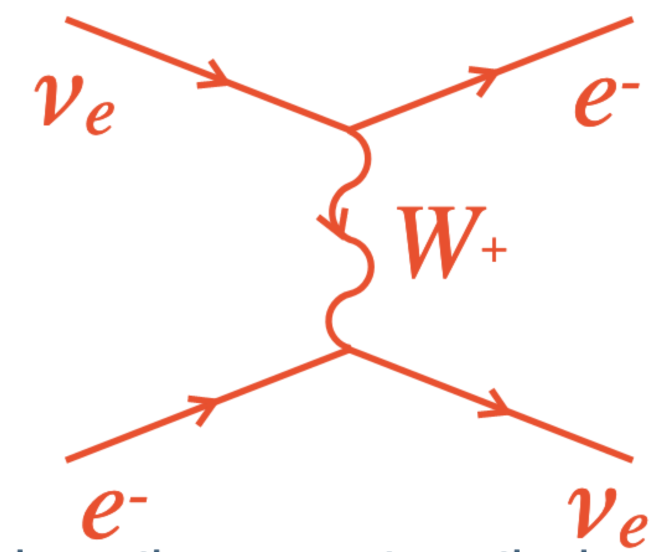
Neutrino-electron elastic scattering

Exercise 4



What's the equivalent for ν_e - e^- scattering?
Can you find another ν_e - e^- scattering with he same final state as the first one you found?





- Electrons are fundamental particles
- Weak scattering is well understood
- Calculate neutrino energy from electron kinematics: good way to study neutrino flux *e.g. Phys. Rev. D 93, 112007 (2016)*

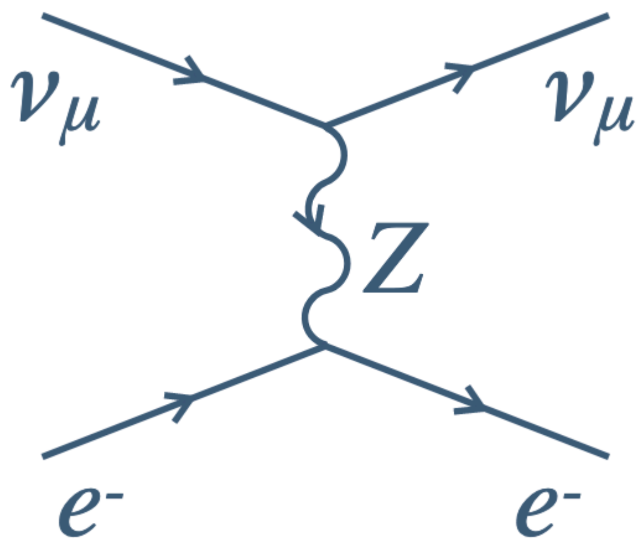
All lepton interactions have the same strengths in the weak interaction (**lepton universality**), but because of **interference** with the CC diagram, the ν_e - e^- cross section is different from the ν_μ - e^-

The Flux

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{E_\alpha \boxed{\Phi T} (\Delta x)}$$

Neutrino-electron elastic scattering

Exercise 4



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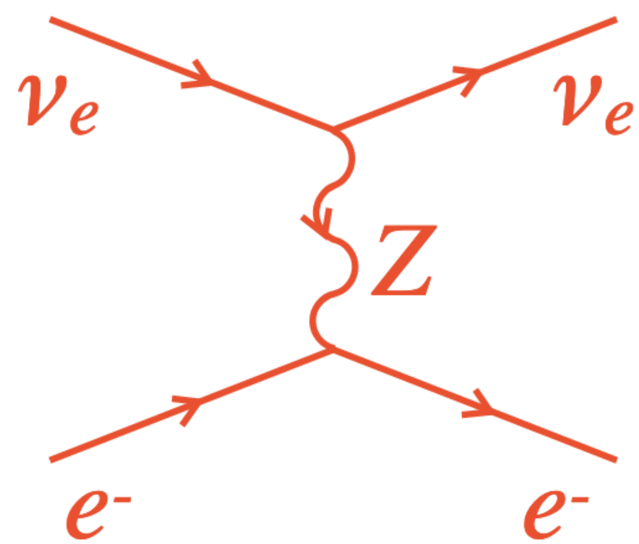
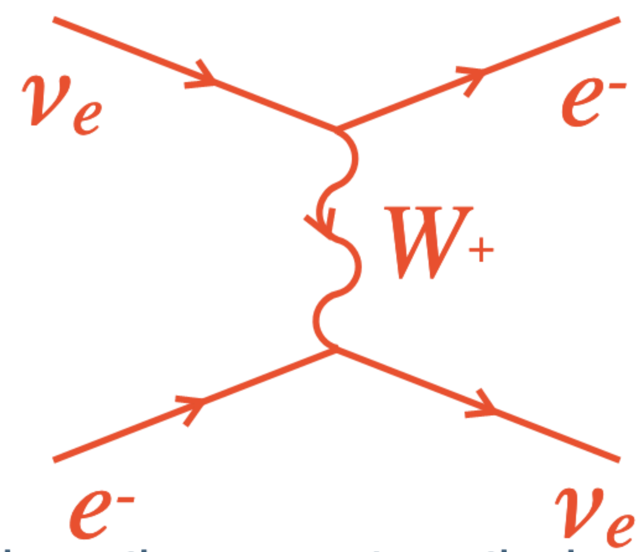




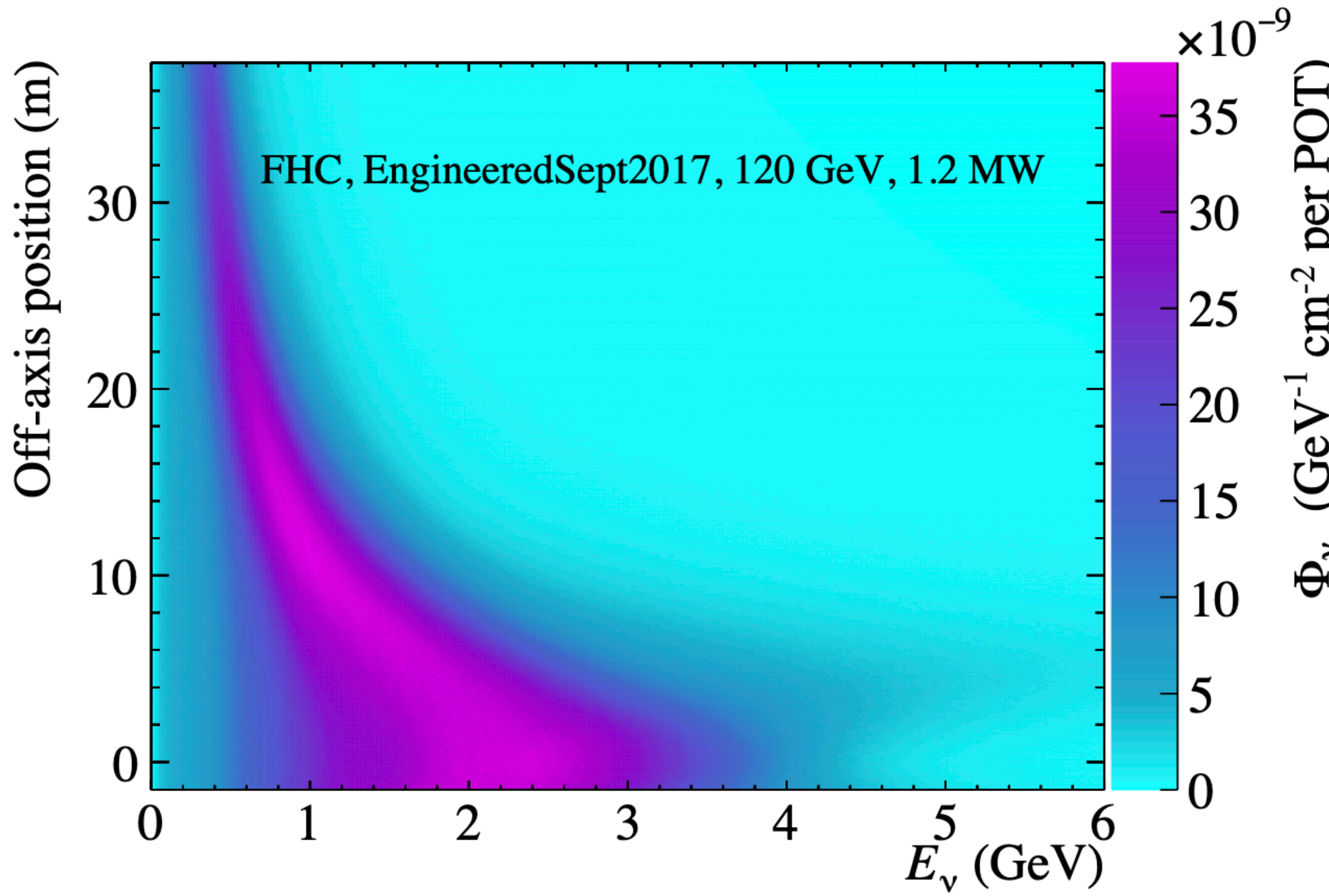
- Electrons are **fundamental** particles
- Weak scattering is well understood

Can tell us the total number of neutrinos, but no shape information about the flux because it's a neutral current process

The Flux

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha \boxed{(\Phi T)} (\Delta x)}$$

- Advertisement for upcoming mini-talk!
- DUNE PRISM also looks to tackle the problems of the flux by looking at off axis components



T. Cai et al, Document here

Cross Section Formula

Cross Section in bin alpha

Unfolding Matrix

Selected Events

Subtract Backgrounds

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{E_\alpha (\Phi T)(\Delta x)}$$

Efficiency in bin alpha

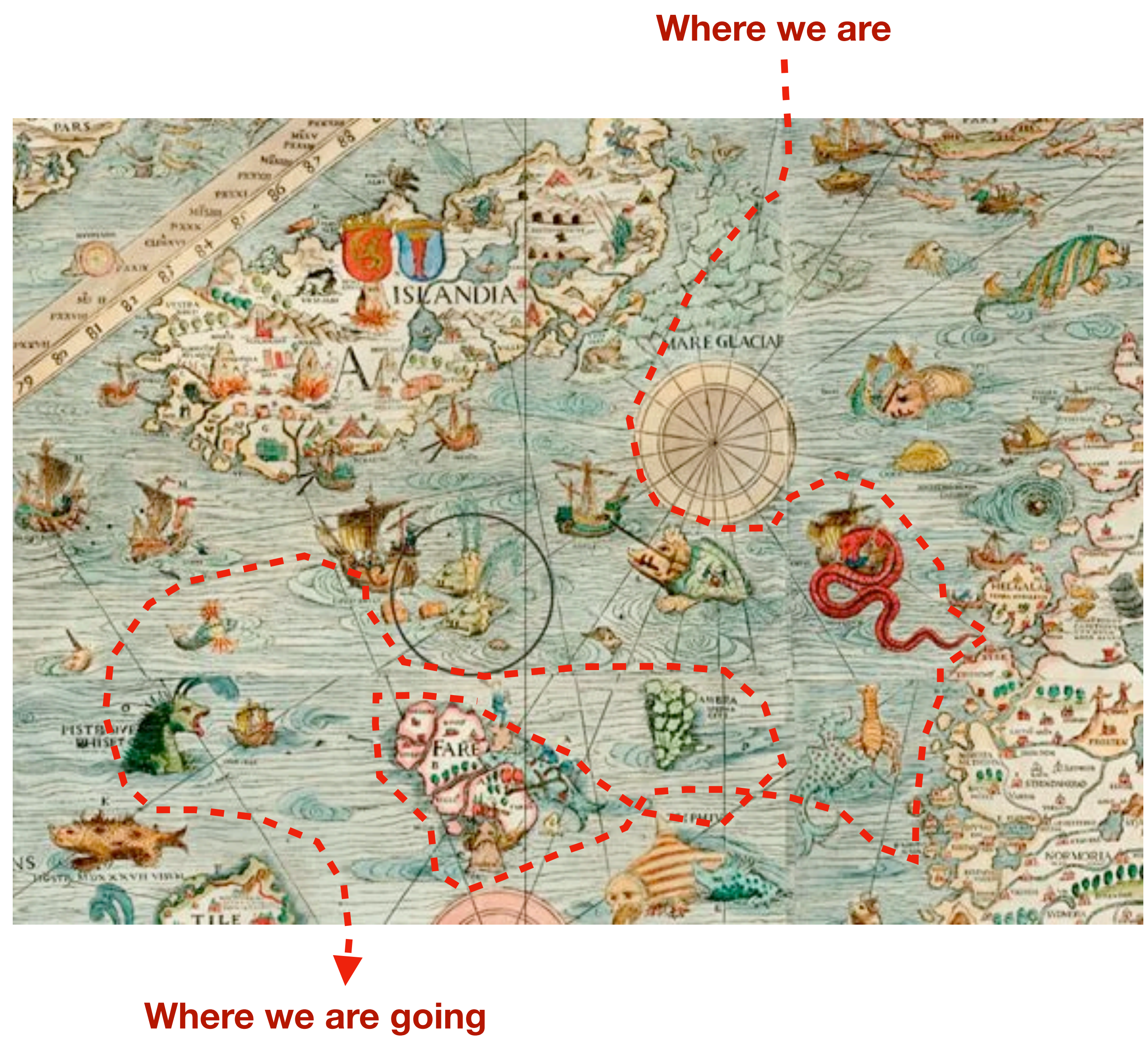
Flux times the number of scattering centers

Bin Width Normalize

- We've now walked the full path of the cross section equation!

Conclusions

- This was my impressionistic path of how to do a cross section analysis.
- There are many dragons and places that can trip you up.
- Model dependence is a mostly-necessary evil, and cross section measurements end up being iterative, making measurements that feed the models and round and round we go.
- There is interesting and challenging physics here, where you can generally take a measurement from start to finish yourself, so it’s fun!



Me at the end of this talk