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PhyStat-Nu, Kavli IPMU

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Neutrino Nucleus Cross Section Experiments

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Outline

- Introduction to accelerator neutrinos
- Neutrino oscillation: the motivation for new cross section measurements
- Common analysis methods
- Model independent measurements
- Personal perspective on what else we could do
- Conclusion

Accelerator Neutrinos

- Accelerator neutrino experiments were born in the 1960s and came of age in the 1970s
- 1960s - First pion decay beam, first focussing horns
- 1970s - Development of big bubble chambers
- Important physics legacies
  - Discovery of 2nd generation of neutrinos
  - Discovery of neutral currents
  - Tests of EW theory

first accelerator neutrino beam

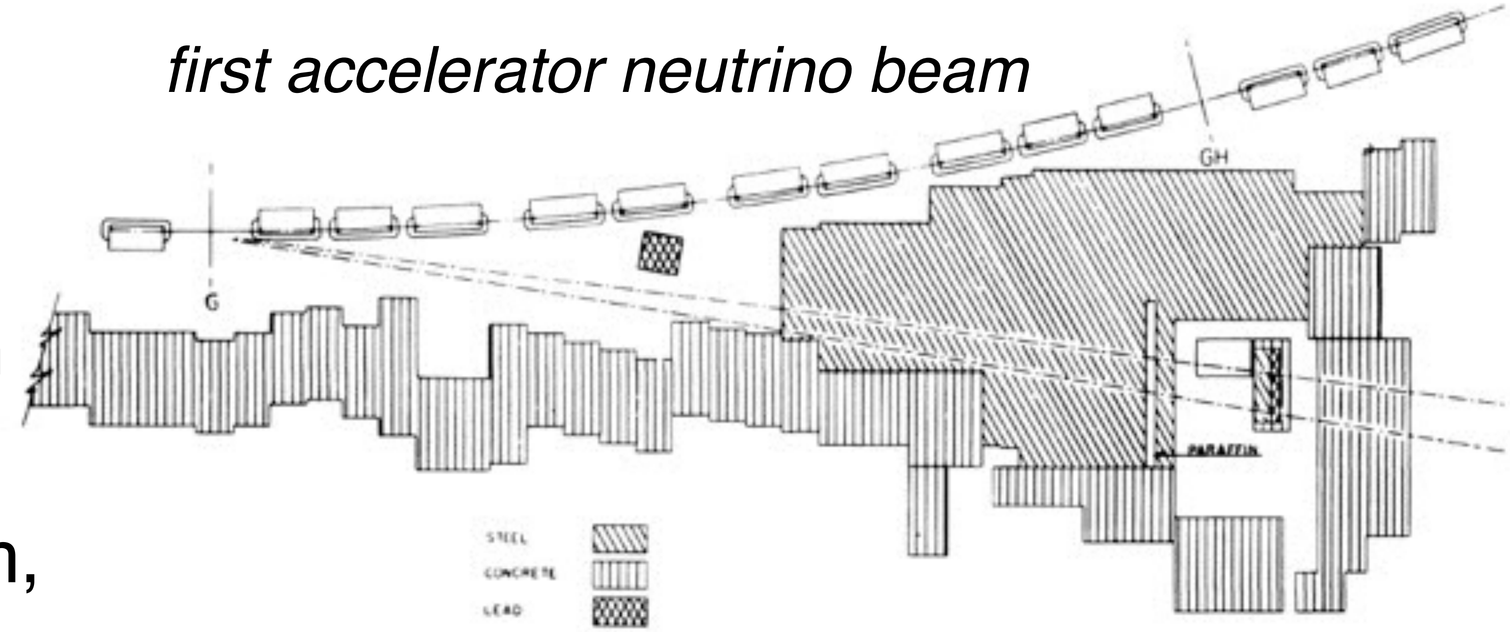
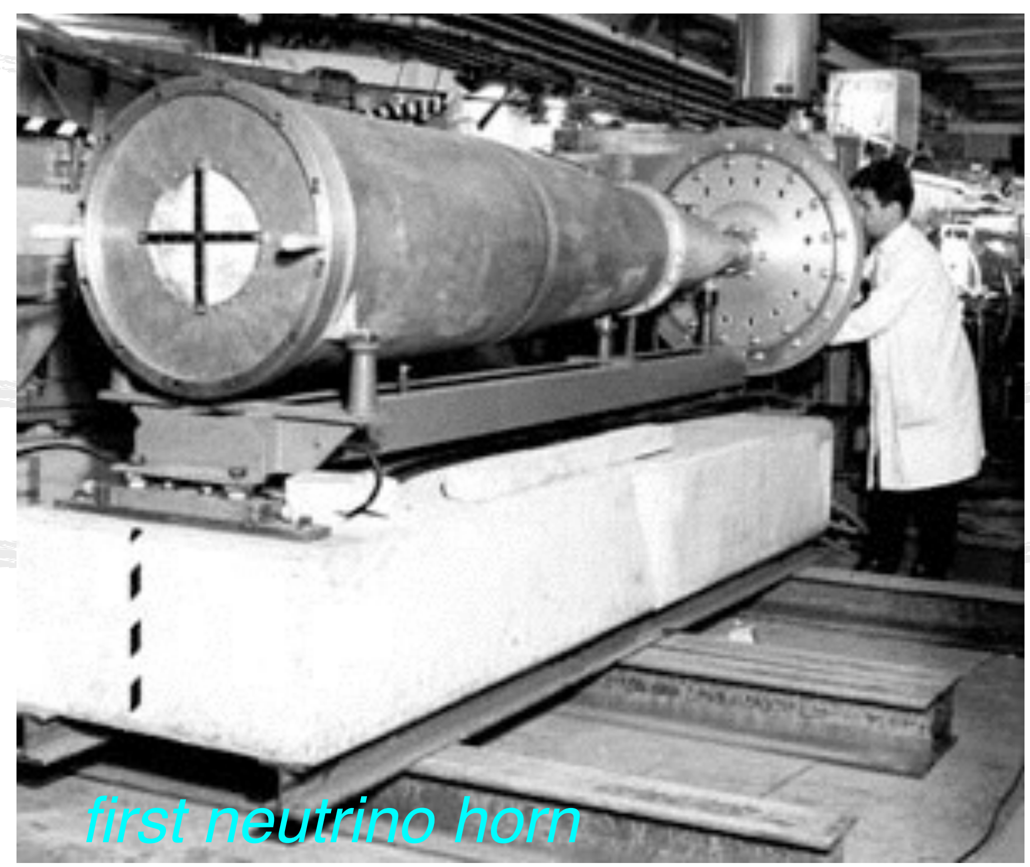
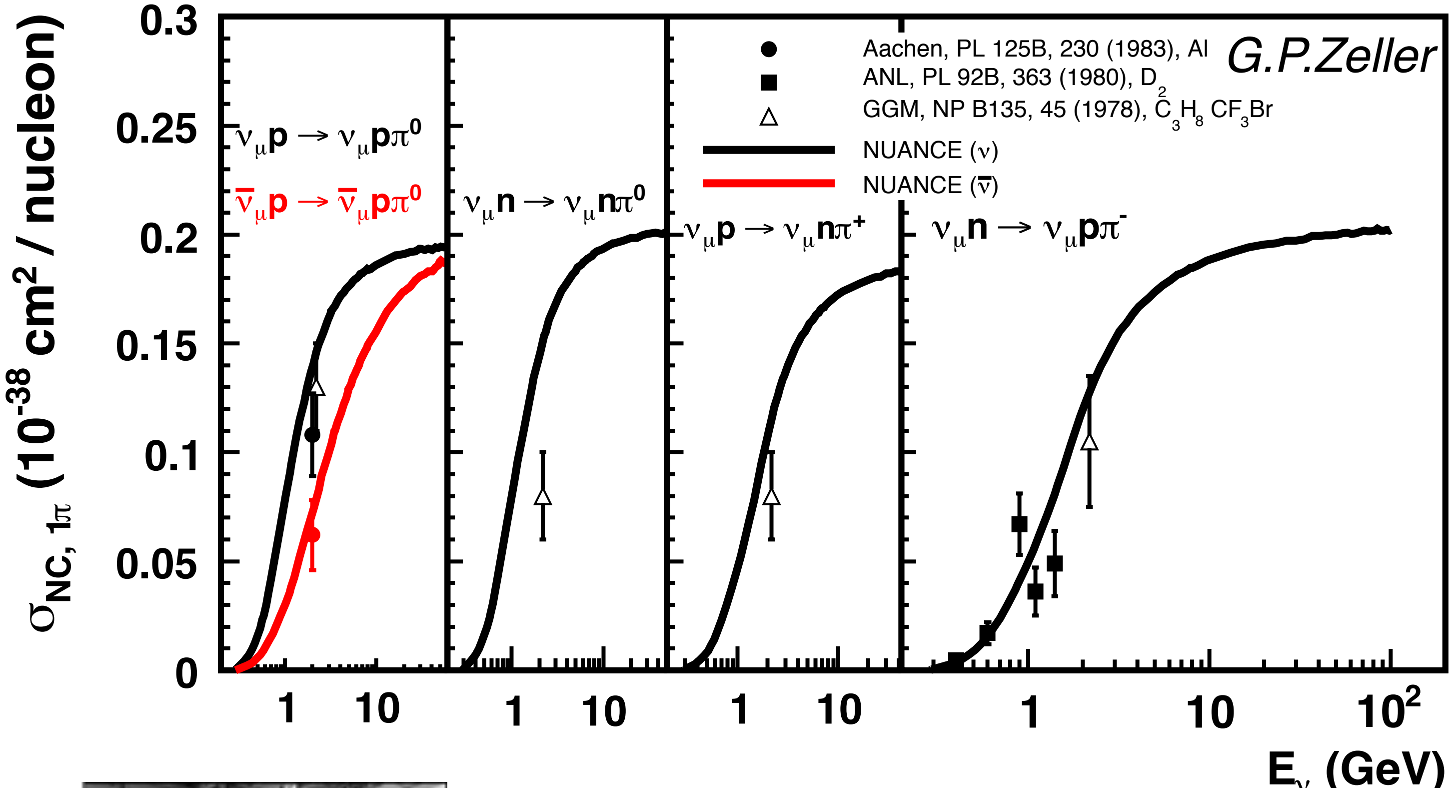


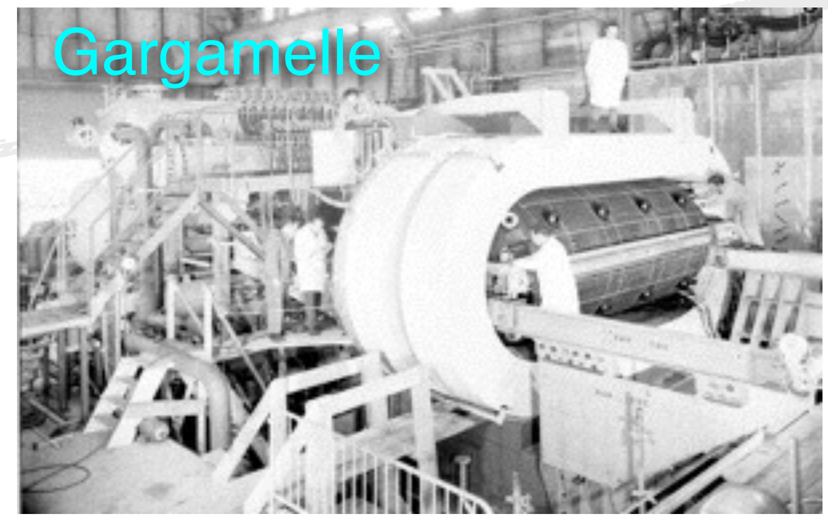
FIG. 1. Plan view of AGS neutrino experiment.

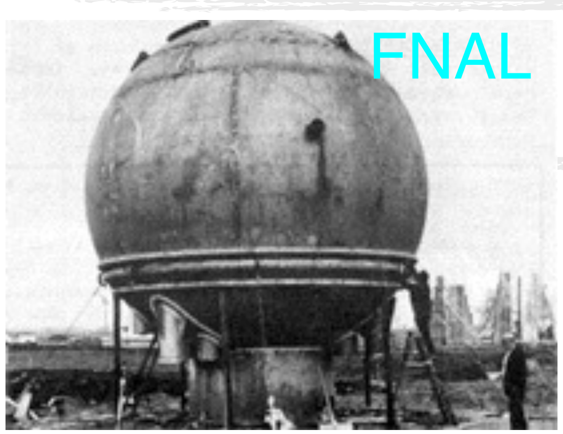


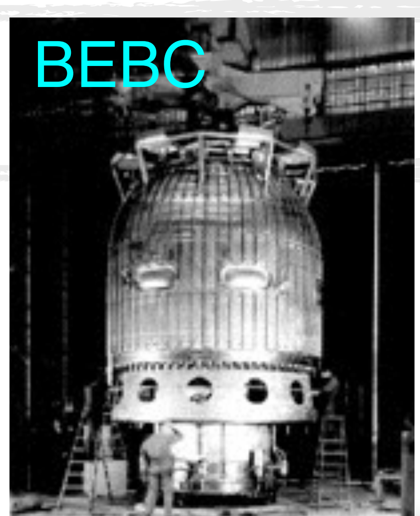
Early neutrino data

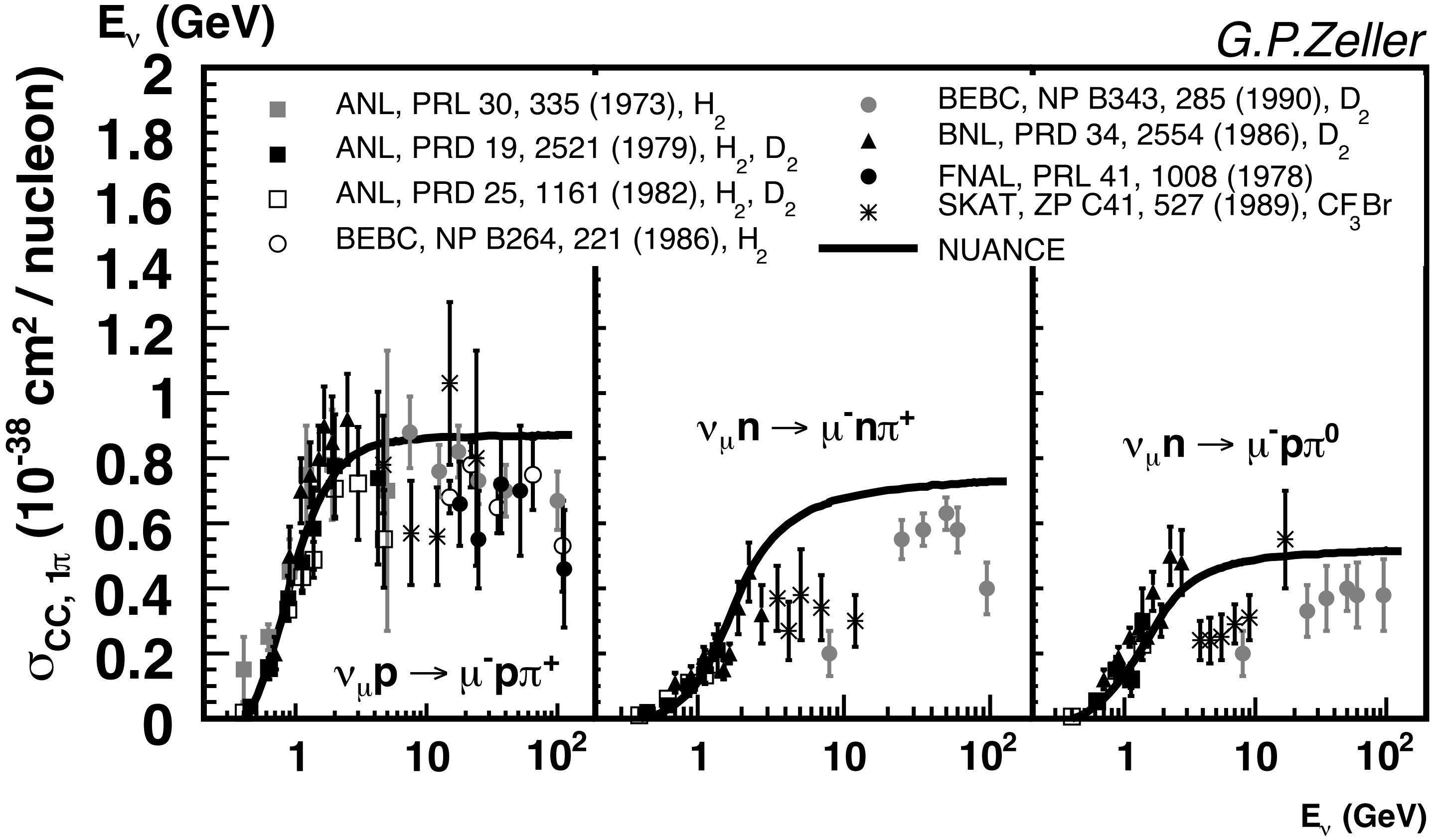


From discovery to (precision) measurements...



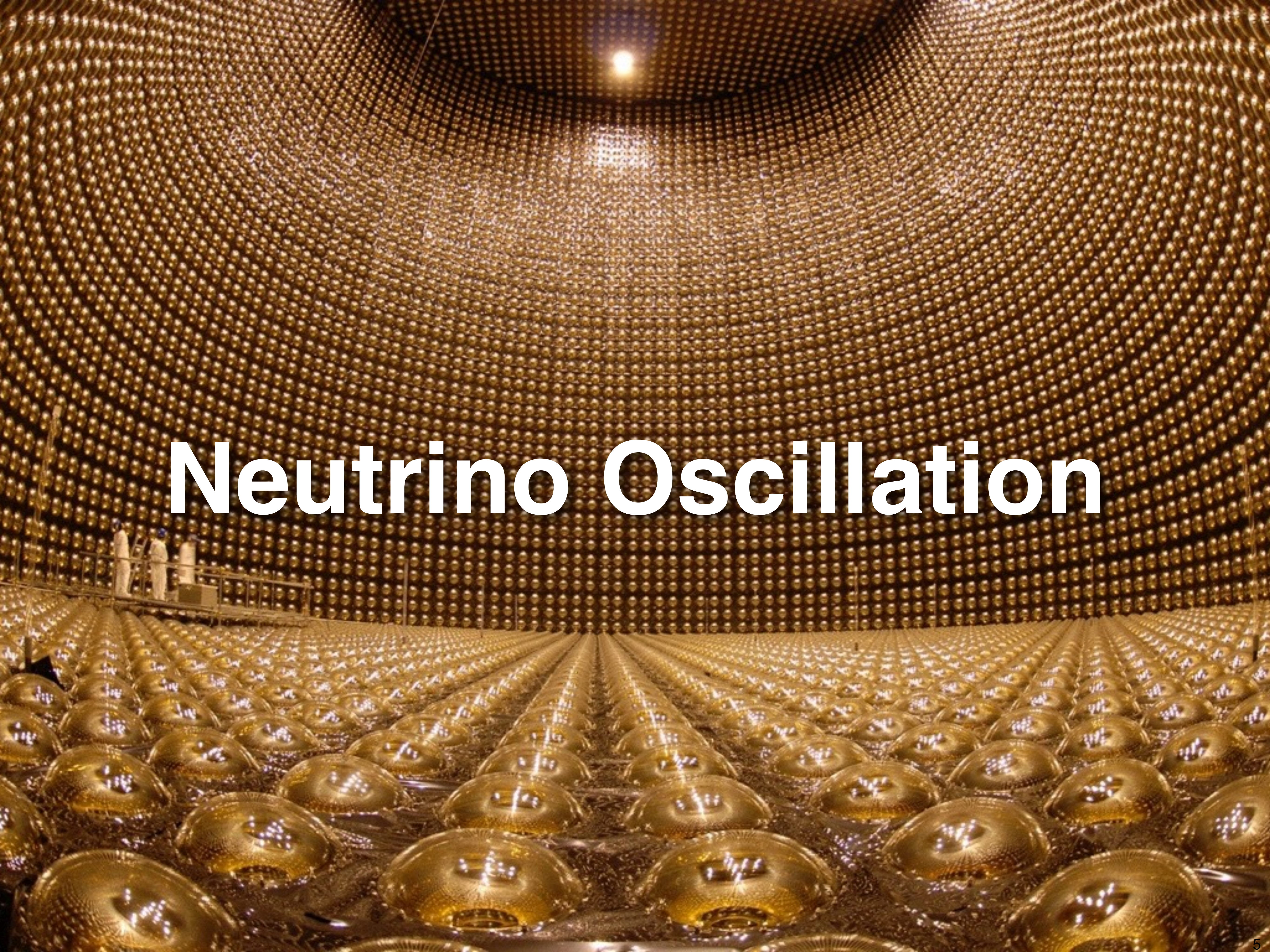






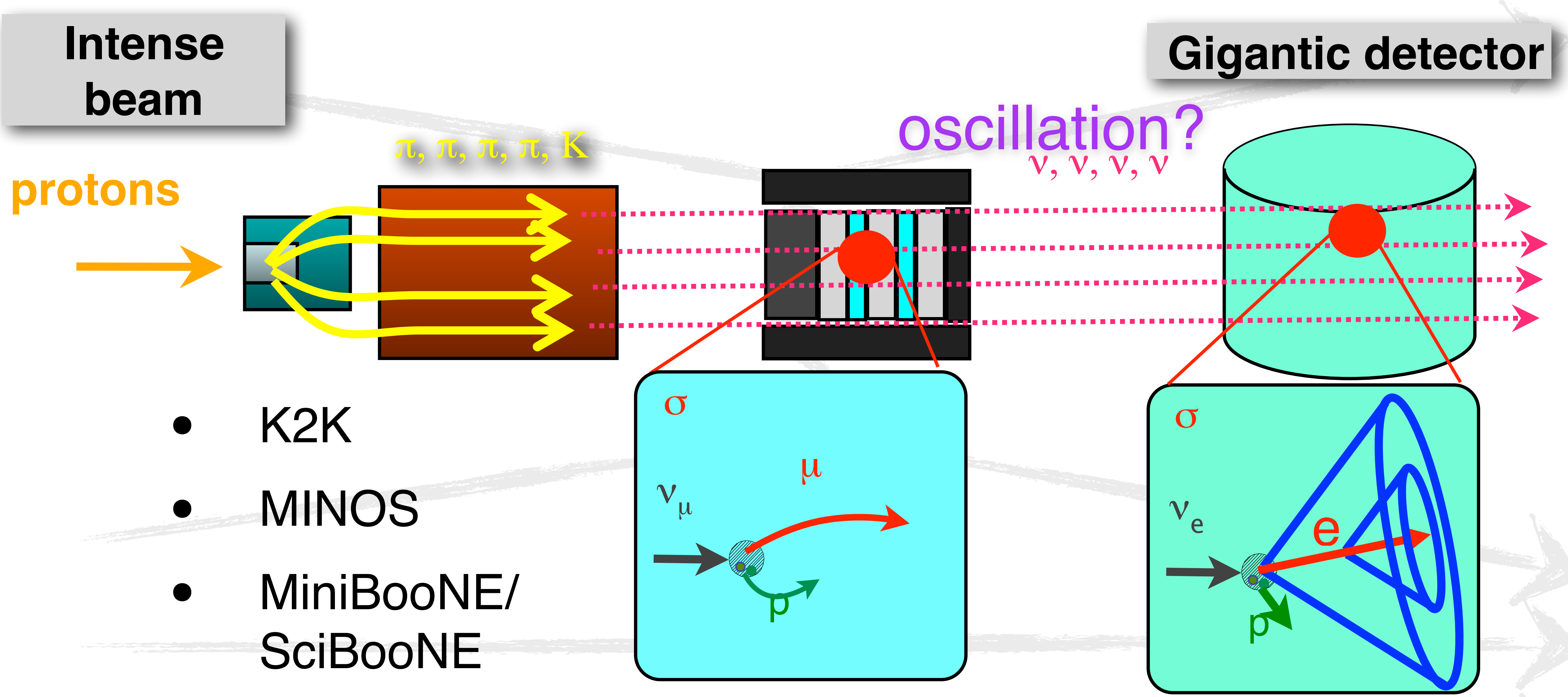
Plots from the PDG!

Neutrino Oscillation



Accelerator ν Experiments

Search for δ_{CP} by comparing $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$.



- K2K
- MINOS
- MiniBooNE/ SciBooNE
- T2K
- NOvA
- DUNE

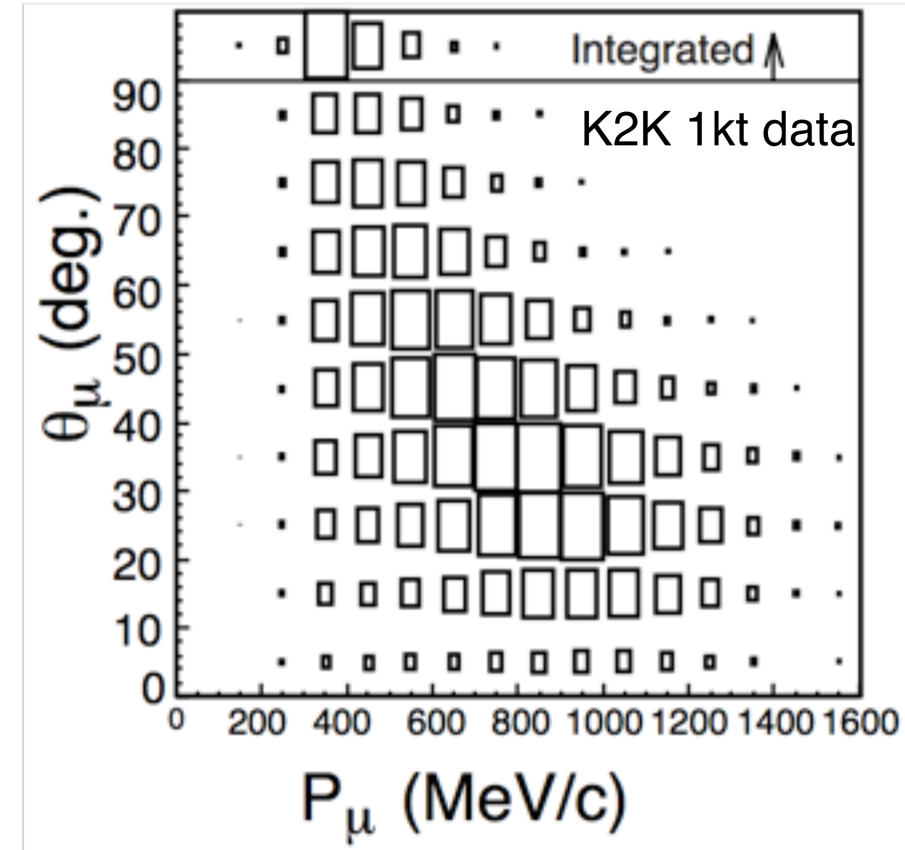
$$\Phi_\nu^{near}(E)\cdot\sigma^{near}(E)\cdot\varepsilon^{near}(E) \Leftrightarrow \Phi_\nu^{far}(E,\theta,\Delta m^2,\delta)\cdot\sigma^{far}(E)\cdot\varepsilon^{far}(E)$$

What do we need?

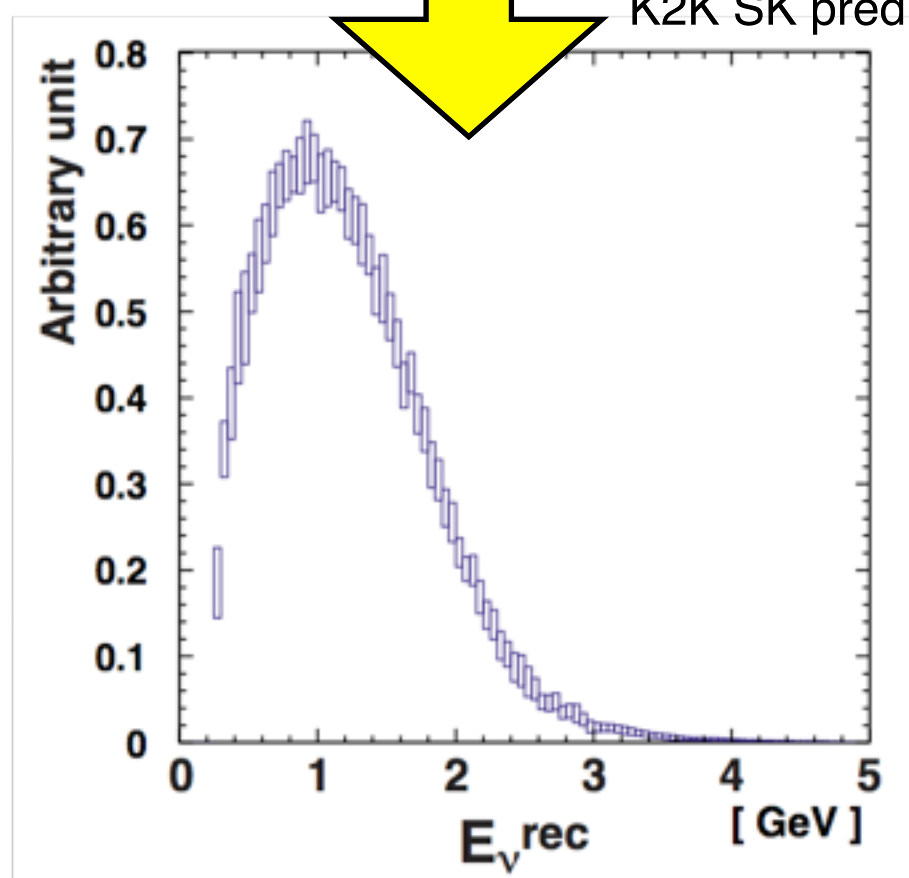
- Need to predict event rates and kinematics of final state particles
- Need to accurately calculate inferred (physics) variables from our observed variables
  - For oscillations, need to reconstruct neutrino energy
    - different ways to do this
    - all beams are relatively wideband
- Need to accurately predict background contamination

➡Need to understand neutrino-nucleus cross-sections precisely

➡Need good models



K2K SK prediction



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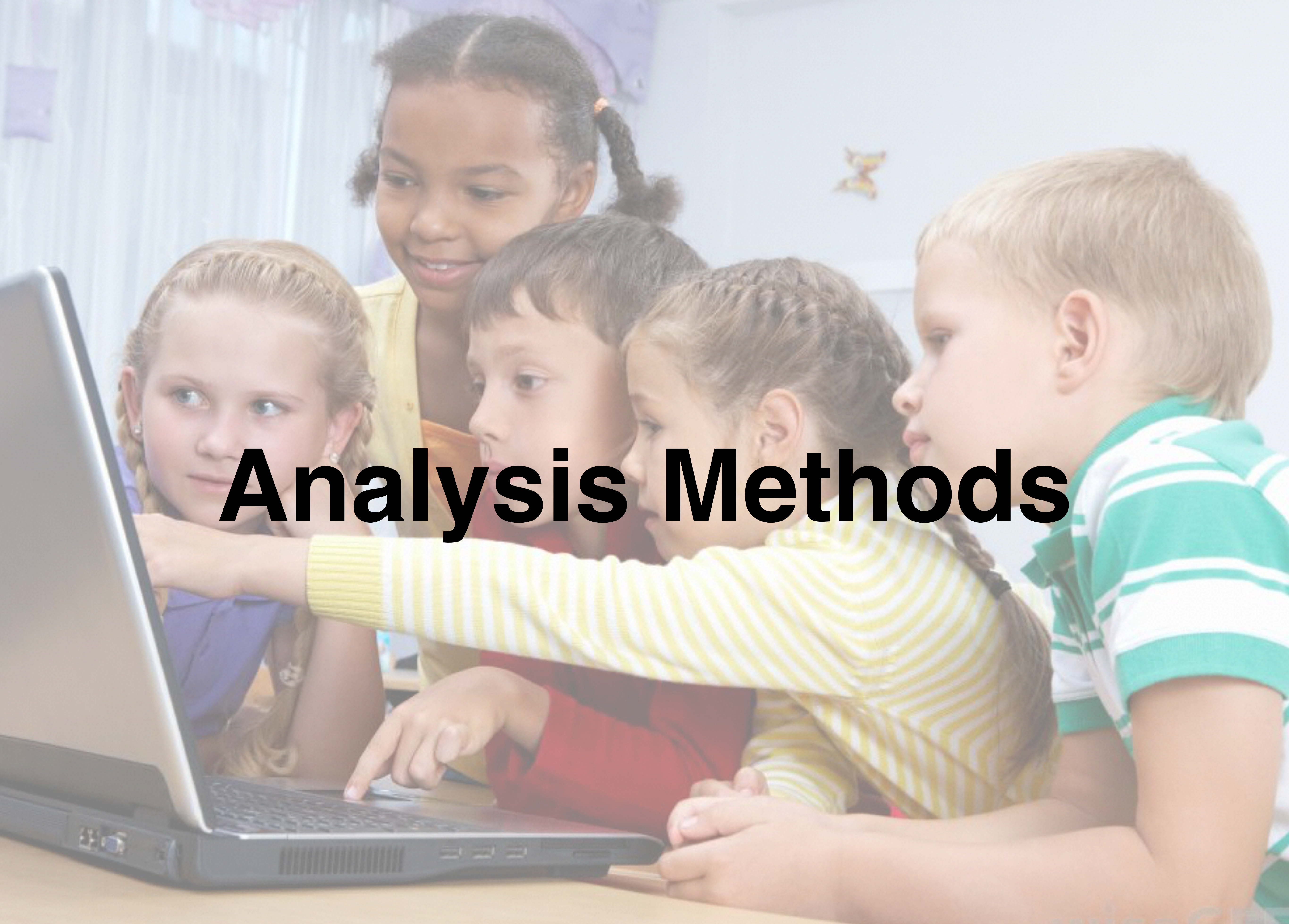
Xsecs and Oscillations

- Cross section **models** used by experiments cannot describe observations by: K2K, MiniBooNE, SciBooNE, MINERvA, T2K, …
  - Leads to inflation of systematic uncertainties
- Model dependence often injected into data analysis
  - Inferred variables
    - Energy, Q^2 reconstruction
  - Background subtraction
- Using these models will always give such uncertainties.
  - Need to use better models!

Systematic uncertainties reported by the world's most sensitive ν_e appearance experiments vs. time

Experiment	xsec err (%)	total err (%)
MiniBooNE (2007)	12.3	17.6
T2K (2012)	7.5	10.3
T2K (2016)	4%	6%

How are we improving the errors? Using better models!



Analysis Methods

Method 1: template fit

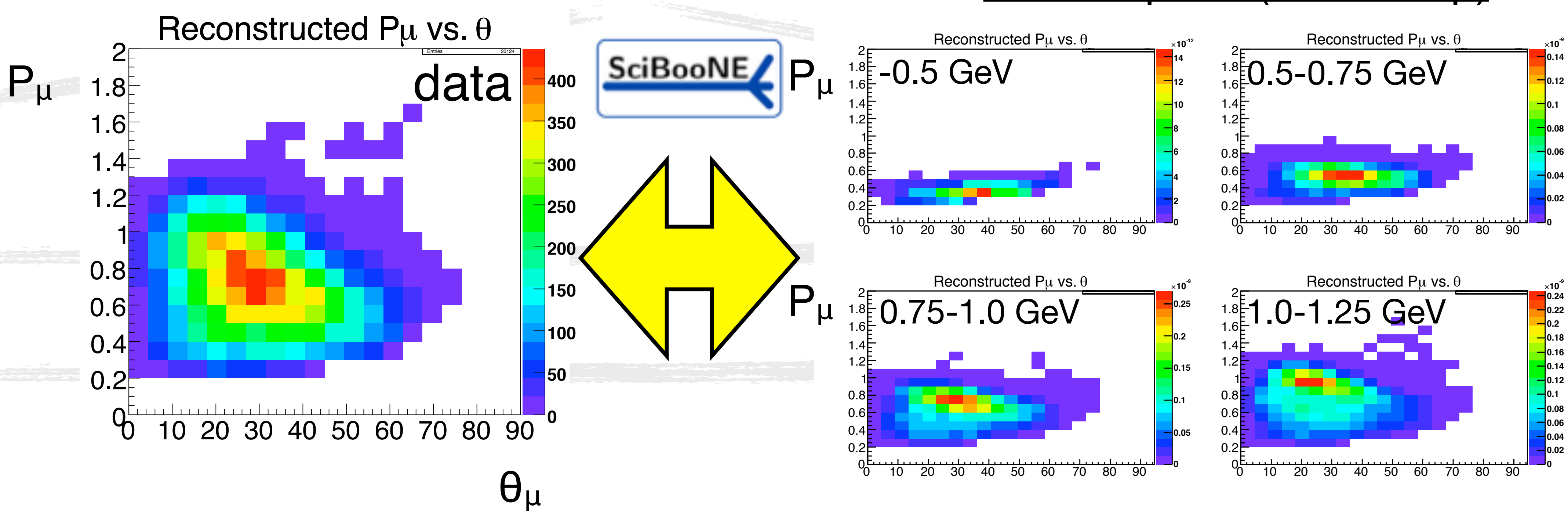
Compare data to MC, within context of a model, using templates.

$$\sigma_i = f_i < \sigma^{pred} >_i = \frac{f_i N_i^{pred} P_i}{\epsilon_i T \Phi_i}$$

i = bin of xsec variable
f_i = normalisation factor
N_i^{pred} = predicted # of events
P_i = purity
ϵ_i = efficiency
T = number of nuclear targets
Φ_i = neutrino flux per bin

Templates can be produced in observed dynamical variables, different from xsec variable.

MC template (MRD-stop)

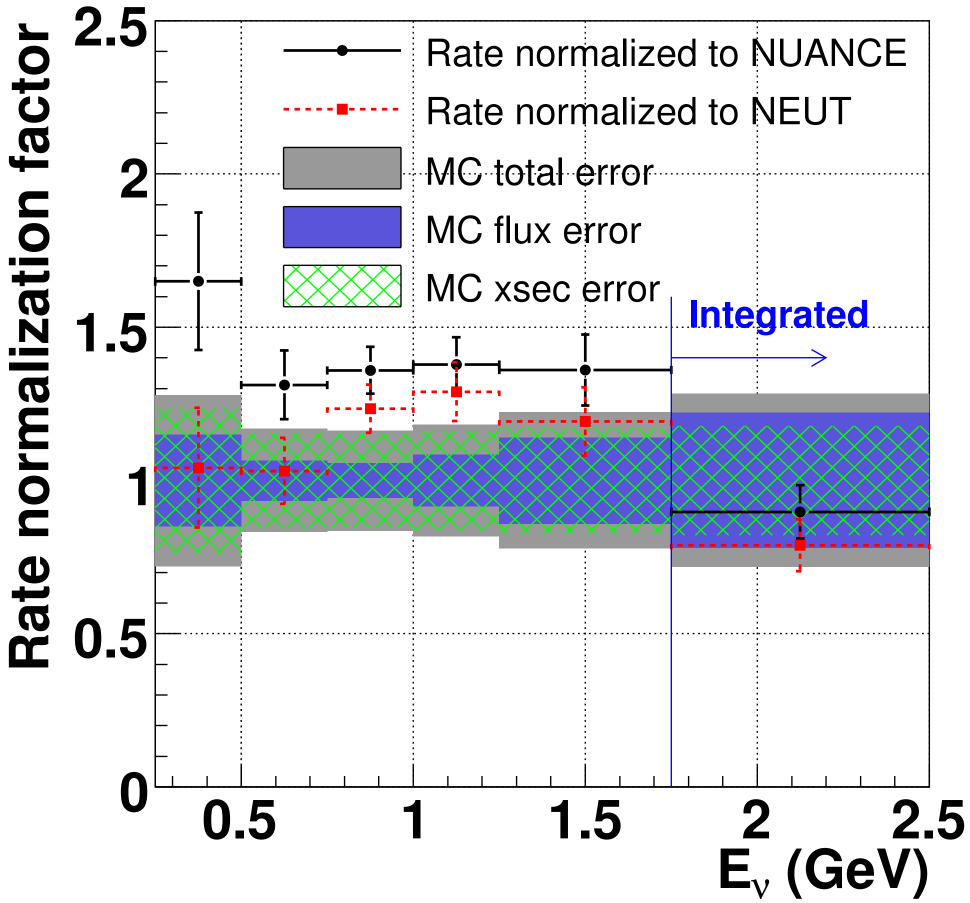


Method 1: template fit

Fit for values of f_i that minimise some GoF parameter (χ^2, likelihood), and use MC to infer the measured value of cross section.

$$\chi^2 = \sum_{j,k}^{Nbins} (N_j^{obs} - f_j N_j^{pred})(V^{sys} + V^{stat})^{-1}_{jk}(N_k^{obs} - f_k N_k^{pred})$$

Uncertainties: estimated with fake data studies by repeating the template fit with MC variants.



Advantage: This method is especially useful for measuring cross sections as functions of inferred variables, like the input variable E_ν or internal variable Q^2.

Drawback: This method is susceptible to model bias. If your MC model differs from nature in some important way, you can easily infer the wrong answer!

Method 2: Matrix unfolding

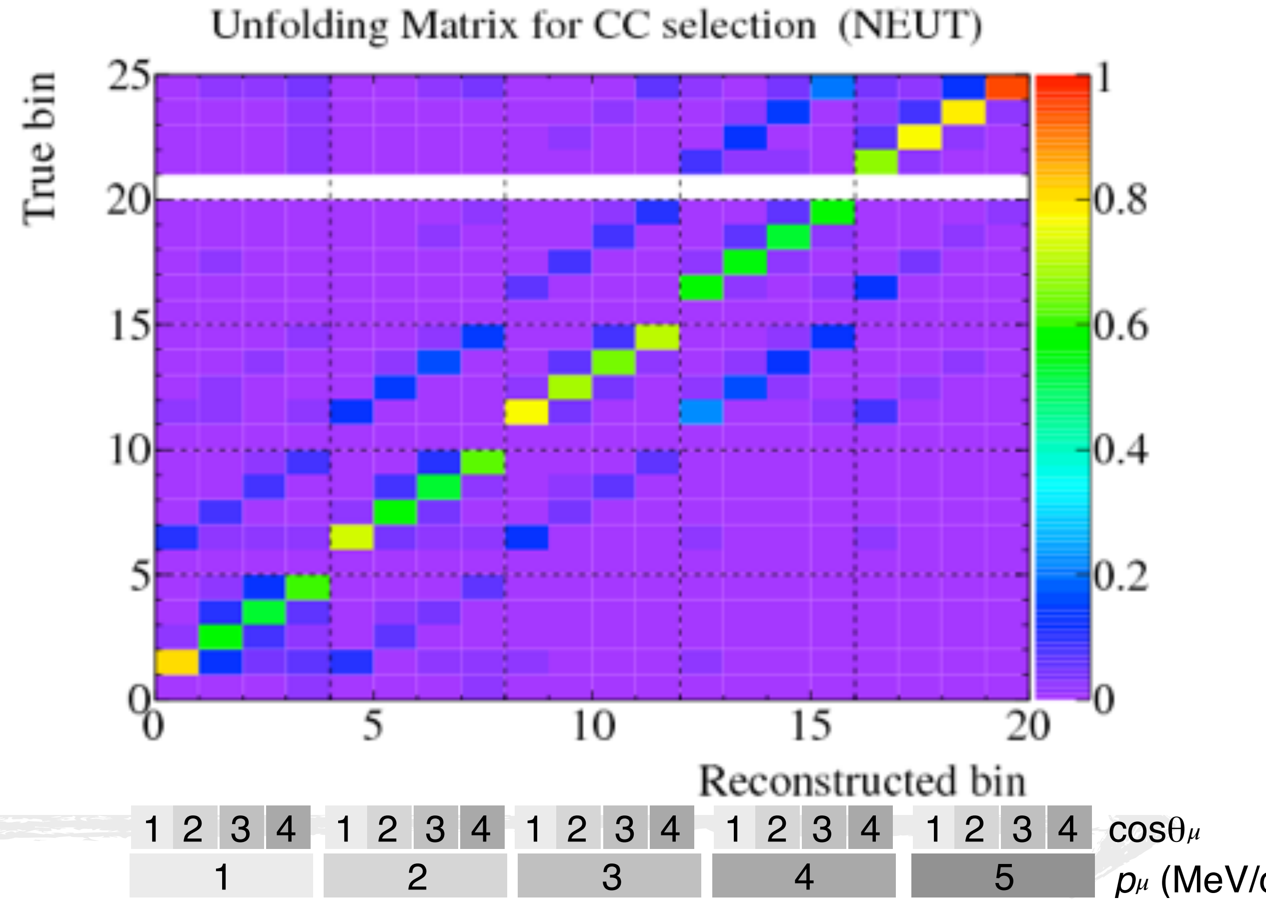
- Calculate cross section directly from number of events

$$\hat{N}_i = \frac{\sum_j U_{ij}(N_j^{obs} - B_j)}{\epsilon_i}$$

1. Apply purity correction
2. Unfold to correct detector smearing
3. Apply efficiency correction
4. Normalise with neutrino flux and number of nuclear targets to get cross section

➡ Result is flux averaged differential cross section

j = bin of reconstructed variable
i = bin of corrected ("true") variable
N_j^{obs} = observed # of events
B_j = background events
U_{ij} = unfolding matrix
ϵ_i = efficiency



$$\frac{d\sigma}{dx_i} = \frac{1}{T\Phi_\nu}\frac{\hat{N}_i}{\Delta x_i}$$

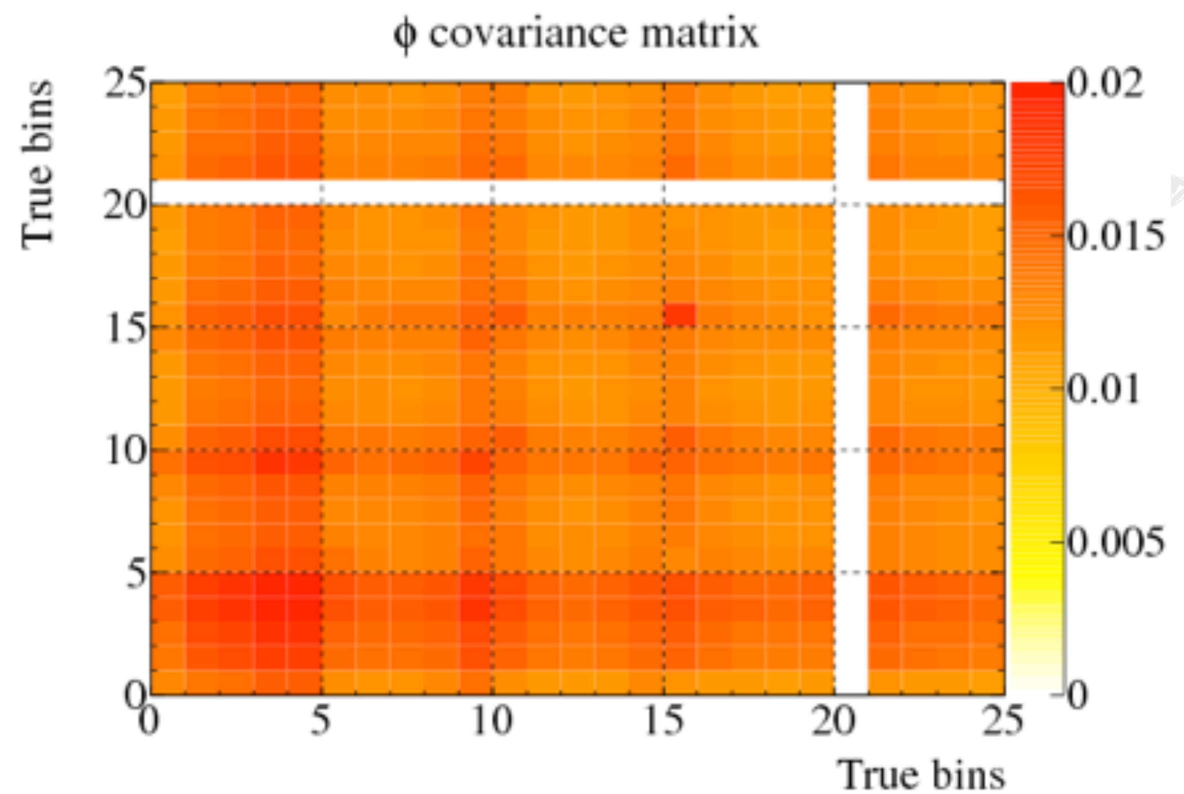
T = number of nuclear targets
Φ_ν = total integrated neutrino flux
Δx_i = bin width

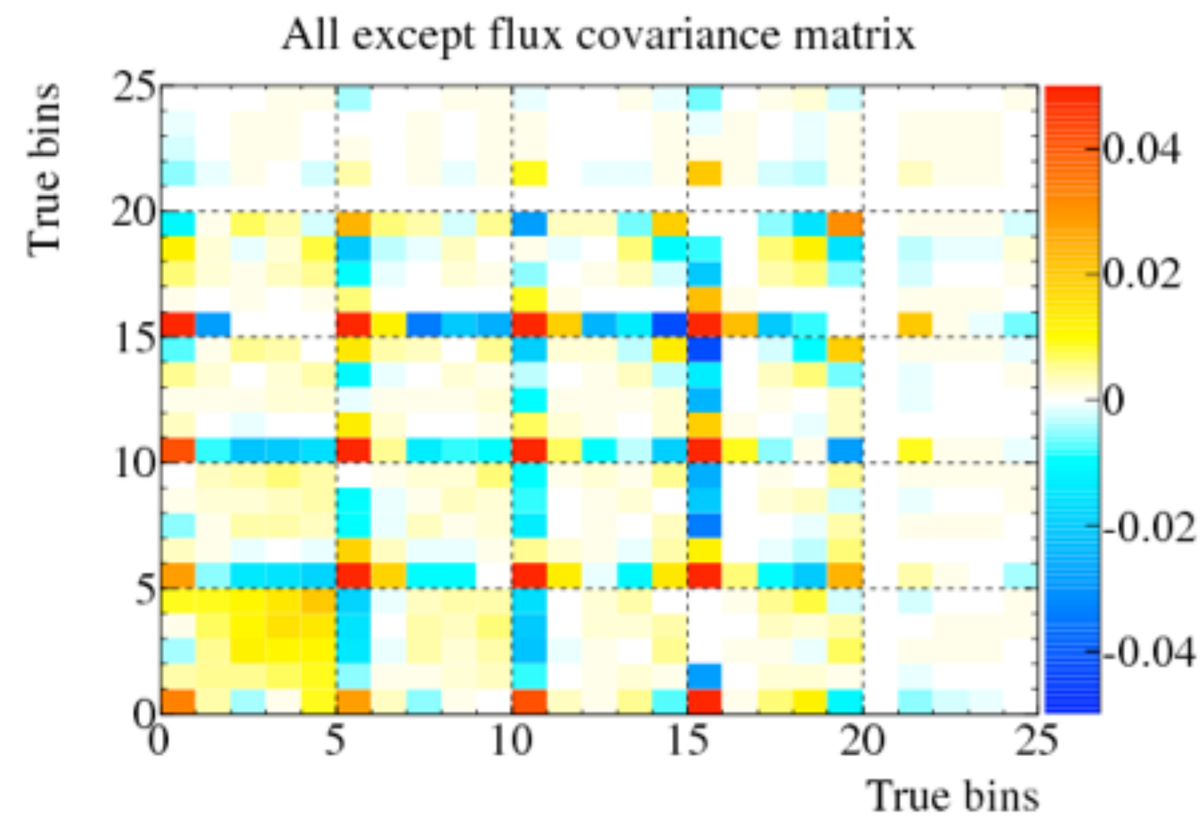
Method 2: Matrix unfolding

$$V_{kl} = \frac{1}{N_{var}} \sum_{s}^{N_{var}} (\sigma_k^s - \sigma_k^{nom})(\sigma_l^s - \sigma_l^{nom})$$

- Use MC variants to create covariance matrix
- Neutrino flux is (usually) just a normalisation error
  - We do, of course, propagate the full shape covariance
- Very useful to separate out the flux error

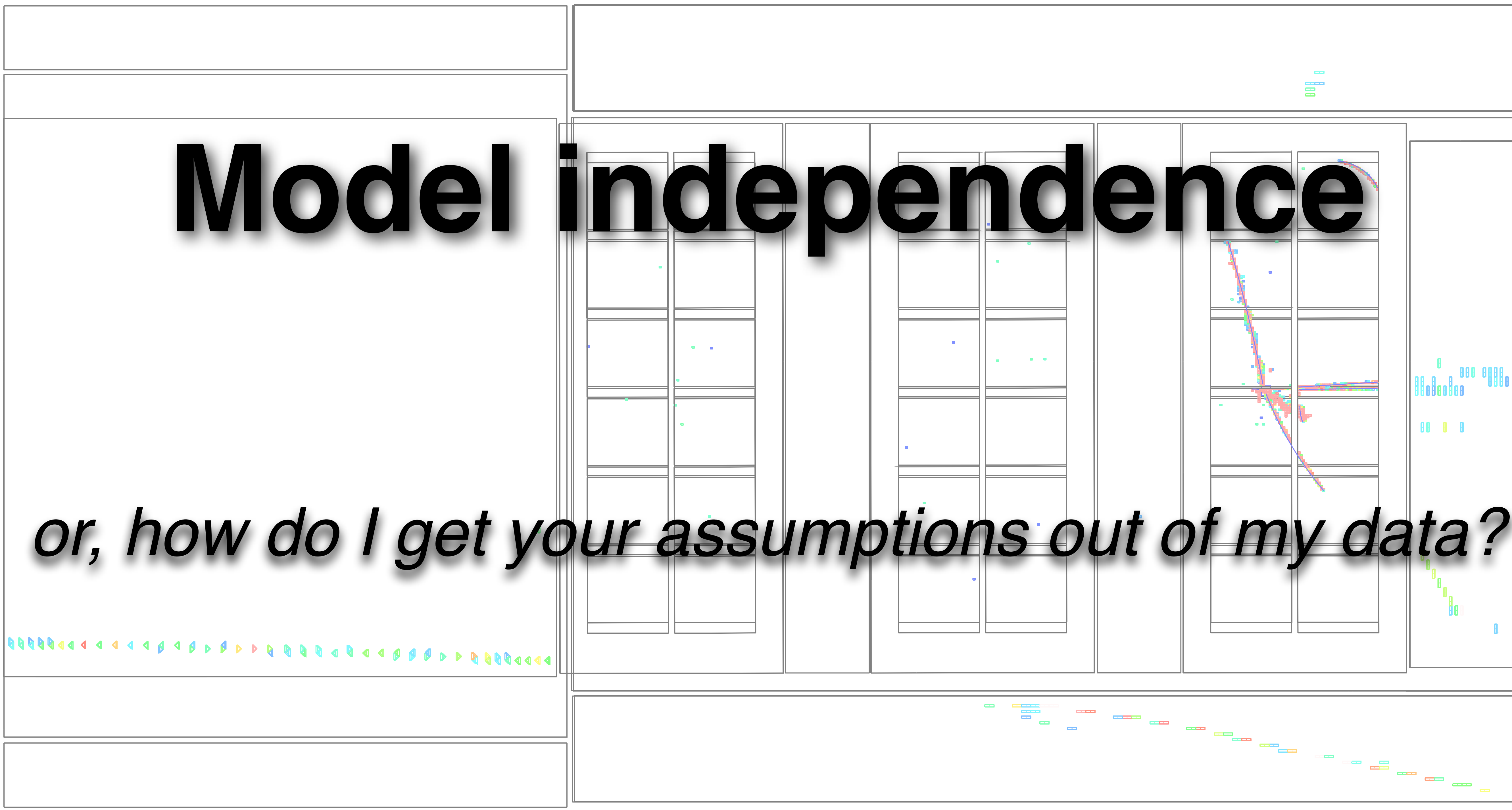
➡Potential for reducing model dependence with this method





Model independence

or, how do I get your assumptions out of my data?



What does model dependence mean?

- Distinguish between σ model and detector model
  - Any MC-derived quantity is, of course, model-dependent
- Restricting unsmearing, BG corrections, and efficiencies to detector MC quantities, not cross section processes is probably the best we can do
- This is why we should always publish final state particle cross sections first, and then proceed to process measurements, etc.
- Can we move to generator-less measurements??

Absolute flux-averaged differential cross section formula

U_{ij} :unsmearing matrix

N_j^{obs} : data

$$\hat{N}_i = \frac{\sum_j U_{ij}(N_j^{obs} - B_j)}{\epsilon_i}$$

ε_i :efficiency

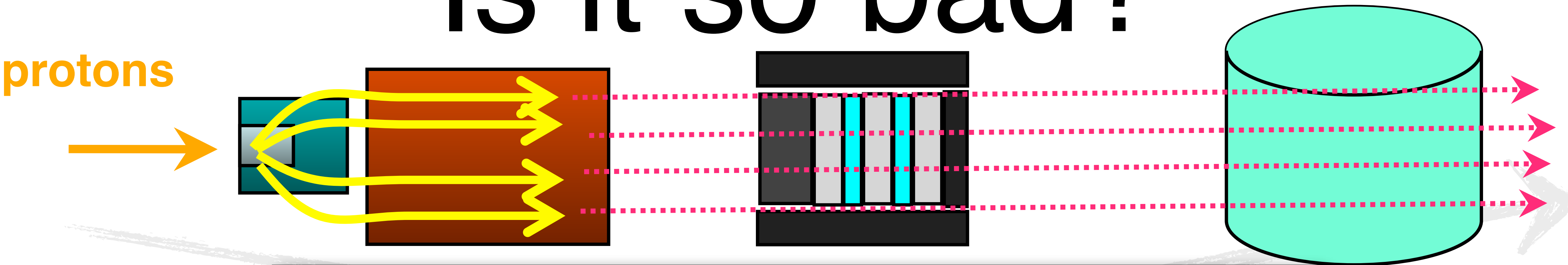
b_j : background

$$\frac{d\sigma}{dx_i} = \frac{1}{T\Phi_\nu}\frac{\hat{N}_i}{\Delta x_i}$$

T :integrated target number

Φ :integrated ν-flux

Is it so bad?



$$\Phi_\nu^{near}(E)\cdot\sigma^{near}(E)\cdot\varepsilon^{near}(E) \Leftrightarrow \Phi_\nu^{far}(E,\theta,\Delta m^2,\delta)\cdot\sigma^{far}(E)\cdot\varepsilon^{far}(E)$$

- Interaction models are useful:
  - Relate final state particles to neutrino energy, estimate systematic errors.
  - Cannot do oscillation analysis without a model, but error cancellation only works if the model matches Nature!
- Ulrich Mosel's observation, NuInt11:
  - Theorist's paradigm: "A good generator MC does not have to fit the data, provided its model is correct"
  - Experimentalist's paradigm: "A good generator MC does not have to be correct, provided it fits the data"
- We really do need model independent measurements!
  - Provide enough info for later physicists to cleanly use data with a new model.
  - Confront each model with multiple data sets

- "But I love the 70s! I want to fit for M_A!"

- Me too! But let's do the model independent measurements as well.

- Provide the data that theorists (and future you) need to make our models better!

Can we do it differently?

" I would do some things differently if I had a chance to do it all over again. '

Best way to present data?

- *Measured quantities vs inferred quantities? How to interpret unfolded data? Generator dependencies?*

- Can we provide the tools to allow theorists to fit our data in the same way we do?
- Other fields publish data in different (and creative) ways - maybe we should consider some of these.

Best way to present data?

- To get better models, we need theorists to use our data effectively
  - It's in our best interest to make that as easy as possible
- Typically, our goal is to produce cross section measurements
  - We use the detector MC to model the efficiency and smearing,
  - We then correct those effects with unfolding matrices and efficiency functions

Best way to present data?

- We could alternatively provide theorists with the tools to analyze our data *the way that we do*
  - For example, when fitting for M_A, we use the detector MC to make fake data sets, and modify the fake data sets until the MC matches data
    - For example, numbers of events in bins of p_μ, θ_μ
  - We obviously don't want to give away the detector MC, but we could provide efficiency functions (including smearing) with systematics and our measured data
  - The efficiency function could be applied to inclusive fake data samples, allowing theorists to perform analysis the way we do
    - Obviously need to provide neutrino fluxes, too, but we already do that.

Show the whole story

- All neutrino data samples are rife with backgrounds.
    - MiniBooNE: CCQE $\leftrightarrow$ CC1π^+ $\leftrightarrow$ CC1π^0 $\rightarrow$? NC1π^0
    - but really: $\mu \leftrightarrow \mu$+p $\leftrightarrow \mu+\pi^+ \leftrightarrow \mu+\pi^0 \rightarrow ?\ \pi^0$
- Knowing what we do (about MEC) from e-A experiments, we cannot have confidence in one sample without seeing all the others.
    - We've already learned that seeing them all isn't enough!

- For example, to extract M_A from neutrino data:
    - Requires nuclear model & background predictions match Nature.
    - Predicated on assumption that F_A is a dipole.

Crazy idea 1

- Experimentalists use *uncorrected* data to perform parameters fits.
  - We use detector MC to naturally handle efficiencies and smearing,
    - by comparing smeared MC samples after cuts to data after cuts.
  - We use MC samples/reweighting techniques to adjust MC until it matches data.
- Why not publish uncorrected data along with appropriate smearing and efficiency functions?
  - Turn detector MC into a lookup table.

Crazy idea 2

- Apply efficiency/smearing corrections to individual events.
- Publish an ntuple of events: reconstructed final state particles.
  - Each event comes with a cross-section weight derived with POT numbers, flux & detector MC.
  - Allows one to make a plot giving cross sections instead of number of events.

➡ Gives unprecedented knowledge to future analysers since it would allow analysis of <u>new variables</u>

Summary

- Measuring cross sections is a tricky business
- We need to learn our own lessons!
  - When we use external data sets to constrain cross section models, we ought to take note of what works and what doesn't
    - See Callum Wilkinson's talk for that
  - And we need to remember not to inflict the same problems on the people using our own measurements
- The world has lots of good data analysis ideas
  - This workshop is a good chance to learn some!

J-PARC Neutrino beam decay tunnel

Photo by ED Zimmerman

Thank you!

ありがとうございました！