What do next generation experiments need?

Callum Wilkinson

BERKELEY LAB

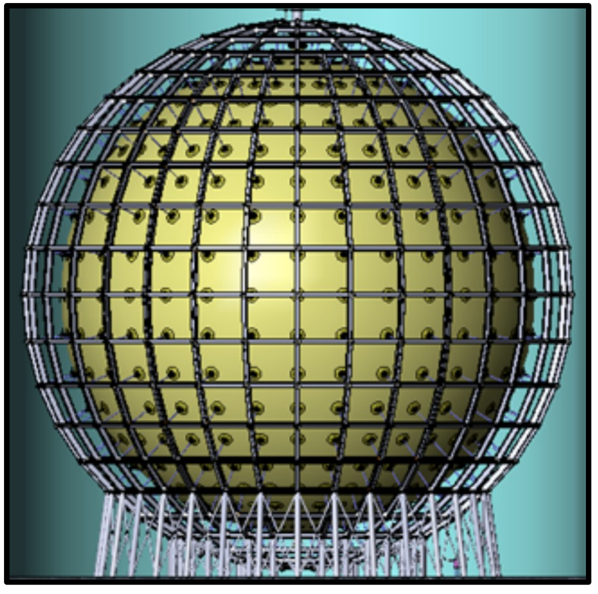
Potential for bias

T2K collaborator since 2011

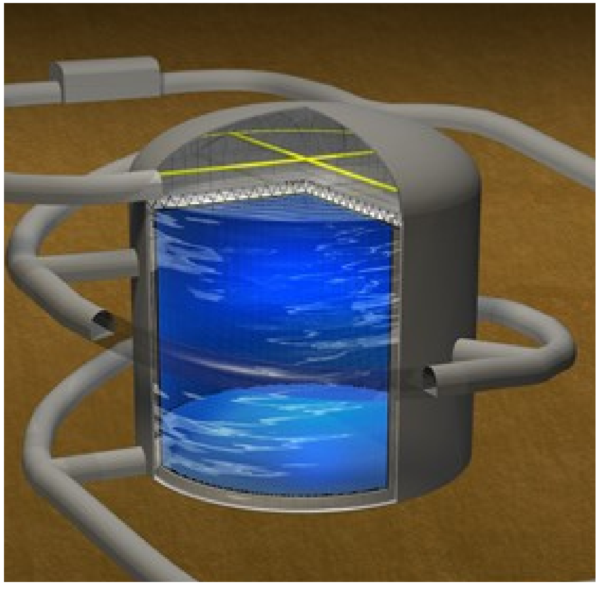
DUNE collaborator since 2017,
current long-baseline convener

Co-developer of NUISANCE

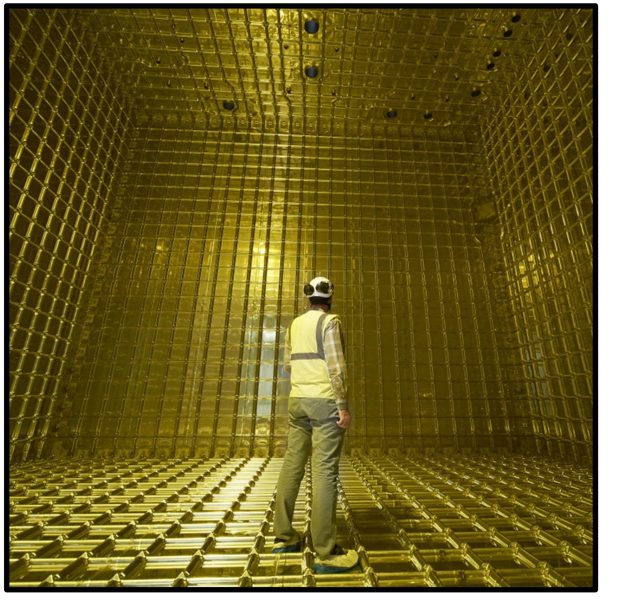
Next generation experiments – precision era



JUNO



Hyper-K

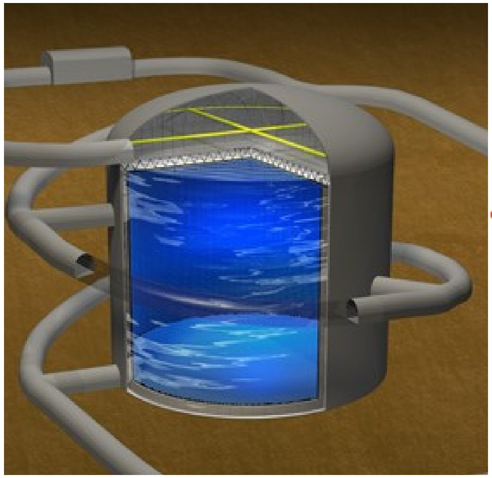


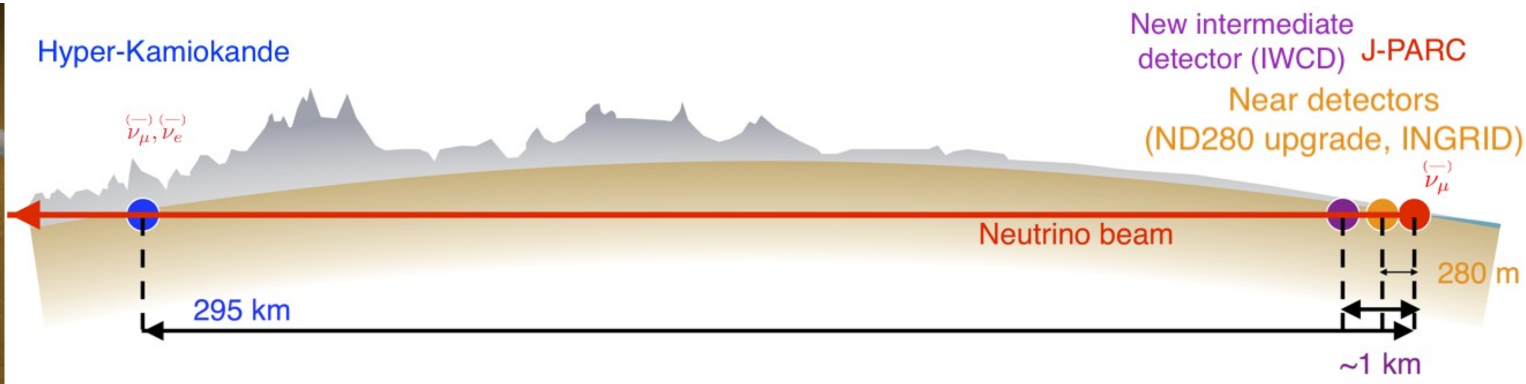
DUNE

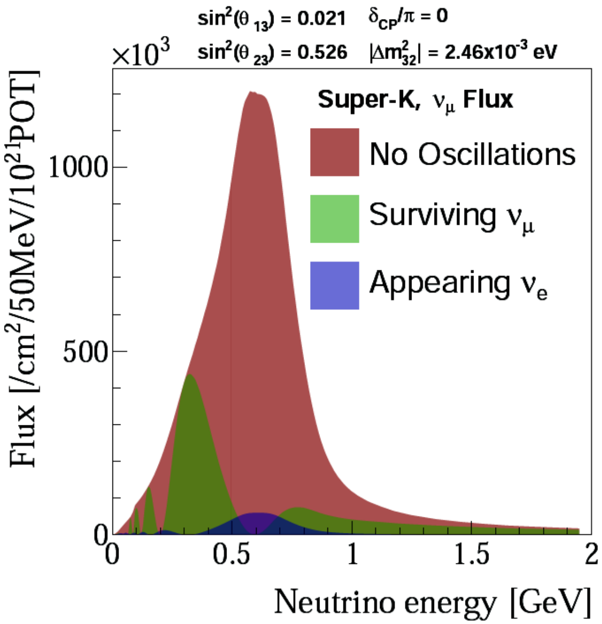
Reactor

Accelerator
(and this talk)

Hyper-K overview



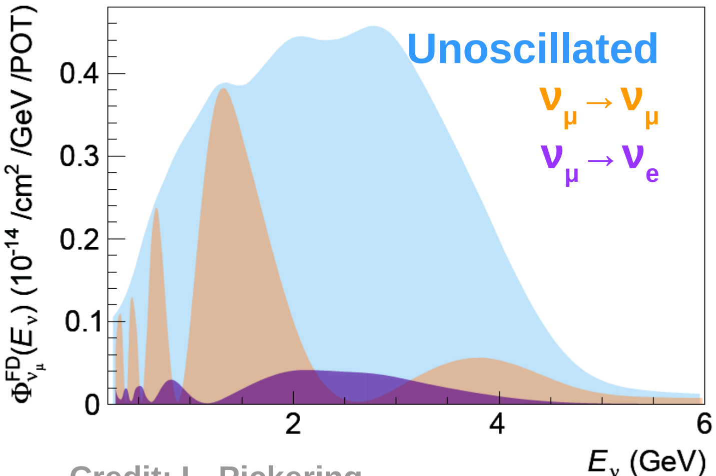




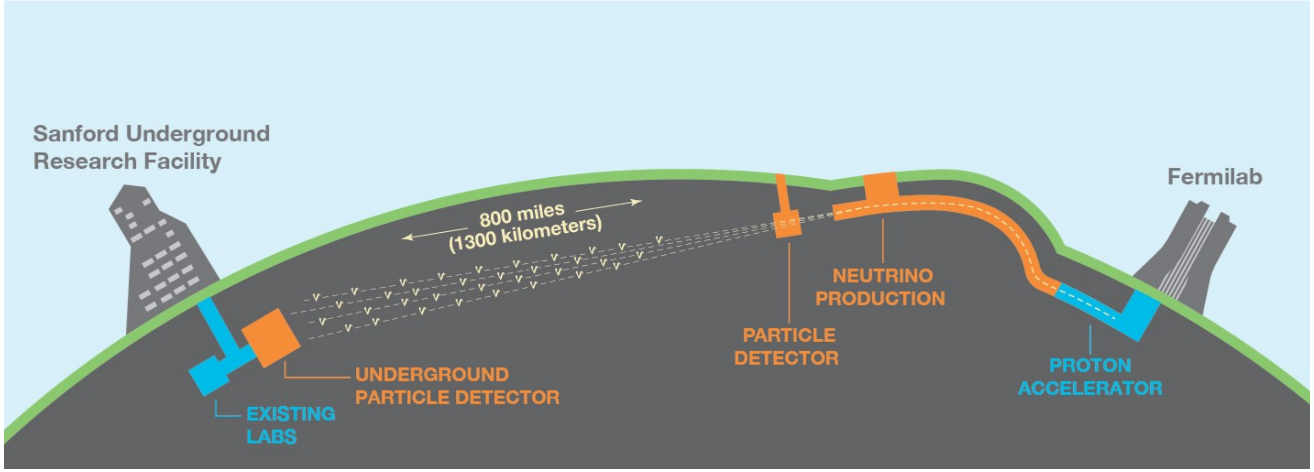
Credit: L. Pickering

- L ≈ 295 km; E_ν ≈ 0.6 GeV (*narrow band*); water Cherenkov detector
- Significant upgrade to T2K design:
  - 1.3 MW beam (~2.2x current)
  - Upgraded near detector complex
  - 187 kt FV tank (~7x Super-K FV)
- Civil construction started, physics ~2027

DUNE



Credit: L. Pickering



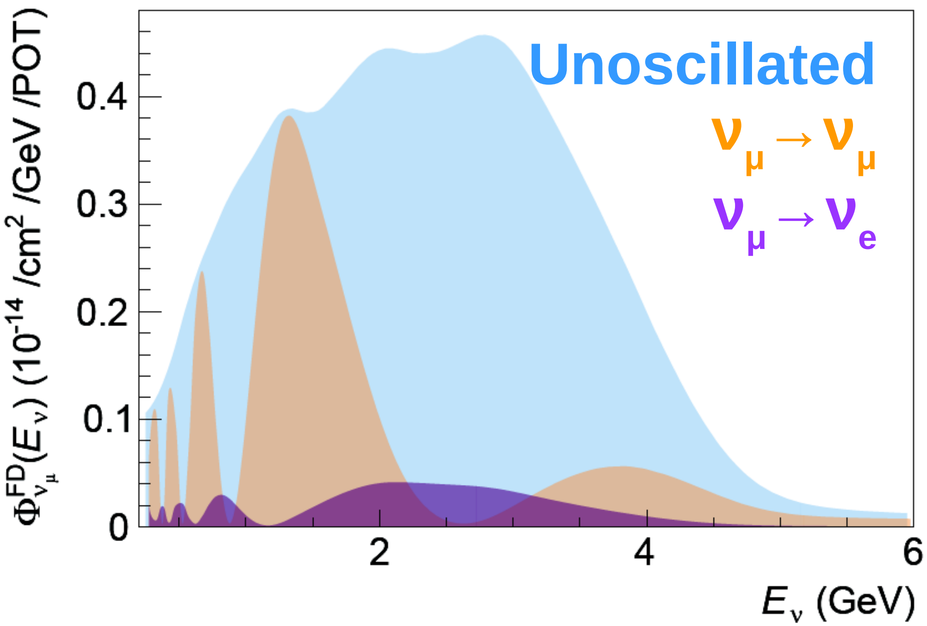
- L ≈ 1285 km; E_ν≈ 2.5 GeV (*broad band*); liquid argon time projection chamber (LArTPC)
- High-intensity neutrino beam (1.2→2.4 MW)
- Near detector system at Fermilab
- 4 x 17 kt LAr far detector modules at SURF

Why are cross sections important?

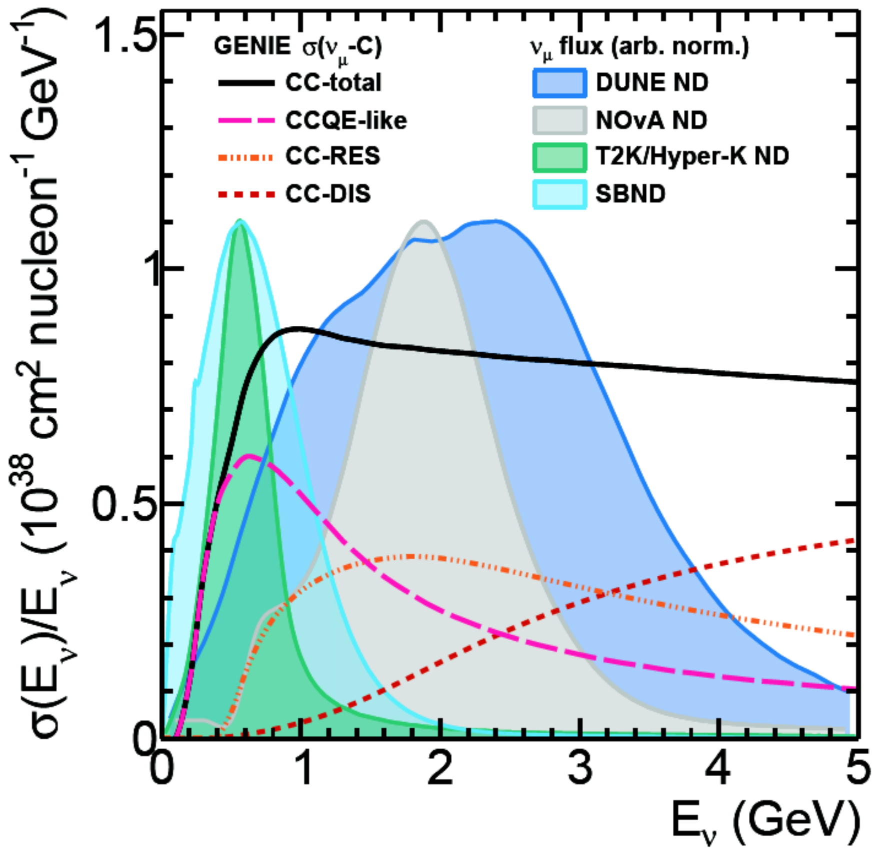
Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

$$R(\vec{\mathbf{x}}) = \overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \underbrace{\times P(E_\nu; \nu_A \rightarrow \nu_B)}_{\text{Far}}$$

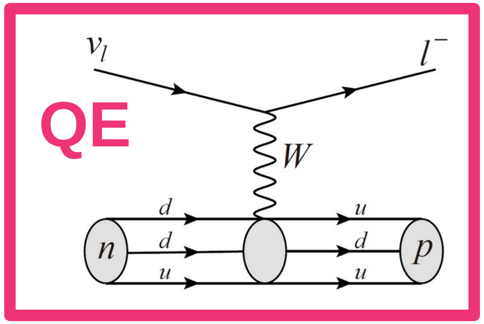
- Dramatic E_ν or flavor change
- Near/far ratios don't fully cancel systematics
- Cross section relates E_ν with what we actually measure!

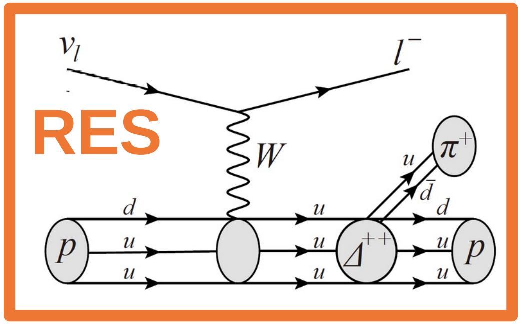


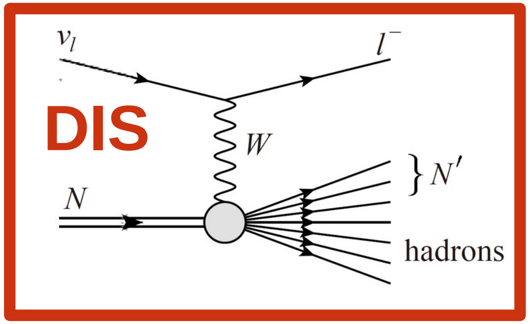
Why are cross sections such a challenge?



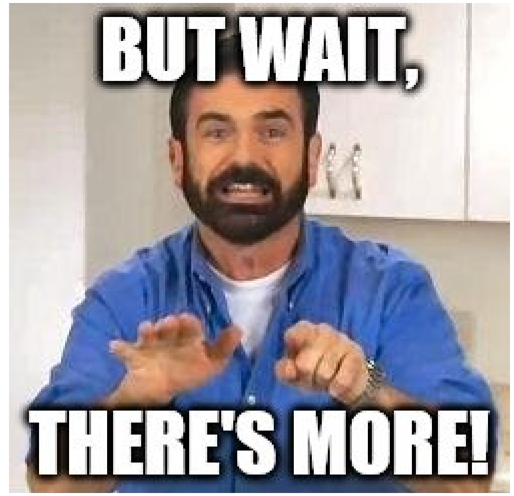
Region of interest spans a number of distinct interaction modes, with different physical descriptions!

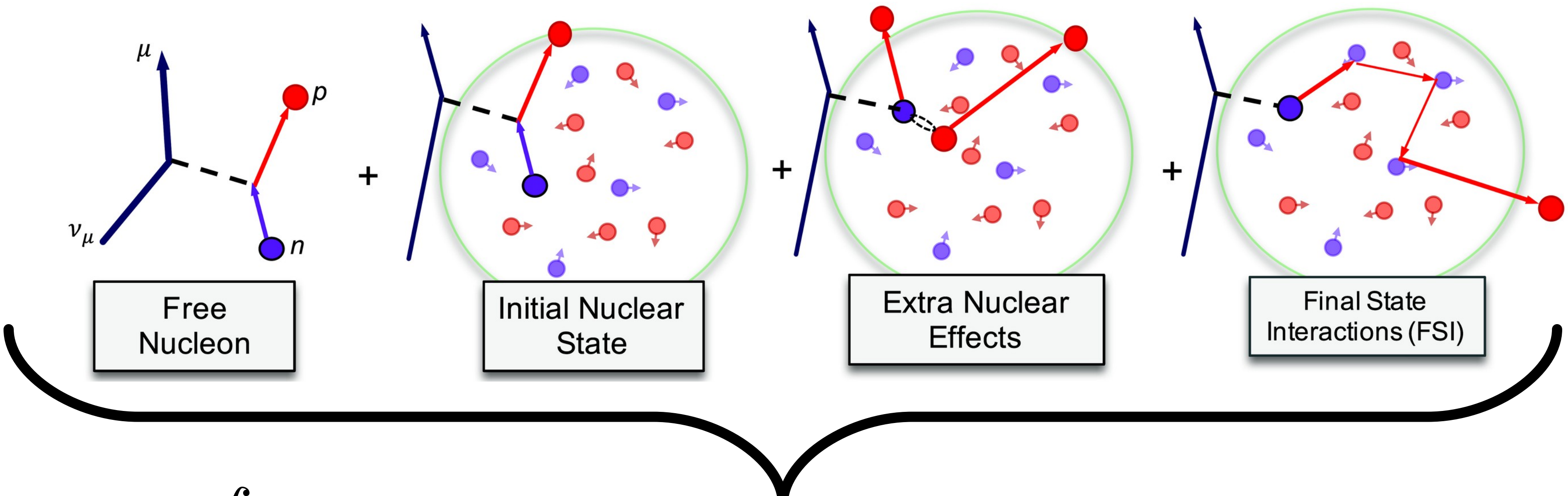






Energy transfer





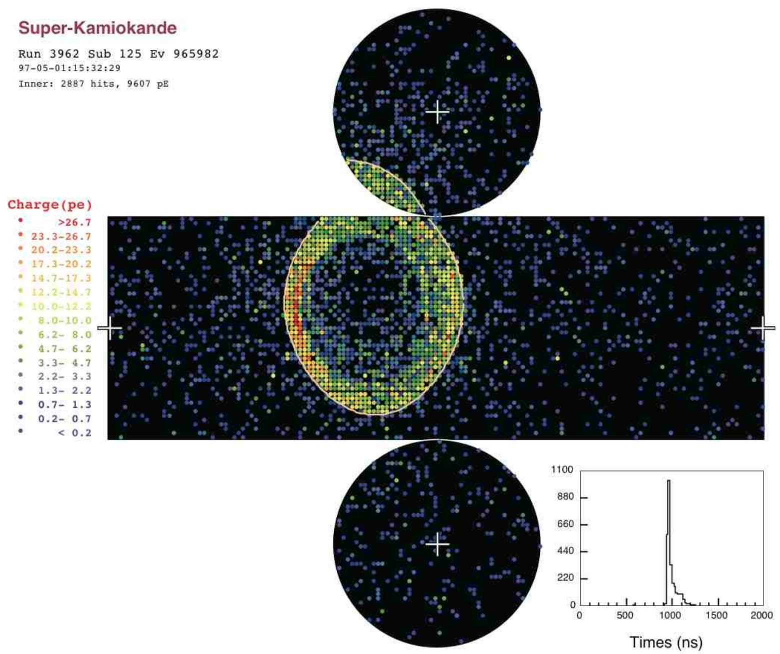
$$R(\vec{\mathbf{x}}) = \int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(E_\nu; \nu_A \rightarrow \nu_B)$$

Many confounding nuclear effects to model

E_ν reconstruction methods

(1) **Leptonic** variables only:

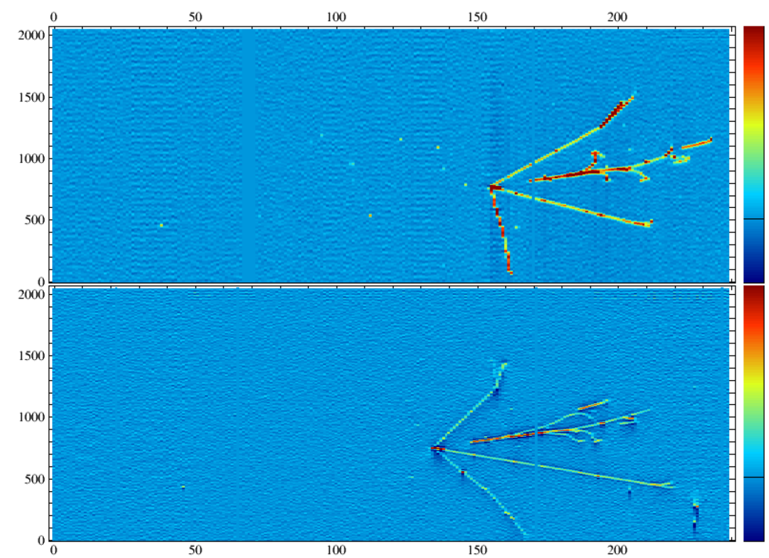
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$



Water Cherenkov: T2K, Hyper-K

(2) **Leptonic** and **hadronic** information:

$$E_\nu = E_\mu + E_{\text{had}}$$



Tracking calorimeter: NOvA; **Liquid Argon TPCs:** DUNE

So what do we really need to know?

(1) **Leptonic** variables only:

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

- CC0π
- Non-CCQE contributions
- Pion production < threshold
- Pion prod. + absorption rate
- Smearing from nuclear model

(2) **Leptonic** and **hadronic** information:

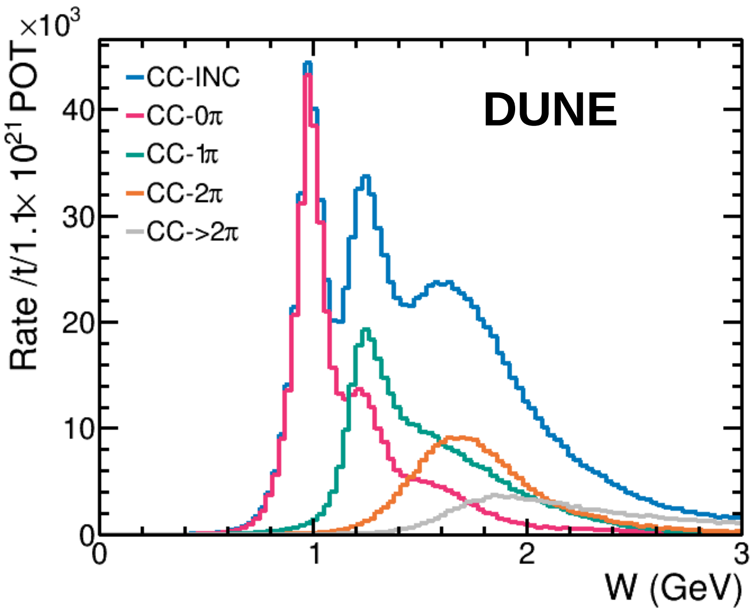
$$E_\nu = E_\mu + E_{\mathrm{had}}$$

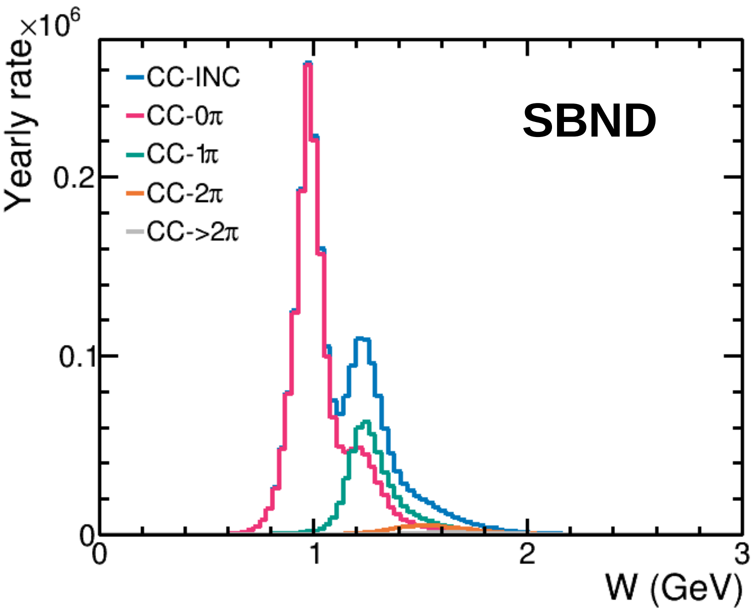
- CC-inclusive
- Pion production rate below experimental threshold
- Neutral energy fraction
- Nuclear model initial and final state effects

+ E_ν dependence for all of the above!

Other challenges

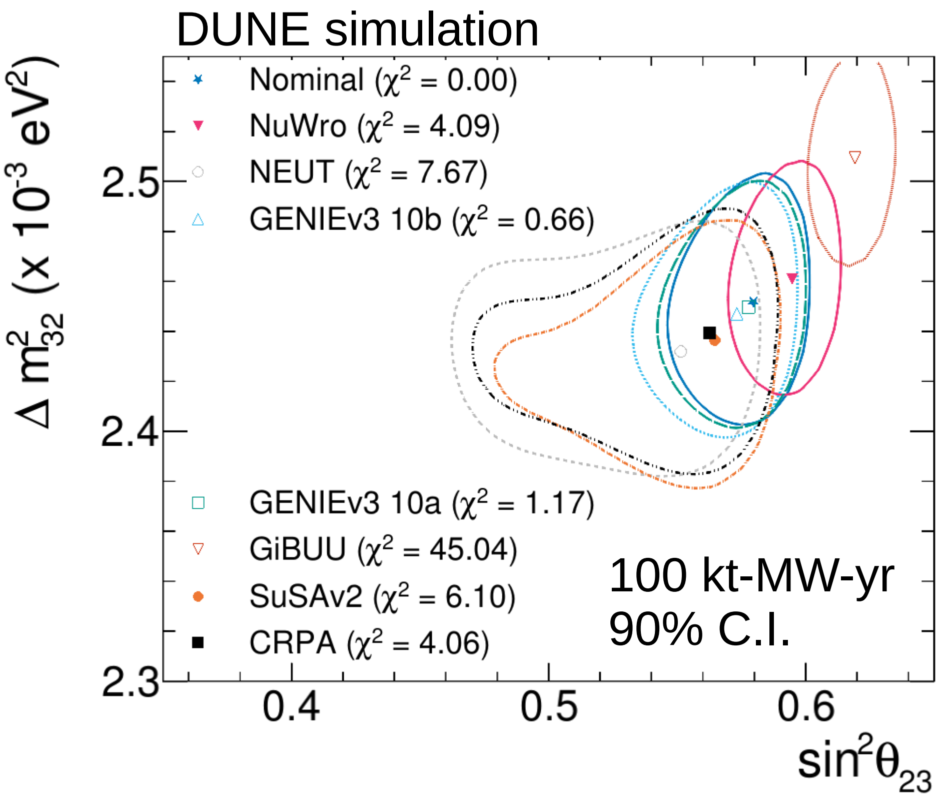
- $\bar{\nu}_\mu$ measurements are rarer than ν_μ
- ν_e and $\bar{\nu}_e$ measurements are even rarer!
- Most NC processes
- A-scaling dependence
- High-W pion production (for DUNE)





What does precision mean anyway?

- The residual uncertainties between ND and FD must be ≈percent level… but what does that mean…
- Current fake data studies (FDS) at T2K are already not-negligible, suggesting potential issues at greater precision



- DUNE FDS show significant biases between current models
- **Our current level of precision is not sufficient**

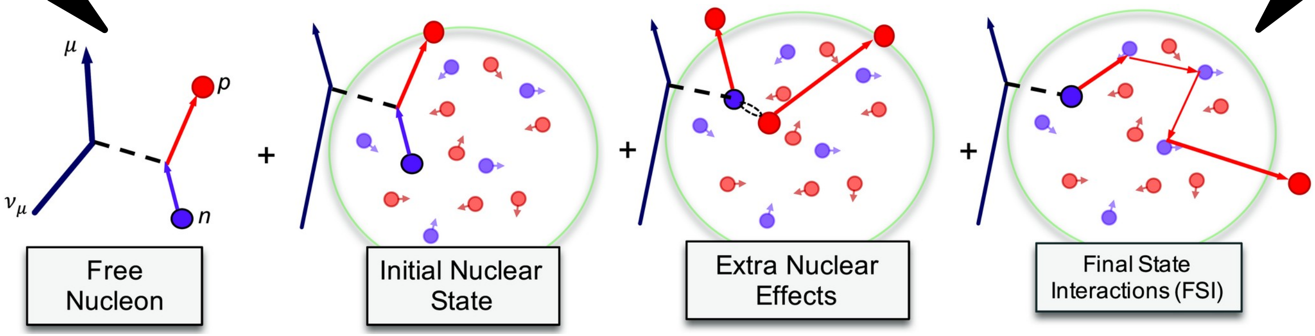
How can we improve the situation?

ν-H_2/D_2 bubble chambers, LQCD

e-A scattering (1970s-present)

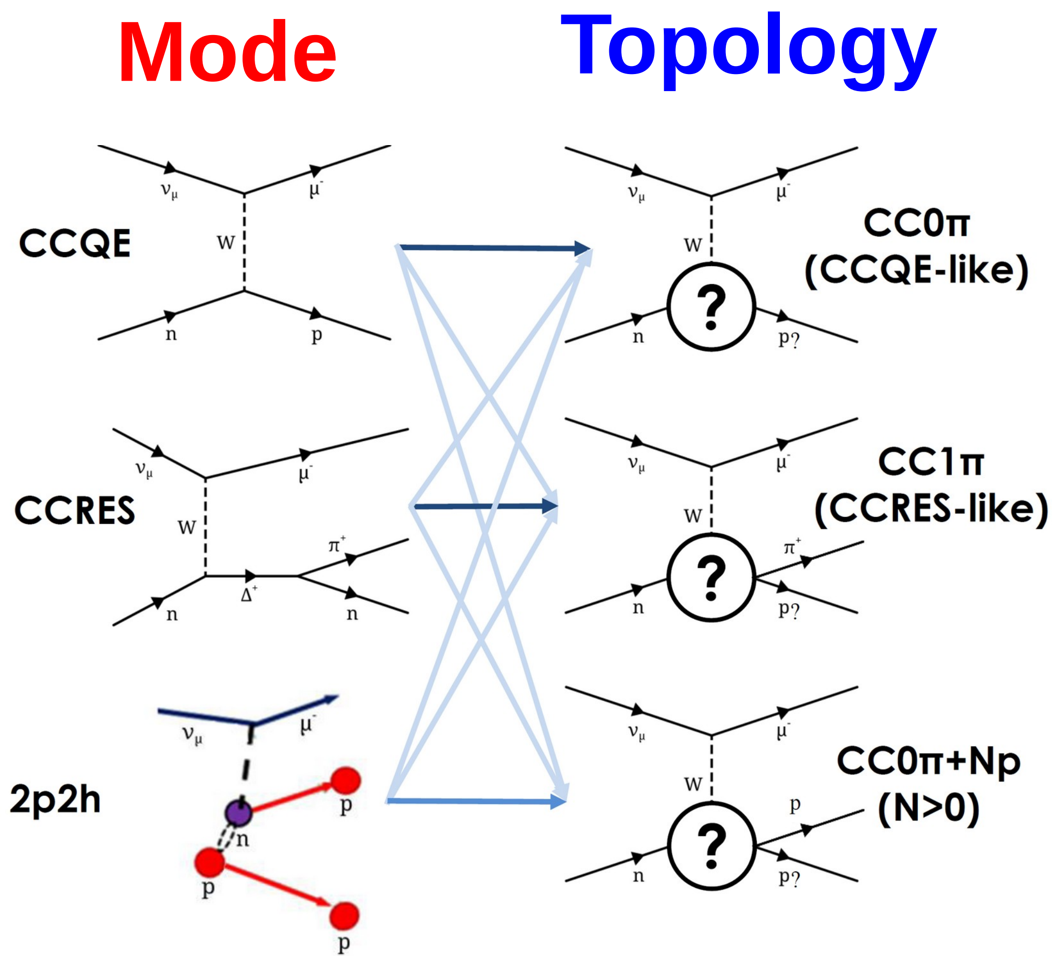
π-A, γ-A

THEORY



Neutrino-nucleus experiments

Neutrino-nucleus scattering measurements



Many modes contribute to any measurement

Complicated FSI effects

Integrated over broad E_ν/q_0 region

Theory—data linked through generators

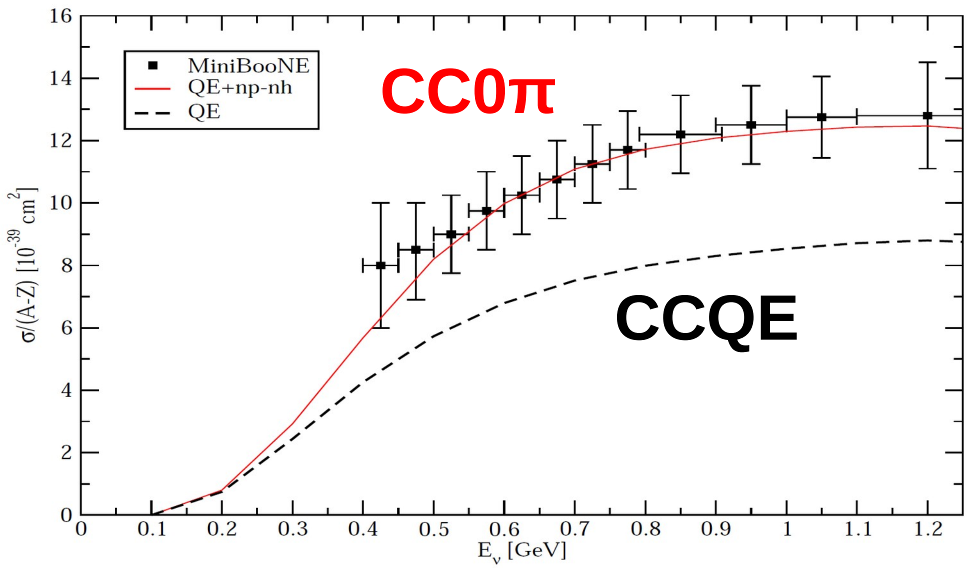
$$\widetilde{\sigma}_k(\vec{\mathbf{y}}) = \sum_i \int_{E_{\min}}^{E_{\max}} \sigma_i(E_\nu, \vec{\mathbf{x}}) \times \mathrm{FSI}(\vec{\mathbf{x}}, \vec{\mathbf{y}}) dE_\nu$$

Tuning models to data

- Tuning σ_i parameters requires multiple post-FSI datasets to break degeneracies!
  - Multiple fluxes
  - Different selections
  - Different acceptance
  - Detector technologies
  - Multiple targets

- This necessity has motivated a lot of work measuring neutrino cross sections in a lot of different ways – **a vital first step!**

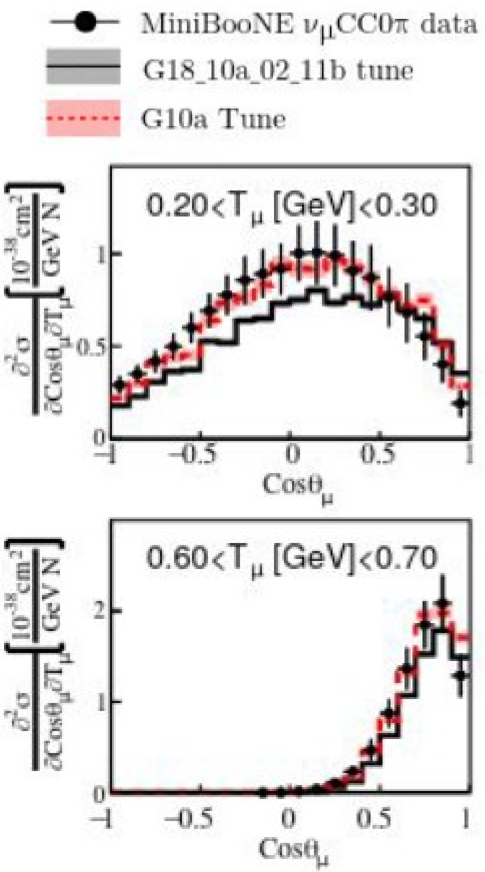
Counter examples exist



PRC 80 (2009) 065501

- That's not to say that a single dataset can't show that a model is insufficient to explain data!
- **Example:** MiniBooNE CC0π results motivated model development to explain the huge data-MC difference
- More recent examples include STV variables

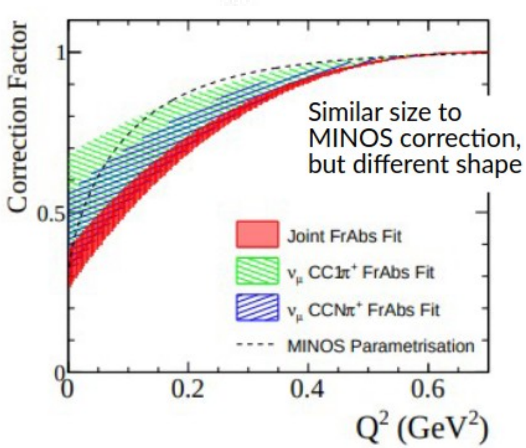
Emergence of “model fitters”

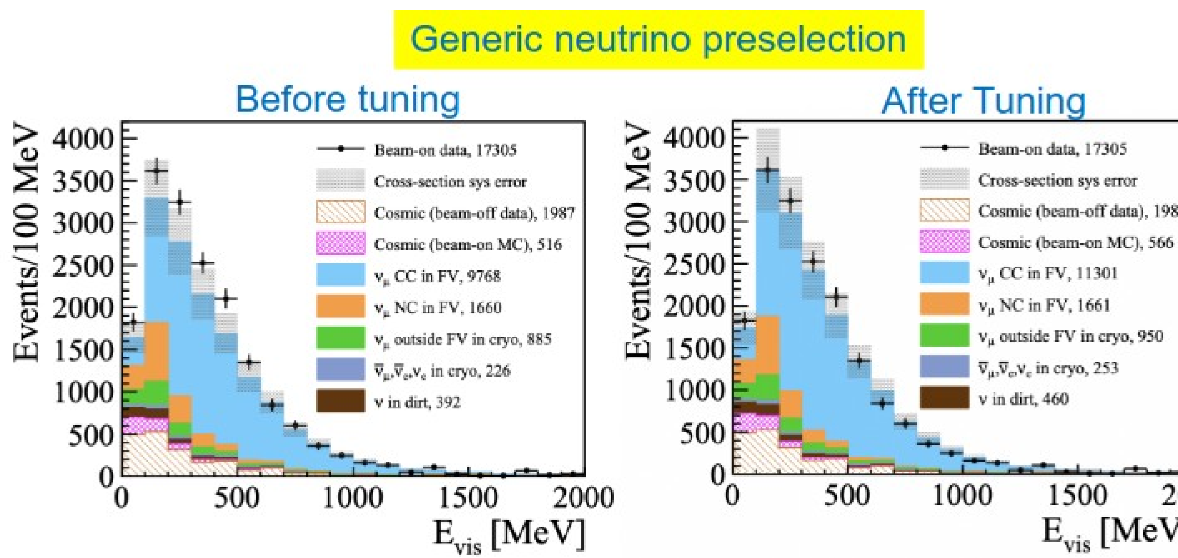


Event generators provide necessary link between data and theory to make suite of comparisons

Various groups tune MC to data, including oscillation experiments *(GENIE, DUNE, T2K, NUISANCE, uBooNE, NOvA, …)*

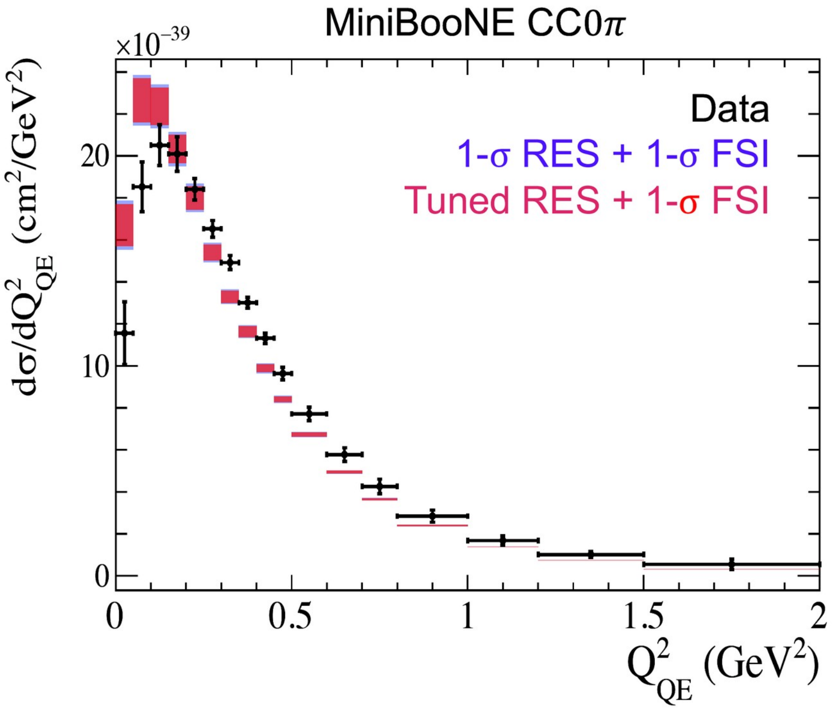
Trying to understand the impact of data on ν-A models, and the uncertanties in analysis

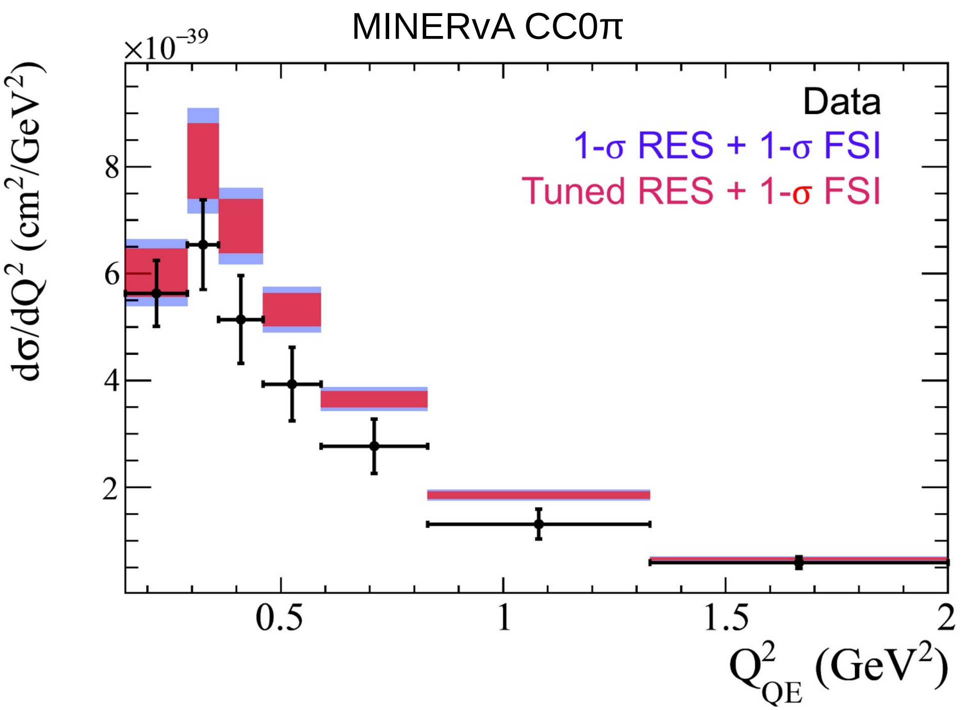




How do we develop a precision cross-section model? And what are the challenges?

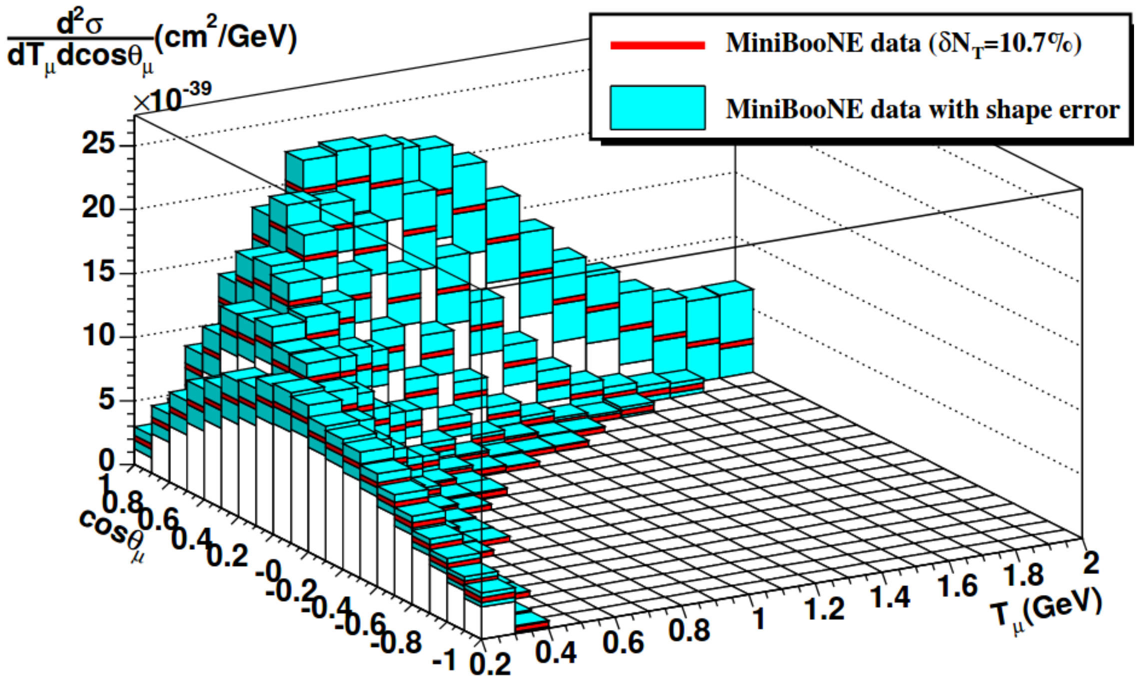
Challenge #1: difficult to factorize problem





- Difficult to isolate regions of the model to tune with data
- **Example:** pion production + pion FSI uncertainties shown for two CC0π samples
- Can’t tune the CCQE/2p2h models alone without making assumptions about these!

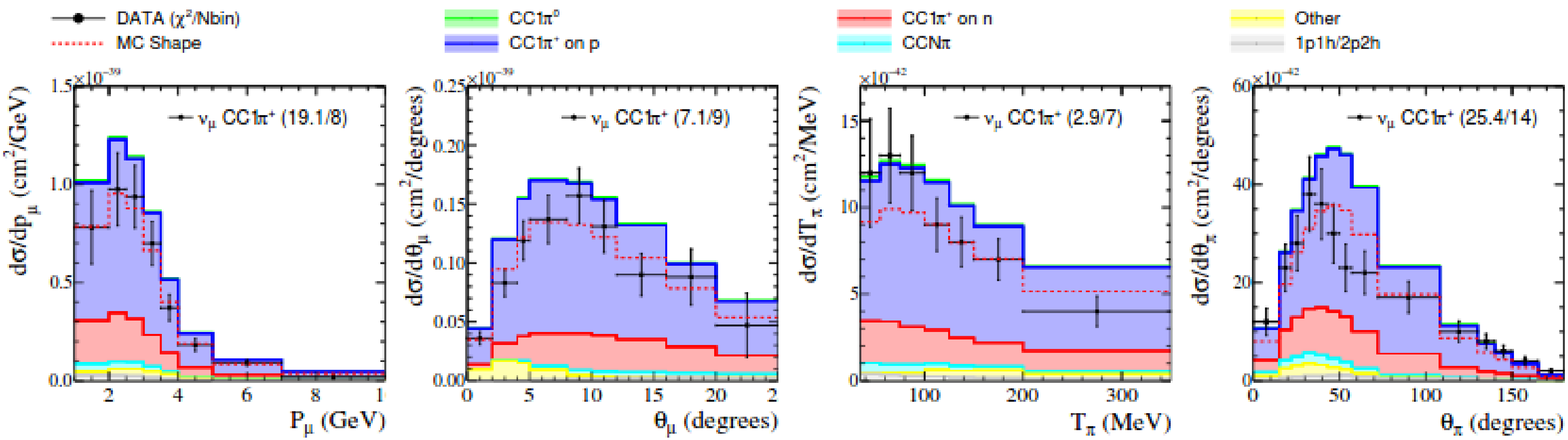
Challenge #2: missing information



PRD 81 (2010) 092005

- Some older datasets are missing vital information
- **Example:** MiniBooNE CC0π data – bin-to-bin correlations are obviously strong, but no covariance provided
- Naively using the information provided yields χ^2/DOF ≈ 0.1…

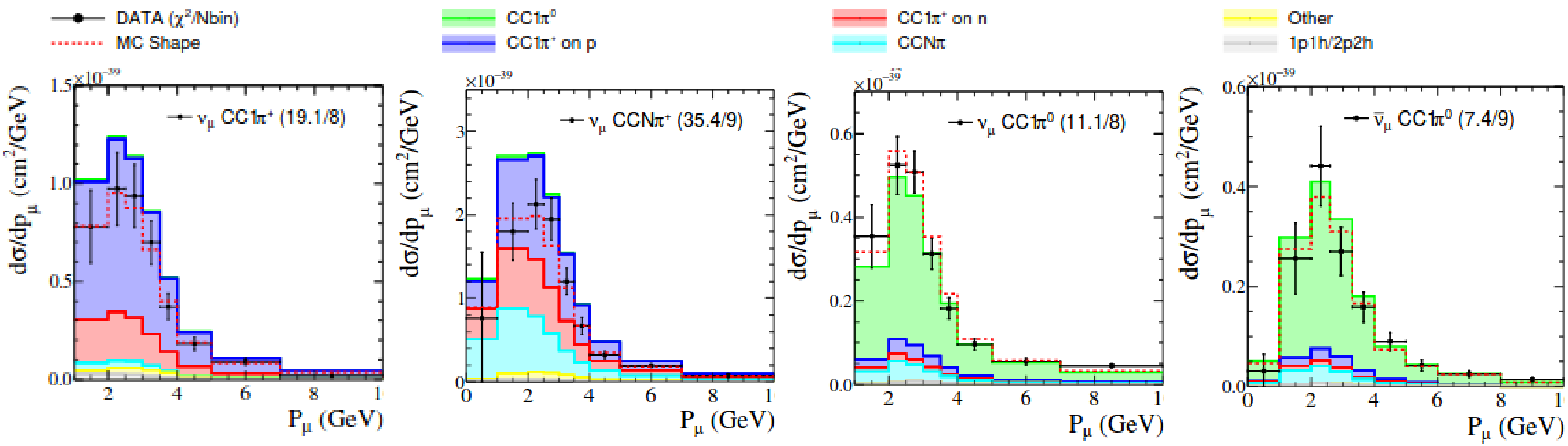
Challenge #3: cross-correlations



PRD 100 (2019) 072005

- Measurements often include produce multiple projections
- Without correlations *between* projections, including all of these pieces of information is challenging → *ad hoc* solutions
- Typically, correlations are large for all experiments due to flux normalization uncertainties of 5-15%

Challenge #3: cross-correlations



PRD 100 (2019) 072005

- Different analyses from the same experiment are also correlated, at least through the flux, and may contain a subset of the same events
- Experiments in the same beamline may complicate this issue further, all leading to underestimated tension in global fits…
- Large covariances matrices help, but quickly become unwieldy. Producing correlations with old datasets may not be possible

Challenge #4: model dependence

$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}_{ij}^{-1} (N_j - B_j)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

- Common assumption that cross-section extraction takes the measured rate and presents it in a slightly massaged form
- “The data is the data”, right?

Challenge #4: model dependence

Some unfolding methods introduce bias

The signal definition and background subtraction can be model dependent

$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}^{-1}_{ij} (N_j - B_j)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

The choice of variables can rely on an implicit model correction

Efficiency corrections couple to model in complex ways

- Common assumption that cross-section extraction takes the measured rate and presents it in a slightly massaged form
- “The data is the data”, right?

Why is model-(in)dependence important?

- **Oscillation analyses are flux and cross-section model dependent**

$$R(\vec{\mathbf{x}}) = \overbrace{\underbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \to \nu_B)}_{\text{Far}}$$

- We try to minimize the impact of these assumptions with sophisticated ND complexes – but can't remove them

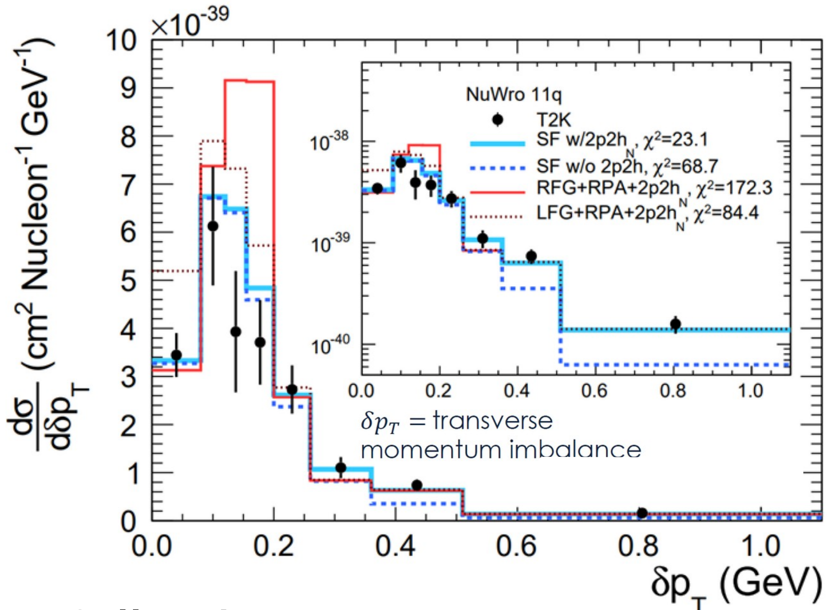
- We use a model, tuned and validated with external data (that's you!) to formulate and apply those assumptions

- **Cross-section measurements cannot make the same assumptions → must strive for model independence**

Challenge #4: model dependence

- A problem for all fitting efforts (e.g., PDG, parton PDFs) is the need to select or “deweight” problematic or untrusted datasets…
- As XSEC data producers, we want to ensure our work is as “future proof” as possible, and will be used
- Conversely, as XSEC consumers, we need to ensure that we don’t allow imperfect data to bias our analyses!

Challenge #5: (almost) nothing works



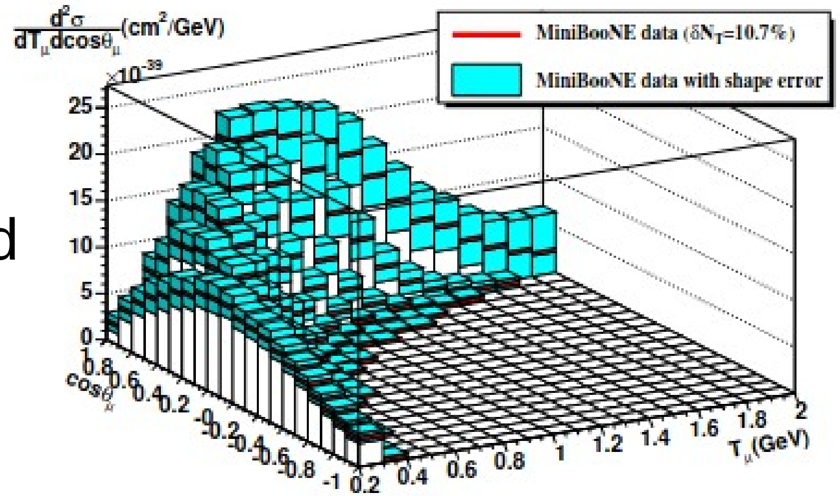
T2K CC0π
PRD 98 (2018) 032003

- Most fitting efforts find one of the following:
  - Poor agreement (at least in some regions of phase space)
  - Very small uncertainties on fitted parameters
  - Parameters pulled to surprising values
- **Unclear why… untangling this will be a long conversation: fits/theory motivate new data, fits/data motivate new theory**

Thorough documentation: a MiniBooNE legacy

Extended lifetime through detailed descriptions of results:

- **Example:** the CC0π result we all know and love is in the appendix of the MiniBooNE paper
- We do not trust the CCQE-corrected "main result" of the paper



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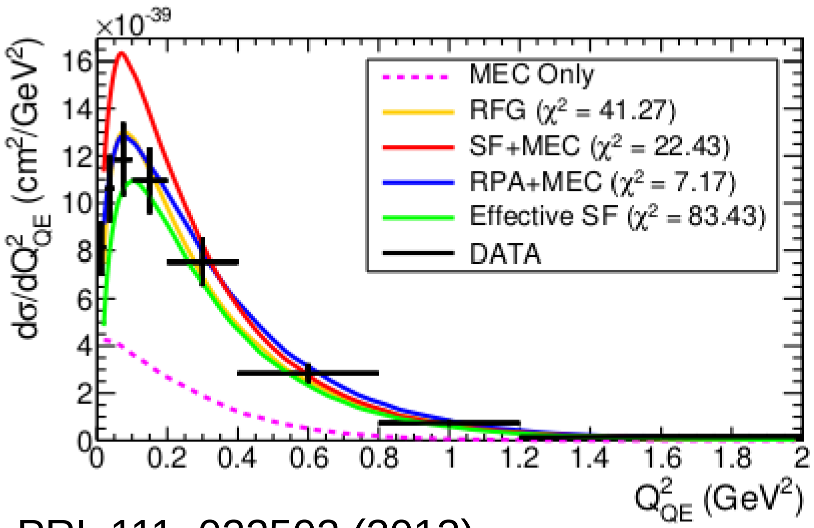

PRL 111, 022502 (2013)

Discussions with the community can improve results:

- **Example:** MINERvA added a θ_μ < 20° cut after publication
- Also, released neutrino—antineutrino correlations

Thorough documentation #2: document harder

- **FDS** are now commonly used for assessing model dependence
  - They are an integral part of the result and documentation of it
  - Impossible to cover all possible biases, but they demonstrate the analysis is robust to potential types of bias
- Initiatives to make data easier to access/reanalyze are challenging: MINERvA preservation, HepData initiatives, uBooNE public notes
- **The more detail the better:** what cuts and why; phase-space restrictions; unfolding methods and regularization criteria; …

Summary

- We are your primary customers! -- **without you, we will fail**
- **A long way to go** to reach our required precision! Progress requires strong theory – data – generator – fitter links
- **Emergence of “model fitters”**: interface between theory and data, and between data providers and consumers
- **Model-independence**, we need to “future-proof” new data to ensure its continued use in the precision oscillation era
- **Documentation of methodology and validation**: in 10-20 years, someone will trawl PhD theses looking for details you omitted from the paper