A bit of a NUISANCE: constraining neutrino cross-section systematics

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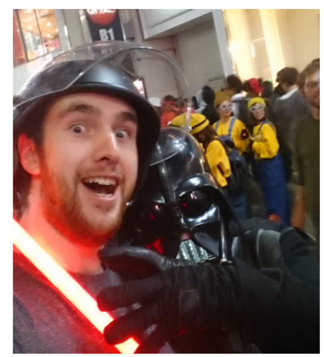

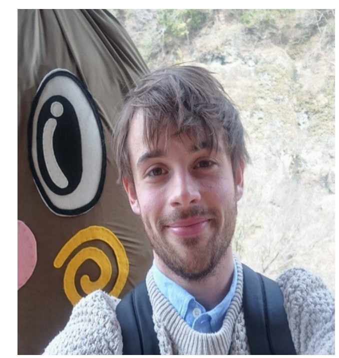

T2K

NUISANCE

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FOR FUNDAMENTAL PHYSICS

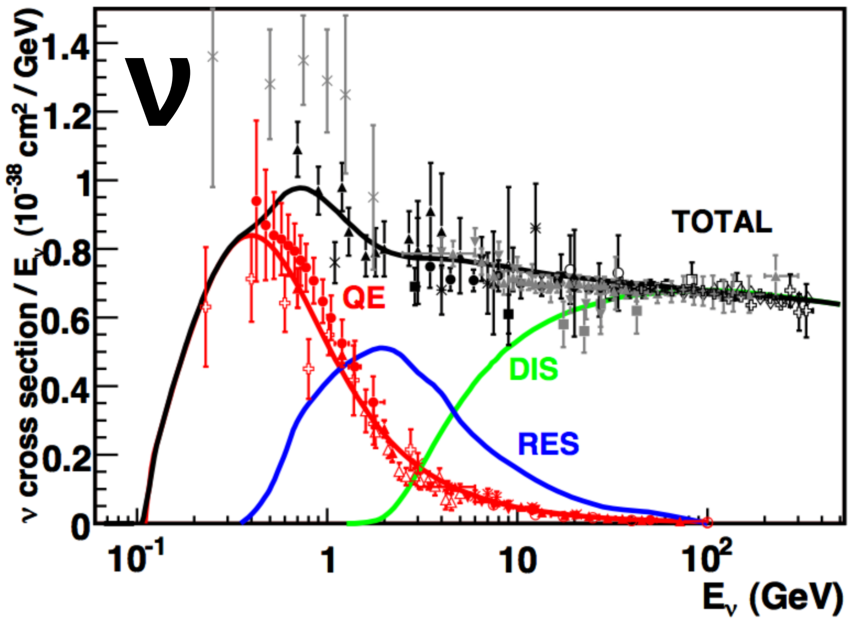
Introduction

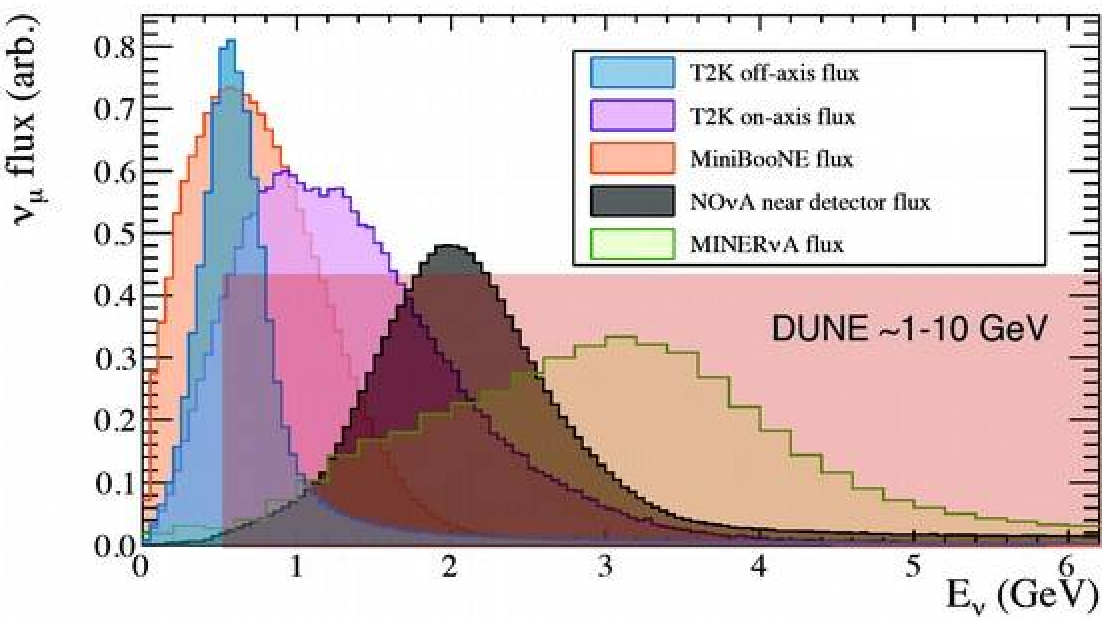
- Importance of cross sections for oscillation analyses
- The NUISANCE framework for tuning and comparisons to cross section data
- Example usage: T2K approach to constraining the NEUT cross section model
- NUISANCE future plans

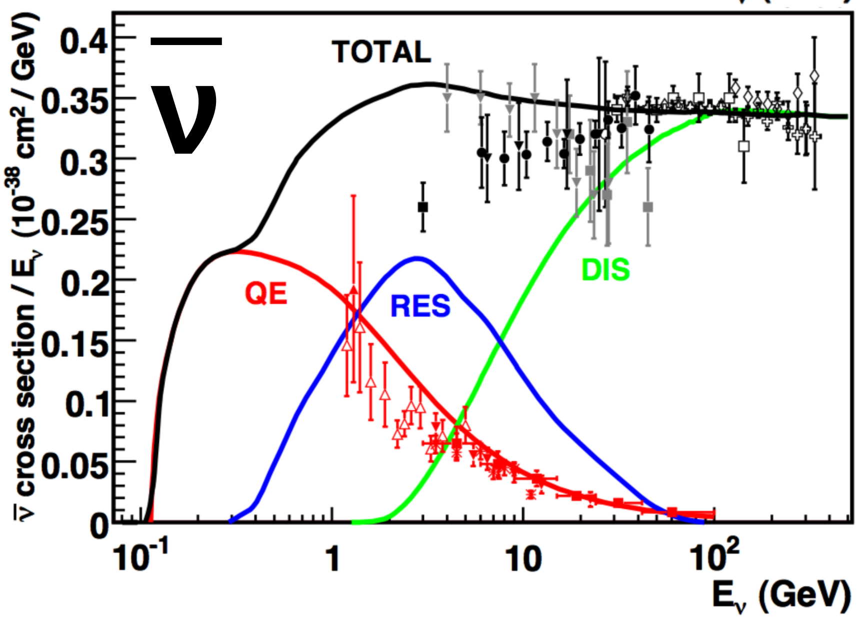
Cross section basics

All oscillation experiments live in the 0.1-10 GeV transition region.

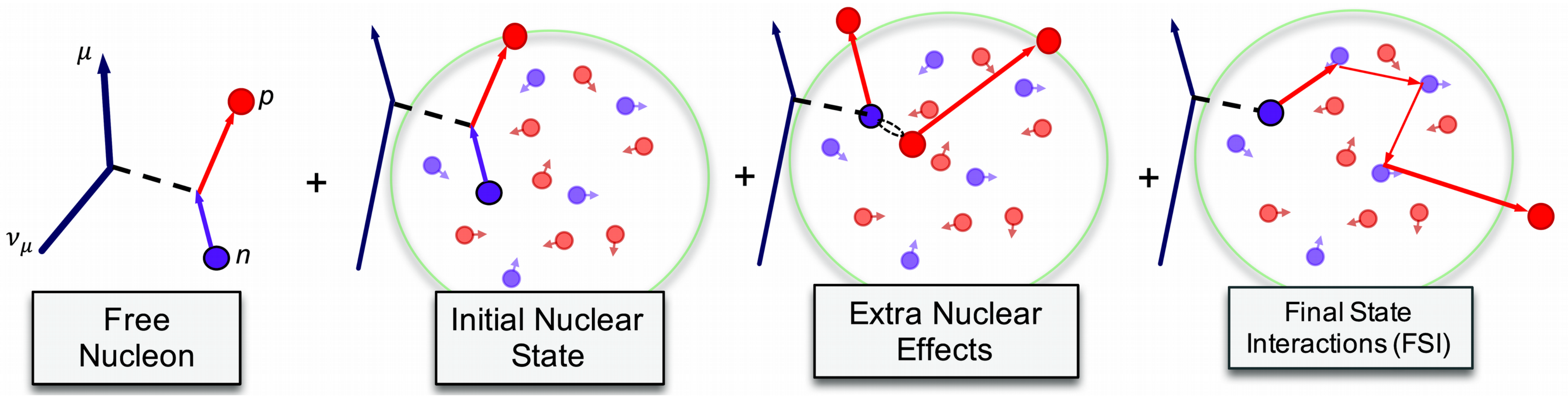
Multiple models required with different physical assumptions.







Nuclear targets



- **Free nucleon:** the interaction level cross section, including hadronization at high energy transfer
- **Initial nuclear state:** how nucleons behave inside the nucleus. E.g., Relativistic Fermi Gas.
- **Nuclear effects:** additional effects due to the presence of multiple nucleons. E.g. np-nh interactions.
- **Final State Interactions:** subsequent interactions before interaction products exit the nucleus.

Importance for oscillation analyses

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

- **Event rate; Neutrino flux; Cross section; Detector smearing; Oscillation probability.**
- Near/far E_ν spectra are different (no $\sigma(E_\nu, \bar{x})$ cancelation)
- Different near/far detector acceptances
- Different targets for some near/far detectors

Cross section uncertainties will be a limiting factor for current and future oscillation experiments.

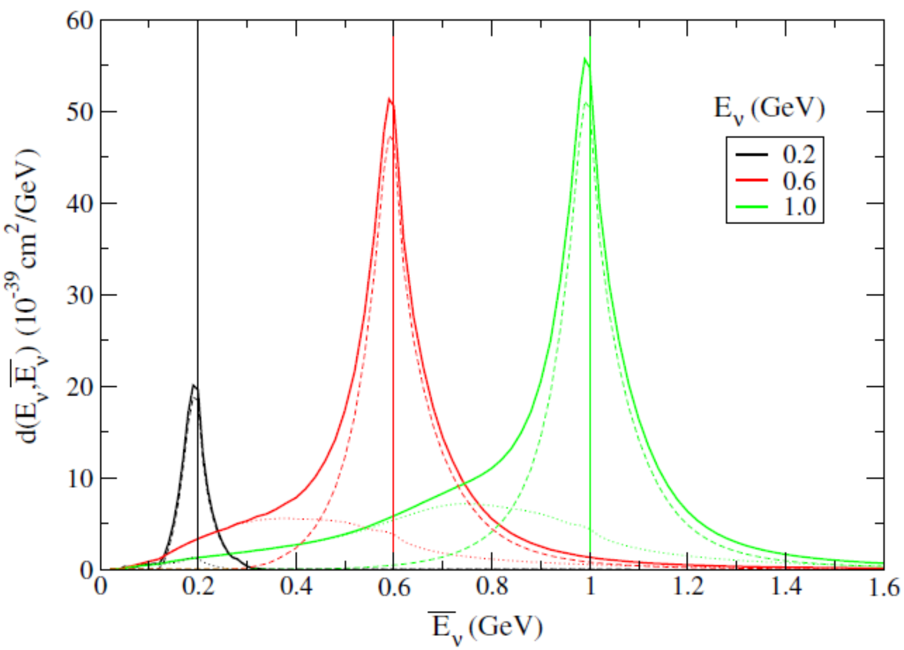
Importance for oscillation analyses

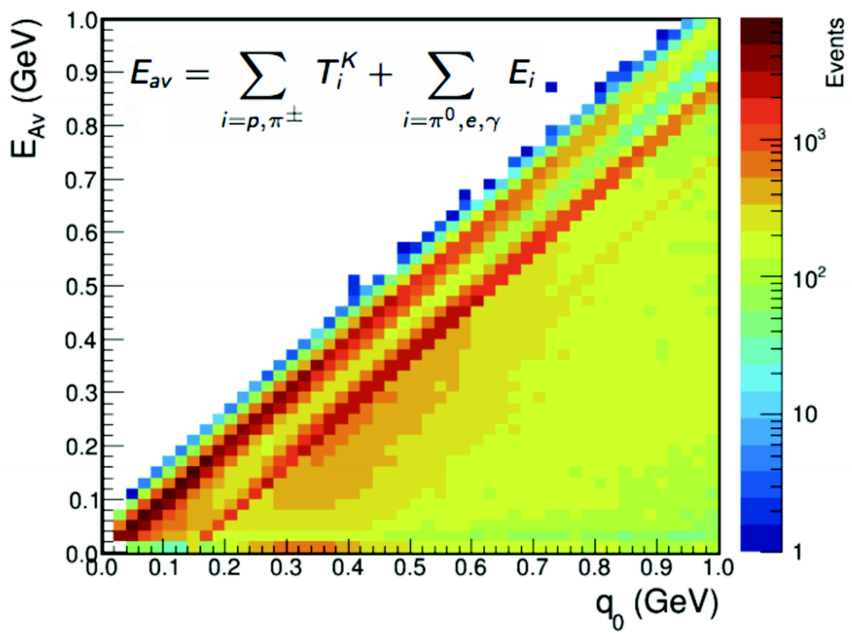
- We have to use a cross section model to infer the neutrino energy from the observed events.
- Can use **leptonic** or **hadronic** information:

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

$$E_\nu = E_\mu + \sum E_{hadronic}$$

PRD 87 (2013) 013009





What can we actually measure?

- Only ***post-FSI*** cross sections are model-independent:

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

CC0π = 1p1h + 2p2h + CC1pi(+abs) + ...

- Need to integrate out all degrees of freedom other than ***y***
  FSI makes this difficult/impossible analytically
  - Direct theory comparisons to data are very difficult
  - ***Require*** **Monte Carlo generators** for numerical integration

Tuning models to data

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

- Cannot fit parameters of a single interaction channel, without making assumptions about (or fitting) others

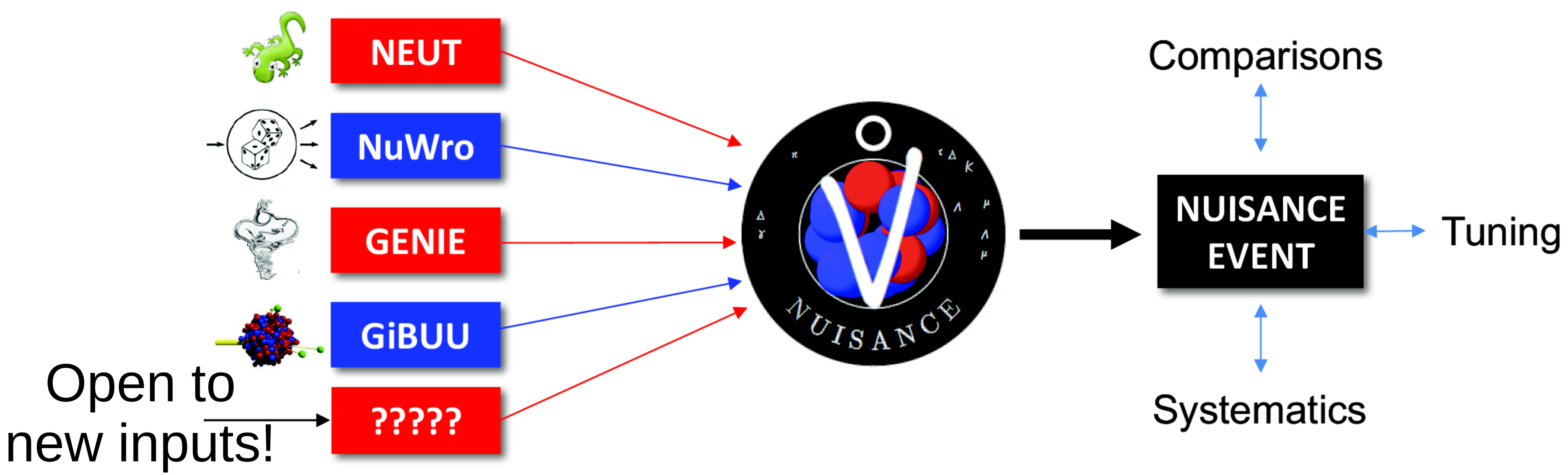
Not possible to isolate one interaction process in a model-independent way!

Monte Carlo generators

- Several MC generators under active development:
  GENIE, NEUT, NuWro, GiBUU

- OA or cross section experiments use one primary generator, and (some) use another for comparisons or bias tests

- High barrier to entry to use an unfamiliar generator...



NUISANCE

- NUISANCE is a general purpose cross section comparison and tuning framework.
  - Large collection of datasets already included (~130)
  - Support for multiple generators

- ***Open source software*** (GNU GPLv3)
  nuisance.hepforge.org

- ***Paper:*** JINST 12 P01016 (2017), arXiv:1612.07393

- Grew from T2K work with external data comparisons

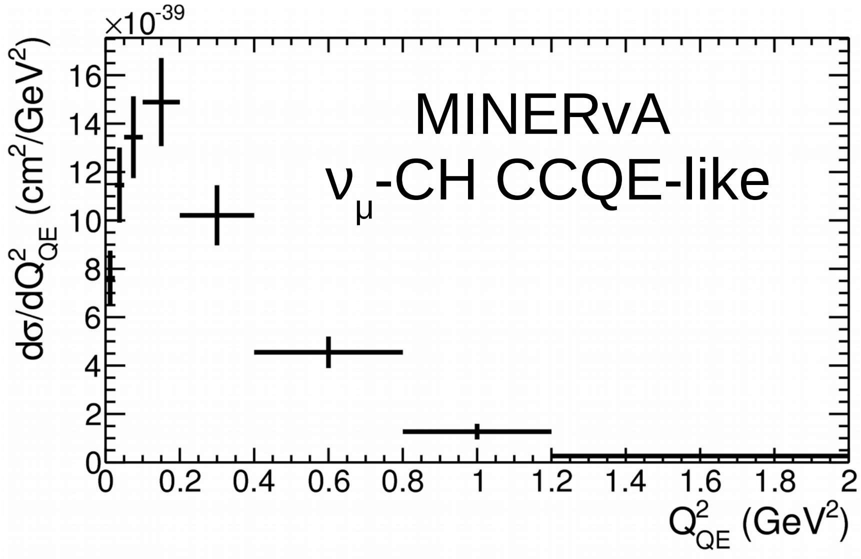
NUISANCE: adding a measurement

Input data: histogram and covariance from data release

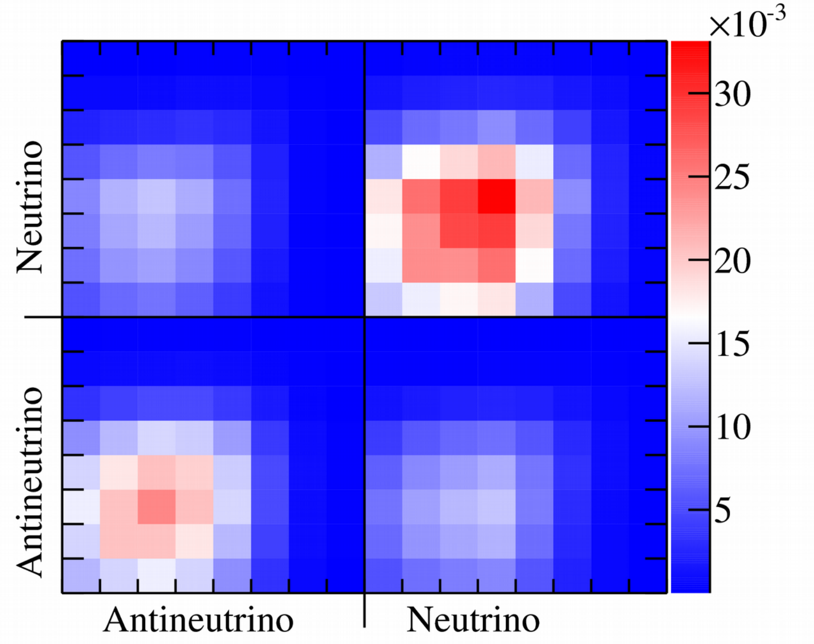
Signal definition:
- Selected particle content, e.g., $1\mu^-$, 0π, ...
- Phase space restrictions, e.g., $\theta_\mu < 20°$

Binning definition: method to calculate Q^2_{QE} (utility functions)

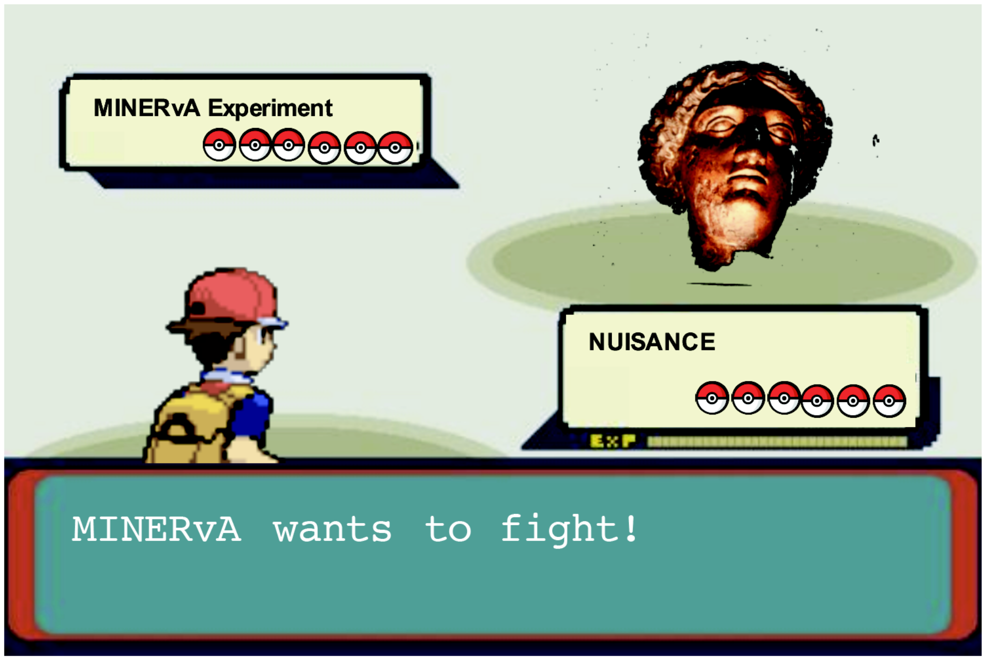
Additional support:
- Smearing matrices
- Ratio measurements
- Shape-only (floating norm)

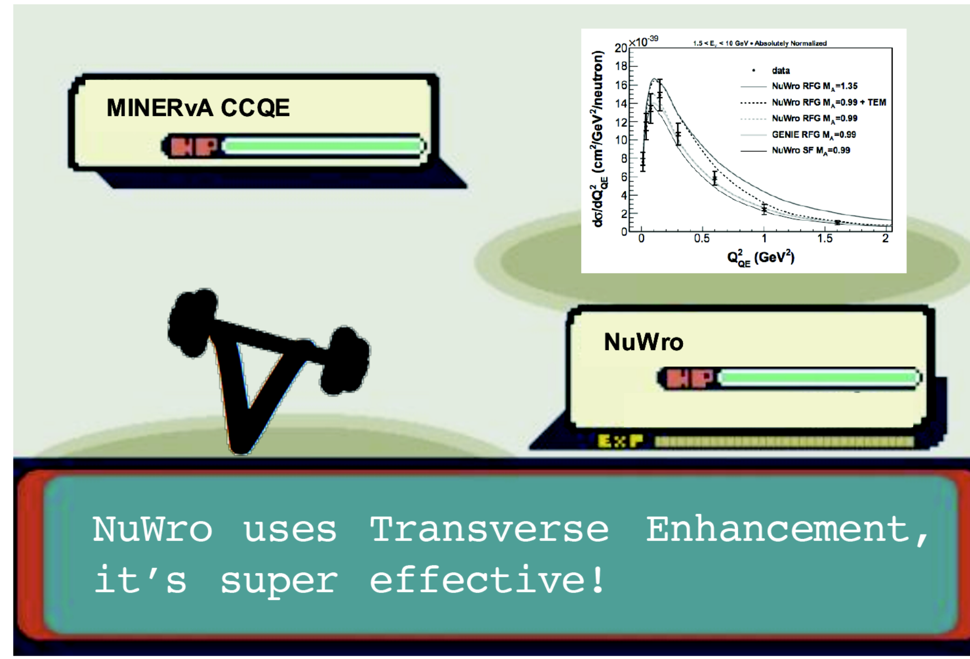


PRL 111:022502 (2013)



NUISANCE: adding a measurement





That's all that's required!

Ready for any generator / NUISANCE routine!

The (reweightable) players

NuWro
(v12)

GENIE
(v2.12.0)

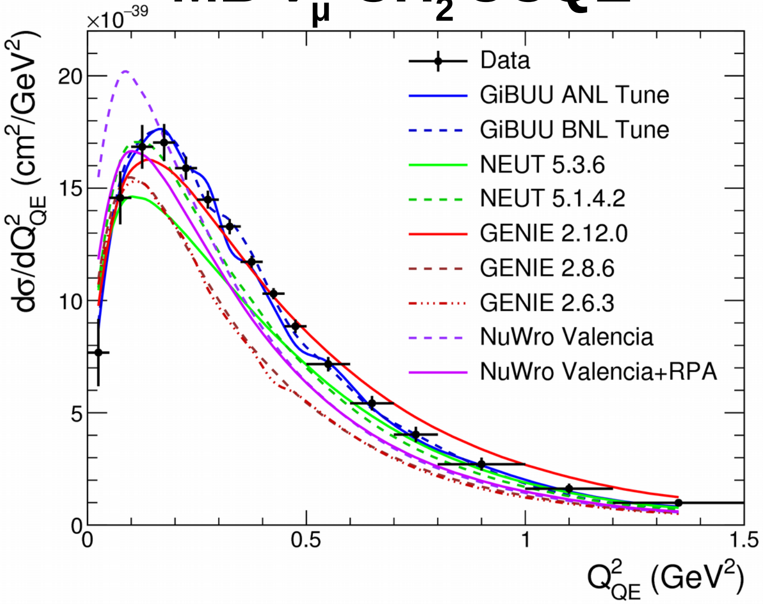
NEUT
(v5.3.6)

Disclaimer: generator comparisons use default model choices and parameters

Just a snapshot, not a detailed comparison between generators

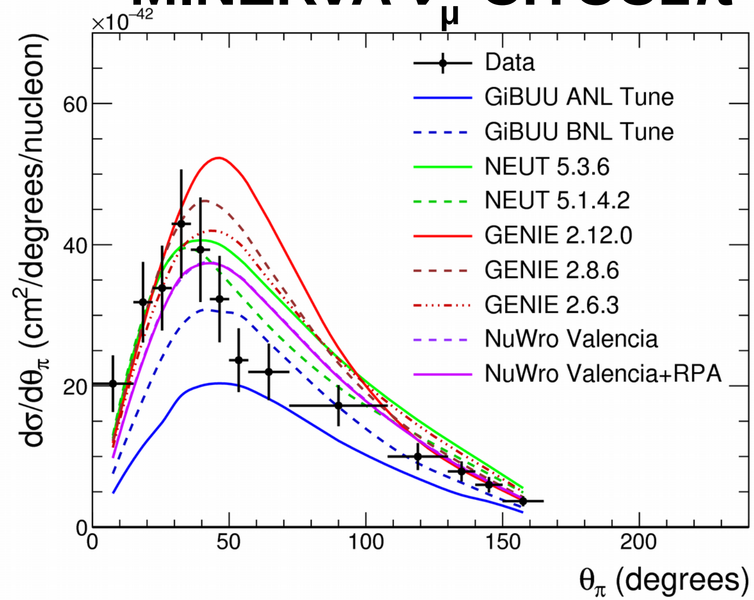
NUISANCE comparisons

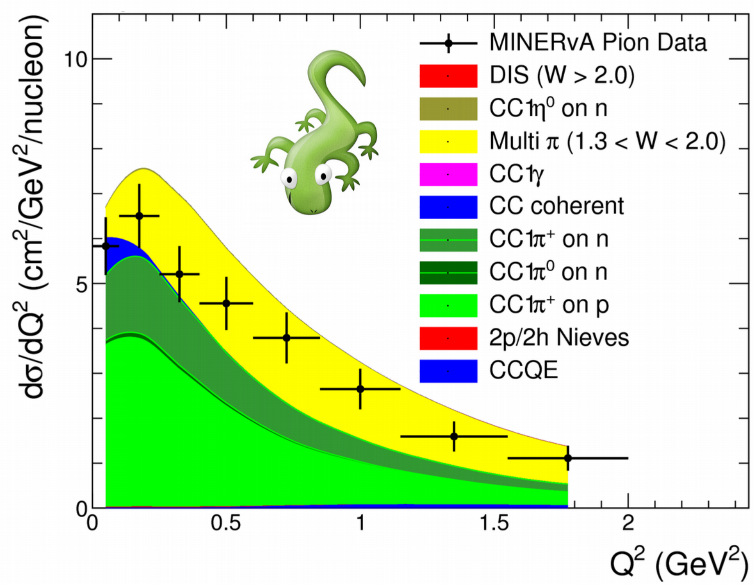
MB ν_μ-CH_2 CCQE



PRD 81 (2010) 092005

MINERvA ν_μ-CH CC1π^+

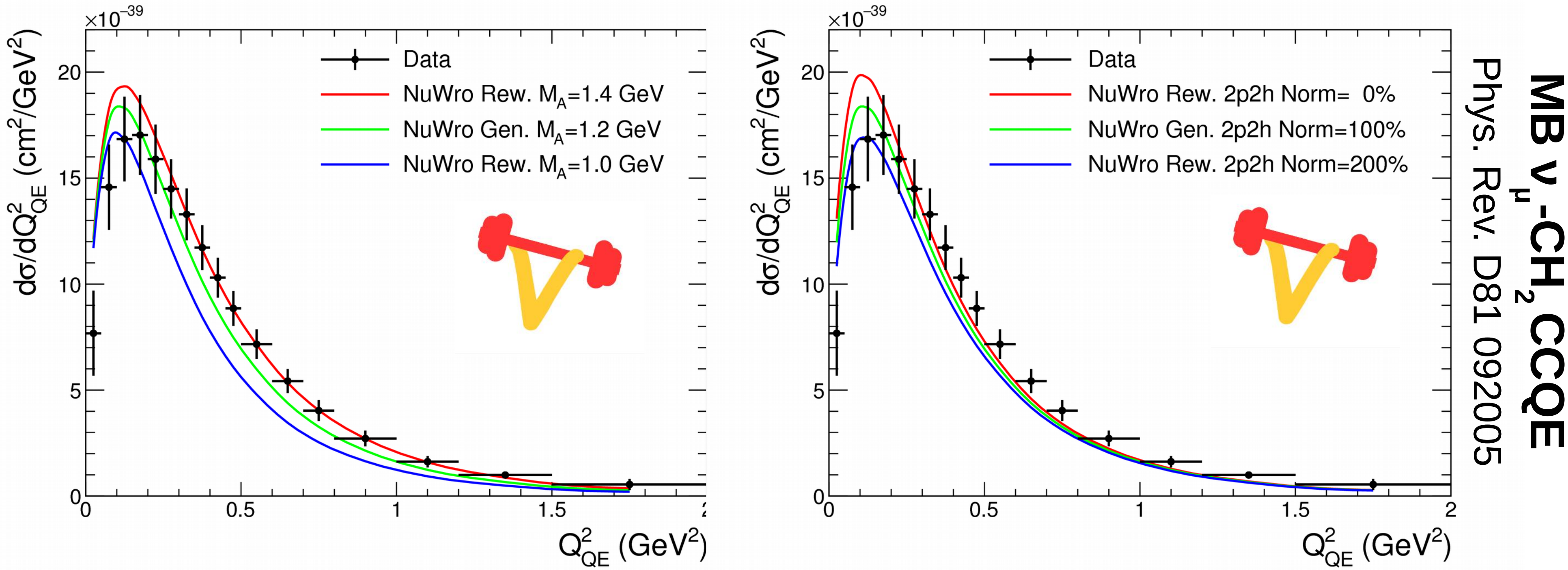




PRD 92 (2015) 092008

- Easy to compare generators to data
- No detailed generator knowledge required
- Encouraging experiments to publish new data with a variety of MC comparisons

NUISANCE validation (1)

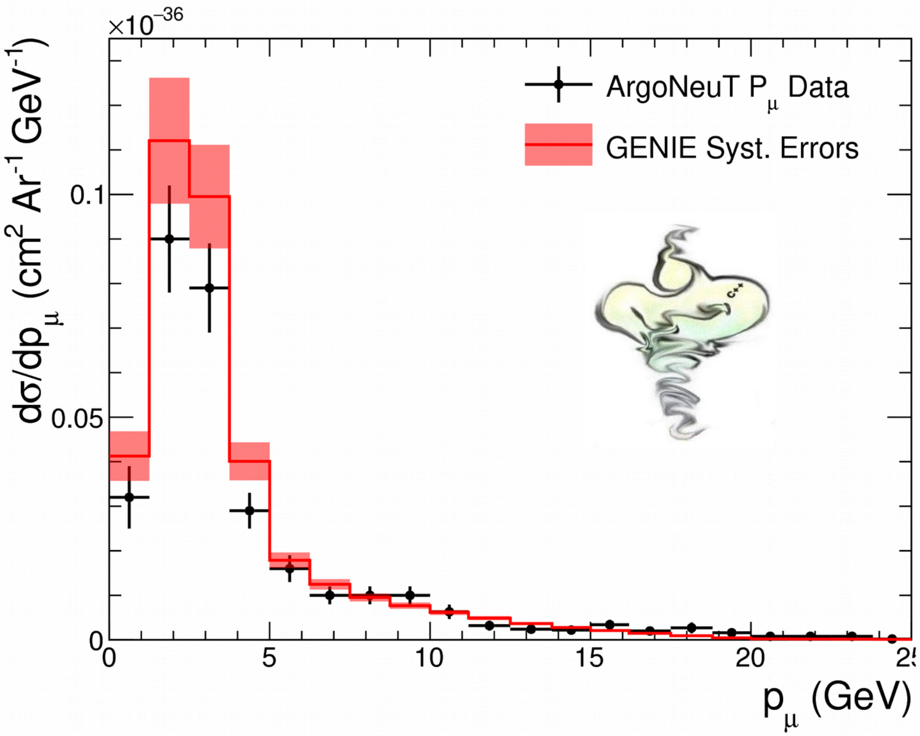


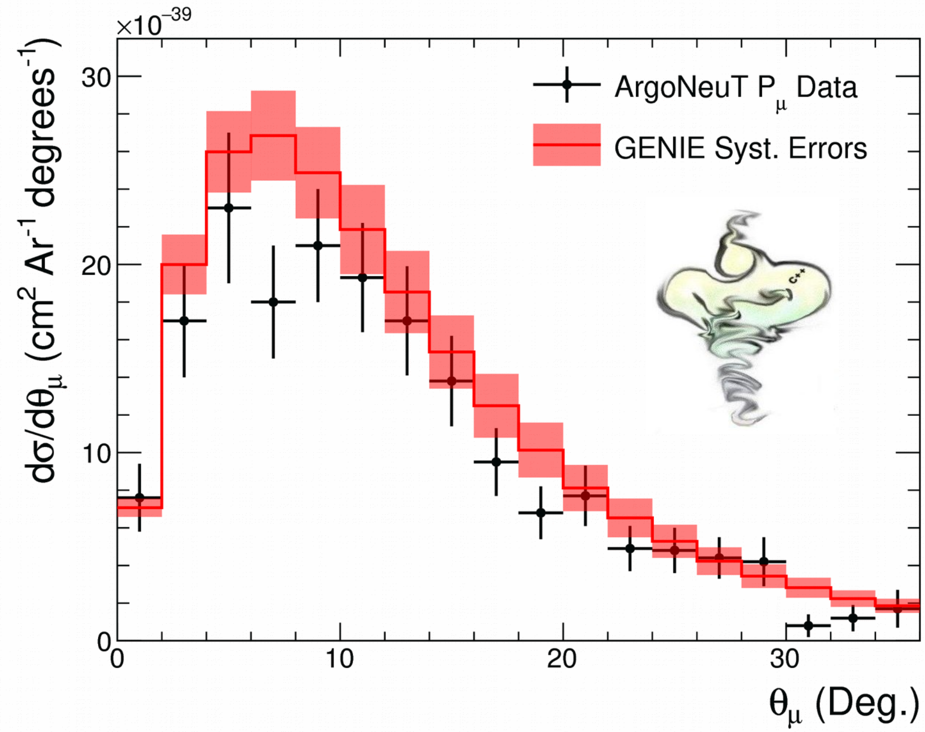
- Interfaces with generator reweighting libraries:
  GENIE, NuWro*, NEUT

- Provides simple validation tools → validate analysis inputs

**NuWro reweighting currently uses unofficial repository*

NUISANCE validation (2)





PRD 89 (2014) 112003

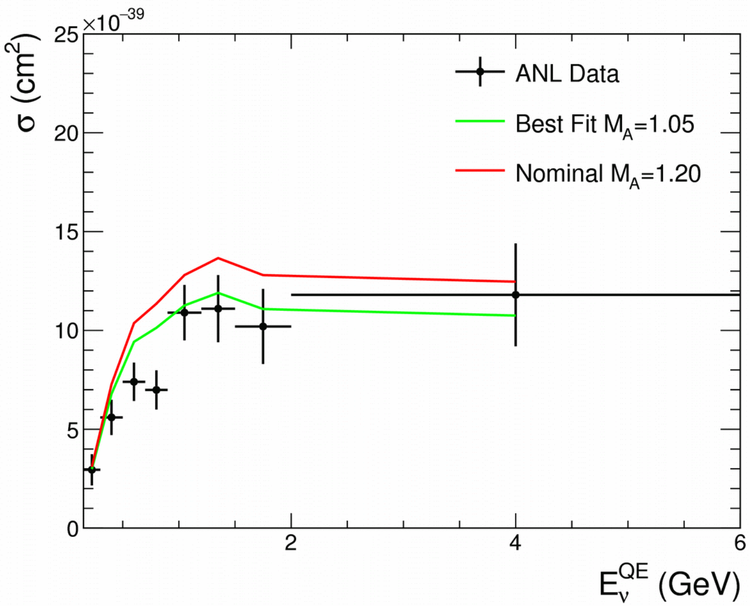
- Support for producing systematic error bands
- Example: default GENIE prediction and uncertainties compared with ArgoNeut CC-inclusive data

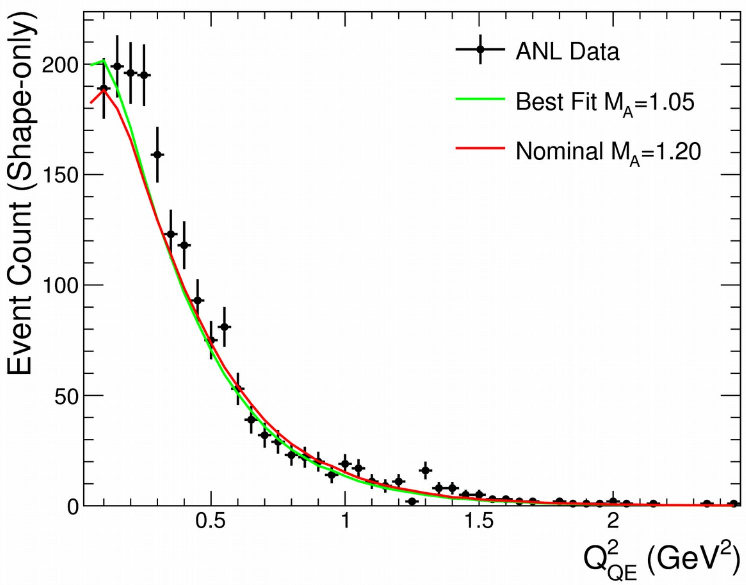
Model tuning with NUISANCE

- NUISANCE uses ROOT minimization routines to tune model parameters.

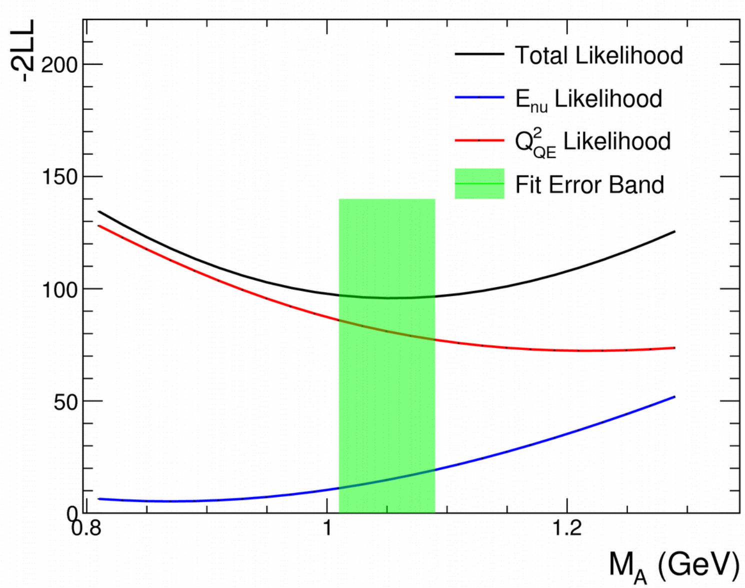
- The user can specify:
  - Parameters to vary
  - Any parameter bounds
  - Prior parameter contraints
  - *Distributions* to include in the fit
  - Which fit algorithm to use
  - How to define the test statistic

Model tuning with NUISANCE





ANL ν_μ-D_2 CCQE
PRD 16 (1977) 3103



Datasets: ANL CCQE E_ν and Q^2 (shape-only)

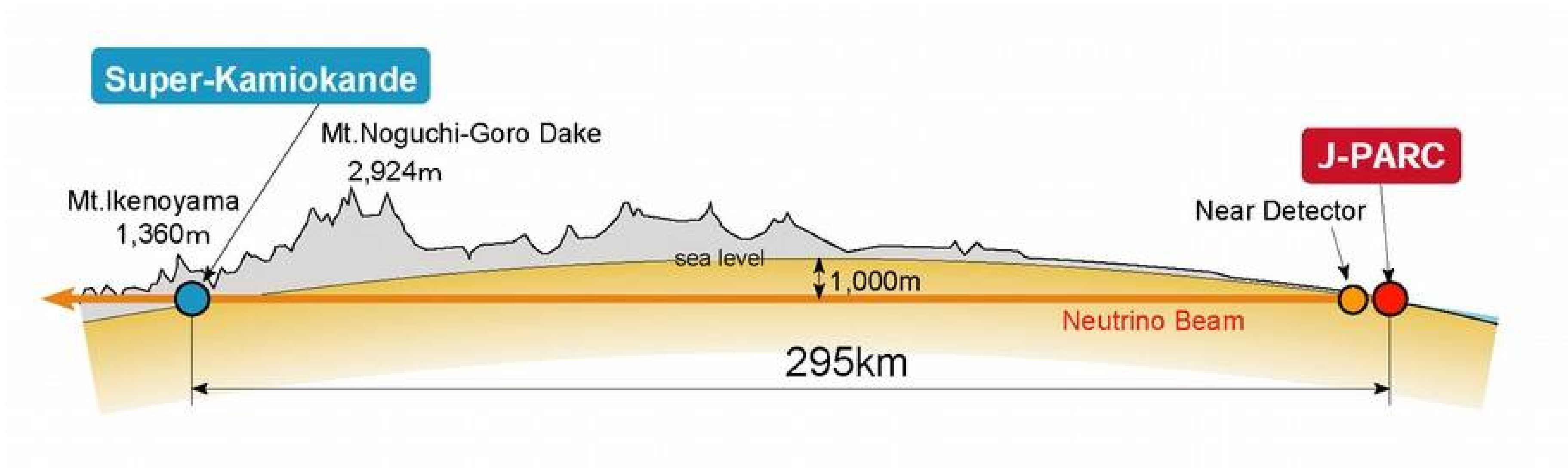
Parameters: M_A, Q^2 *norm.*

Output: M_A = 1.05 ± 0.04 GeV²
(Dipole F_A in MC)

Model tuning caveat

- NUISANCE is just a tool to perform phenomenological studies with generators.
- In the ***short term***, experiments may be happy with black box tuning of generators
- But in the ***long term***, robust physics conclusions require collaboration between experiments, theorists and generator experts
- On T2K, we have the huge benefit of NEUT experts, and a great deal of invaluable theory input

Cross section modeling for T2K



- T2K constrains cross section model with ND fit before propagating to FD
- **Concerns:**
  - ND acceptance is forward, little sensitivity to high-Q^2 events
  - FD has 4π acceptance
  - FD is water, ND has scintillator and water
- Aim to constrain all cross section parameters with external data before the ND fit

NEUT model

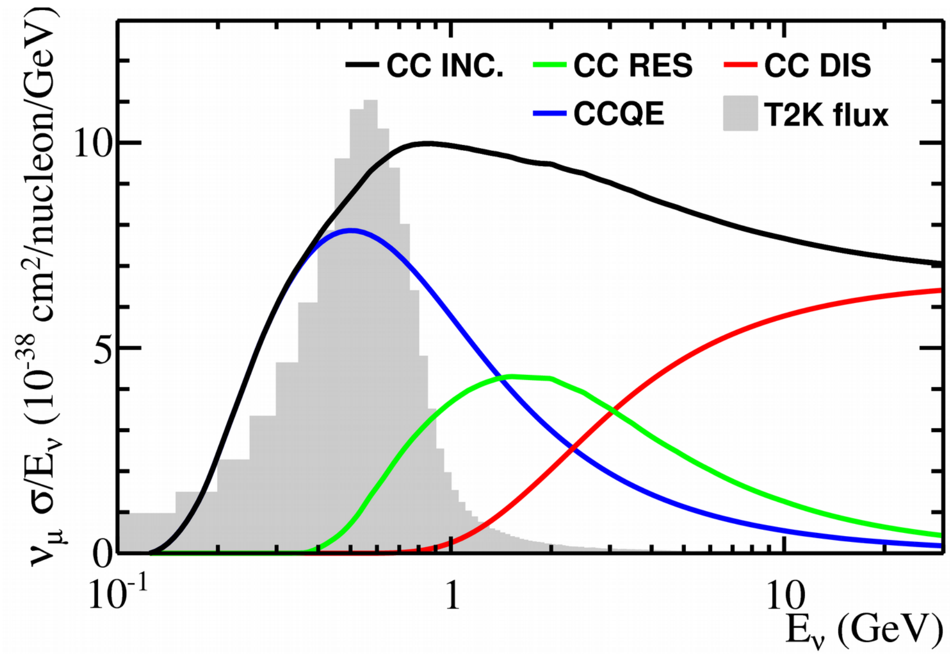
Category	Description	Parameters
CCQE	Llewelyn-Smith	M_A, p_F, E_b, RPA-Shape
2p2h-lepton	Nieves	$\Delta - \mathrm{Non}\Delta$ shape, pn/nn ratios
2p2h-hadron	Sobczyk ejection model	
RES	Rein-Sehgal	M_A^{RES}, C_A^5, $I_{1/2}$
COH	Berger-Sehgal	Rein-Sehgal alternative option
FSI	Oset Model	Pion/Nucleon FSI Fractions
DIS	PYTHIA 5.7	
Nuclear	RFG	SF alternative option
Other		Channel Norms, $\nu_\mu - \nu_e$ ratio

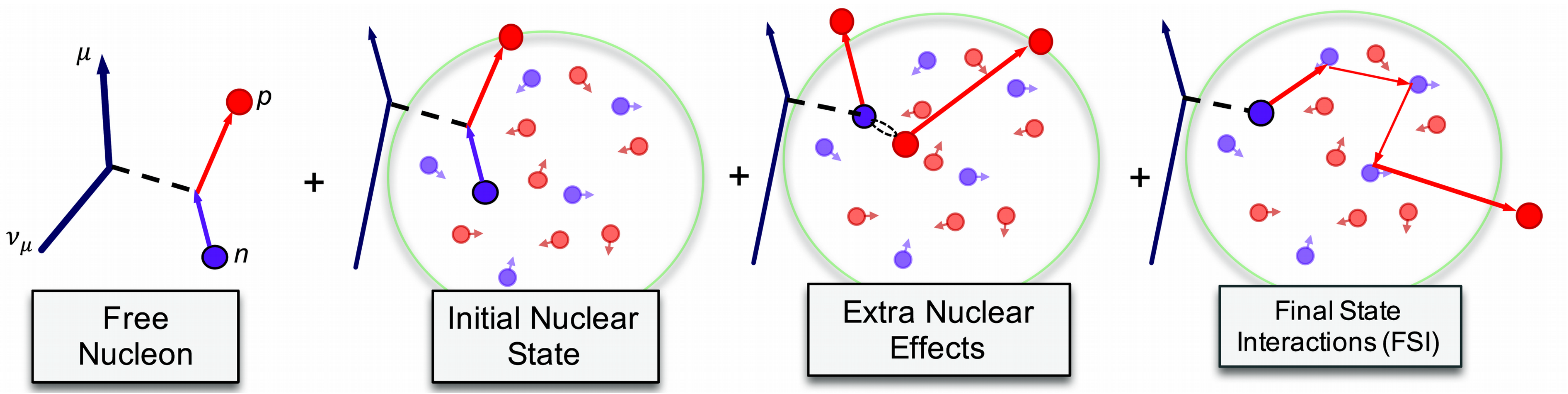
- Just for reference because I'll talk about NEUT in detail
- Many channels to be considered, each has variable parameters: >20 for full T2K analyses!

Cross section modeling for T2K

Aim: constrain all cross section parameters with external data

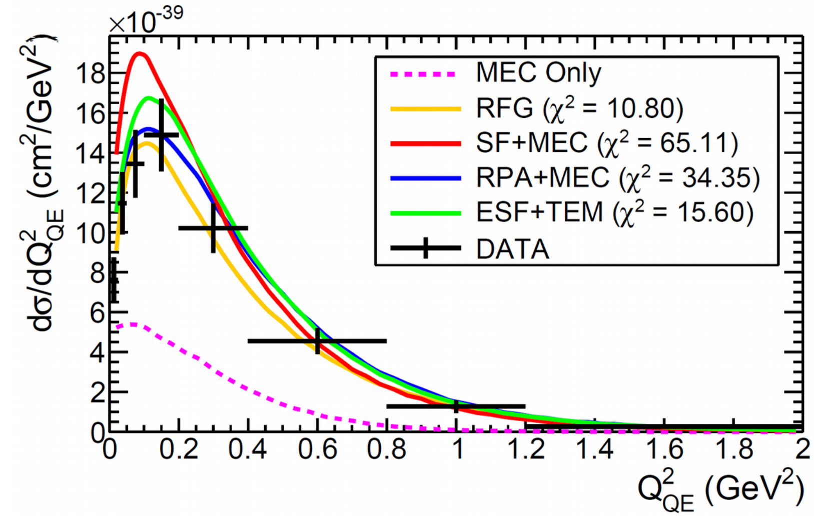
That's a lot of parameters!

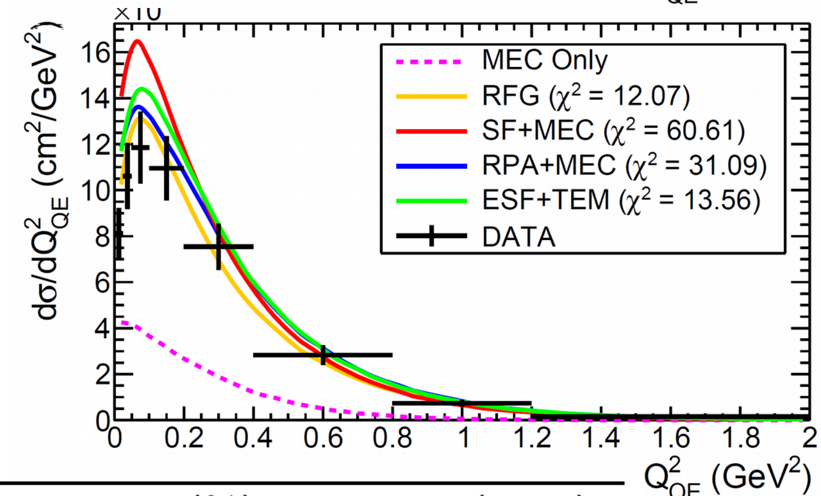




Previous attempt

- Attempt to fit all CC0π data:
  - MiniBooNE T_μ-$\cos\theta_\mu$ ν_μ
  - MiniBooNE T_μ-$\cos\theta_\mu$ $\bar{\nu}_\mu$
  - MINERvA Q^2 ν_μ & $\bar{\nu}_\mu$ (with corr.)
- Many NEUT model improvements: SF, 2p2h,…
- Unable to fit the data, **surprising** and **unsatisfactory** results.

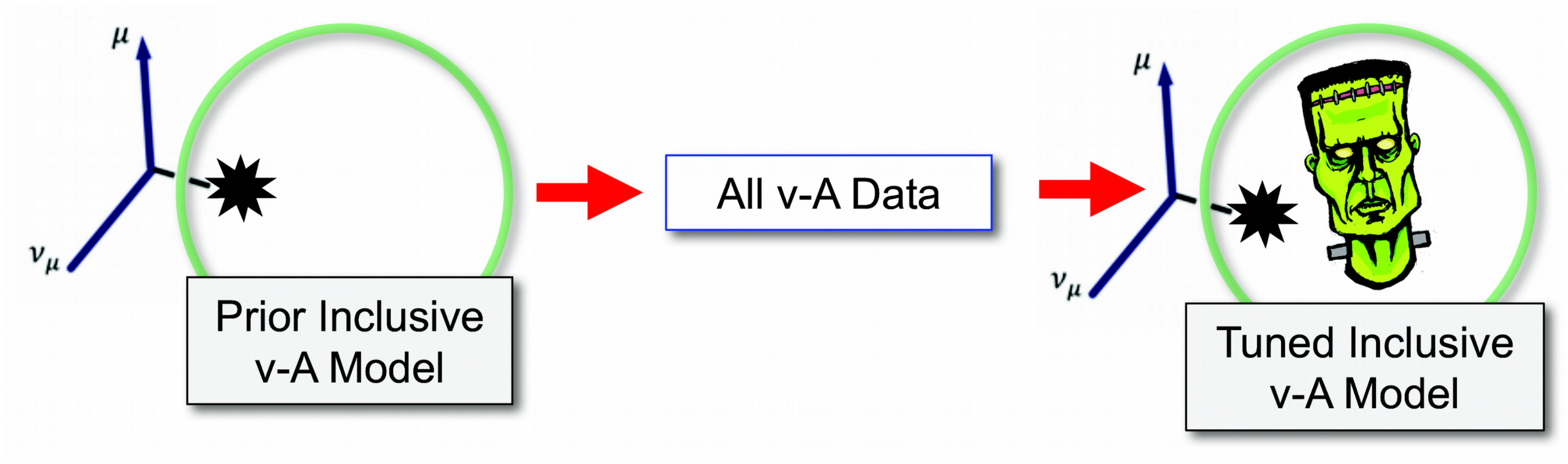




Model	χ^2/DOF	$\mathbf{p}_1$: M_A (GeV)	$\mathbf{p}_2$: 2p2h (%)	$\mathbf{p}_3$: p_F (MeV)
Theory expectation		$\sim$1.00	$\sim$100	$\sim$217
A: SF+2p2h	97.5/228	1.33±0.02	0 (at limit)	234±4
B: RFG+RPA+2p2h	97.8/228	1.15±0.03	27±12	223±5

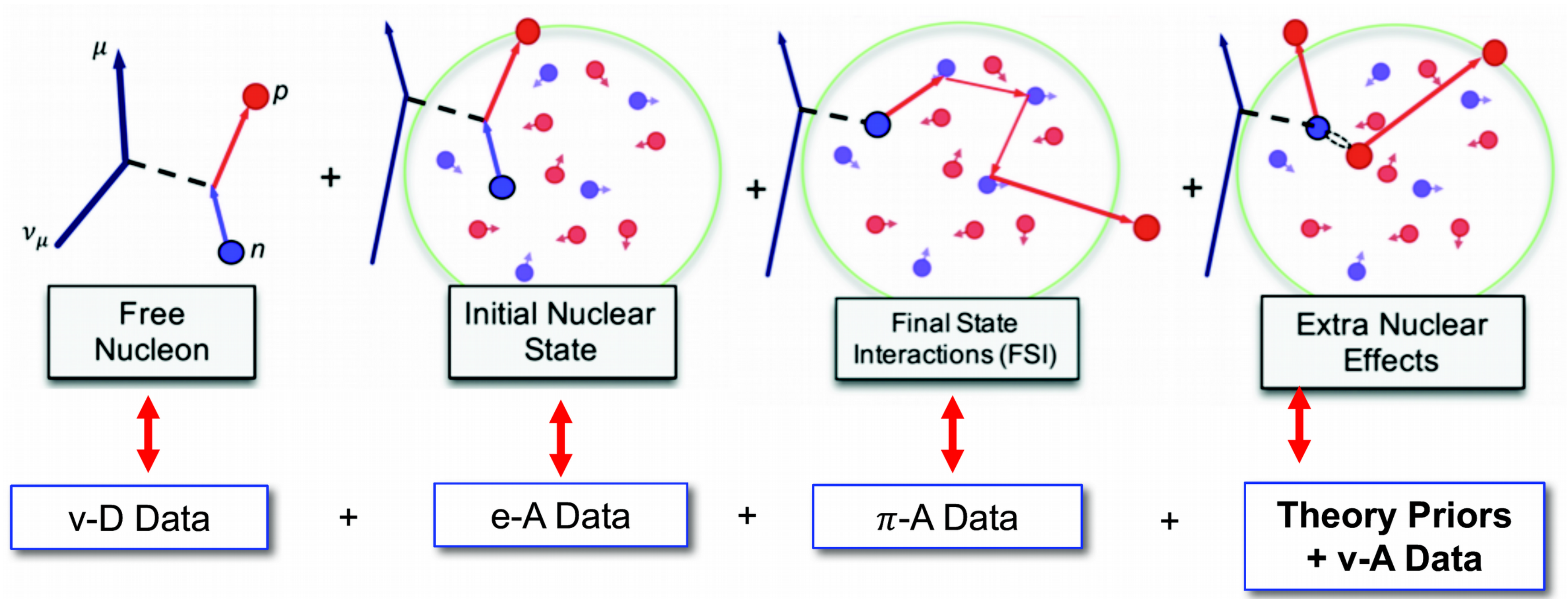
See PRD 072010 (2016) for the gory details!

Frankenmodels



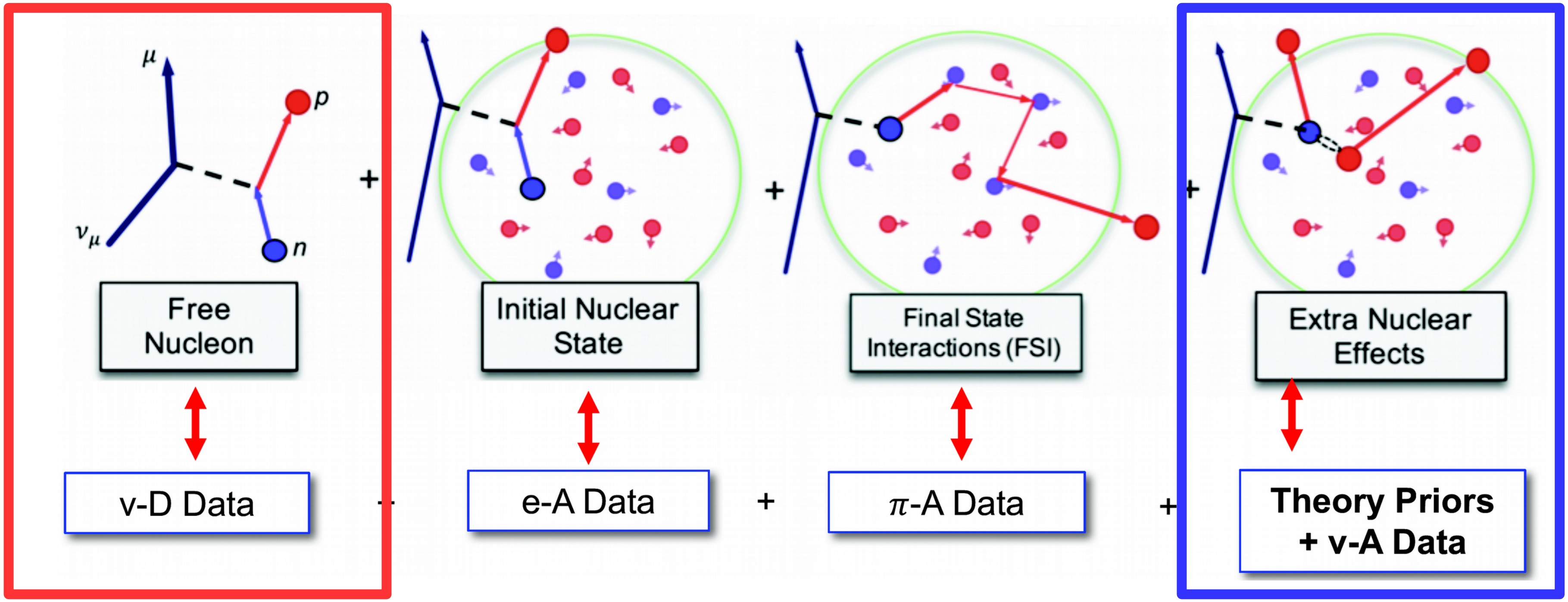
- Incomplete models lead to unphysical ***effective*** parameters (large axial mass!)
- Not always clear where the deficiency lies, need to change how we think
- Common issue for all neutrino experiments and model tunings!

New *modular* approach



- Tune different aspects of the model to ***appropriate data***
- Develop models in the generators (NEUT) to include new theory / fill in the gaps
- **Reminder: theory and generator expertise essential!**

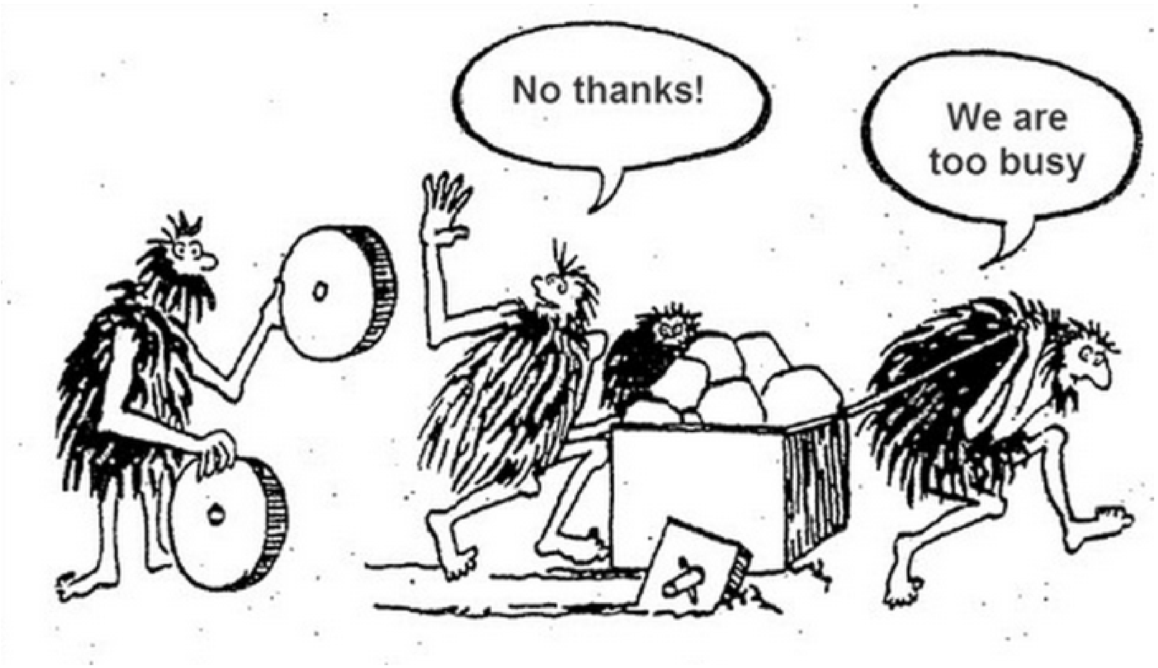
Current work



Tune fundamental interaction parameters to ν-N data

Compare tuned model to ν-A data and try to diagnose deficiencies

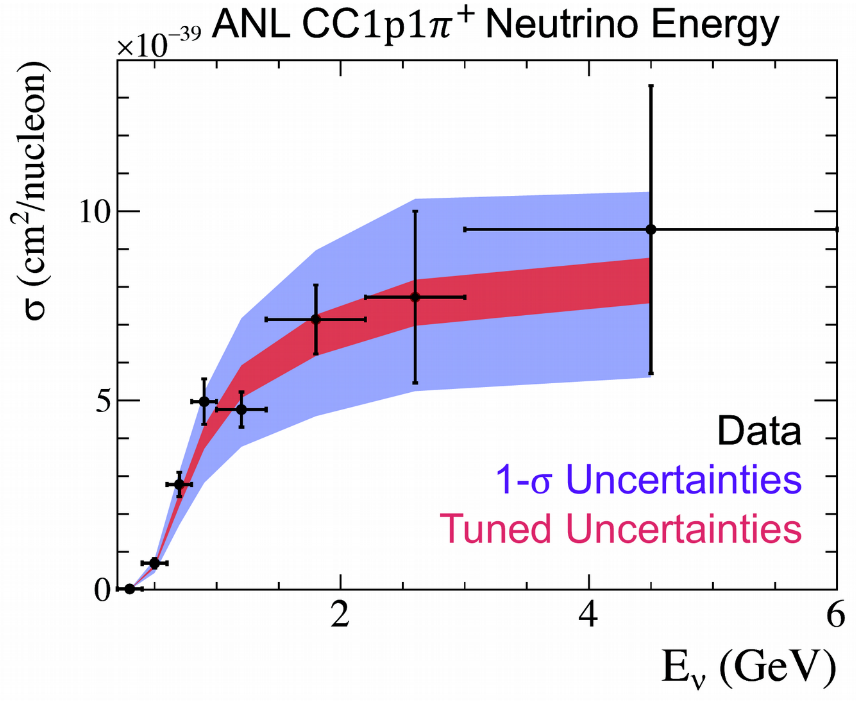
Reinventing the wheel?

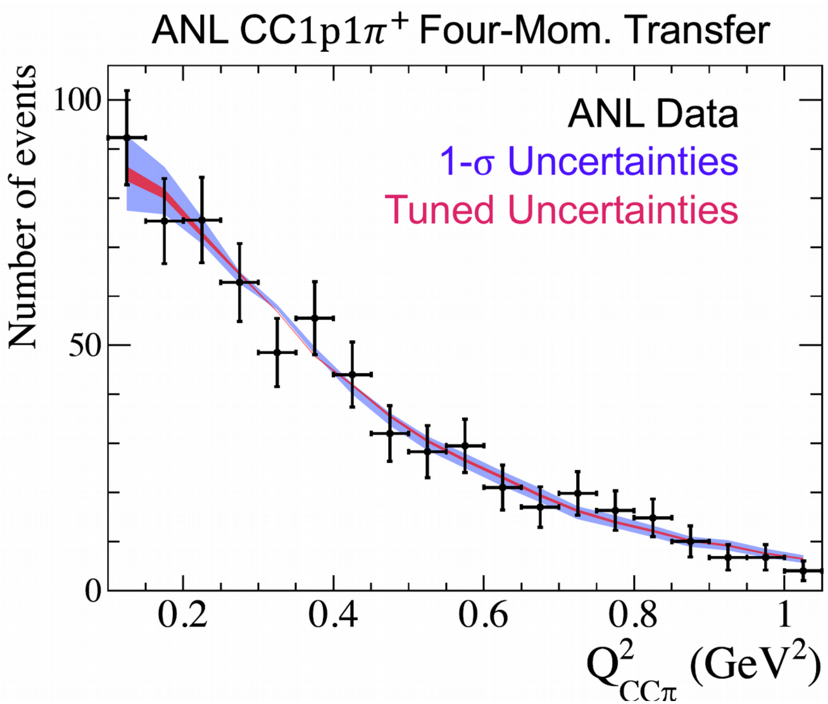


- Studies of ν-N data are nothing new… so why do them?
- Need to build up robust validation framework for the future → make sure there are no hidden issues
- Use all information available from early experiments

Single pion bubble chamber tuning

- Parameters tuned to a limited set of bubble chamber data:
  - ANL and BNL, E_ν and Q^2 distributions
  - $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^0 + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^+ + n$
- Then compared to all available distributions (many available!)





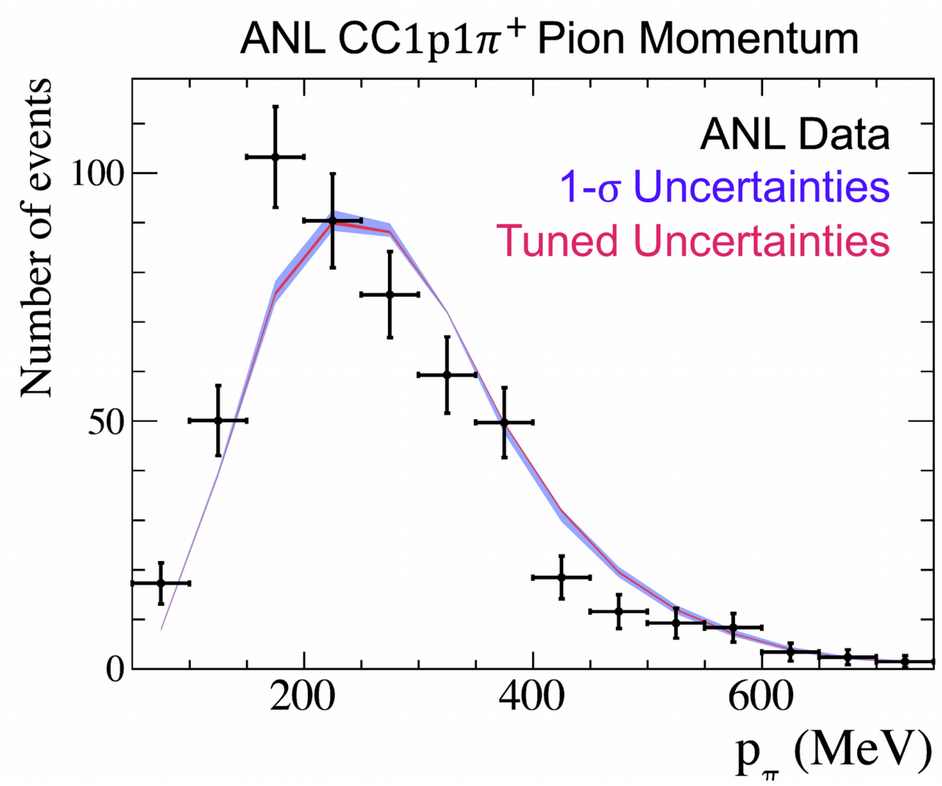
Single pion bubble chamber tuning

- Plan to update tuning with more datasets:

  NEUT, GENIE, *NuWro(?)*

(We would welcome help!)

- Not all ν-N/ν-D data can be well described by the NEUT model

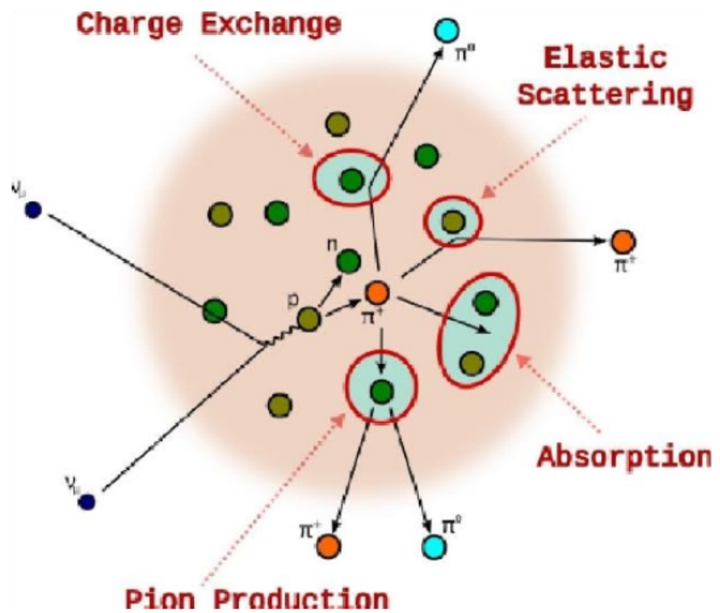


- Need to consider future model development / inclusion of more parameters to improve agreement with pion kinematic distributions.

Aside: NEUT FSI model

- Nucleons and pions undergo FSI before leaving the nucleus

- Introduces migration between topologies for ν-A data



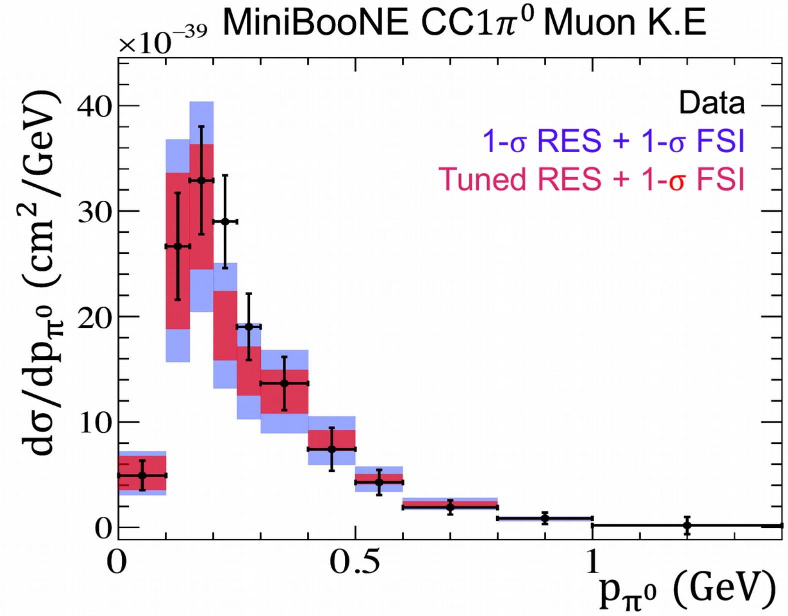
Future plan to include N-A and π-A scattering in NUISANCE

- Like most generators (except GiBUU) NEUT uses a simple cascade model

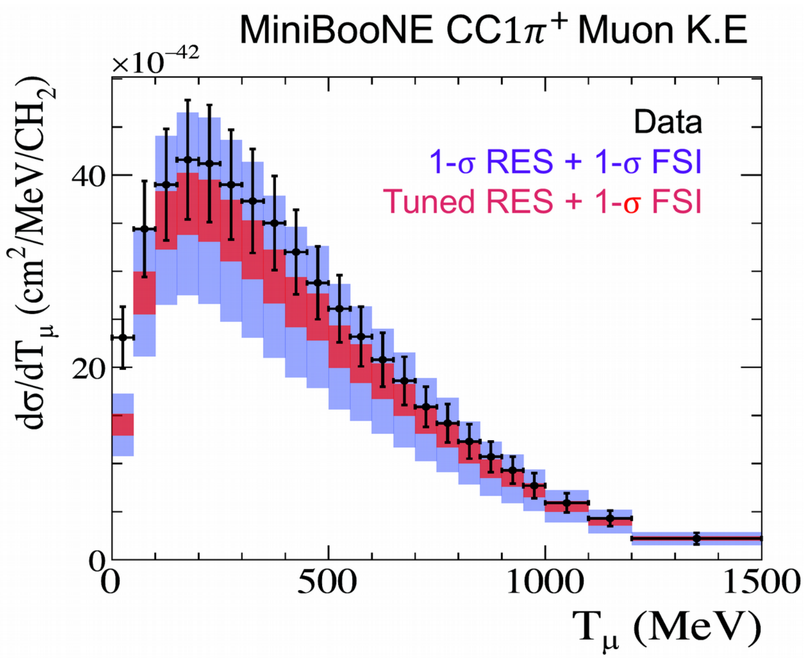
- Tuned to a large body of N-A and π-A scattering data (PRD D91 (2015) 072010)

Comparison with nuclear data

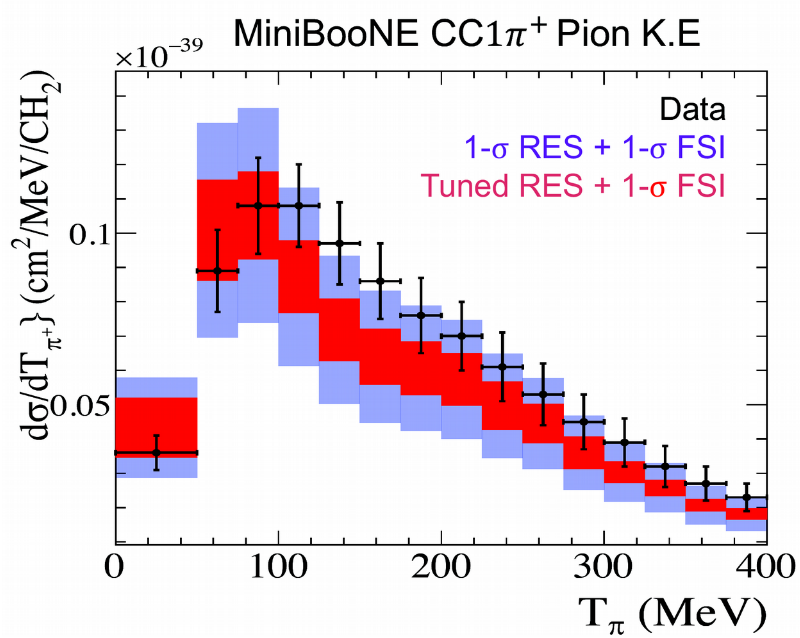
- Reasonable agreement with outgoing **muon kinematics**
- Not for pion kinematics. Inadequate FSI model?
  … but poor for ν-N data too!



MB ν_μ-CH_2 CC1π^0
PRD 83 (2011) 052009



MB ν_μ-CH_2 CC1π^+
PRD 83 (2011) 052007



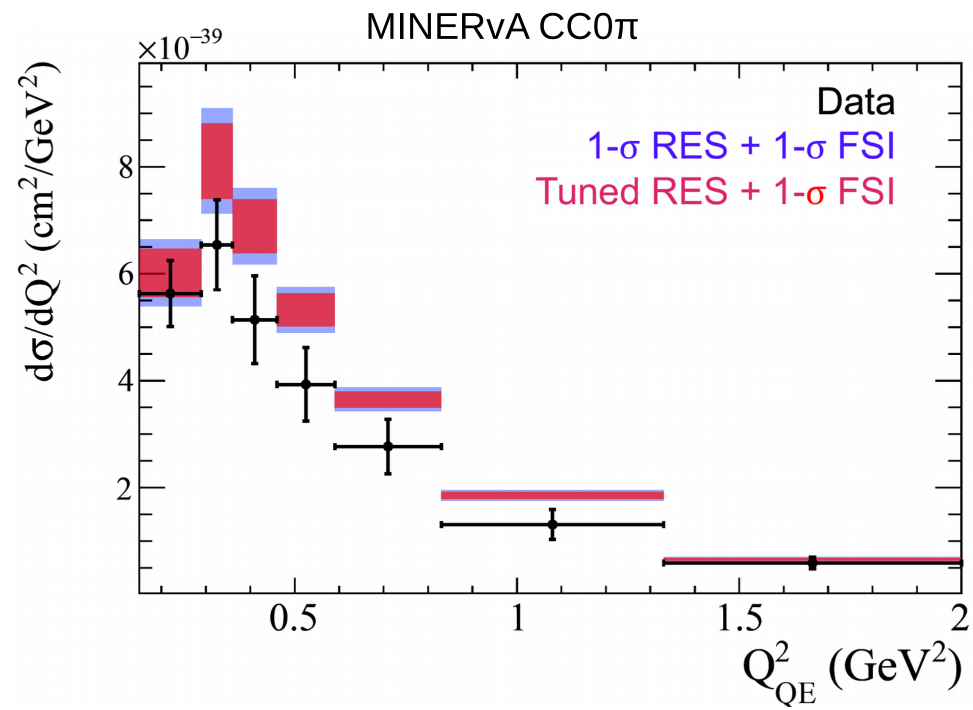
Lessons from single pion tuning

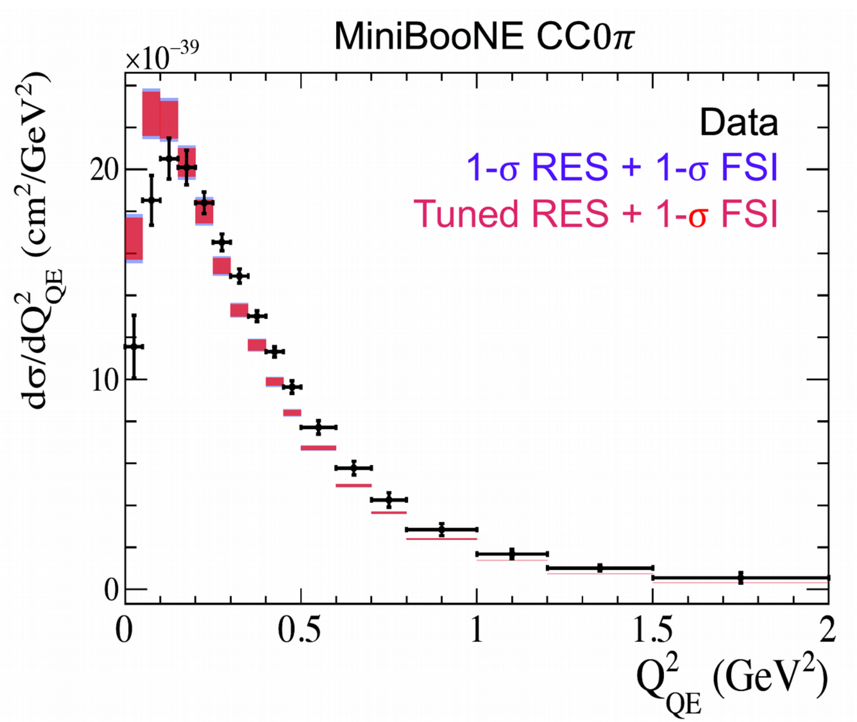
- Broad agreement between simple R-S model in NEUT and bubble chamber data in **muon kinematics**
- ν-A data also reasonably well described in **muon kinematics**
- Poor agreement with **pion kinematics** for both ν-N and ν-A data!
  - **<u>Interaction model improvements required!</u>**
  - FSI model might also be insufficient
- **Side note:** several possible **model dependence** problems with the ν-A data, unclear how to interpret disagreements.

Why can't I fit whatever I like?

- Tempting to fit ν-A data for individual topologies such as CC0π

- But they all depend on other interaction channels

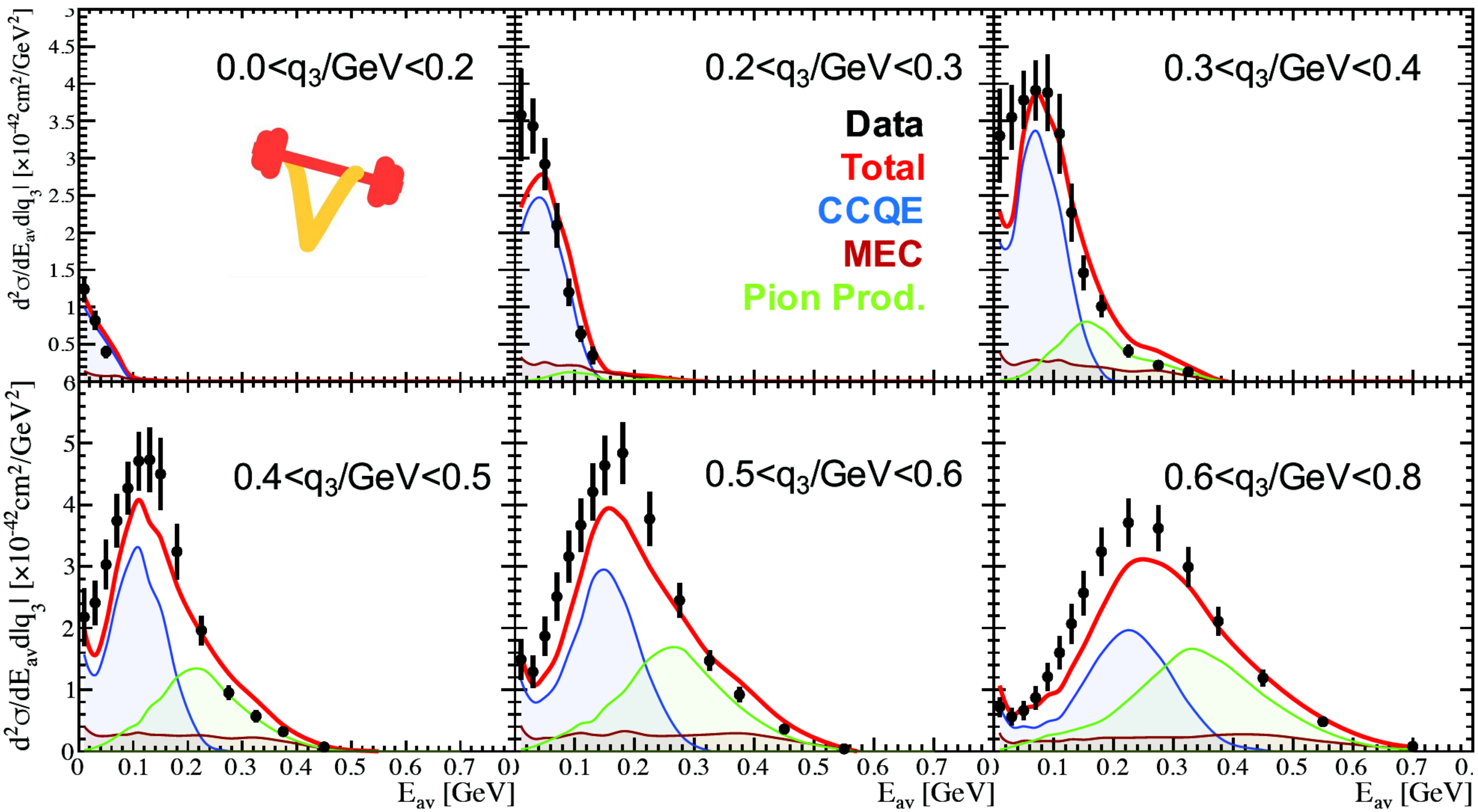




- Developing NUISANCE routines to marginalize over these as nuisance parameters

- Ultimate goal is a simultaneous fit to all data, but that's a lot way away...

MINERvA CC-inclusive



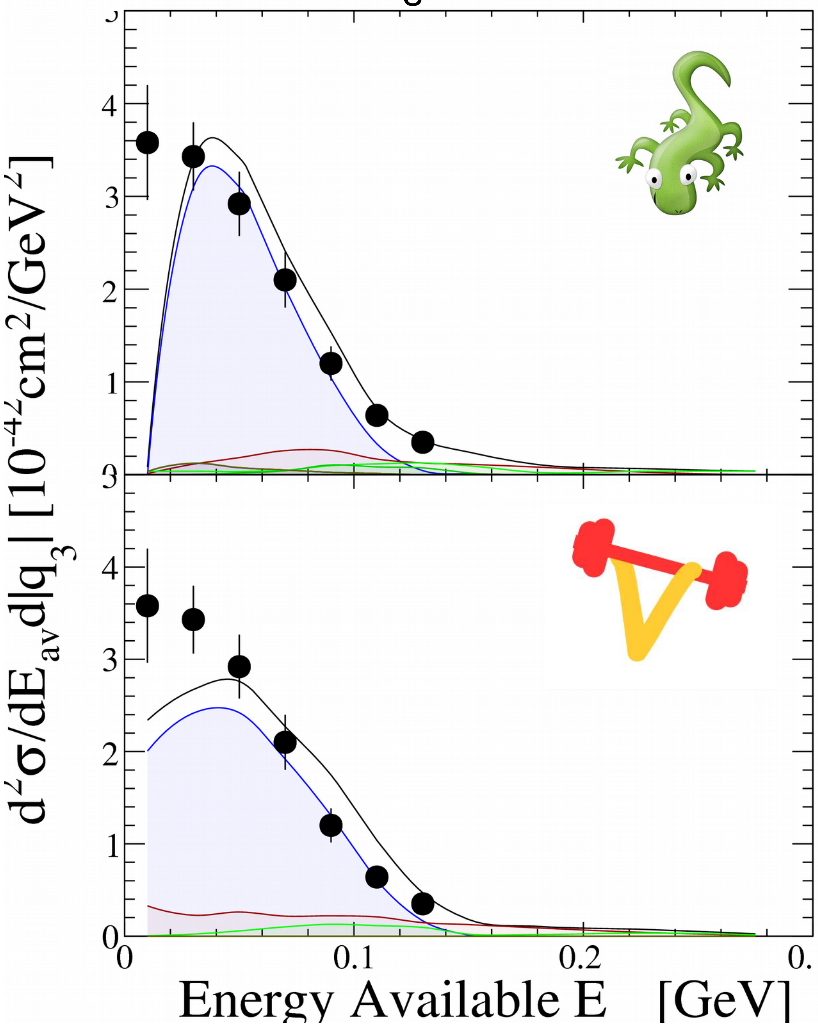
PRL 116 (2016) 071802

$$E_{av} = \sum_{i=p,\pi^\pm} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$

Is disagreement due to the CCQE model? MEC? Pion production?

MINERvA CC-inclusive

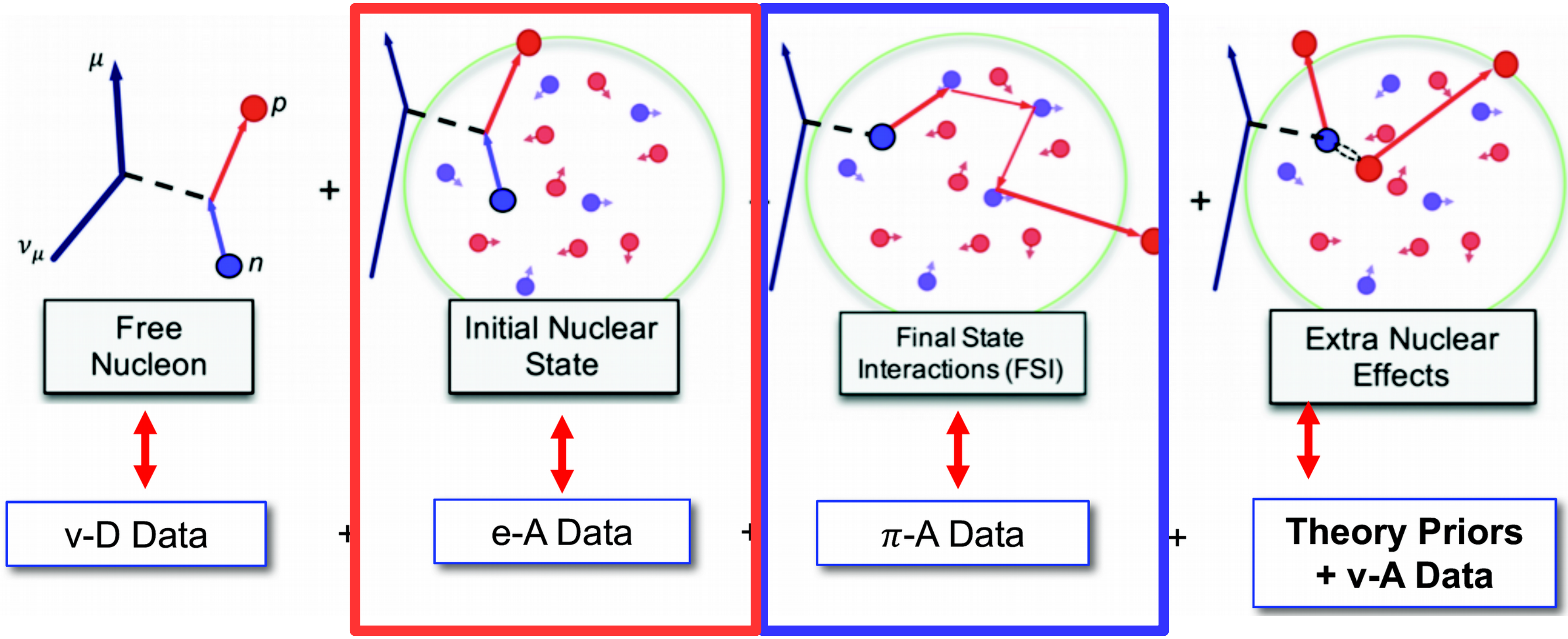
$0.2 < q_3/\text{GeV} < 0.3$



$$E_{av} = \sum_{i=p,\pi^{\pm}} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$

- Inclusive data can still highlight model deficiencies
- NEUT clearly deficient at very low energy transfers (QE-dominated)
- Difference in the nuclear model → motivated further NEUT development
- Limited use, but important cross check!

Future work



Starting to include e-A data, important validation for our models.

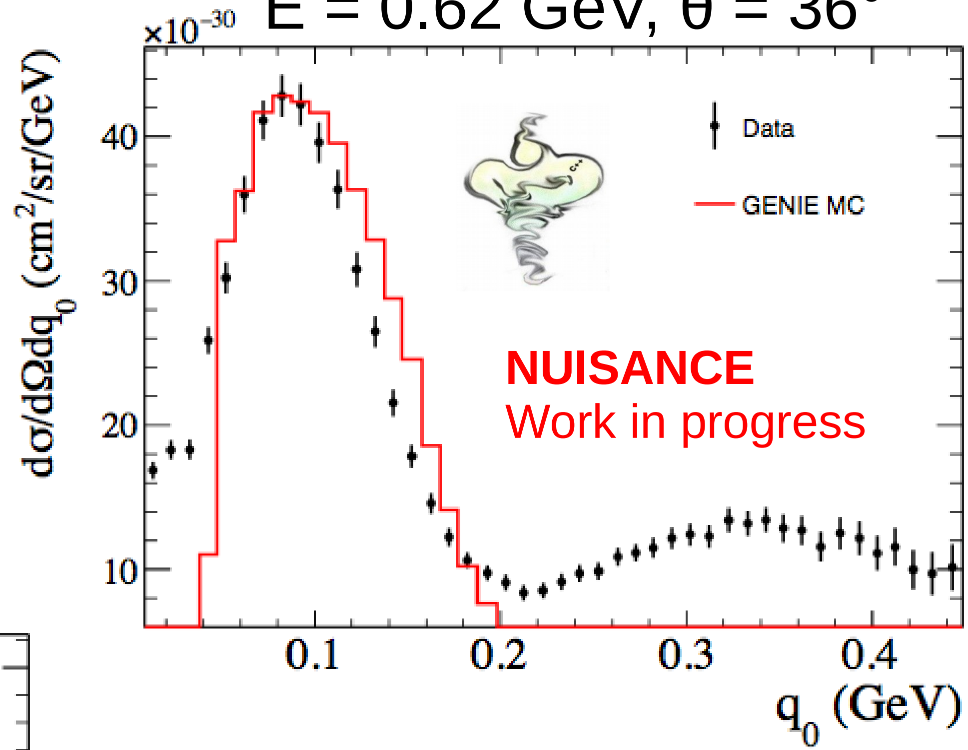
Currently, π-A and π-A comparisons done outside NUISANCE framework, plan on unifying in future.

Dependent on generator capabilities!

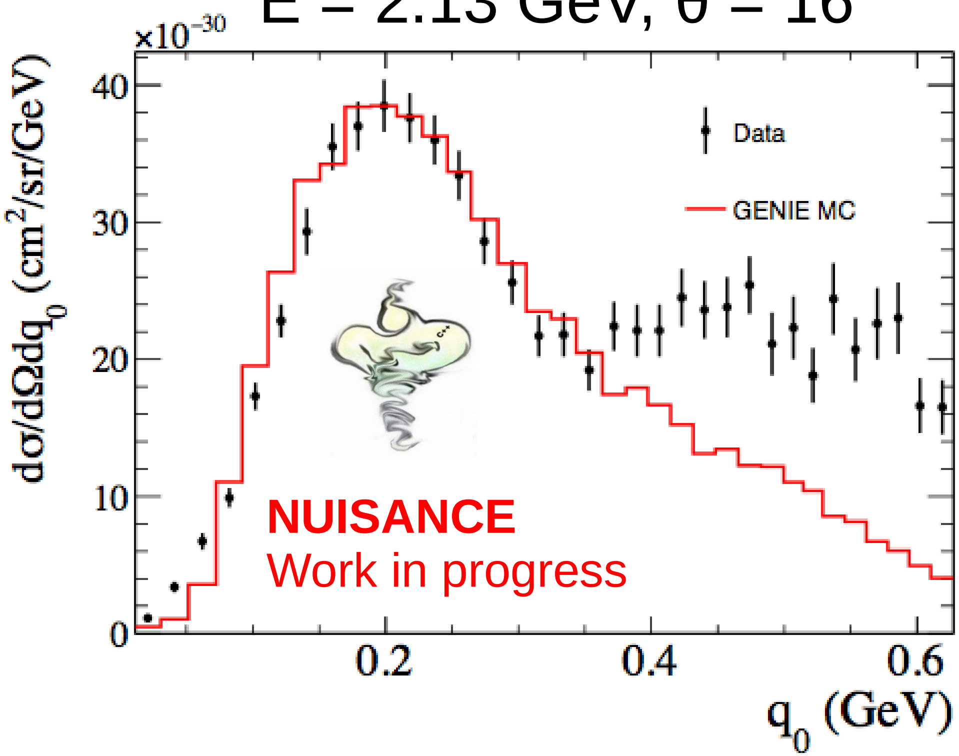
Electron scattering in NUISANCE

- Support for e-A in GENIE, GiBUU and eWro(?)
  Help very welcome!
- Currently only GENIE e-A in NUISANCE, but its easy to add other inputs

E = 0.62 GeV, θ = 36°

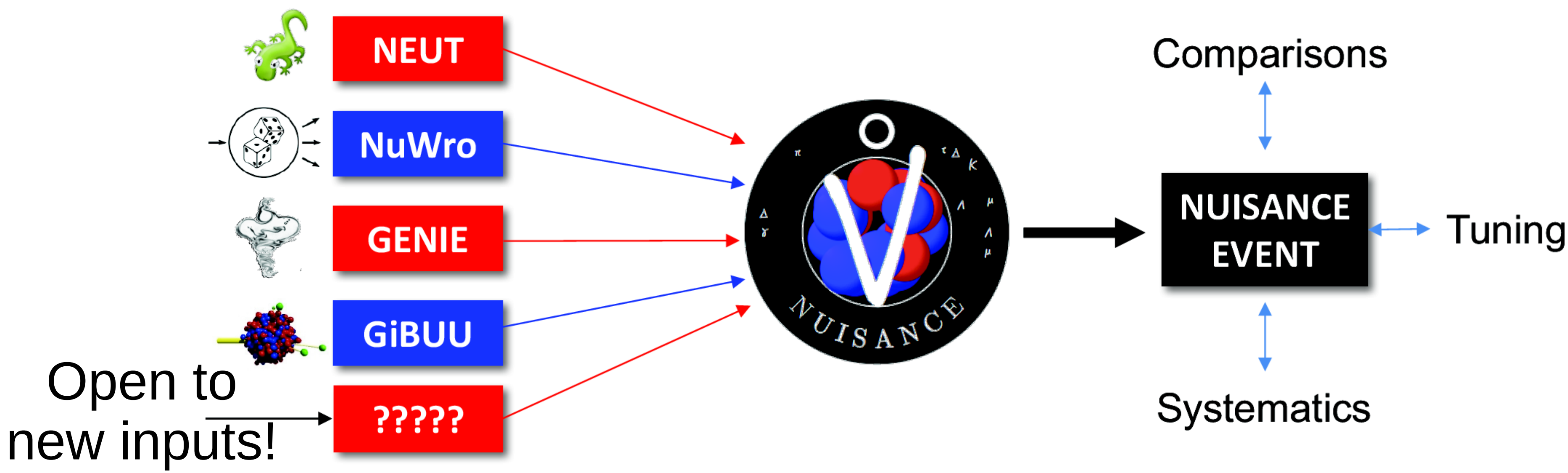


E = 2.13 GeV, θ = 16°



- Data taken from interface to Virginia QE e-A archive
- Shape-only, and very preliminary!

Alternative input formats



- Delay for new theory to enter generators limits use of NUISANCE
- Theorists/phenomenologists sometimes struggle to interpret data
- In collider world, tools like RIVET read events from text files, and apply relevant selection/smearing for data comparison. **More useful for theorists**
- We hope to encourage similar work through NUISANCE.

If you have strong opinions, please help!

Summary

- Constraining cross section errors is tough. Multi-parameter, many dataset fits are necessary, but very challenging
  - **NUISANCE:** new tool to help make model comparisons and tuning easier

nuisance.hepforge.org

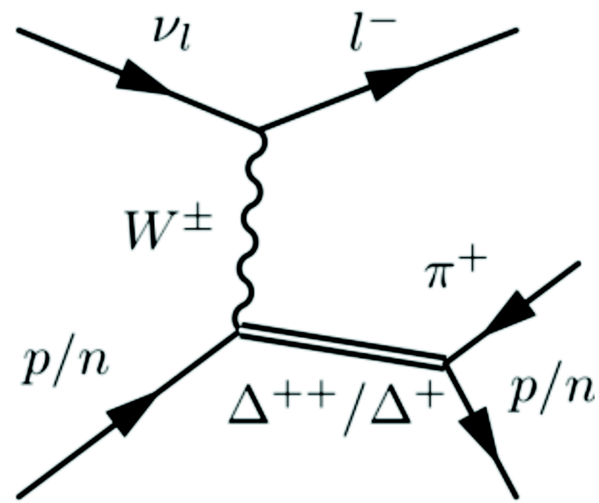
- ***Only a tool***, we ***need*** more theory and generator input to make worthwhile physics conclusions!
- ***Open source software***, so if it's useful for you, use it freely!
- **Very open to collaboration!**
  - e-A expertise required
  - Generator expertise necessary
  - Engagement with theorists/phenomenologists

nuisance@projects.hepforge.org

Backup

NEUT single pion production

- Modified Rein-Sehgal, similar to GENIE (AP 133 (1981))
- All 18 original resonances included, updated PDG branching fractions
- Includes lepton mass corrections



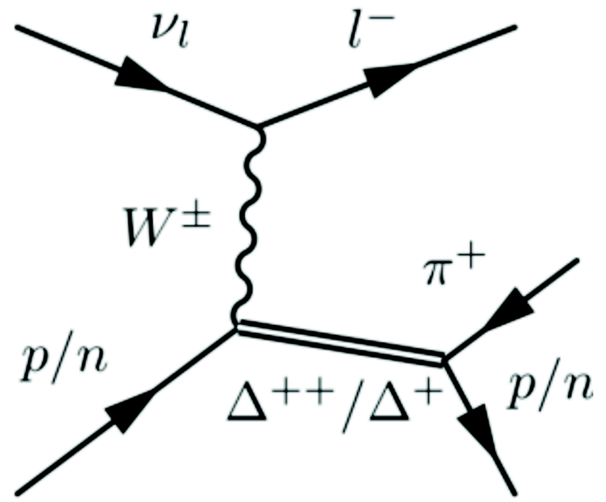
- Updated Graczyk and Sobczyk FFs (PRD 80 (2009) 093001)
  - Vector FFs tuned to e-A data
  - Axial dominated by C_5^A FF (N-Δ transition)

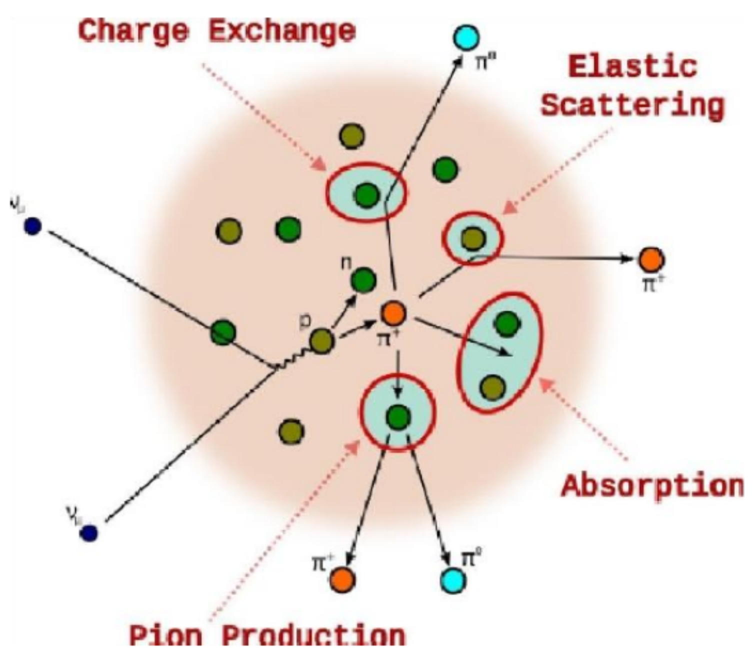
$$C_5^A(Q^2) = \frac{C_5^A(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

- Includes non-interacting Isospin-½ background from R-S

Final State Interaction (FSI) model

- Nucleons and pions undergo FSI before leaving the nucleus
- FSI for pions, nucleons, kaons, and etas are modelled, only pion FSI is currently *reweightable*





- Like most generators (except GiBUU) NEUT uses a simple cascade model
- Tuned to a large body of N-A and π-A scattering data (PRD D91 (2015) 072010)

Cross section model dependence

The signal definition and background subtraction can be model dependent

Some unfolding methods introduce bias

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

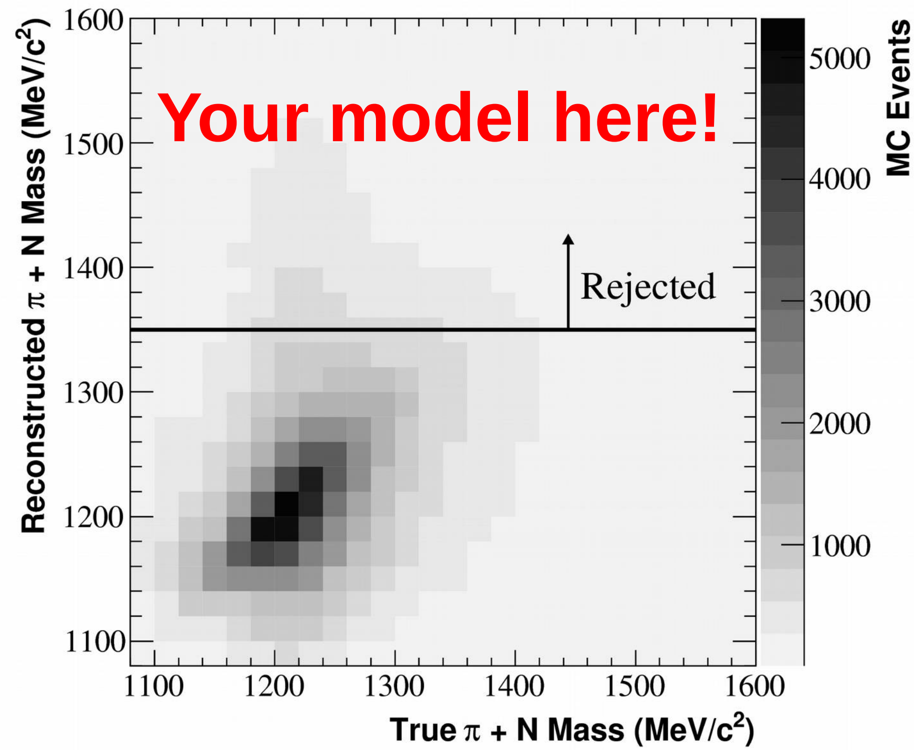
Choice of variables

Efficiency corrections couple to model in complex ways

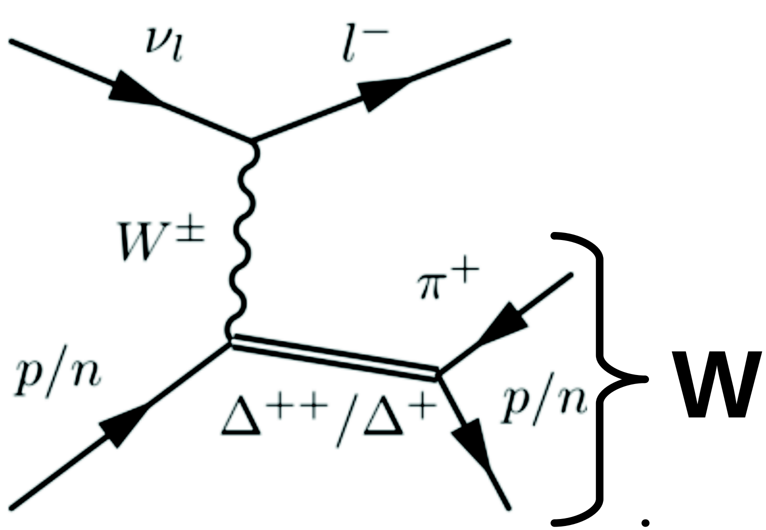
MiniBooNE CC1π^+

- Cut made on reconstructed invariant mass, but not reflected in signal definition

- ~30% correction to published cross section comes from MB MC.

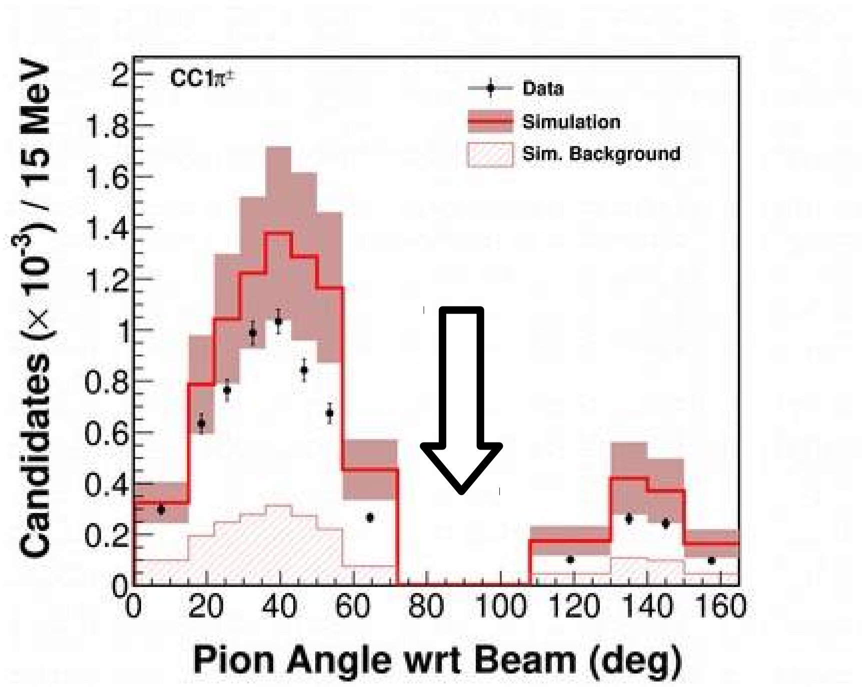


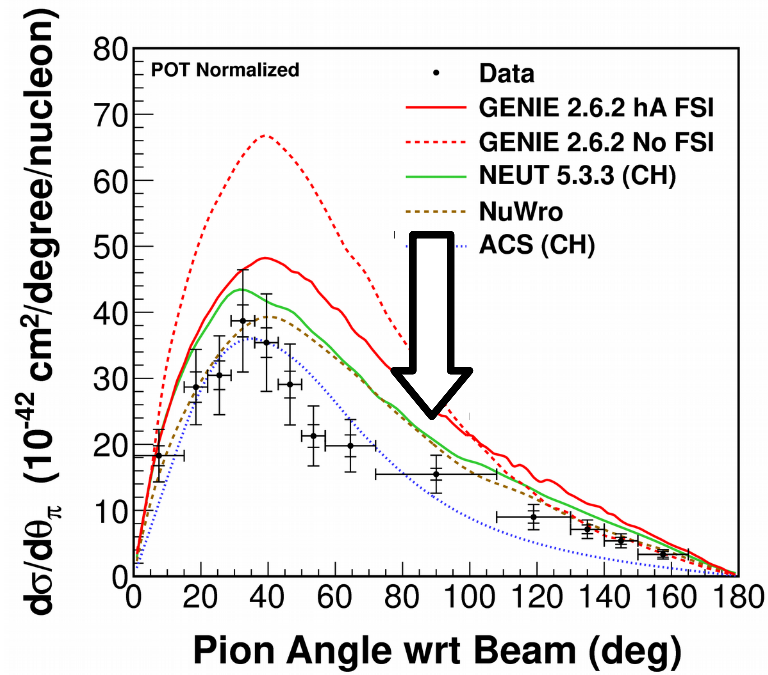
PRD 83 (2011) 052007

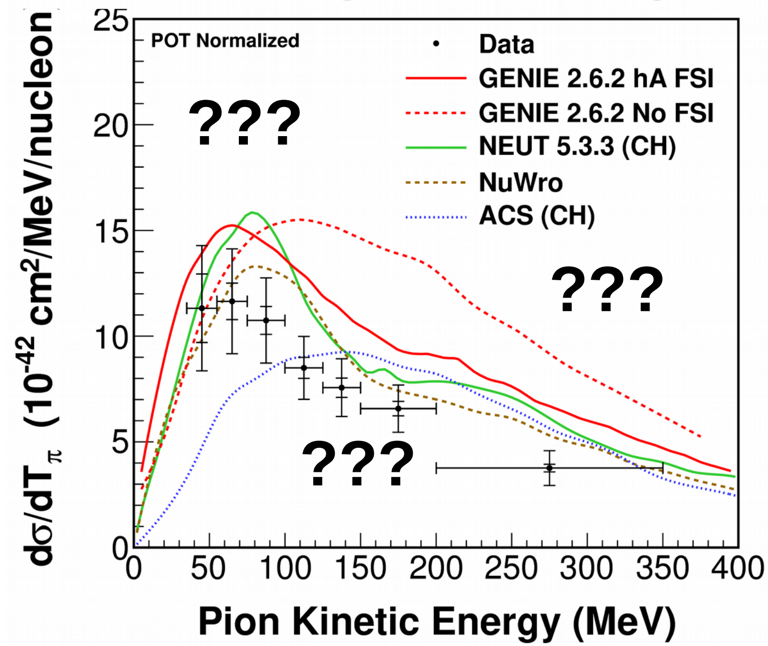


- Cannot assess where this bias lives… it might dominate some kinematic bins.

MINERvA CC1π^+







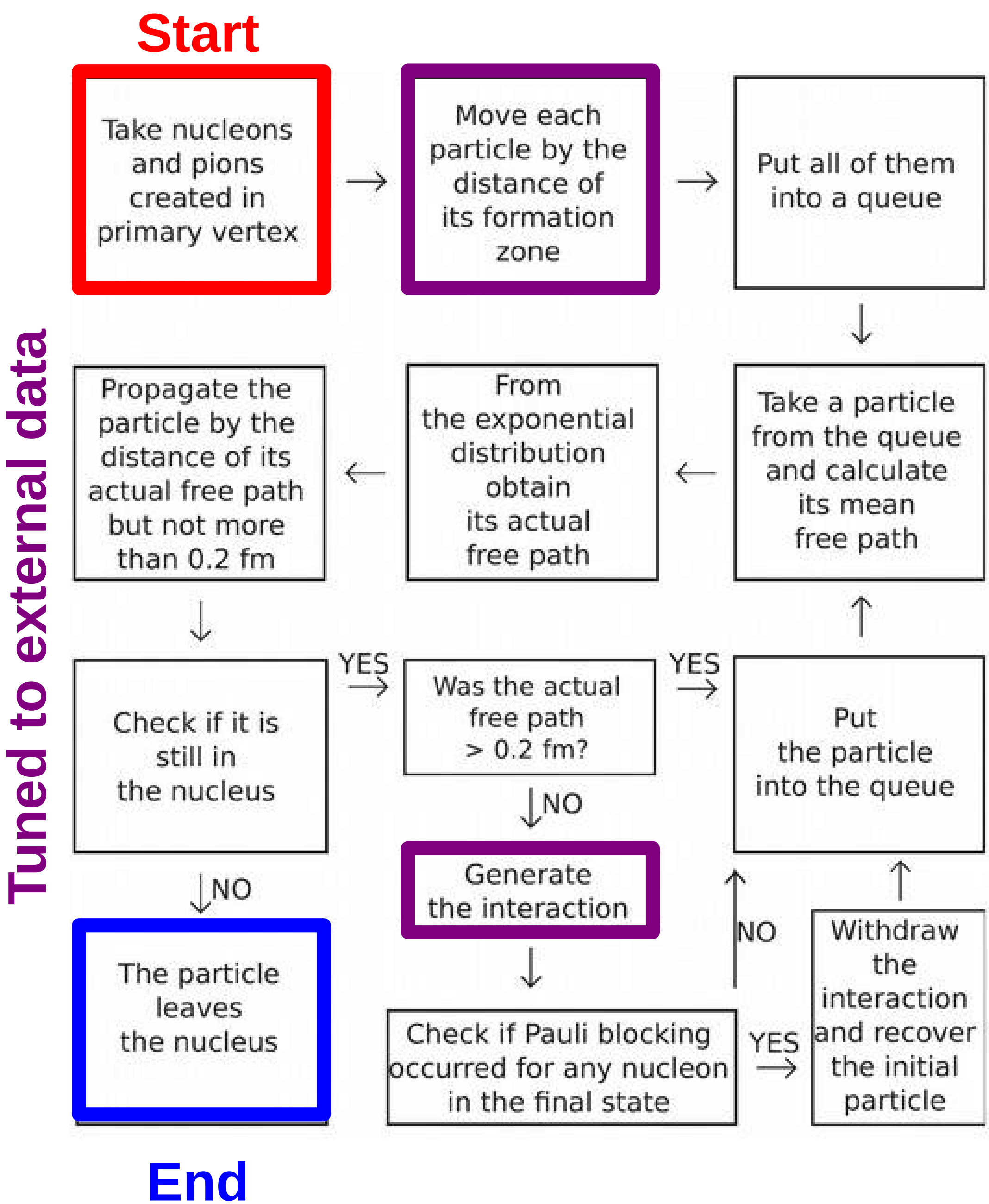
PRD 92 (2015) 092008

- One angular bin is filled in with MC.
- Unclear where this correction affects the pion KE spectrum.
- Hard to interpret as a result.

Model dependence

- Most results which have been published use methods which suffer from some model-dependence.
  - Possibly unavoidable! And things are improving a lot
  - Discussed at many workshops etc, so likely to keep improving
  - Implementing new models in generators is critical
- Important for current/future OA experiments to be aware of the problems with cross section datasets.
- Important for cross section analyzers to be aware of the possible pitfalls and make their results future proof!

Cascade model



Neglect interactions between outgoing particles, propagate each individually (except for GiBUU).

Formation zones are motivated by data (high E, high Q^2). Interaction cross sections suppressed after production.

- NuWro: all modes
- GENIE & NEUT: DIS only
- Others: no formation zone

Re-interactions depend on local density of the nucleus.

NUISANCE: basic structure

Measurement classes

Input data: values, covariance,...

Signal def.: particle content, any kinematic restrictions

Basic functionality handled in base classes: event loop, filling histograms,...

Input handlers

Convert input MC to common flat format.

No knowledge of input MC required for anywhere else in the software

Core

Parse user defined input from cards, parameter file and command line.

Interface between the requested routine and the measurement classes.

Fitting classes

Evaluate joint likelihood for all distributions of interest.

Interface between ROOT fitting routines and generator reweighting classes.