A bit of a NUISANCE: constraining neutrino cross section systematics

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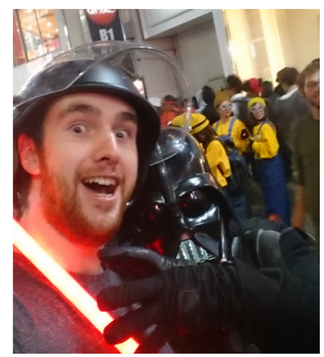
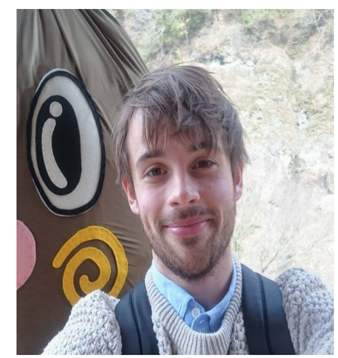

T2K

NUISANCE

UNIVERSITÄT BERN

AEC
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FOR FUNDAMENTAL PHYSICS

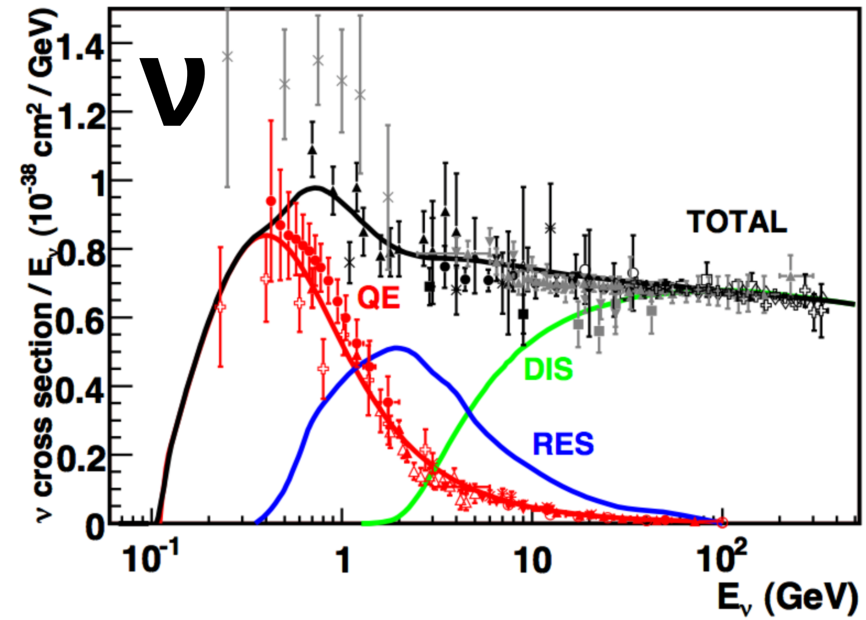
Introduction

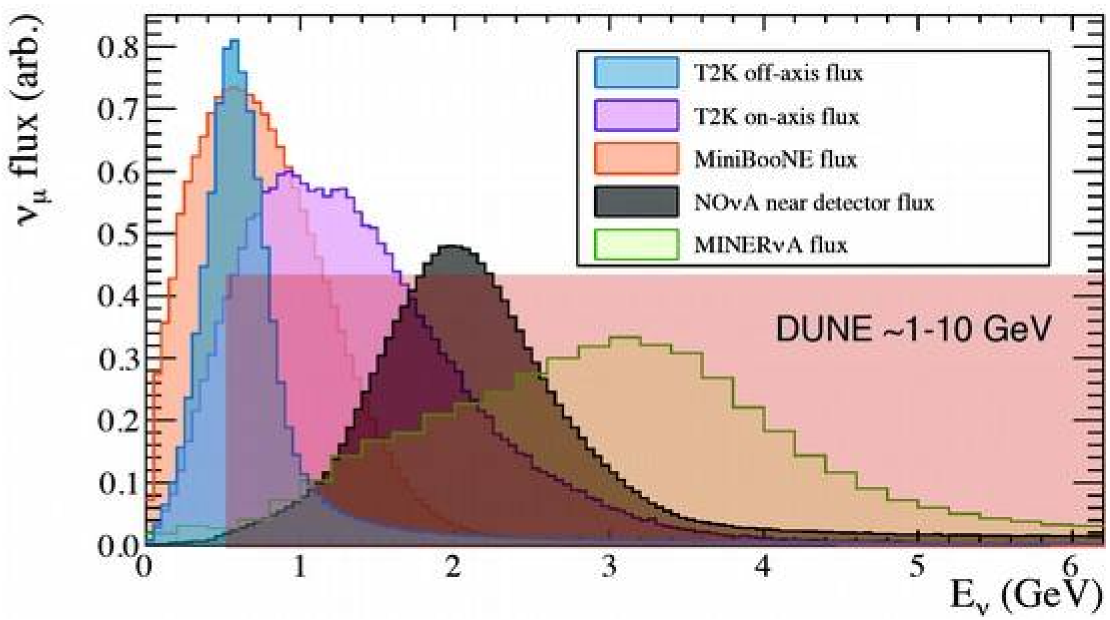
- Importance of cross sections for oscillation analyses
- The NUISANCE framework for tuning and comparisons to cross section data
- T2K approach to constraining the cross section model:
  - Early days, more questions than answers!
  - Single pion production as an example

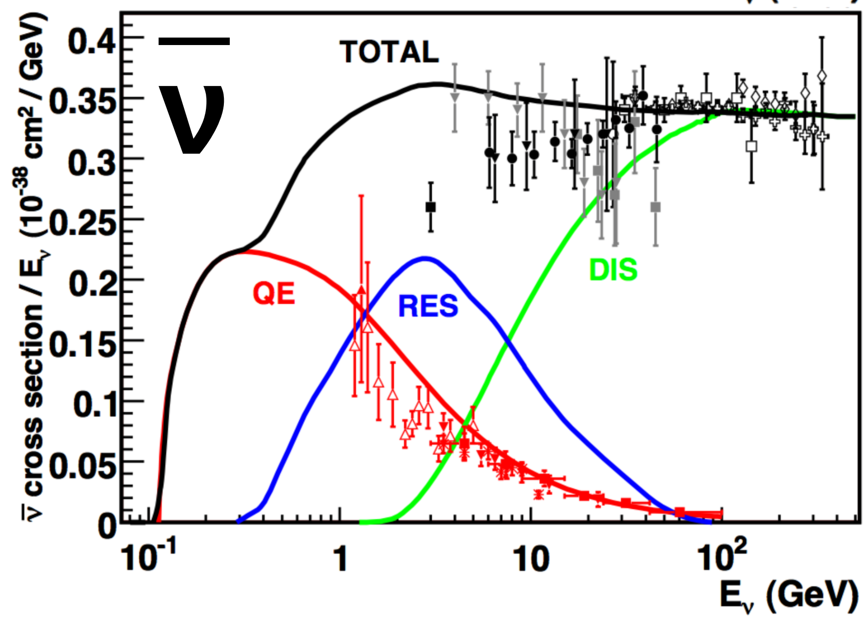
Cross section basics

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

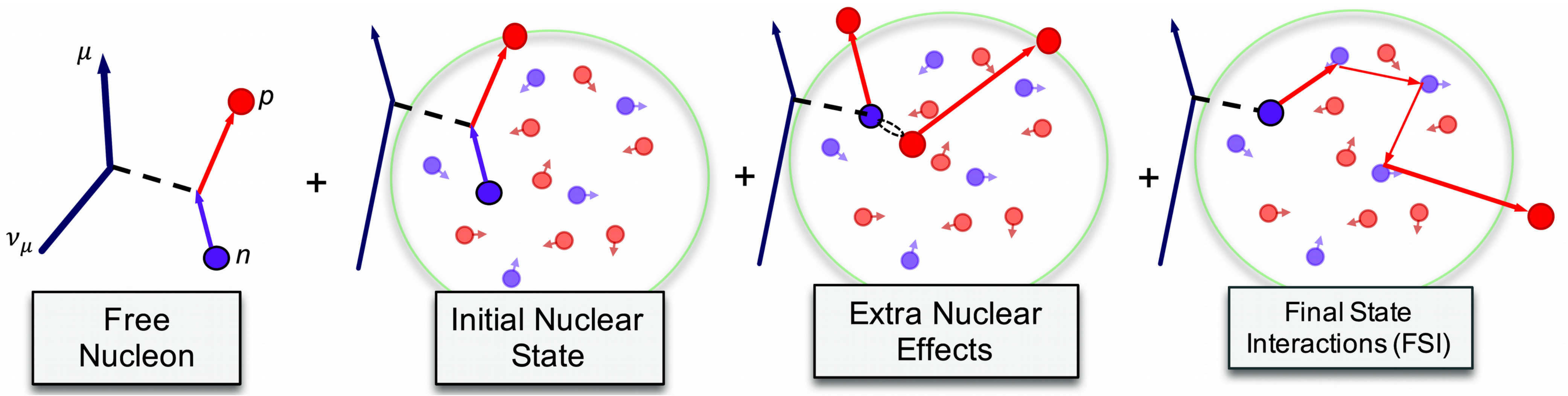
Multiple models required with different physical assumptions.







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

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

- **Event rate; Neutrino flux; Cross section; Detector smearing; Oscillation probability.**
- Near/far E_ν spectra are different (no $\sigma(E_\nu, \overline{x})$ 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.

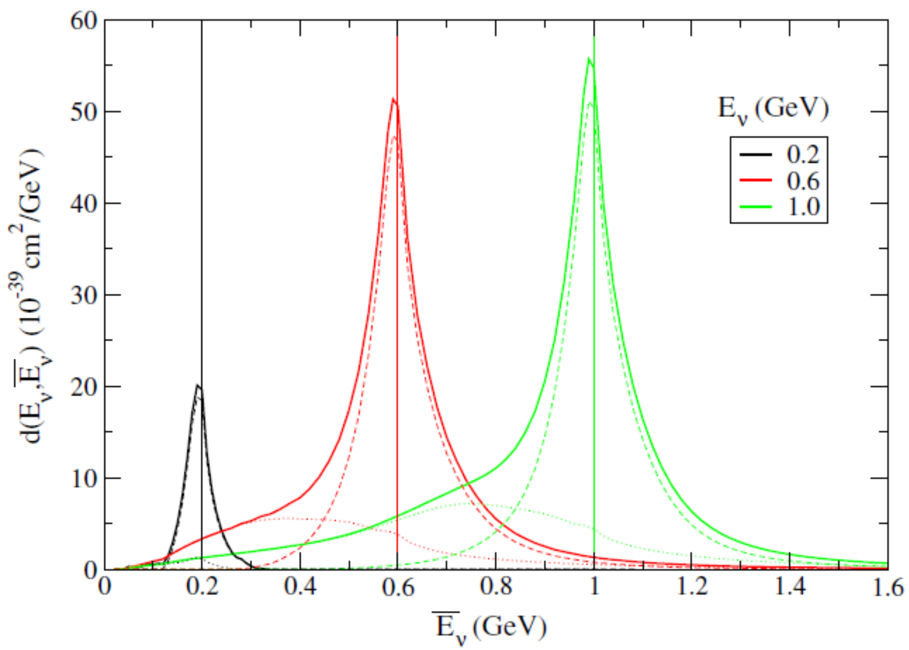
Importance for oscillation analyses

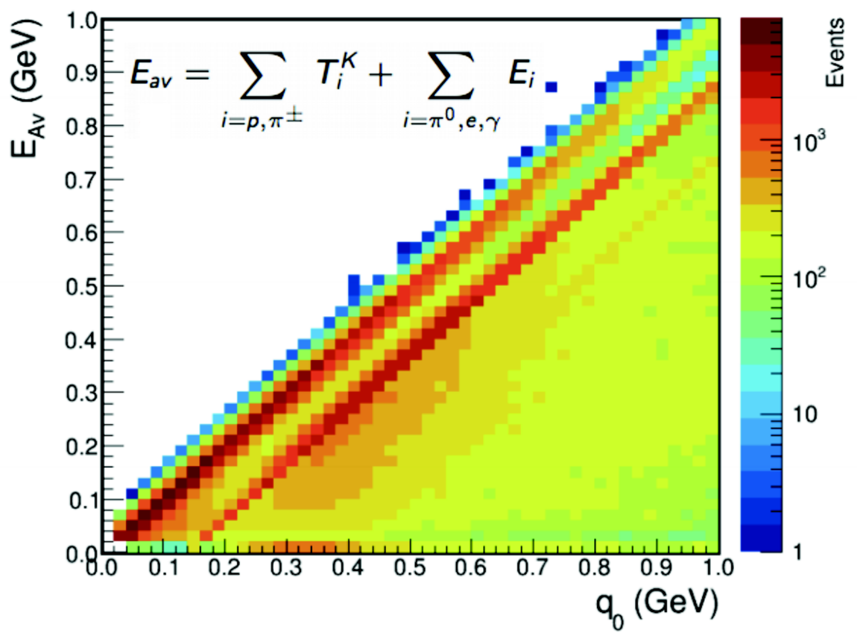
- We have to use a cross section model to infer the neutrino energy from the observed events.
- Can use **leptonic** or **hadronic** information:

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

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

PRD 87 (2013) 013009





What can we actually measure?

$$R(\vec{\mathbf{x}}) = \sum_i \int_{E_{min}}^{E_{max}} dE_\nu \;\; \Phi(E_\nu) \times \sigma_i(E_\nu, \vec{\mathbf{x}}) \times \epsilon_i(\vec{\mathbf{x}})$$

- **Event rate; Neutrino flux; Cross section; Detector smearing**
- Many initial interactions, σ_i, contribute, each with a different efficiency, ε_i
- Integrated over a broad neutrino flux and over all detector targets
- ***x*** are not interaction level variables, generally it's only possible to measure final state particle kinematics.

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

What can we actually measure?

- Only ***topological* cross sections** are independent of a model:

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

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

- Need to integrate out all degrees of freedom other than ***x***. **FSI** makes this integral difficult/impossible analytically
  - Direct theory comparisons to data are difficult
  - Require Monte Carlo generator to do integrals numerically

Monte Carlo generators

- Several MC generators under active development:

  GENIE, NEUT, NuWro, GiBUU

- Arguably each has different advantages, and have been developed separately, but many similarities between models

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

- Difficult to use all generators consistently, which means we aren't testing our analyses/data against all the models we can

- It would be nice if we could easily compare data to all of the generators!

NUISANCE

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

GENIE, NEUT, NuWro, NUANCE, GiBUU

- Grew out of the T2K work external data comparisons studies. Now the main analysis tool for tuning cross section uncertainties on T2K

- Open source software (GNU GPLv3)

nuisance.hepforge.org

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.

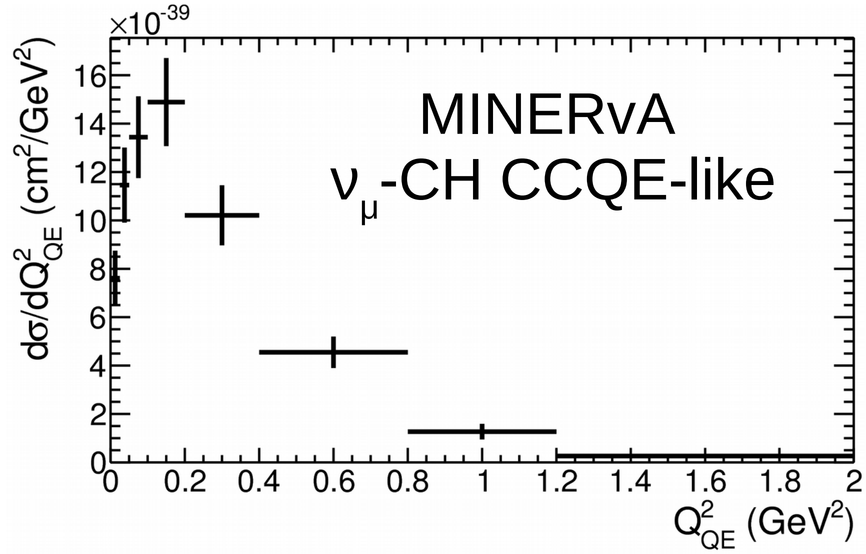
NUISANCE: adding a measurement

Input data: histogram and covariance from data release

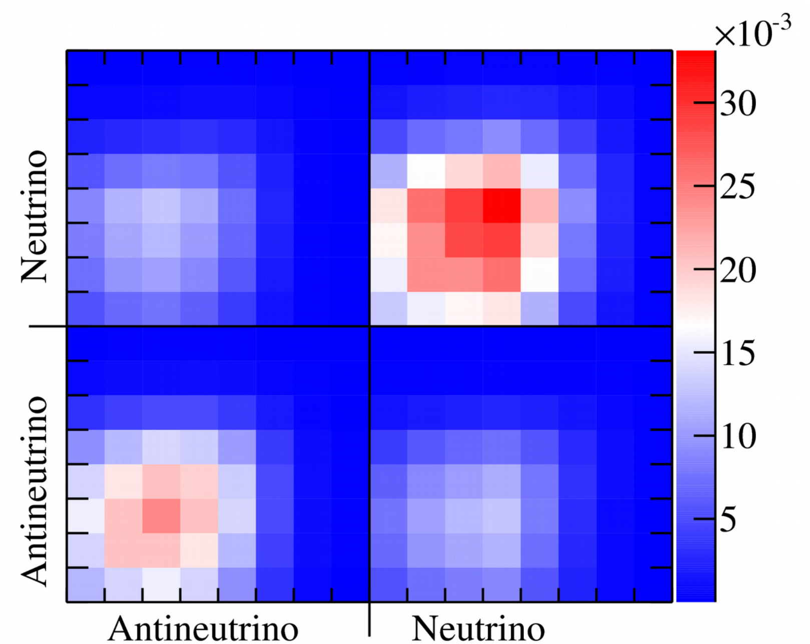
Signal definition:
- Selected particle content, e.g., $1\mu^-$, 0π, ...
- Phase space restrictions, e.g., $\theta_\mu < 20°$

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

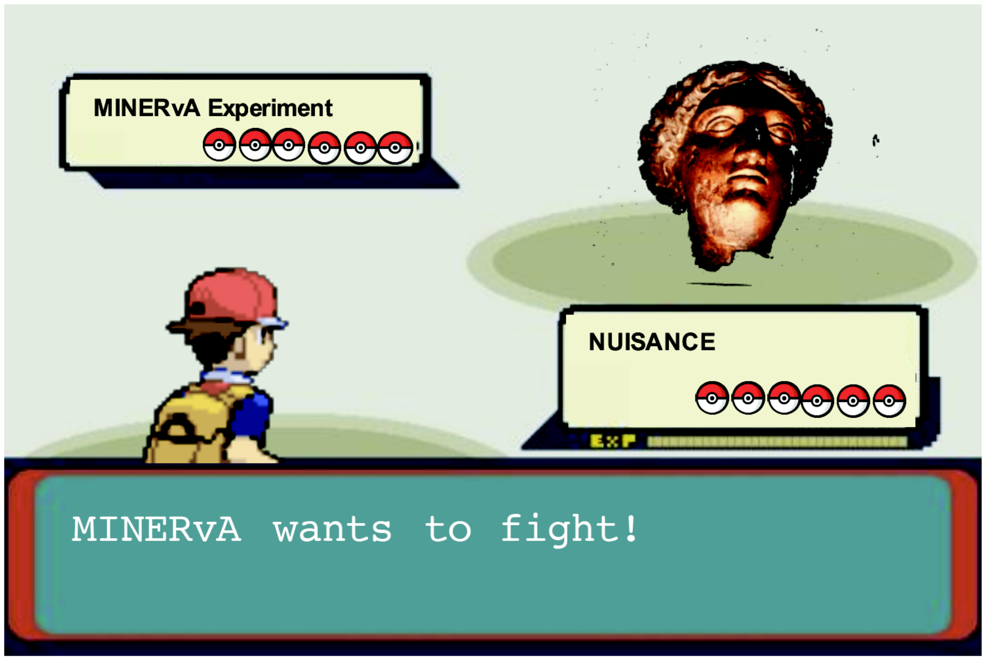
Additional support:
- Smearing matrices
- Ratio measurements
- Shape-only (floating norm)

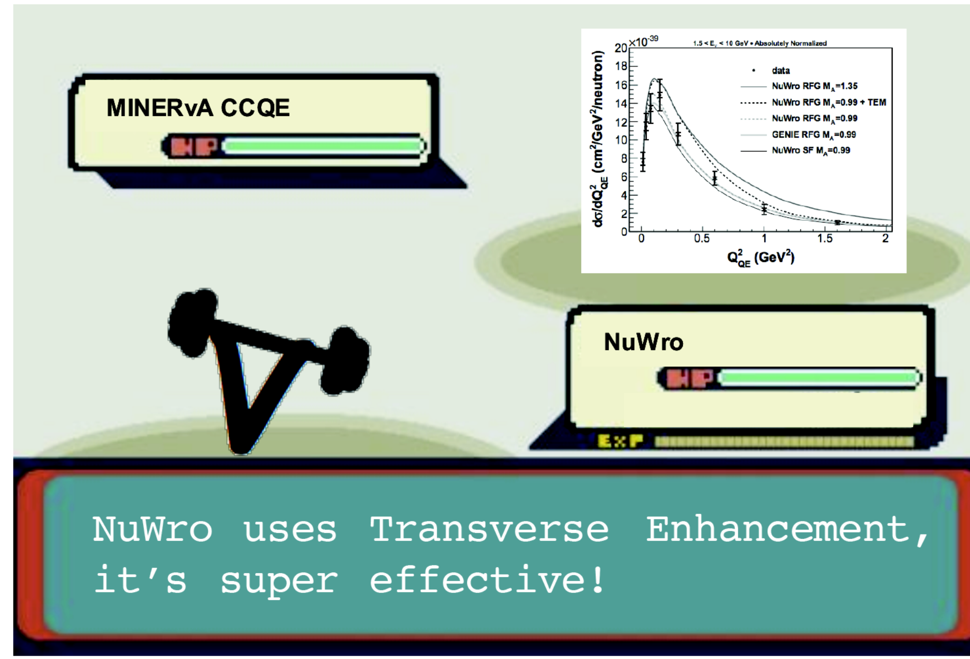


PRL 111:022502 (2013)



NUISANCE: adding a measurement





That's all that's required!

Ready for any generator, and any NUISANCE routine!

The (reweightable) players

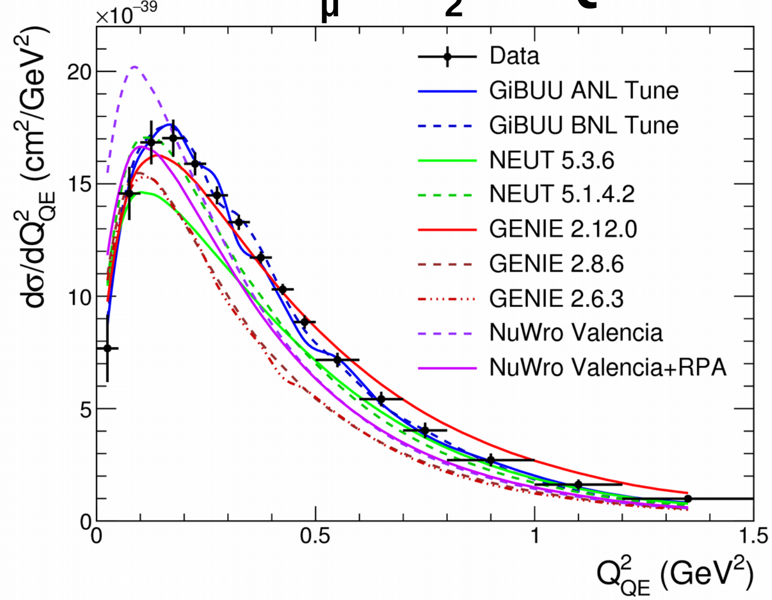
NuWro
(v12)

GENIE
(v2.12.0)

NEUT
(v5.3.6)

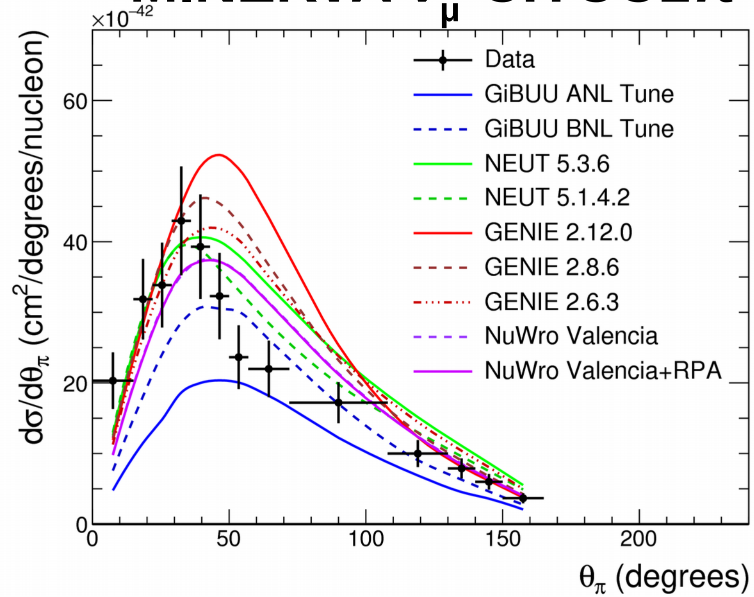
NUISANCE comparisons

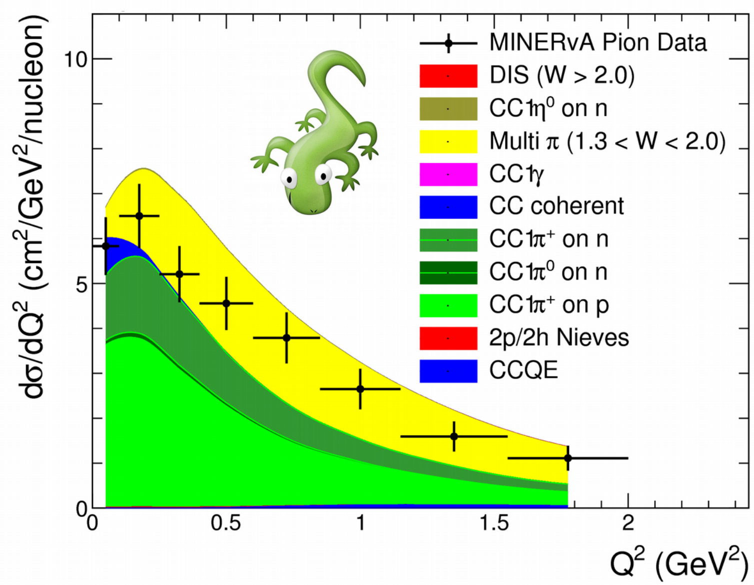
MB ν_μ-CH_2 CCQE



PRD 81 (2010) 092005

MINERvA ν_μ-CH CC1π^+

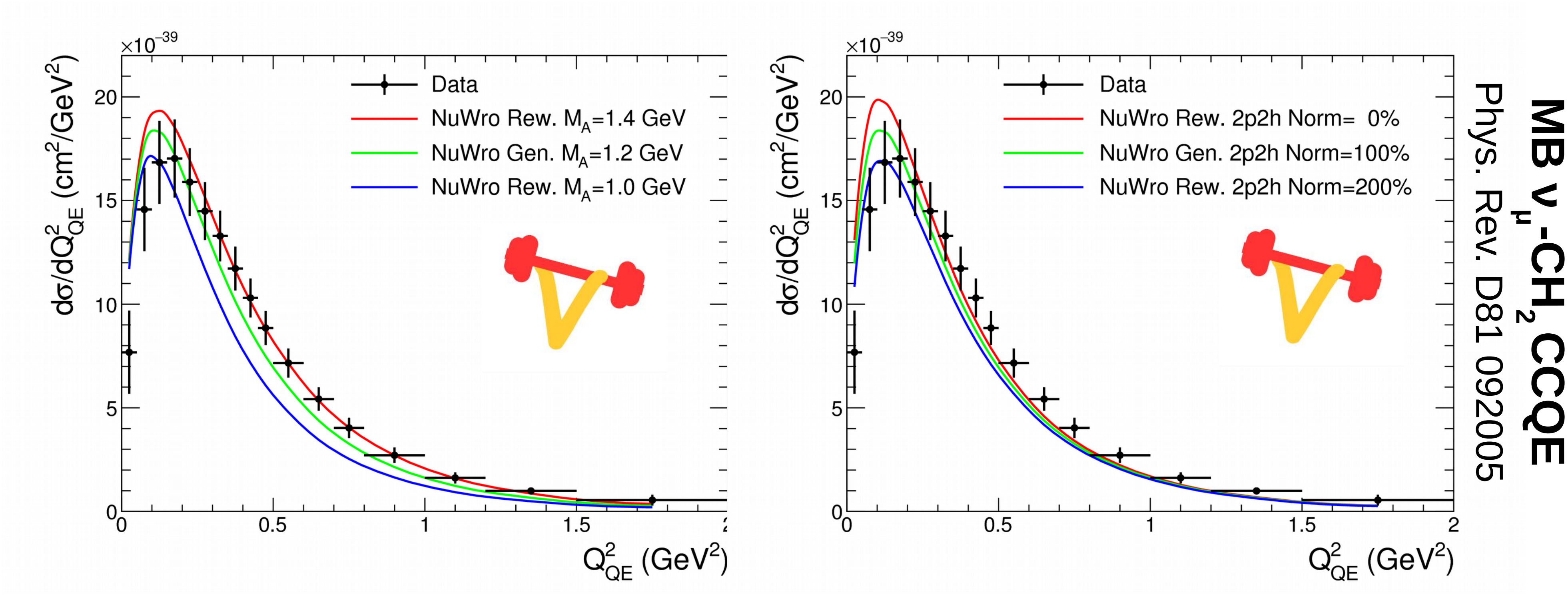




PRD 92 (2015) 092008

- Simple to compare any generators to any dataset
- No detailed generator knowledge required
- All comparisons can easily be done by one person

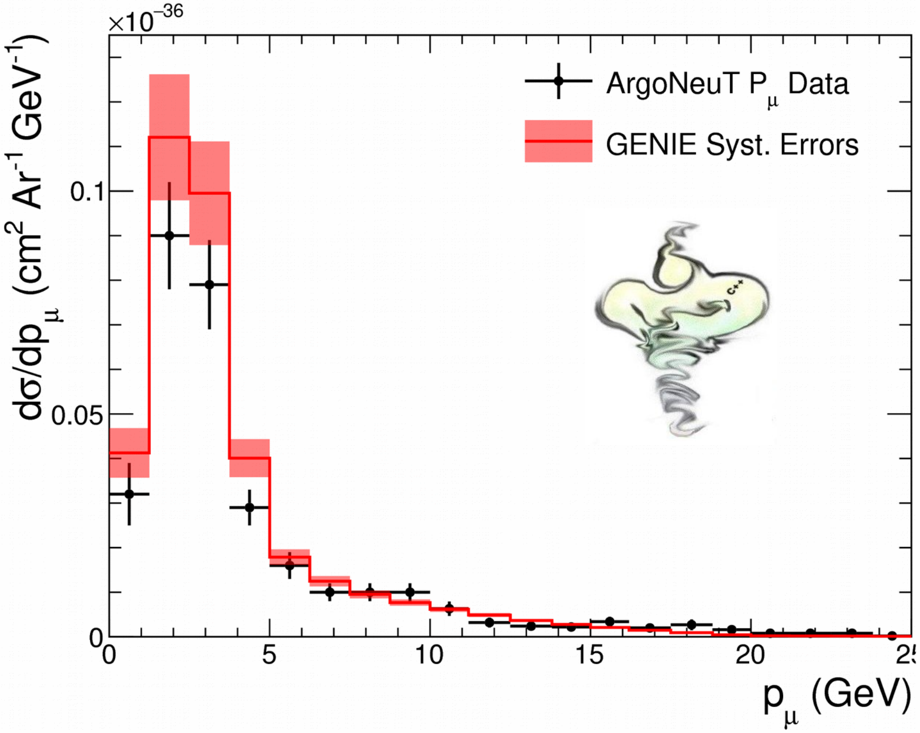
NUISANCE validation (1)

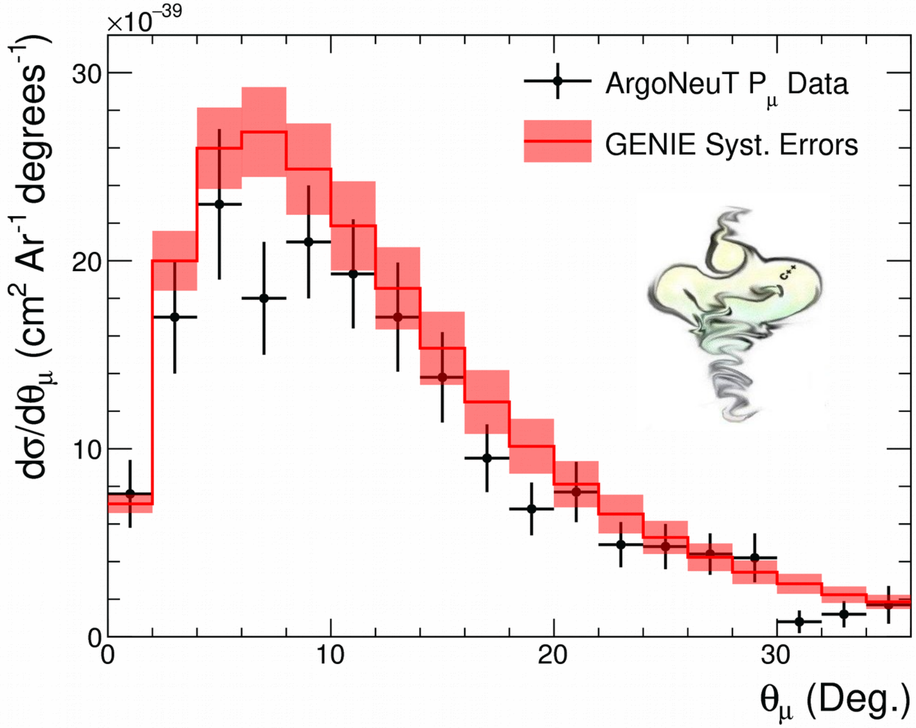


- Interfaces with the generator reweighting packages:
  GENIE, NuWro, NEUT

- Provides tools for some simple validation studies.

NUISANCE validation (2)





PRD 89 (2014) 112003

- When provided a list of uncertainties or a covariance matrix, it will produce an error band for any datasets requested.
- This example shows the GENIE uncertainties thrown according to its default errors compared with ArgoNeut CC-inclusive data.

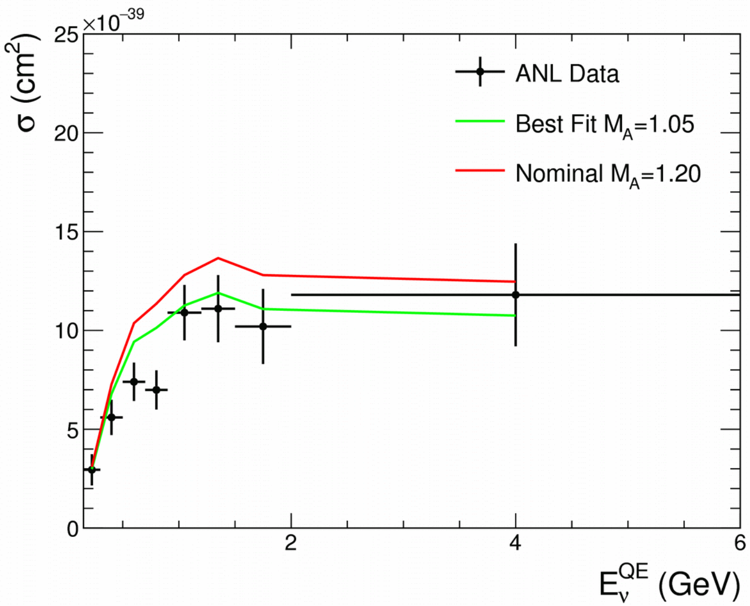
Model tuning with NUISANCE

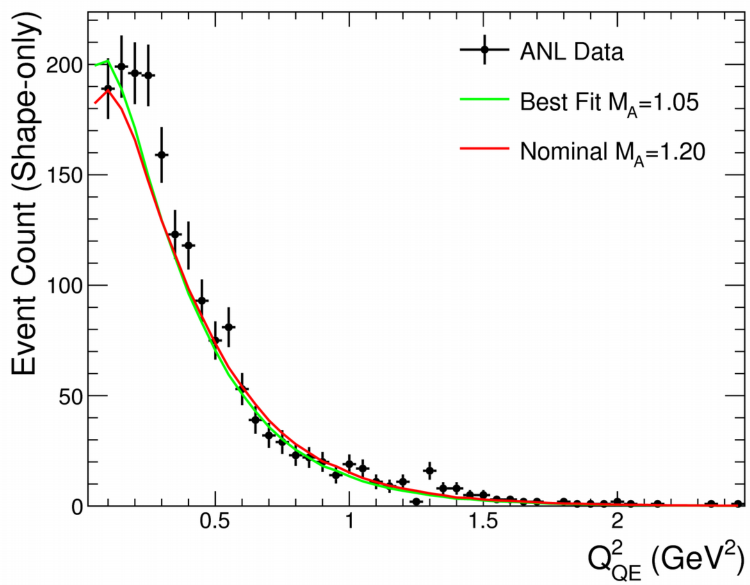
- NUISANCE uses ROOT minimization routines to tune model parameters.

- 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

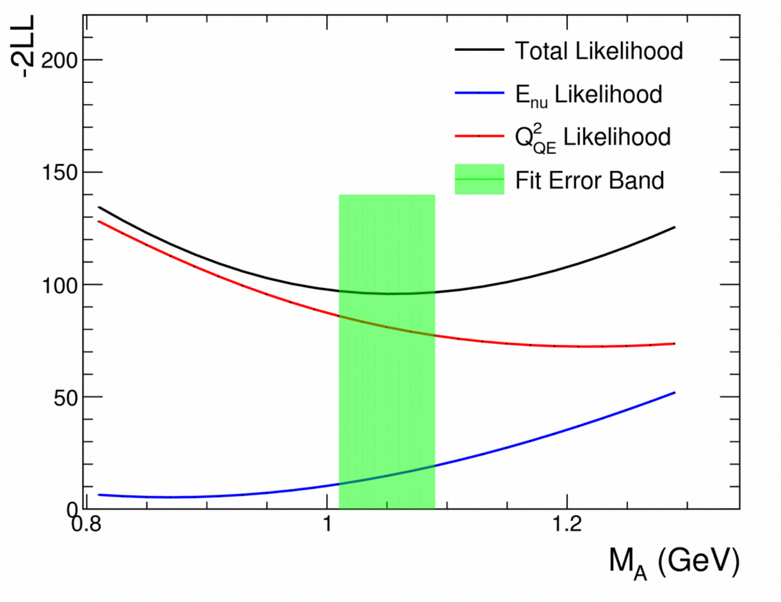
- Can use NUISANCE output files as fake datasets for fit validation studies if required.

Model tuning with NUISANCE





ANL ν_μ-D_2 CCQE
PRD 16 (1977) 3103



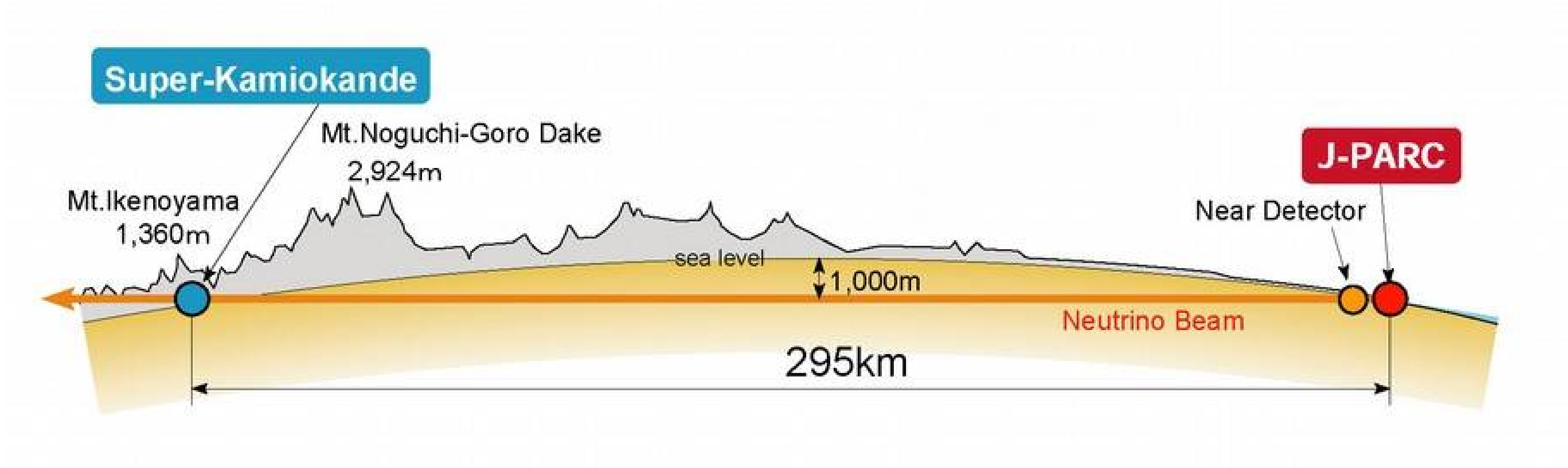
Datasets: ANL CCQE E_ν and Q^2 (shape-only)

Parameters: M_A, Q^2 *norm.*

Output: $M_A = 1.05 \pm 0.04$ GeV^2 (Dipole F_A in MC)

Constraining a cross section model

Cross section modeling for T2K

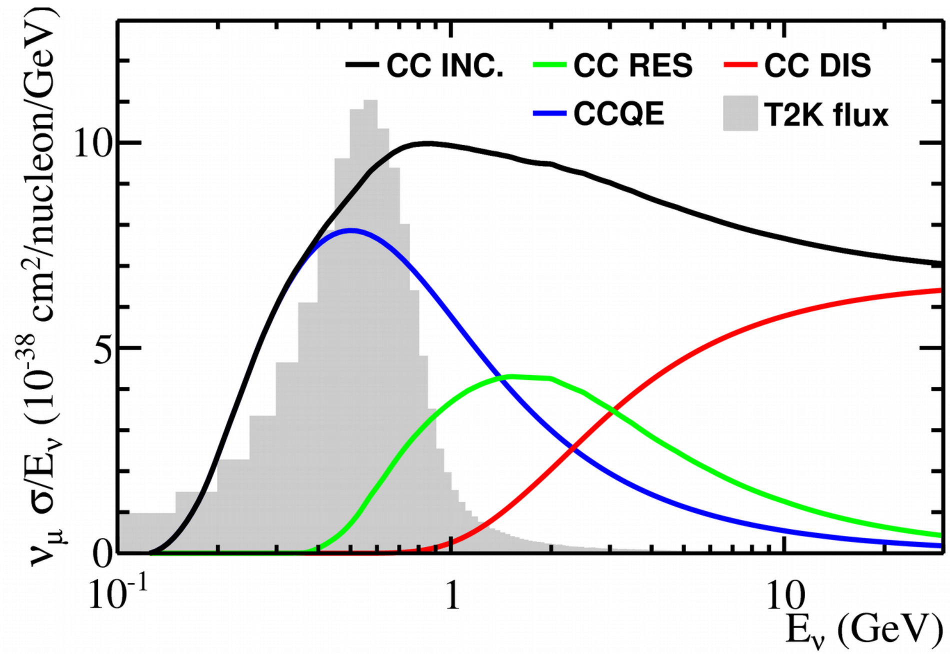


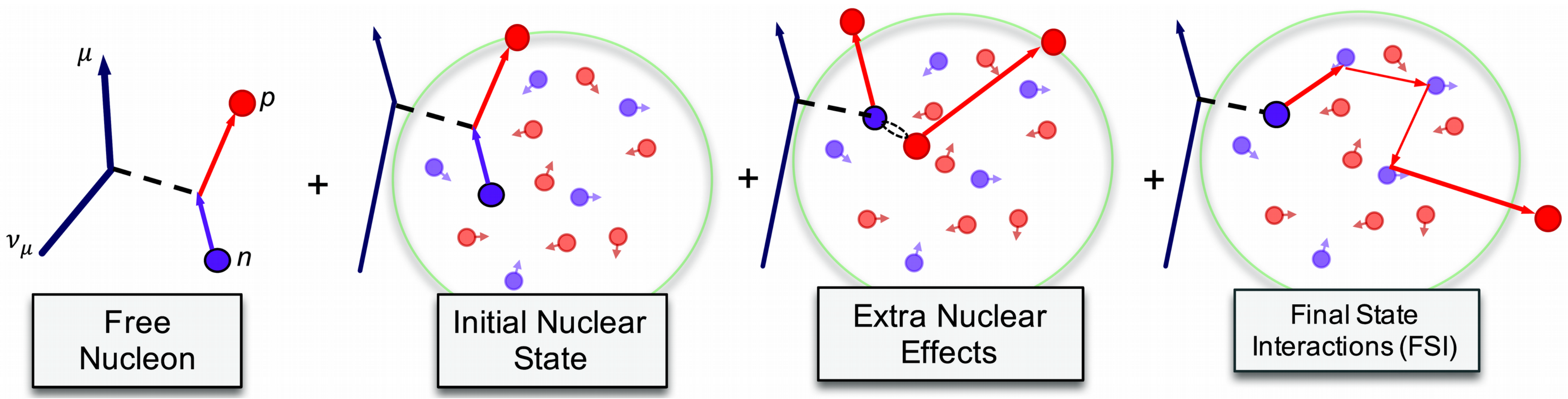
- T2K constrains cross section model with ND fit before propagating to FD
- **Concerns:**
  - ND acceptance is forward, little sensitivity to high-Q^2 events
  - FD has 4π acceptance
  - FD is water, ND has scintillator and water
- Aim to constrain all cross section parameters with external data before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

Cross section modeling for T2K

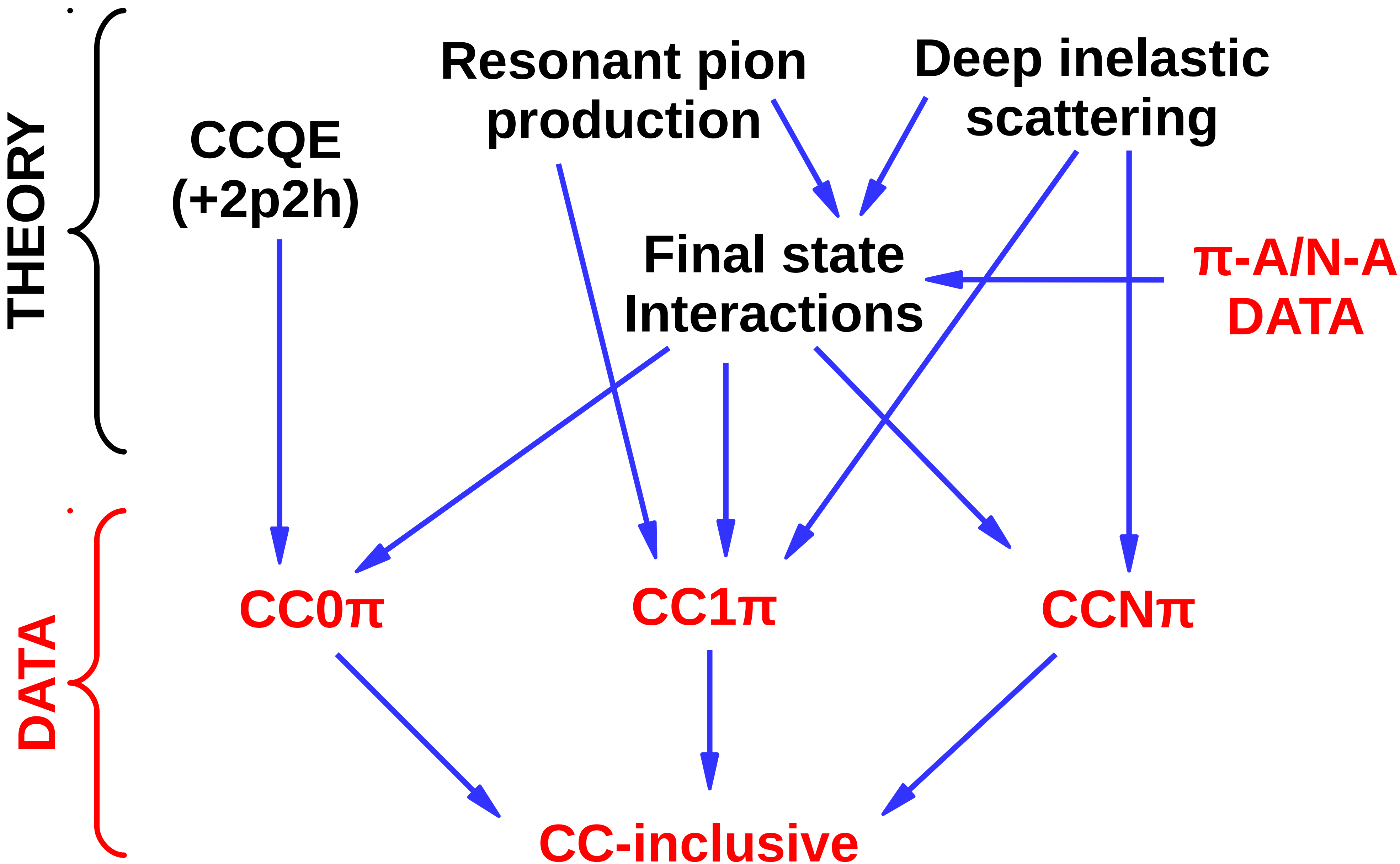
- Aim to constrain all cross section parameters with external data before the ND fit

- That's a lot of parameters!

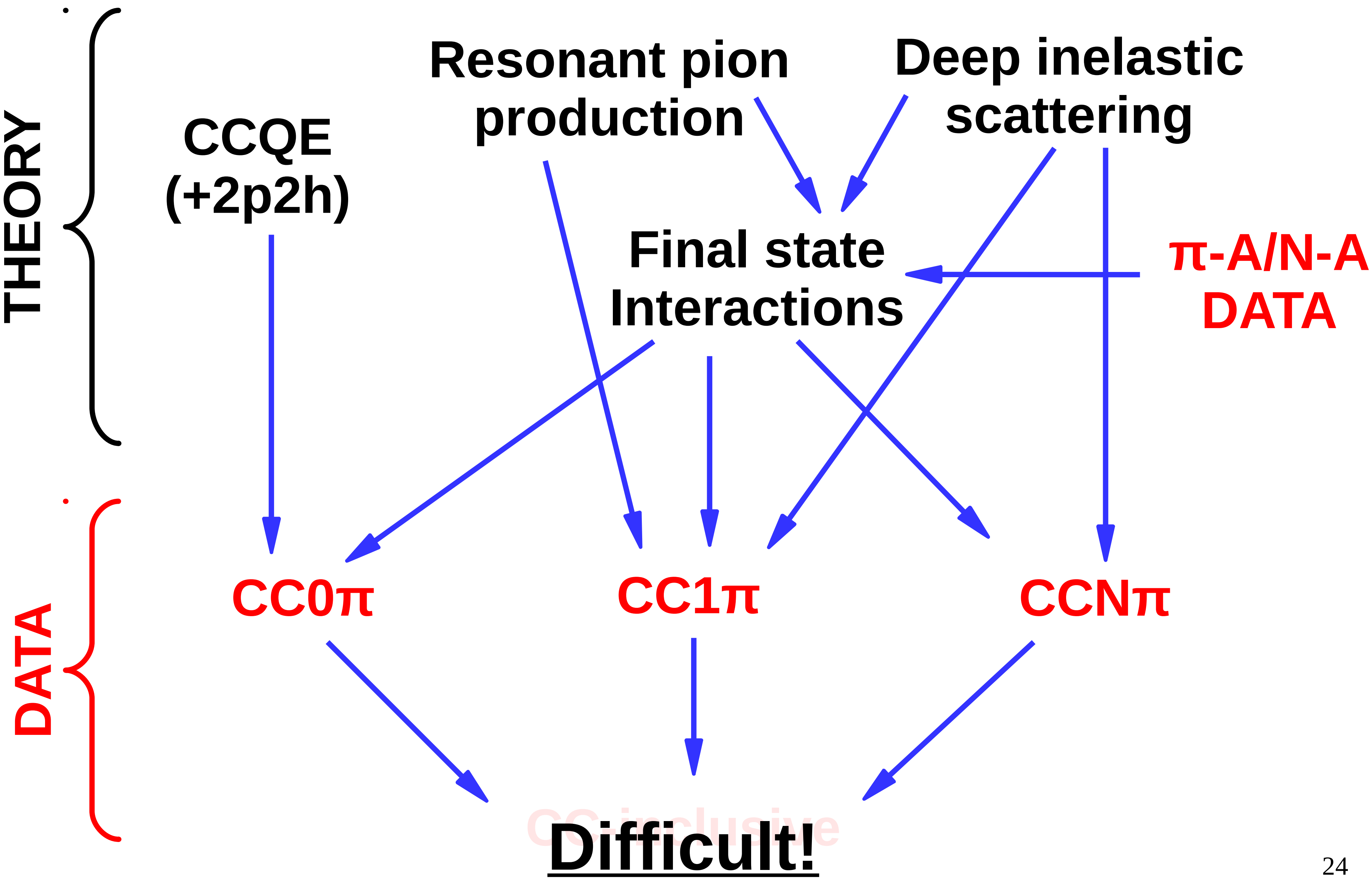




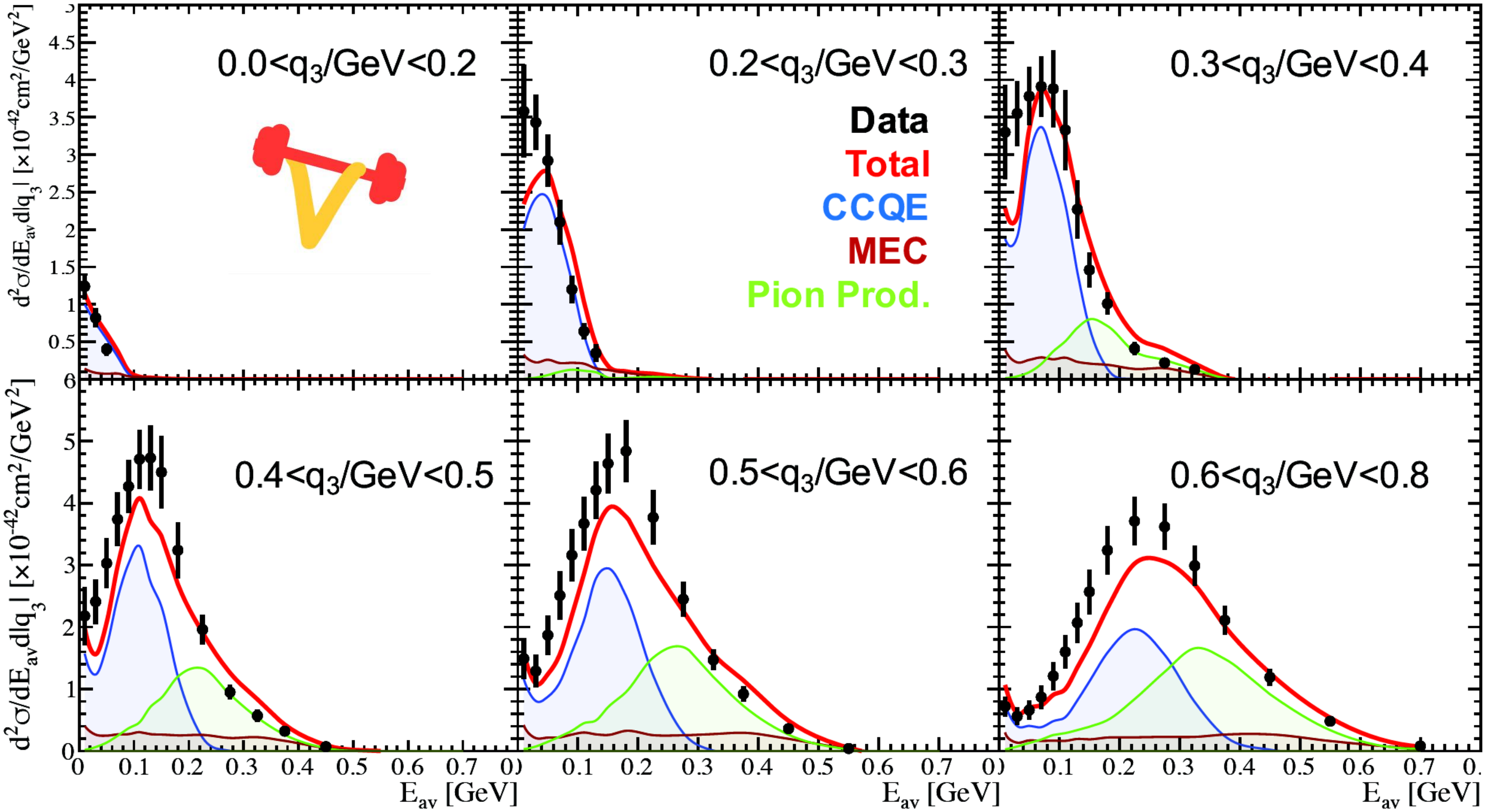
Constraining an MC CC-inclusive model



Constraining an MC CC-inclusive model



MINERvA CC-inclusive

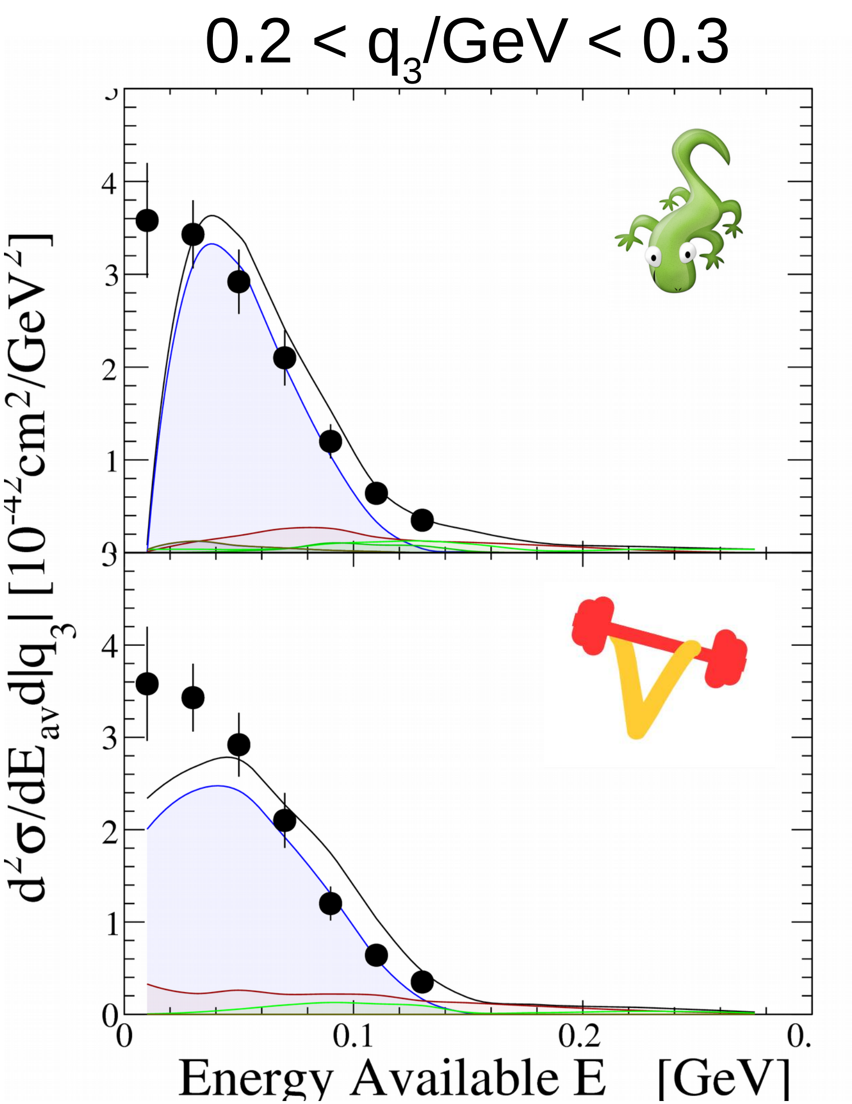


PRL 116 (2016) 071802

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

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

MINERvA CC-inclusive

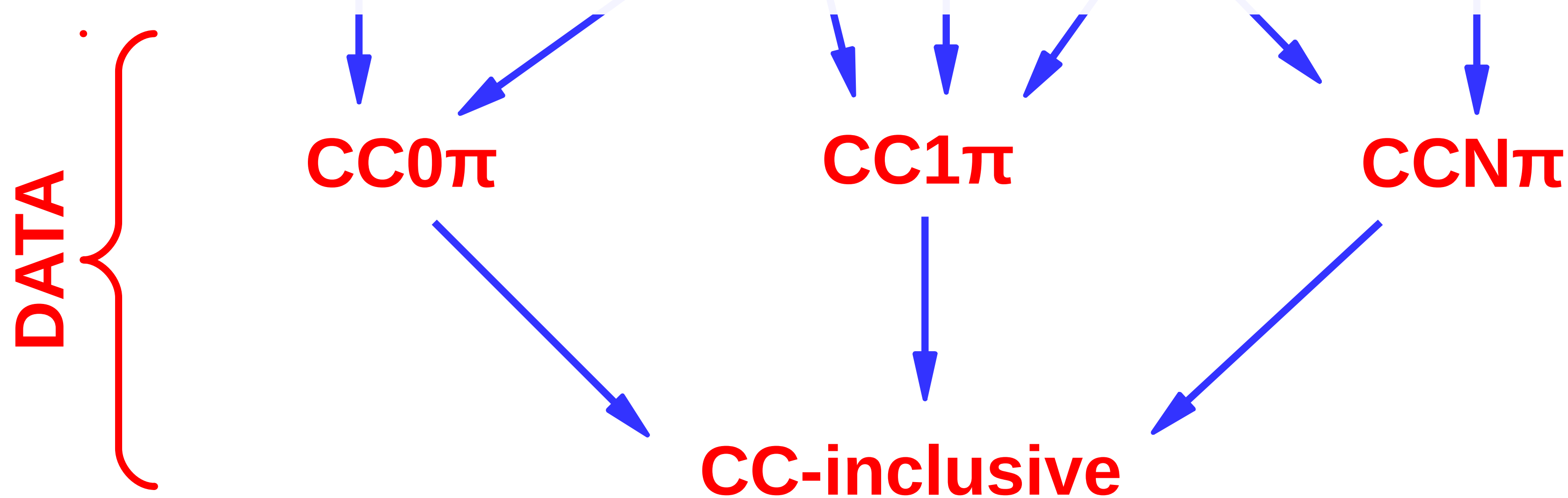


$$E_{av} = \sum_{i=p,\pi^{\pm}} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$

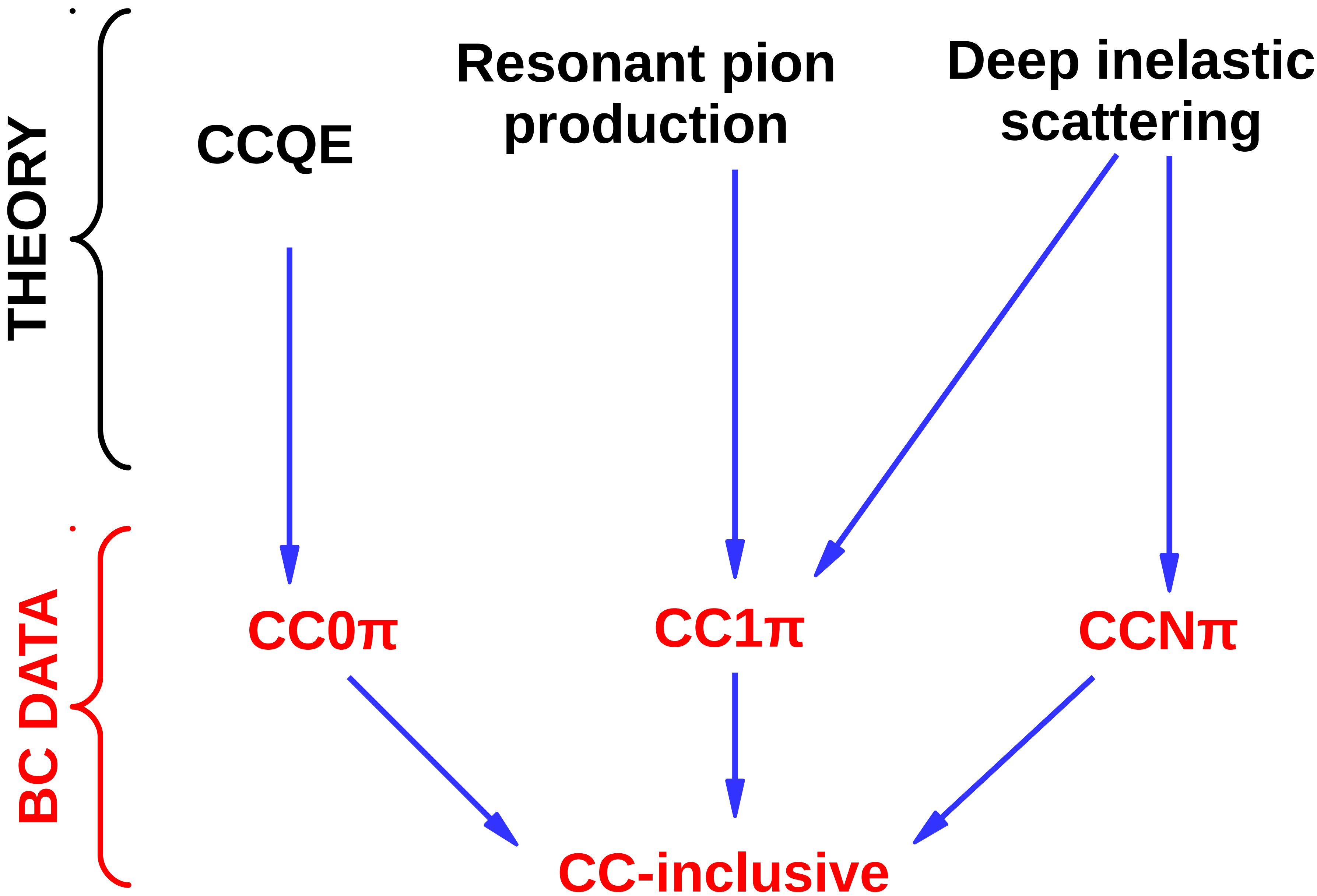
- Inclusive data can still highlight model deficiencies
- NEUT clearly deficient at very low energy transfers (QE-dominated)
- Difference appears to be the nuclear model → motivates further NEUT development

Constraining an MC CC-inclusive model

- Need to use exclusive data to break degeneracies in CC-inclusive parameters!
- Better constraints are obtained using multiple datasets:
  - Various wideband fluxes
  - Large flux normalization errors
  - Different detector acceptances



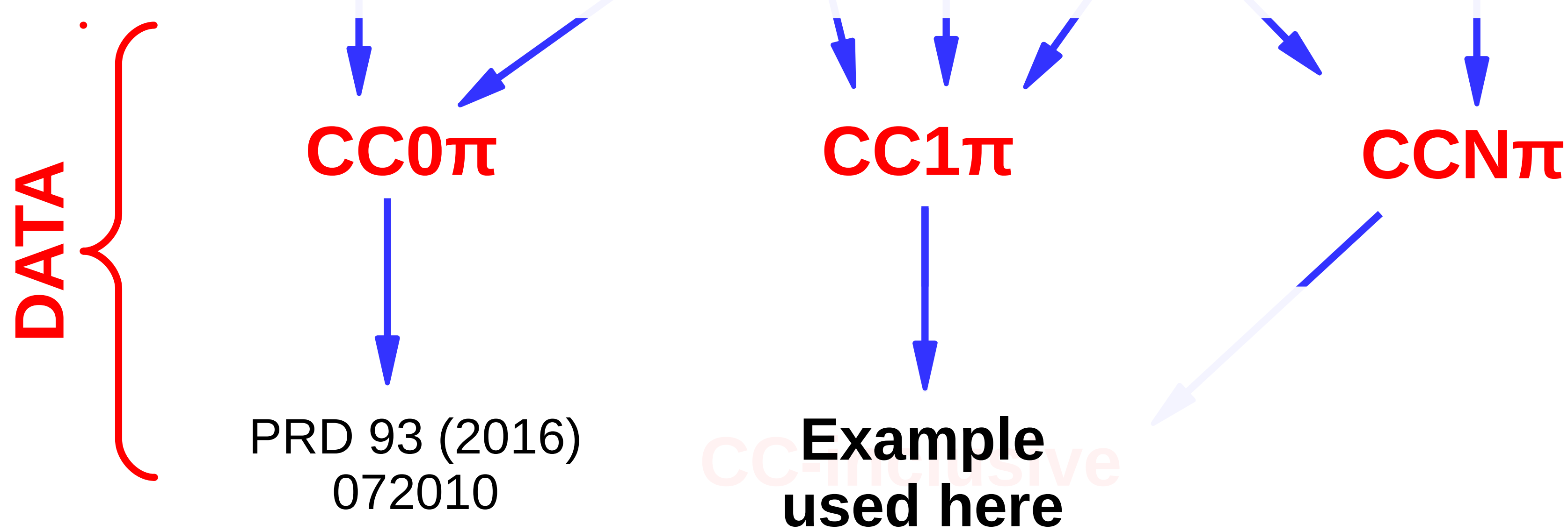
Bubble chamber data



Constraining an MC CC-inclusive model

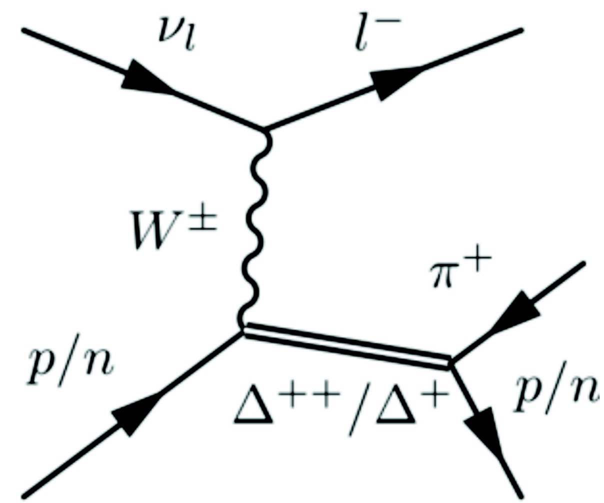
T2K strategy:

- Tackle each class of data separately
- Constrain interaction model with **ν-N** data
- Compare to **ν-A** data and look for deficiencies
- **Add model flexibility where necessary**
- Build up machinery to move to “kitchen sink” fits



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



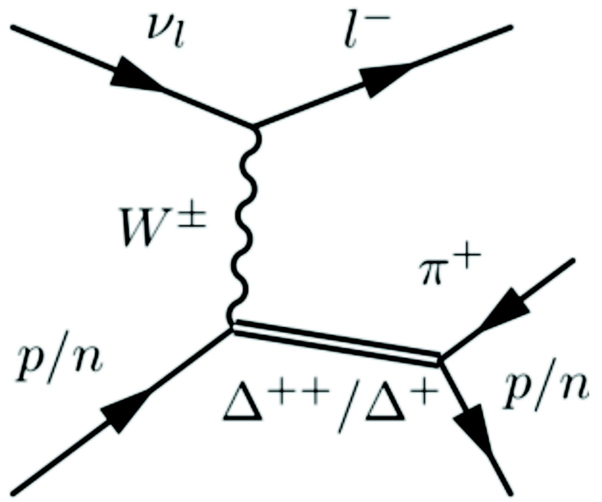
- Updated Graczyk and Sobczyk FFs (PRD 80 (2009) 093001)
  - Vector FFs tuned to e-A data
  - Axial dominated by C_5^A FF (N-Δ transition)

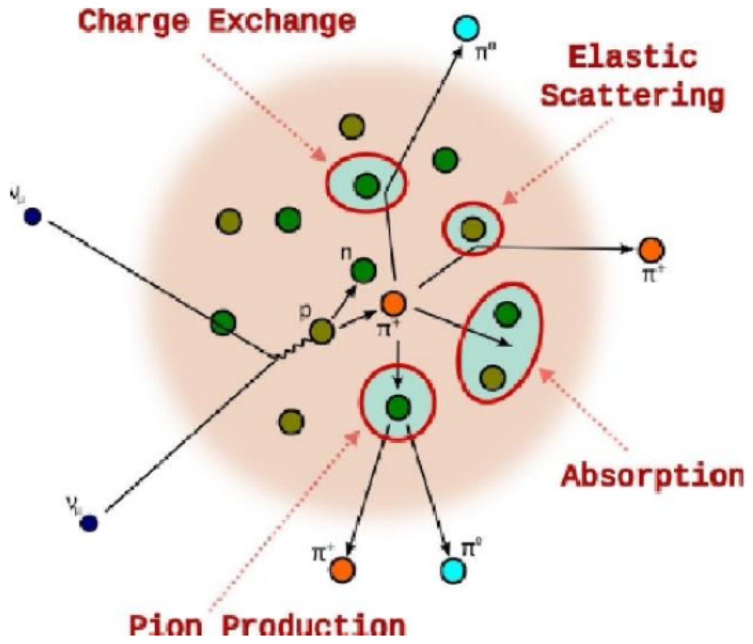
$$C_5^A(Q^2) = \frac{C_5^A(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

- 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*

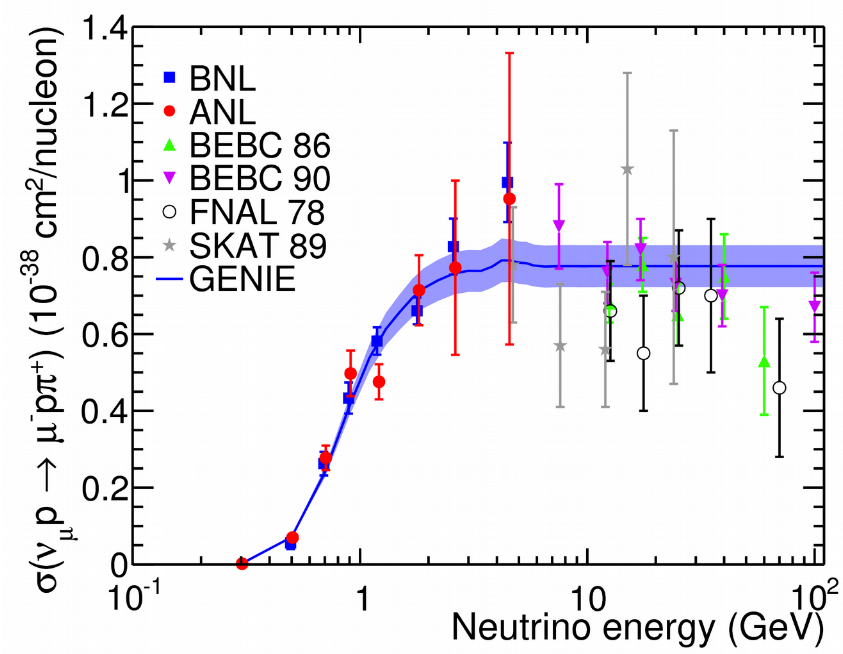


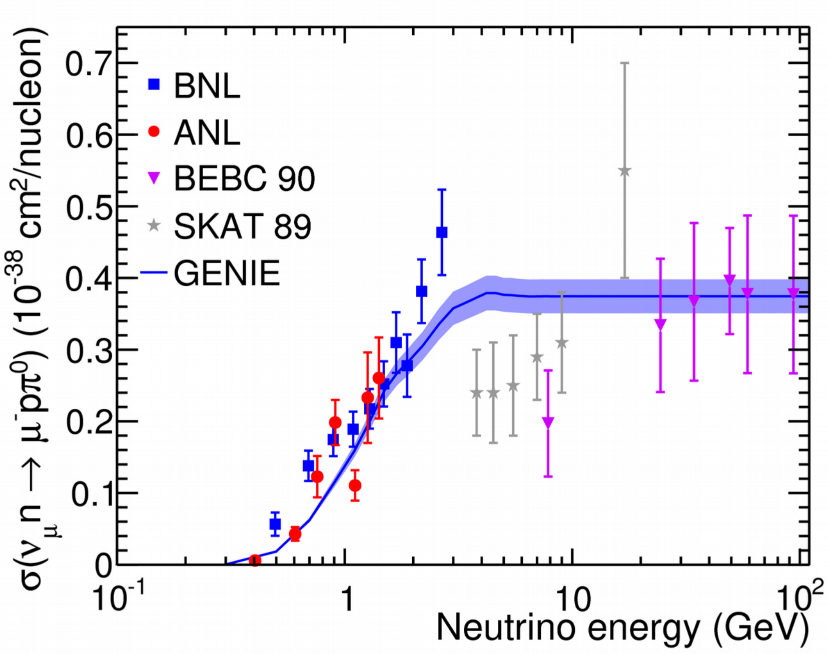


- Like most generators (except GiBUU) NEUT uses a simple cascade model
- Tuned to a large body of N-A and π-A scattering data (PRD D91 (2015) 072010)

Bubble chamber tuning

- Parameters tuned to a limited set of bubble chamber data:
  - ANL and BNL, E_ν and Q^2 distributions
  - $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^0 + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^+ + n$
- Similar to tuning of the GENIE model for MINERvA (pictured)



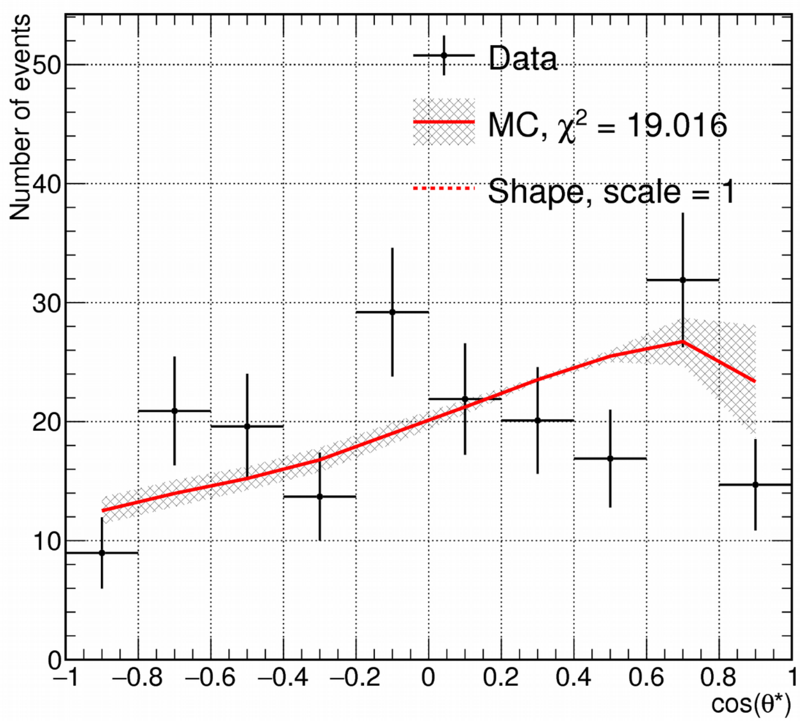


EPJC 76 (2016) 76:474

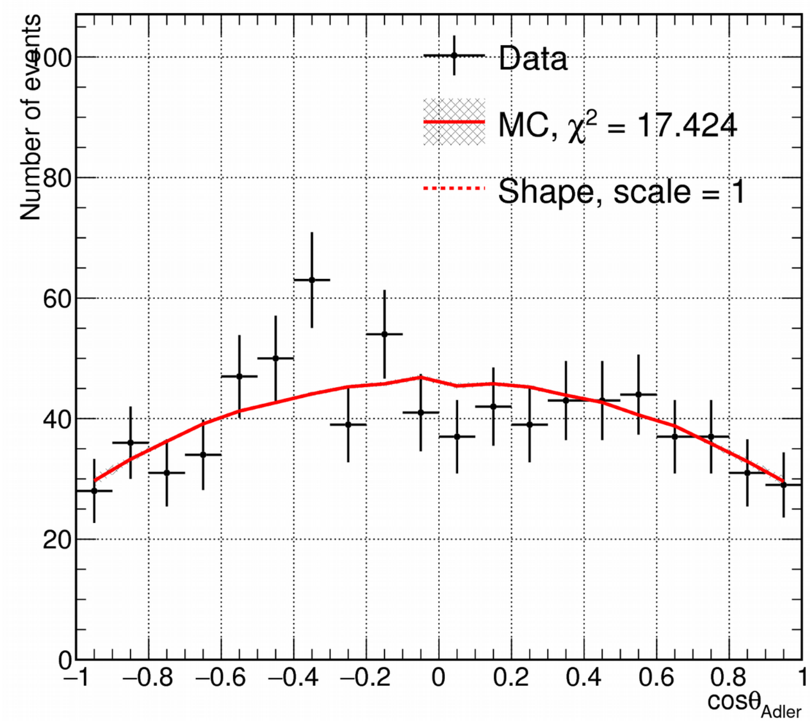
Bubble chamber tuning

- Ongoing work to compare to **all** available BC distributions to stress test the interaction models
- Many weird and wonderful QE and 1π distributions in NUISANCE, along with NC and 2π data

ANL ν_μ-D_2 $\nu_\mu p \rightarrow \mu^- \pi^+ p$
PRD 25 (1982) 1161



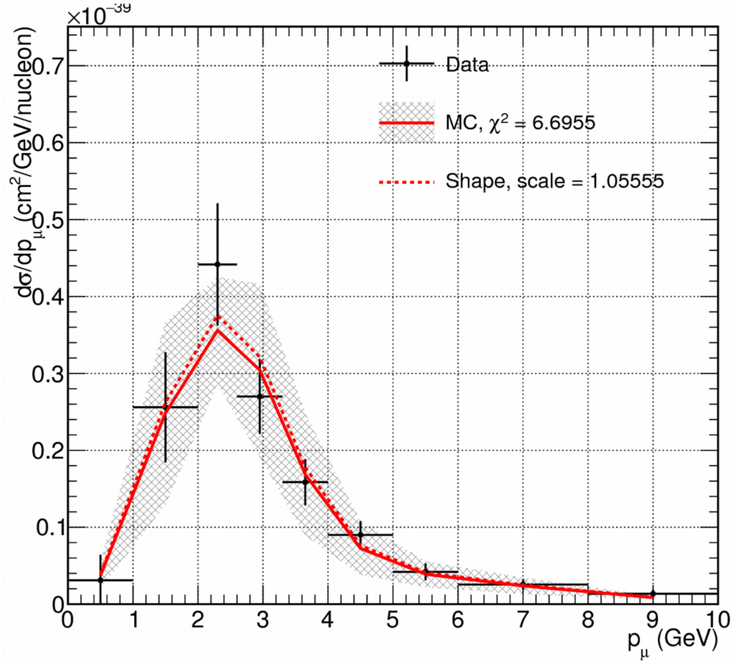
$\cos\theta_{\mu\nu}$ (COM)



Angle between (p_ν-p_μ) and p_π in the resonance rest frame

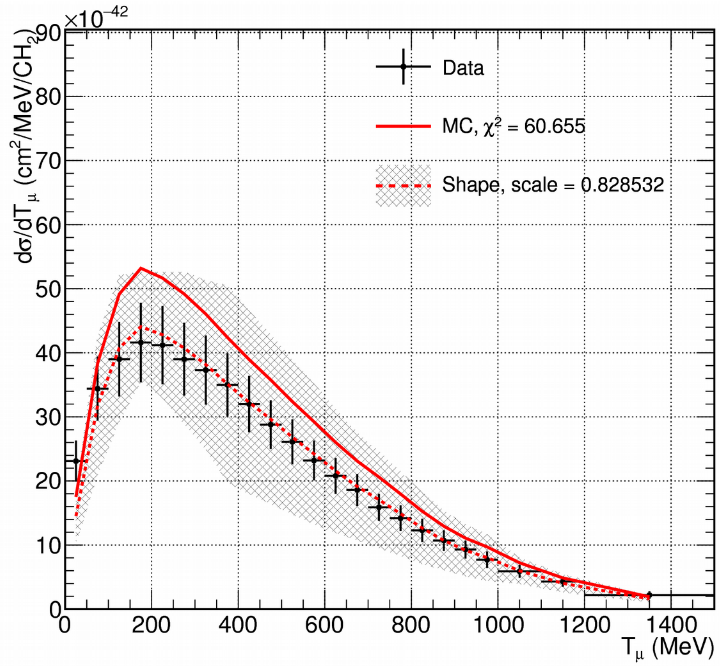
Comparison with nuclear data

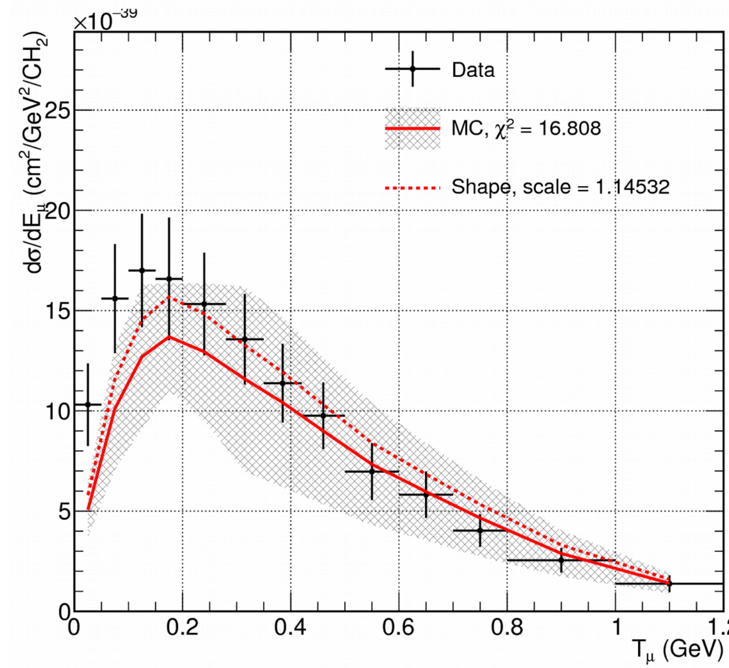
- Reasonable agreement with outgoing **muon kinematics**
- Poor agreement with pion kinematics. Often interpreted as inadequacies in the FSI model…



MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005

MB ν_μ-CH$_2$ CC1π^+
PRD 83 (2011) 052007

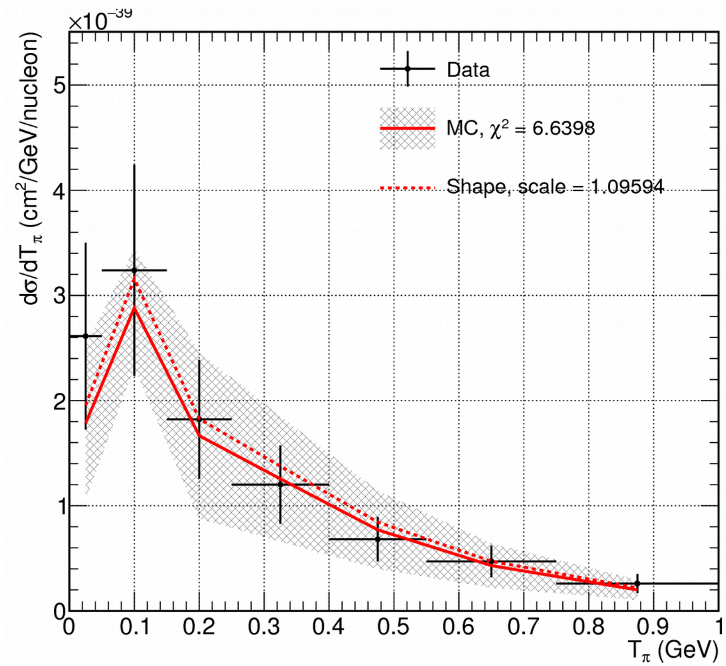




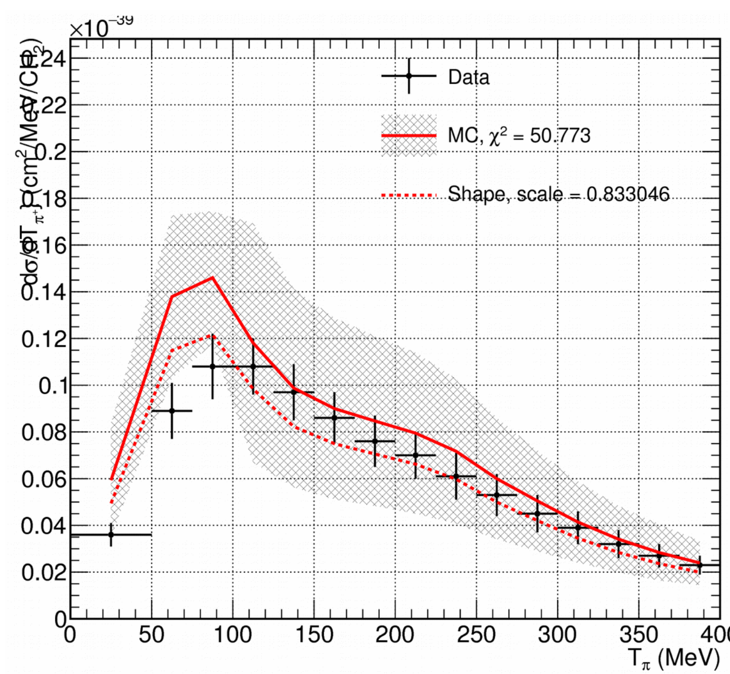
MB ν_μ-CH$_2$ CC1π^0
PRD 83 (2011) 052009

Comparison with nuclear data

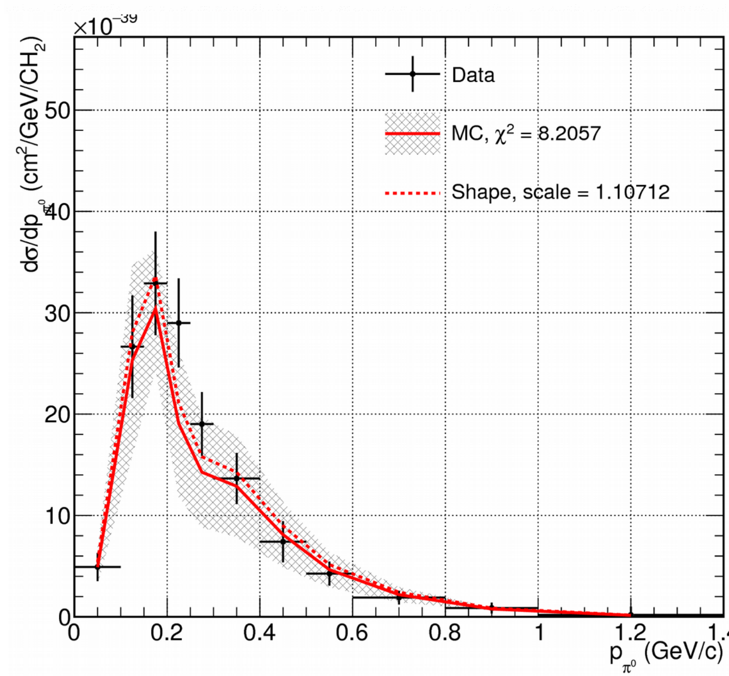
- Reasonable agreement with outgoing muon kinematics
- Poor agreement with **pion kinematics**. Often interpreted as inadequacies in the FSI model…



MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005



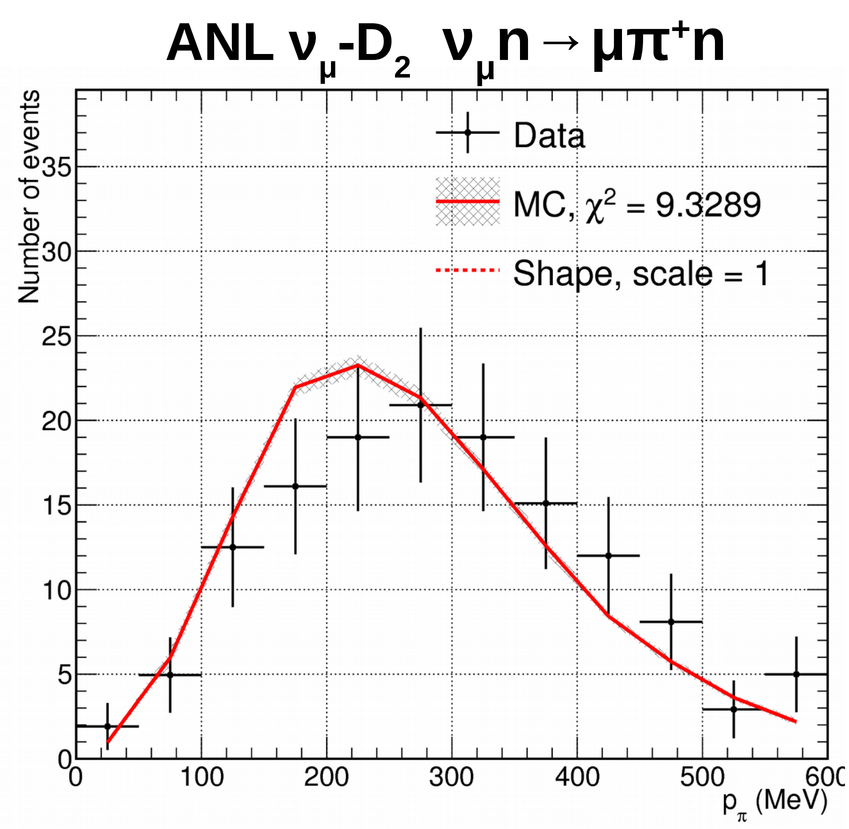
MB ν_μ-CH$_2$ CC1π^+
PRD 83 (2011) 052007

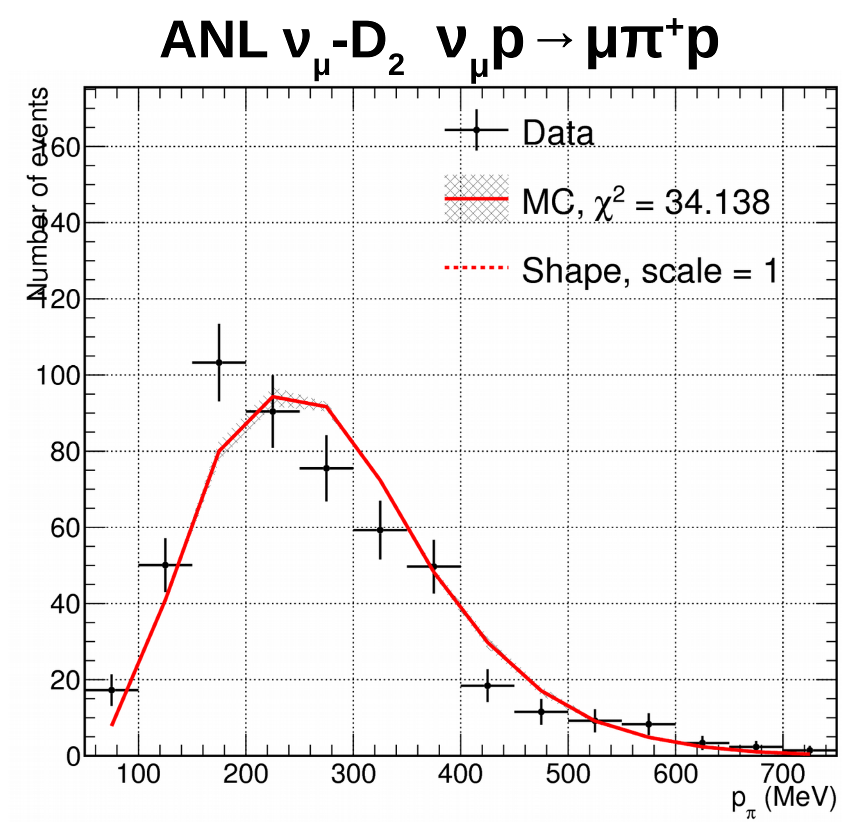


MB ν_μ-CH$_2$ CC1π^0
PRD 83 (2011) 052009

Throwing gasoline on the fire

- Very little flexibility in the interaction model to change the pion kinematics.
- Agreement with ANL data not amazing. More work required before moving onto FSI uncertainties/ nuclear effects.

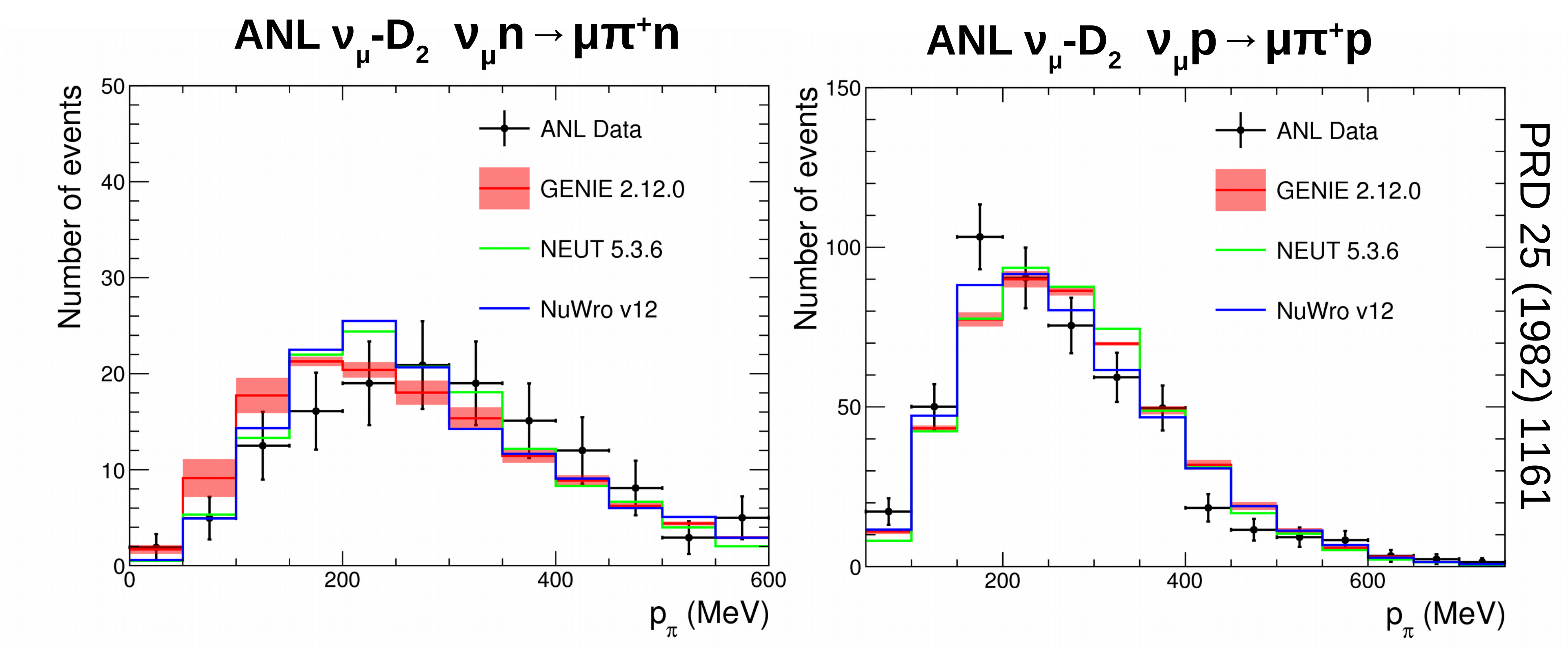




PRD 25 (1982) 1161

Throwing gasoline on the fire

- Very little flexibility in any generator (GENIE errors shown)
- Different generators agree because they use very similar models...



PRD 25 (1982) 1161

Lessons from single pion fits

- Broad agreement between simple R-S model in NEUT/GENIE 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.

Summary

- Constraining cross section errors is a tough business!
- Multi-parameter, many dataset fits are necessary, but very challenging
- **NUISANCE:** new tool to help make model comparisons and tuning easier
- Cross section models in generators are becoming more sophisticated, but far from agreement with all ν-A data.
- External data can highlight deficiencies in generator models, key to focused generator development

We need more high quality data!

Backup

Cross section model dependence

Some unfolding methods introduce bias

The signal definition and background subtraction can be model dependent

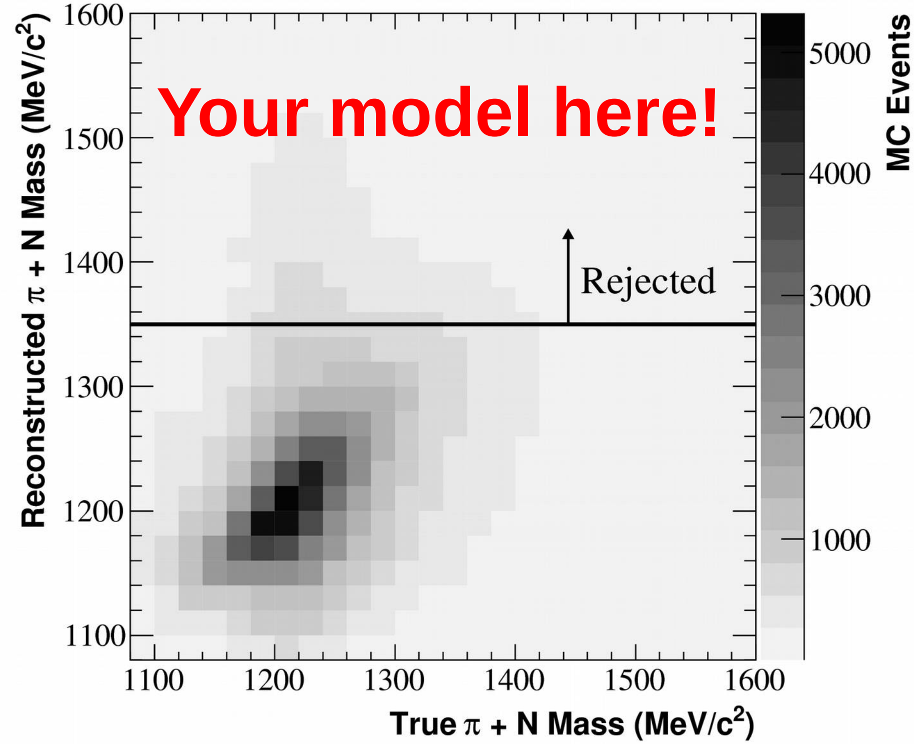
$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}^{-1}_{ij} (N_j - B_j)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

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.



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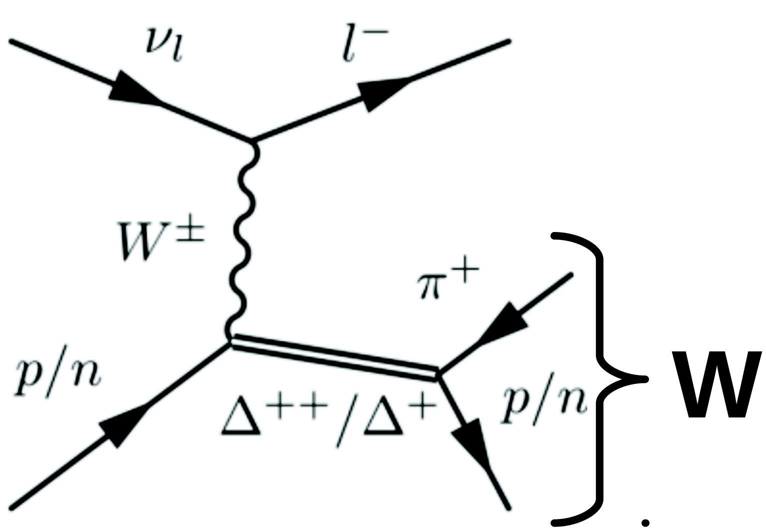
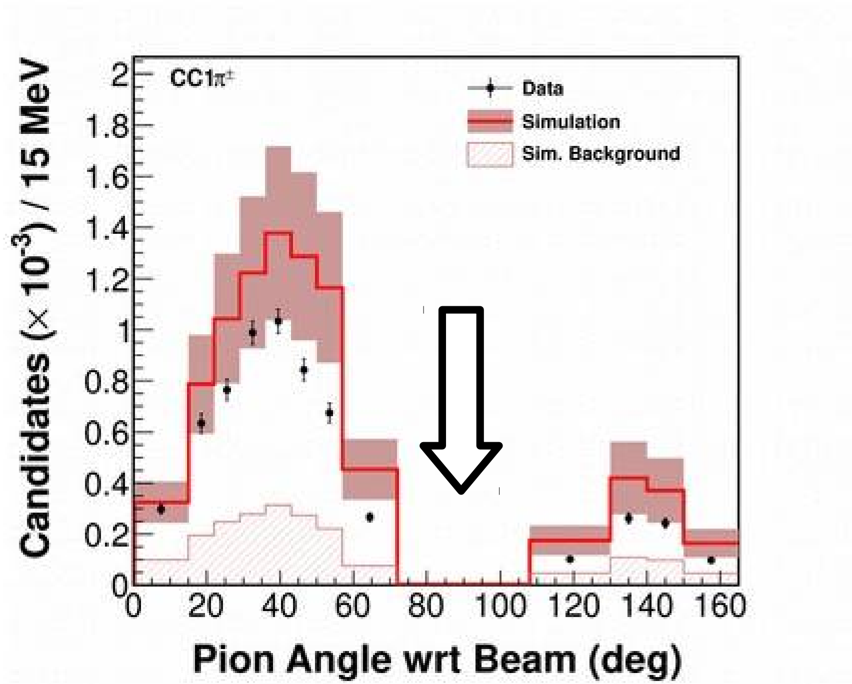
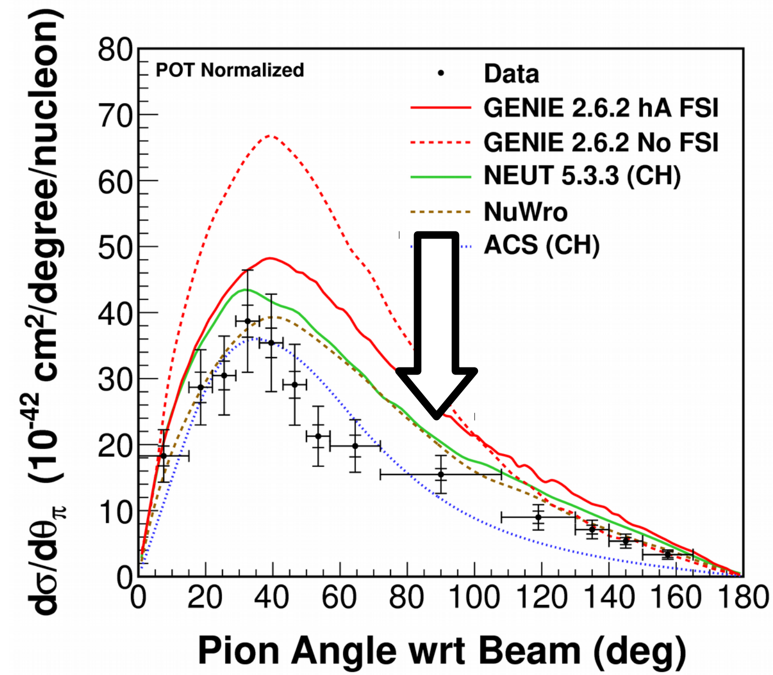
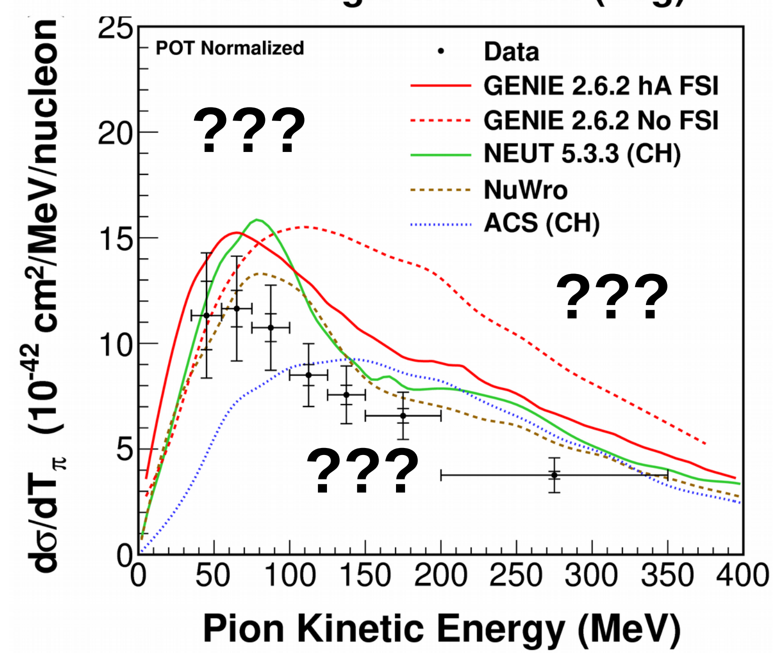


- Cannot assess where this bias lives… it might dominate some kinematic bins.

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!

T2K external data fitting

Current (imperfect) factorization:

- **CCQE-like** (CCQE+2p2h)

  Need to understand the main signal contribution

- **Single pion production**

  Constrain CC and NC channels for both signal and background

- **Final State Interaction:**

  Constrain various interaction modes with a large body of p-A and π-A scattering data

  Fundamental assumption that the cross section inside the nucleus can be simply related to the external datasets.

Purpose of external data fits

External data fits:

- Identify deficiencies in MC
- Tune model parameters

Other constraints

- Flux prediction
- Detector model

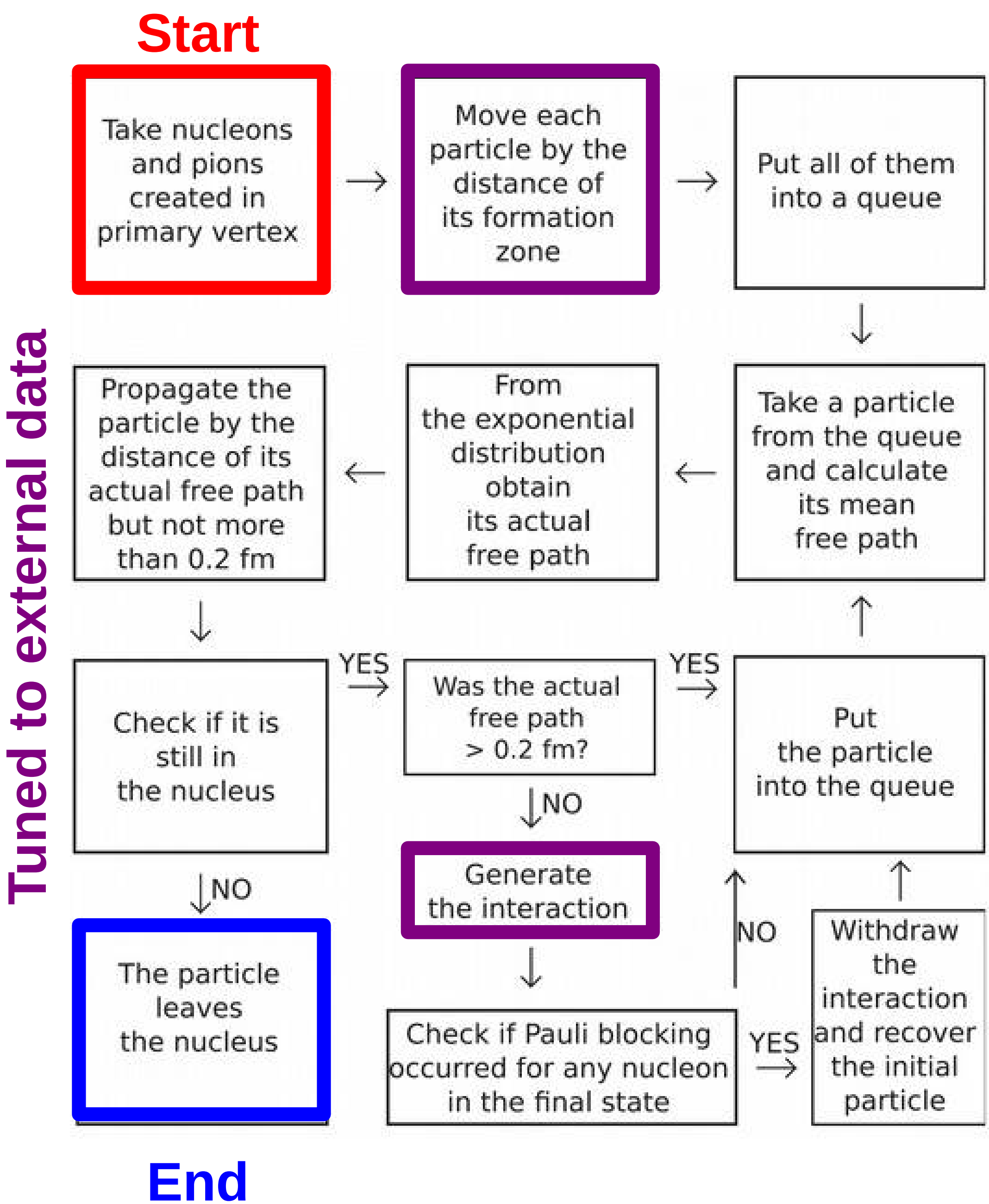
ND280 fit

- Constrain all input parameters
- Cannot fix broken input models
- Limited phase space

Oscillation (SK) fit

- Use ND best fit parameters with SK detector model
- Extract oscillation parameters

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.