# Interface between NUISANCE and the Generators

Luke Pickering
on behalf of NUISANCE

Generator Tools Workshop,
Fermilab, Illinois
2020/01/08

MICHIGAN STATE UNIVERSITY

# This Talk

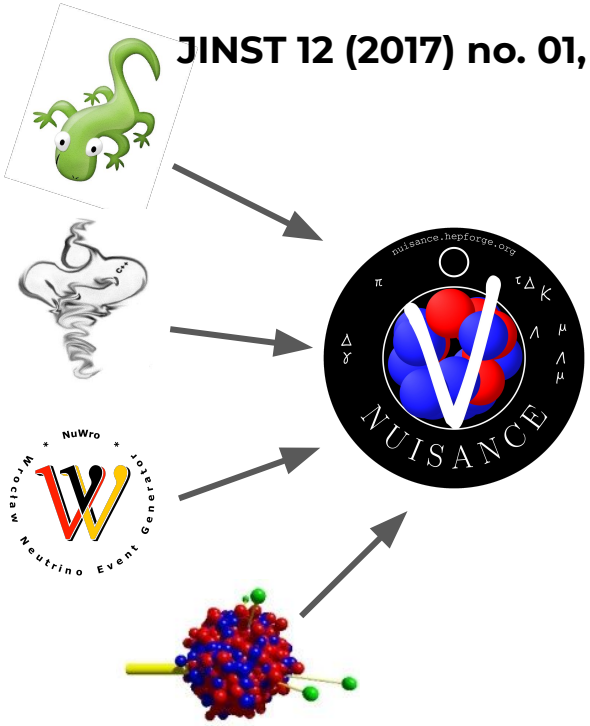
- What is NUISANCE?
- How does NUISANCE talk to the generators?
  - My unstructured thoughts on generator API/linkage
- The NUISANCE event format
  - My unstructured thoughts on event format

# This Talk

- My Apologies, this will be text heavy...
  - Feel free to stop me, shout at me, ask me to clarify!

# What a NUISANCE

- Consumes generator event output from GENIE, NuWro, NEUT, GiBUU and NUANCE
- Uses a common, internal event format




**JINST 12 (2017) no. 01, P01016**

Analyses are then written using this internal event format:

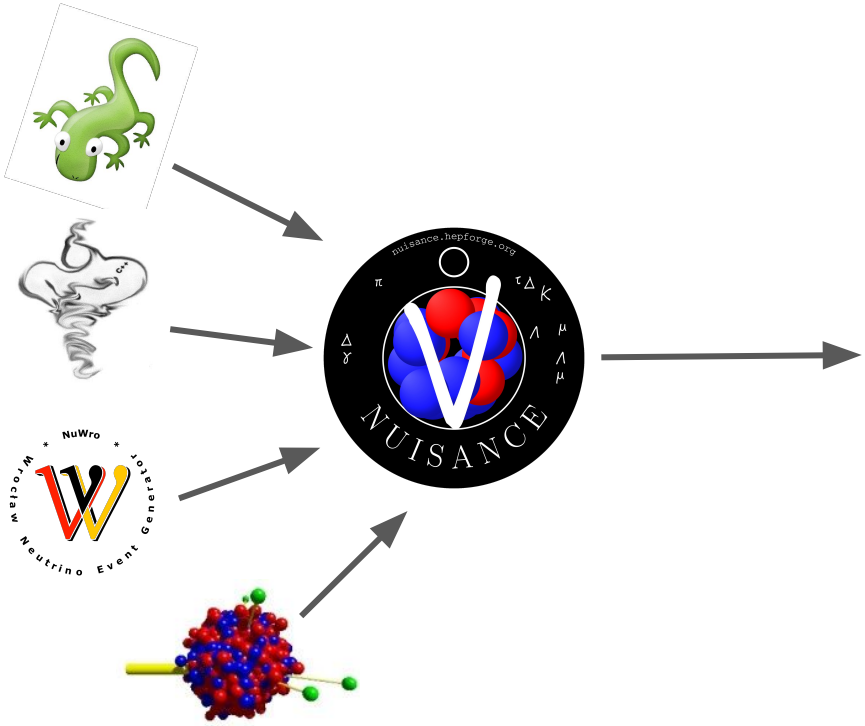
- Generator-to-generator comparisons (CI, Implementation validations, model comparisons)
- Comparison to data

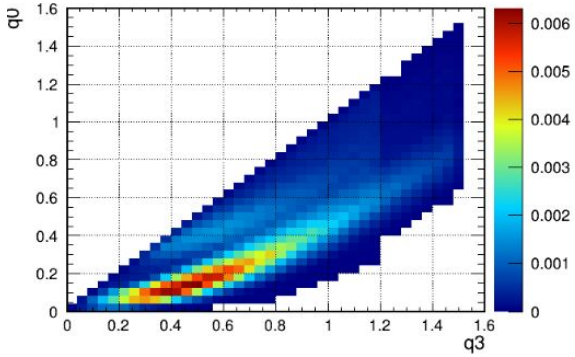
- If systematic variation tools are available (GENIE, NEUT, NuWro):
  - Fit parameters to data
  - Evaluate uncertainty bands against data
  - Evaluate model variations against each other

- **It doesn't generate events for you**, but some 'no warranties' helper scripts can be found for specific flux/target combinations.

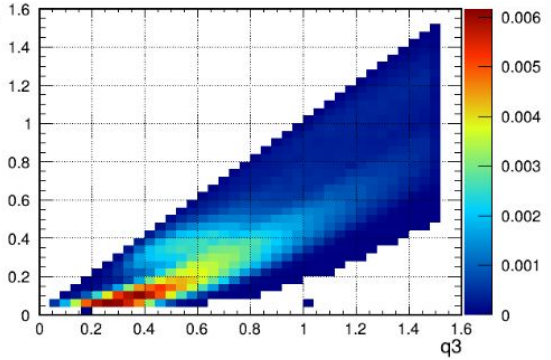
# What a NUISANCE

Compare different generators and their models



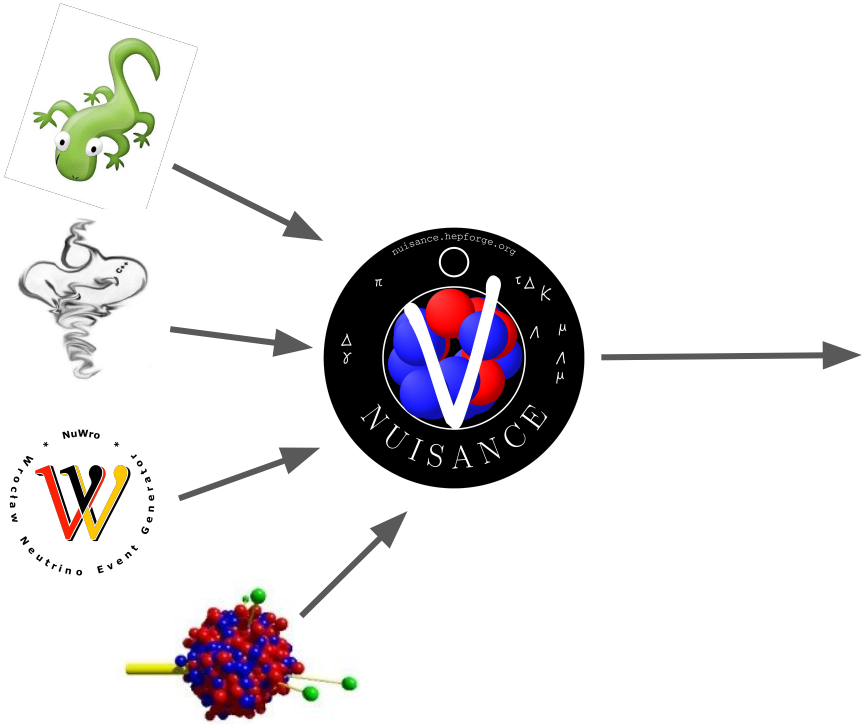

CC0π final state from NuWro with Nieves 2p2h



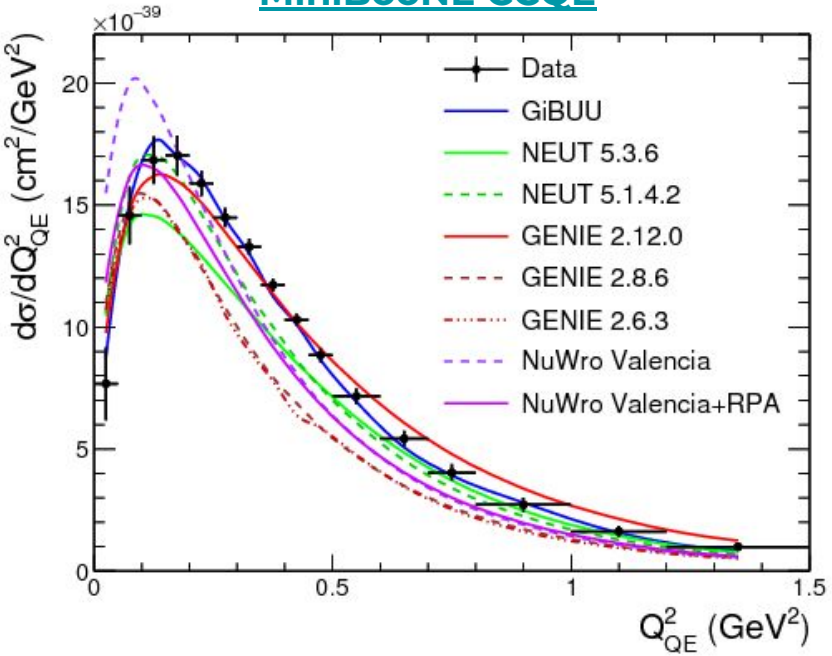

CC0π final state from GENIE with Empirical 2p2h

# What a NUISANCE

Compare your favourite generators and models, which does best/worst?

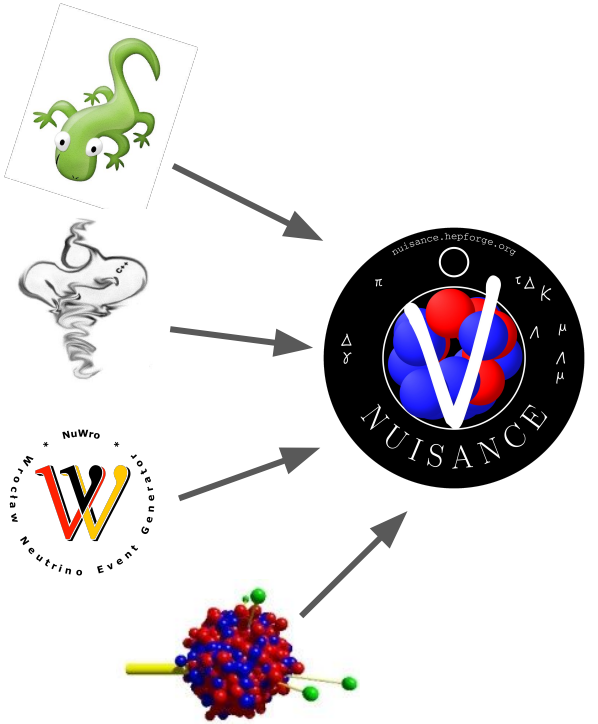


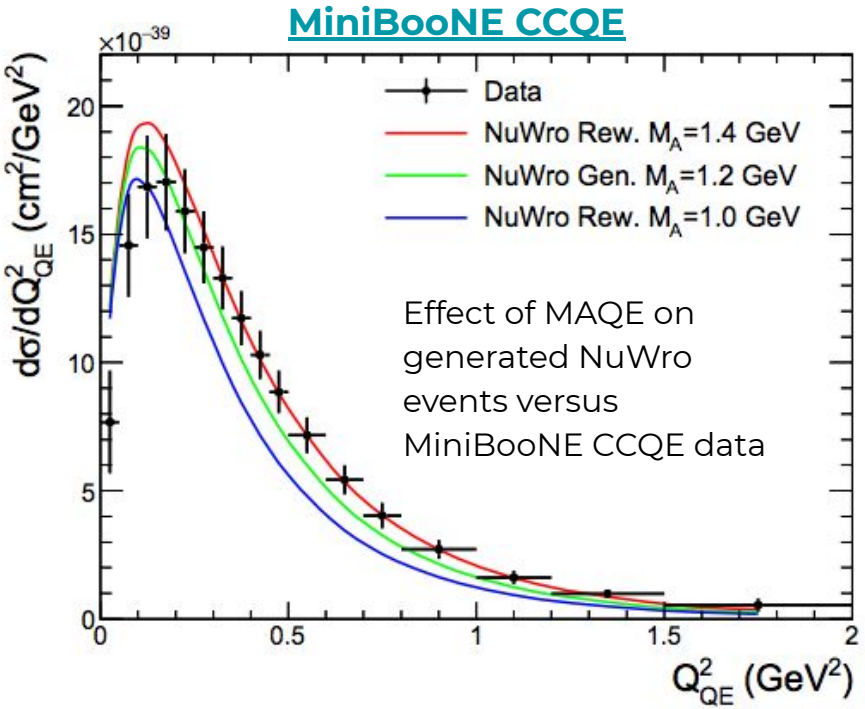

**MiniBooNE CCQE**



# What a NUISANCE

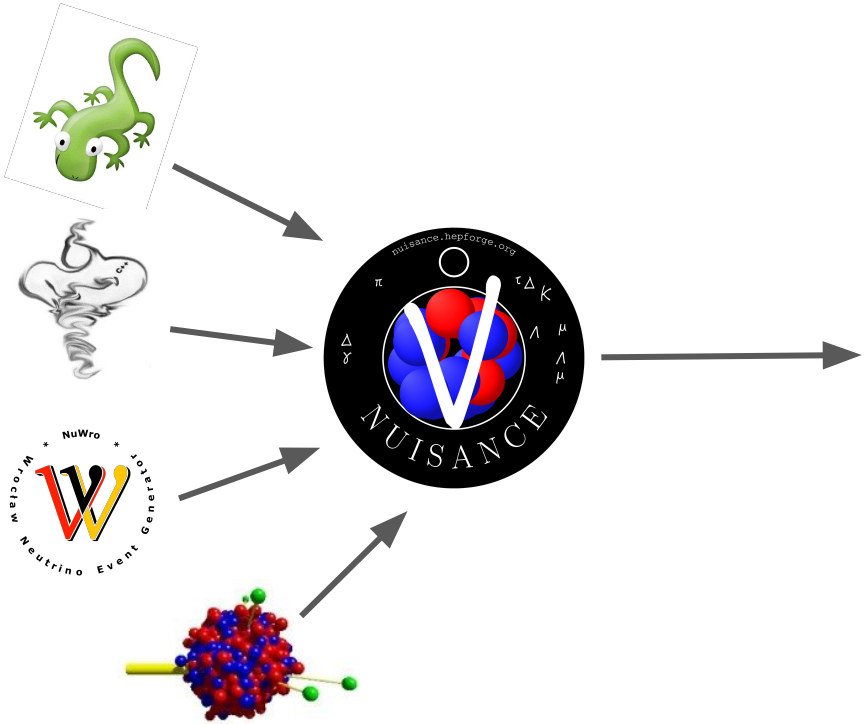
Compare effect of systematics on distributions from the same generator

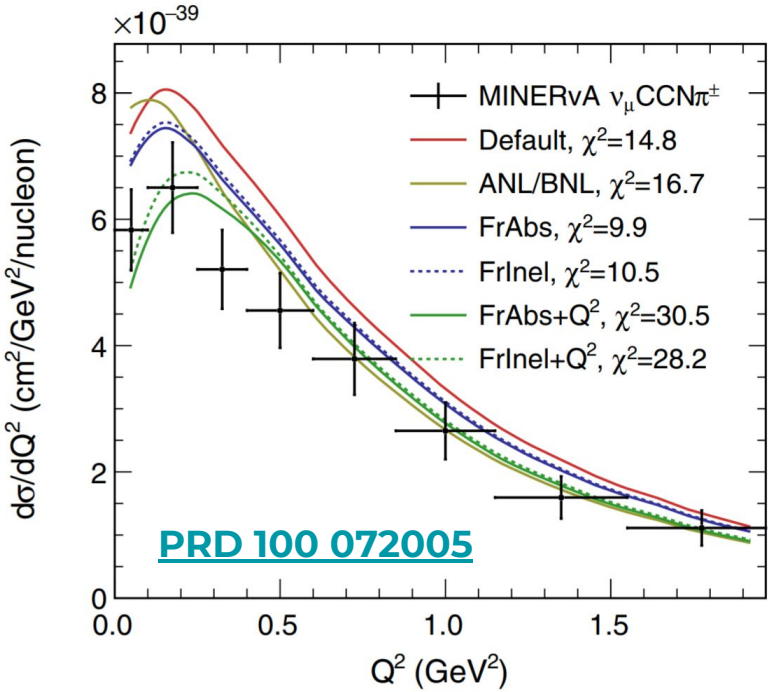


# What a NUISANCE

Fit ReWeightable parameters to data sets (can also brute-force scan non-reweightable parameters, but no helper scripts for that yet)



# Who are we?

- T2K, MINERvA, DUNE collaborators
- Experience using GENIE, NuWro, NEUT, GiBUU
- Have worked on neutrino cross-sections measurements, generator dev. and oscillation analyses on T2K and DUNE
- **Started as PhD project, now junior postdocs**

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+ Critical contributions from S. Dolan, A. Mastbaum

+ Data comparison implementations from T2K, MINERvA, UBoone collaborators

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- Started as PhD project, now junior postdocs
- **We want collaboration, and contributions!**
  - **Code is OS with a permissive licence, collaborations/pull requests welcome!** https://github.com/NUISANCEMC/nuisance

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# Who are we working with?

T2K

NuWro Wrocław Neutrino Event Generator

μBooNE

NOvA ♥ T2K

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

MINERvA

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# The Moving Parts of NUISANCE

- Presented as monolithic, NUISANCE is actually quite modular:
  - A ‘generic’ particle stack-based event format
  - An interface and implementations for reading in generator-specific events and converting them on the fly to the NUISANCE event format
  - ~120 published dataset implementations with corresponding experimental signal definitions
  - Common helper functions that act on events to calculate useful kinematical quantities or apply selection cuts e.g. `bool IsMiniBooNECCQE(event const &)` and `double GetQ2QE(event const&)`
  - Systematic tools for applying model variations and experimental ‘tunes’.
  - Statistical tools for determining GOF and running samplers/minimizers
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# NUISANCE: Reading In Events

- When Reading/Converting Events, NUISANCE needs two bits of information for itself:
  - Initial+final state particle stack
  - Flux-averaged total cross-section
- This is handled by per-format sub-classes of an ABC interface.
  - Adding a new input format requires a new sub-class
  - Any generator details are then encapsulated.
  - Have added ‘input handlers’ for StdHep, HEPMC.
  - New formats are ‘easy’.

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# Flux-averaged Total Cross Section

Property of the interaction model

We supply the flux shape
*e.g.* mono-energetic, NOvA ND, SuperK,...

Number of things that happened,
*i.e.* number of events

$$\sigma^{\mathrm{FA}} = \frac{\int \phi(E_\nu) \times \sigma(E_\nu) \mathrm{d}E_\nu}{\int \phi(E_\nu) \mathrm{d}E_\nu} = \frac{N}{\Phi}$$

Number of chances to happen,
*i.e.* flux

- But, we asked for fixed *N*, and the cross-section tables/splines dictate $\sigma(E_\nu)$
  - We really asked for $N' = A \times N$
- You can put the scaling anywhere, but I find it easiest to think of *A* like:
  - The generator only uses the flux shape information,
  - *A* is the exposure (*c.f.* POT) needed to get the event rate that we asked for.
- We need it to plot cross sections or correctly-normalized event rate predictions.
  - *A* is a property of the specific 'run' of a generator (target, flux, NEvents).

# How we get the FATC

$$\mathcal{S} = \frac{1}{A} = \frac{N}{N'} = \frac{\int \phi(E_\nu) \times \sigma(E_\nu) \mathrm{d}E_\nu}{N'}$$

- Different generators supply it differently:
  - **NEUT**:
    - Output ROOT file contains the total event rate and total flux histograms
    - TH1D::Integrate and Quotient!
  - **NuWro**:
    - It is given directly as the `EvtWgt` branch in the output vector
  - **GENIE**:
    - Read/reconstruct relevant XSec splines from event vector, taking account of what `EventGeneratorList` was used
    - Sum together correctly (target ratios *e.g.* CH vs. CH2)
    - Calculate FATC!
    - This is fiddly and so is done by a pre-processing stage in NUISANCE `'PrepareGENIE'`.
    - This is not ideal, has required lots of time to write/validate/maintain. This number is known during generation...
- Other details: True energy cuts in measurements adds to the pain here... as they have to be applied when calculating *A*.

# How does NUISANCE talk to the Generators?

- In short, via their ROOT I/O libraries and C++ APIs
  - Requires build time linkage, so generator dependencies become NUISANCE dependencies.
- NUISANCE/Generator interface used in two places in standard workflow:
  - Read generator event ‘vectors’ and use generator-event format-provided convenience functions to convert to the NUISANCE format.
  - Using systematic variation tools to get event variation.

# Pros

- The usual with compiling in dependencies:
  - Many potential problems show up at configure/build time rather than runtime
  - Fast
- No manual event file parsing:
  - ROOT handles deserializing the binary format to fully functional generator object instances!
- Can use utility methods provided by generator libraries for interacting with events.
- (Even though there will be more ‘cons’ I think this is probably the only reasonable approach)

# Cons

- Complex build/dependency system:
  - Either go for lean build system that expects specific environments:
    - Has been very problematic for non-expert users
  - Or, have to have a complex build system that checks/accounts for different environments:
    - This is what we have gone for, but is tough to maintain
    - Recently, containerized distribution has  begun to help a lot…
- Generator versioning:
  - Many switches to turn on/off various parts of the codebase depending on what generators, with what features, are available.
  - Have to target multiple in-use versions of the generator code
  - Practically, the generator changes are slow enough and simple enough that this hasn't been a huge time sink.
- ROOT I/O:
  - Works great when it works, which is most of the time, but can be very fragile to seemingly insignificant changes when using TObject subclasses.

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# A Word on ReWeighting/Systematic Tools

- Reweighting interfaces are (understandably) written in terms of the generator-specific formats.
  - Would need non-destructive two way conversion to a common format (c.f. NuTools `simb` ⇔ `ghep` interface).
  - These converters would be a likely failure mode and maintenance headache
  - But, writing the ReWeighting in terms of a common format would be a very significant undertaking, and not pain-free/natural unless the whole generator framework moved to a common format.
  - I doubt that there is much appetite for that.
- The NUISANCE way:
  - Since the conversion is done ‘on the fly’ the original generator event is still in memory, a pointer to it is kept in the NUISANCE event format and is passed to the reweighting interface when needed.
  - This is not really feasible if we want to persist the common format.
  - Could have the common format provide ‘original’ file/event meta-data and require that when interacting with the systematic tools both the common format and the generator format be loaded in.

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  - Could have the common format provide 'original' file/event meta-data and require that when interacting with the systematic tools both the common format and the generator format be loaded in.
- But, a larger point:
  - **What is the medium-term future of the reweighting tools?**
  - Not worth the time/hassle if we think they will be replaced with some other error propagation methodology (*e.g.* regen + ML weightings).

# NUISANCE Wants!

- Easy access to the flux-averaged total-xsec:
  - Robert H. has brought up that for multi-species generator runs, this might not be as simple as I suggested before, needs a bit of thought.
- Better `XXX-config` apps:
  - `genie-config` is okay, but not ideal, but **much** better than the non-existent ones for NuWro/NEUT though (neut-config is on the way in the development version)
  - I shouldn't have to set up the `libxml2` environment that GENIE was built with manually, I should just be able to do `genie-config --some-opt` to query the relevant compiler/linker flags.
- I have plenty of wants/suggestions for the ReWeighting APIs, that I don't think we want to go into today:
  - But based on whether we decide that ReWeighting is a tool to be used going forward, I think there is both low- and high-hanging fruit!

# What NUISANCE Might Offer This Effort

- Working on development/testing of a new community-driven common event format.
- Separate off the Generator -> Common event converter as a separate package.
- Separate off the utility functions for working with the common event format as a separate package
  - or as part of the event format package... but I'd probably vote for the common event format code-base to be very small and focussed. #SmallAndFocussed2020
- Use the the data comparisons as a CI:
  - Build and run each generator, make comparisons to 'all' the data and the previous versions and checks.

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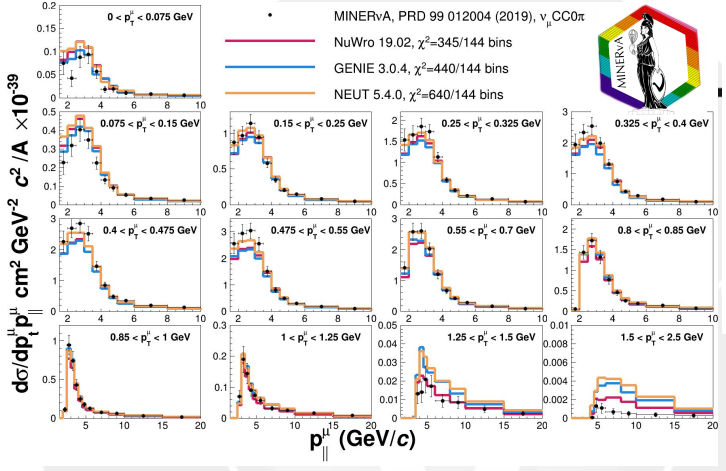
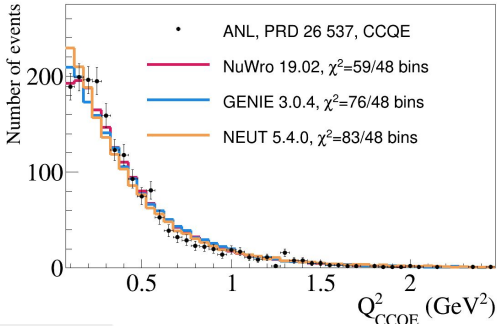
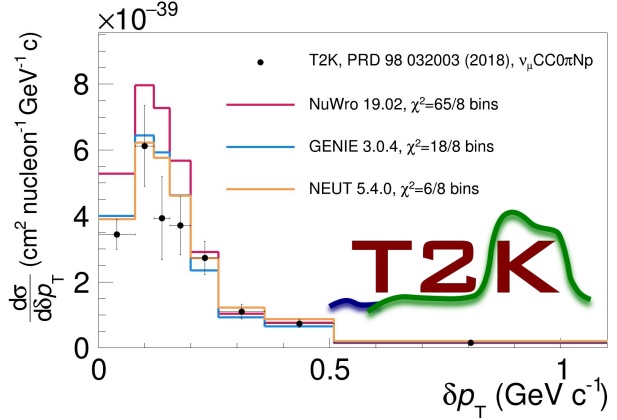
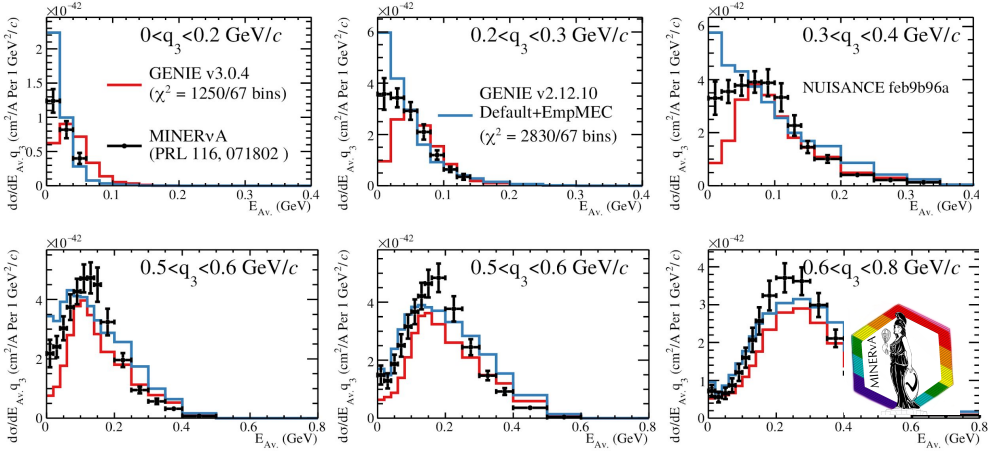
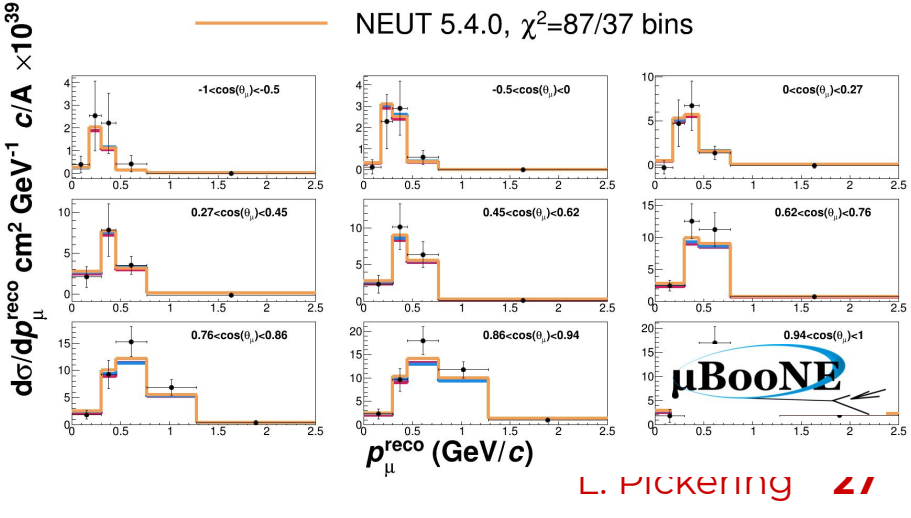



MicroBooNE, arXiv:1905.09694, $\nu_\mu$CCInc
NuWro 19.02, $\chi^2$=73/37 bins
GENIE 3.0.4, $\chi^2$=84/37 bins
NEUT 5.4.0, $\chi^2$=87/37 bins



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- Use the the data comparisons as a CI:
  - Build and run each generator, make comparisons to 'all' the data and the previous versions and checks.
- We are overworked postdocs (whinge whinge), but **really really** want NUISANCE to be a community project and community driven.
  - We might need a little help with direction…

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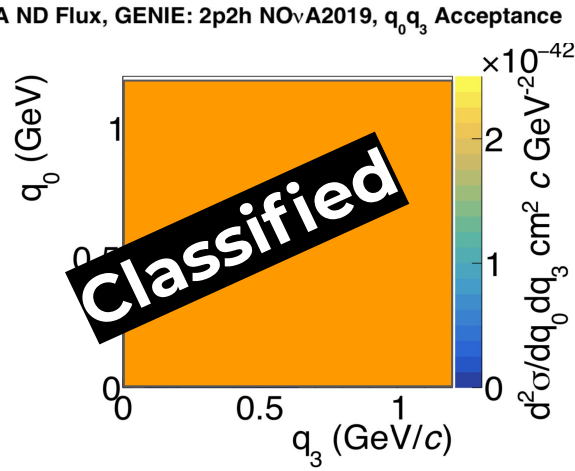
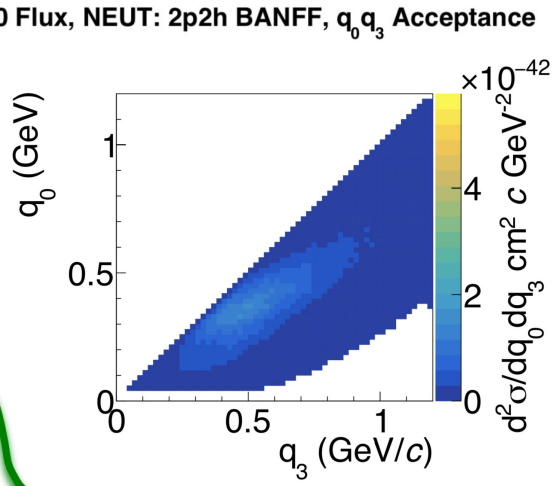
# Event Summary Trees

- Ability in NUISANCE to write a simple ‘analysis’ that takes common-format events and writes out an arbitrary analysis tree:
  - Write common analysis for NEUT/GENIE/NuWro/(GiBUU)
  - Useful at NuSTEC and cross-collaboration workshops
  - Currently being used extensively in T2K-NOvA studies int- cross-correlating systematic uncertainties for a joint fit.
- Reading multi-generator input, applying experimental tunes, and approximate acceptances, and writing out ‘flat’ trees has been useful to users!

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# My Unstructured Thoughts on Event data structure

- My personal preferences (hopefully nothing controversial…):
  - POD (i.e. structs of primitives, no fancy constructors)
  - Composition over inheritance (an event has a vector of particles, not it is a vector of particles, etc…)
  - Minimal use of strings (enums/int codes instead, possibly with a meta-data tree that specifies the mapping between `int` and `string` in a given file but with minimal per/event strings)
  - No fancy methods for non-exhaustive specifics. *e.g.* `event.GetW()`
  - Shouldn't be nu scattering-specific (e-scat, pi-scat useful too)
- Comes with (or separately, but dependent) a library of helper methods:
  - `double CEFUtils::GetW(event);`
  - `std::vector<CEF::Particles> const &GetFSPiPlus(event);`
  - (shame about no UFCS in `c++20`…)

# My Unstructured Thoughts on Event Serialization

- ROOT I/O is useful, but...
  - I hate TObject subclass formats. They work well in strictly controlled environments (e.g. FNAL computing), but we have ended up with TBs of unreadable events because of insignificant changes in the data model (or compiler differences between events thrown on SL6, and tools built with SCD-provided:e17).
  - (containers can also help here...)
  - This would be rectifiable if the format was just a tree of primitives (possibly std::vectors or primitives).
- ASCII formats can be nice, readable, flexible... but can be inefficient
- HDF5? (community uses ROOT extensively... if we are going to have a serialized binary format, maybe just stick with ROOT)
- Nice if seralization is somewhat modularized from the class implementation itself...

# Recap: Luke's Questions that want Answers

- Is XSec ReWeighting on its last legs, or just getting started?
  - I'd guess that there are a few things that we will want to be able to reweight exactly, but that more tools are needed to fill the gaps…
- Do we want a common 'event' format?
  - If we do, will generators use it directly?
  - Should we 'standardize' a community format converter?
- If we have new code-bases that are dependent on the generators, can we work on their dependency/build interfaces:
  - GENIE is a long way ahead here, but if we're going to do this, it's worth writing down what we need before deciding whether we already have it.
- I haven't gone into the details of all that we use NUISANCE for, but does the community see it as a useful part of the 'generator tools'?

# Thanks for listening

L. Pickering


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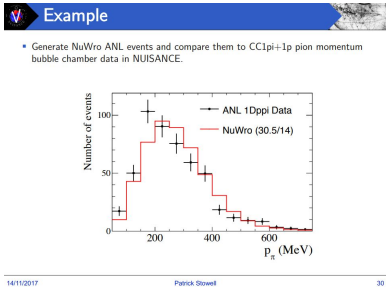
# Tutorials, how-to's

- Hosted tutorials at FNAL, J-PARC, NuSTEC, NuInt, and to interested experiments at collaboration meetings (MINERvA, MicroBooNE, T2K)
- https://nuisance.hepforge.org/nuisancetalks.html, https://nuisance.hepforge.org/tutorials/general.html and https://nuisance.hepforge.org/trac/wiki contains information on how to **run generators**, how to **run NUISANCE**, how to **include new data**, and so on
- Users range from Master's students to senior lecturers, **accessibility was key goal**
- Code is **open source** so analyses can be reproduced and extended


Pittsburgh, summer 2019


MINERvA school, Summer 2017




NuSTEC school, Autumn 2017


Oprah, Summer, 2004

# Some Example Comparisons

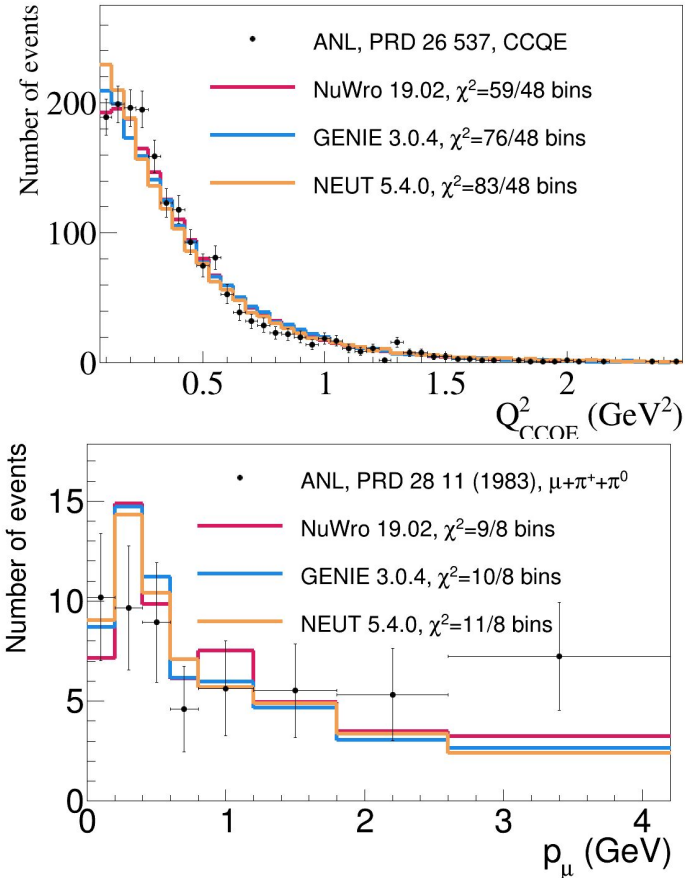
- Bubble Chamber lepton variables
- Nuclear-target CC0$\pi$ lepton variables
- Nuclear-target CC0$\pi$ lepton-hadron correlation variables
- (more than 300 measurements in NUISANCE)

# Meet the Generators

| | Version/ Tune Used | Nuclear-model + QE-like | Single Pion Production | Higher W | Fragmentation | FSI |
|---|---|---|---|---|---|---|
| NEUT | 5.4.0 | Valencia:<br>- 1p1h+RPA<br>- 2p2h | Rein-Sehgal + lepton mass effects | Bodek-Yang low $Q^2$ | Pythia 5 | Tuned Salcedo-Oset cascade |
| GENIE | v3.0.4 G1810a_0211 + bug-fixed splines | Valencia:<br>- 1p1h+RPA<br>- 2p2h | Rein-Sehgal 16 resonances non-interfering (BC Tuned) | Bodek-Yang low $Q^2$ | AGKY+Pythia 6 | Tuned effective single interaction (hA) |
| NuWRO | v19.02 | - Benhar SF w/ opt. pot.<br>- Valencia: RPA & 2p2h | Delta + Pythia Low W | Bodek-Yang low $Q^2$ | Pythia 6 | Tuned Salcedo-Oset cascade |

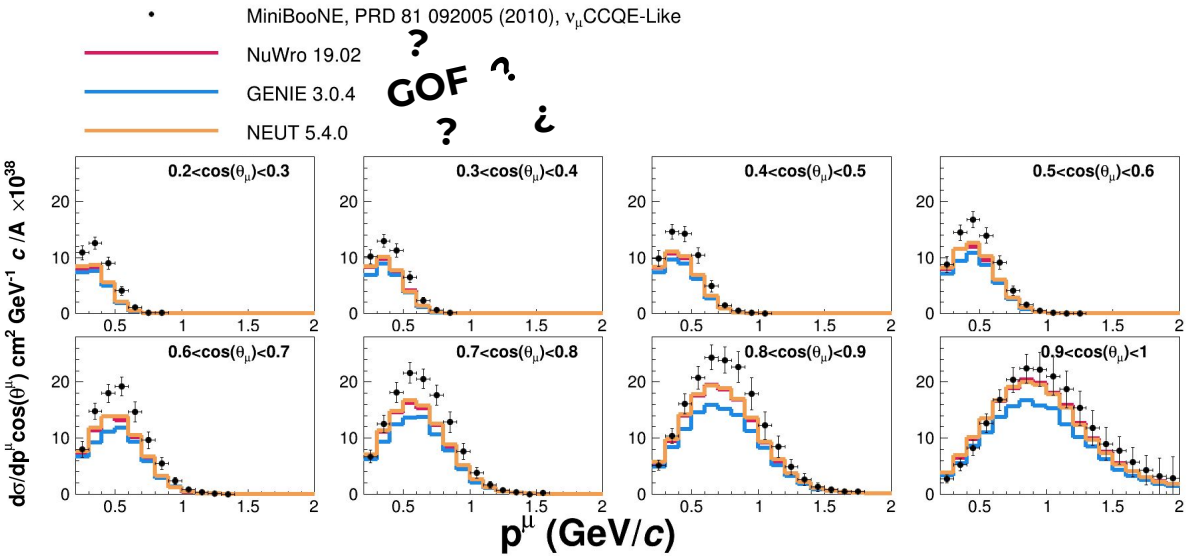
# Comparisons to Bubble Chamber data

- (quasi-)free of any nuclear effects.
  - Granular reconstruction and unambiguous final state topologies.
  - Allows tuning of ‘primary’ neutrino nucleon/part interaction.
- Data is old with large statistical errors and often unknown systematic errors (largely flux).

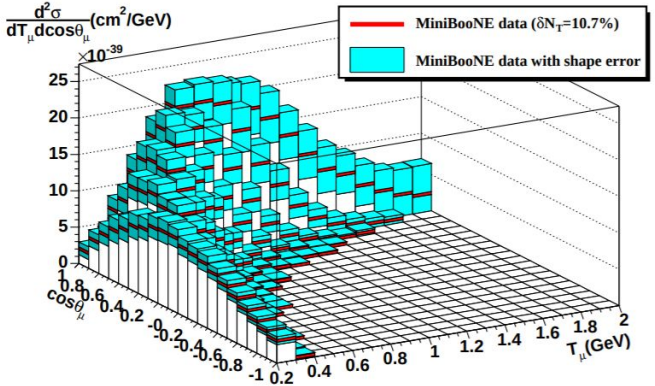


# Nuclear data: MiniBooNE CCQE

- Data sets without published, correlated errors are difficult to use in a global fit.
- MiniBooNE CCQE(like):
  - Many bins, no published error matrix.




PRD 81 092005

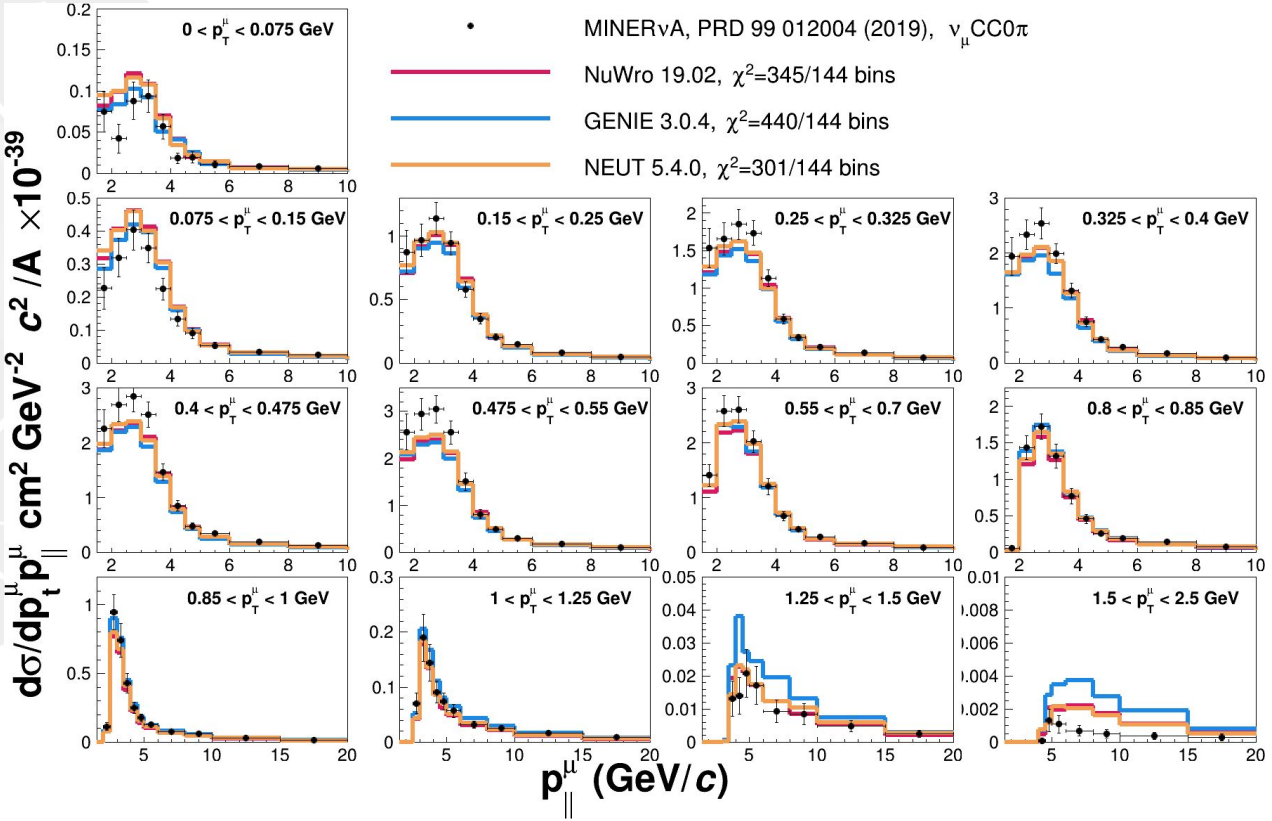



PRD 93 072010

| | $\chi^2_{min}/N_{DOF}$ |
|---|---|
| All | 117.9/228 |
| MINER$\nu$A | 30.3/13 |
| MiniBooNE | 65.7/212 |
| $\nu$ | 69.1/142 |
| $\bar{\nu}$ | 46.1/83 |
| M$\nu$A vs MB | 117.9/228 |
| $\nu$ vs $\bar{\nu}$ | 117.9/228 |

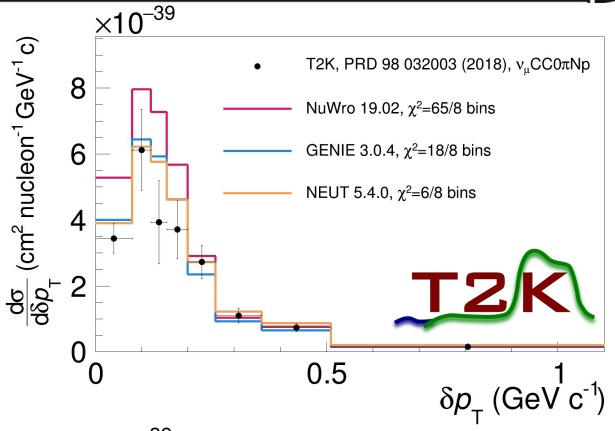
# MINERvA 0pi neutrino-mode

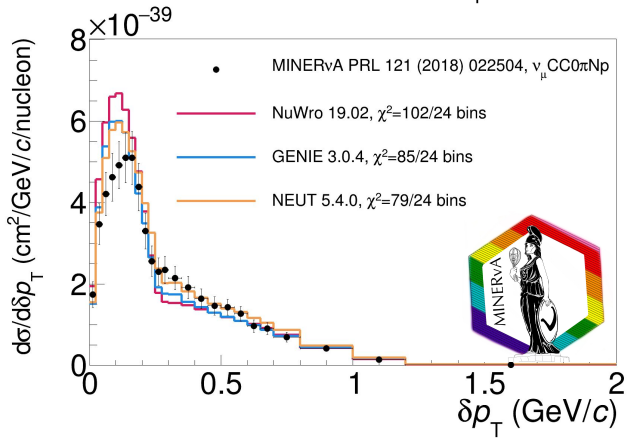
- Sensitive to neutrino energy ($p_{||}$) and momentum transfer ($p_t$) in a known flux



# Transverse missing momentum

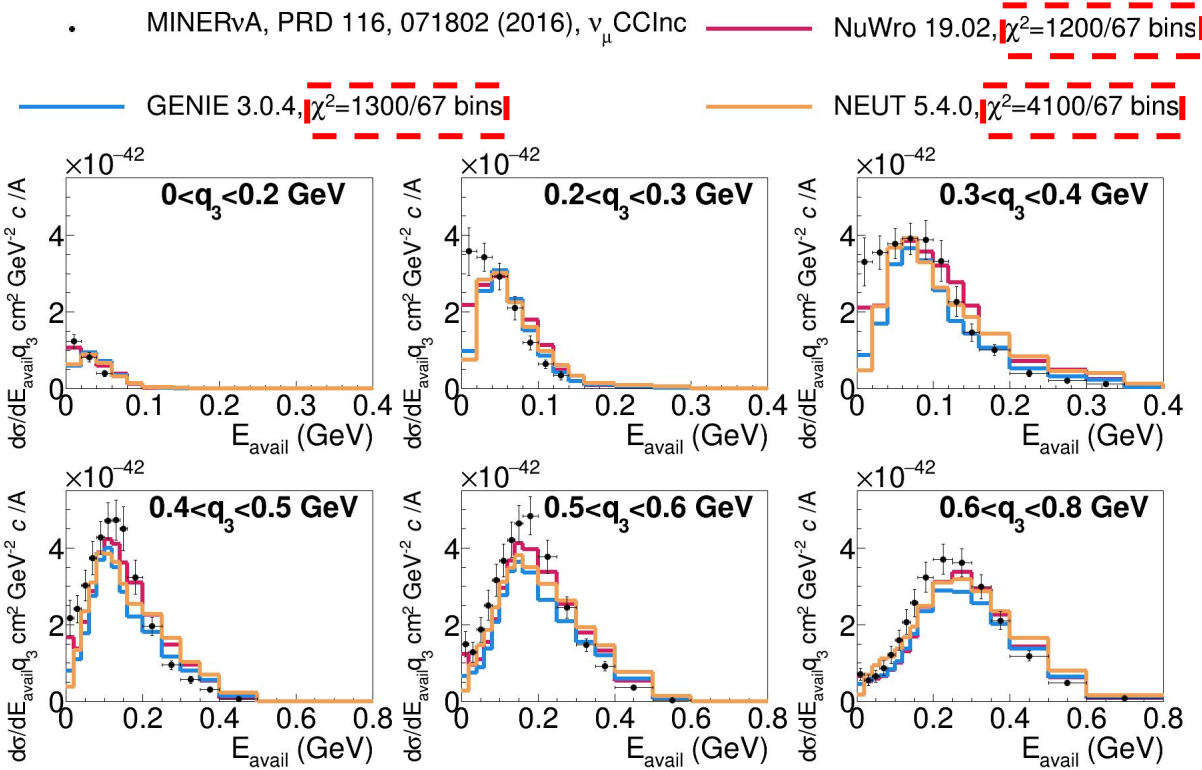
- Signal phase space cuts chosen for detector capabilities:
  - Results in less model-dependent efficiency correction.
  - T2K:
    - 500 MeV < $p_p$
    - 250 MeV < $p_\mu$, 1 < cos($\theta_\mu$) < -0.6
  - MINERvA:
    - 450 < $p_p$ < 1200 MeV, 0 < $\theta_p$ < 70°
    - 1.5 < $p_\mu$ < 10 GeV, 0 < $\theta_\mu$ < 20°



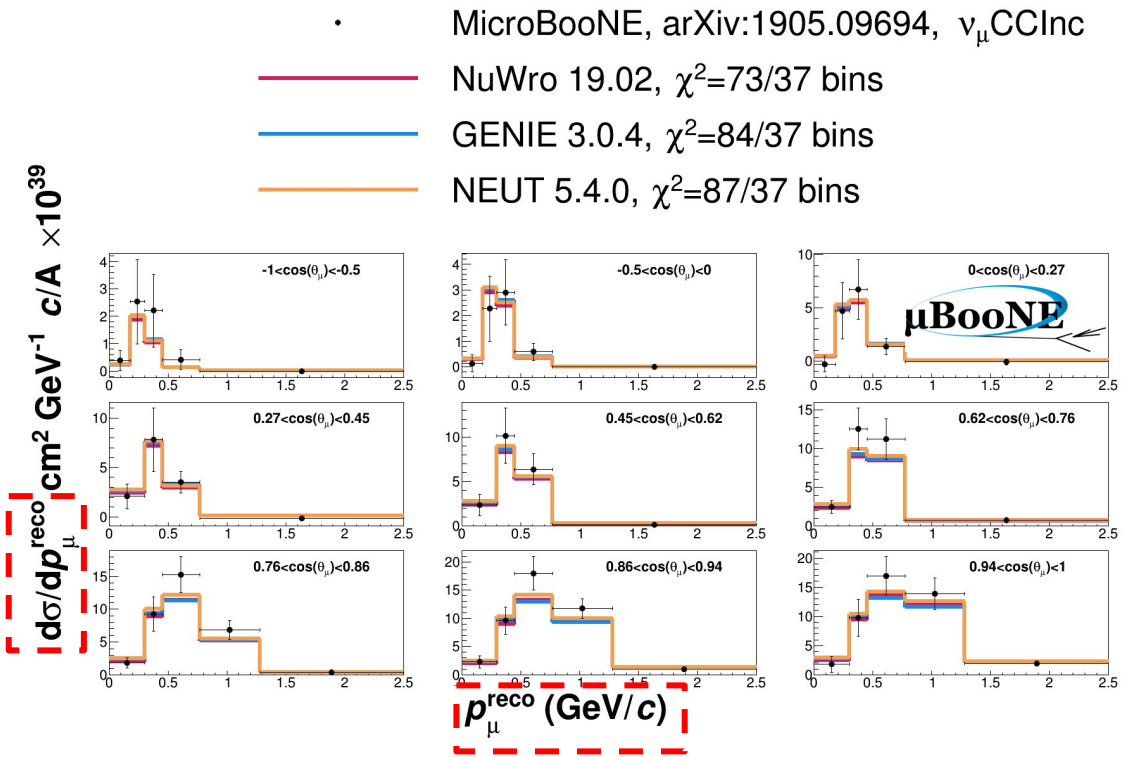
# MINERvA CCInclusive: Low recoil

- Inclusive models described by q0/q3:
  - Requires model-dependent reconstruction of EAvail and true momentum transfer.
- GOF is awful for all available models:
  - Inconclusive when comparing one bad fit to another bad fit.



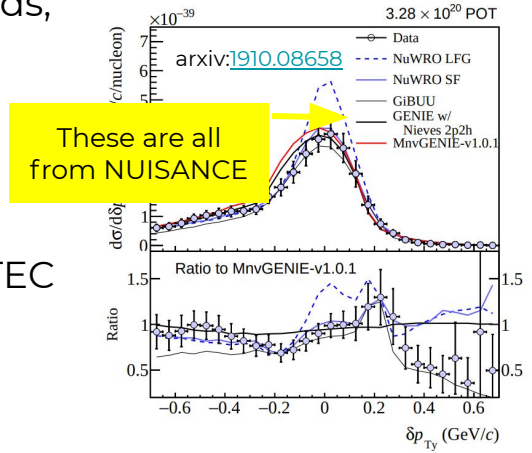
# Comparisons to Nuclear data: MicroBooNE

- Need to understand neutrino interactions on Ar40 target.
- Data release:
  - Reconstructed distributions
  - True→reco folding matrix
- Potentially useful technique to reduce model bias in published data.



# What have we done so far?

- Uncertainties on interaction systematics T2K oscillation analysis from external data and comparisons to other generators (see T2K oscillation papers)
- Evaluating goodness of new NEUT models for T2K analyses choices (PRD93, 072010)
- Pittsburgh Tensions cross-experiment cross-generator workshops, evaluating generator vs generator vs data (Physics Reports 773–774)
- MINERvA-NOvA workshop: comparing MINERvA fit (MnvGENIE) to NOvA fit and data
- NOvA-T2K workshop: comparing models and uncertainty bands, Find overlap in treatment of systematics
- T2K, MINERvA publications for multi-generator predictions
- MINERvA pion tuning paper (PRD 100, 072005)
- Discussions about the future of data releases, e.g. NuInt, NuSTEC




## Shared goals with NuSTEC and NuInt

# What do we want to do?

- Large survey of the current generators, publish in some reference journal
  - Hopefully happening this winter/spring
- Continue providing community with ad-hoc tunes
  - Does not replace good solid theory! We're accounting for uncertainties, not trying to build a wholesome model

- Formalise suggestions for future data releases in high statistics era
- Expand NUISANCE to have representatives on each experiment?
- Neutrino experiments often have their own tune: compare and discuss these
  - e.g. MINERvA, T2K, NOvA, MicroBooNE tunes
- Produce a container with all generators and tools pre-installed for easy use
  - Prepared for recent T2K-NOvA workshop, largely successful

- Expand electron scattering interface
- Support pion and nucleon scattering

## Shared goals with NuSTEC and NuInt

# Summary

- NUISANCE is a tool for generator--data comparisons
  - Contains a large number of datasets and associated signal definitions for you to use.
  - Has tools for performing ‘global’ cross-section comparisons and tunes.
  - **But: You have to be aware of the details of the data you comparing to!**
- We’ve worked with experiments and generators on making predictions, evaluating models, producing ad-hoc tunes
- **Many goals shared with NuSTEC and NuInt**
- If any of this sounds interesting, **get in touch**, plenty of work and development that can be done by people with a range of experiences!

# Thanks for listening

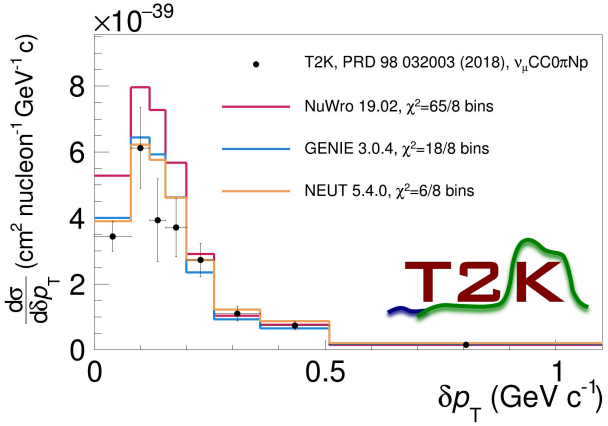
L. Pickering


MICHIGAN STATE UNIVERSITY

(NuFACT2018, VT, Blacksburg)

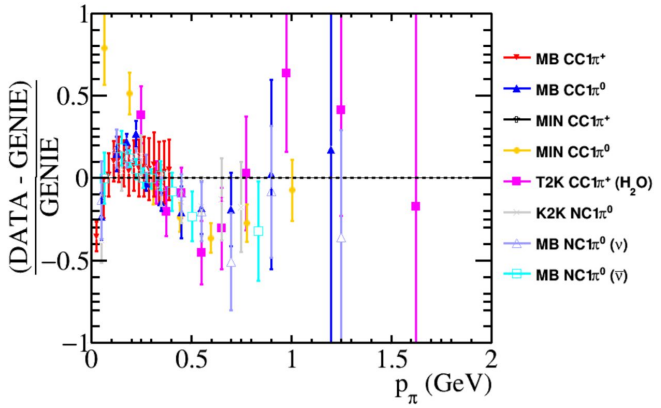
# What is needed from Data Measurements

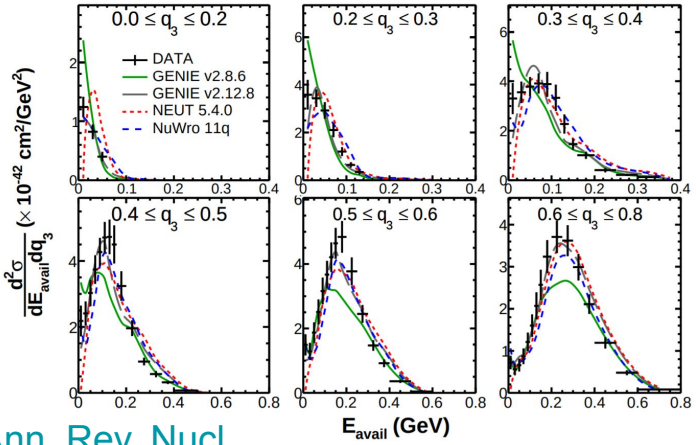
- Minimize model bias while maximising efficacy of data:
  - Well-understood selection efficiency over signal phase space.
  - Projections the require minimal MC correction.
- Publish errors with bin-to-bin correlations.



# Why NUISANCE might be right for you

- Consistently comparing your model predictions to many data-sets.
- Producing comparisons to your new data set with a variety of MCs --- without having to be an expert.
- **Ensure that comparisons to your data are done correctly.**
- Tools make cross-section parameter fitting mechanically simple:
  - **But, garbage in → garbage out.**
  - Choice of data, choice of parameters, structure of fit is the tough bit.



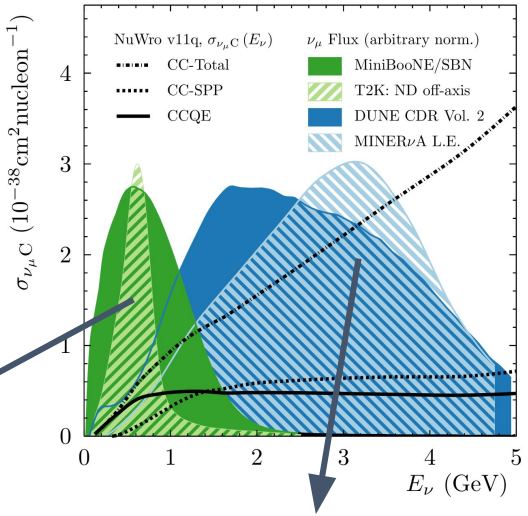



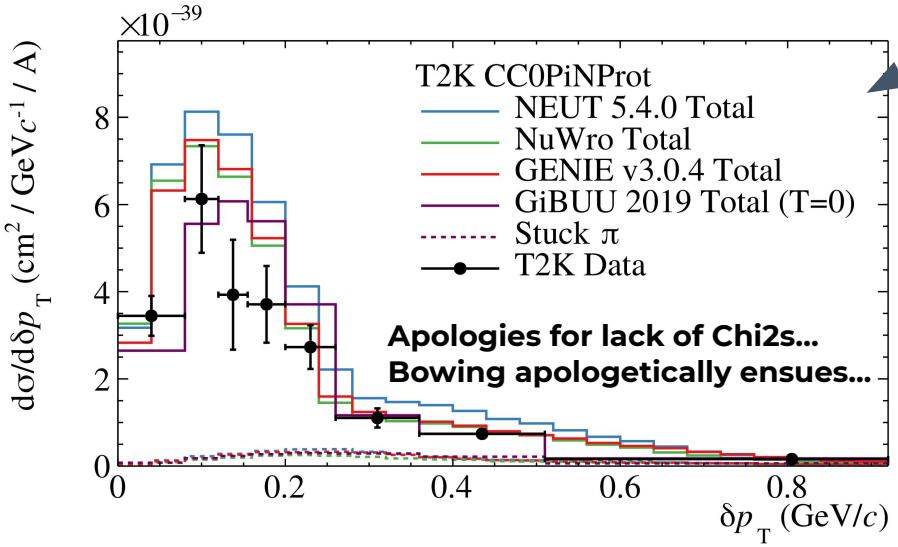

Ann. Rev. Nucl. 101917 020930

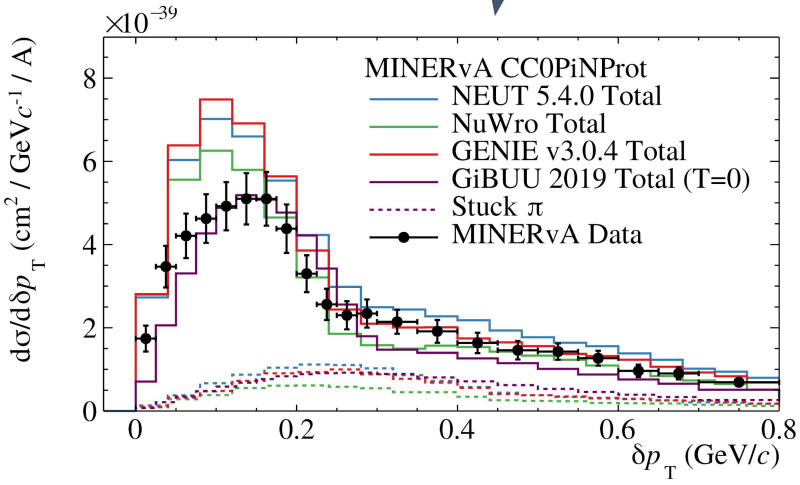
https://doi.org/10.1016/j.physrep.2018.08.003

# Data Comparison: $\delta p_T$

- T2K: 1802.05078
- MINERvA: 1805.05486
- (GENIE norm may not be quite right to a few %, its fine for here, but probably not best to show these plots as is elsewhere)



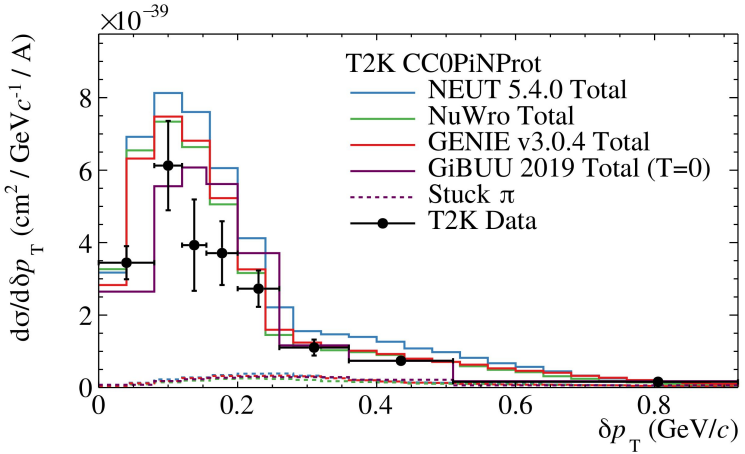



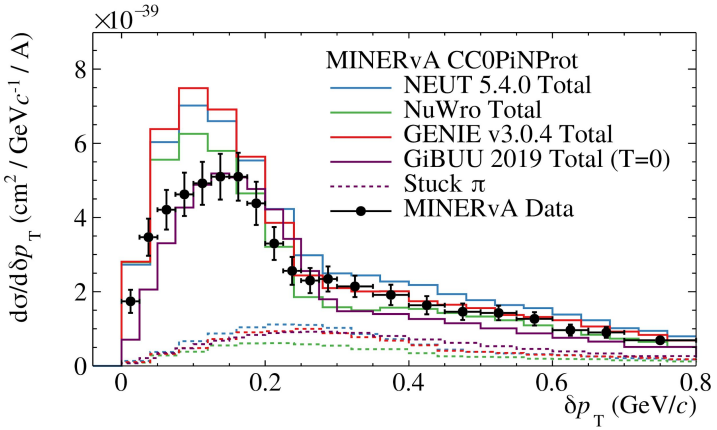
# Signal definitions

- T2K: 1802.05078
- MINERvA:  1805.05486
- (GENIE norm may not be quite right to a few %, its fine for here, but probably not best to show these plots as is elsewhere)

**500 MeV < pp**
**250 MeV < pmu, 1 < cos(theta_mu) < -0.6**

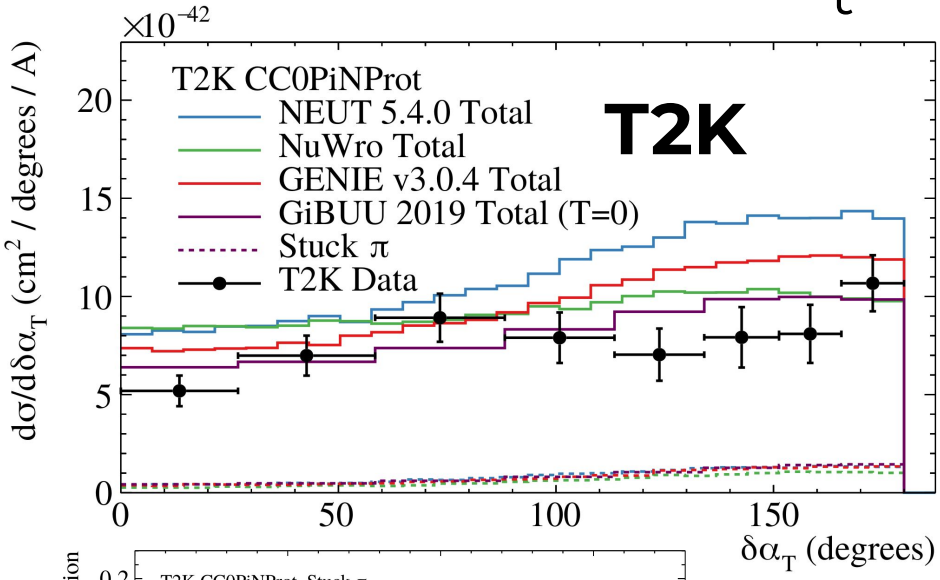


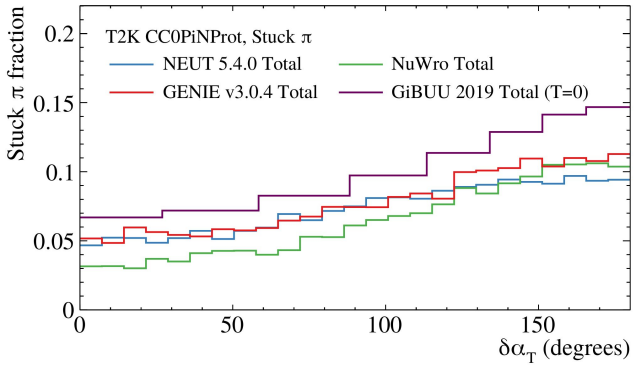

**450 < pp < 1200 MeV, 0 < theta_p < 70°**
**1.5 < pmu < 10 GeV, 0 < theta_mu < 20°**

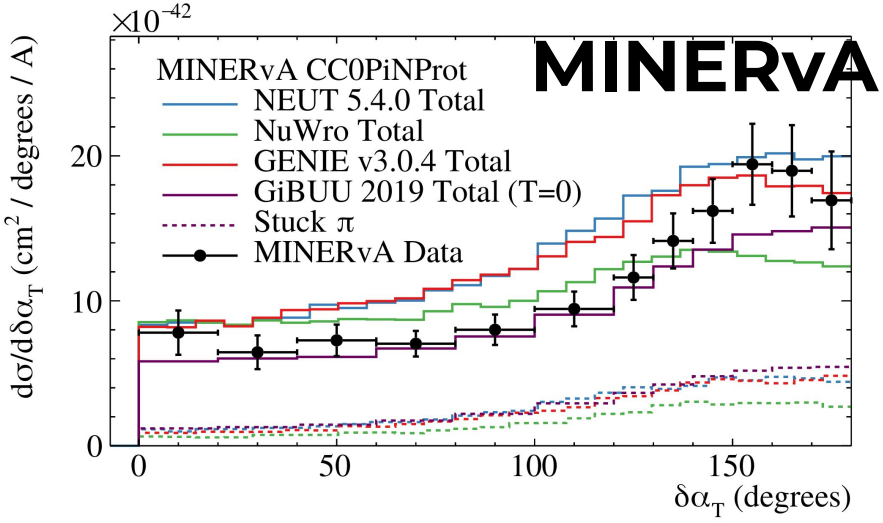


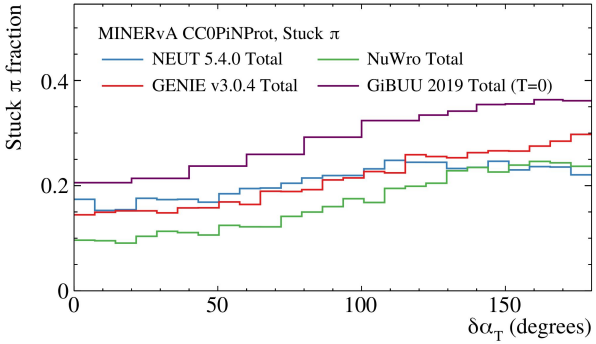
# Stuck pion rate: $\delta\alpha_t$

QEL-pure at low δαt
FSI and stuck pion rich at higher δαt



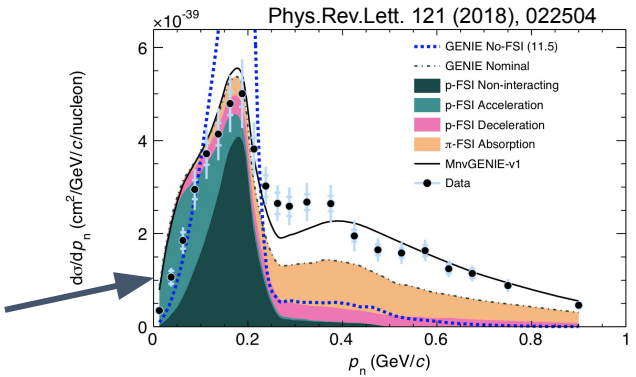



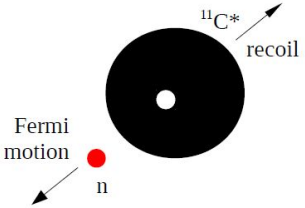



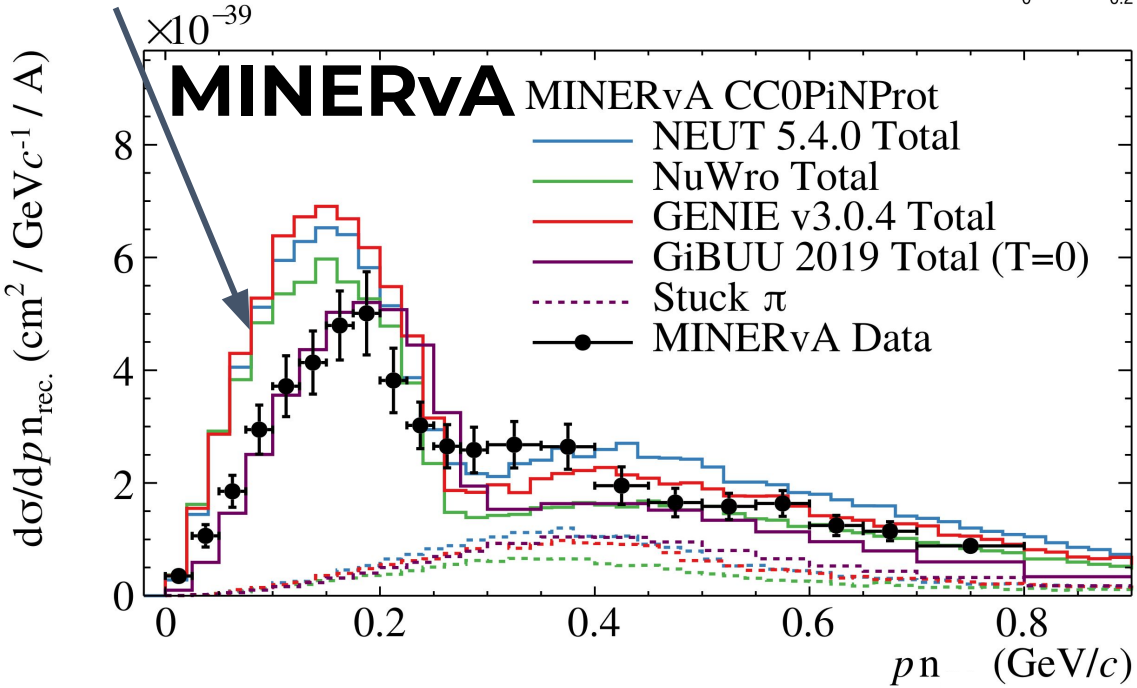
# pn

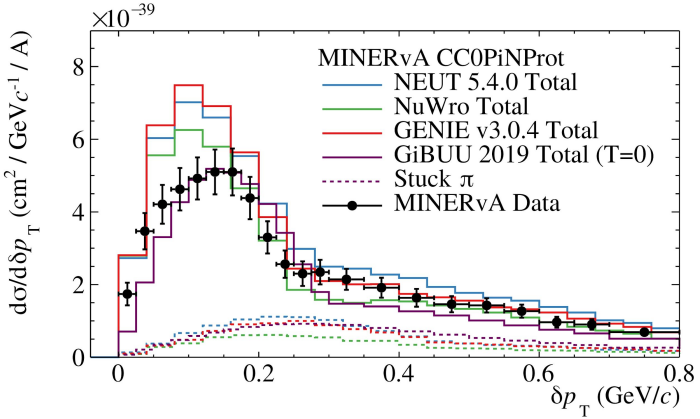
Phys.Rev. C95 (2017) 065501,
see definition in BACKUP

- S. Dolan: Relative to dpt, stuck pions more away from QEL peak **(all non-QE, see later, backup)**
- GENIE V304 below no longer has elastic hA, less lumpy



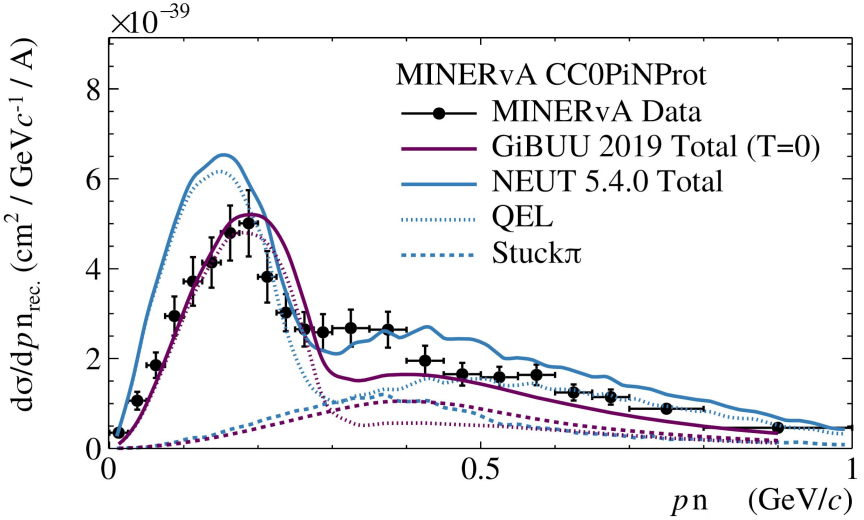



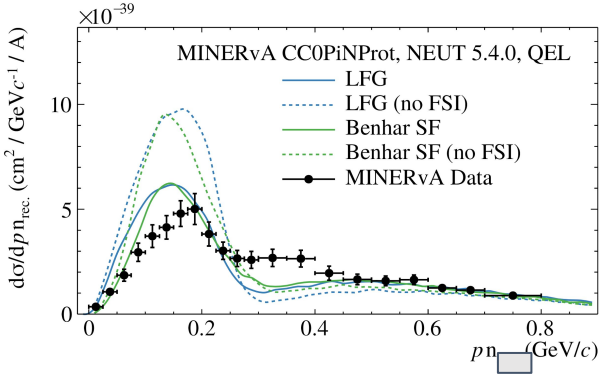



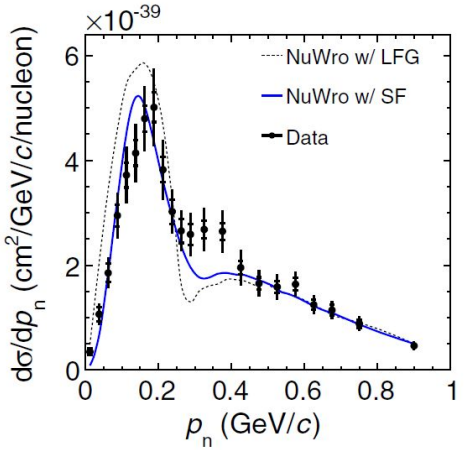



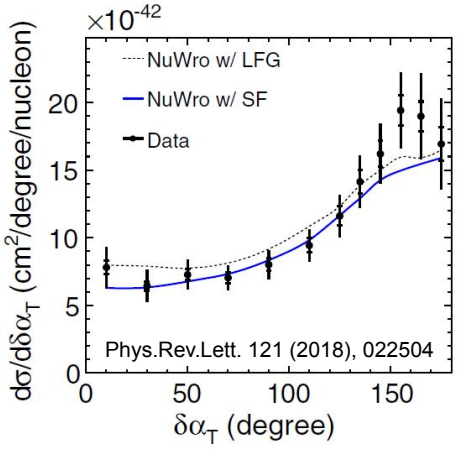
# More pn

- Also wanted to look at stuck pi vs. 2p2h
  - GiBUU predicts no second peak for QEL, but NEUT does.
- And FSI/Nuclear momentum/binding model changes:
  - LFG/SF in NEUT qualitatively similar, **contrary to NuWro**
  - FSI mostly interacts with signal selections
- May be interesting to look at energy evolution as well (see last BACKUP)



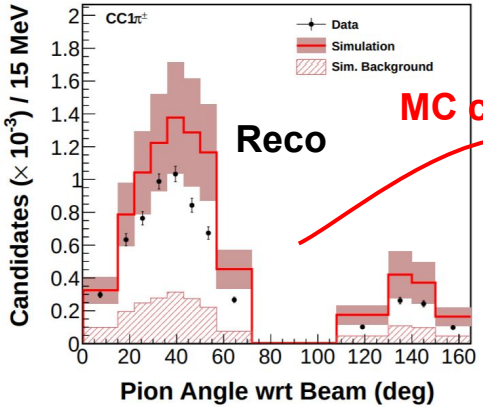



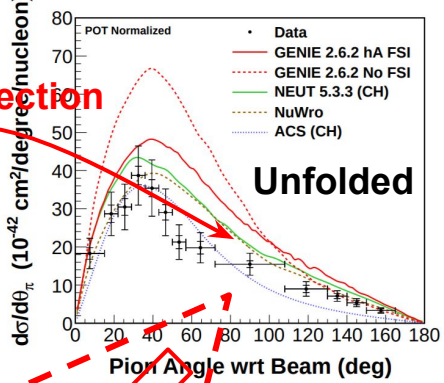
# MINERvA 1pi neutrino-mode

- For the charged pion analyses:
  - ~100% efficiency correction at high angle.
  - Where is this ‘MC fill-in’ in other distributions?
- Upcoming re-analysis still no phase space cuts.
- No covariance between distributions ($p_\mu$, $\theta_\mu$, $T_\pi$, $\theta_\pi$, $Q^2$) or samples ($\pi^+$, $\pi^0$, $\nu$, $\bar{\nu}$):
  - Difficult to consistently use together in a meta-analysis.

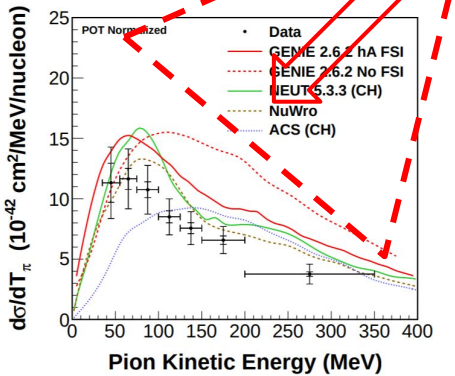
PRD 92 092008




MC correction

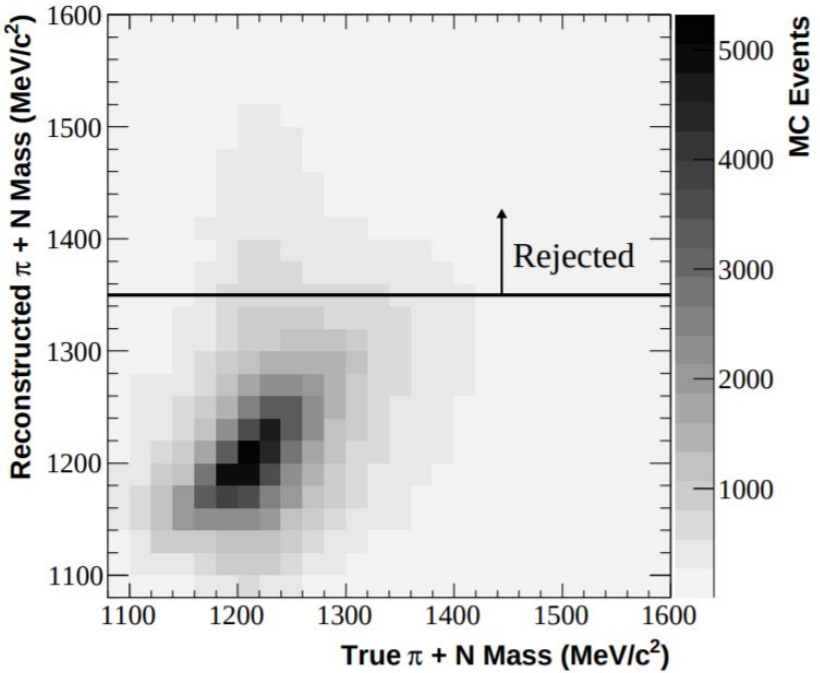



Where is MC in different projection…?



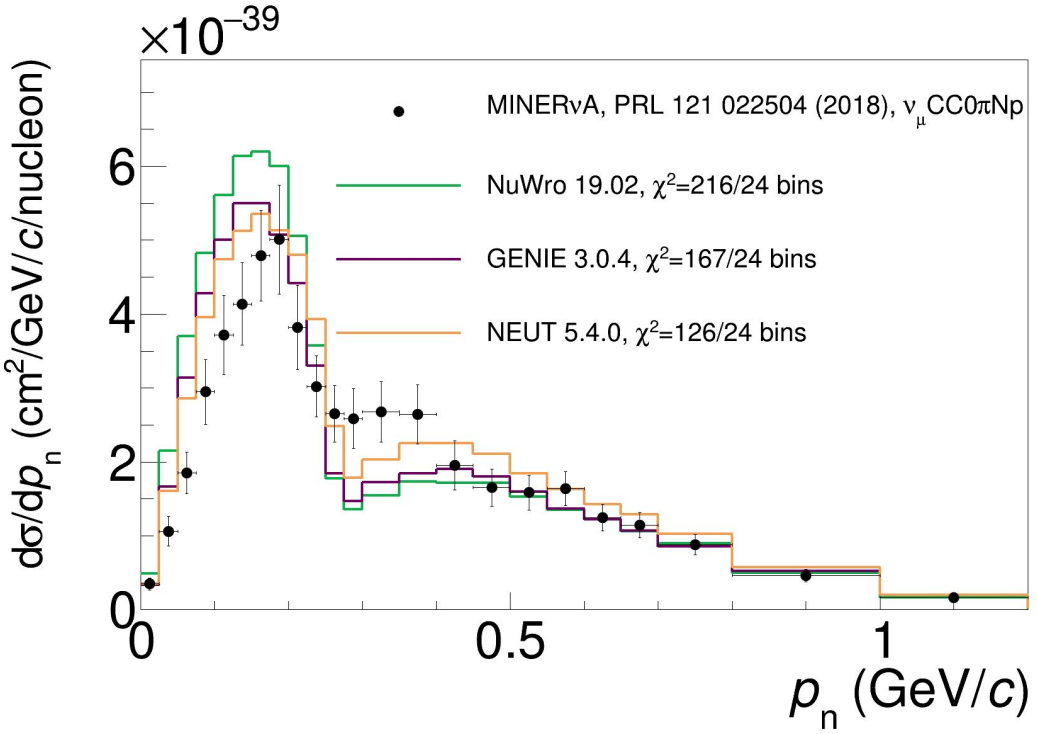
# MiniBooNE 1Pi+

- Rejection only in selection, not signal definition:
  - Will be efficiency corrected back with NUANCE-calculated efficiency.
  - Better to include analysis cuts in both signal and selection where possible, then handle new out-of-phase space backgrounds, but smaller, less model dependent efficiency corrections.



# MINERvA: Initial state neutron momentum

- Momentum imbalance in all three dimensions is sensitive to initial state fermi nucleon momentum distribution.
  - GOF is poor for all models.



# Notable Recent Developments

- NEUT:
  - Nieves 1p1h, LFG nuclear model
  - Improved multi-pion production from BC tune
  - MK pion production, Bug fixes in R-S pion production

# Notable Recent Developments

Phys. Rev. C 100, 015505 (2019)

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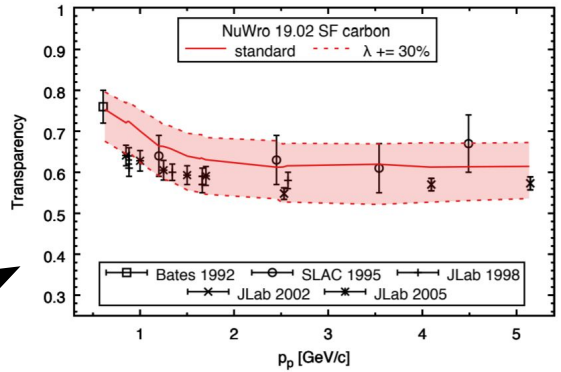
  - MK pion production, Bug fixes in R-S pion production
- NuWro:
  - Updates to spectral function
  - Update of FSI cascade by comparison to nuclear transparency data.
  - Integration of electron scattering simulation.



# Notable Recent Developments

Phys. Rev. C 100, 015505 (2019)

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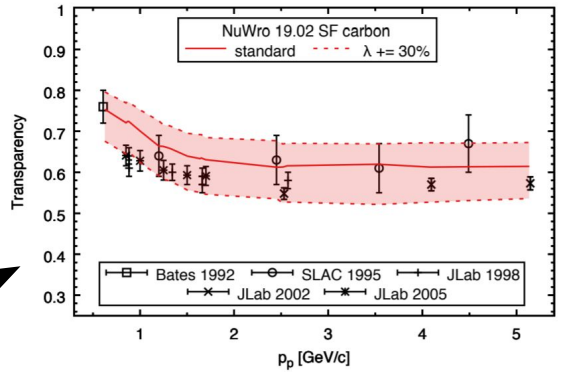
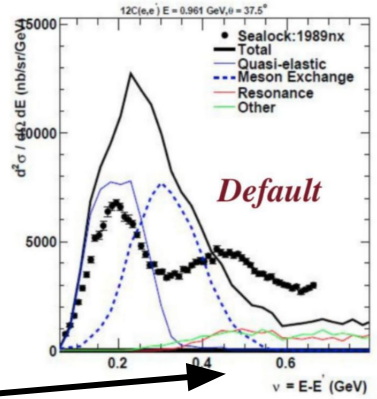
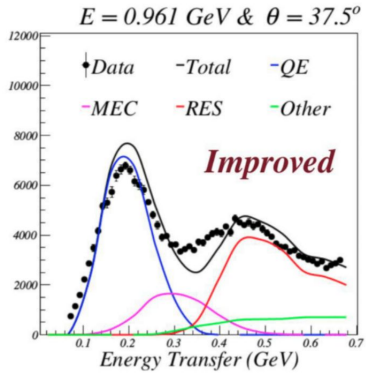
  - Improved multi-pion production from BC tune
  - MK pion production, Bug fixes in R-S pion production
- NuWro:
  - Updates to spectral function
  - Update of FSI cascade by comparison to nuclear transparency data.
  - Integration of electron scattering simulation.
- GENIE:
  - Version 3 released!
  - Extensive $\nu$-N tuning to bubble chamber data
  - **Many improvements to electron scattering simulation (c.f. Or Hen e4nu Plenary)**
  - Some significant bug fixes



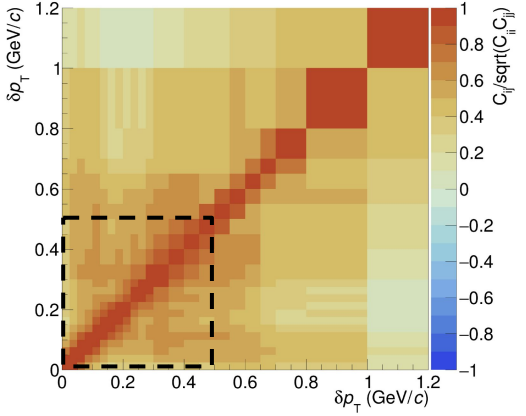



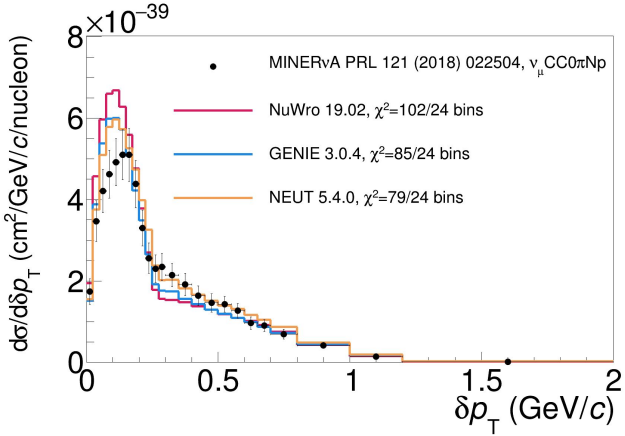

*Genie R-2_12_10

# Transverse missing momentum

- MINERvA error matrix provides a tight shape constraint around the peak which drives the high GOF.

MINERvA: PRL 121 (2018) 2, 022504

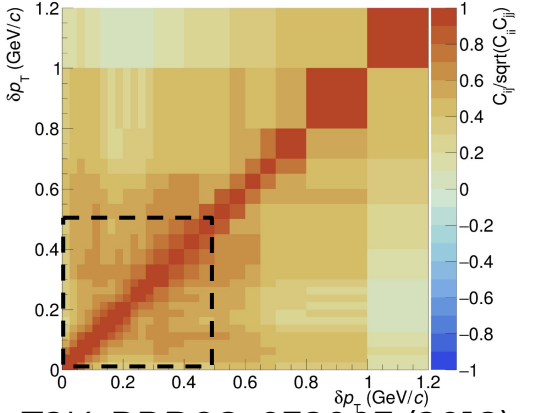


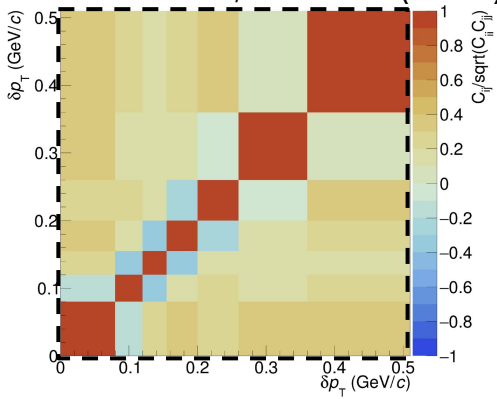
# Transverse missing momentum

- MINERvA error matrix provides a tight shape constraint around the peak which drives the high GOF.
- Equivalent matrix for the T2K result exhibits anti-correlations between neighbouring bins:
  - More expected for uncertainties that cause bin migrations.

MINERvA: PRL 121 (2018) 2, 022504




T2K: PRD98, 032003 (2018)



# Gen Summary

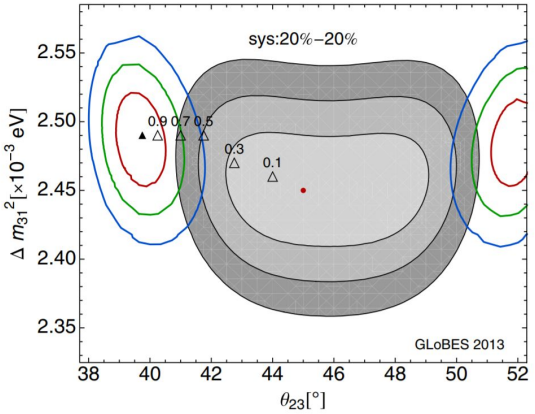
- The loftiest goals of neutrino oscillation physics depend on the accuracy of event generator predictions and associated uncertainties.
- Recent $\nu_\mu \rightarrow 0\pi$ data releases have been more statistically robust, but GOF between available models is generally poor
  - Room for improvement in generator predictions, xsec analyses and data releases and global fitting methodology.
  - Correct, correlated errors are a comparators best friend!
- More recent work on removing assumptions in generator factorization and implementing state-of-the-art predictions is promising!

# Why do we need good interaction Models?

- The aim is to perform measurements of neutrino oscillations.
  - Oscillation occurs as a function of true neutrino energy, which is **not observable**.
- We use models to estimate: $\mathbf{D}\left(\mathbf{x}_{\mathrm{obs}}|\mathbf{x}_{\mathrm{true}}\right)$: *If we see* $\mathbf{x}_{\mathrm{obs}}$, *what was the true neutrino energy?* We need to understand:
  - Selected backgrounds
  - Selection efficiency
  - Exclusive channel interaction rates and kinematics
- Wrong model → wrong inferred $P_{osc}\left(E_{\nu}\right)$.

$$N_{\mathrm{near}}\left(\mathbf{x}_{\mathrm{obs}}\right)=\int d\mathbf{x}_{\mathrm{true}}\underbrace{\mathbf{D}_{\mathrm{near}}\left(\mathbf{x}_{\mathrm{obs}}|\mathbf{x}_{\mathrm{true}}\right)}_{\text{Smearing, Eff., Pur.}}\underbrace{N_{\mathrm{targ}}\sigma\left(\mathbf{x}_{\mathrm{true}}\right)\Phi\left(E_{\nu}\right)}_{N_{\mathrm{Int}}\left(\mathbf{x}_{\mathrm{true}}\right)}$$

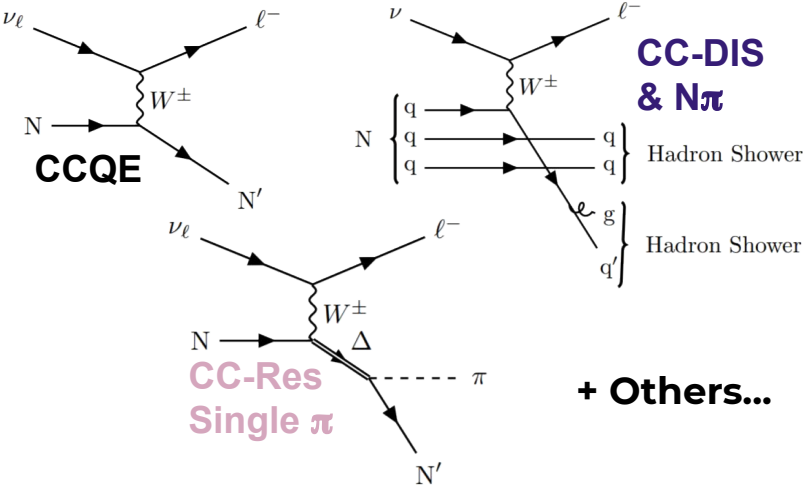
$$N_{\mathrm{far}}\left(\mathbf{x}_{\mathrm{obs}}\right)=\int d\mathbf{x}_{\mathrm{true}}\underbrace{\mathbf{D}_{\mathrm{far}}\left(\mathbf{x}_{\mathrm{obs}}|\mathbf{x}_{\mathrm{true}}\right)}_{\text{Smearing, Eff., Pur.}}\underbrace{N_{\mathrm{targ}}\sigma\left(\mathbf{x}_{\mathrm{true}}\right)\Phi\left(E_{\nu}\right)P_{osc}\left(E_{\nu}\right)}_{N_{\mathrm{Int}}\left(\mathbf{x}_{\mathrm{true}}\right)}$$

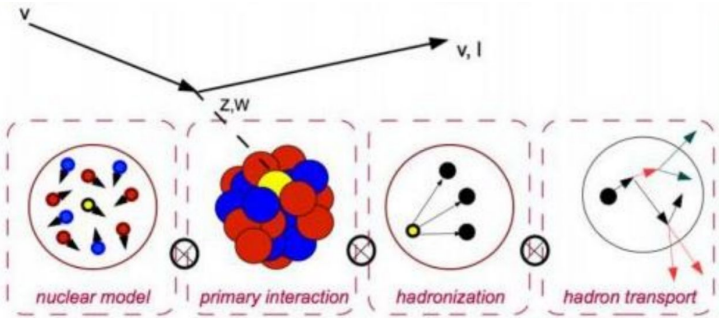



PRL 111.221802

# What is a Neutrino Event Generator

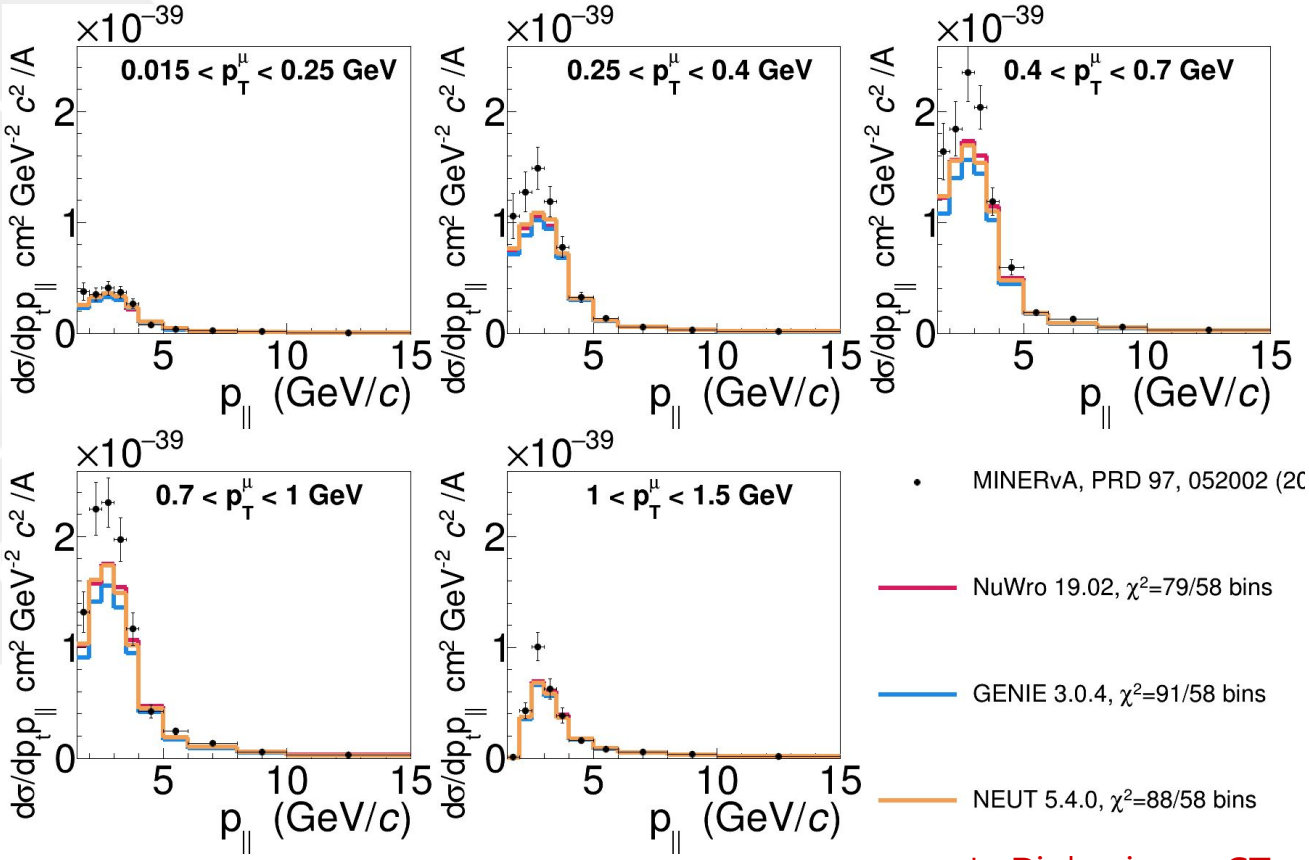
- Selects neutrino ‘events’ from interaction models:
  - **Over a range of neutrino energy and species,**
  - **For a number of ‘primary’ channels**:
    - Neutrino--nucleus (COHPi, CvNS)
    - Neutrino--multi-nucleon (2p2h)
    - Neutrino--nucleon (QE, RESPi)
    - Neutrino--parton (DIS)
  - **In a nuclear environment**:
    - Fermi motion distribution
    - Removal energy
    - Collective effects (RPA)
    - Final state re-interactions of primary particles
- Often factorises the simulation of nuclear model, primary interaction, and FSIs.



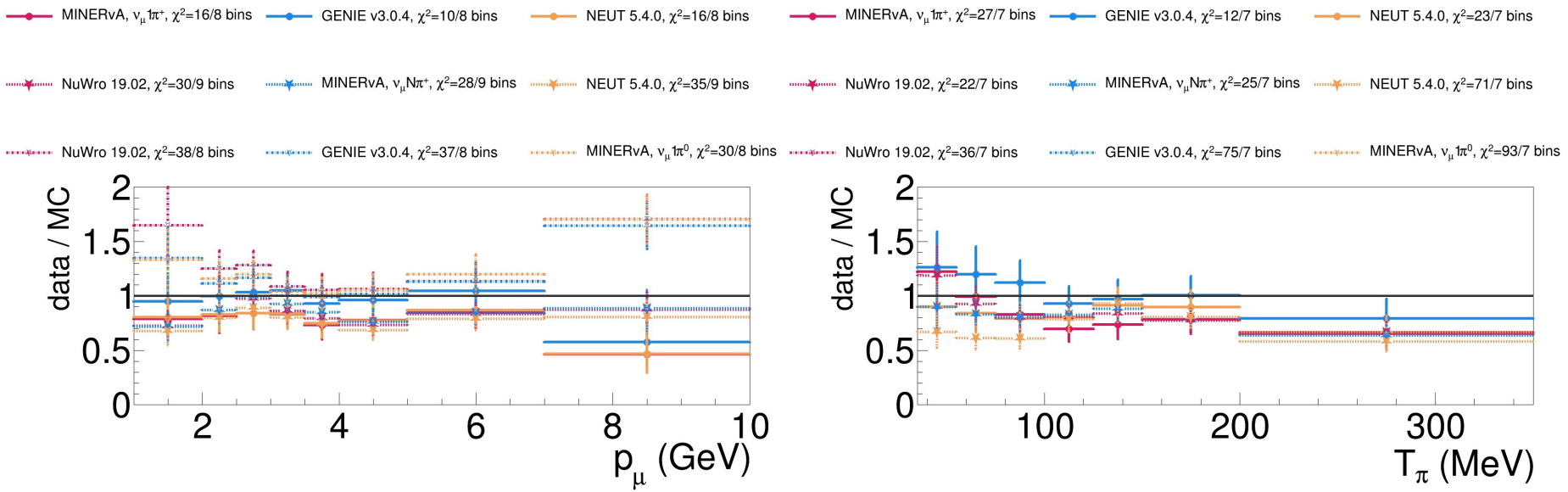
# MINERvA 0pi anti-neutrino-mode

- $\chi$-by-eye GOF seems worse (to me) than calculated GOF.
- Possibly because of PPP:
  - Smaller MC normalization can give 'artificially' low $\chi^2$ if uncertainty is not fully characterized.
- Need to be wary of PPP when fitting.



# MINERvA 1pi neutrino-mode

- MINERvA have released a number of pion datasets, each with multiple projections
  - Lots of information, much more than shown here.
  - Fairly poorly predicted all around.
- arXiv:1903.01558: discusses some of the difficulties seen fitting these data.



# Gen Future: 1

- Last few years seen increase in sophistication of 0pi analyses
  - Lepton/hadron correlations
  - Less Model-dependent selections and projections
  - Would be very useful to see similar renaissance in pion production datasets.
- Future MicroBooNE (and SBND) data sets will be critical for model builders to benchmark and develop before DUNE and Fermilab Short Baseline program.

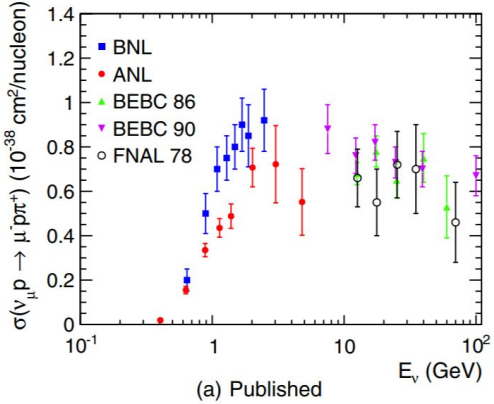
# Gen Future: 2

- These last two years have seen an uptick in model development:
  - GENIE tuning, v3, NEUT and NuWro model developments, ECT* Trento workshops
  - Lots of progress due to closer interaction with theory community, need to continue!
- But given how much LBL programs will rely on the predictions and uncertainties, the community is quite under person-powered…
  - Plenty of room for important work and novel intellectual contribution
- Can learn a lot of the necessary nuclear physics from electron scattering: GENIE + NuWro have e-A modes, ongoing work by **e4nu**.
- See what GiBUU has to say for itself…

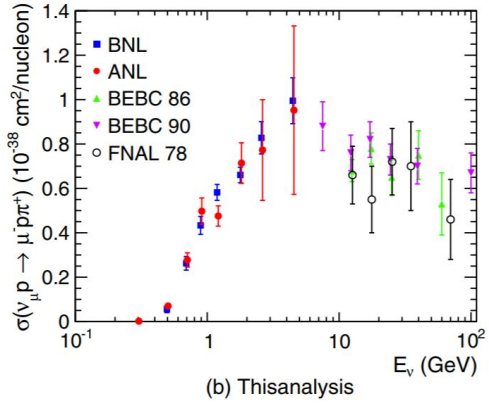
# The data is the data is the data

PRD 90 112017

- Sometimes the data is not the data is not the data.
- ANL/BNL CC1pi+1proton discrepancy:
  - Data biased by problems in the neutrino flux models
  - ~ Reconciled by re-analysis.
  - **But, no correction for Q2 distribution!**
- Need to be familiar with included data sets and tensions between them.
  - May need to assign *confidence* weights to samples in the global GOF.



(a) Published

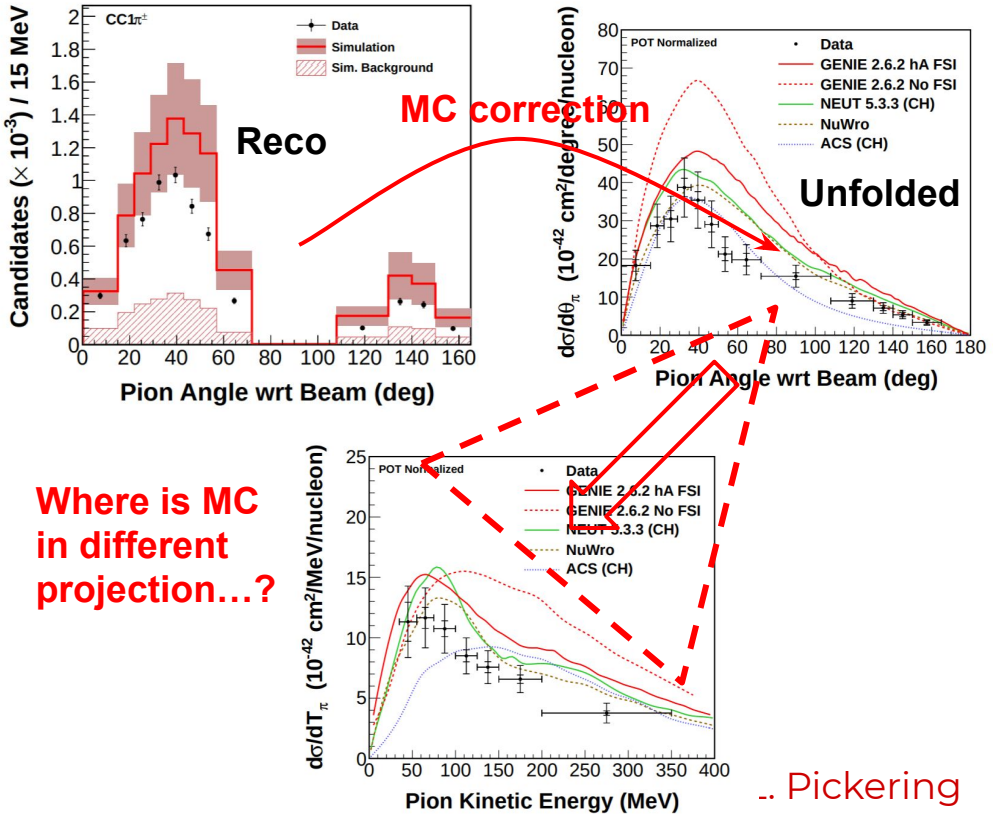


(b) Thisanalysis

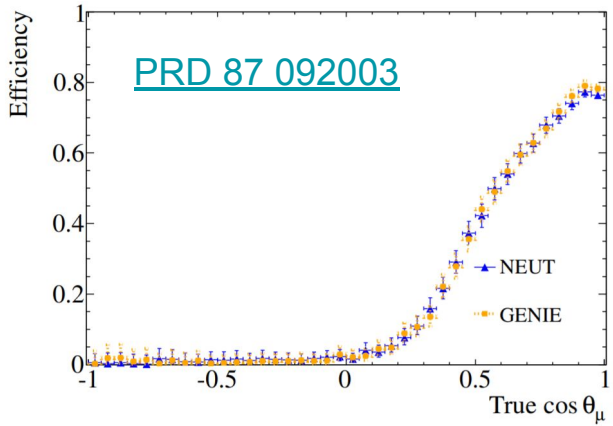
# Hidden Model Biases 1

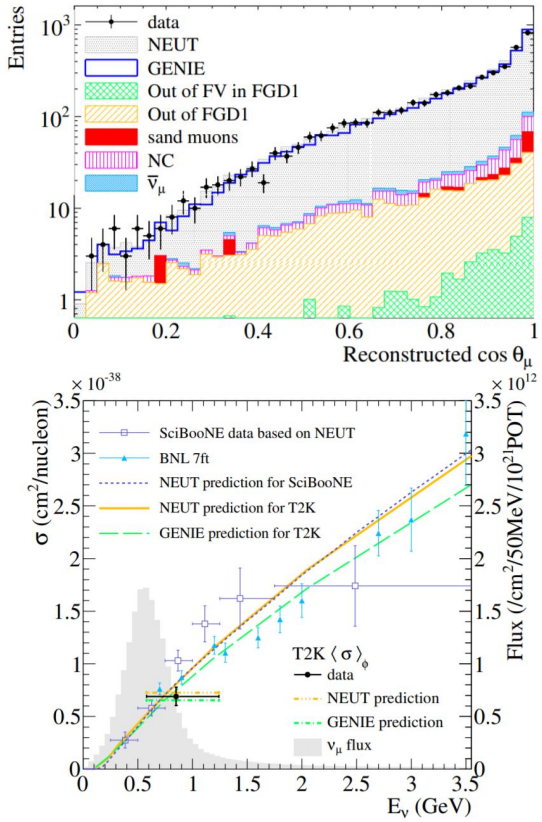
- Un-smearing and efficiency corrections introduce bias.
- From a fitters point of view, it is better to cut out regions of very poor efficiency:
  - Don't want to compare to *model-of-the-day* contaminated 'data'.
- Very helpful that such plots are in the publication!
- *N.B.* These problems are tricky and ubiquitous, not specifically calling out this publication.

PRD 92 092008



# Hidden Model Biases 2: Stealth mode

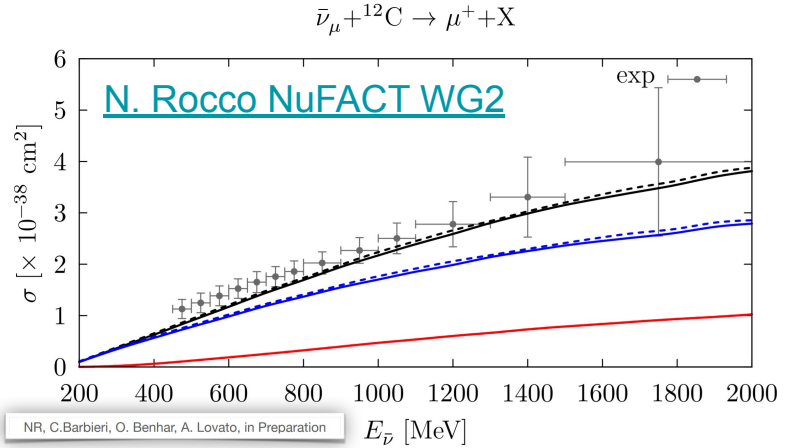


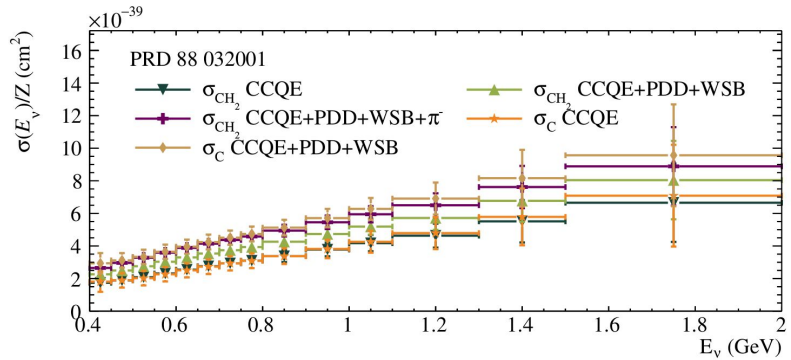




- It isn't always so clear: *e.g.* ND280 CCIncl
  - Practically cannot measure cos(θμ) < 0.
  - But, publish total cross-section.
- Similar out-of-acceptance corrections in many recent measurements: *Fiducial* cross-sections are much preferred!

# Experimental Signal Definitions

- Not always fully clear from the publication:
  - Getting this correct is essential for interpreting the data.
- *e.g.* MiniBooNE CCQE C12 data, subtracts:
  - Wrong-sign background CH2.08 component
  - H2.08 component
  - non-QE component (PDD)
  - Mis-ID'd π-
- All predicted by **NUANCE**…
- But, the background subtractions are provided:
  - Might be better to produce H and ν-C12 predictions and compare to the less-corrected data.

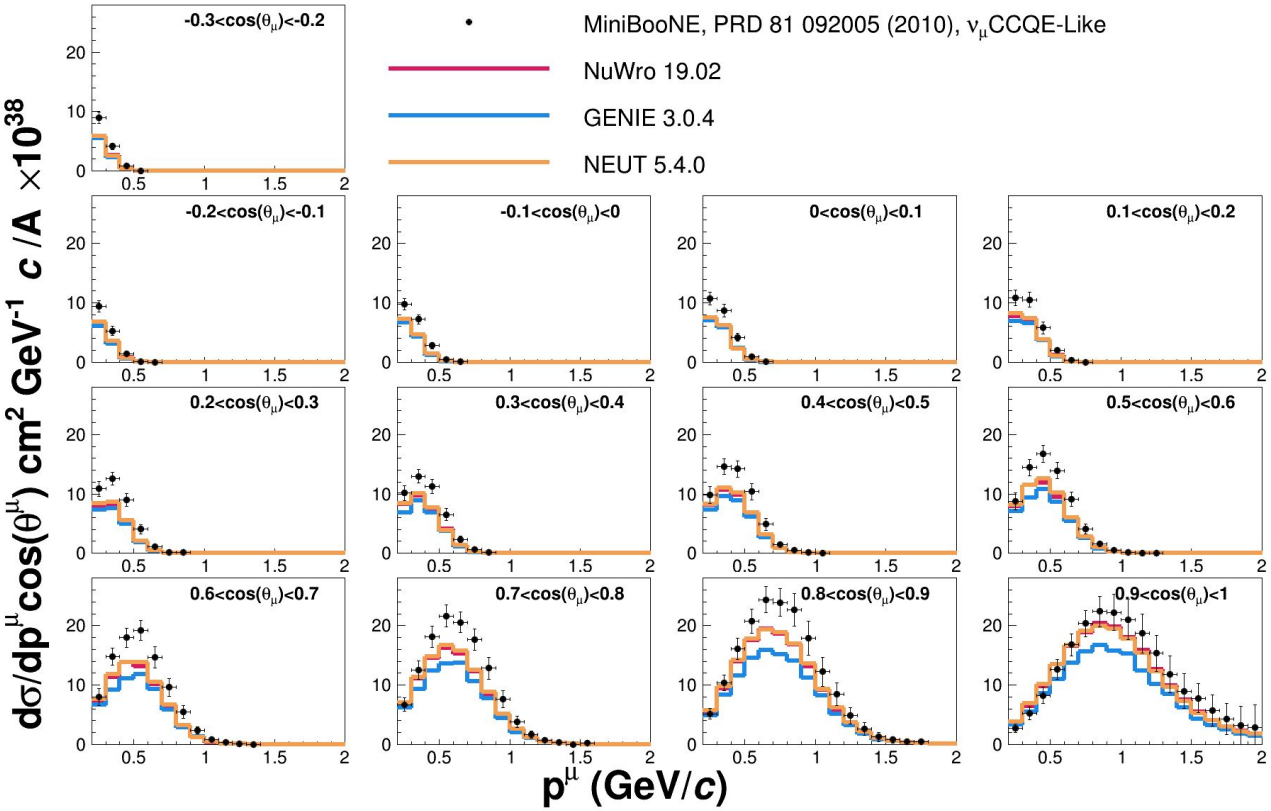



PRD 88 032001

# MiniBooNE CCQE-Like

- Not possible to calculate useful GOF, so I'm not going to attempt to…
- The data here is the 'less corrected' CCQE-like data:
  - No pionless delta decay subtraction (subset of MEC diagrams).



# Data In NUISANCE

**Bubble Chamber:**

- **ANL:** 7 selections, 56 projections
- **BEBC:** 6 sel. nu+nubar, 11 proj.
- **BNL:** 4 sel., 15 proj.
- **FNAL:** 3 sel., nu+nubar, 5 proj.
- **Gargamelle:** 1 sel., 1 proj.

**Nuclear:**

- **C:**
  - **MINERvA:** 3 sel., 6 proj.
- **CH:**
  - **T2K:** 9 sel. 24 proj.
  - **MINERvA:** 10 sel., nu+nubar, 106 proj.
  - **SciBooNE:** 1 sel. 16 proj.
- **$CH_2$:**
  - **MiniBooNE:** 5 sel., 33 proj.

**Nuclear:**

- **$H_2O$:**
  - **K2K:** 1 sel., 1 proj.
  - **T2K:** 1 sel. 7proj.
- **Ar:**
  - **ArgoNeuT:** 3 sel., nu+nubar, 12 proj.
  - **MicroBooNE:** 1 sel. 1 proj.
- **Fe:**
  - **MINERvA:** 3 sel., 6 proj.
- **Pb:**
  - **MINERvA:** 3 sel., 6 proj.

**Electron Scattering:**

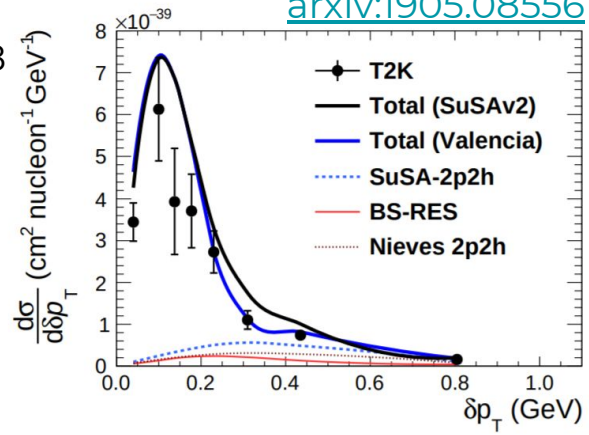
- **Virginia QE Archive**

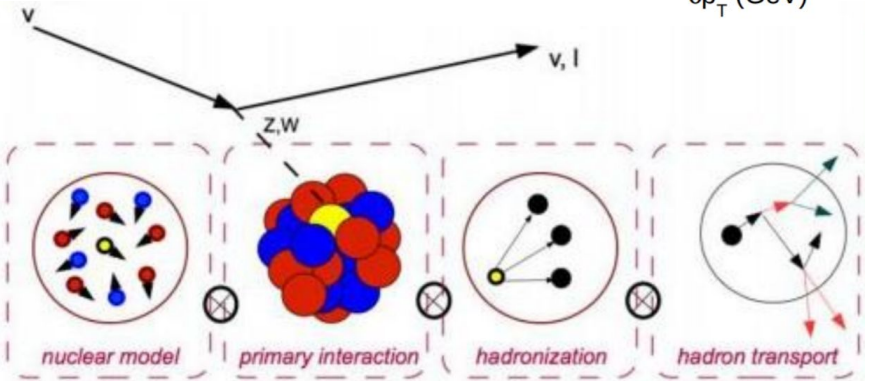
# How do we try and improve them: Theory

- Improve nuclear response models in generators:
  - *e.g.* SuSAv2 1p1h+2ph2 **PRD 94, 093004 (2016)**
- Improve primary interaction models in generators:
  - *e.g.* MK single pion production **PRD 97, 013002 (2018)**
- Improve simplifications in the MC:
  - Un-doing factorisation
  - Better-capture:
    - initial and final state physics
    - lepton-hadron correlations.

arxiv:1905.08556

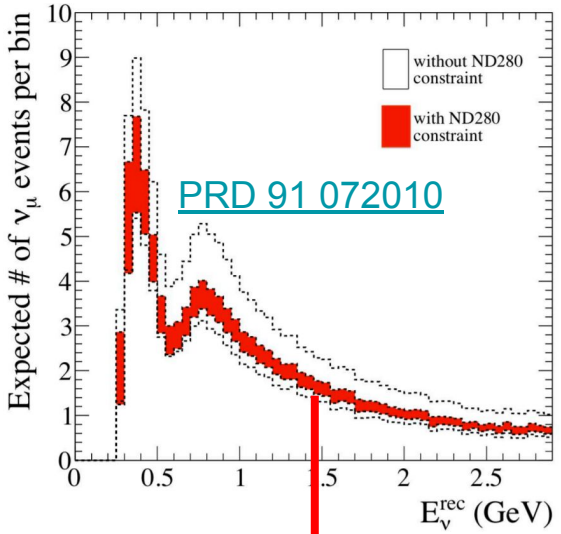
$\chi^2$ SuSA: 21/8
$\chi^2$ Val.: 27/8



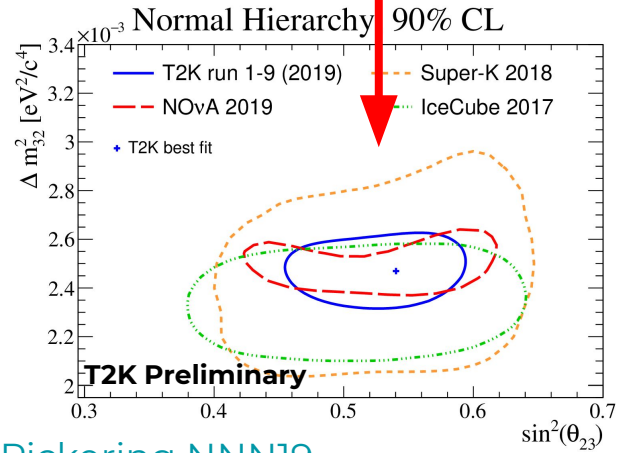



# What about uncertainties?

- Need plausible variations of models that can 'cover' the extant data.
- Compare to historic data ⇒ well-motivated prediction and uncertainties:
  - Then assume model is predictive for new data
- If experimentalists don't have the ability to vary 'theory' parameters:
  - Have to make something up…




PRD 91 072010

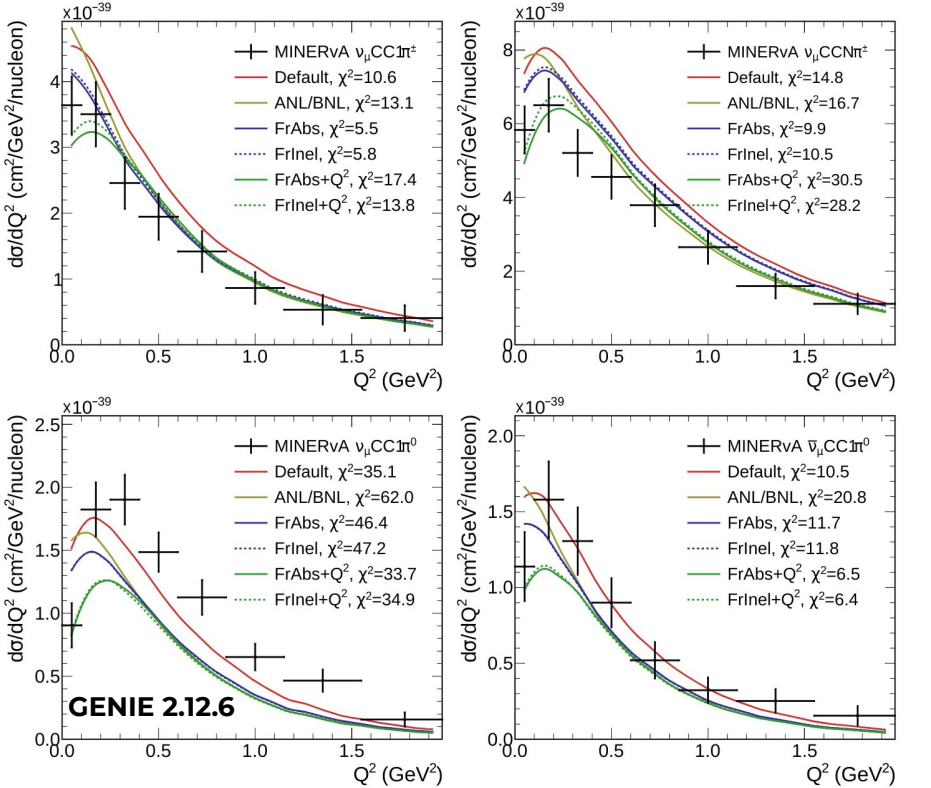



L. Pickering NNN19

# How do we try and make them right: Tune

- **Ideal world:** model describes nature up to some unknown parameter values.

**MINERvA Single pion production comparisons**

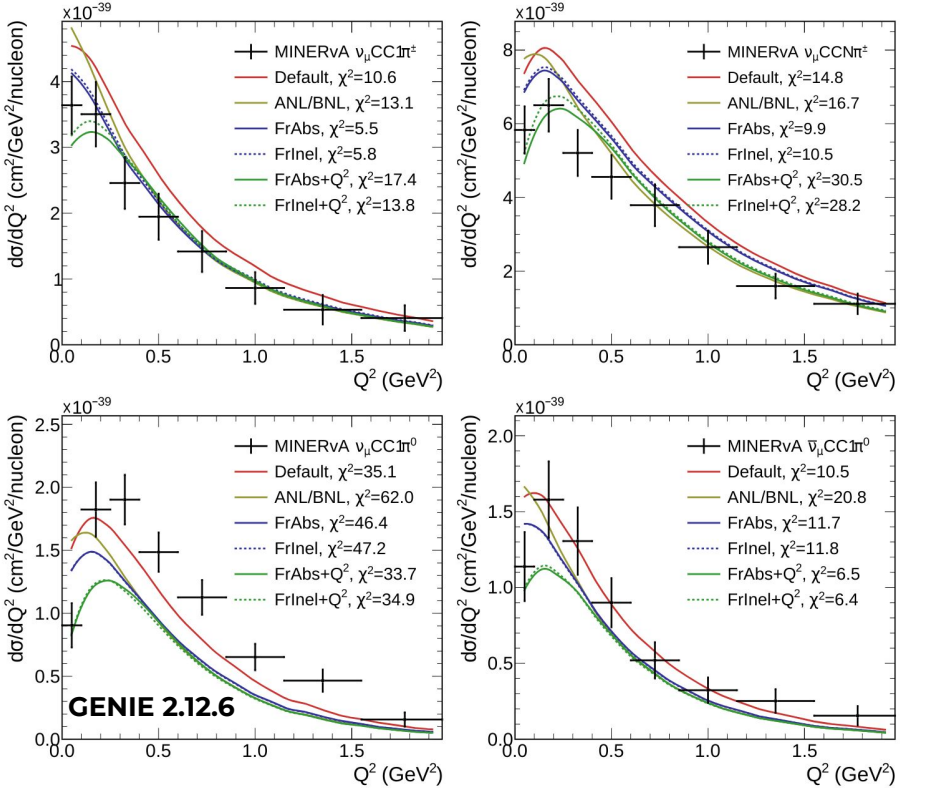



Phys. Rev. D 100, 072005 (2019)

# How do we try and make them right: Tune

- **Ideal world:** model describes nature up to some unknown parameter values:
  - We don't live in that world.

**MINERvA Single pion production comparisons**




Phys. Rev. D 100, 072005 (2019)

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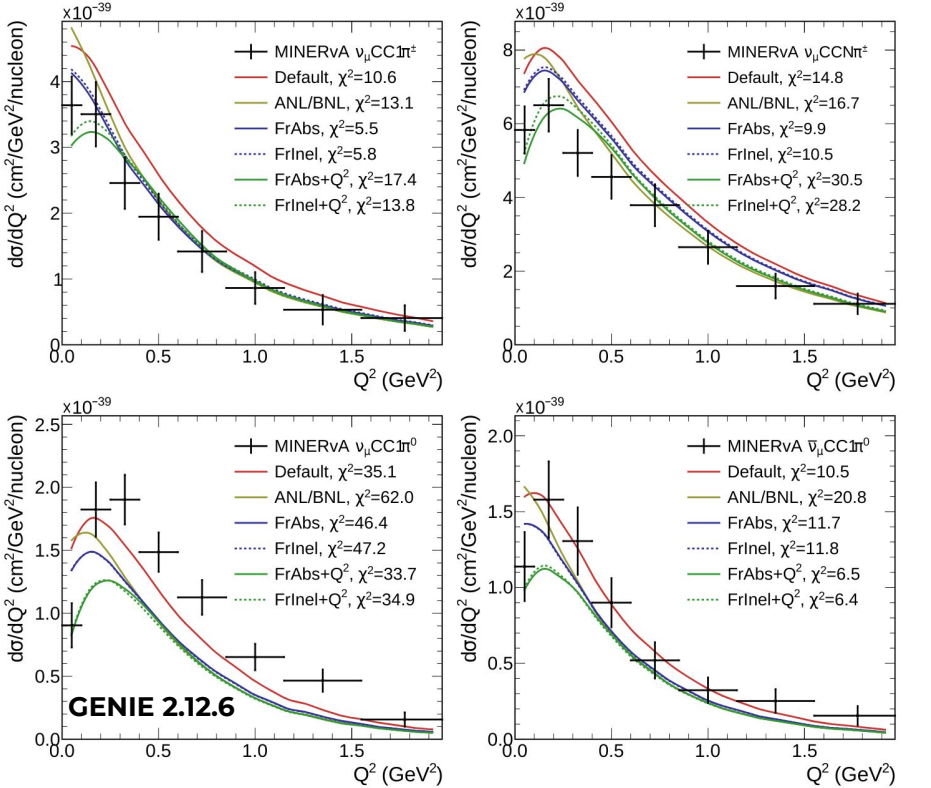
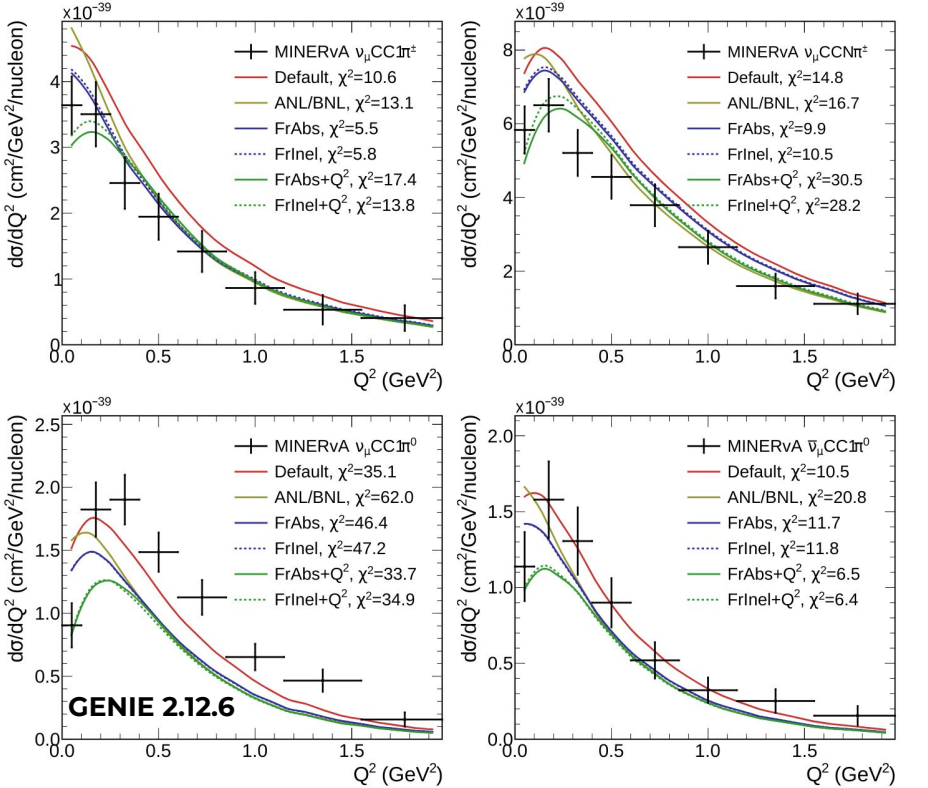



Phys. Rev. D 100, 072005 (2019)

# How do we try and make them right: Tune

- **Ideal world:** model describes nature up to some unknown parameter values:
  - **We don't live in that world.**
- **Dangers of tuning:**
  - Absorb data/MC discrepancy into poor parameterization.
  - Propagate CV+uncerts from well-described projection to poorly described projection.
  - *e.g.* Tune in inclusive lepton variables and predict hadronic shower.

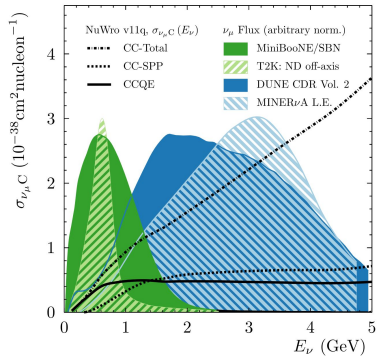
**MINERvA Single pion production comparisons**




Phys. Rev. D 100, 072005 (2019)

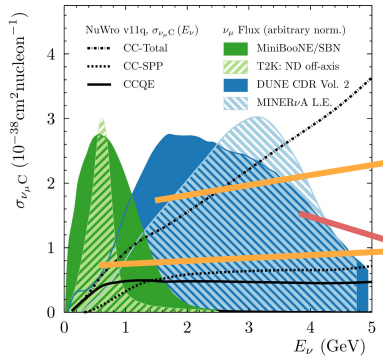
# What we want out of comparisons to data

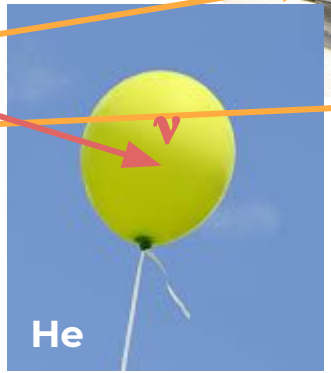
- Range of:
  - Neutrino energies

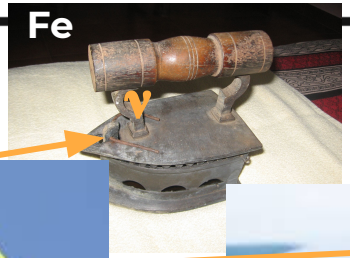


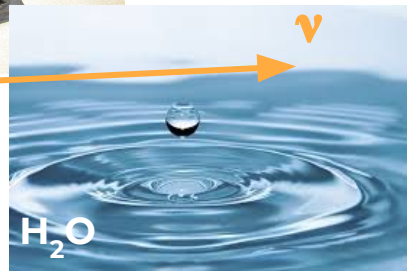
# What we want out of comparisons to data

- Range of:
  - Neutrino energies
  - Targets



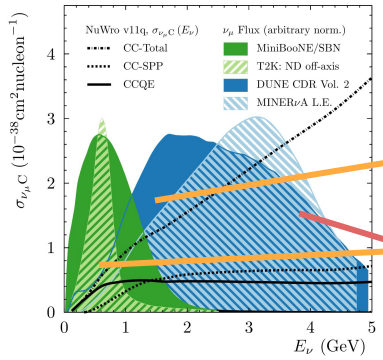



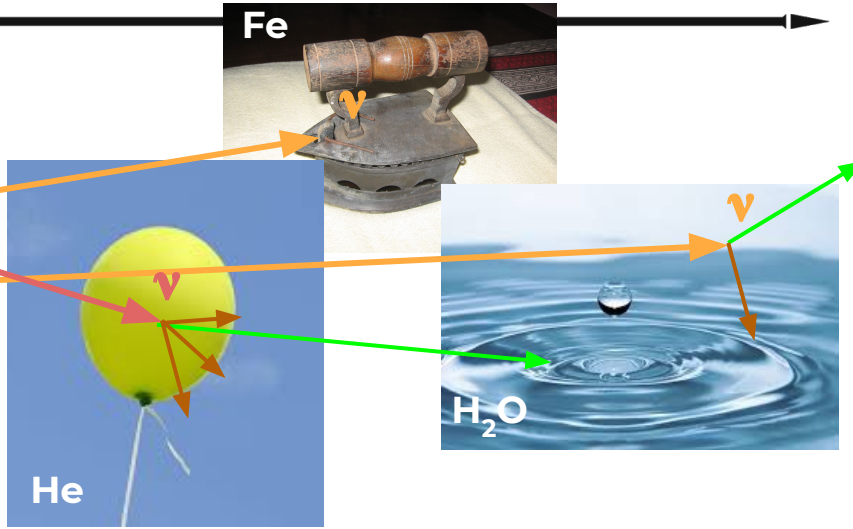



# What we want out of comparisons to data

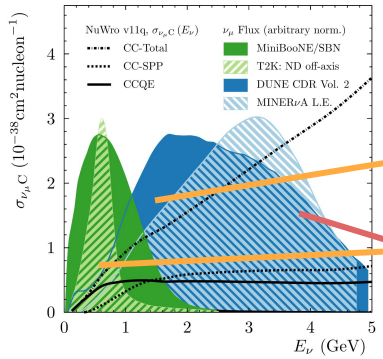
- Range of:
  - Neutrino energies
  - Targets
  - Final state topologies
  - Observable projections



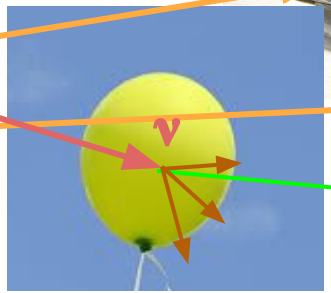



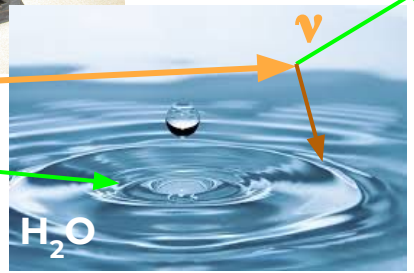
# What we want out of comparisons to data

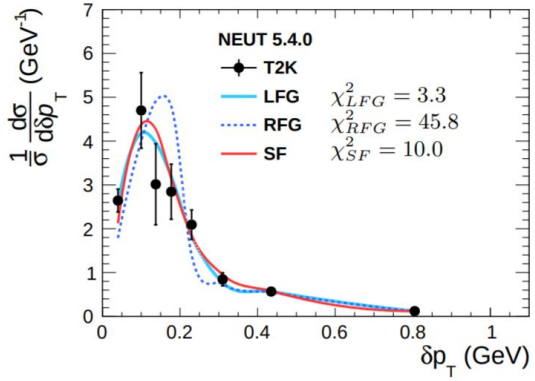
- Range of:
  - Neutrino energies
  - Targets
  - Final state topologies
  - Observable projections
- Sensitivity to:
  - Model choice
  - Free parameter central values
  - Free parameter uncertainties







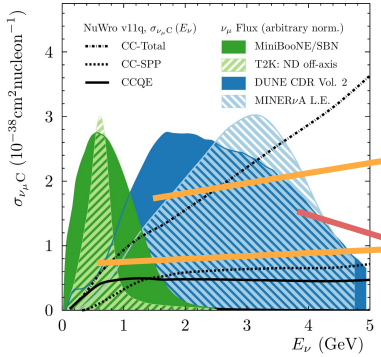



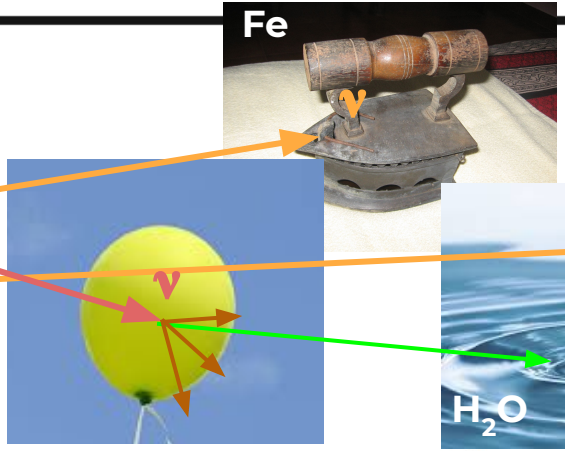



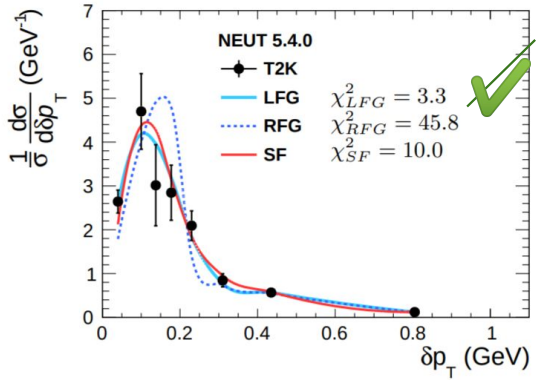

**T2K data**: PRD98, 032003 (2018)
**Plots**: arXiv:1810.06043

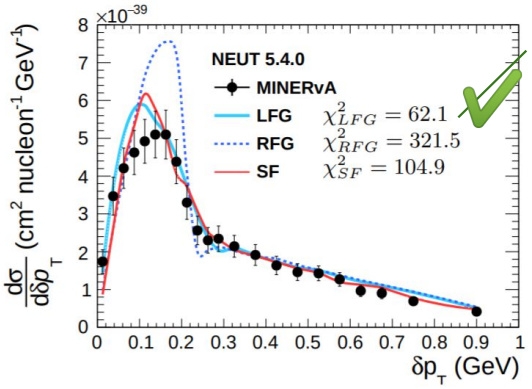
# What we want out of comparisons to data

- Range of:
  - Neutrino energies
  - Targets
  - Final state topologies
  - Observable projections
- Sensitivity to:
  - Model choice
  - Free parameter central values
  - Free parameter uncertainties
- Ability to make quantitative statements about GOF






**T2K data**: PRD98, 032003 (2018) **MINERvA data**: PRL 121 (2018) no.2, 022504
**Plots**: arXiv:1810.06043

# Anatomy of a Cross-section Fit

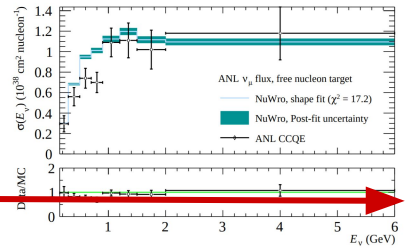
**Choose model parameters**

Interaction model

ANL CCQE

Data + Errors

Th. Prediction



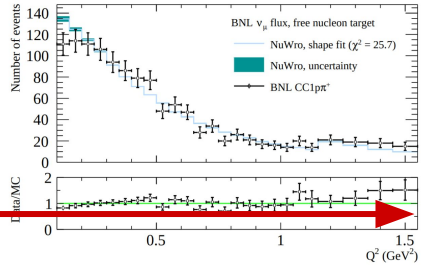

**χ2**

**+**

BNL CC1pi+

Data + Errors

Th. Prediction




**χ2**

**+ …**

**+ Model parameter prior penalties**

**= Global χ2**

Minimize χ2 by varying model parameters

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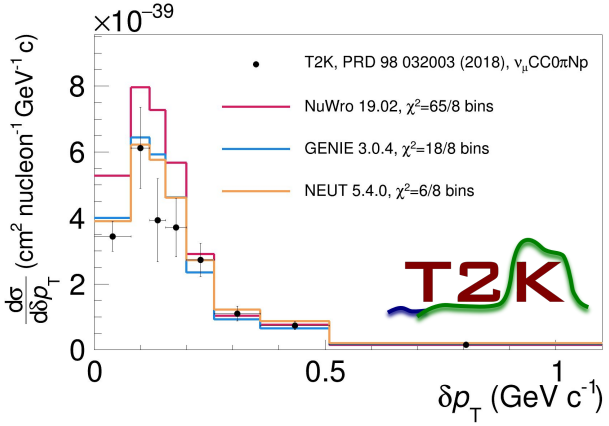
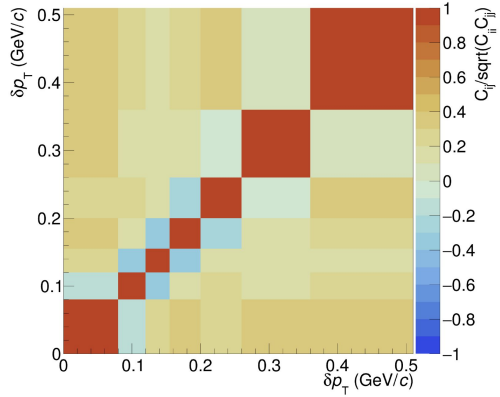
- But… have to take care:
  - Model parameterizations can be hard to uniquely constrain.
  - Hard to consistently evaluate test statistics.
  - Incomplete data coverage:
    - *e.g.* Many measurements focus on just charged lepton kinematics.
    - Need to be predictive in hadron kinematics…
  - Signal definitions not always clear/well defined in the context of an experiment.
- **These are problems that the community is working on together:** we know things now that we didn't before, but it is still worth highlighting specifics in historic data to be aware of.

# What is needed from Data Measurements

- Minimize model bias while maximising efficacy of data:
  - Well-understood selection efficiency over signal phase space.
  - Projections the require minimal MC correction.
- Publish errors with bin-to-bin correlations.



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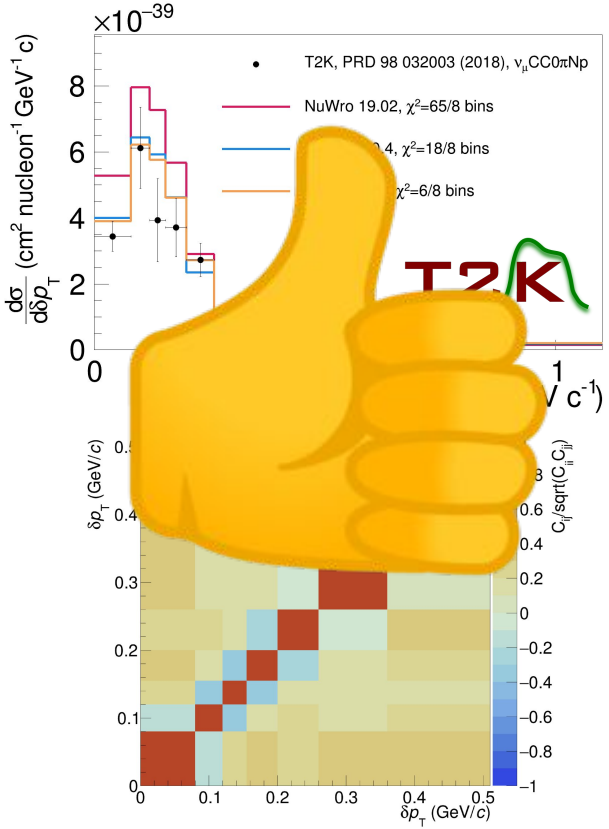

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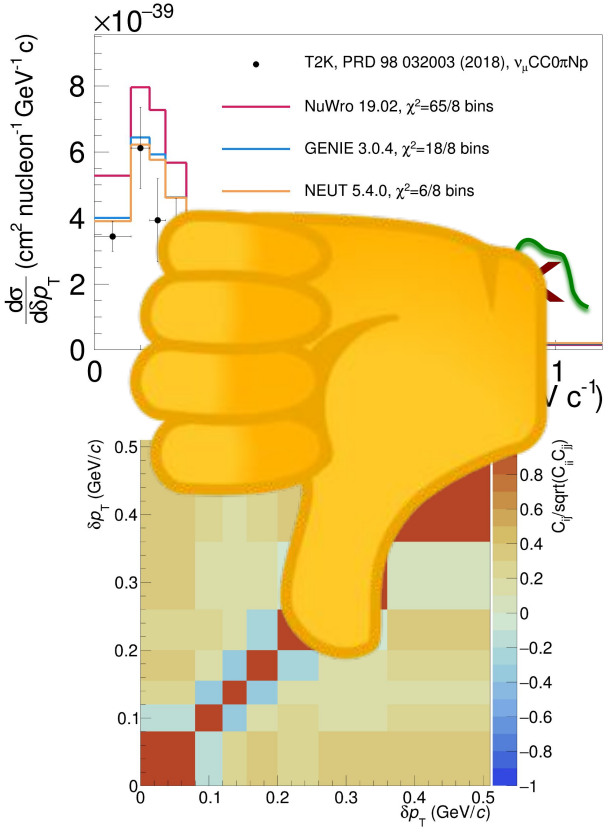
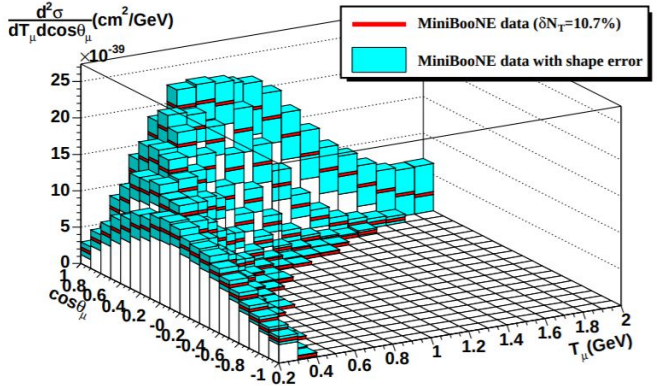
- Minimize model bias while maximising efficacy of data:
  - Well-understood selection efficiency over signal phase space.
  - Projections the require minimal MC correction.
- Publish errors with bin-to-bin correlations.
  - **Wherever possible:**
    - **Between projections**
    - **Between datasets.**



# Nuclear data: MiniBooNE CCQE

- Data sets without published correlated errors are difficult to use in a global fit.
- MiniBooNE CCQE(like):
  - Many bins, no published error matrix.
  - What should the contribution to the global GOF be
    - **Fully uncorrelated**: $\sim \sum_{i \in \text{bins}} (\text{Data} - \text{MC})_i^2$
    - **Fully correlated**: $\sim \sum_{i \in \text{bins}} (\text{Data} - \text{MC})_i^2 / \text{NBins}$
  - In reality, probably somewhere in between.
  - If used naively, will incorrectly dominate a tune **and more data won't help**...
- But, we want to use the information that this data holds, unsatisfactory to just ignore it...

PRD 81 092005

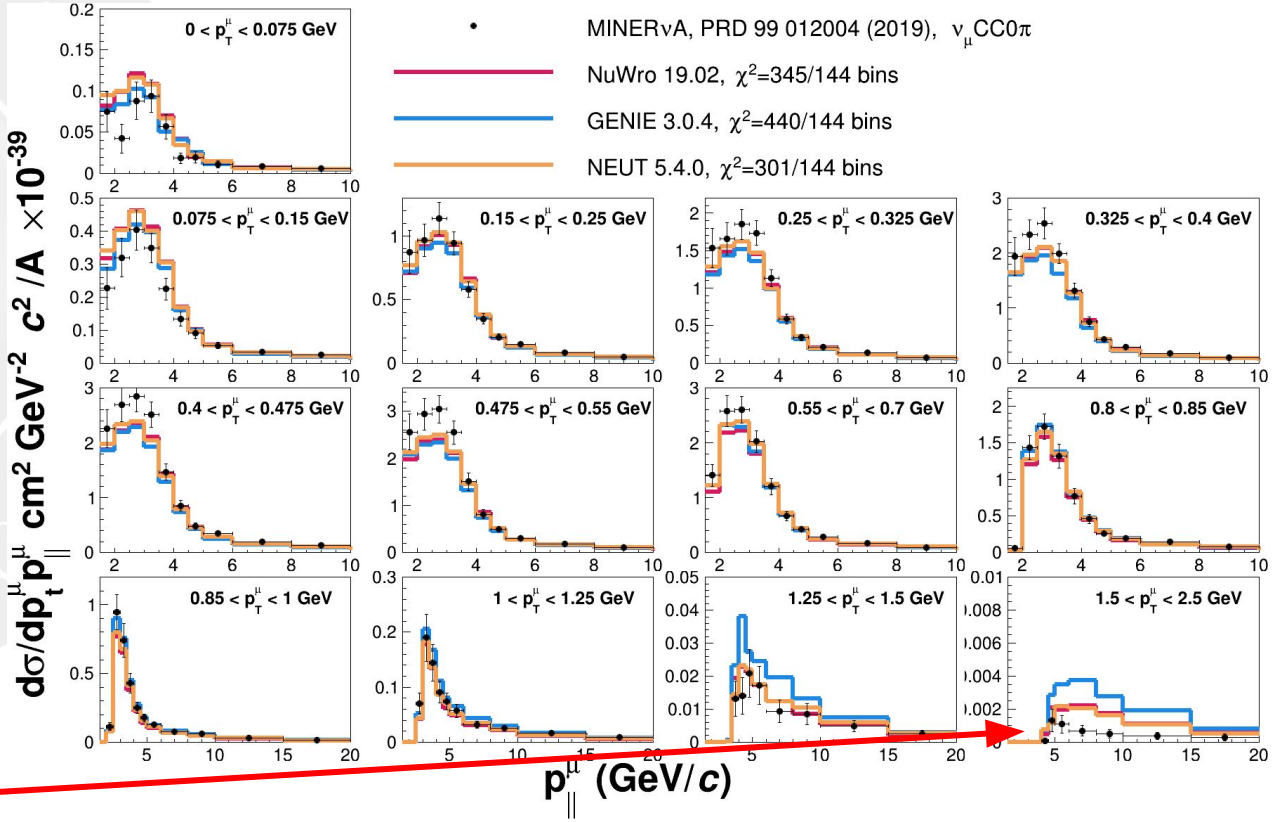



PRD 93 072010

| | $\chi^2_{\text{min}}/N_{\text{DOF}}$ |
|---|---|
| All | 117.9/228 |
| MINER$\nu$A | 30.3/13 |
| MiniBooNE | 65.7/212 |
| $\nu$ | 69.1/142 |
| $\bar{\nu}$ | 46.1/83 |
| M$\nu$A vs MB | 117.9/228 |
| $\nu$ vs $\bar{\nu}$ | 117.9/228 |

# MINERvA 0pi neutrino-mode

- Sensitive to neutrino energy ($p_{||}$) and momentum transfer ($p_t$) in a known flux
- Predicted ~well for bulk of distribution:
  - Higher angle poorly predicted



# Single Transverse Variables

- Recent interest in lepton-hadron correlations:
  - Can be more sensitive to certain effects than lepton-/hadron-only
  - Efficiency/smearing corrections need to be treated with more care.
- Direction/magnitude of momentum imbalance is sensitive to initial and final state effects PRD 98 032003 (2018).