NUISANCE

nuisance.hepforge.org

github.com/NUISANCEMC/nuisance

nuisance-xsec.slack.com

nuisance@projects.hepforge.org

Luke Pickering

on behalf of NUISANCE

NuSTEC board meeting 2019

MICHIGAN STATE UNIVERSITY

Who are we?

- T2K, MINERvA, DUNE collaborators
- A breadth of experience using GENIE, NuWro, NEUT, GiBUU
- Have worked on neutrino cross-sections measurements, generators dev. and oscillation analyses on T2K and DUNE
- Stared at, thought about, and discussed a lot of neutrino interaction measurements (at NuSTEC and elsewhere)
- Developed interaction systematics for T2K and DUNE analyses
- **Started as PhD project, now junior postdocs**

L. Pickering

MICHIGAN STATE UNIVERSITY

C. Wret

UNIVERSITY of ROCHESTER

C. Wilkinson

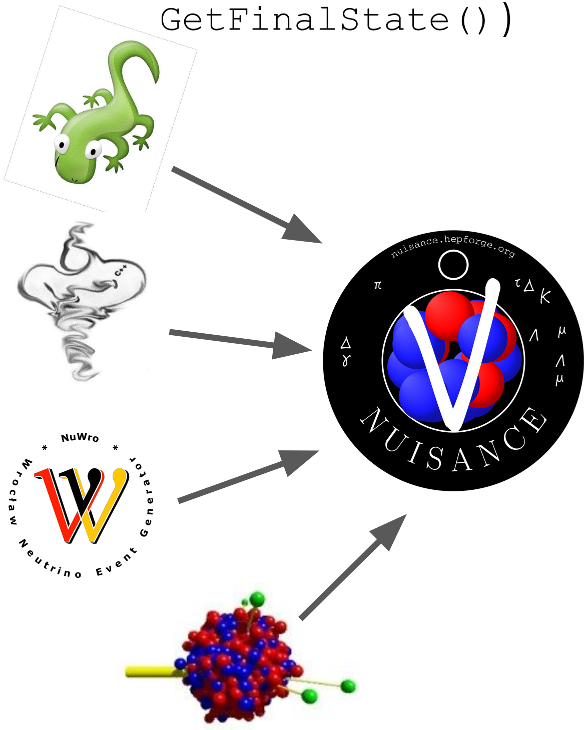
UNIVERSITÄT BERN

This Talk

- What is NUISANCE?
- What have we done with NUISANCE?
- What do we plan to do with NUISANCE?
- How can NUISANCE be used in conjunction with NuSTEC?

What a NUISANCE

- Converts generator output from GENIE, NuWro, NEUT, GiBUU and NUANCE
- Uses a common event format with common functions (e.g. `GetLepton()`, `GetQ2()`, `GetFinalState()`)



With all generators in the same format, it's easy to produce

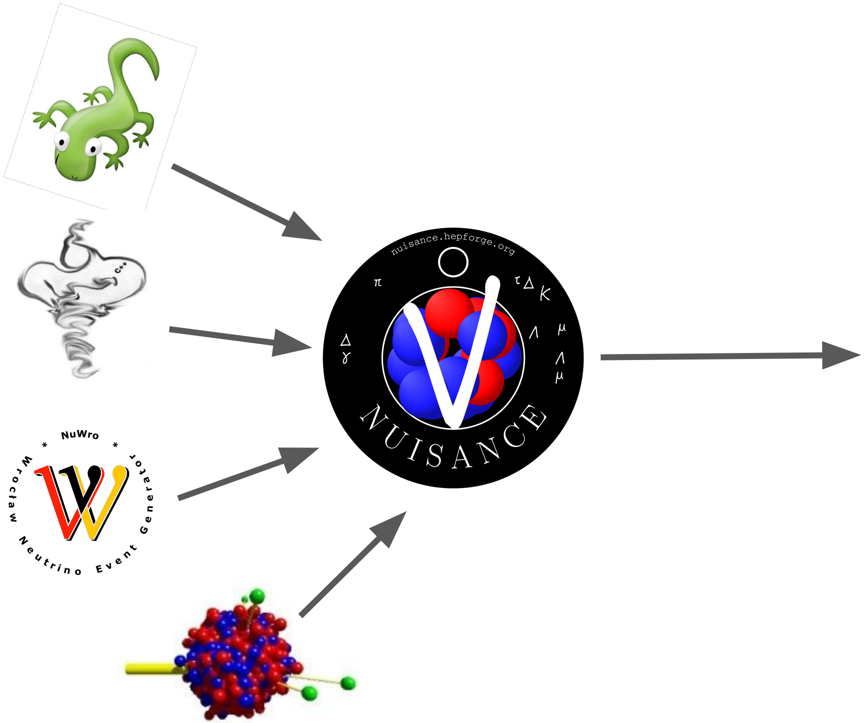
- Generator-to-generator comparisons
- Model to model comparisons
- Comparison to data

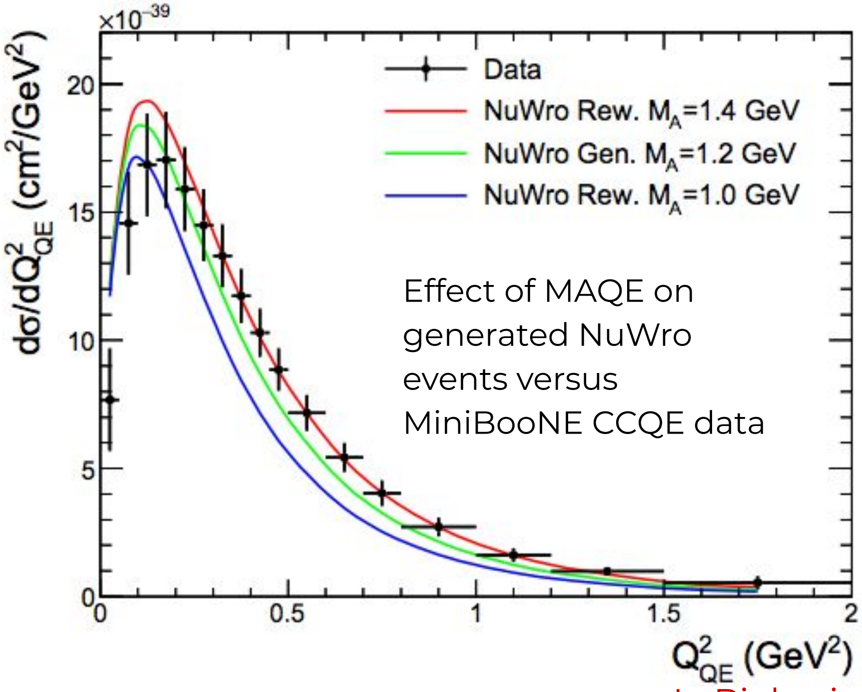
- If event reweighting is available (GENIE, NEUT, NuWro):
  - Fit parameters to data
  - Evaluate uncertainty bands against data
  - Evaluate uncertainties against each other

JINST 12 (2017) no. 01, P01016

What a NUISANCE

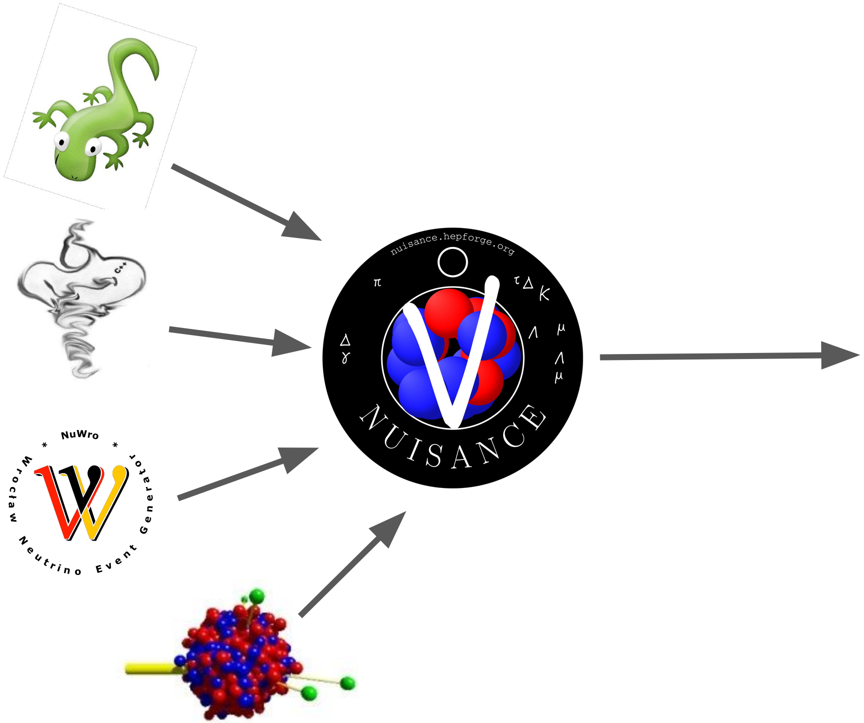
Compare effect of systematics on distributions from the same generator

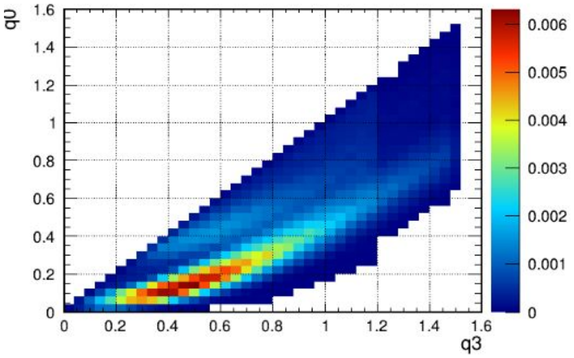




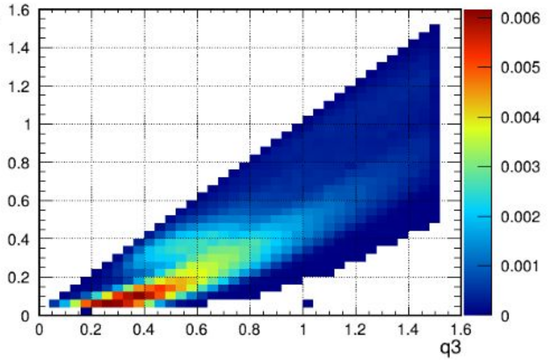
What a NUISANCE

Compare different generators and their models in a “flat-tree” format





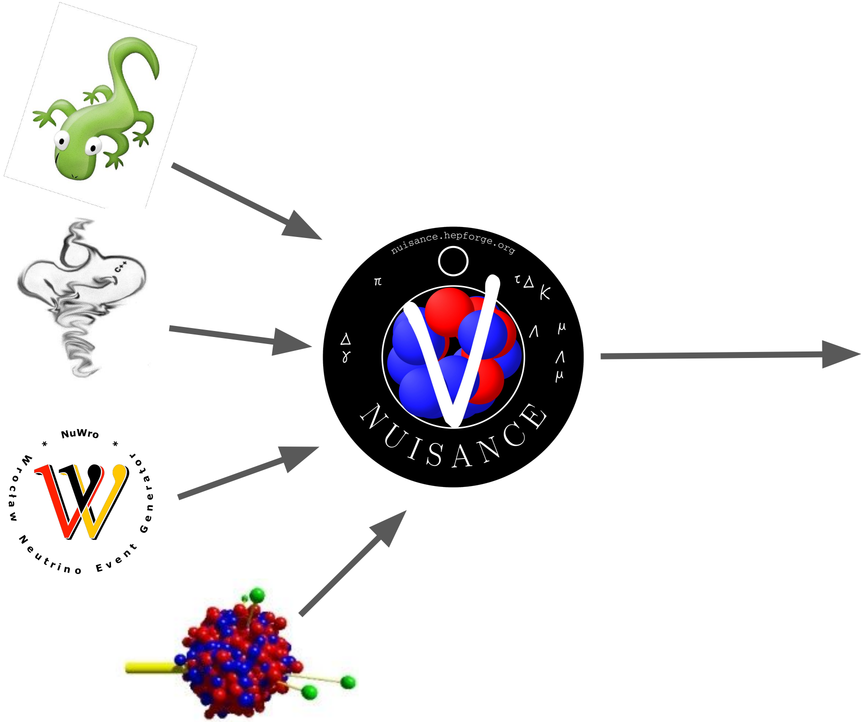
CC0π final state from NuWro with Nieves 2p2h

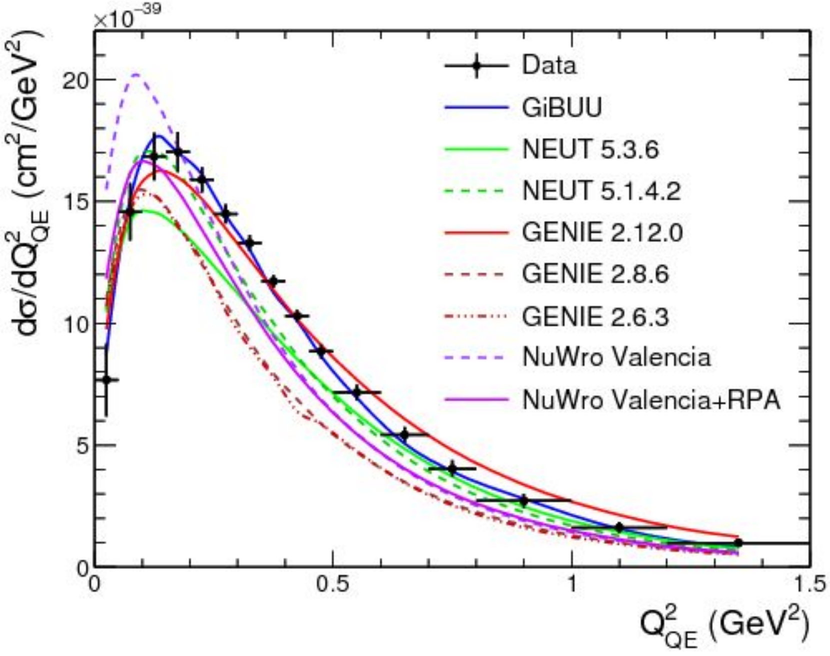


CC0π final state from GENIE with Empirical 2p2h

What a NUISANCE

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

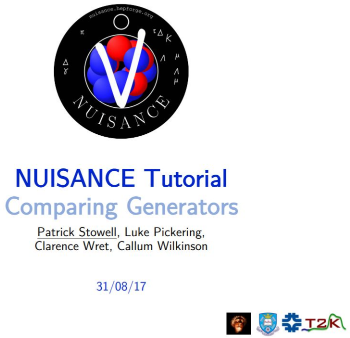




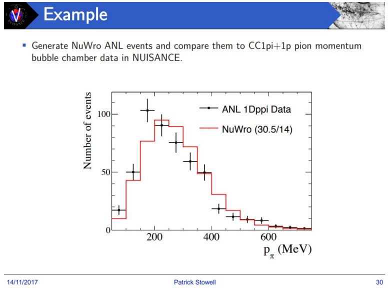
Tutorials, how-to’s

- 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

Who are we working with?

T2K

DUNE

NOvA ♥ T2K

e4ν

μBooNE

MINERvA

NuWro
Wroclaw Neutrino Event Generator

Some Example Comparisons

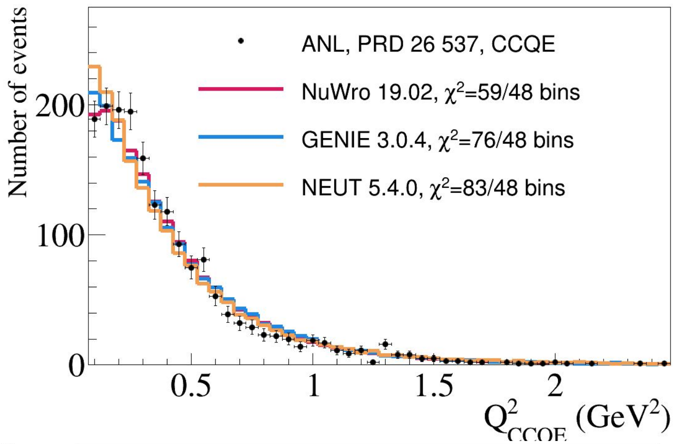
- Bubble Chamber lepton variables
- Nuclear-target CC0π lepton variables
- Nuclear-target CC0π lepton-hadron correlation variables
- (more than 300 measurements in NUISANCE)

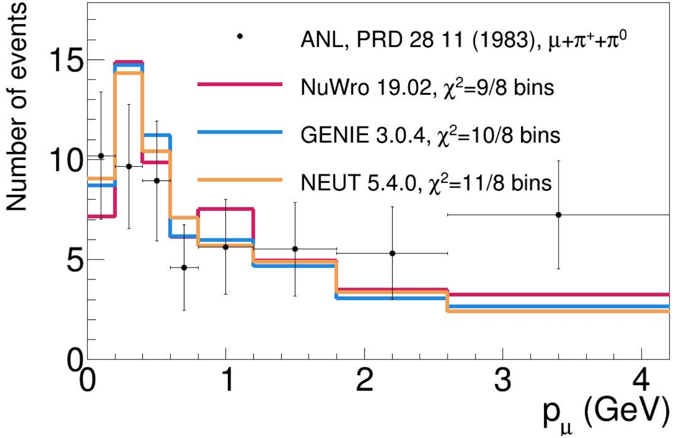
Meet the Generators

	Version/ Tune Used	Nuclear-model + QE-like	Single Pion Production	Higher W	Fragmentation	FSI
NEUT	5.4.0	Valencia: - 1p1h+RPA - 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: - 1p1h+RPA - 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. - 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).





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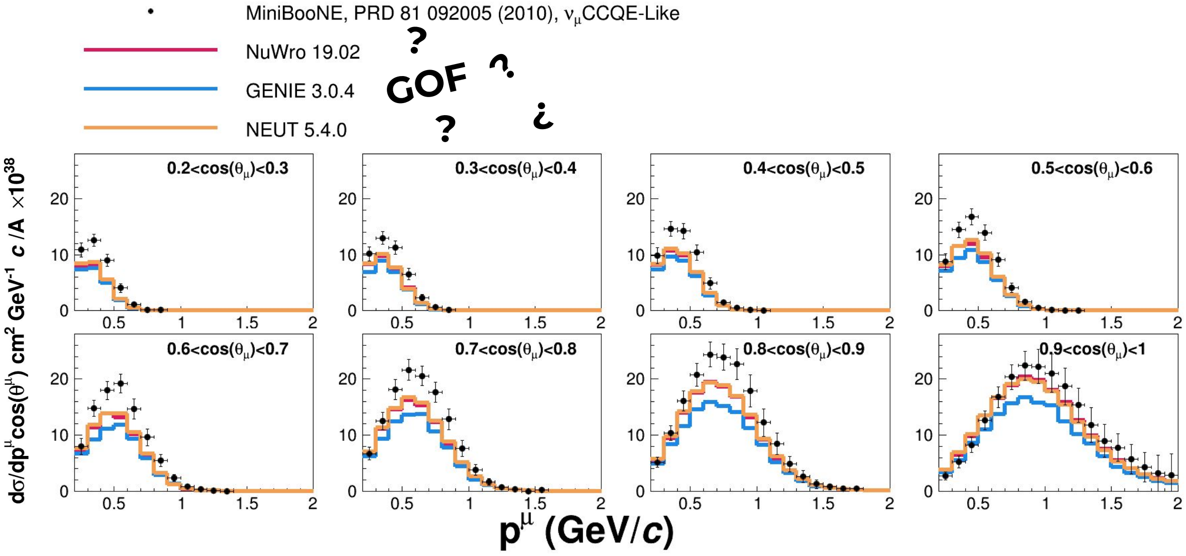
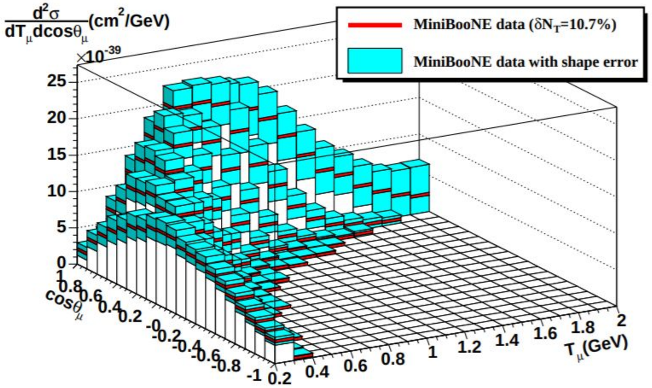
Nuclear data: MiniBooNE CCQE

- 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

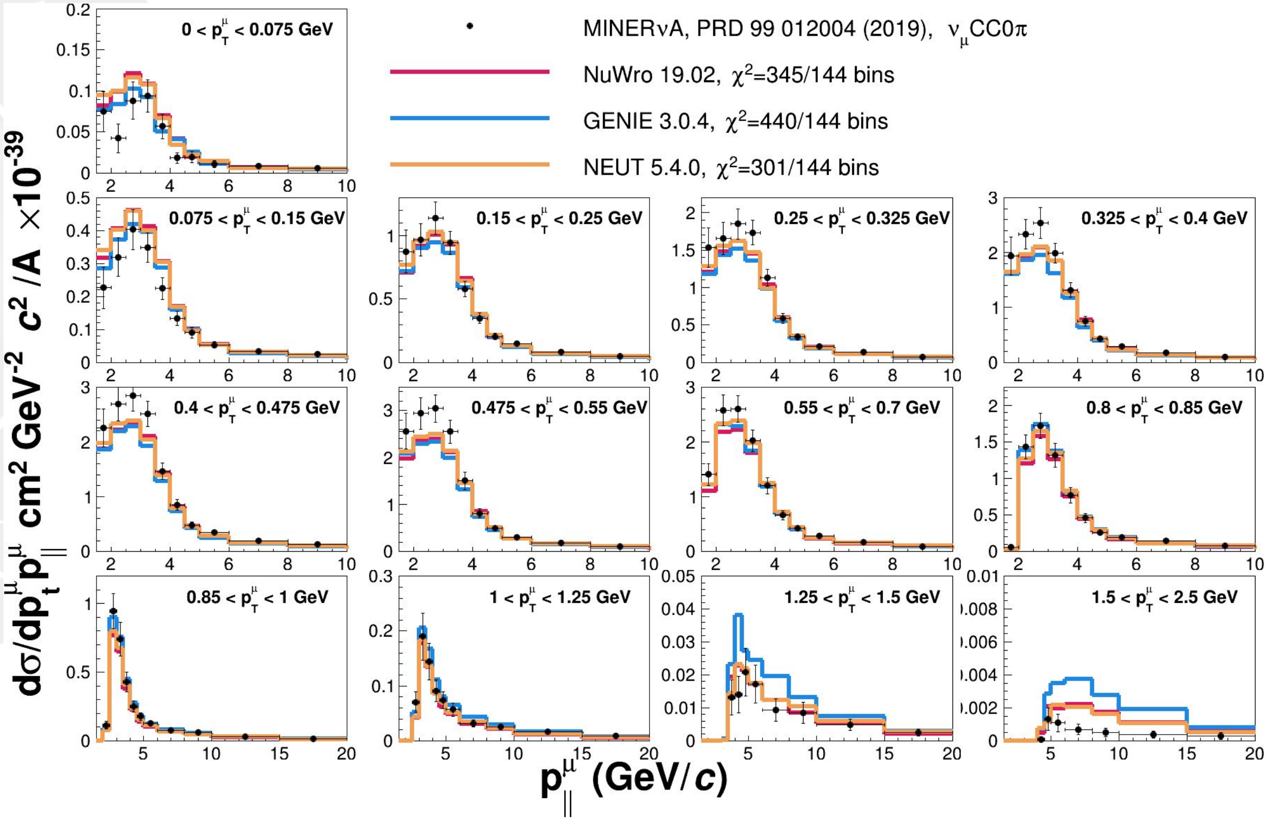


PRD 93 072010

	$\chi^2_{\mathrm{min}}/N_{\mathrm{DOF}}$
All	117.9/228
MINERνA	30.3/13
MiniBooNE	65.7/212
ν	69.1/142
$\bar{\nu}$	46.1/83
MνA vs MB	117.9/228
ν vs $\bar{\nu}$	117.9/228

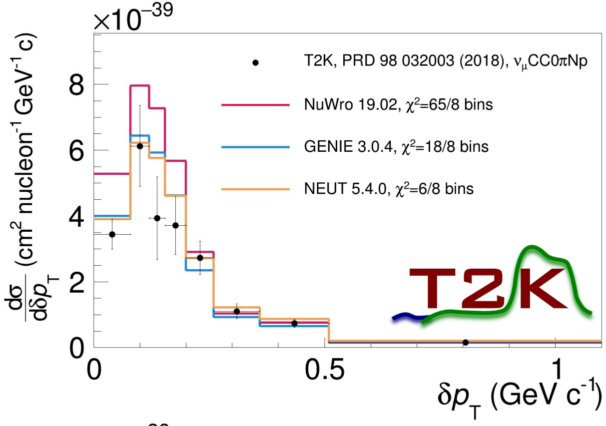
MINERvA 0pi neutrino-mode

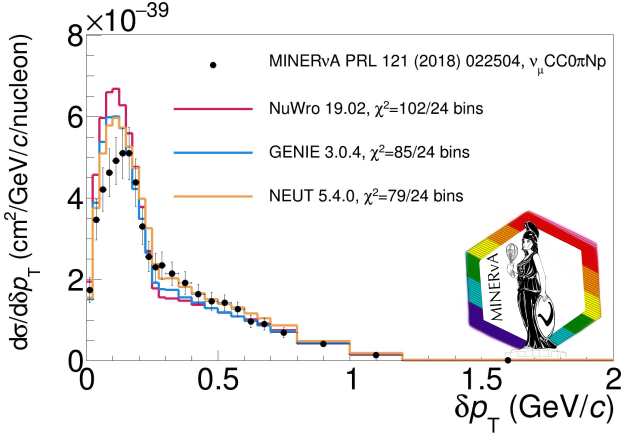
- Sensitive to neutrino energy ($p_{||}$) and momentum transfer (p_t) in a known flux



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_μ, 1 < $\cos(\theta_\mu)$ < -0.6
  - MINERvA:
    - 450 < p_p < 1200 MeV, 0 < θ_p < 70°
    - 1.5 < p_μ < 10 GeV, 0 < θ_μ < 20°





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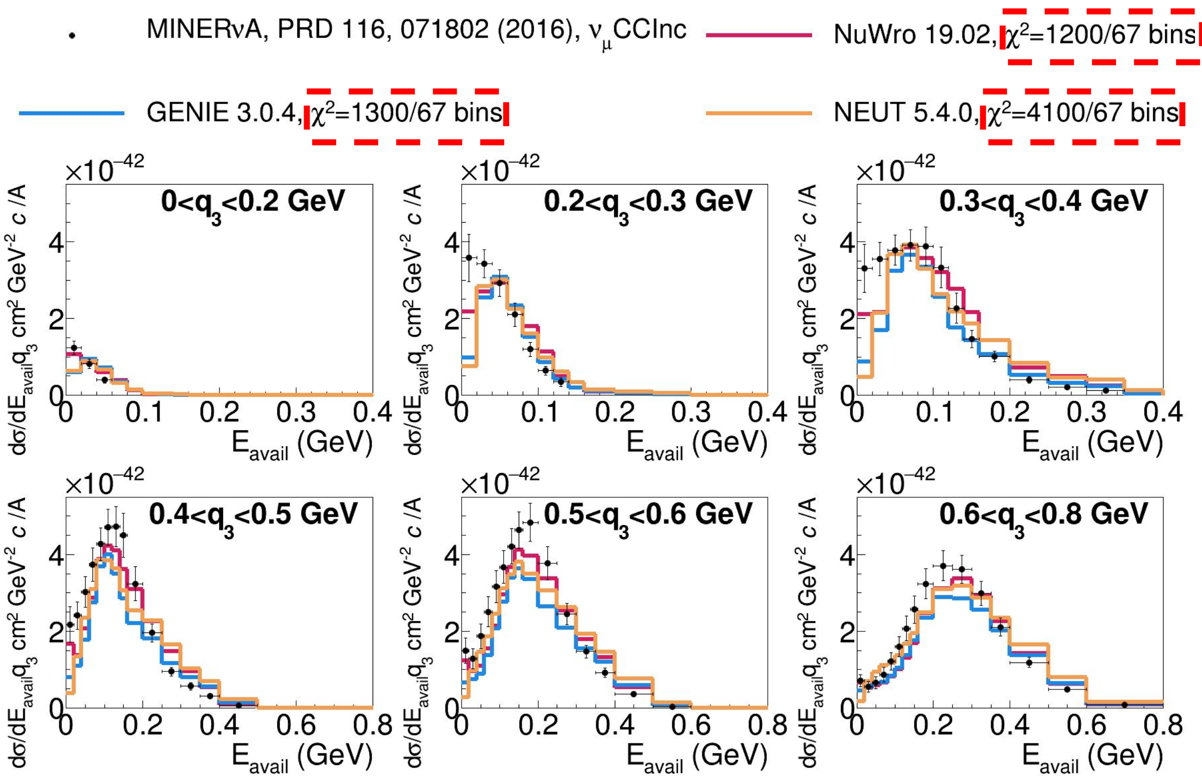
MINERvA CCInclusive: Low recoil

- 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.



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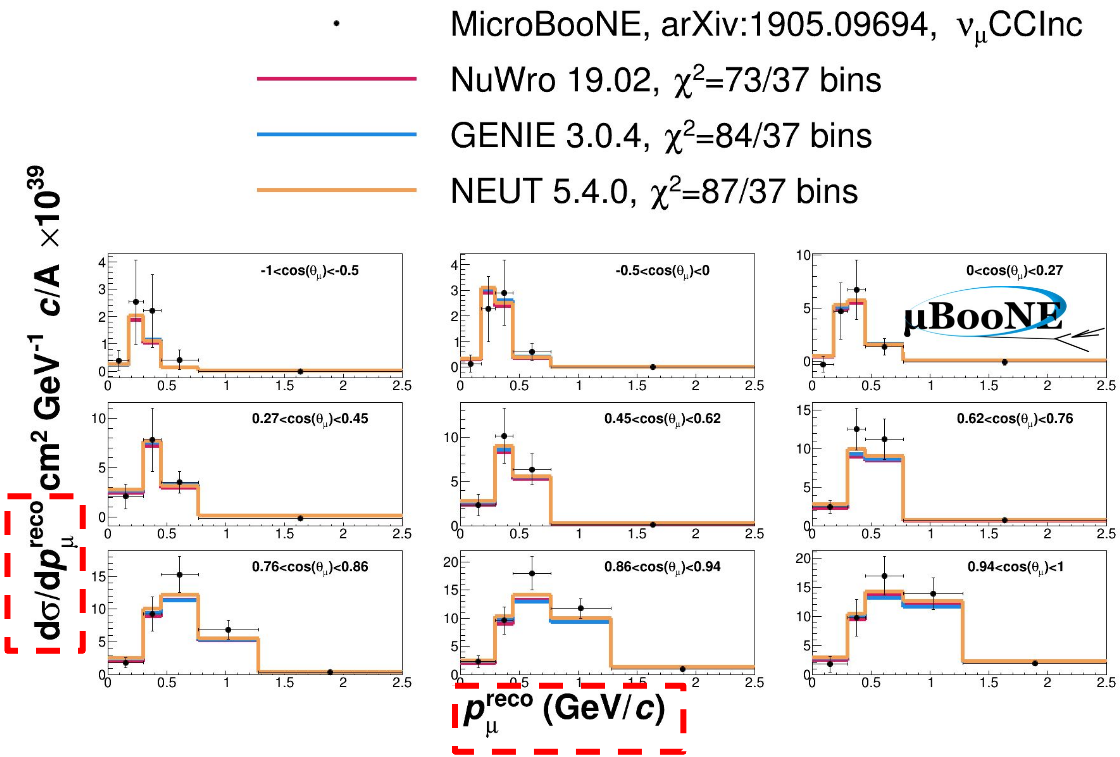
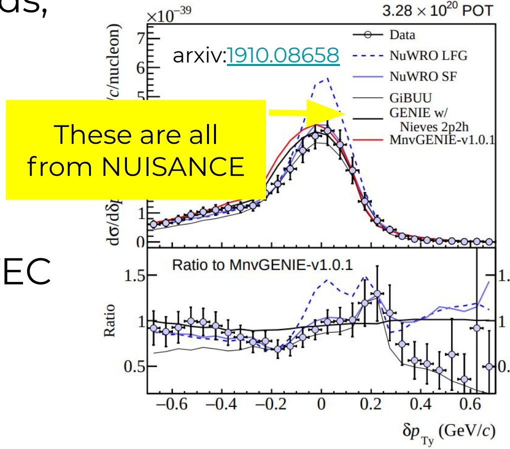
Comparisons to Nuclear data: MicroBooNE

- 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!

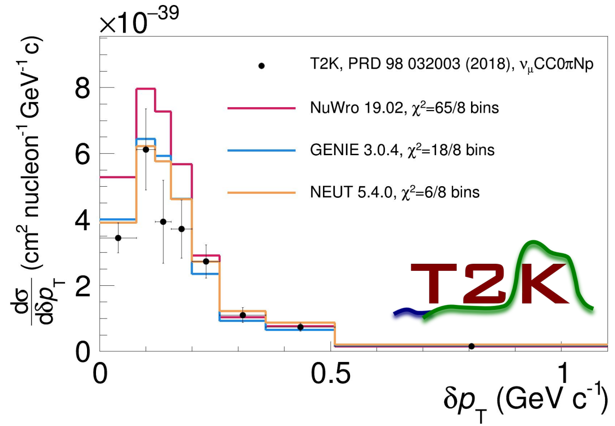
Thanks for listening

L. Pickering

(NuFACT2018, VT, Blacksburg)

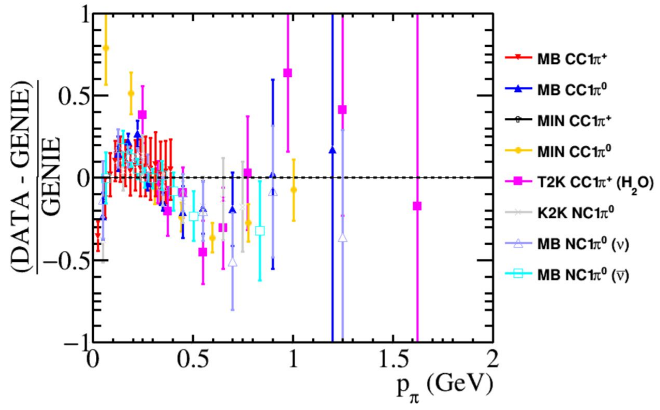
What is needed from Data Measurements

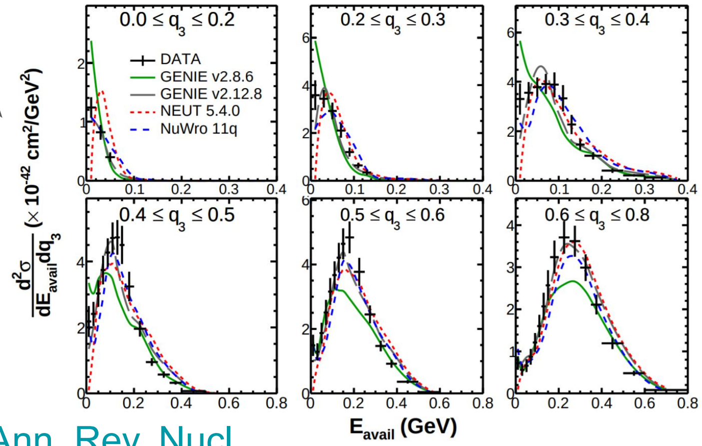
- Minimize model bias while maximising efficacy of data:
    - Well-understood selection efficiency over signal phase space.
    - Projections the require minimal MC correction.
- Publish errors with bin-to-bin correlations.



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.



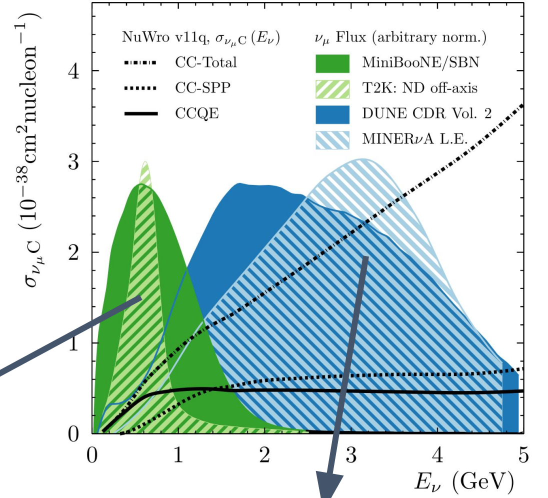


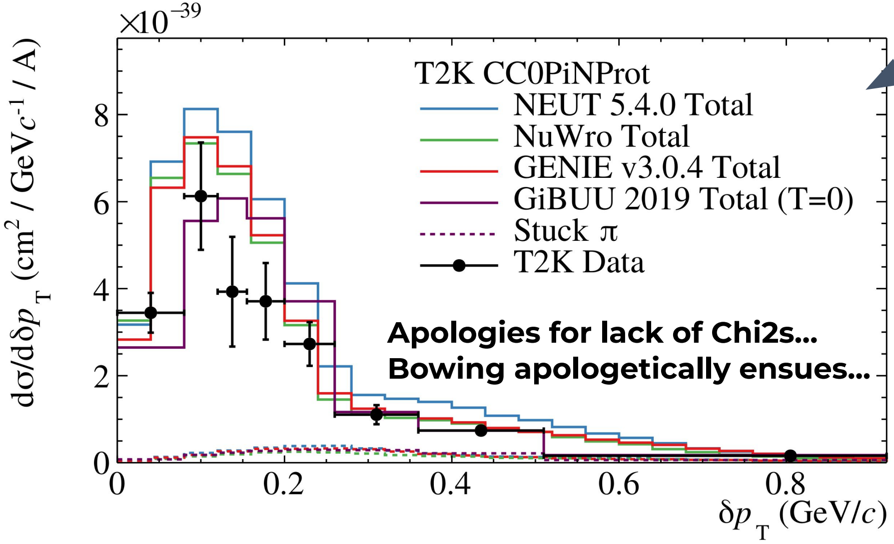
[Ann. Rev. Nucl. 101917 020930]

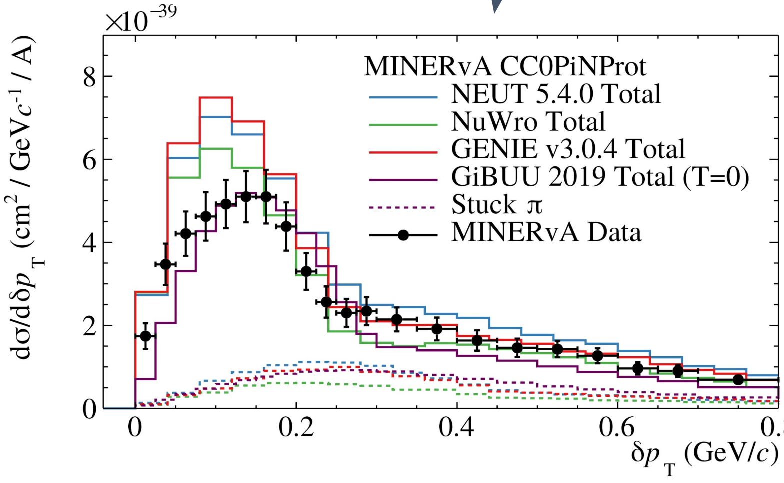
https://doi.org/10.1016/j.physrep.2018.08.003

Data Comparison: δp_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)



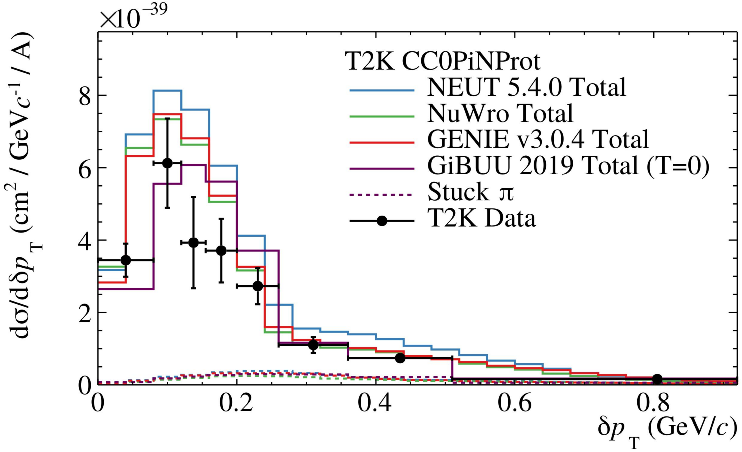




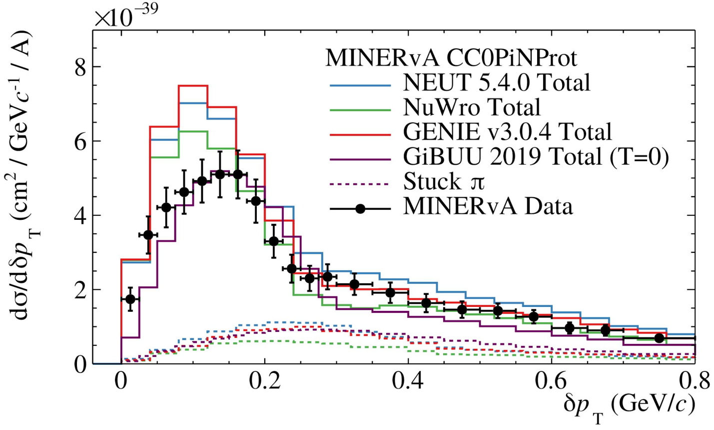
Signal definitions

- 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

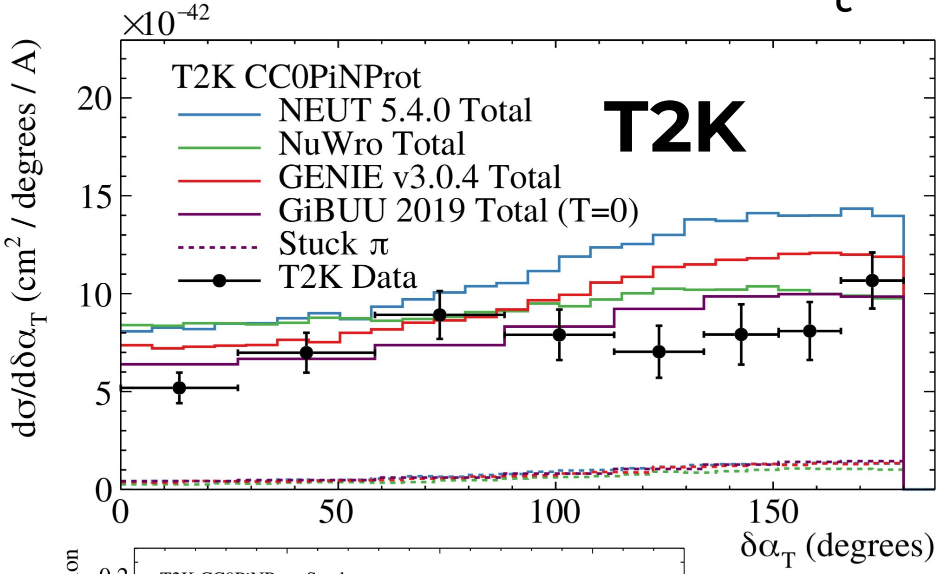


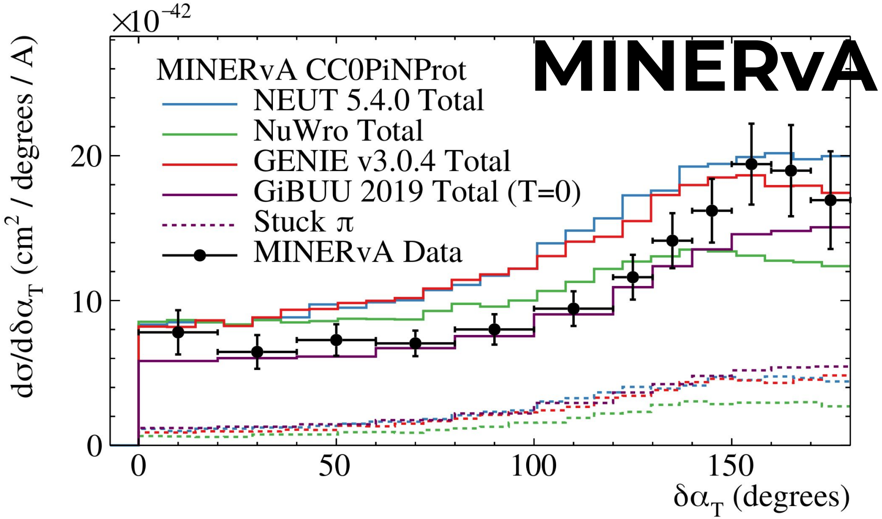
450 < pp < 1200 MeV, 0 < theta_p < 70°
1.5 < pmu < 10 GeV, 0 < theta_mu < 20°

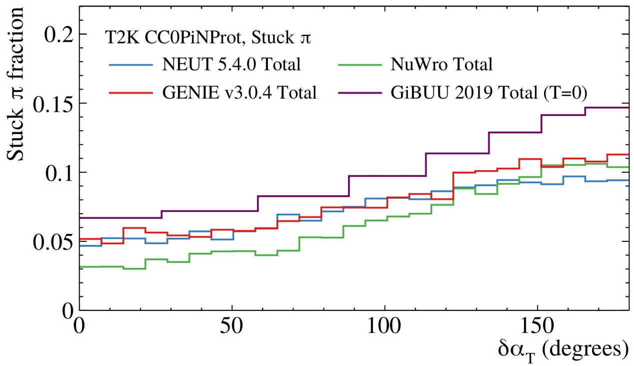


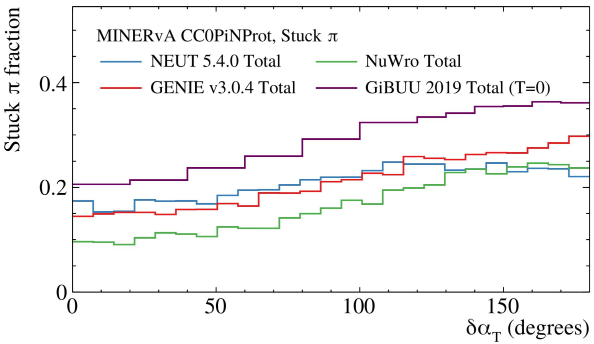
Stuck pion rate: δα$_t$

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





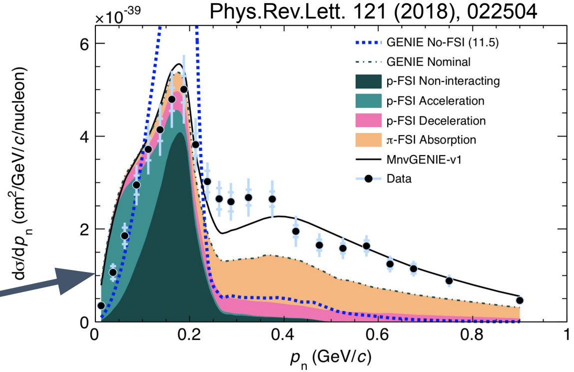


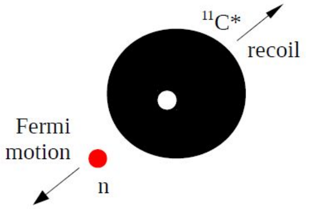


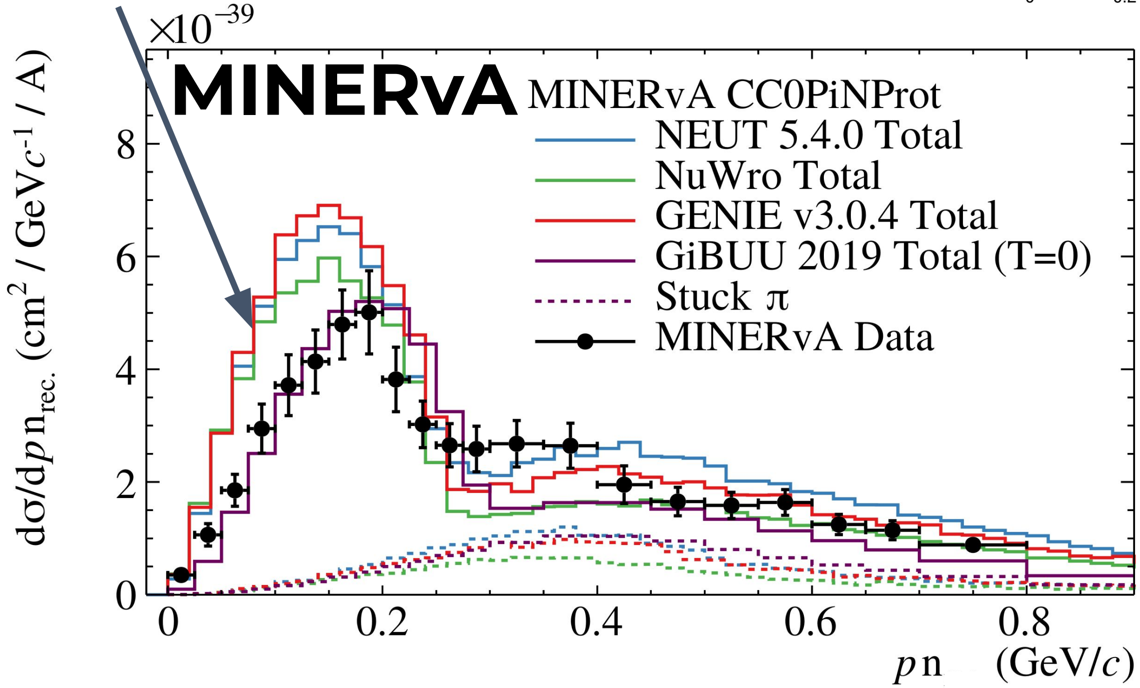
pn

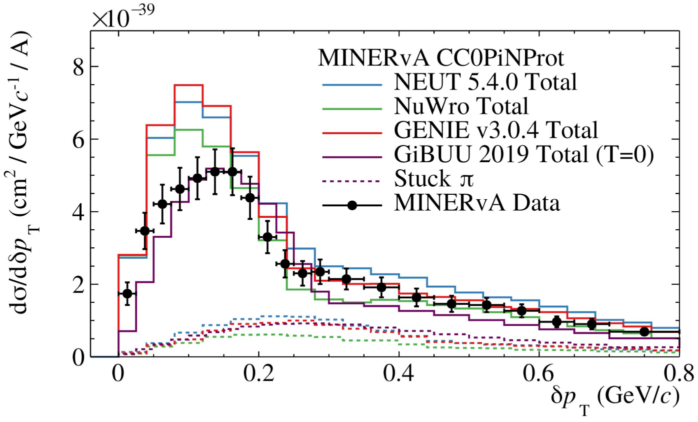
Phys.Rev. C95 (2017) 065501,
see definition in BACKUP

- 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



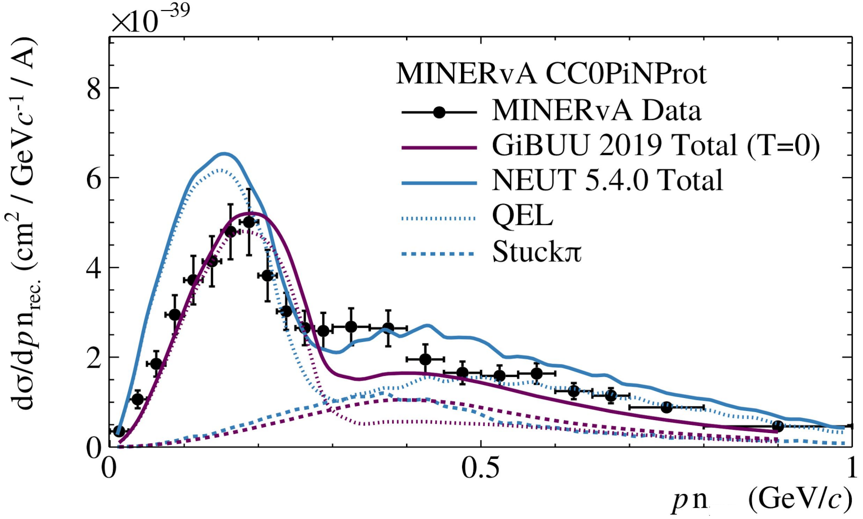


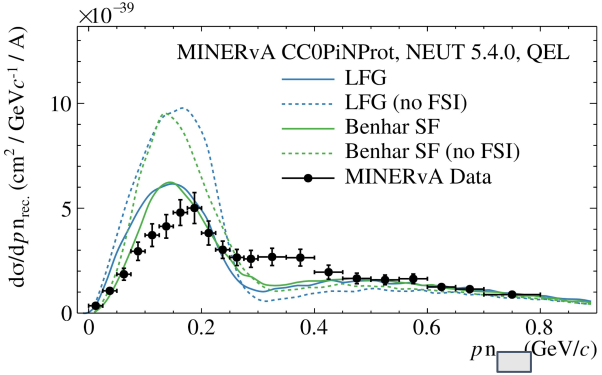


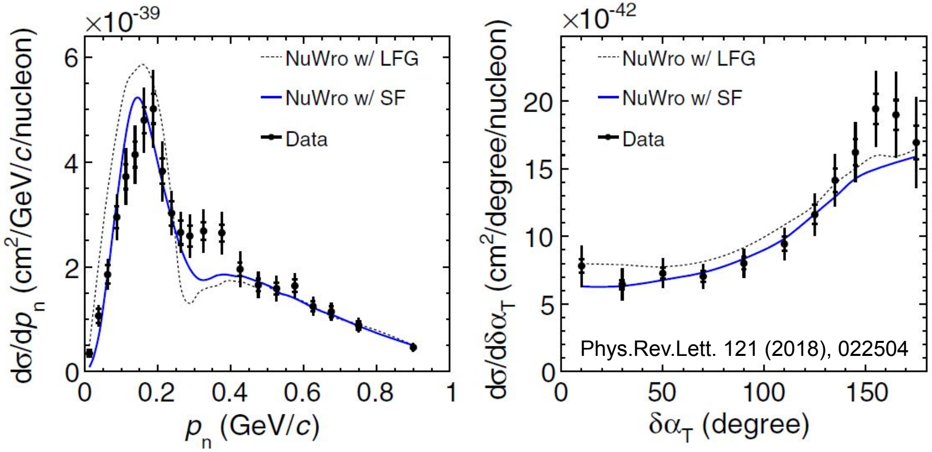


More pn

- 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)



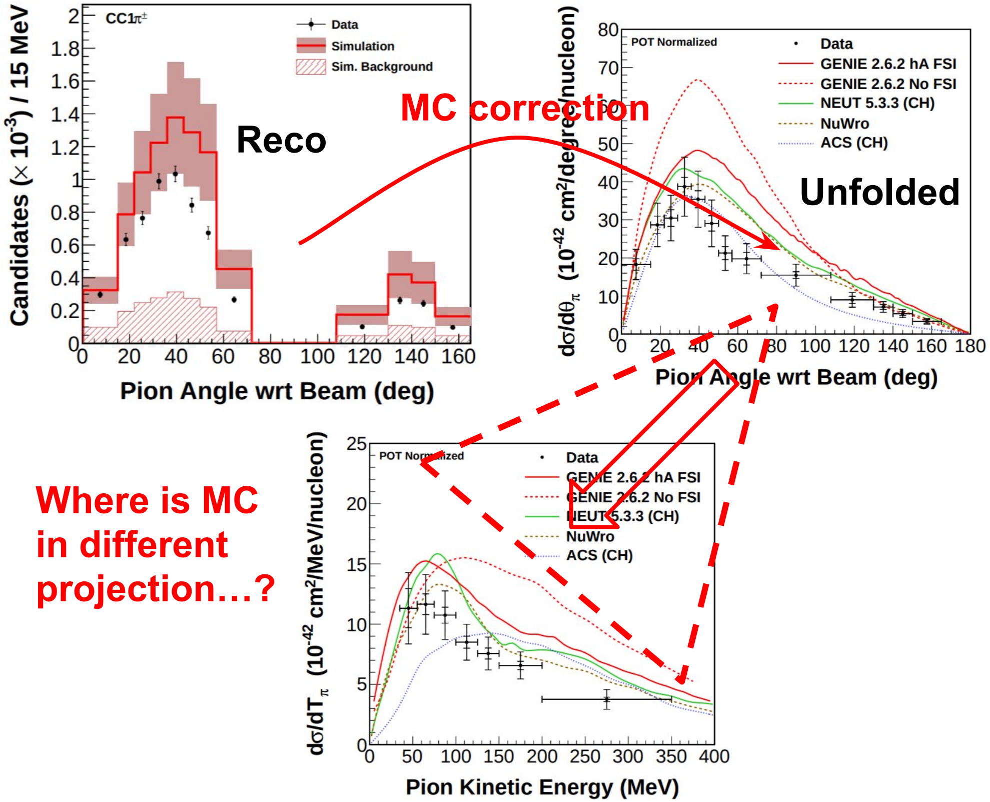




MINERvA 1pi neutrino-mode

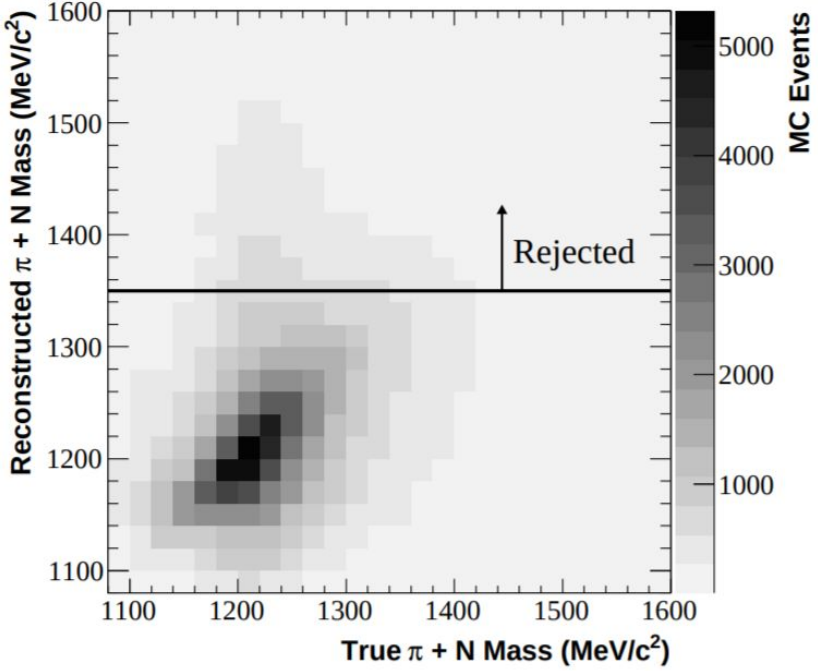
PRD 92 092008

- 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 ($\pi+$, $\pi0$, ν, $\bar{\nu}$):
  - Difficult to consistently use together in a meta-analysis.



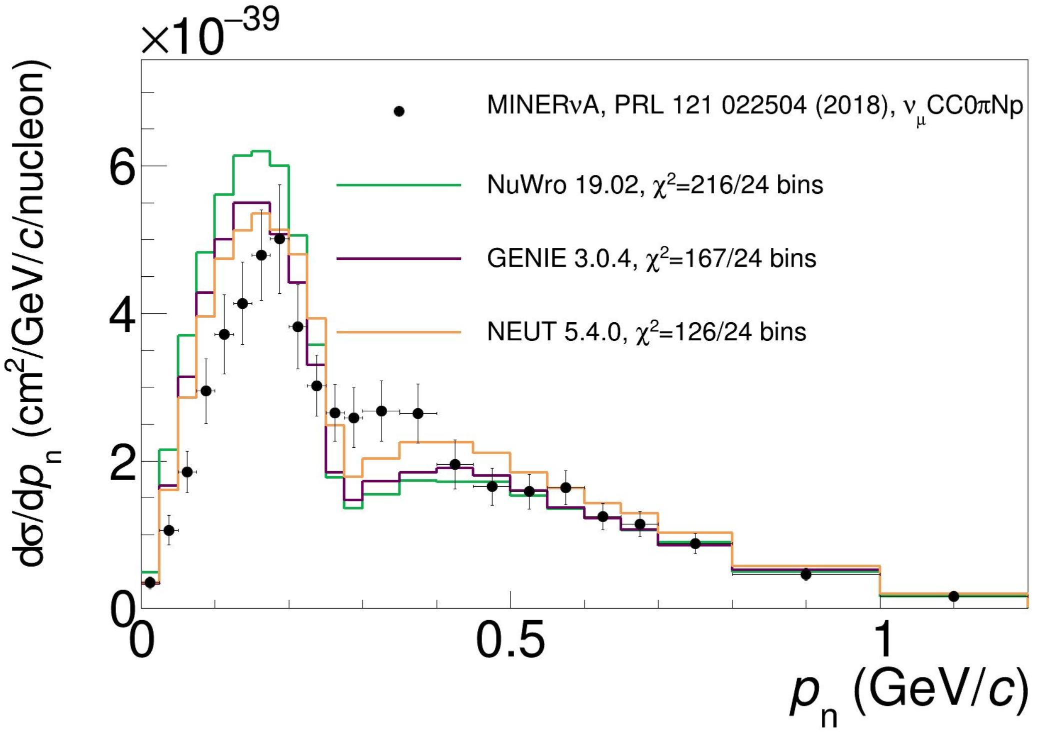
MiniBooNE 1Pi+

- 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)

- NEUT:
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  - Improved multi-pion production from BC tune
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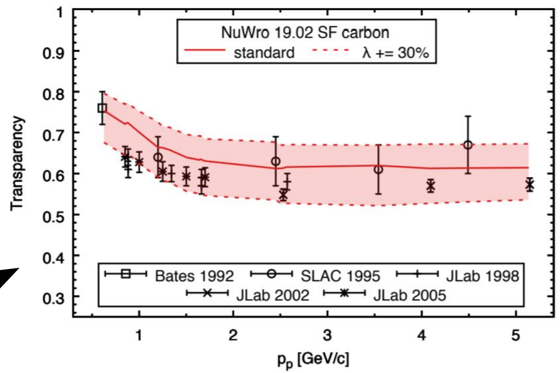
- NuWro:
  - Updates to spectral function
  - Update of FSI cascade by comparison to nuclear transparency data.
  - Integration of electron scattering simulation.



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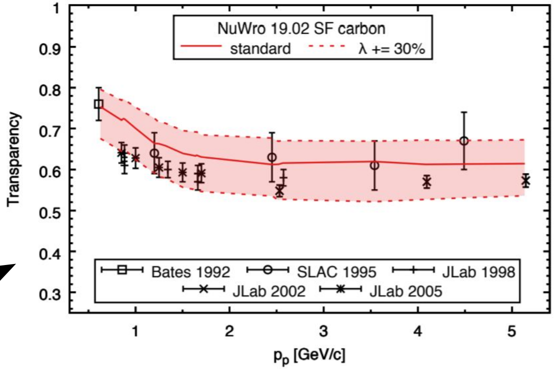
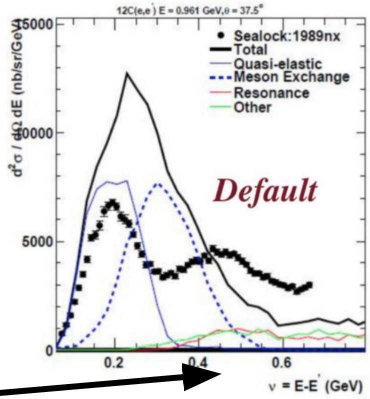
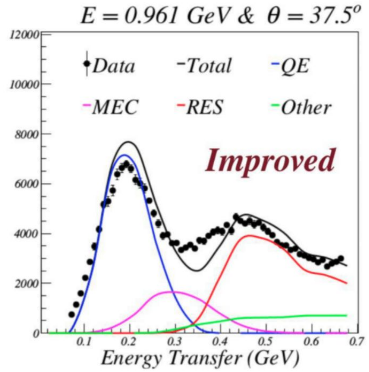
- NuWro:
  - Updates to spectral function
  - Update of FSI cascade by comparison to nuclear transparency data.
  - Integration of electron scattering simulation.
- GENIE:
  - Version 3 released!
  - Extensive ν-N tuning to bubble chamber data
  - **Many improvements to electron scattering simulation (c.f. Or Hen e4nu Plenary)**
  - Some significant bug fixes







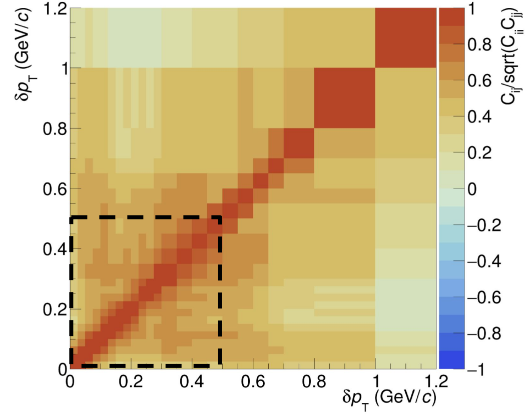
*Genie R-2_12_10

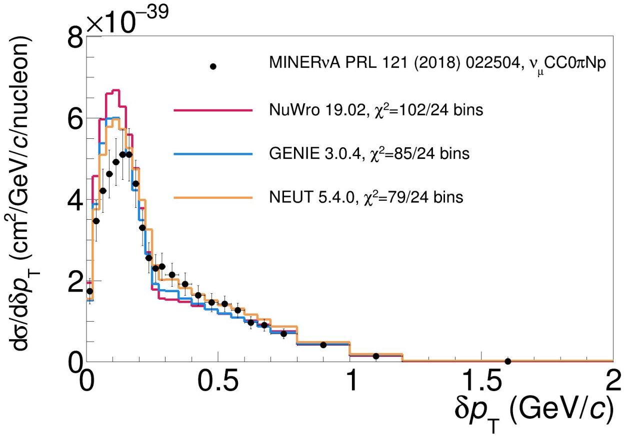
A. Papadopoulou @ NuInt18

Transverse missing momentum

MINERvA: PRL 121 (2018) 2, 022504

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

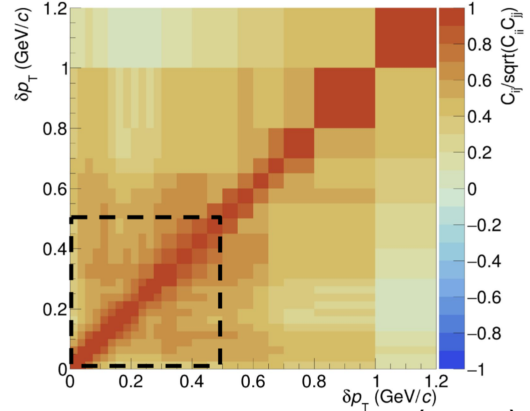




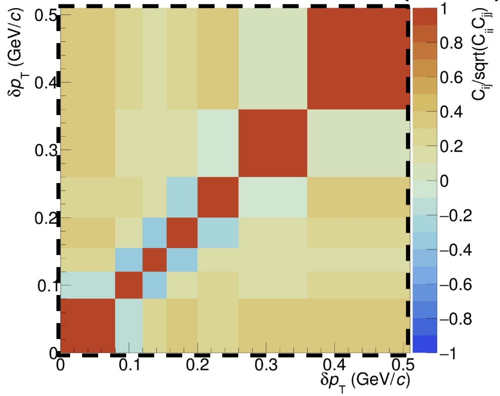
Transverse missing momentum

- 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

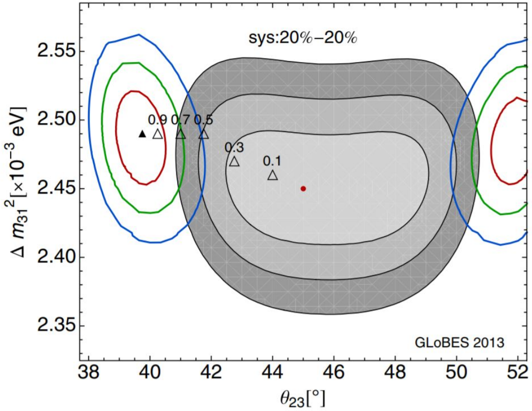
- The loftiest goals of neutrino oscillation physics depend on the accuracy of event generator predictions and associated uncertainties.
- Recent $\nu_\mu \rightarrow 0\pi$ data releases have been more statistically robust, but GOF between available models is generally poor
  - Room for improvement in 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 $P_{osc}\left(E_{\nu}\right)$.

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

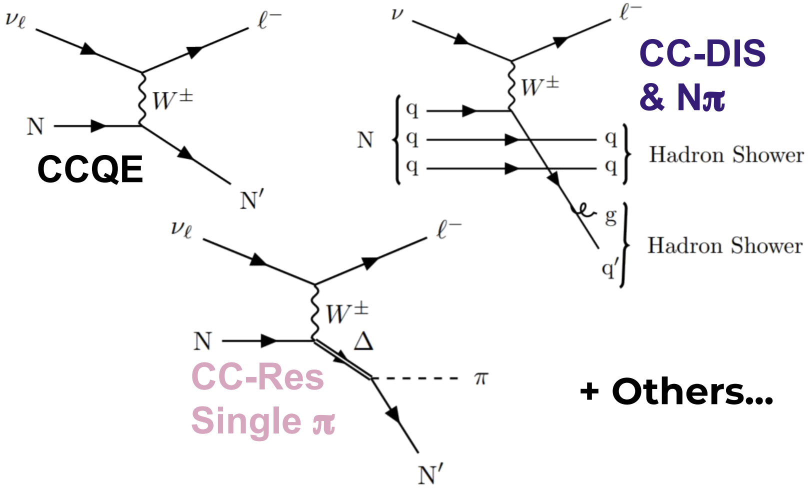
$$N_{\mathrm{far}}\left(\mathbf{x}_{\mathrm{obs}}\right)=\int d\mathbf{x}_{\mathrm{true}}\underbrace{\mathbf{D}_{\mathrm{far}}\left(\mathbf{x}_{\mathrm{obs}}|\mathbf{x}_{\mathrm{true}}\right)}_{\mathrm{Smearing,\ Eff.,\ Pur.}}\underbrace{N_{\mathrm{targ}}\sigma\left(\mathbf{x}_{\mathrm{true}}\right)\Phi\left(E_{\nu}\right)P_{osc}\left(E_{\nu}\right)}_{N_{\mathrm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



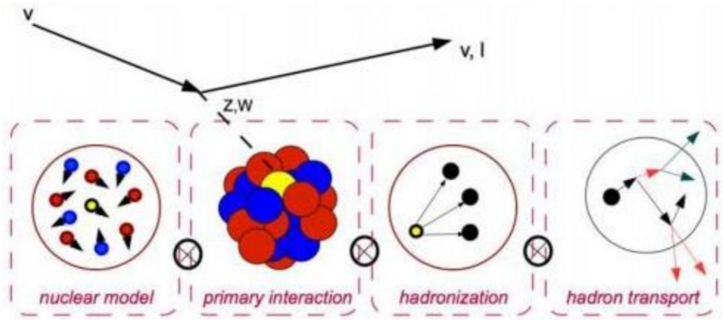
PRL 111.221802

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.

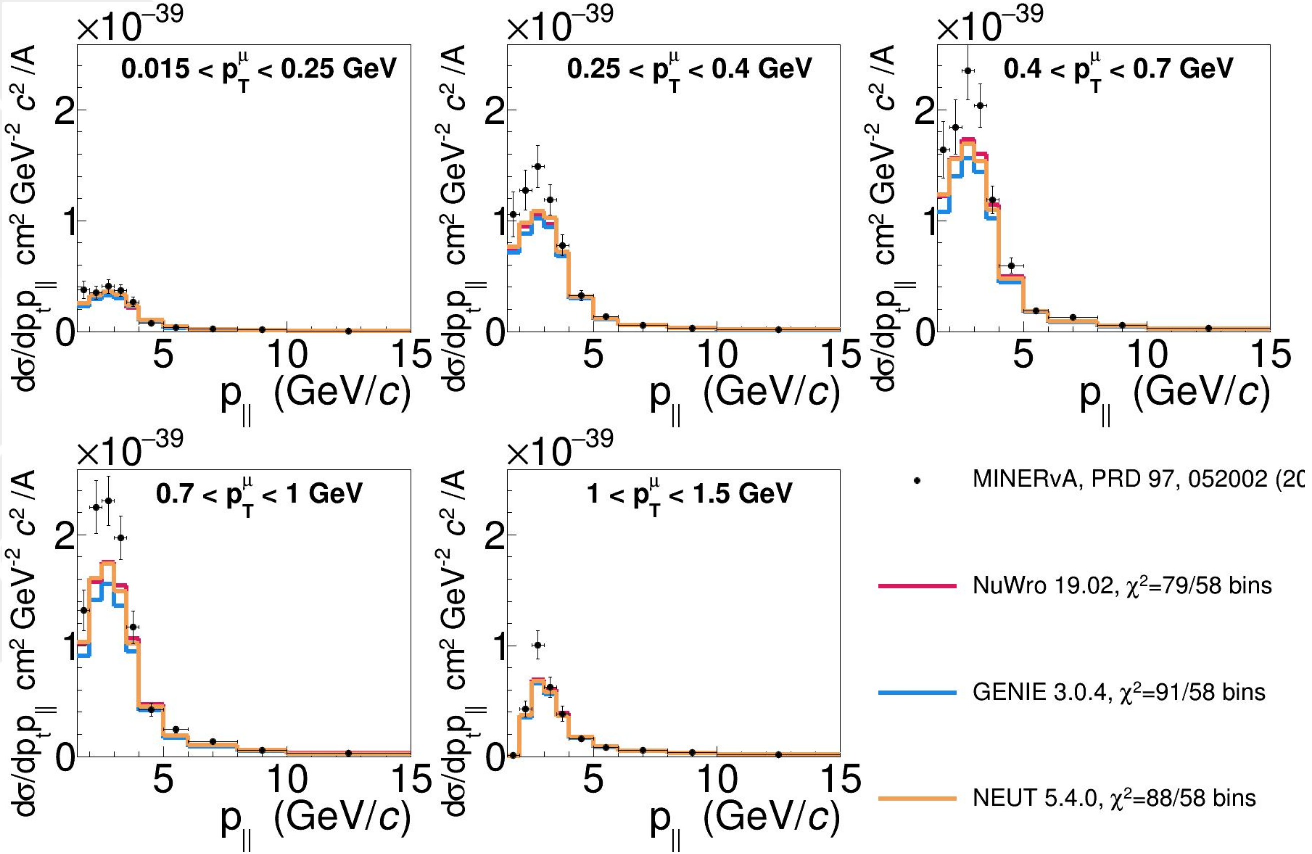


+ Others...



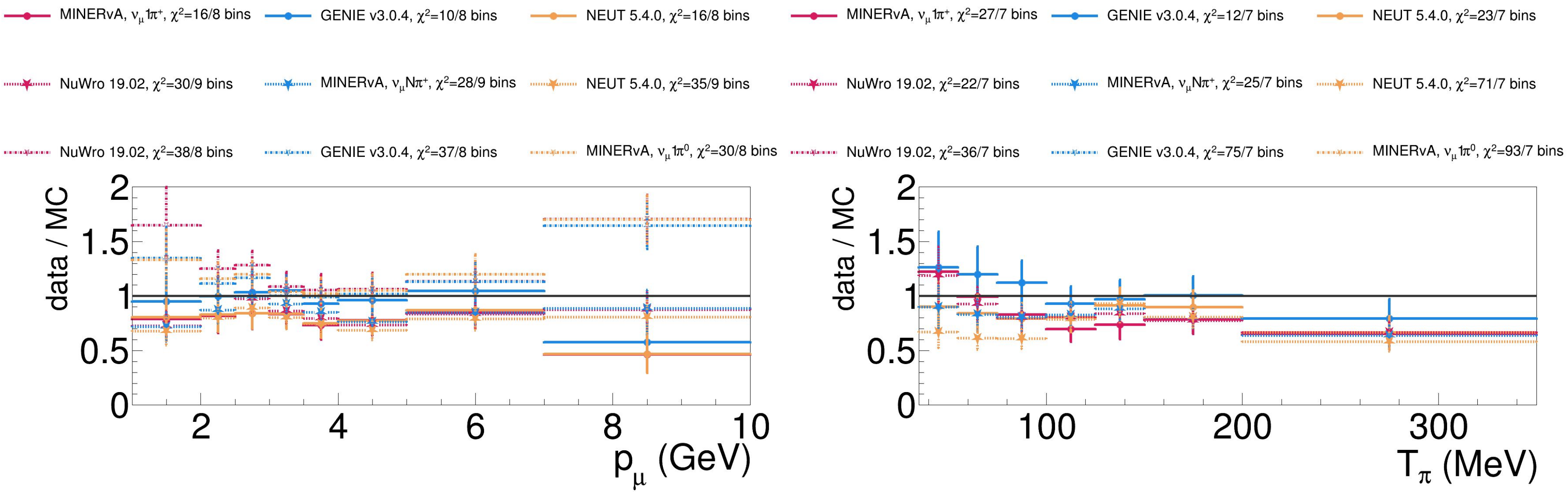
MINERvA 0pi anti-neutrino-mode

- χ-by-eye GOF seems worse (to me) than calculated GOF.
- Possibly because of PPP:
  - Smaller MC normalization can give 'artificially' low χ^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.

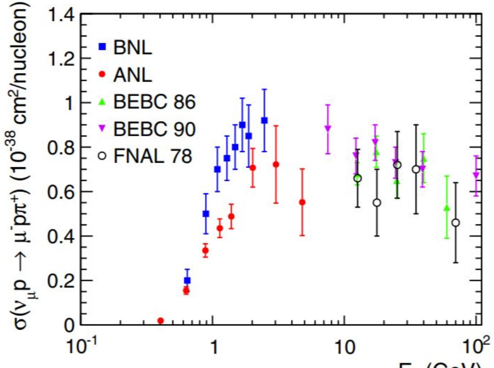
Gen Future: 2

- 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…

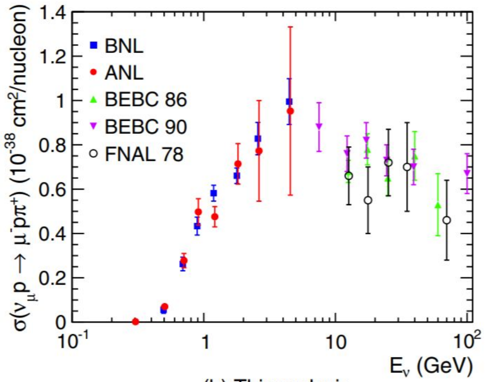
The data is the data is the data

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

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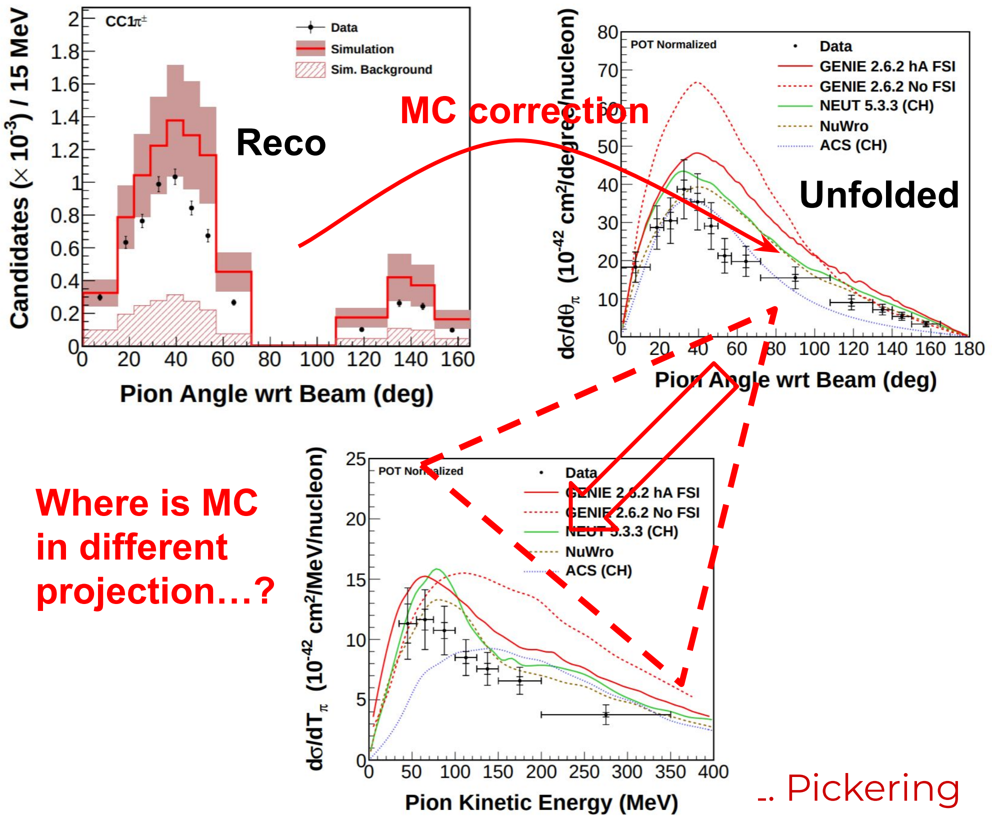
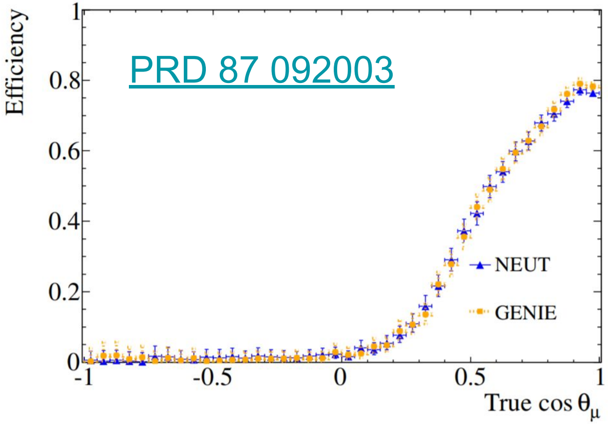
Hidden Model Biases 1

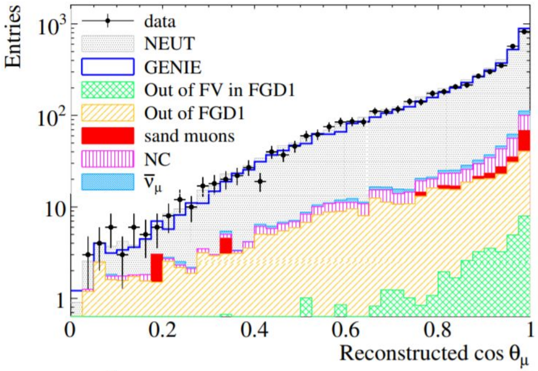
- Un-smearing and efficiency corrections introduce bias.
- From a fitters point of view, it is better to cut out regions of very poor efficiency:
  - Don’t want to compare to *model-of-the-day* contaminated ‘data’.
- Very helpful that such plots are in the publication!
- *N.B.* These problems are tricky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

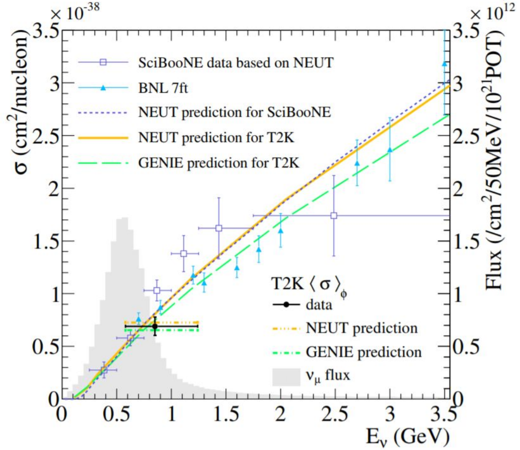
PRD 92 092008



Hidden Model Biases 2: Stealth mode



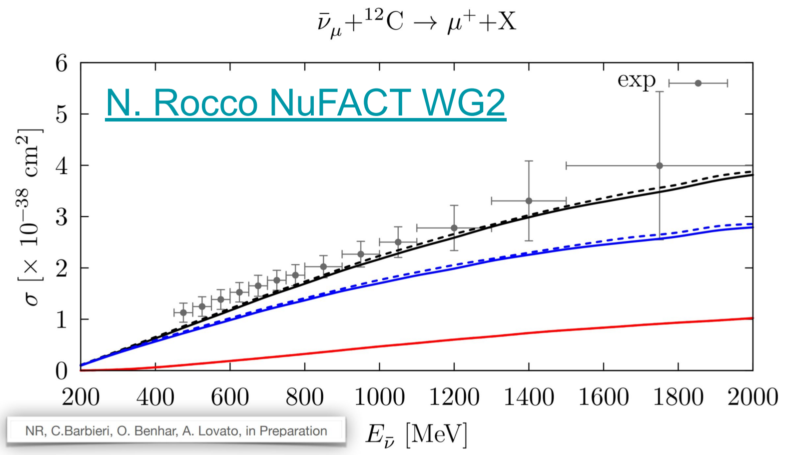


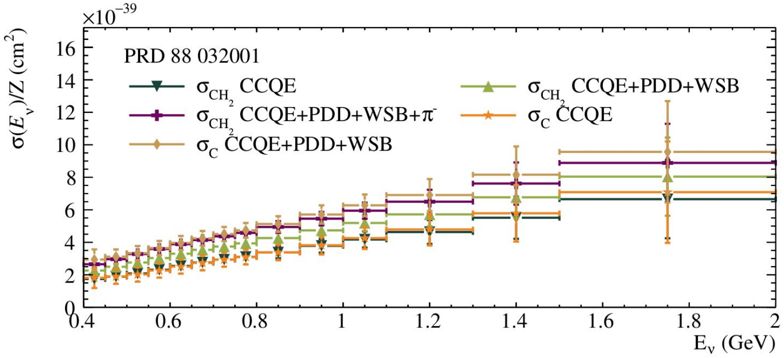


- It isn't always so clear: *e.g.* ND280 CCIncl
  - Practically cannot measure cos(θμ) < 0.
  - But, publish total cross-section.
- Similar out-of-acceptance corrections in many recent measurements: *Fiducial* cross-sections are much preferred!

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.

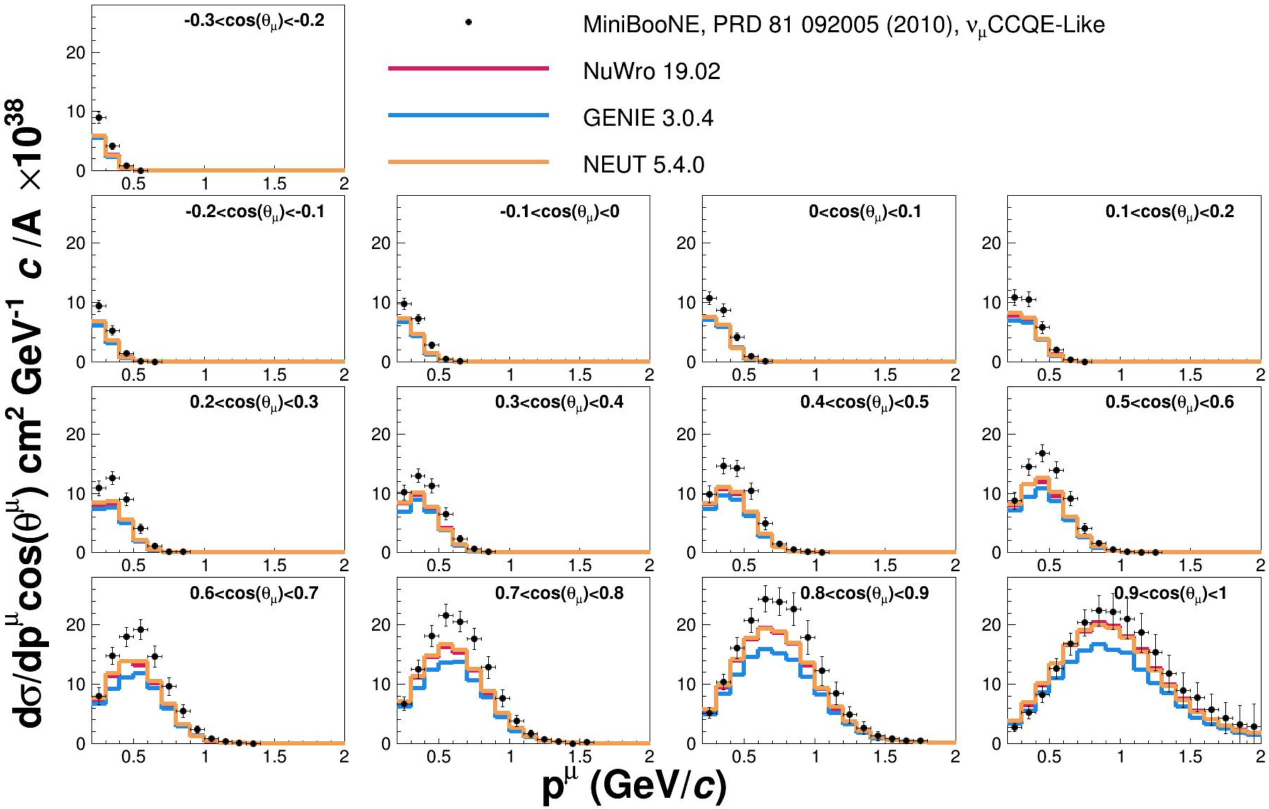




PRD 88 032001

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:

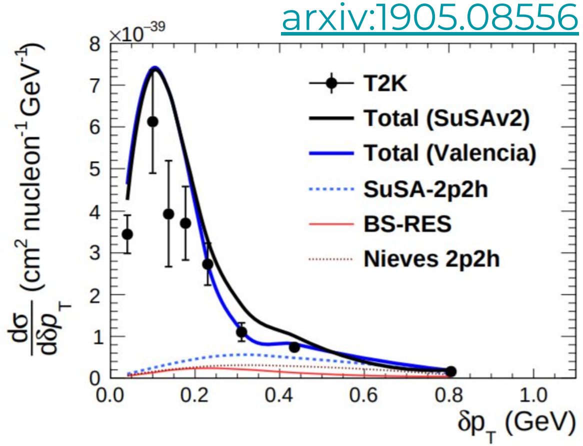
- **Virginia QE Archive**

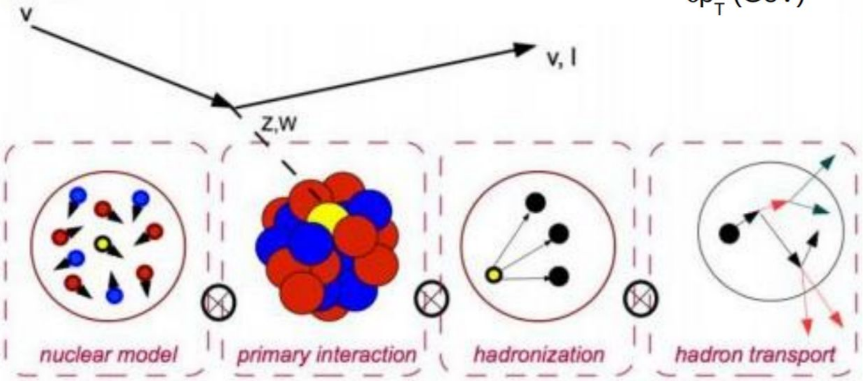
How do we try and improve them: Theory

- 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

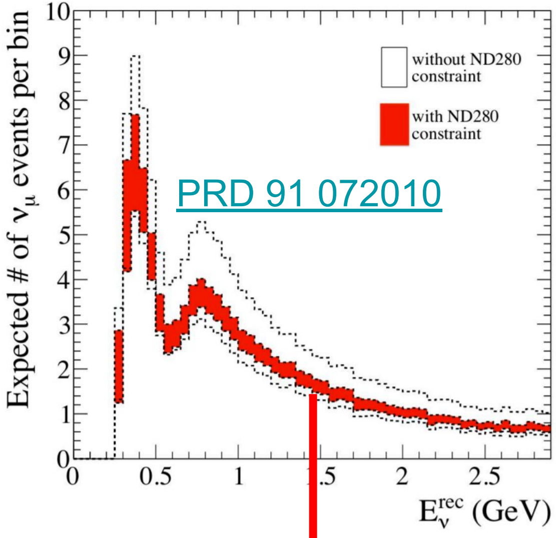
χ2 SuSA: 21/8
χ2 Val.: 27/8



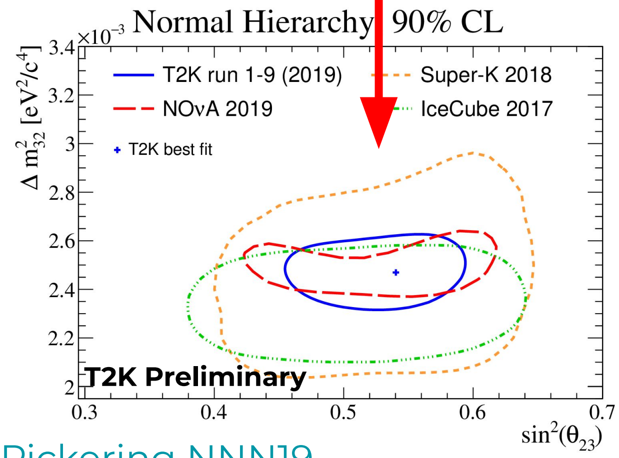


What about uncertainties?

- 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

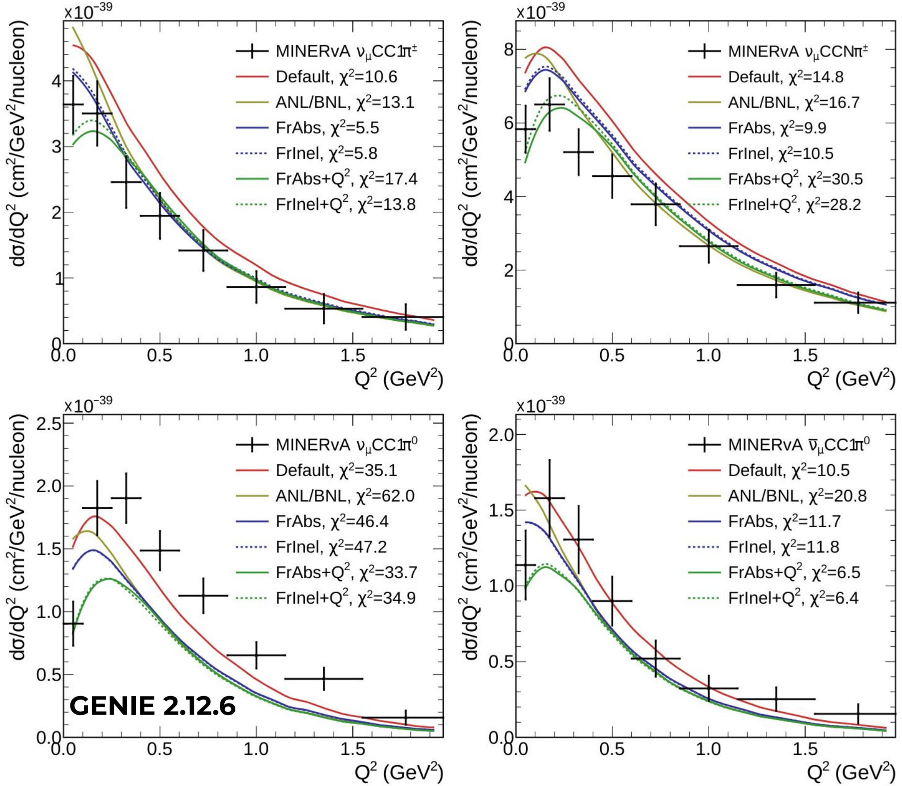


L. Pickering NNN19

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.

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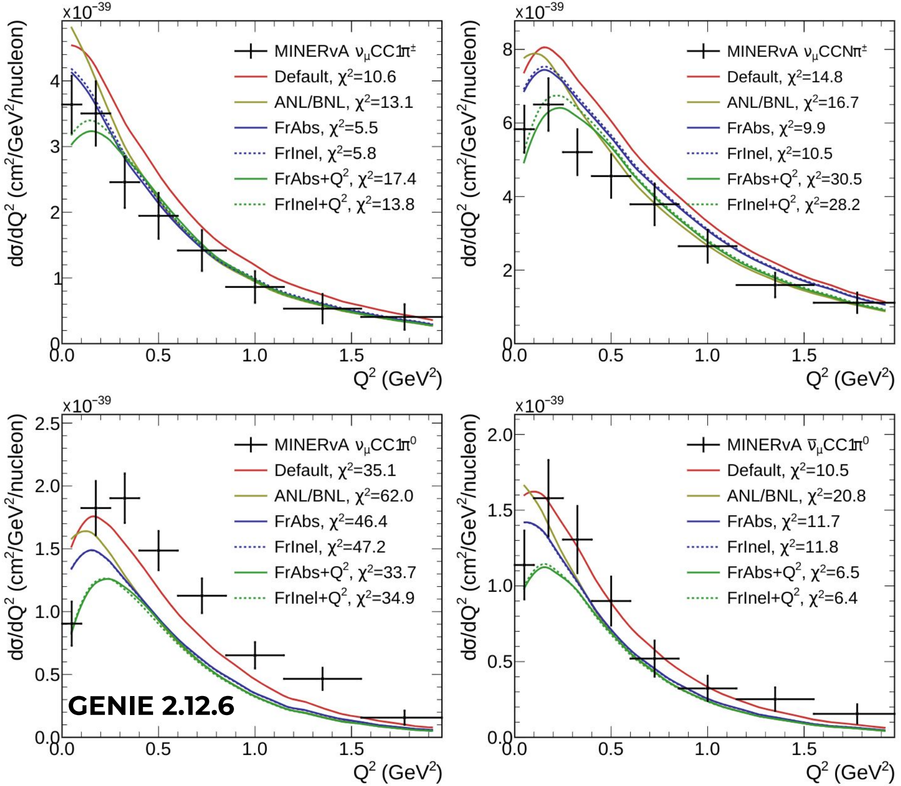

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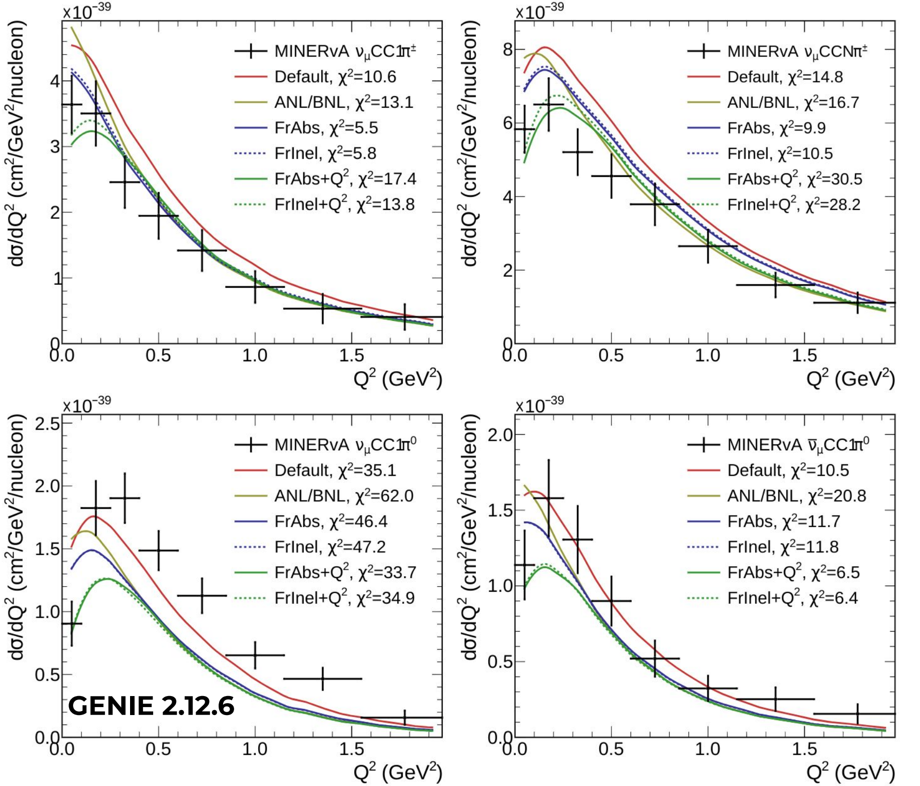
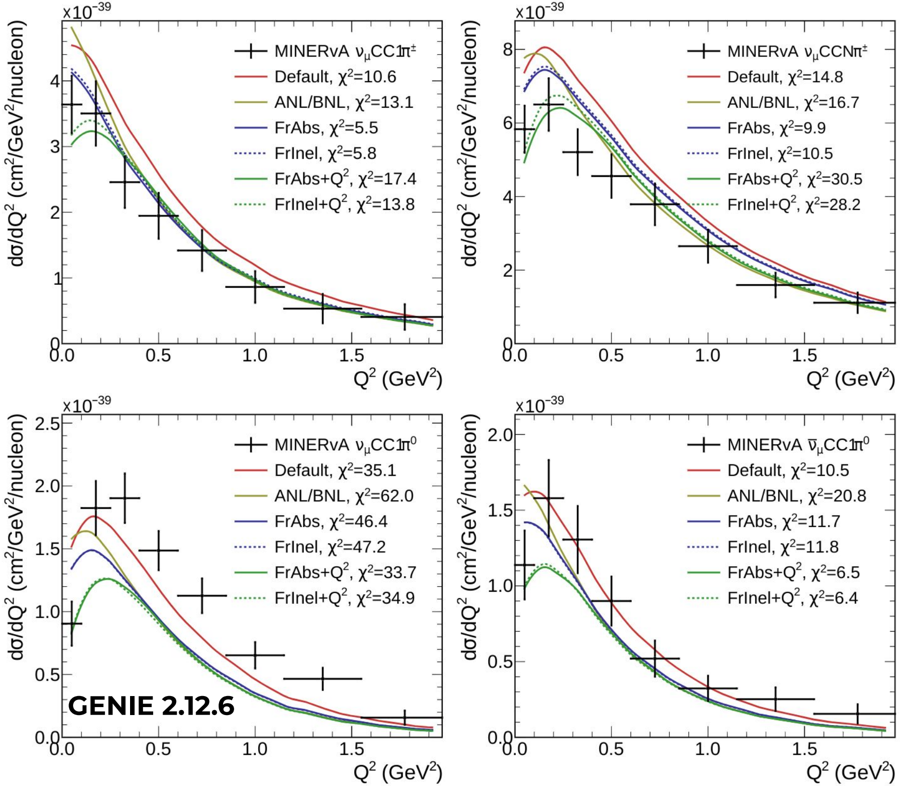


Phys. Rev. D 100, 072005 (2019)

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.

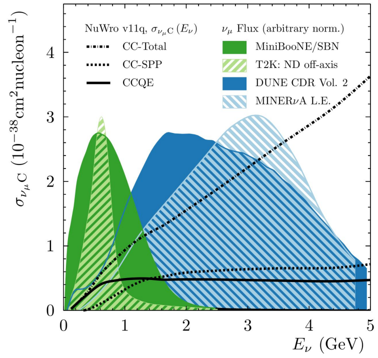
MINERvA Single pion production comparisons



Phys. Rev. D 100, 072005 (2019)

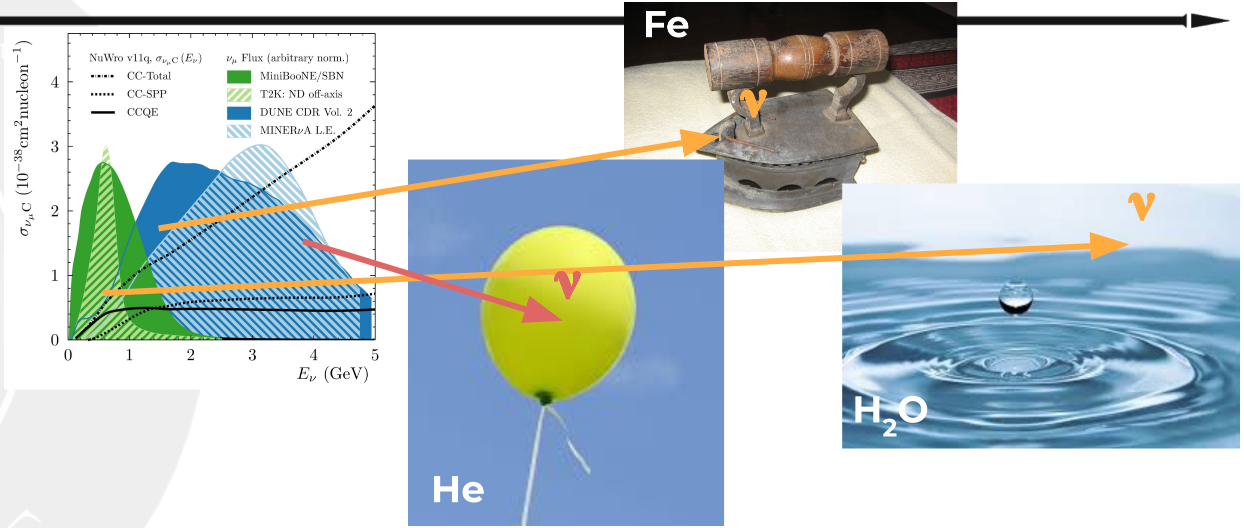
What we want out of comparisons to data

- Range of:
  - Neutrino energies



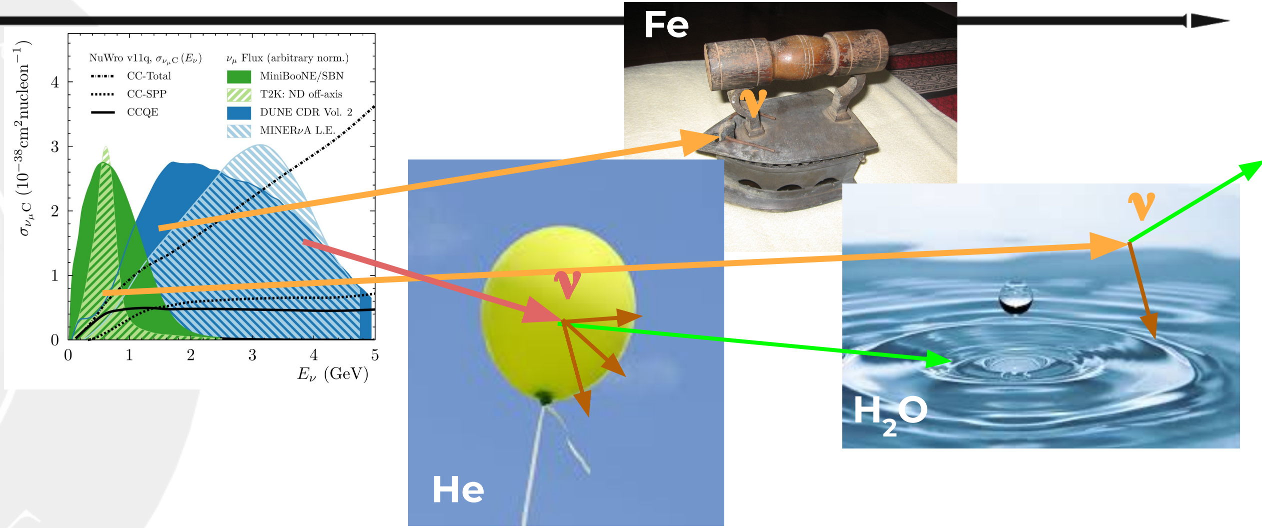
What we want out of comparisons to data

- Range of:
  - Neutrino energies
  - Targets



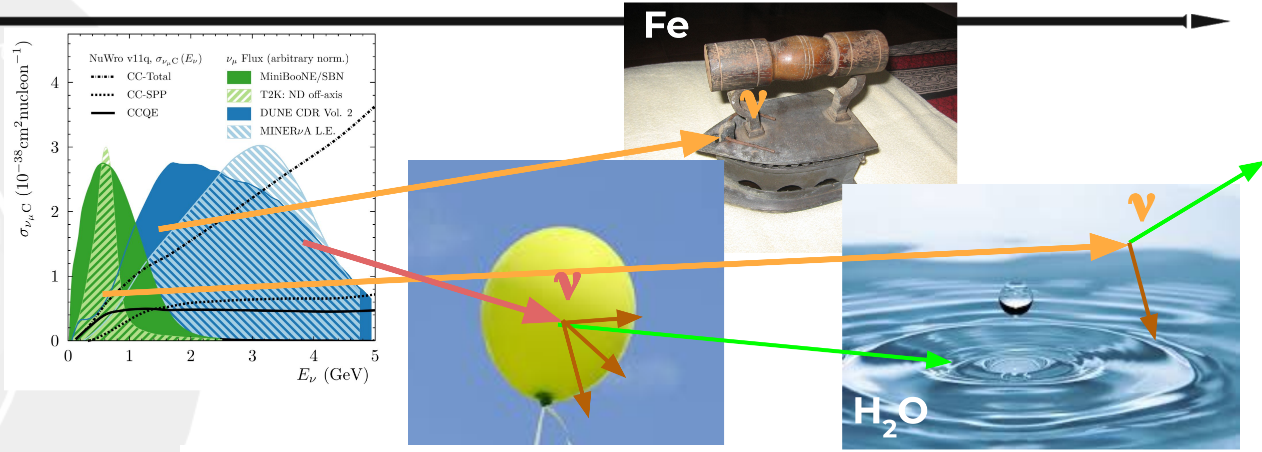
What we want out of comparisons to data

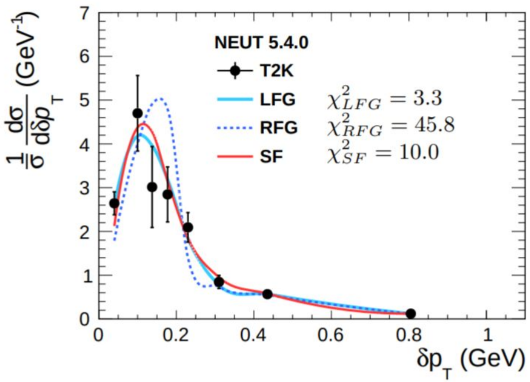
- Range of:
  - Neutrino energies
  - Targets
  - Final state topologies
  - Observable projections



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

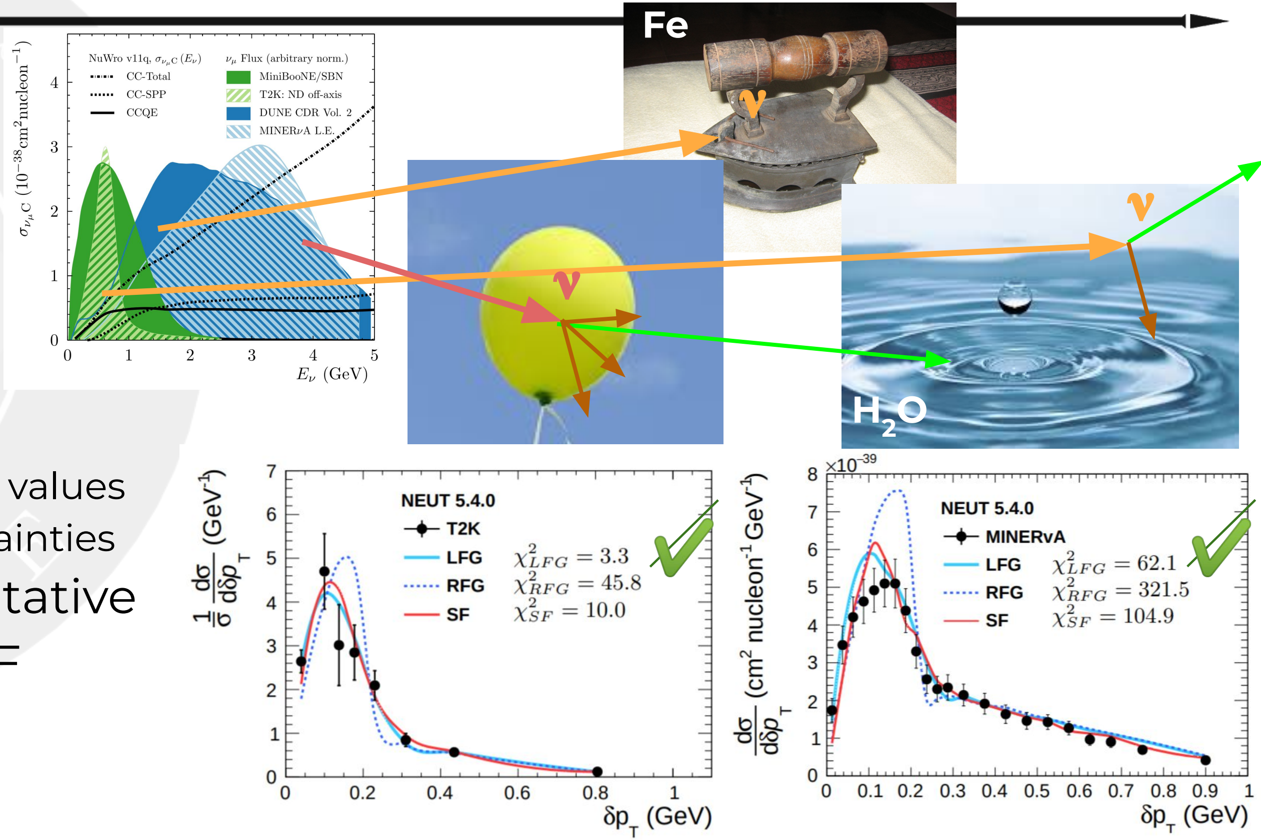




T2K data: PRD98, 032003 (2018)
Plots: arXiv:1810.06043

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



Anatomy of a Cross-section Fit

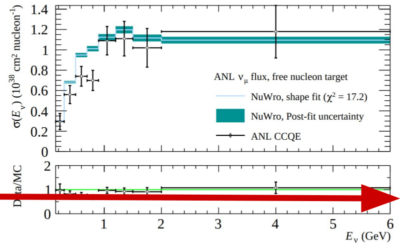
Choose model parameters

Interaction model

ANL CCQE

Data + Errors

Th. Prediction



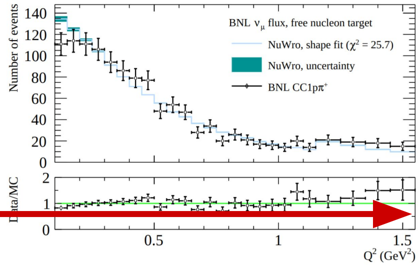
χ2

\+

BNL CC1pi+

Data + Errors

Th. Prediction



χ2

⋮

+ …

+ Model parameter prior penalties

= Global χ2

Minimize χ2 by varying model parameters

Simple, Right?

- Cross-section tune recipe:
  - Add all the data you can find

Simple, Right?

- Cross-section tune recipe:
  - Add all the data you can find
  - Stir free parameters until mixture is golden brown

Simple, Right?

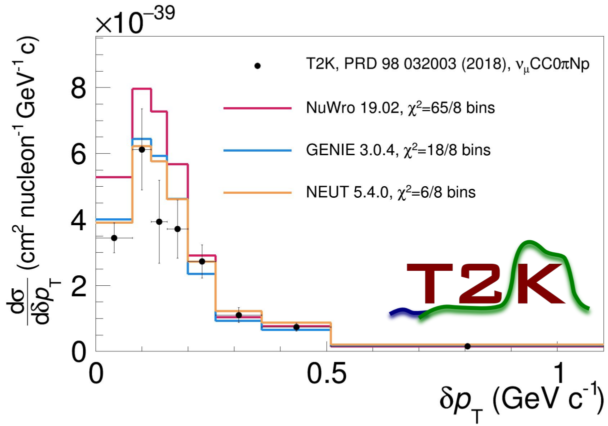
- Cross-section tune recipe:
  - Add all the data you can find
  - Stir free parameters until mixture is golden brown
  - Serve for updated interaction model and correlated uncertainties!

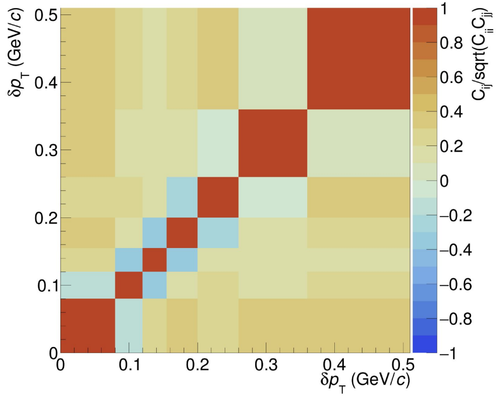
Simple, Right?

- Cross-section tune recipe:
    - Add all the data you can find
    - Stir free parameters until mixture is golden brown
    - Serve for updated interaction model and correlated uncertainties!
- 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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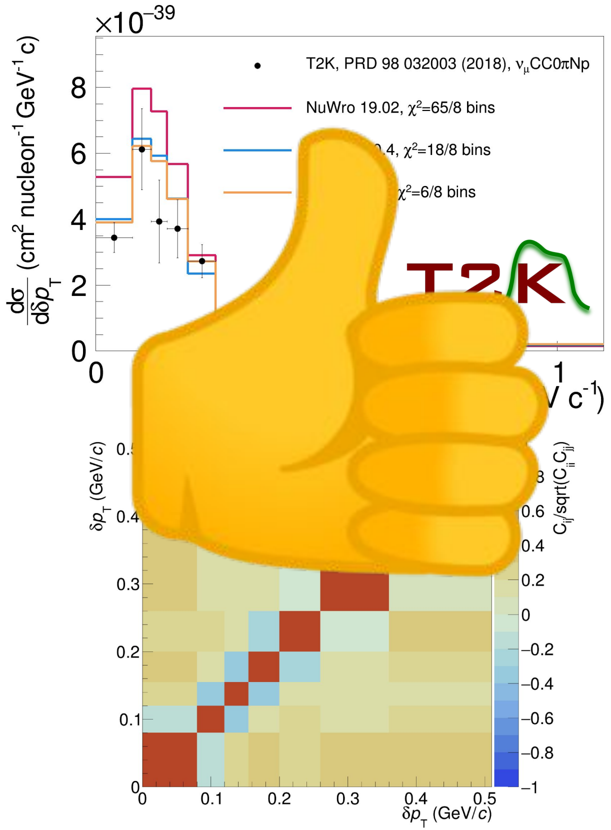

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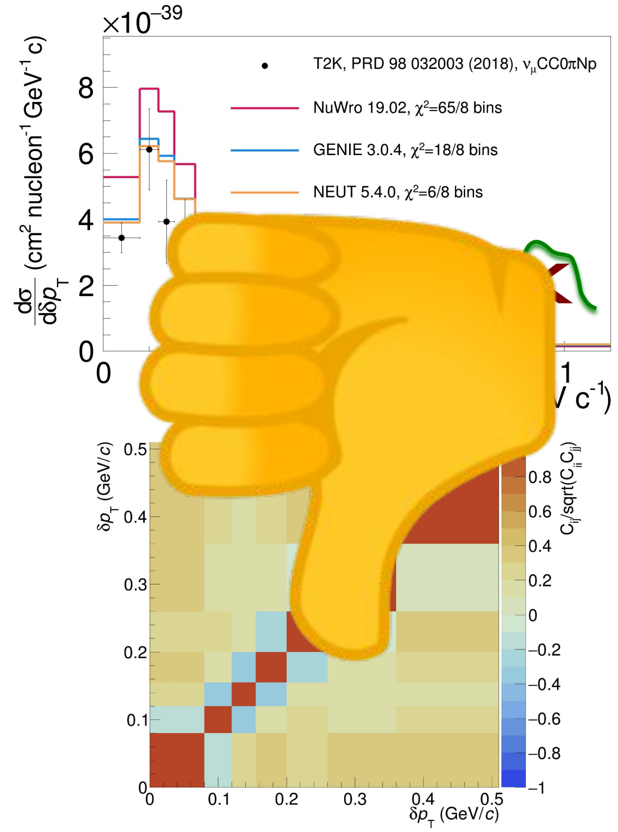
What is needed from Data Measurements

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

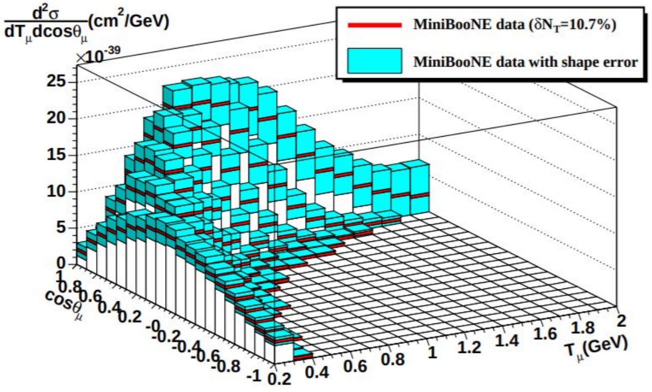
- Publish errors with bin-to-bin correlations.
  - **Wherever possible:**
    - **Between projections**
    - **Between datasets.**



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

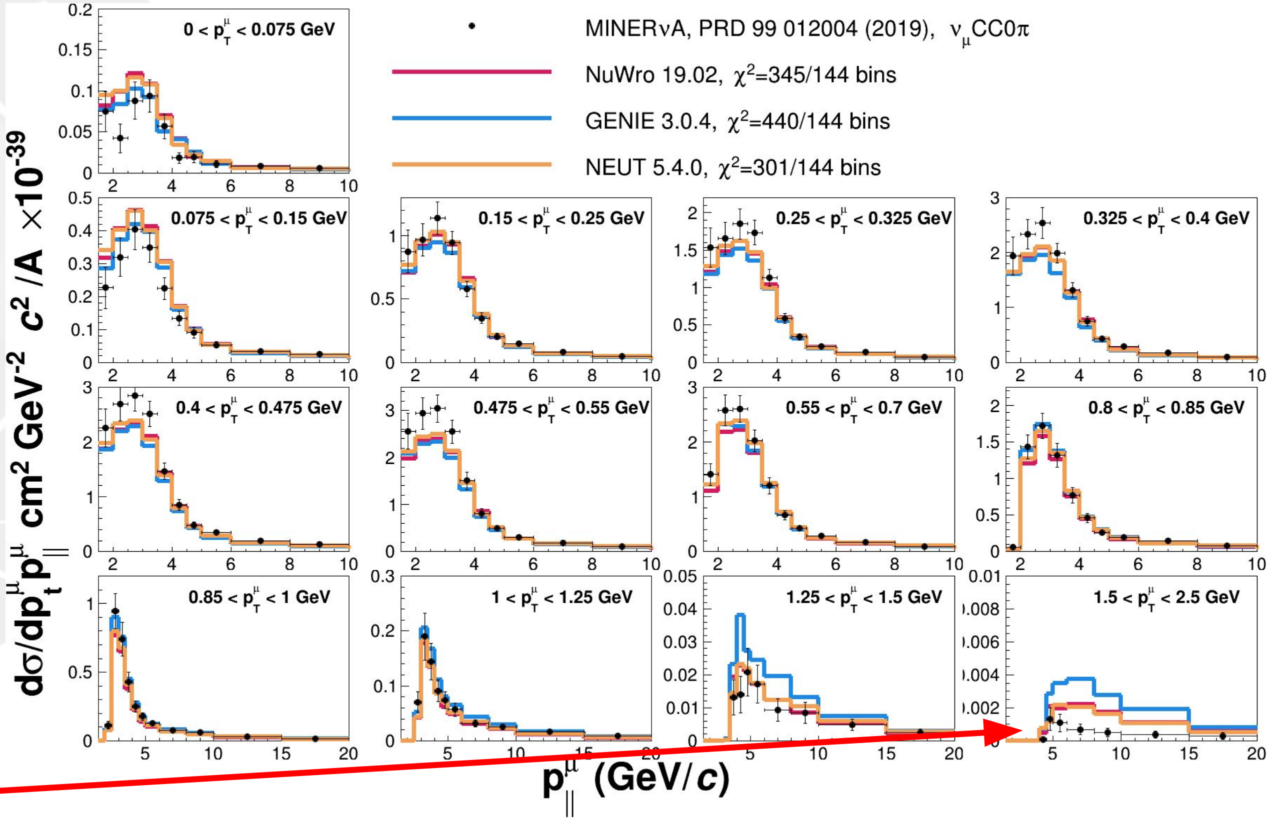


PRD 93 072010

	$\chi^2_{\text{min}}/N_{\text{DOF}}$
All	117.9/228
MINERνA	30.3/13
MiniBooNE	65.7/212
ν	69.1/142
$\bar{\nu}$	46.1/83
MνA vs MB	117.9/228
ν 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).