Building the interaction uncertainty model for DUNE

Rik Gran
U Minnesota Duluth
INT-23-86W workshop
30 Oct 2023

"Saint surrounded by three pi mesons"
Salvador Dali 1957

I’m representing the DUNE NIUWG

Were a task force DIRT and DIRT2 on Interaction Uncertainties
Then elevated to a physics working group (aka “new”-group)
We’re supporting oscillation sensitivity for the Near Detector TDR

Logo by Asher Kaboth, before we became NIUWG

I’m representing the DUNE NIUWG

Were a task force DIRT and DIRT2 on Interaction Uncertainties
Then elevated to a physics working group (aka “new”-group)
We’re supporting oscillation sensitivity for the Near Detector TDR

Our product is an external add-on to GENIE
called “nusystematics”, is framework agnostic
Simple enough professors can code for it

Customer(s) are oscillation sensitivity analysis
DUNE long baseline fitting group
DUNE near detector groups

I’m representing the DUNE NIUWG

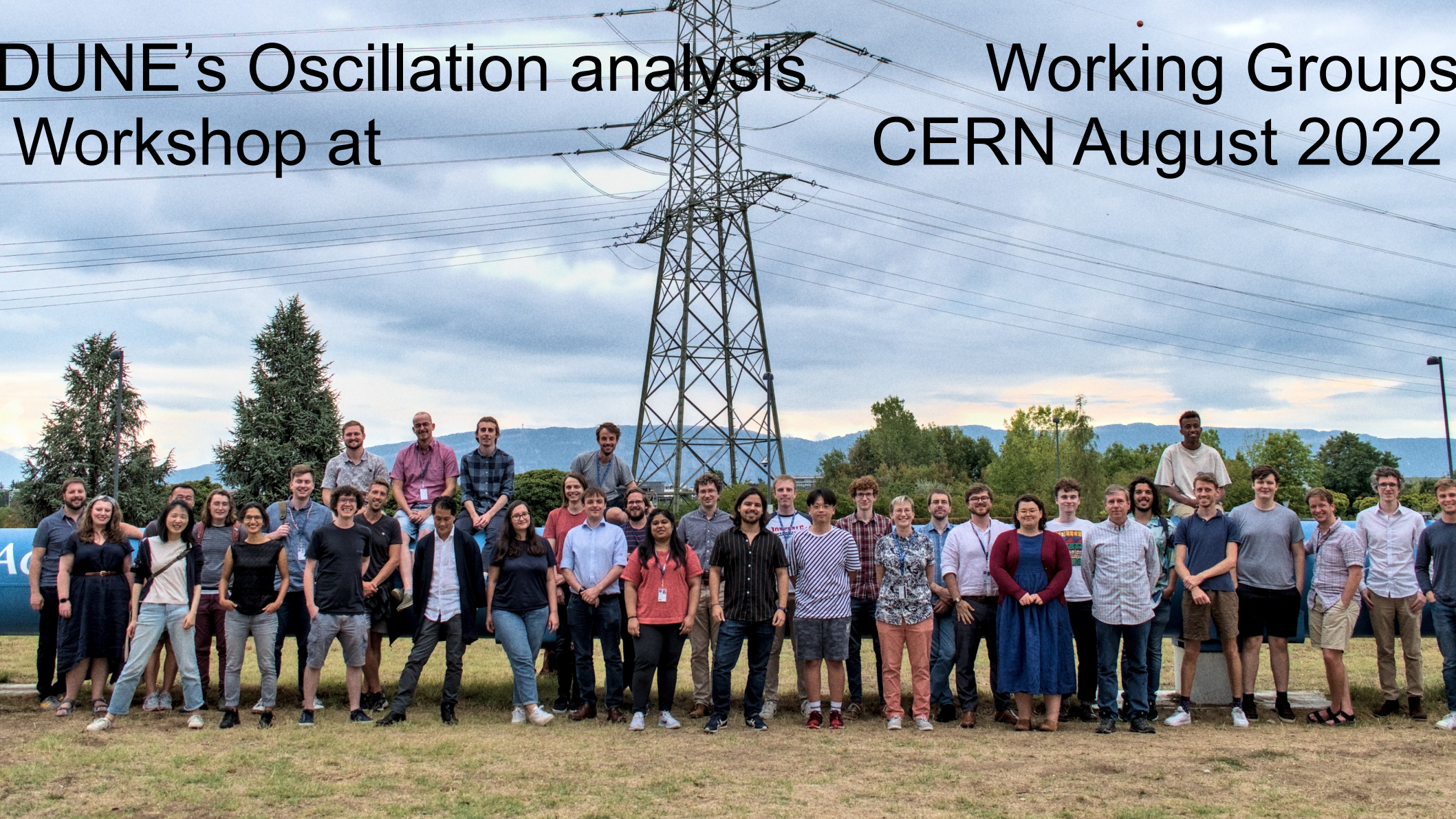
Were a task force DIRT and DIRT2 on Interaction Uncertainties
Then elevated to a physics working group (aka “new”-group)
We’re supporting oscillation sensitivity for the Near Detector TDR

Our product is an external add-on to GENIE
called “nusystematics”, is framework agnostic
Simple enough professors can code for it

Customer(s) are oscillation sensitivity analysis
DUNE long baseline fitting group
DUNE near detector groups

and
Icarus, SBND, DUNE 2x2, ?NOvA, ?T2K

DUNE's Oscillation analysis Working Groups Workshop at CERN August 2022



Working WG model, talk takeaway messages

Identify a minimum set of distributions
unique to one or more DUNE near detectors, highlight hadrons
those will be the oscillation fit ND constraint samples
For sensitivity analysis for the near detector technical design report

Expand the functional expression of systematic uncertainties
especially parameter count to ensure realistic degeneracies
as many as possible physically realistic and theory motivated

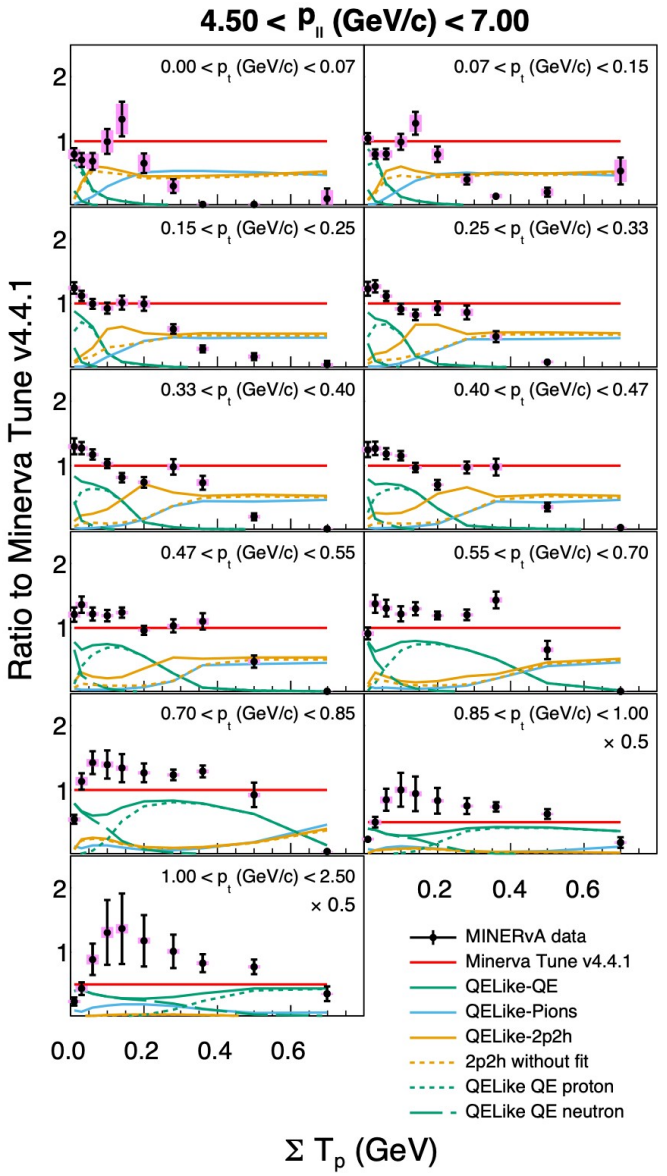
Working WG model, talk takeaway messages

Identify a minimum set of distributions
unique to one or more DUNE near detectors, highlight hadrons
those will be the oscillation fit ND constraint samples
For sensitivity analysis for the near detector technical design report

Expand the functional expression of systematic uncertainties
especially parameter count to ensure realistic degeneracies
as many as possible physically realistic and theory motivated

Craft some adhoc parameters or fake data configurations
break stuff, cause havoc in the oscillation parameter determination

Share developments among active experiments in near real-time



Example distribution from MINERvA

3D: two lepton and one hadron quantity
In liquid Ar, divide zero-pion and 1+ pion

Separates different components of model and different features of those components is quicker to access than TKI variables

Also looking carefully at
hadron multiplicity SAND, NDGAr, 2x2
especially FSI & neutron driven ones
and CH-C for SAND

The NIUWG could be your first customer

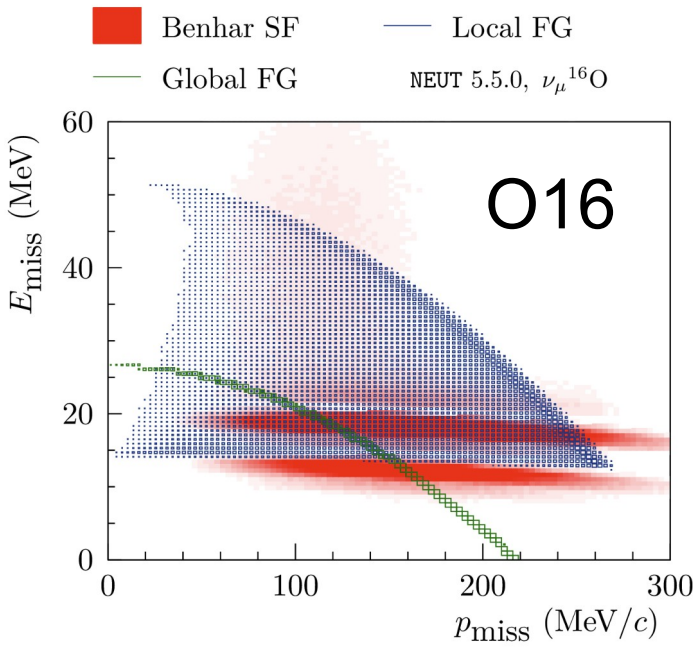
Four weeks ago I was talking with someone with a model who had a new path to make direct comparisons to GENIE (and by extension our baseline model)

If your model is at that point, then someone near the NIUWG doesn't need huge experience with your model or code to code the connections into nusystematics

An interested DUNE student could partner to do this

Deep dive example: ground state and QE

Innovation; expanded ground state phase space



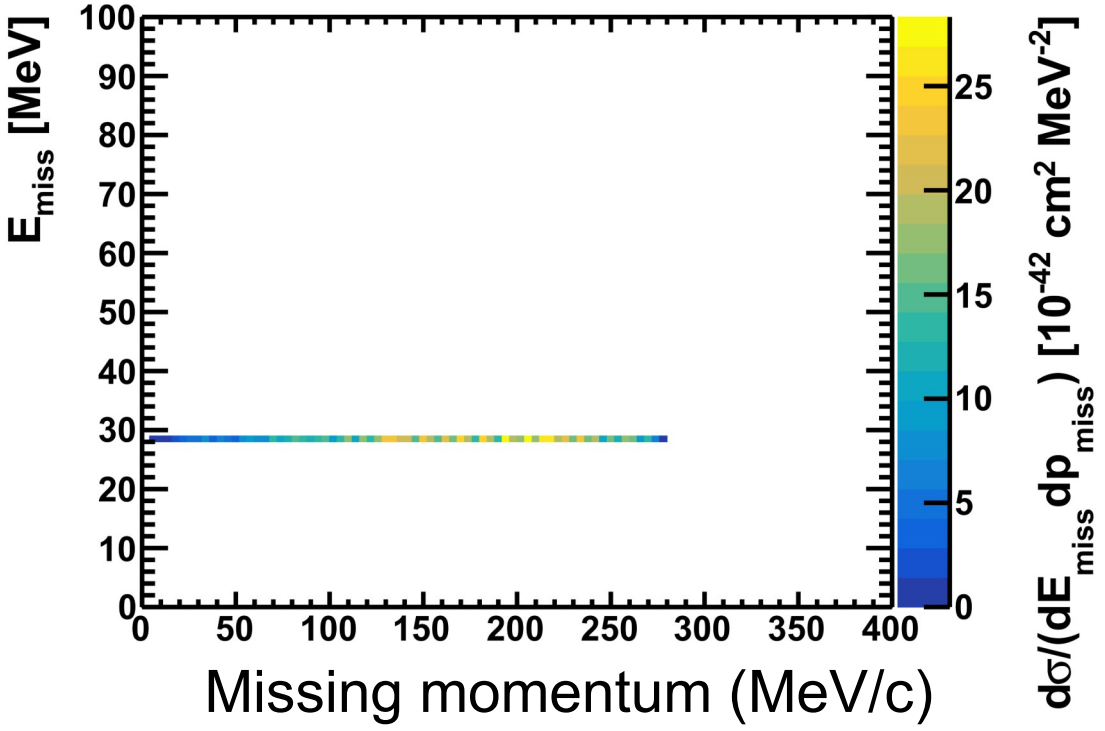
Today's detectors measure Ehad to ~MeV
And missing pT and θμ with great resolution

Absolutely essential to short-term program
a model with good coverage of this space.

A year ago, the GENIE SF was not working
So selected the local Fermi Gas for coverage

Eur.Phys.J.ST 230 (2021) 24, p4469

GENIE 3 LFG out of the box is a problem

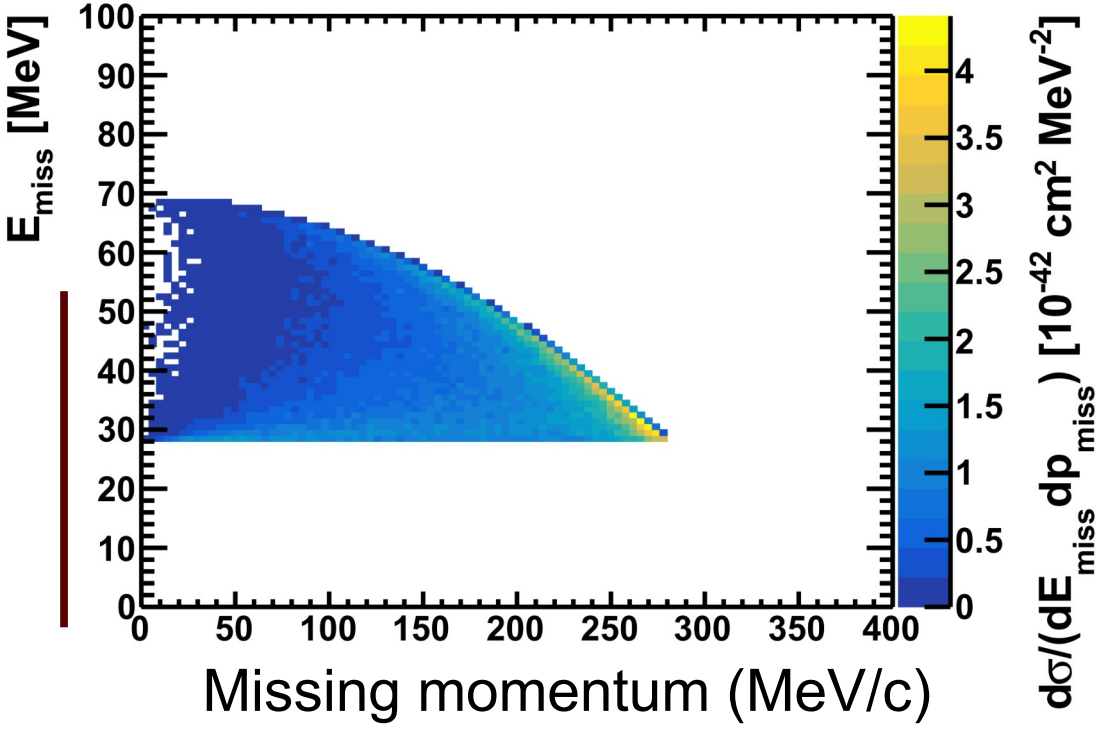


Has no variation in missing energy

GENIE3 development on LFG stopped before taking next step

No events to reweight

GENIE3 LFG with NEUT-like Valencia-like LFG



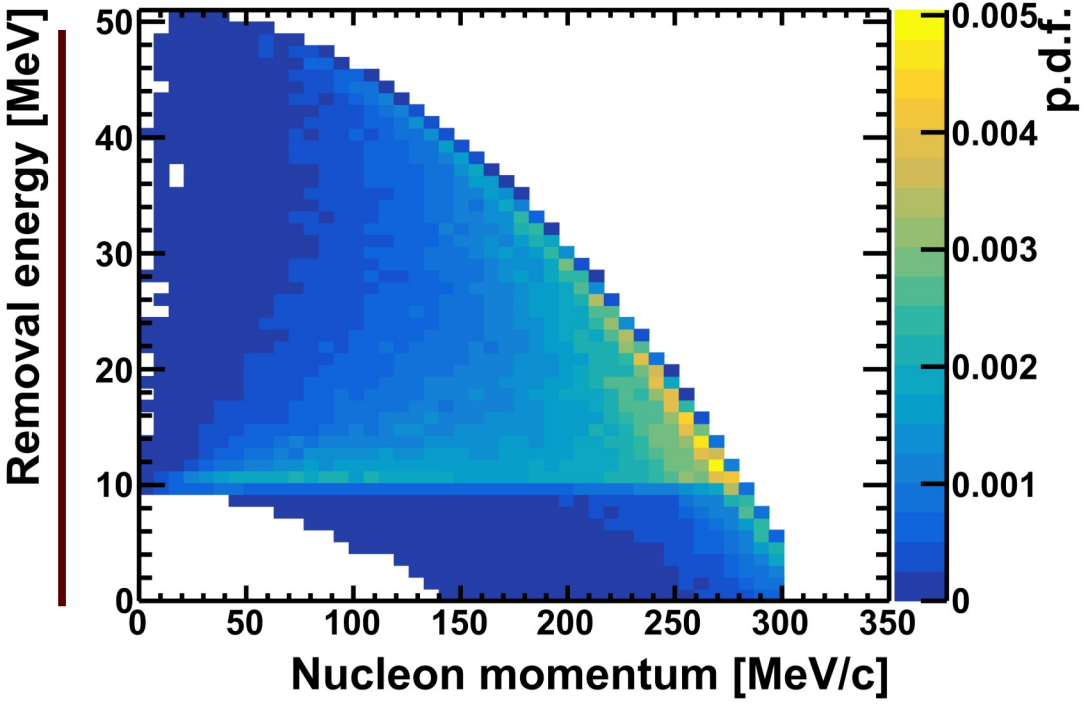
Not-invasive code change

Option is accessible in config file

Is shifted about 20 MeV high making unphysical gap at low end with no events to weight up

And no high momentum tail

GENIE3 LFG with NEUT-like LFG



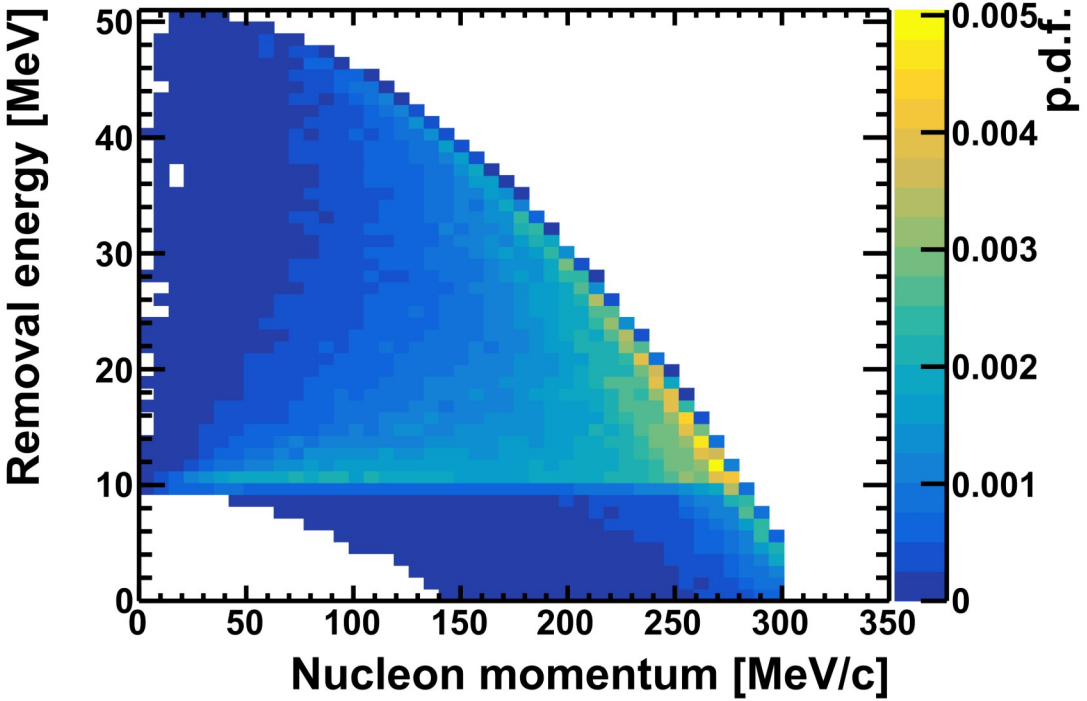
Distribution moved down 20 MeV (also vertical scale changed)

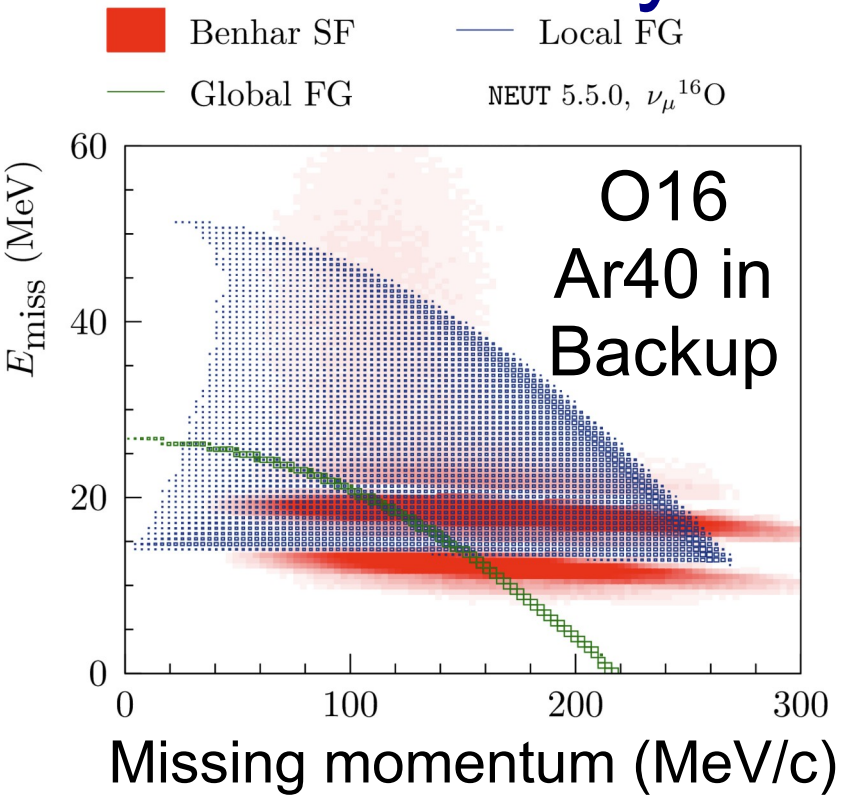
And extended up to 300 MeV/c
Wanted to go further

And below to 0 with RFG character

Slightly invasive change to code.

We have gained access and flexibility

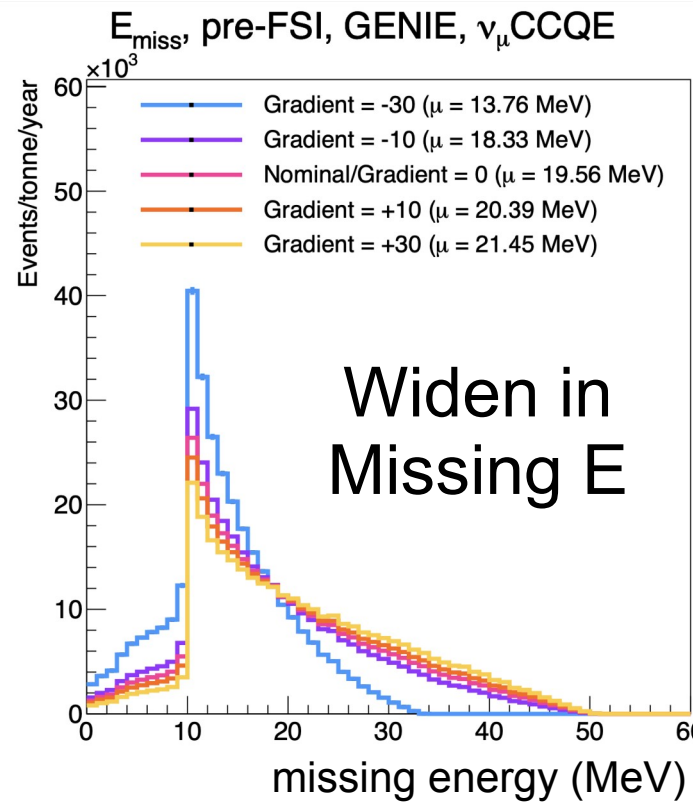


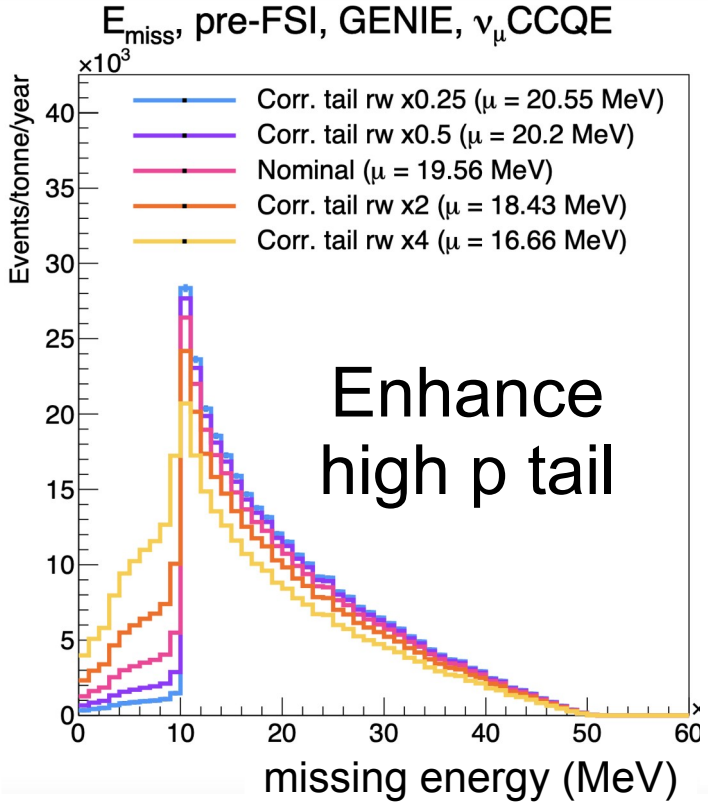


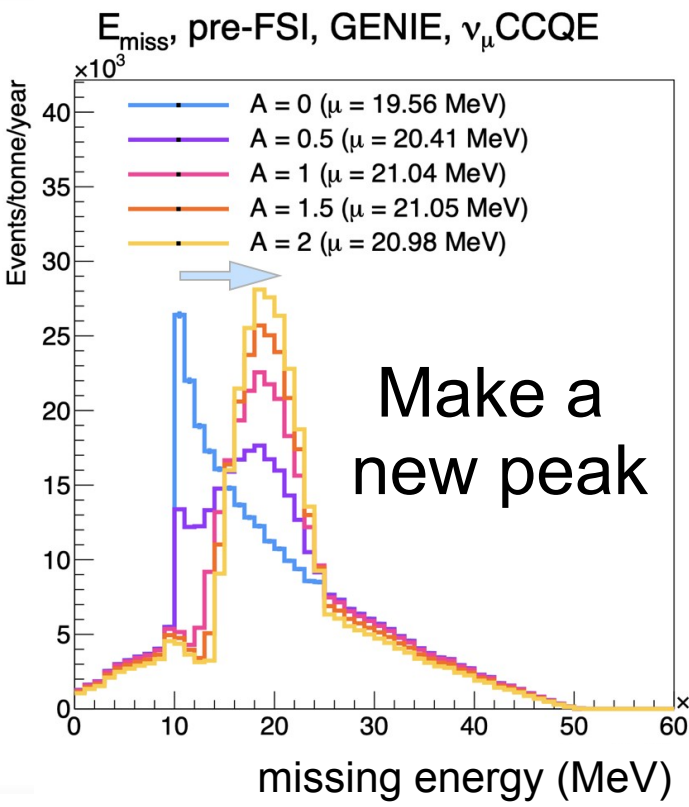
Can approximate variations on RFG, LFG, and SF and SRC tail ? Yes !
Can test how much ND samples (for oscillation fits & interaction analysis) are sensitive to these inputs.

Examples of weight variations in Emiss space

Tom Holvey, Oxford







This propagate this to lepton, hadron, and TKI observables in ND samples

Low energy transfer reach

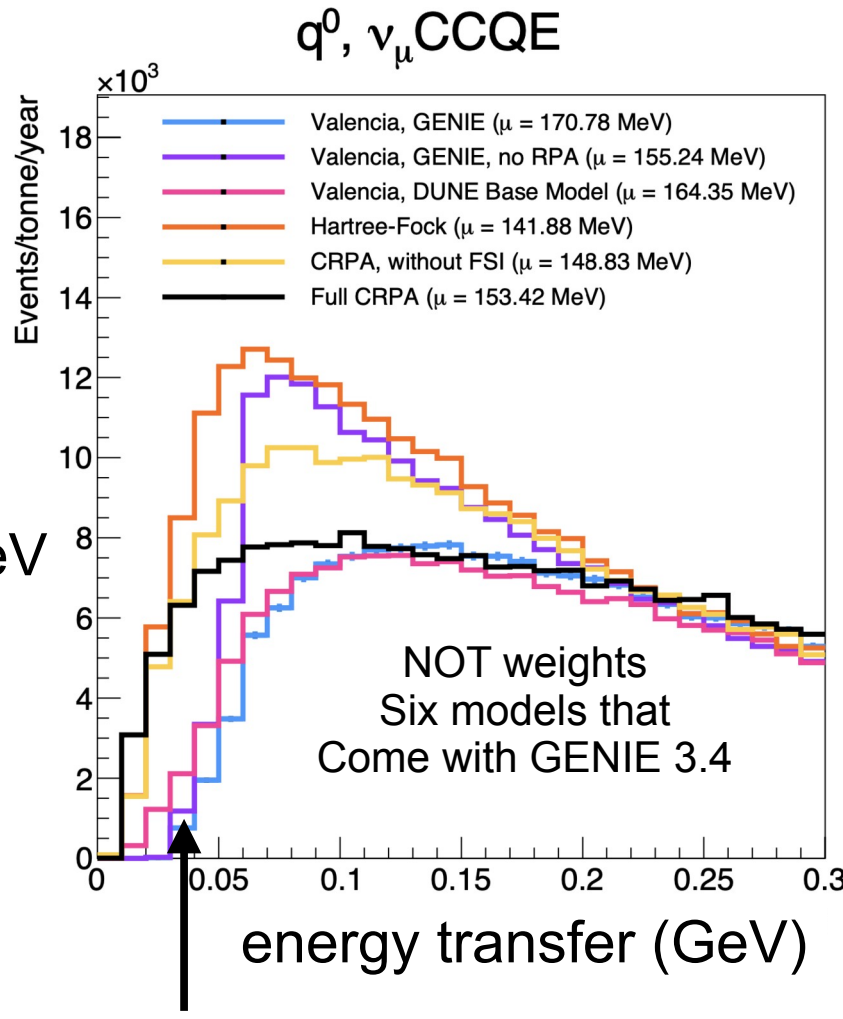
Previous GENIE3 has 30 MeV threshold

Shows up as missing low proton KE strength compared to data

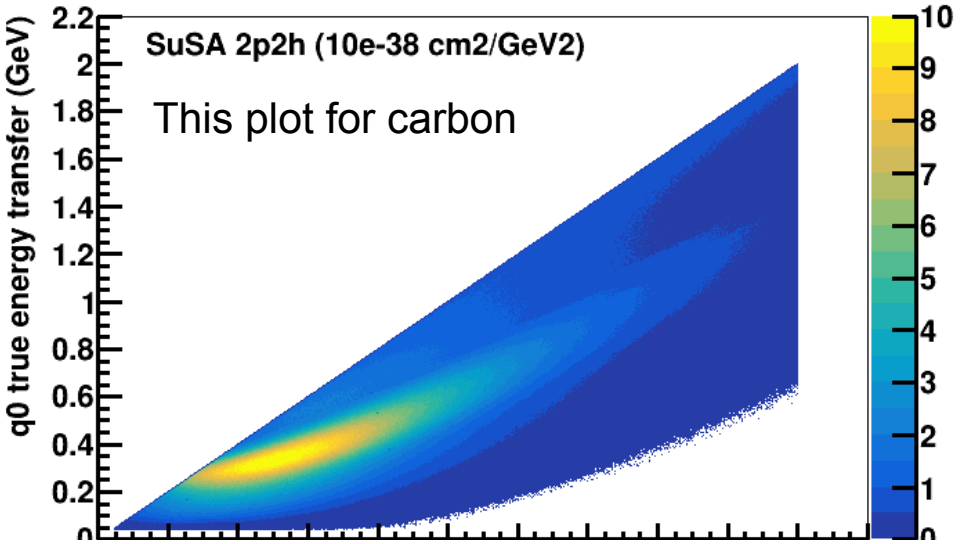
If no events generated, nothing to weight up.

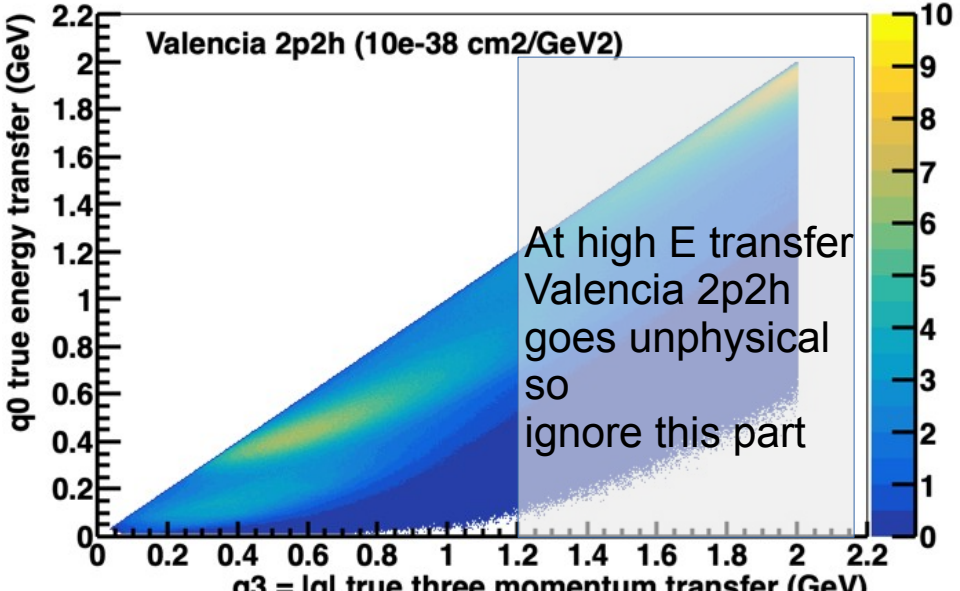
Modified version has good event rate to 10 MeV
And a little rate all the way down to zero.

MINERvA and also T2K also added freedoms on reco and true hadron energy to approximate this effect in a different way



2p2h process





Innovation #2: 2p2h process

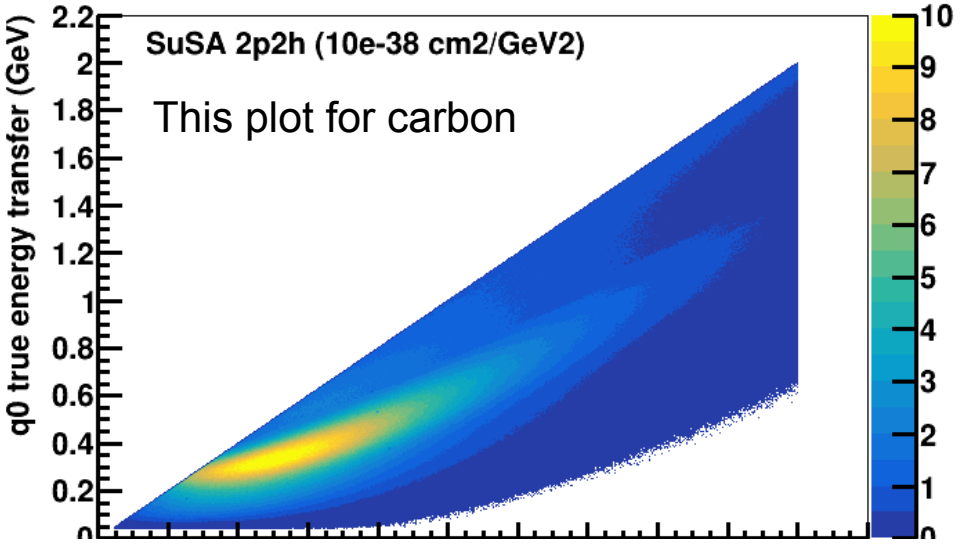
Generate SuSA 2p2h up to 2 GeV/c

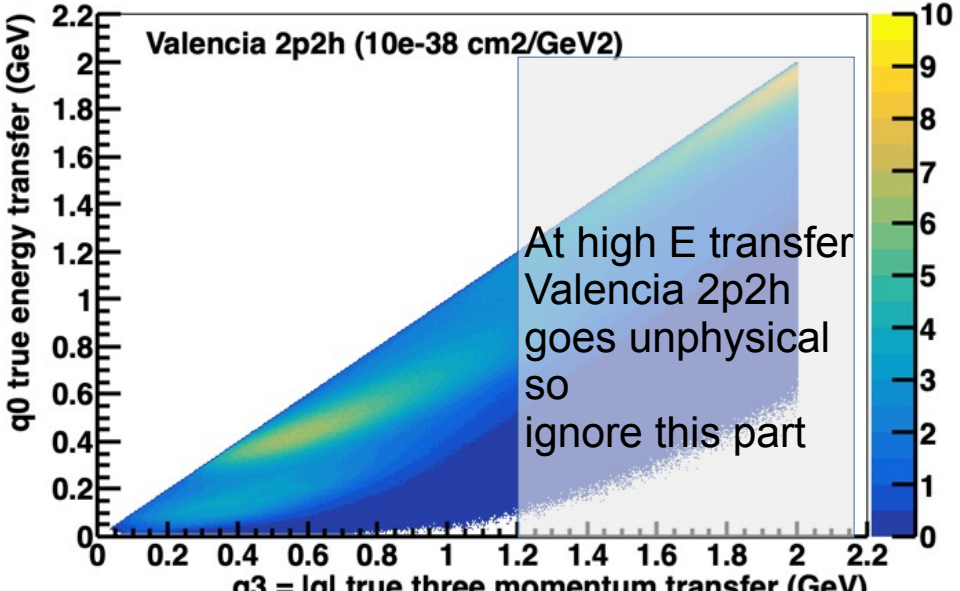
separate for pn and !pn

Two outgoing nucleons are “decayed” isotropically in their CM frame

Reweight to Valencia or other predictions

MicroBooNE put it in GENIE 3.4
Also done previously by MINERvA



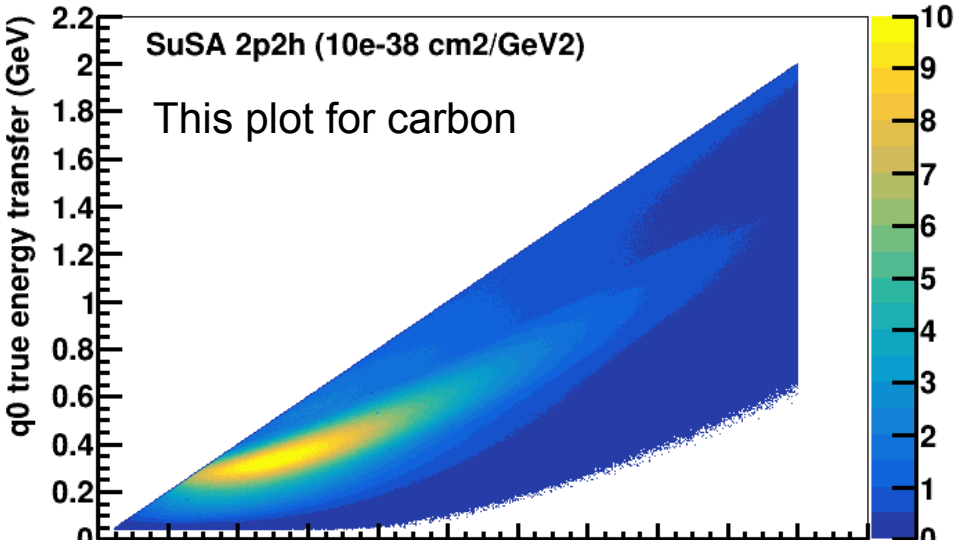


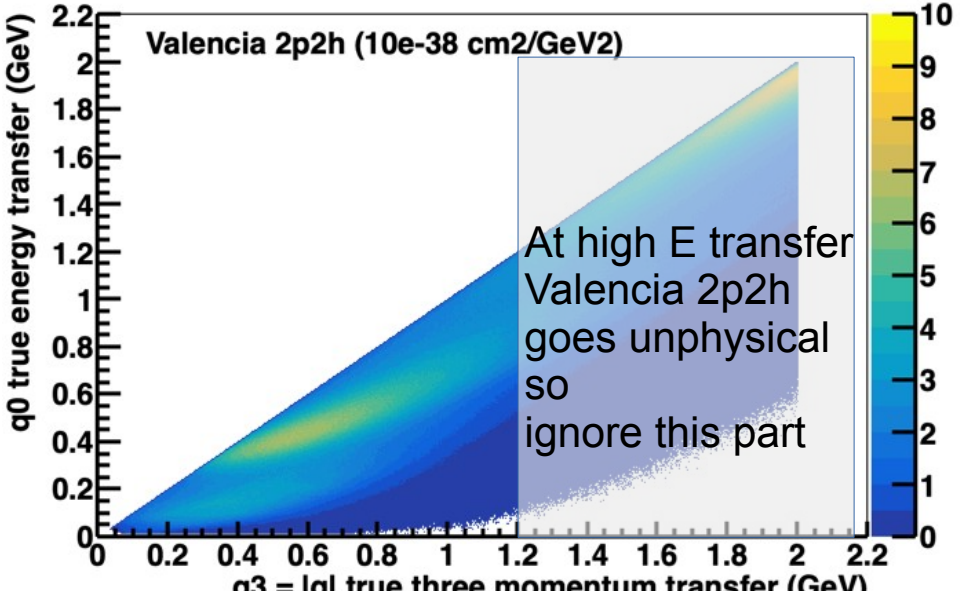
Need advice

Asking for a friend...

Our full simulation + reconstruction chain
Provides these two, each with pn and !pn
decays the resulting two nucleon system

What freedoms with physical meaning
should we engineer from this starting point
that would cause fits to near detector data
to impact DUNE oscillation sensitivity.
to give adequate systematics coverage for





Need advice

Asking for a friend...

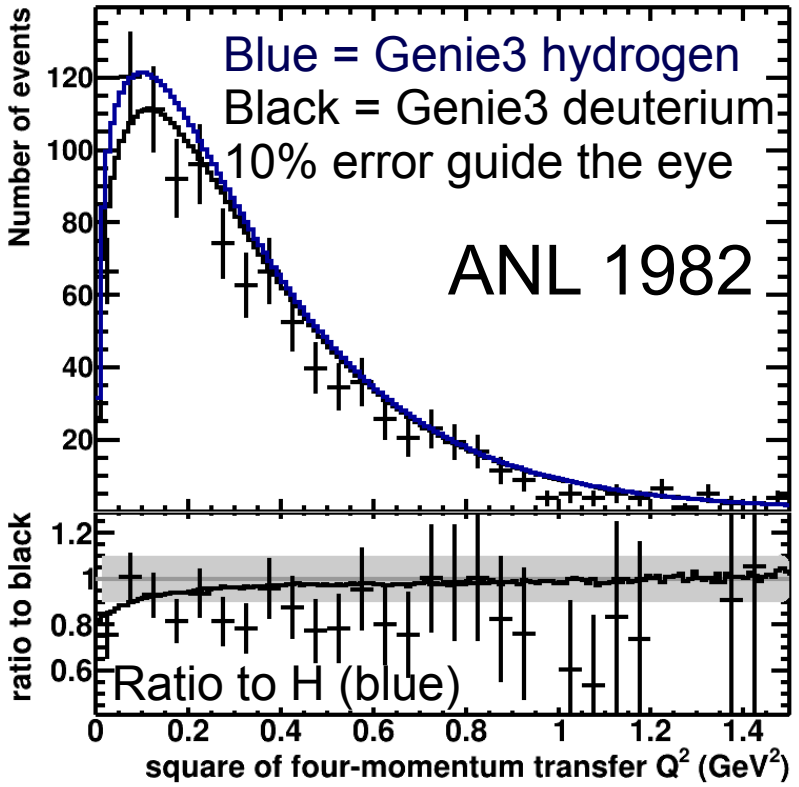
Our full simulation + reconstruction chain
Provides these two, each with pn and !pn
decays the resulting two nucleon system

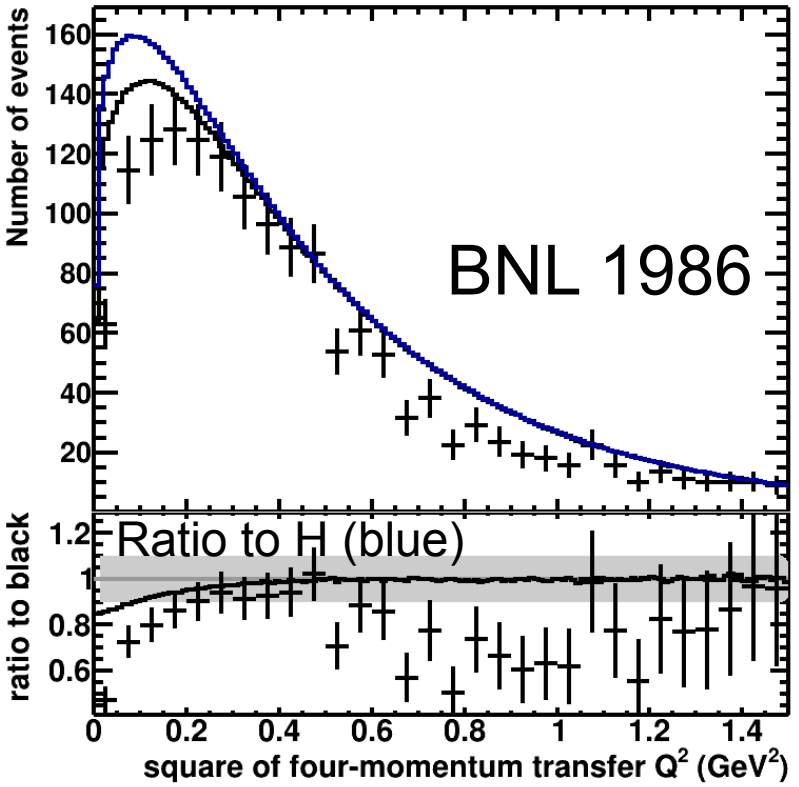
What freedoms with physical meaning
should we engineer from this starting point
that would cause fits to near detector data
to impact DUNE oscillation sensitivity.
to give adequate systematics coverage for

Rhetorical question:
Does your answer change if your friend
(unlike DUNE) has data already ?

Pion production

Genie3 is higher than deuterium Δ++ data



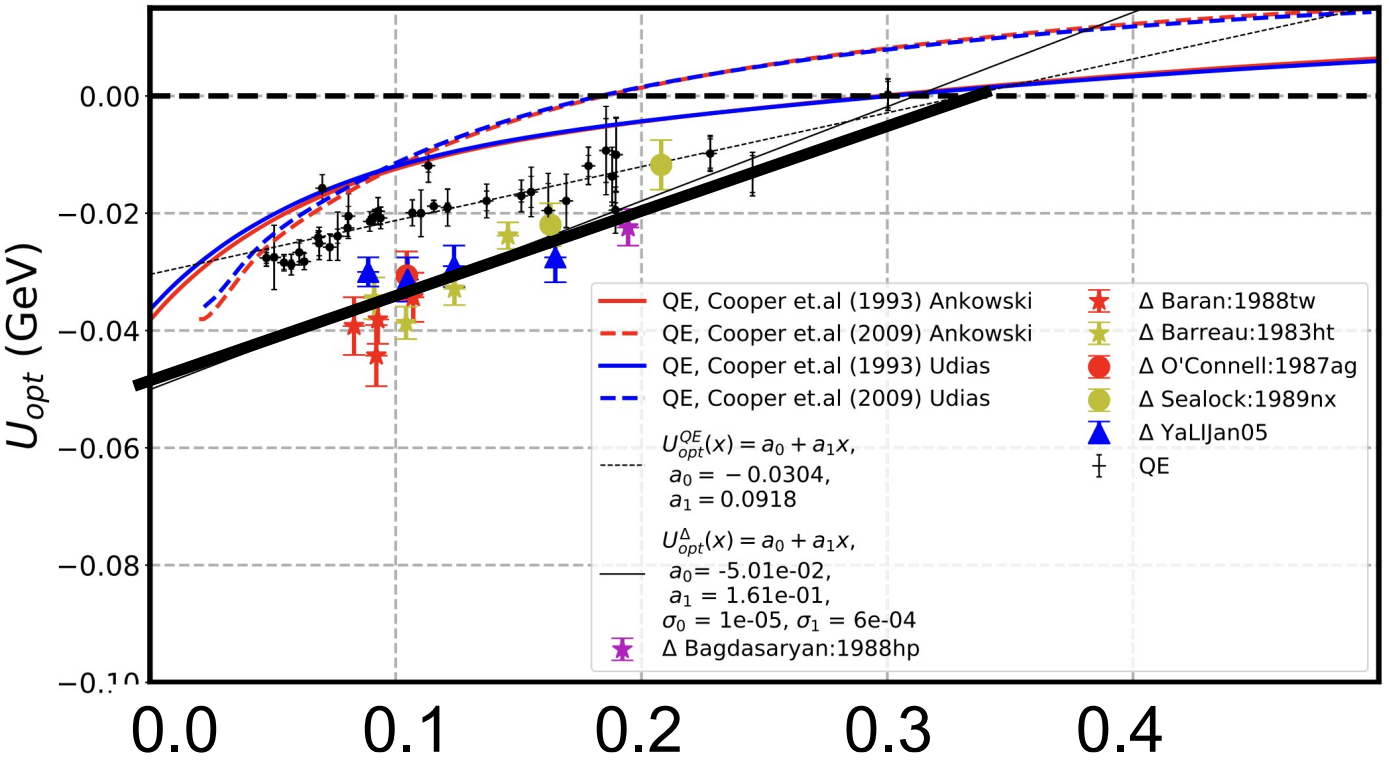


Genie2 was tuned to these data, mostly different functions for FF

However Genie3 better describes Carbon

Repackage form factors and nuclear effects like we did with QE

Shift location of Delta and QE peaks



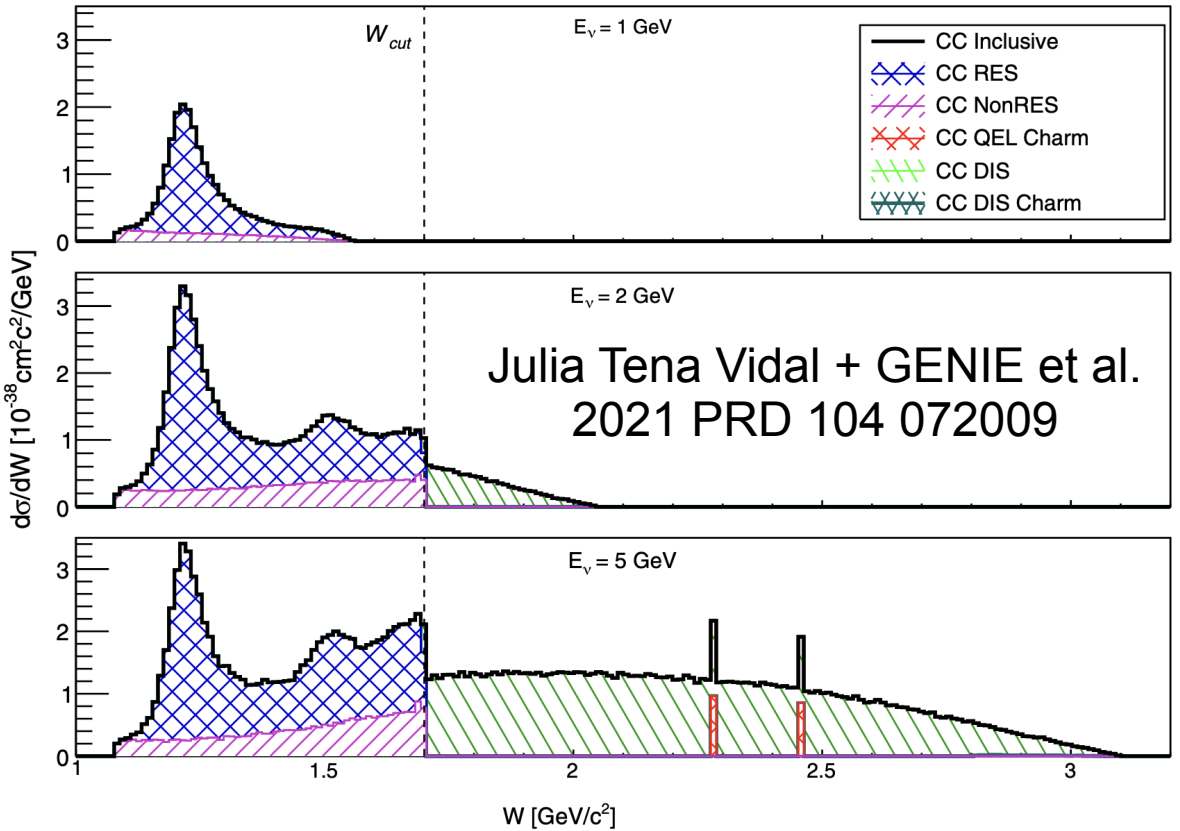
Empirical observation
Prior literature and
Bodek and Cai
Eur.Phys.J.C
80 (2020) p.655

Implied in-medium
Delta & QE move
down in W, ω

T = Kinetic energy of baryon (GeV) → correlates with q3

Plan to use ground state weights and/or hadron energy shifts
Magnitude of shift is -40 to 0 MeV from KE = 0 to 300 MeV

Expand physics motivated Δ and SIS freedoms



Resonance and SIS are a large fraction of DUNE event rate and change rapidly across oscillation max

New data on C, Ar coming out these days

Some “easy” things to do

Trying to expand effort here, nusystematics can be a playground internal to DUNE and 2x2 demonstrator, and from present company

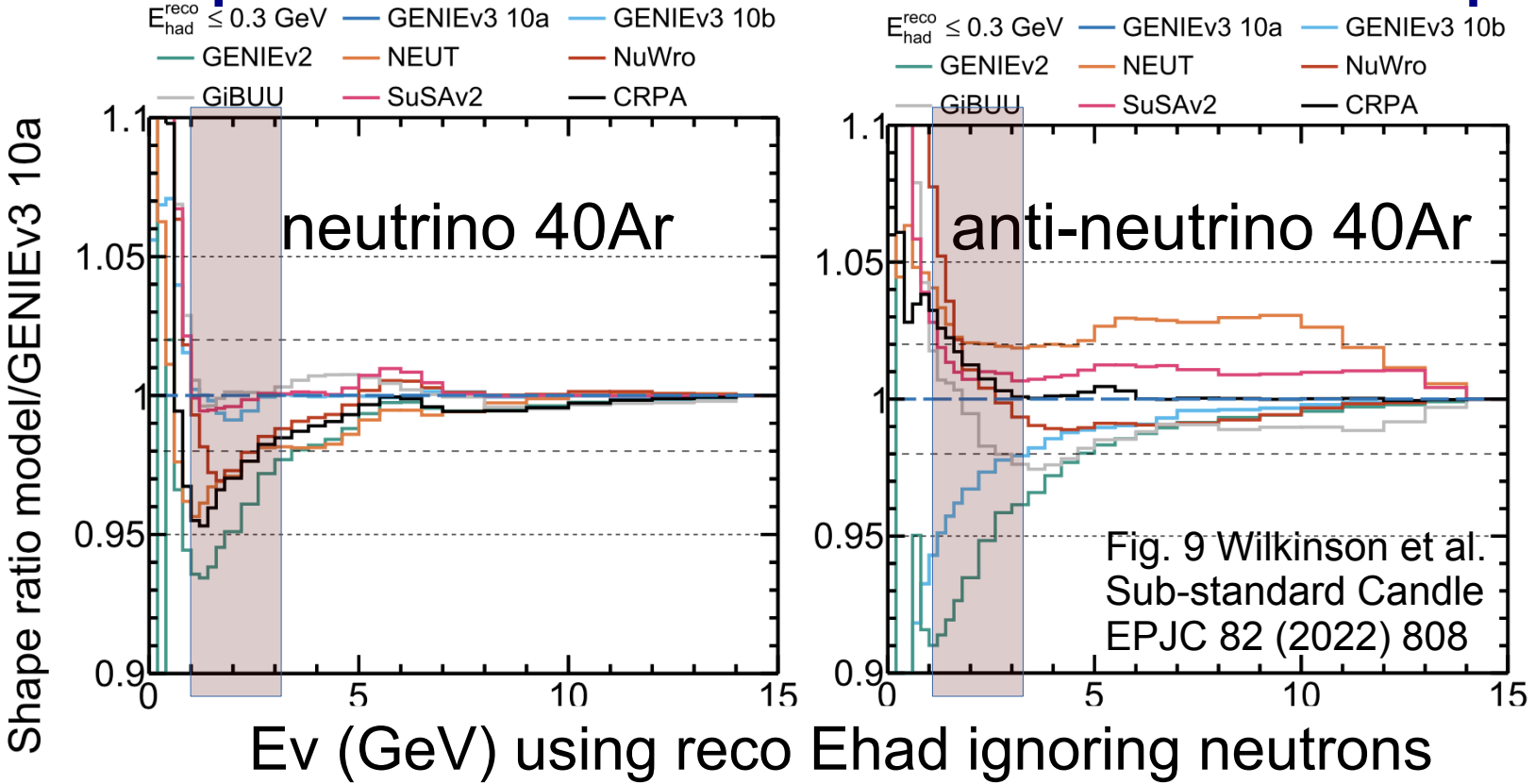
Guiding idea repeat

It looks like we're fussing over ~10 MeV of Ehad
Which is a 1% effect on Enu on the low side of the peak
Smaller than calibration uncertainties so negligible. Hmm.

Actually Near Detectors are going to see the Ehad distribution
And this will be the width of a typical reco bin we will use.
Will try to fit out form factors, final state topology
neutron content, nuclear effects and final state interactions.
All of which have different Enu dependence.

Fitting the wrong thing (or degeneracy) leads to uncertainty

Ev shape for ND Ehad < 0.3 GeV samples



Take these as simply predictions for low Ehad bins of ND LAr data.
Want coverage and storyline for these models

Other processes can talk over break

Only have 25 minutes + 5 for questions

Final State Interactions using simple hA model
DIS and hadronization models
coherent/diffractive scattering
nue/numu uncertainties
processes used for flux constraints
deexcitation photons and neutron constratins

Conclusions

The NIUWG is dramatically expanding the parameter space
And will use this for DUNE oscillation sensitivity studies
That support the Near Detector technical design report

This code nusystematics, is our deliverable product.
It has a GENIE systematics pass-through interface
several T2K and MINERvA weights and we're going further

DUNE does not have tens of millions of data events yet
We are partnering with several experiments that have data
Who will likely take from and contribute to this.

Sun Tzu Org Chart

Measurement owes its existence to Earth

Estimation of quantity to Measurement

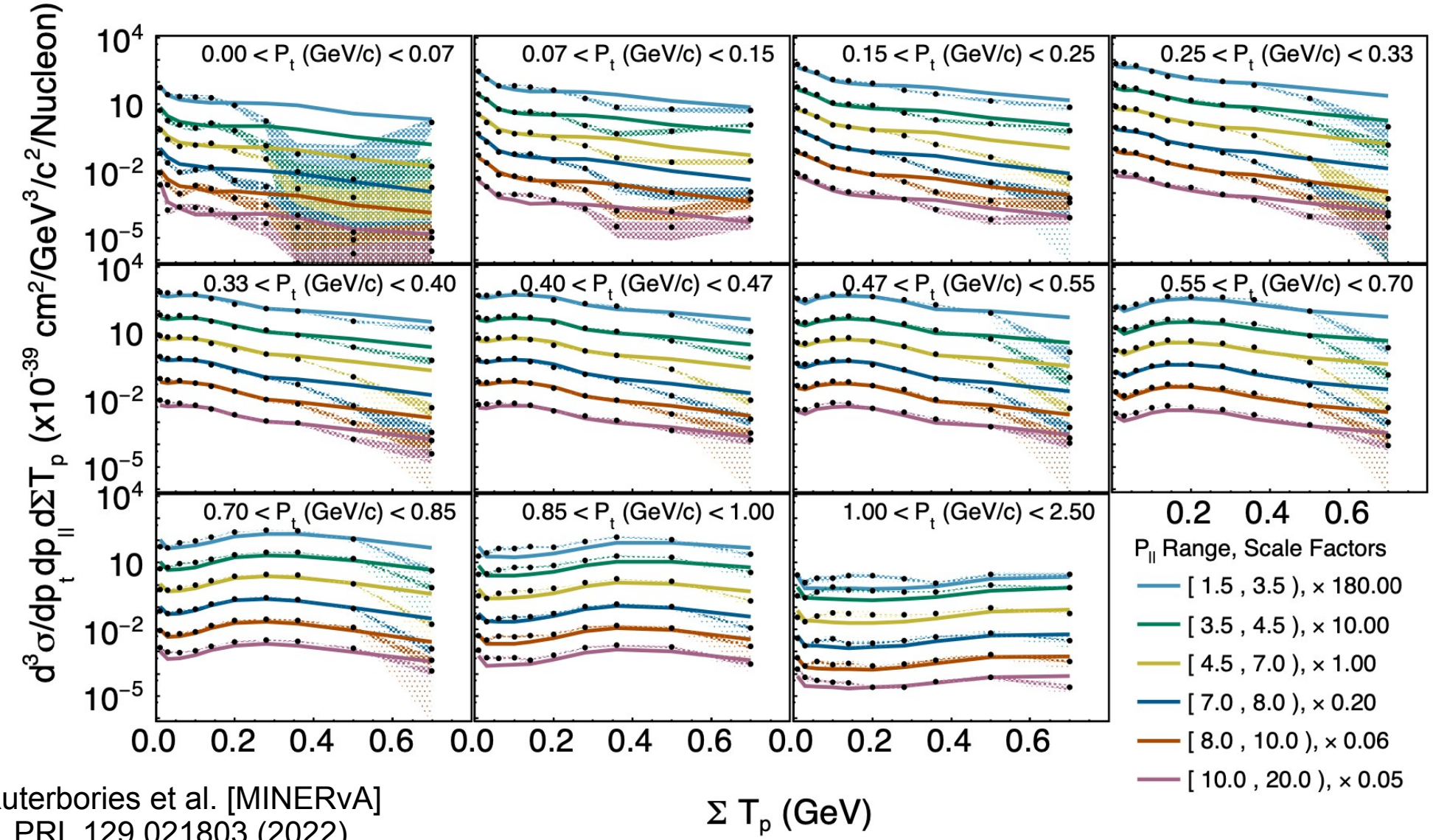
Calculation to Estimation of quantity

Balancing of Chances to Calculation

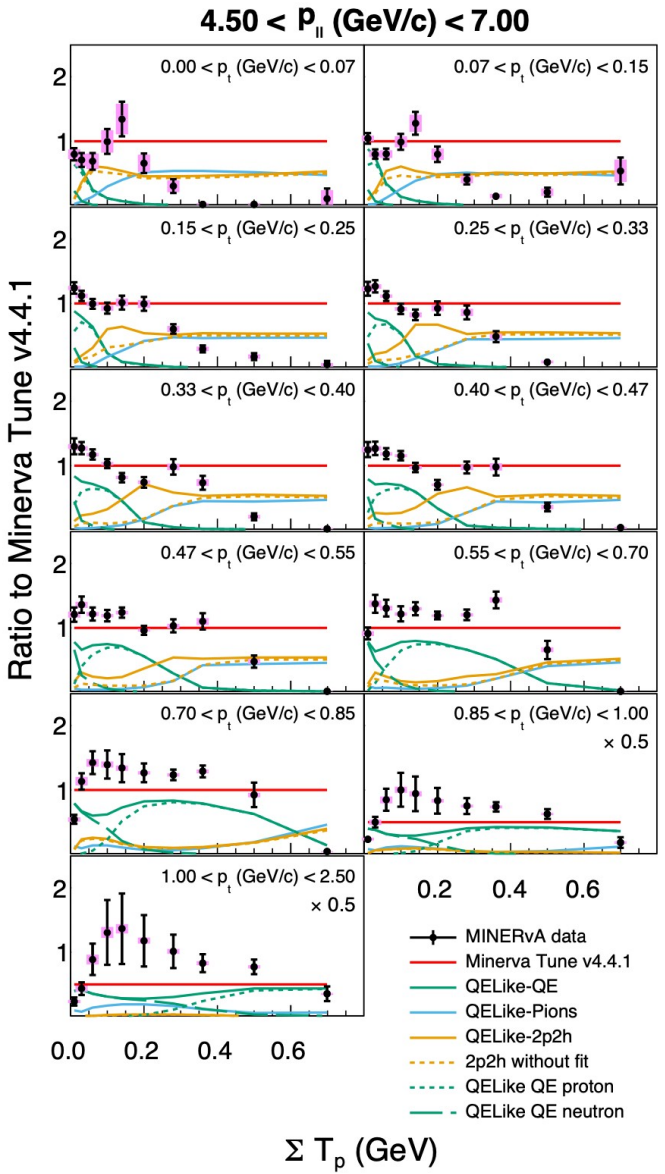
and

Victory to Balancing of Chances

Backup



Ruterbories et al. [MINERvA]
PRL 129 021803 (2022)



Ratio plot of previous yellow line

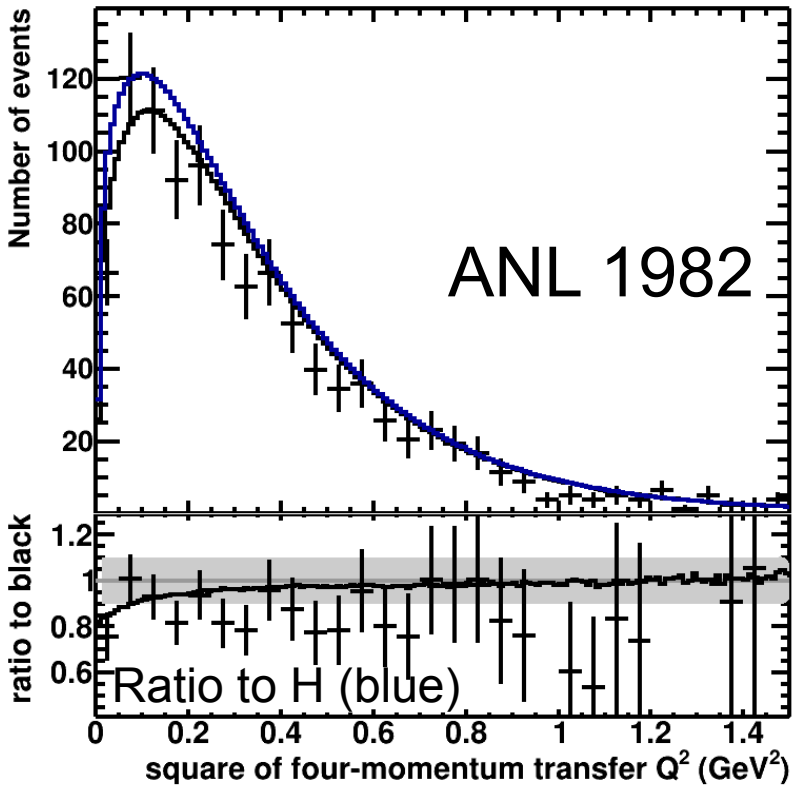
We would use DUNE reco distributions
Thinking NDLAr especially
This happens to be zero pion sample
Longitude momentum ~ Enu

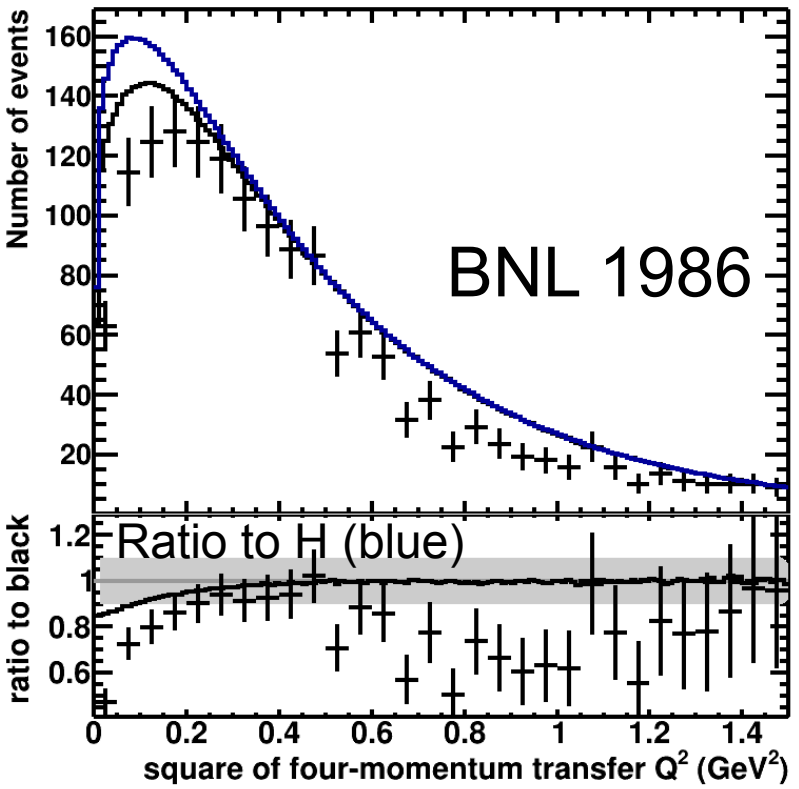
MINERvA Tp is calorimetric sum here

Separates different components of model and different features of those components is easier than TKI variables

multiplicity for NDGar, CH-C for SAND

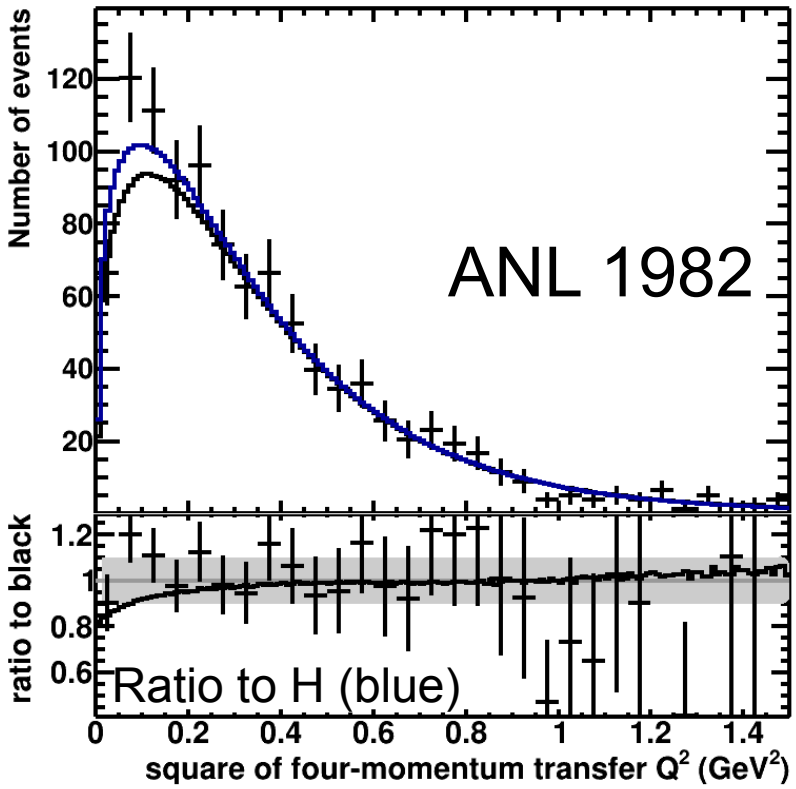
G18_02a (RFG+hA) with new (default) form factors

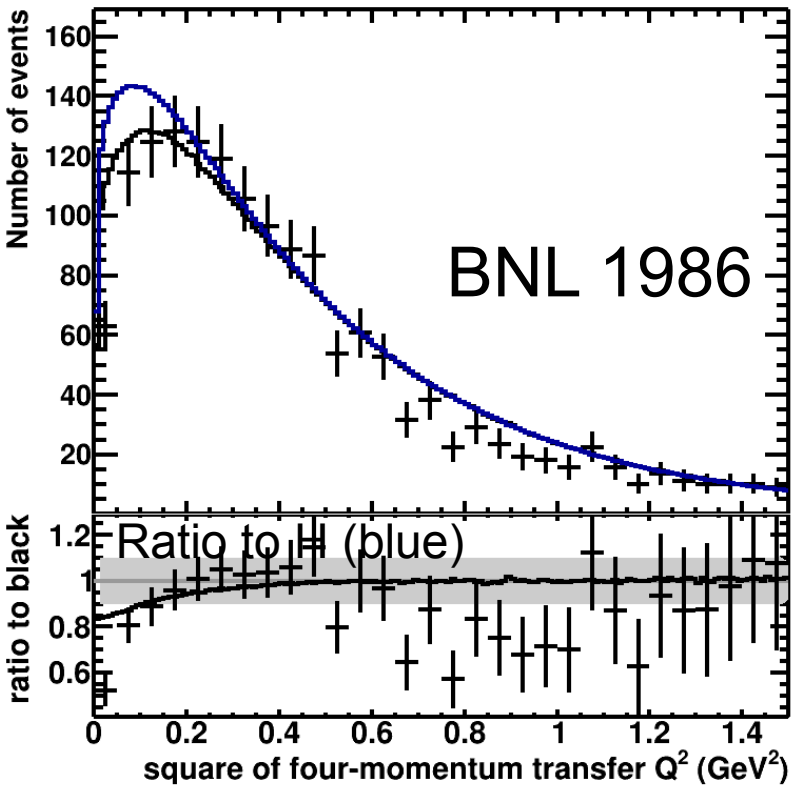




This is ok, I guess. Its clearly not tuned to these data. Not stupid-bad.
Is there more?

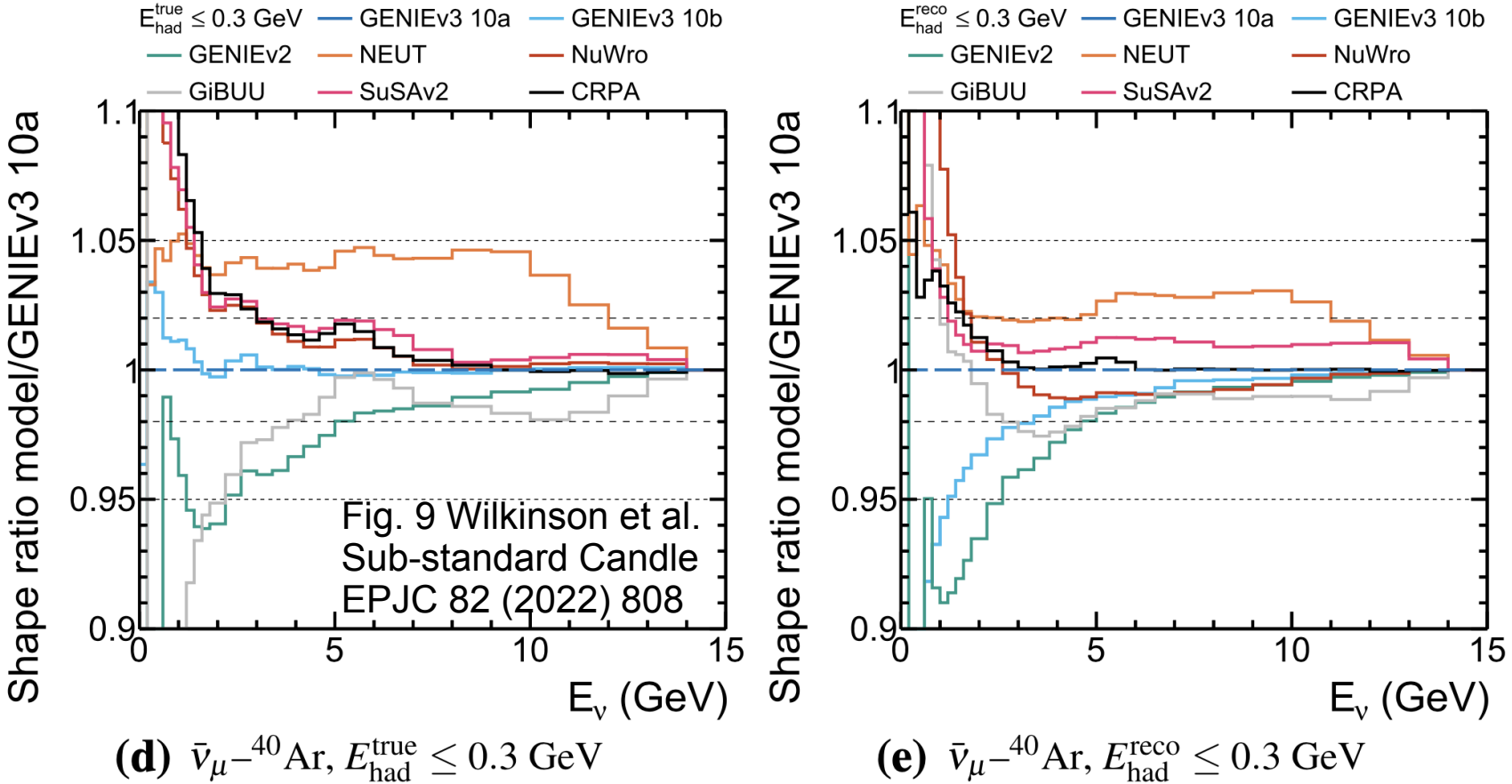
G18_02a (RFG+hA) with old Rein Sehgal Form Factors





This prediction is a lot lower. Hard to tell by eye, but the shape is different.
MA=1.12 fit this model to these data, but before the Callum+Phil modification.
probably this one has a somewhat better joint chi2 depending on error band?

Raw Energy Dependence and guiding idea again

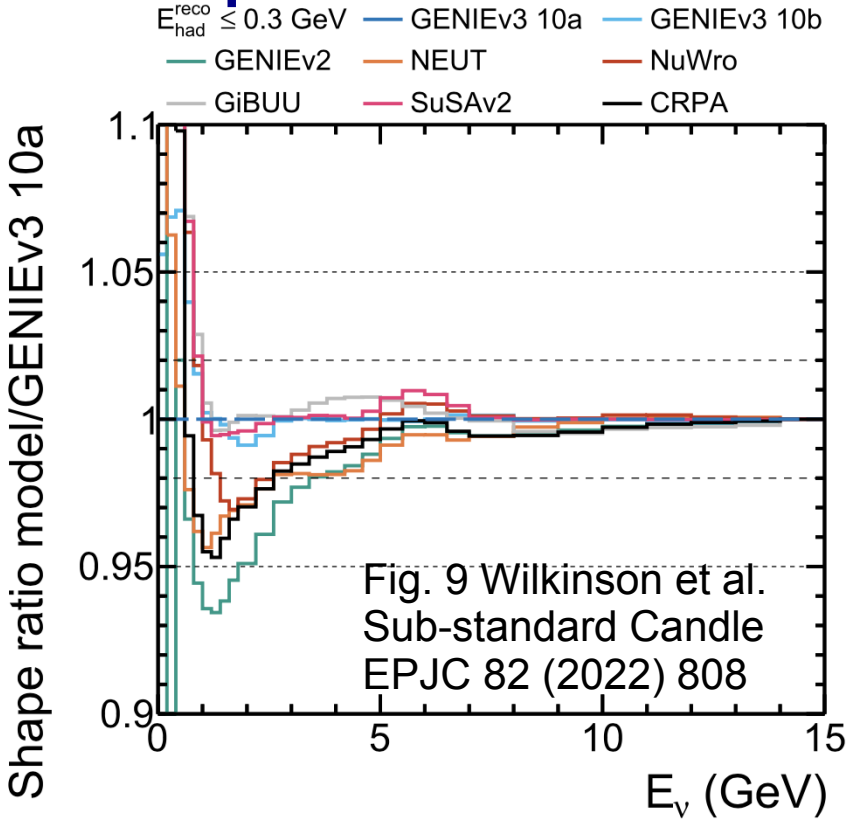


(d) $\bar{\nu}_\mu$–^{40}Ar, $E^{\text{true}}_{\text{had}} \leq 0.3$ GeV

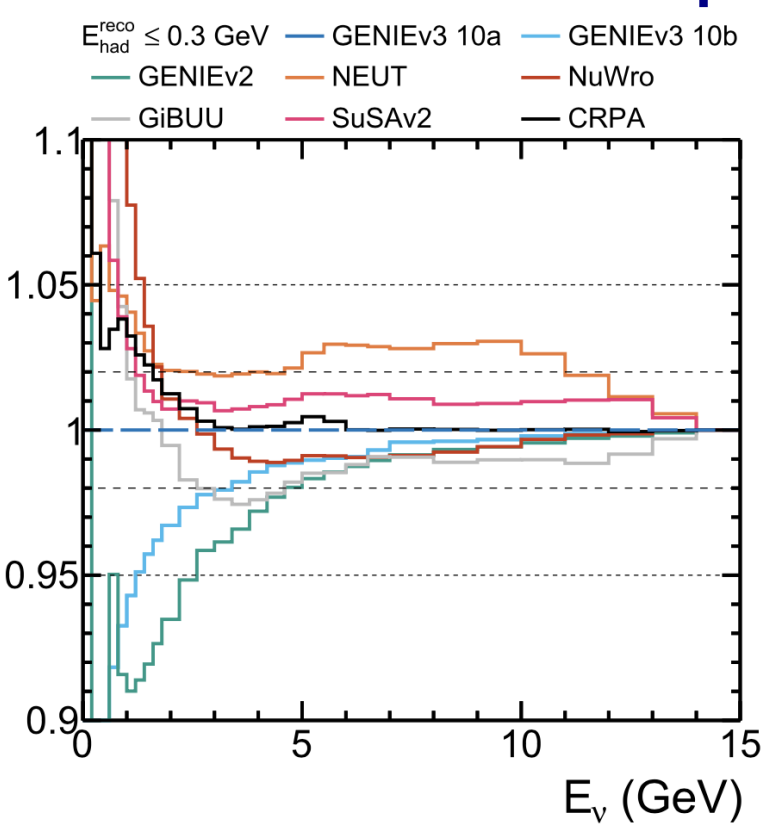
(e) $\bar{\nu}_\mu$–^{40}Ar, $E^{\text{reco}}_{\text{had}} \leq 0.3$ GeV

Take these as simply predictions for low Ehad bins of ND LAr data.

Ev shape for ND Ehad < 0.3 GeV samples

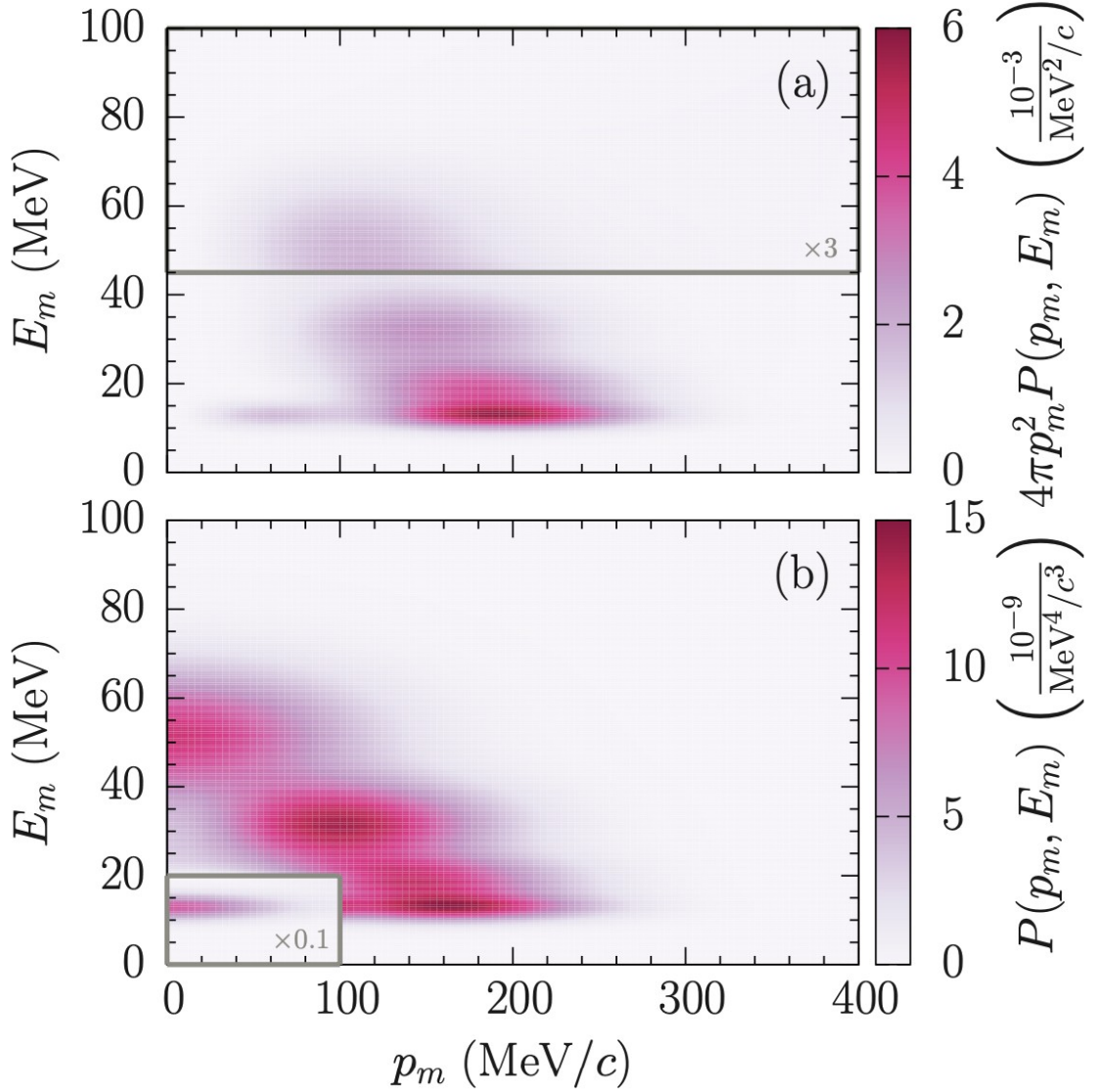


(b) ν_μ–^{40}Ar, $E_{\text{had}}^{\text{reco}} \leq 0.3$ GeV



(e) $\bar{\nu}_\mu$–^{40}Ar, $E_{\text{had}}^{\text{reco}} \leq 0.3$ GeV

Take these as simply predictions for low Ehad bins of ND LAr data.



Ar40 spectral function

protons in Ar40
test function
before fitting
spectroscopic factors
to (e,e'p) data

Jiang et al. (JLAB HallA)
PRD 105 (2022) 112002

With and without
factor of $4\pi p^2$

Under the hood Ar40 spectral function physics

Jiang et al. (JLAB HallA) PRD 105 (2022) 112002

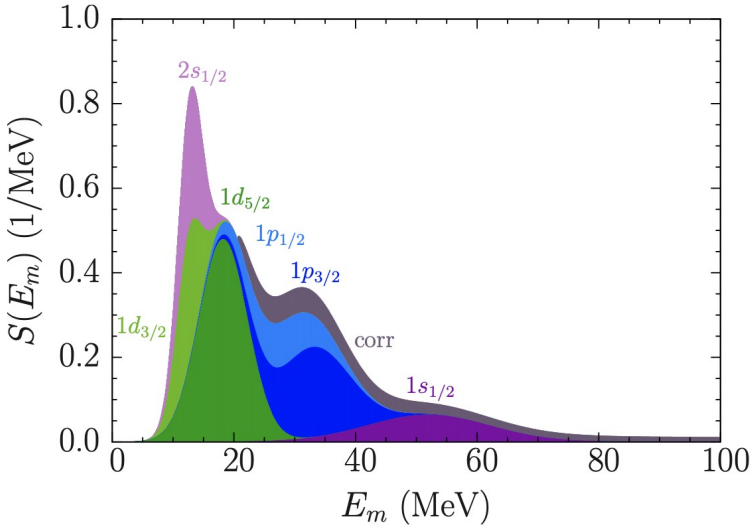


FIG. 2. Missing energy distribution of protons in argon in the test spectral function.

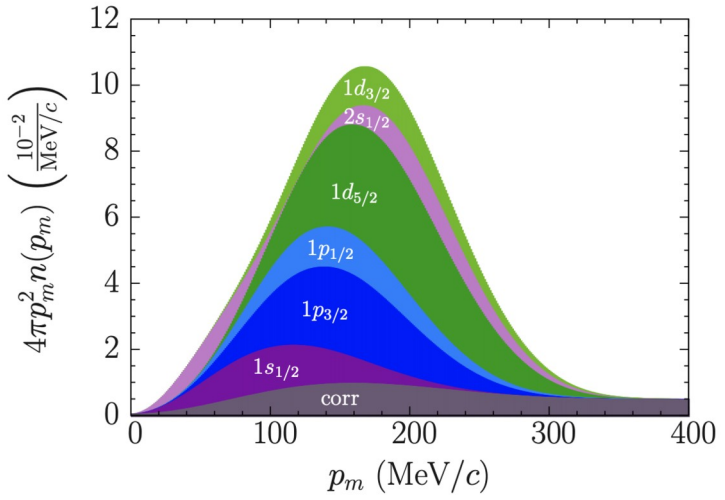


FIG. 1. Missing momentum distribution of protons in argon in the test spectral function, presented with the geometric factor of $4\pi p_m^2$.

Components for protons in Ar40 before fitting to (e,e'p) data.
The publication gives a best fit model and discusses uncertainties.

Final state reinteractions, talk over break?

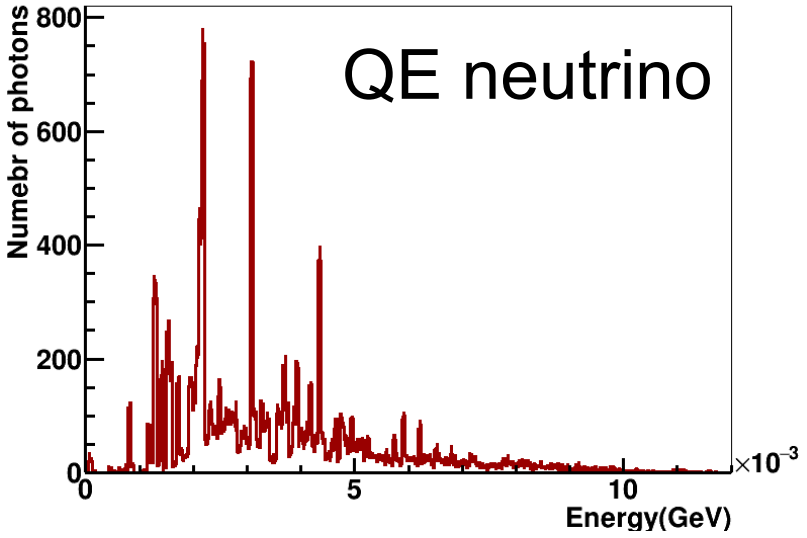
We are using the simplest hA configuration
One step + parameterizations instead of full cascade
Makes for easiest and most accessible reweighting schemes

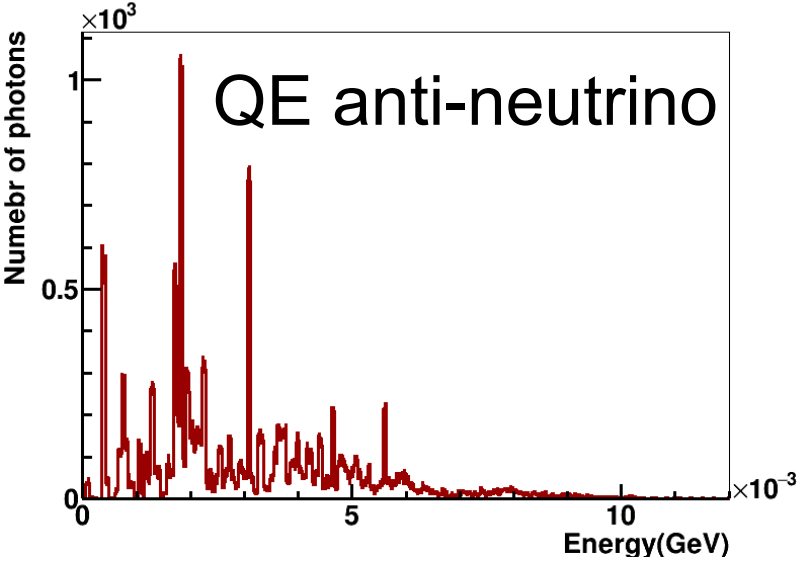
Good but not perfect coverage of final state topology in ND
Easy access to neutron-specific outcomes

Processes
Hadron leading to additional nucleon knockout
Pion absorption leading to 2+ nucleon knockout
Charge Exchange
Additional pion production

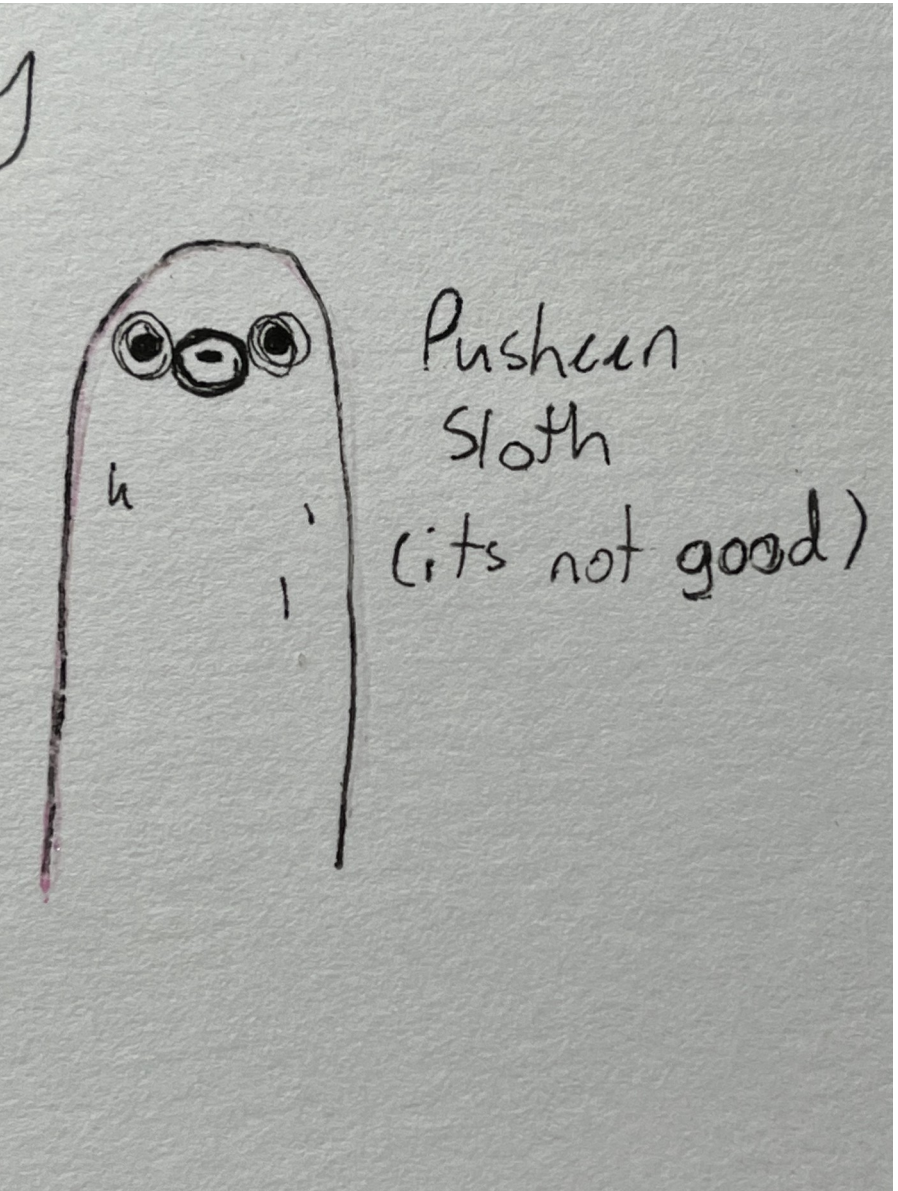
Deexcitation photons for C12 and Ar40

Not previously in GENIE (only Oxygen)
These will show up in neutron constraint studies
that use ~MeV activity thresholds





Ar40 from MARLEY/Gardiner C12 from Kamyshkov+Kolbe



Made you look

Conceptual art by
my niece
L. Mitchell