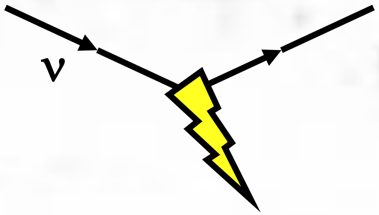


Neutrino Interactions

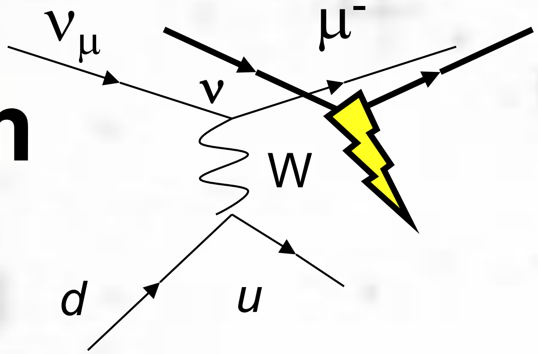
Kevin McFarland,
University of Rochester

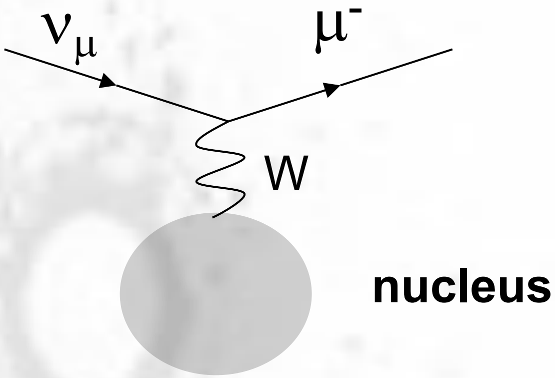
Neutrino Physics and Beyond
IAS, HKUST

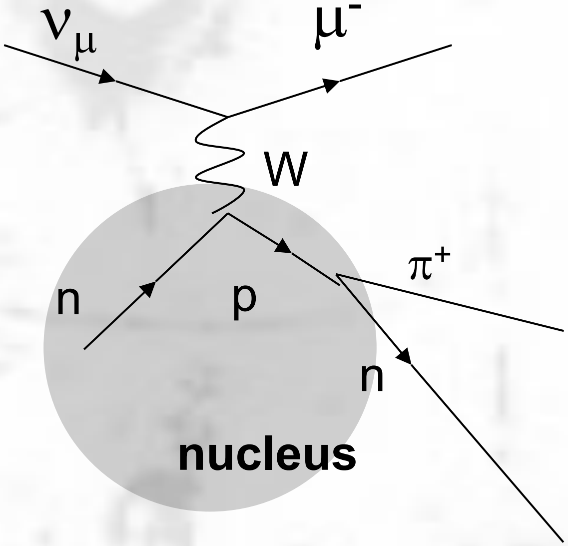
20 February 2024

ν interactions: the problem

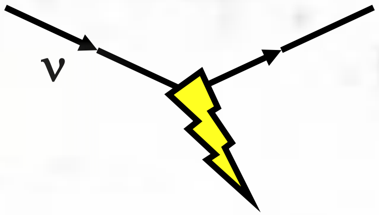
- We know a lot about neutrino interactions.
  - Weak interactions of quarks and leptons, and even neutrinos, have been extensively studied with $W^\pm$ and Z^0 boson precision production and decay measurements.
- Our quark targets are bound.
  - This is a problem, but not always a hard one.
  - Reactor experiments don't have interaction problems with small momentum transfers and therefore nearly static, elastic interactions.
- GeV neutrinos on nuclei are a special pain point that nature has gifted us at accelerator and atmospheric oscillation experiments.



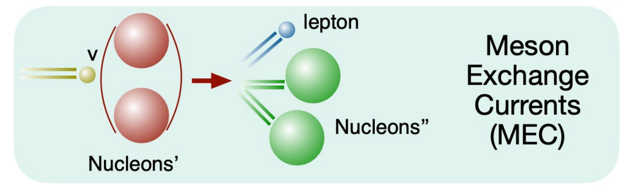




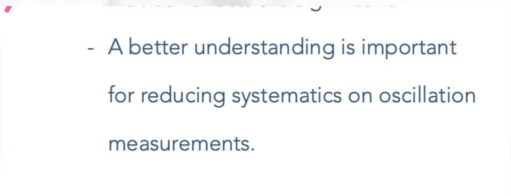
“Pain point”?



- Yesterday’s speakers seemed to think so!
- Elaborate near detectors, measurements of interactions integrated into physics program, careful attention to systematic uncertainties.

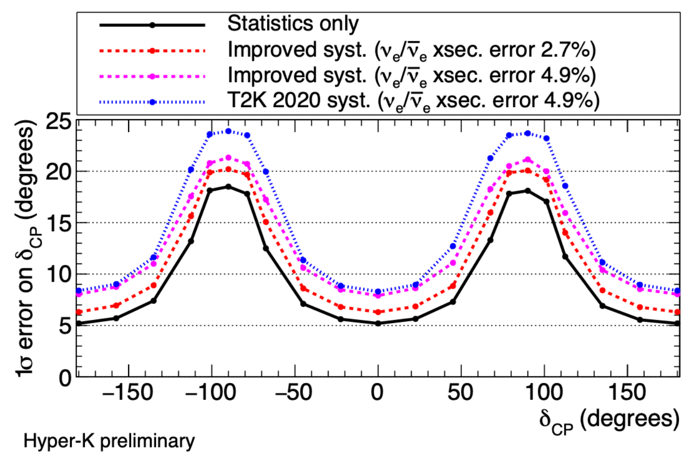


Booth, NOvA

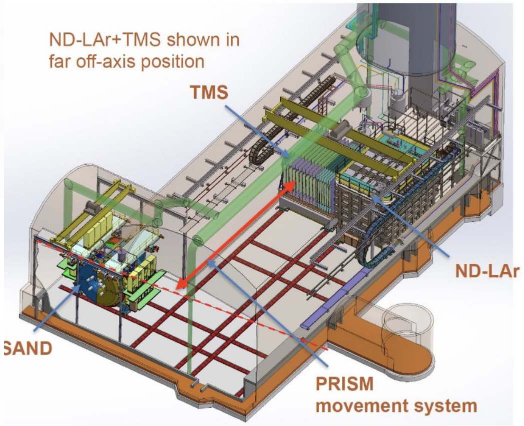


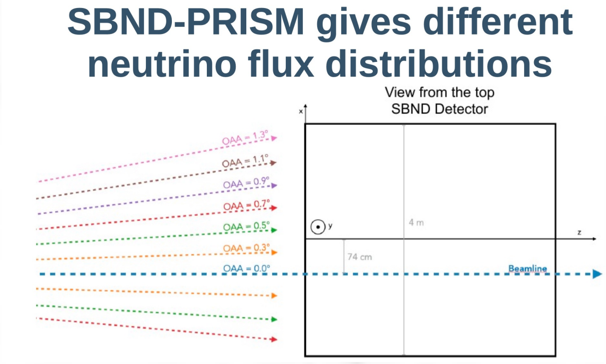
- A better understanding is important for reducing systematics on oscillation measurements.

Pallavicini, DUNE



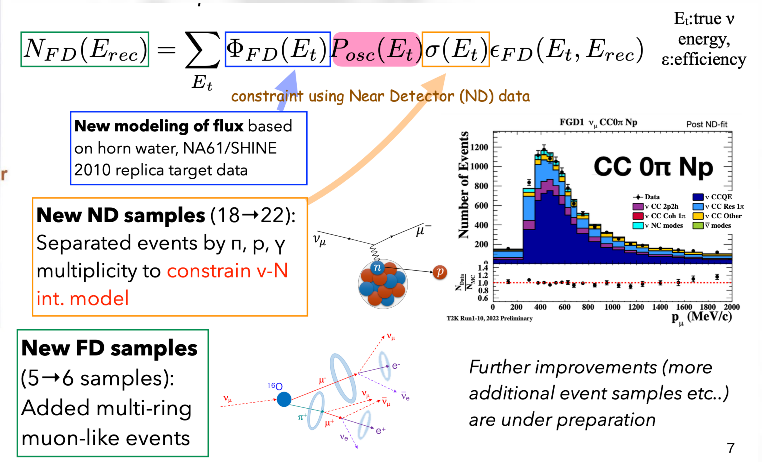
Di Lodovico, Hyper-K





SBND-PRISM gives different neutrino flux distributions

Marshall, SBN



$$\boxed{N_{FD}(E_{rec})} = \sum_{E_t} \boxed{\Phi_{FD}(E_t)} P_{osc}(E_t) \boxed{\sigma(E_t)} \epsilon_{FD}(E_t, E_{rec})$$

E_t:true ν energy, ε:efficiency

constraint using Near Detector (ND) data

New modeling of flux based on horn water, NA61/SHINE 2010 replica target data

New ND samples (18→22): Separated events by π, p, γ multiplicity to constrain ν-N int. model

New FD samples (5→6 samples): Added multi-ring muon-like events

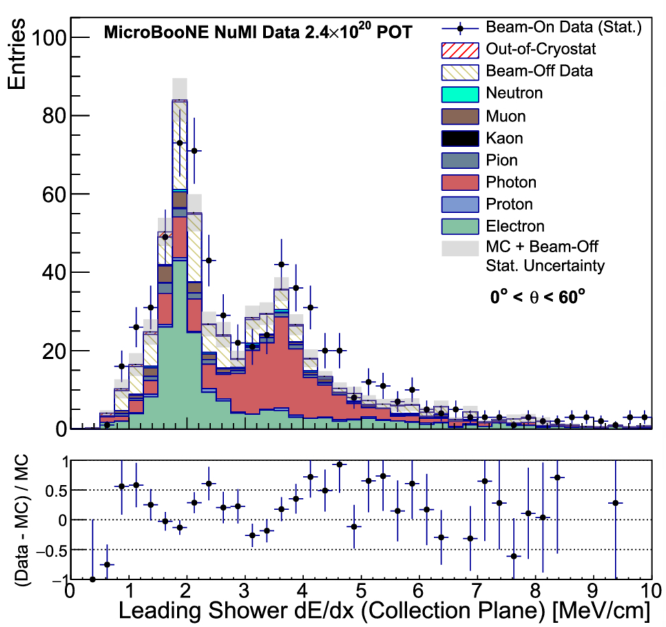
Further improvements (more additional event samples etc..) are under preparation

7

Sakashita, T2K

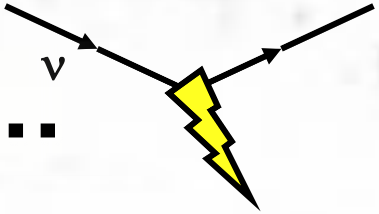
How do ν interactions matter?

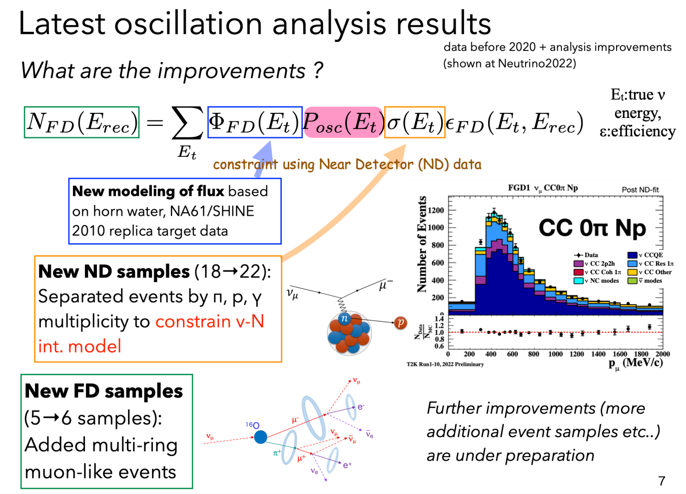
- A neutrino oscillation experiment infers the parameters of interest in a single event, neutrino flavor and energy, by measuring the final state.
- Energy: detectors are imperfect and lack uniform response:
  - Energy is lost to nuclear mass, excitation.
  - Response to an energetic neutron is scant and stochastic, but energetic protons steadily lose energy by ionization.
  - A π^- interacting in a detector tends to produce neutrons in its inelastic interactions, e.g., $\pi^- p \rightarrow \pi^0 n$. But a π^+ doesn't.
  - A π^0 cleanly deposits all its energy, including its rest mass.
- Flavor: photons, primarily from π^0, can't be perfectly separated from electrons.



The European Physical Journal Special Topics **volume 230**, pages4275–4291 (2021)

Or, borrowing from yesterday…





Latest oscillation analysis results

data before 2020 + analysis improvements
(shown at Neutrino2022)

What are the improvements ?

$$\boxed{N_{FD}(E_{rec})} = \sum_{E_t} \boxed{\Phi_{FD}(E_t)}\,P_{osc}(E_t)\,\boxed{\sigma(E_t)}\,\epsilon_{FD}(E_t, E_{rec})$$

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K. Sakashita, T2K

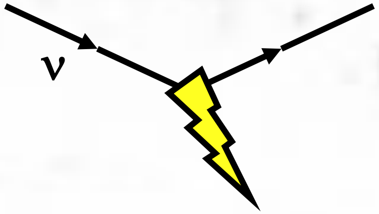
$$\boxed{N_{FD}(E_{rec})} = \sum_{E_t} \boxed{\Phi_{FD}(E_t)}\,P_{osc}(E_t) \times \boxed{\sigma(E_t)}\,\epsilon_{FD}(E_t, E_{rec})$$

E_t:true ν energy,
ε:efficiency

A friendly amendment to this point is that…

$$\boxed{\sigma(E_t)}\,\epsilon_{FD}(E_t, E_{rec}) \rightarrow \boxed{\sigma(E_t)}\boxed{\epsilon_{FD}(E_t, E_{rec})}$$

It's not only rate, but energy reconstruction, reconstruction efficiency, and background processes that may impact the oscillation analysis.

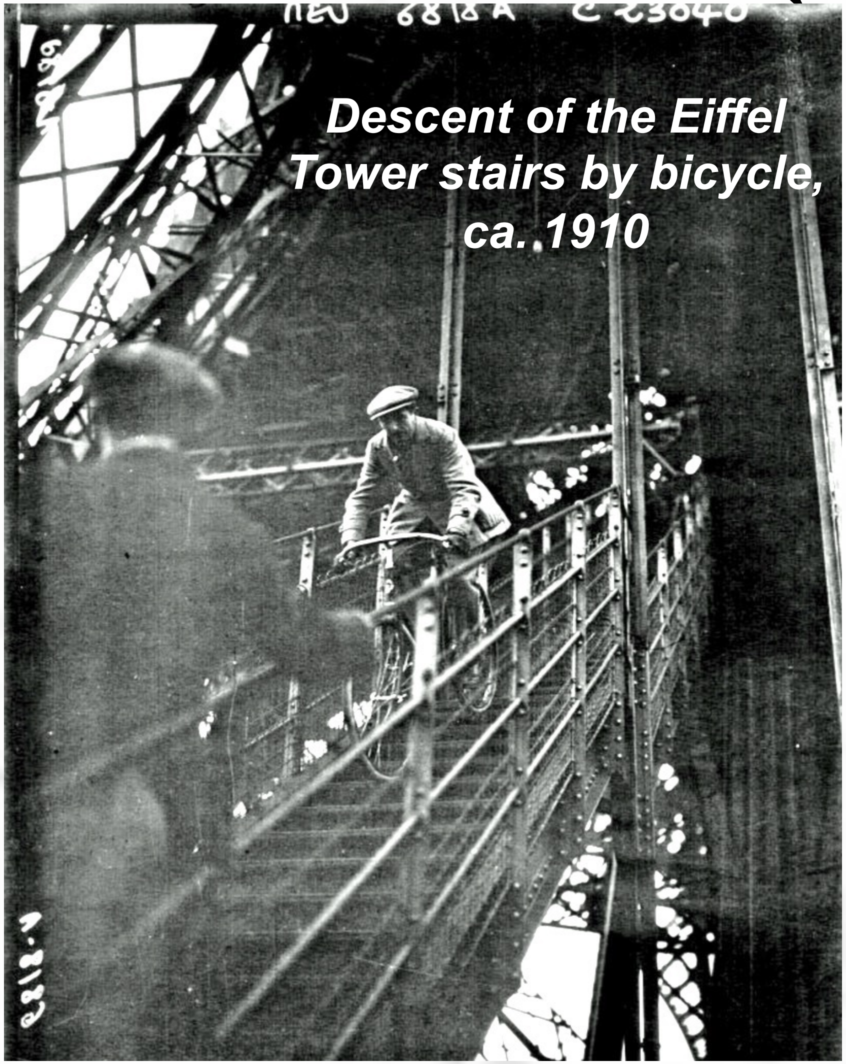


Theory and Experiment

Failed Multi-Scale Problems

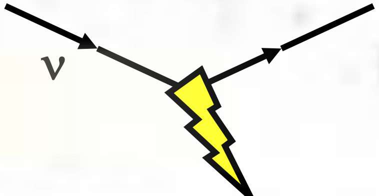
Consider a bicycle rider at right, descending the stairs of the Eiffel Tower

- *A bicycle wheel is ~1m in diameter.*
- *If steps were ~1cm height or the steps were ramps of ~100m, we could predict the cyclist’s trajectory.*



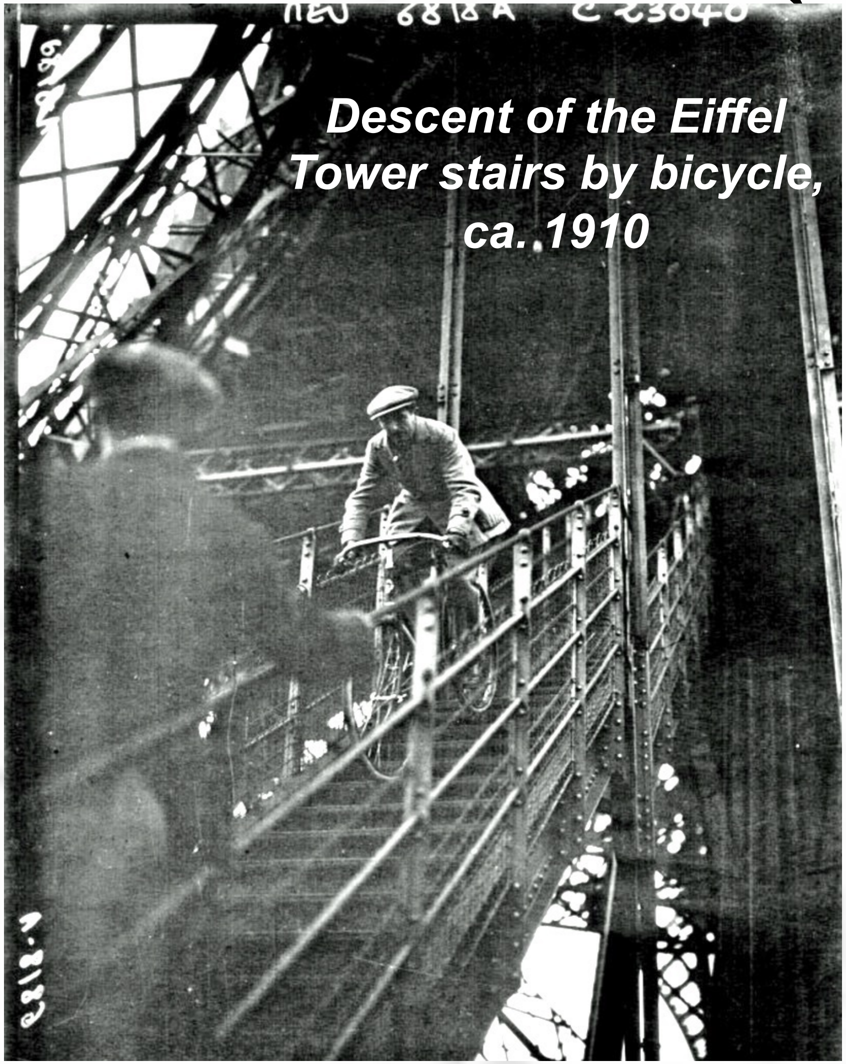
Descent of the Eiffel Tower stairs by bicycle, ca. 1910

Failed Multi-Scale Problems



Consider a bicycle rider at right, descending the stairs of the Eiffel Tower

- *A bicycle wheel is ~1m in diameter.*
- *If steps were ~1cm height or the steps were ramps of ~100m, we could predict the cyclist's trajectory.*
- *Since the wheel size is too close to the step size, the only reliable prediction is that it is going to be painful.*



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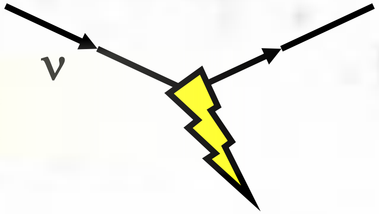
This Failed Multi-scale Problem

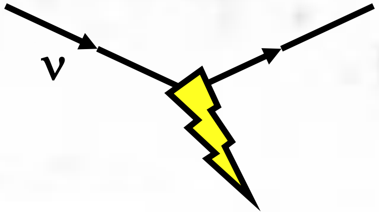


- *We have* $E_\nu \sim 200 - 5000$ *MeV, and therefore energy transfers from ~zero to* $\mathcal{O}(1000)$ *MeV.*
- *Nuclear response at these neutrino energies spans elastic, metastable excitations, quasielastic (knockout), and inelastic (new particles).*
- *Single nucleon separation energy in* ^{40}*Ar is* ~ 30 *MeV, and* $m_\Delta - m_N \sim 250$ *MeV.*
- *Processes cannot be cleanly separated, and models can't approximate away nuclear structure nor final state degrees of freedom.*

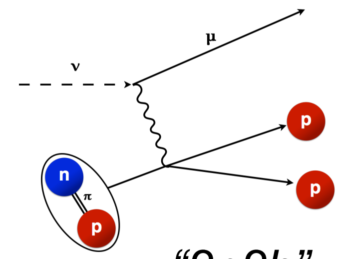
- Our usual toolbox is nearly empty!

- Nothing akin to QCD factorization to rescue us.
- Approximations, such as the impulse approximation, summing scattering from independent nucleons, are doomed.
  - But we use them anyway!

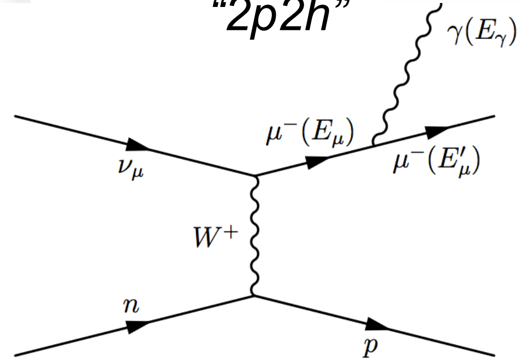
More Problems in ν Interactions

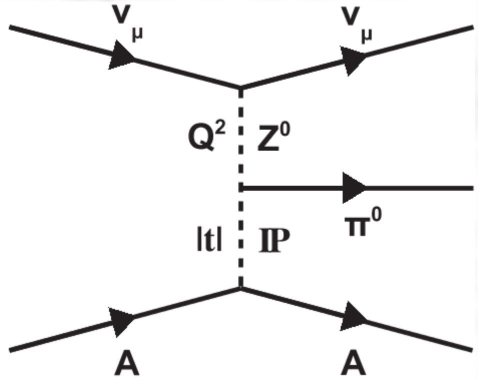


- There are other, subleading processes that are also difficult to model, but potentially important.
- Knocking out multiple nucleons (“2p2h”, two-particle-two-hole, or more) is surprisingly common and difficult to model.
- Radiative corrections to neutrino interactions will be different for muon and electron neutrinos.
- Coherent inelastic (not CEvNS) π^0 production produces energetic photons with little in the event to warn it isn’t a ν_e.
- And so forth…



“2p2h”





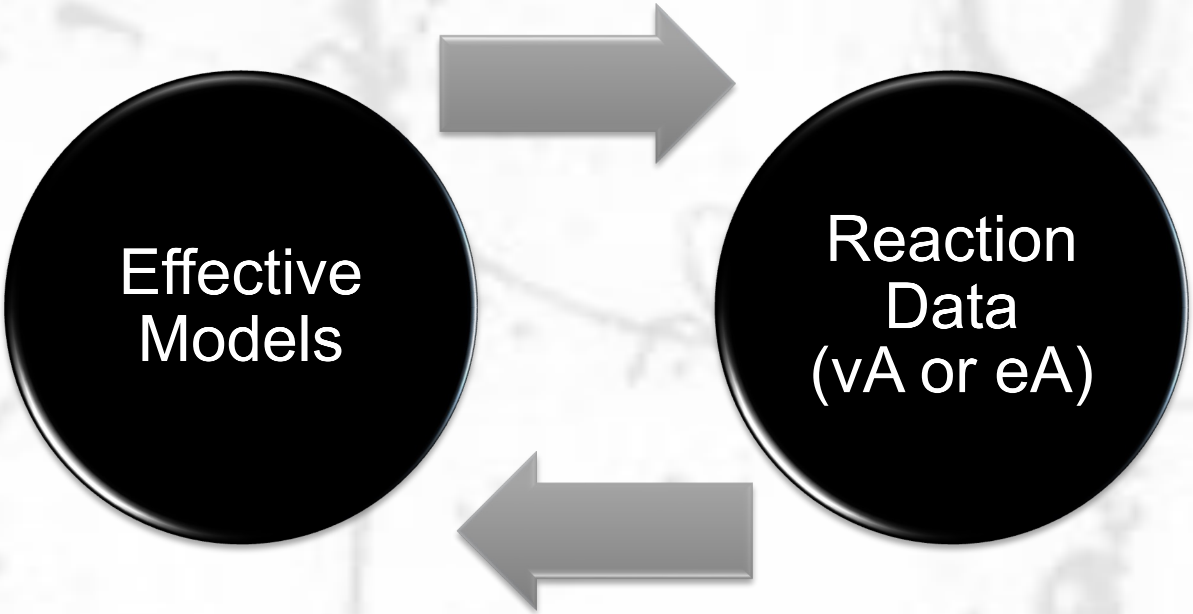
Many New Experiments!

- Short baseline oscillation experiments have enough rate to also measure neutrino interactions: LSND, MiniBooNE, MicroBooNE.
- Oscillation experiments have near detectors which measure interactions with varying degrees of effort: K2K, MINOS, T2K, NOvA, SBN.
- A few dedicated experiments: SciBooNE, MINERvA, ANNIE.

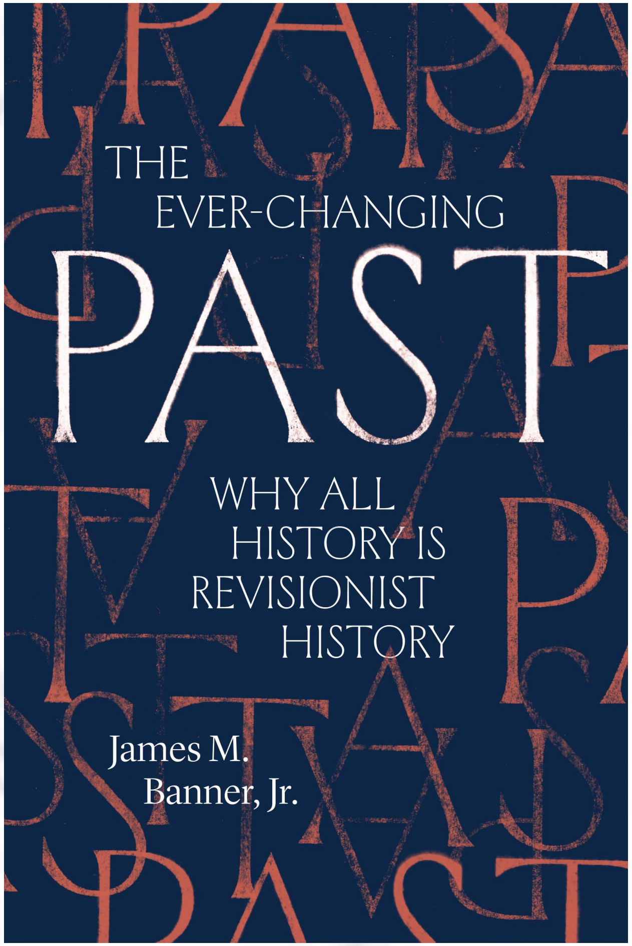
DONE, PUBLISHING, SOON

Theory and Experiment

- Both are critical, and both are limited in what they can offer.
- Theory, as noted, uses necessary approximations, is limited in phase space, or calculates overly inclusive reactions ill suited to generator implementation.
- Data are good at pointing out modeling deficiencies, but often poor at pinpointing the problem.



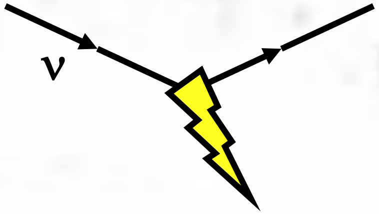
Some (Revisionist) History



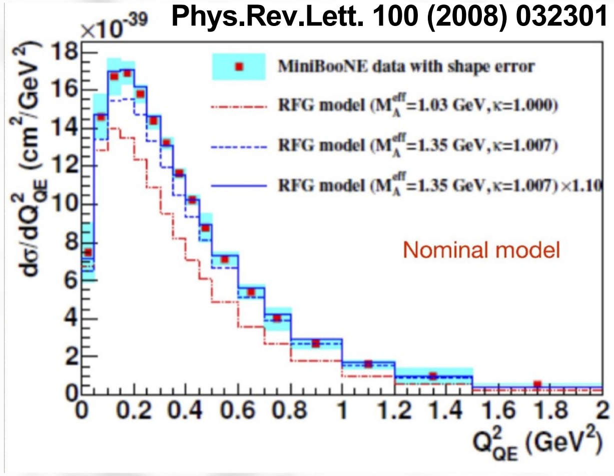
THE
EVER-CHANGING
PAST
WHY ALL
HISTORY IS
REVISIONIST
HISTORY

James M.
Banner, Jr.

Hypothesis: Improved Data Leads to Improved Models



- Canonical exhibit is MiniBooNE.
- Primary detector capability was (excellent) lepton detection and identification.
- Single detector experiment: observed a discrepancy in the transverse momentum of muons, related to "Q^2_{QE}".
- With the data in hand, there could have been many culprits. But it was interpreted as a change in the free nucleon cross-section, as seen through ^{12}C nuclei.
  - Large "axial mass".

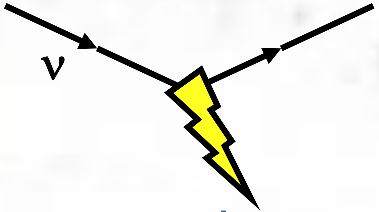


Phys.Rev.Lett. 100 (2008) 032301

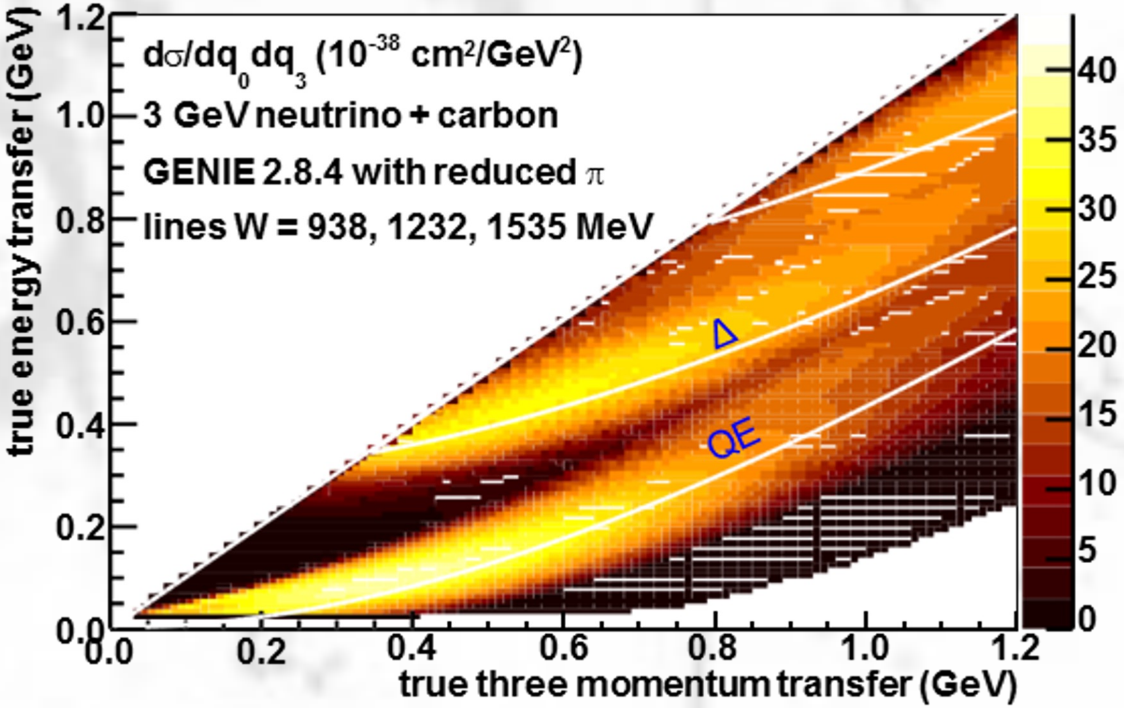
$$F_A(Q^2)=F_A(0)/(1+Q^2/M_A^2)^2$$

snarky poster courtesy of Teppei Katori

Why was this important



- Response of carbon (from a GENIE model) in momentum and energy transfer is below.
- Lepton detecting experiments, like MiniBooNE and T2K/Hyper-K rely on the relationship between transverse momentum transfer and energy transfer to estimate neutrino energy.

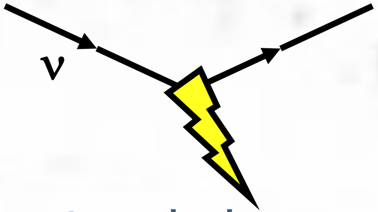


- *W (recoil mass) is fixed in this space*

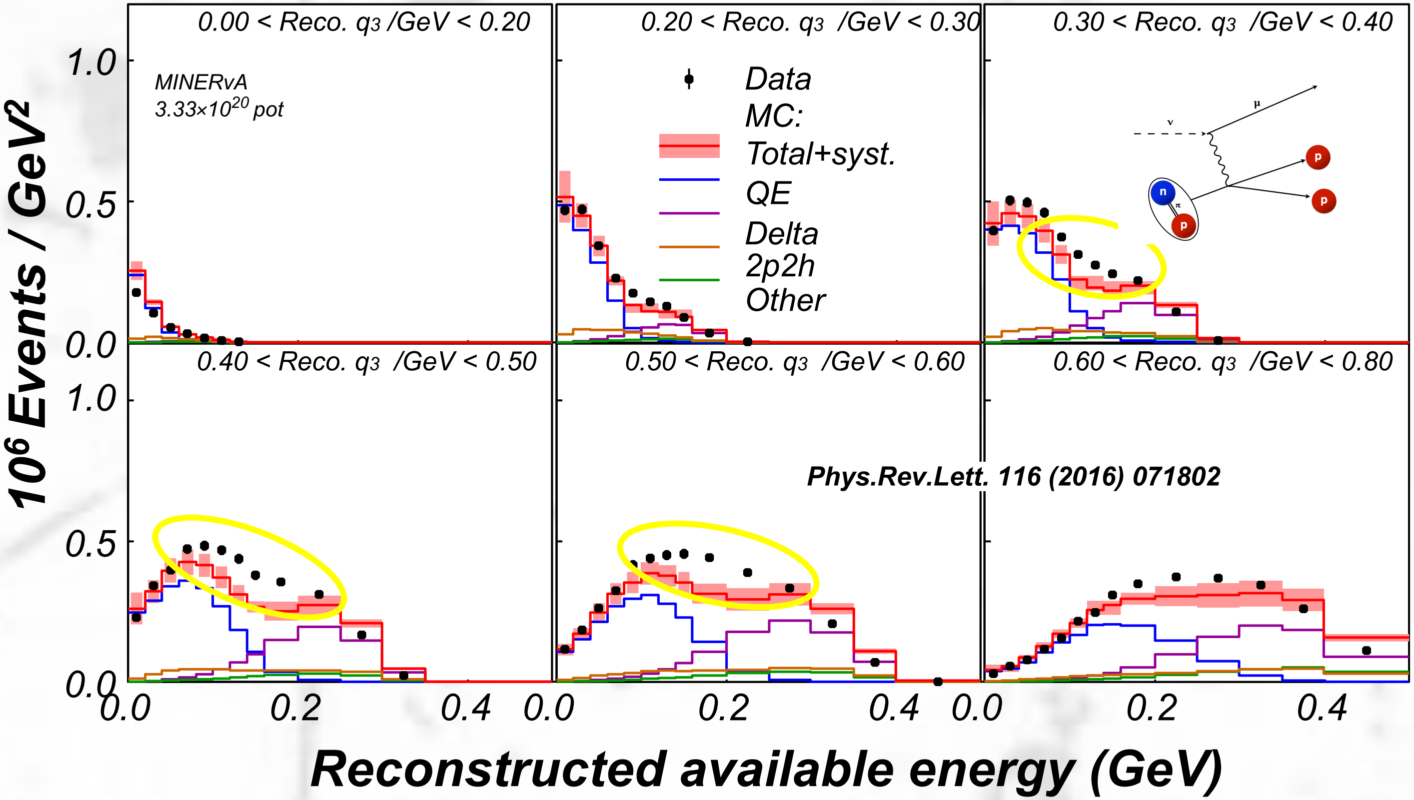
  $$W^2=(M+q_0)^2-q_3^2$$

- *Quasielastic band, at low W, is shown broadened by nuclear effects.*
- *MiniBooNE assumption was that the fix left interactions in the QE band.*

How to solve this puzzle

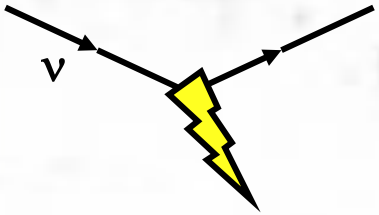


- Easy in retrospect… correlation of recoil and the lepton to try to mimic the measurement of energy and momentum transfer.
- Requires detector technology (scintillator calorimetry) and high statistics.

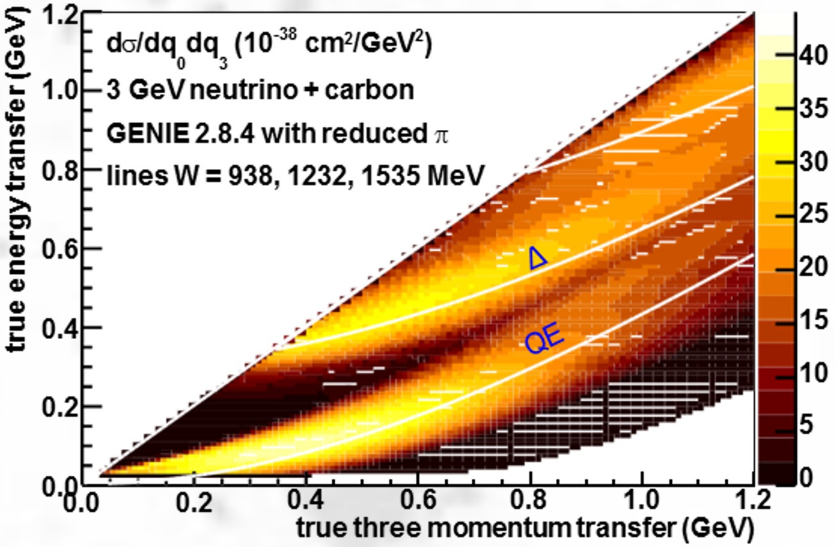


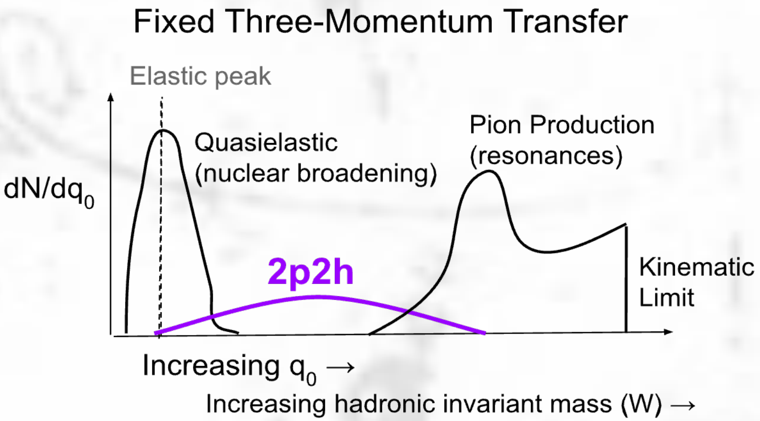
Phys.Rev.Lett. 116 (2016) 071802

Interpretation: Multinucleon Knockout, a.k.a., “2p2h”



- In brief, this data was interpreted as significant evidence for a large “2p2h” event rate.
- And significantly larger than predicted by models.
- Why does it matter? 2p2h sits at higher energy transfer for fixed momentum transfer.
- Interpretation of this rate as quasielastic leads to the wrong neutrino energy reconstruction.





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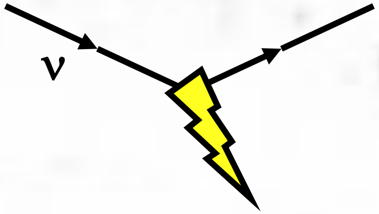
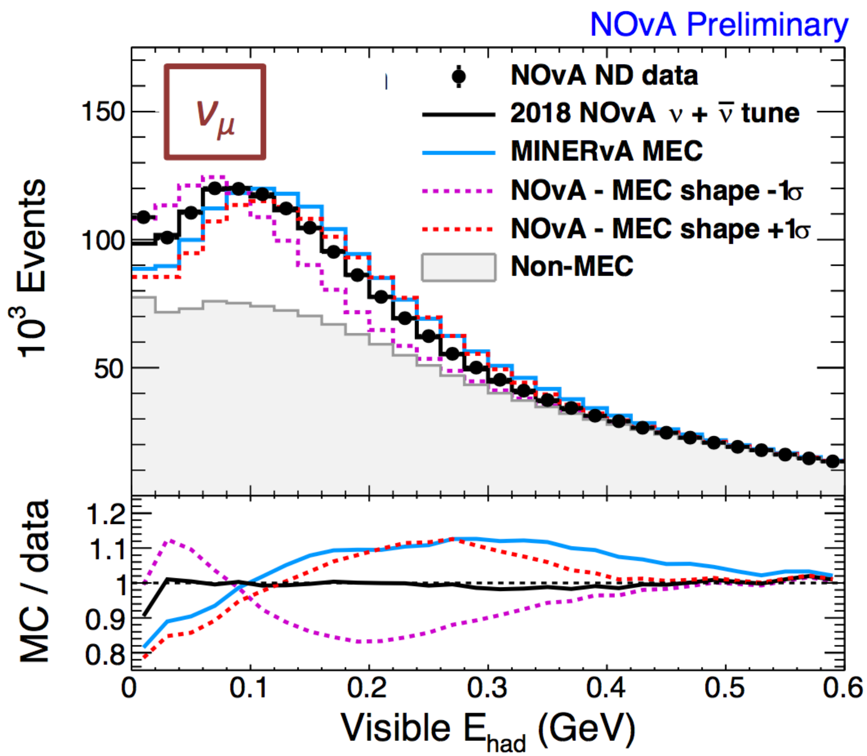
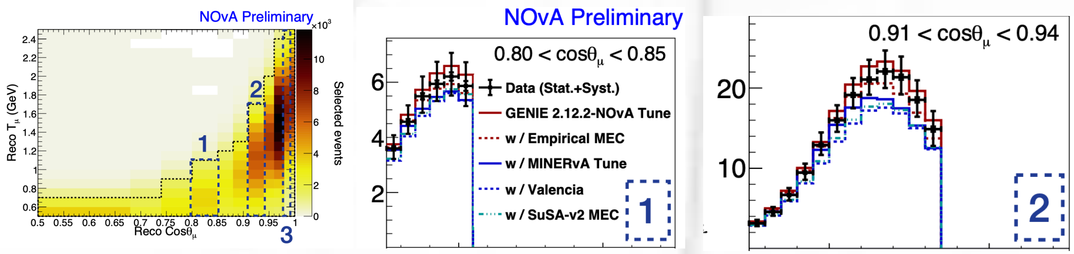


- “2p2h” interpretation was corroborated by other measurements of the recoil system, in correlation with the leptons.
- Technique now used by NOvA as an important part of their oscillation analysis.

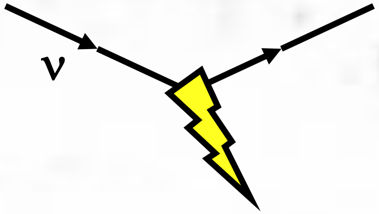


see also Alexander Booth’s talk yesterday

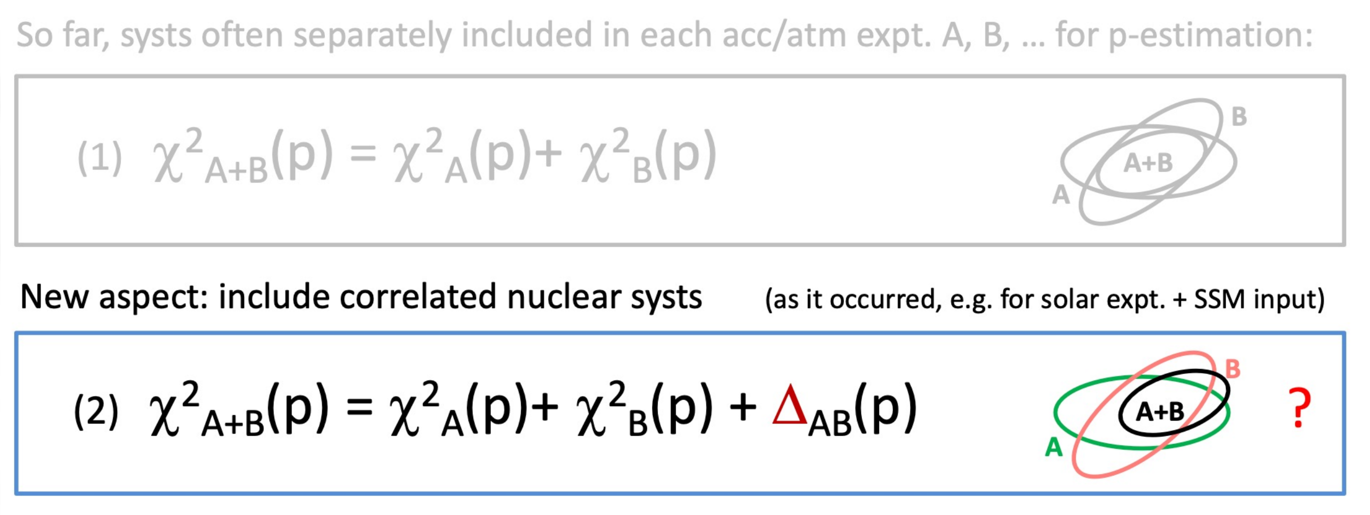


Alex Himmel, JETP Seminar, June 2018

A comment on tuning…



- NOvA, as we just saw, and T2K also, are tuning their models independently to reflect discrepancies in their data and outside data. This tuning doesn't attribute a cause to the discrepancies, so are done without knowledge of correlations.
- As Eligio Lisi pointed out yesterday, this leads to a problem when combining results to extract new information.

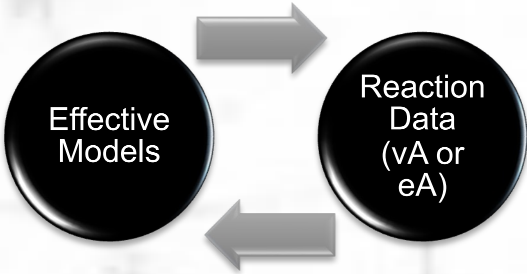


So far, systs often separately included in each acc/atm expt. A, B, … for p-estimation:

(1) $\chi^2_{A+B}(p) = \chi^2_A(p)+ \chi^2_B(p)$

New aspect: include correlated nuclear systs (as it occurred, e.g. for solar expt. + SSM input)

(2) $\chi^2_{A+B}(p) = \chi^2_A(p)+ \chi^2_B(p) + \Delta_{AB}(p)$



Effective Models

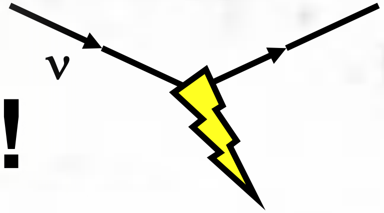
Reaction Data (νA or eA)

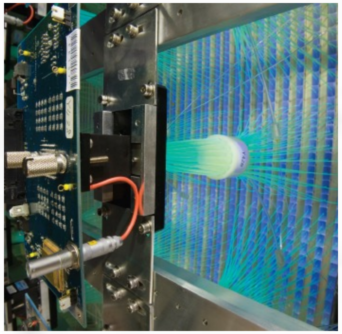
Another comment on tuning…

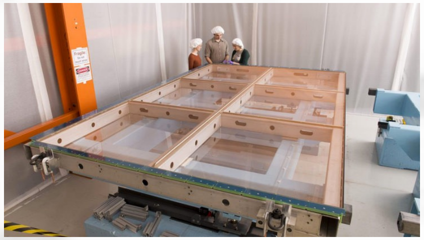
- NOvA, as we just saw, and T2K also, are tuning their models independently to reflect discrepancies in their data and outside data. This tuning doesn't attribute a cause to the discrepancies, so are done without knowledge of correlations.
- And since we learned this morning from Prof. Shaposhnikov that

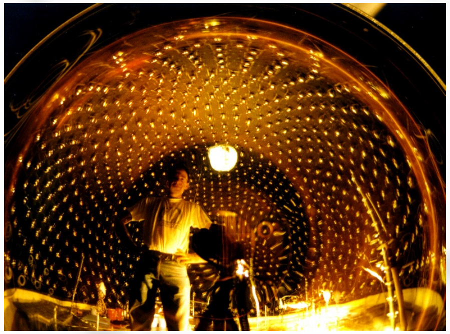
$$\#\ \textit{theories} \sim C_S/(\#\ \textit{data points})^{\alpha},\ \alpha > 0$$

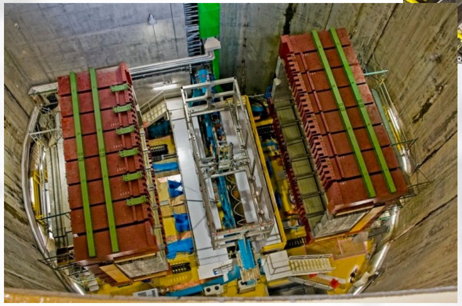
But
Many New Experiments!











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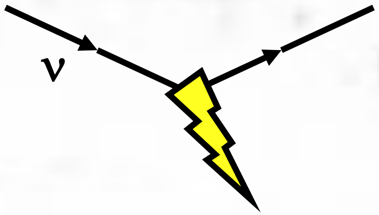

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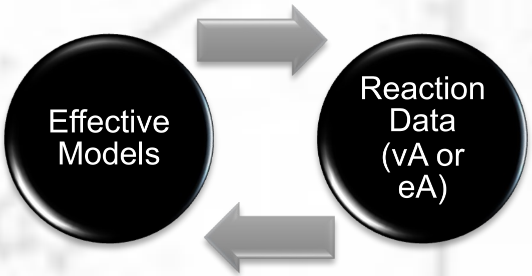
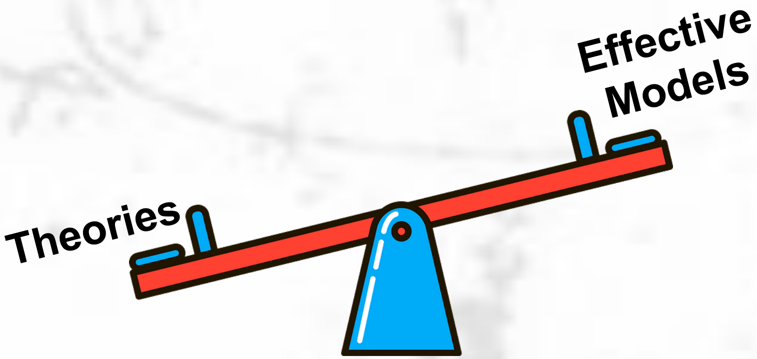
- And since we learned this morning from Prof. Shaposhnikov that

$$\#\ theories \sim C_S/(\#\ data\ points)^{\alpha},\ \alpha > 0$$

$$\therefore \text{ for neutrino interactions, } \#\ theories \rightarrow 0$$

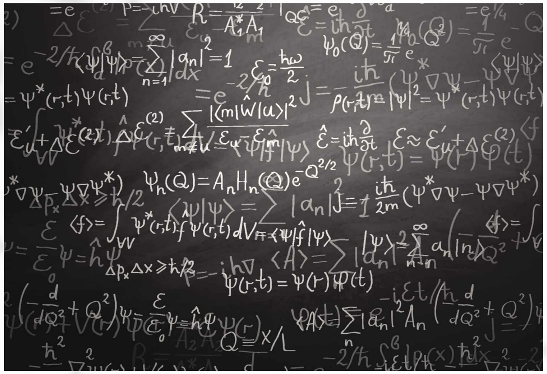

Effective Models

Reaction Data (vA or eA)



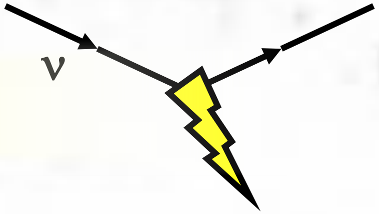
Some Recent Results…

MINERvA

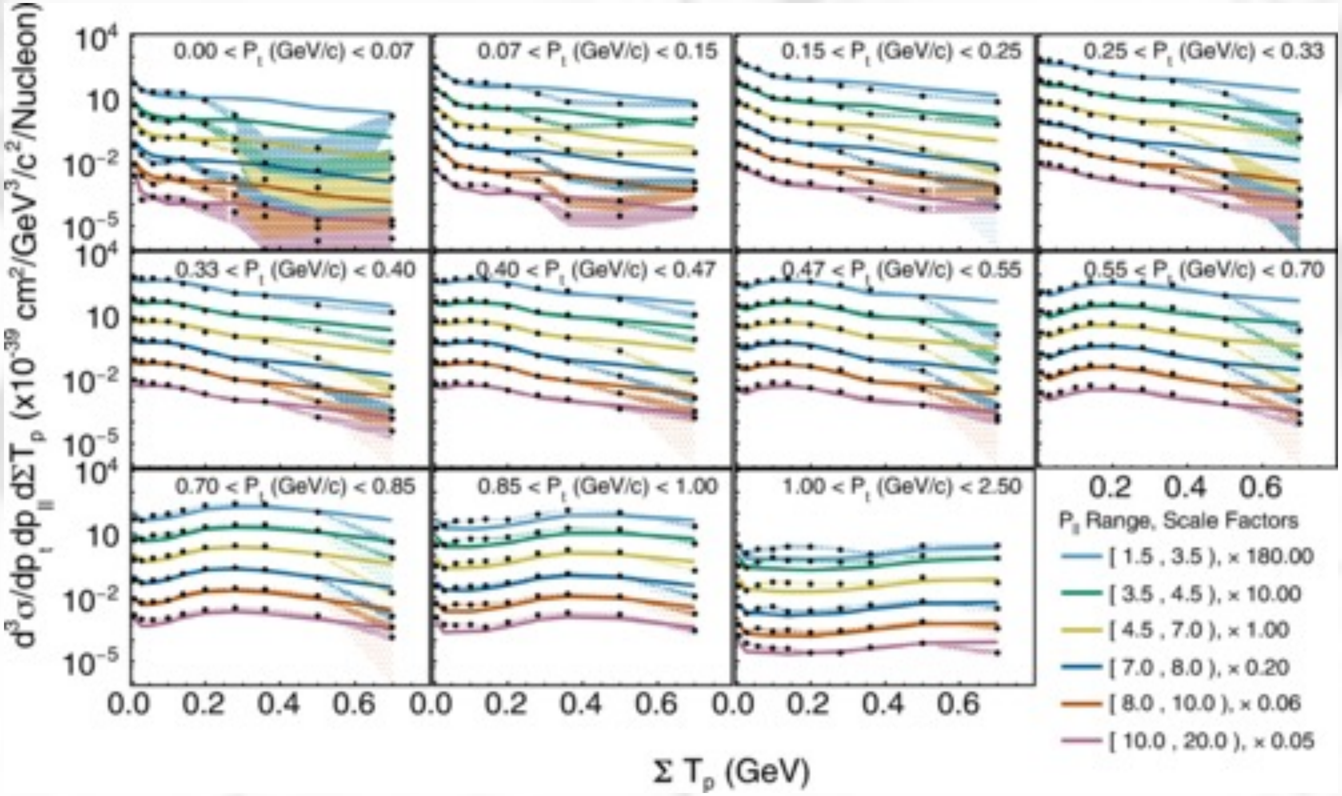


e4ν

Lepton-Hadron Correlations



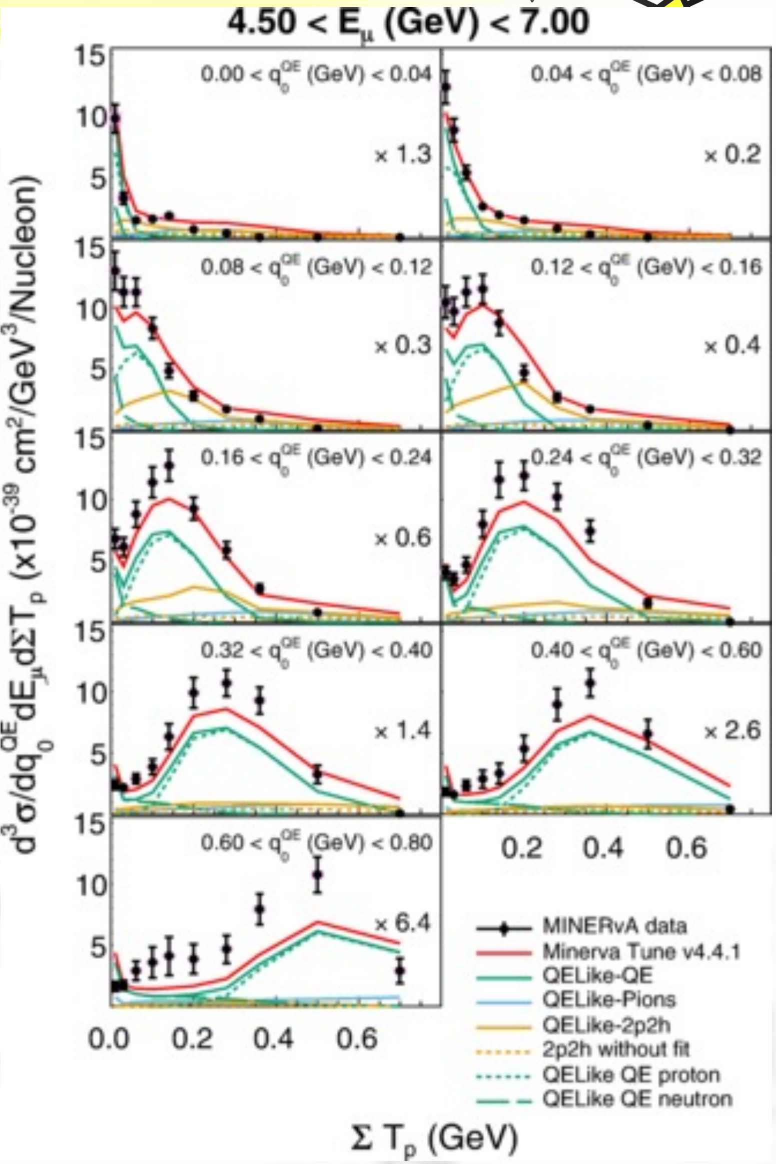
- New MINERvA result correlating recoil with lepton kinematics.
- Key technologies: control of backgrounds, to isolate final states with only nucleons, and overwhelming statistics.



Simultaneous Measurement of Proton and Lepton Kinematics in Quasielastic like ν_μ-Hydrocarbon Interactions from 2 to 20 GeV
D. Ruterbories *et al.* (MINERvA Collaboration)
Phys. Rev. Lett. **129**, 021803 – Published 6 July 2022

Why it matters

- Ability to compare lepton-only energy reconstruction (MiniBooNE, T2K) with calorimetric reconstruction (NOvA, DUNE) against a model, since both are accessible in this data.
- GENIE model has generally poor agreement on tails, and misses peaks by tens of MeV on recoil.
- This model can't simultaneously be (successfully) used to estimate neutrino energies in the two types of experiments.



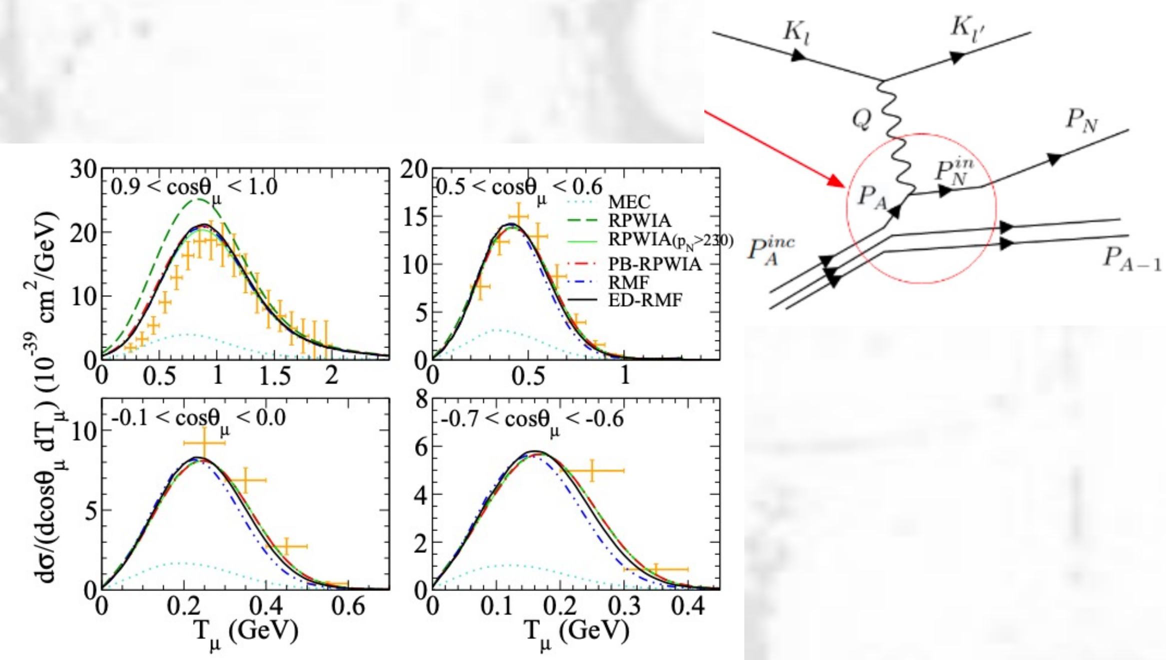
RMF Single Knockout Calculations

- Calculation in relativistic mean field approach of full kinematics of single nucleon knockout.
- Takes advantage of new techniques for treatment of distorted wave, nuclear wavefunction parameterizations.

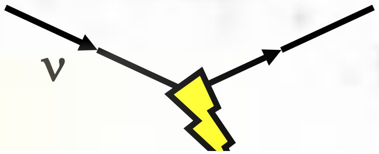
R. González-Jiménez et al. Phys. Rev. C 00.4 (2019).

A. Nikolakopoulos et al. Phys. Rev. C105.5 (2022)

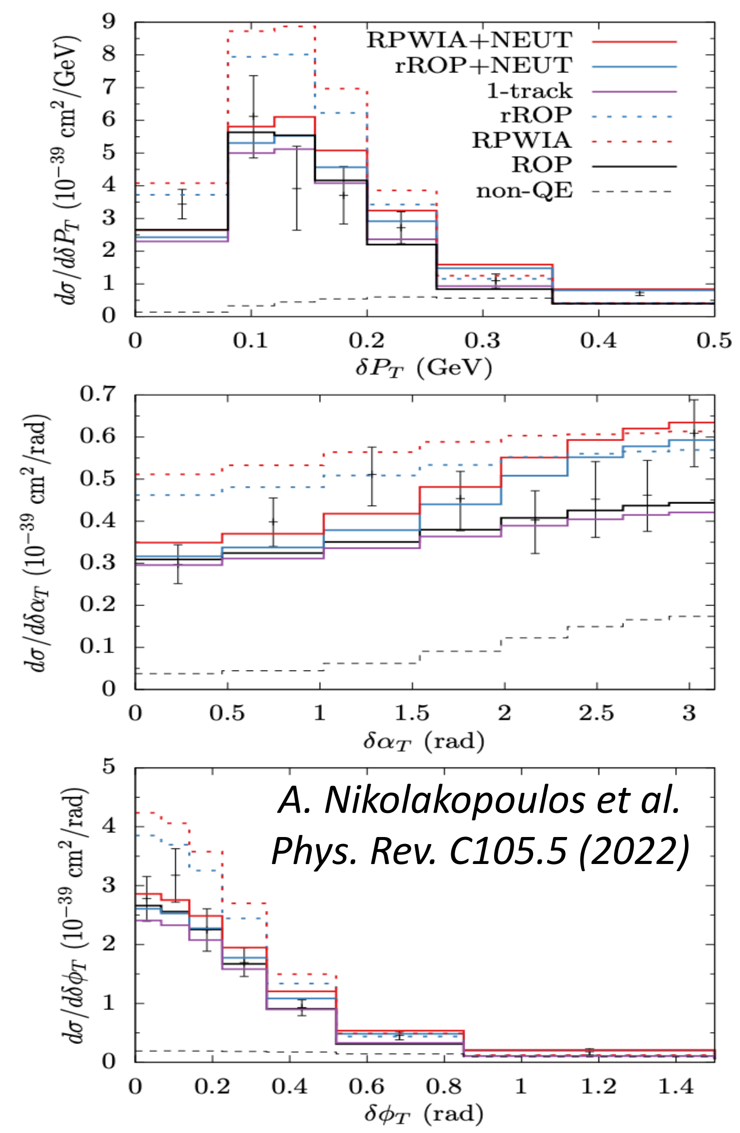
- Promises to be able to more reliably predict the correlation between the lepton and hadron kinematics than the usual plane wave impulse approximation (PWIA).
- All models can reproduce lepton kinematics only, but…



Why it matters



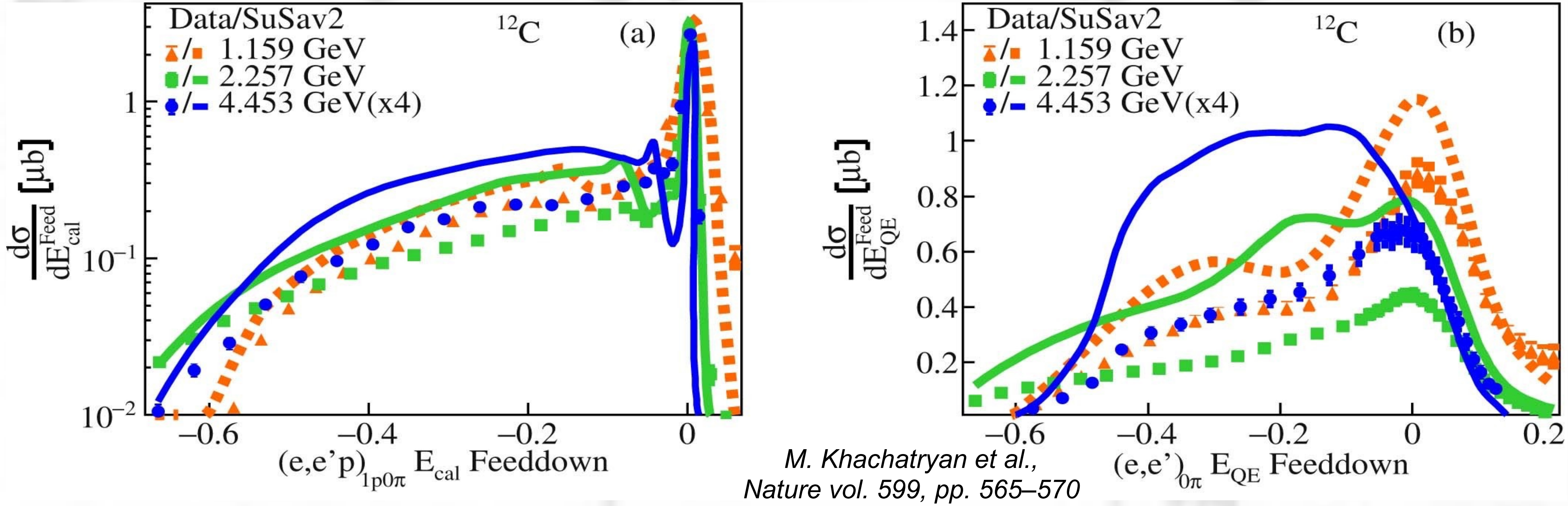
- This calculation is a much more sophisticate treatment of correlations between the lepton and hadron side.
- These correlations impacts both neutrino energy reconstruction and the ability to use these correlations to test models.
- Comparison to T2K transverse kinematic imbalance (TKI) data shown at right.
- T2K is now working to incorporate the RMF model into its simulations.



A. Nikolakopoulos et al. Phys. Rev. C105.5 (2022)

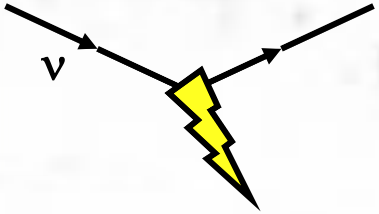
e4nu Energy "Feed-down"

- In electron scattering, knowledge of the true electron energy allows measurement of the difference between reconstructed and true energy.
- Model (SuSAv2 in this case) misses shape and rate in "feed-down" tail where electrons are reconstructed at much lower energy than reality, using neutrino reconstruction techniques.



M. Khachatryan et al., Nature vol. 599, pp. 565–570 (2021)

Why it matters



- Although electron scattering doesn't probe all parts of the reaction, key features, the nuclear initial state, and final state interactions, are common to electron and neutrino scattering.
- Deficiencies in the models used in neutrino scattering, when they fail to predict electron scattering, point squarely at deficiencies in the models used for E_ν reconstruction.

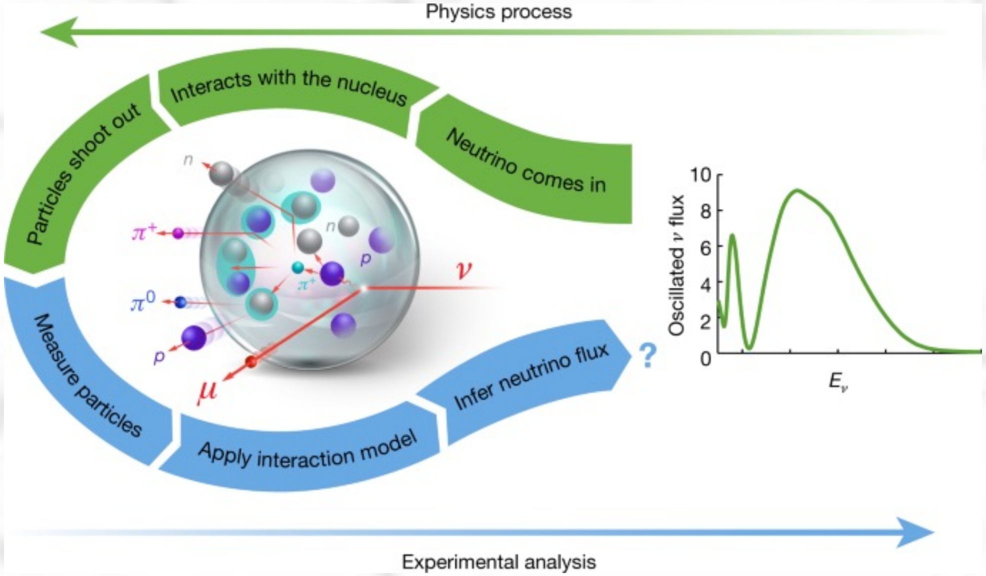
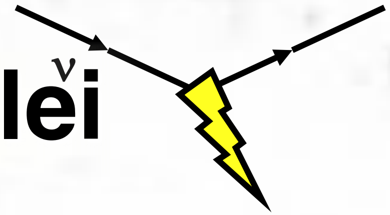


Figure from M. Khachatryan et al., Nature vol. 599, pp. 565–570 (2021)

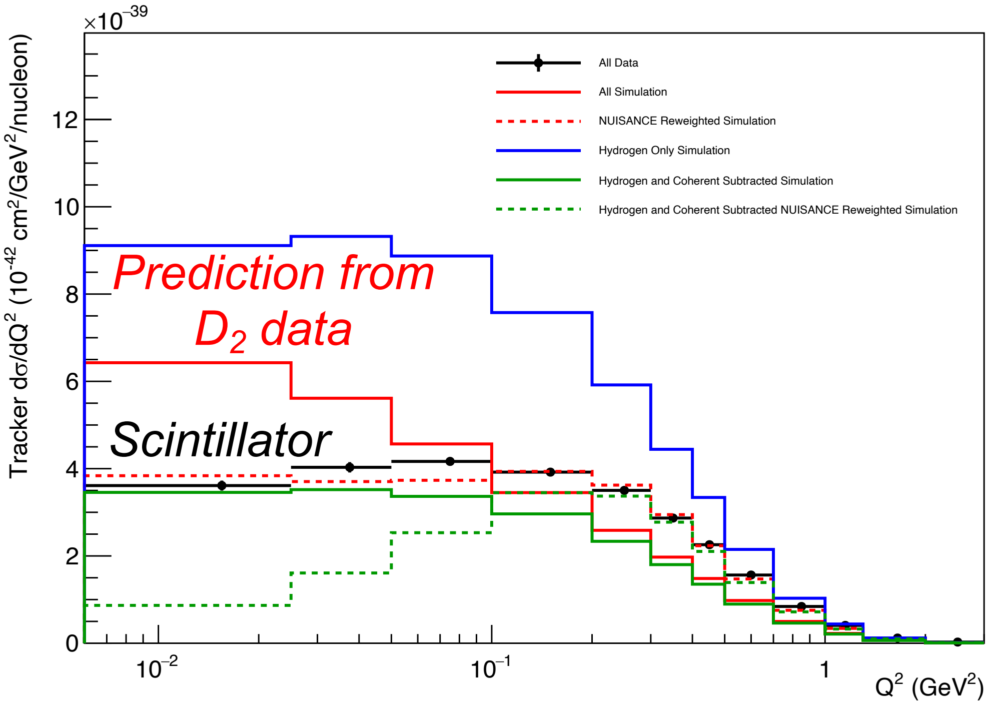
π^+ production on different nuclei



- MINERvA single π^+ (Δ dominated) measurement that takes advantage of efficient/pure π^+ identification, multiple targets.

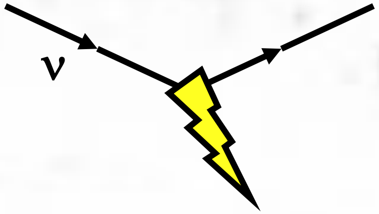
- A two part story….
- Low Q^2 suppression in the scintillator is clearly present in data, as seen by the unpredicted turnover.
- Tune coherent pion production to match our exclusive coherent results, and nuclear suppression to match these results on scintillator.

A. Bercellie et al,
Phys.Rev.Lett. 131 (2023) 1, 1



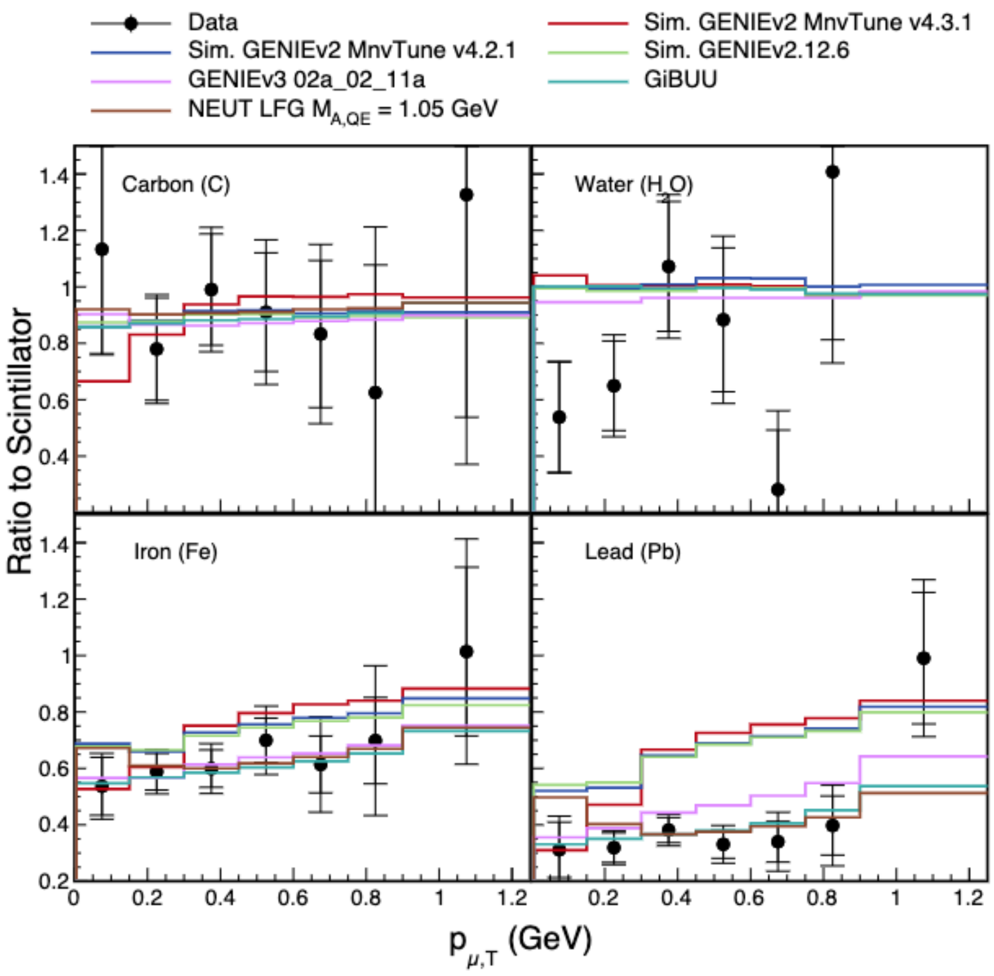
Prediction from D_2 data

Scintillator



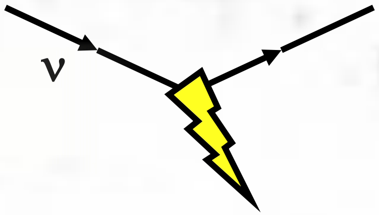
Why it matters

- Ratios between targets (carbon, water, iron, lead) and scintillator should be insensitive to this large correction.
- They appear to be well modeled, in other words, the correction appears independent of nucleus.
- Form factors? Nuclear effect?
- Models with intranuclear cascades simulating the final state π^+ interactions do better.
- Impact on inferred energy (and direction) depends modeling rate vs. momentum transfer.

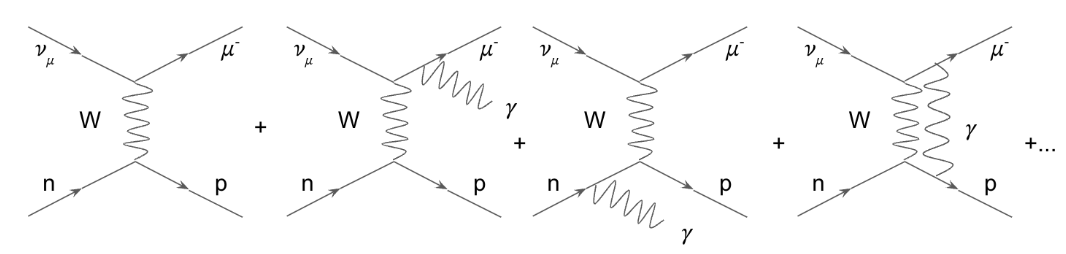


A. Bercellie et al, Phys.Rev.Lett. 131 (2023) 1, 1

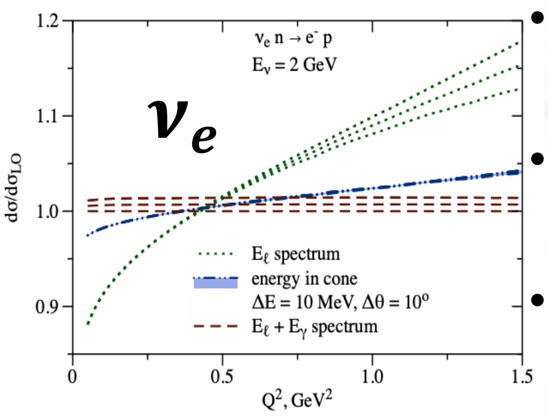
Radiative Corrections



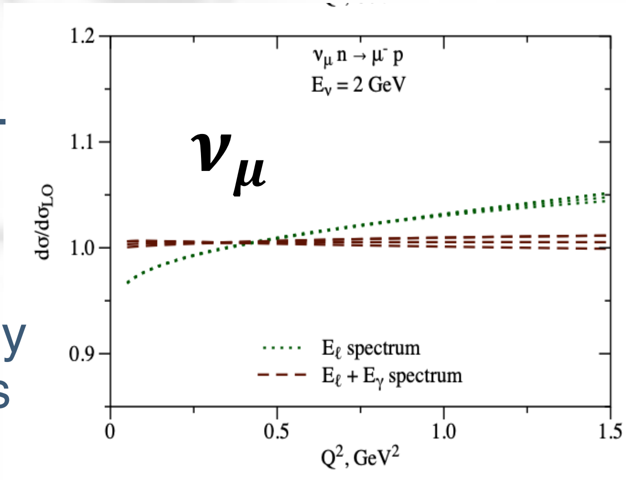
- Recent calculations have (finally) used the modern tools of electrodynamic radiative corrections to neutrino scattering.
- Essentially came about because of joining expertise in two disparate subfields, orchestrated by Richard Hill.



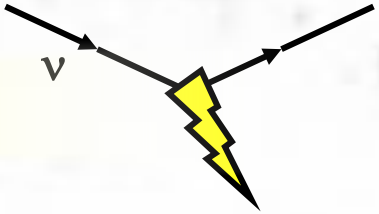
O. Tomalak et al., including KSM, Nature Commun. 13 (2022) 1, 5286; Phys.Rev. D106 (2022) 9, 093006.



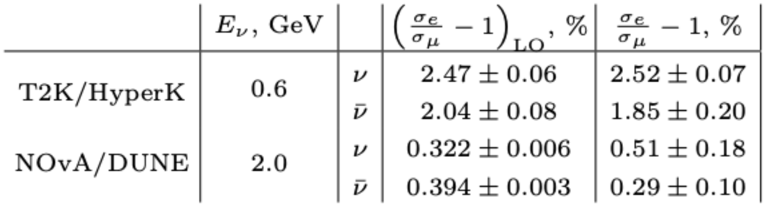
- Observationally relevant treatment of photons is critical.
- For electron neutrinos, often clustered with final lepton.
- For muon neutrinos, separately observable if above thresholds for showering in detector.



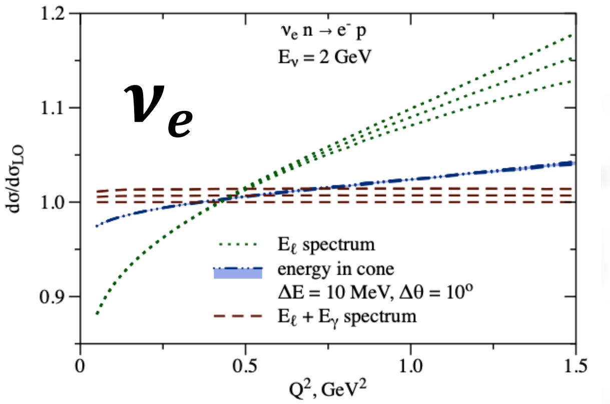
Why it matters

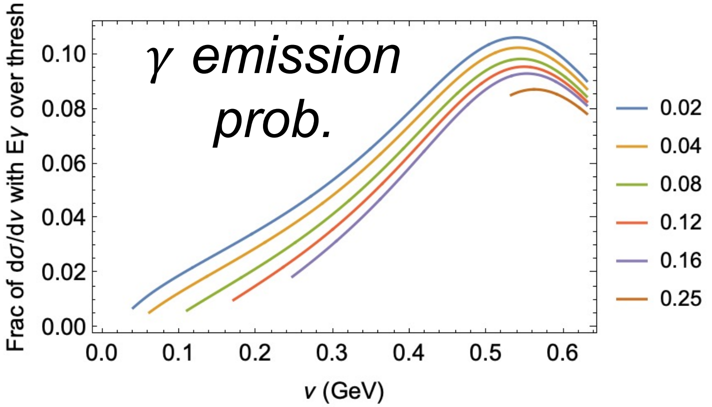


- As alluded to on the last slide, effects are significantly different for electron and muon neutrinos.
- Ignoring the corrections makes prediction of interaction rates of one flavor from the other unreliable.
- Total cross-section changes little, as expected from KLN theorem.
- But leptons become softer in the presence of radiative corrections.
- Radiated real non-collinear photons spoil detection efficiency or confuse flavors detection.



	E_ν, GeV		$\left(\frac{\sigma_e}{\sigma_\mu}-1\right)_{\mathrm{LO}}$, %	$\frac{\sigma_e}{\sigma_\mu}-1$, %
T2K/HyperK	0.6	ν	2.47 ± 0.06	2.52 ± 0.07
		$\bar{\nu}$	2.04 ± 0.08	1.85 ± 0.20
NOvA/DUNE	2.0	ν	0.322 ± 0.006	0.51 ± 0.18
		$\bar{\nu}$	0.394 ± 0.003	0.29 ± 0.10



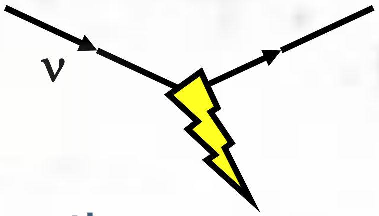


O. Tomalak et al., including KSM, Nature Commun. 13 (2022) 1, 5286; Phys.Rev. D106 (2022) 9, 093006.

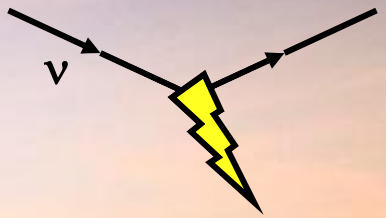
Neutrino Interactions Outlook?

my view from Lugard Road,
Victoria Peak, this Sunday morning

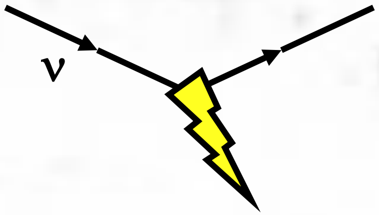
Interactions Outlook



- Both theory and data are required to make progress on the understanding of neutrino interactions needed for precision oscillation experiments.
- New capabilities in neutrino experiments…
  - improved detectors,
  - high statistics,
  - creative analysis ideas,
- … have led to improvements in models which have proved critical for correct interpretation of oscillation data.
- Needs of future accelerator and atmospheric neutrino experiments will benefit from new capabilities, such as PRISM "quasi mono-energetic beams" and electron neutrinos at high statistics, that we will use to explore neutrino interactions.



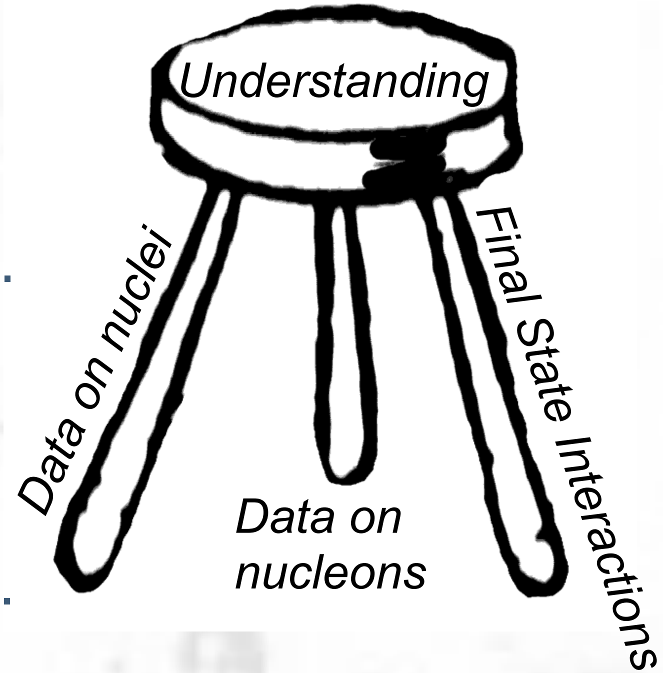
So maybe…
Neutrino Interactions Outlook!



Backup

Measurements on Nucleons

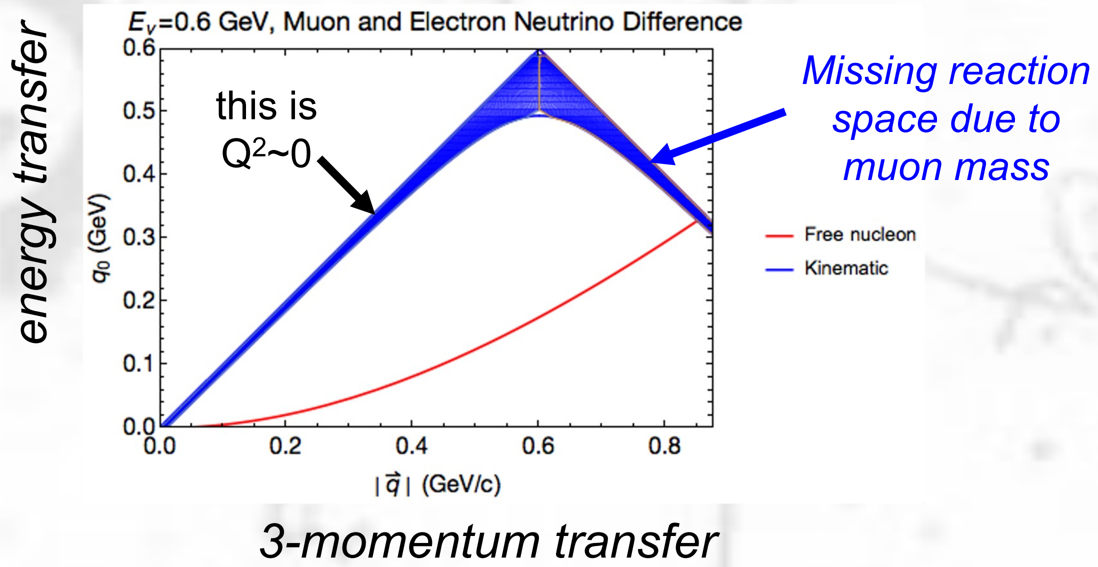
- As the MiniBooNE story illustrates, a challenge data on nuclei is whether we are seeing a nucleAR effect, or a neutrino-nucleON effect.
- Mine safety considerations means we are unlikely to have significant new datasets using hydrogen targets, and nature doesn't give us free neutrons.
- Measurements that can measure scattering on hydrogen by comparing carbon to hydrocarbon will may fill the gap.
- MINERvA recently measured $\bar{\nu}_\mu H \to \mu^+ n$, *Nature 614, pp. 48–53 (2023).*
- Capable DUNE near detectors with CH will have overwhelming statistics to exploit.



The ν_e Problem…

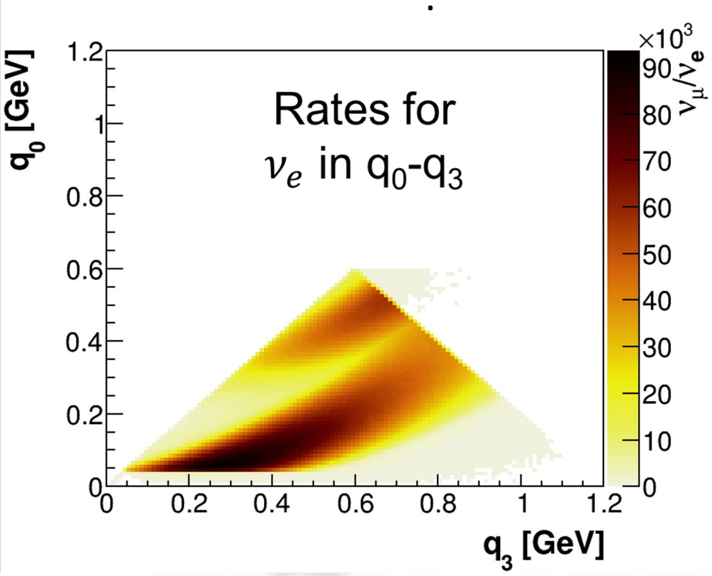
- By necessity, our ν_μ rich beams have few ν_e in them to allow us to study any difference between ν_μ and ν_e interactions.
- Therefore, we infer ν_e interactions from studies of ν_μ
  - But what we study can't give us the whole picture.
  - Phase space (below), radiative corrections, etc.

(O. Tomalak et al., *Nature Commun.* 13 (2022) 1, 5286; *Phys.Rev.D* 106 (2022) 9, 093006)



this is Q^2~0

Missing reaction space due to muon mass



Rates for ν_e in q_0-q_3