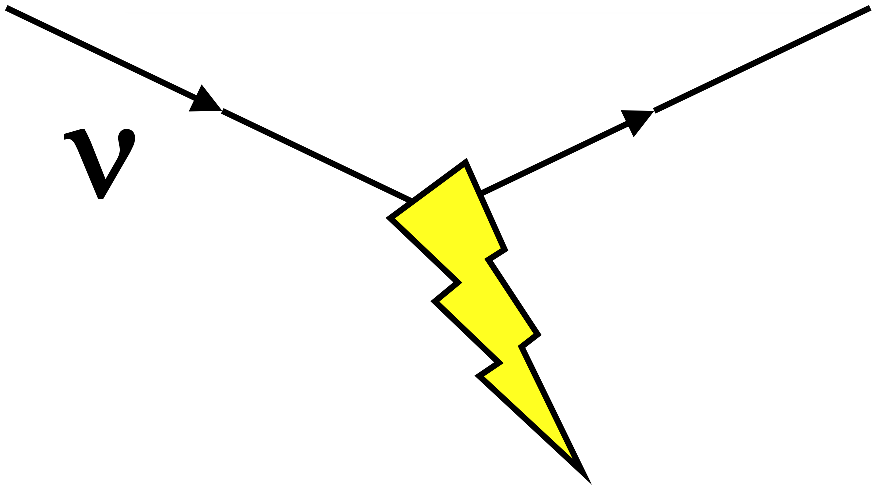
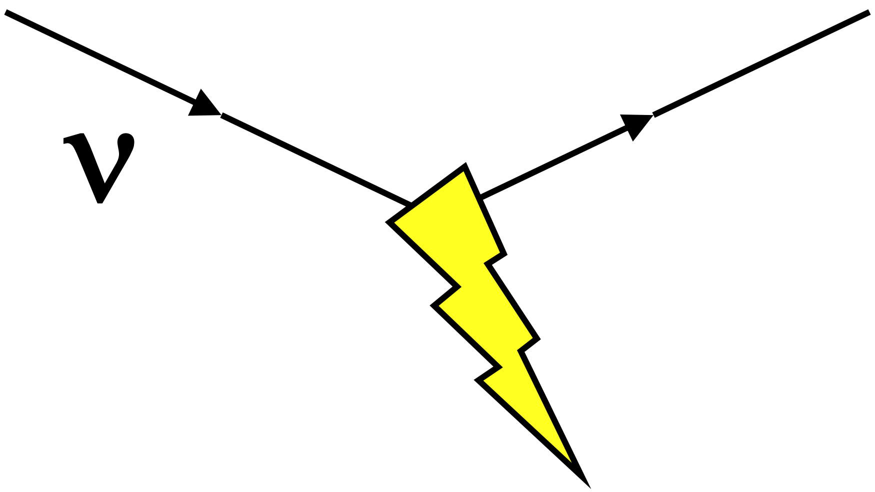
Neutrino Cross Sections



Kevin McFarland
University of Rochester

6 May 2019
FPCP@Victoria

Neutrino Interactions



Kevin McFarland
University of Rochester

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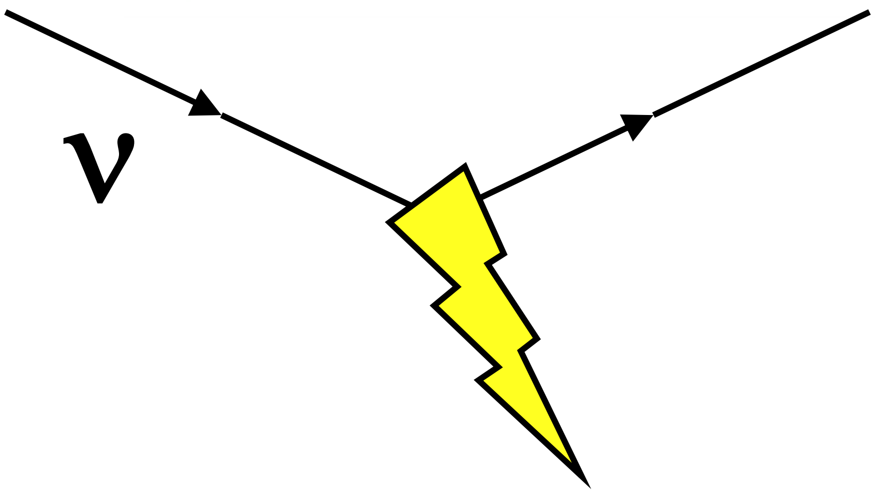
FPCP@Victoria

[GeV] Neutrino Interactions [the difficult ones]



Kevin McFarland
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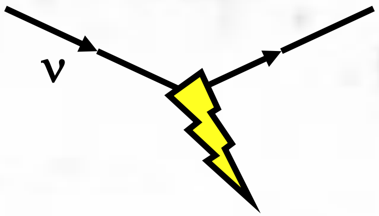
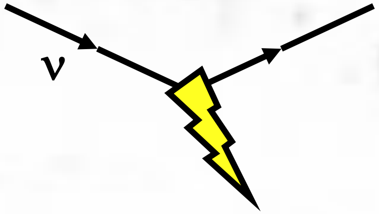
Outline



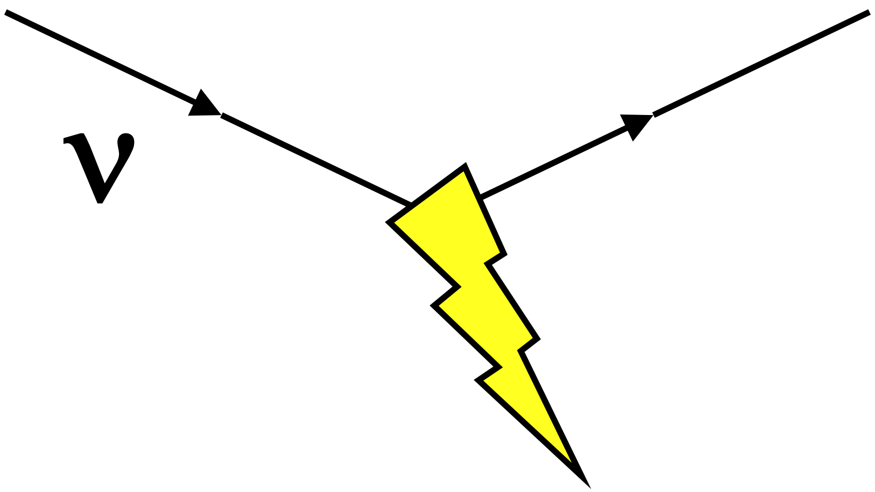
- Why progress on understanding GeV neutrino interactions is needed
- Tools for progress: theory, electron scattering and neutrino scattering
- Why progress has been difficult.
- Neutrino experiments that make progress.
- Highlights of progress.

Outline



- Why **progress** on understanding GeV neutrino interactions is needed
- Tools for **progress**: theory, electron scattering and neutrino scattering
- Why **progress** has been difficult.
- Neutrino experiments that make **progress**.
- Highlights of **progress**.

Recent Progress in Understanding GeV Neutrino Interactions



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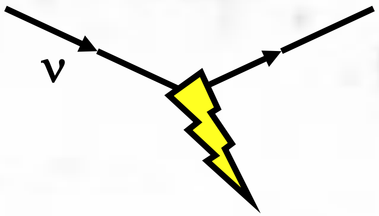
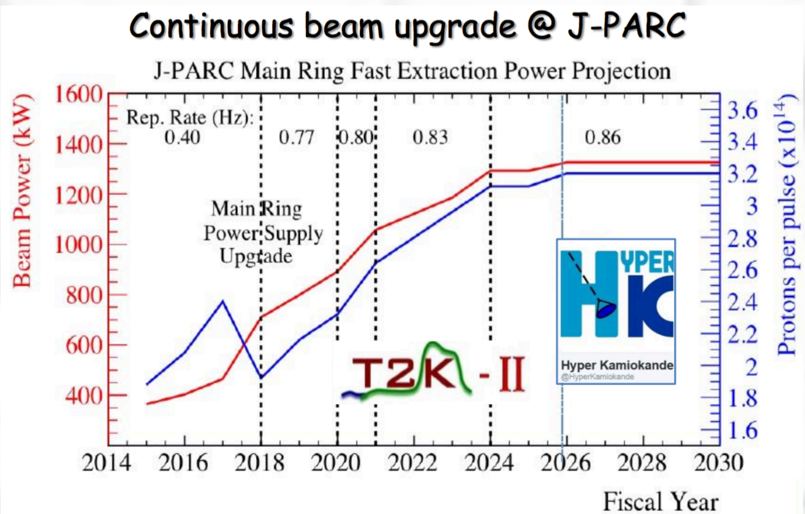
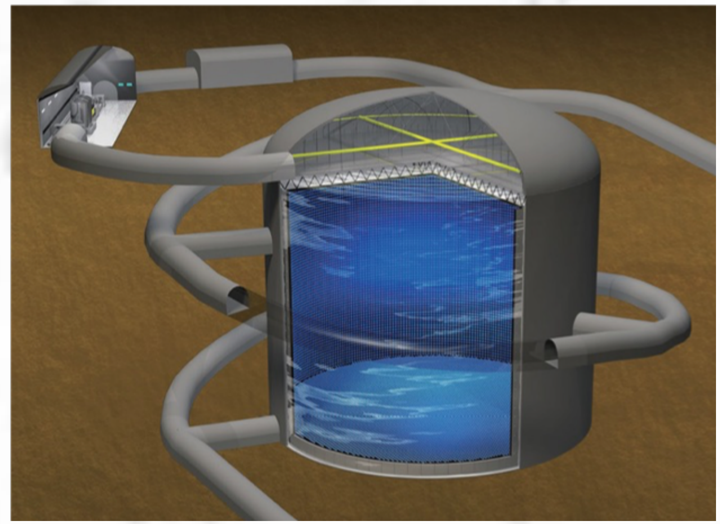


Next Steps in Neutrino Oscillations and GeV Neutrino Interactions

Next Steps: Hyper-Kamiokande

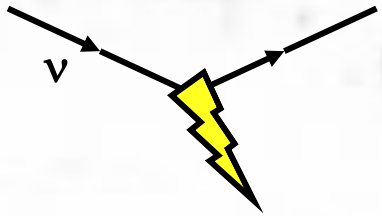
- Effectively an upgrade of the T2K experiment with more intense beam and larger detector at same sites



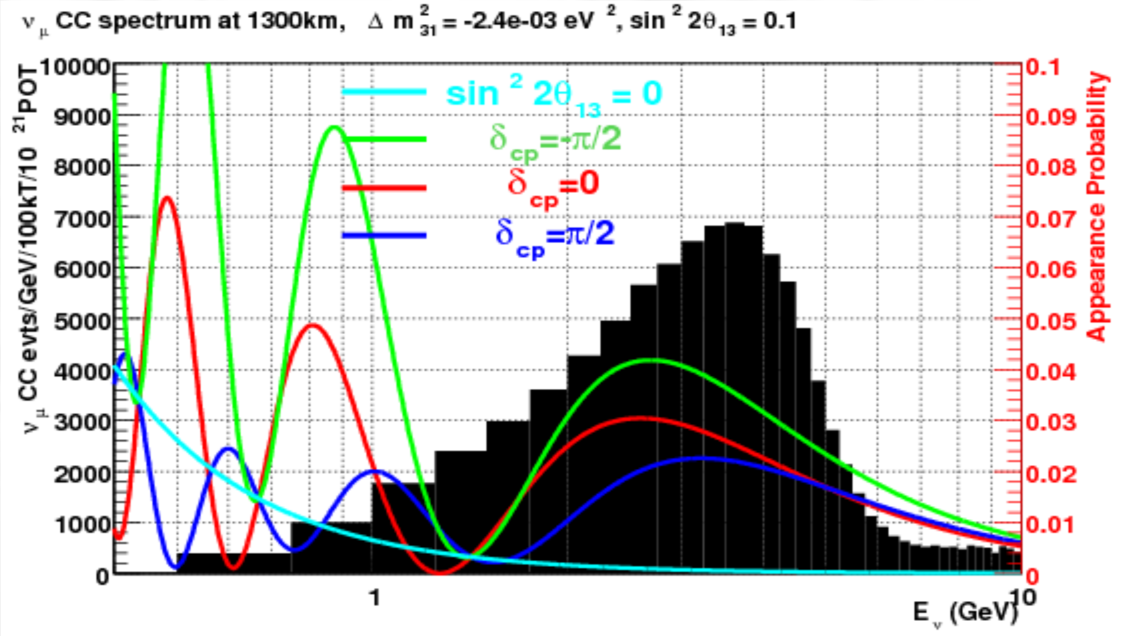


- Greater than 1 MegaWatt of proton power (>2x current)
- Build new detector, five times the size of Super-Kamiokande with 0.26 MegaTons of water
- Challenges in excavating cavern, photosensors, etc.

Next Steps: DUNE

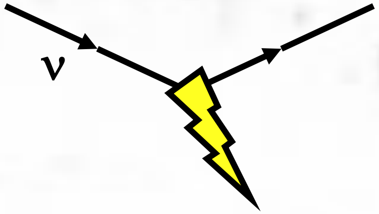


- Happy coincidence of location of Sanford lab (the former Homestake mine where solar neutrinos were discovered!) and location of high power multi-GeV proton sources

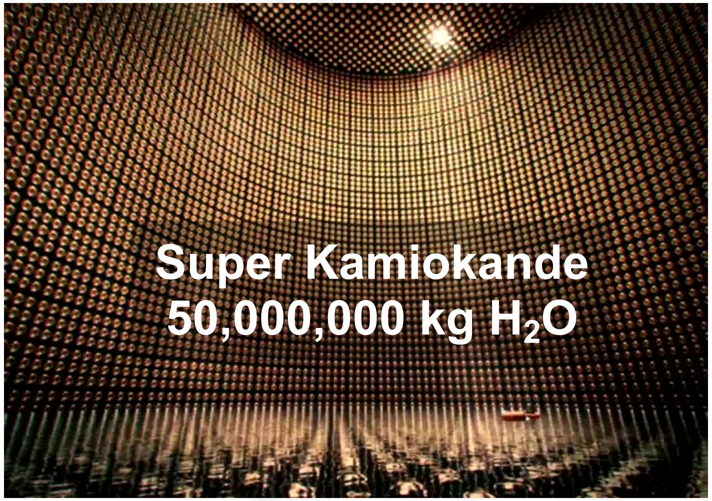


- *Wideband beam can study the oscillation effect across a range of energies. Requires good energy reconstruction!*

Necessary: Keep Every Neutrino Possible

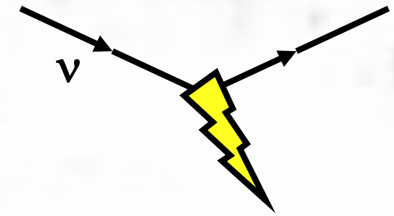


- Neutrinos rarely interact, even in detectors as thick as we can build them.
  - Example: T2K sends its beam 295km across Japan to the Super-Kamiokande detector.
  - T2K has put ~10 TJoule of protons on target, and observed ~10 nJoule of particles from electron neutrino interactions in SK.

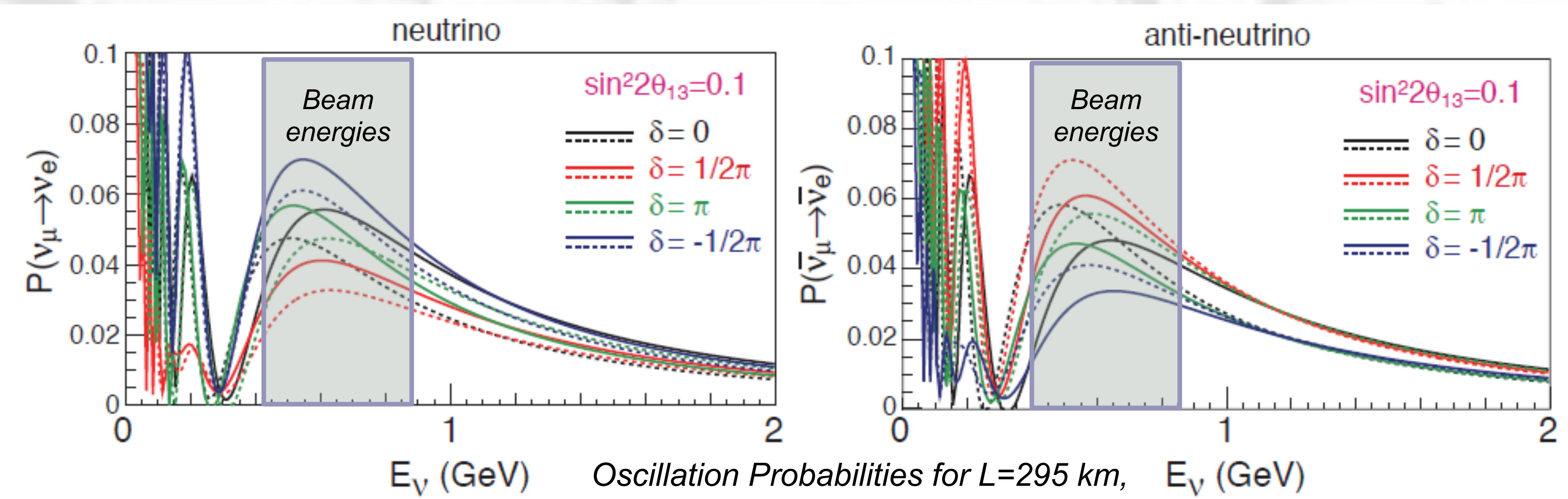


- Cherry-picking the best understood interactions comes at an untenable cost. Need to keep as many neutrinos in the samples as possible.

Necessary: Energy Reconstruction

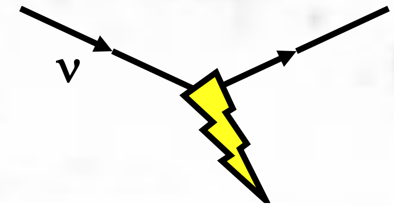


- Neutrino oscillation measurements require measurement of neutrino energy to determine oscillation probability.
- Even “narrow band” neutrino beams have an energy spectrum width that can’t be ignored.
- Must estimate energy from the final state.



Oscillation Probabilities for L=295 km, Hyper-K LOI

Necessary: Energy Reconstruction



- Now consider the effect of multinucleon (2p2h) processes on energy reconstruction from leptons as in T2K and HyperK.

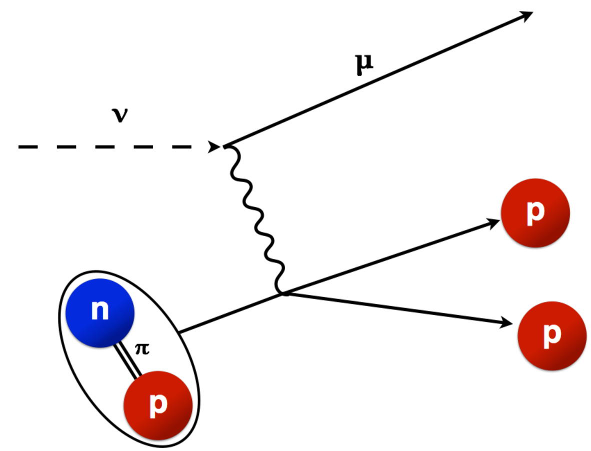
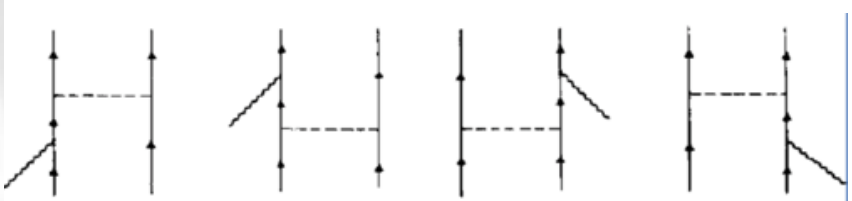
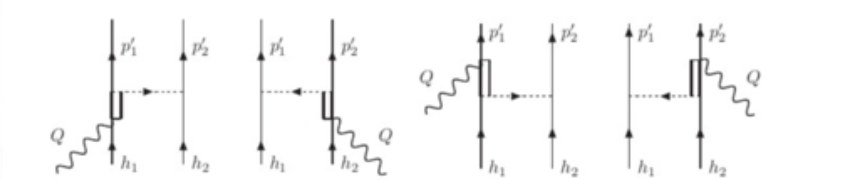


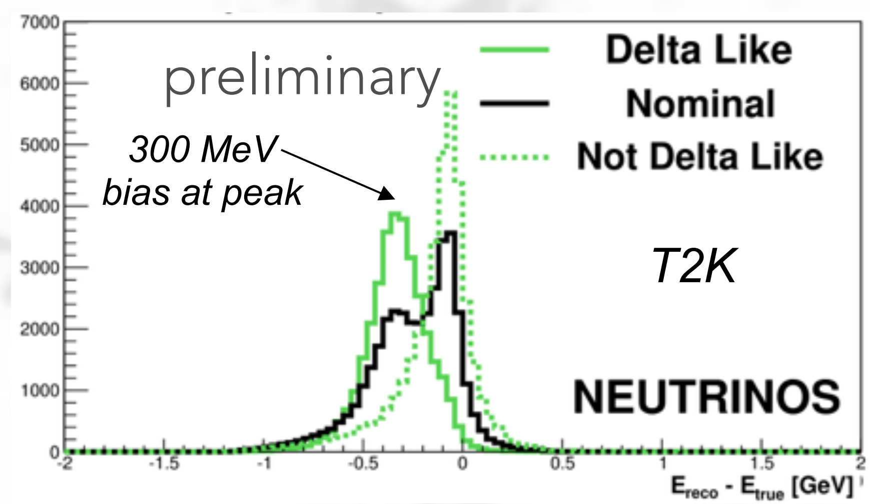
Figure courtesy M. DelTutto

Pair Correlation



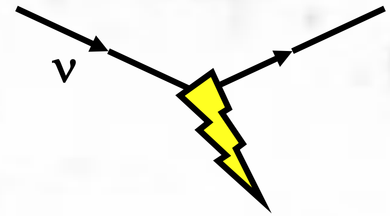
Delta absorption



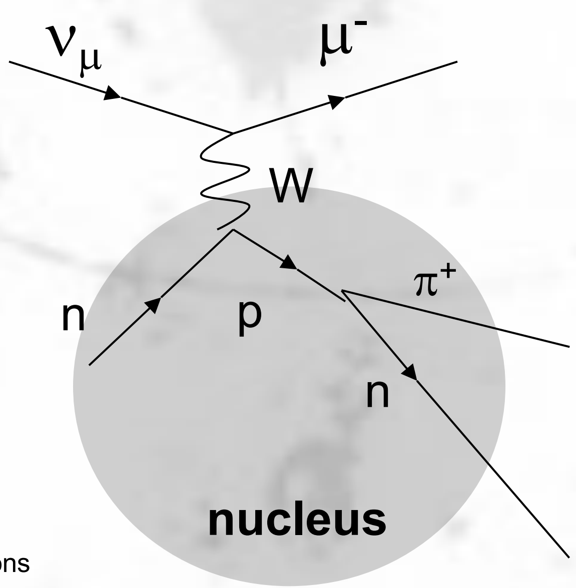


K. Nakamura @ NuFact 2017

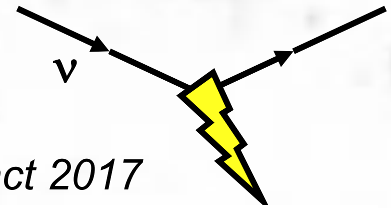
Necessary: Final States

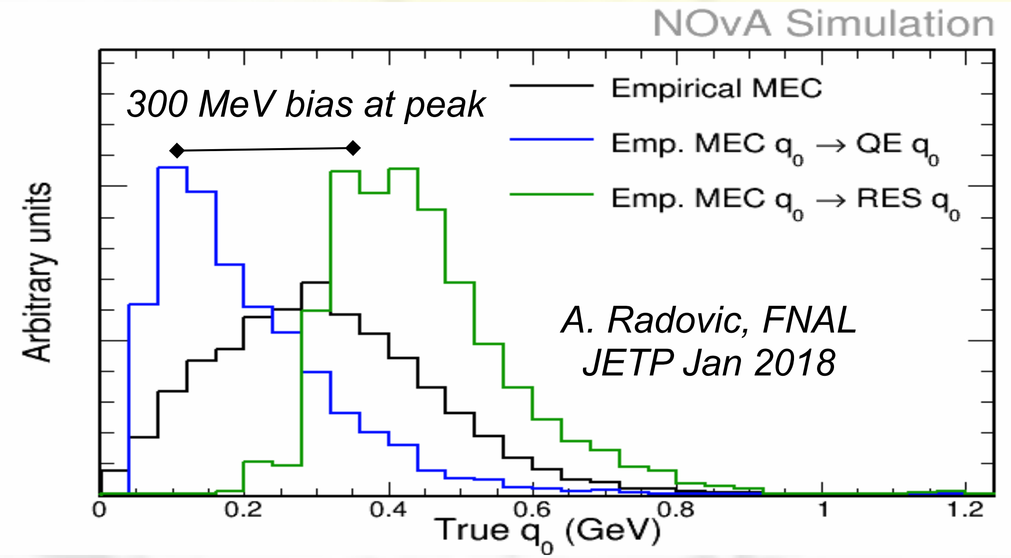


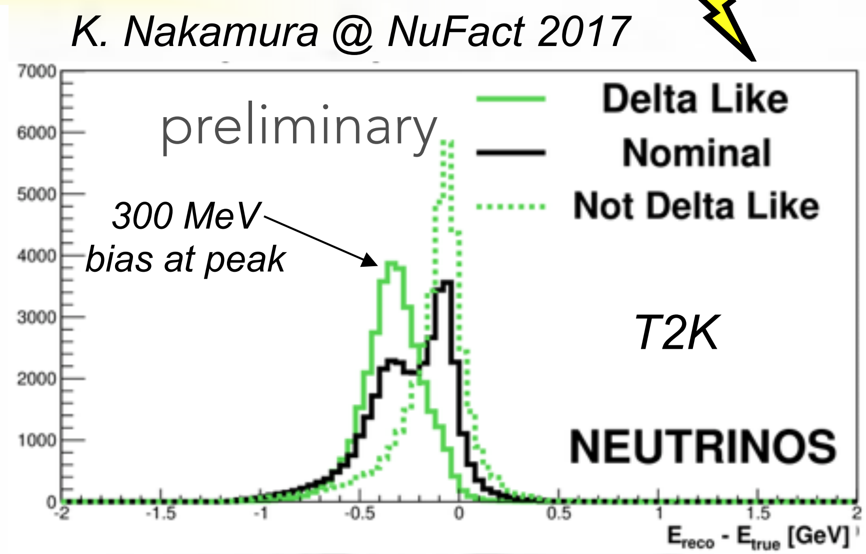
- Neutrino event selection is rarely inclusive
  - T2K selects events without visible pions in the final state, and that veto is nearly 100% efficient for π^0.
  - NOvA requires lepton energies large enough to identify muons and electrons efficiently among hadrons.
- Final state also affects energy reconstruction in some detectors (scintillator, LAr)
  - Response to neutrons is not the same as to protons is not the same as to $\pi^{\pm}$ is not the same as to π^0…
- Now consider modification of the final state in the nucleus.
- This must be understood.



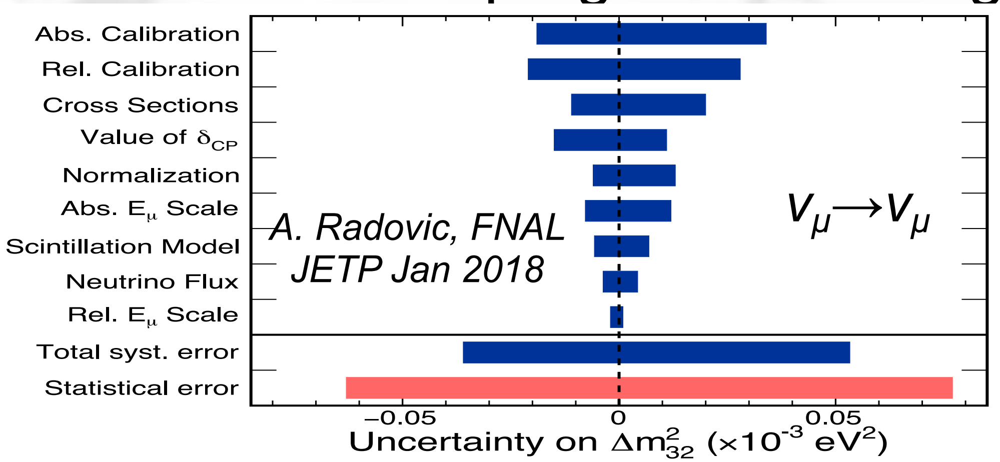
NOvA's Uncertainties

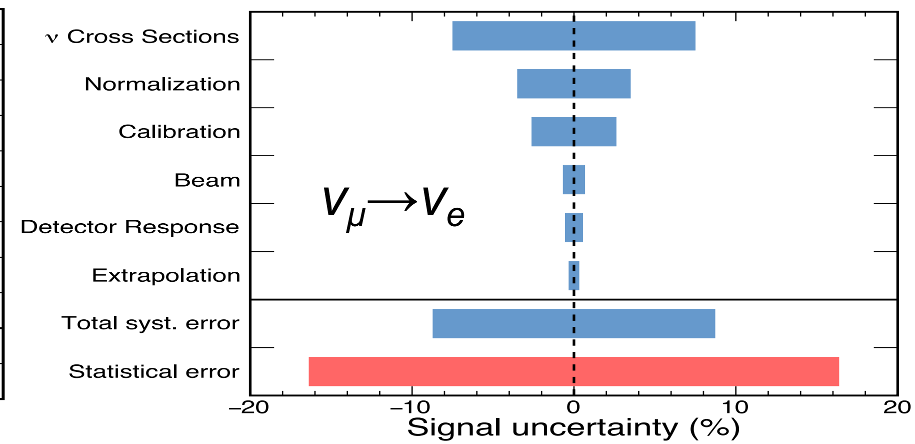






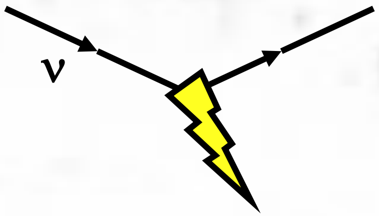
- Multinucleon (2p2h) effect is large even at higher energies
- NOvA needs progress on energy and final state uncertainties





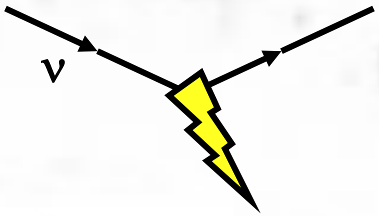
Tools for Progress

Theory of a Failed Multi-Scale Problem



- We have $E_\nu \sim 300 - 5000\ GeV$, $m_\Delta - m_N \sim 250\ MeV$, $E_{\text{Binding}} \sim 30\ MeV$ in ^{12}C
- Nuclear response at these neutrino energies spans elastic, quasielastic and inelastic
- Even the last two cannot be cleanly separated since the effect of binding of nucleons cannot easily be factored from inelastic excitations of nucleons
- Most common approach is to ignore or simplify multibody nuclear dynamics.
  - *Exact prediction of nuclear response becomes akin to system at the right if energy required to uncouple springs is comparable to energy required to break them.*

Tools: Theory



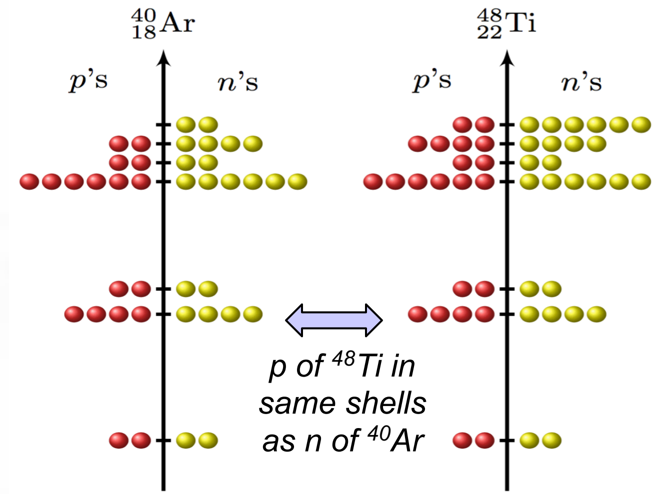
- Arguably our most important tool, my comments about the difficulties not withstanding.
- However, we don't have reliable theory on nuclei over the full range of targets, kinematics and final states relevant for oscillation experiments.
- And consequently, framework for interpretation of data is incomplete. The results of incorporating new neutrino data are not always predictive.
  - Often one learns about failings of the model.

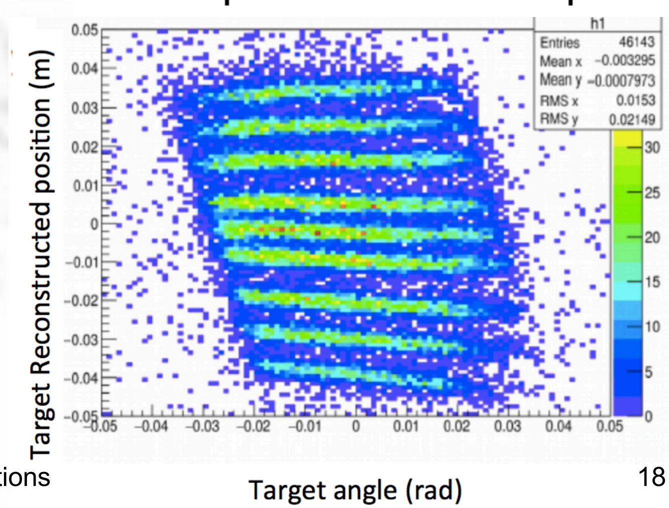
Tools: Electron Scattering

- There is a wealth of information available from electron/muon scattering experiments which cannot be matched with neutrino data.
  - Helpful for common effects, e.g., disappearance of energy into nucleus (spectral function), final state interactions
- But weak CC and EM NC are fundamentally different.
  - o New form factors
  - o Charge change (isospin rotation)
  - o Need theoretical corrections for interpretation and applications.
- New data arriving!

JLAB-E12-14-012

$$e + A \to e' + p + (A-1)$$



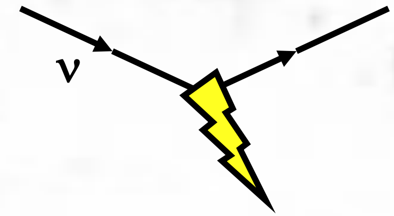


Tools: Neutrino Data

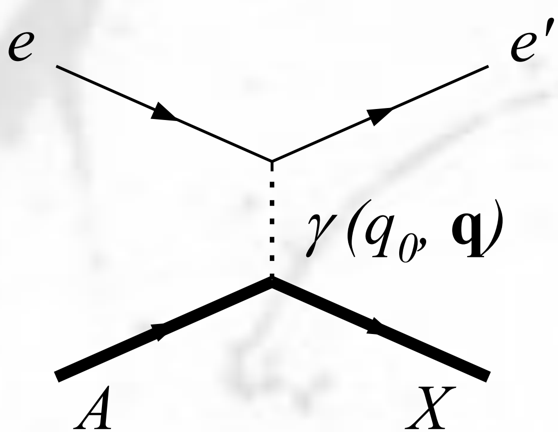
- Neutrino data has access to what we need. Just catalog reactions! But…

- Experimentally **challenging to get a capable detector and high statistics**
  - But many groups are trying!
- Most neutrino sources (not muon decay sources) give us ν_μ, but **also need** $\boldsymbol{\nu_e}$.
  - Theory will get us most of the way, but need to cleanly handle lepton mass dependent terms and reactions in phase space missing for muon neutrinos.

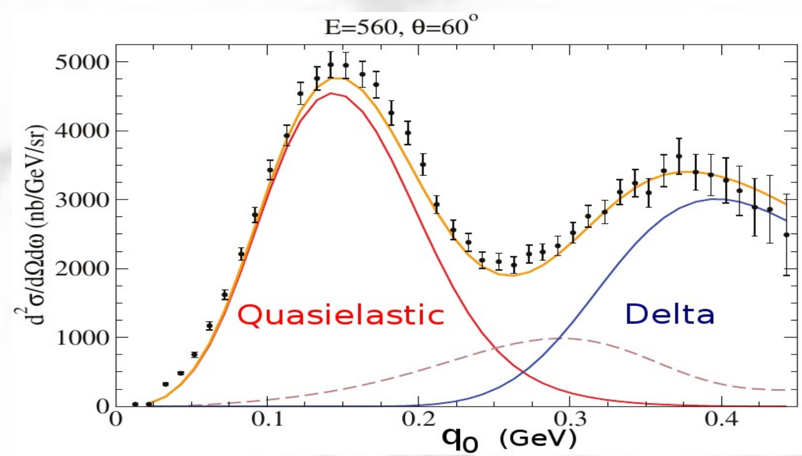
Tools: Neutrino Data



- Biggest limitation is the neutrino beam
  - Flux as a function of energy may not be well constrained, despite *in situ* and *ex situ* work.
  - But even if flux is understood, still **don't have event-by-event neutrino energy**.
  - If we had a tunable, high rate source of monochromatic neutrinos, we would repeat single arm electron scattering experiments and measure nuclear response.

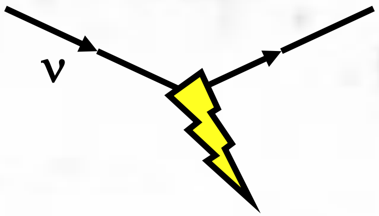


Adapted from G. D. Megias, NuFact 2015

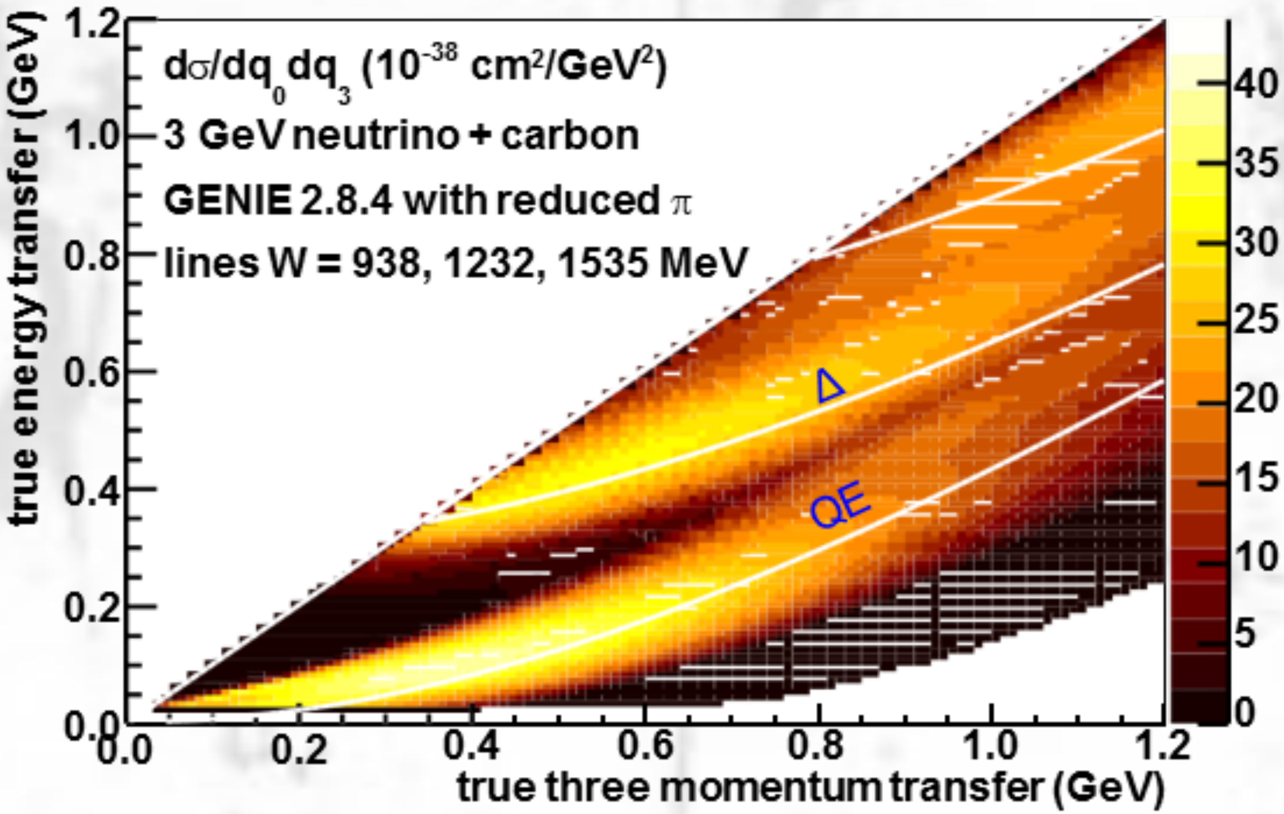


$$q_0 = E_e - E_{e'}$$

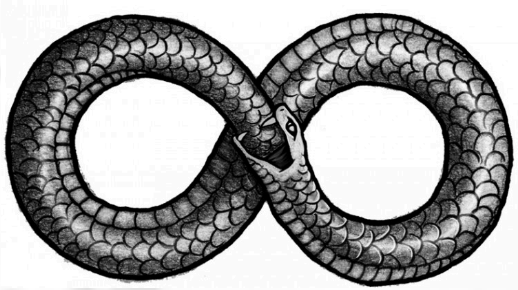
Tools: Neutrino Data



- More precisely, since single arm experiments would be wasteful ☺, we would measure these distributions of energy and momentum transfer.



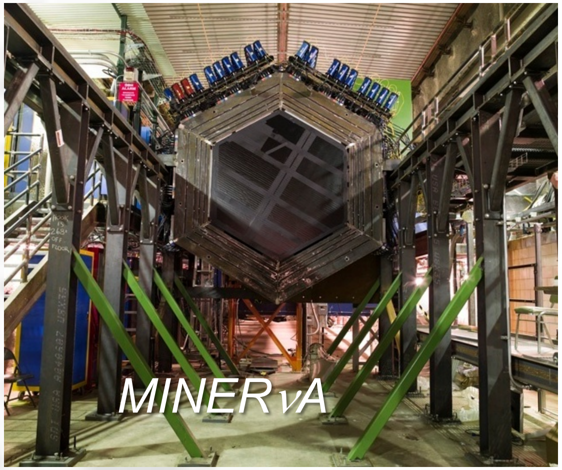
Unfortunately, we cannot do this without reference to the final state of the neutrino interactions to measure neutrino energy.

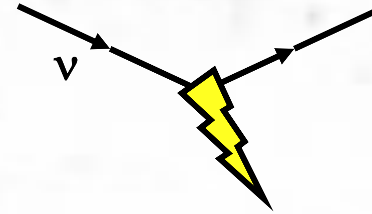


Neutrino Experiments that are Making Progress

Current Experiments

- MINERνA: in NuMI at Fermilab
  - Fine-grained scintillator detector
  - Nuclear targets of He, C, H_2O, Fe, Pb
- T2K 280m Near Detector at J-PARC
  - Fine-grained scintillator, water, and TPC's in a magnetic field
- NOνA near detector: running, early results
  - Segmented Liquid scintillator in off-axis beam
- MicroBooNE: running, early results
  - Liquid Argon TPC in FNAL Booster Beam
  - Some data from ArgoNeuT, a test in NuMI

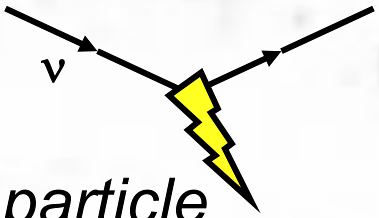



ν


Ask your physician about
OMNEUSCIA
10mg minerboontokiiumnovaephosphate
Daily tablet for understanding
of neutrino interactions
MINERvA. Strengths: established and publishing on high statistics sample. Multiple nuclear targets in same beam. ν-e scattering for flux. Neutron reconstruction. Weakness: wideband w/ flux puzzles. relatively high tracked/IDd particle thresholds (T_p>90 MeV, T_π>50 MeV)
MicroBooNE. Strength: lower particle thresholds (T_p>80 MeV, T_π>35 MeV done, hope for factor of 1.5 lower), excellent PID if particles don't hadronically interact. Weakness: statistics >order of magnitude lower than MINERvA (SBND will be ~MINERvA), cosmic ray backgrounds.
T2K Strengths: established and publishing. Narrow band beam w/ best hadroproduction constraint. Excellent PID for particles making it to gas TPCs. Weaknesses: very low statistics, relatively high tracked & identified particles threshold. π^0 reconstruction problematic.
NOvA Strengths: narrow band beam, albeit with some flux worries, factors of two better statistics than MINERvA, neutron reconstruction?. Weaknesses: higher thresholds than MINERvA, all plastic so containment is not great, "cocktail" not easily compared to other results.

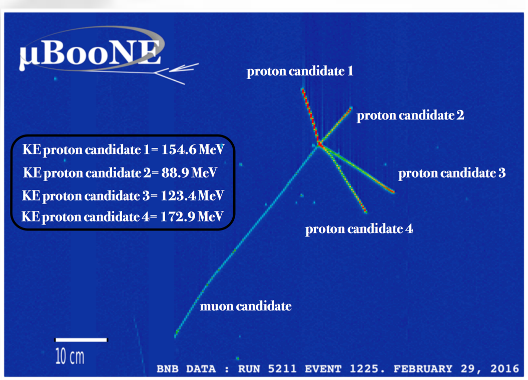
An Illustration: Progress toward low thresholds and lepton selection in Liquid Argon

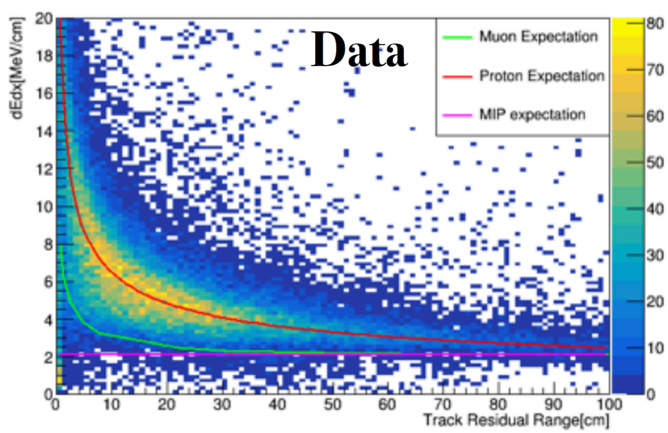
Protons @ MicroBooNE

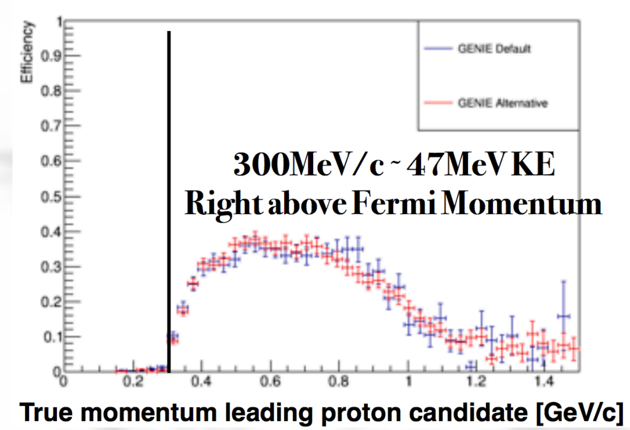


- MicroBooNE is developing its calorimetric tools for particle ID and energy measurement
- First analyses: proton multiplicities and kinematics
- Current threshold for proton reconstruction is 47 MeV proton kinetic energy. Work is on-going to lower the threshold towards the technical limit of ~20 MeV.
- MicroBooNE proton measurements (e.g. 1μ + 2p channel) will provide large statistics measurements of hadronic final states

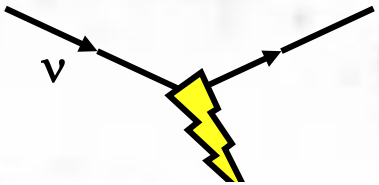
Raquel Castillo Fernandez, NuINT 2018





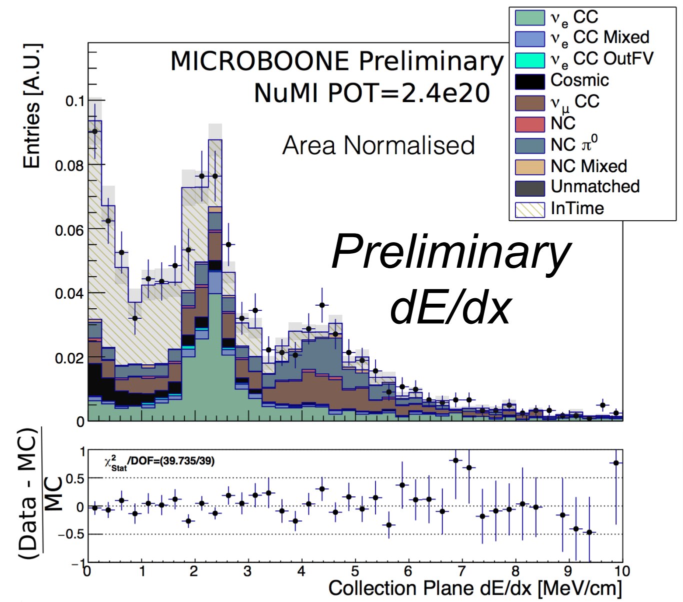


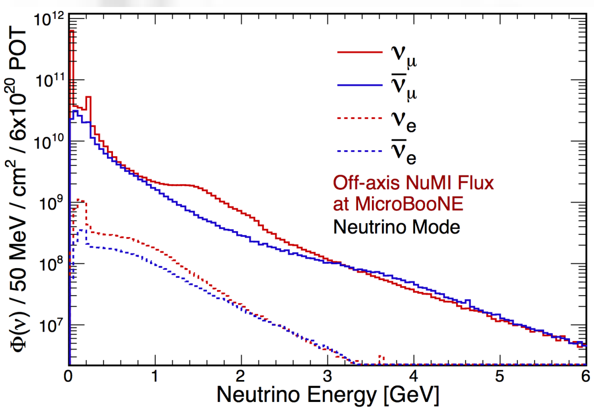
MicroBooNE: Electron neutrinos

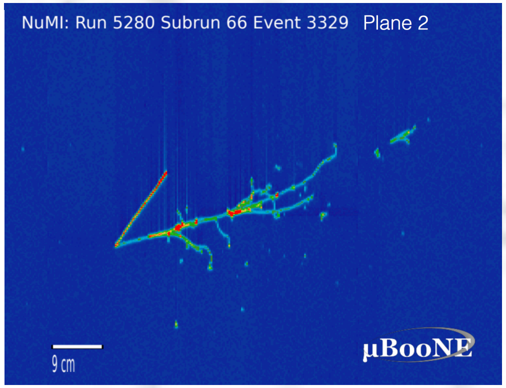


ν_e reconstruction and selection

- *NuMI off-axis flux has large (5%) ν_e contribution to flux, ~640 MeV average energy -> unique opportunities for ν_e cross section measurements:*
    - *Can identify electrons by dE/dx*
    - *Selection purity currently at 40%*







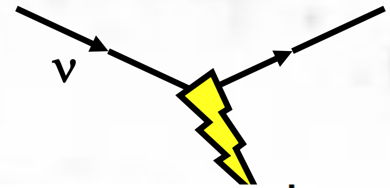
Colton Hill, NuINT 2018

- *Flux-integrated NuMI ν_e -Argon cross section measurement in preparation*
- *Transfering ν_e reconsruction and selection technologies to MicroBooNE low-energy excess analysis, SBN and DUNE*

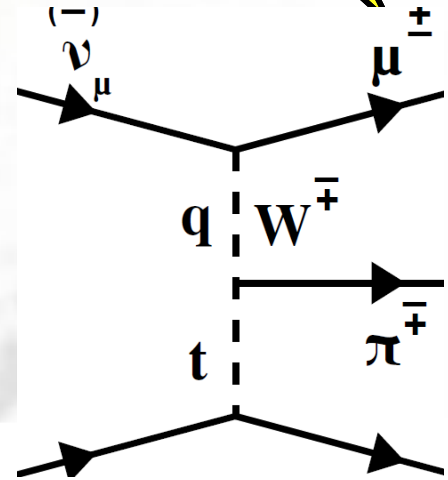
Some Highlights of Progress

Coherent Pion Production

A Very Strange Reaction…



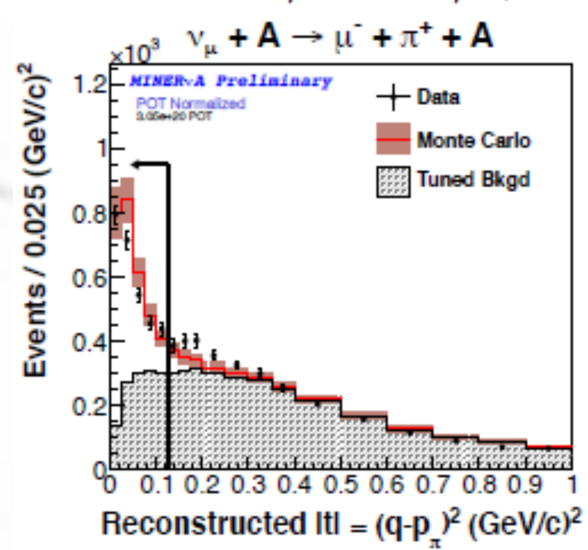
- Despite small binding energy of nucleus (few-10s MeV), a pion can be created from the off-shell W boson and leave the nucleus in its ground state
- Reaction has small 4-momentum transfer, t, to nucleus
- Can reconstruct |t| from final state
- Reconstruction of |t| gives a model-independent separation of coherent signal and background
  - Tune background at high |t|
  - Measure signal
- MINERvA, T2K and ArgoNeuT have all measured this in charged current.



$$E_\nu = E_\mu + E_\pi$$

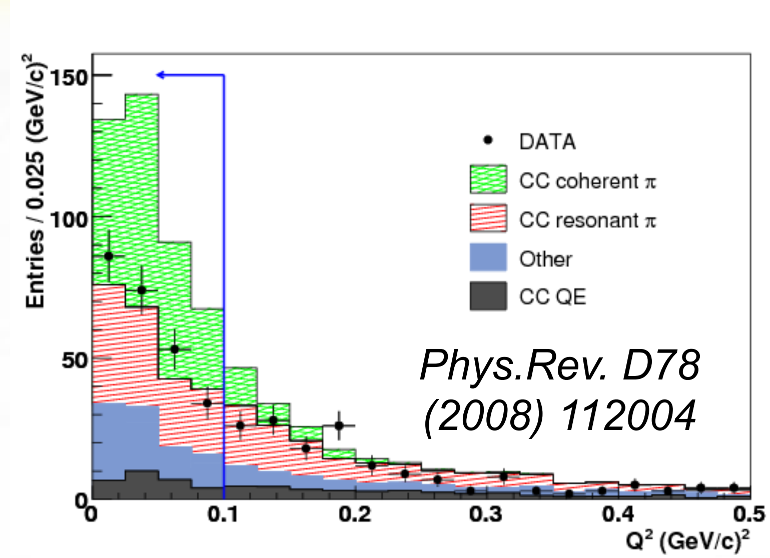
$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

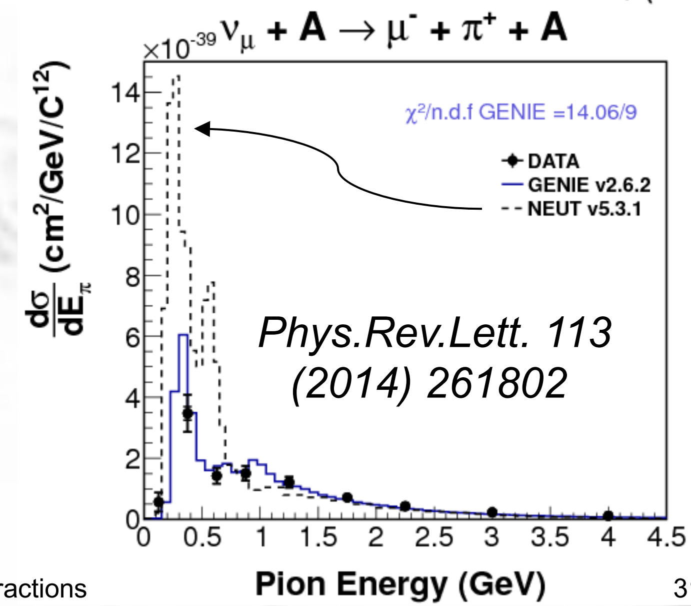
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$



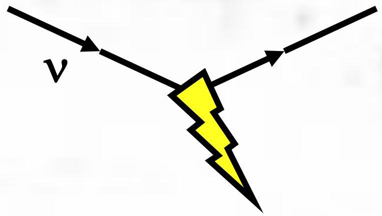
With a strange past…

- The SciBooNE experiment with a beam energy ~1 GeV didn't see this reaction at the expected level
  - This reaction has a special role in backgrounds for oscillations
  - It mimics "clean" single lepton events if pion is misreconstructed as a lepton and reaction is common.
- MINERvA showed that the expectation of the signal model was too generous at low energy.

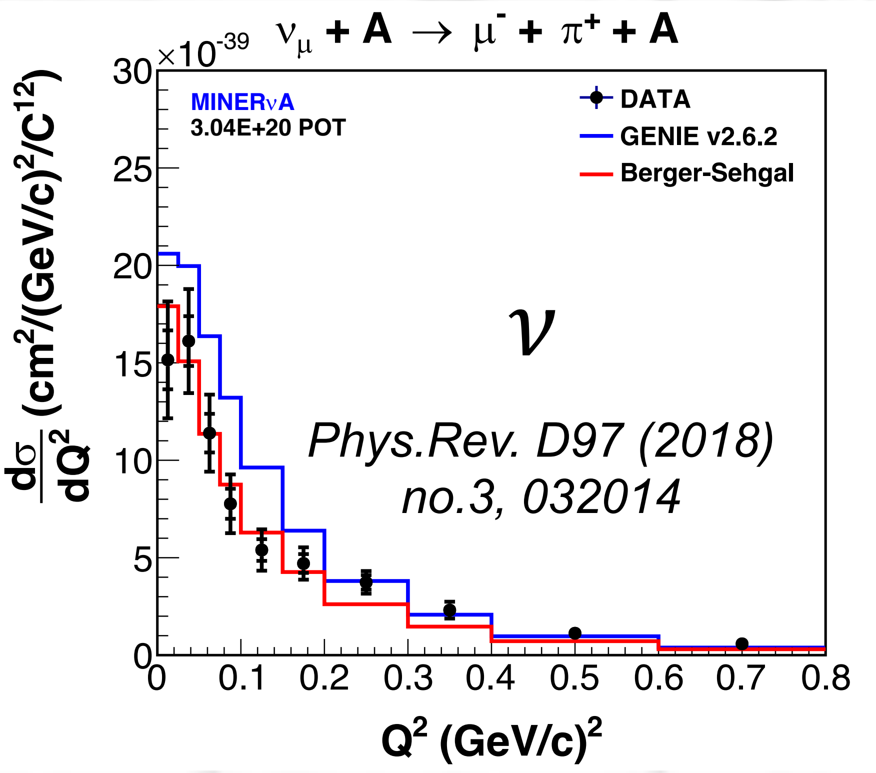


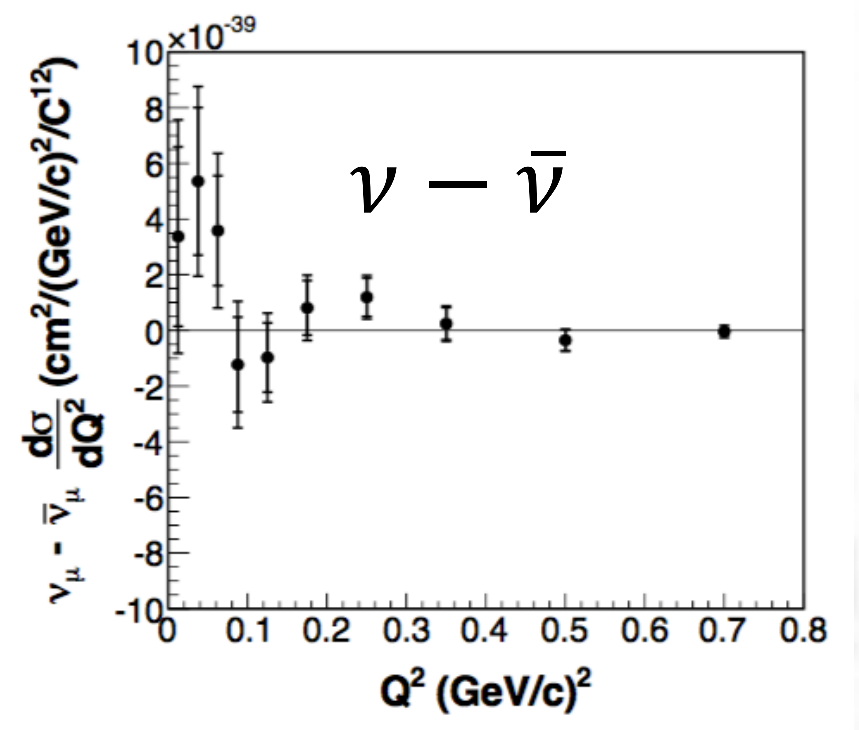


Comparison of Neutrinos and Antineutrinos, and $d\sigma/dQ^2$

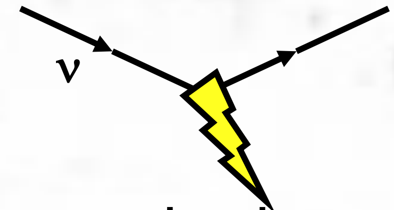


- Updated MINERvA results include $d\sigma/dQ^2$ and a direct check of the consistency of neutrino and antineutrino cross-section to check if process is purely axial vector.

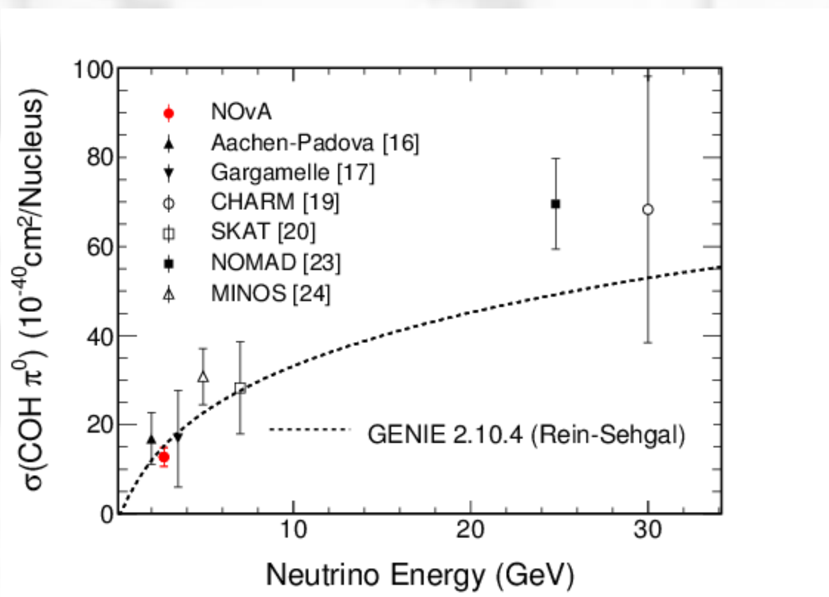


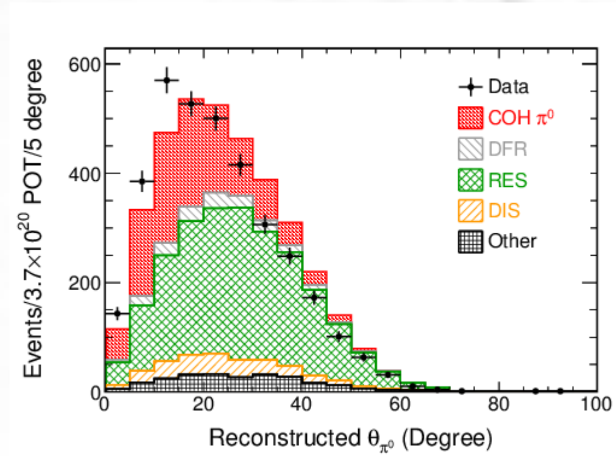


NOvA NC Coherent



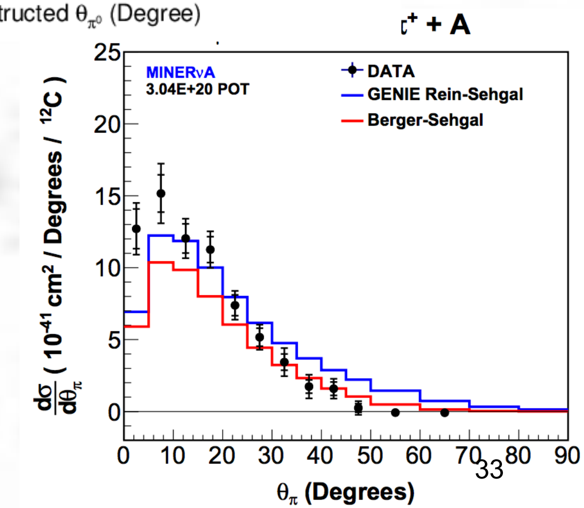
- NOvA has excellent π^0 reconstruction and has searched for this by looking at forward events
- Powerful check of model that works for charged current

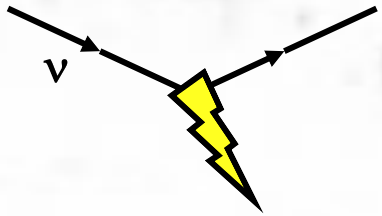




arXiv:1902.005

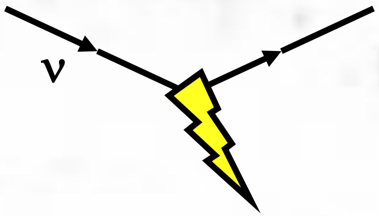
Note that MINERvA sees the similar shift to forward π in charged current!





"Least Inelastic" Pion Spectrum

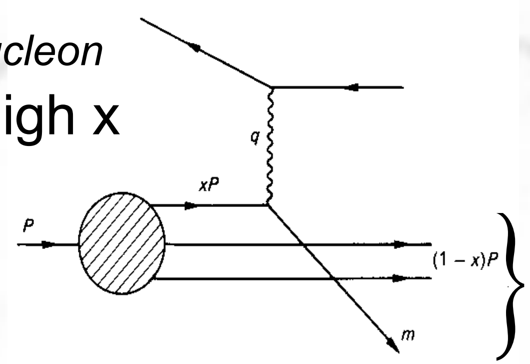
Pion Production by Baryon Resonances



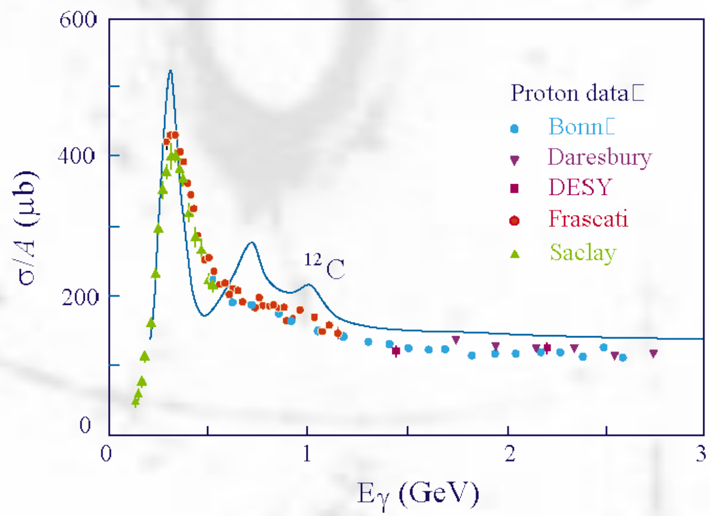
- "Least inelastic" processes are dominated by baryon resonance production
  - Mass² of hadronic final state is given by

$$W^2 = M_T^2 + 2M_T\nu - Q^2 = M_T^2 + 2M_T\nu(1-x)$$

  - At low energy, nucleon-pion states dominated by N* and Δ resonances
- Leads to cross-section with significant structure in *W* just above $M_{nucleon}$
  - Low ν, high x

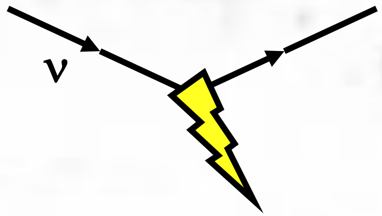


W^2

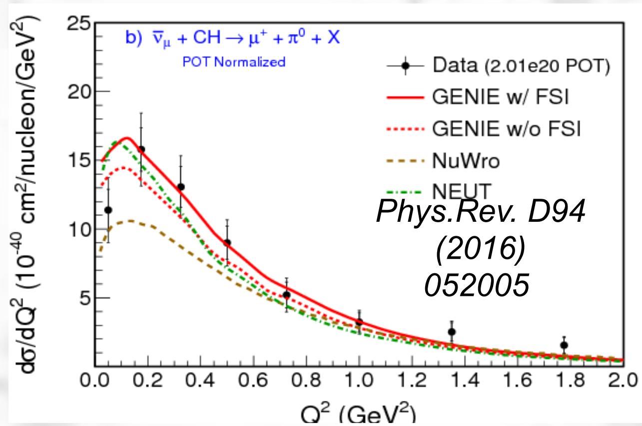


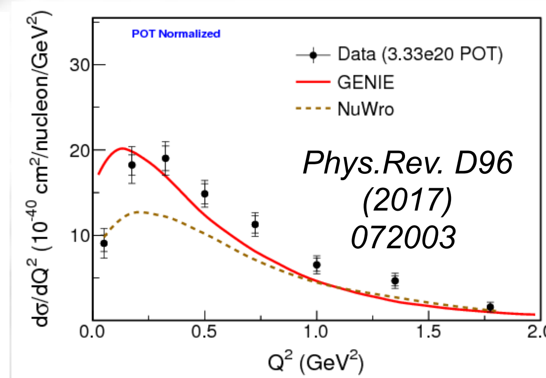
photoabsorption vs Eγ. Line shows protons.

Resonant pion production on Nuclei

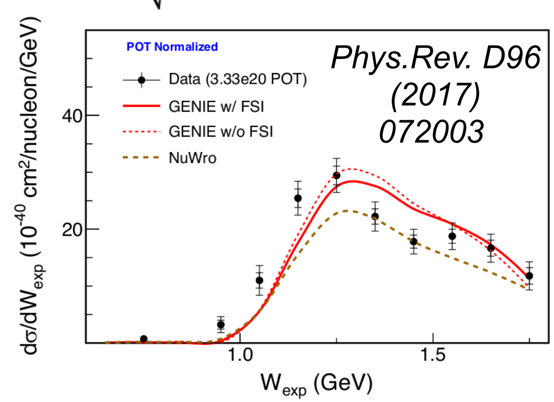


- MINERvA sees a strong deficit of pion production at low Q^2 in several channels.
  - MINOS has also seen a low Q^2 suppression in "resonance region".
- MINERvA also sees a shift in the pion spectra to slightly lower values, which look to be consistent with a shift in the Δ(1232) peak.
  - Maybe resonant-non resonant interference that is absent from model?

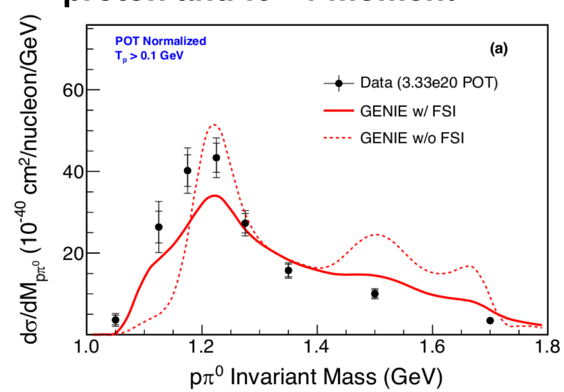




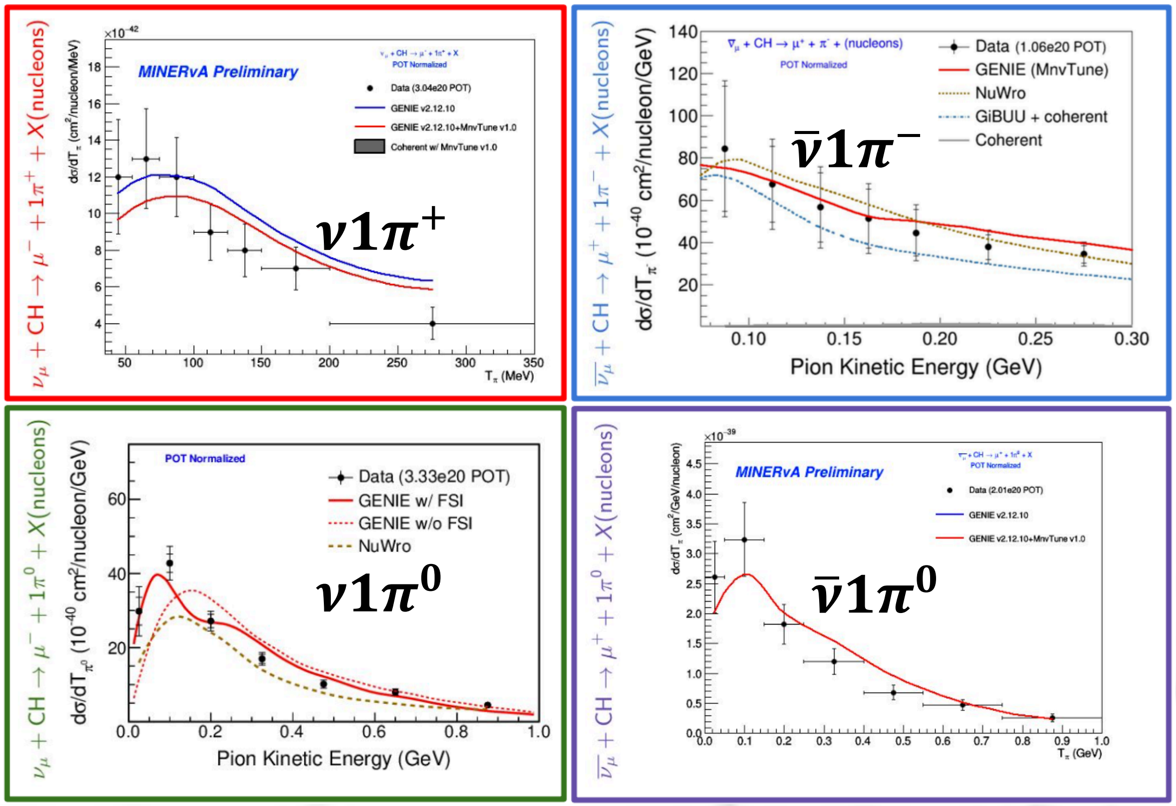
$$W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$$



Invariant Mass calculated with proton and π^0 4-momenta



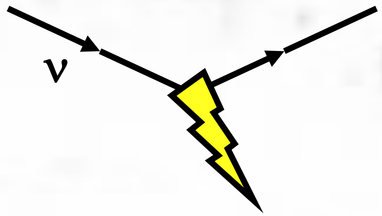
MINERvA's Four Charged-Current Single Pion Channels: T_π



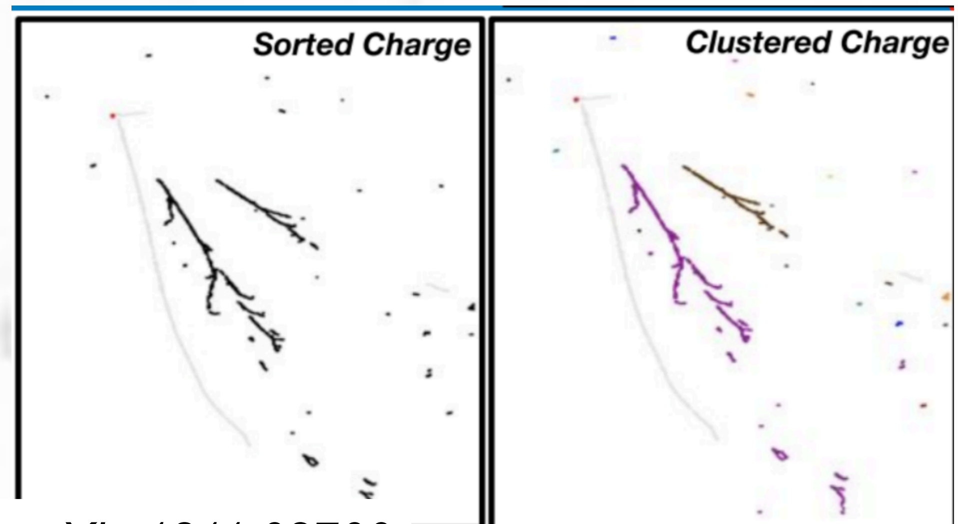
Pion Kinetic Energy (GeV)

- Generally adequate description from MINERvA tuned GENIE 2.12.x
- Some tendency for more strength at lower energies
- Maybe consistent with shift of Δ? Maybe consistent with FSI alteration?

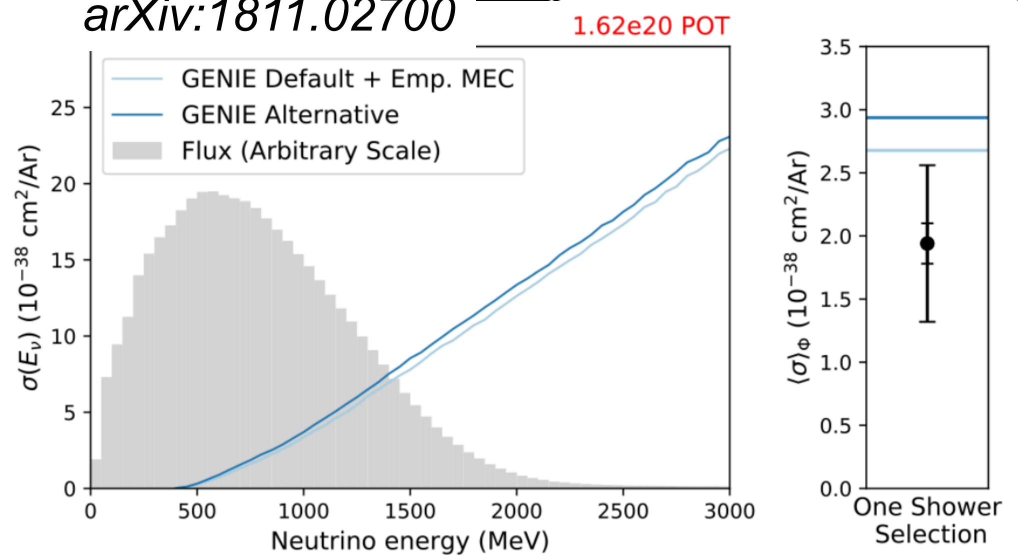
MicroBooNE First Results



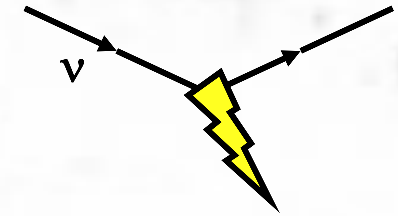
- ν_μ **CC** π^0
  - *First exercise of shower reconstruction in MicroBooNE*
  - *Use image recognition for track and shower reconstruction.*
  - *Semi-inclusive integrated cross-section consistent with GENIE's A-scaling.*



arXiv:1811.02700

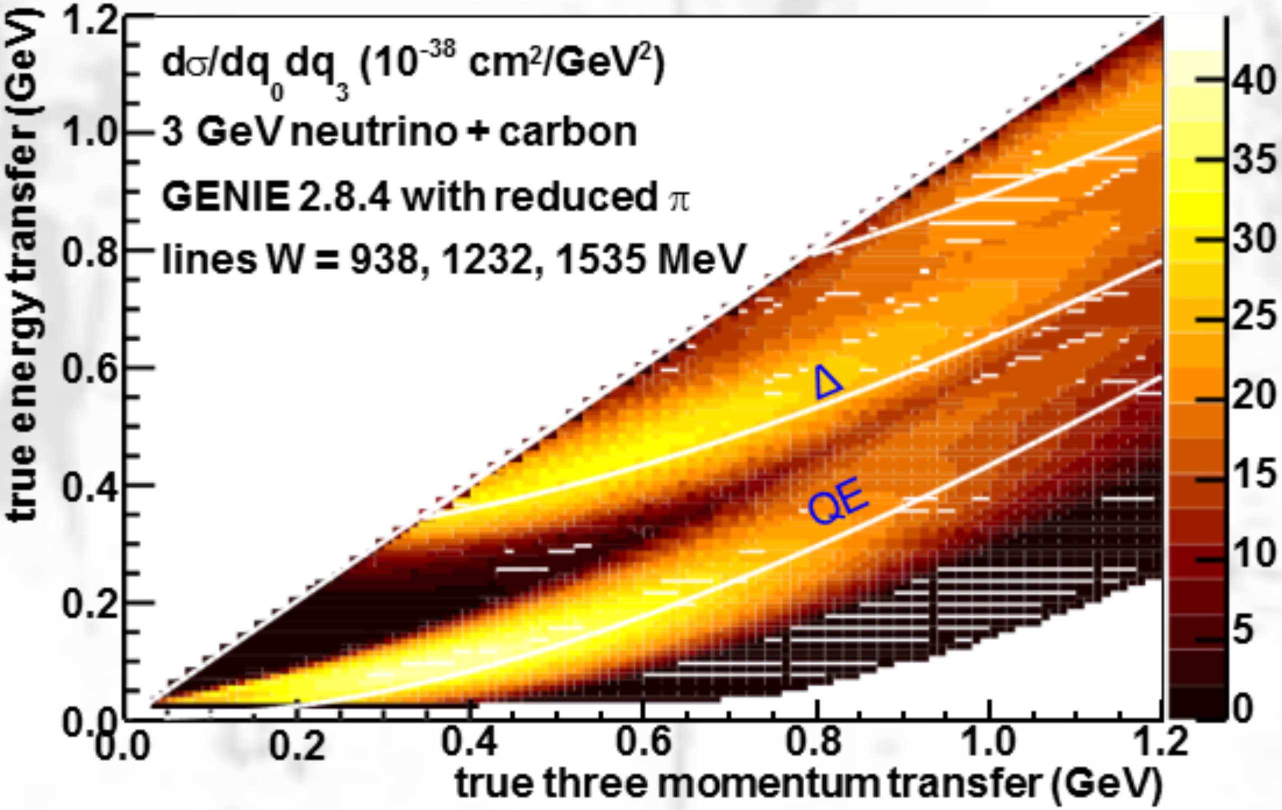


Progress Towards a Descriptive CC0π Model

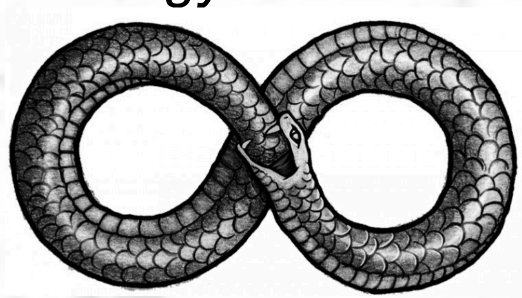


Recall… energy

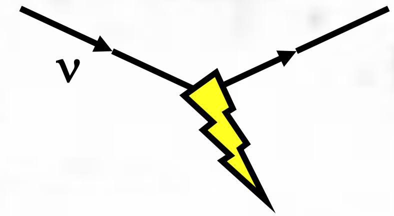
- More precisely, since single arm experiments would be wasteful ☺, we would measure these distributions of energy and momentum transfer.



Unfortunately, we cannot do this without reference to the final state of the neutrino interactions to measure neutrino energy.



If we can't measure energy…



- Must determine neutrino energy from the final state energy.
- If that is known,
  - Neutrino direction fixed
  - Outgoing lepton is well measured.
- *MINERvA's approach is to use calorimetry for all but the final state lepton*
  - *Don't measure energy transfer, q_0, but a related quantity dependent on the details of the final state, "available energy"*

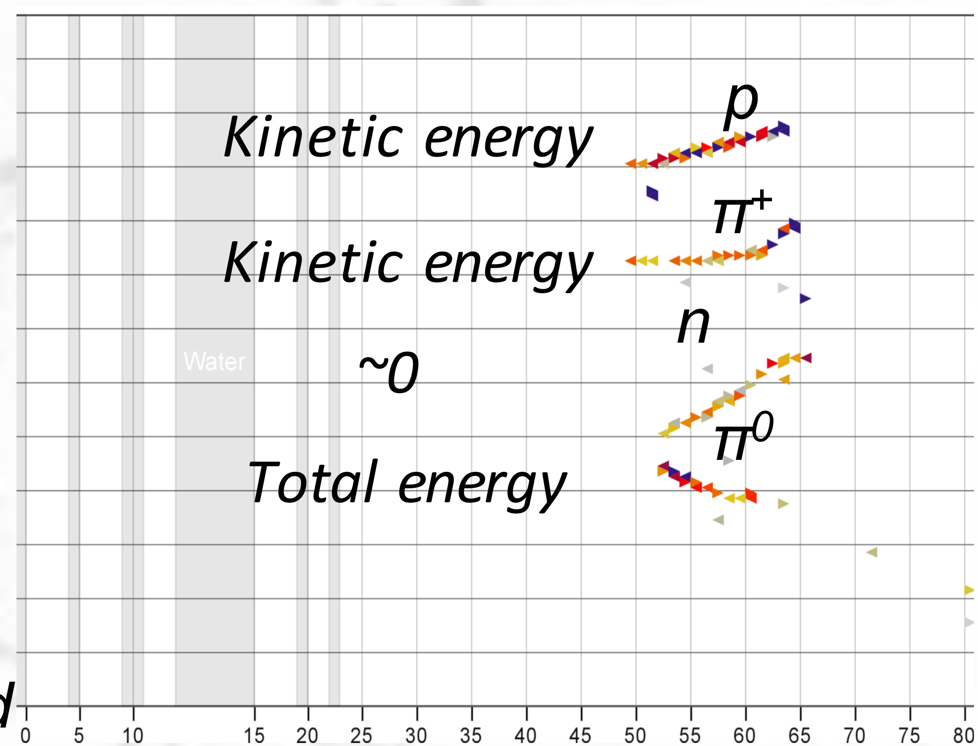
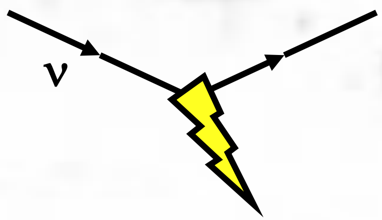
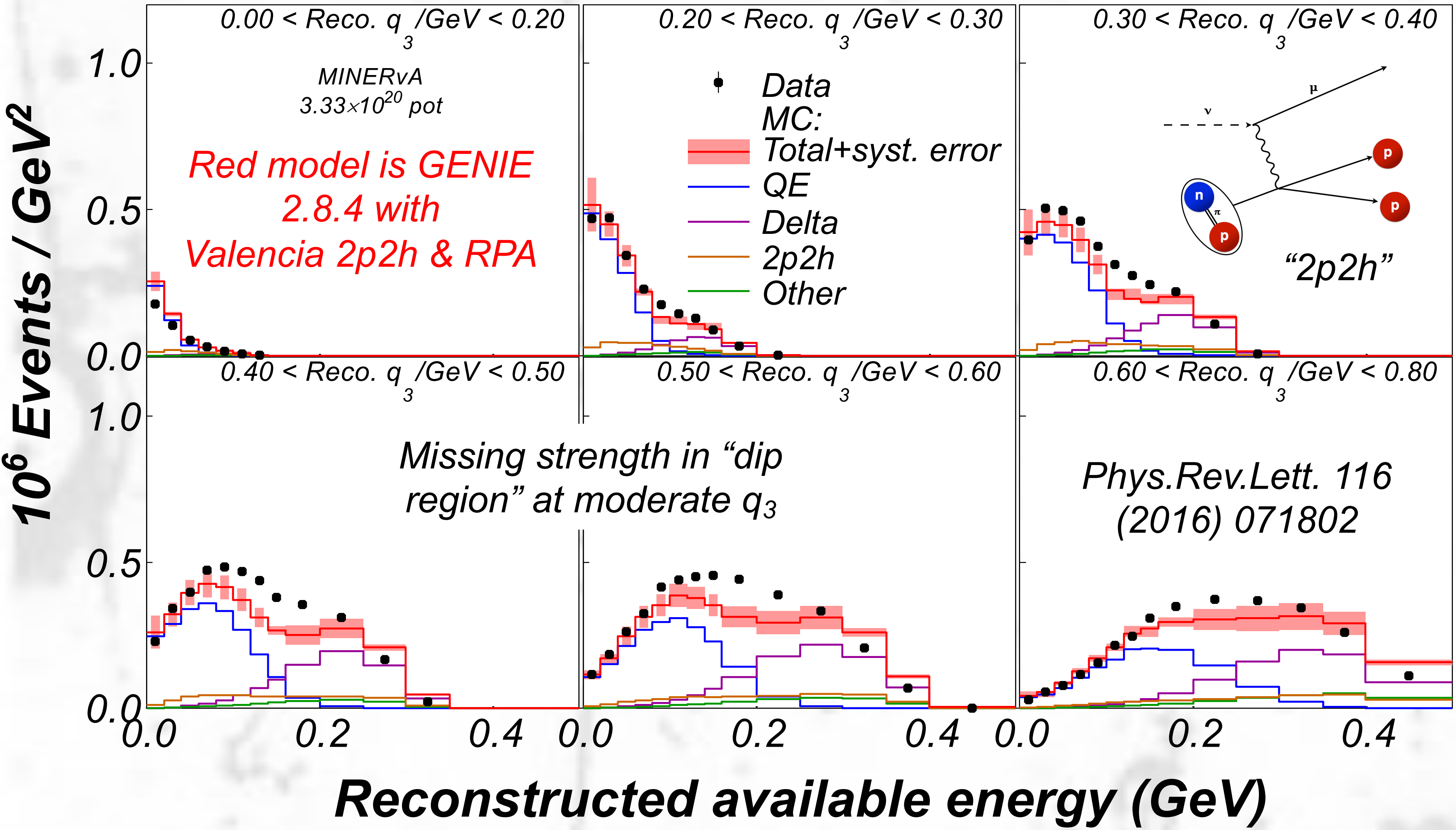


Figure courtesy P. Rodrigues

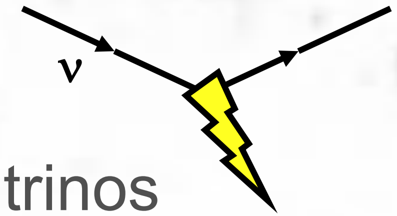
$$E_{avail} \equiv (\text{Proton and } \pi^{\pm}\ KE) + (E \text{ of other particles except neutrons})$$

Data vs. Model (GENIE++)



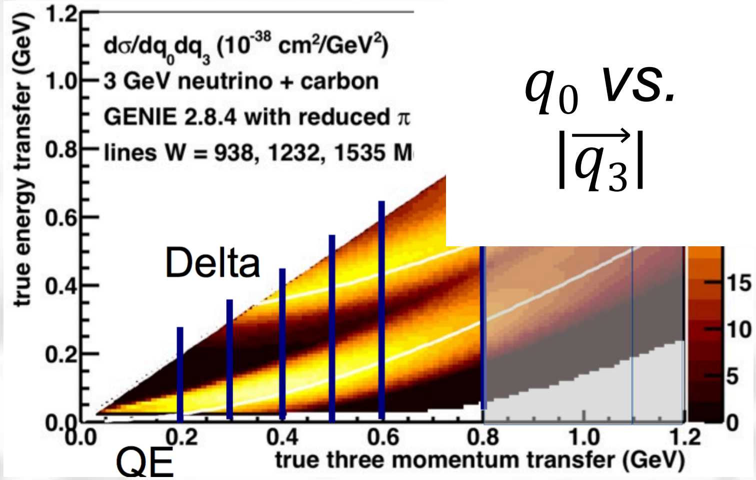


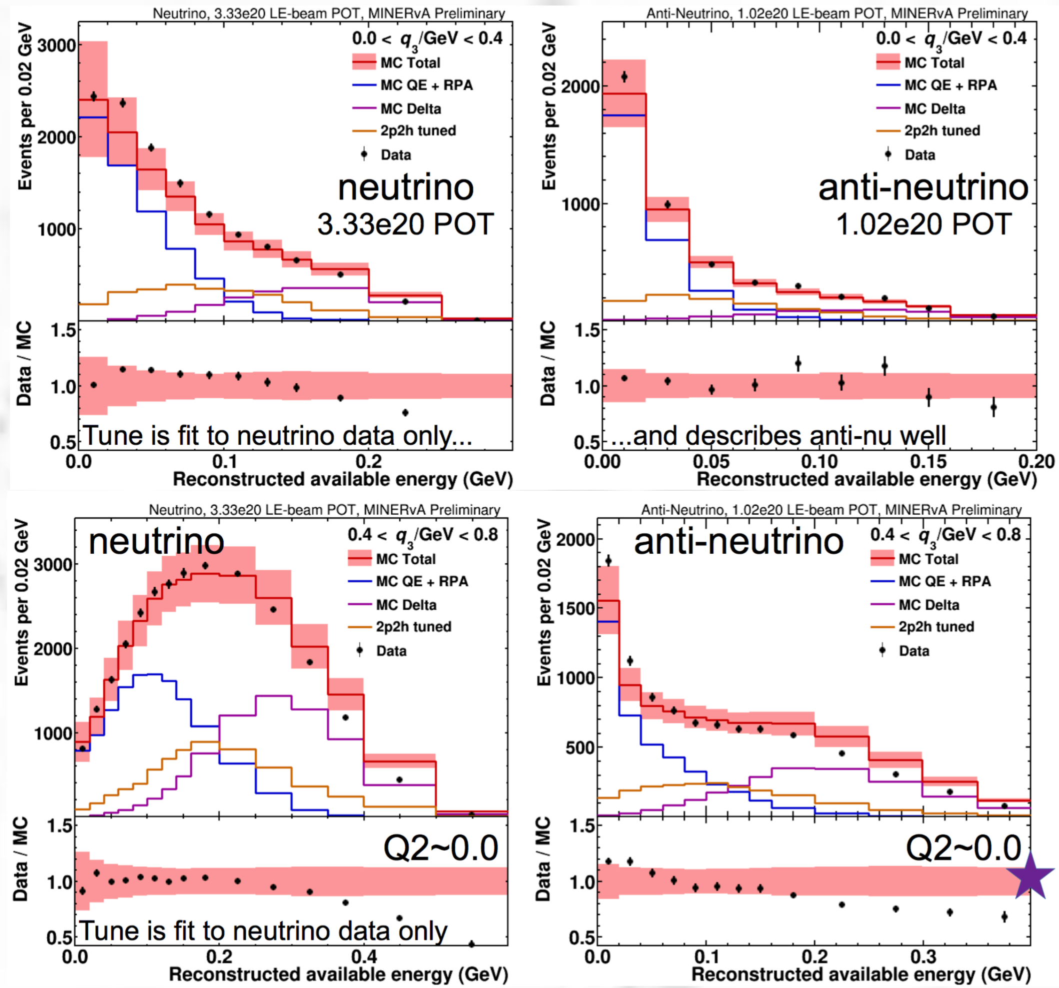
MINERvA ν_μ and anti-ν_μ "low q"



- Low recoil "Inclusive" ν_μ cc interactions in antineutrinos

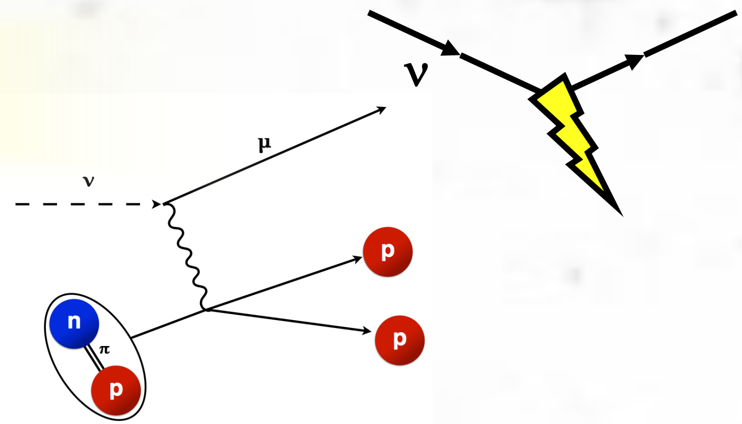
Phys. Rev. Lett. 116, 071802 (2016) and Phys. Rev. Lett. 120, 221805 (2018)



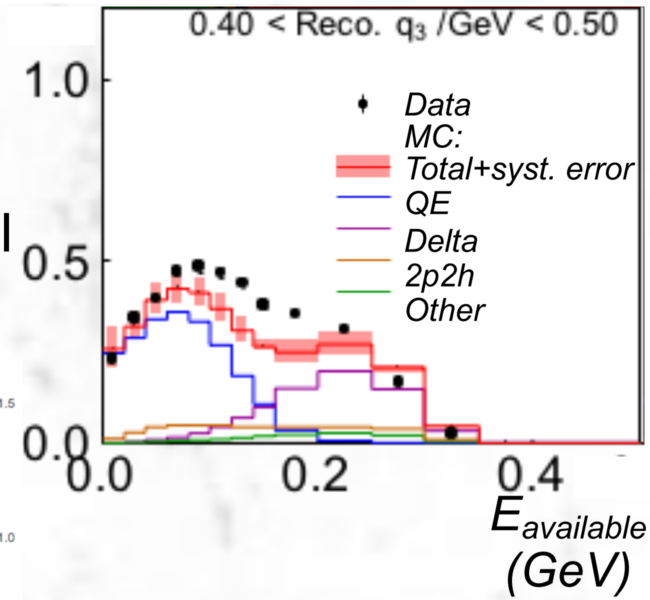


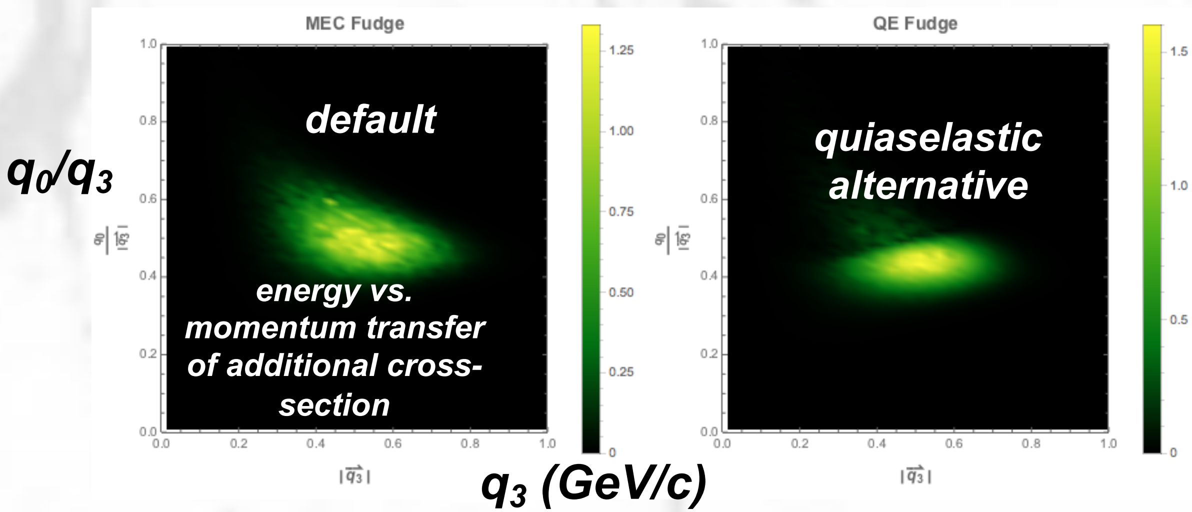
- *Tune model (extra 1p1h or 2p2h) to fill in dip region between QE & Δ.*
- *This tune from neutrino data also agrees with antineutrino data!*

How to fix this?

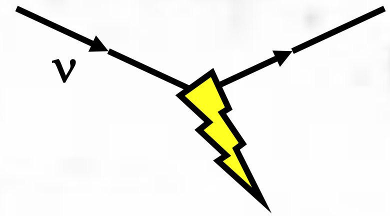


- MINERvA's low recoil data identifies missing strength, but it doesn't identify if $\nu_\mu A(n) \rightarrow \mu^- p A'$ or $\nu_\mu A(nn) \rightarrow \mu^- p n A'$ or $\nu_\mu A(np) \rightarrow \mu^- p p A'$ is the most likely source.
  - Different choices mean different $E_{\mathrm{avail}}(q_0)$.
- Default tune augments ratio of 2p2h nn/np initial state as per Nieves' model of 2p2h.

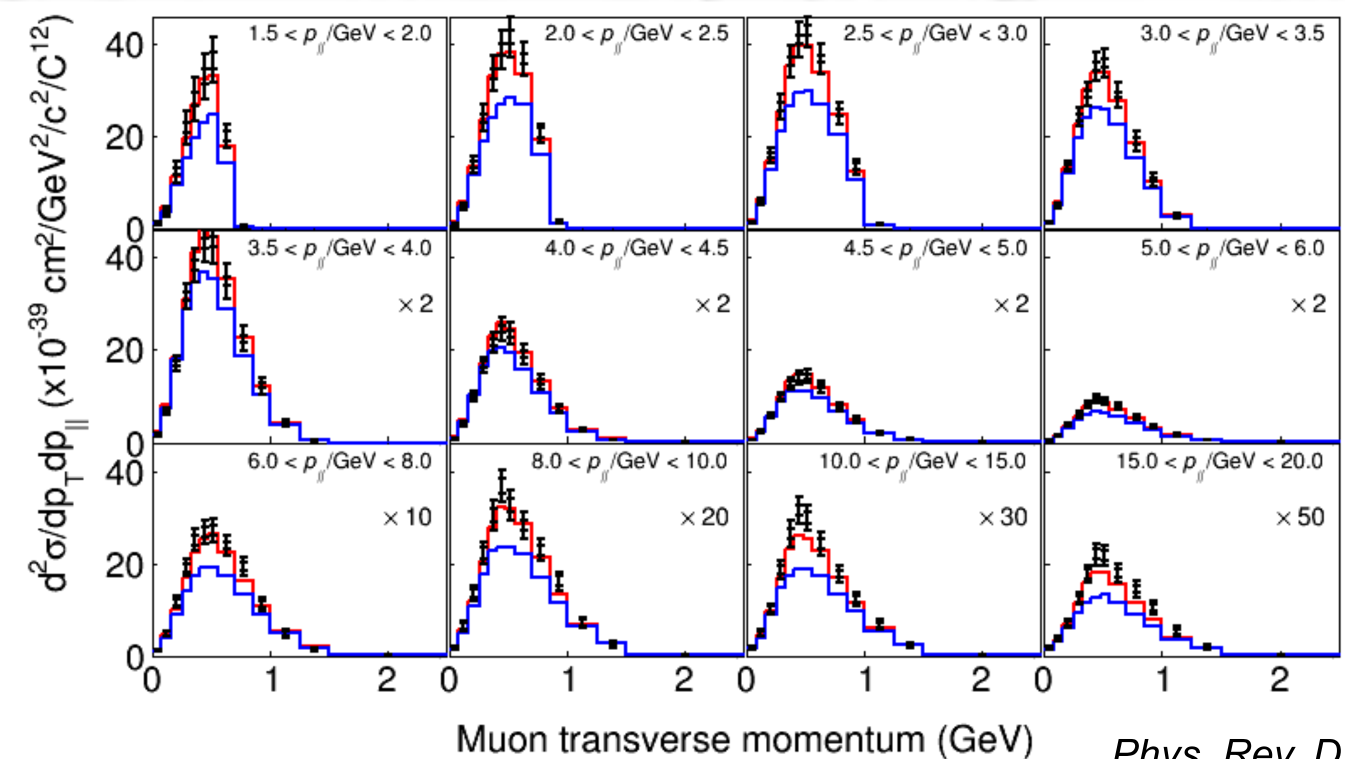




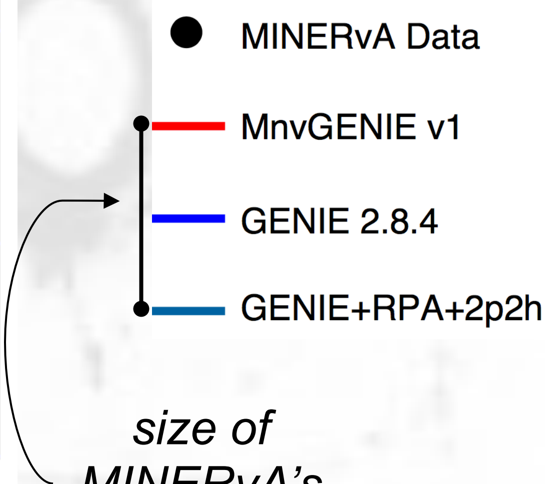
MINERvA ν pionless events (CC0π)



- Tuned vs untuned in an exclusive channel



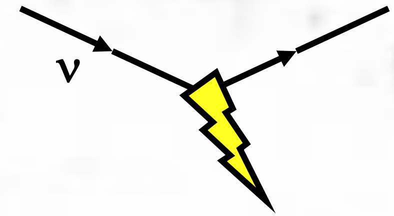
$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T\,dp_\parallel} \quad \boldsymbol{\nu}$$



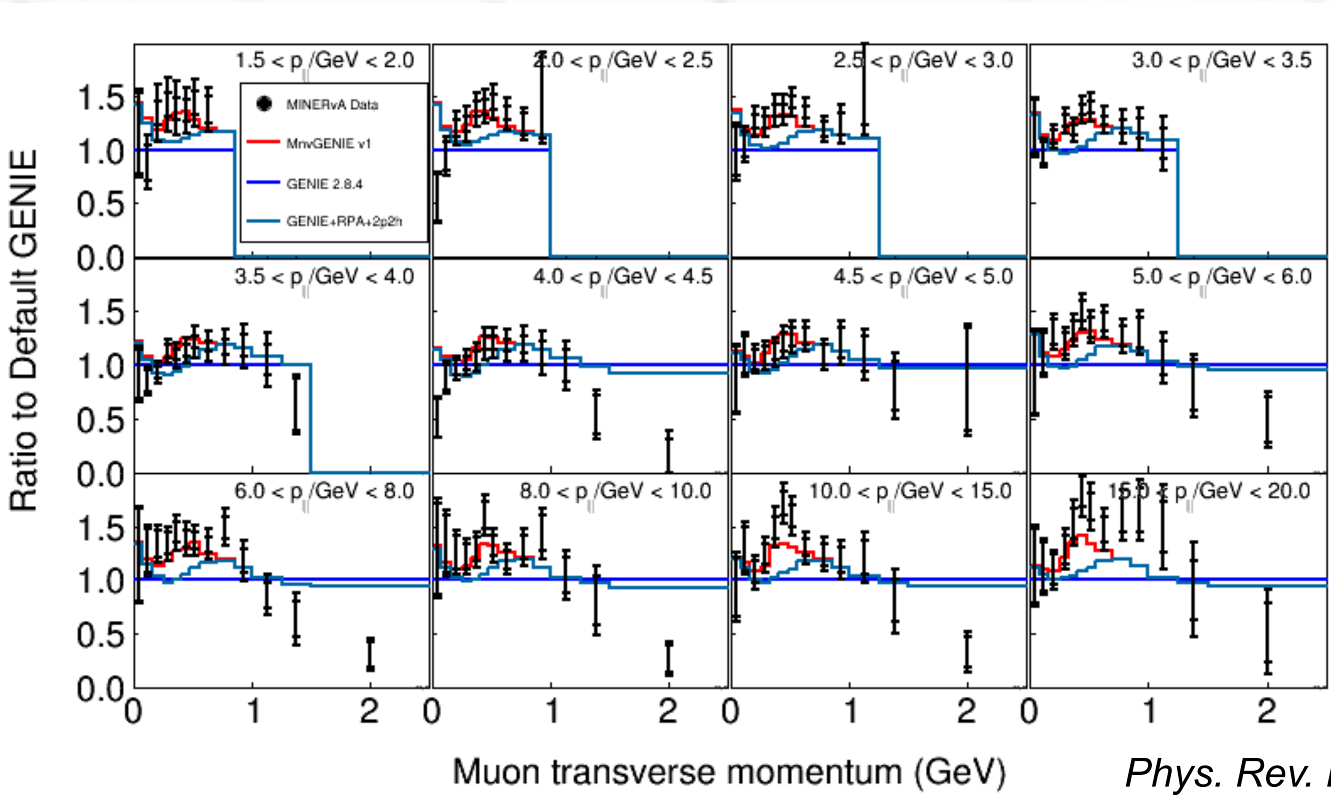
size of MINERvA's tune

Phys. Rev. D99, 012004 (2019)

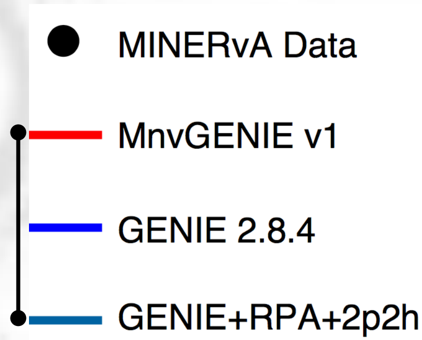
MINERvA ν pionless events (CC0π)



- Tuned vs untuned in an exclusive channel



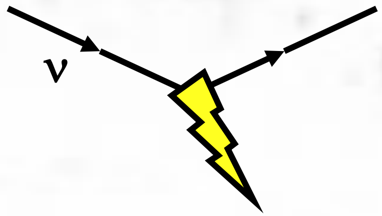
$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T\,dp_{\parallel}} \quad \boldsymbol{\nu}$$



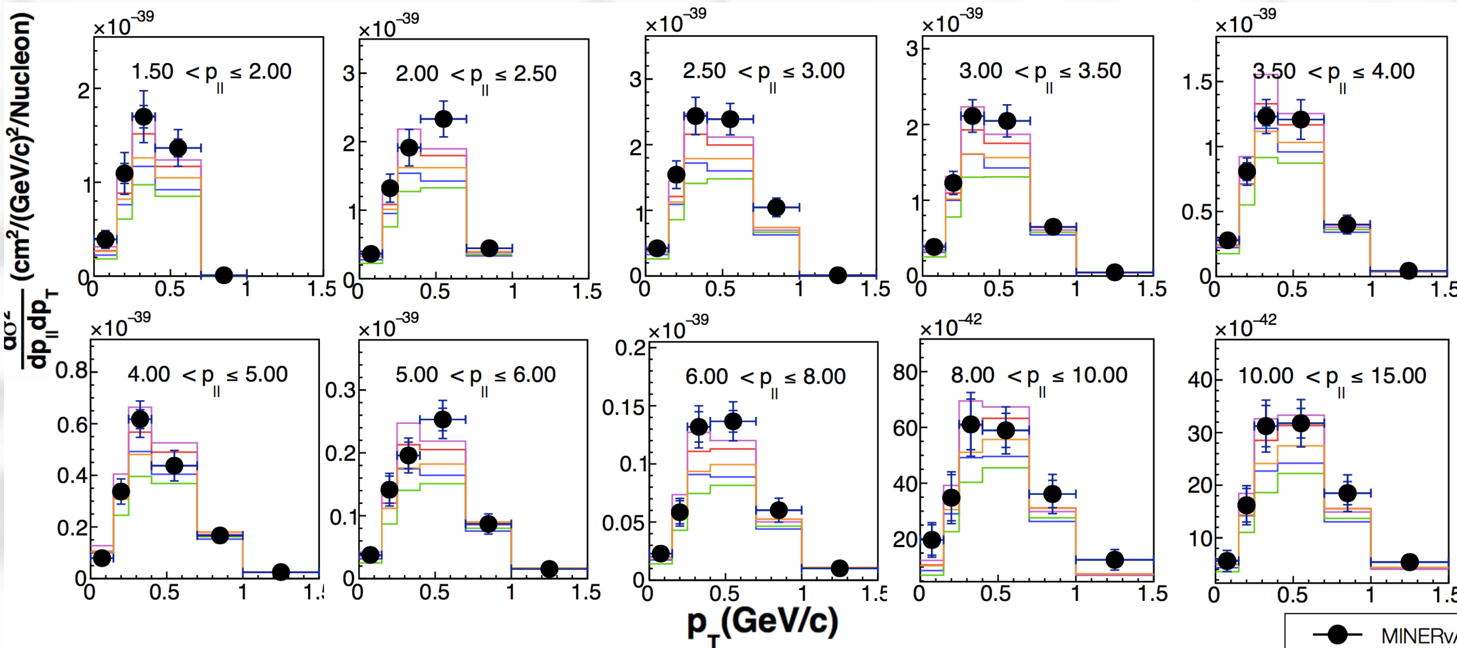
size of MINERvA's tune

Phys. Rev. D99, 012004 (2019)

MINERvA $\bar{\nu}$ pionless events (CC0π)



- Tuned vs untuned in an exclusive channel



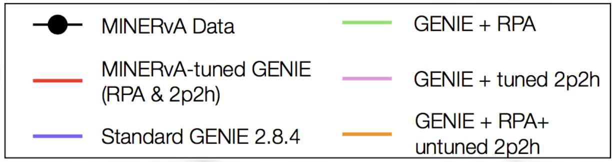
$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T\,dp_{\parallel}}$$

$\bar{\nu}$

MINERvA-tuned GENIE (RPA & 2p2h)

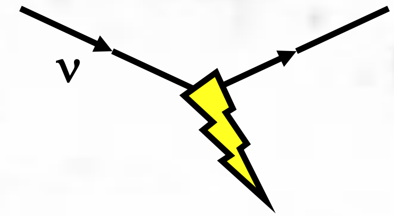
MINERvA's tune

GENIE + RPA+ untuned 2p2h

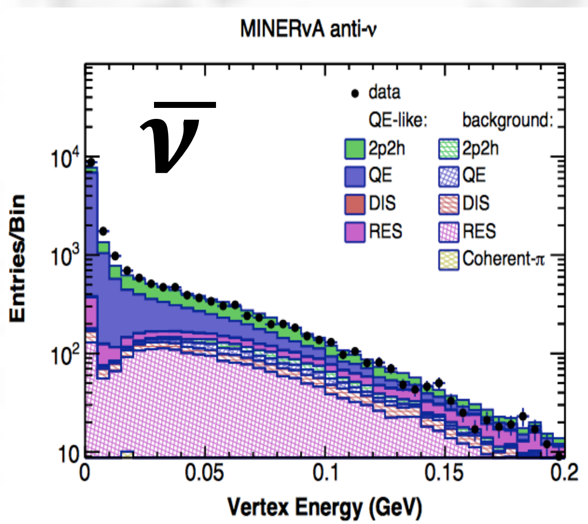


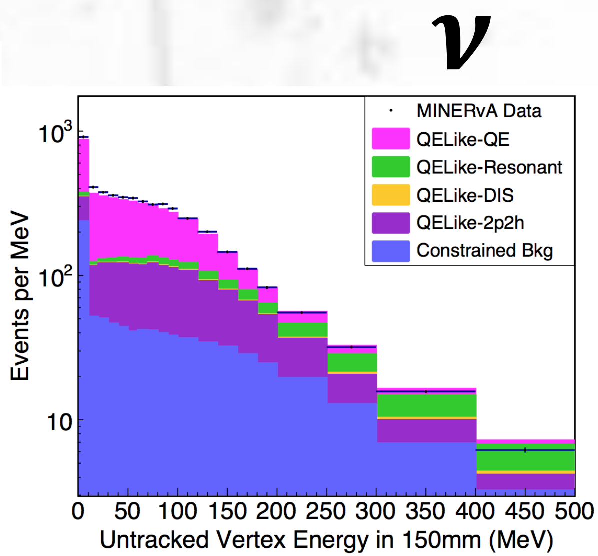
Phys.Rev. D97 052002 (2018)

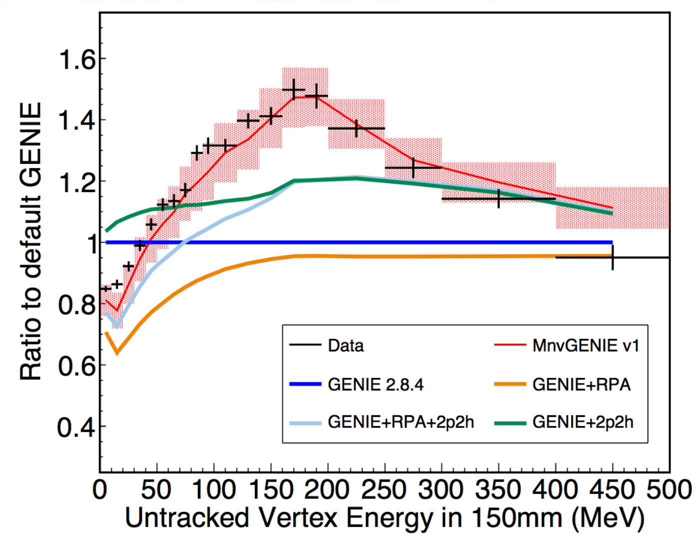
Low energy protons in CC0π events

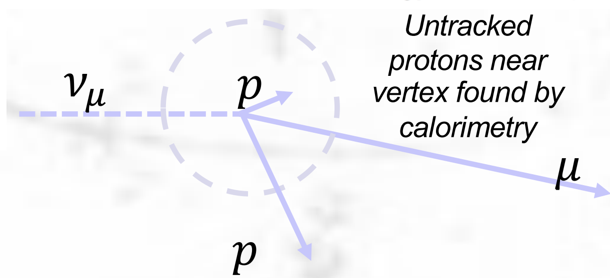


- Does this tune get details right, like energy from protons below tracking threshold ("vertex energy")?



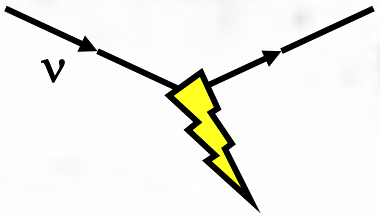


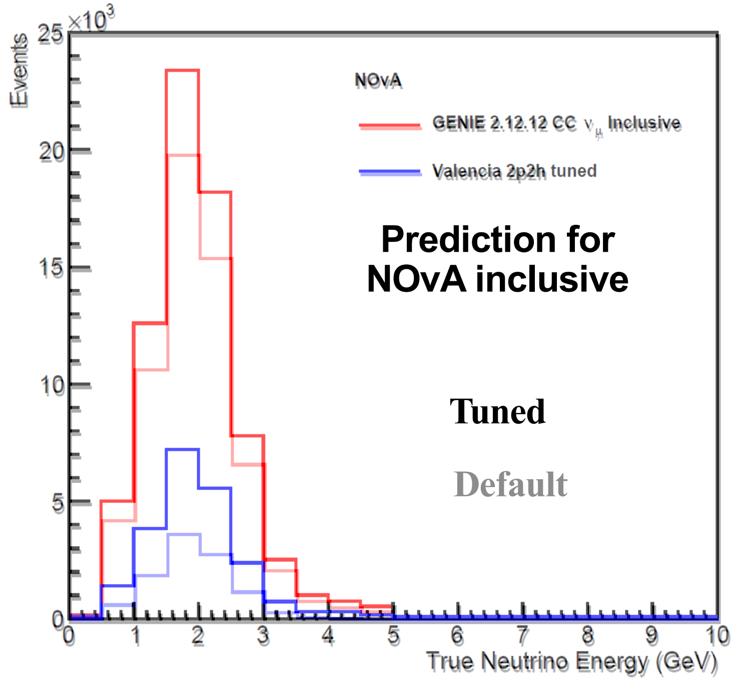


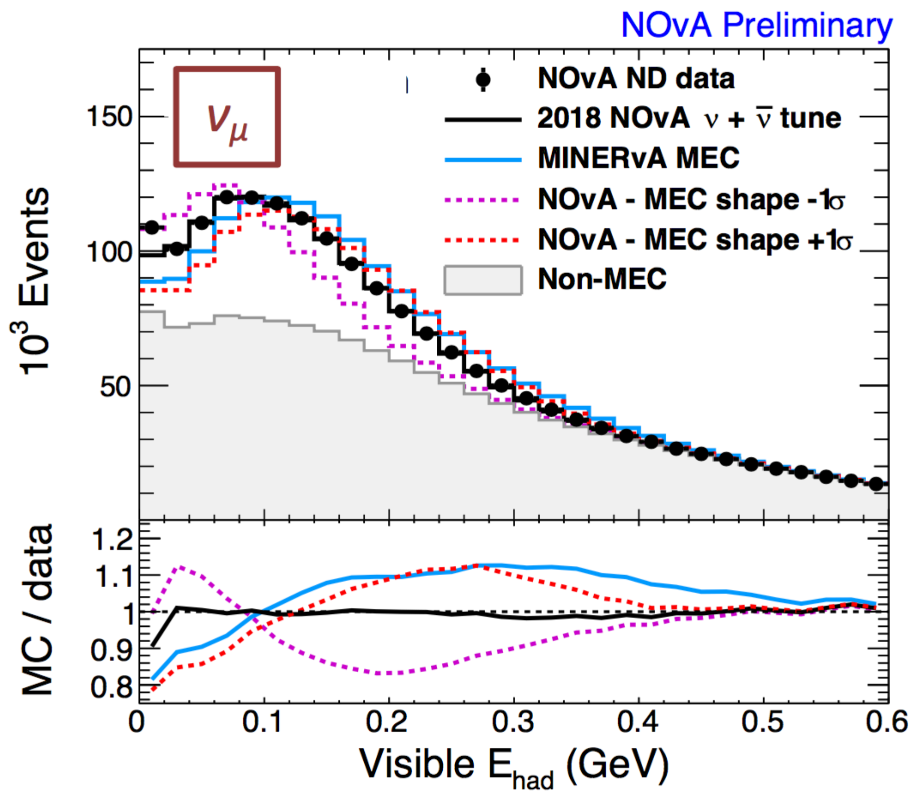


Phys.Rev. D97 (2018), 052002 and Phys. Rev. D99, 012004 (2019)

Implications of this tune for NOvA

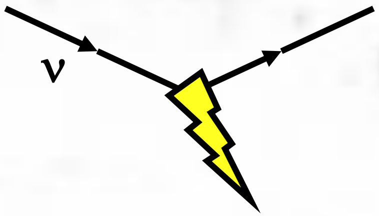






- Beam energy ~ 2 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible change in inclusive energy spectrum at NOvA energy
- NOvA puts in their own, similar, tune.

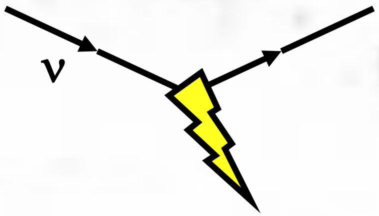
Alex Himmel, JETP Seminar, June 2018



Summary of CC0π Model

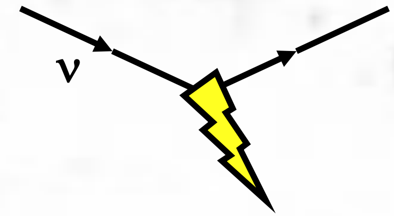
- For these "least inelastic" events, we seem to have found a model which explains
  - Lepton energy distributions over MINERvA flux
  - Details of proton (visible) recoil
  - Neutrino and antineutrino

- "Model" is tuned to inclusive data which suggest an additional 2p2h (and/or some "regular" 1p1h) at moderate, ~0.4 GeV, three-momentum transfer
- Not theoretically motivated (=magic?), but identifies particular energy-momentum transfer.
- Can it be applied to T2K, MicroBooNE energies?



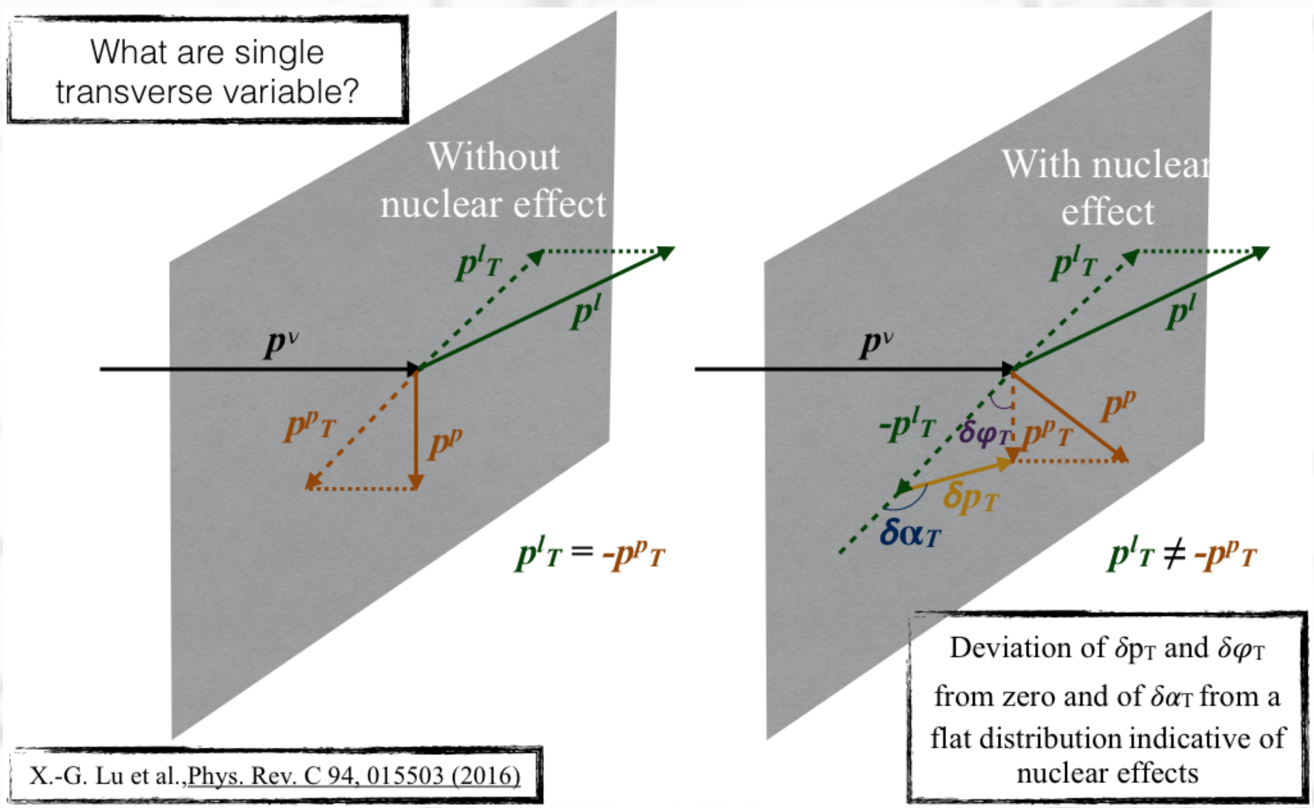
Proton-Muon Correlations in Pionless Events (CC0π)

Lepton-Hadron correlations and nuclear effects

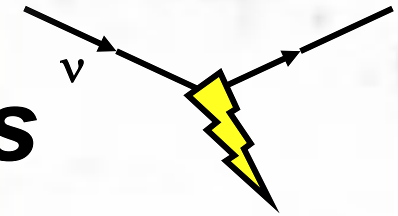


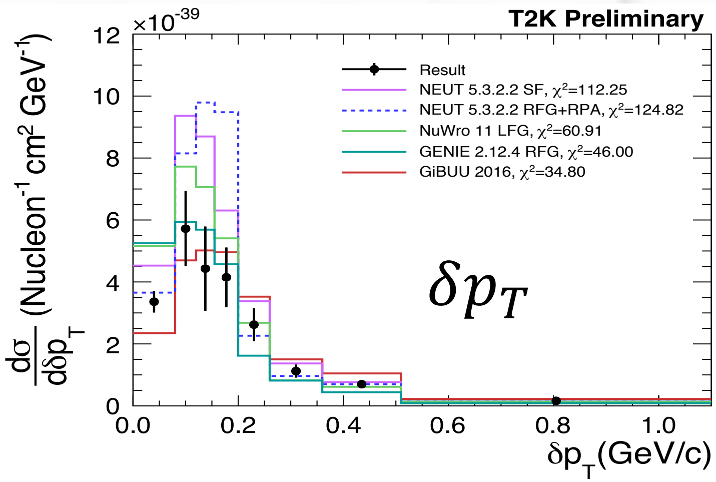
- Often it is very difficult to separate initial state (Fermi motion, in medium modifications) from final state (rescattering or "FSI") effects
- Need new observables… correlations between protons and muons in CC0π events!

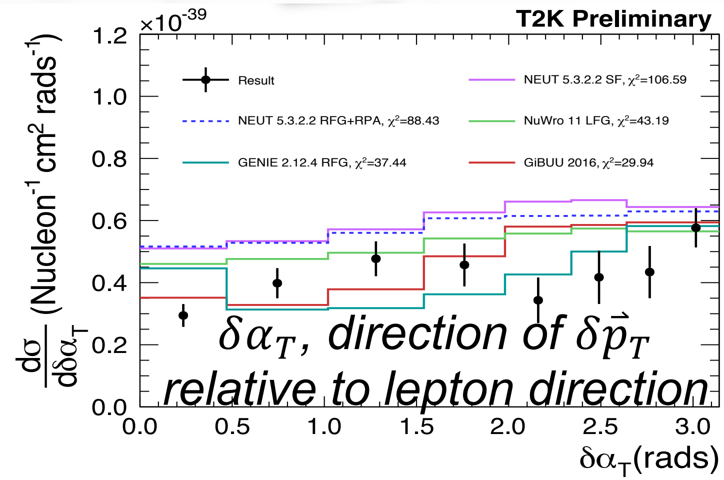
Figure compiled by C. Riccio

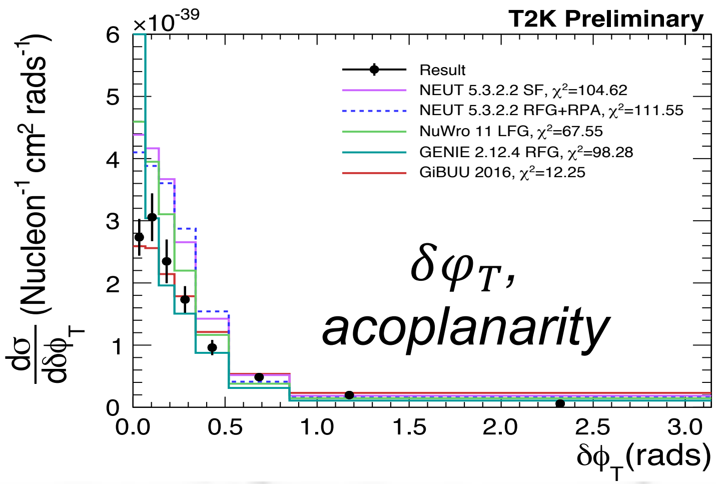


Identification of nuclear effects





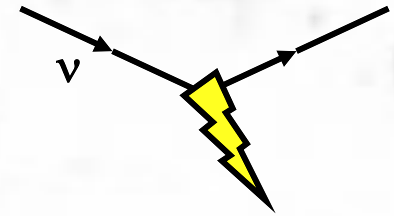


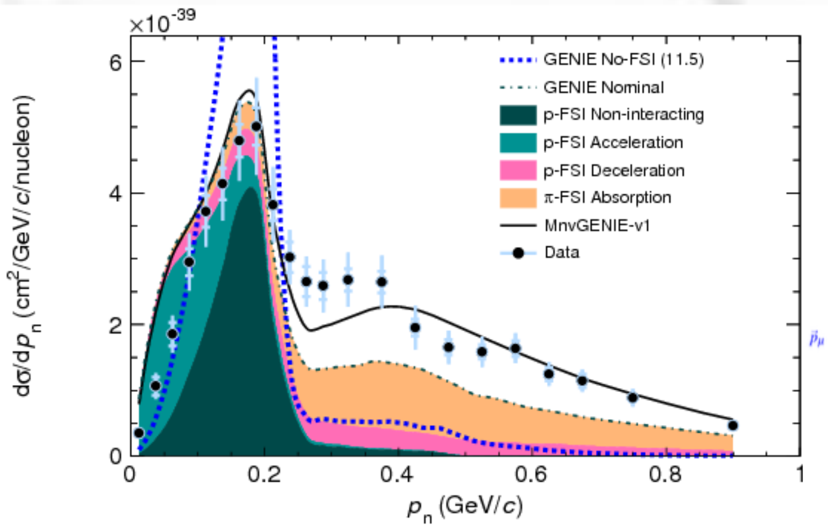


Phys.Rev. D98 (2018) no.3, 032003

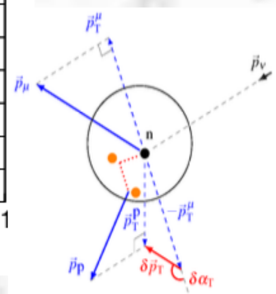
- Current comparisons have initial state and final state effects together for different models.
- GENIE excess in first bins related to a feature of (="bug in") FSI model
- Data favors more realistic local Fermi Gas and Spectral function models over global Fermi Gas

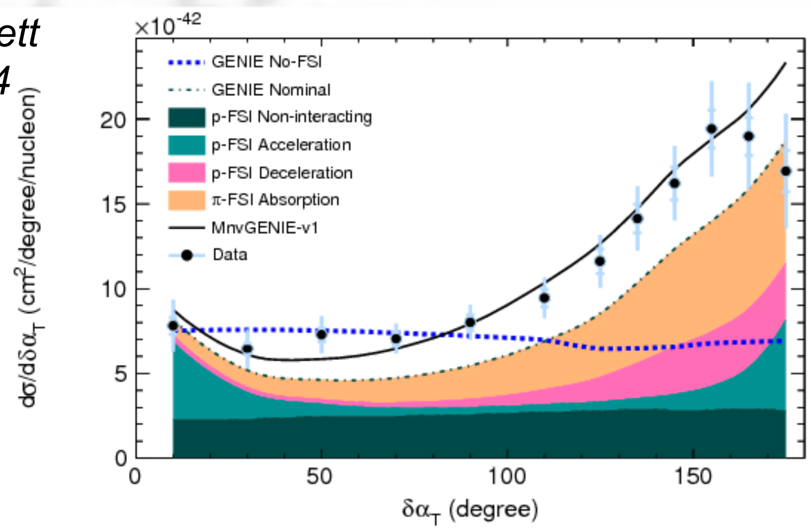
MINERvA's Transverse Projections in CC0π





Phys. Rev. Lett 121 022504 (2018)



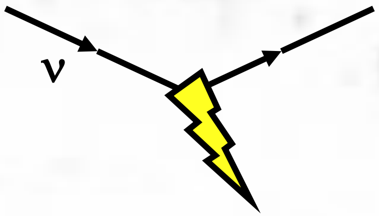


Neutron momentum under exclusive μp hypothesis

Missing p_T direction (decelerating process is 180^o)

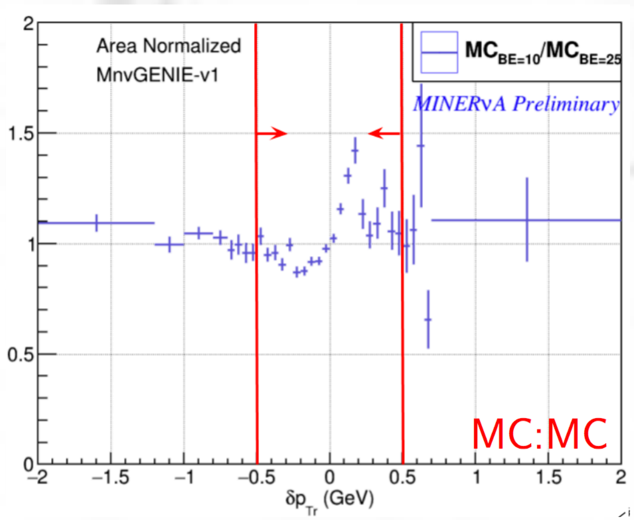
- MINERvA 2p2h tune helps! But by studying reconstructed neutron momentum and transverse variables in CC0π events, we have evidence for deficiencies in the initial and final state models (and tune?).

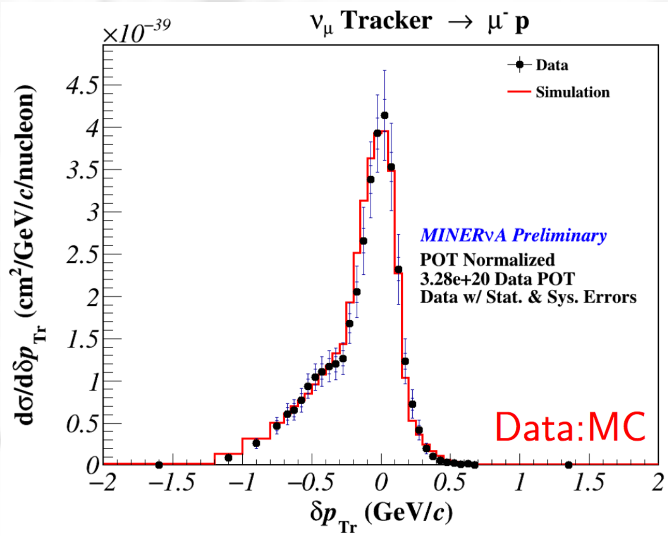
Transverse Variables and Energy of Bound Nucleons



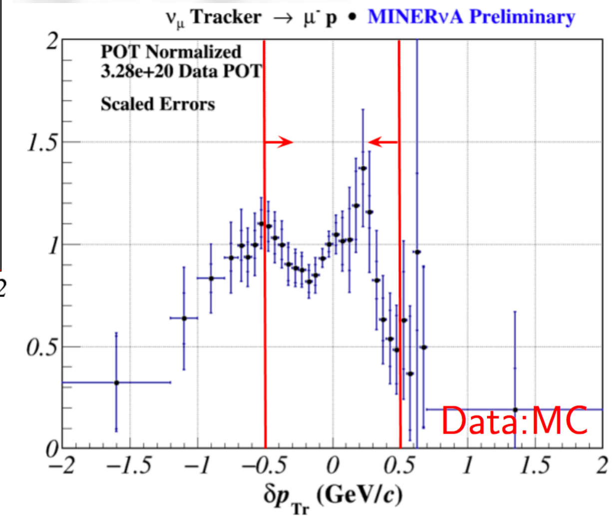
- Transverse balance projected into the reaction plane is biased by binding energy.

Peak shift from GENIE's default binding energy to correction proposed by Arie Bodek in Eur.Phys.J. C79 (2019) no.4, 293

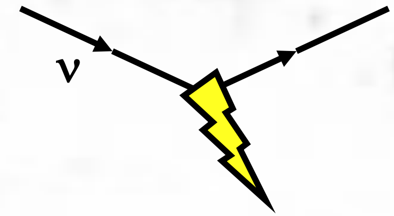




As it turns out, there is a similar shift near the peak. (Features in tail also.)

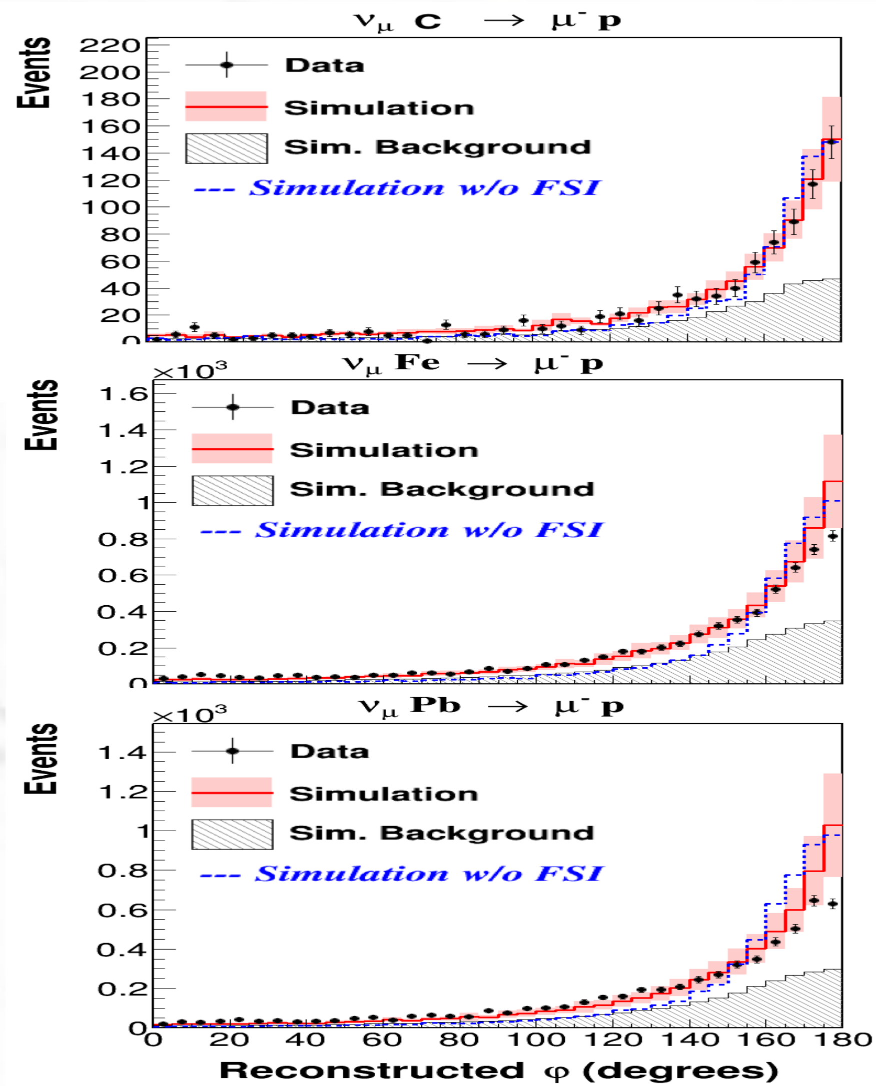


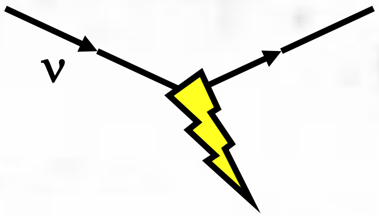
Proton-Muon Correlations on Different Nuclei



- MINERvA analysis comparing scintillator (CH) to Fe and Pb
  Phys. Rev. Lett. 119 082001 (2017)

- This is one of the transverse variables from three slides back,
  $$\pi - \delta\varphi_T \rightarrow \varphi$$
- Model describes carbon, but fails to describe Fe, Pb



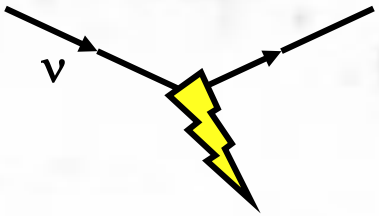


Conclusions

Conclusions

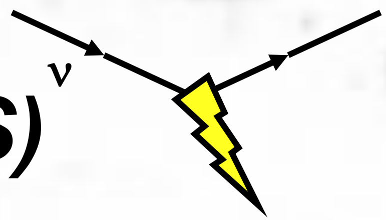
- We are approaching a plausible, data-driven description of the zero pion reactions that are most/much of T2K/NOvA and HK signals.
  - Theory has some work to do to catch up.
- Single pion is ~ready for same approach.
- We have a longer, more difficult, path to follow to reach the understanding necessary for all DUNE final states, but we have demonstrated techniques.

Backup



The other major neutrinos interaction news… Coherent Elastic

Coherent elastic neutrino-nucleus scattering (CEvNS)



$$\nu + A \rightarrow \nu + A$$

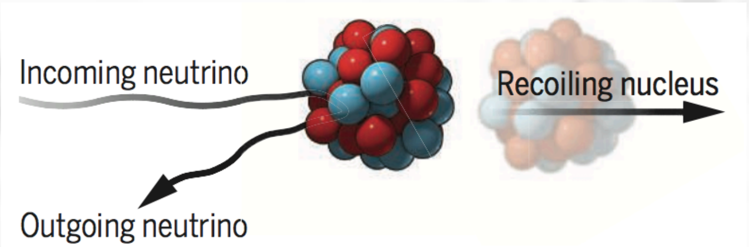
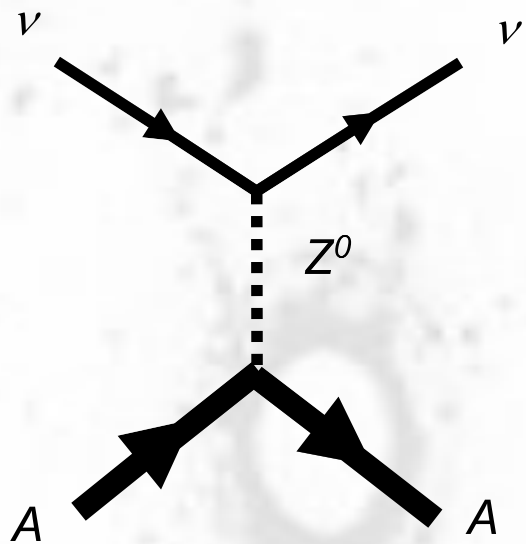
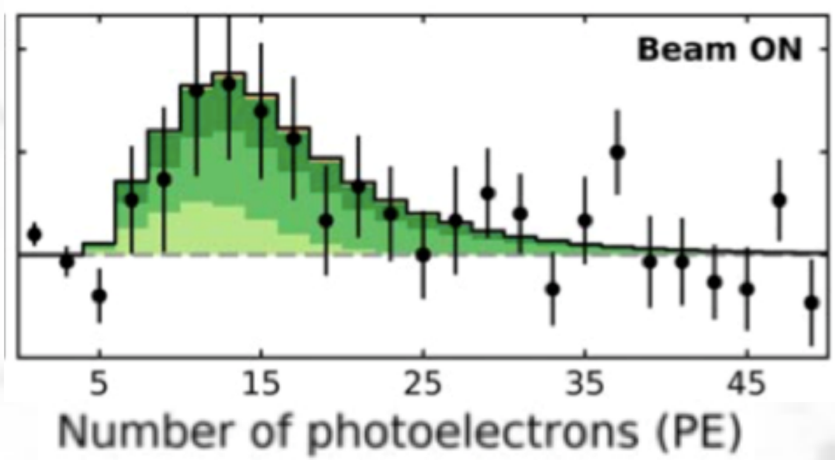


Image: J. Link Science Perspectives



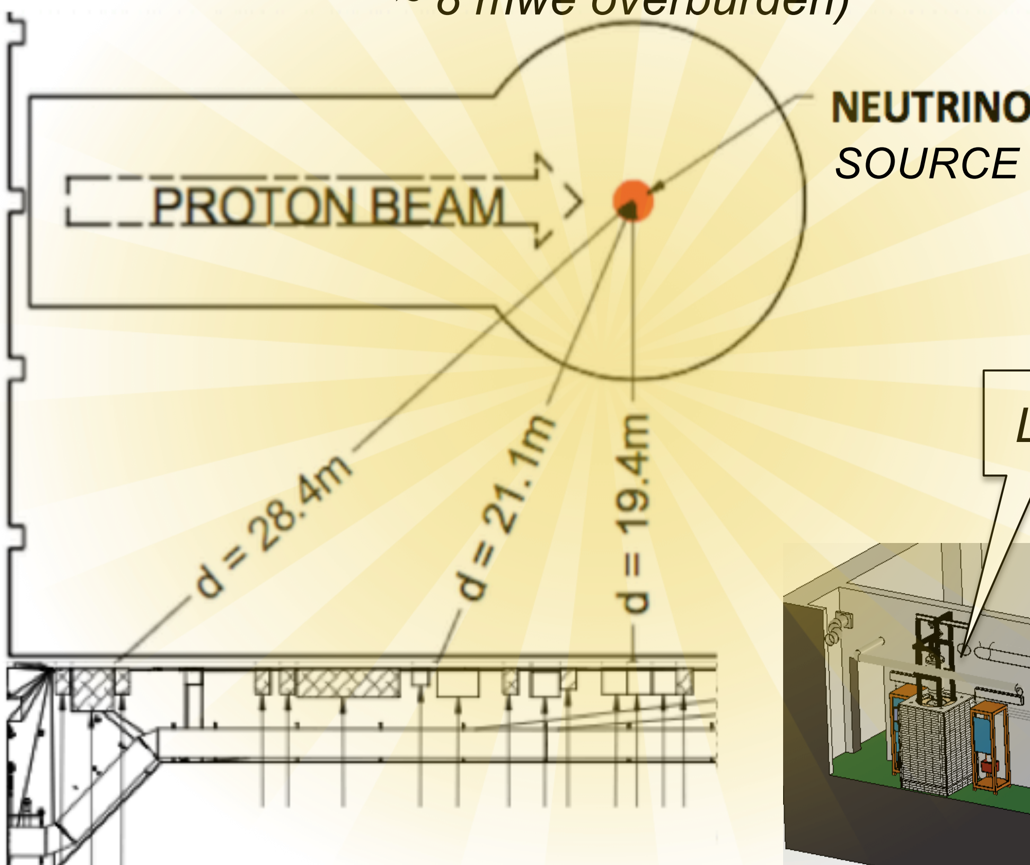
Science 357 (2017) no.6356, 1123-1126

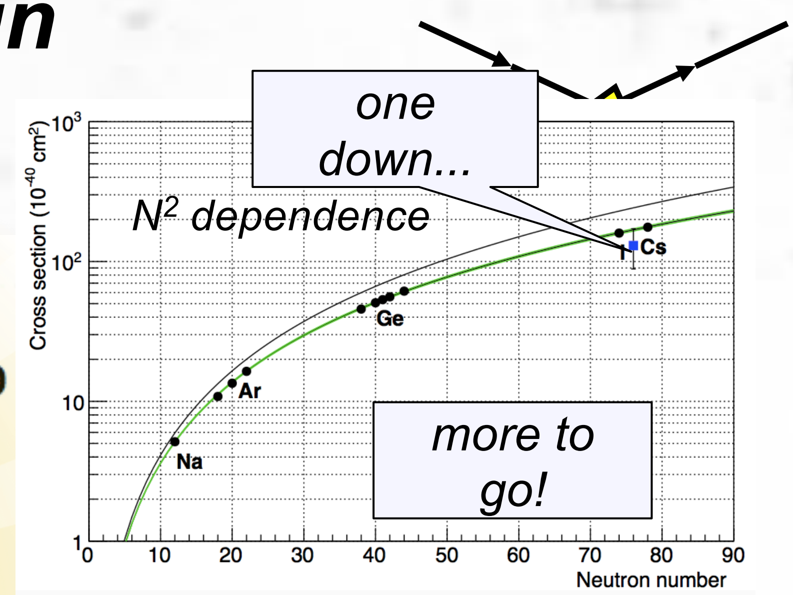
- *first light at the SNS stopped-pion source w/ 14.6 kg CsI[Tl] detector*
  - *➔meaningful BSM bounds*
- *2.4σ statistical indications from CONUS at reactor*

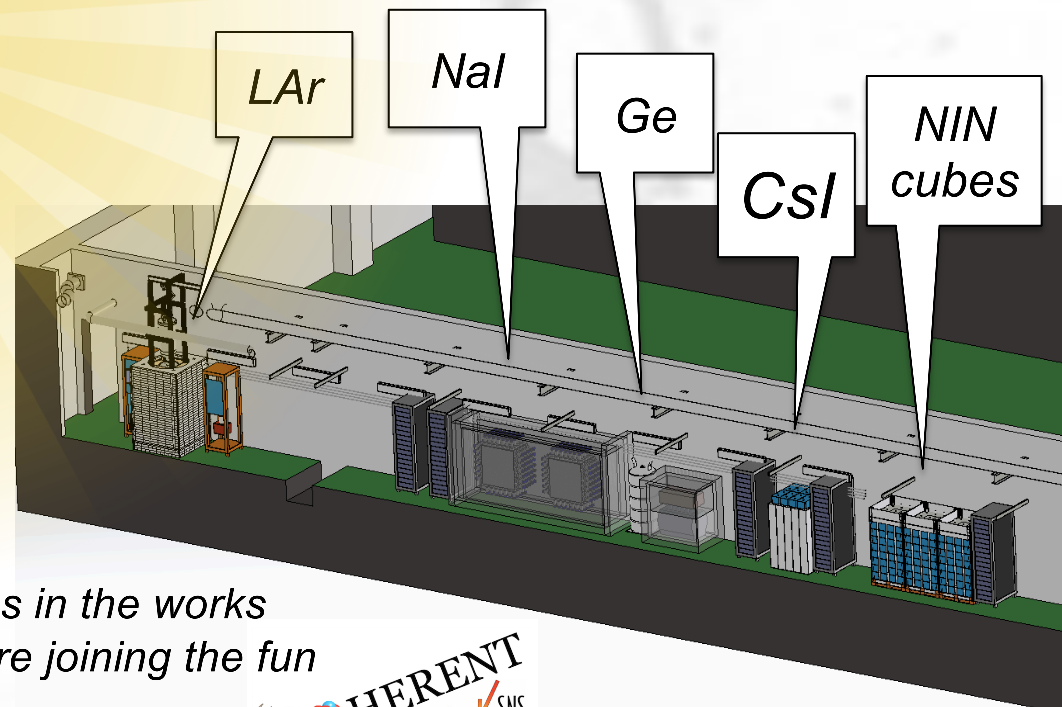


COHERENT deployment in SNS basement

(measured neutron backgrounds low, ~ 8 mwe overburden)







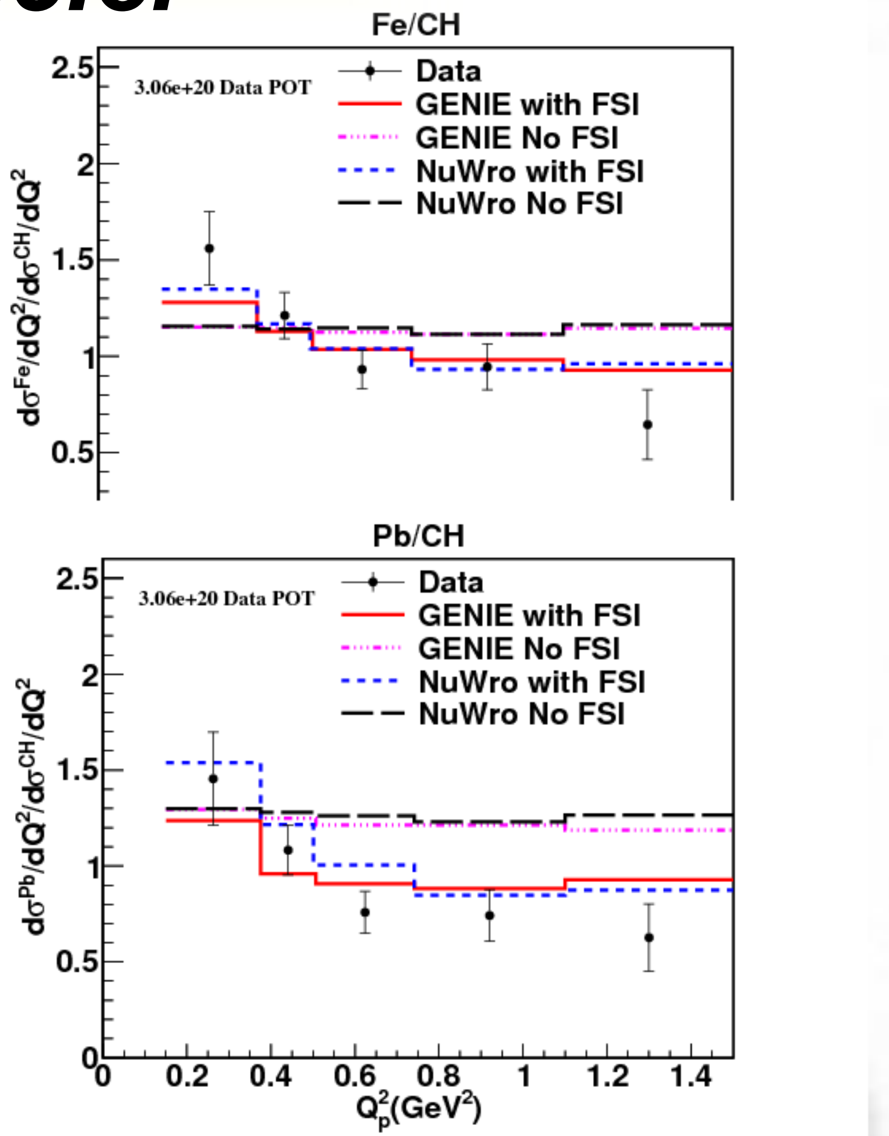
- *Just at the beginning....*
- *Multiple targets, upgrades and new ideas in the works*
- *Other CEvNS experiments at reactors are joining the fun*

+D_2O for flux

MINERvA Q_{P2} Target Ratios

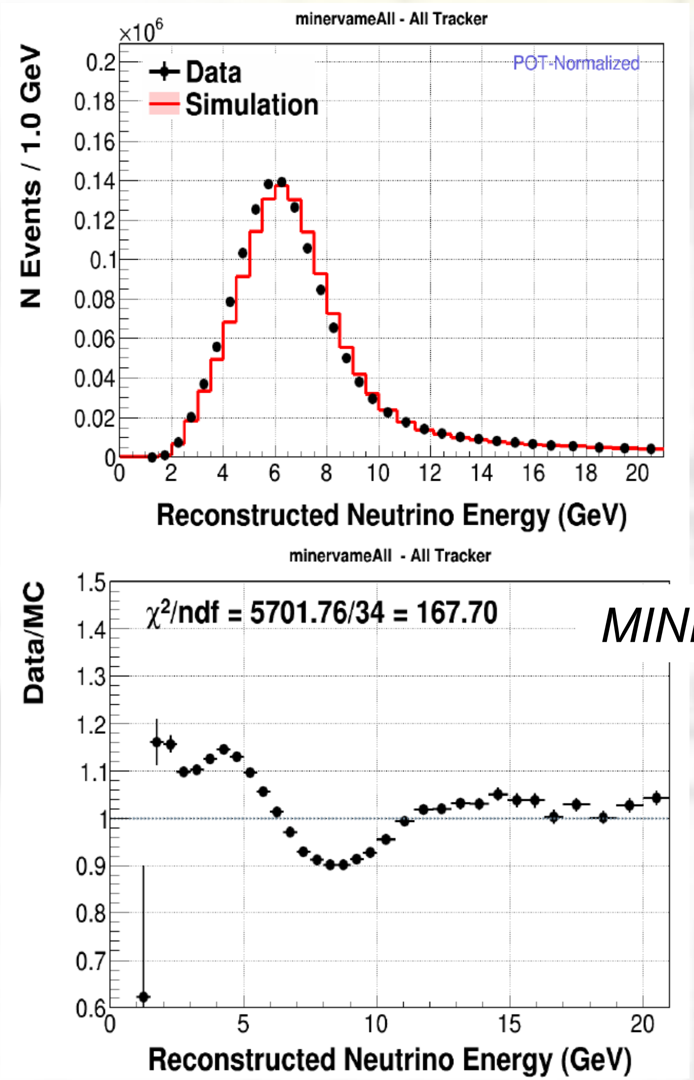
Proton-Muon Events on Different Nuclei

- Ratio of Fe and Pb to scintillator (CH) as a function of recoiling proton energy also shows model discrimination.
  Phys. Rev. Lett. 119 082001 (2017)
- Next steps are to follow T2K's lead of looking at complete set of correlations.

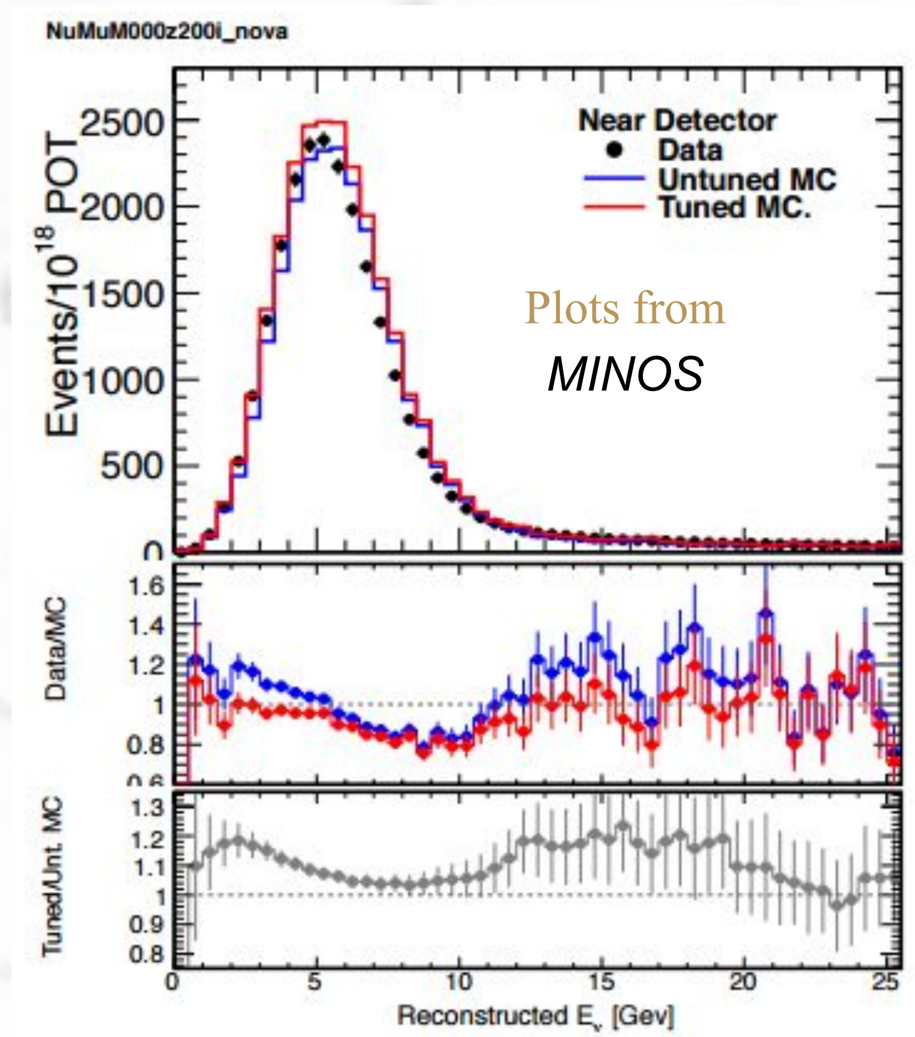


NuMI Flux

NuMI Flux Puzzle



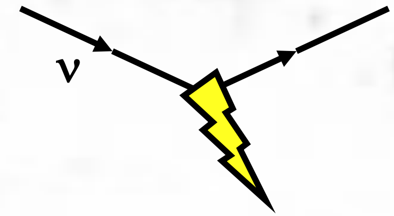
MINERvA

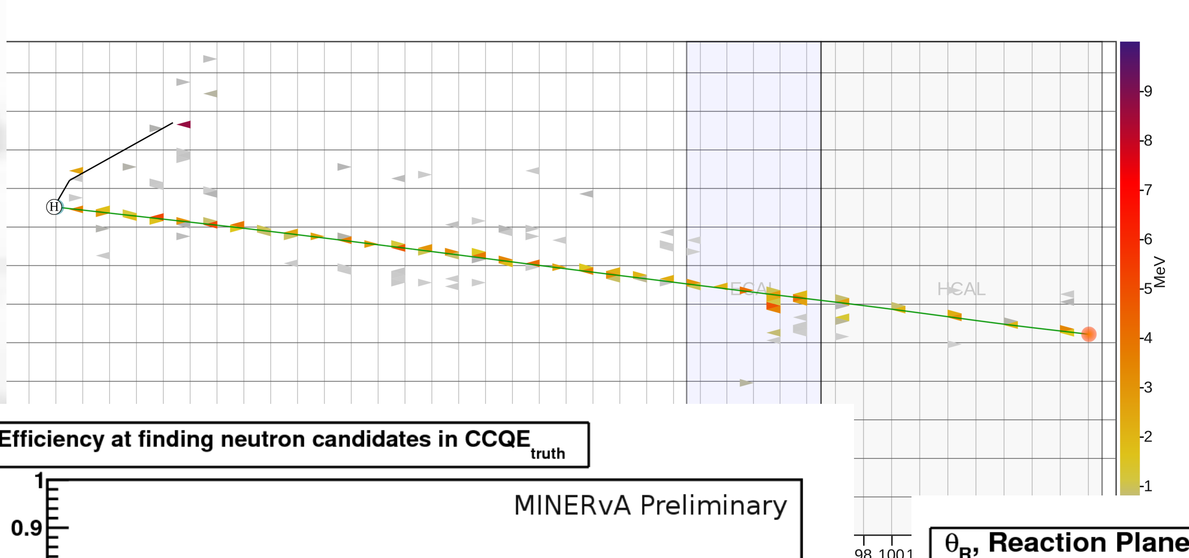


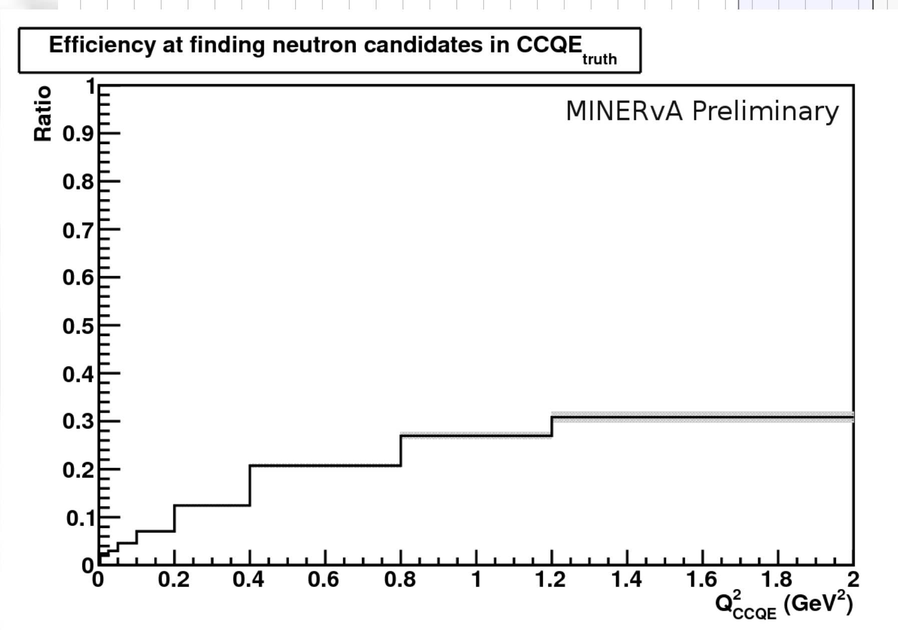
Plots from *MINOS*

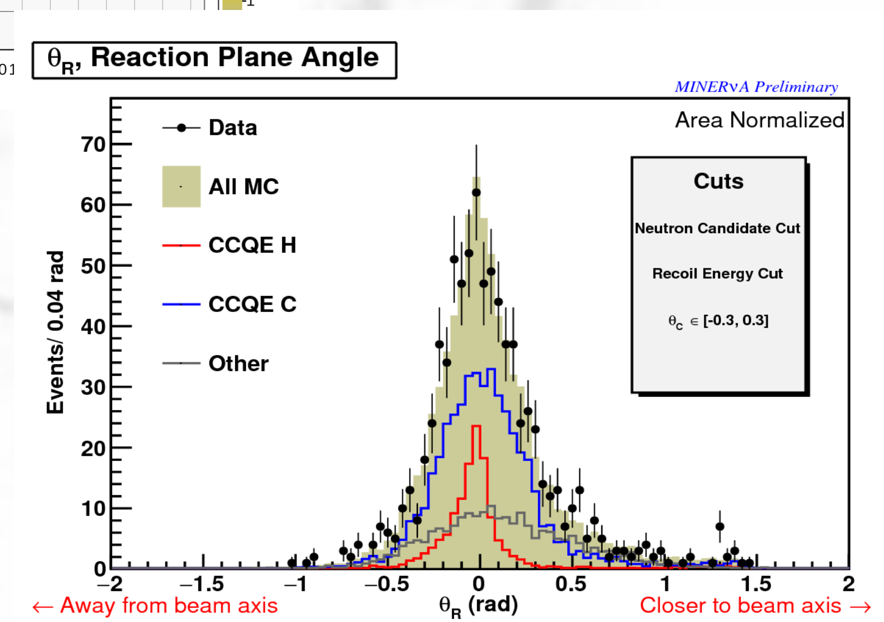
Detecting Neutrons in MINERvA

MINERvA's neutrons



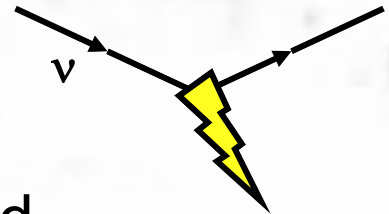






Under the hood of Rein-Sehgal Resonance model

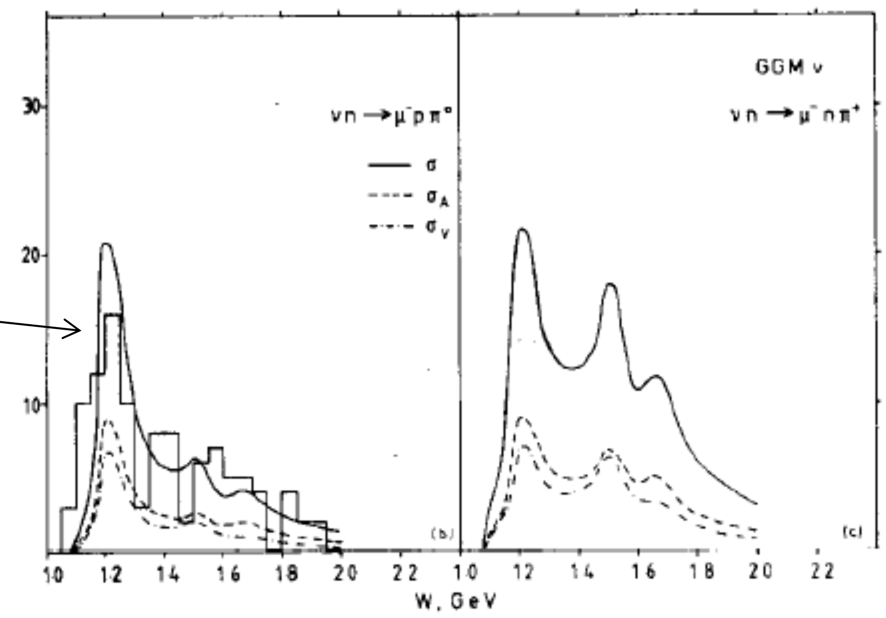
Resonance Region Models



- Models of the resonance region are complicated
  - In principle, many baryon resonances can be excited in the scattering and they all can contribute
  - They de-excite mostly by radiating pions
- Most single pion production is from resonance decay

Nucleon Resonances below 2 GeV/c² according to Ref. [4]

Resonance Symbol[a]	Central mass value M [MeV/c²]	Total with Γ_0[MeV]	Elasticity $x_E = \pi\mathcal{N}$ branching ratio	Quark-Model/ SU_6-assignment
$P_{33}(1234)$	1234	124	1	$^4(10)_{3/2}\,[56, 0^+]_0$
$P_{11}(1450)$	1450	370	0.65	$^2(8)_{1/2}\,[56, 0^+]_2$
$D_{13}(1525)$	1525	125	0.56	$^2(8)_{3/2}\,[70, 1^-]_1$
$S_{11}(1540)$	1540	270	0.45	$^2(8)_{1/2}\,[70, 1^-]_1$
$S_{31}(1620)$	1620	140	0.25	$^2(10)_{1/2}\,[70, 1^-]_1$
$S_{11}(1640)$	1640	140	0.60	$^4(8)_{1/2}\,[70, 1^-]_1$
$P_{33}(1640)$	1640	370	0.20	$^4(10)_{3/2}\,[56, 0^+]_2$
$D_{13}(1670)$	1670	80	0.10	$^4(8)_{3/2}\,[70, 1^-]_1$
$D_{15}(1680)$	1680	180	0.35	$^4(8)_{5/2}\,[70, 1^-]_1$
$F_{15}(1680)$	1680	120	0.62	$^2(8)_{5/2}\,[56, 2^+]_2$
$P_{11}(1710)$	1710	100	0.19	$^2(8)_{1/2}\,[70, 0^+]_2$
$D_{33}(1730)$	1730	300	0.12	$^2(10)_{3/2}\,[70, 1^-]_1$
$P_{13}(1740)$	1740	210	0.19	$^2(8)_{3/2}\,[56, 2^+]_2$
$P_{31}(1920)$	1920	300	0.19	$^4(10)_{1/2}\,[56, 2^+]_2$
$F_{35}(1920)$	1920	340	0.15	$^4(10)_{5/2}\,[56, 2^+]_2$
$F_{37}(1950)$	1950	340	0.40	$^4(10)_{7/2}\,[56, 2^+]_2$
$P_{33}(1960)$	1960	300	0.17	$^4(10)_{3/2}\,[56, 2^+]_2$
$F_{17}(1970)$	1970	325	0.06	$^4(8)_{7/2}\,[70, 2^+]_2$

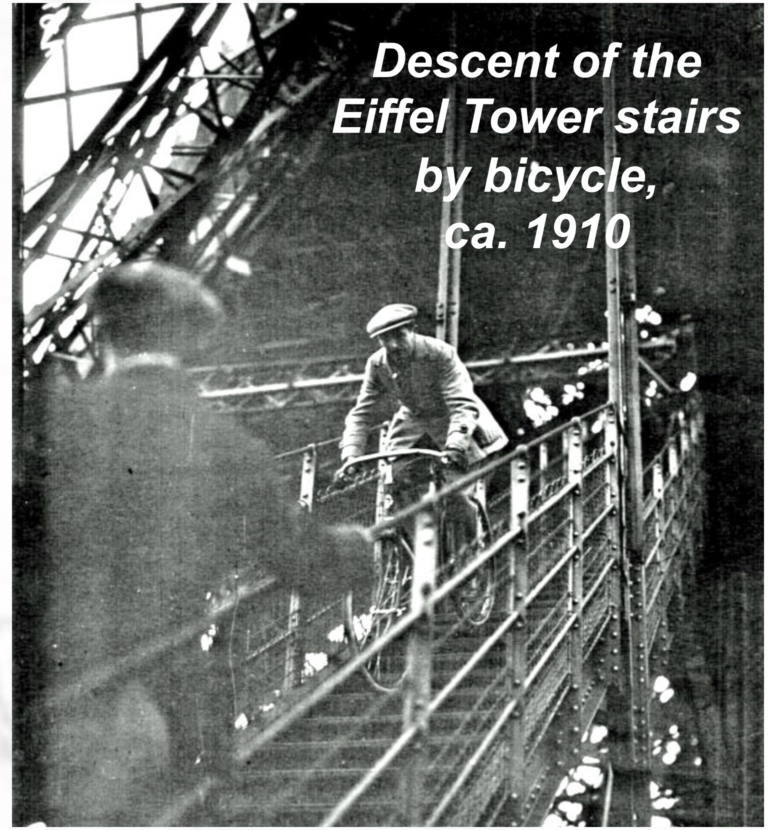


D. Rein and L. Sehgal, Ann. Phys. 133, 79 (1981)

Theory amusements

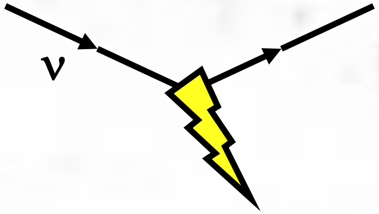
Difficult Multi-Scale Problems

- 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



- *But since the wheel size is too close to the step size, all we know is that it is going to be painful.*

A Problem Hidden in Plain Sight for Neutrino Experiments

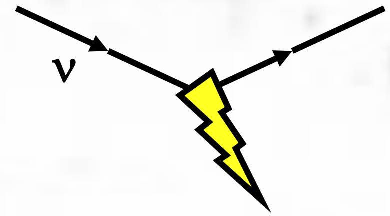


- What do we do when confronted with a problem we can't solve? We ignore it!
- This community started with modeling of neutrino interactions that was too naïve to support the precision needed for future experiments.
- People who had confronted charged lepton scattering data for decades told us what we were facing.
- Gradually, and painfully, we have learned to listen…

Artist Liu Bolin, imitating the nucleus?

NOvA's low q fit

NOvA low-q Analysis

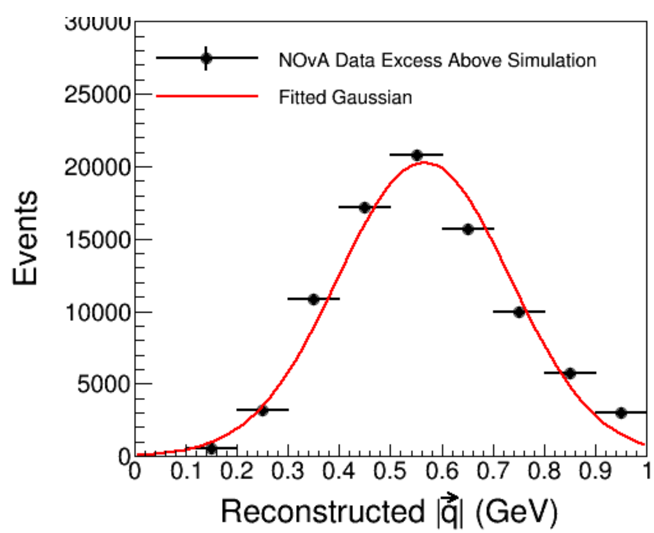


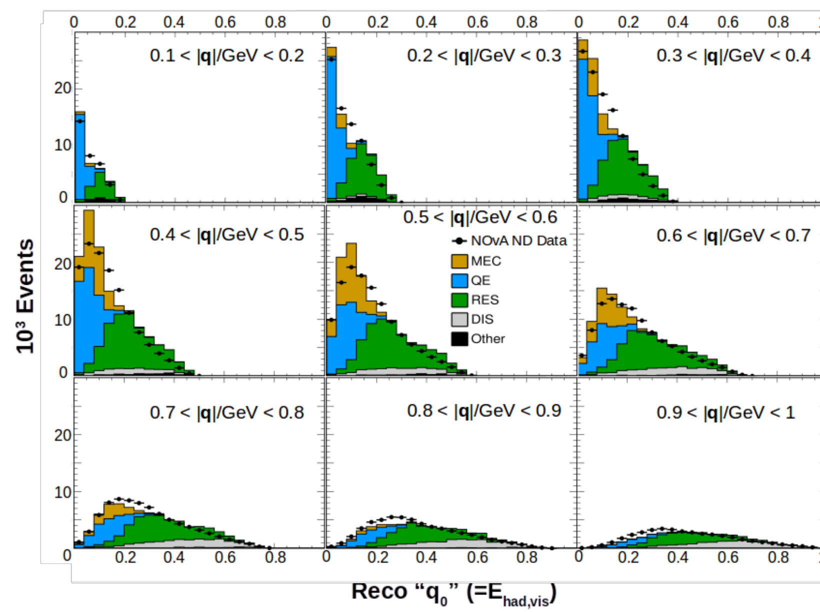
- NOvA is doing something very similar as part of its oscillation analysis evaluation of systematics

Second analyses (2016):

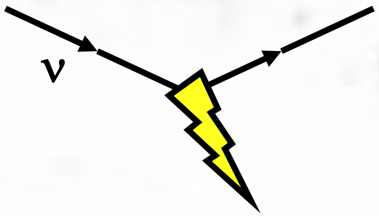
K. Bays @NuFact 2017

- Dytman 'empirical MEC' model is included in GENIE and used by NOvA
- Momentum transfer distribution fit to ND data; energy transfer set to match QE
- A 50% normalization uncertainty is taken





NOvA low-q Analysis



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Third ~~Second~~ analyses (2018) ~~(2016)~~:

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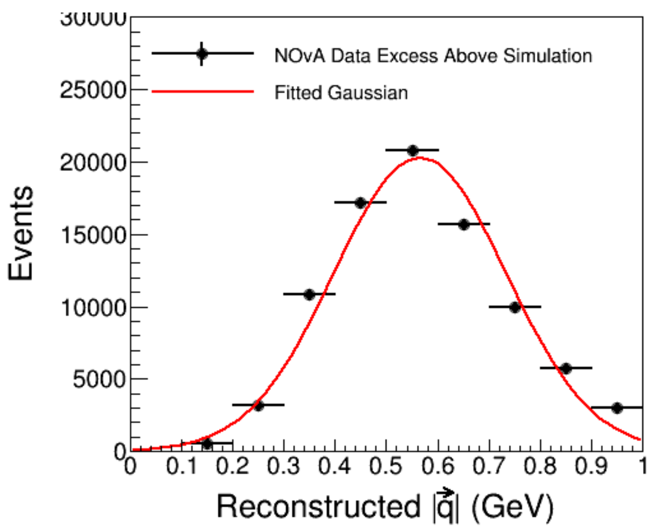
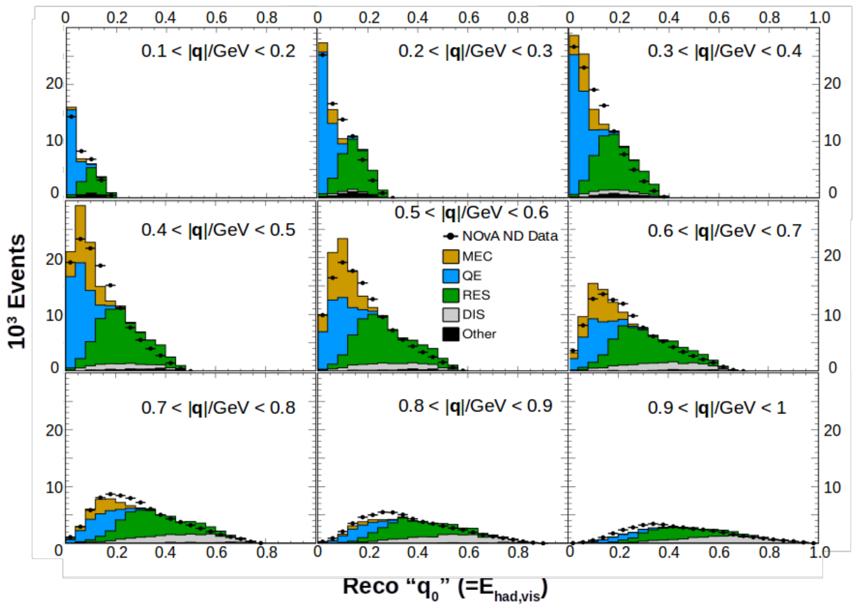
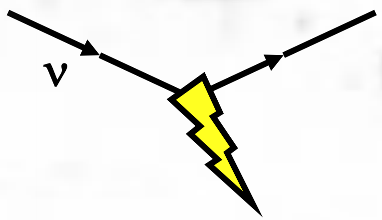


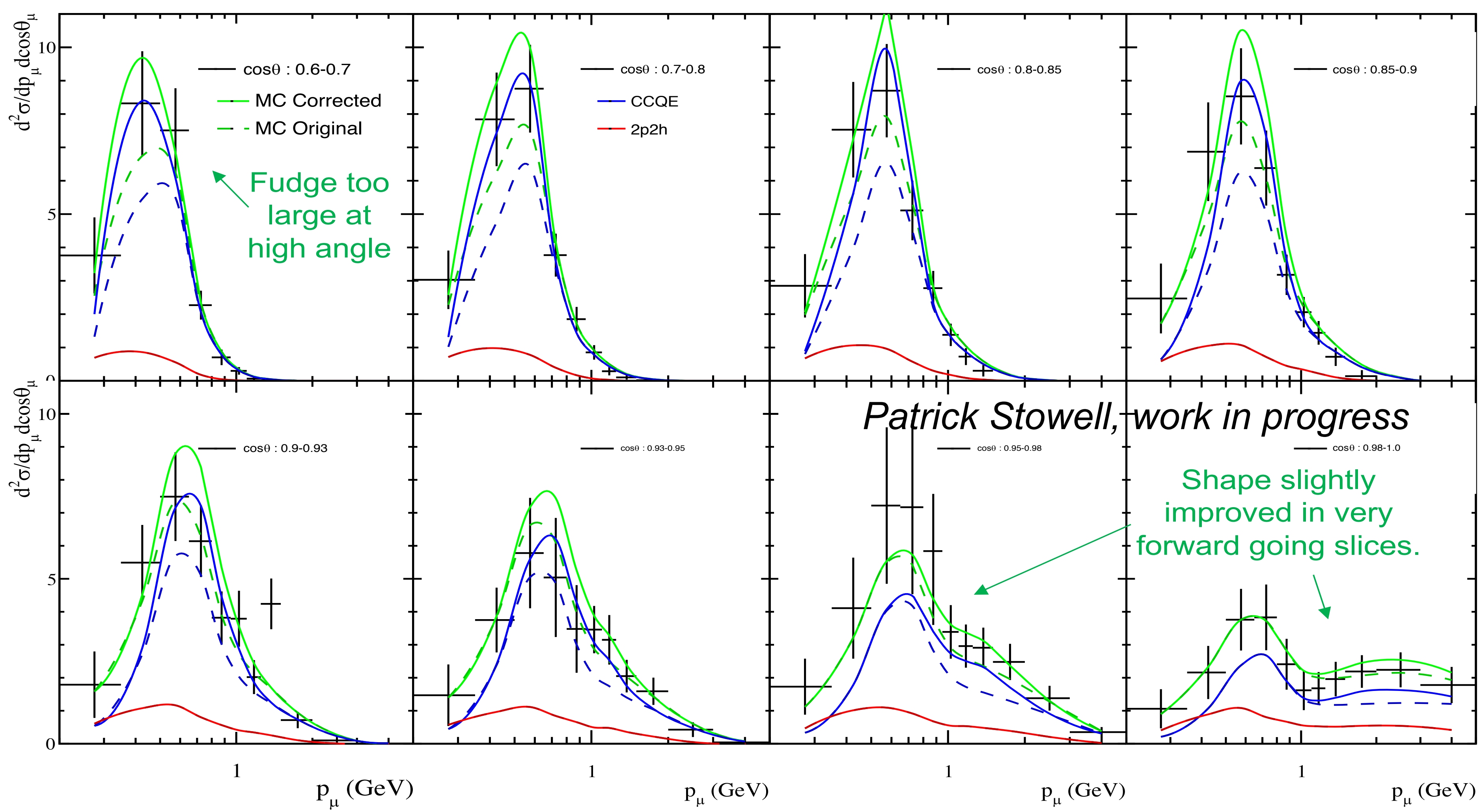
Use Δ-like and non Δ-like energy transfer



Energy Dependence of CC0pi Tune

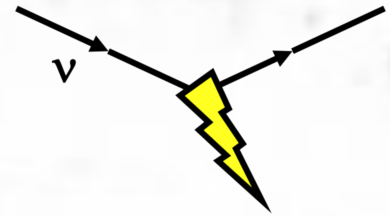
Apply to T2K CC0π… fails



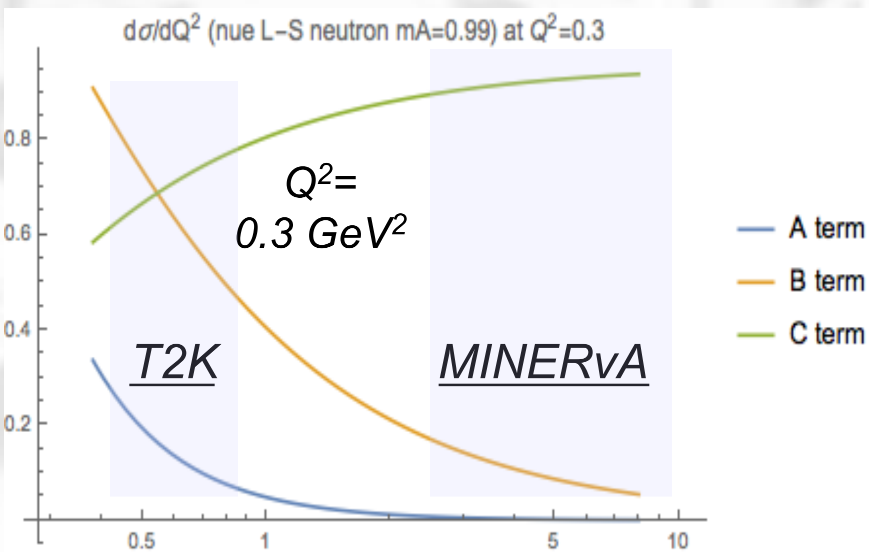


Phys. Rev. D93, 112012 (2016)

Could the "MINERvA tune" be Energy Dependent?



- At MINERvA energies, should we expect any? Not much.



CCE on free neutrons E_ν *(GeV)*

- *What are the A, B, C terms?*

- It turns out that there is a general form for energy dependence in exclusive and inclusive reactions on nucleons

$$E_\nu^2 \frac{d\sigma}{dQ^2 d\nu} = \breve{A} + \breve{B}E_\nu + \breve{C}E_\nu^2$$

  - *This holds for QE, 2p2h, etc.*

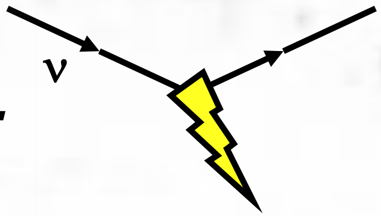
An expansion similar to eq. (2.5) holds for $\bar{\sum}\sum m_{\mu\nu}$ in terms of k and q. Hence, whatever the explicit form of the lepton and hadron currents:

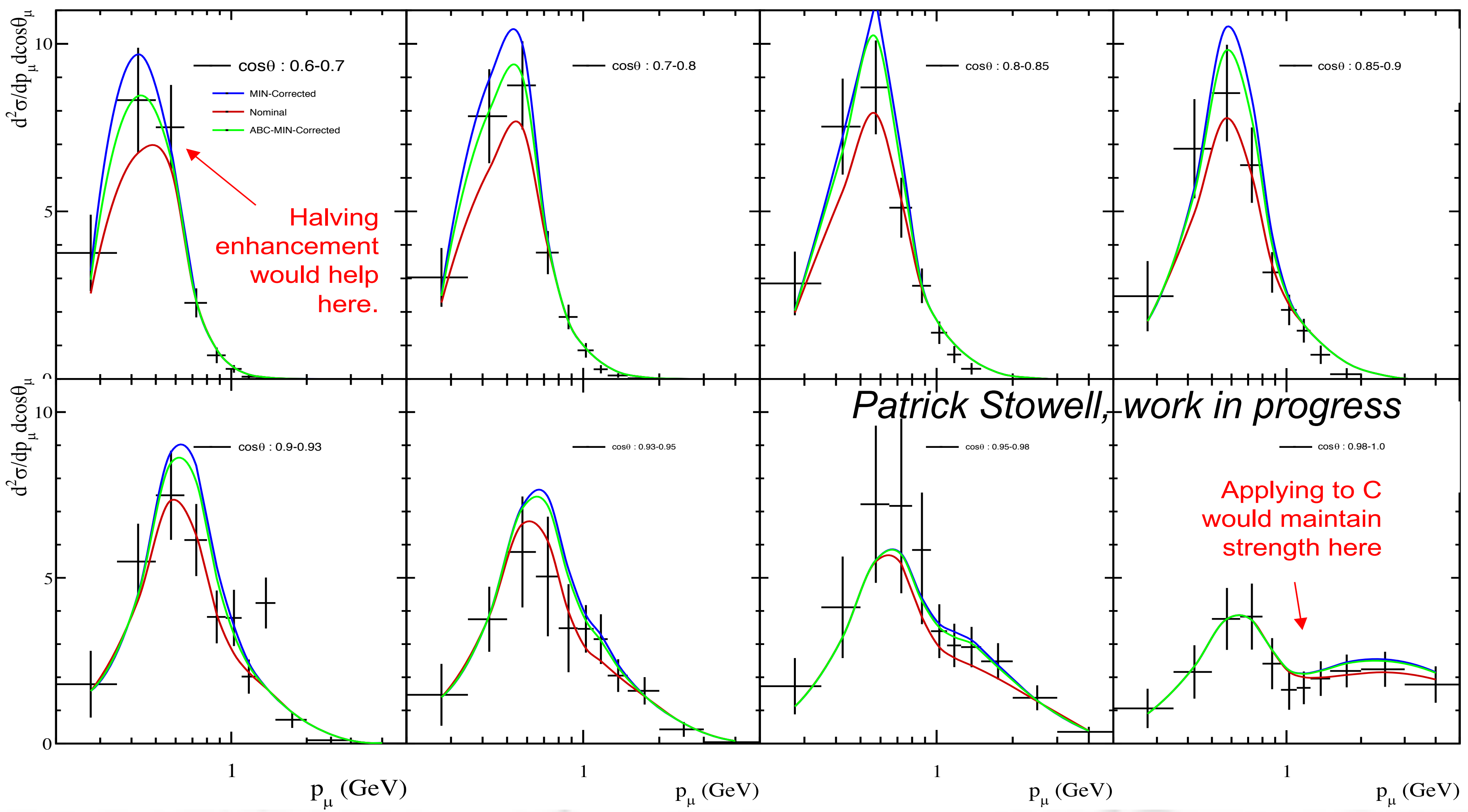
$$\bar{\sum}\sum m_{\mu\nu} \; \bar{\sum}\sum W^{\mu\nu} = A + B\,k\cdot P + C(k\cdot P)^2\,, \tag{2.7}$$

a quadratic polynomial in the laboratory energy $E_{\bar{\mu}} = k\cdot P/M$ whose coefficients A, B and C depend on ν, q^2, and the reaction in question [L14, P2], It follows that if the interaction is of the current-current form *then* $E_\nu^2\, d^2\sigma/dq^2 d\nu$ *is a quadratic polynomical in* E_ν (cf. eqs. (2.10) and (2.11)) and therefore *only three combinations of structure functions are obtained if the final lepton polarization is not observed*. An alternative way to obtain the same result is to note that

C.H. Llewellyn Smith, Phys. Rep. 3 261-379 (1972), p. 280

Apply to T2K C term for CC0π





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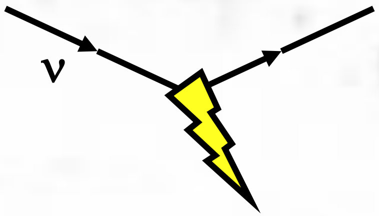
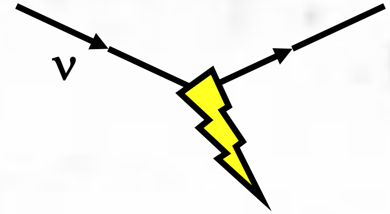
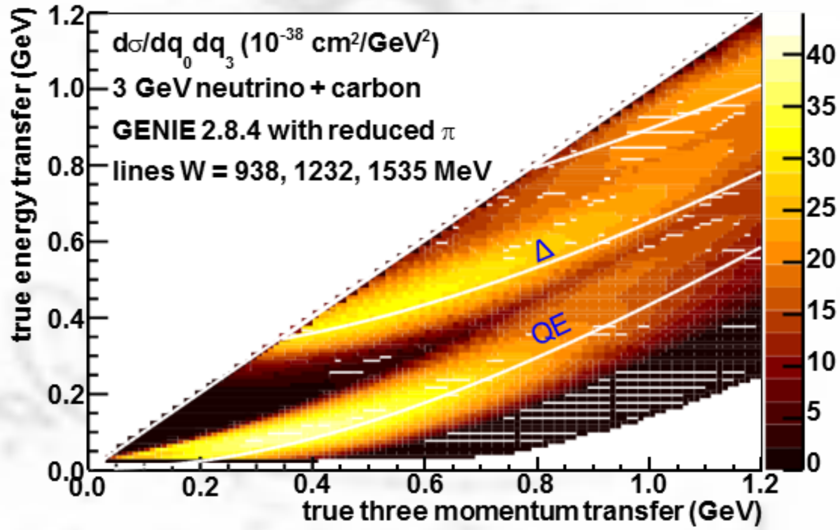


Neutrino Experiments energies

First a Comment about Neutrino Energy

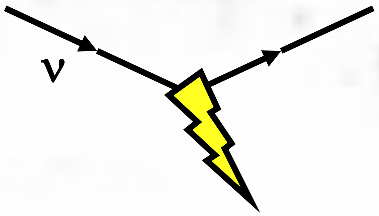


- Neutrino energy is not the most important criterion of usefulness of a data set, as long as the reaction(s) of interest are accessible
  - Response of the nucleus for a given final state is given by energy and momentum transfer. Not neutrino energy*.



- Ability to measure a final state, get good statistics and measure kinematics are much more important.

** near q_0 boundary, lepton mass effects become important. Often predictable.*



Neutrino Experiment Opinions

Strengths and Weakness of Experiments *(warning: opinions)*

- MINERvA. Strengths: established and publishing on high statistics sample. Multiple nuclear targets in same beam. ν-e scattering for flux. Neutron reconstruction. Weakness: wideband w/ flux puzzles. relatively high tracked/IDd particle thresholds (T_p>90 MeV, T_π>50 MeV)
- MicroBooNE. Strength: lower particle thresholds (T_p>80 MeV, T_π>35 MeV done, hope for factor of 1.5 lower), excellent PID if particles don't hadronically interact. Weakness: statistics >order of magnitude lower than MINERvA (SBND will be ~MINERvA), cosmic ray backgrounds.
- T2K Strengths: established and publishing. Narrow band beam w/ best hadroproduction constraint. Excellent PID for particles making it to gas TPCs. Weaknesses: very low statistics, relatively high tracked & identified particles threshold. π^0 reconstruction problematic.
- NOvA Strengths: narrow band beam, albeit with some flux worries, factors of two better statistics than MINERvA, neutron reconstruction?. Weaknesses: higher thresholds than MINERvA, all plastic so containment is not great, "cocktail" not easily compared to other results.

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- T2K Strengths: established and publishing. Narrow band beam w/ best hadroproduction constraint. Excellent PID for particles making it to gas TPCs. Weaknesses: very low statistics, relatively high tracked & identified particles threshold. π^0 reconstruction problematic.
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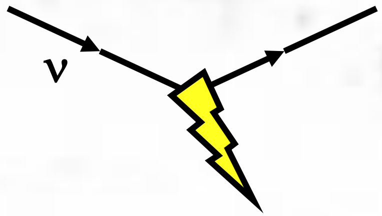
Strengths and Weakness of Experiments *(warning: opinions)*



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Ask your physician about

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Daily tablet for understanding of neutrino interactions

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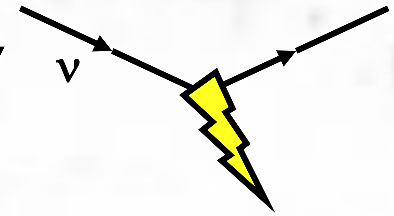
Kaon Decay-at-rest

An exception to "Can't Know Neutrino Energy"



- There is one idea for knowing the neutrino energy
- Kaons stopped in a production target or beam dump that decay by $K^+ \rightarrow \mu^+\nu_\mu$ produce monoenergetic neutrinos of 236 MeV.

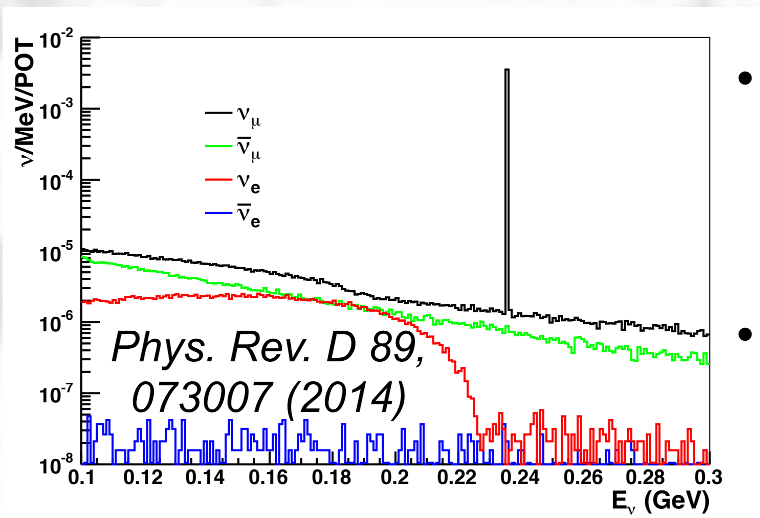


FIG. 1. The neutrino flux from 100-300 MeV provided by the 3 GeV proton-on-mercury JPARC-MLF source. The 236 MeV charged kaon decay-at-rest daughter ν_μ is easily seen.

- *Recently, MiniBooNE isolatied these events in the NuMI beam at FNAL by timing*
- *Low statistics, only ~4σ significance*

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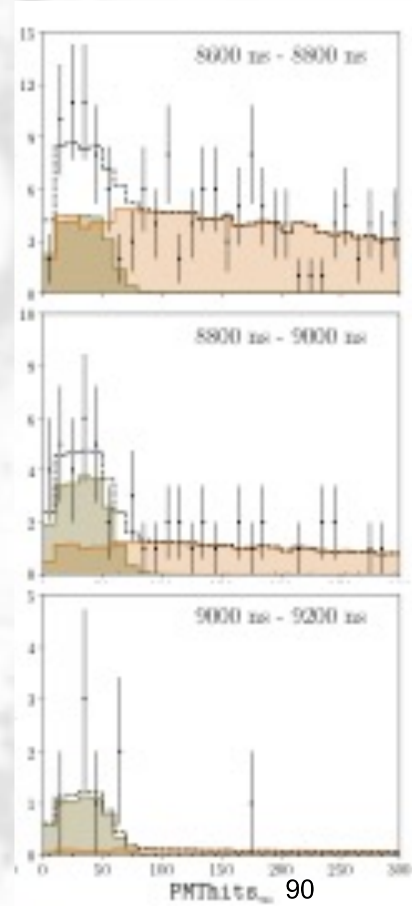
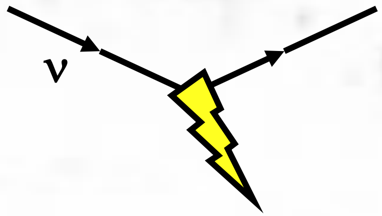
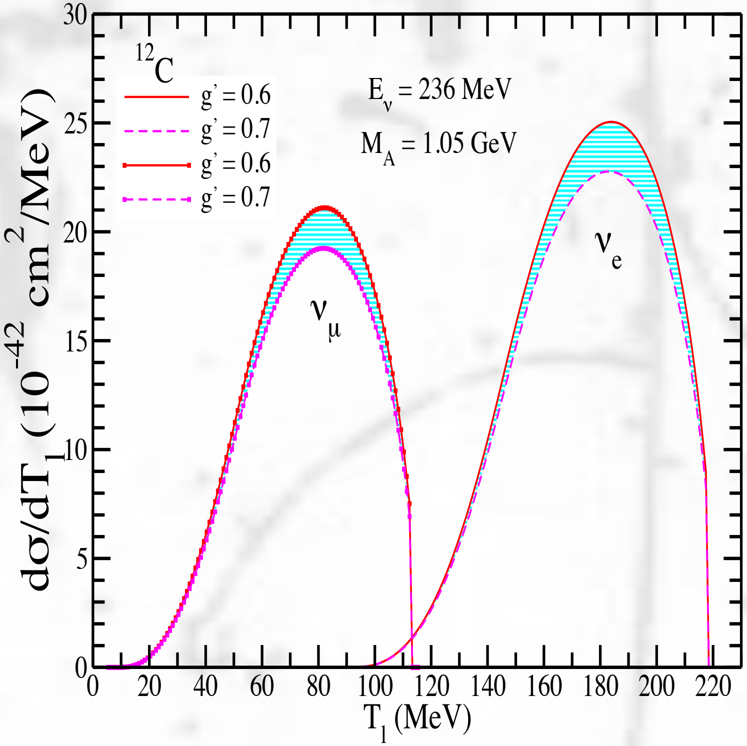


Extracted Constraint on Energy Loss



- Low statistics, so little power. But a precision effort can provide a detailed test of nuclear model.

Models from J.Phys. G44 (2017) no.12, 125108



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