

Experimental Neutrino Cross Sections

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International Neutrino Summer School

Summary from Yesterday

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(N(x_m) - B(x_m)) U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

- Questions:
 - How do you know what your efficiency is?
 - Doesn't the migration matrix depend on the flux?
 - How does DUNE-Prism work?

Going back to the original Recipe:

- Note that in order to measure cross sections, you need to get several ingredients from a simulation

- Backgrounds

- Flux

- Unsmearing Matrix

- Efficiency

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(N(x_m) - B(x_m)) U_{mt}}{\Phi_\nu(x_t) M \Delta x}$$

- That simulation uses a generator that you have heard from Stephen Dolan is not perfect
- How can you make sure that you are not reporting a biased result?
- Hint: use data wherever possible!

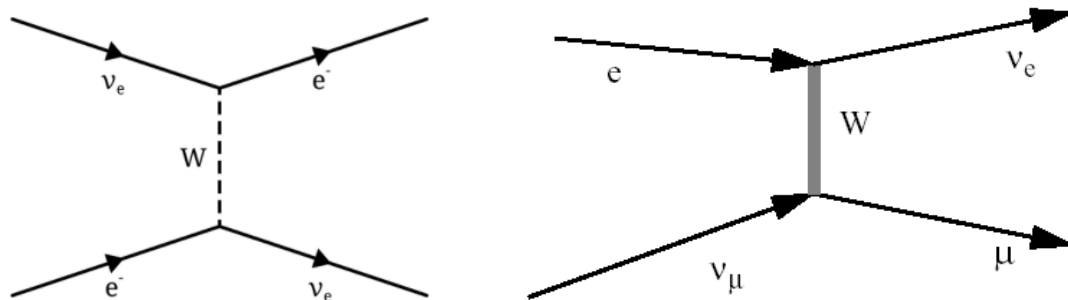
MINERvA: using Data to constrain Φ_ν

- Any neutrino detector has an electron for every proton

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi} \quad s = (\underline{p}_{\nu_\mu} + \underline{p}_e)^2 = m_e^2 + 2m_e E_\nu \text{ (e}^-\text{ rest frame)}$$

$$= 17.2 \times 10^{-42} \text{ cm}^2 / \text{GeV} \cdot E_\nu (\text{GeV})$$

- Consider these diagrams:

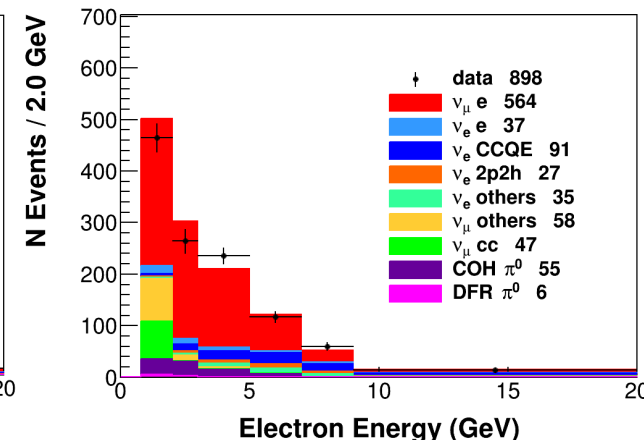
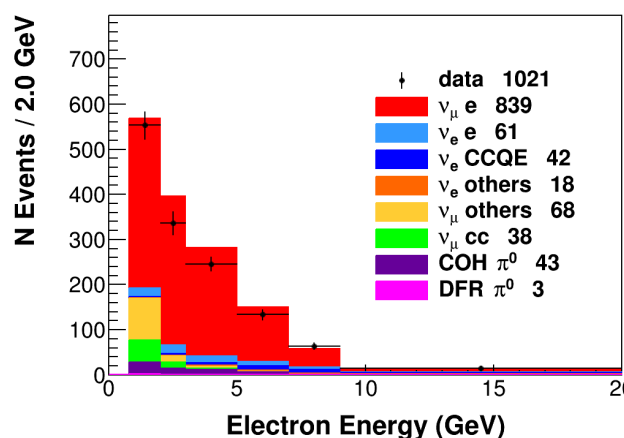
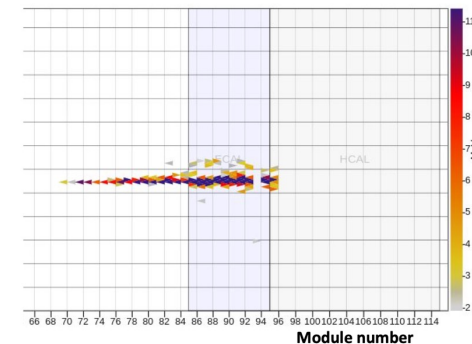


Use this equation:

$$N(E_{e,\mu}) = \frac{d\sigma(E_\nu, E_e)}{dE_e} \Phi_\nu(E_\nu) \epsilon(E_{e,\mu}, E_\nu) M$$

and that signal to constrain $\Phi_\nu(E_\nu)$!

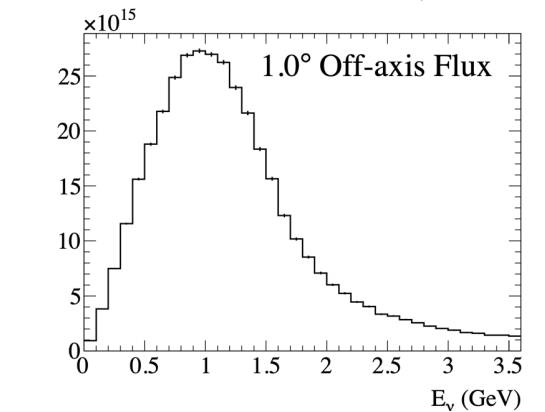
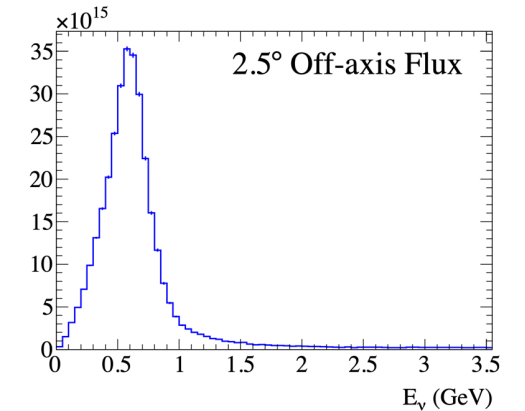
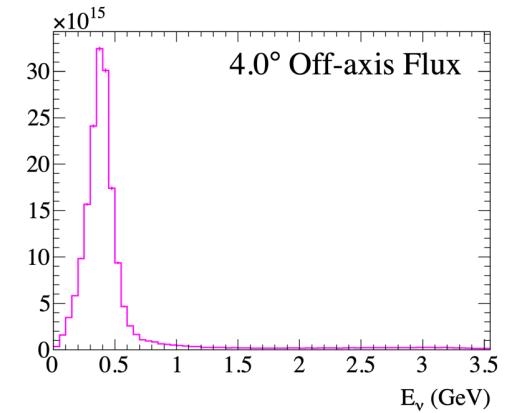
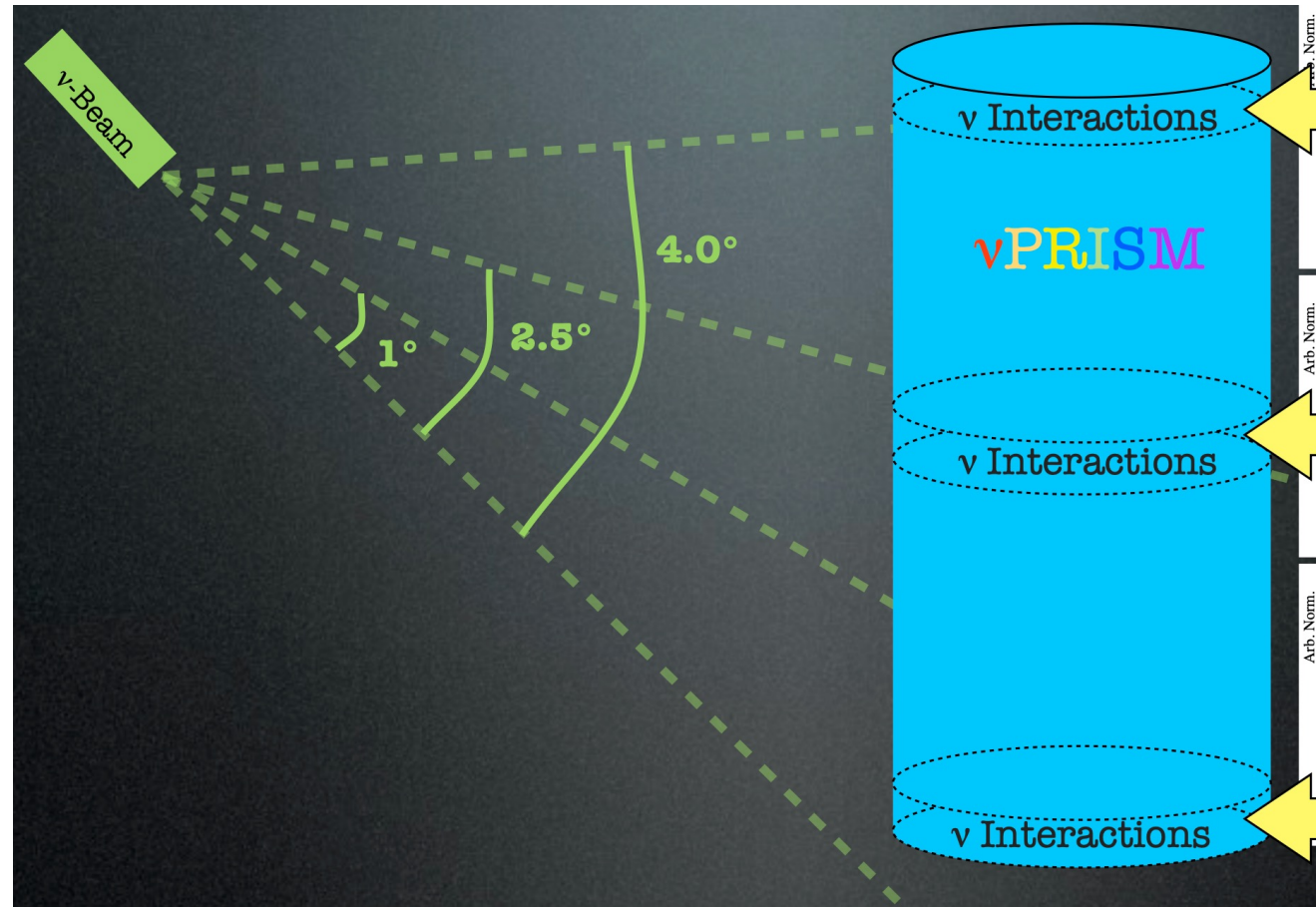
What's the catch?
Still can't measure E_ν



Phys.Rev.D 100 (2019) 9, 092001, Phys.Rev.D 107 (2023) 1, 012001

"PRISM" concept: making a "mono-chromatic" neutrino beam

- 2-body decay of pions to neutrinos mean specific relationship between flux and angle between detector and beamline axis



Graphics from M. Wilking, Lepton-Nucleus Scattering XIV, 2015

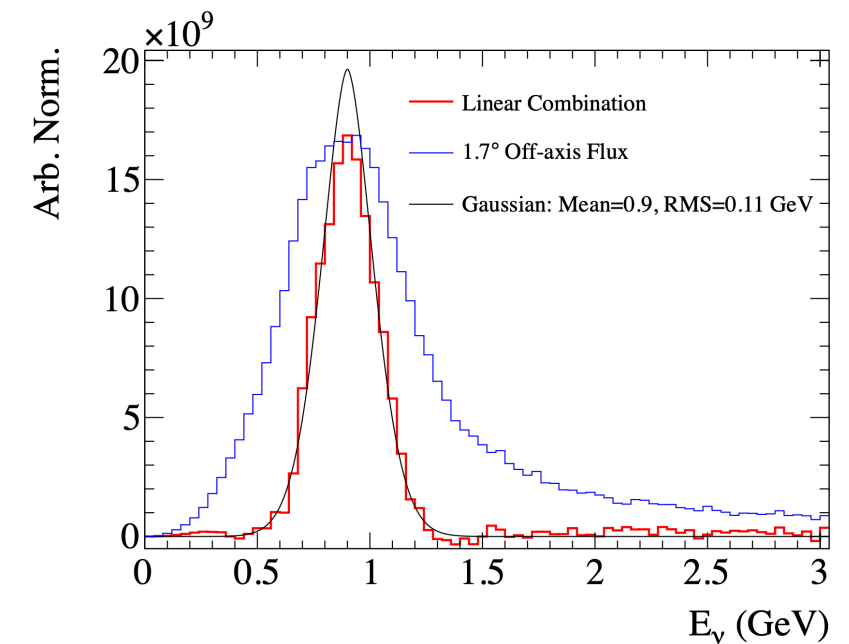
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Experimental Neutrino Cross Sections

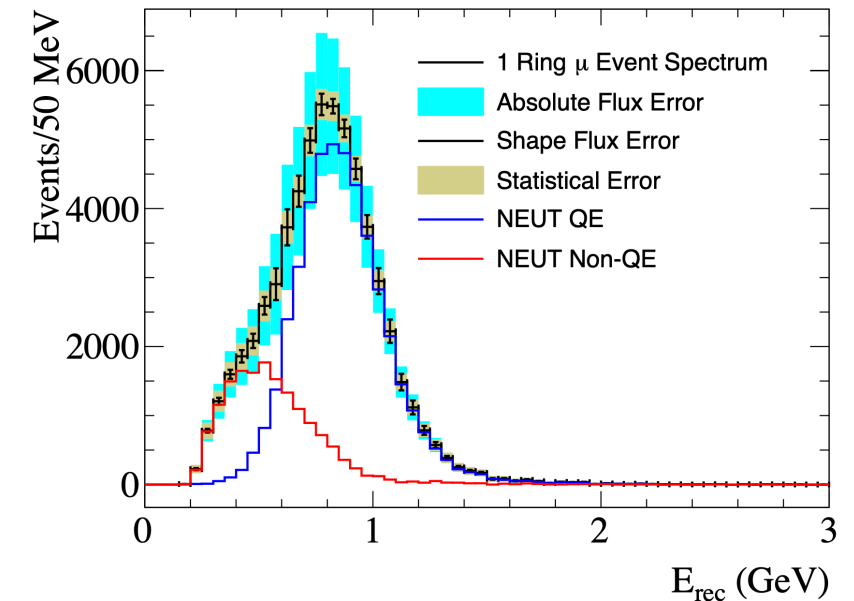
PRISM concept, II

- First steps:
 - Take lots data at several different angles
 - Plot the observable you have in mind for each angle
- Take linear combinations of the data you took
 - Take linear combinations of the predicted fluxes
- Two options:
 - Create the most monochromatic flux you can
 - Create the flux that looks like the “oscillated flux”
- “Energy calibration”
 - Pick your favourite energy reconstruction method: how different does that look for your monochromatic beam?
 - To test this, flux has to be narrower than the smearing effect you are trying to measure

Graphics from M. Wilking, Lepton-Nucleus Scattering XIV, 2015

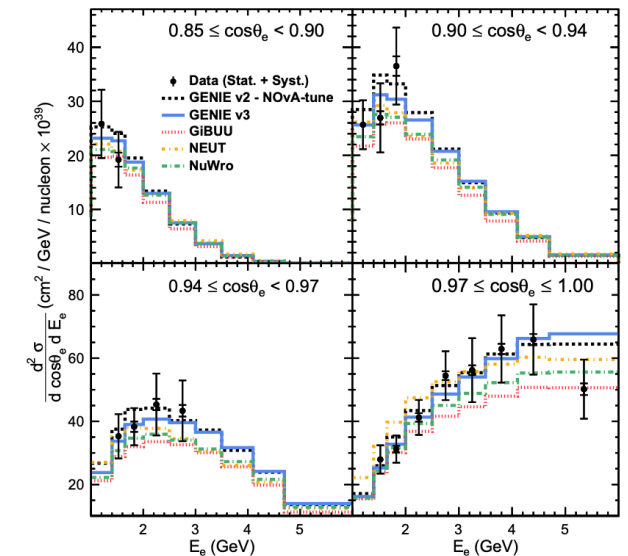
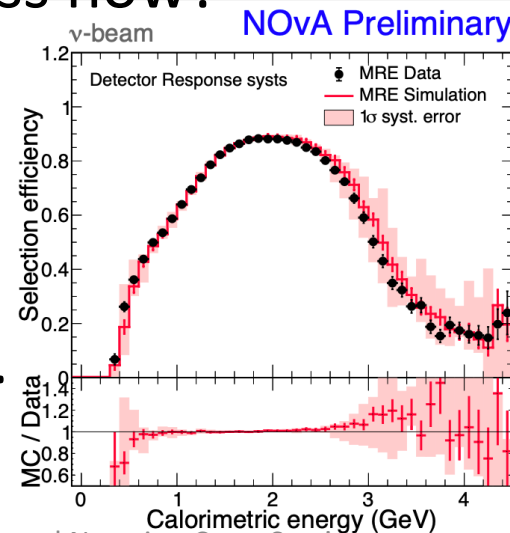
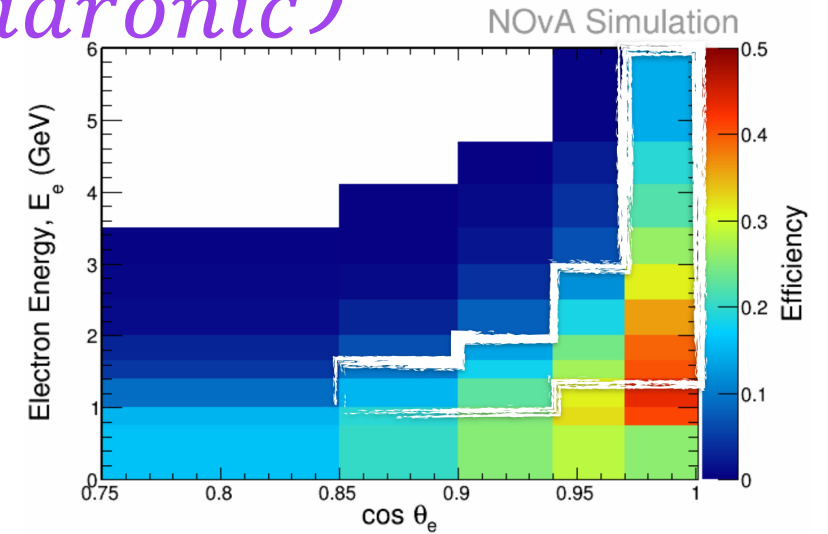


Linear Combination, 0.9 GeV Mean



NOvA: Using Data to test $\epsilon(E_{hadronic})$

- NOvA has produced first double differential cross section for electron neutrino charged current inclusive scattering
- Use Boosted Decision Tree to identify electrons
- How do they know that they model the efficiency of the BDT correctly given uncertainties in hadron energy? Use the Data! Can you guess how?
- “Muon Removal” Technique: remove muon from ν_μ CC data events, add electron at same angle and energy, then measure efficiency, and compare to the efficiency for original simulation.

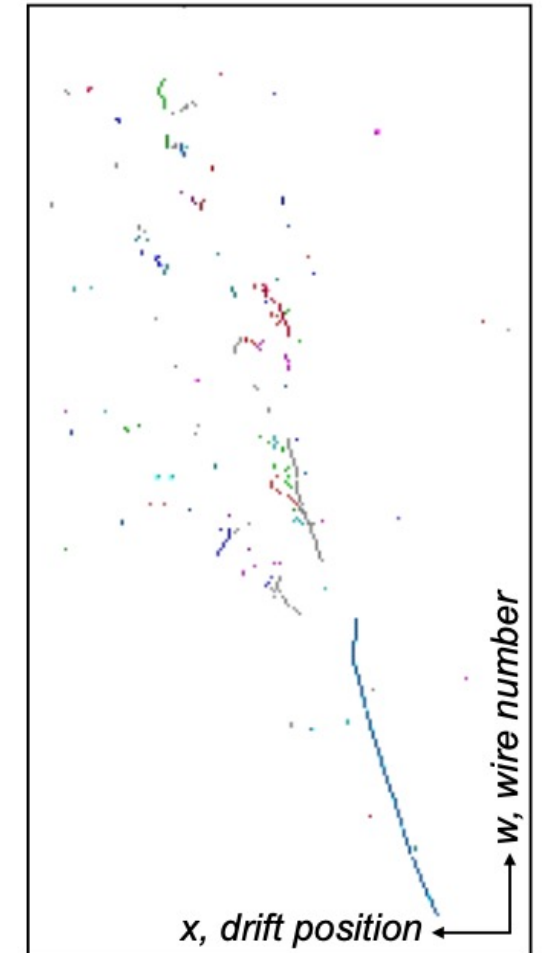
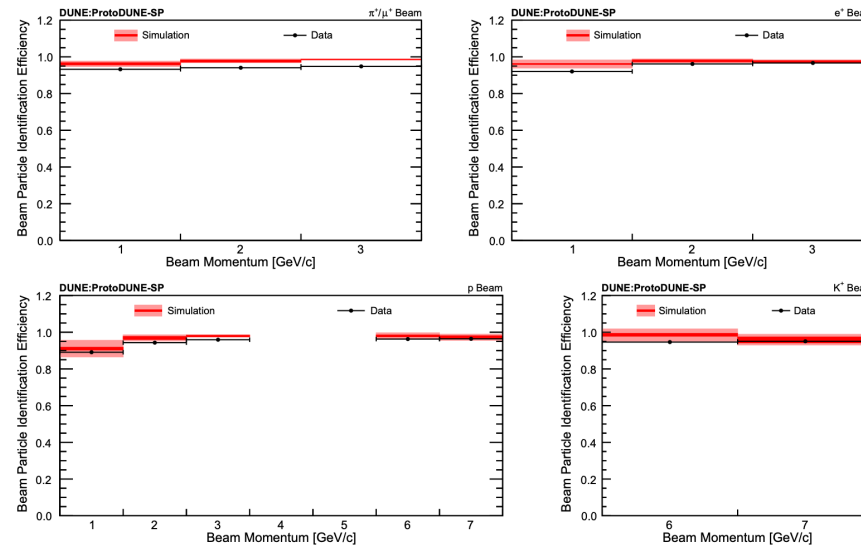


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Can DUNE test prediction of $\epsilon(E_{had})$?



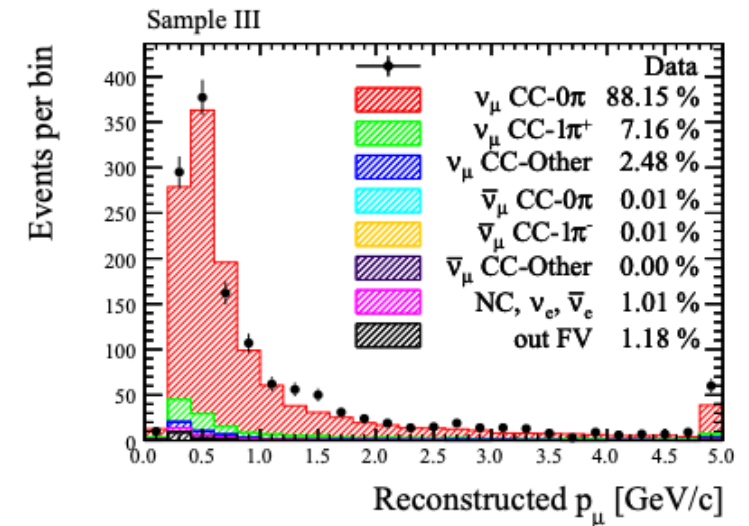
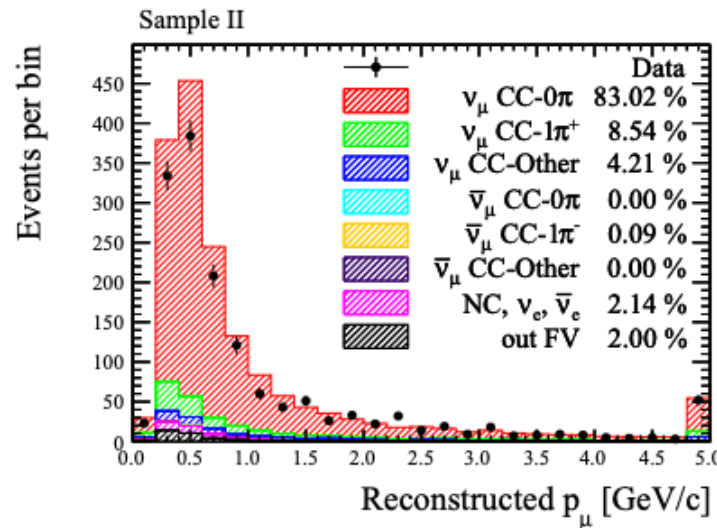
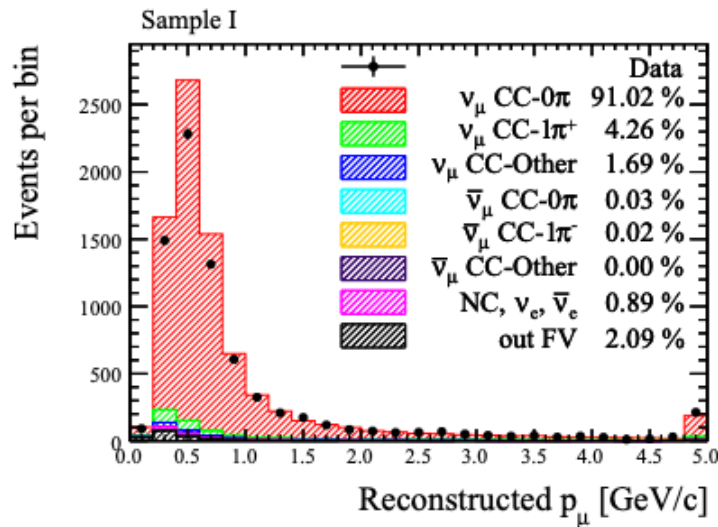
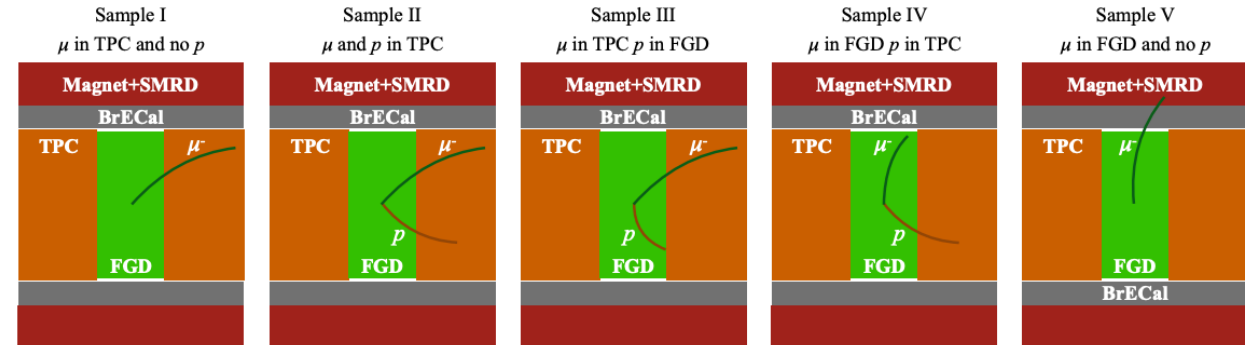
- Answer: Yes, Test Beam program (ProtoDUNE)!
- Many experiments have done this:
 - take well-measured charged hadron beam
 - shoot it at your detector
 - make sure your simulation matches your data
- Can also use cosmic rays (or beam-induced muons) as “ $\epsilon(x_m)$ calibration crosscheck”



Eur.Phys.J.C 83 (2023) 7

T2K: Letting U_{mt} vary

- T2K: Showing 3 out of 5 samples
- “CC0 π ” Analysis for ν_μ
- Try to get as many μ as possible!



• *Phys.Rev.D* 101 (2020) 11, 112001

T2K: Letting U_{mt} vary

- In order to incorporate systematic uncertainties on cross section model, T2K parameterizes the uncertainties and then lets them float in a fit that incorporates not only the signal region but also two control samples

Likelihood:

$$\chi^2 \approx -2 \log \mathcal{L} = -2 \log \mathcal{L}_{\text{stat}} - 2 \log \mathcal{L}_{\text{syst}}$$

statistic term (Barlow-Beeston)

$$2 \sum_j^{\text{reco bins}} \left(\beta_j N_j^{\text{MC}} - N_j^{\text{obs}} + N_j^{\text{obs}} \log \frac{N_j^{\text{obs}}}{\beta_j N_j^{\text{MC}}} + \frac{\beta_j^2 - 1}{2\sigma_j^2} \right)$$

Where:

$$\beta_j = \frac{1}{2} \left(-(N_j^{\text{MC}} \sigma_j^2 - 1) + \sqrt{(N_j^{\text{MC}} \sigma_j^2 - 1)^2 + 4 N_j^{\text{MC}} \sigma_j^2} \right)$$

systematic term

$$(\vec{p} - \vec{p}_{\text{prior}}) \mathbf{V}_{\text{syst}}^{-1} (\vec{p} - \vec{p}_{\text{prior}})$$

Cross-Section Flux Detector

Example:



Event prediction (as a function of models parameters):

$$N_j^{\text{MC}} = \sum_i^{\text{true bins}} \left(c_i w_{ij}^{\text{sig}}(\vec{p}) N_{ij}^{\text{sig}} + w_{ij}^{\text{bkg}}(\vec{p}) N_{ij}^{\text{bkg}} \right)$$

• Jesus-Valls, NuINT 2022, and Phys.Rev.D 101 (2020) 11, 112001

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Experimental Neutrino Cross Sections

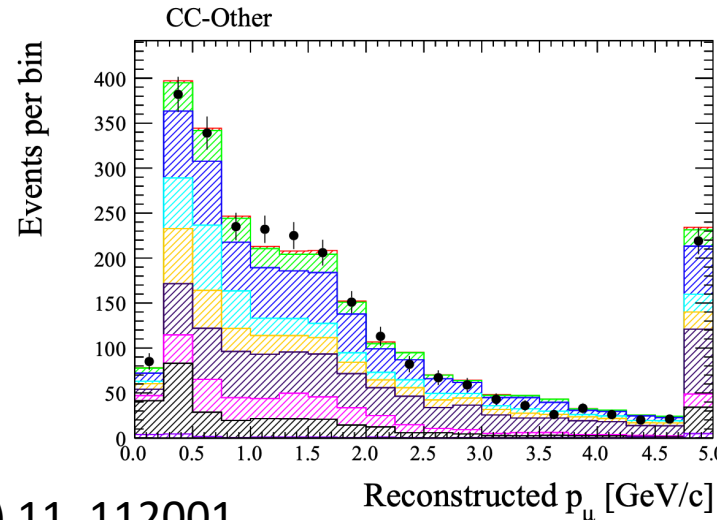
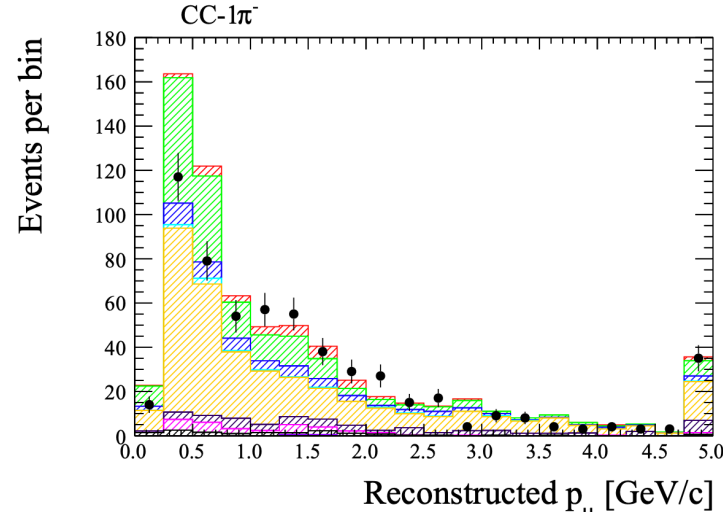


TABLE II. Prior values and errors of the cross section model parameters used in this analysis.

Parameter	Prior	Error
M_A^{QE} (GeV/c ²)	1.2	0.3
p_F^C (MeV/c)	217	30
E_B^C (MeV)	25	9
2p2h ν	1	1
2p2h $\bar{\nu}$	1	1
C_A^5 (GeV/c ²)	1.01	0.12
M_A^{Res} (GeV/c ²)	0.95	0.15
$I_{1/2}$	1.3	0.2
DIS Multiple pion	0.0	0.4
CC Coherent on C	1.0	1.0
CC-1 π $E_\nu < 2.5$ GeV	1.0	0.5
CC-1 π $E_{\bar{\nu}} < 2.5$ GeV	1.0	1.0
CC-1 π $E_\nu > 2.5$ GeV	1.0	0.5
CC-1 π $E_{\bar{\nu}} > 2.5$ GeV	1.0	1.0
CC Multile π	1.0	0.5
CC-DIS ν	1.0	0.035
CC-DIS $\bar{\nu}$	1.0	0.065
NC Coherent	1.0	0.3
NC Other	1.0	0.3
Pion production	0.0	0.5
Pion absorption	0.0	0.41
Pion quasi-elastic int. for $p_\pi < 500$ MeV/c	0.0	0.41
Pion quasi-elastic int. for $p_\pi > 400$ MeV/c	0.0	0.34
Pion charge exchange for $p_\pi < 500$ MeV/c	0.0	0.57
Pion charge exchange for $p_\pi > 400$ MeV/c	0.0	0.28

T2K: Letting U_{mt} vary

NB: this is like Scott's lecture yesterday with the two rulers with different coefficients of expansion: letting the data tell you something about a systematic effects

Likelihood:

$$\chi^2 \approx -2 \log \mathcal{L} = -2 \log \mathcal{L}_{\text{stat}} - 2 \log \mathcal{L}_{\text{syst}}$$

statistic term (Barlow-Beeston)

$$2 \sum_j^{\text{reco bins}} \left(\beta_j N_j^{\text{MC}} - N_j^{\text{obs}} + N_j^{\text{obs}} \log \frac{N_j^{\text{obs}}}{\beta_j N_j^{\text{MC}}} + \frac{\beta_j^2 - 1}{2\sigma_j^2} \right)$$

Where:

systematic term

$$(\vec{p} - \vec{p}_{\text{prior}}) \mathbf{V}_{\text{syst}}^{-1} (\vec{p} - \vec{p}_{\text{prior}})$$

Cross-Section Flux Detector

Event prediction (as a function of models parameters):

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• Jesus-Valls, NuINT 2022, and Phys.Rev.D 101 (2020) 11, 112001

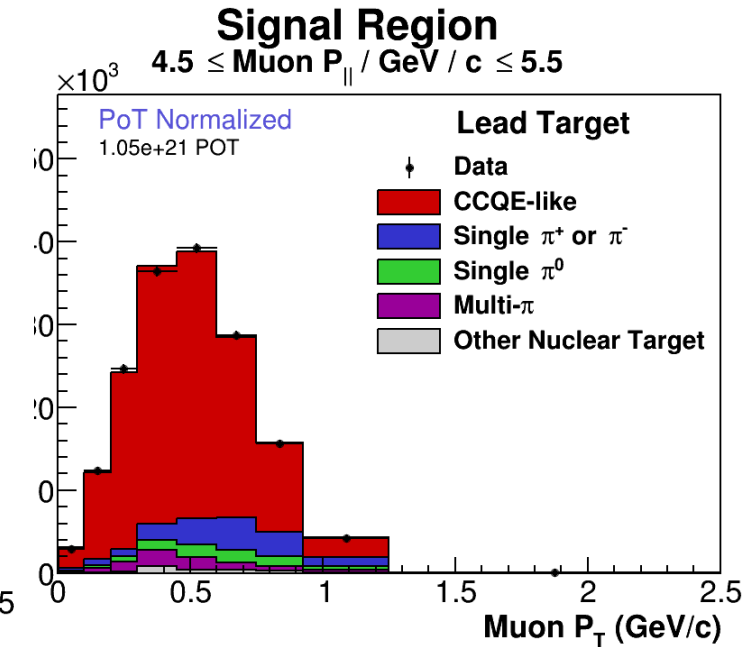
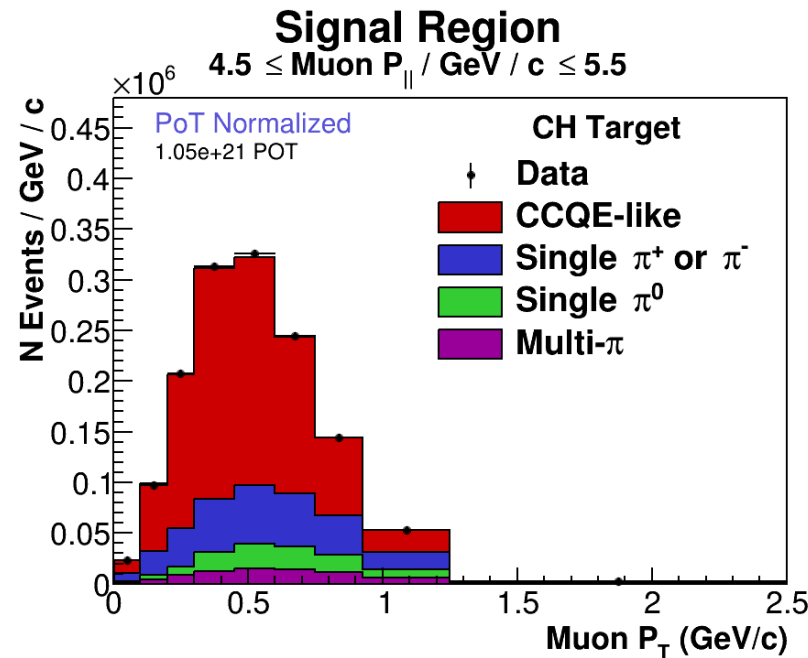
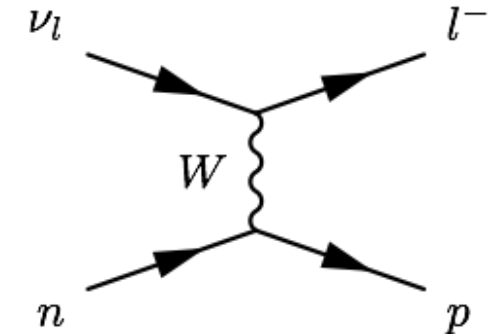
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Experimental Neutrino Cross Sections

Reconstructed p_μ [GeV/c]

Using data to predict $B(x_m)$

- Quasi-elastic neutrino scattering should have an easily-identifiable signature: one muon and one proton
- Example from MINERvA: if you only require a muon ($p > 1.5 \text{ GeV}/c$)
- and NO other energy deposits far from the nucleus, here are the backgrounds:

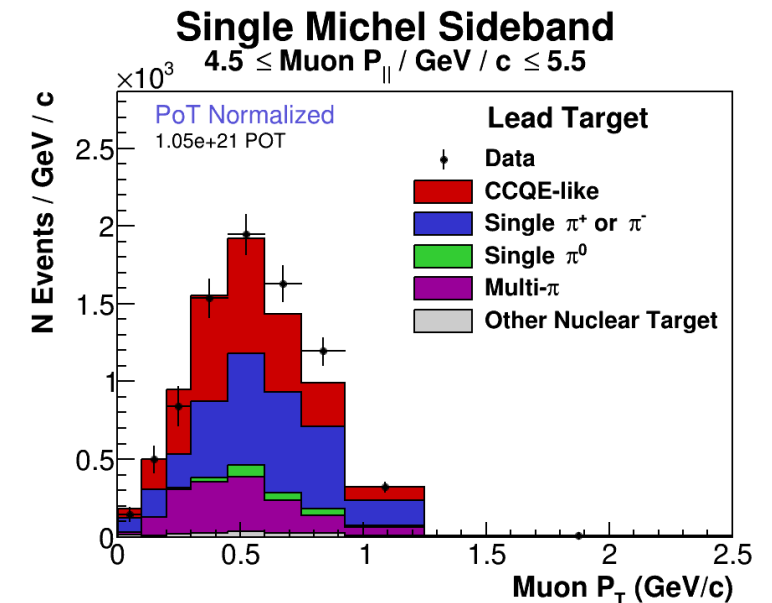
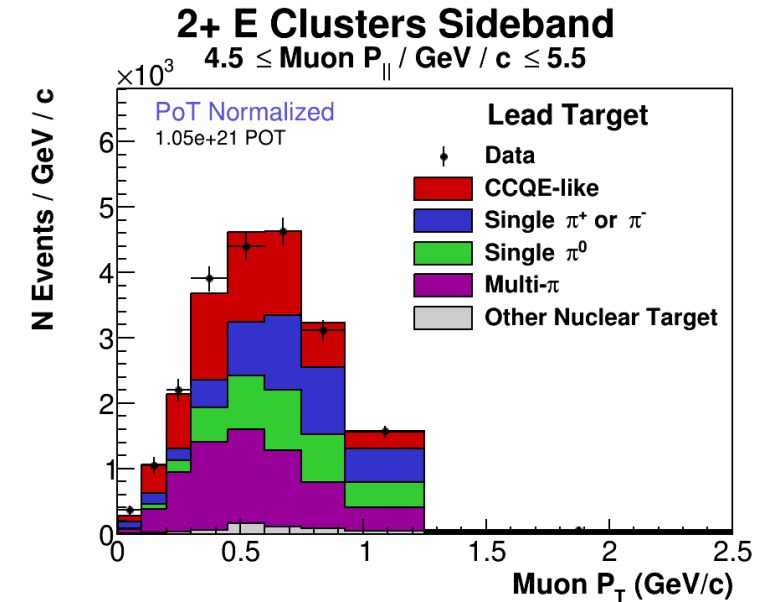


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Using Data to predict $B(x_m)$

- Remember: the CCQE process is probably the best known neutrino-nucleus process, how could you trust your simulation to tell you the background levels?
- Solution: Use the data itself, but try to isolate each background by looking at the events you REMOVED from the signal process
- How to find events with π^+ ?
- How to find events with π^0 ?
- Remember, red is signal: can't always find event samples that have all one background, or no signal events in them...

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NOvA: Charged Current π^0 Production

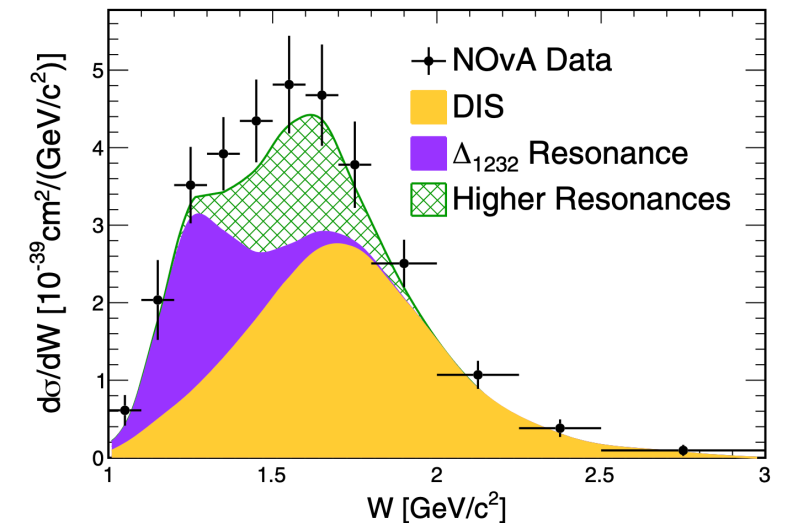
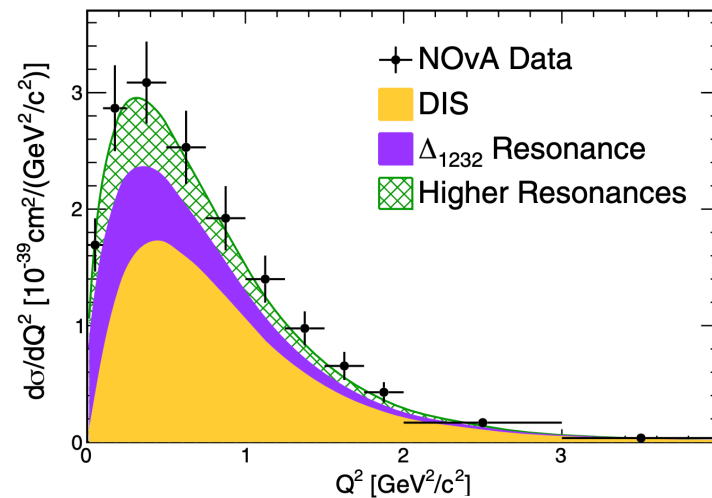
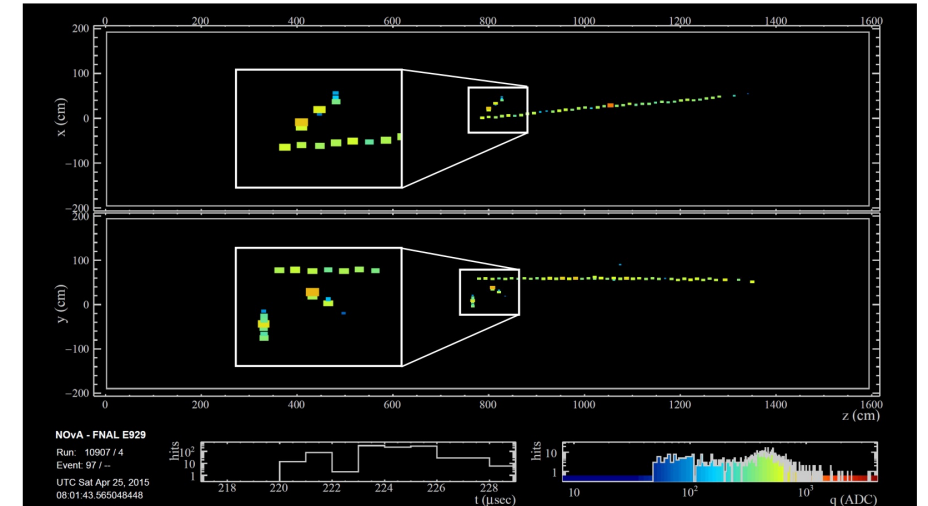
- NOvA: 165,000 events
- How would you isolate a CC π^0 event?
- What would you guess the backgrounds are?
- How would you estimate the backgrounds?
- What would the variables of interest be?

$$Q^2 = -(P_\mu - P_\nu)^2$$

$$= \frac{2E_\nu}{c} \left(\frac{E_\mu}{c} - p_\mu \cos \theta_\mu \right) - m_\mu^2 c^2$$

$$W = \frac{1}{c} |P_N + P_\nu - P_\mu|$$

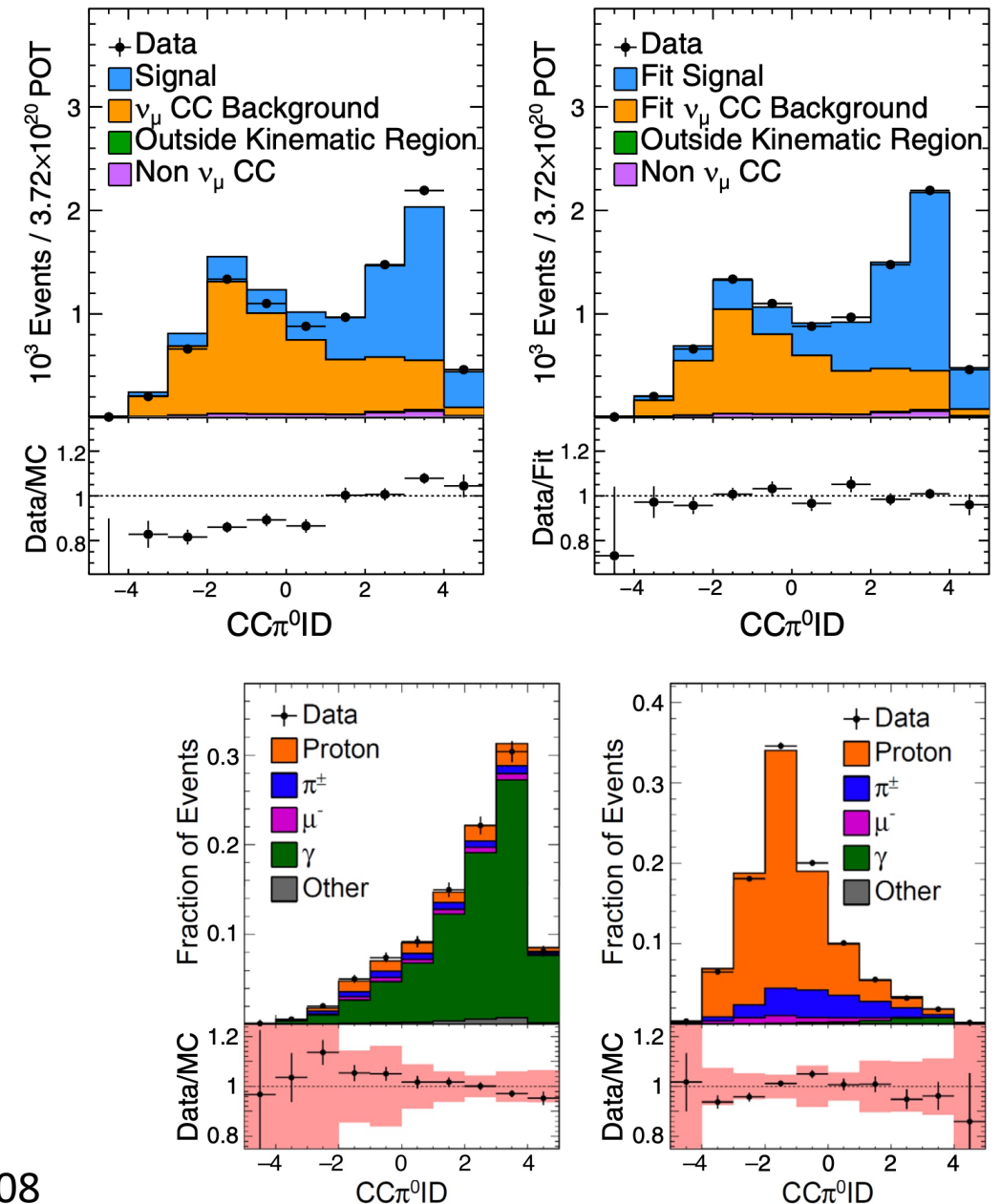
$$= \frac{1}{c} \sqrt{m_N^2 c^2 - Q^2 + 2m_N(E_\nu - E_\mu)},$$



NOvA: Predict $B(x_m)$

- NOvA uses a $\text{CVN}\nu_\mu$ Classifier to identify $\nu_\mu\text{CC}$ events
- Classified using GENIE, reports what type of interaction it was
- Remove events consistent with CCQE or Coherent π^+ production, since those would only have π^0 's through FSI
- THEN, use a $\text{CC}\pi^0\text{ID}$ classifier, and fit resulting distribution to data in order to determine signal and background fractions
- Test on identified protons and photons in the data

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Why is measuring Hadron Energy Difficult?

- What could you measure about final state hadronic system
 - Do you track charged particles so you can measure their total kinetic energy?
 - Can you distinguish between p , π^+ , π^+ , π^0
 - What about neutrons, do you see those?

Example from MINERvA at right,
3.3cm plastic granularity

Similar in spirit to ~ 3 cm wire pitch Liquid Argon (but different density, Z)

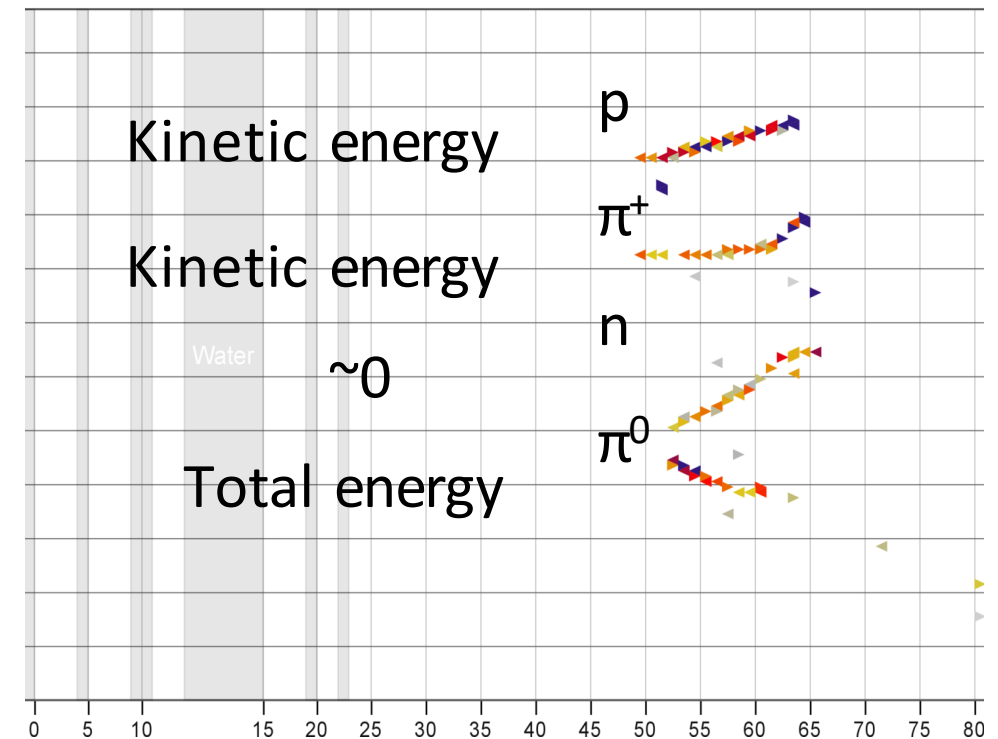


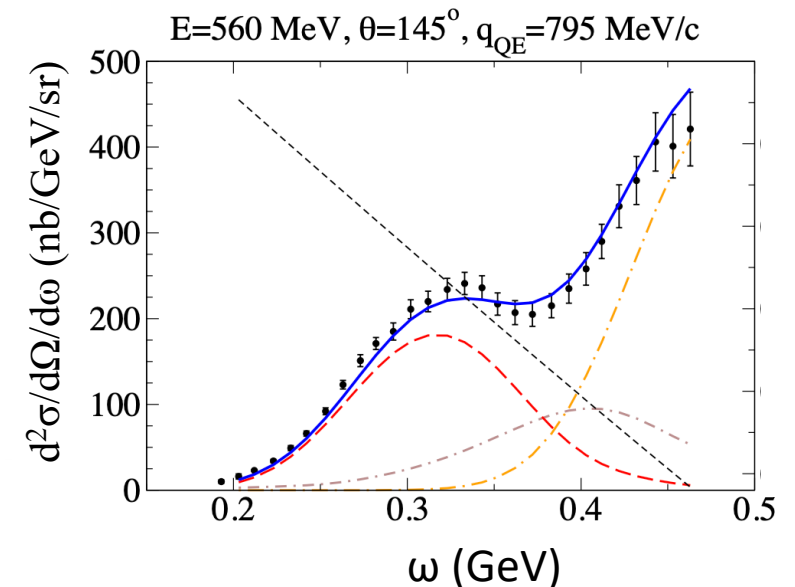
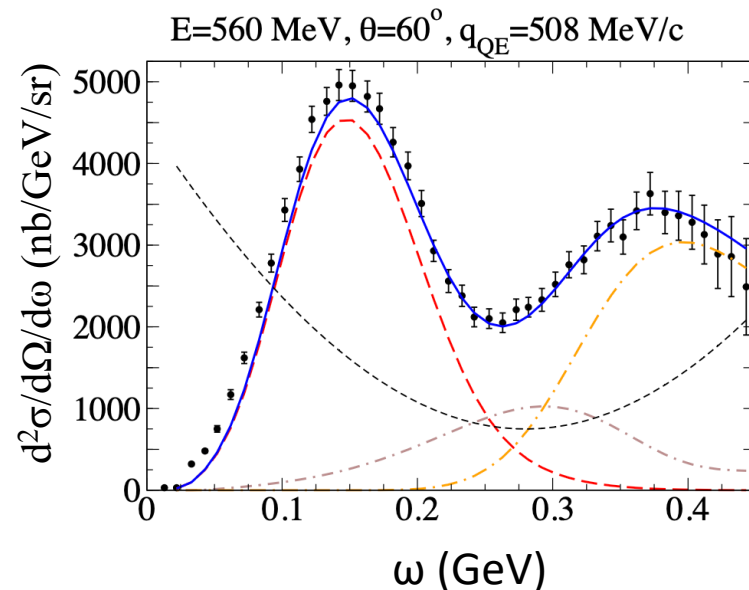
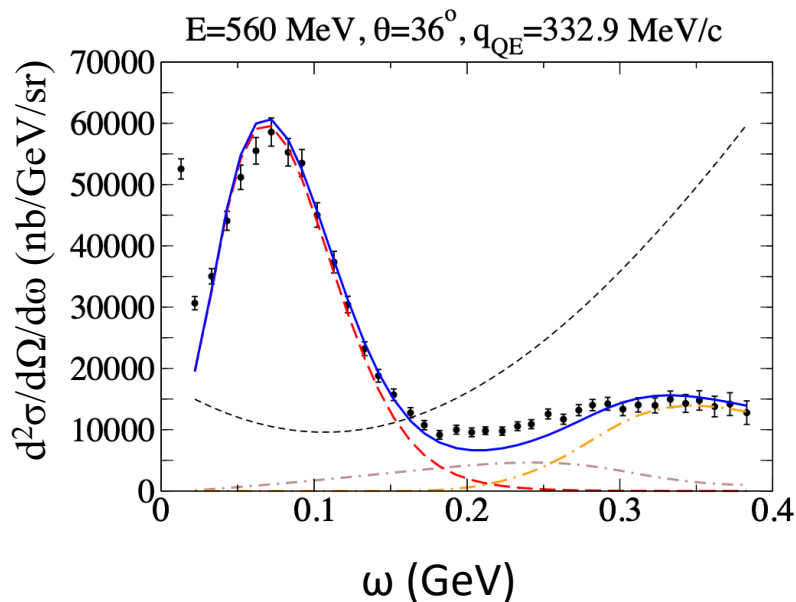
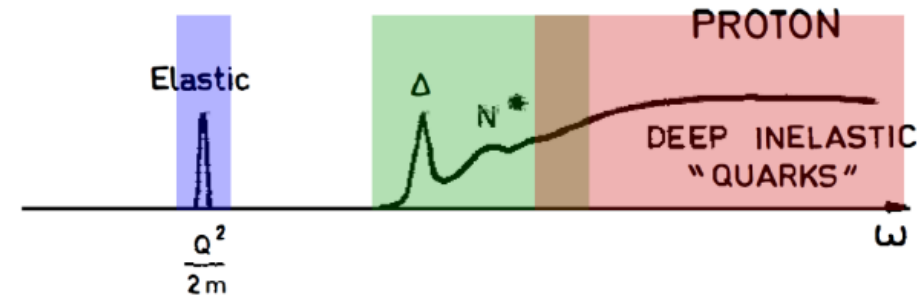
Figure courtesy P. Rodrigues

Neutrino Observables: what should x_m be?

- Let's say you have measured the following quantities:
 - Final lepton charge and momentum 3-vector: can determine $p_{lep}, E_{lep}, \theta_{lep}$
 - Total hadronic energy
(**pretend** you can see all of it, even the neutron energy) E_{had}
- Can define a few quantities:
 - Estimated Neutrino Energy $E_v = E_{lep} + E_{had}$
 - Estimated Momentum Transfer (squared) to the nucleus:
(remember, W is virtual) $-q^2 = Q^2 = 2 E_v (E_\mu - p_\mu \cos \theta_\mu) - M_\mu^2$
 - Estimated Energy transferred to the nucleus = $\omega = E_{had}$
 - 3-momentum transferred to the nucleus: $Q^2 + \omega^2 = q_3^2$

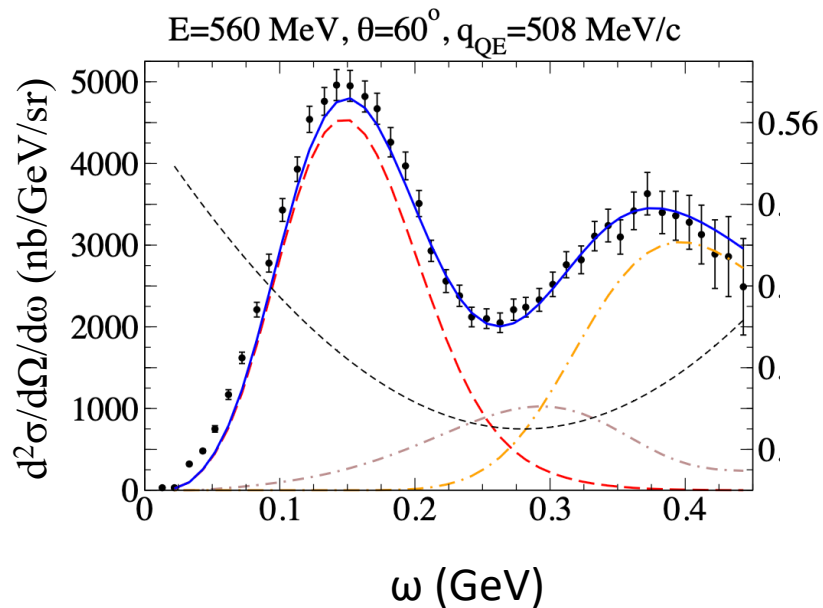
Neutrino Observables: what should x_m be?

- This picture comes from electron scattering: electron beam (energy E) comes in, scatters, you measure the outgoing electron energy distribution (E') at some angle, and $\omega = E - E'$



Neutrino Observables: what should x_m be?

- Translating this picture to Neutrino Scattering

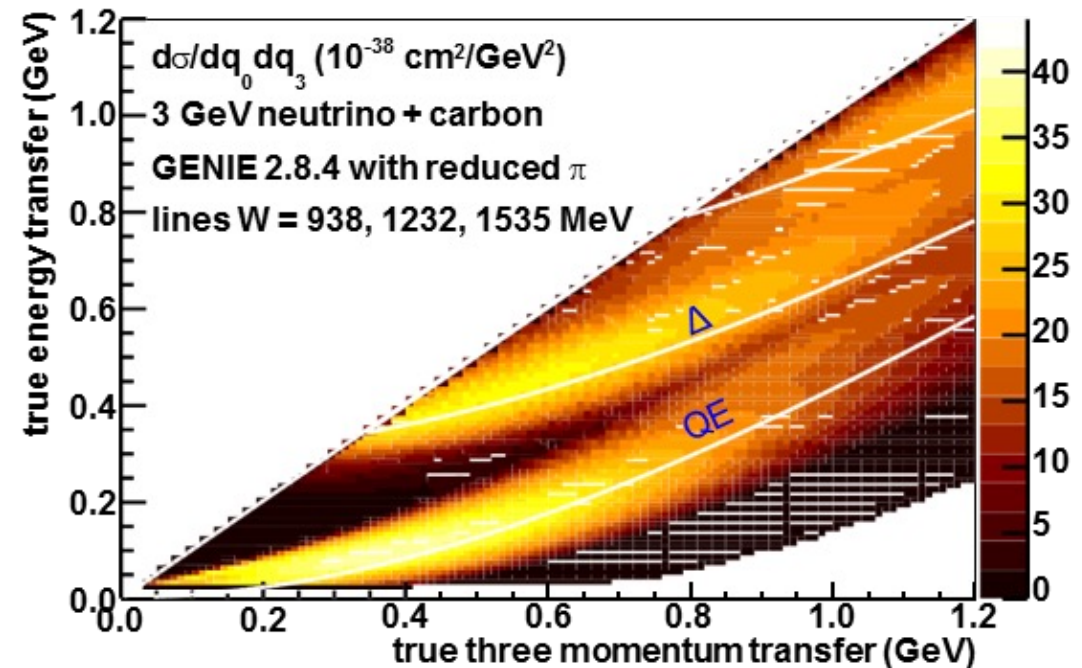


Initial and Final
Electron energy and
angle define a 3-
momentum transfer

For neutrinos:
True Energy
transfer: ω

True 3-momentum
transfer: $Q^2 + \omega^2 = q_3^2$

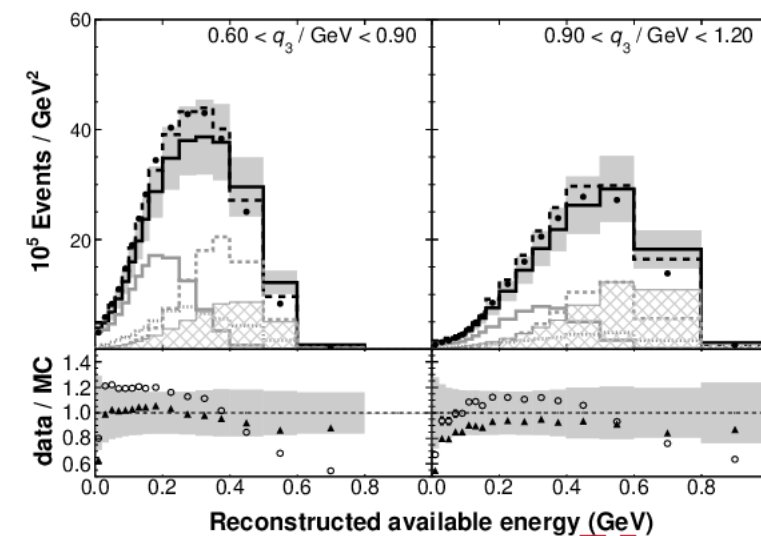
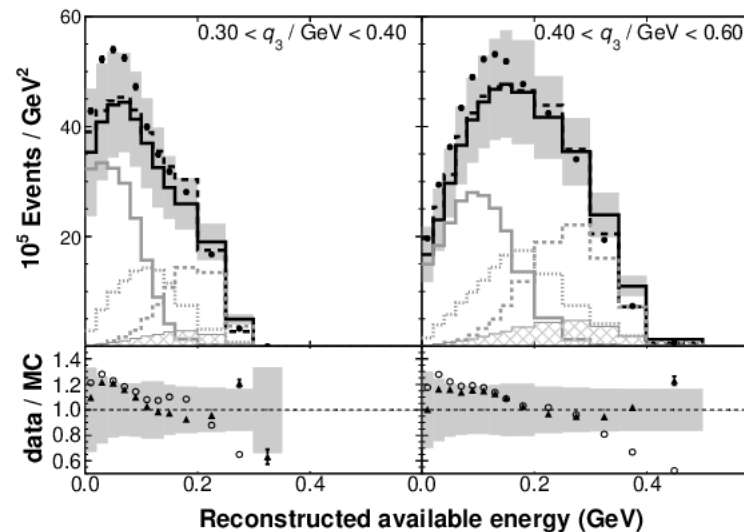
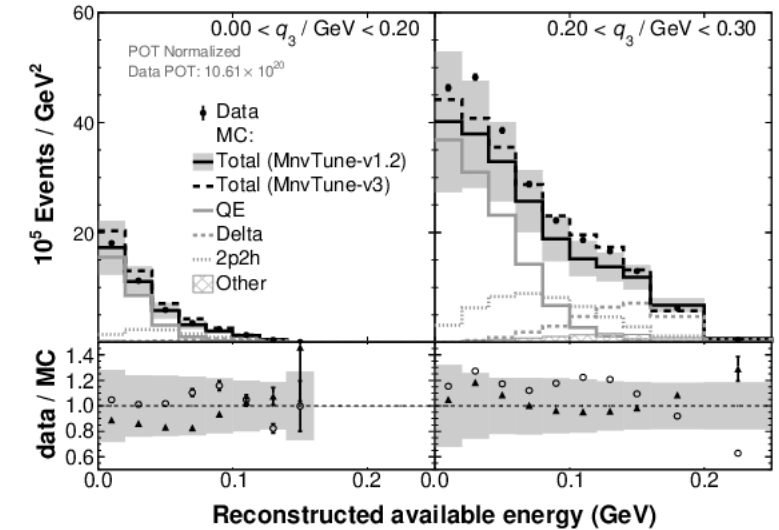
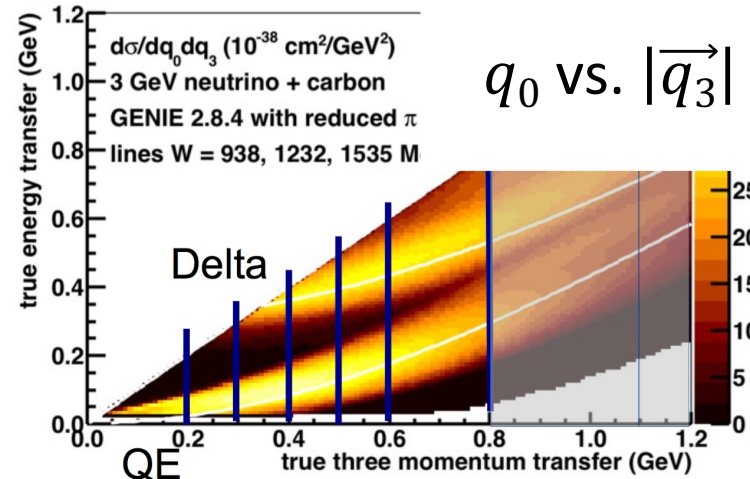
Graphics courtesy R. Gran



What does the Data Look like in this space?

- Look at inclusive sample of events as function of energy AND momentum transferred
- Showing event distributions, but cross sections were extracted
- Cross sections were also extracted from these distributions
- Unfolding this was tricky!

M. Ascencio et al,
Phys.Rev.D 106 (2022) 3, 032001

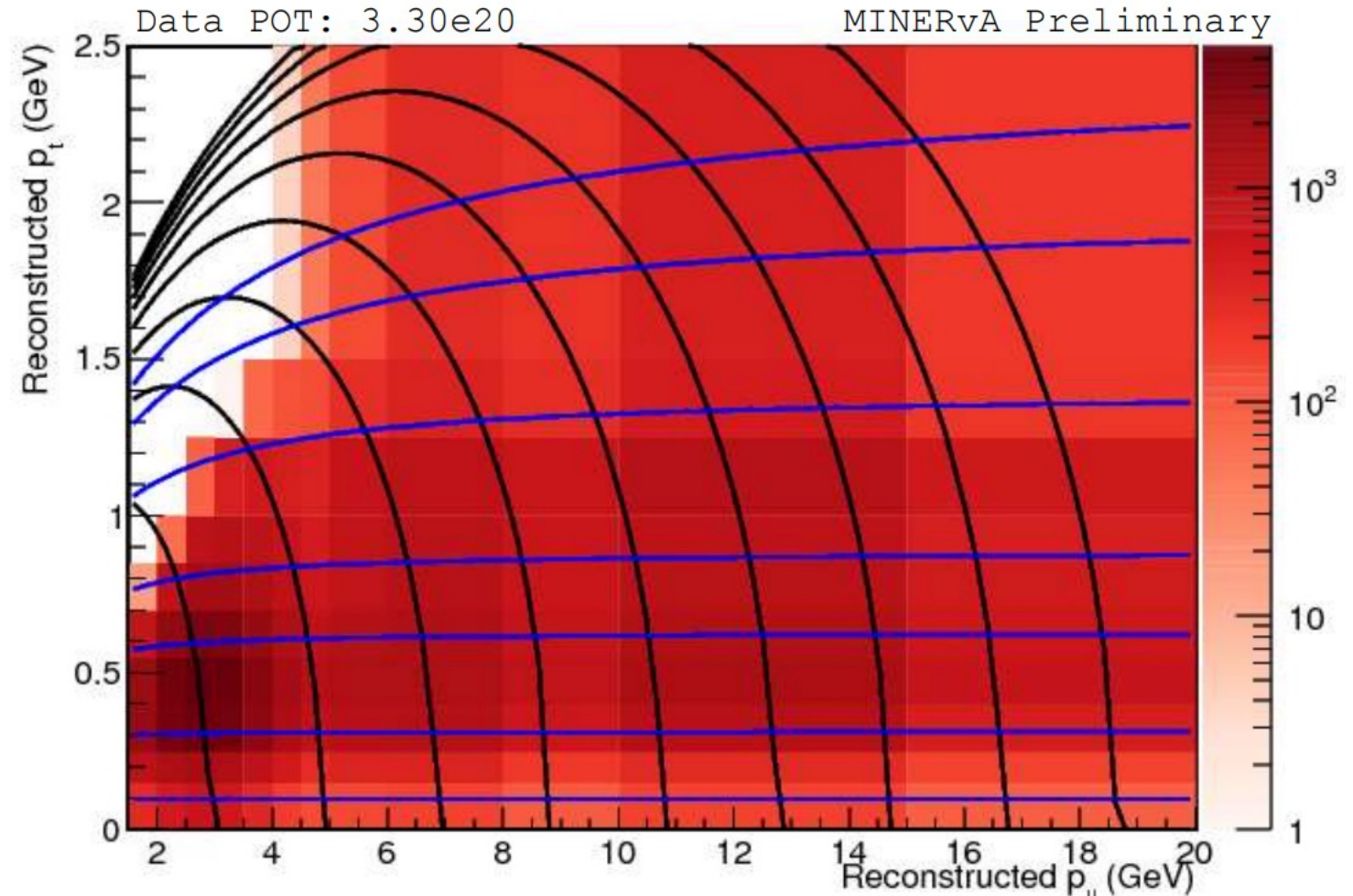


What about using lepton kinematics alone?

- Since it's hard to model hadron energy resolution at low E_{had}
- If hadron energy was very small compared to muon energy (QE interactions), maybe you could use muon momenta (p_{\parallel} , p_t) as a proxy for E_{ν} and Q^2 ?
- Example at the right:

Lines of constant $E_{\nu, \text{qe}}$
[3,7,11,15,19GeV]

Lines of constant Q^2_{qe}
[0.01,0.1,0.4,0.8,2.0,4.0,6.0GeV²]



D. Ruterbories, FNAL W&C March 2017

Observables in Quasielastic Interactions

- If you have a quasielastic interaction, *and* the initial nucleon is at rest, you can estimate the neutrino energy and momentum transfer from the lepton kinematics ALONE
- This is how T2K makes its (most precise) oscillation measurements!
 - Require ONLY one lepton in the final state
 - Require conservation of energy and momentum
- You heard from Stephen Dolan why this is a problem, but it's still an observable
- Just don't call it true energy if you are scattering off a big nucleus!

$$E_{\nu}^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_{\mu}^2 + 2(m_p - E_b)E_{\mu}}{2(m_p - E_b - E_{\mu} + p_{\mu} \cos \theta_{\mu})}$$

$$Q_{QE}^2 = 2E_{\nu}^{QE}(E_{\mu} - p_{\mu} \cos \theta_{\mu}) - m_{\mu}^2,$$

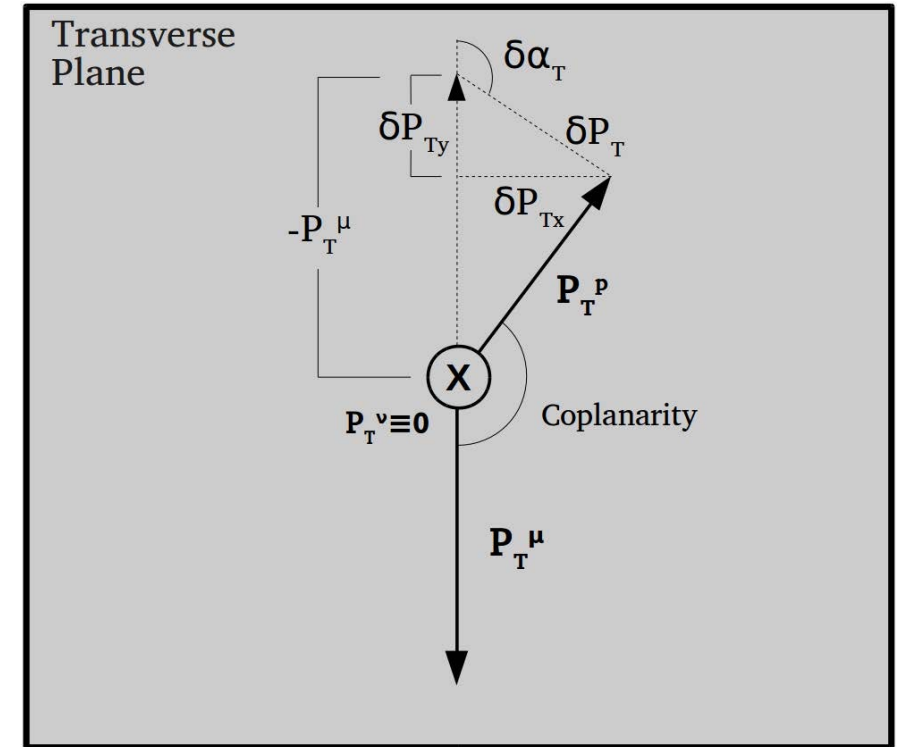
New Neutrino Observables: Transverse Kinematic Imbalance (TKI)

- If you know you're starting with a neutrino, and you see a muon and a proton in the final state, you can calculate kinematics in the plane transverse to the neutrino direction if you measure 3-vector of both final state particles, and you are SURE they are a muon and a proton

$$\delta p_T = |\delta \mathbf{p}_T| = |\mathbf{p}_T^\mu + \mathbf{p}_T^p|,$$

$$\delta \alpha_T = \arccos \left(-\frac{\mathbf{p}_T^\mu \cdot \delta \mathbf{p}_T}{p_T^\mu \delta p_T} \right),$$

$$\delta \phi_T = \arccos \left(-\frac{\mathbf{p}_T^\mu \cdot \mathbf{p}_T^p}{p_T^\mu p_T^p} \right).$$

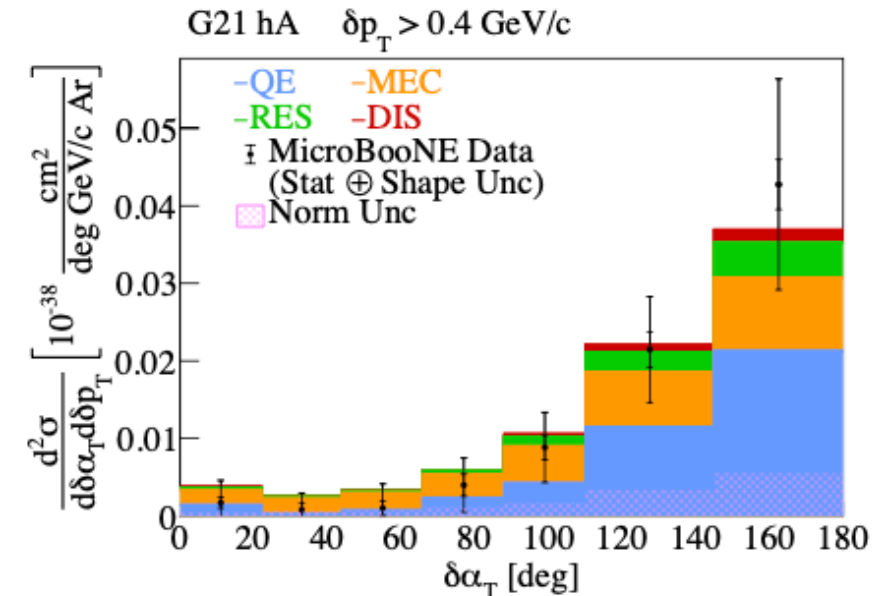
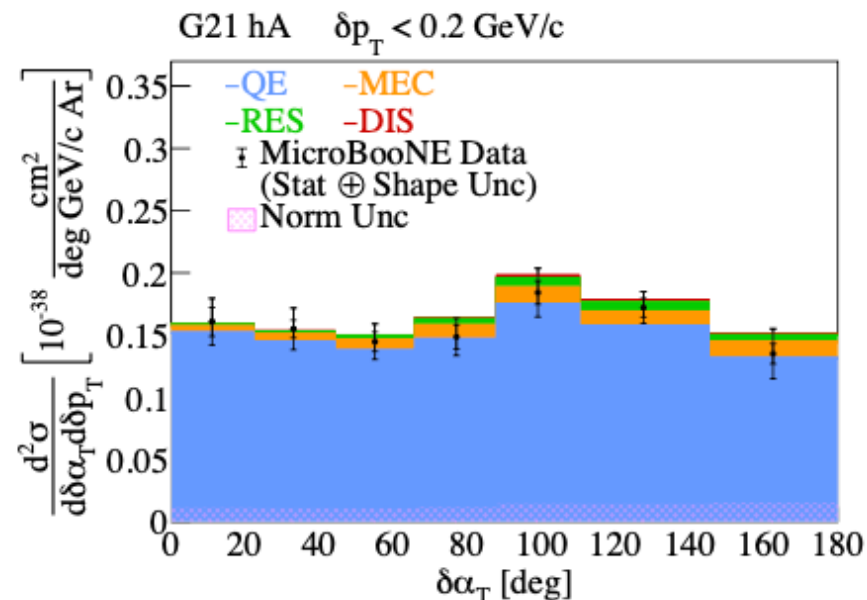
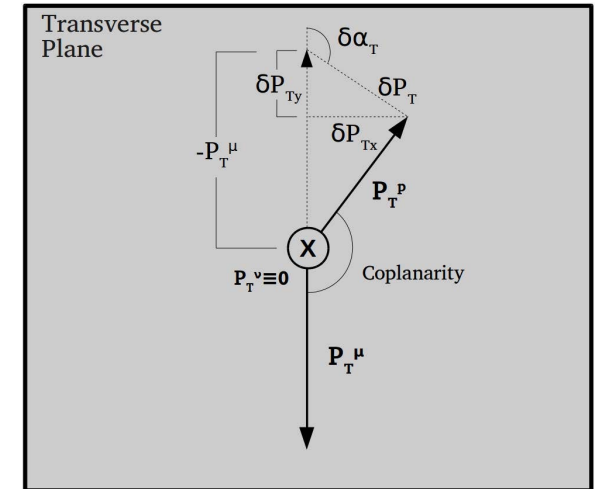


$$P_n \equiv \sqrt{\delta P_T^2 + \delta P_L^2}$$

Phys. Rev. C **94**, (2016) 015503

MicroBooNE: Looking at TKI in 2 dimensions

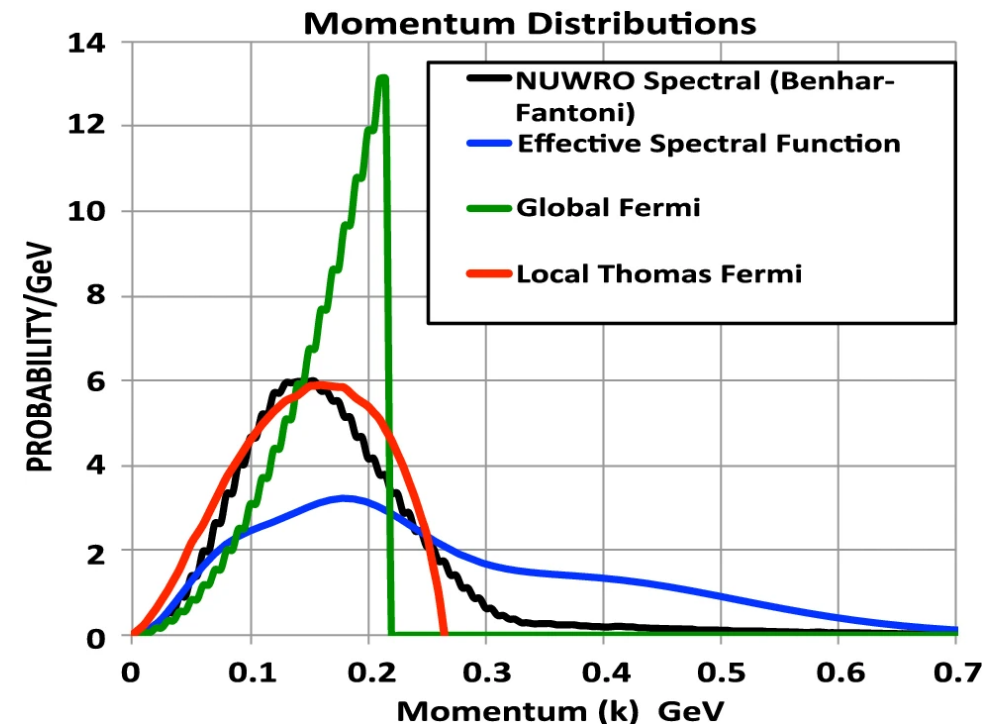
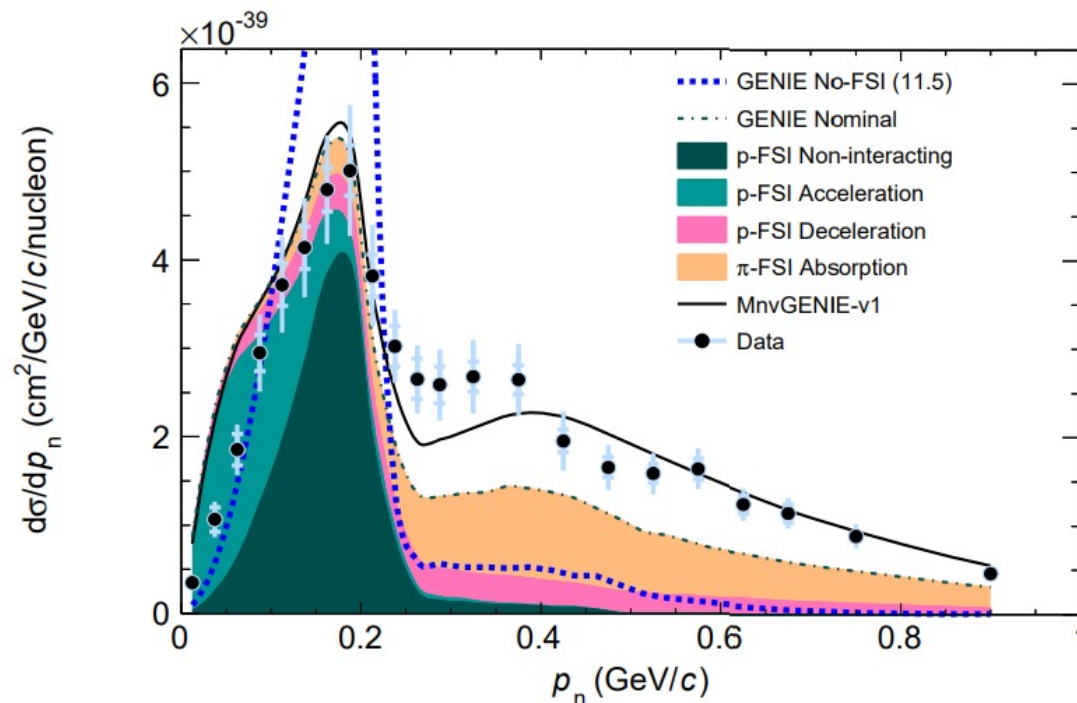
- MicroBooNE split these distributions up into “QE-rich” samples and “everything else” samples
- Plus: Another tool of the trade: “Fake Data Studies”
 - Put in different interaction models see if your procedure extracts predictions from the new model or the one in your unfolding matrix



[arXiv:2301.03700](https://arxiv.org/abs/2301.03700)

“Initial Nucleon Momentum” as observable?

- Another “transverse kinematic imbalance variable”: if you assume conservation of momentum for events with a final state proton and muon, can calculate the initial nucleon momentum

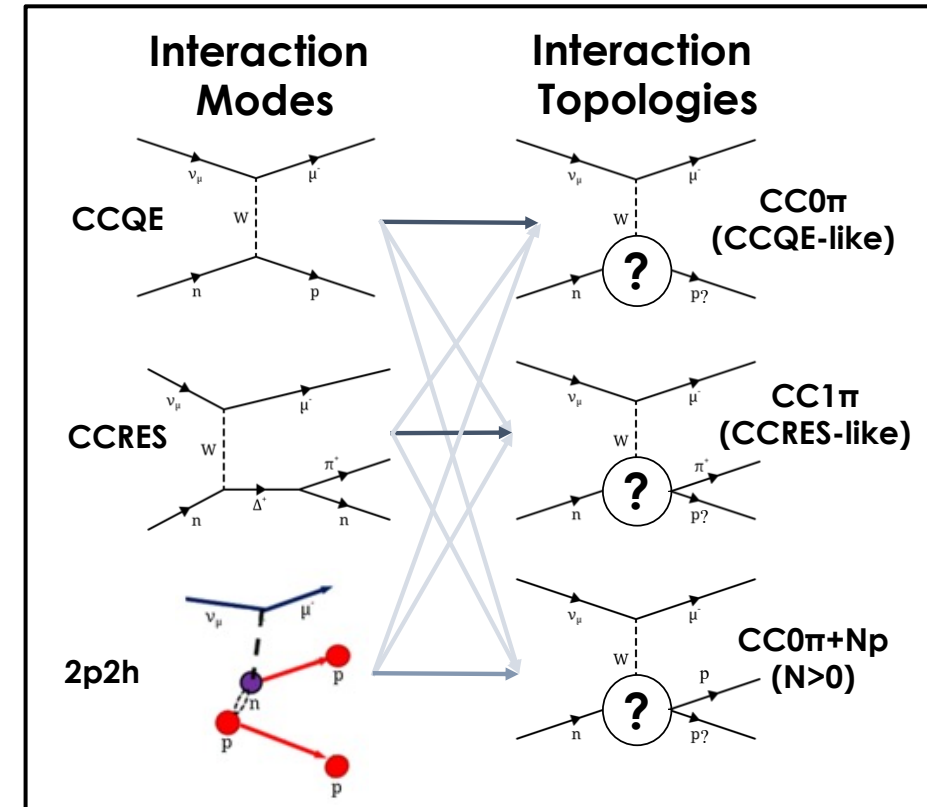


Current Cross Section Measurements

- Quasielastic-like (“CC0 π ”) Cross sections
 - As function of lepton kinematics
 - As function of lepton AND hadron energies
 - As function of “transverse variables” (come back tomorrow!)
- Pion Production Cross Sections
 - As function of lepton kinematics
 - As function of pion kinematics
 - As function of Q^2 or W , or even “transverse variables”
- Inclusive Cross Sections
 - As function of lepton kinematics
 - As function of q_0 and q_3

Have to map on to Cross Section Models

- Quasielastic Scattering
- 2p2h (correlated nucleon pairs) Scattering
- Resonant Pion Production (Δ 's, etc.)
- Continuum Pion Production
- Coherent Pion Production
- Shallow Inelastic Scattering (?)
- Deep Inelastic Scattering
- Plus models for initial and final state effects



S. Dolan, INSS 23

Challenges

- Goal: make measurements that can constrain models
- Why is this difficult?
 - Given the **flux**, you never know precisely what neutrino energy you have for any one event
 - Given the analysis cuts to **isolate the signal** you are trying to find, the detector limitations mean you may have backgrounds in your sample
 - Given detector limitations you never know precisely what energy you missed from neutrons
 - If that's not bad enough, there's also the fact that nuclear effects can make one process look like another even if your detector was perfect

How to summarize this field?

- Want to cover “current cross sections” but...
- Consider the various combinations: 6x4x5x6



Interaction
Inclusive Scattering
CC 0π Production
CC $1\pi^+$ Production
CC $1\pi^0$ Production
CC Shallow or Deep Inelastic Scattering
Rare Channels (ν -e, coherent scattering)

Flavour, Helicity
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

Target Nucleus
CH
H ₂ O
H, He, C, Pb
Ar
Pb

Observable (x_m)
Lepton Kinematics
Q^2
q_0 vs q_3
Proton Kinematics
Pion Kinematics
Transverse Kinematic Imbalance variables (many)
“Neutrino Energy”

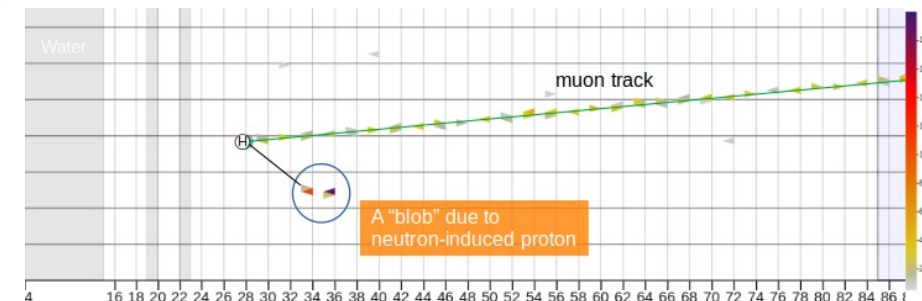
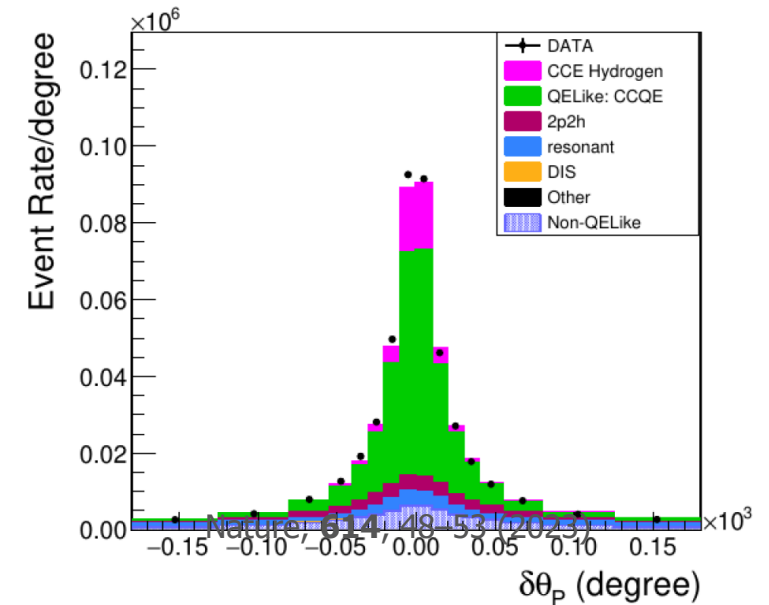
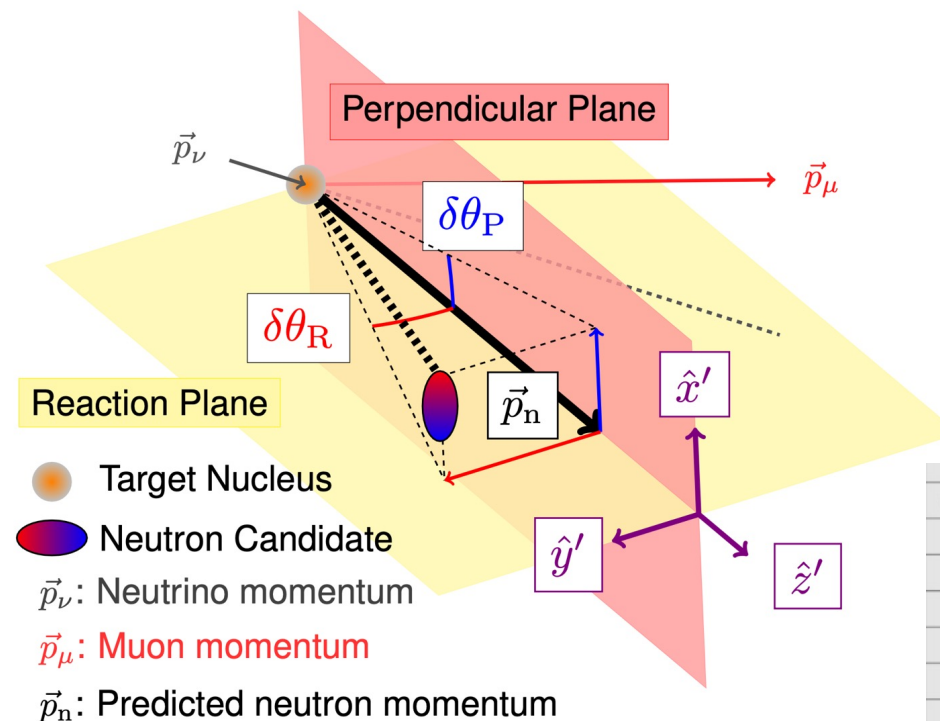
Number of Dimensions
1
2
3

If only we could measure a cross section on H first...

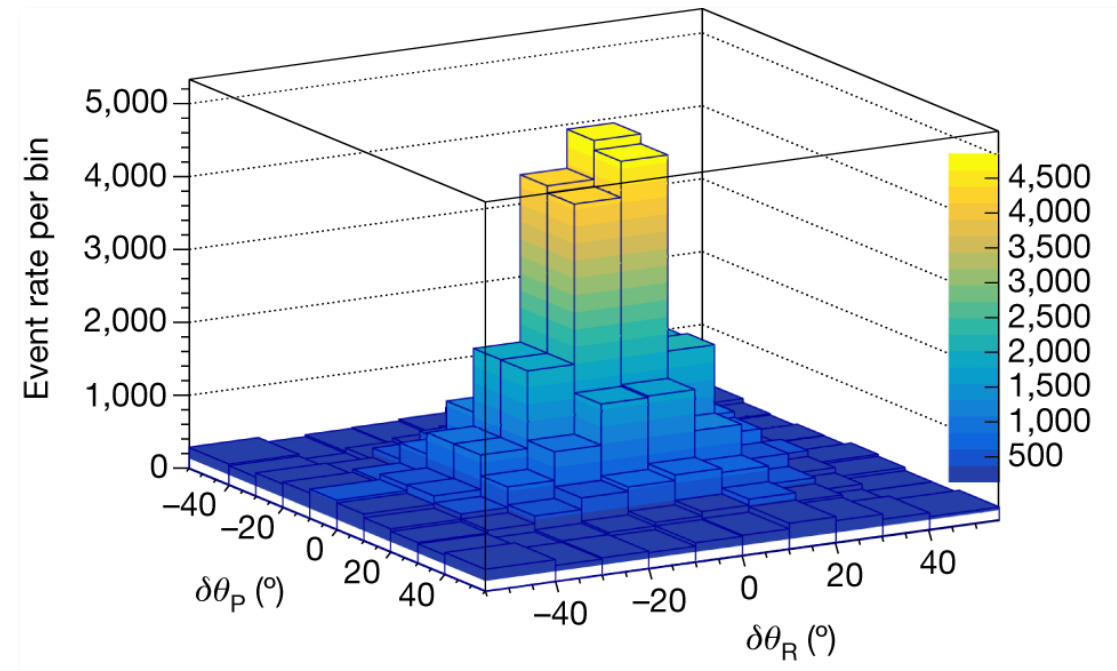
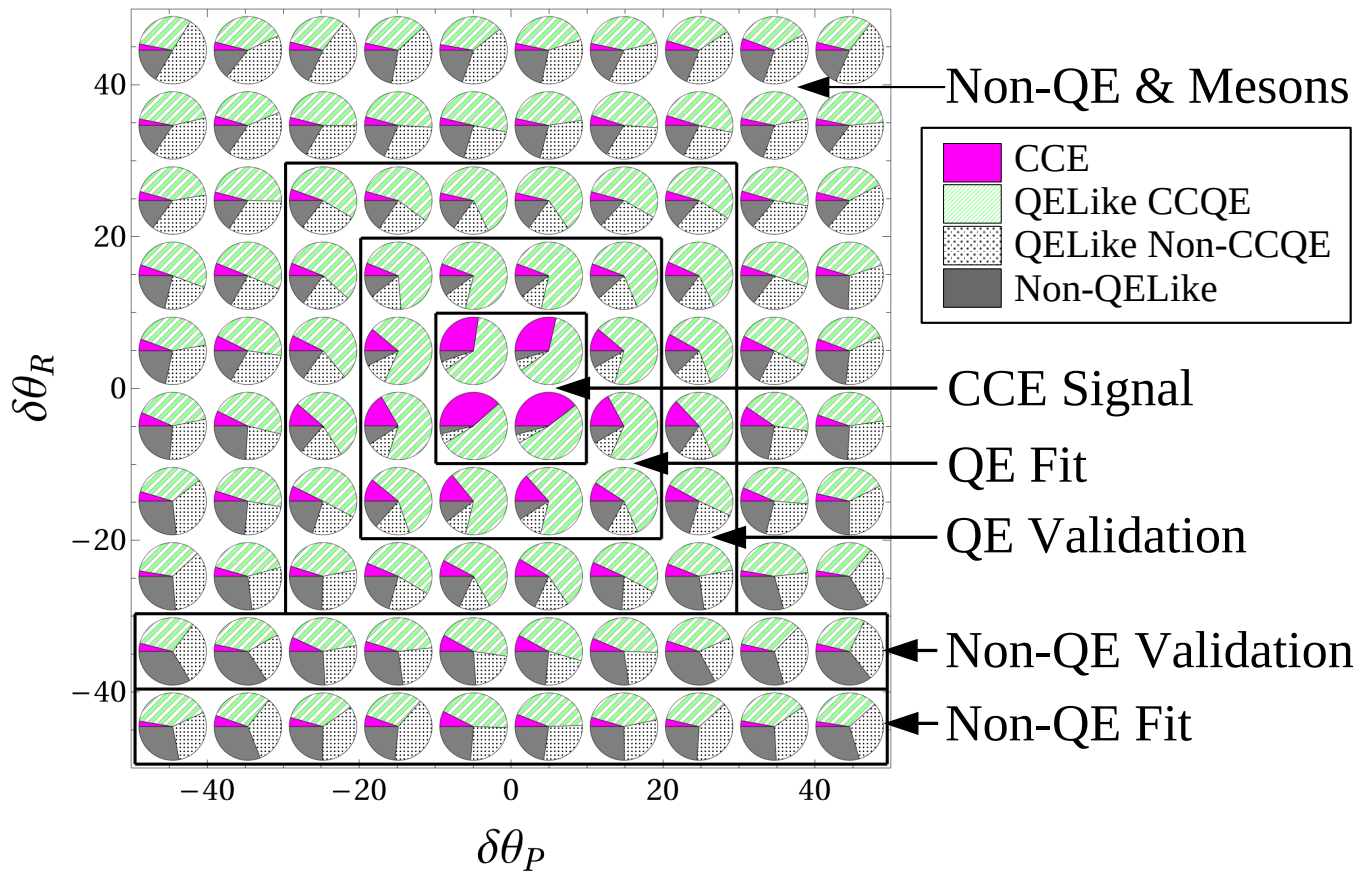
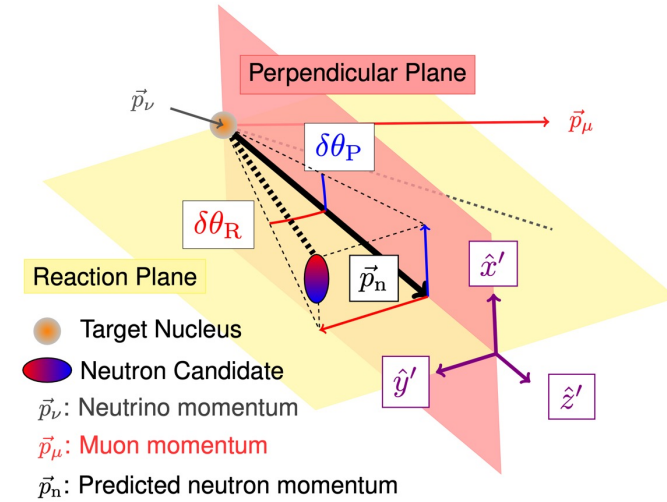
Using what you've learned to see H by itself

- Remember this plot from Stephen's talk?
- Consider antineutrino QE-like scattering:

- $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- If you have a plastic target, you have C and H
- If you are trying to measure CCQE on H, then CCQE on C is a background
- Use nuclear effects to isolate H!

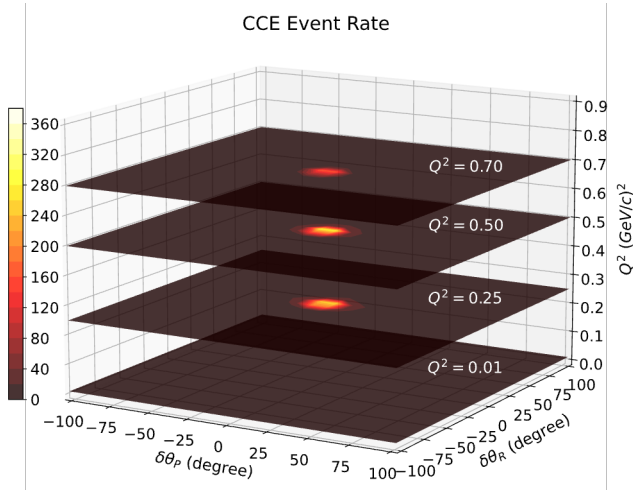


When life gives you lemons... make lemon meringue pie



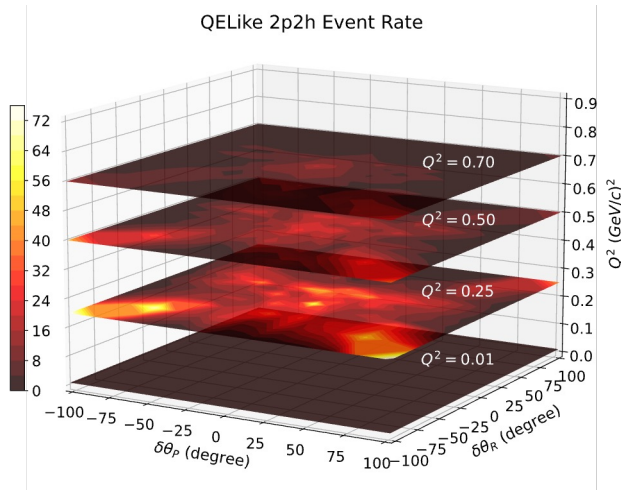
Different Reactions populate different regions

CCE Event Rate

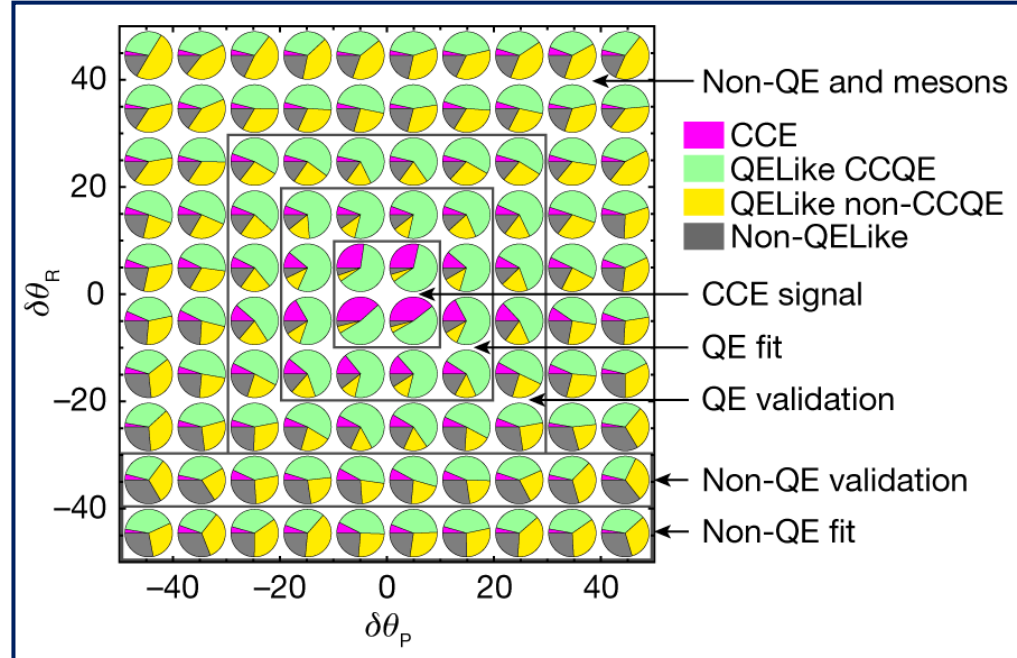


SIGNAL: Elastic on H

QELike 2p2h Event Rate

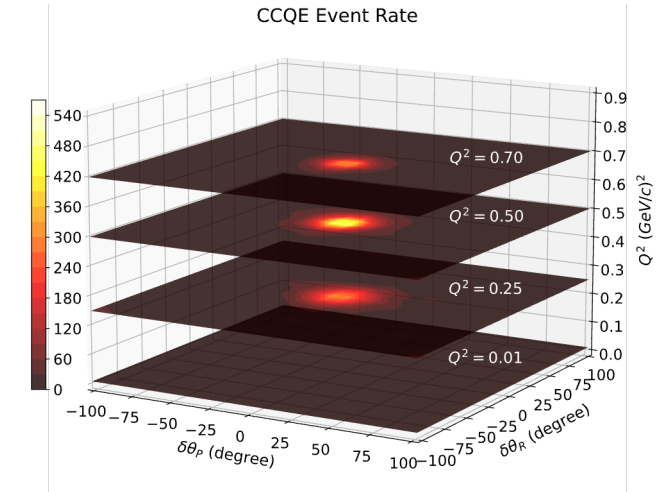


Background: QELike 2p2h



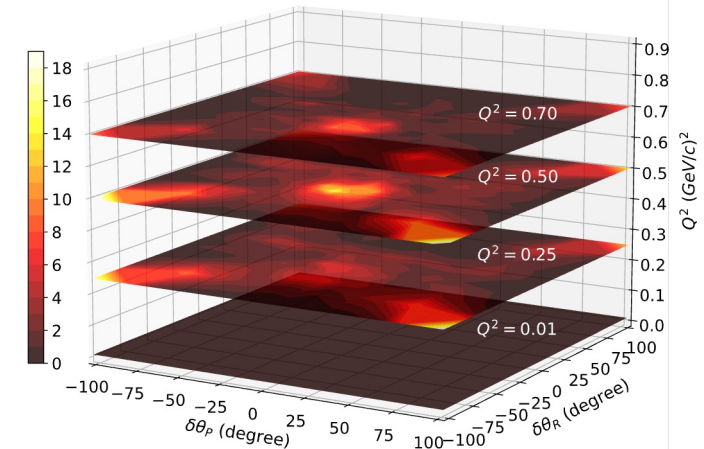
Regions of the 2D angular distribution used to fit the backgrounds proportion in the signal region.

CCQE Event Rate



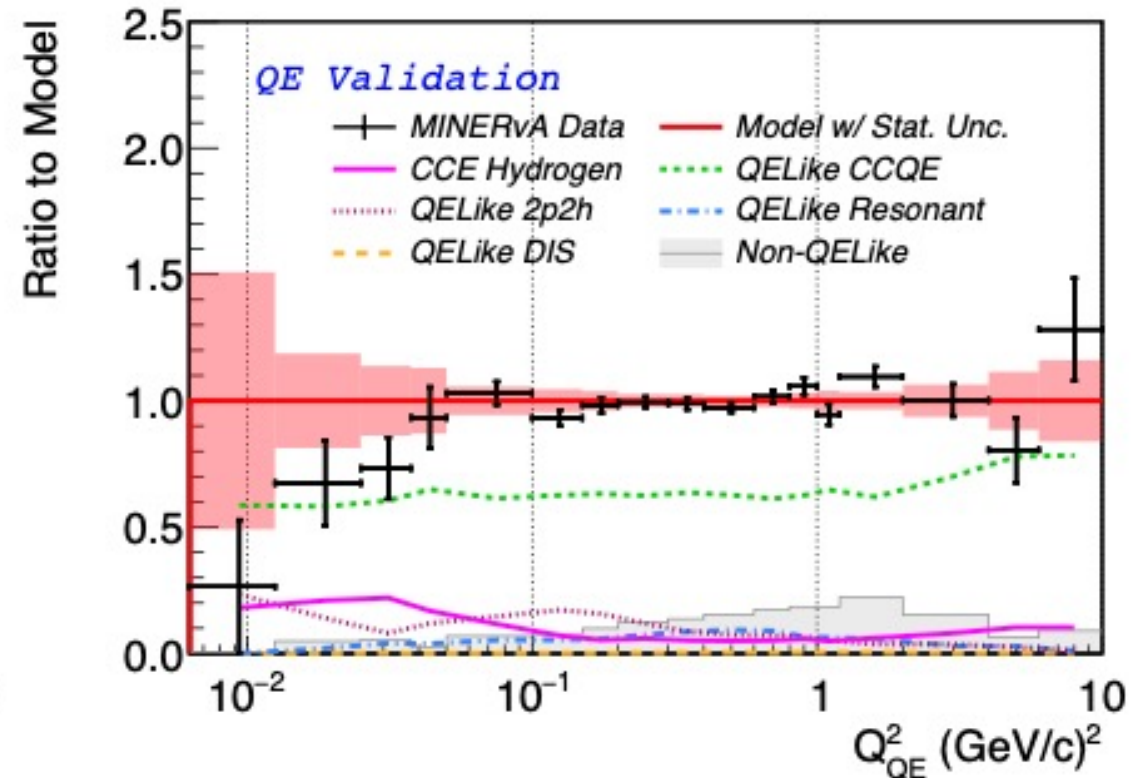
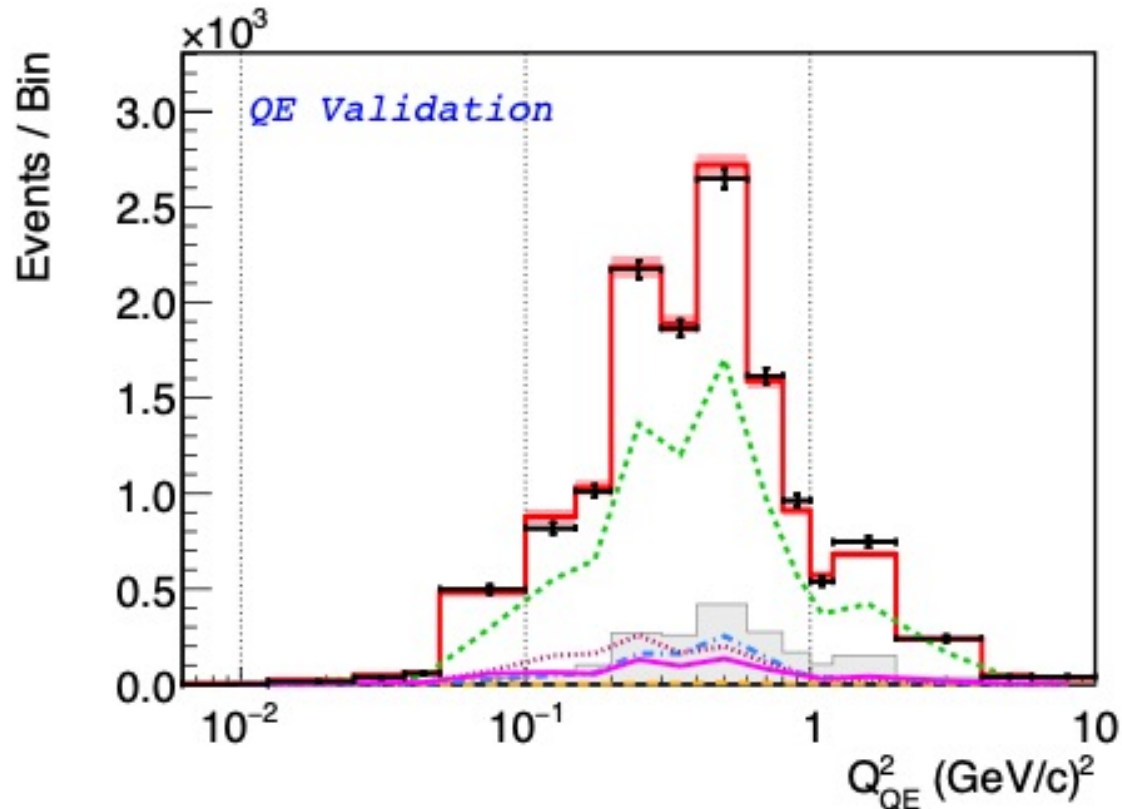
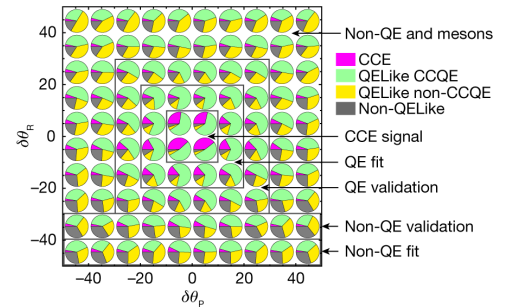
Background: QELike CCQE (on C)

QELike Resonant Event Rate



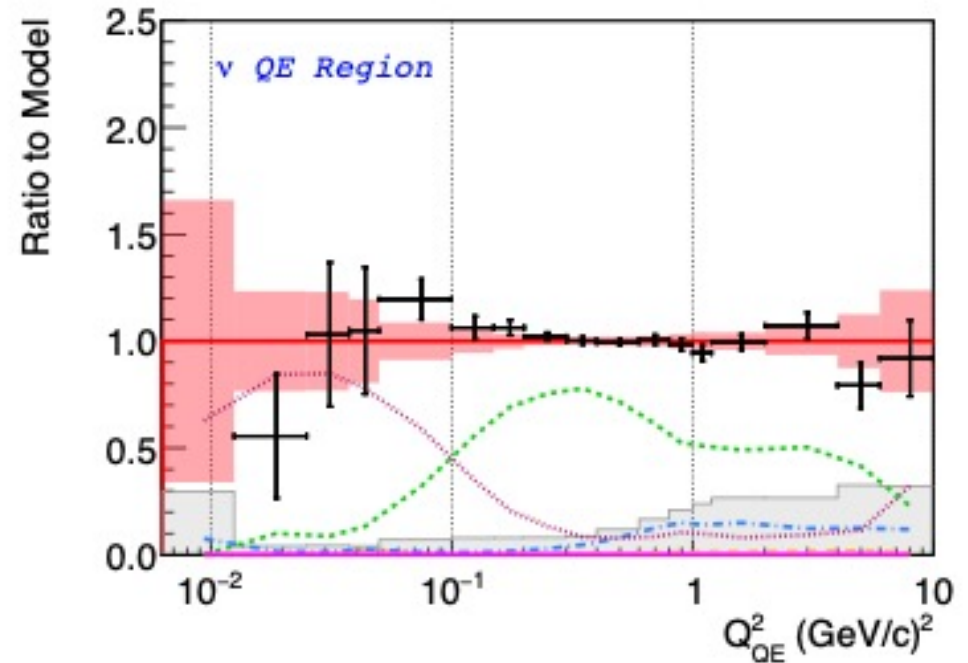
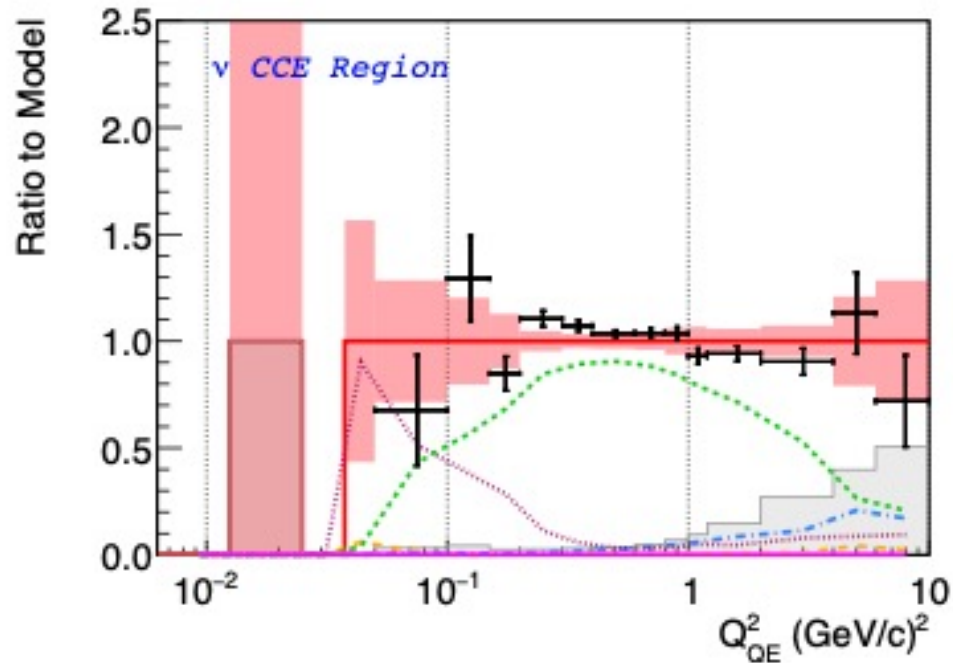
Background: QELike Resonant

Validating the Background Prediction



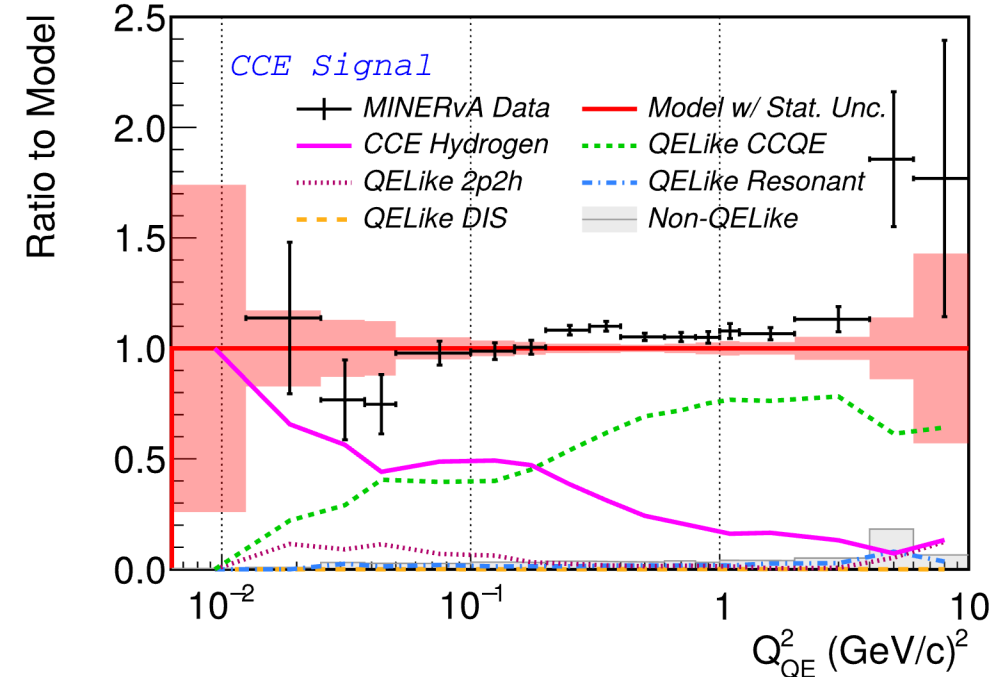
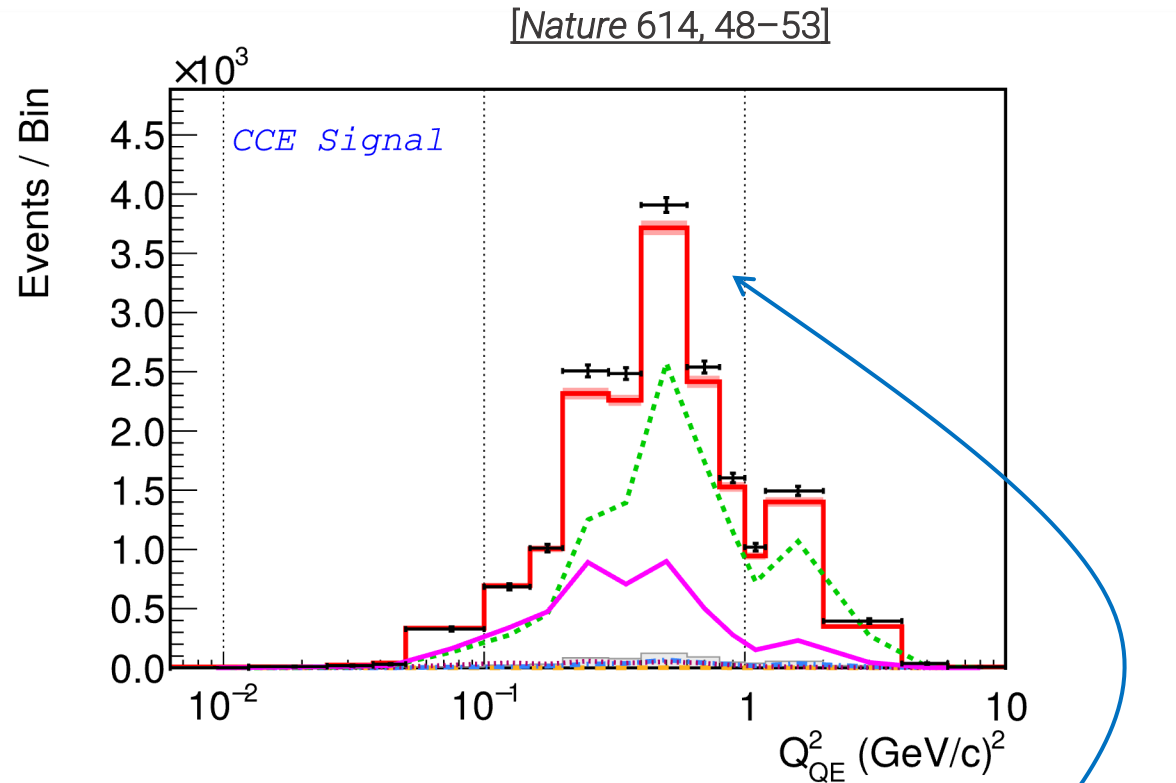
- CCQE is the dominant background. Small 2p2h, inelastic (absorbed), and Non-QELike contributions. The fitted model are well constrained by data.

Another test: Neutrino Beam $\nu_\mu + n \rightarrow \mu^- + p$



- Recipe: select events with trackable protons in a neutrino sample. Different final states and available kinematics. Apply same fitting mechanism. Data and MC mostly agree within uncertainty. Data and MC mostly agree. Disagreement can be explained by $2p2h$ uncertainty.

Cross-section Extraction

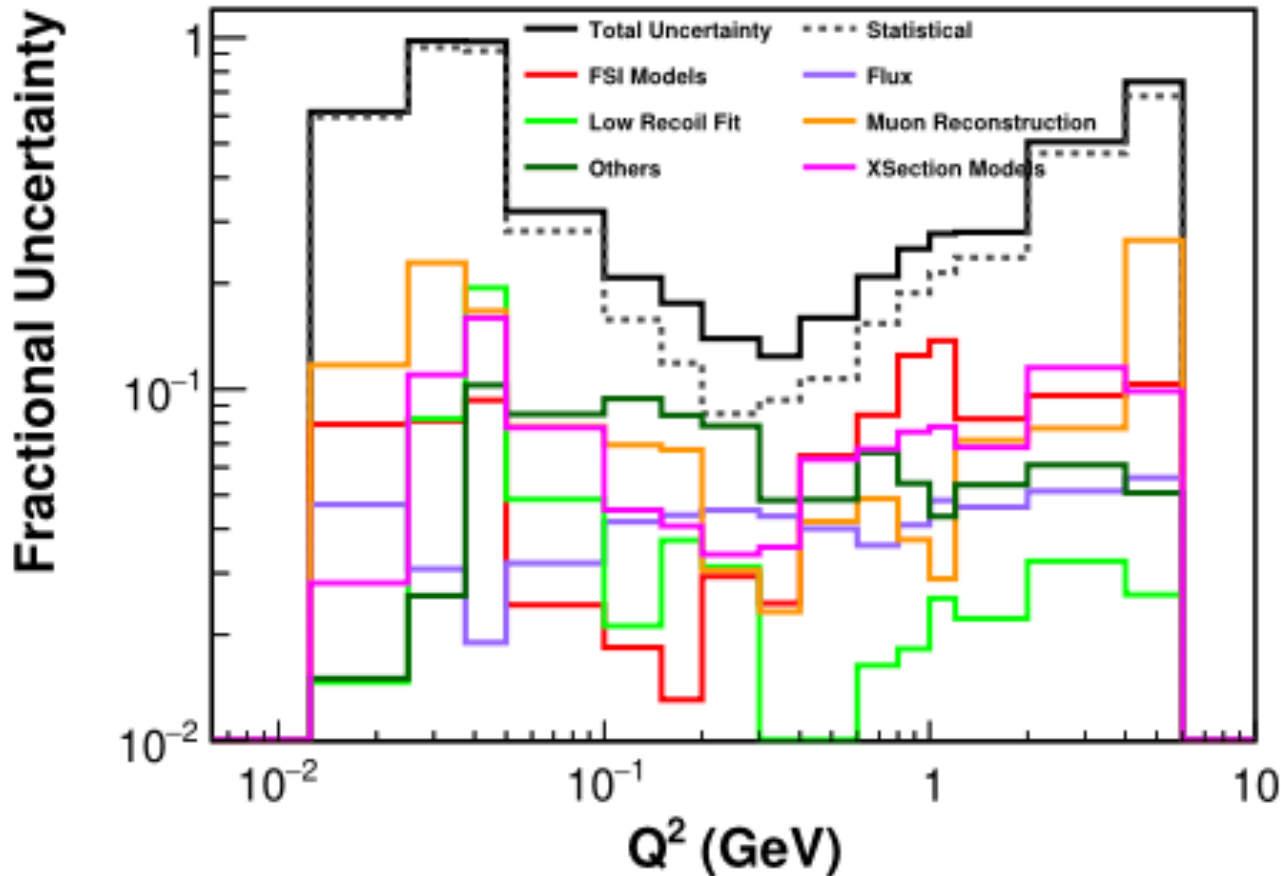


Ingredients:

- Unfolding matrix and efficiency from Data and Simulation studies
- Flux from models and data measurements ($\nu e \rightarrow \nu e$)
- Number of Hydrogen targets from the detector assay.
- **Measured signal** from data – predicted background

$$\left(\frac{d\sigma}{dQ^2} \right)_i = \frac{\sum_j U_{ji} (N_j^{\text{data}} - N_j^{\text{bkg-pred}})}{\Phi N_H \epsilon_i (\Delta Q^2)_i}$$

Uncertainties in the Axial Form Factor Cross-Sections



- Dominated by statistical uncertainty after the background subtraction.

Systematic uncertainties from residuals of background subtraction

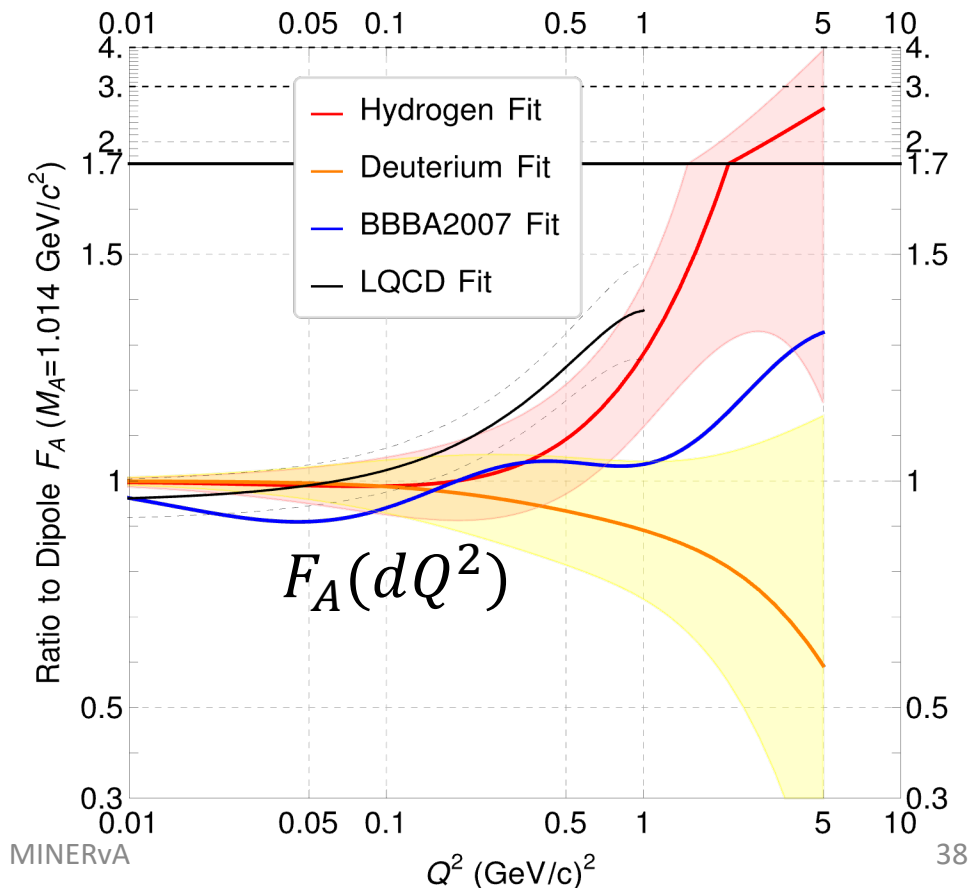
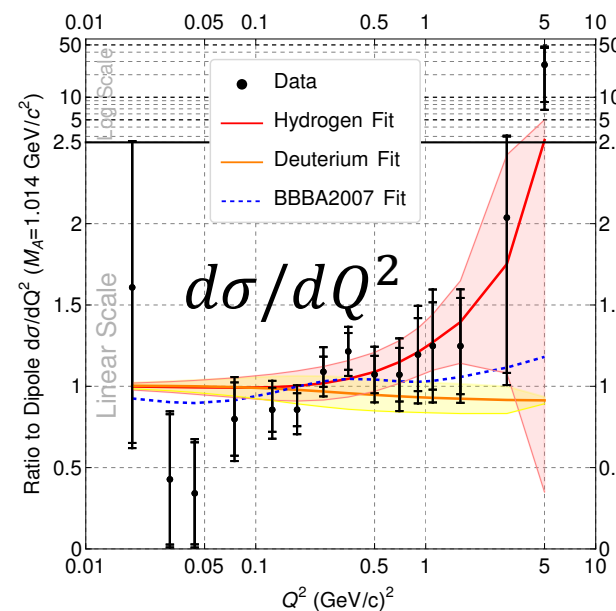
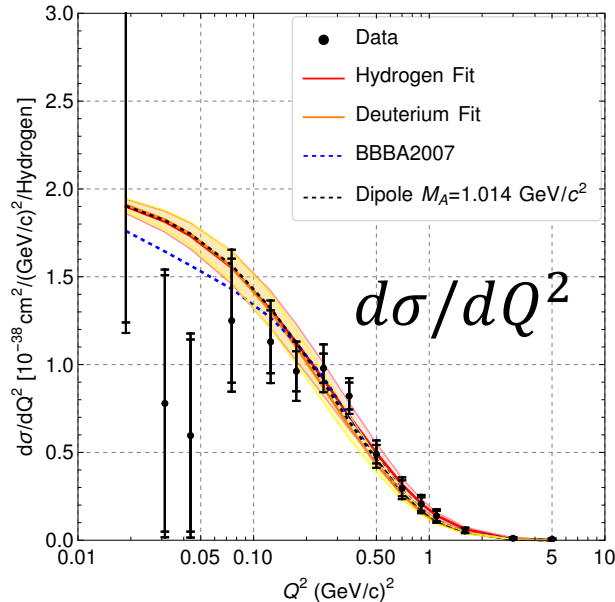
Particle responses in the “other” category, dominated by neutron systematics.

Always
ask
to see
uncertainties!



Free Nucleon Axial Form Factor

- MINERvA found ~ 5800 such events on a background of ~ 12500 .
- Shape is not a great fit to a dipole at high Q^2 .
- LQCD prediction at high Q^2 is close to this result, but maybe not at moderate Q^2 .



Summary of these two lectures

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(N(x_m) - B(x_m)) U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

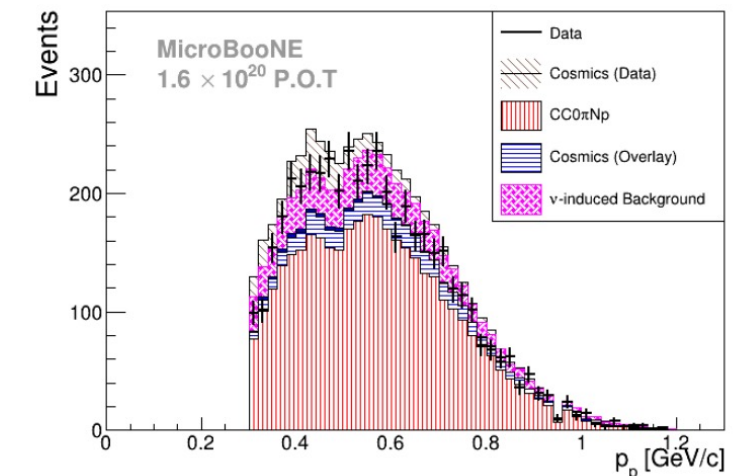
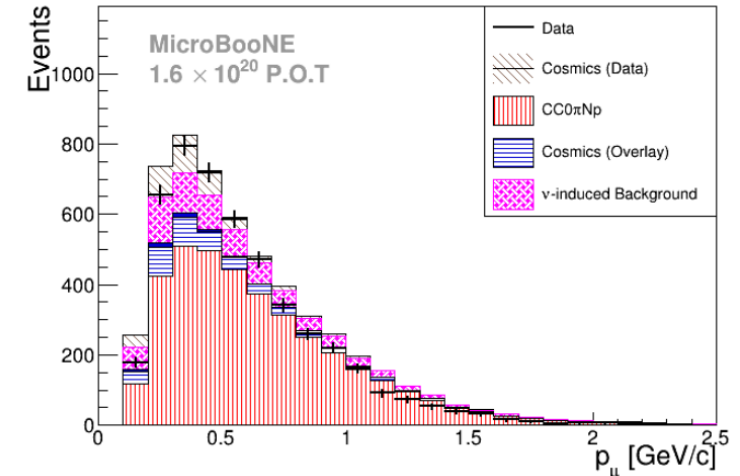
- So many interactions, so little time!
- Measuring Cross Sections all use the same formula
- Challenges with making a robust measurement
 - Flux
 - Detector
 - Cross section
- Clever ideas of new observables and ways to reduce backgrounds are yours to discover!

Uncertainties

Different Detectors will have different cuts

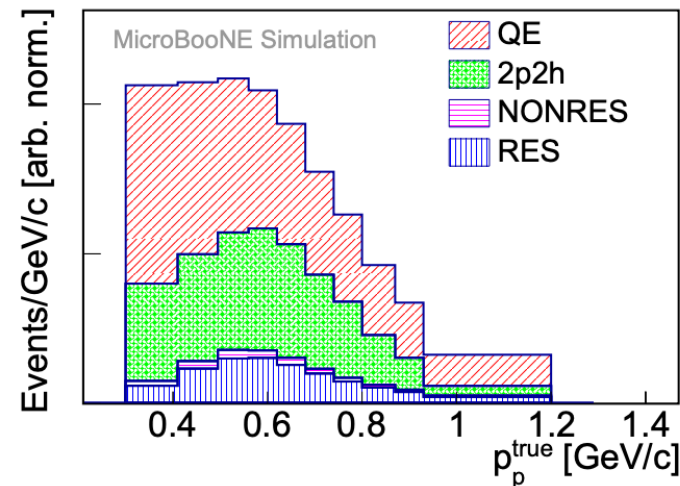
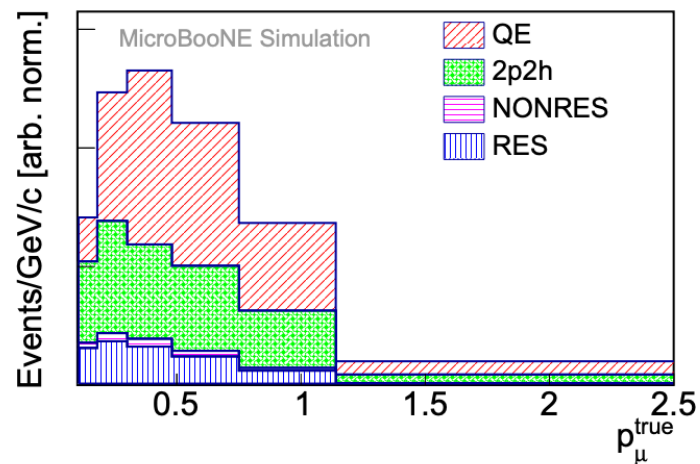
- MicroBooNE example: ν_μ CC0 π Cross section
- Event with muon and proton candidate
- Leading Muon candidate has $p > 100 \text{ MeV}/c$
- Leading Proton candidate has $p < 1.2 \text{ GeV}/c$
 - Proton candidate has to be shorter than muon candidate

• *Phys.Rev.D* 102 (2020) 11, 112013



CCQE versus “CCQE-like” versus “CC0 π ”

- Since so many other processes can look like a CCQE event even if you have a perfect detector, we have defined a new term
- How would you make a CCQE-like event that is not CCQE?
- Example from MicroBooNE: breakdown of signal events after background subtraction:



• *Phys.Rev.D* 102 (2020) 11, 112013