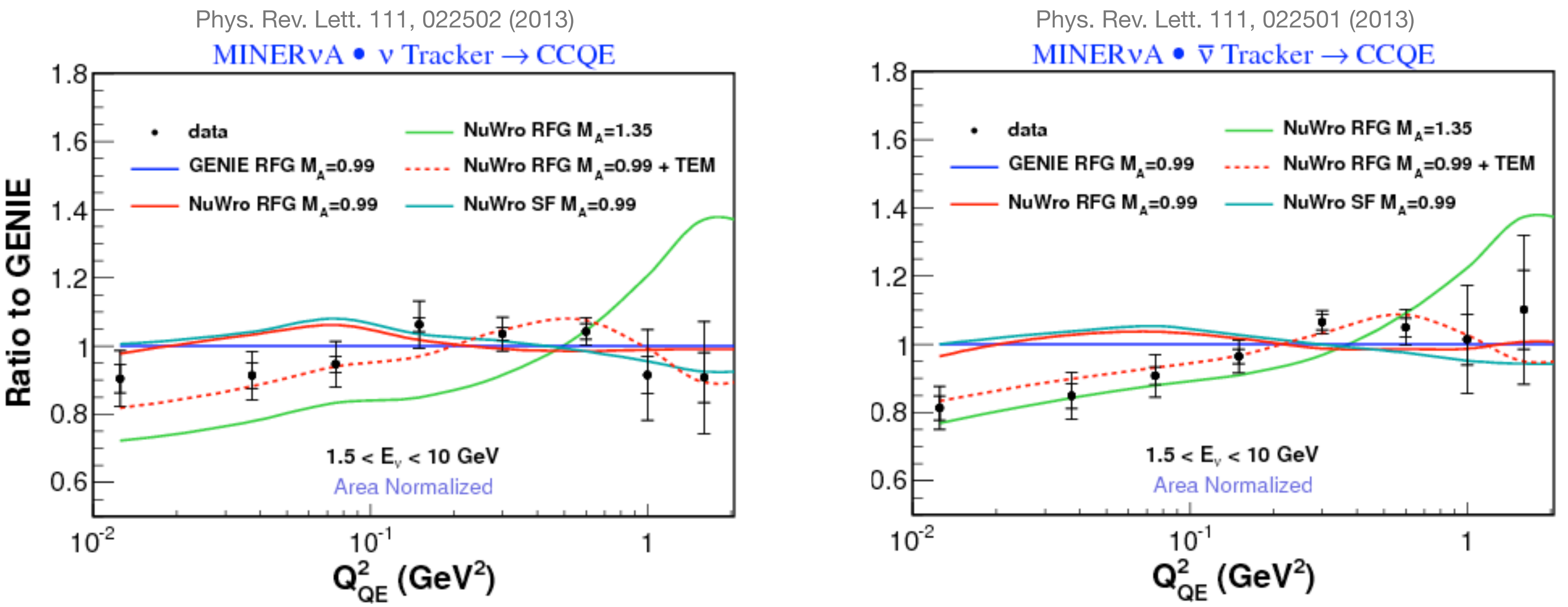
Quasi-elastic scattering at MINERvA

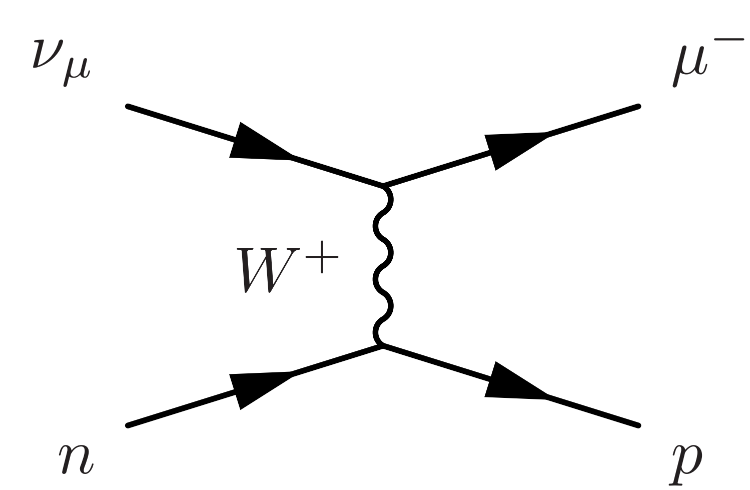
Cheryl Patrick,
University College London (previously Northwestern University)

NuFact 2017, Uppsala, Sweden

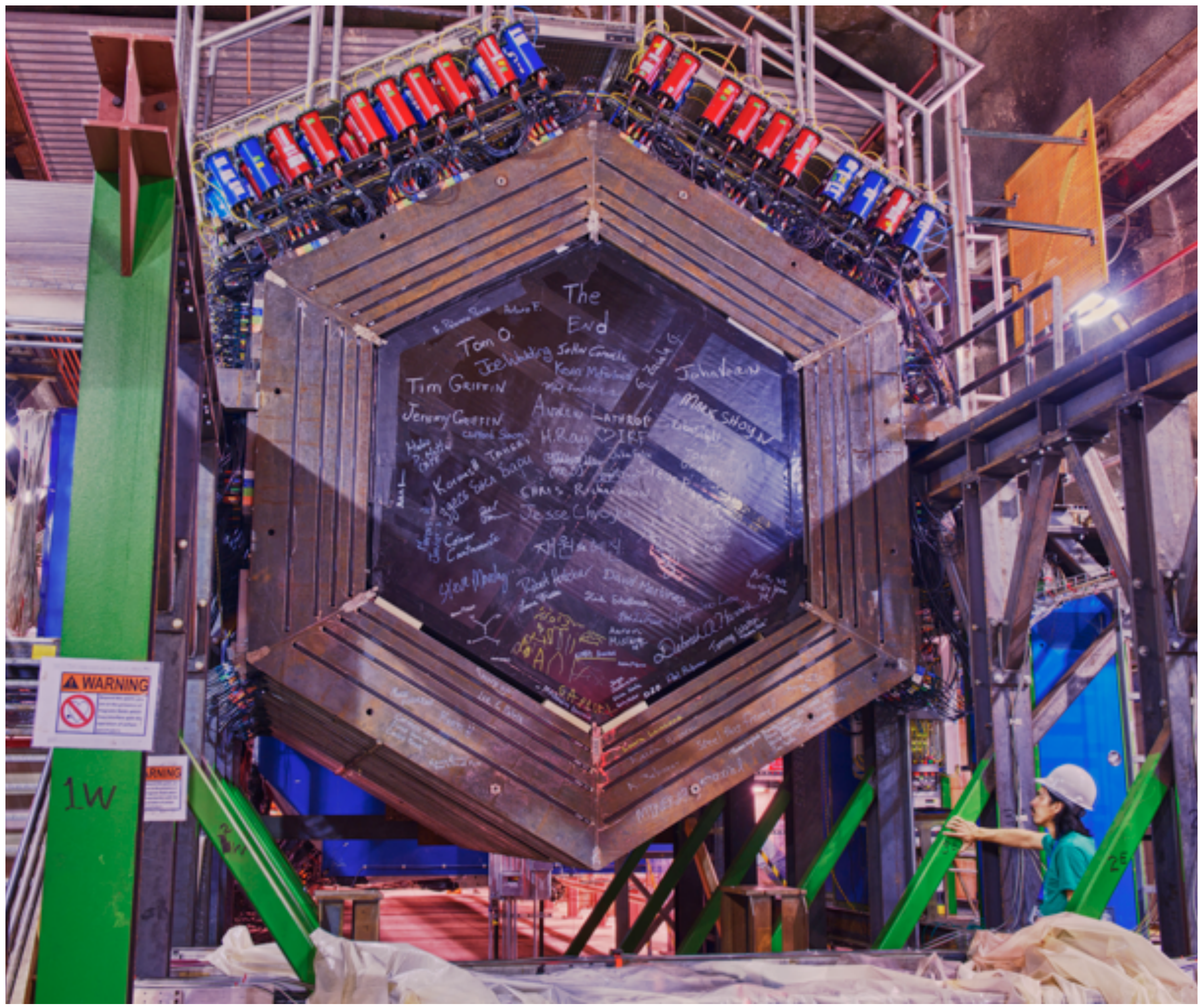
The way we were: 2013



- MINERvA published charged-current quasi-elastic cross section (CCQE) results vs. Q^2 for both muon neutrinos and antineutrinos on carbon-based scintillator
- Data did not agree with our simulation (GENIE 2.6.2, relativistic Fermi gas model), hinting at additional nuclear effects
- How can we investigate further?

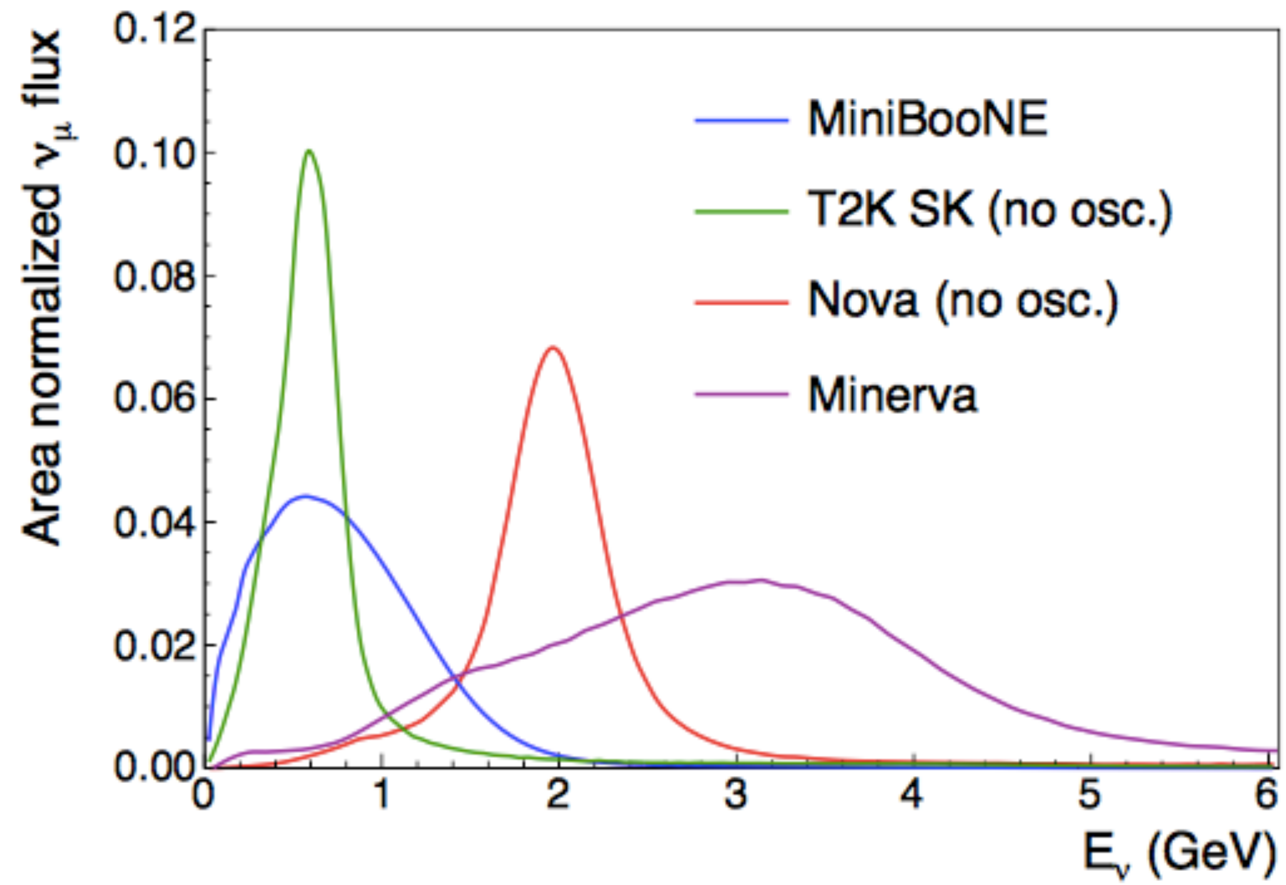


The MINERvA Experiment



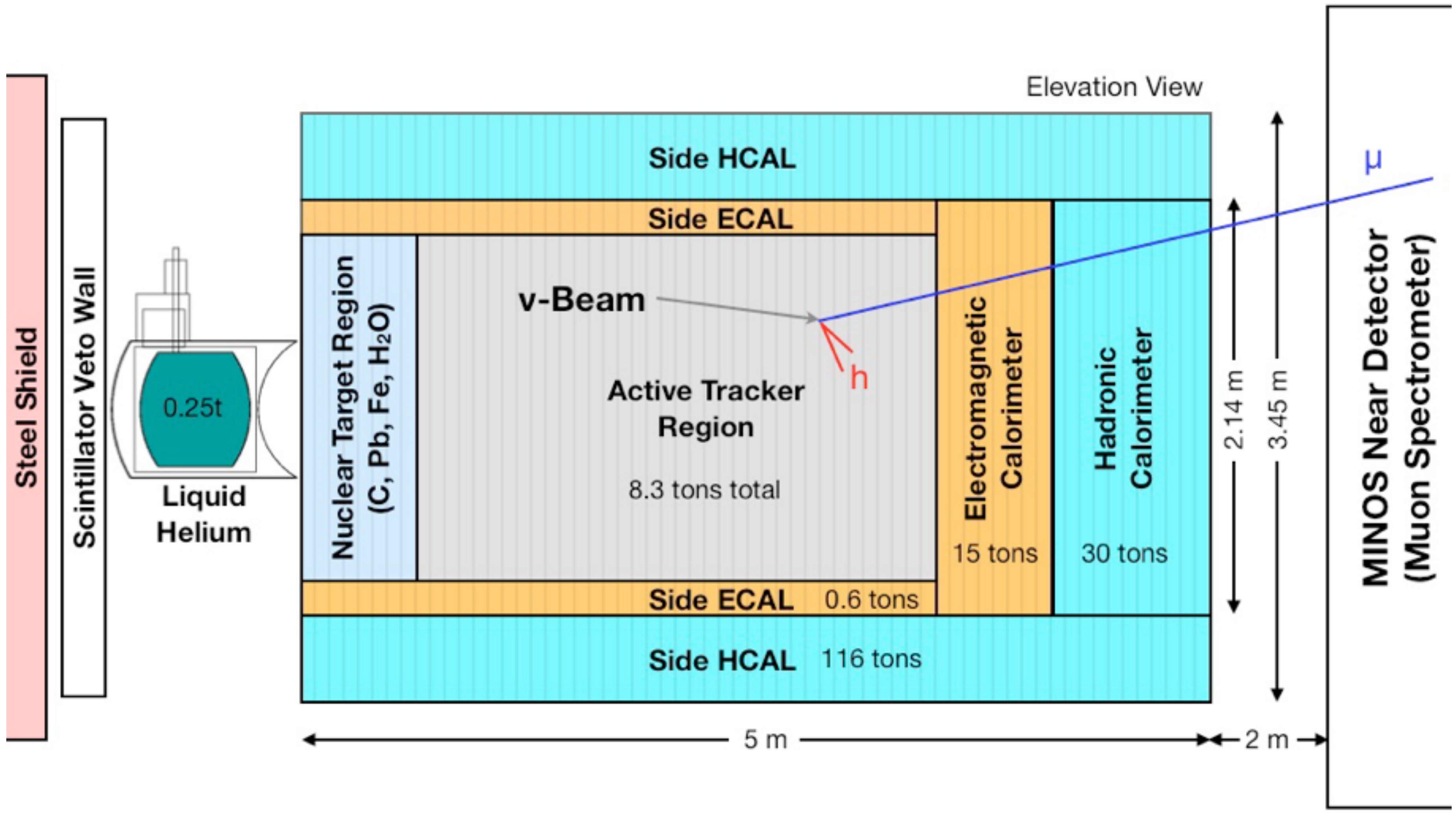
- Fully-active scintillator detector, designed specifically to measure cross sections
- Located in Fermilab's NuMI beam line

P. Rodrigues, Fermilab wine and cheese 11 Dec 2015



- Around 3×10^{20} POT of ν_μ and 10^{20} of $\bar{\nu}_\mu$ data at peak energy around 3 GeV (this talk)
- Since 2013: taking data at peak energy around 6 GeV

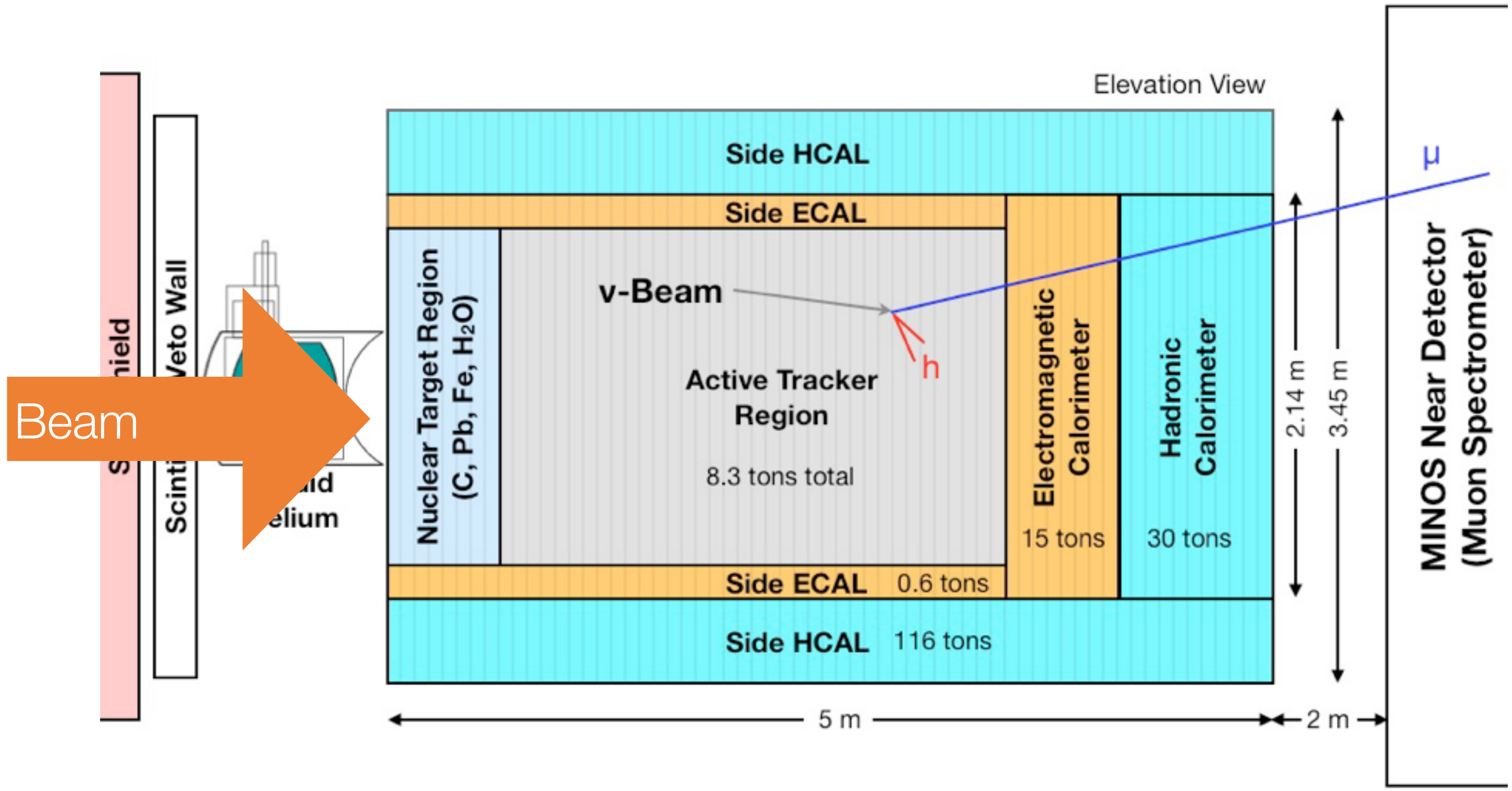
The MINERvA detector



All photographs: Reidar Hahn, Fermilab visual media services

Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

The MINERvA detector



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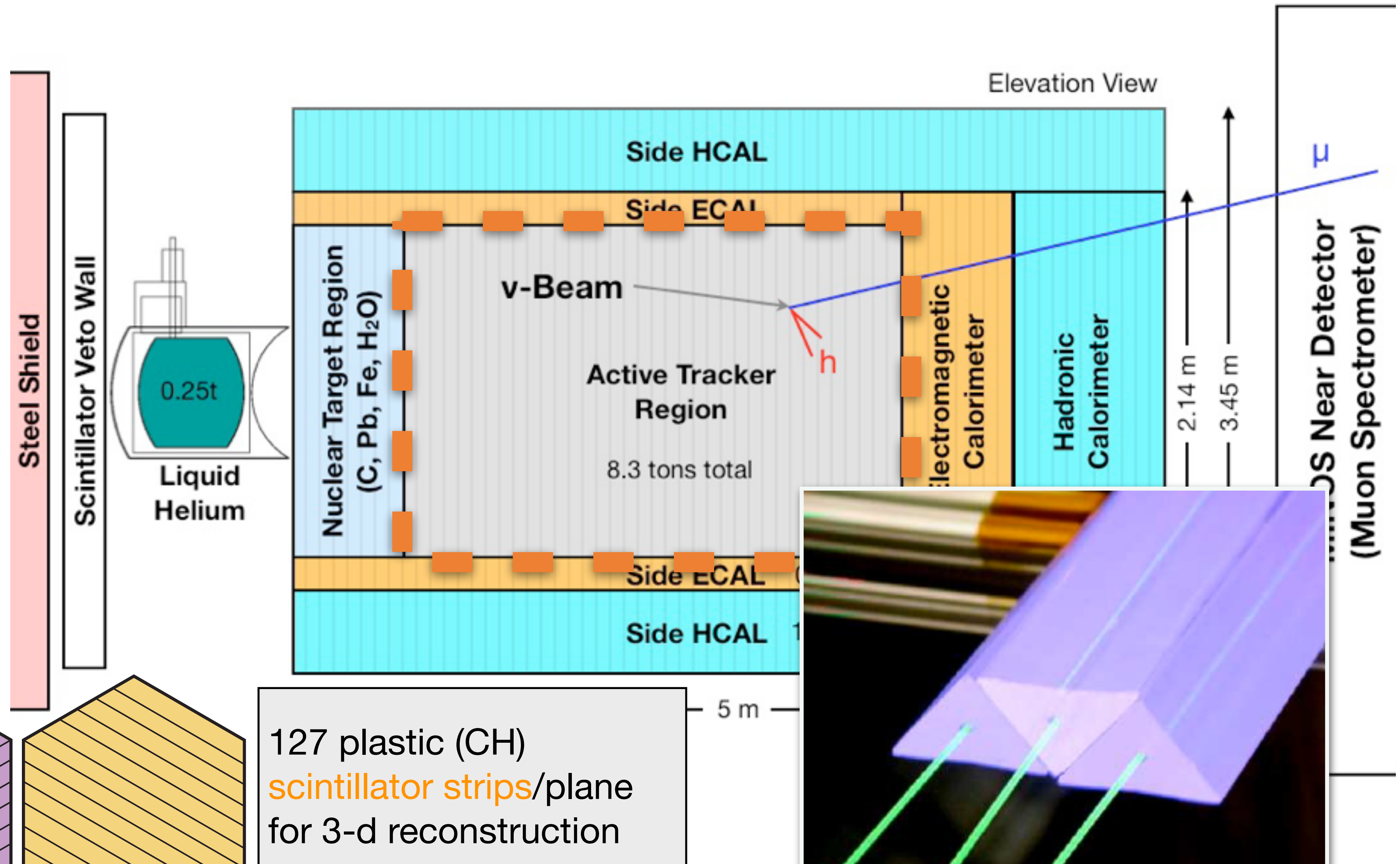
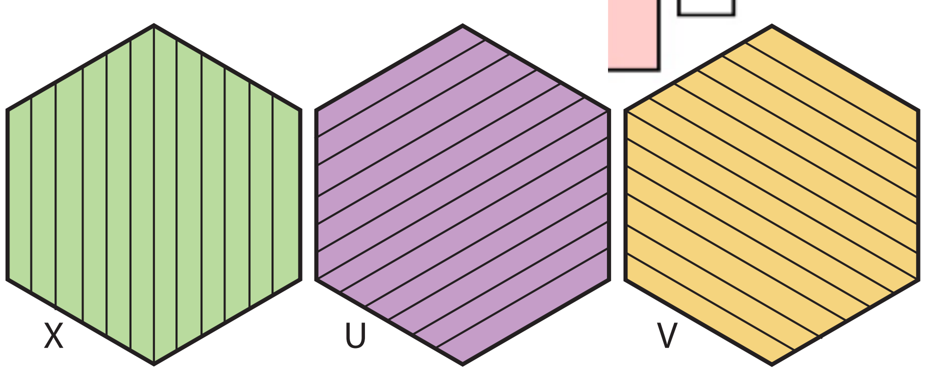
The MINERvA detector





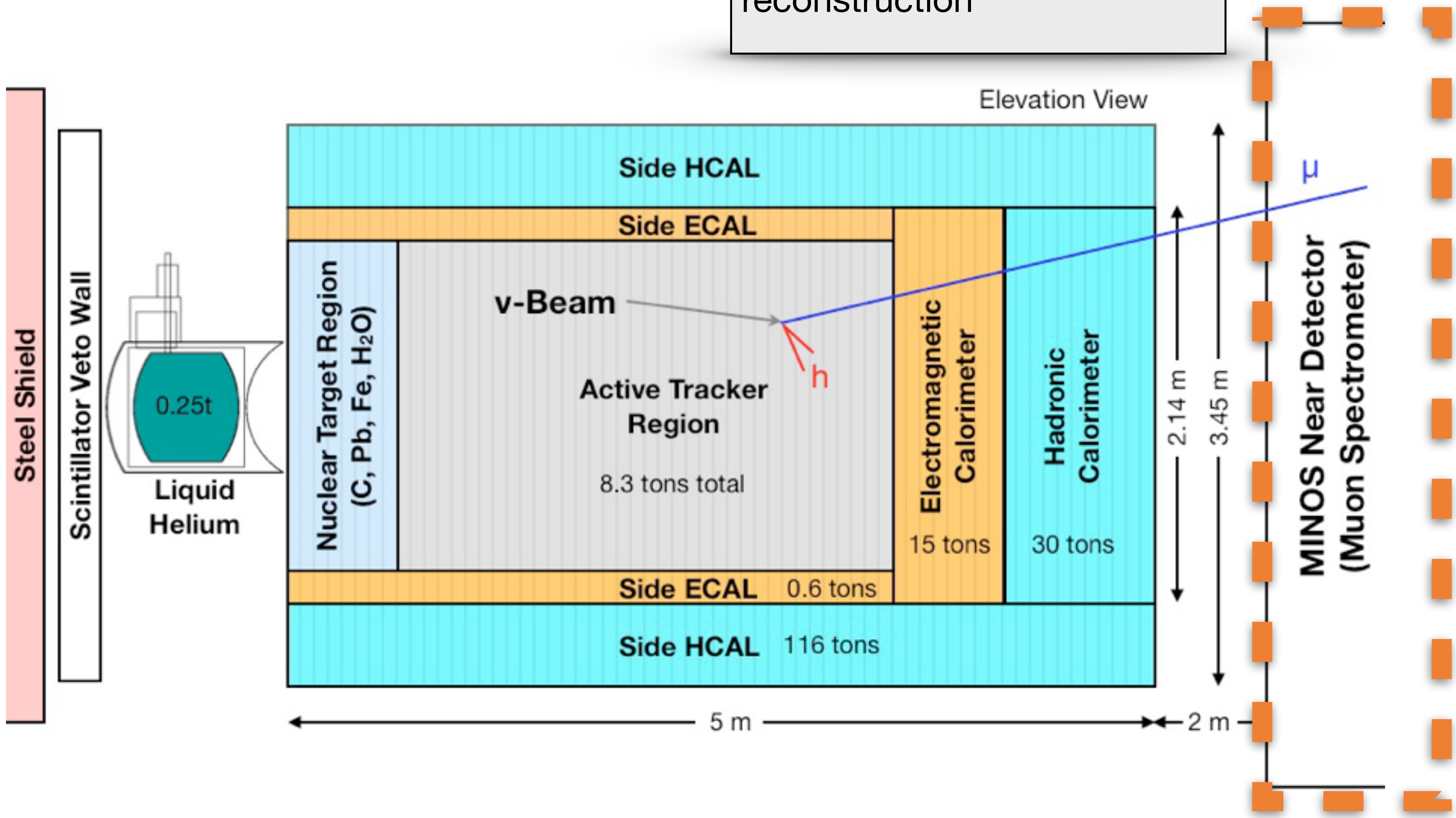
127 plastic (CH) scintillator strips/plane for 3-d reconstruction

All photographs: Reidar Hahn, Fermilab visual media services

Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

The MINERvA detector

Magnet allows muon charge reconstruction

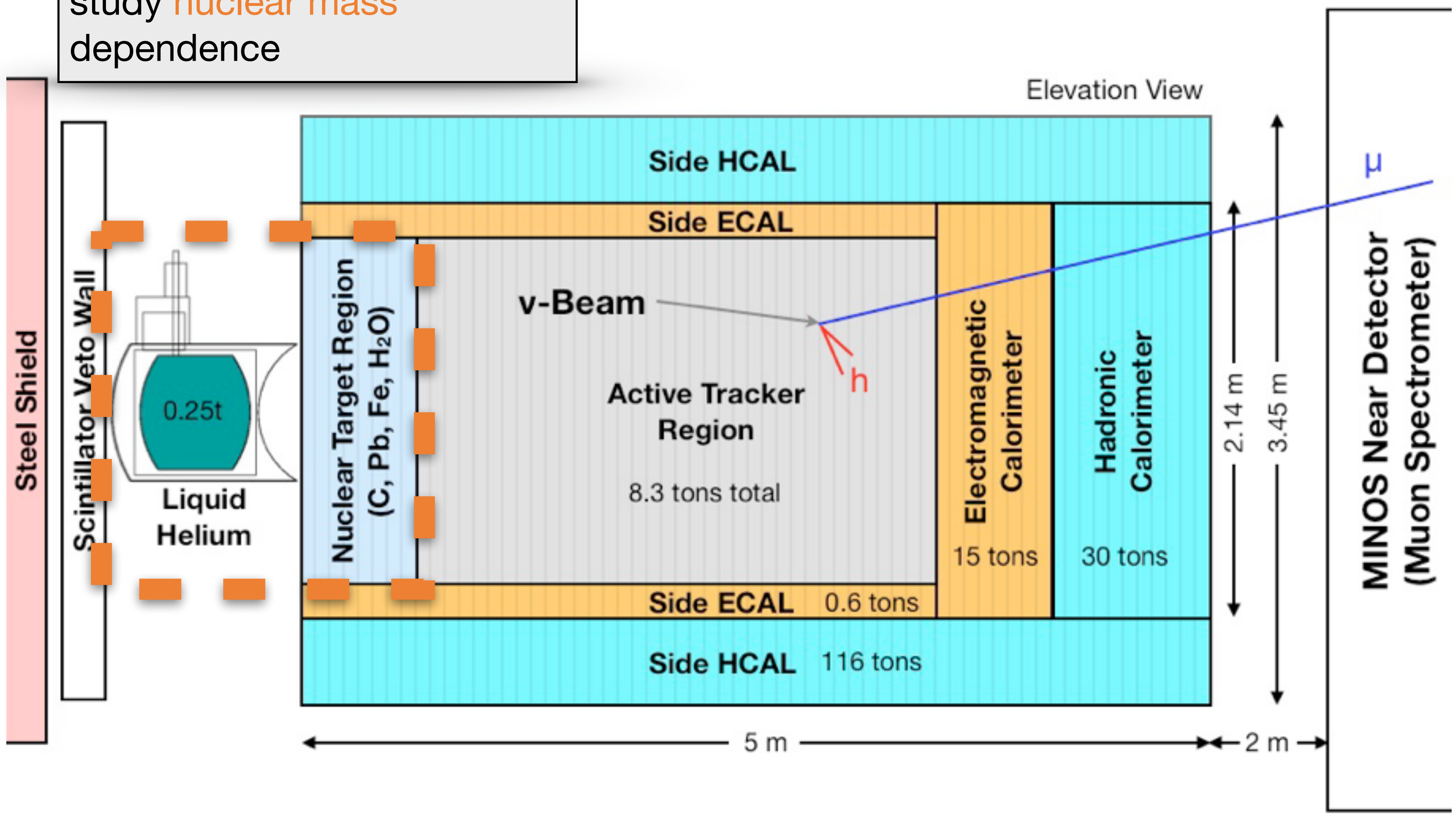


Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

All photographs: Reidar Hahn, Fermilab visual media services

The MINERvA detector

Nuclear targets allow us to study nuclear mass dependence



Nucl. Inst. and Meth. A743 (2014) 130
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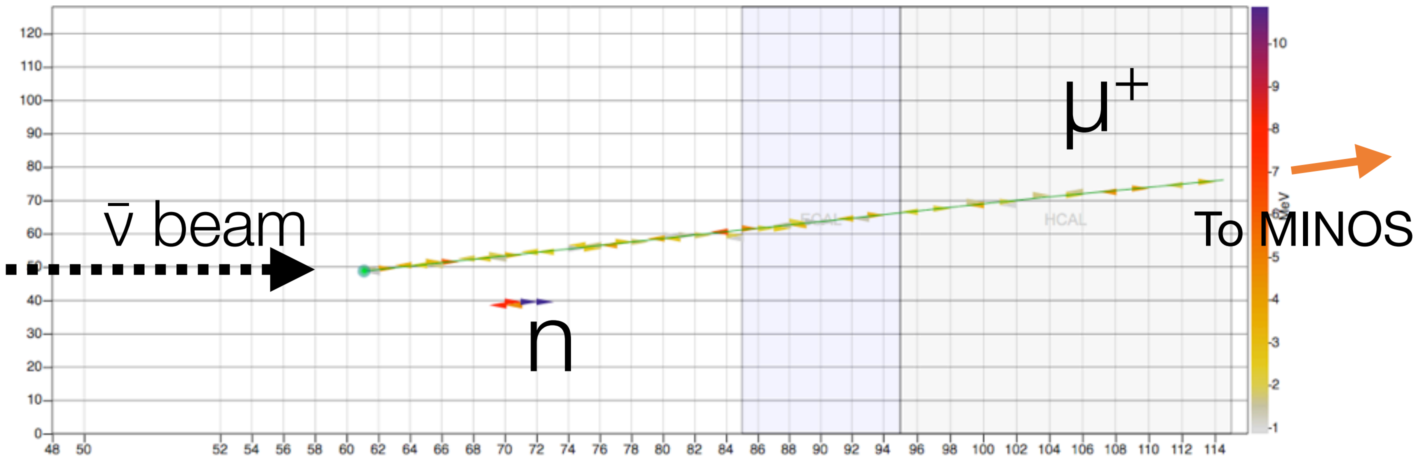
All photographs: Reidar Hahn, Fermilab visual media services

Quasi-elastics at MINERvA

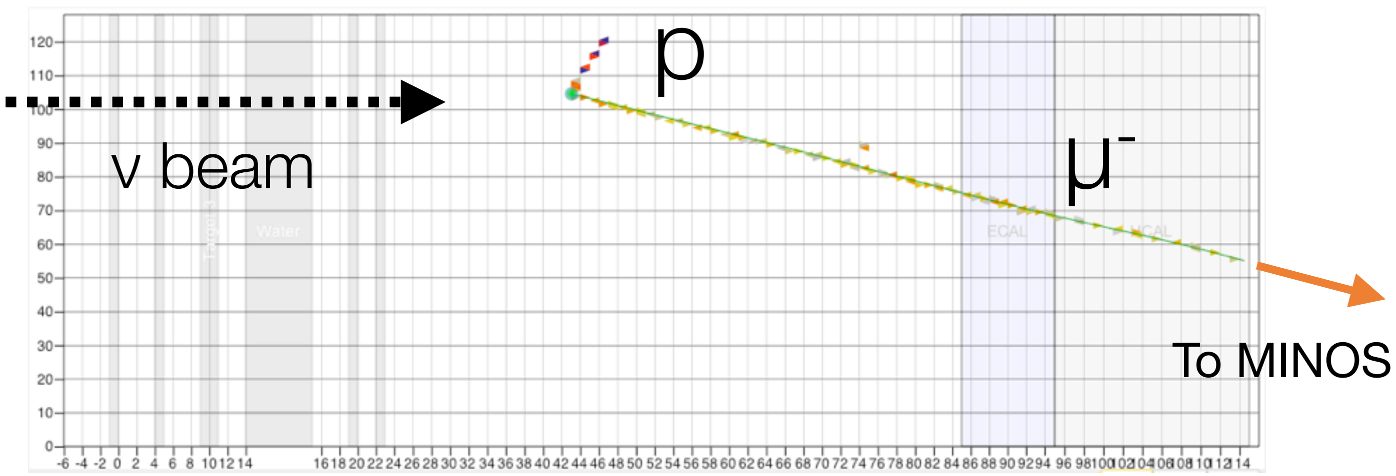
Neutrino scattering $\nu + n \rightarrow \mu^- + p$

Antineutrino scattering $\bar{\nu} + p \rightarrow \mu^+ + n$

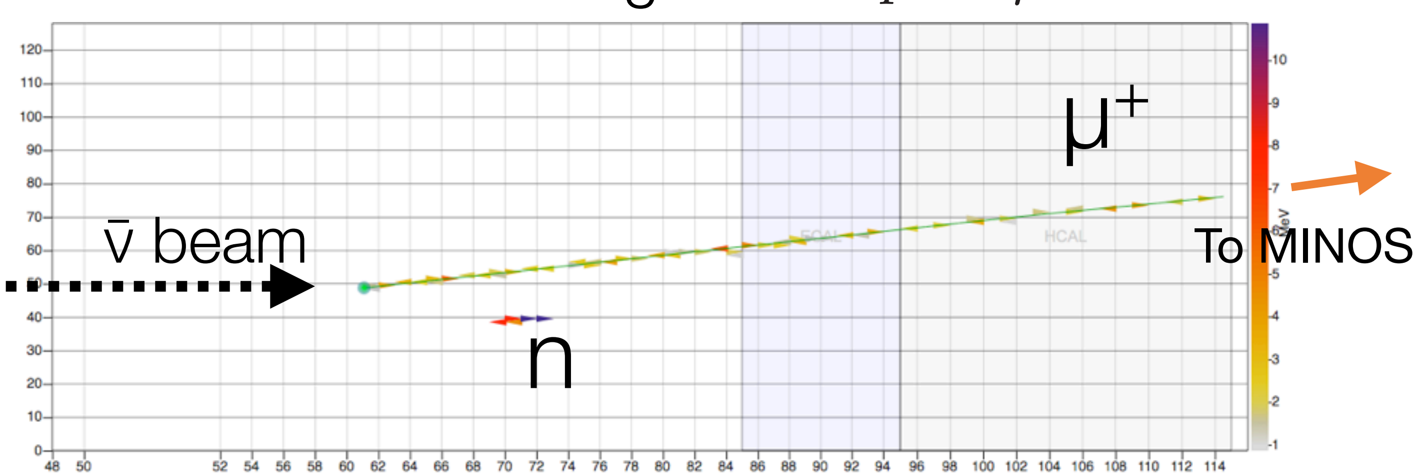


Quasi-elastics at MINERvA

Neutrino scattering $\nu + n \to \mu^- + p$



Antineutrino scattering $\bar{\nu} + p \to \mu^+ + n$



Muons - matched to MINOS

- 🙂 Good energy and angle reconstruction (but misleading if not true CCQE)
- 🙂 Charge reconstruction eliminates wrong-sign background
- 🙁 Limited energy and angle acceptance due to geometry
- 🙁 No information about hadronic system and what happens near the interaction vertex

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

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

Quasi-elastics at MINERvA

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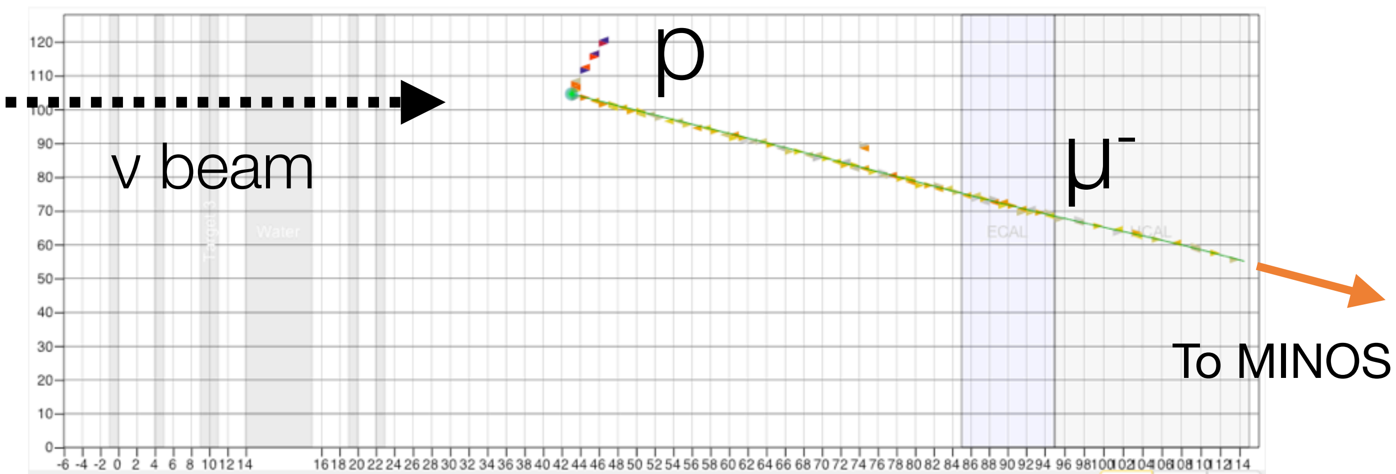

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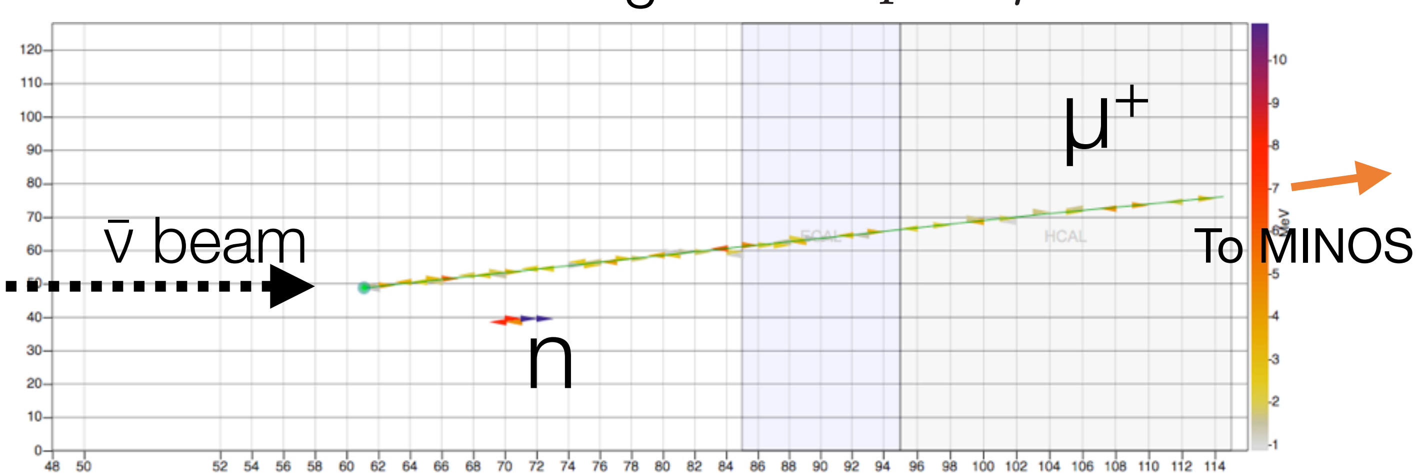

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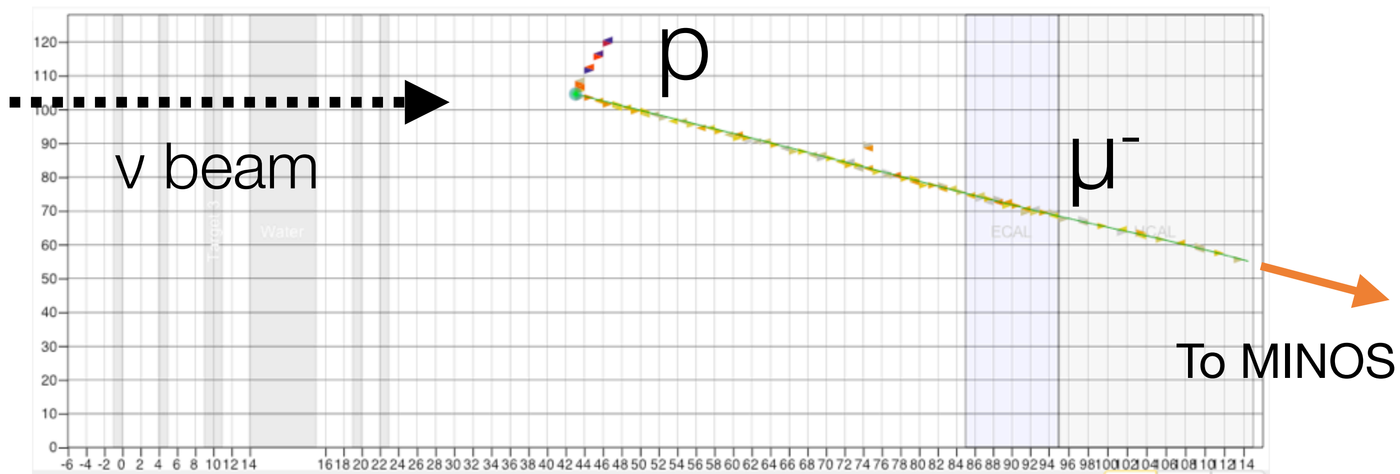
Protons

- ☺ Provide information about post-FSI hadronic system
- ☹ Neutrino mode only (for true CCQE)
- ☹ Harder to reconstruct (confusion with pions etc)

Quasi-elastics at MINERvA

Neutrino scattering $\nu + n \rightarrow \mu^- + p$



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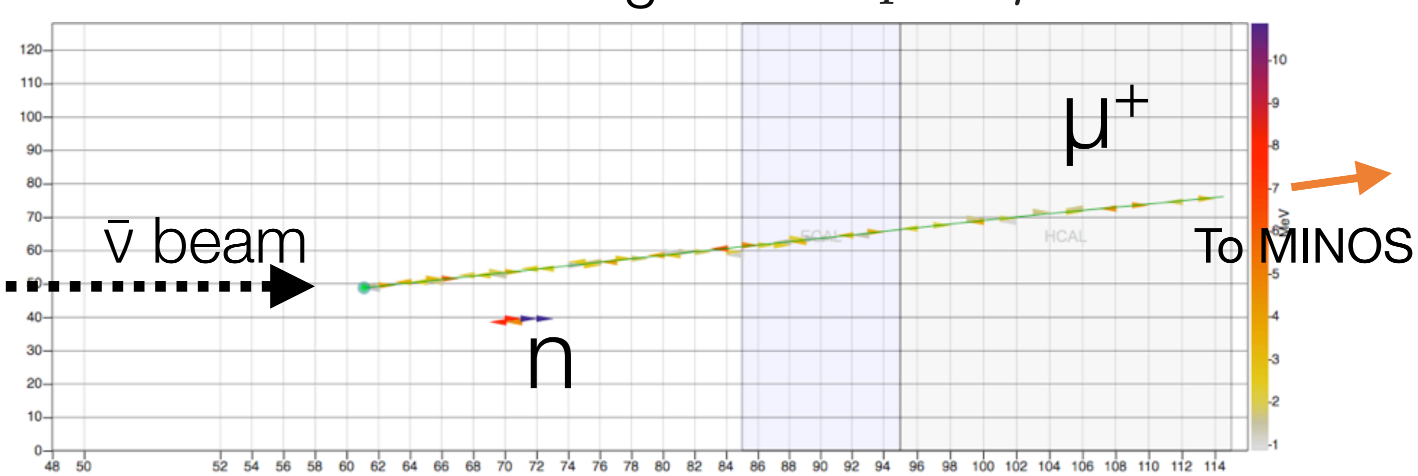

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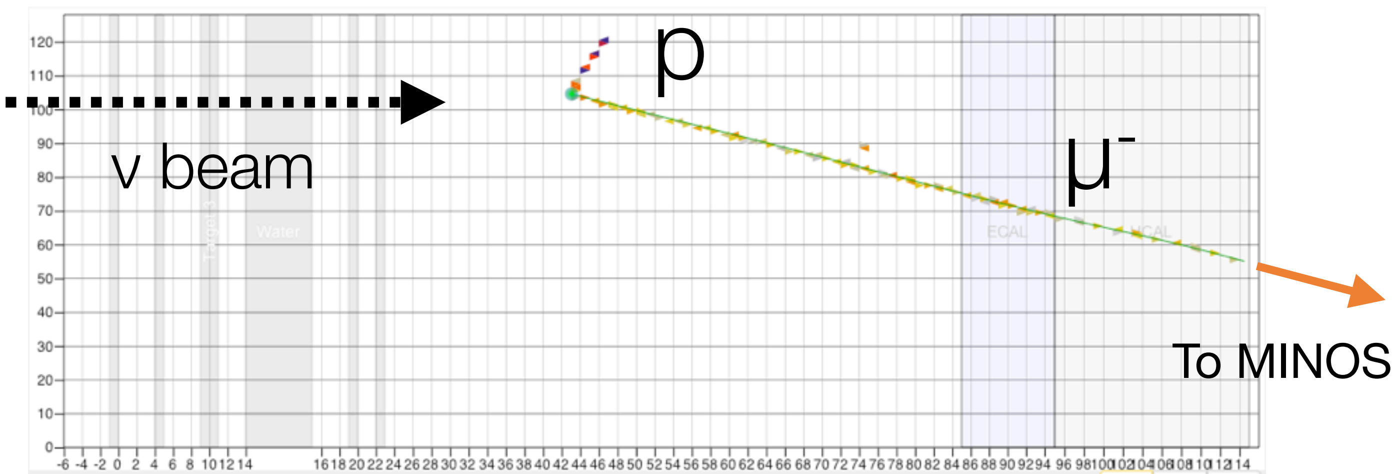
Neutrons

- 🙁 Antineutrino mode only (for true CCQE)
- 🙂 We can count them…
- 🙁 …but not reconstruct their energy

Quasi-elastics at MINERvA

Neutrino scattering $\nu + n \rightarrow \mu^- + p$



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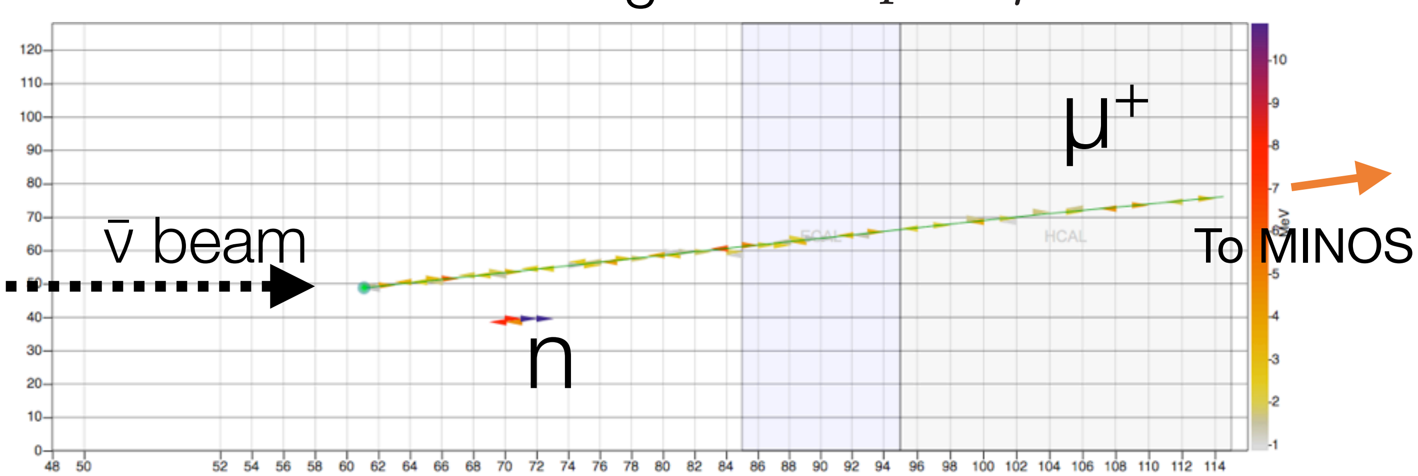

Muons - matched to MINOS

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Protons

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- ☹️ Harder to reconstruct (confusion with pions etc)

Neutrons

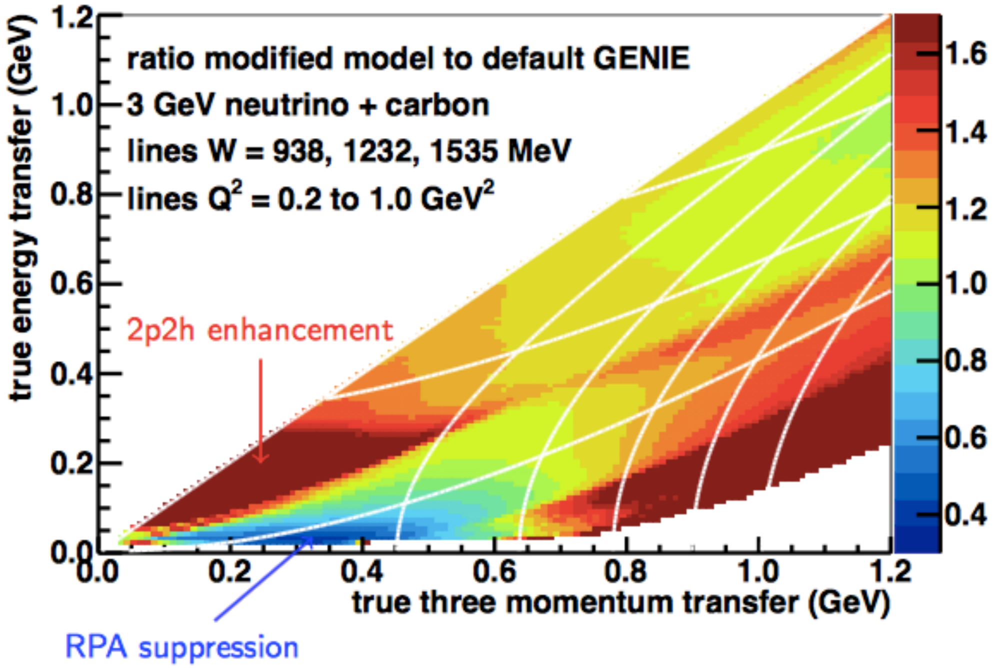
- ☹️ Antineutrino mode only (for true CCQE)
- 🙂 We can count them…
- ☹️ …but not reconstruct their energy

Pions

- ☹️ None in true CCQE but may be produced by FSI or from RES interactions. Can mimic protons.

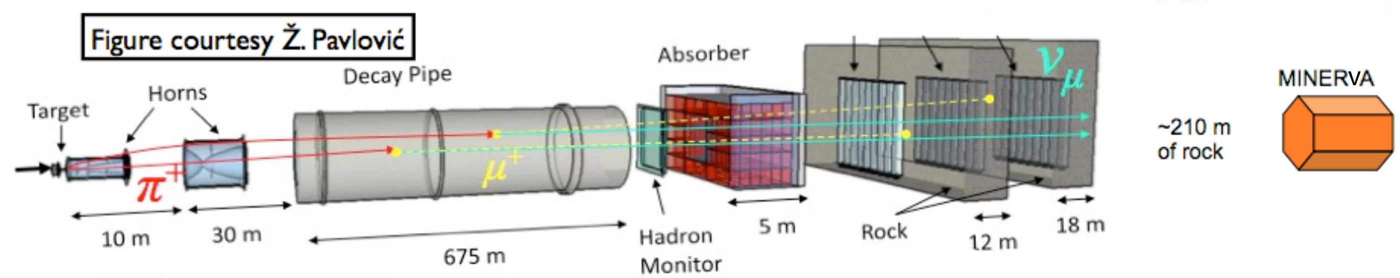
Our strategy

Evaluate multi-nucleon effects

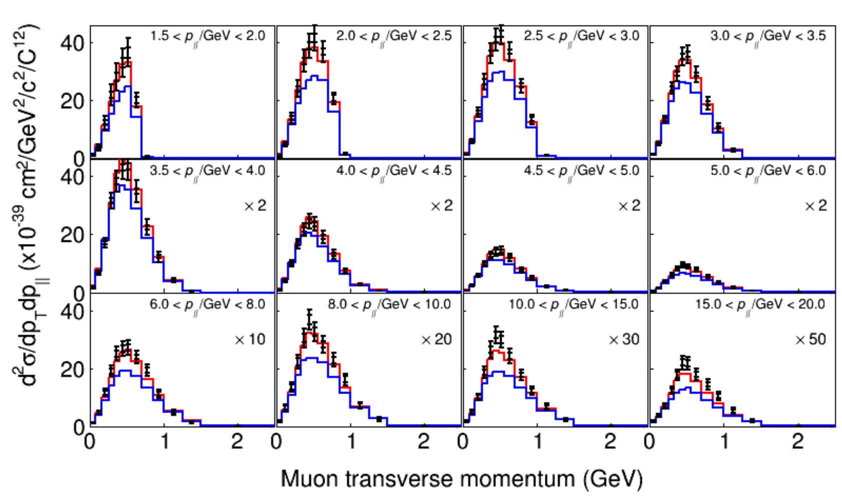


Update simulation

- Update GENIE with multi-nucleon effects
- Use latest NuMI flux

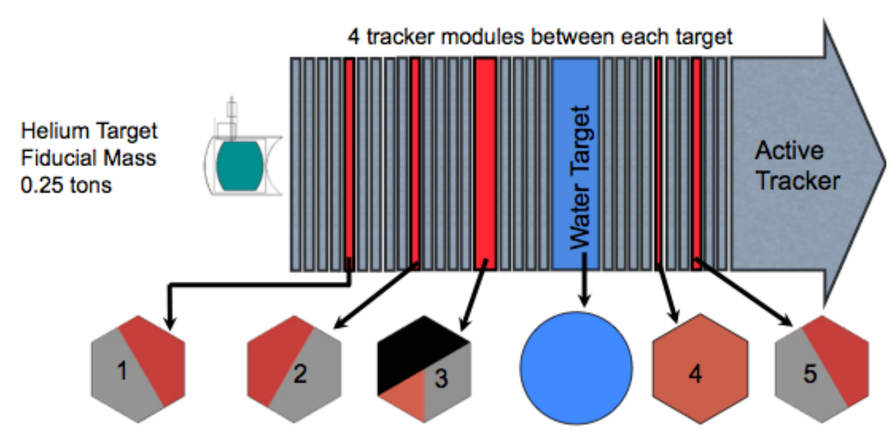


Double-differential ν_μ and $\bar{\nu}_\mu$ cross sections using muon kinematics



Nuclear dependence of CCQE rates using muon and proton kinematics

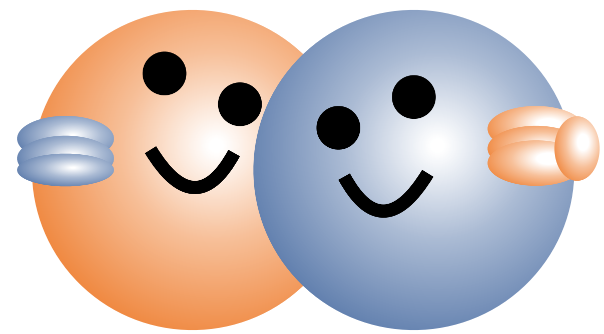
Phys.Rev.Lett. 119, 082001 (2017)



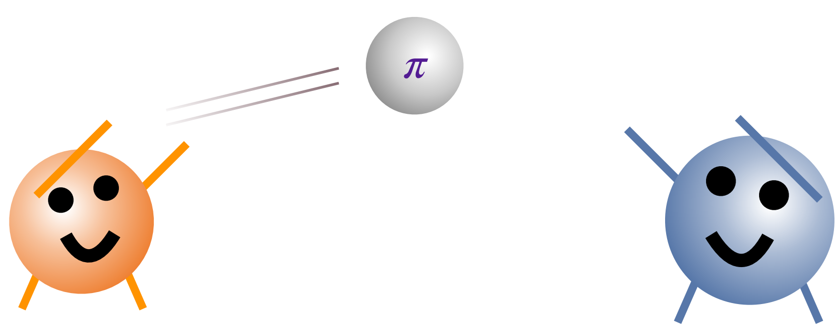
Multi-nucleon correlation effects

Correlations can be short range…

- Bodek-Ritchie tail to RFG
- Included in our default simulation

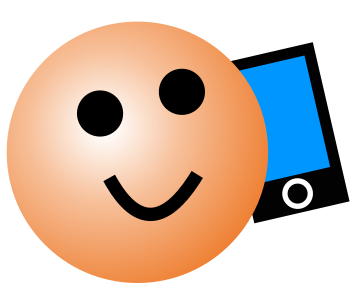


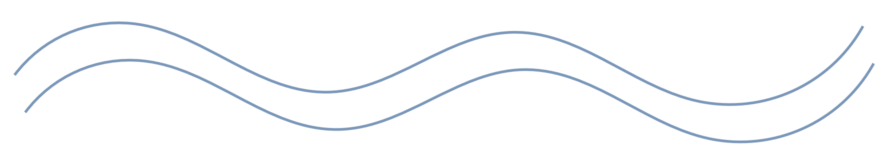
… medium range…



Meson exchange currents (MEC)

… or long range…



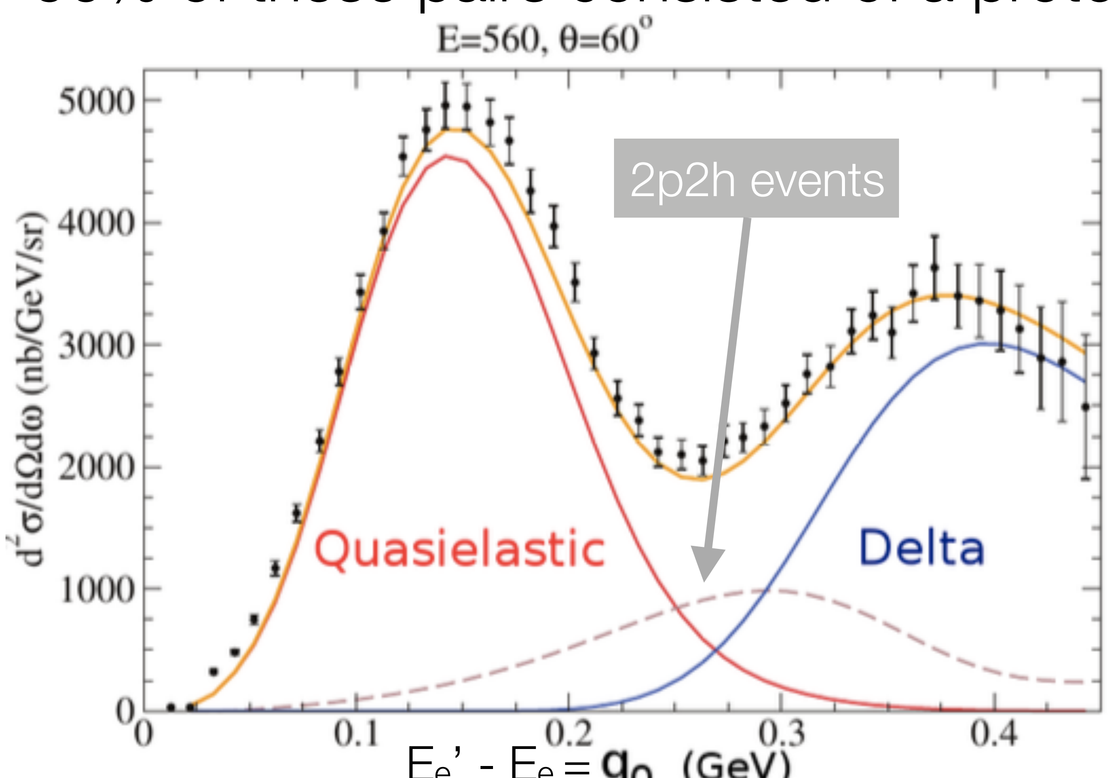


Random phase approximation (RPA)

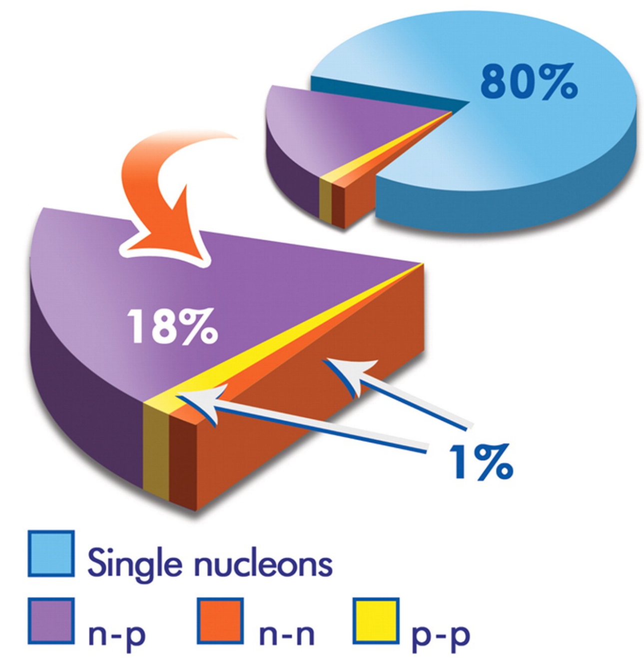
Multi-nucleon effects: beyond the Fermi Gas model

Electron-scattering experiments found that, approximately 20% of the time, electrons scattered from correlated pairs of nucleons instead of single nucleons.

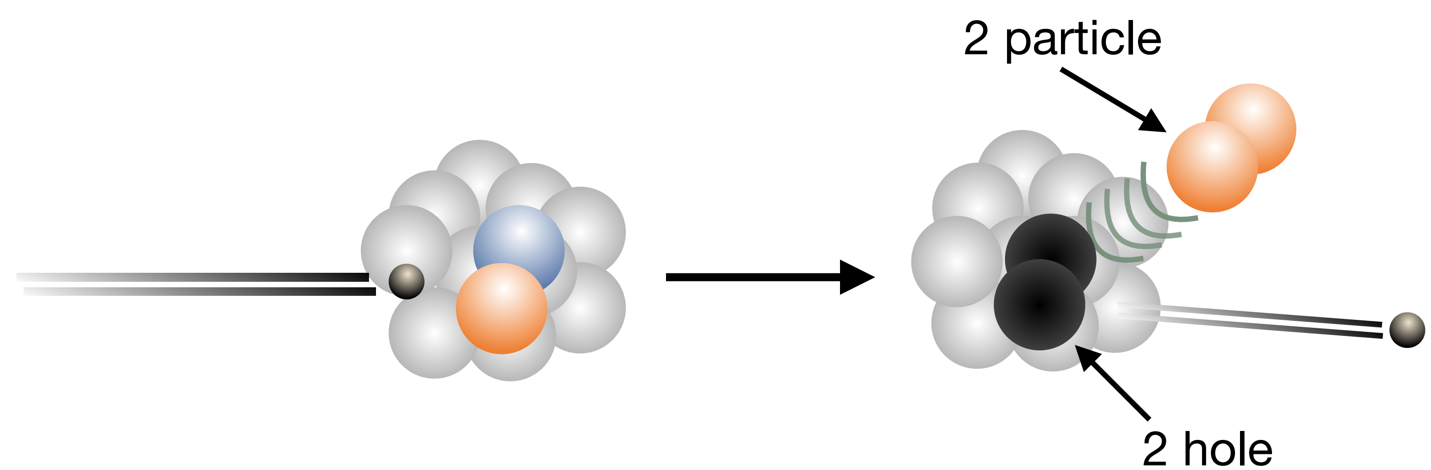
90% of these pairs consisted of a proton and a neutron.



Adapted from G. D. Megias, NuFact 2015



R. Subedi et al. Science, 320(5882):1476–1478, 2008

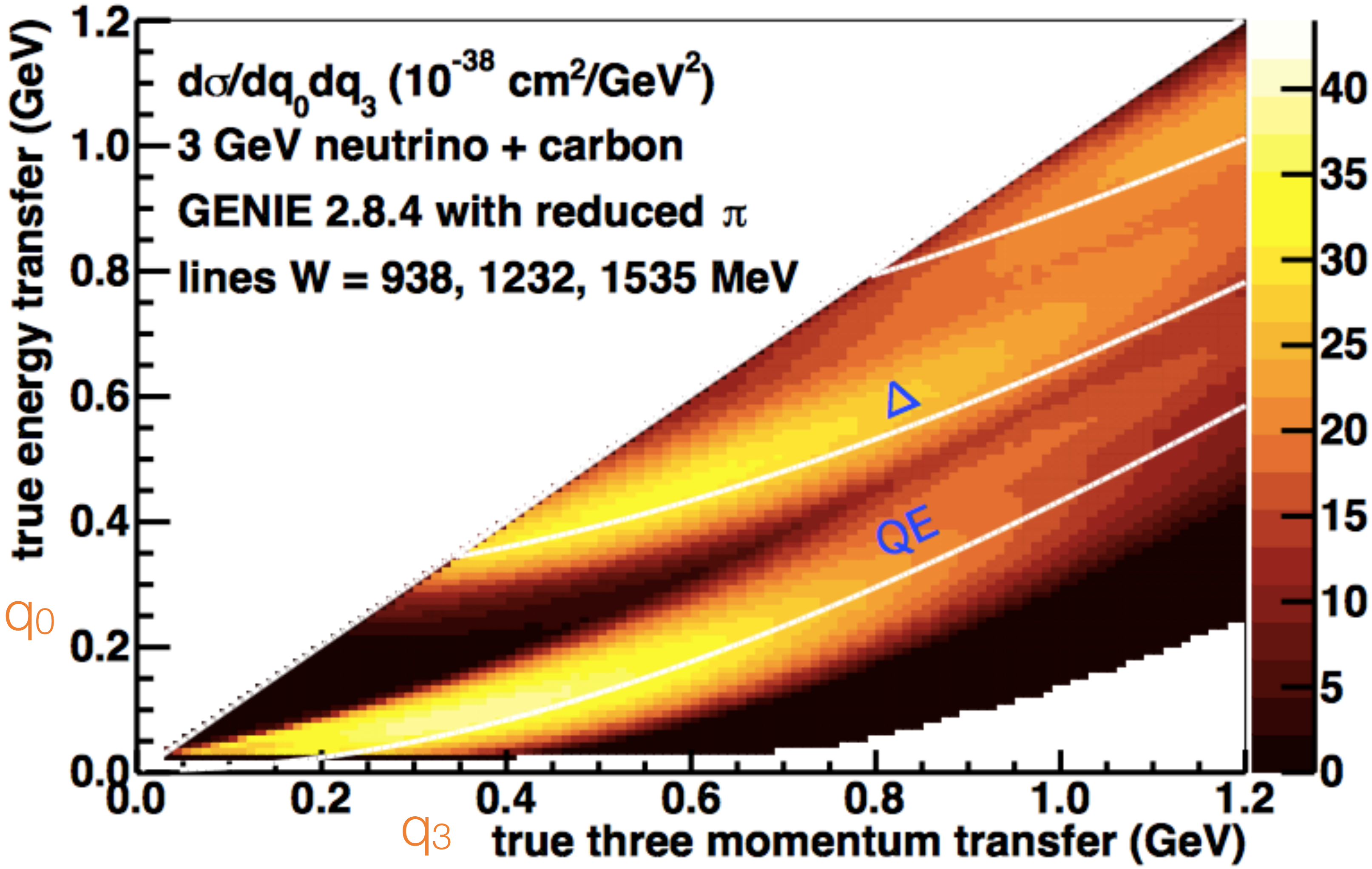


- The CCQE hypothesis reconstructs E_ν incorrectly if scattering from correlated pairs
- The final state may change as the partner nucleon is ejected ("2 particle, 2 hole")

Looking at multi-nucleon processes

Simulation with GENIE v2.8.4

Nucl.Instrum.Meth.A614 (2010) 87-104



P. Rodrigues, Fermilab wine and cheese 11 Dec 2015

To reconstruct those variables:

q_0 = total hadronic (non muon) energy

Measured calorimetrically, but "available" energy may not include neutrons.

$E_\nu = E_\mu + q_0$

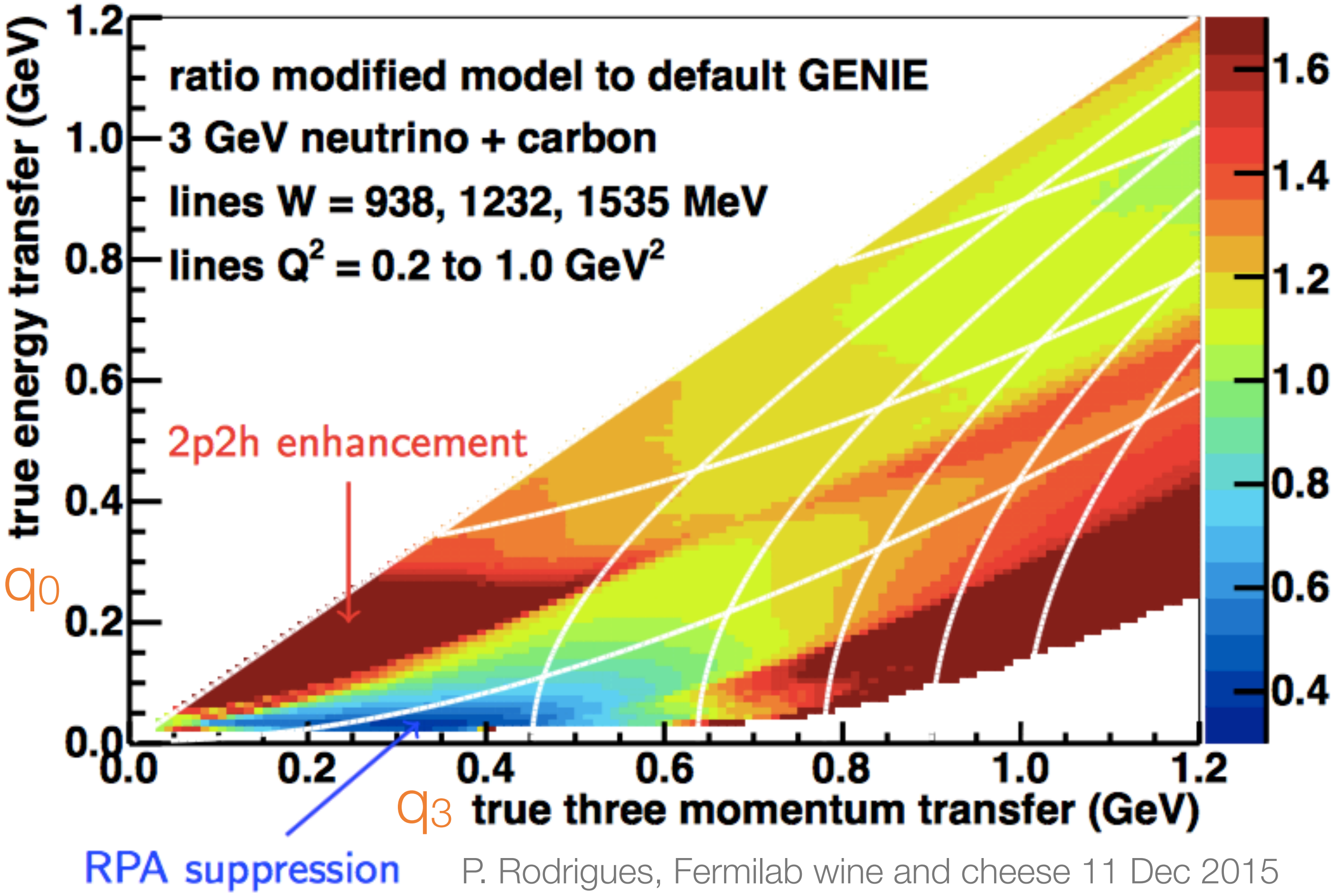
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

$$q_3 = \sqrt{Q^2 + q_0^2}$$

- Looking at inclusive cross section in terms of energy transfer (q_0) and three-momentum transfer (q_3) allows us to separate out interaction types
- Because of FSI, both resonant and QE contribute to the CC0π cross section

Multi-nucleon processes affect the cross section in this phase space

Effect of IFIC Valencia model 2p2h and Nieves model RPA on default GENIE 2.8.4



P. Rodrigues, Fermilab wine and cheese 11 Dec 2015

2p2h effects such as meson exchange currents enhance the cross section, especially at higher energies and momentum transfers

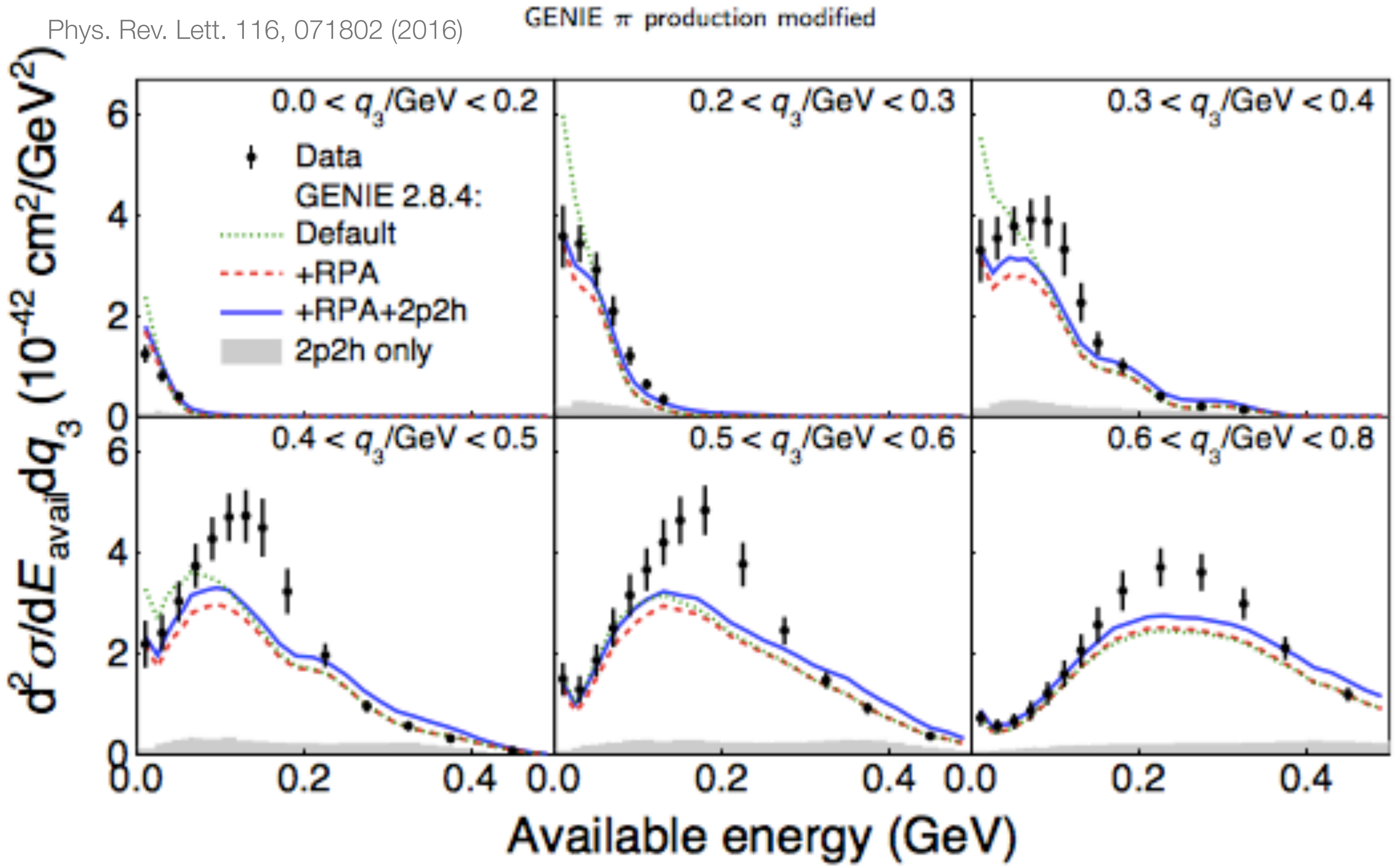
Phys. Rev. D **89**, 073015 (2014)
Phys. Rev. D **88**, 113007 (2013)
arXiv:1601.02038 [hep-ph]

RPA (screening due to W polarisation) suppresses cross section at low energy and momentum transfer

Phys. Rev. C **70**, 055503 (2004)

RPA and 2p2h give better agreement than nominal* GENIE in this phase space

Phys. Rev. Lett. 116, 071802 (2016)



V

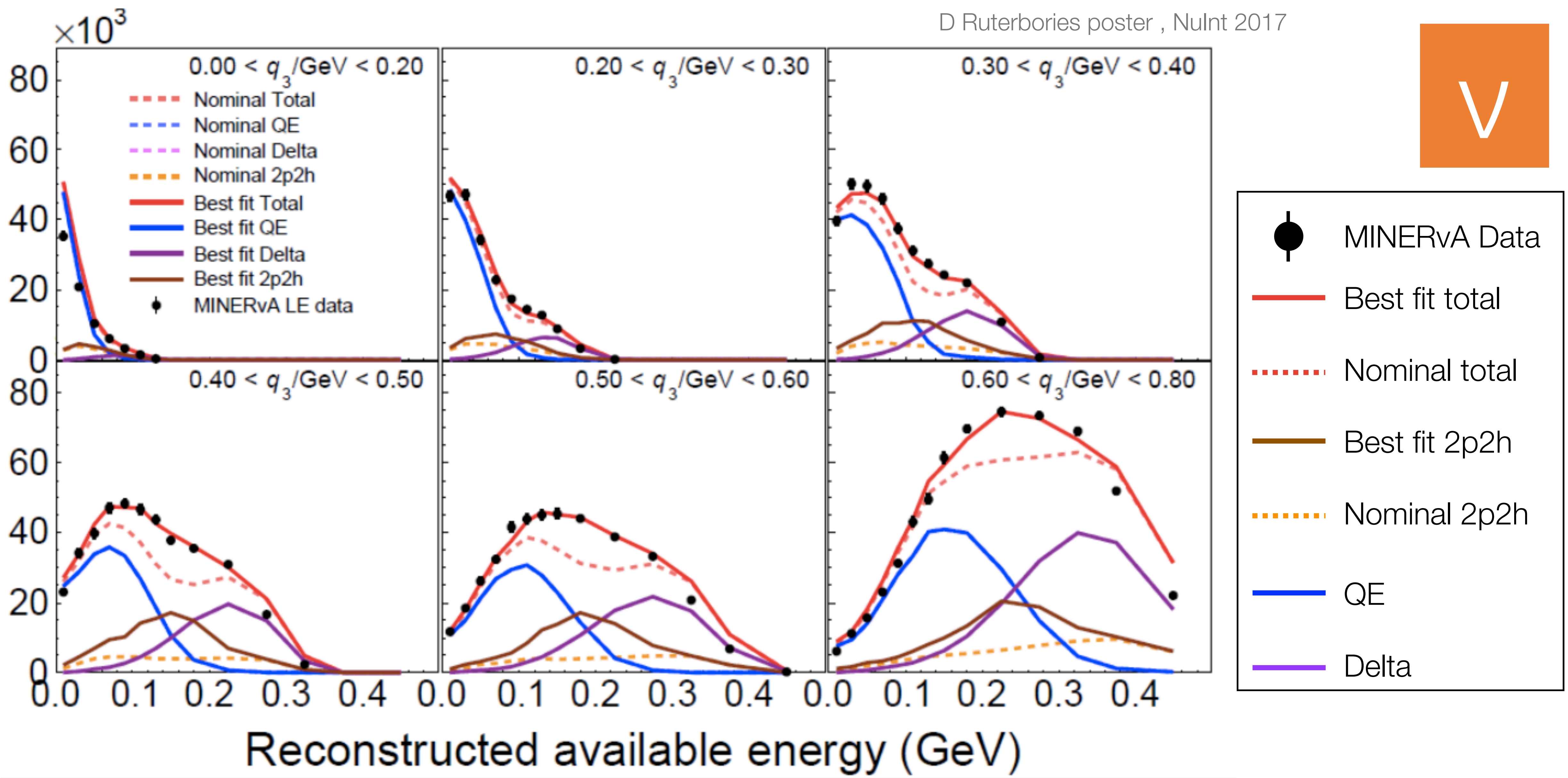
* "Nominal" GENIE actually has non-resonant pion production rates tuned to deuterium and MINERvA data

Phys. Rev. D 90, 112017 (2014)

Available energy = q_0 - neutron energy (unreconstructable)

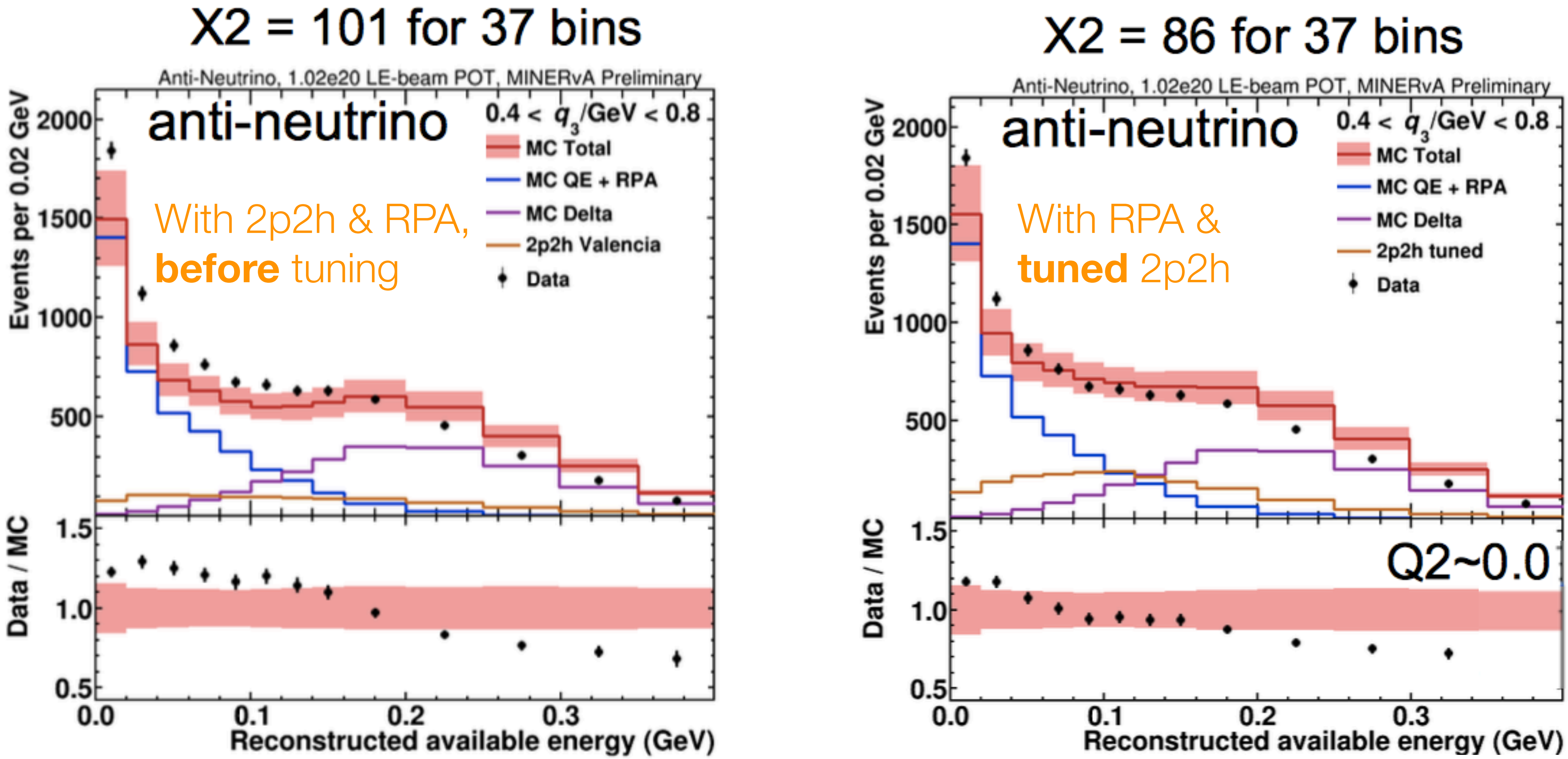
- Adding RPA significantly improves agreement, especially at low energy
- Adding 2p2h also helps, but it is insufficient in the mid-energy "dip" region
- This region also has higher proton multiplicity (identified by Bragg peak at >20MeV) than simulation

More 2p2h agrees better still



- Weighting up the 2p2h contribution with a 2-d Gaussian multiplier in q_0-q_3 space improves the fit
- The increase is due to additional events from *np* pairs (*pp* final state)
- Total increase is around 60%, but concentrated in dip region between QE and Δ

Try with antineutrino events

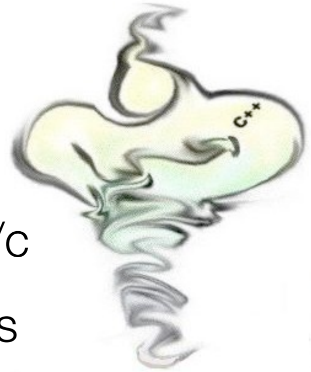


- Applying to antineutrino event counts also gives an improvement
- Available energy is not such a good quantity for ν̄ as we can't measure neutron energy
- This introduces uncertainty when trying to convert to a cross section

R Gran talk & M Elkins poster, NuInt 2017

Tuning our simulation with the study results

GENIE v 2.8.4

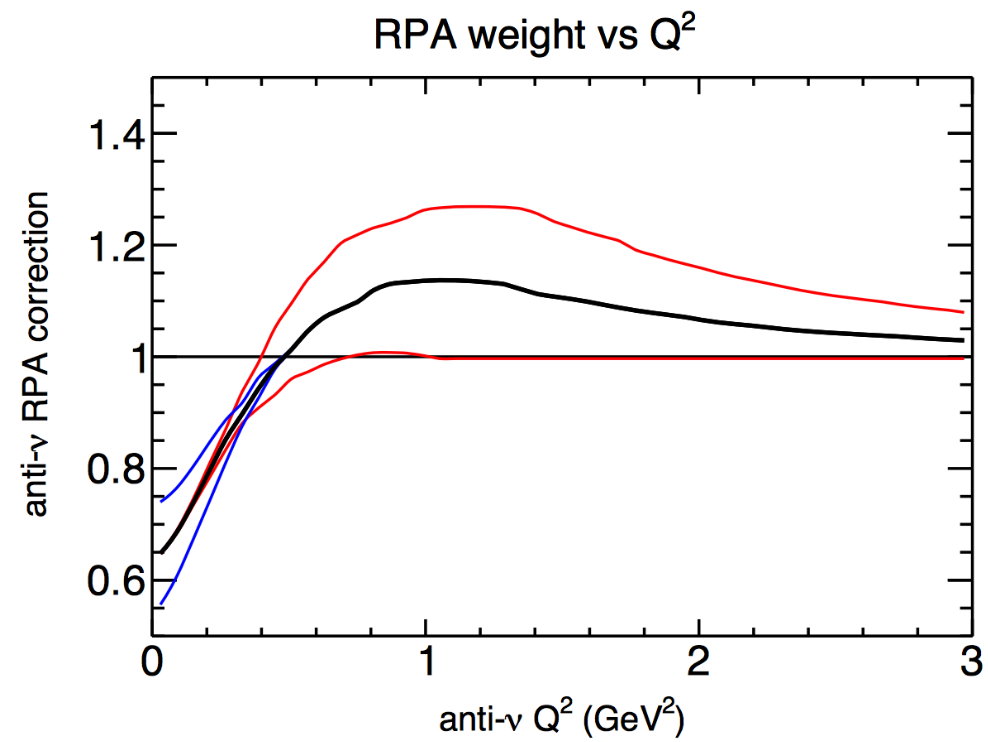


- RFG model, k_F=0.221 GeV/c
- BBBA05 vector form factors
- Dipole axial form factor, M_A=0.99 GeV/c^2,
- Bodek-Ritchie tail for short-range correlations
- Rein-Sehgal resonant model

Nucl.Instrum.Meth.A614 (2010) 87-104

Reweight quasi-elastic events to add RPA (Valencia model)

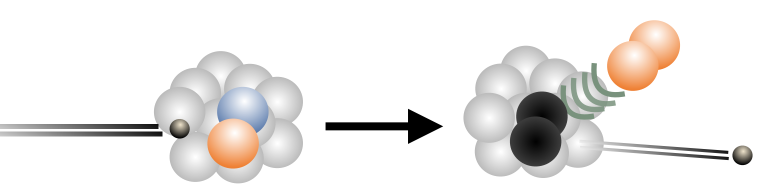
- Black line: RPA weight
- Red line: Uncertainty between relativistic/non-relativistic calculation
- Blue line: Model uncertainty compared to muon capture data



Phys. Rev. Lett. 116, 071802 (2016)

Add multi-nucleon interactions

- Valencia IFIC model
- Tuned to match best fit to MINERvA data



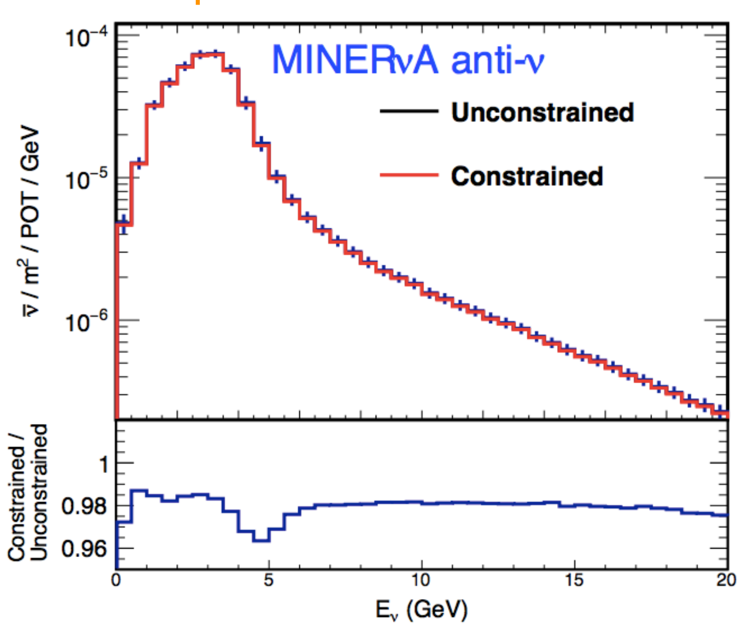
Phys. Rev. Lett. 116, 071802 (2016)

Reweight non-resonant pion production

- GENIE overestimates by 43% compared to bubble chamber experiments
- Scale down accordingly

Eur Phys J. C 76:474 (2016)

Updated flux measurement



- PPFX gen-2 NuMI flux
- Constrained by ν-e scattering rate

Phys. Rev. D 94, 092005 (2016)

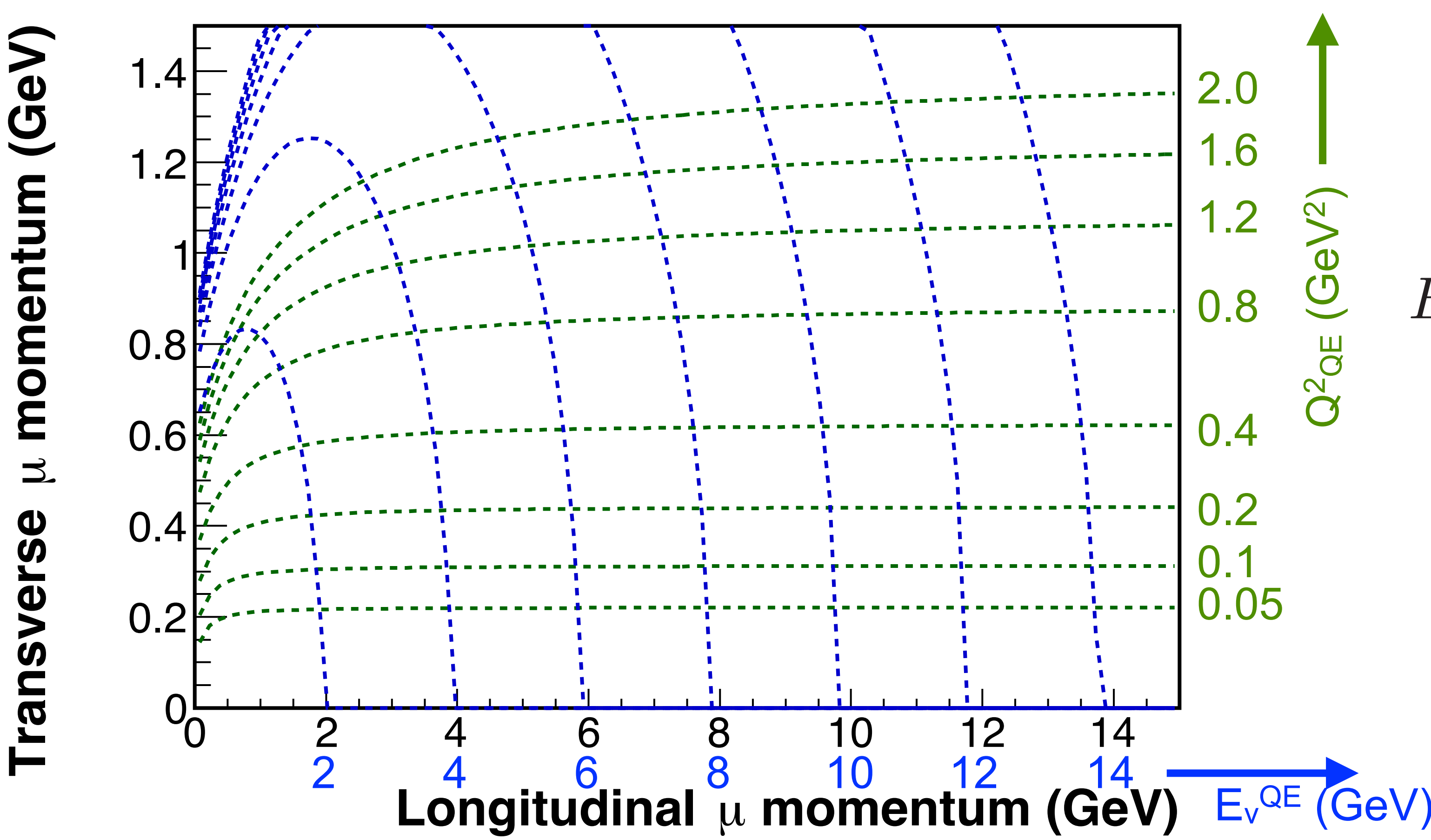
Calculating a double-differential cross section: variables

Muon p_T and $p_{||}$

- measurable
- good phase space coverage

Q^2_{QE} and E_ν^{QE}

- physics effects depend on these
- but reconstruction introduces model dependence



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

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

$Q^2_{QE} \sim p_T$

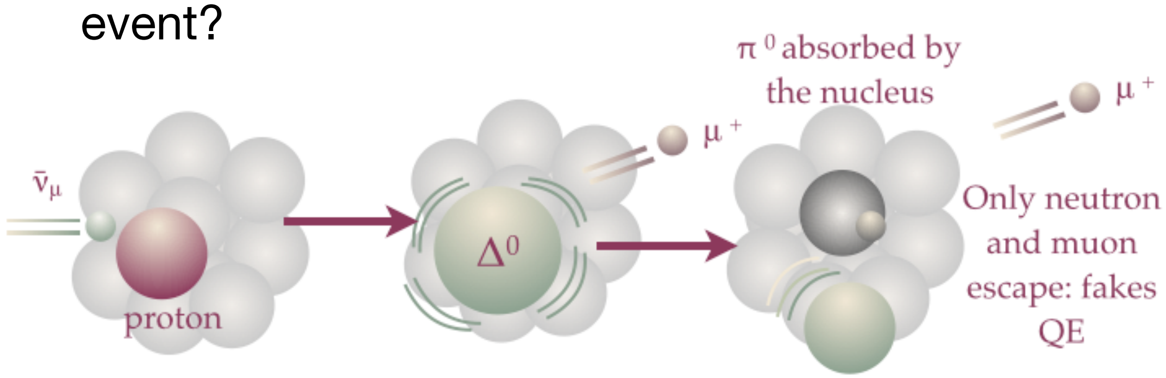
$E_\nu^{QE} \sim p_{||}$

(Formulas for neutrino mode; switch neutron and proton for antineutrino)

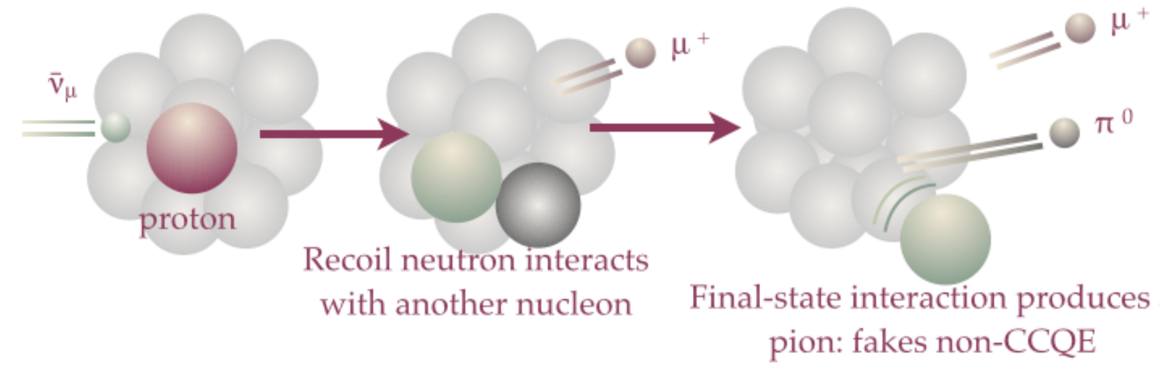
Defining our signal: or What is CCQE anyway?

We know that a true CCQE event produces a muon and single nucleon, but what about…?

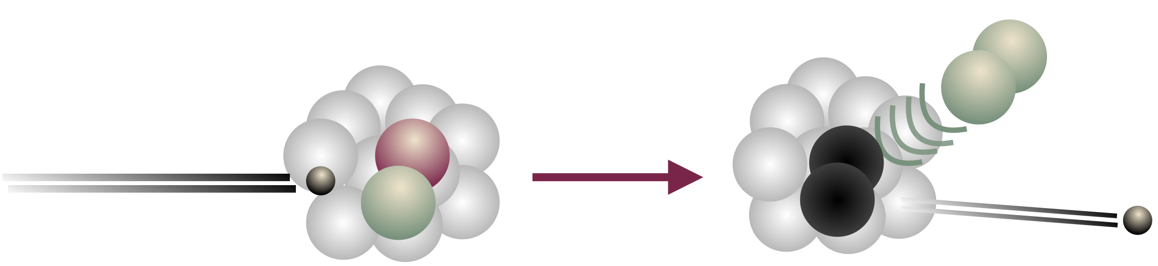
Resonant events where pion is absorbed in FSI, leaving a final state identical to a CCQE event?



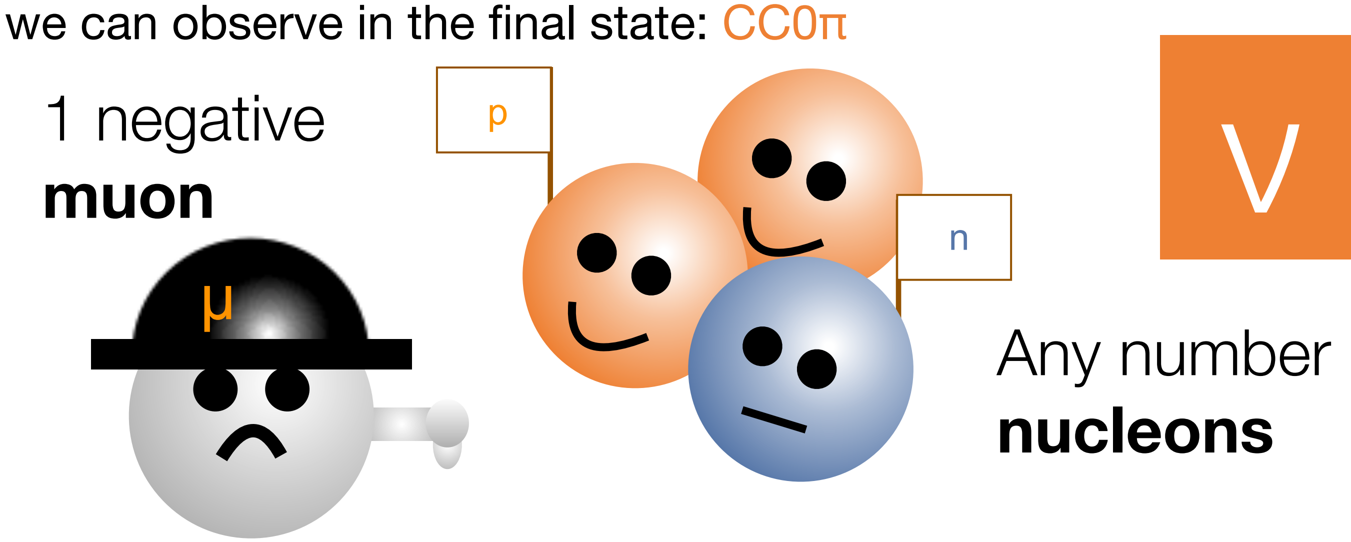
CCQE events where FSI produces pions in the final state?



2p2h events with CCQE scattering from a correlated pair of nucleons?



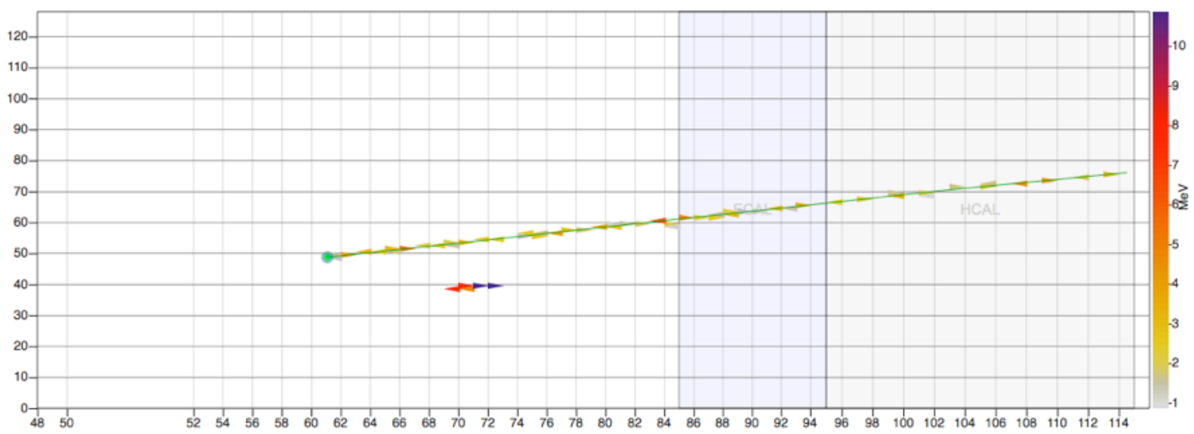
To reduce model dependence, and follow the lead of other experiments, we choose a signal definition that is based on what we can observe in the final state: CC0π



Signal definition for neutrino “QE-like”

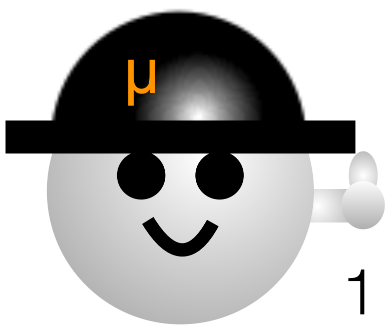
Signal definition: the antineutrino dilemma

$$\bar{\nu} + p \rightarrow \mu^+ + n$$

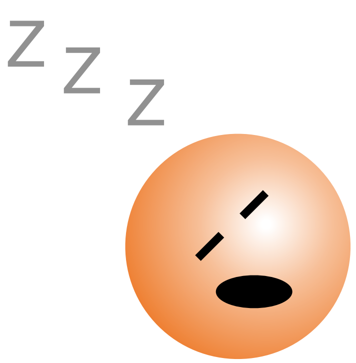


$\bar{\nu}$

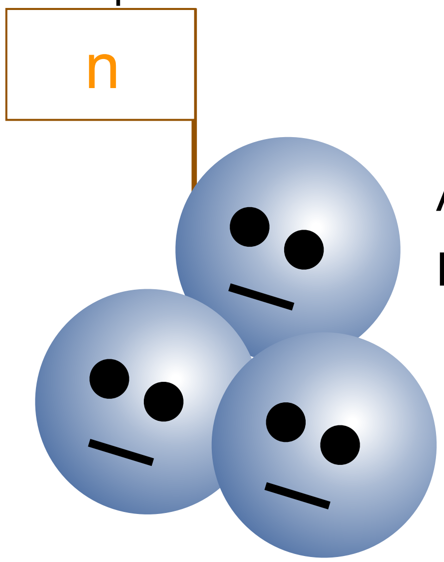
- Antineutrino CCQE events have no non-muon tracks and little "recoil" energy in the final state
- But other CC0π $\bar{\nu}$ events (2p2h, RES+FSI) could contain protons, which we can detect in MINERvA if over 120 MeV
- We need a signal that mimics what we can actually identify, with good acceptance



1 positive **muon**



Only **low-energy protons** (below 120 MeV)



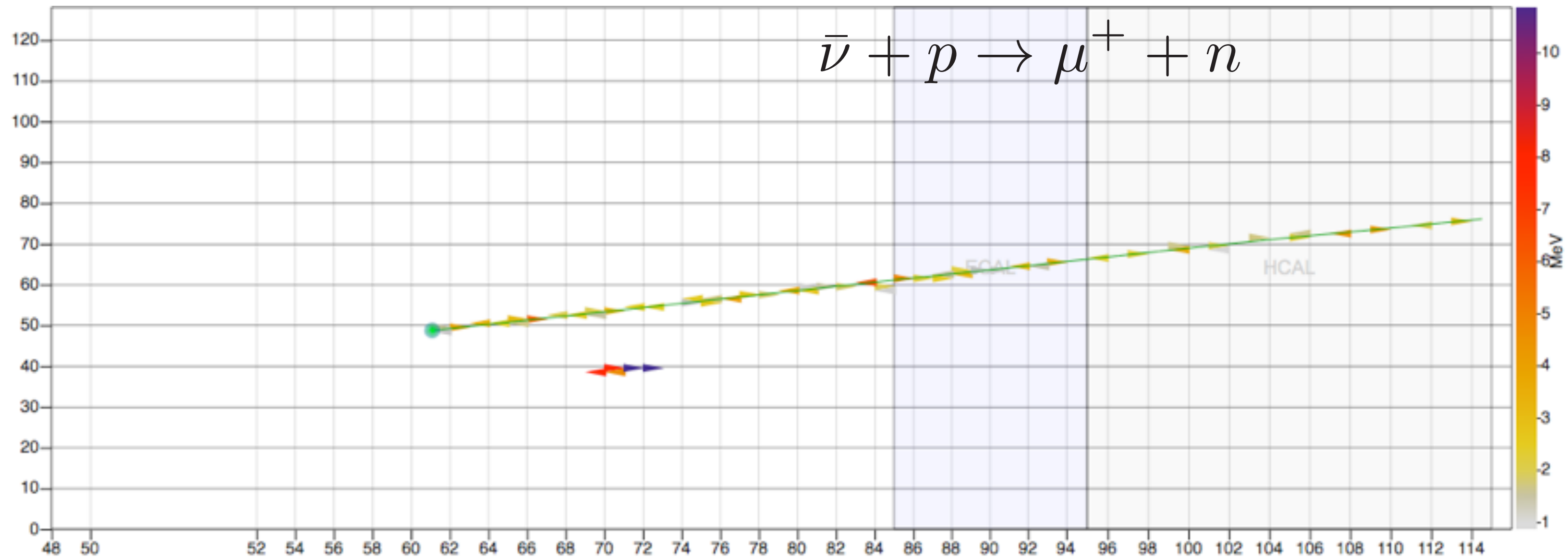
Any number of **neutrons**

Signal definition for antineutrino "QE-like"

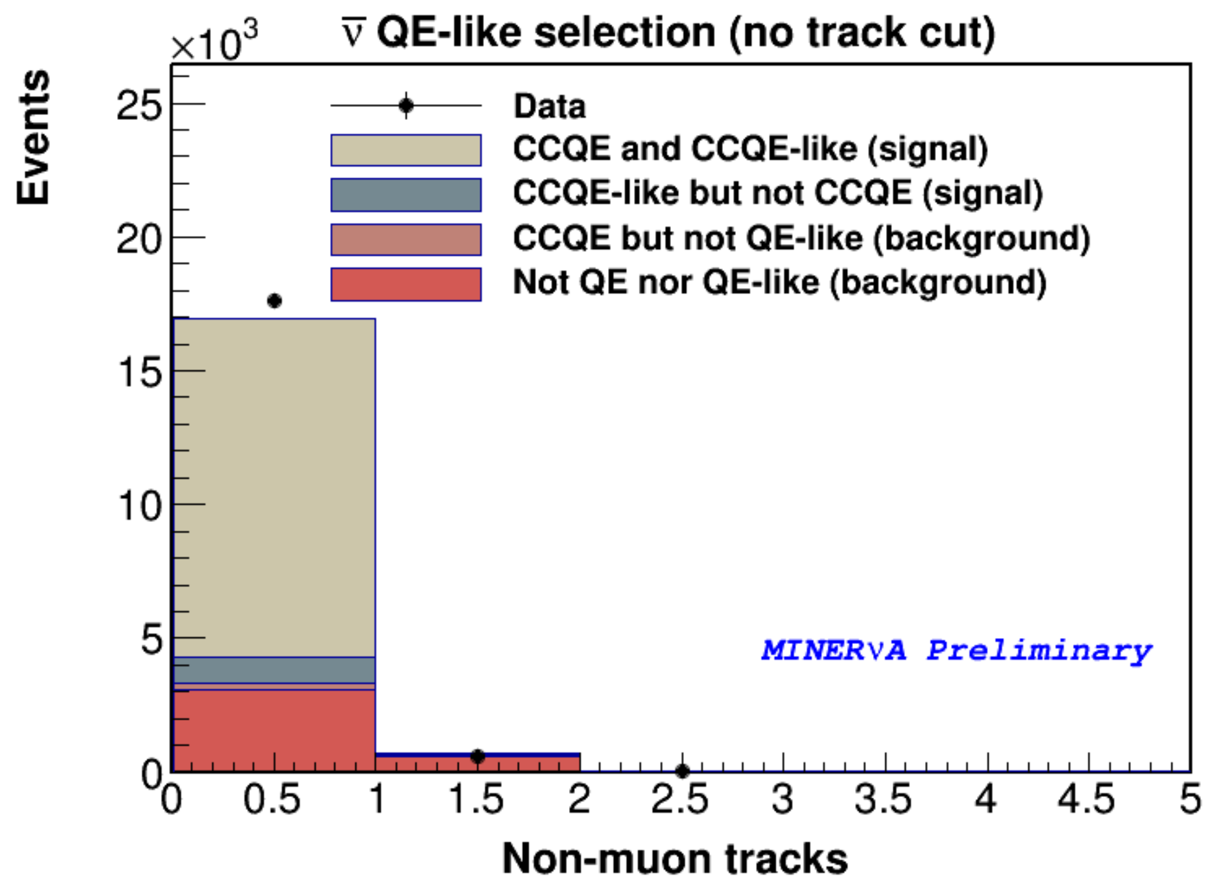
- Due to MINOS match requirement, we also require a muon angle < 20°

Selecting antineutrino events

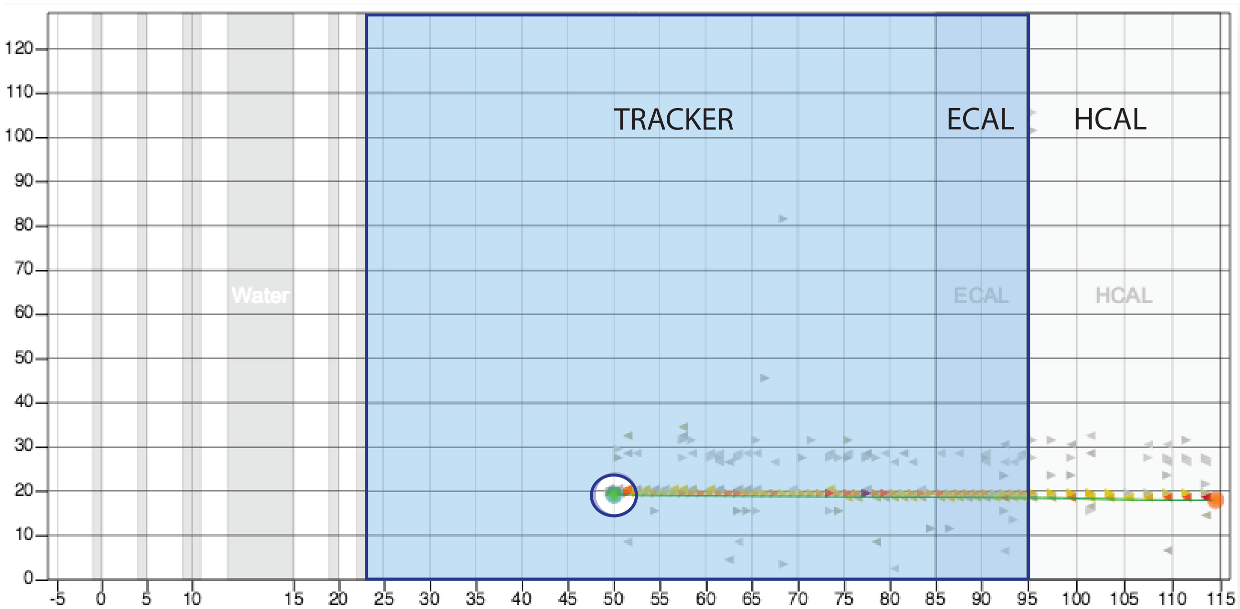
$\bar{\nu}$



- 1 muon track matched in MINOS as μ^{+}
- No other tracks



Selecting antineutrino events

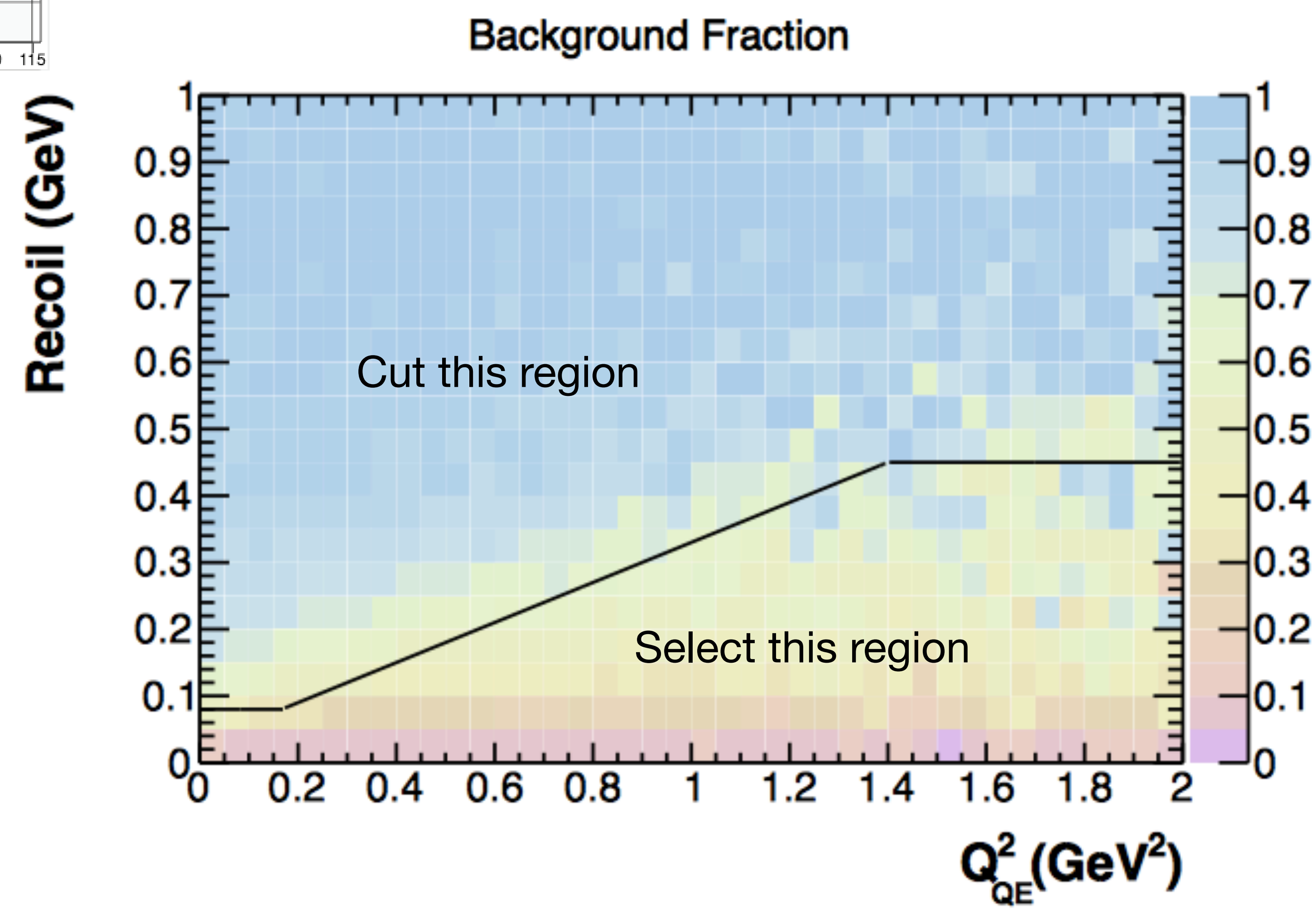


Recoil = total energy deposited in blue area

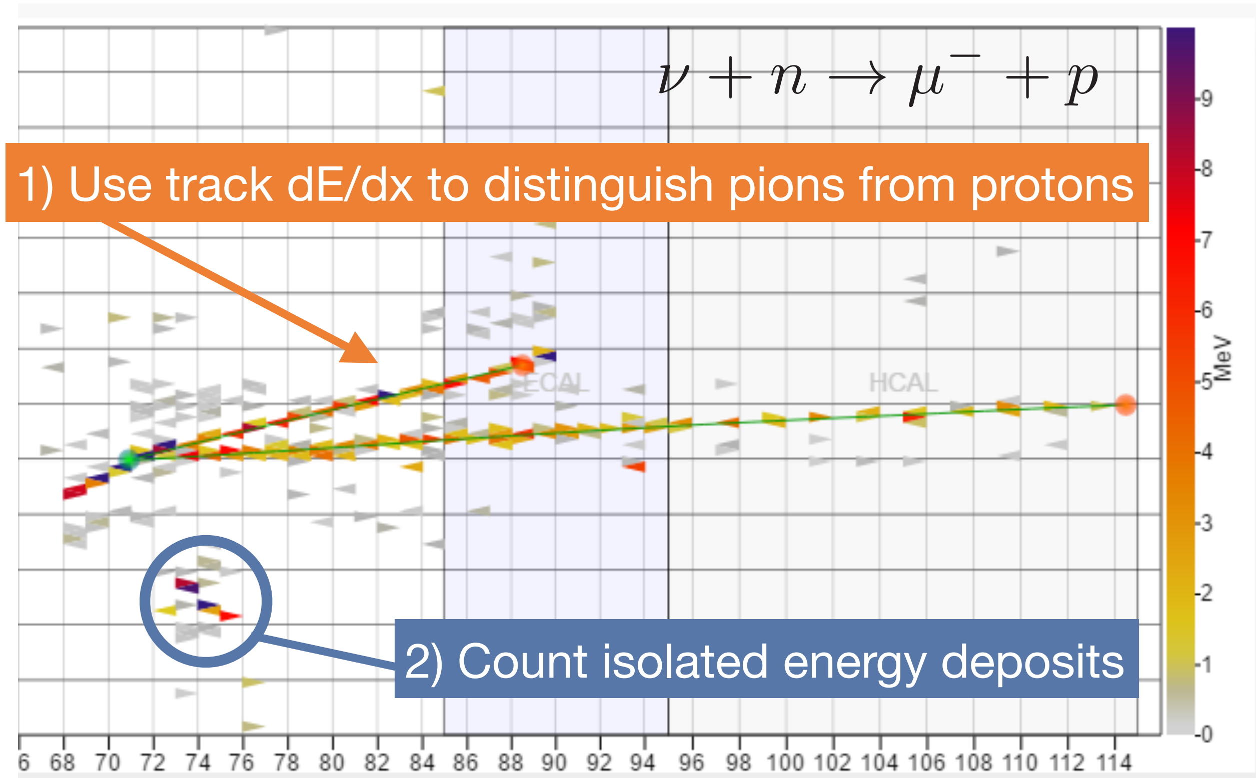
(10cm sphere around vertex area ignored as it contains non-trackable low-energy protons)

$\bar{\nu}$

- 1 muon track matched in MINOS as μ^+
- No other tracks
- Q^2-dependent cut on recoil energy

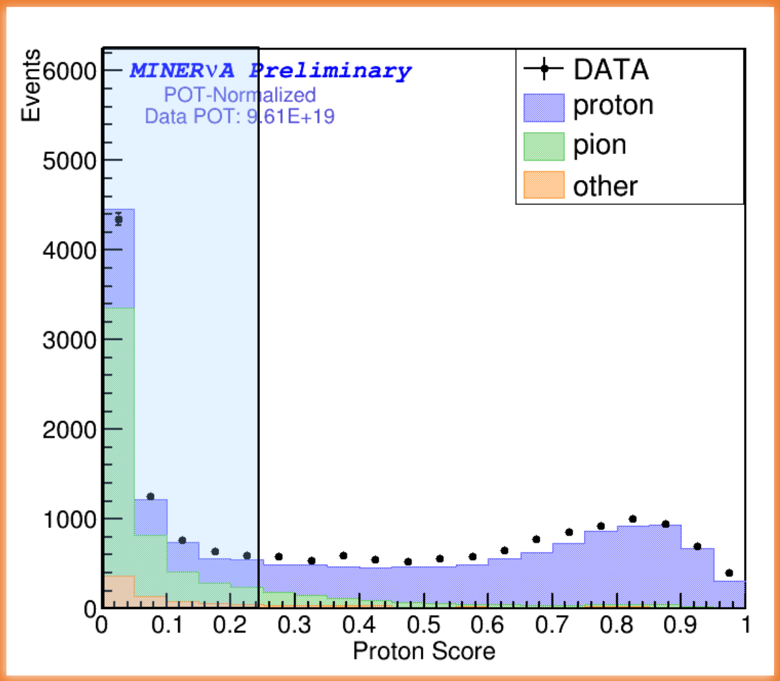


Selecting neutrino events



Neutrino events have an additional track: different strategy!

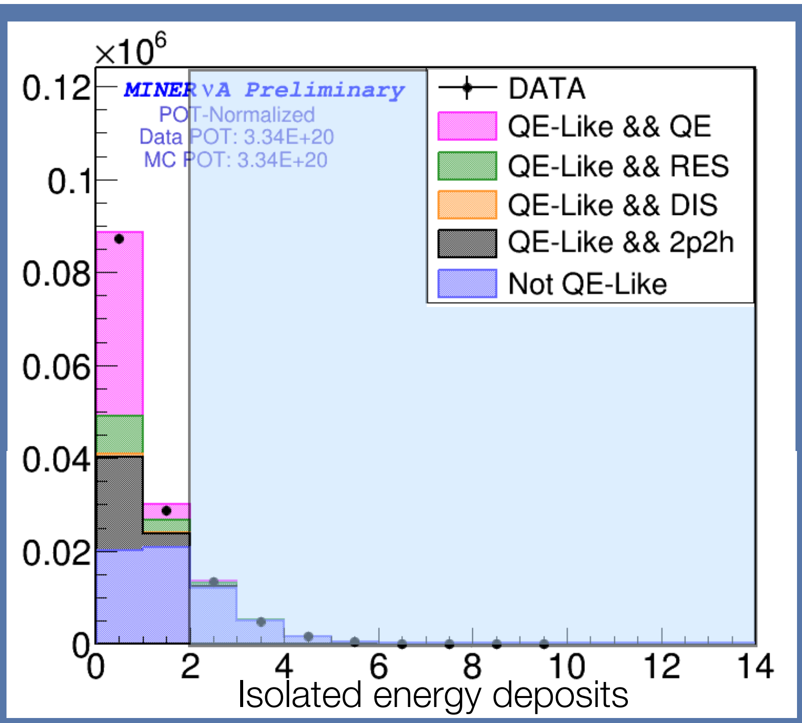
ν



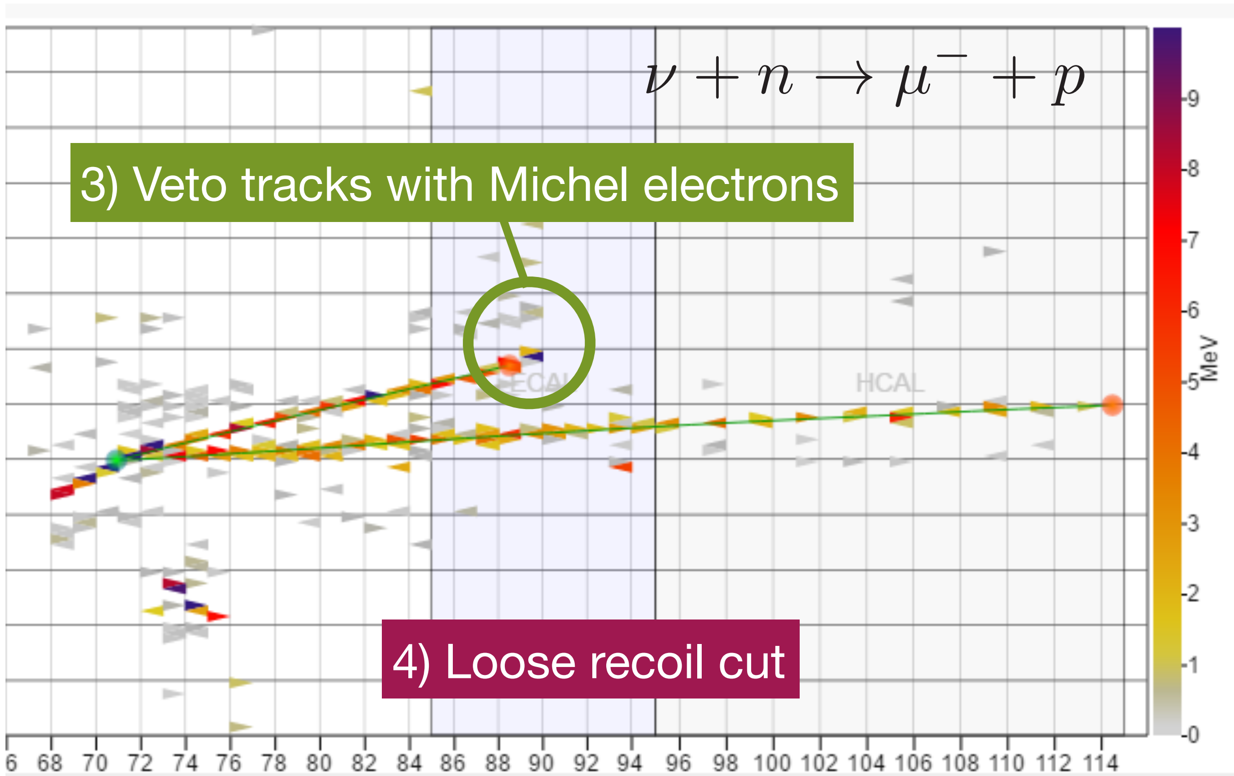
1) Proton score

Depends on dE/dx and on Q^2_{QE} - cut loosens at high Q^2

2) Maximum 1 isolated energy deposit

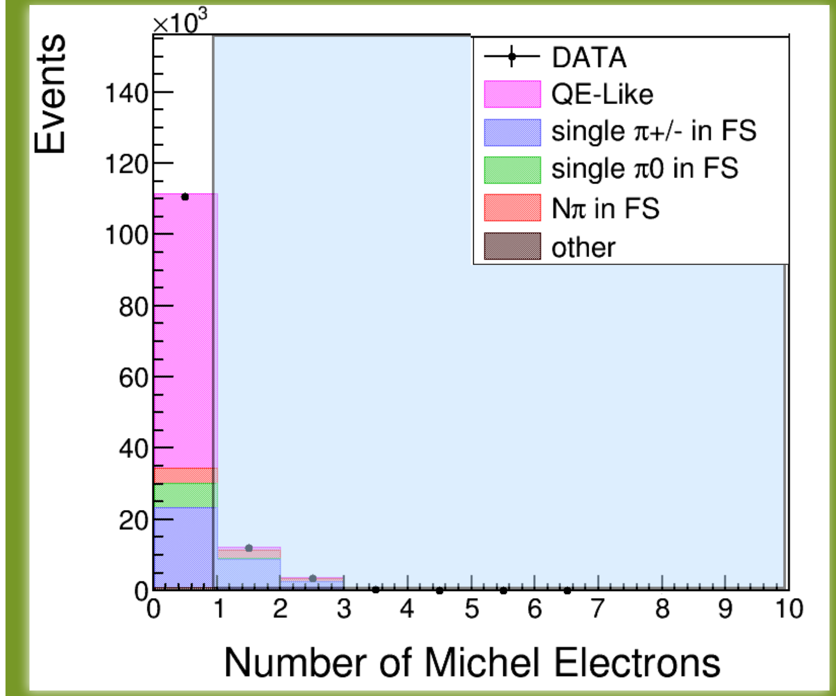


Selecting neutrino events



Neutrino events have an additional track: different strategy!

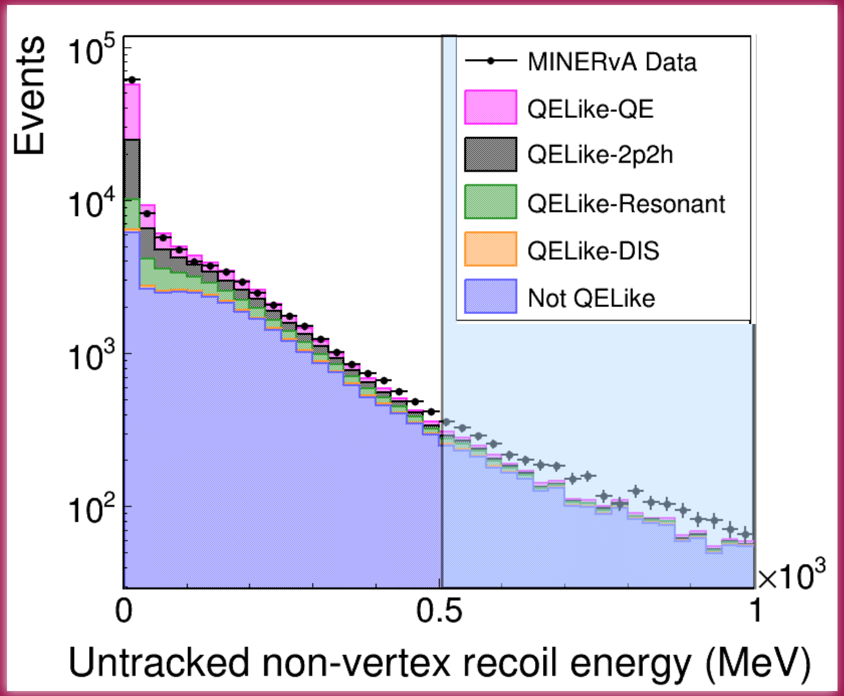
V



3) Michel electrons

Delayed electron at the end of a short track is characteristic of charged pion decay chain : veto it

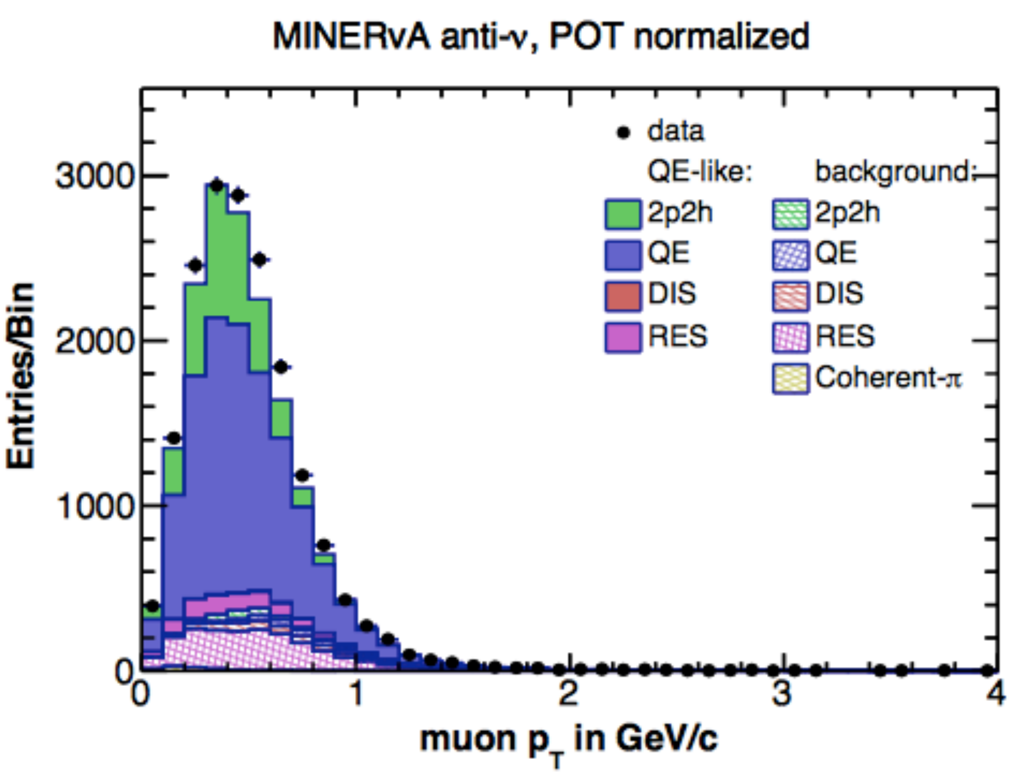
4) Reject events with recoil energy > 500MeV



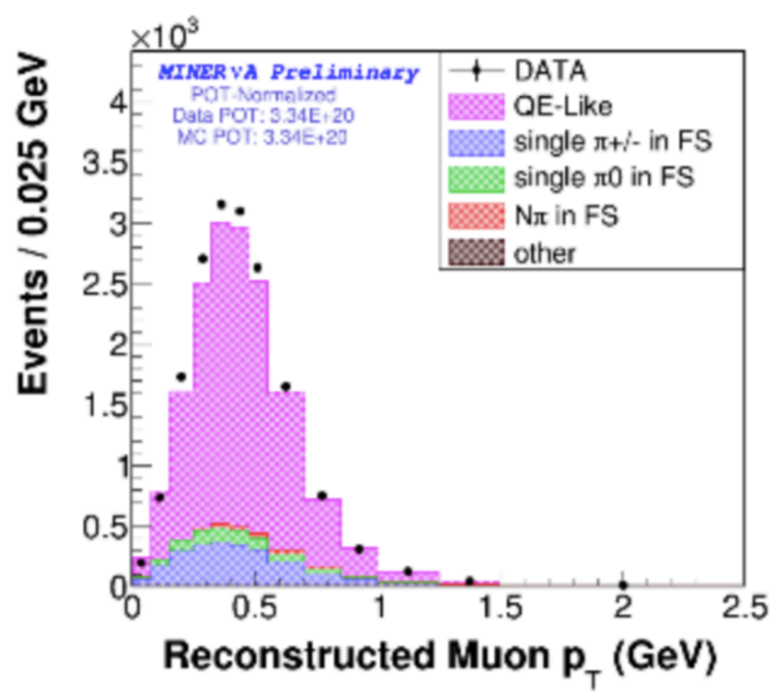
Calculating a cross section:
1) Select events that pass cuts

$$\left(\frac{d^2\sigma}{dx\,dy}\right)_{ij} = \frac{\sum_{\alpha\beta} U_{\alpha\beta ij}\left(N_{\text{data},\alpha\beta} - N^{bkgd}_{\text{data},\alpha\beta}\right)}{\epsilon_{ij}(\Phi T)(\Delta x_i)(\Delta y_j)}$$

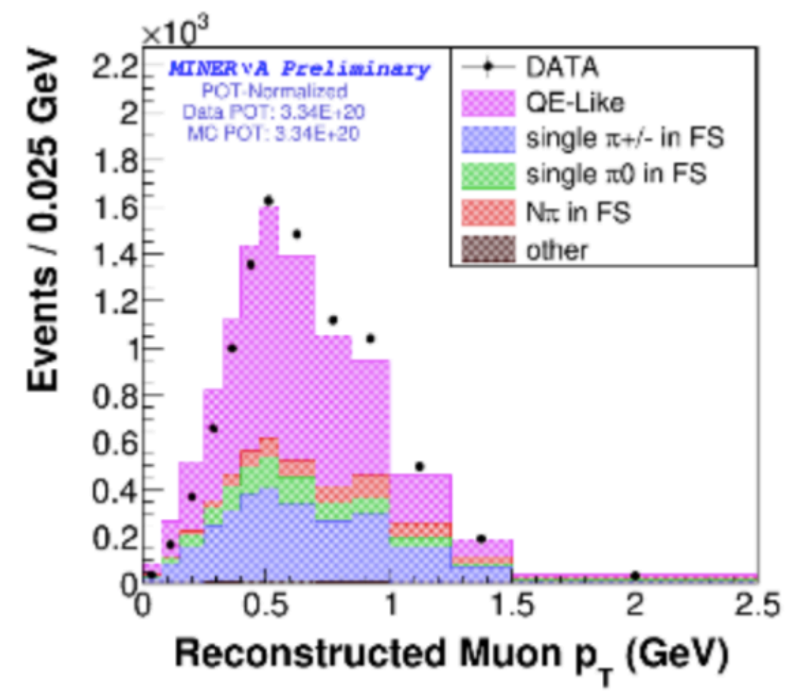
$\bar{\nu}$



ν



1-track

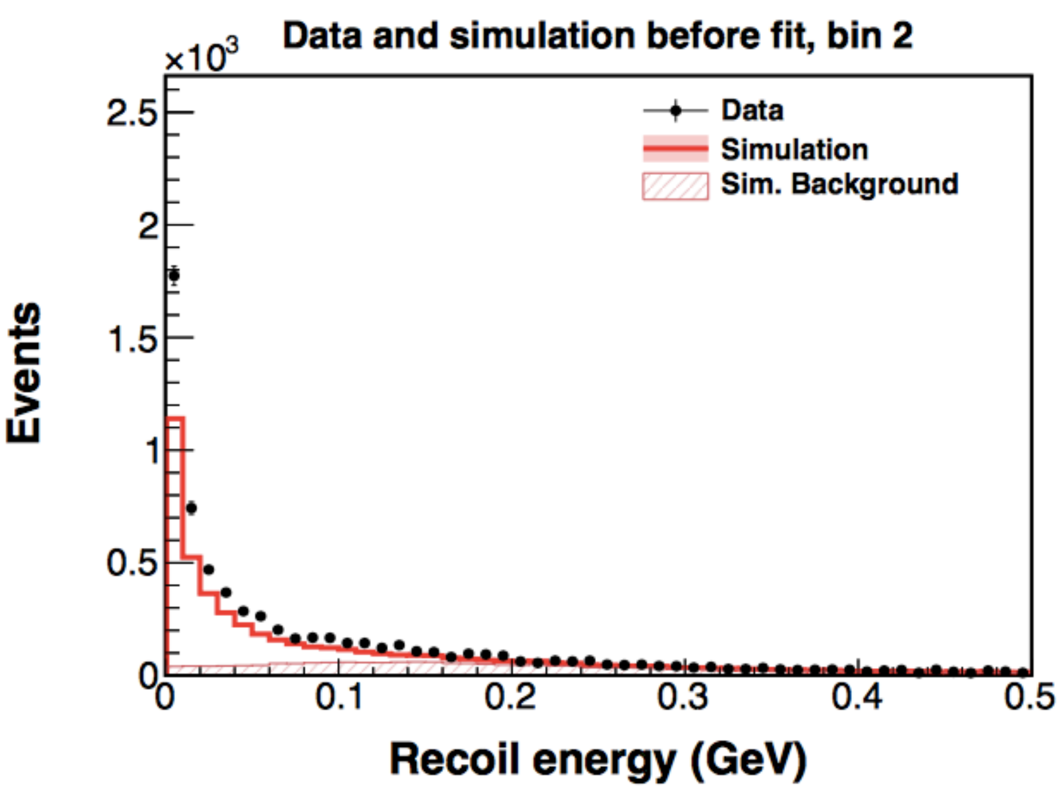


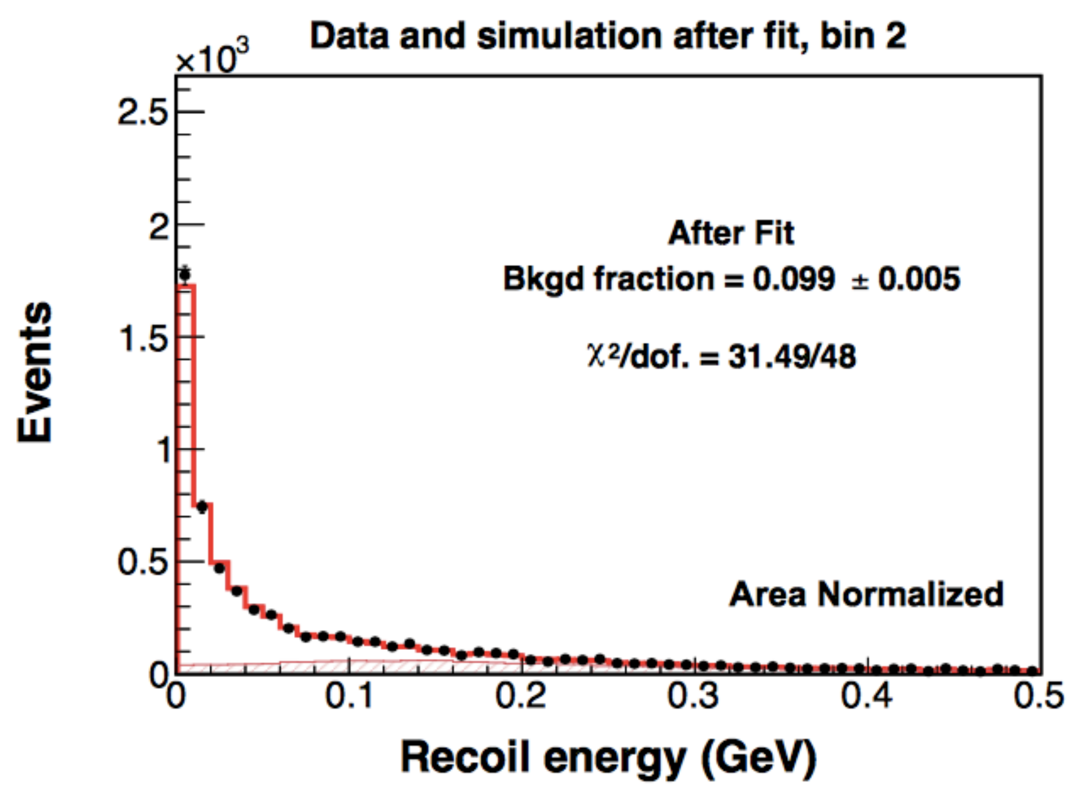
2-track

Calculating a cross section:
2) Subtract scaled backgrounds: ν̄ mode

ν̄

$$\left(\frac{d^2\sigma}{dx\,dy}\right)_{ij} = \frac{\sum_{\alpha\beta} U_{\alpha\beta ij}\left(N_{\mathrm{data},\alpha\beta} - N^{bkgd}_{\mathrm{data},\alpha\beta}\right)}{\epsilon_{ij}(\Phi T)(\Delta x_i)(\Delta y_j)}$$



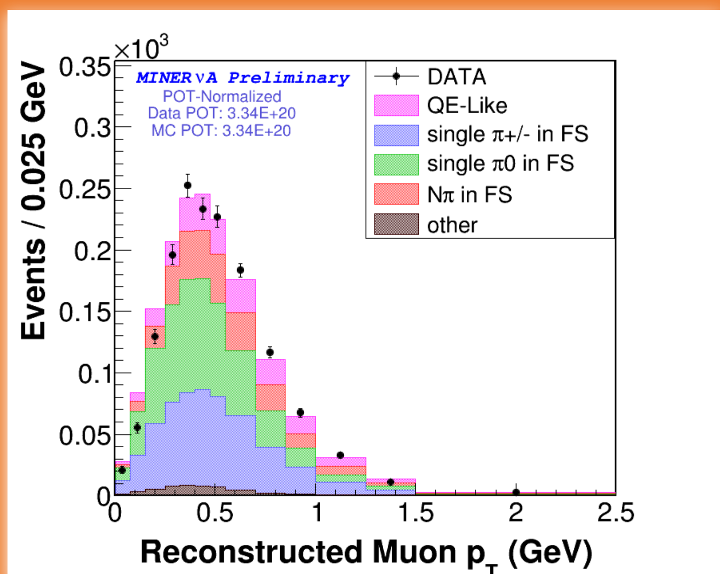


To reduce bias from the simulation's relative signal and background normalization, we fit the shape of the recoil energy in each of 5 bins to the predicted shapes of signal and background to determine the background fraction in each bin

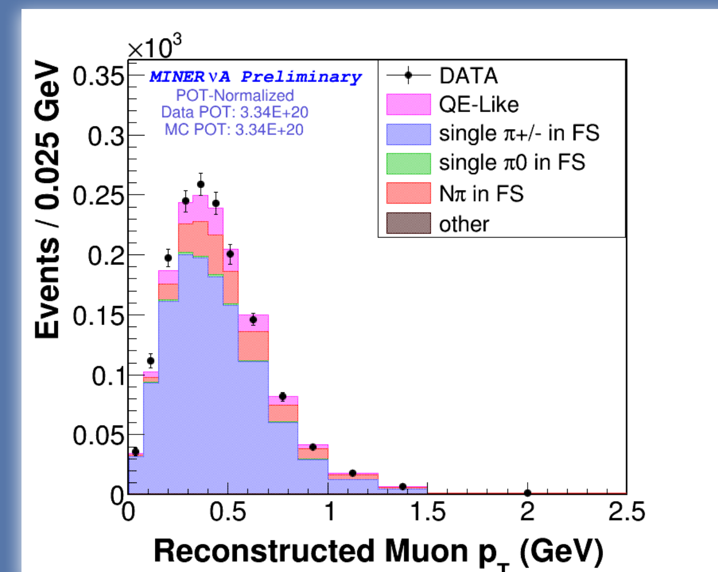
Calculating a cross section:
2) Subtract scaled backgrounds: ν mode

For neutrinos, we fit data to the shapes of p_T distributions in 3 background categories to get background scales. (Separate fits for 1- and 2-track samples).

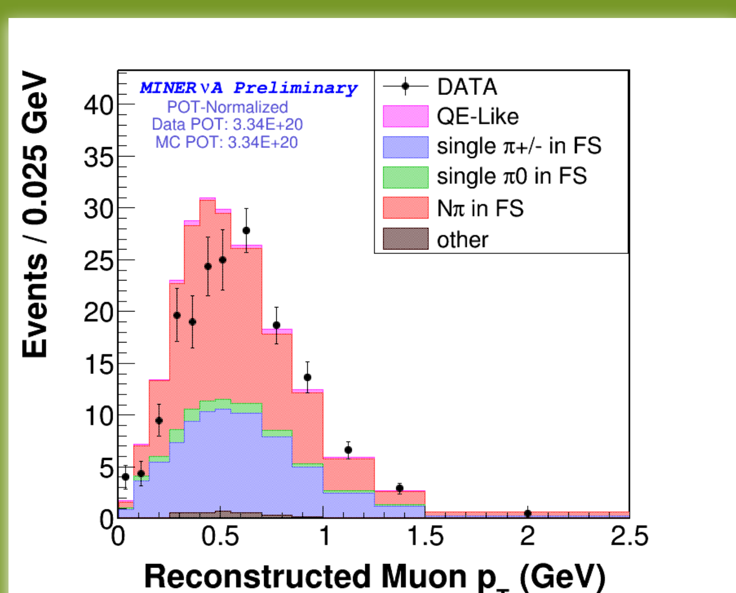
ν



Events with Michel electrons



Events with more than 1 isolated energy deposit

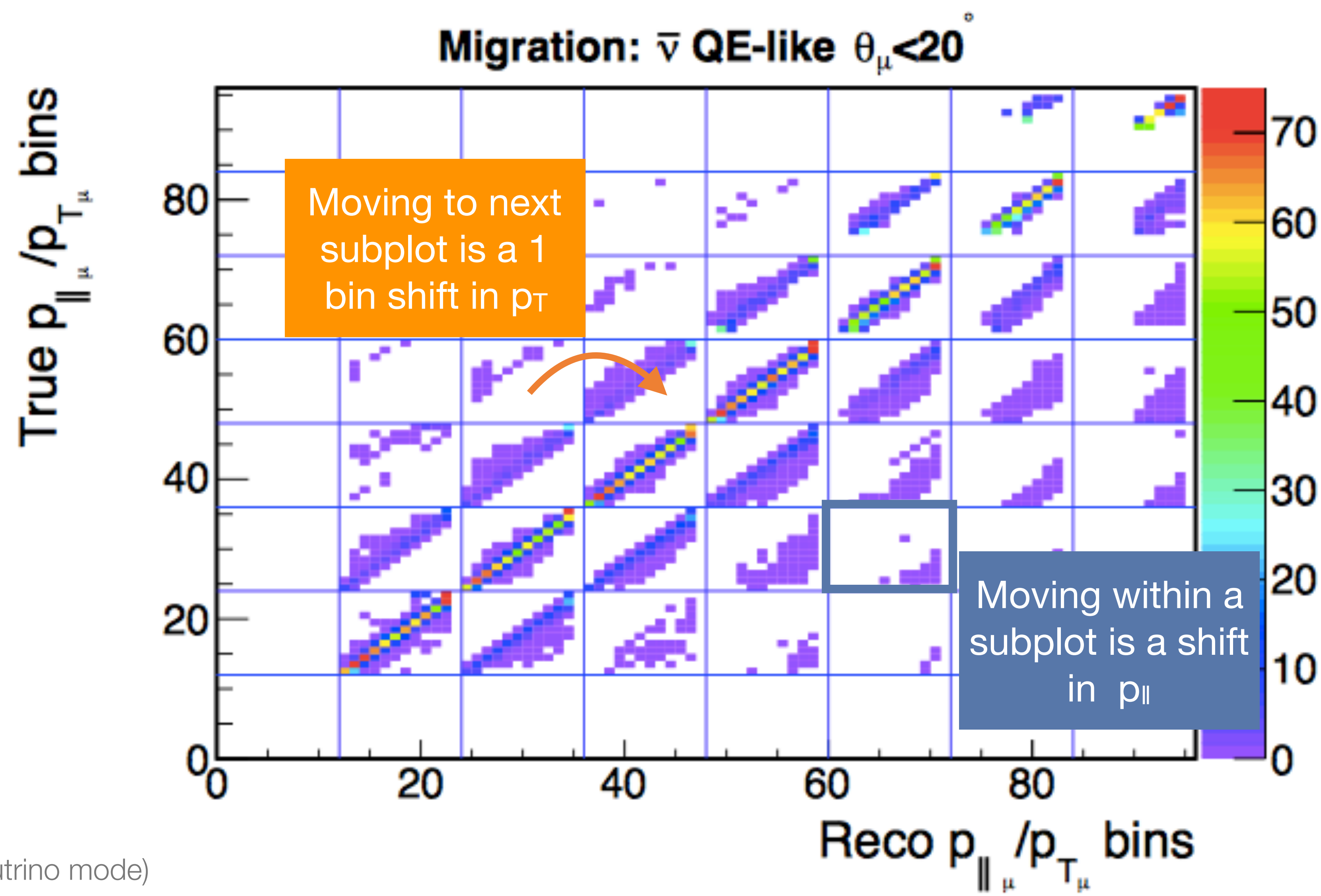


Michel electrons and isolated deposits

- DATA
- QE-like
- Single $\pi^{+/-}$ in final state
- Single π^0 in final state
- More than one π in final state
- Other

Calculating a cross section:
3) Unsmearing

$$\left(\frac{d^2\sigma}{dx\,dy}\right)_{ij} = \frac{\sum_{\alpha\beta} U_{\alpha\beta ij}\left(N_{\mathrm{data},\alpha\beta} - N^{bkgd}_{\mathrm{data},\alpha\beta}\right)}{\epsilon_{ij}(\Phi T)(\Delta x_i)(\Delta y_j)}$$

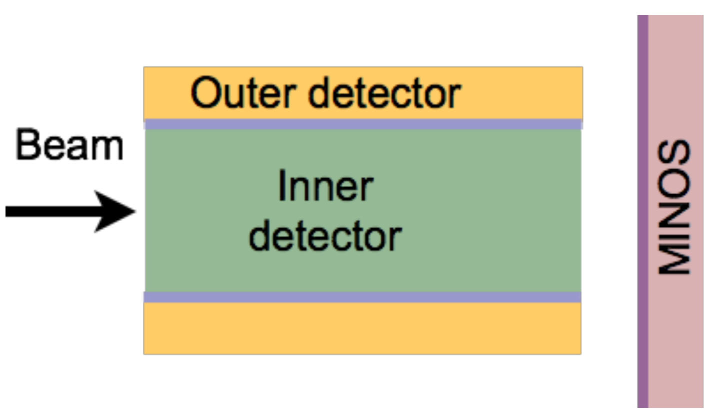


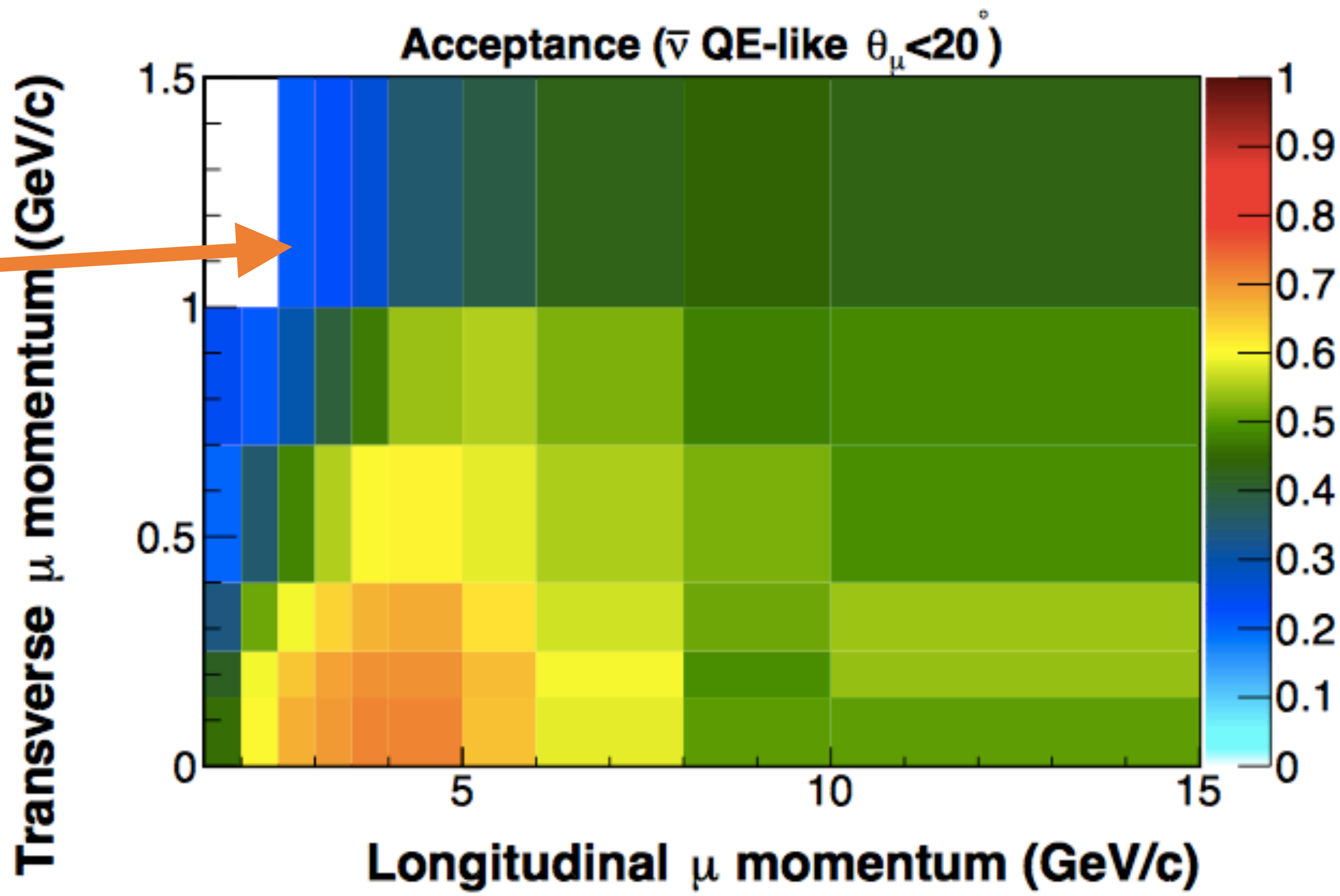
(Migration matrix for antineutrino mode)

4) Efficiency and acceptance correction

$$\left(\frac{d^2\sigma}{dx\,dy}\right)_{ij} = \frac{\sum_{\alpha\beta} U_{\alpha\beta ij}(N_{\text{data},\alpha\beta} - N^{bkgd}_{\text{data},\alpha\beta})}{\epsilon_{ij}(\Phi T)(\Delta x_i)(\Delta y_j)}$$

MINOS match requirement limits acceptance at high angles



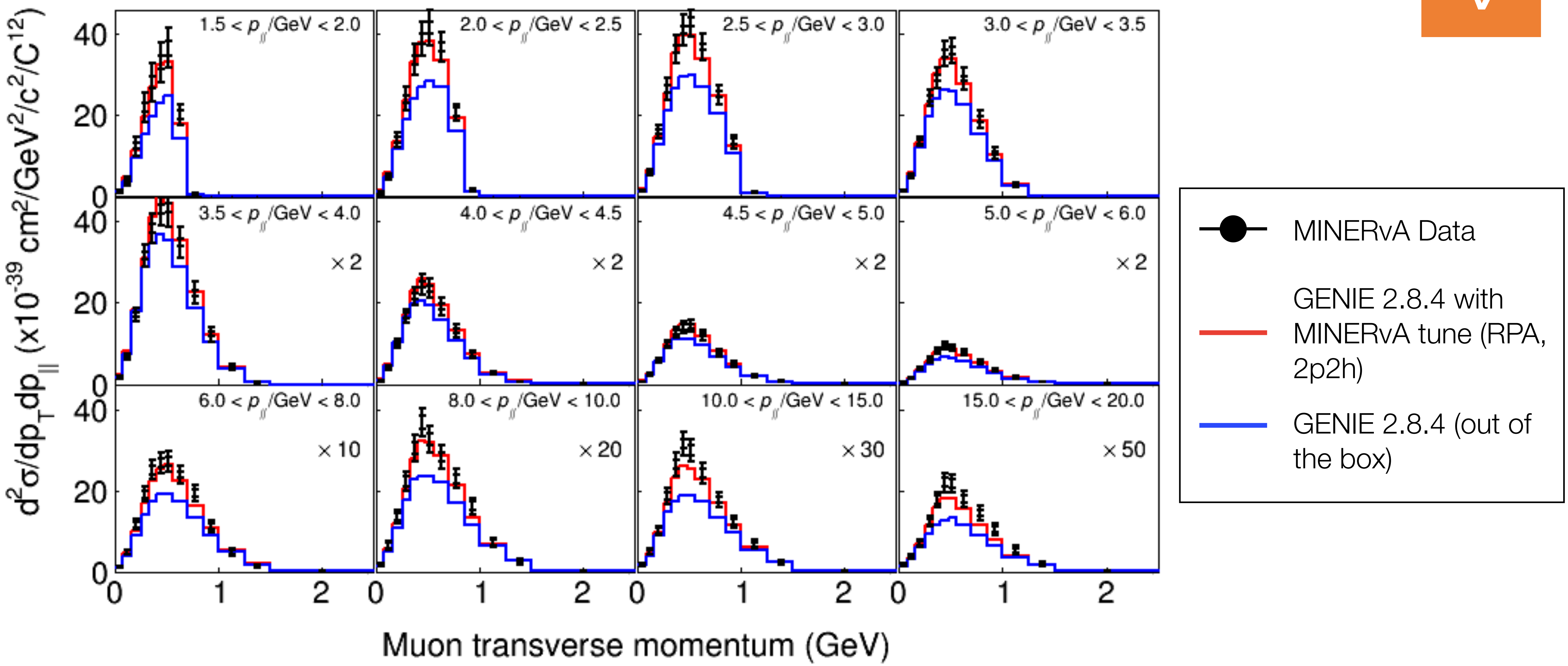


(Plot for antineutrino mode)

Overall efficiency x acceptance = 50.6%

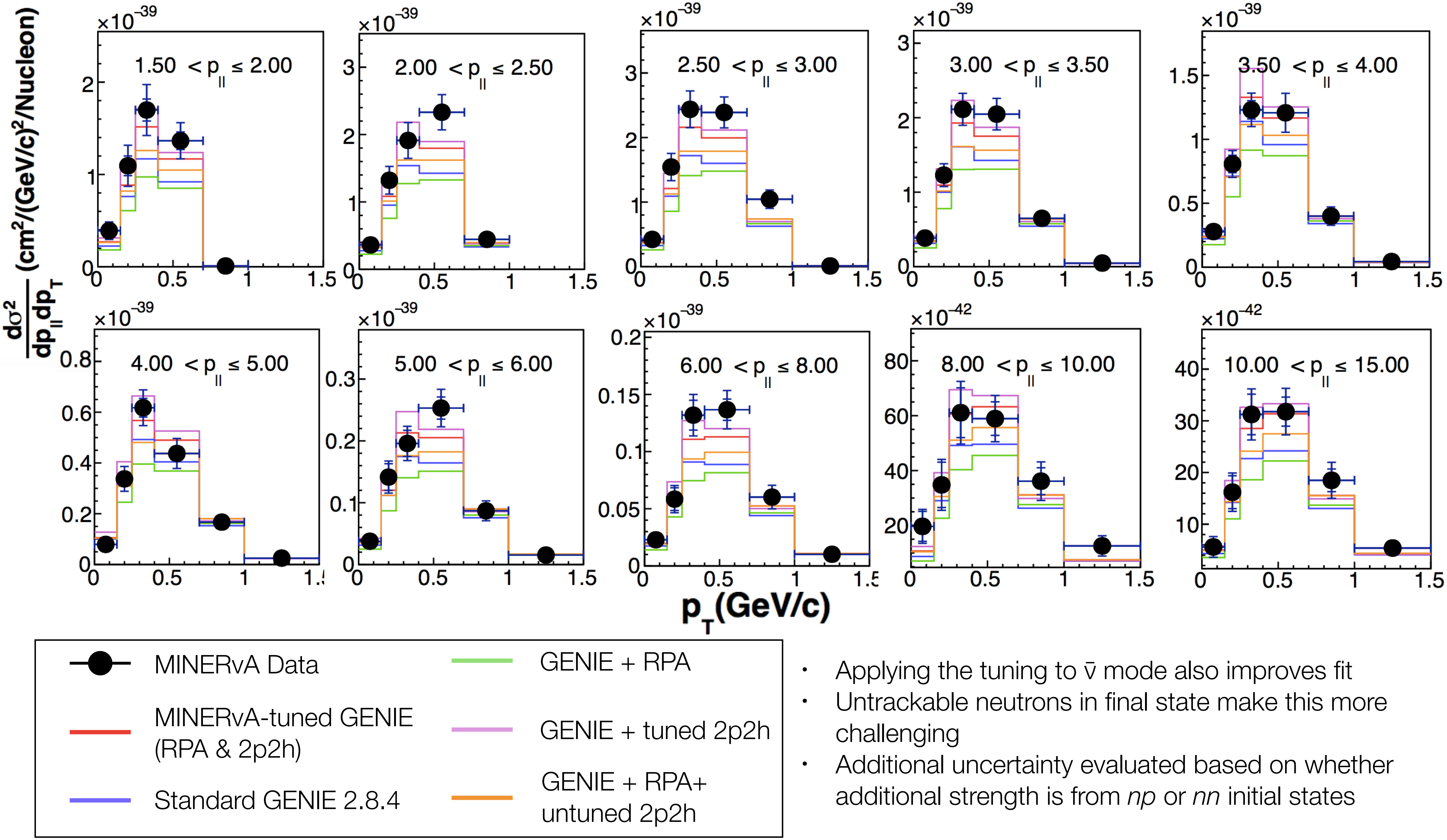
Double-differential cross section - neutrino mode

ν



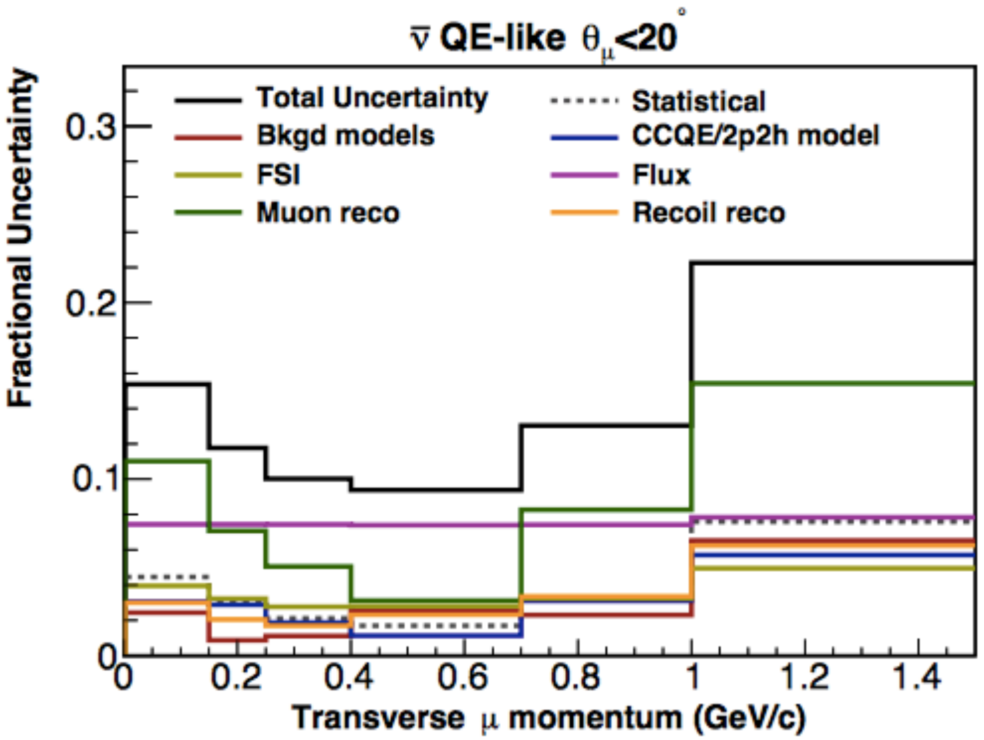
(Remember this was tuned to neutrino-mode data)

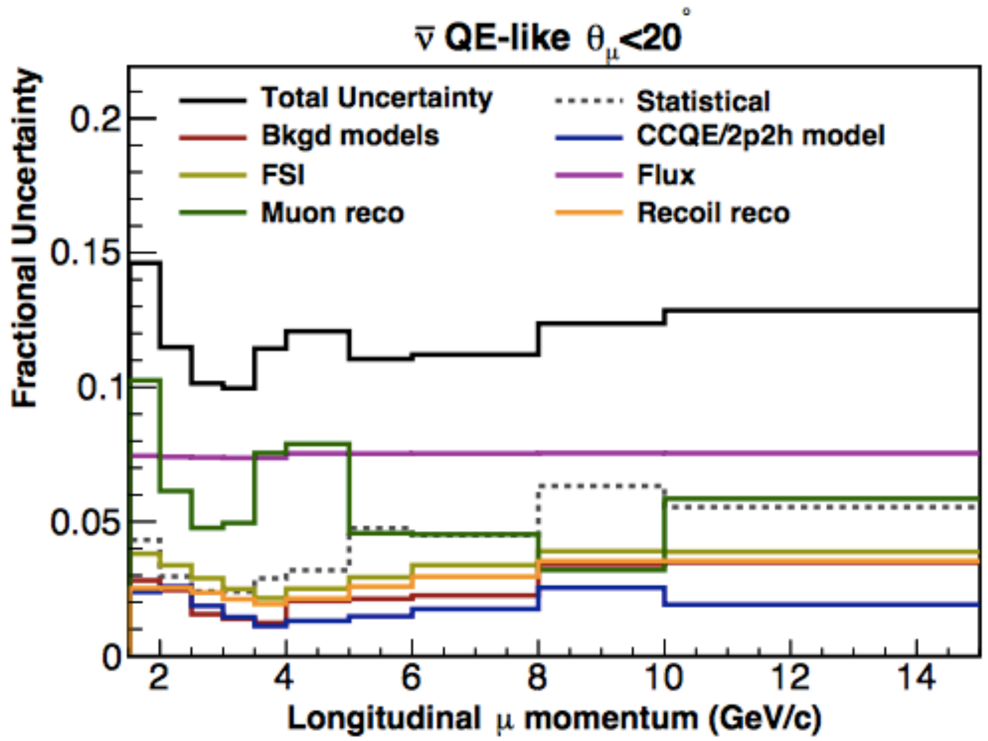
Double-differential cross section - antineutrino mode



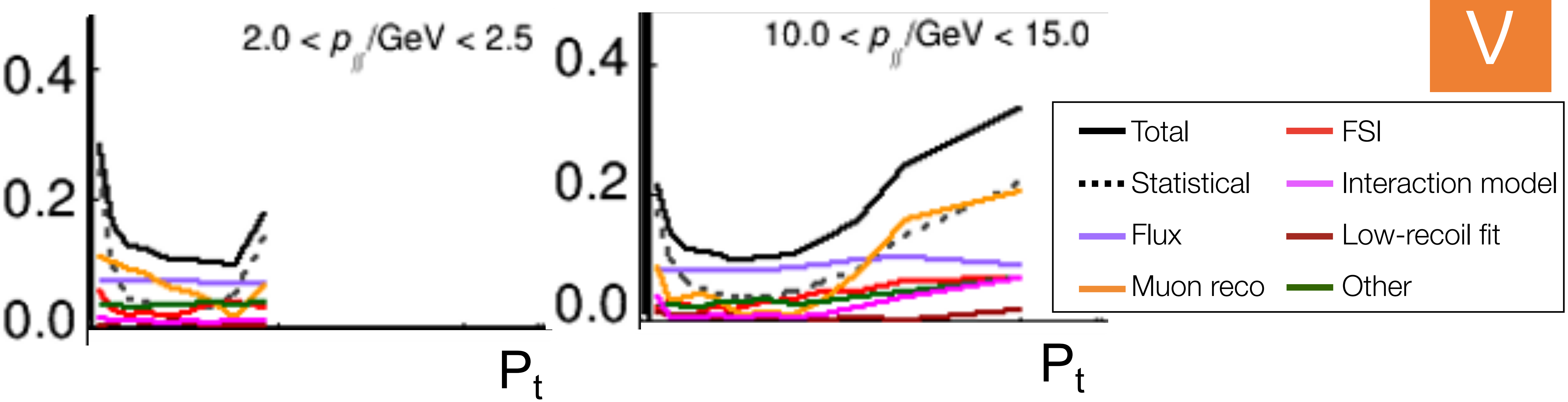
- Applying the tuning to $\bar{\nu}$ mode also improves fit
- Untrackable neutrons in final state make this more challenging
- Additional uncertainty evaluated based on whether additional strength is from *np* or *nn* initial states

Systematic uncertainty



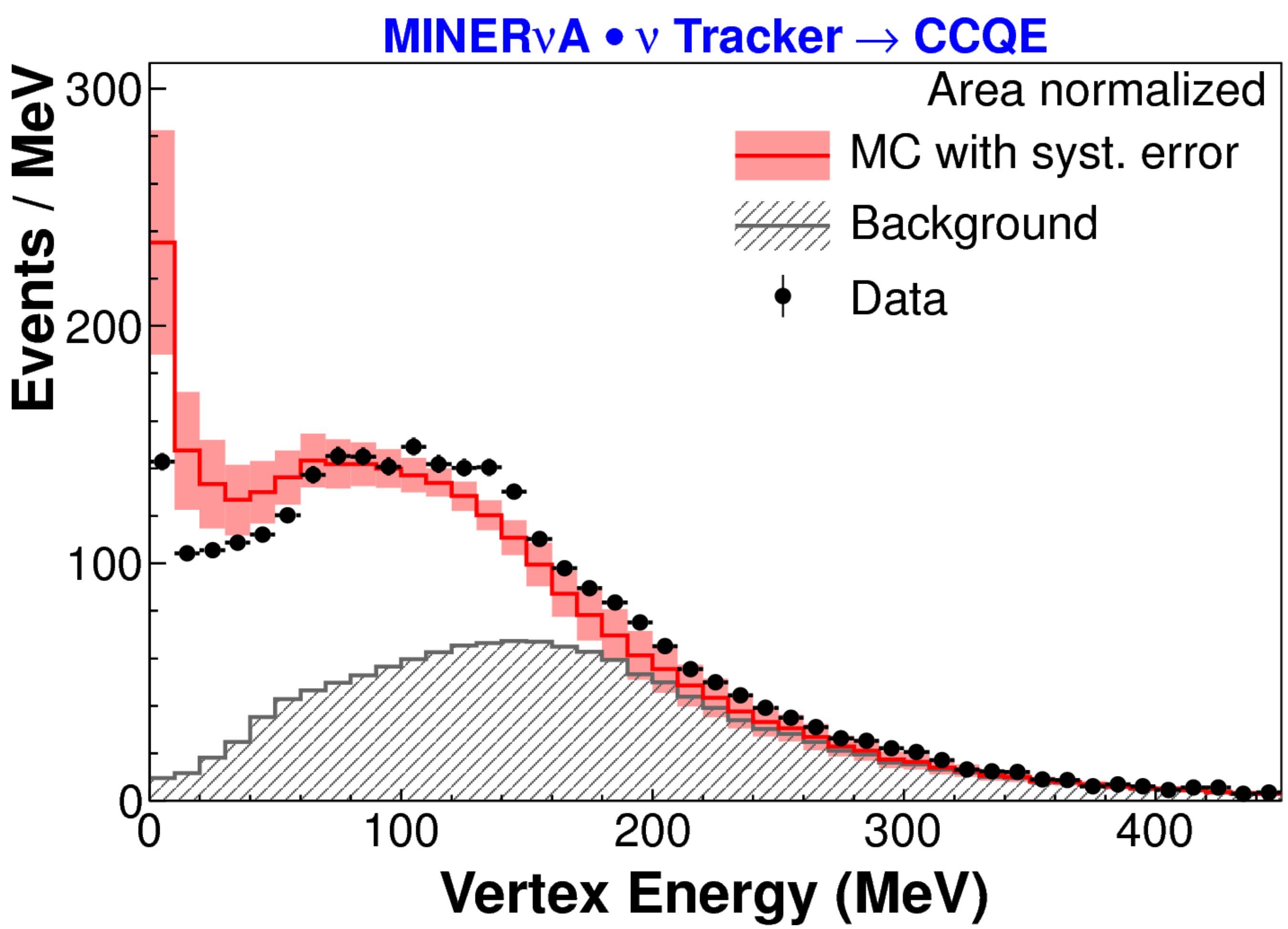


$\bar{\nu}$



ν

Vertex energy distributions: 2013

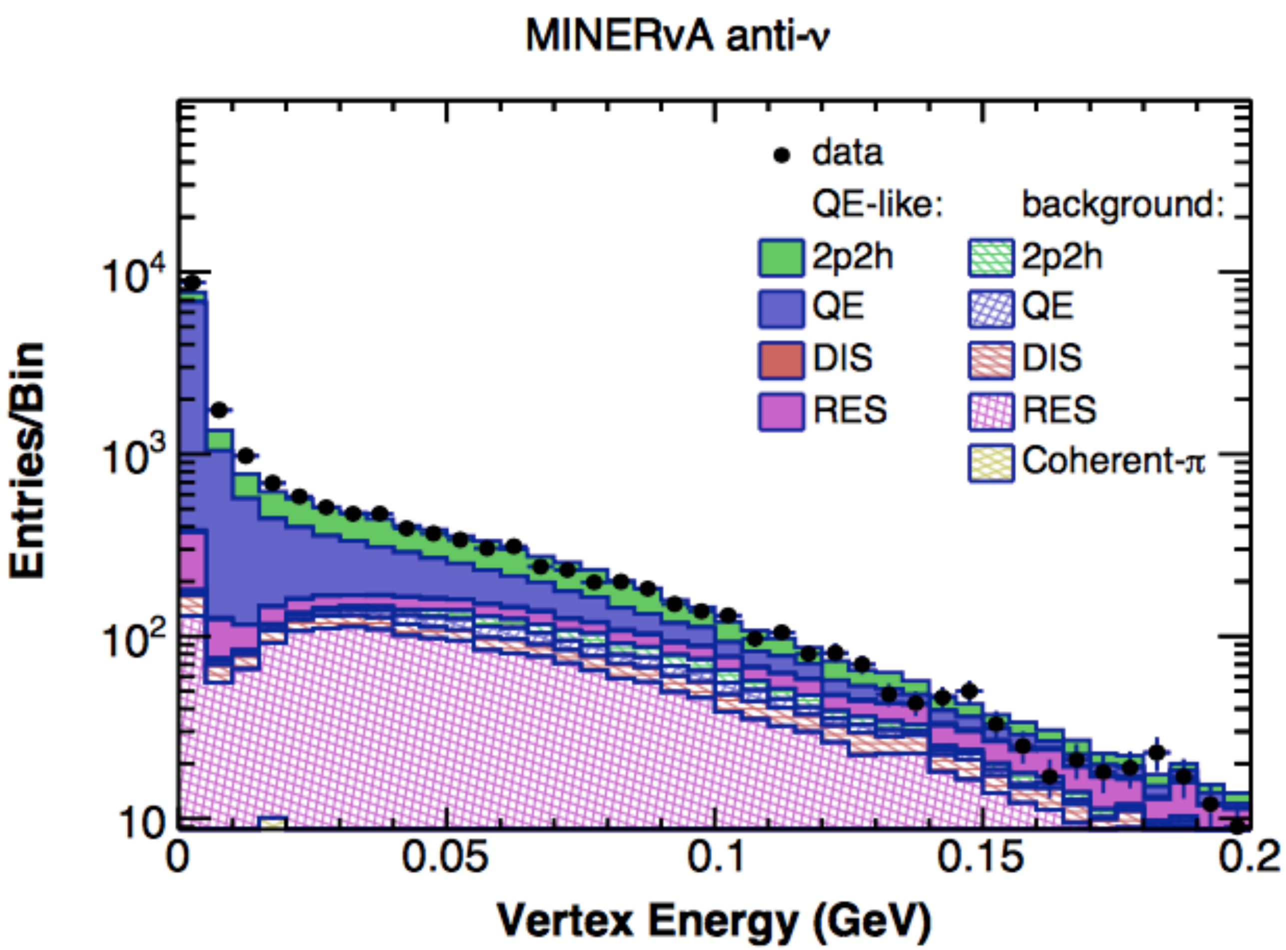


ν - 2013

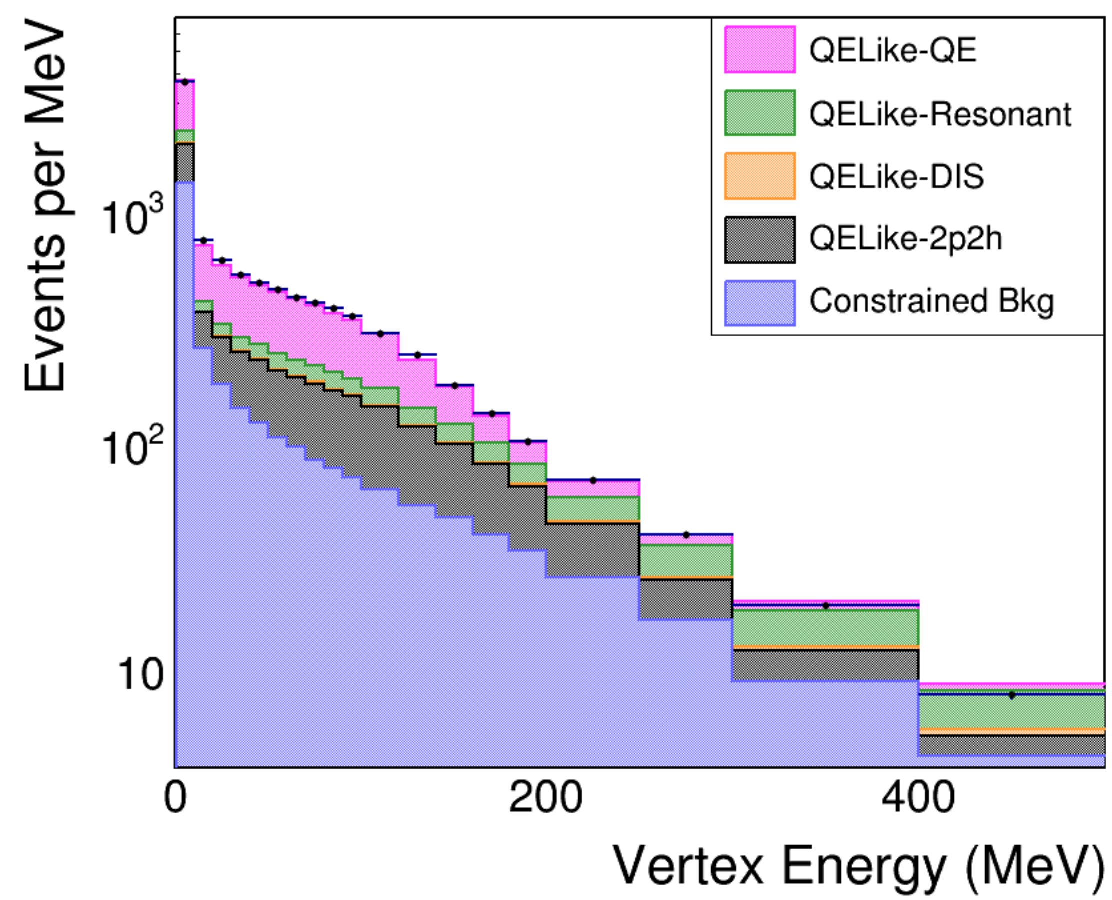
In 2013, the energy distribution around the vertex was markedly different from our simulation (GENIE 2.6.2, no 2p2h or RPA)

Vertex energy: 2017

$\bar{\nu}$



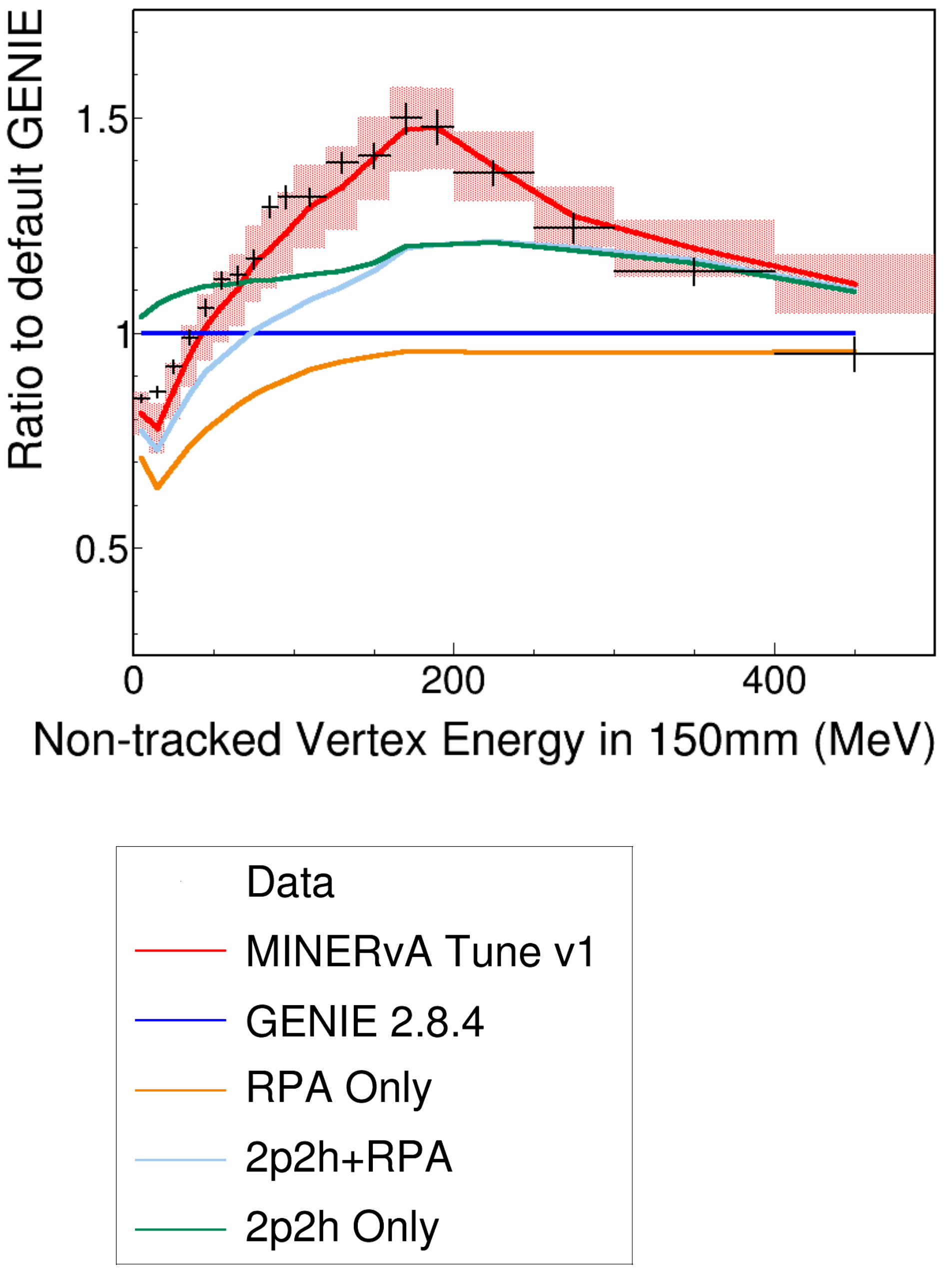
ν

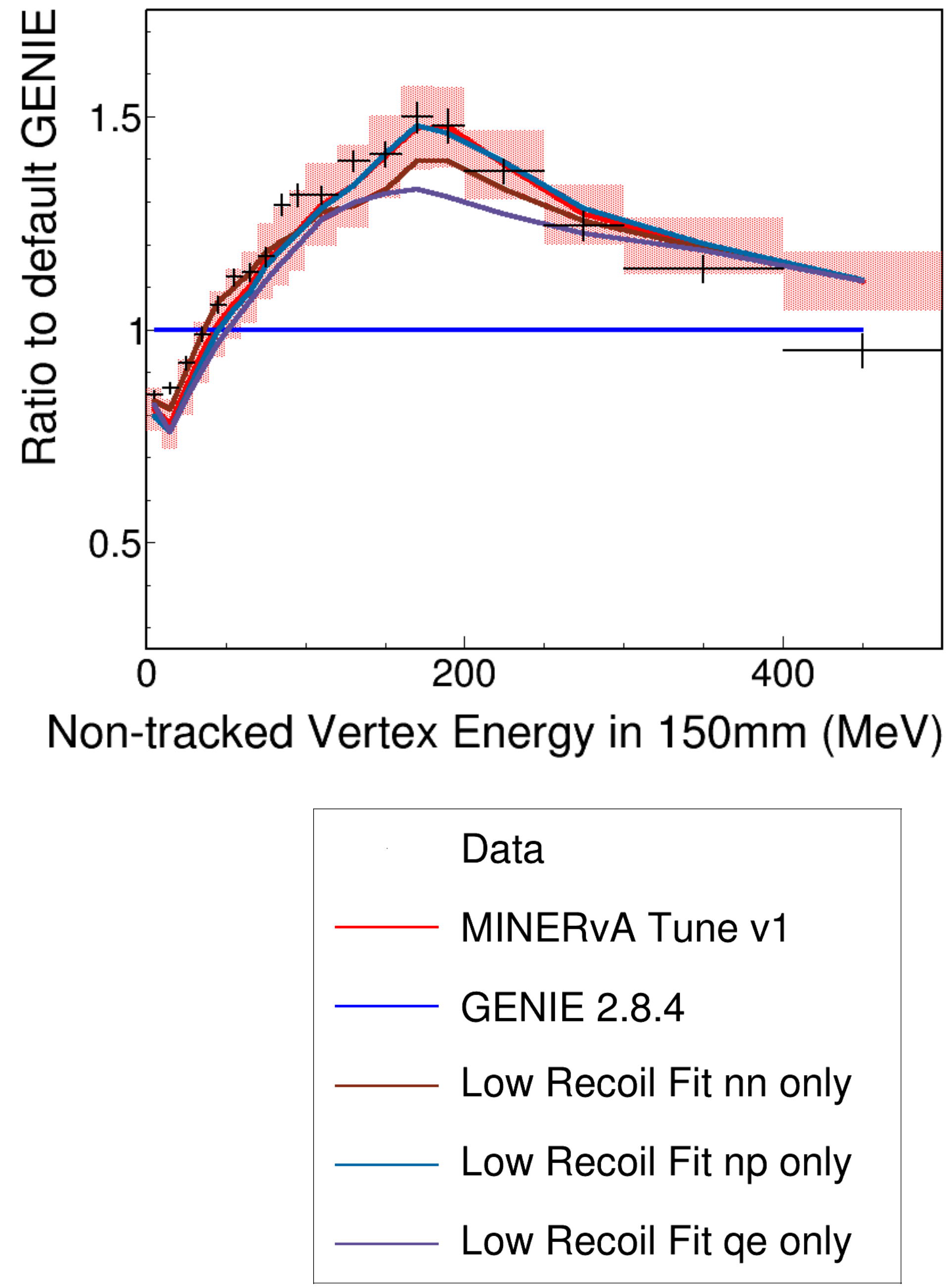


The tuned GENIE does a much better job of modelling this distribution, but is there more we can learn?

Vertex energy

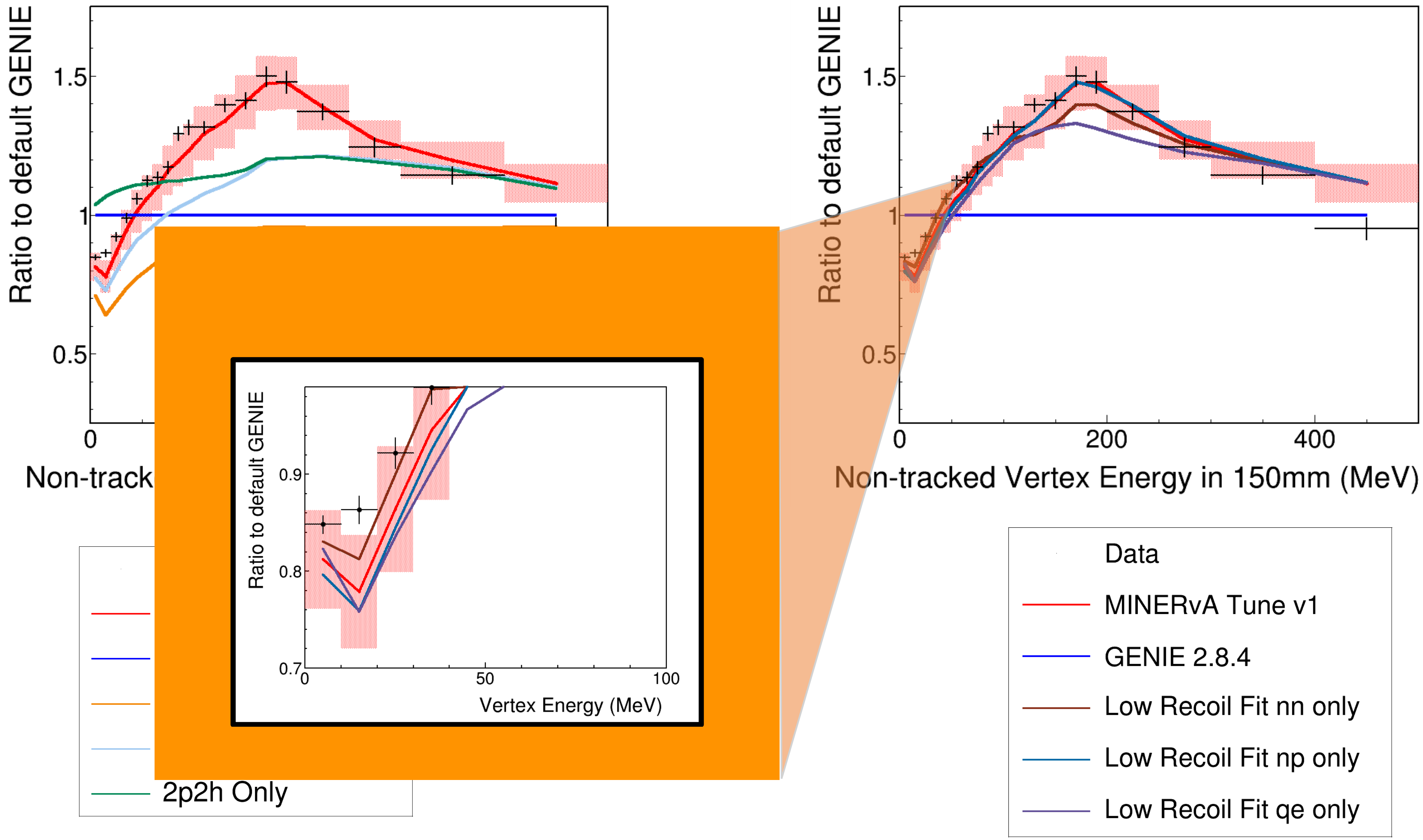
V





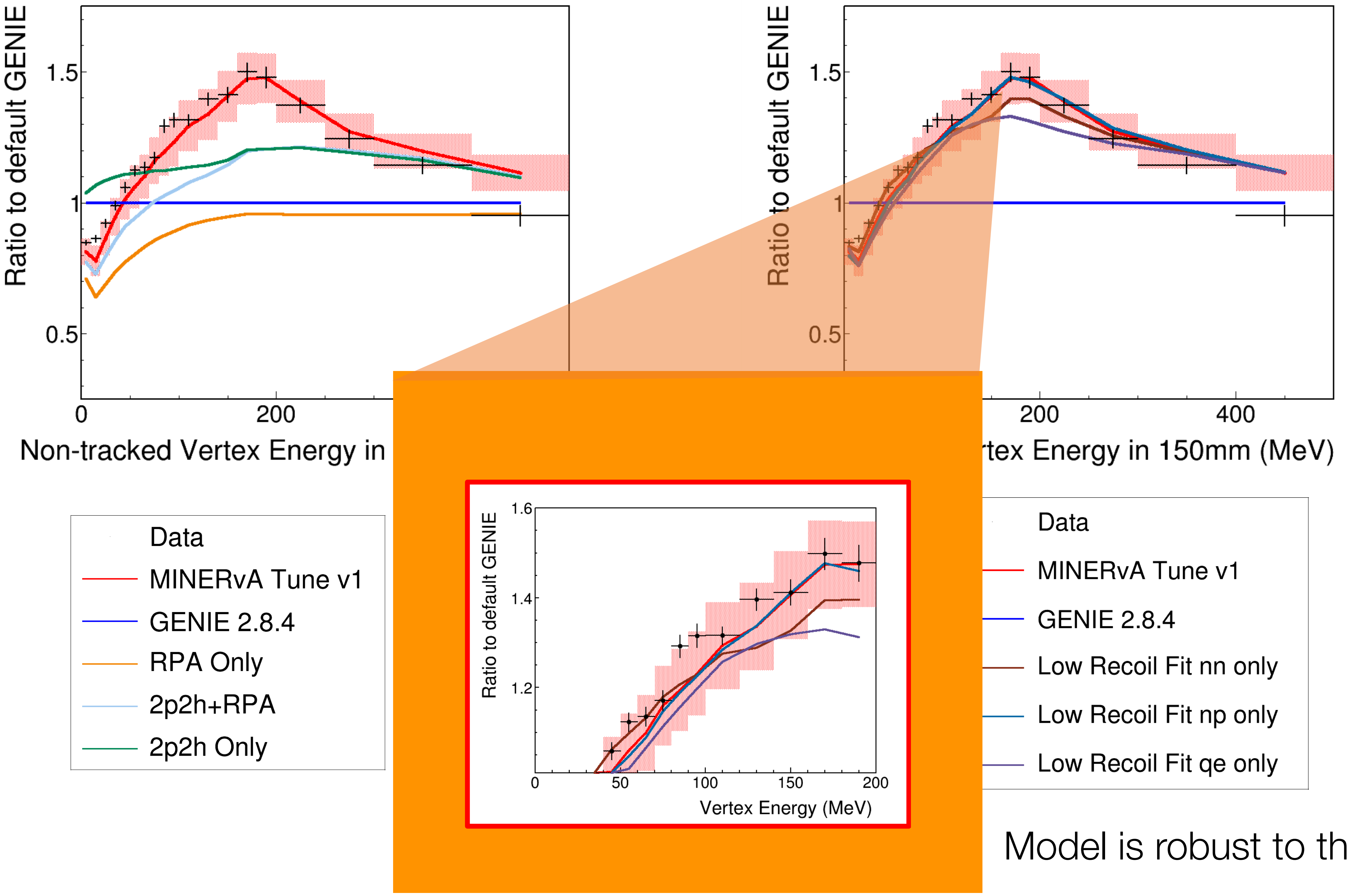
Vertex energy

V



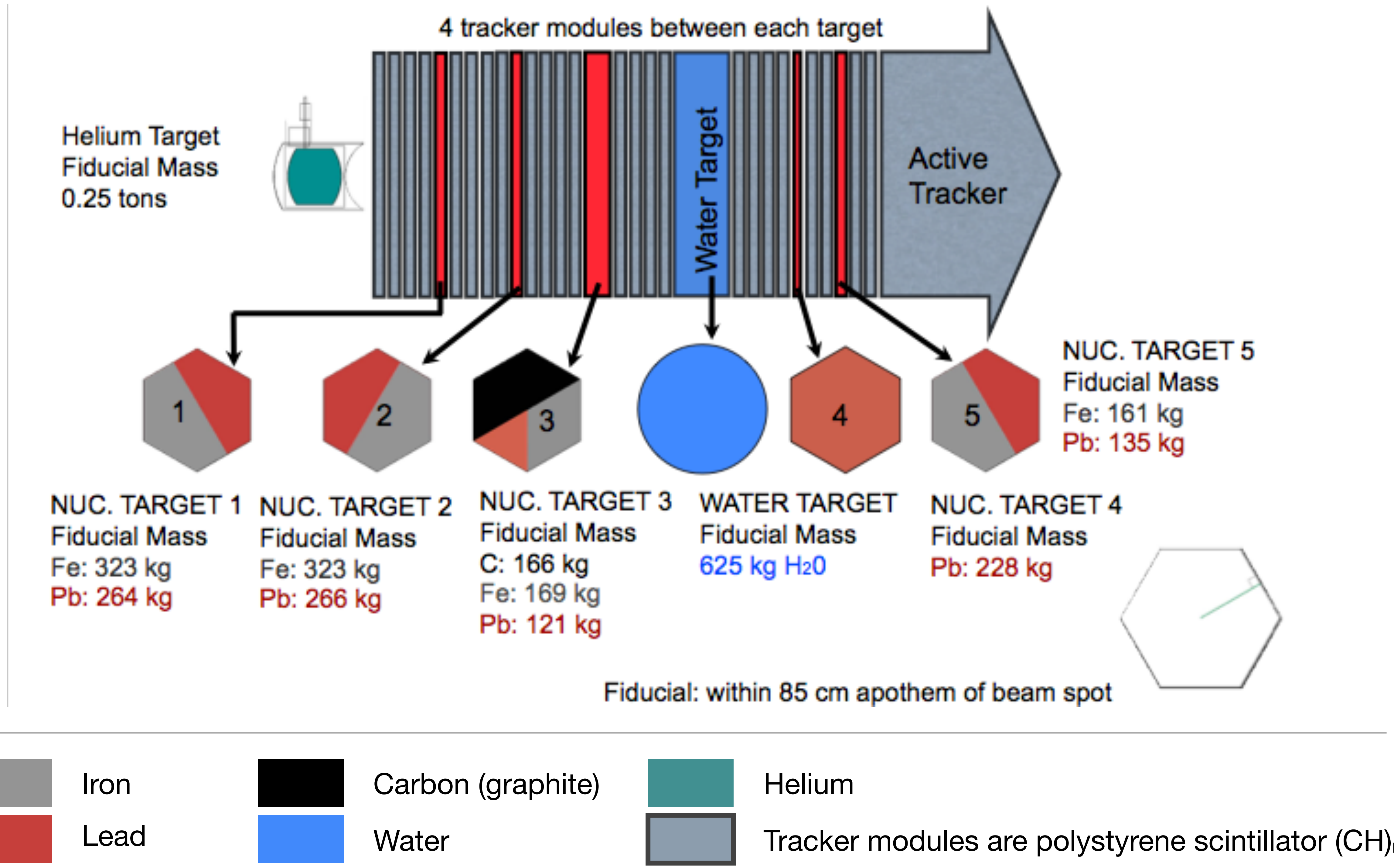
Vertex energy

V



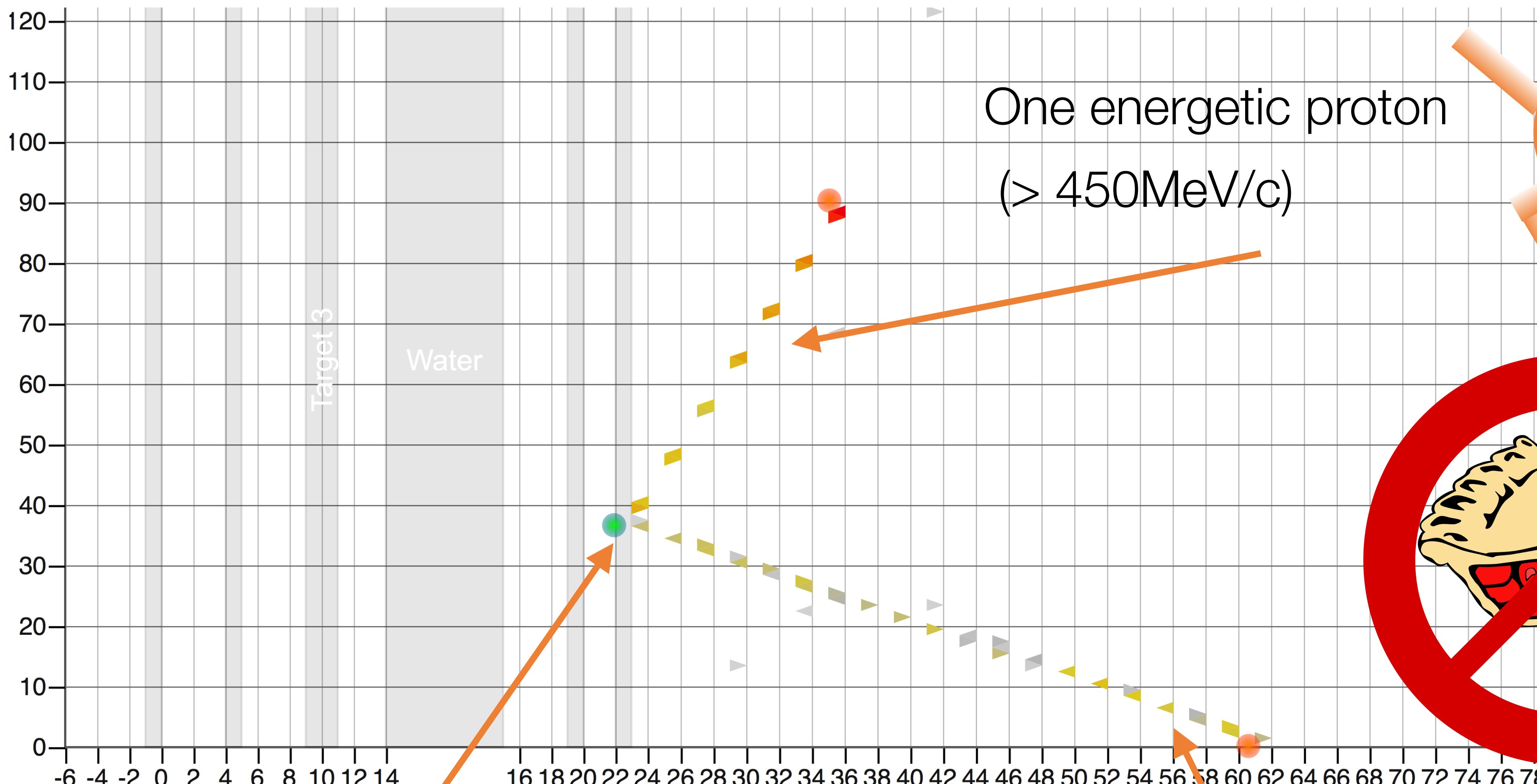
Model is robust to these variations

Something different: Nuclear targets

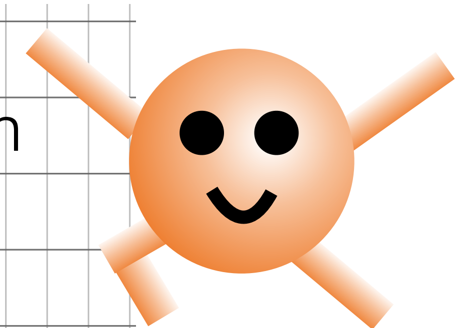


Signal for nuclear target analysis (neutrino mode only)

ν

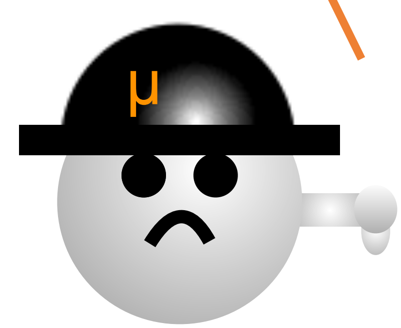


One energetic proton (> 450MeV/c)



No pions

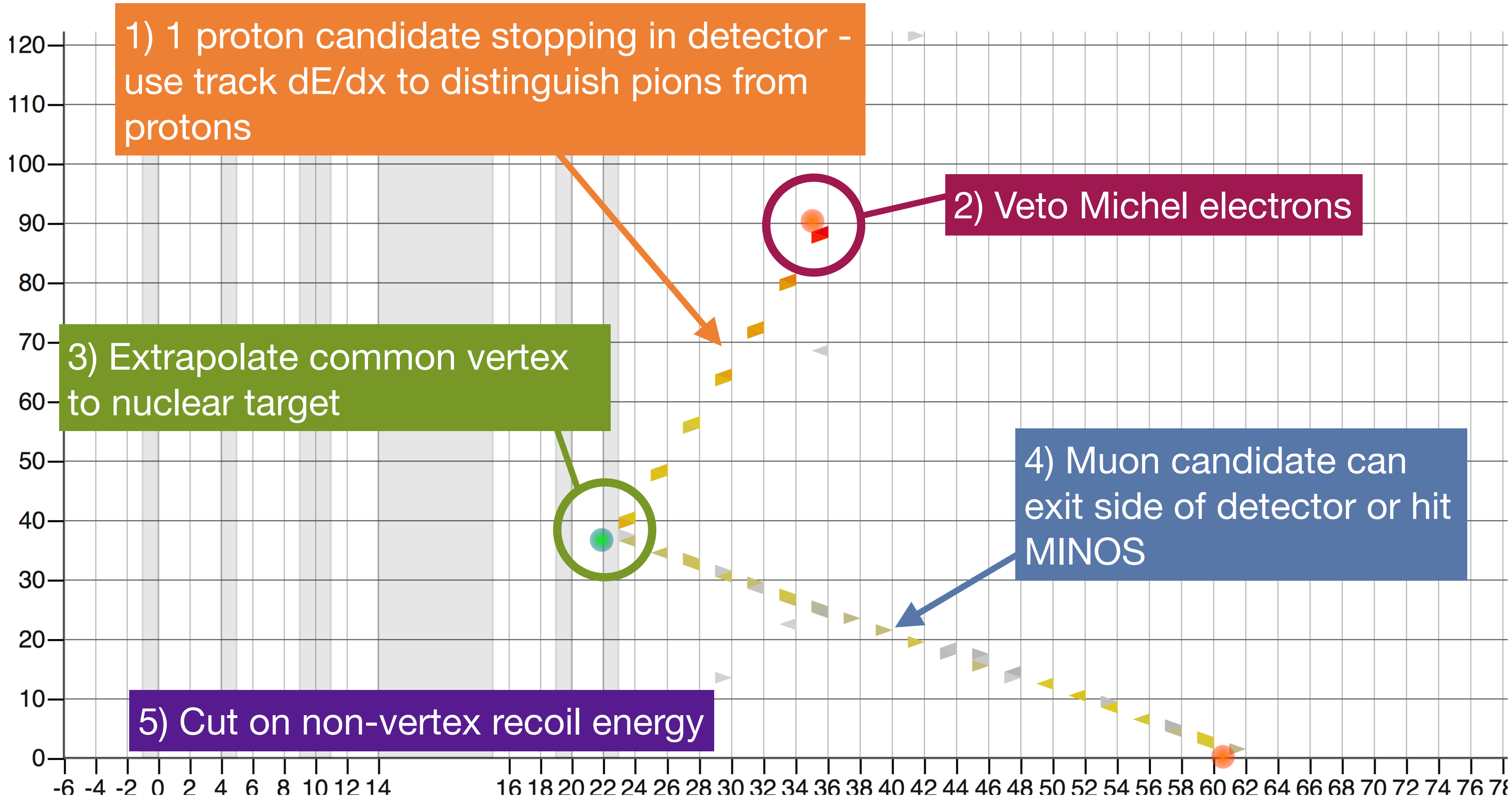
Vertex in the nuclear target of choice



One negative muon (no angle requirement but no MINOS charge match either)

By ensuring we have a trackable proton, we can remove the MINOS-matched muon requirement

Nuclear targets - event selection



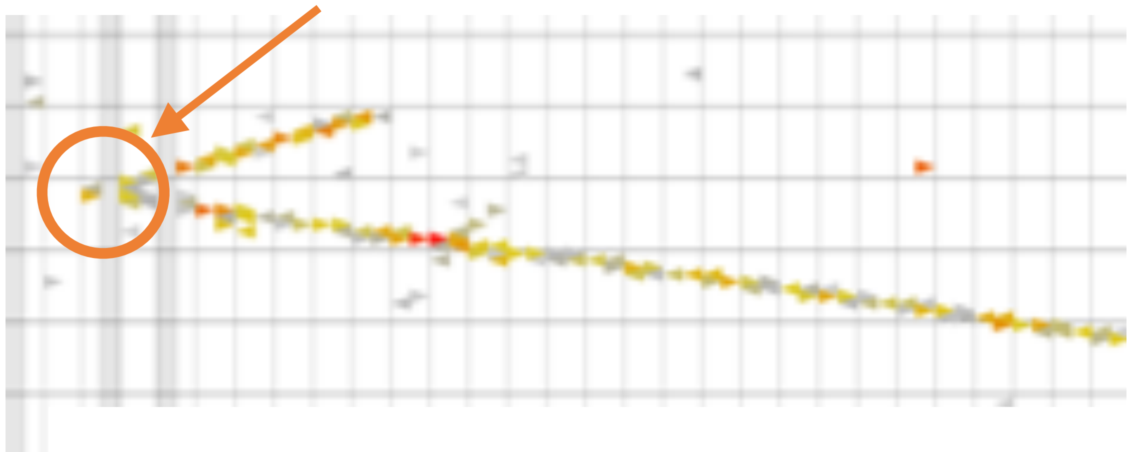
Calculate $d\sigma/dQ^2$ using Q^2 calculated from proton kinematics in quasi-elastic hypothesis

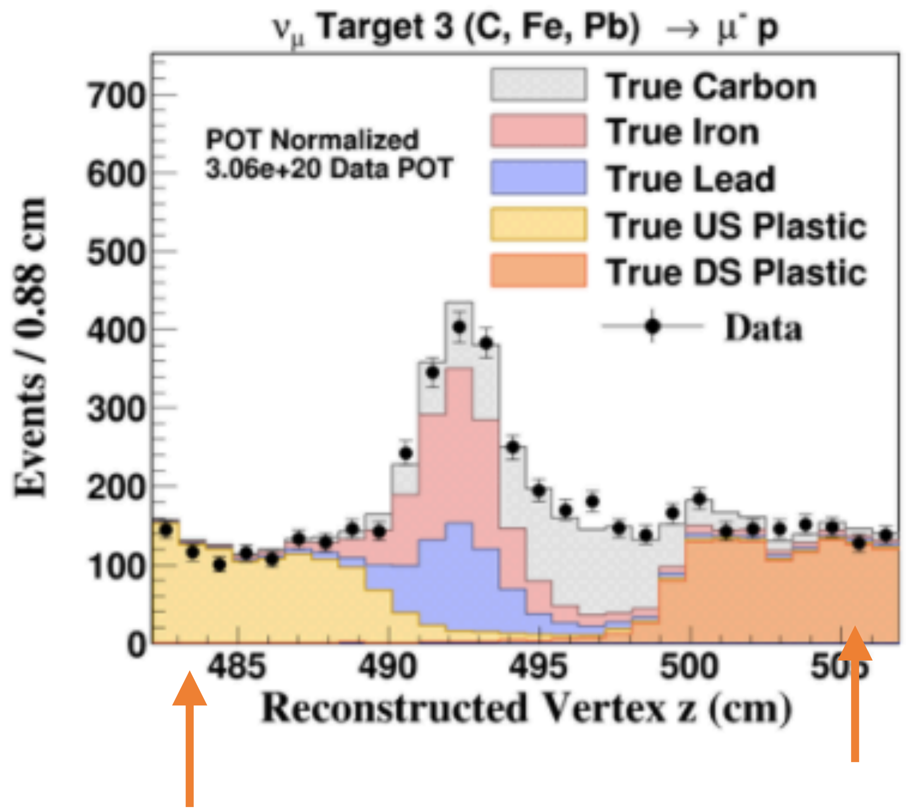
$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

$M' = M_n - E_b$
E_b is the binding energy
T_p is the proton kinetic energy
M_n is the mass of the neutron
M_p is the mass of the proton

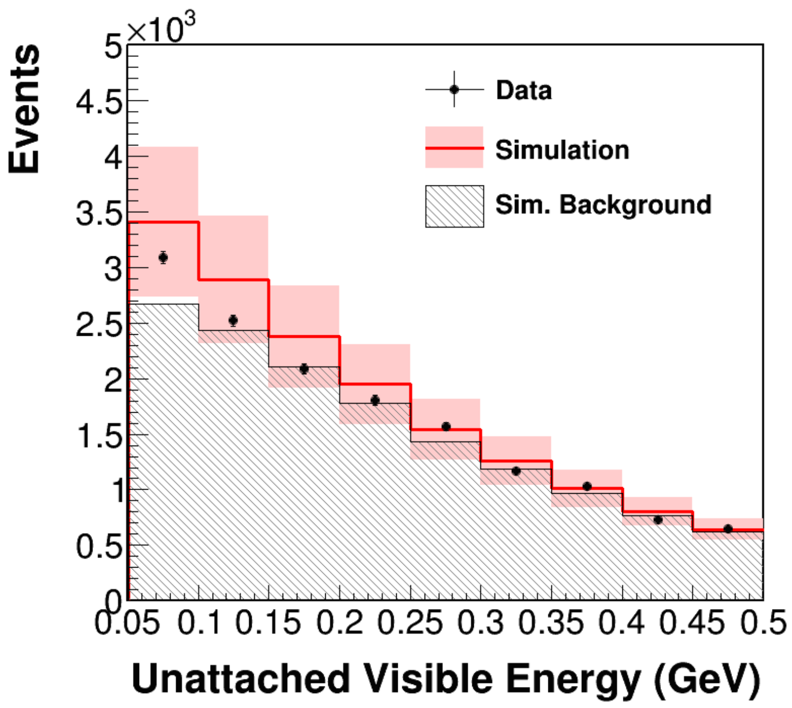
Backgrounds

Scattering from scintillator may be reconstructed on the targets



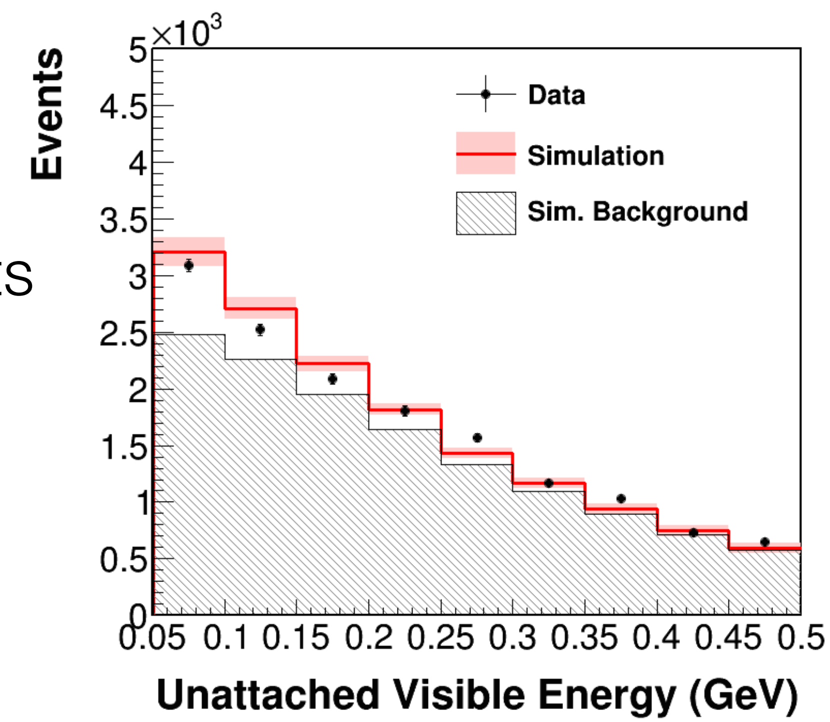


Determine scintillator background scale by looking at upstream and downstream sidebands



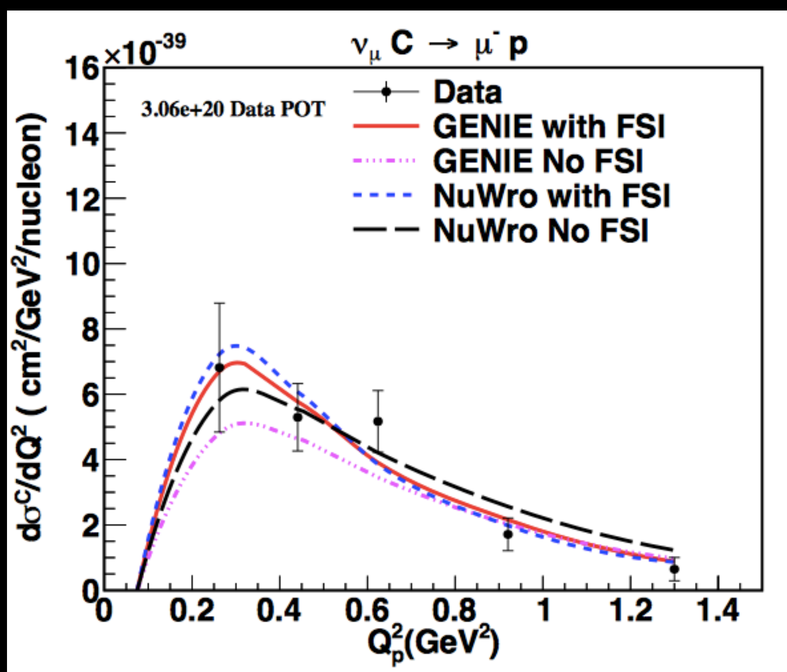
Events from backgrounds with pions are tuned with a fit in recoil energy, as with the scintillator analysis

Separate fits are performed for events with Q^2 greater and less than 0.5 GeV^2

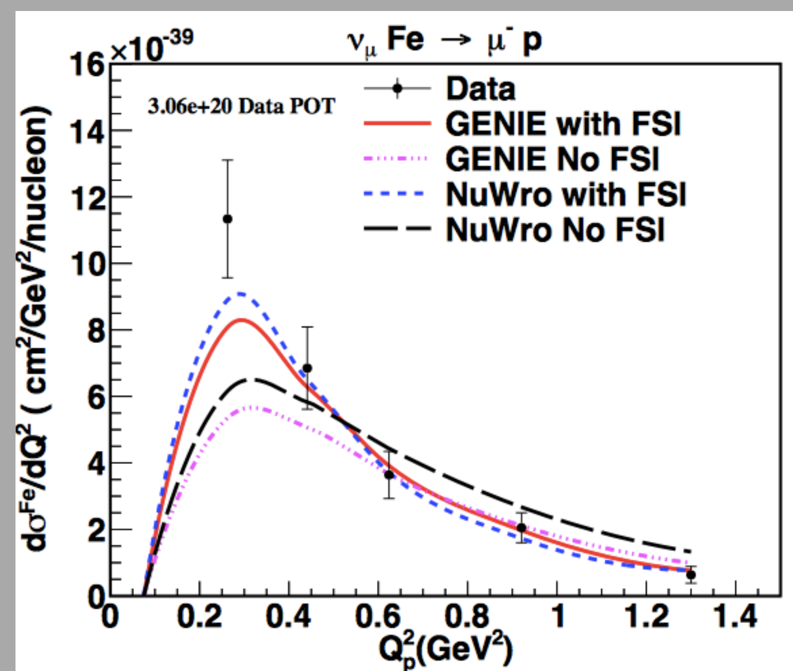


Cross sections

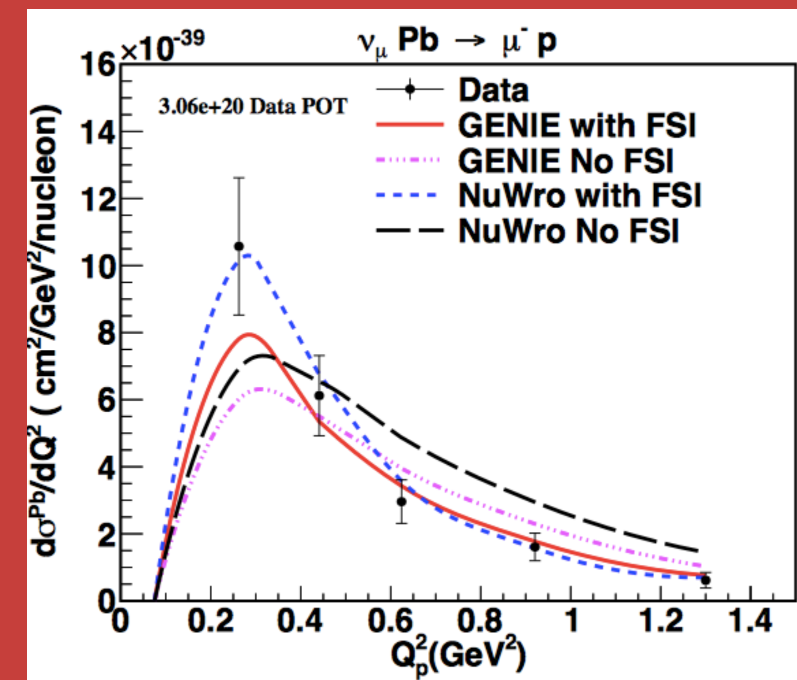
Carbon



Iron



Lead



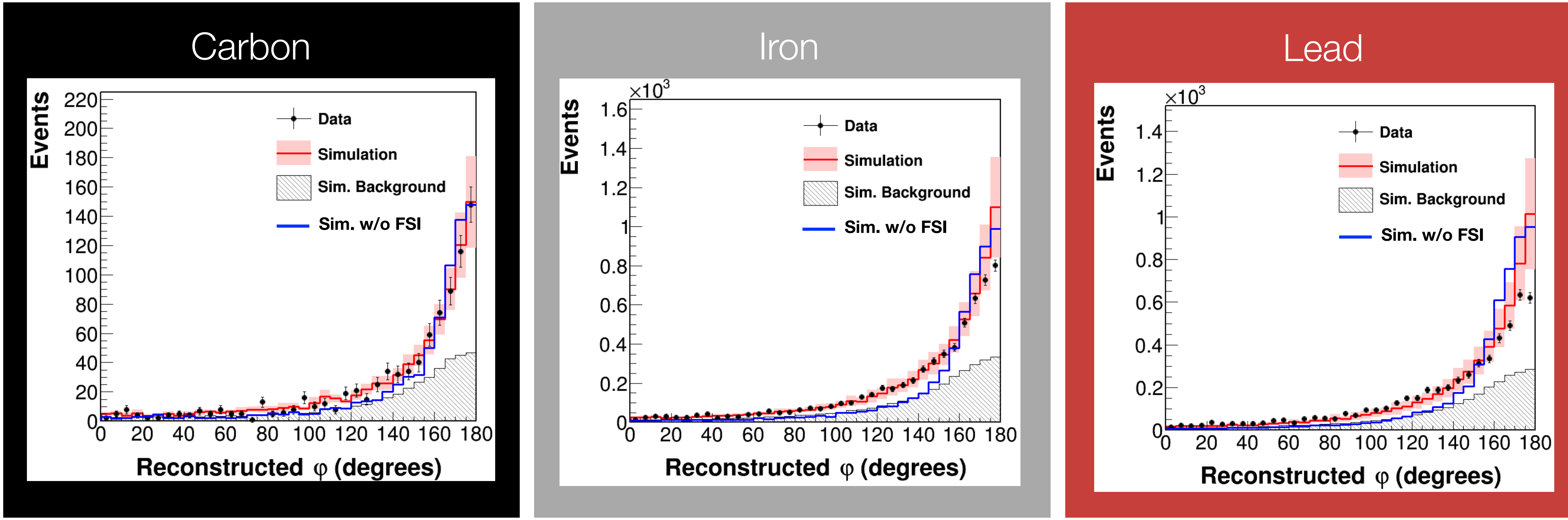
Both GENIE and NuWro include similar 2p2h and RPA effects

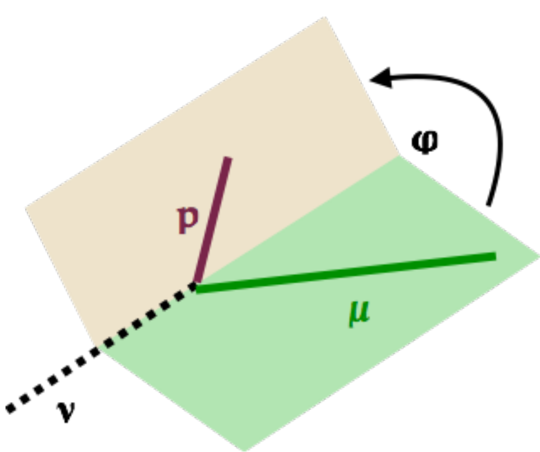
Model	Carbon	Iron	Lead
GENIE RFG	11.0	63.8	41.1
GENIE RFG + 2p2h	5.9	18.9	16.3
GENIE RFG + 2p2h + RPA	5.9	19.9	17.5
NuWro RFG + 2p2h + RPA	6.0	14.6	11.0

χ^2 for 5 degrees of freedom

NuWro has an A-dependent pion absorption FSI model that is not included in GENIE

Coplanarity angle probes FSI

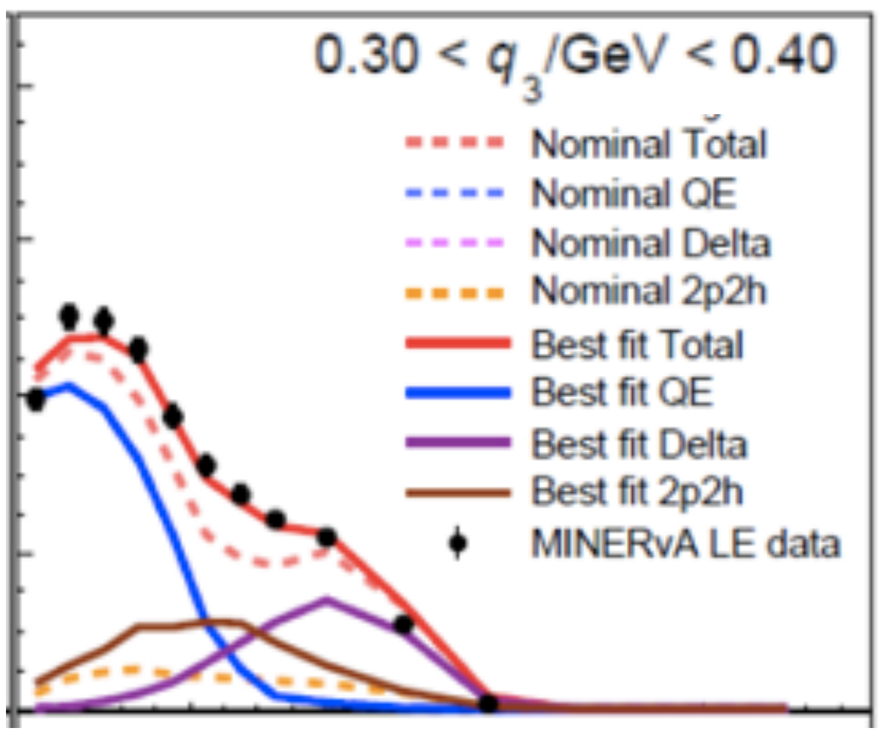


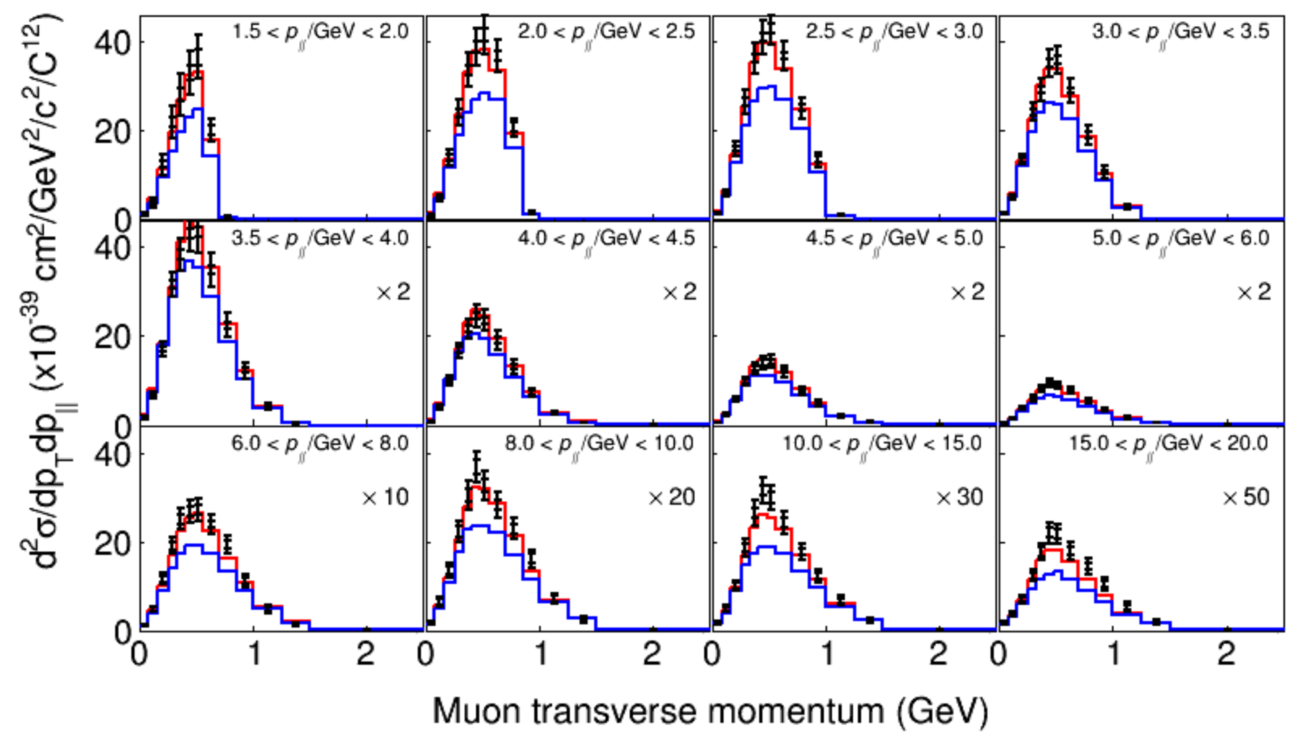


- True angle between ν-μ and ν-p planes would be 180° if scattering from stationary neutron
- Both initial nucleon momentum distribution and final-state interactions smear this
- GENIE's FSI model is not sufficient to describe the smearing, with the discrepancy increasing for heavier elements

So what comes next?

With our tuned models, we are getting better than ever at being able to reproduce our data…





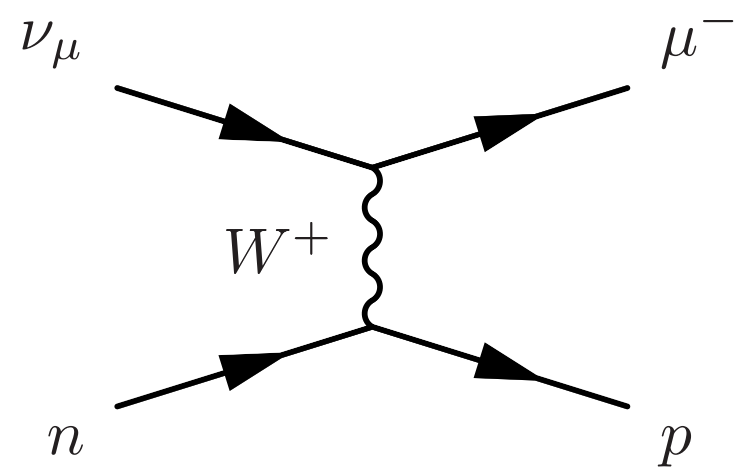
… but we don't have a theoretical motivation for our tuning - why does it work?

Now we need theorists' help to find a physics-motivated model that can match our data!

Backup Slides

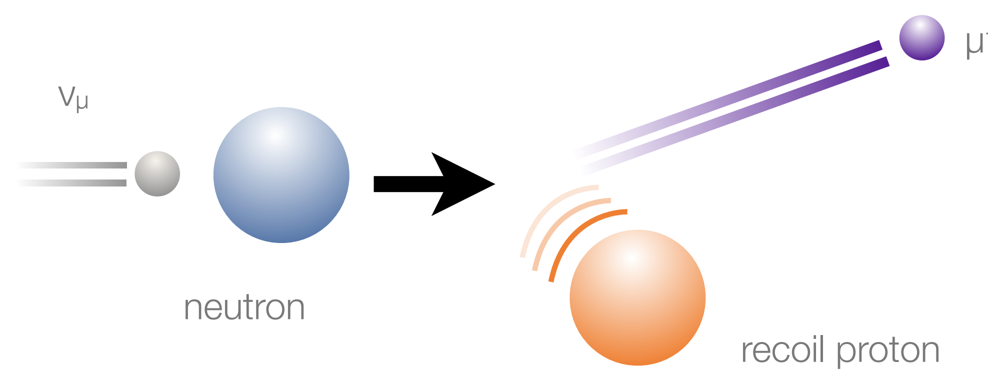
Quasi-elastic scattering from nucleons

- A relatively "simple" interaction process
- There is a single charged muon in the final state, plus the recoil nucleon (no pions etc)
- Oscillation experiments can reconstruct the neutrino energy and 4-momentum transfer Q^2 from just the muon kinematics



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

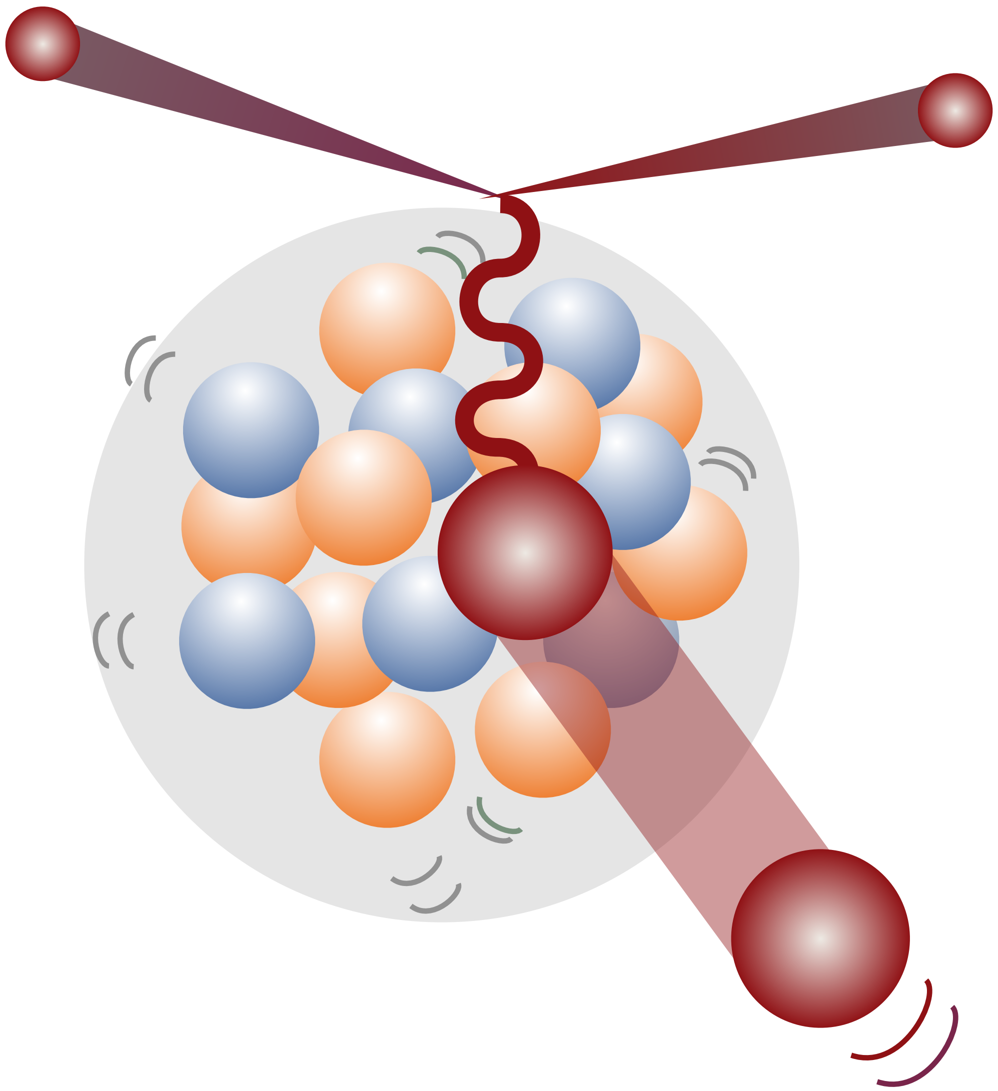
$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$



- But this assumes scattering from a **free, stationary nucleon**
- Once we know Q^2, there is a reliable cross-section model for free-nucleon scattering: Llewellyn-Smith (*C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972)*)

Nucleons in the nucleus: the Fermi Gas Model

- In a heavy nucleus, nucleons are not stationary
- They interact with the other nucleons
- A commonly-used simulation of this is the Relativistic Fermi Gas model
  - Treat nucleons as independent particles, but in a mean field generated by the rest of the nucleus
  - Initial-state momenta are Fermi distributed
  - Pauli blocking
- Cross-sections can be modelled by a multiplier to the Llewellyn Smith cross-section



Default model in GENIE

R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972); Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, J.Phys.Conf.Ser. 110, 082004 (2008)