MINERvA Low-Recoil Tune and its Implications

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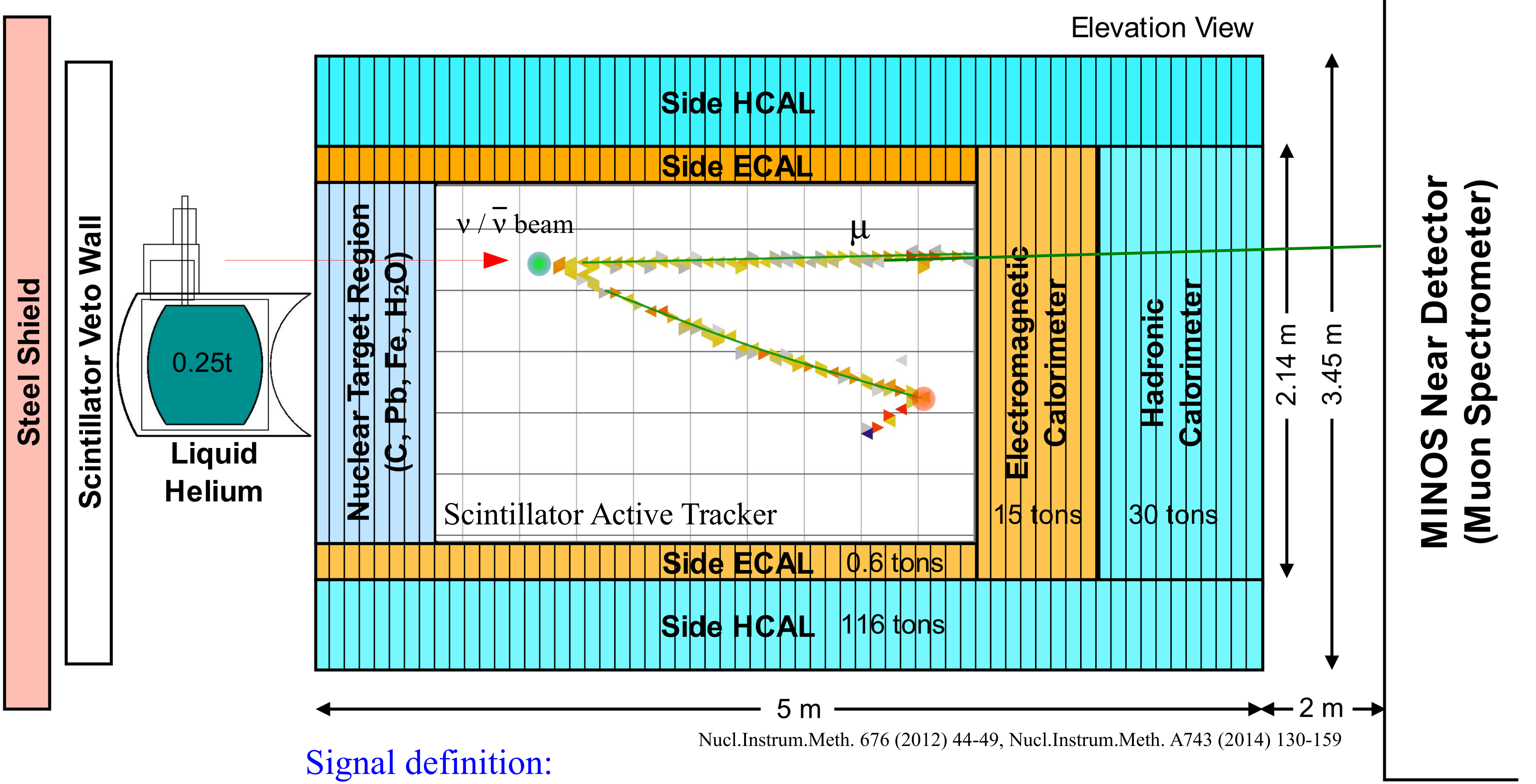
on behalf of the MINERvA Collaboration
NuInt 2018, L'Aquila, 16 October 2018

Low-Recoil Analyses (CC inclusive sample)

[ν: Phys.Rev.Lett. 116 (2016) 071802, **NEW** $\bar{\nu}$: Phys.Rev.Lett. 120 (2018) 221805]



Nucl.Instrum.Meth. 676 (2012) 44-49, Nucl.Instrum.Meth. A743 (2014) 130-159

Signal definition:

- ν ($\bar{\nu}$) on CH in energy range 2-6 GeV (LE flux $\langle E_\nu \rangle \sim 3$ GeV)
- CC muon energy (momentum) > 1.5 GeV, θ < 20 degrees
- 3-momentum transfer $q_3 < 0.8$ GeV/c

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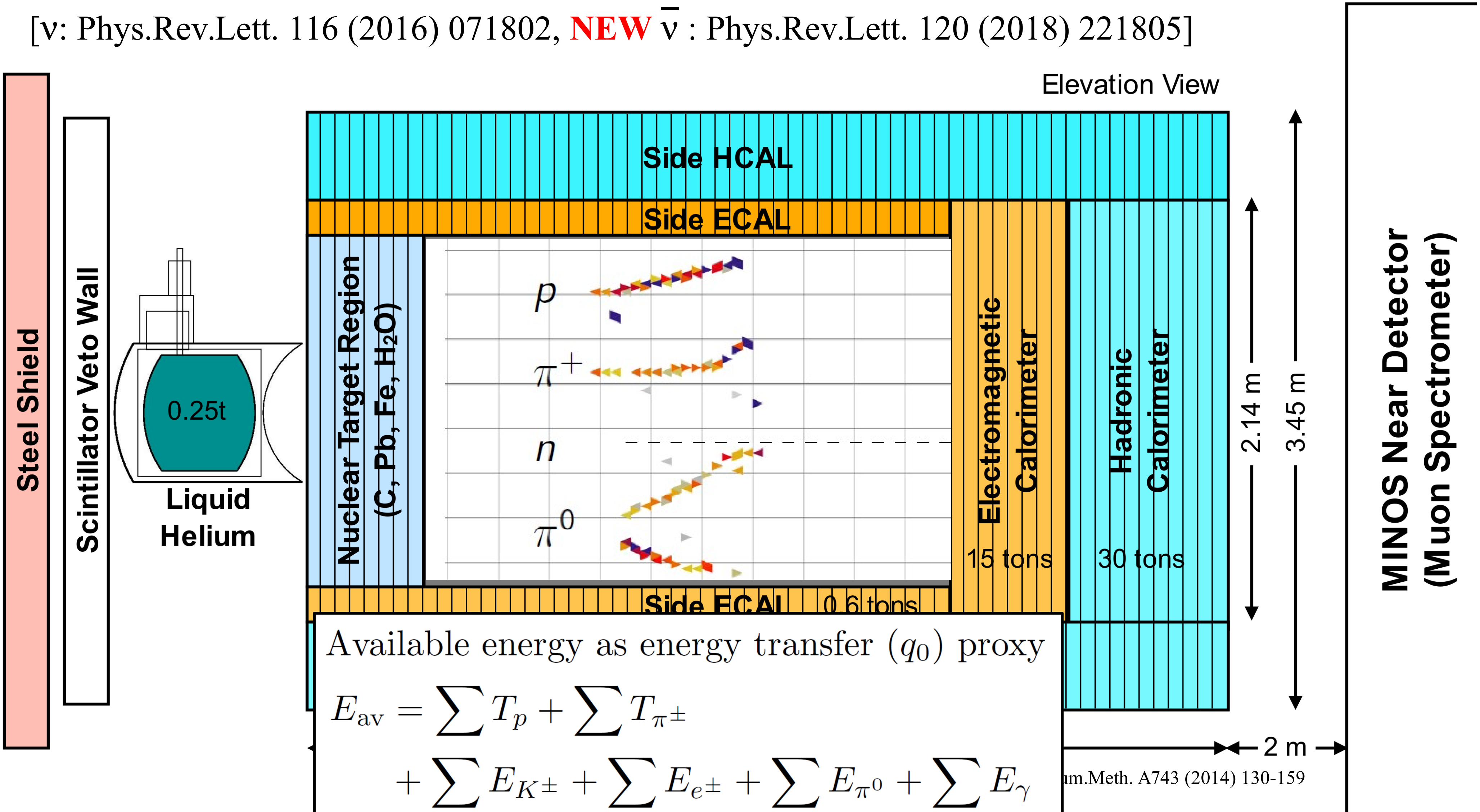


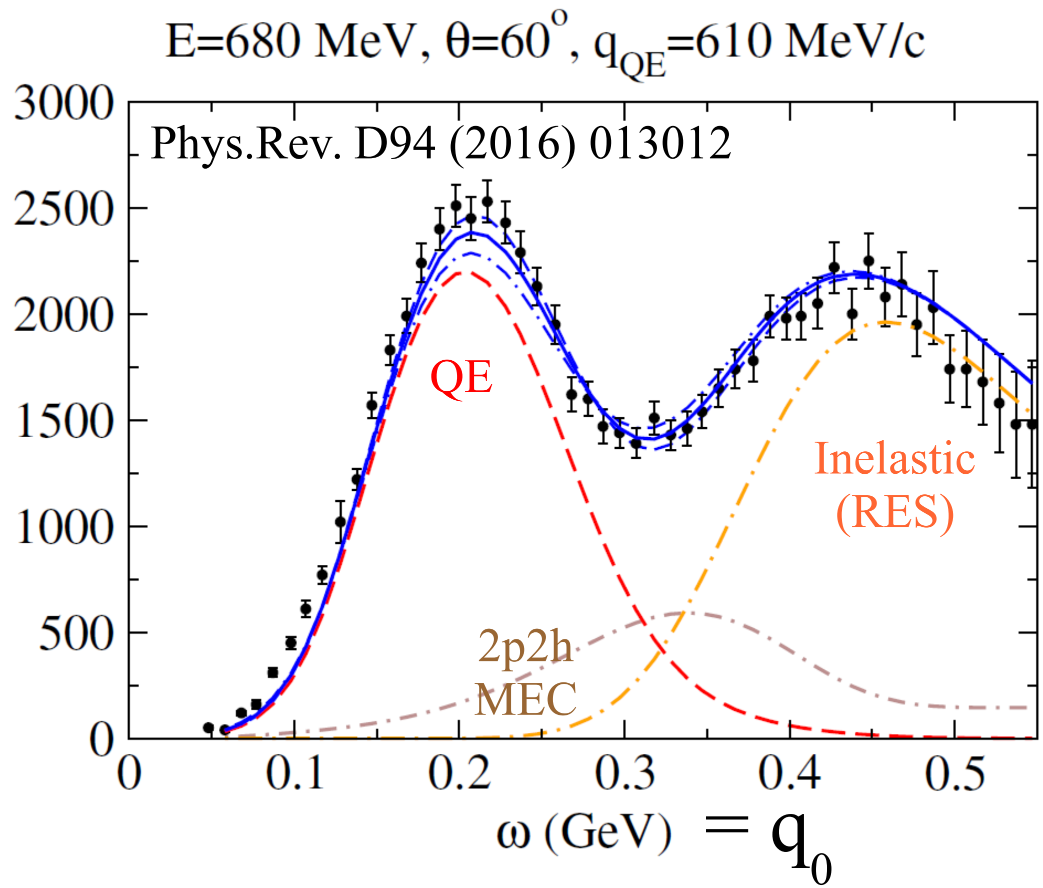
Available energy as energy transfer (q_0) proxy

$$E_{\rm av} = \sum T_p + \sum T_{\pi^\pm} + \sum E_{K^\pm} + \sum E_{e^\pm} + \sum E_{\pi^0} + \sum E_\gamma$$

~ single proton kinetic energy spectrum in QE

~ π(+p) kinetic energy spectrum in RES

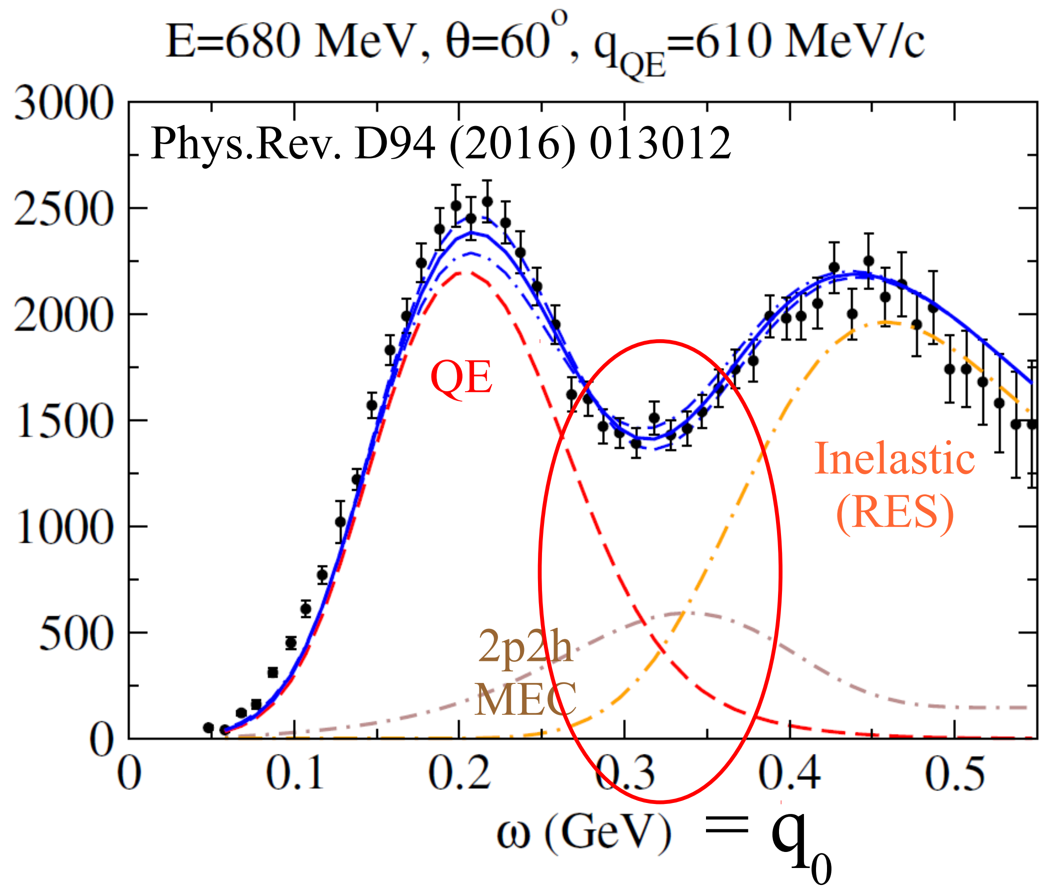
Expectation from electron scattering



2p2h locates in the dip

FIG. 5. Comparison of inclusive $^{12}C(e, e')$ cross sections and predictions of the QE-SuSAv2 model (long-dashed red line), 2p-2h MEC model (dot-dashed brown line) and inelastic-SuSAv2 model (long dot-dashed orange line). The sum of the three contributions is represented with a solid blue line. The q dependence with ω is also shown (short-dashed black line). The y axis on the left represents $d^2\sigma/d\Omega/d\omega$ in nb/GeV/sr, whereas the one on the right represents the q value in GeV/c.

Expectation from electron scattering



2p2h locates in the dip

Won't be the only time we focus on a dip

FIG. 5. Comparison of inclusive $^{12}C(e, e')$ cross sections and predictions of the QE-SuSAv2 model (long-dashed red line), 2p-2h MEC model (dot-dashed brown line) and inelastic-SuSAv2 model (long dot-dashed orange line). The sum of the three contributions is represented with a solid blue line. The q dependence with ω is also shown (short-dashed black line). The y axis on the left represents $d^2\sigma/d\Omega/d\omega$ in nb/GeV/sr, whereas the one on the right represents the q value in GeV/c.

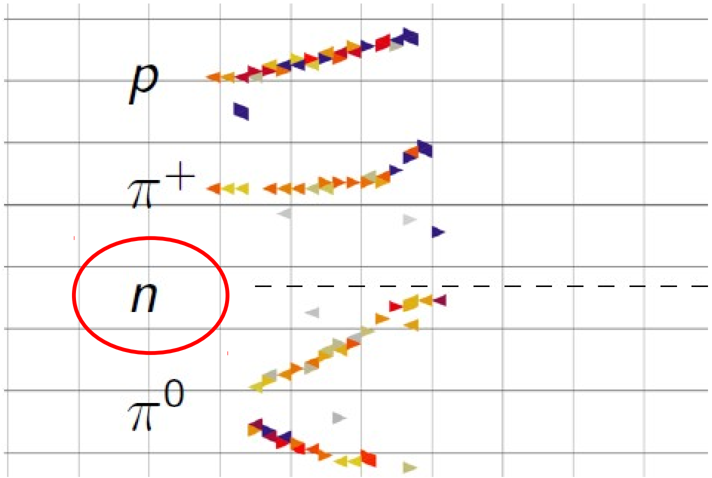
Neutron detection NEW
[manuscript in preparation]

R. Gran, Joint Experimental-Theoretical Physics Seminar
http://theory.fnal.gov/events/event/results-from-minerva-4/
M. Elkins: "Neutron Hide and Seek", NuInt17 Best Poster
https://meetings.triumf.ca/indico/event/6/session/24/contribution/155

- ν and $\bar{\nu}$ measurements as consistent as possible

  Available energy as energy transfer (q_0) proxy

$$E_{\text{av}} = \sum T_p + \sum T_{\pi^\pm} \quad \text{No neutron included}$$
$$+ \sum E_{K^\pm} + \sum E_{e^\pm} + \sum E_{\pi^0} + \sum E_\gamma$$



- Detector response significantly different in QE

  ν n → μ p

  $\bar{\nu}$ p → μ n
- For $\bar{\nu}$ calorimetry, important to understand detector response to neutron
  - ✓ Validated via neutron detection

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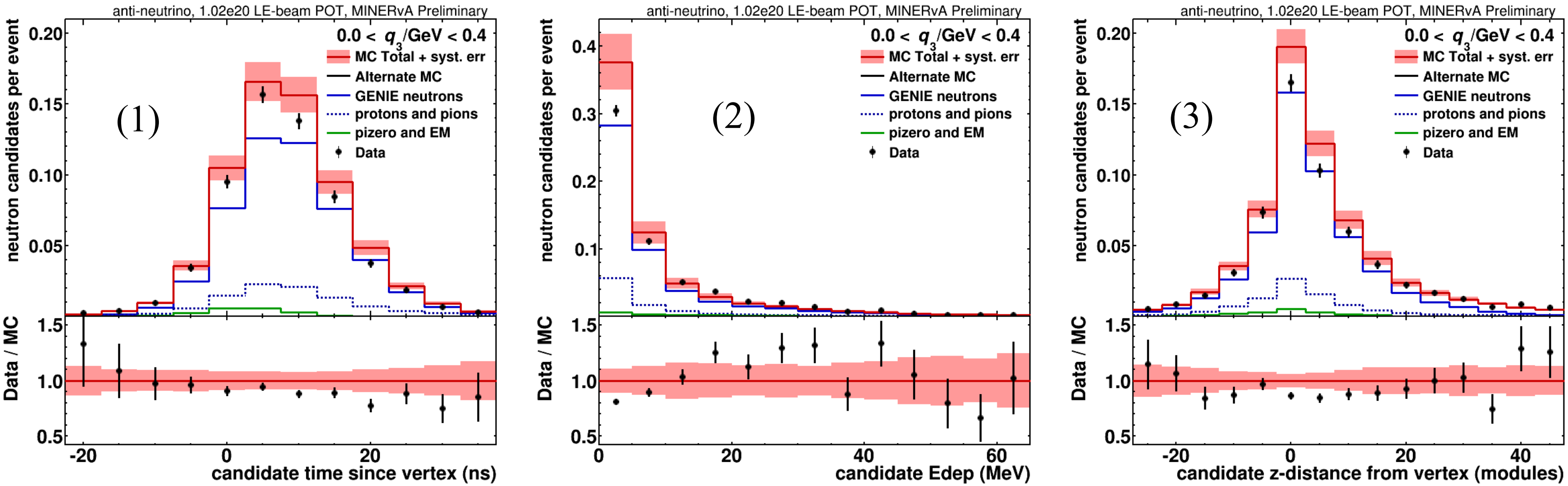
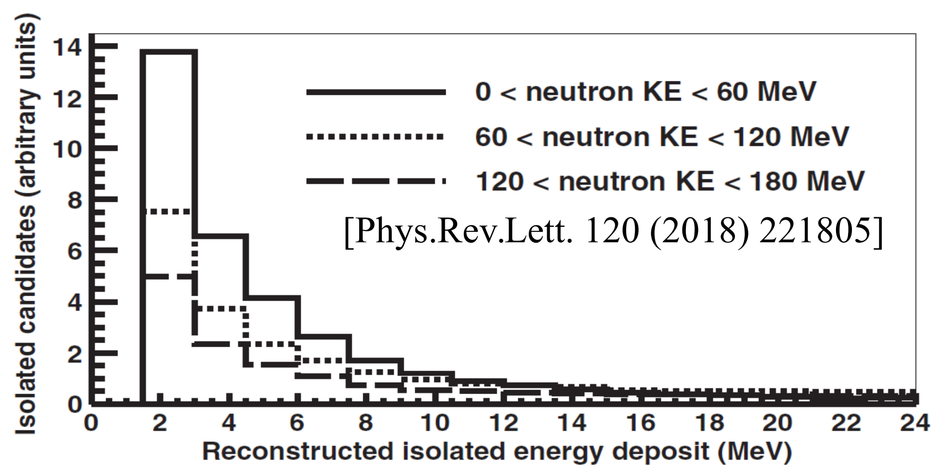


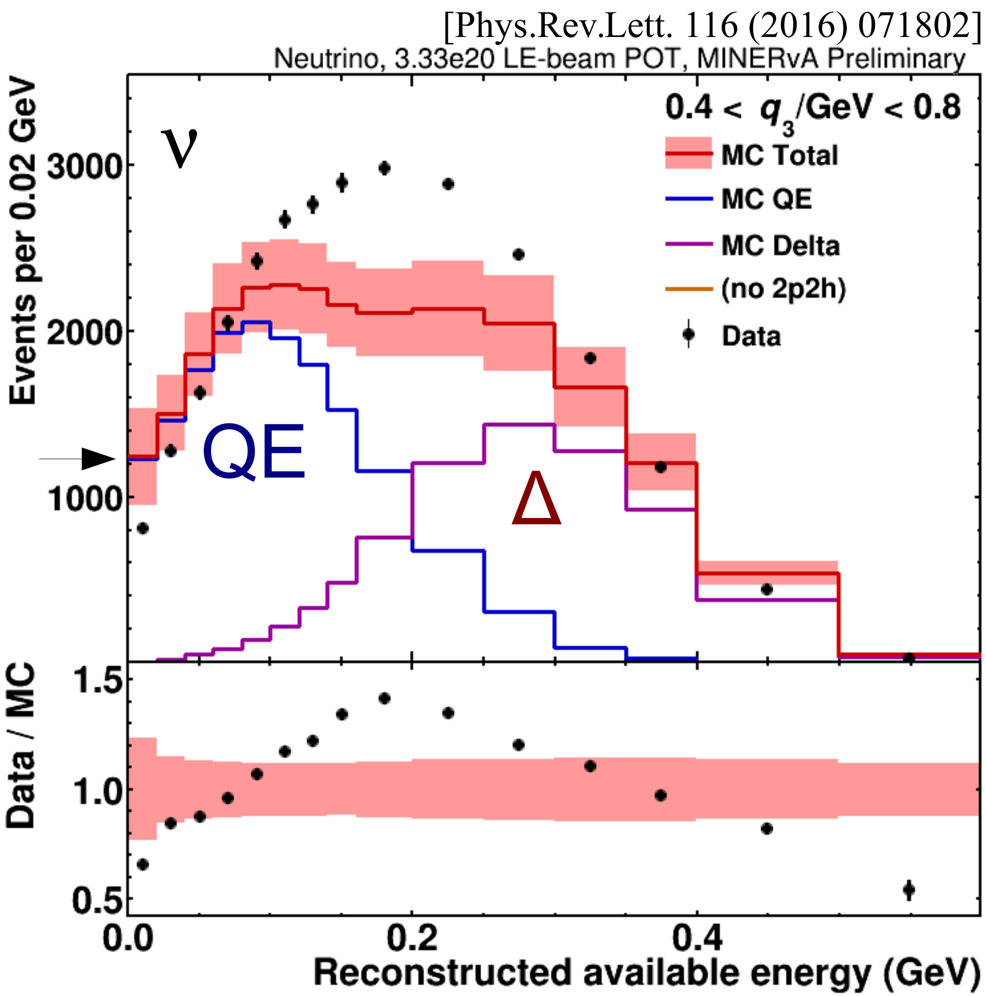
Detector response to neutrons
(1) Reconstructed time since interaction
(2) Reconstructed energy deposition:
10 MeV level and only weekly correlated with KE
(3) Reconstructed position up/downstream

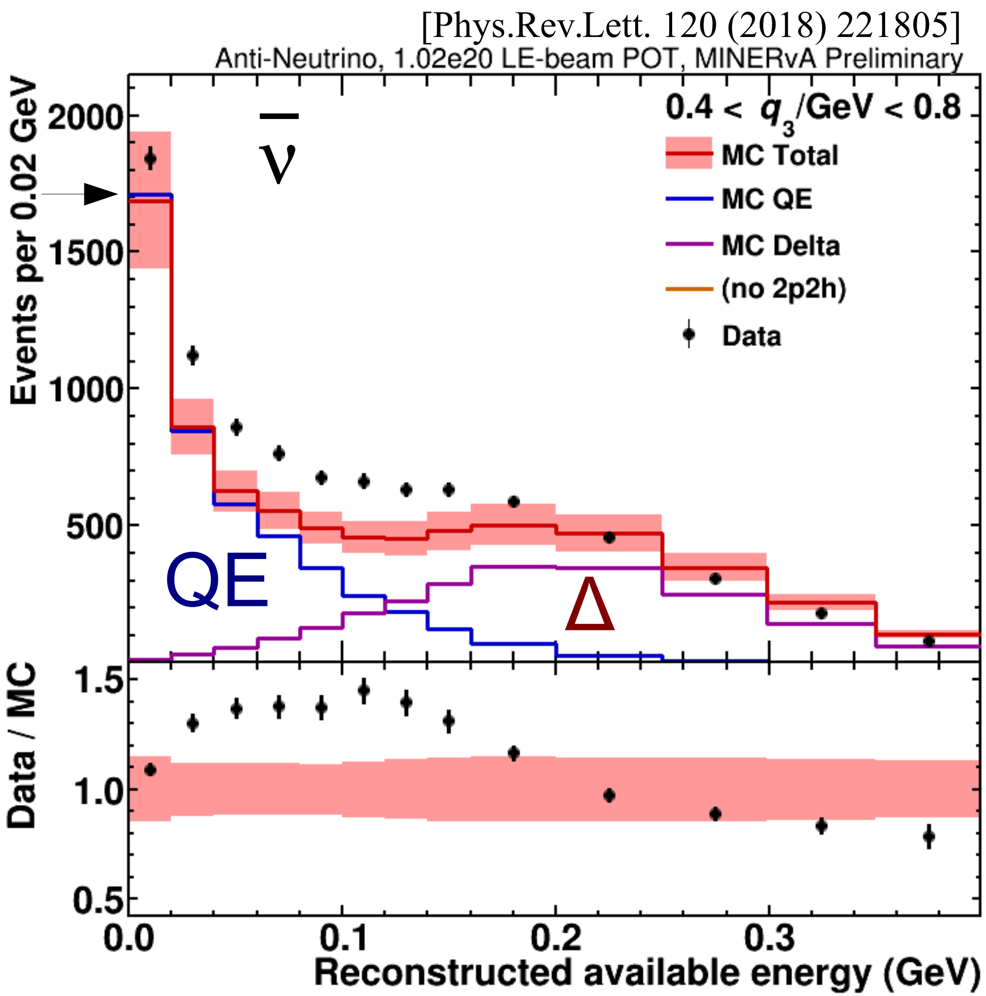


GENIE [Nucl.Instrum.Meth. A614 (2010) 87-104]

- Version 2.8.4
  - global Fermi Gas (RFG) model with Bodek-Ritchie (BR) tail [Phys. Rev. D 23, 1070 (1981)]
  - hA FSI [AIP Conf.Proc. 1405 (2011) 213-218]
- Base model (before tuning)
  - Non-resonance pion production scaled down by 75% [Phys.Rev. D90 (2014) no.11, 112017]
  - Added Random Phase Approximation (RPA) [Phys.Rev. C70 (2004) 055503]
  - Valencia 2p2h [Nieves *et al.*, Phys.Lett. B707 (2012) 72-75, Phys. Rev. C 86, 015504 (2012), Phys.Rev. D88 (2013) no.11, 113007, arXiv:1601.02038]

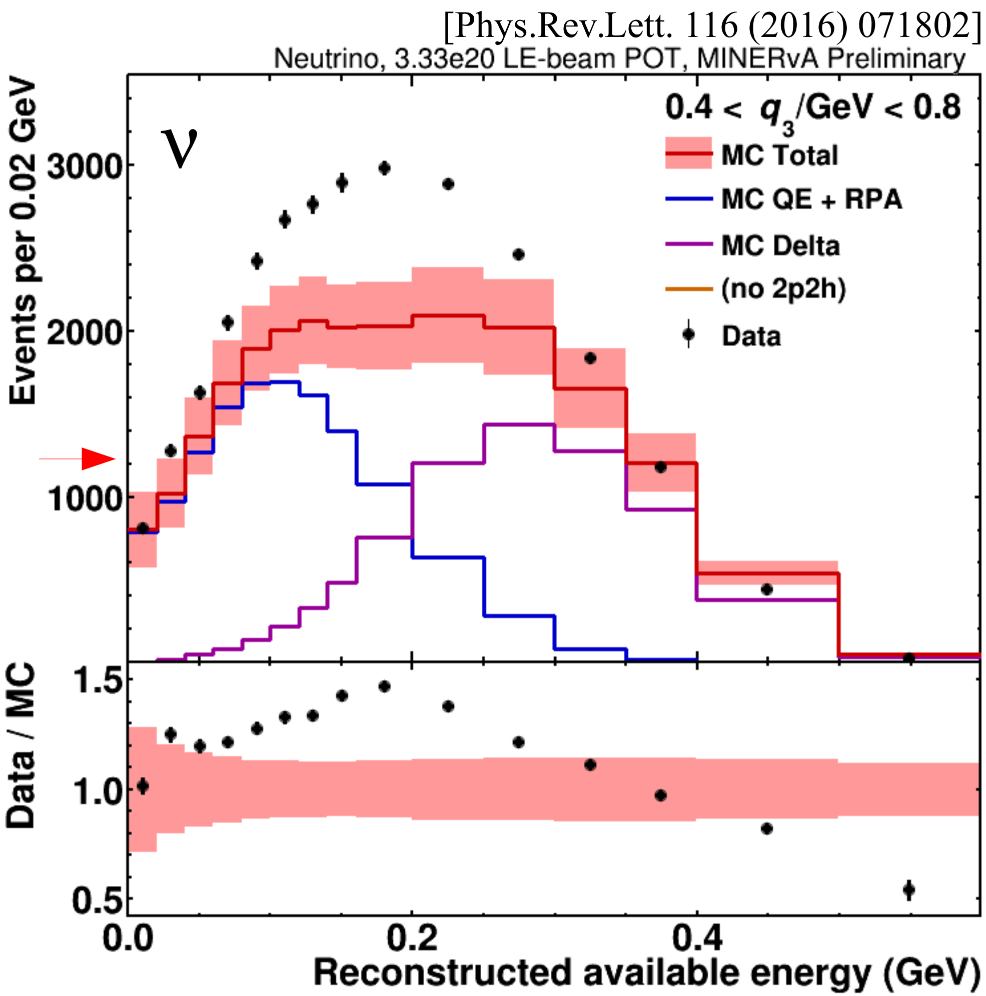
GENIE + pion reweight

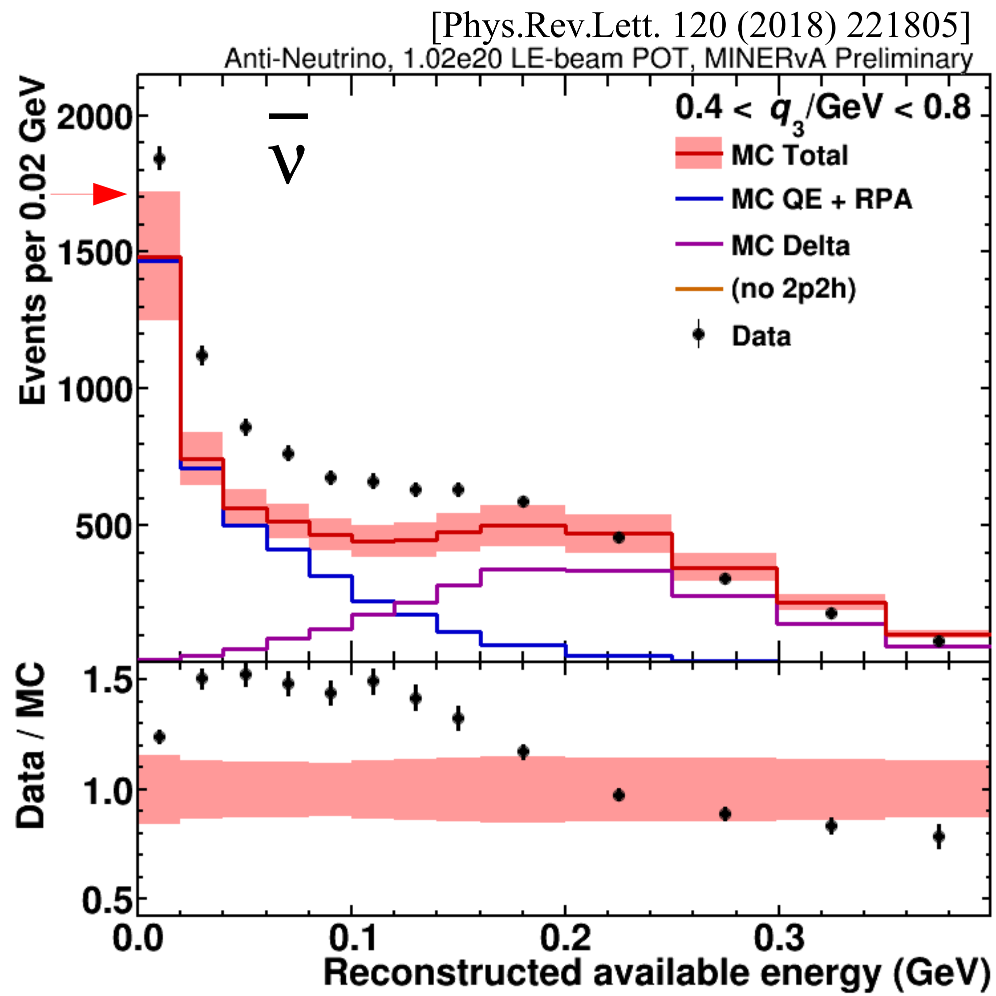




- QE and RES contributions separated

GENIE + pion reweight + RPA

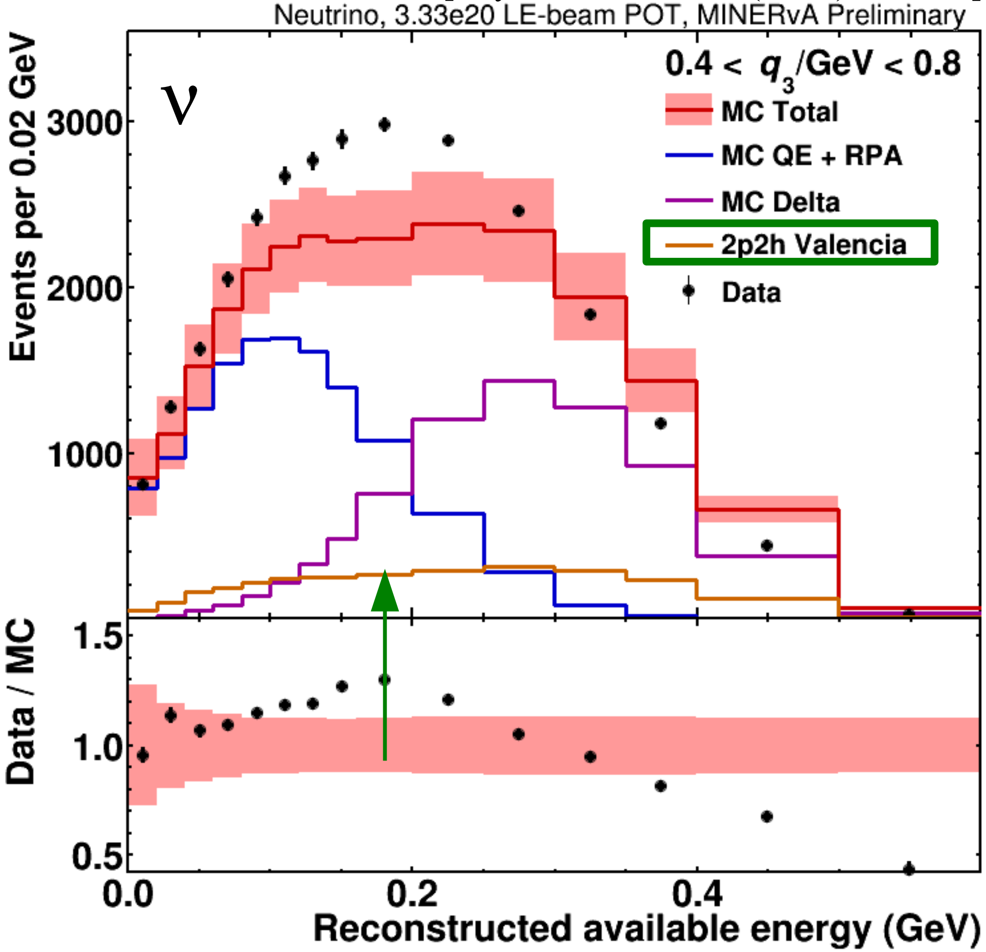




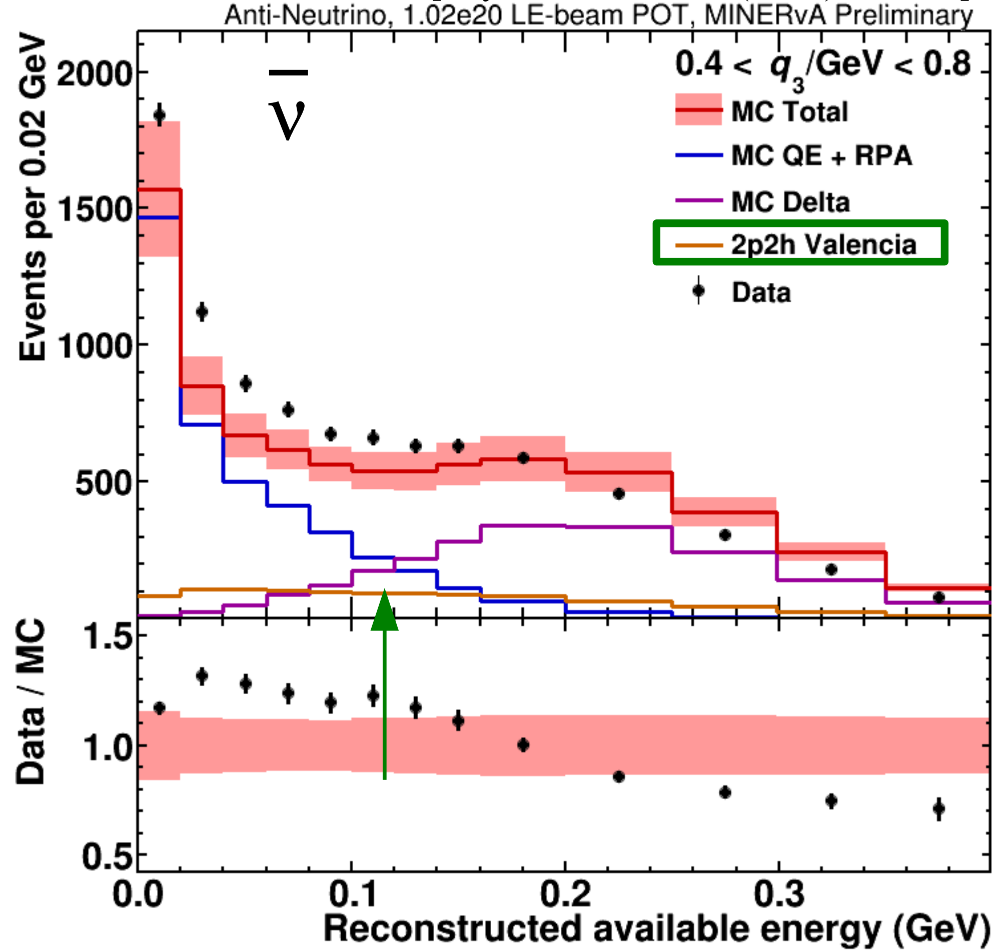
- RPA reduces predictions at low available energy

GENIE + pion reweight + RPA + 2p2h = Base Model

[Phys.Rev.Lett. 116 (2016) 071802]



[Phys.Rev.Lett. 120 (2018) 221805]



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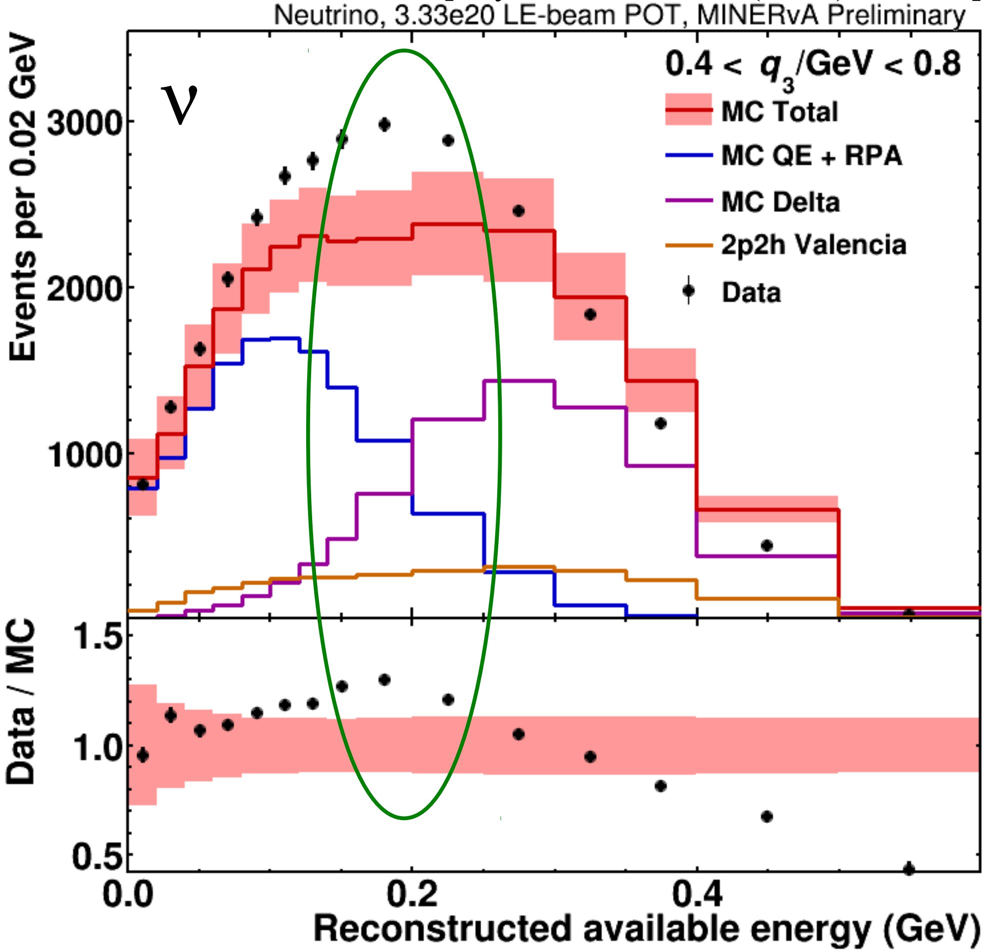

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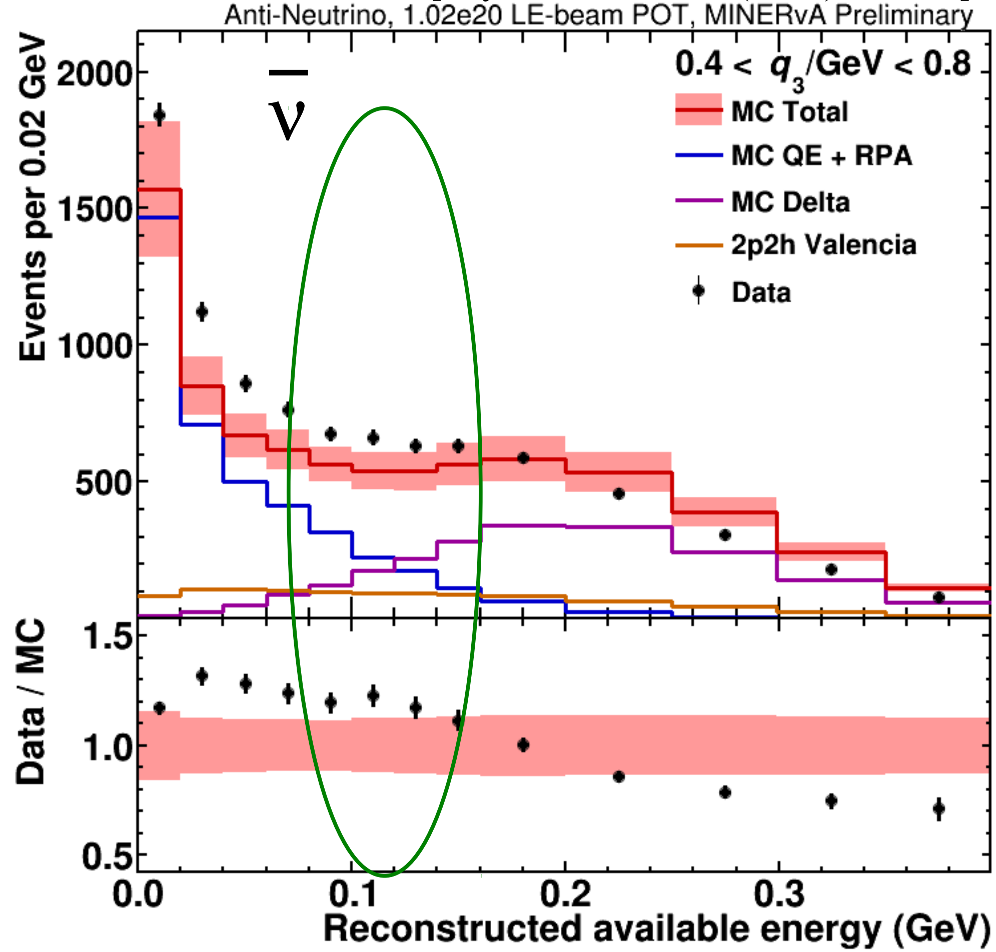
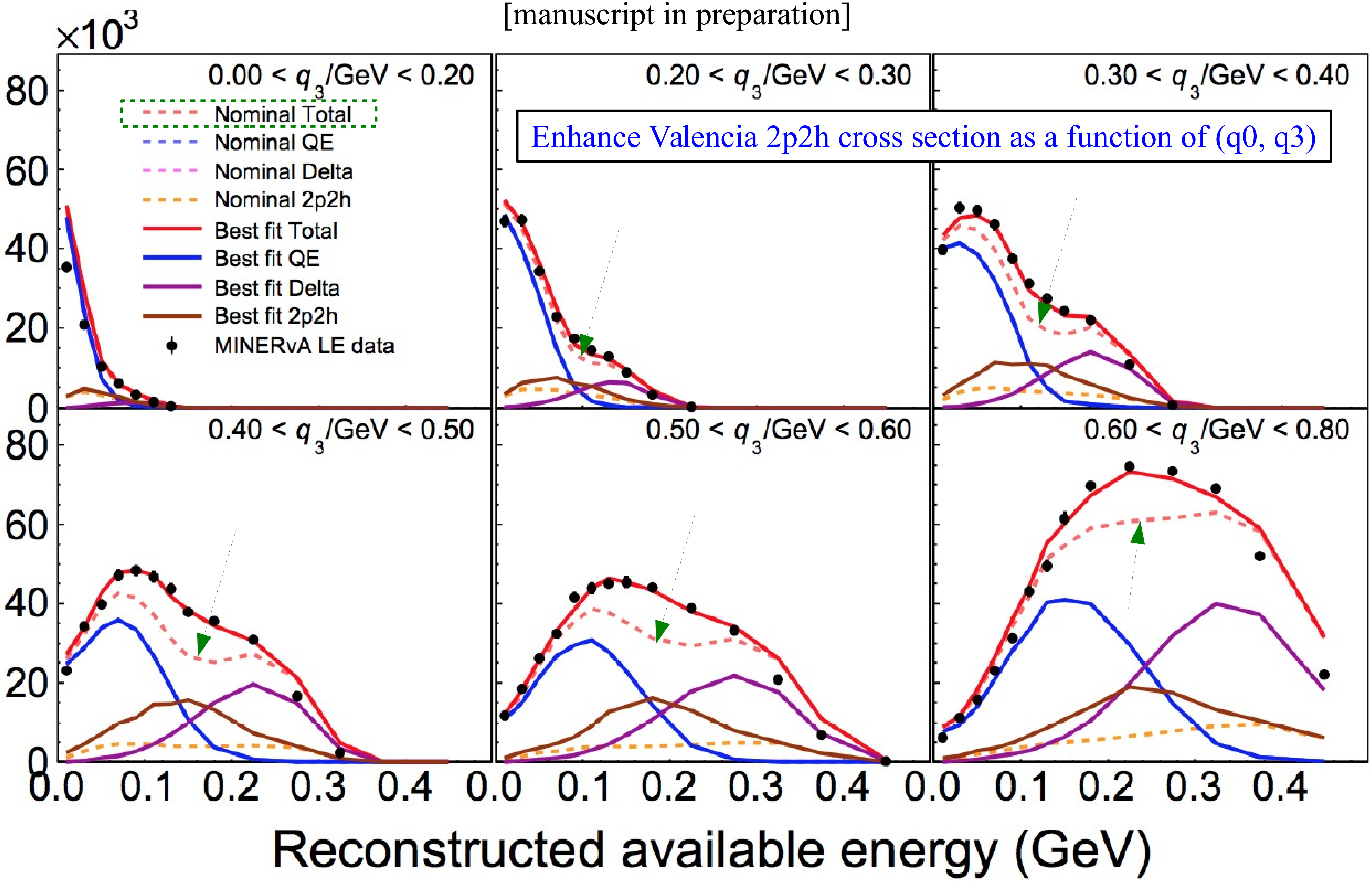


- Missing strength in the dip

Focus on dip #2

Low-Recoil Tune / *2p2h-like enhancement*

[manuscript in preparation]



Low-Recoil Tune / *2p2h-like enhancement*

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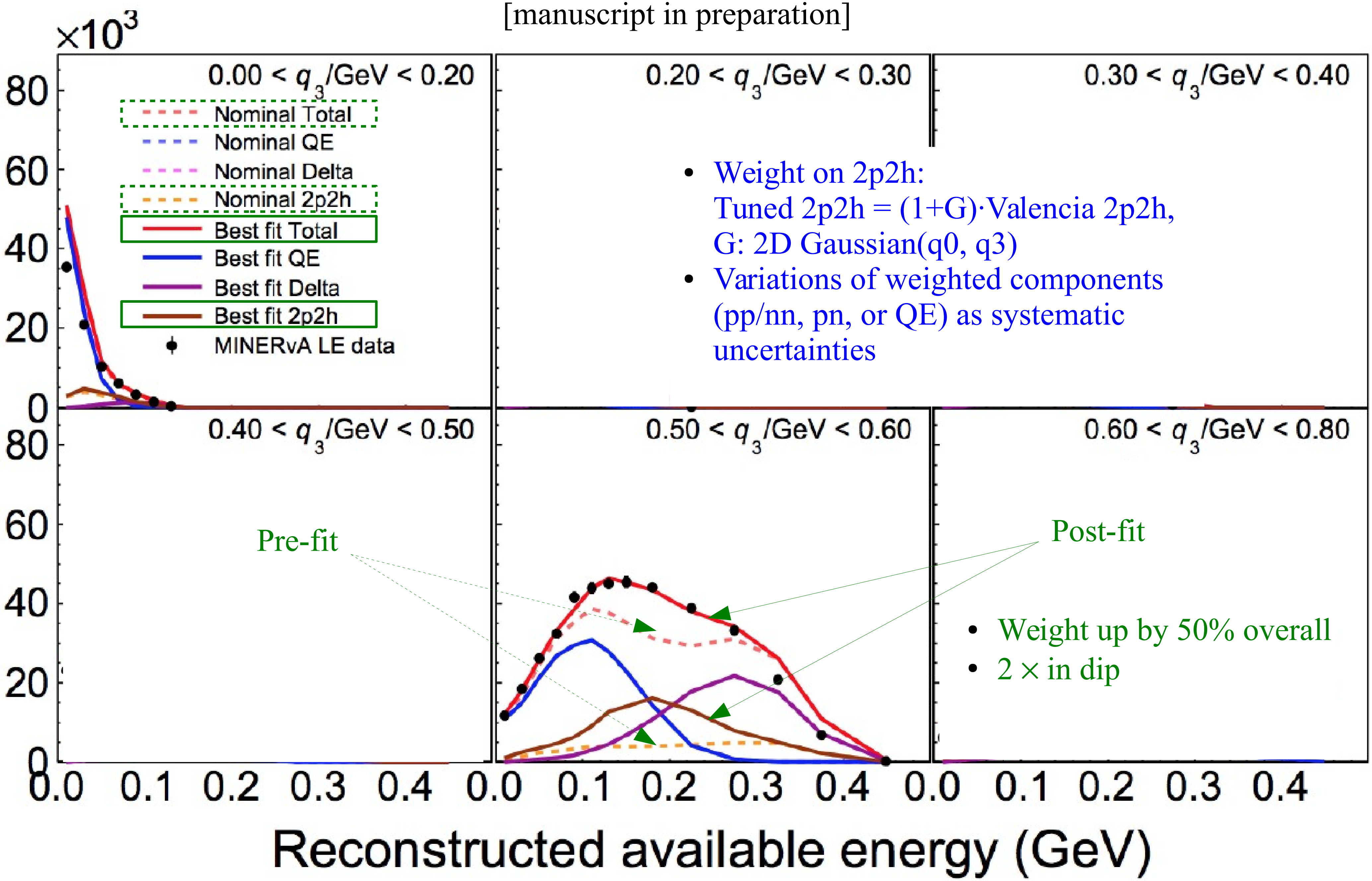


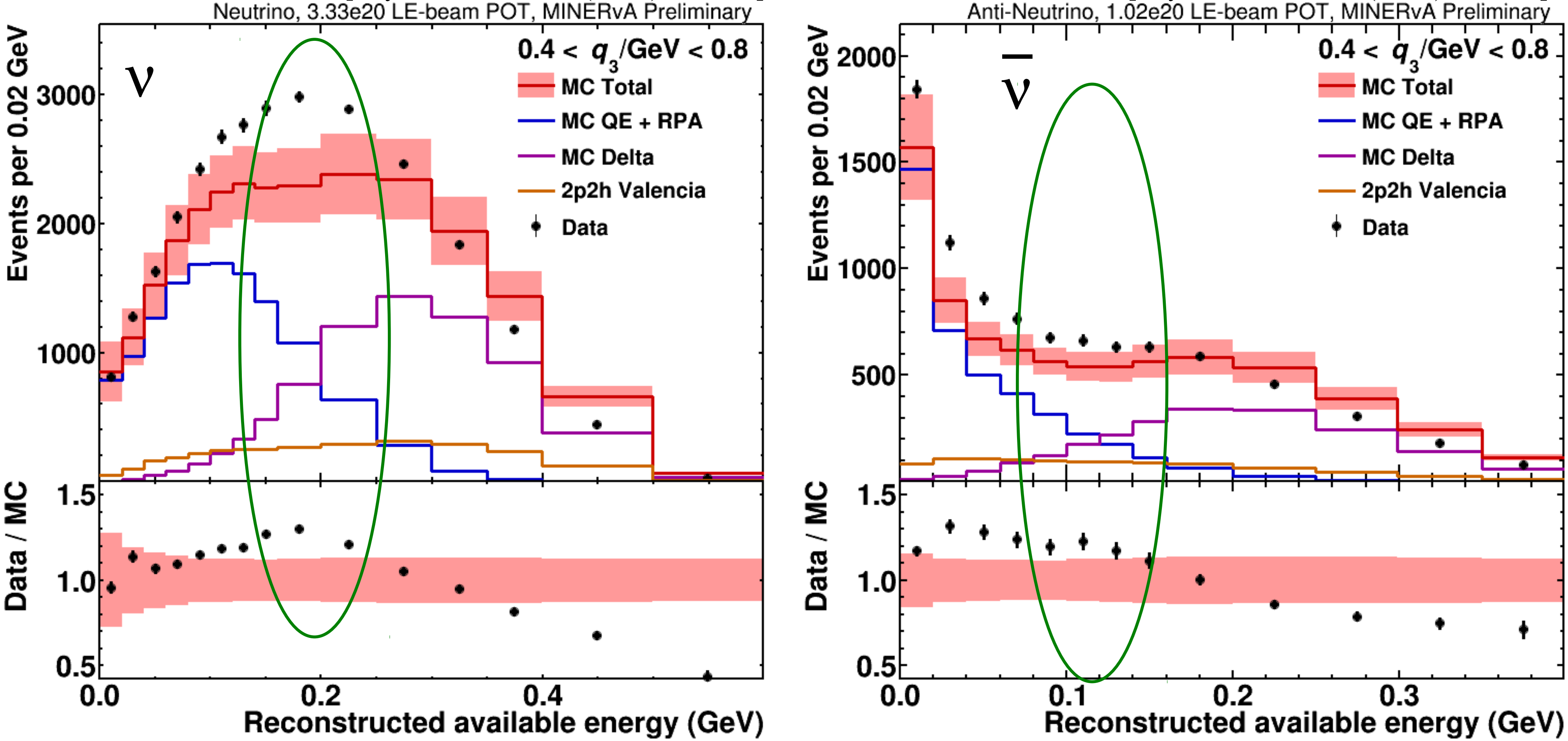
- Weight on 2p2h:
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  G: 2D Gaussian(q0, q3)
- Variations of weighted components (pp/nn, pn, or QE) as systematic uncertainties

- Weight up by 50% overall
- 2 × in dip

GENIE + pion reweight + RPA + 2p2h = Base Model

[Phys.Rev.Lett. 116 (2016) 071802]

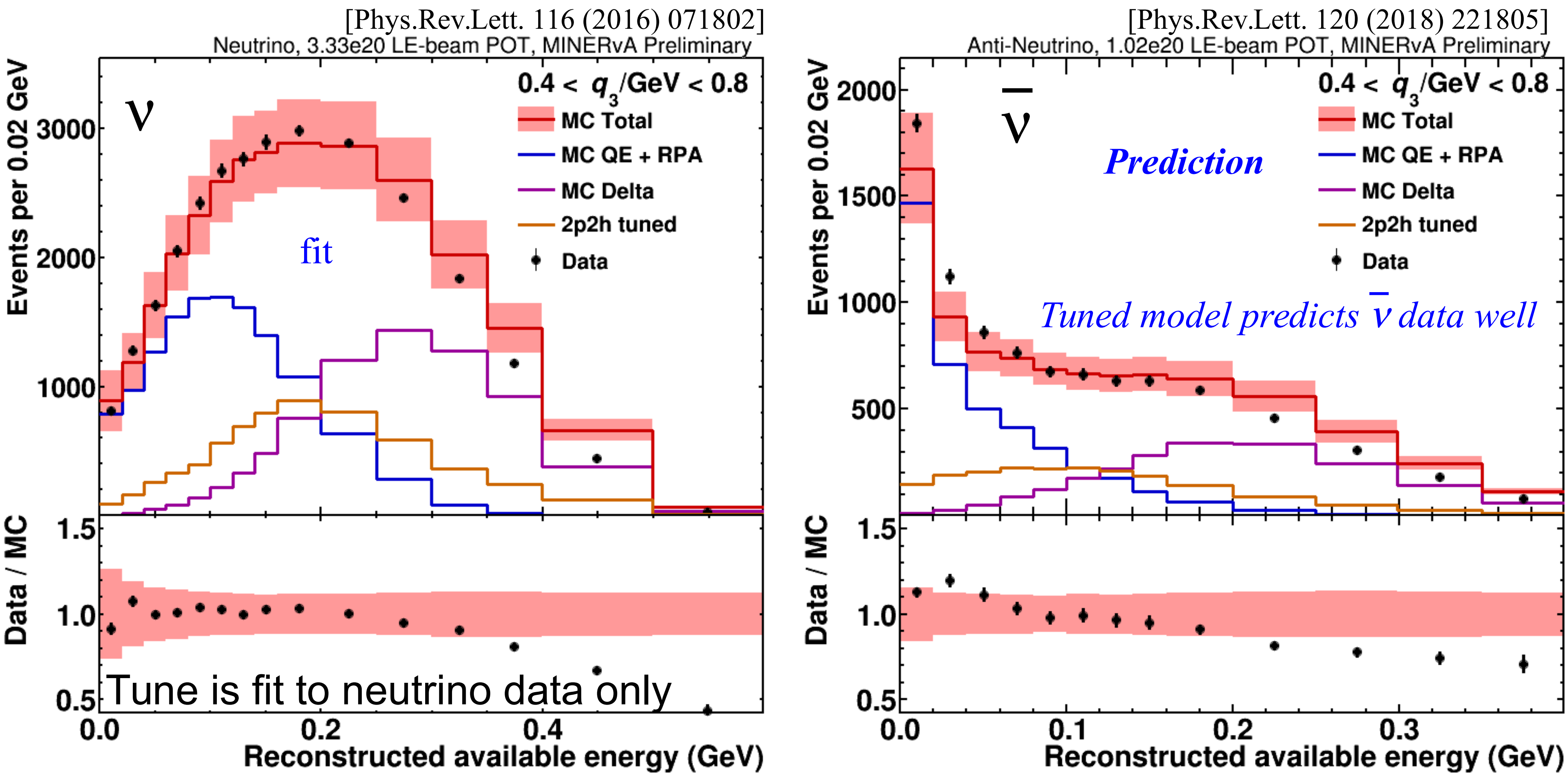
[Phys.Rev.Lett. 120 (2018) 221805]



- Missing strength in the dip

Focus on dip #2

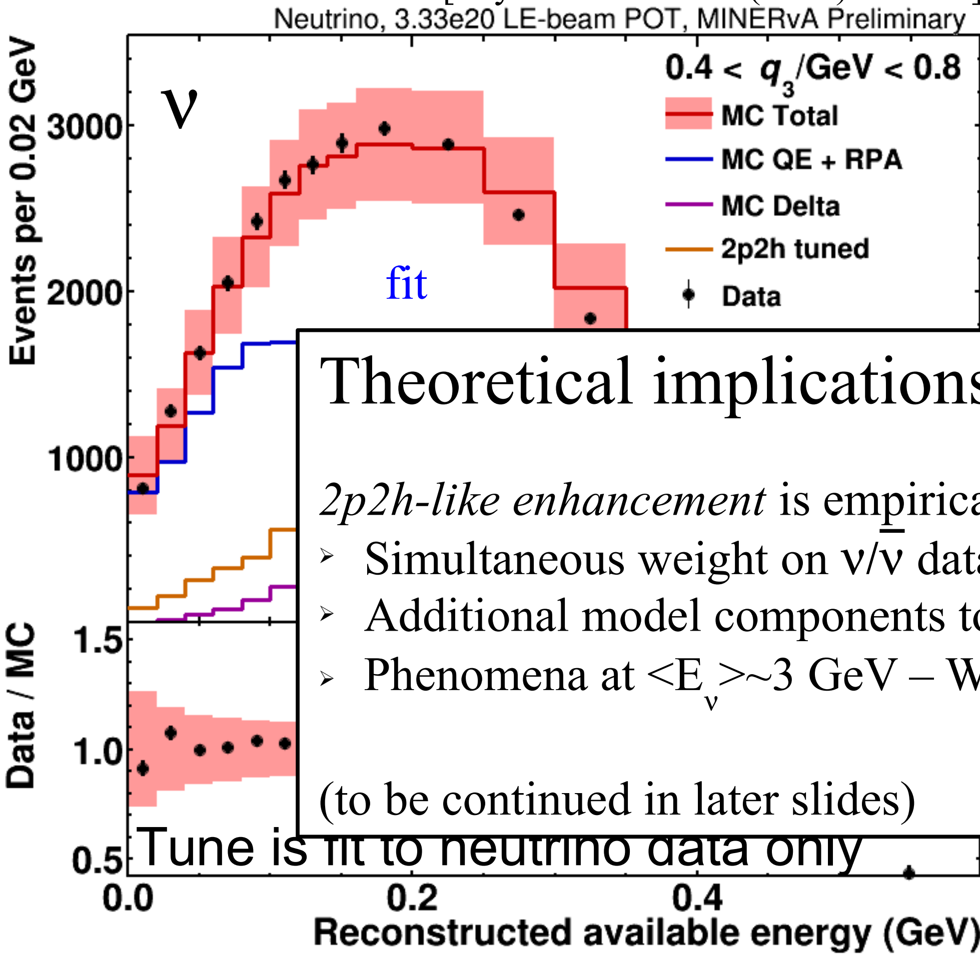
Base Model + Low-Recoil Tune = MnvGENIE-v1



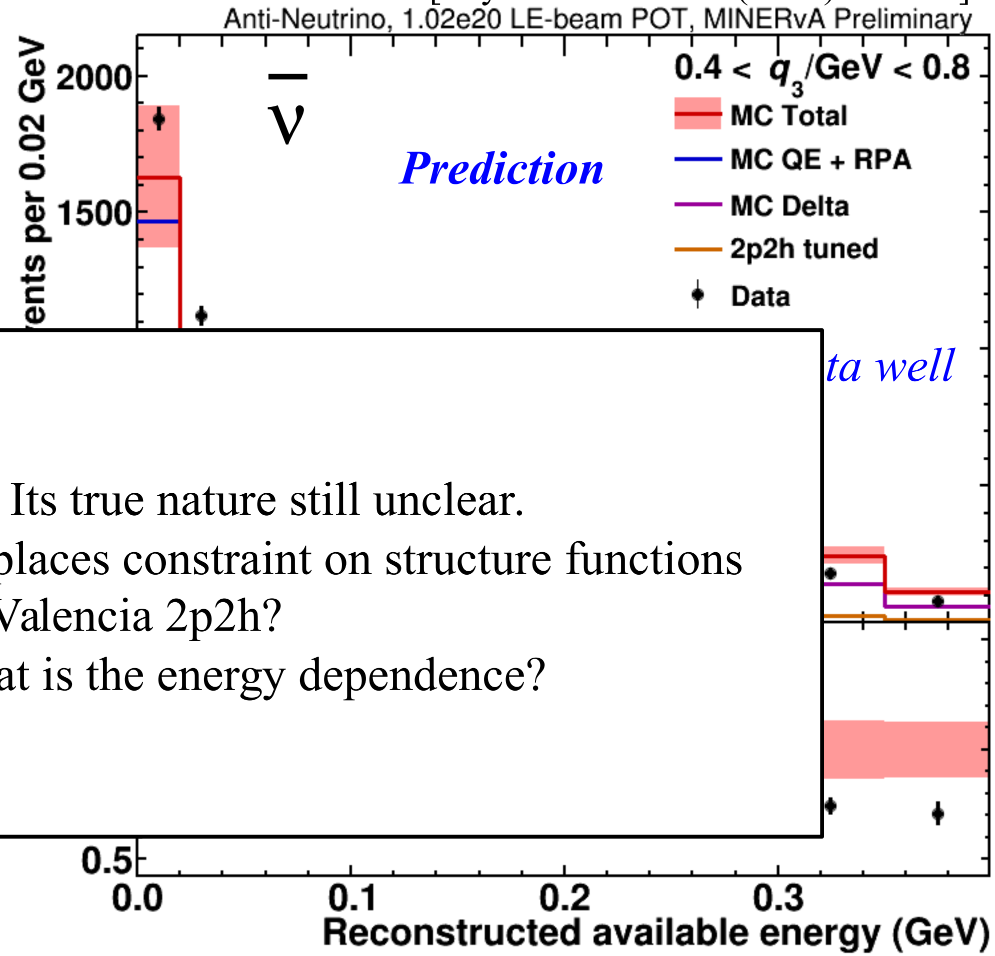
- Apply neutrino tune directly to anti-neutrino
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  G: 2D Gaussian(q0, q3) determined in fit to neutrino data
- *Empirical* modification to 2p2h

Base Model + Low-Recoil Tune = MnvGENIE-v1

[Phys.Rev.Lett. 116 (2016) 071802]



[Phys.Rev.Lett. 120 (2018) 221805]



Theoretical implications

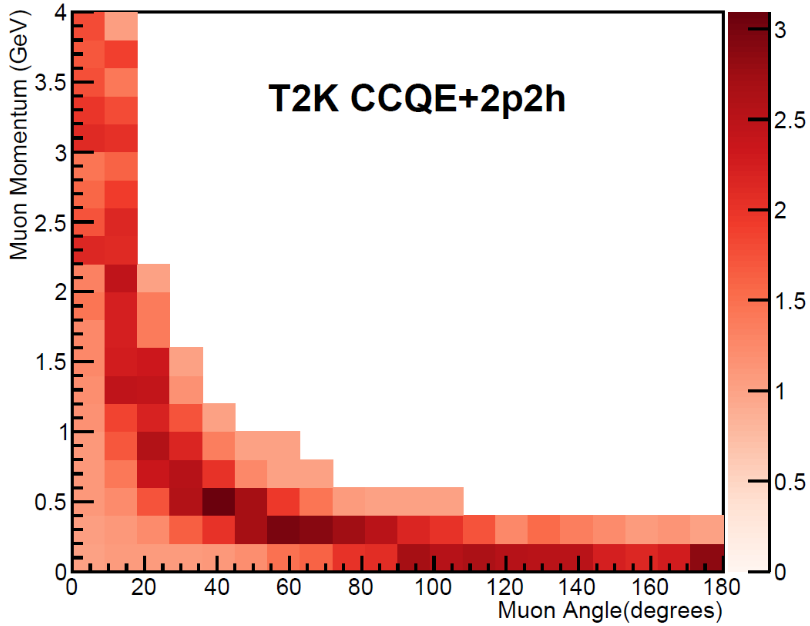
2p2h-like enhancement is empirical. Its true nature still unclear.

- Simultaneous weight on $\nu/\bar{\nu}$ data places constraint on structure functions
- Additional model components to Valencia 2p2h?
- Phenomena at $<E_\nu>$~3 GeV – What is the energy dependence?

(to be continued in later slides)

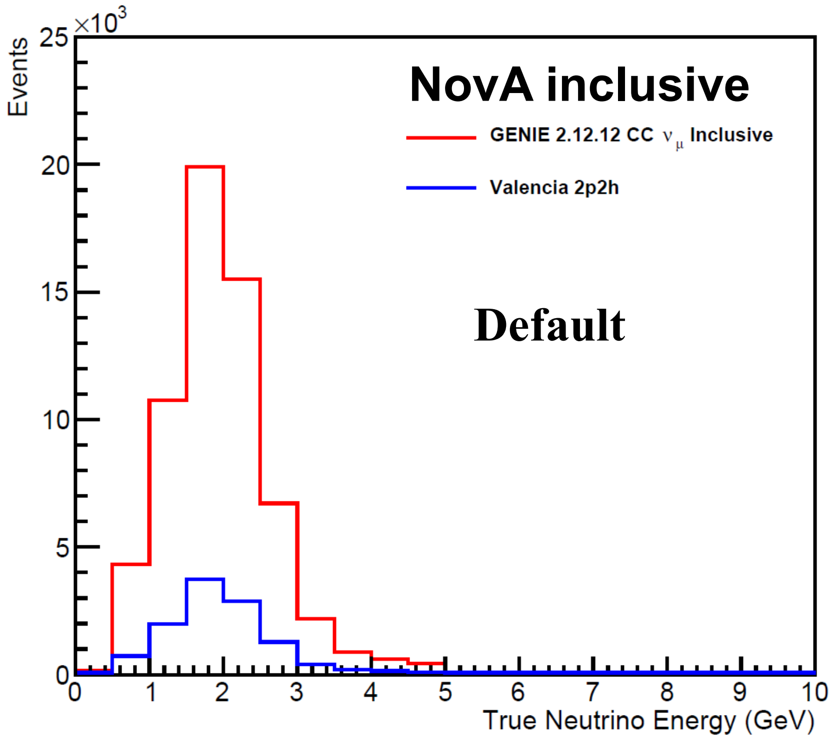
Implications for T2K

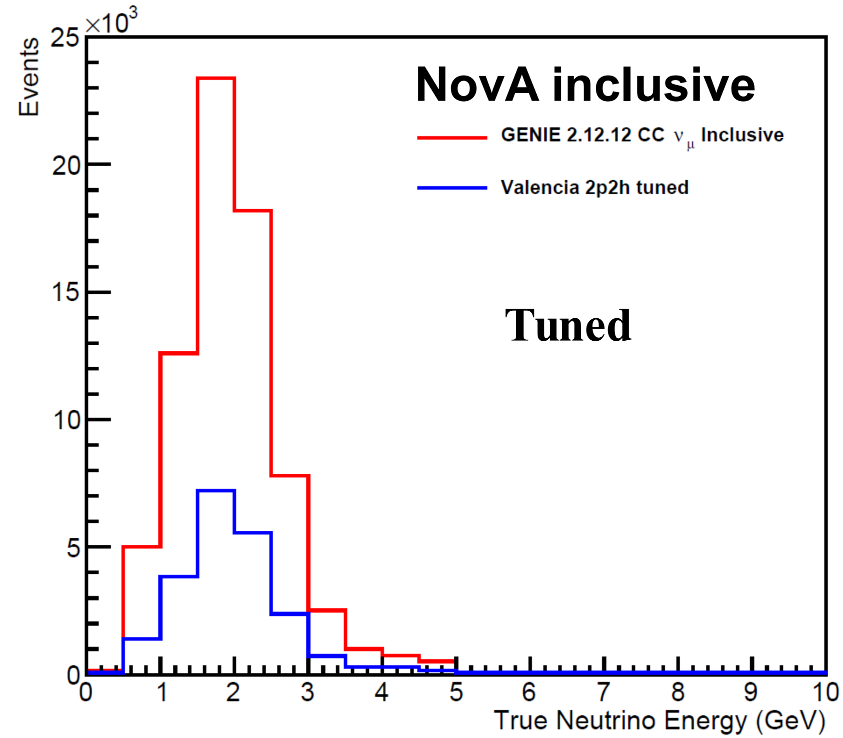
Event count ratio:
Tuned/Default



- Beam energy ~ 0.6 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible impact in CCQE-like full phase space at T2K energy, especially at high angle

Implications for NOvA



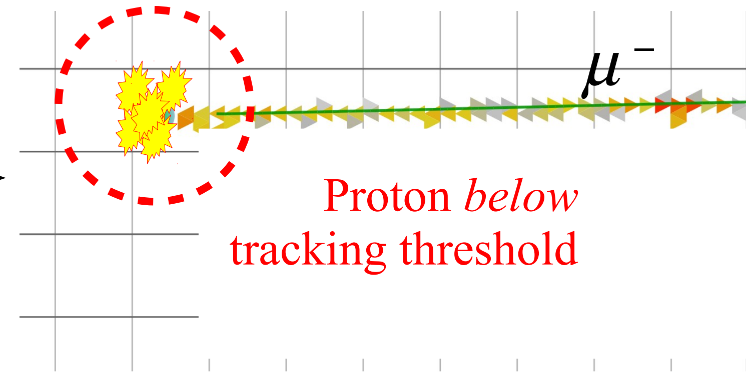


- Beam energy ~ 2 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible change in inclusive energy spectrum at NOvA energy

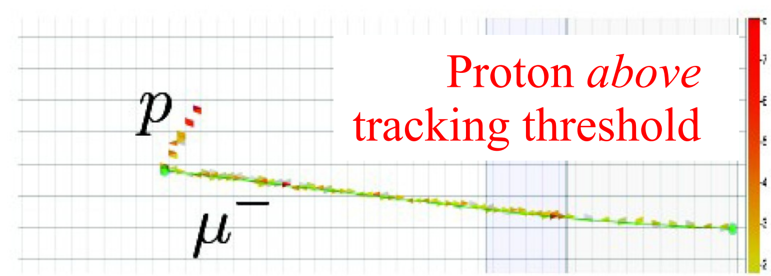
$\bar{\nu}$ Low-Recoil Analysis (CC inclusive)

ν Low-Recoil Analysis (CC inclusive)
→ Low-Recoil Tune (MnvGENIE-v1)

ν double-differential CCQE-like (CC0pi)



ν Final-State Correlation Analysis (CC0piNp)



Untracked Vertex Energy in CCQE-like Analysis

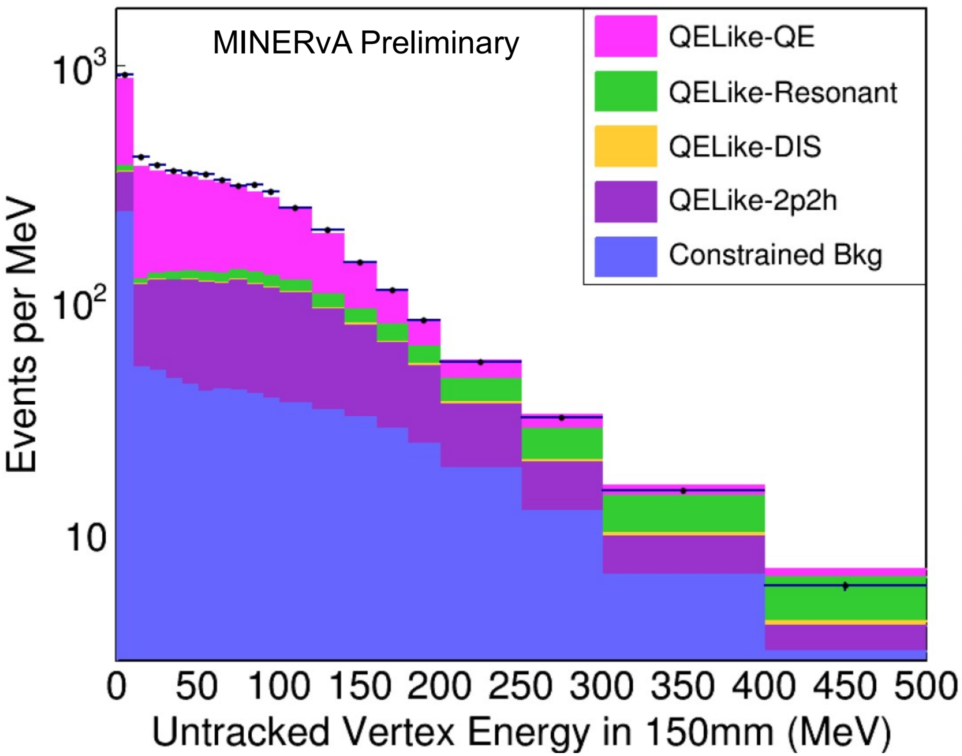
(CC0pi sample)

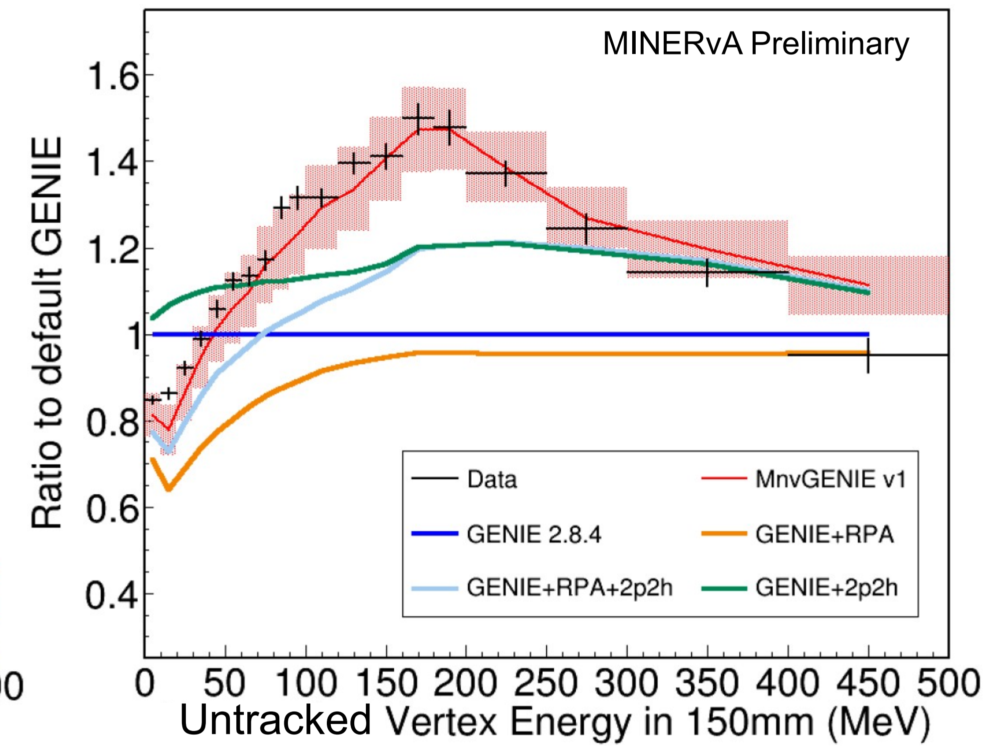
[manuscript on arXiv ***this week***]

D. Ruterbories

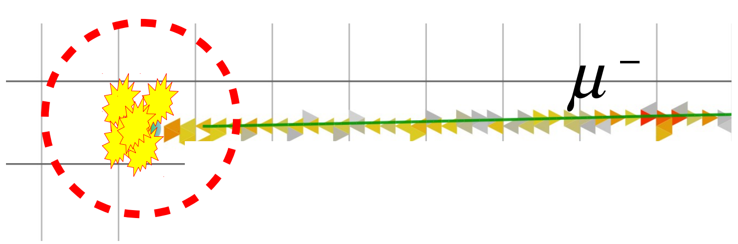
Joint Experimental-Theoretical Physics Seminar

http://theory.fnal.gov/events/event/results-from-minerva-2/



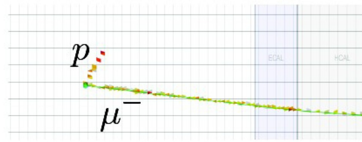


- Sample dominated by QE
- Untracked Vertex Energy (neutrino) $\sim T_p$ (below tracking threshold ~ 100 MeV)
- MnvGENIE-v1 predicts data well



Nuclear Recoil in Final-State Correlation Analysis (CC0piNp sample)

[**NEW** Phys.Rev.Lett. 121 (2018) 022504]



More detail in

Transverse Kinematic Imbalance in MINERvA: Past, Present, and Future – Rob Fine

A more general analysis of kinematic imbalance

Transverse: $$0 = \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'} - \delta\vec{p}_{\mathrm{T}}$$

Longitudinal: $$E_\nu = p_{\mathrm{L}}^{\ell'} + p_{\mathrm{L}}^{\mathrm{N}'} - \delta p_{\mathrm{L}}$$

New variable: $$p_{\mathrm{n}} \equiv \sqrt{\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2}$$

[Phys.Rev. C95 (2017) 065501]

Neutrino energy is unknown (in the first place), equations are not closed.

Assuming exclusive μ-p-A' final states
Use energy conservation to close the equations

$$E_\nu + m_{\mathrm{A}} = E_{\ell'} + E_{\mathrm{N}'} + E_{\mathrm{A}'}$$

$$E_{\mathrm{A}'} = \sqrt{m_{\mathrm{A}'}^2 + p_{\mathrm{n}}^2}$$

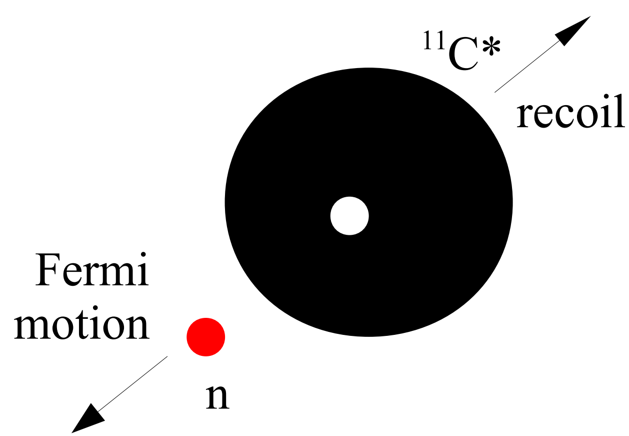
p_n: recoil momentum of the nuclear remnant

final-state

Dual Interpretation

For CCQE, A' = ^{11}C*
No more unknowns
p_n: neutron Fermi motion

initial-state



Nuclear Recoil in Final-State Correlation Analysis (CC0piNp sample)

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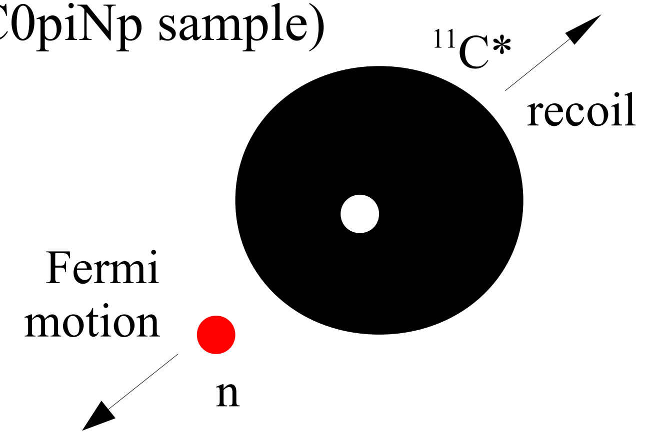

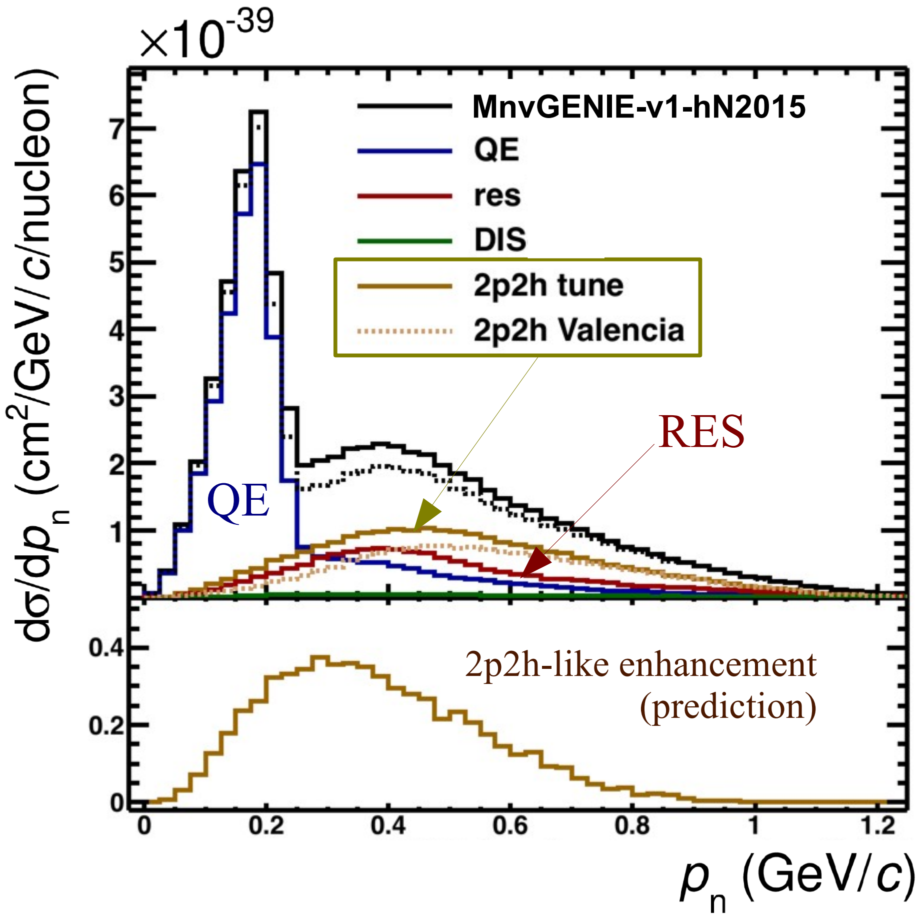

Nuclear Recoil in Final-State Correlation Analysis (CC0piNp sample)

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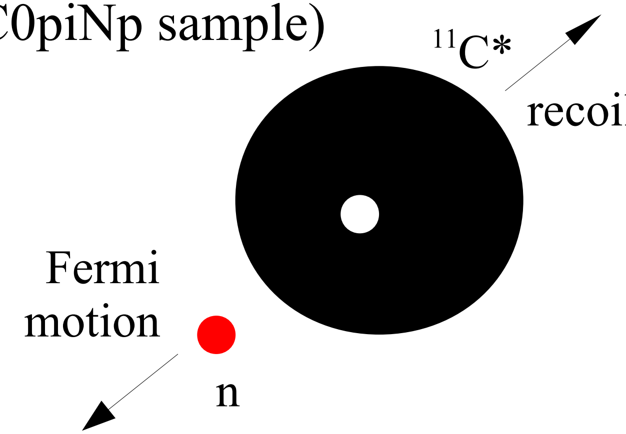
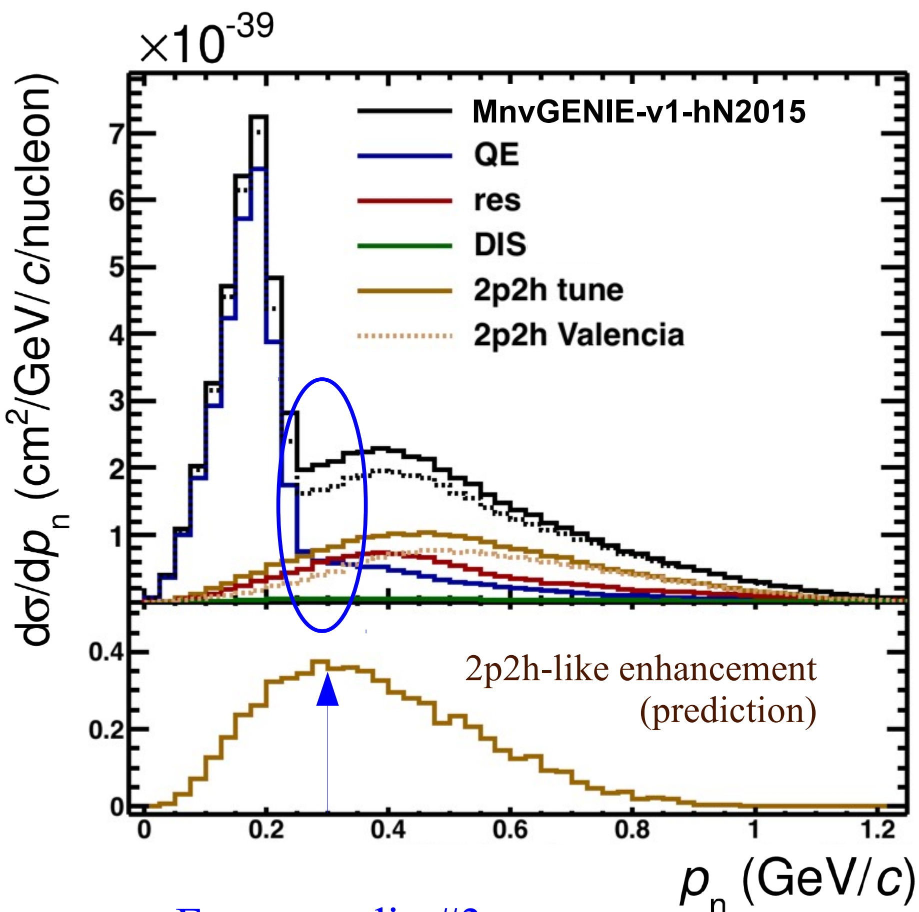
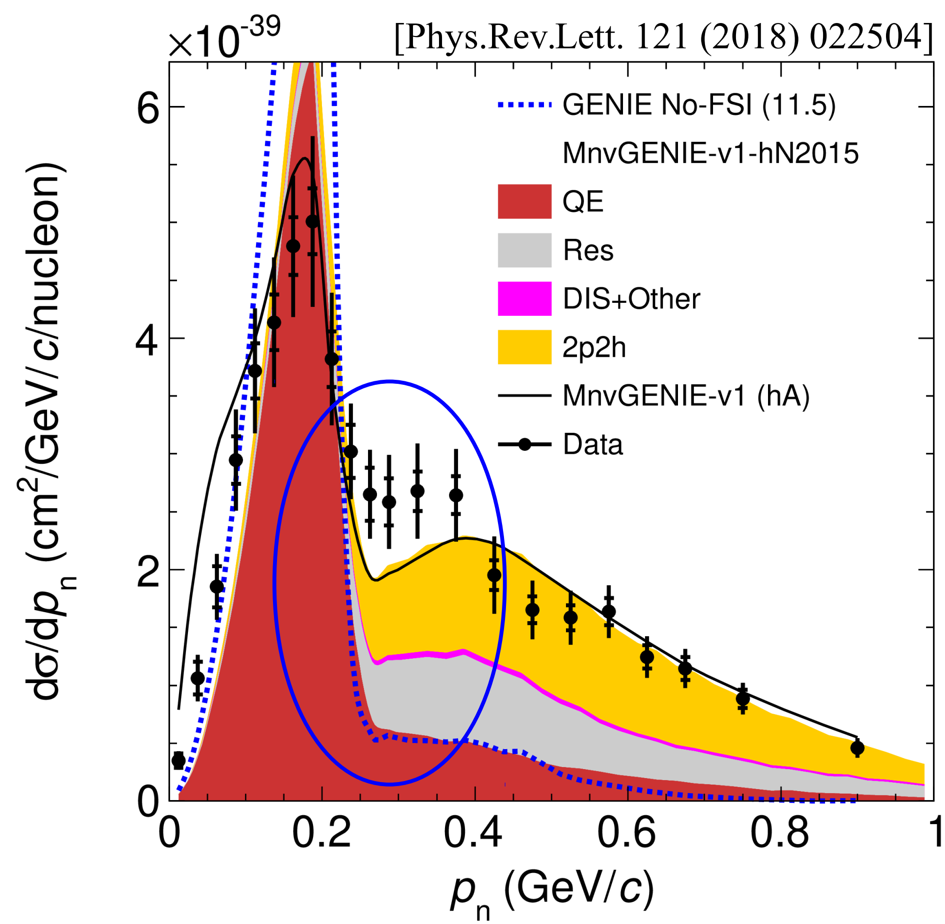


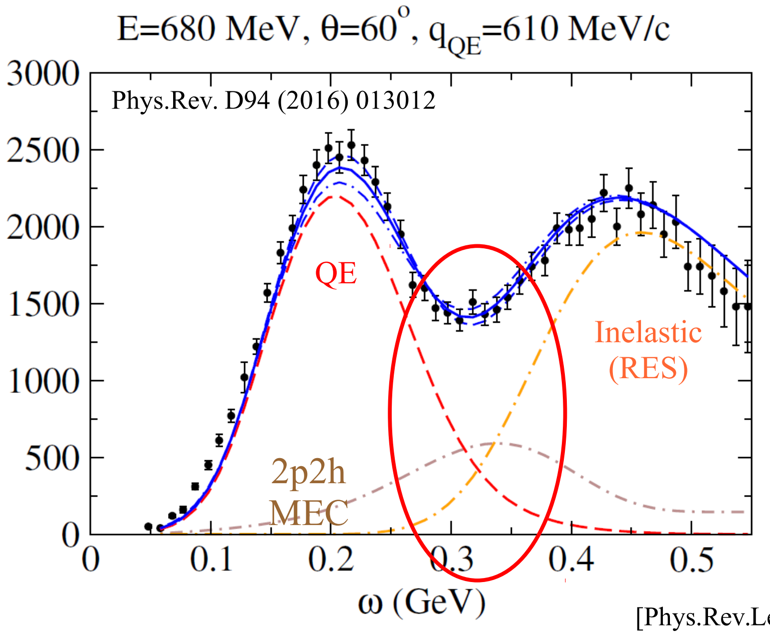
2p2h-like enhancement needs to be even stronger to fill the dip

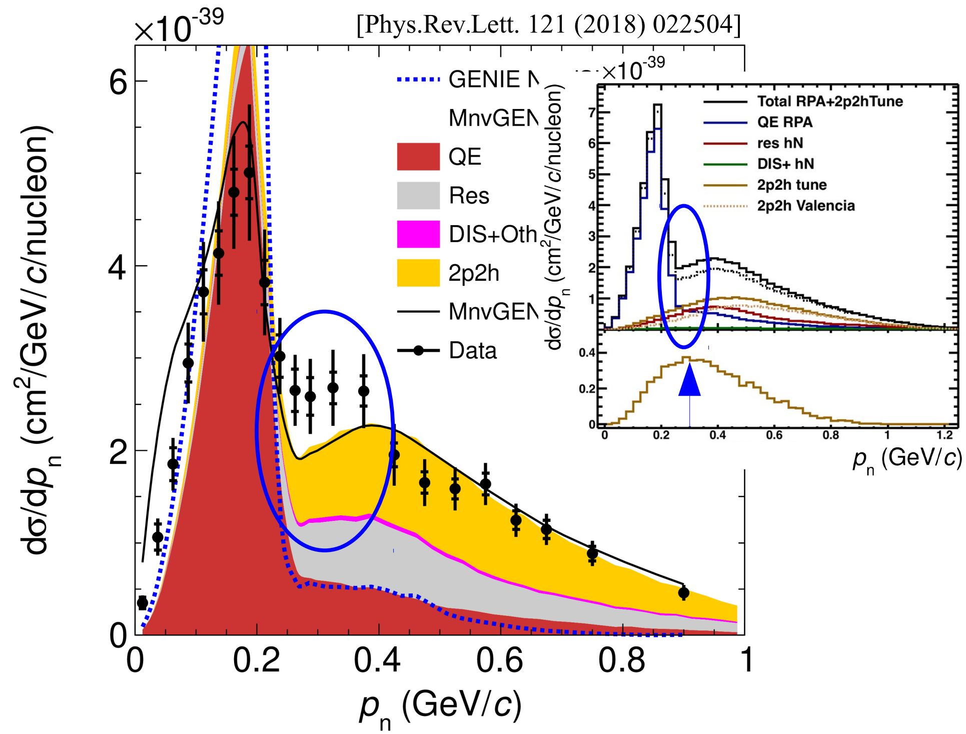




Focus on dip #3

Experimental Implications

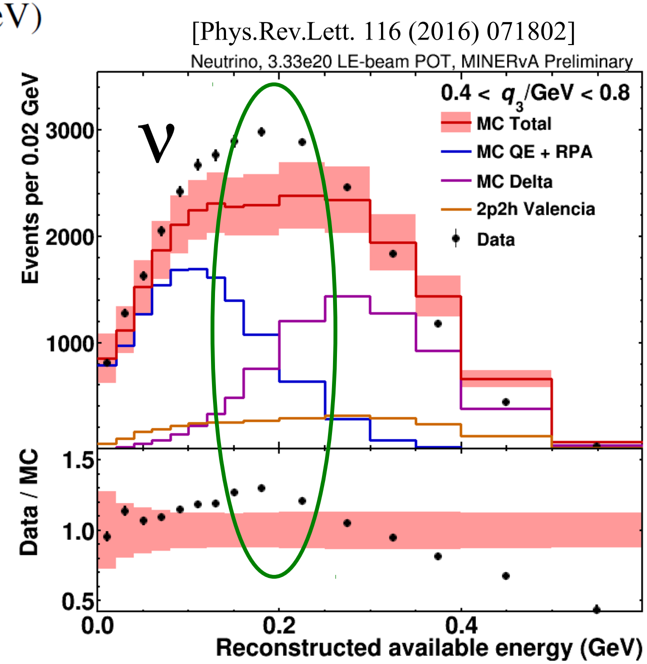


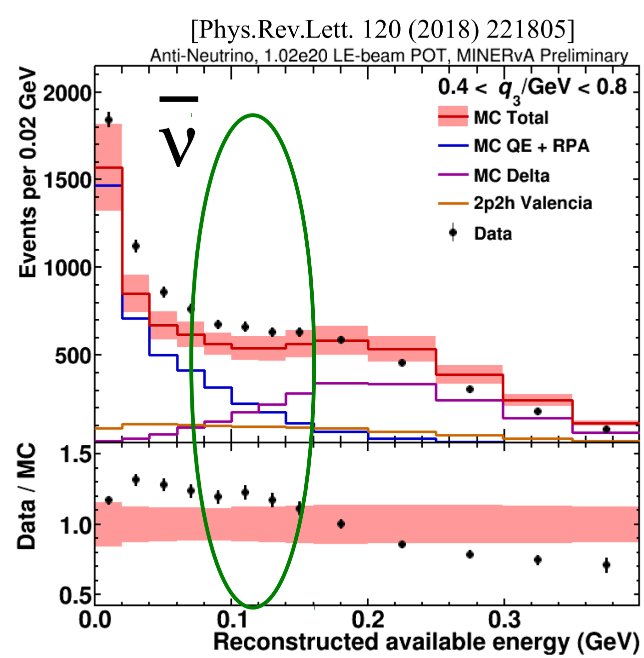


Are we seeing the same thing from different angles?

- Yes – kinematic ordering among QE, 2p2h, and RES

QE/RES separation can be done calorimetrically (E_{av}) or kinematically (p_n)





Experimental Implications

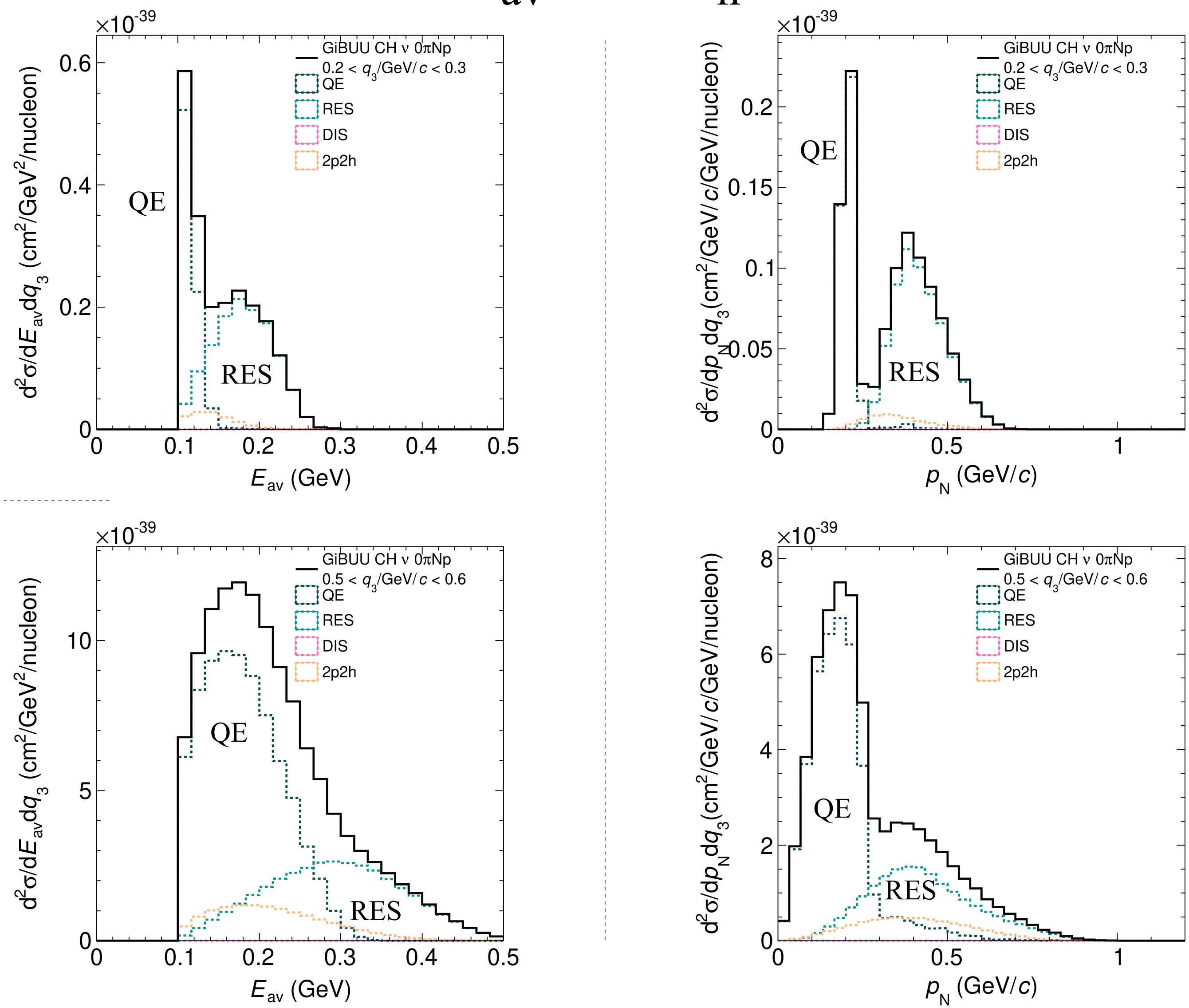
* GiBUU https://gibuu.hepforge.org/trac/wiki

p_n can provides QE/RES separation
at high q3 (> 1 GeV/*c*)

E_{av} vs. p_n

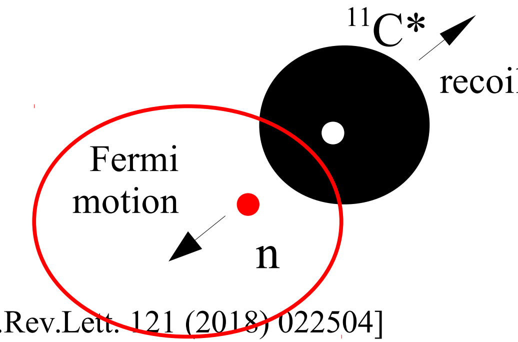
q3 0.2-0.3 GeV/*c*

q3 0.5-0.6 GeV/*c*

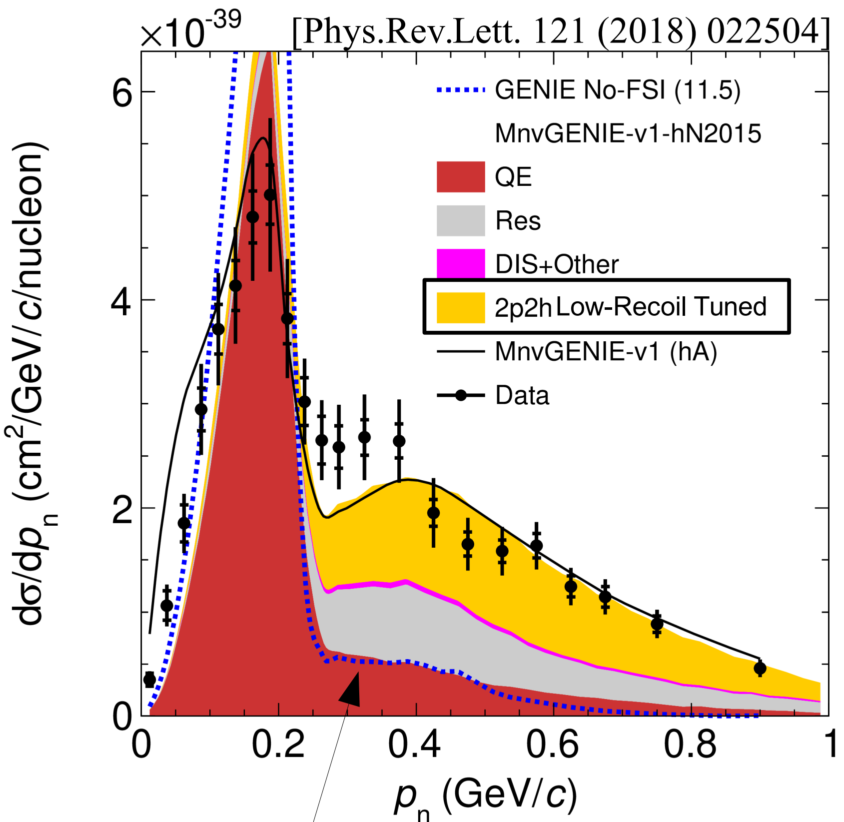


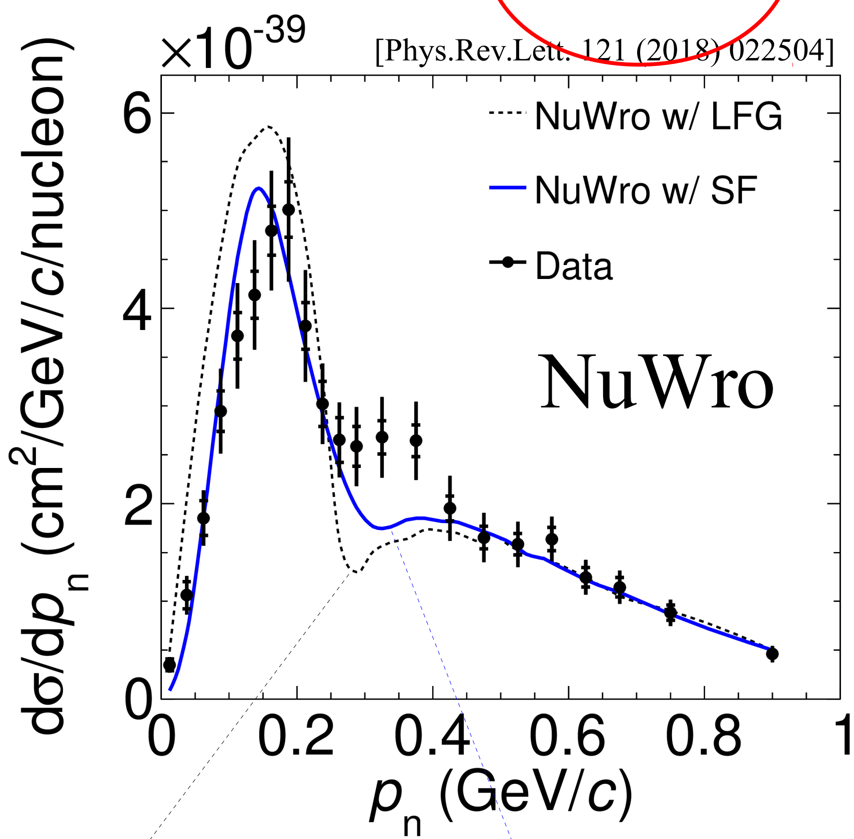
* Compare q3-evolution of QE/RES/2p2h location: only 2p2h moves (GiBUU)

Theory and Experimental Implications



2p2h-like enhancement has Base-Model-dependence





Global Fermi Gas with Bodek-Ritchie tail

Local Fermi Gas

Spectral Function

- Base Model depends on 1p1h and Short Range Correlation (SRC) modeling
- Critical to separate QE and RES to reduce Base-Model-dependence

Summary

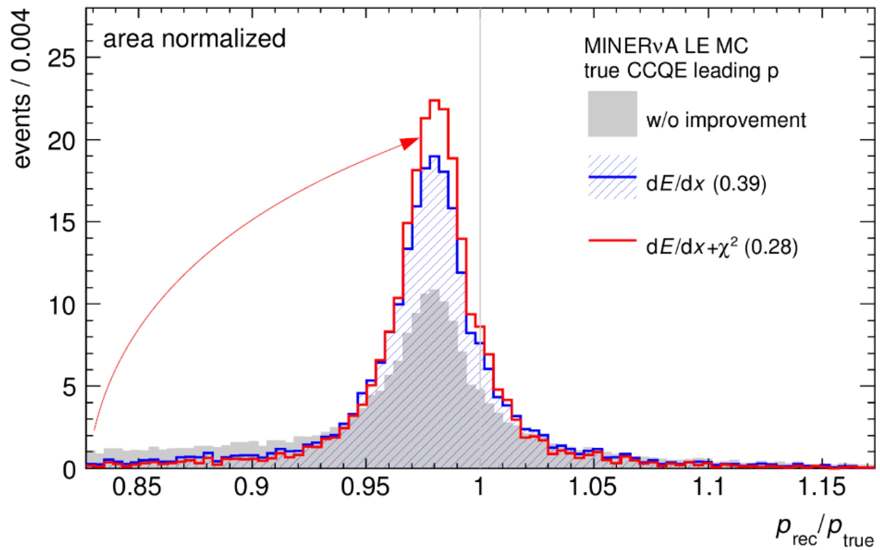
1) An overview of the MINERvA Low-Recoil Tune presented
   - Tune on neutrino data
   - Successful predictions for anti-neutrino data
   - Stay *tuned* for publication
2) Features of the tune
   - *2p2h-like enhancement* on Base Model cross section as function of (q0, q3)
   - Directly applicable from neutrino to anti-neutrino
3) Implications for T2K and NOvA
   - Non-negligible impact (extrapolated from $\langle E_\nu \rangle \sim 3$ GeV)
4) Theoretical implications
   - This tune is *empirical*. True identity still unclear
     - Impact from 1p1h+SRC
     - Constraint on structure functions
     - 2p2h model deficit or totally new mechanism?
5) Experimental implications
   - To unveil true nature of this enhancement, energy dependence needed
     - MINERvA ME low-recoil analyses → stay *tuned*
     - Other experiments could measure E_{av} or p_n at different energies
   - Extracting structure functions will become possible by combining different samples

BACKUP

ESC proton selection NEW

XL, Joint Experimental-Theoretical Physics Seminar
http://theory.fnal.gov/events/event/new-results-from-minerva/

[**NEW** Phys.Rev.Lett. 121 (2018) 022504]



*dE/dx+cleanup cut efficiency 30-40-20%@0.6-0.75-1 GeV/c

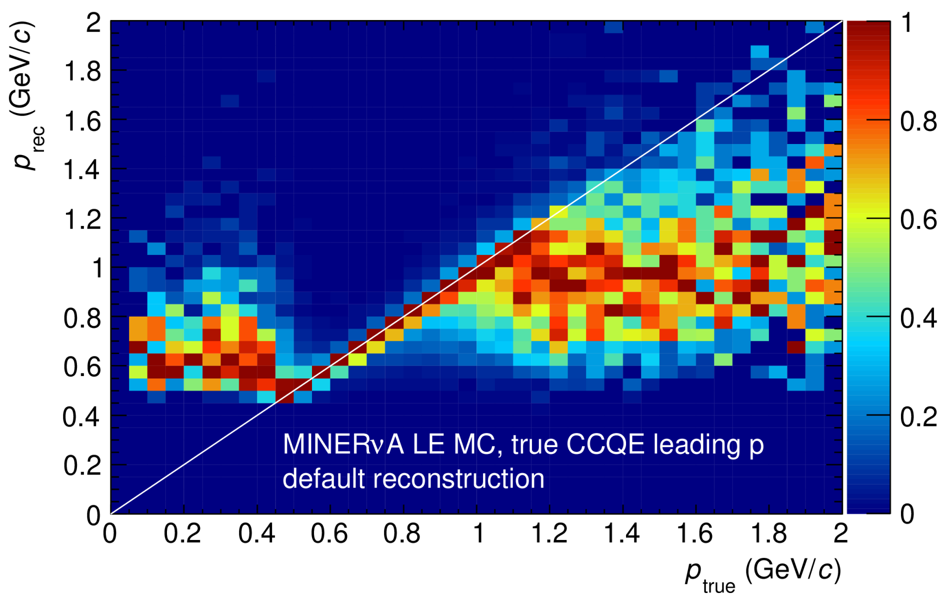
ESC proton selection:

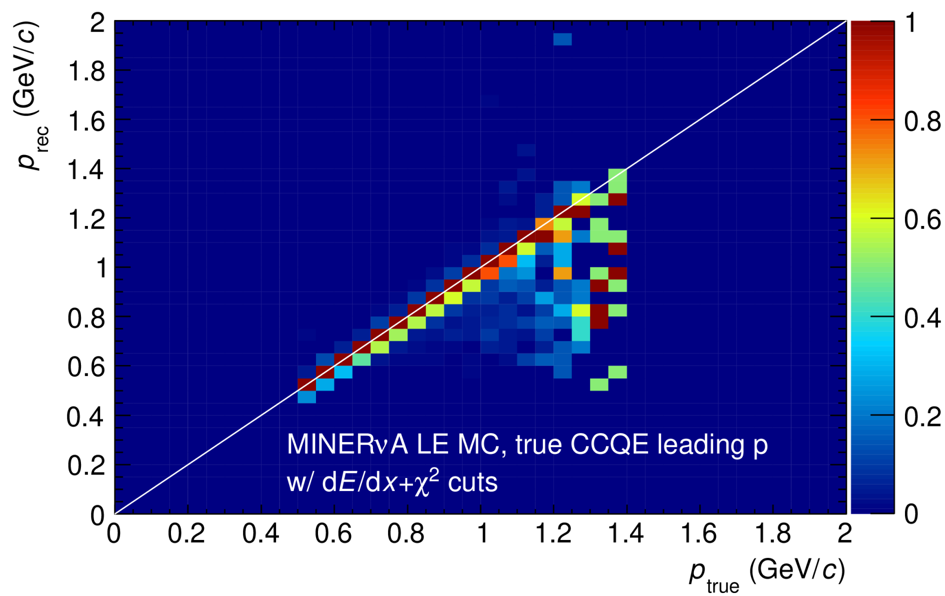
- Cut efficiency ~ 40%
- Reconstructed momentum spread much reduced @ 0.7 – 1.1 GeV, resolution 3% ~ 2%
- 5-10% uncertainty in efficiency

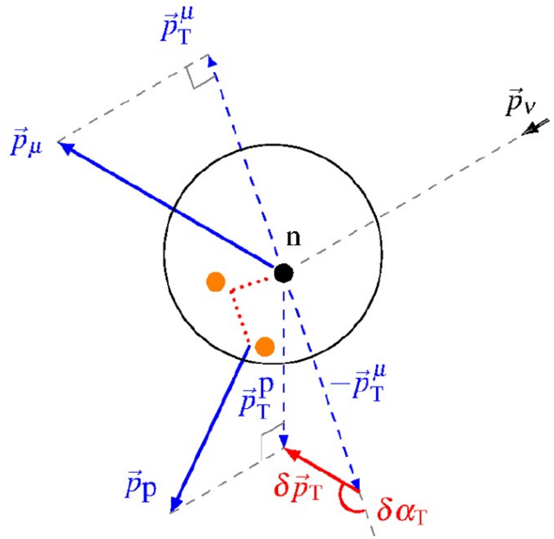
Clean-up cuts to improve proton and muon momentum resolution:

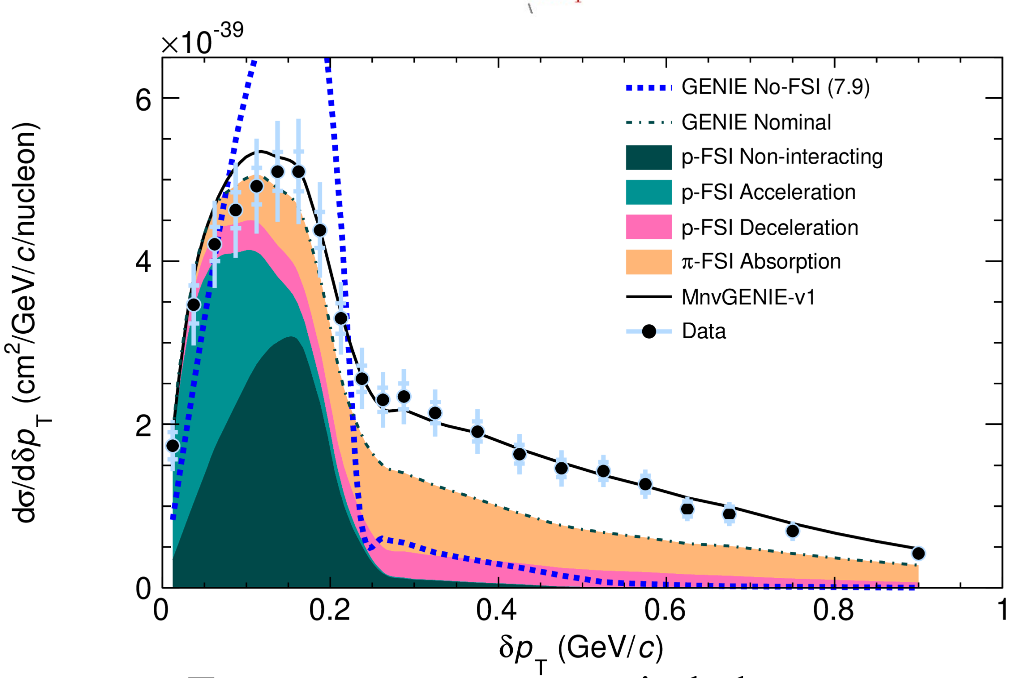
- proton dE/dx profile χ^2
- number of MINOS track nodes

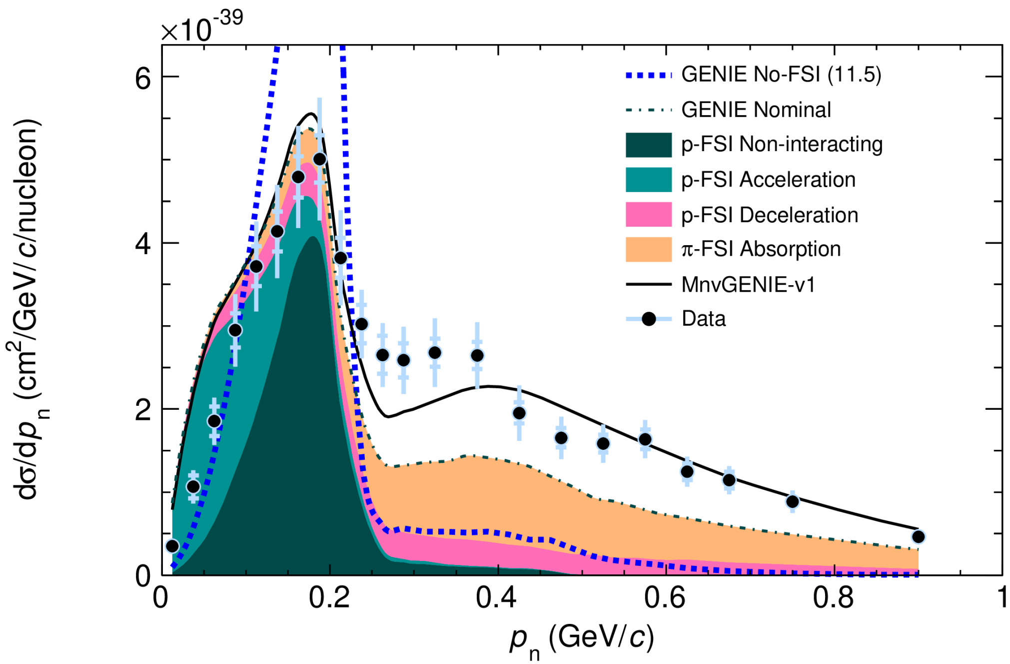
Also need to correct pT scales of both muon and protons.











Transverse momentum imbalance (missing pT) in CC0piNp sample

Upgraded with exclusivity constraint →

Initial neutron momentum

END