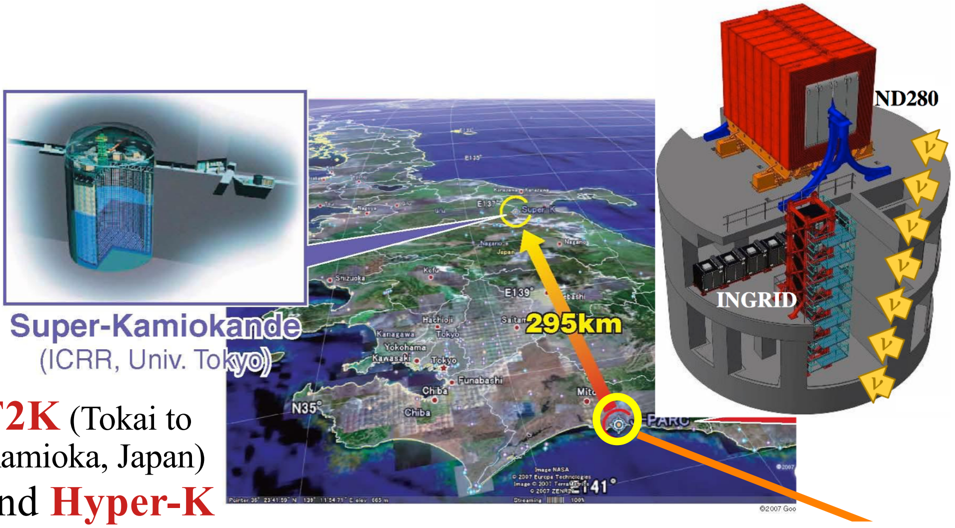
Neutrino Interaction Results from MINERvA

Kang Yang, University of Oxford
on behalf of the MINERvA Collaboration

The XIX International Workshop on Neutrino Telescope
19 February 2021

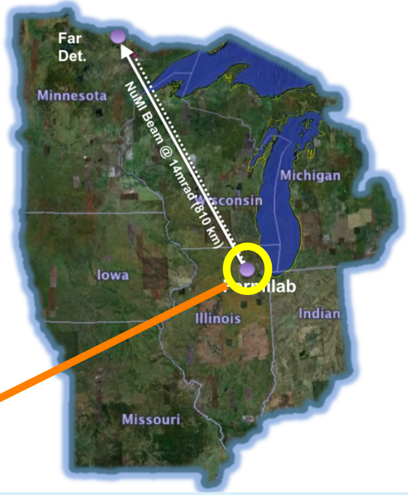
ν and $\bar{\nu}$ interactions @ near detectors

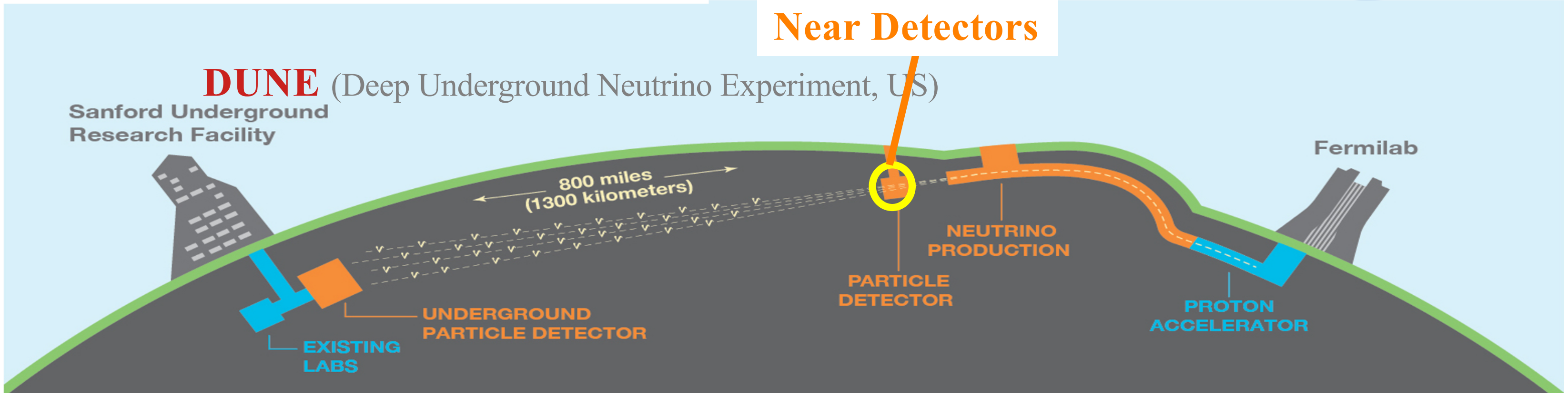
– Critical systematic constraints for oscillation measurements



T2K (Tokai to Kamioka, Japan) and **Hyper-K**

NOvA (NuMI Off-Axis ν_e Appearance, US)





Near Detectors

DUNE (Deep Underground Neutrino Experiment, US)

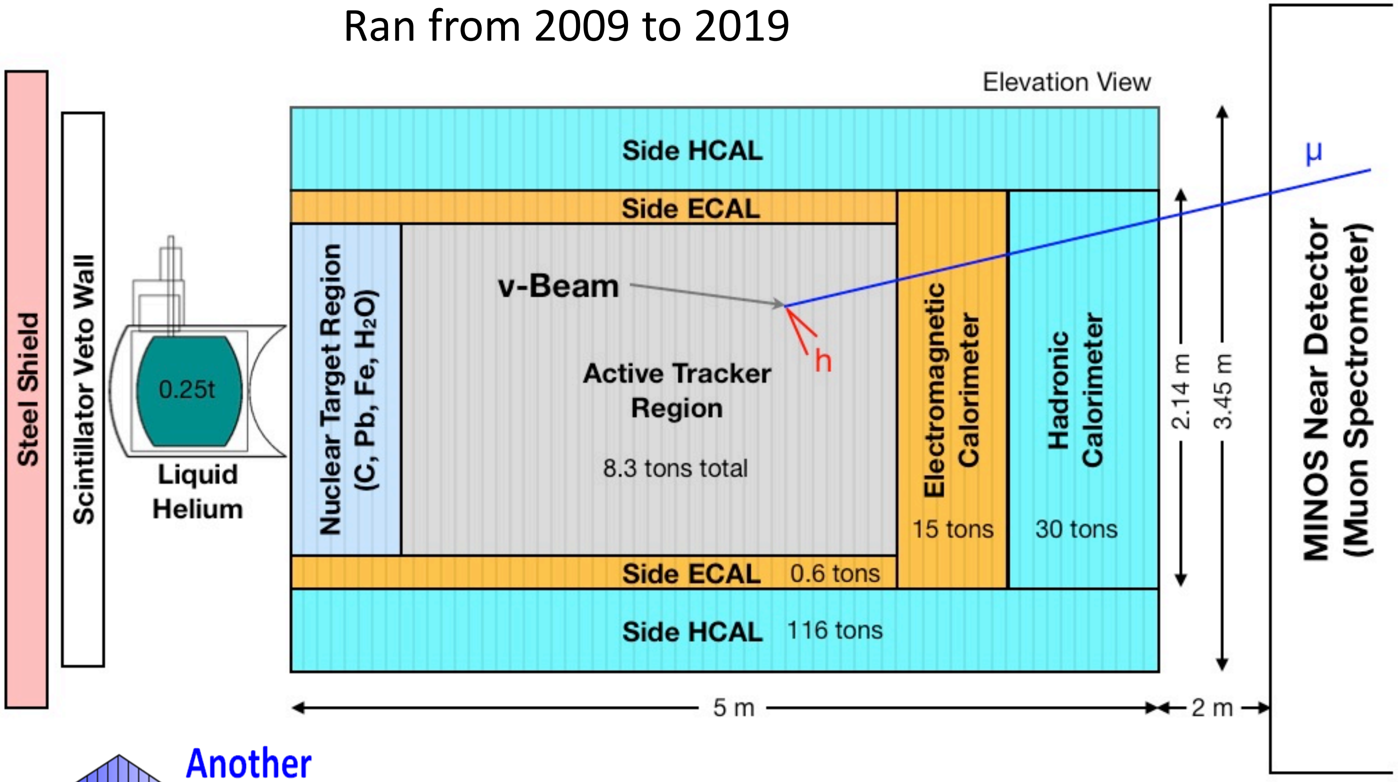
MINERvA A dedicated ν-interaction experiment with *high statistics*, *wide energy range*, *multi-neutrino flavors*, and *multi-nuclear targets*, capable of measuring *different final states*.

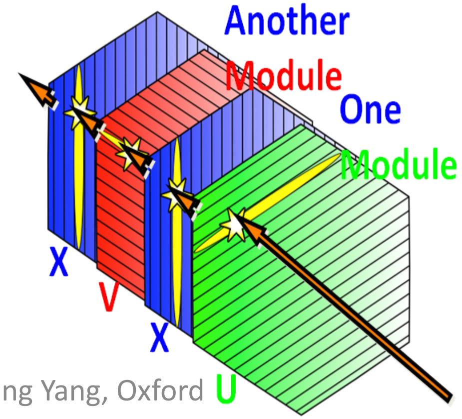
ν and $\bar{\nu}$ interactions @ dedicated experiment: MINERνA

– Constrain models used in oscillation measurements

MINERνA (Main Injector Experiment for ν-A, US)

Ran from 2009 to 2019

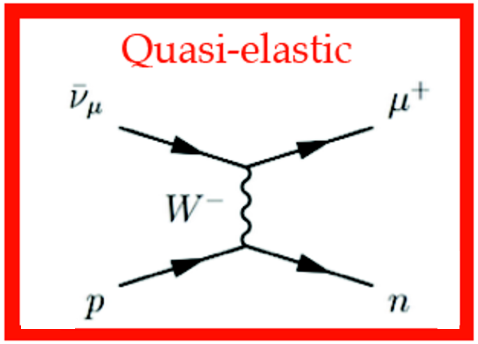




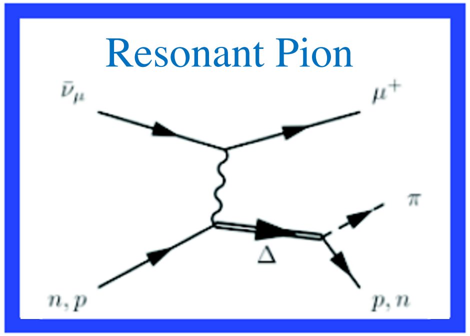
5.4 Ton Active scintillator target:
- Homogeneous non-magnetized tracker
- EM shower reconstruction

MINOS Near Detector:
- Muon spectrometer

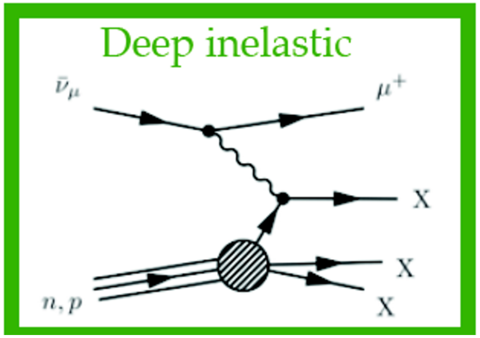
ν and $\bar{\nu}$ interactions @ MINERvA


Quasi-elastic

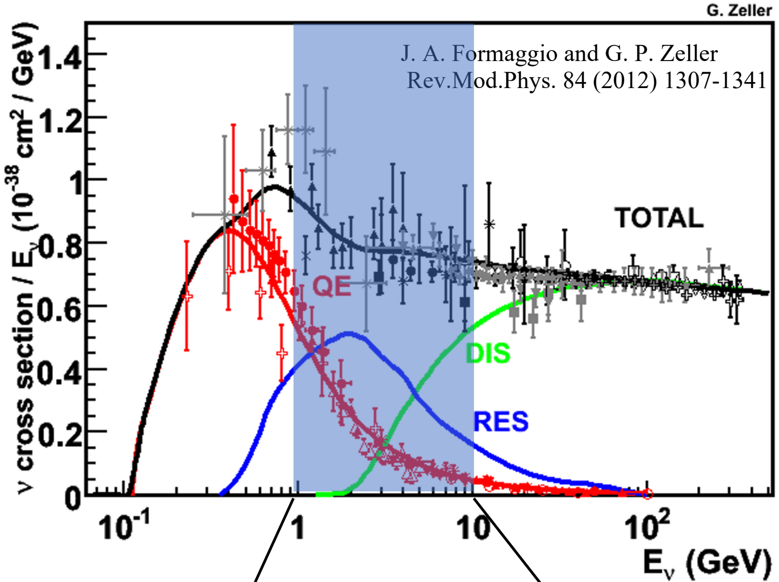
QE


Resonant Pion

RES

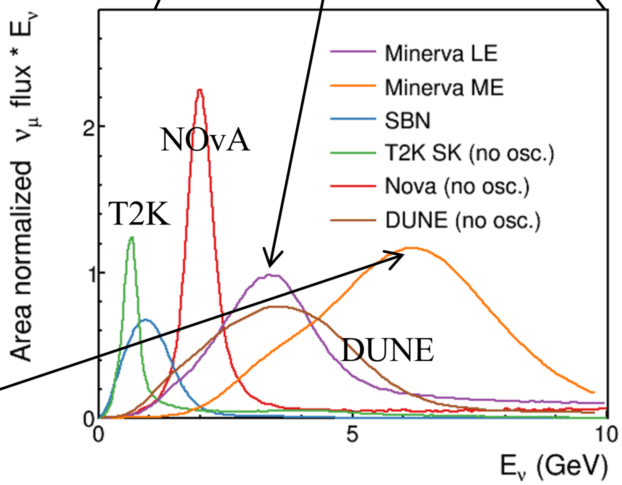

Deep inelastic

DIS



J. A. Formaggio and G. P. Zeller
Rev.Mod.Phys. 84 (2012) 1307-1341

NuMI Low-Energy beam $<E_\nu>$ ~ 3 GeV
(MINERvA LE)

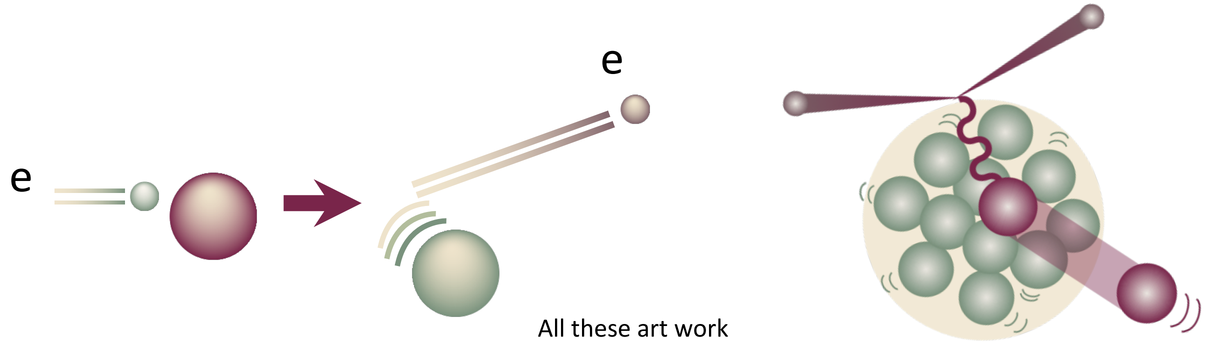


NuMI Medium-Energy beam $<E_\nu>$ ~ 6 GeV
(MINERvA ME)

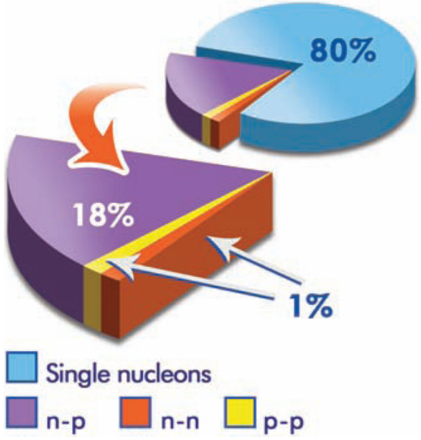
Intranuclear dynamics

e-A scattering

R. Subedi *et al.*, Science 320, 1476 (2008)



All these art work
© Bashyal, Patrick & Schellman



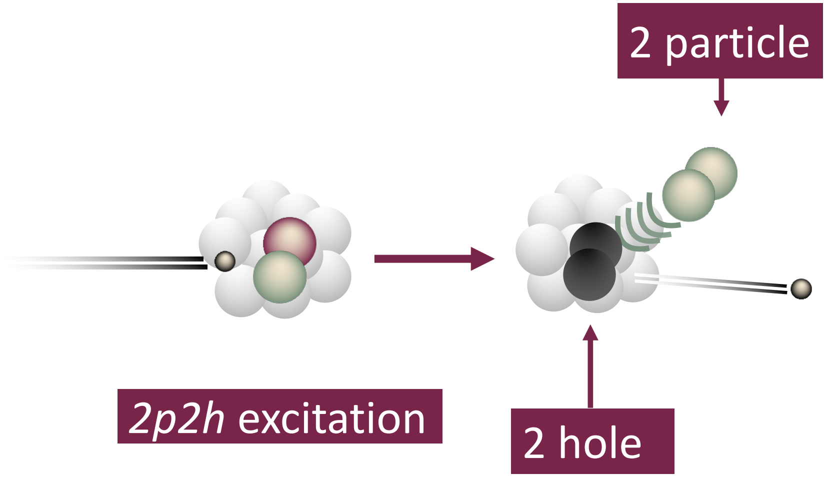
From electron-nucleus scattering

☐ Fermi motion

☐ FSI breaking up nucleus

☐ *2p2h* excitation

All exist in neutrino-nucleus scattering

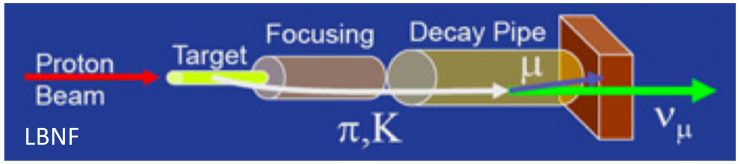


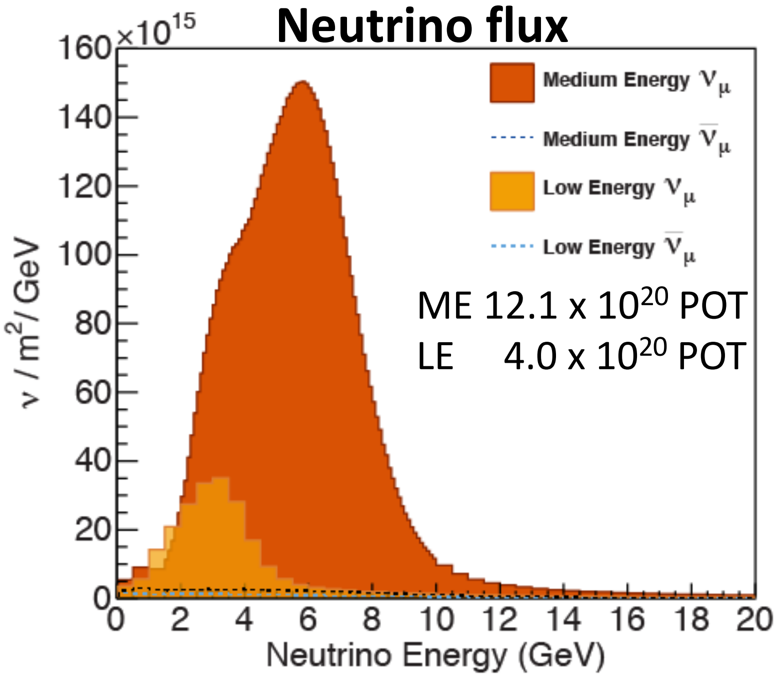
Low Energy & Medium Energy NuMI beam

Data accumulated by proton-on-target (**POT**)

LE: Low Energy, MINOS-era, peak at 3 GeV

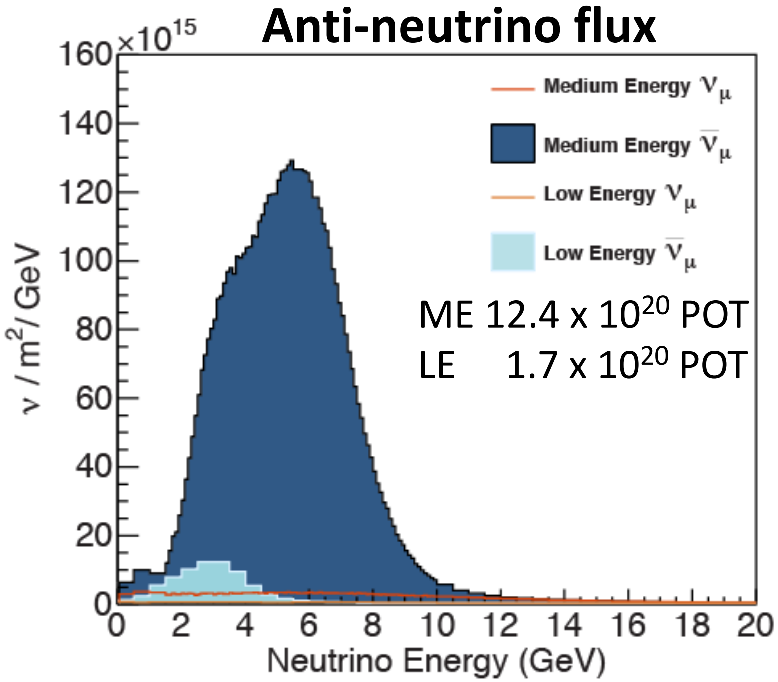
ME: Medium Energy, NOvA-era, peak at 6 GeV




Neutrino flux

ME 12.1 x 10^{20} POT

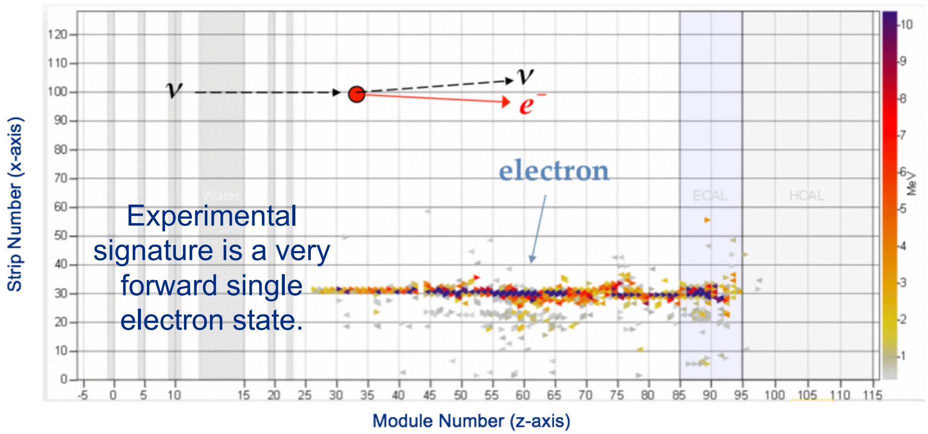
LE 4.0 x 10^{20} POT

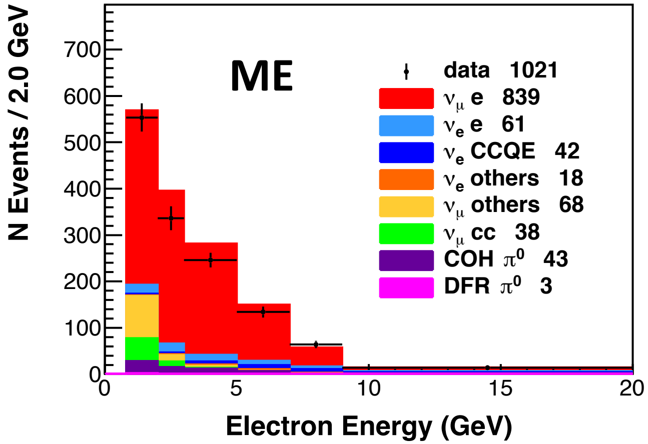

Anti-neutrino flux

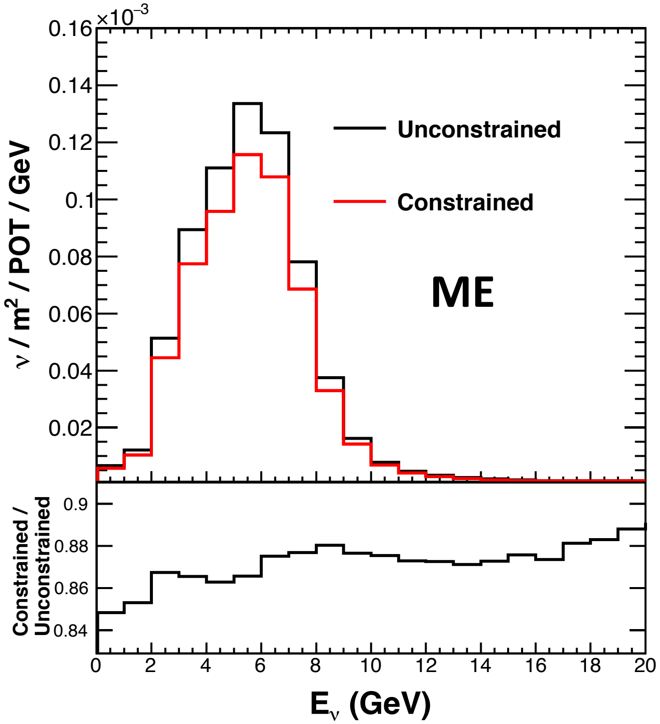
ME 12.4 x 10^{20} POT

LE 1.7 x 10^{20} POT

Neutrino-Electron Elastic Scattering [**LE**: Phys. Rev. D93, 112007 (2016); **ME**: Phys. Rev. D 100, 092001 (2019)]

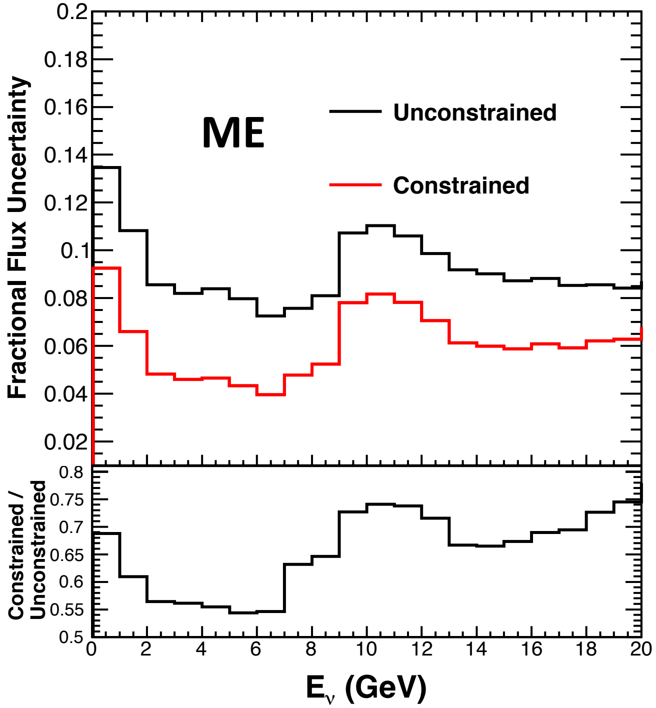






ME ν_μ flux Unconstrained: prediction from GEANT4+hadron production data

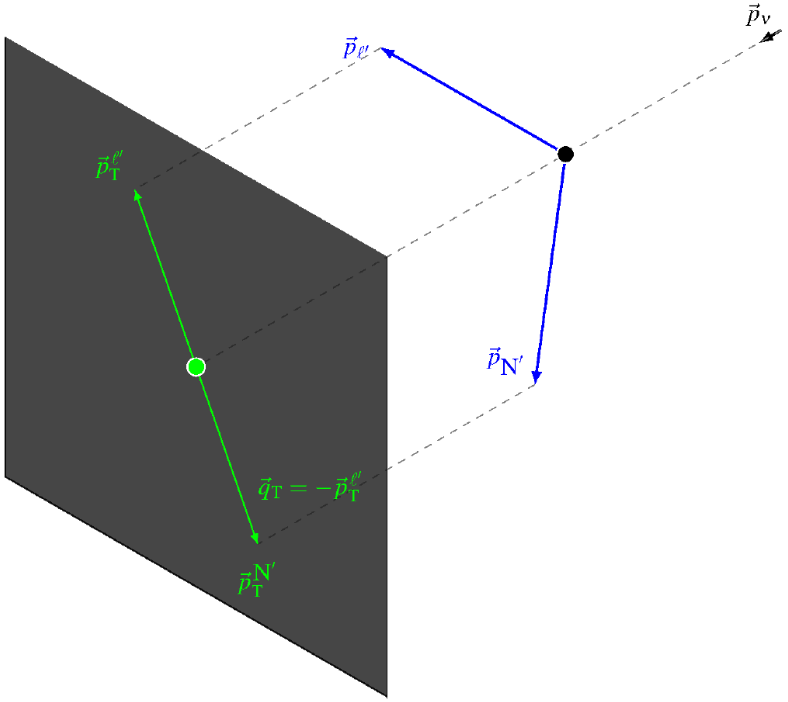
- ❑ reduced by ~ 10% after constraint
- ❑ uncertainty near the peak is reduced from 7.6% to 3.9%



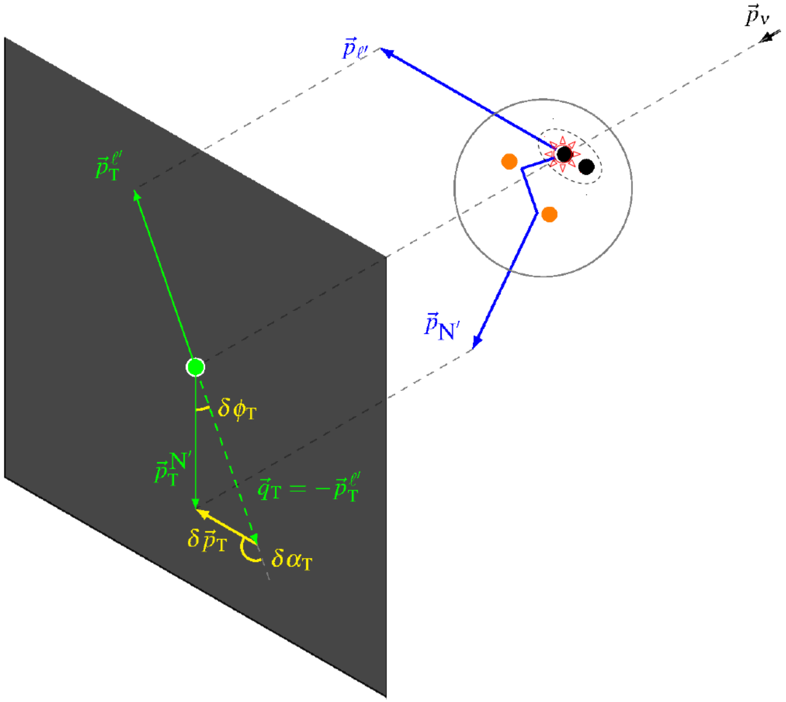
Transverse Kinematic Imbalance (TKI)

Lu *et al.*, Phys.Rev.D 92, 051302 (2015), Lu *et al.*, Phys.Rev.C 94, 015503 (2016)

– Precisely identify intranuclear dynamics and the absence thereof



Stationary nucleon target



Nuclear target
(A>1)

Fermi motion
Final-state interactions
Pion absorption
2p2h
…

Emulated Nucleon Momentum p_N

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

[Furmanski & Sobczyk, Phys. Rev.C 95, 065501 (2017)]

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

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

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

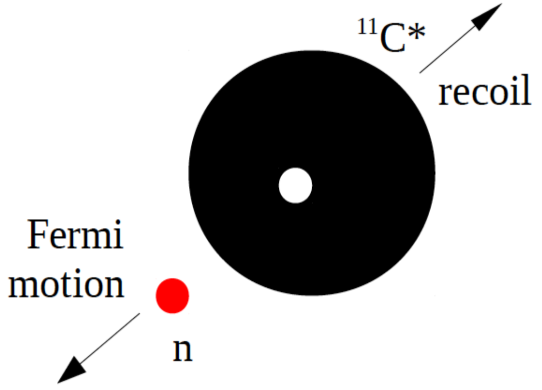
p_n: recoil momentum of the nuclear remnant

final-state

Dual Interpretation

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

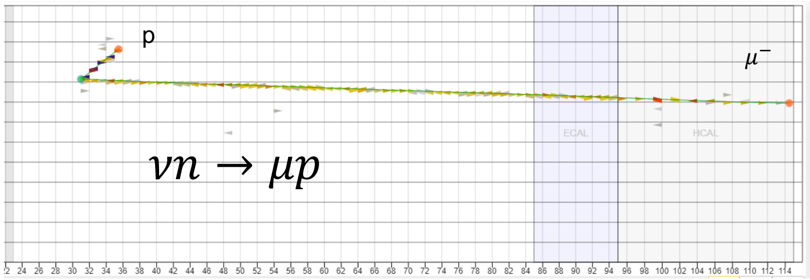
initial-state

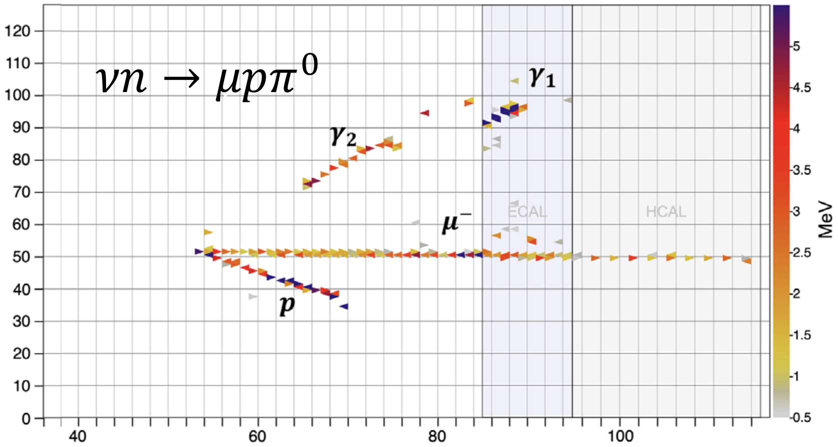


δp_T is promoted to p_N by ~ 10% correction

$$p_\mathrm{N} \sim [1 + O(10\%)] \times \delta p_\mathrm{T}$$

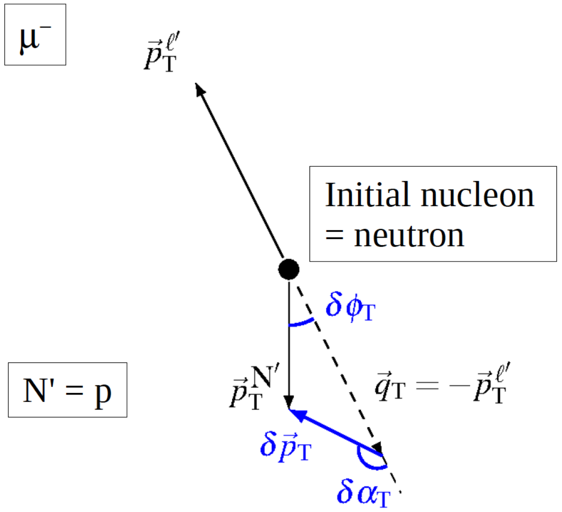
TKI in CCQE-like & CCπ^0 [LE: Phys.Rev.Lett. 121, 022504 (2018), Phys. Rev. D 102, 072007 (2020)]





$\nu\ n \rightarrow \mu^-\ p$

$\nu\ n \rightarrow \mu^-\ p\ \pi^0$

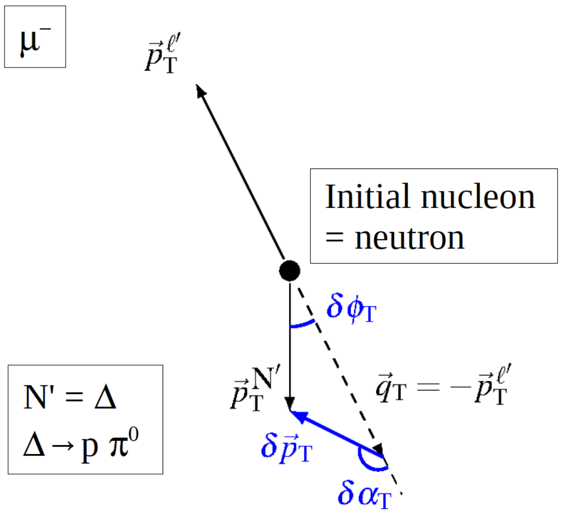


μ^-

Initial nucleon = neutron

N' = p

via QE-like measurement



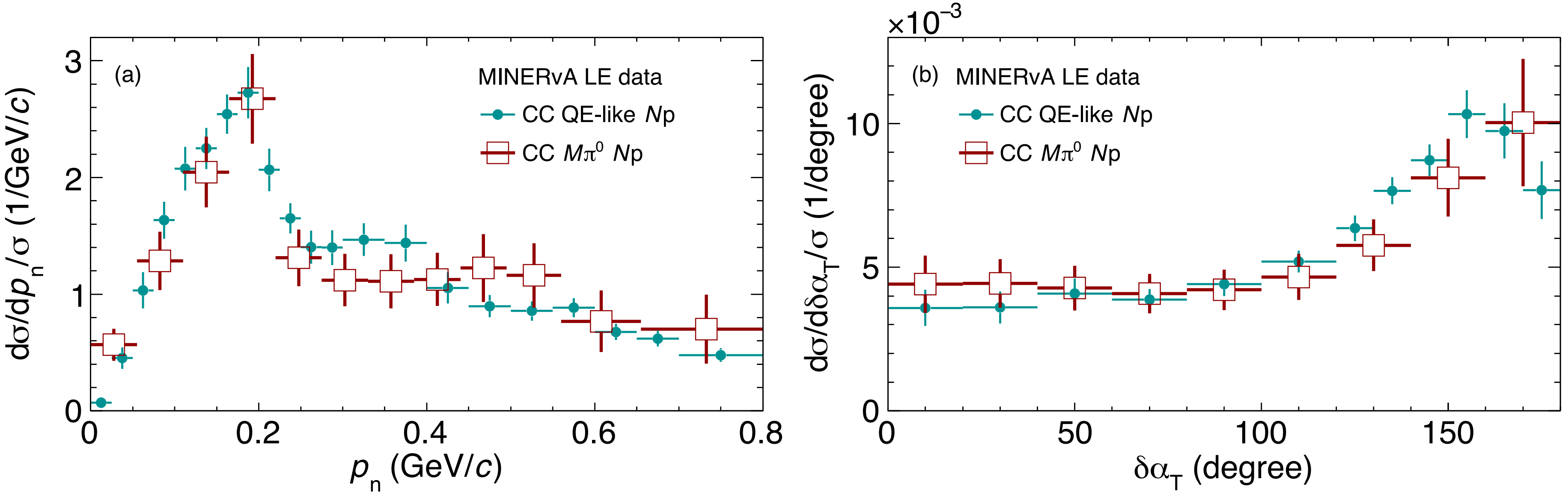
μ^-

Initial nucleon = neutron

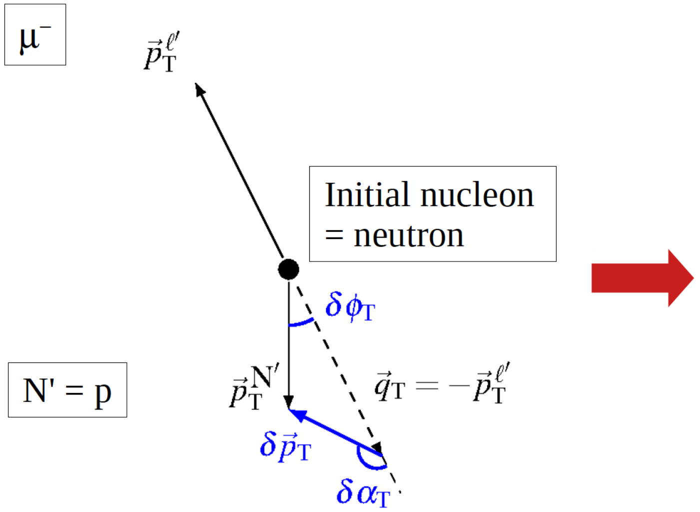
N' = Δ
$\Delta \rightarrow p\ \pi^0$

via inclusive π^0 production

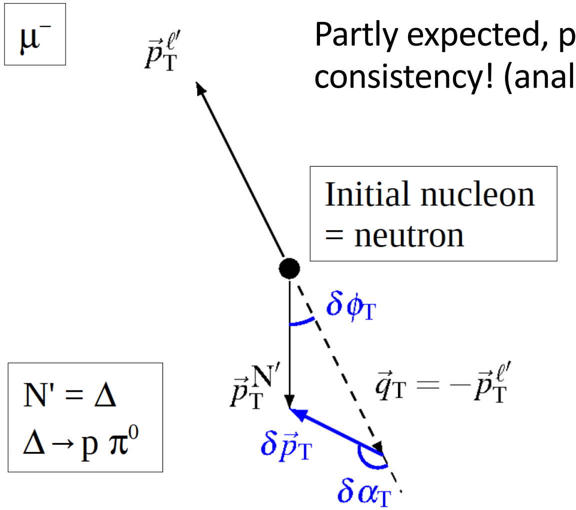
TKI in CCQE-like & CCπ^0 [LE: Phys.Rev.Lett. 121, 022504 (2018), Phys. Rev. D 102, 072007 (2020)]



Partly expected, partly very surprising consistency! (analysis in BACKUP)



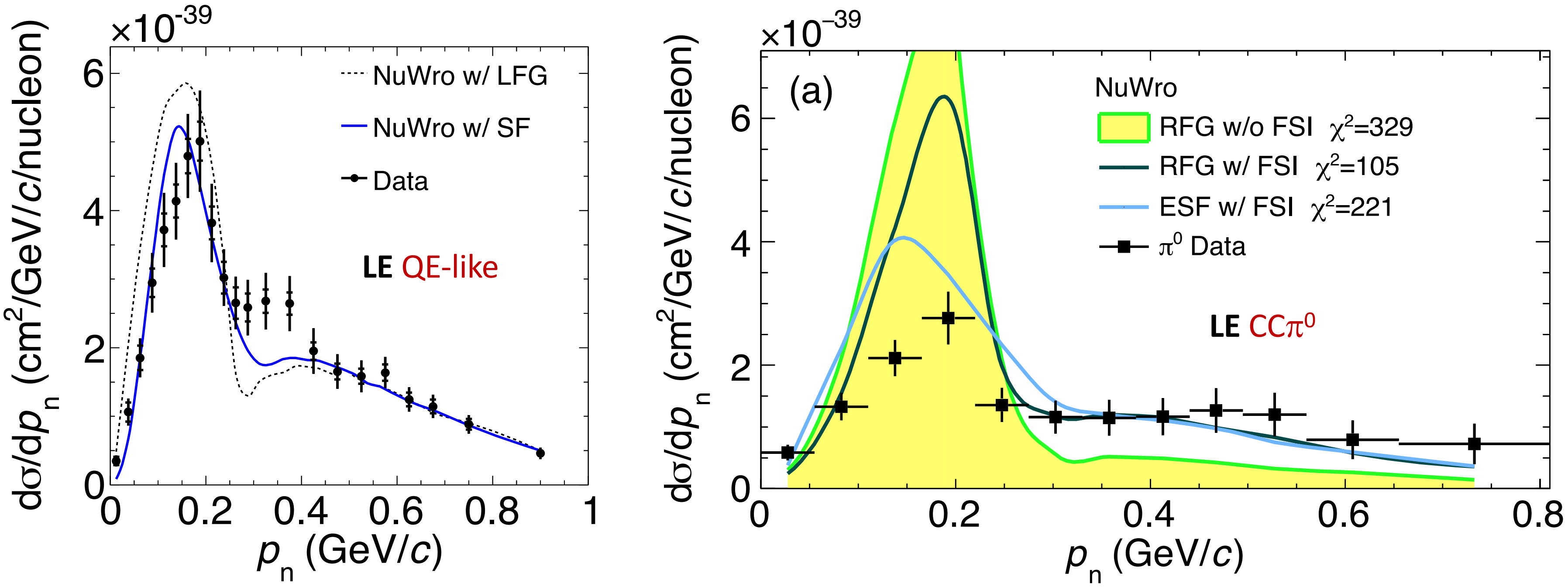
via QE-like measurement



via inclusive π^0 production

TKI—Initial-state effects

[LE: Phys.Rev.Lett. 121, 022504 (2018), Phys. Rev. D 102, 072007 (2020)]



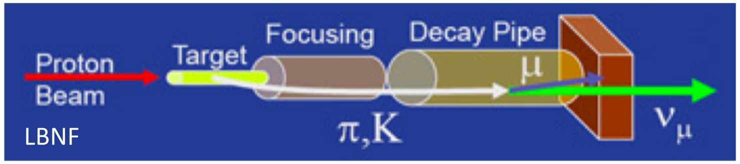
Initial-state models:

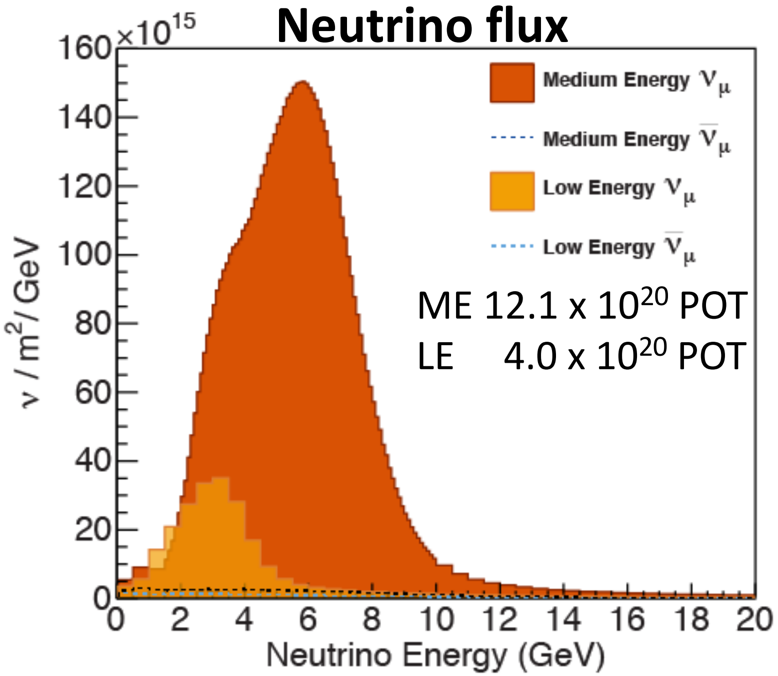
- ❑ **Relativistic Fermi gas (RFG)**—simple Fermi gas model
- ❑ **Local Fermi gas (LFG)**—Fermi motion sampling depends on nucleon location (local density)
- ❑ **Spectral function (SF)** and **effective spectral function (ESF)**—Fermi motion and removal energy sampling, short range correlation (SRC) leading to momentum exceeding Fermi surface
  - ❖ Decent agreement for $\nu n \rightarrow \mu p$, but *not* for $\nu n \rightarrow \mu p \pi^0$

Low Energy & Medium Energy NuMI beam

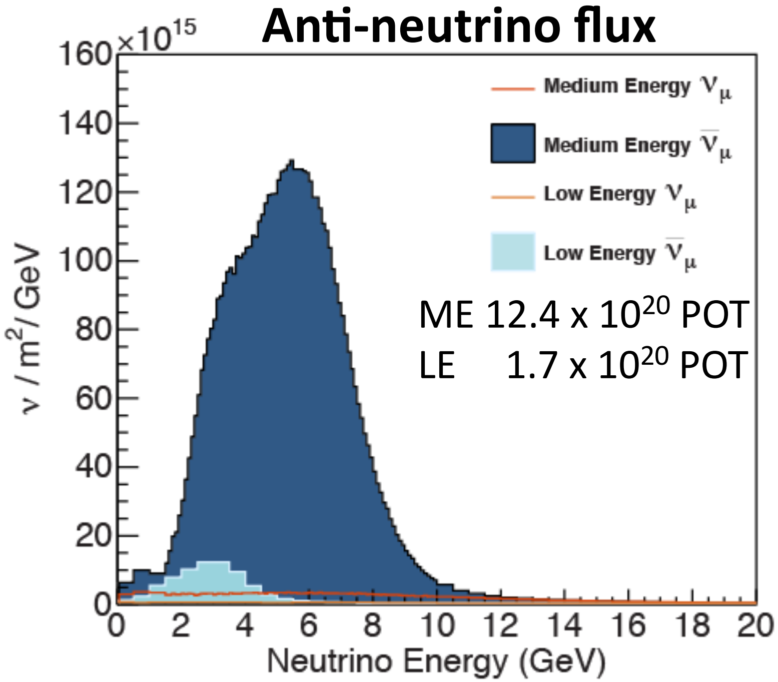
Recap

Data accumulated by proton-on-target (**POT**)
LE: Low Energy, MINOS-era, peak at 3 GeV
ME: Medium Energy, NOvA-era, peak at 6 GeV




Neutrino flux

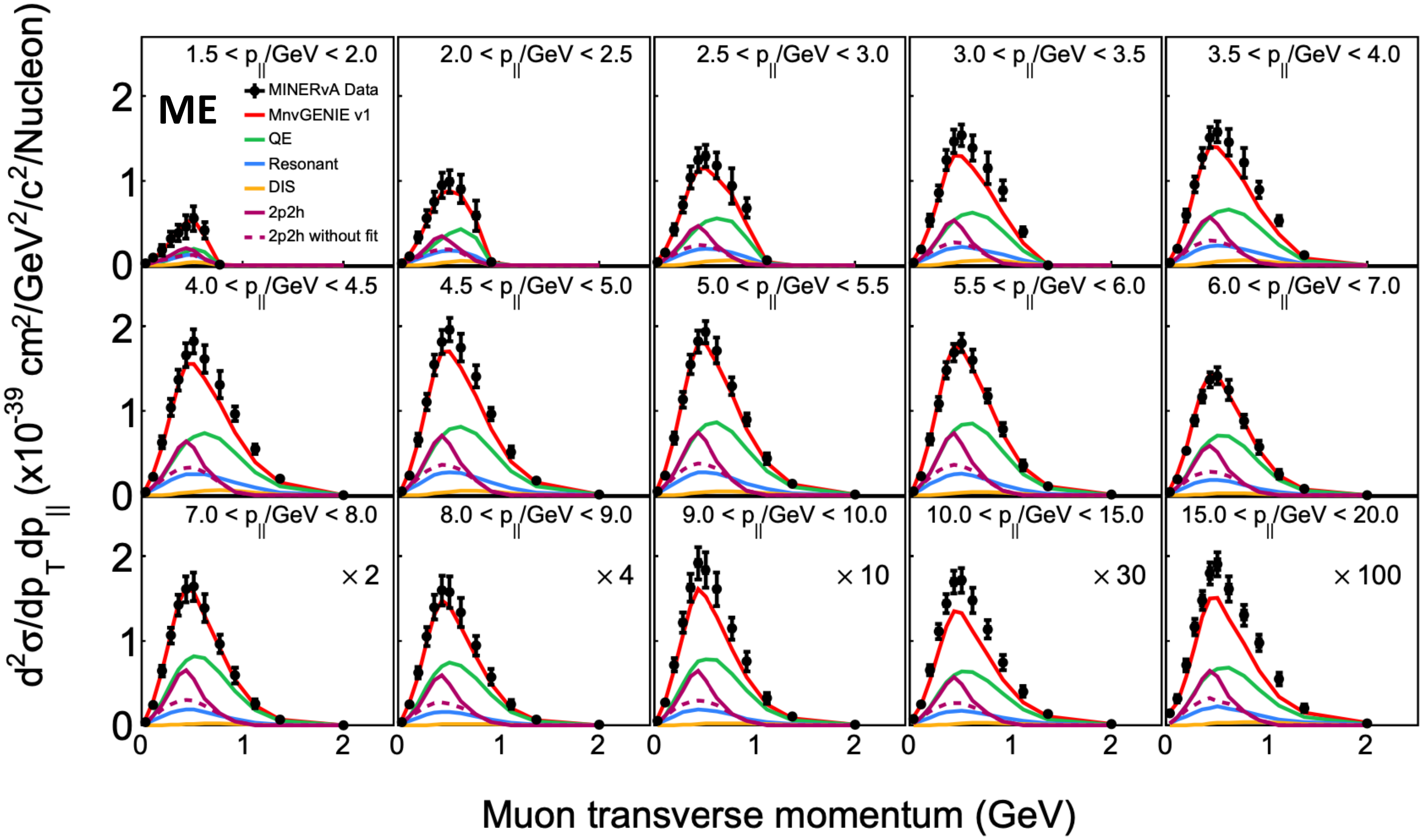
ME 12.1 x 10^{20} POT
LE 4.0 x 10^{20} POT


Anti-neutrino flux

ME 12.4 x 10^{20} POT
LE 1.7 x 10^{20} POT

Physics Reach with ME Data [**ME**: Phys. Rev. Lett. 124, 121801

- ☐ ν_μ CCQE-like events with forward muon ($\theta_\mu < 20°$)
- ☐ Model is MINERvA house-pretuned GENIE (MnvGENIE-v1, detail in BACKUP)

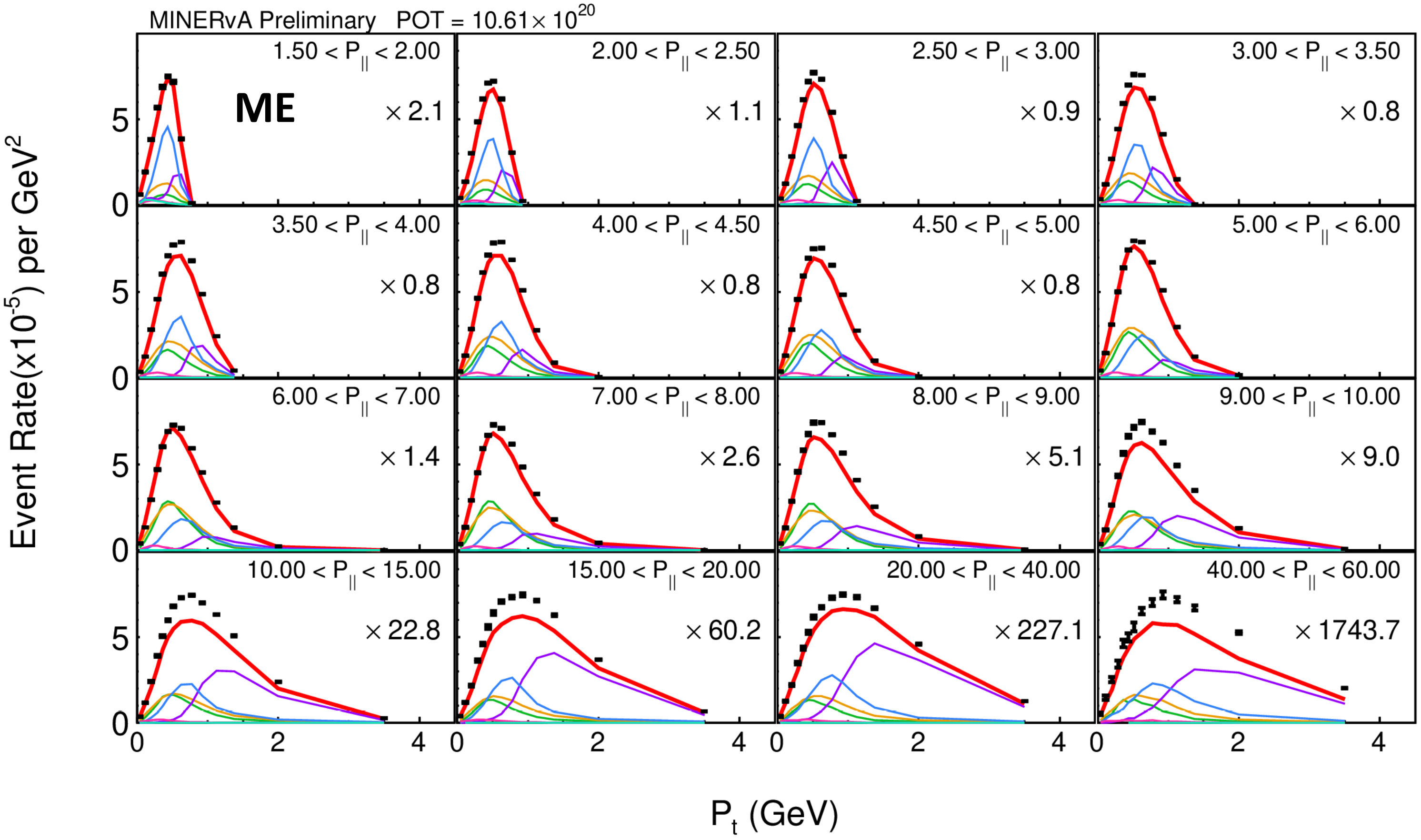


- ❖ QE and 2p2h are the dominant channels.
- ❖ Discrepancies are apparent between $3.0 < p_{||} < 5.0$ GeV above the spectral peak
- ❖ Underprediction of events rate resumes dramatically at $p_{||} > 9.0$ GeV.

Physics Reach with ME Data [Preview]

- ☐ ν_μ CC inclusive events
  - ✓ Muon $p_t \sim Q^2$
  - ✓ Muon $p_{||} \sim$ neutrino energy

True DIS:
W > 2.0 GeV and
a $Q^2 > 1.0\ GeV^2$



- ❖ Soft DIS is dominated at low $p_{||}$
- ❖ Low Q^2 channels (QE/2p2h/RES) start to merge at low p_T
- ❖ Large model deficit is seen for $p_{||}$ > 9 GeV

Summary

- ☐ MINERvA
  - 5.4 t scintillator tracker + calorimeter + magnetized muon spectrometer
  - Cross section and TKI measurements with lower flux uncertainties and high statistics

- ☐ LE program was completed, ME analyses in pipeline with more than 10 times statistics, reaching neutrino energy beyond 50 GeV
  - Nuclear dependence using nuclear targets (Pb, Fe, H_2O, He)
  - Detect neutrons
  - 3D differential cross section measurements and High W events

[see references next slide]

- ☐ Data preservation – long term program
  - Preserve the collected data for publicly use even beyond the end of MINERvA collaboration
  - Provide the "MINERvA Analysis Toolkit" that allow new analysers to reproduce MINERvA published results and perform new analyses.

Recent MINERνA Papers

A. Filkins *et al.* , “Double-differential inclusive charged-current ν_{μ} cross sections on hydrocarbon in MINERvA at E_{ν} ~ 3.5 GeV,” Phys. Rev. D **101**, no.11, 112007(2020)

D. Coplowe et al. , “Probing nuclear effects with neutrino-induced charged-current neutral pion production,” Phys.Rev.D 102 (2020) 7, 072007

M. F. Carneiro *et al.* , “High-Statistics Measurement of Neutrino Quasielasticlike Scattering at 6 GeV on a Hydrocarbon Target,” Phys. Rev. Lett. **124**, no.12, 121801 (2020)

T. Cai *et al.* , “Nuclear binding energy and transverse momentum imbalance in neutrino-nucleus reactions,” Phys. Rev. D **101**, no.9, 092001 (2020)

E. Valencia *et al.* , “Constraint of the MINERνA medium energy neutrino flux using neutrino-electron elastic scattering,” Phys. Rev. D **100**, no.9, 092001 (2019)

T. Le *et al.* , “Measurement of $\bar{\nu}_{\mu}$ Charged-Current Single π^{-} Production on Hydrocarbon in the Few-GeV Region using MINERvA,” Phys. Rev. D **100**, no.5, 052008 (2019)

P. Stowell *et al.* , “Tuning the GENIE Pion Production Model with MINERνA Data,” Phys. Rev. D **100**, no.7, 072005 (2019)

M. Elkins *et al.* , “Neutron measurements from antineutrino hydrocarbon reactions,” Phys. Rev. D **100**, no.5, 052002 (2019)

D. Ruterbories *et al.* , “Measurement of Quasielastic-Like Neutrino Scattering at $< E_{\nu} >$ 3.5 GeV on a Hydrocarbon Target,” Phys. Rev. D **99**, no.1, 012004 (2019)

G. N. Perdue *et al.* , “Reducing model bias in a deep learning classifier using domain adversarial neural networks in the MINERvA experiment,” JINST **13**, no.11, P11020 (2018)

X. G. Lu *et al.* , “Measurement of final-state correlations in neutrino muon-proton mesonless production on hydrocarbon at $<E_{\nu}>$ = 3 GeV,” Phys. Rev. Lett. **121**, no.2, 022504 (2018)

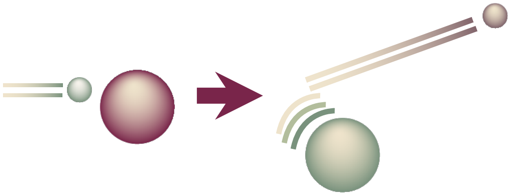
R. Gran *et al.* , “Antineutrino Charged-Current Reactions on Hydrocarbon with Low Momentum Transfer,” Phys. Rev. Lett. **120**, no.22, 221805 (2018)

C. E. Patrick *et al.* , “Measurement of the Muon Antineutrino Double- Differential Cross Section for Quasielastic-like Scattering on Hydrocarbon at $E_{\nu} \sim$ 3.5GeV,” Phys. Rev. D **97**, no.5, 052002 (2018)

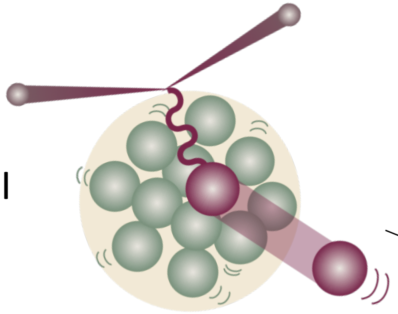
BACKUP

Intranuclear dynamics

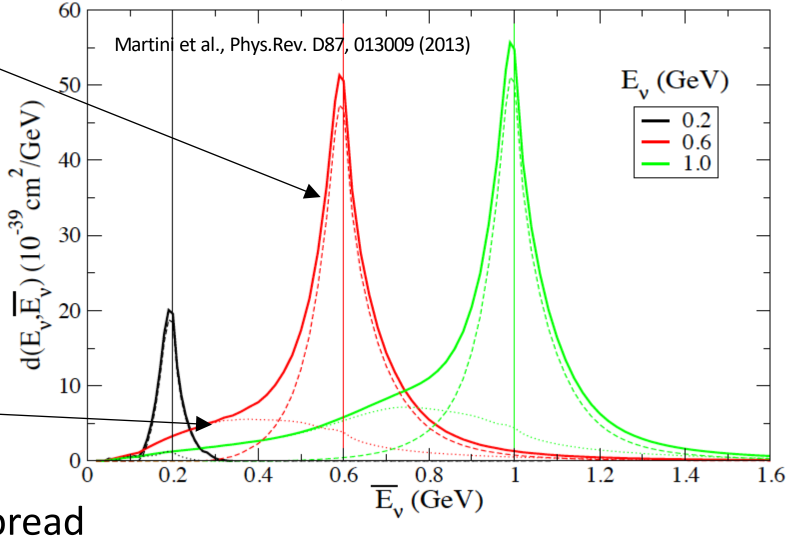
How well can we measure neutrino energy?
(reminder: oscillation very sensitive to energy and baseline, *L/E*)



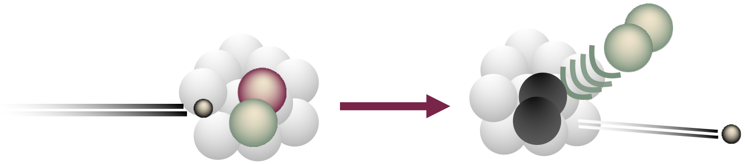
2-body reaction
—precise



Fermi motion, FSI
—spread

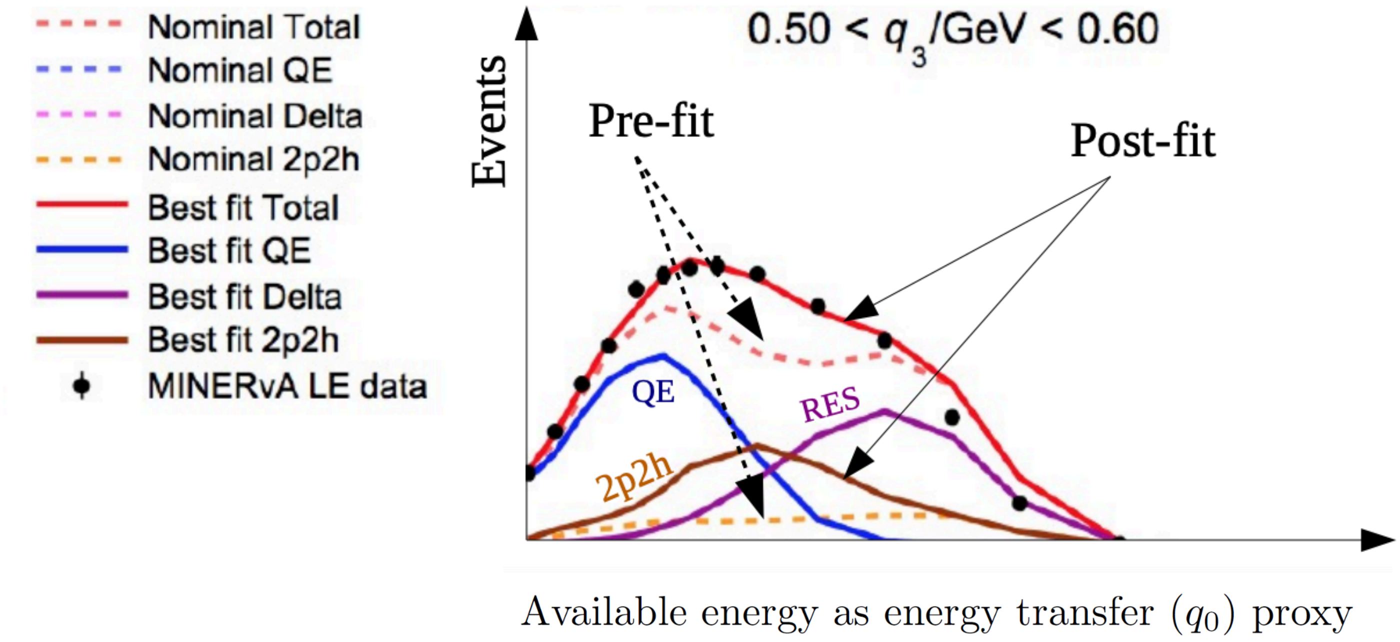


Martini et al., Phys.Rev. D87, 013009 (2013)



2p2h
—large (not well known) fraction of large bias and spread

MINERvA: 2p2h-like enhancement



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

"Low-recoil" fit:

– Enhance Valencia* 2p2h cross section as a function of (q0, q3)

- Enhanced by 50% overall, by up to 200% in dip region
- Fit to neutrino; prediction for antineutrino

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

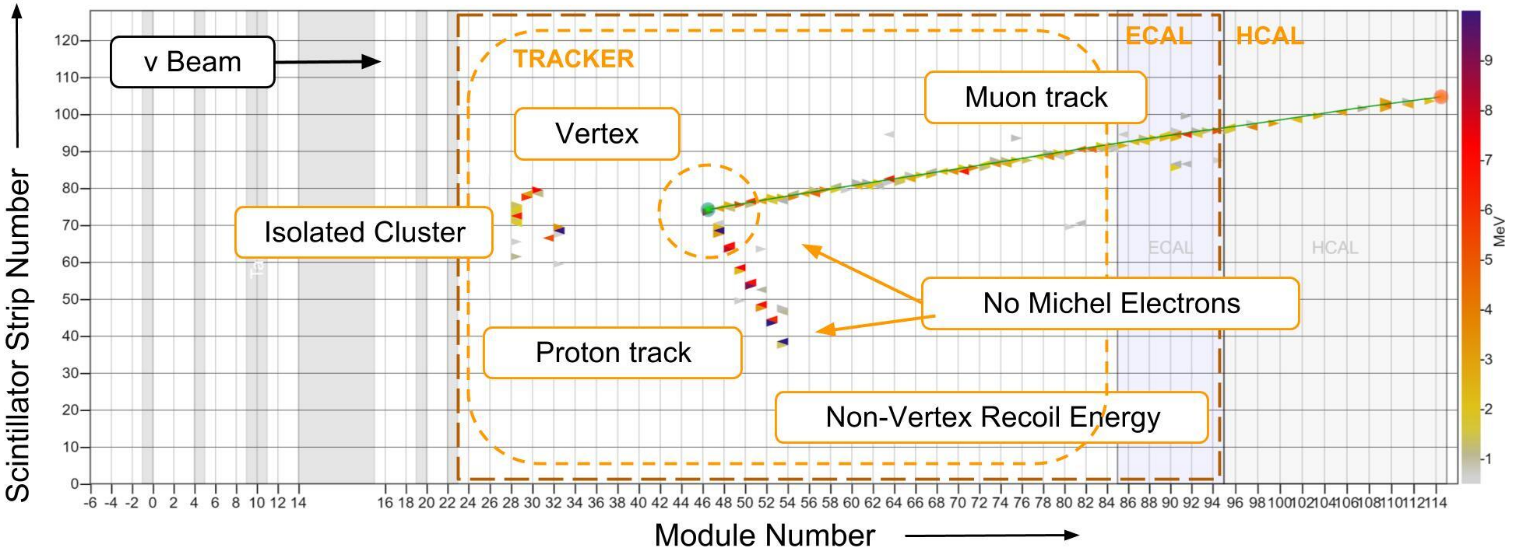
*Phys.Lett. B707, 72 (2012)
Phys. Rev. C 86, 015504 (2012)
Phys.Rev. D88, 113007 (2013)
arXiv:1601.02038

CCQE like measurements @ MINERvA

Muons tracked and momentum analyzed
Protons > 100 MeV KE can be tracked

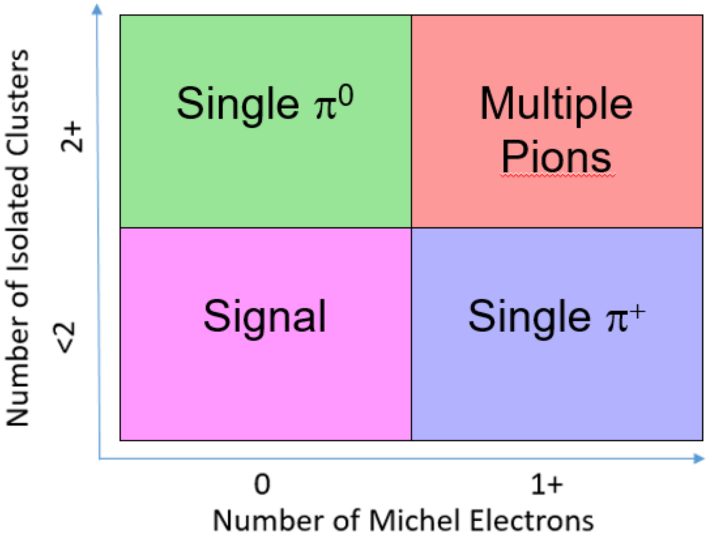
$$\nu_\mu + n \rightarrow \mu^- + p$$

Signal: $1\mu^- Np\ (N \geq 0)$



The main background is π from resonances and FSI faking protons

- Identify π^+ by Michel electron
- π^0 decay showers
- Multiple charged tracks



Single π^0

Multiple Pions

Signal

Single π^+

Number of Isolated Clusters

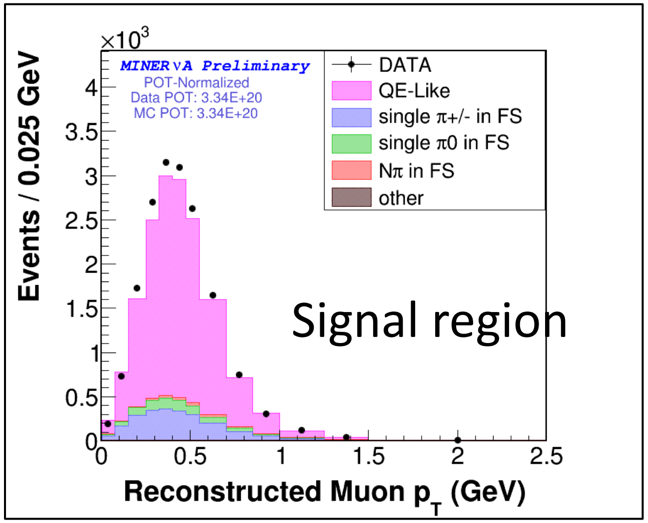
2+

<2

0

1+

Number of Michel Electrons



Signal region

Scaling Factors as Function of p_T:

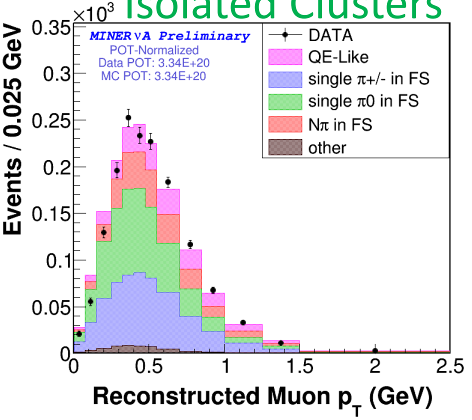
π^0,

$\pi^{+/-}$,

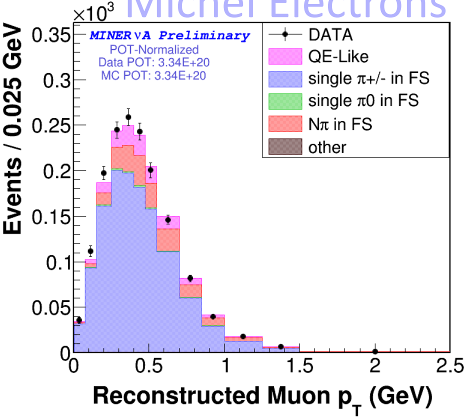
$N\pi$

Fit 3 scaling factors

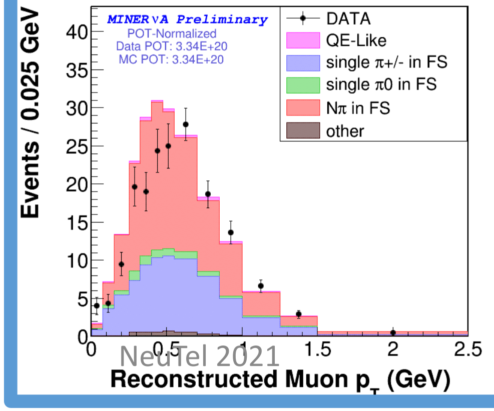
Isolated Clusters



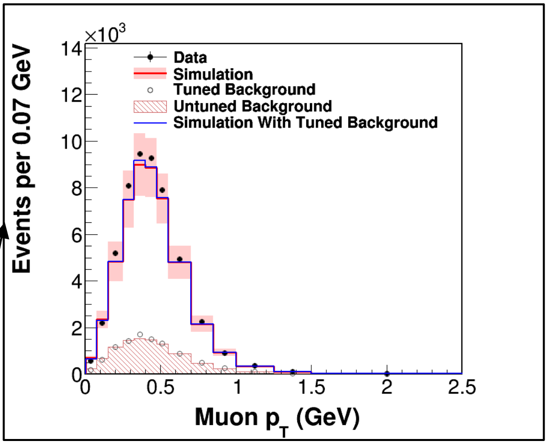
Michel Electrons

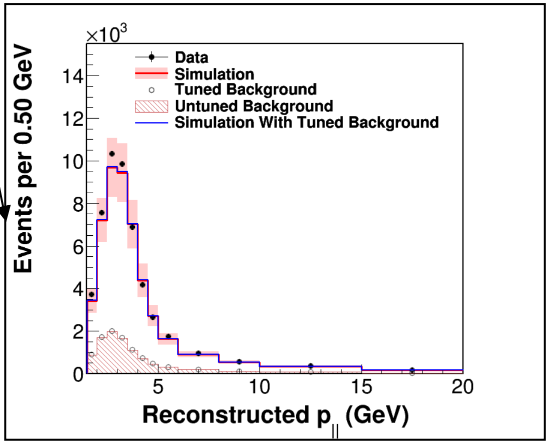


Michel + Iso. Clusters



Estimate background





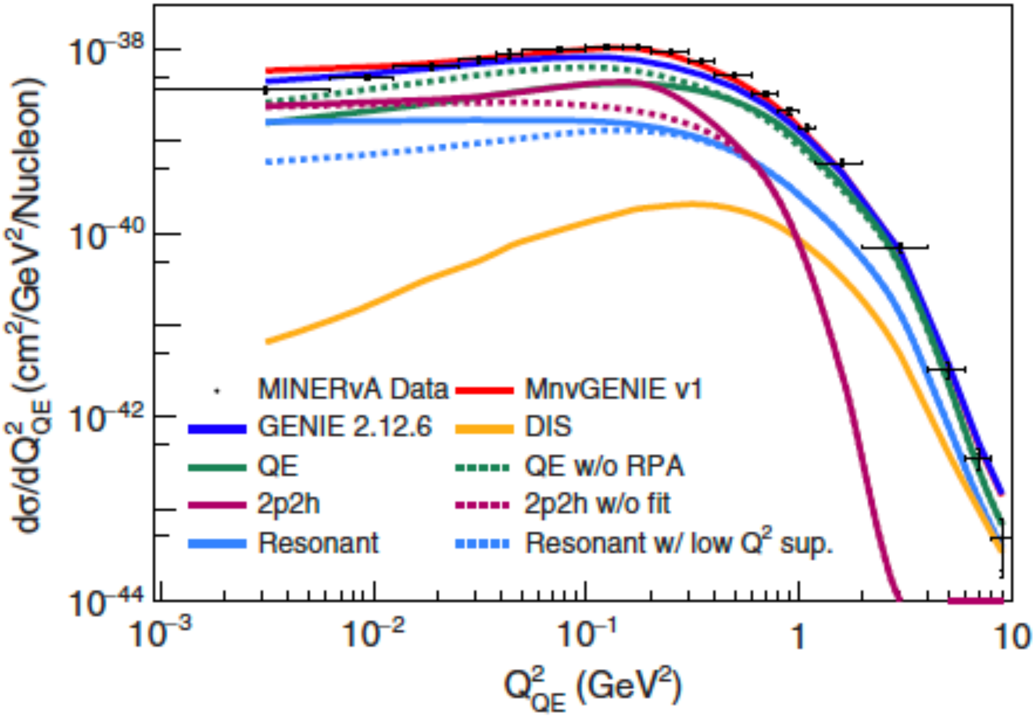
Can we model this?

- Default GENIE 2.12.6
  - (Relativistic Fermi Gas)

- Add in Random Phase Approximation (RPA) to account for screening at low Q^2

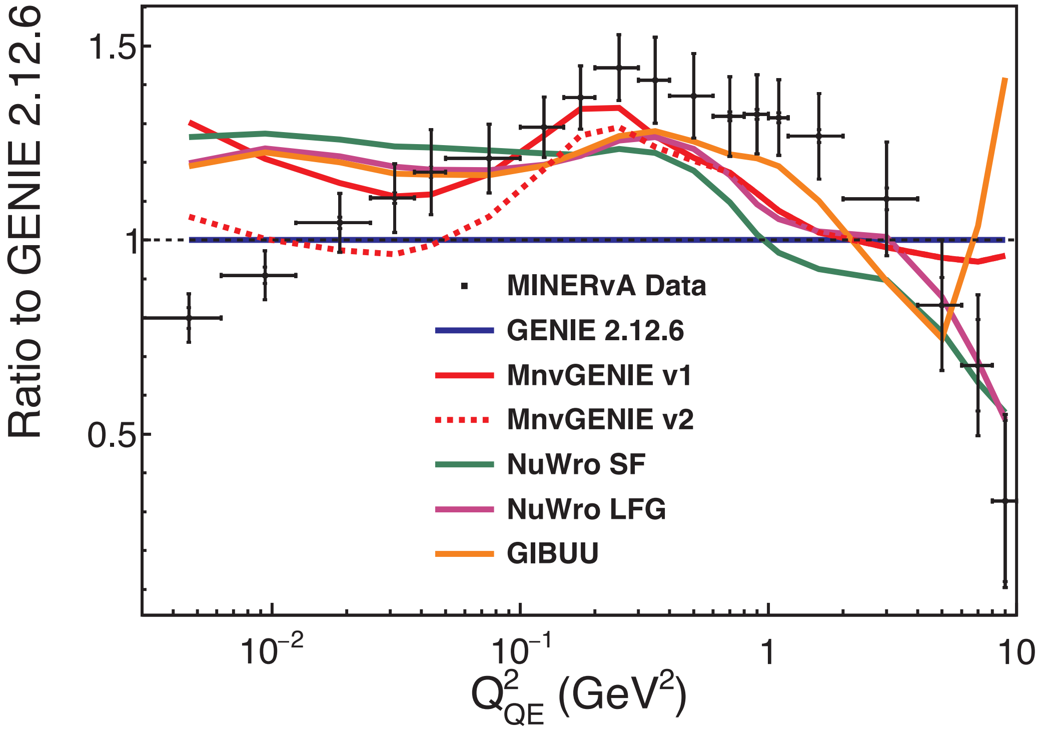
- Enhance 2p2h effects w/o RPA

- Add RPA and tune 2p2h to our neutrino data to get MnvGENIE v1



Carneiro *et al.*, PhysRevLett.124.121801

Compare to GENIE 2.12.6



- Tuned models can reproduce the high Q^2 behavior
- But significant discrepancies at low Q^2 for all models.
- More work is needed, let’s look at other observables

Same data as previous page

TKI measurements @ MINERvA

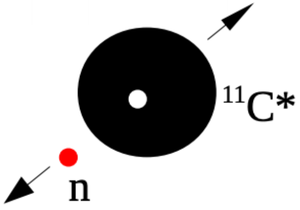
– QE-like measurement on C probing ν n→μ p

Assuming target remnant ^{11}C*

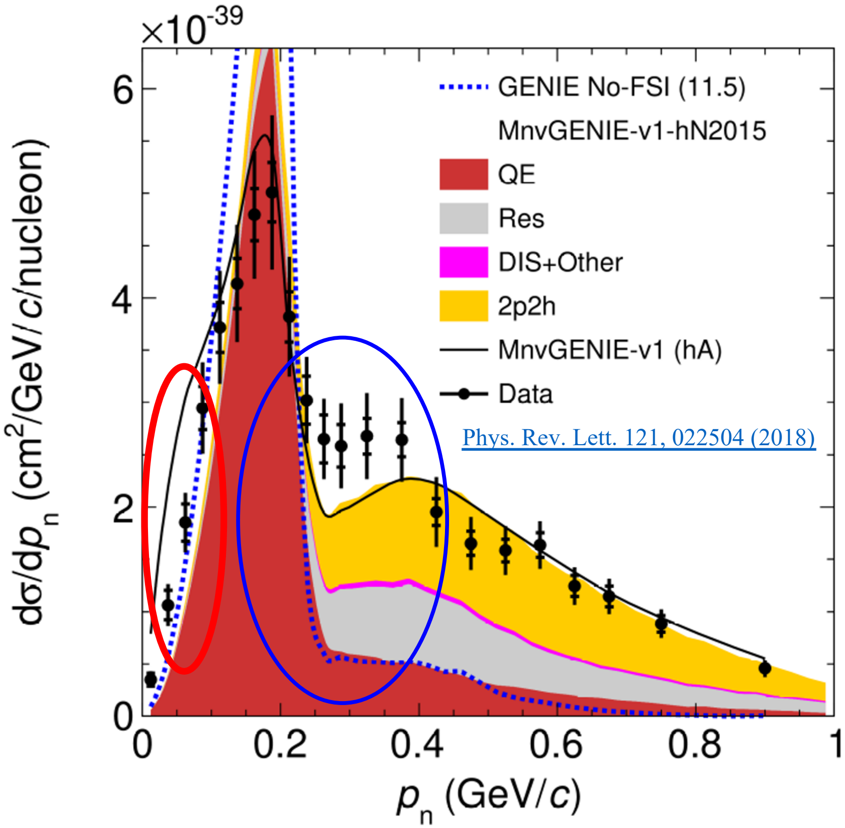
$$p_{\rm n} \equiv \sqrt{\delta p_{\rm T}^2 + \delta p_{\rm L}^2}$$

$$\sim [1 + O(10\%)] \times \delta p_{\rm T}$$

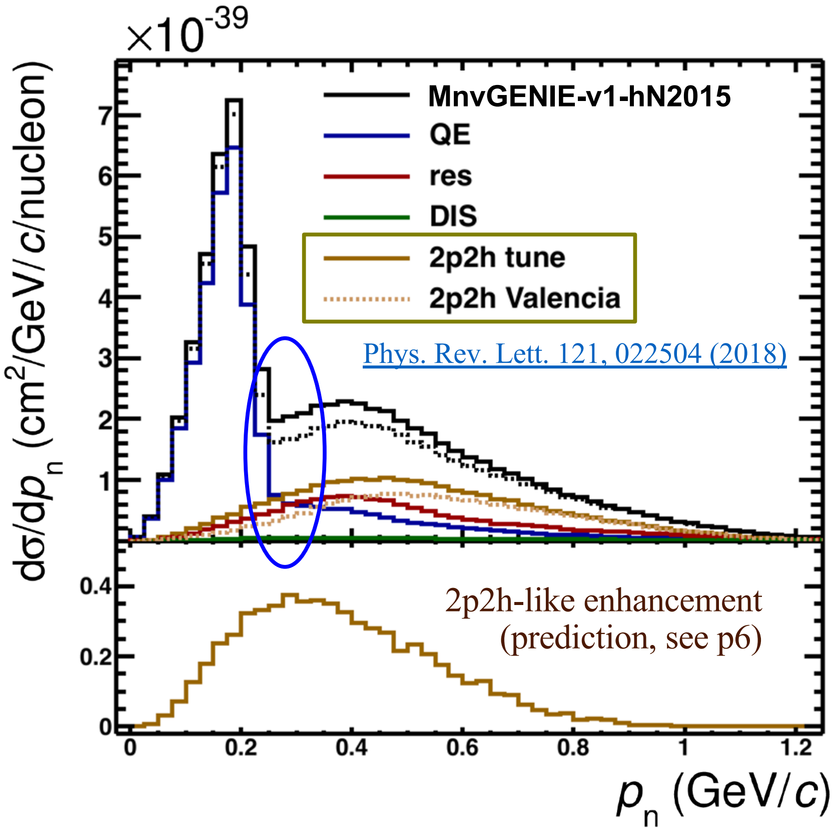
Phys.Rev. C95, 065501 (2017)



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



Phys. Rev. Lett. 121, 022504 (2018)



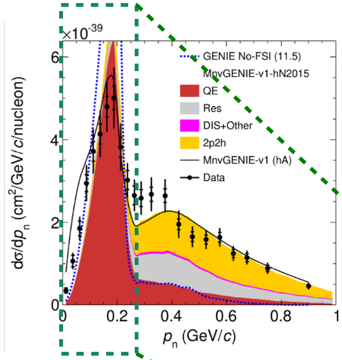
Phys. Rev. Lett. 121, 022504 (2018)

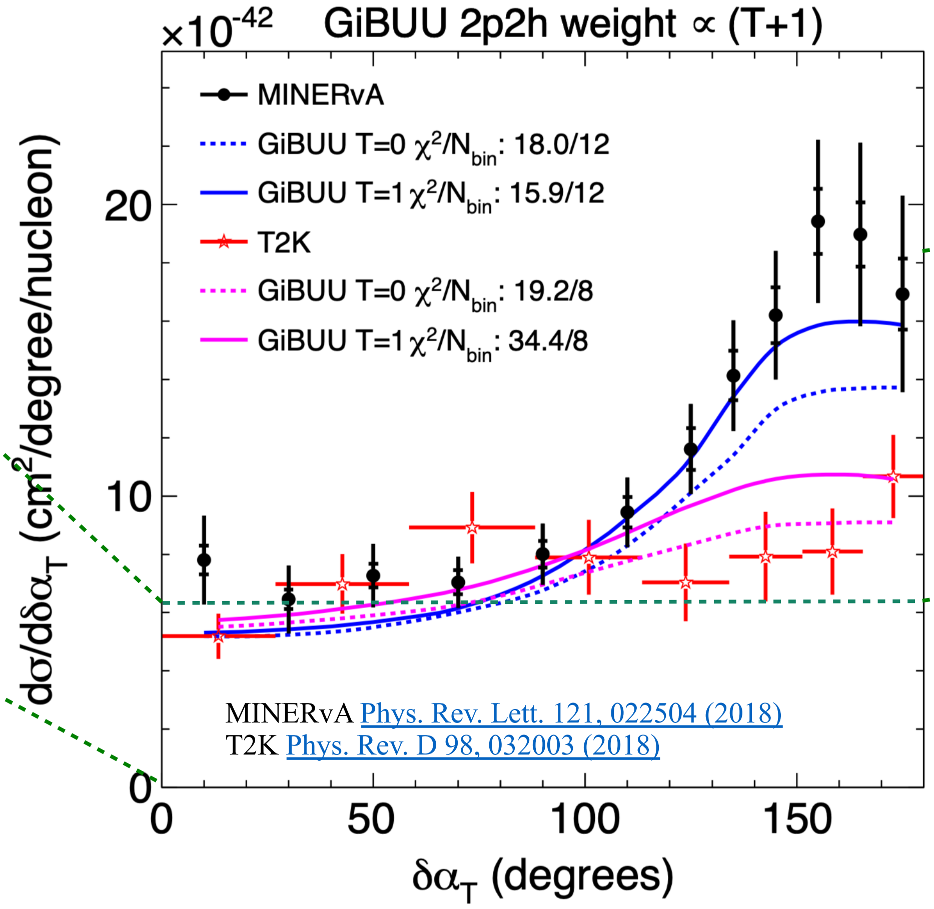
2p2h-like enhancement
(prediction, see p6)

TKI measurements @ MINERvA

– QE-like measurement on C probing ν n→μ p

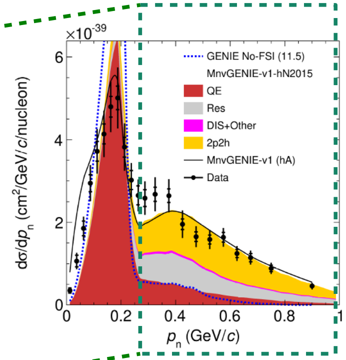
Fermi motion
(QE)



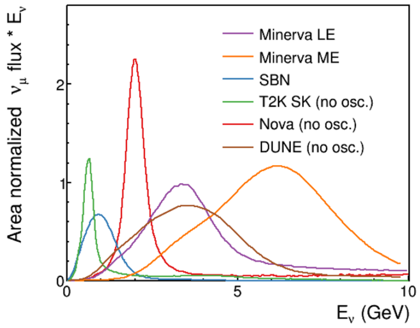


MINERvA [Phys. Rev. Lett. 121, 022504 (2018)]
T2K [Phys. Rev. D 98, 032003 (2018)]

Large missing pT
“**Dissipative**” processes:
FSI-QE/RES/DIS/2p2h

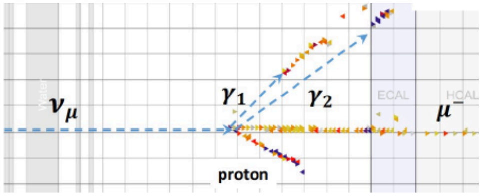


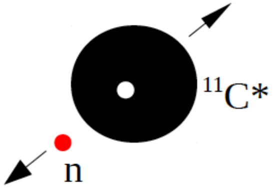
→ Energy-dependent

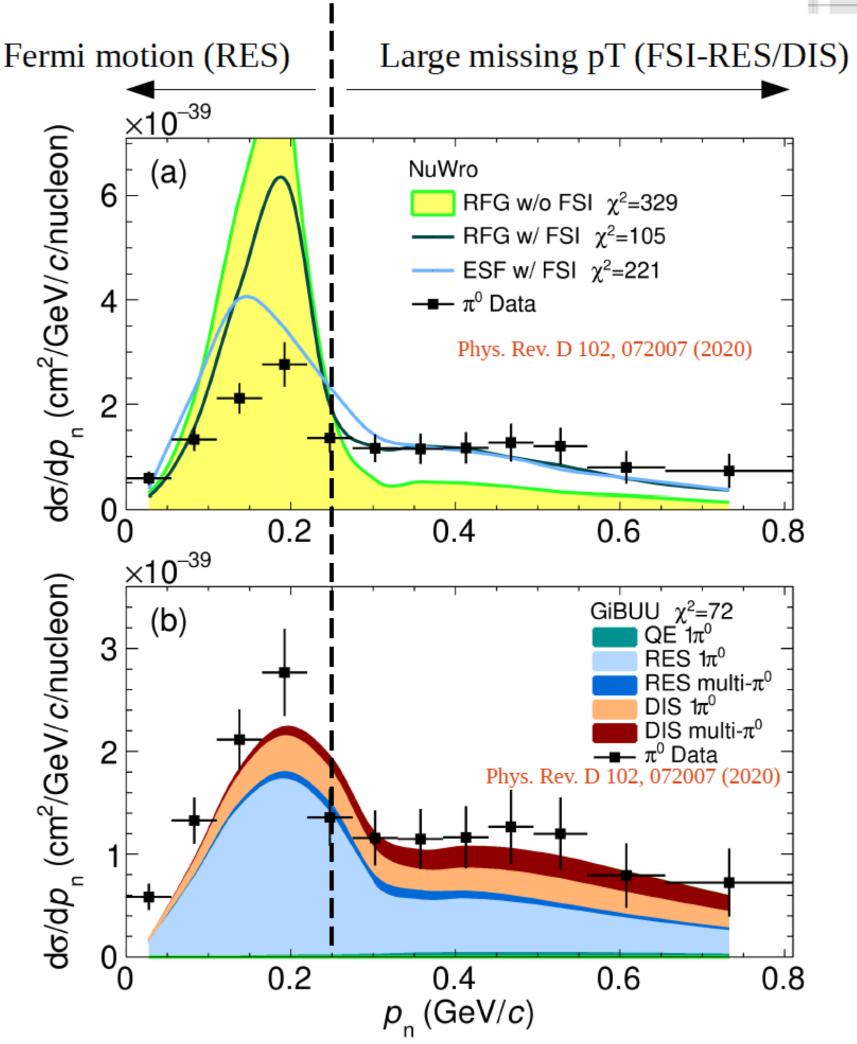


TKI measurements @ MINERvA

– Inclusive π^0 production on C probing $\nu\, n \rightarrow \mu\, p\, \pi^0$





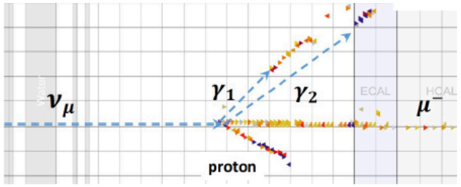


Phys. Rev. D 102, 072007 (2020)

- ✗ Fermi motion peak in pion production worse modeled than in QE
- ✓ Large missing pT region reasonably modeled

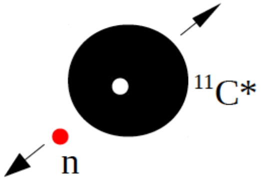
TKI measurements @ MINERvA

– Inclusive π^0 production on C probing $\nu\, n \rightarrow \mu\, p\, \pi^0$



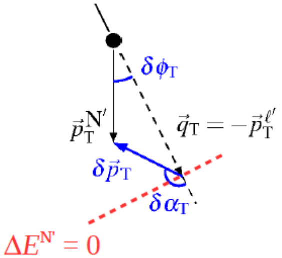
Shape comparison between QE-like and pion production

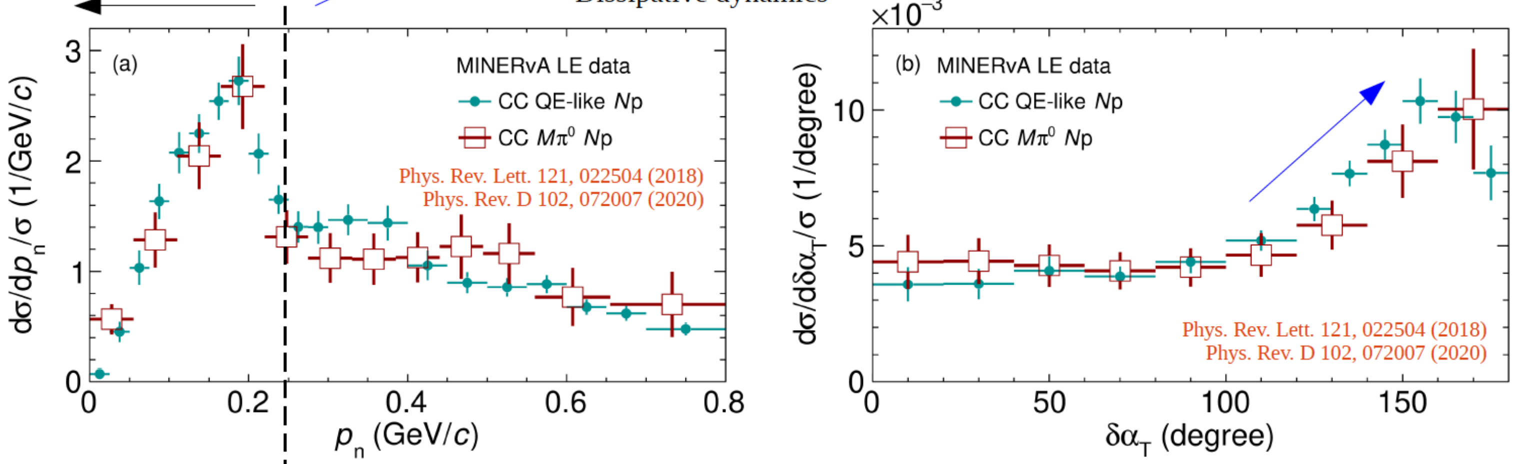
- Probing same neutron Fermi motion in carbon
- Suggests similar dynamics at large missing pT



Large missing pT (δp_T)

Dissipative dynamics





Phys. Rev. Lett. 121, 022504 (2018)
Phys. Rev. D 102, 072007 (2020)

Large missing pT: pion absorption

Open π (pion production)

absorbed π (QE-like)

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Systematic uncertainty breakdown