ICHEP 2020 | PRAGUE

UNIVERSITY OF OXFORD

Neutrino-Nucleus Interaction Physics with the Most Recent MINERvA Low-Energy Beam Data

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on behalf of the MINERvA Collaboration

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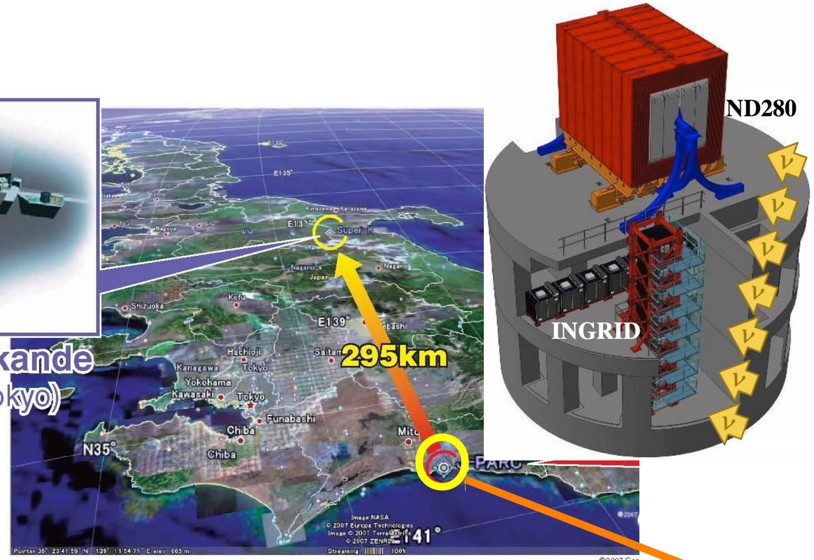
Virtual Conference, 28 July 2020

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

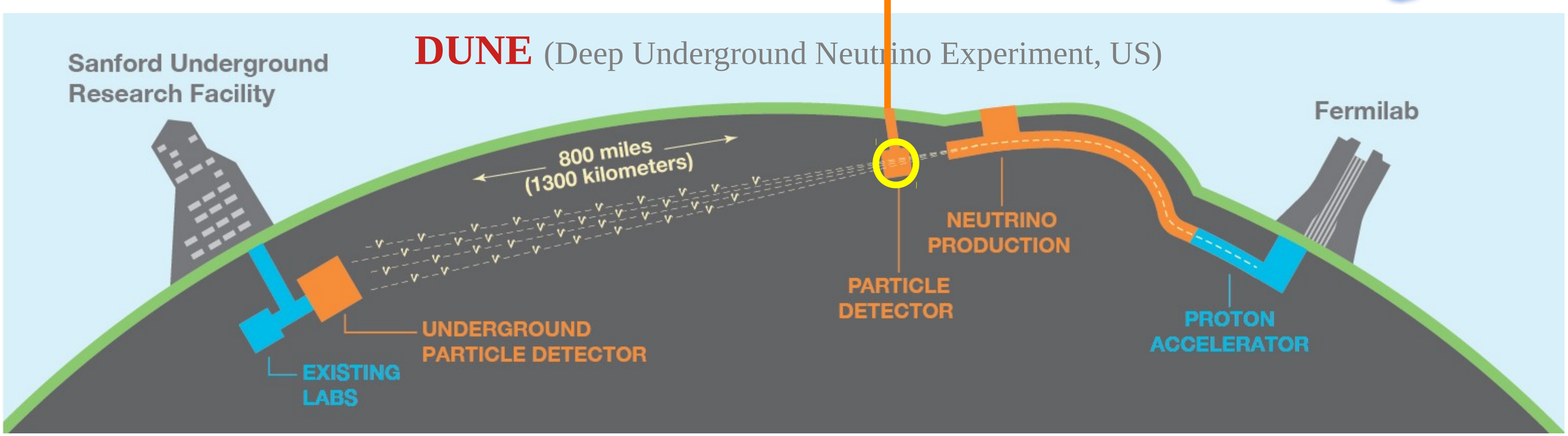
– Critical systematic constraints for oscillation measurements



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

NOvA (NuMI Off-Axis νe Appearance, US)

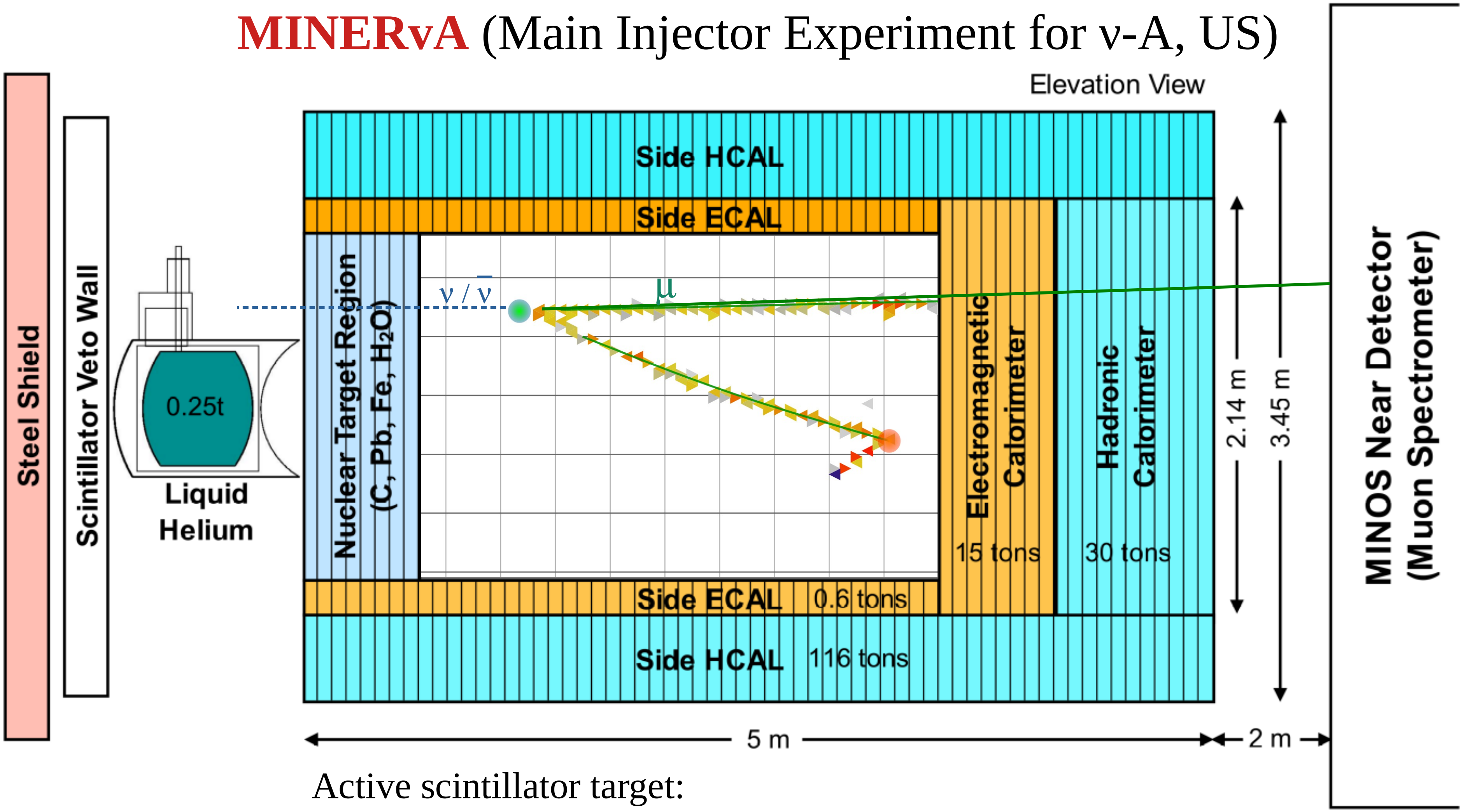
Near Detectors



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

– Constrain models used in oscillation measurements

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



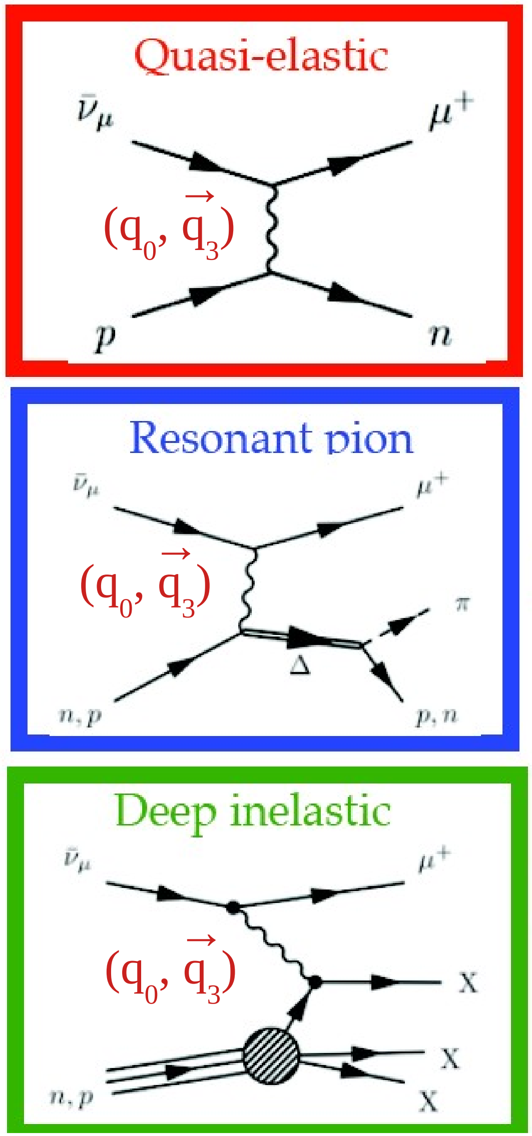
Active scintillator target:

- Homogeneous non-magnetized tracker
- EM shower reconstruction

MINOS Near Detector:

- Muon spectrometer

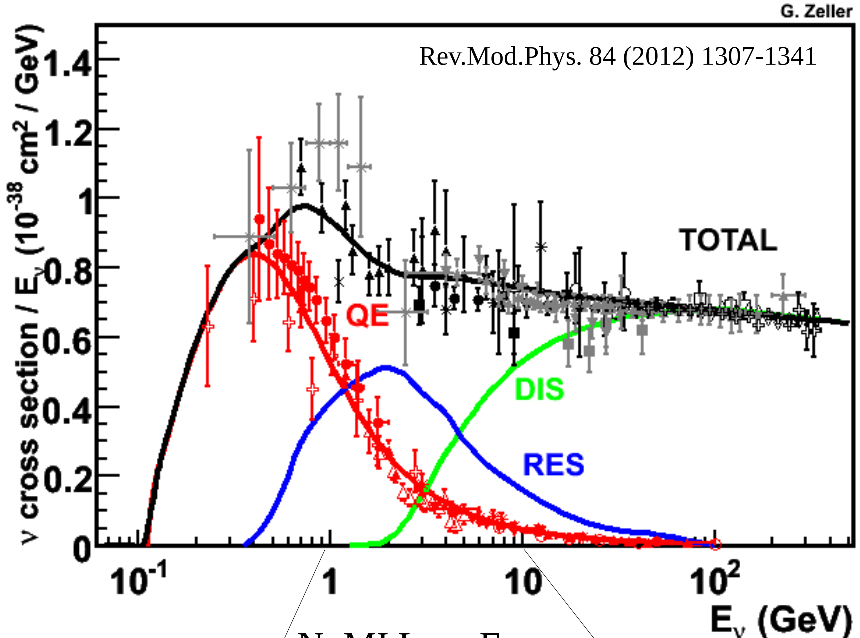
ν and $\bar{\nu}$ interactions @ MINERvA



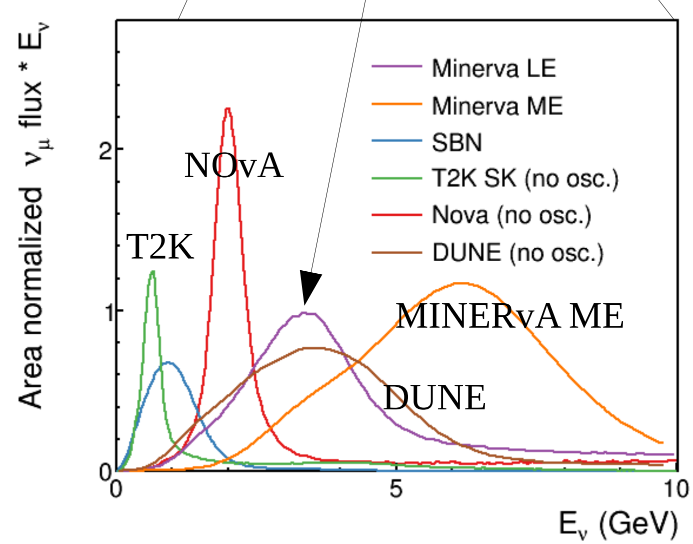
QE

RES

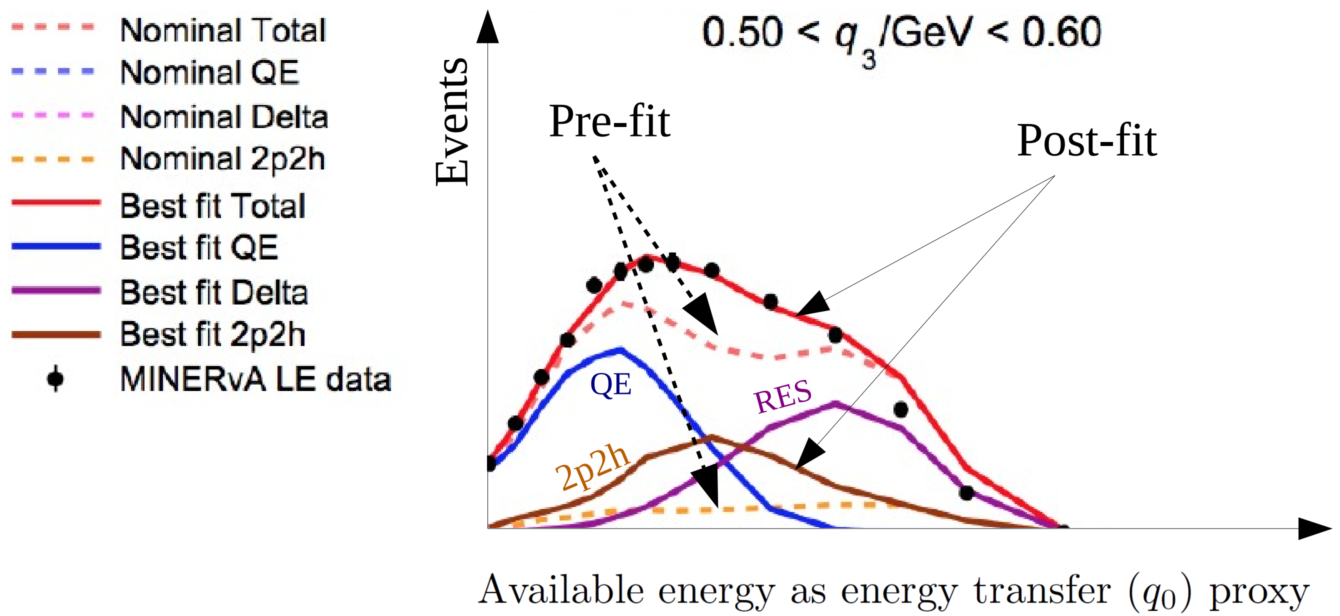
DIS



NuMI Low-Energy beam $\langle E_\nu \rangle \sim 3$ GeV (MINERvA LE)



ν and $\bar{\nu}$ interactions @ MINERvA: 2p2h-like enhancement



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

"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

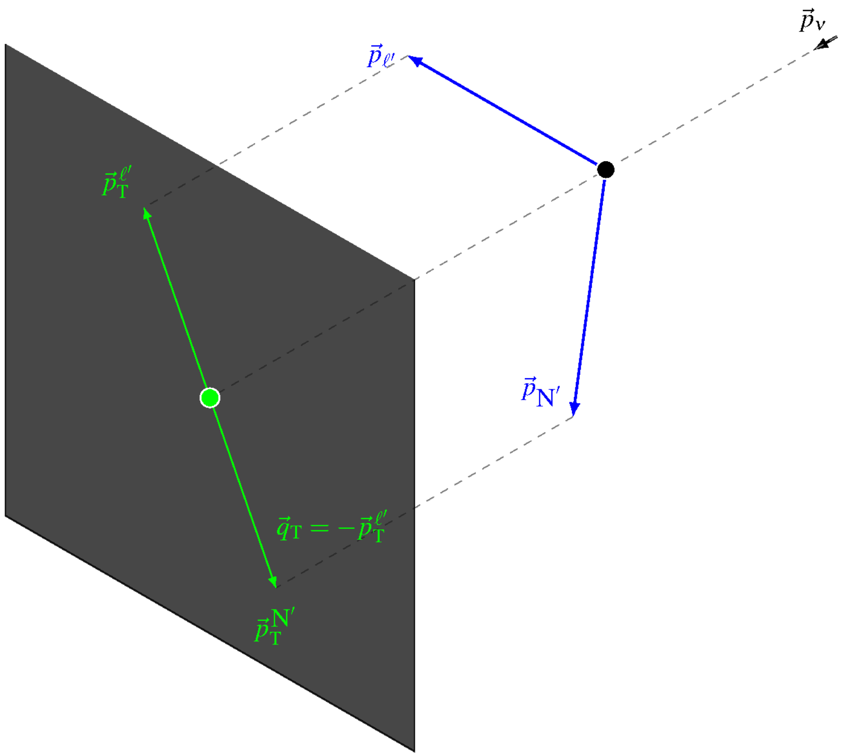
Phys.Rev.Lett. 116, 071802 (2016), Phys.Rev.Lett. 120, 221805 (2018)

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

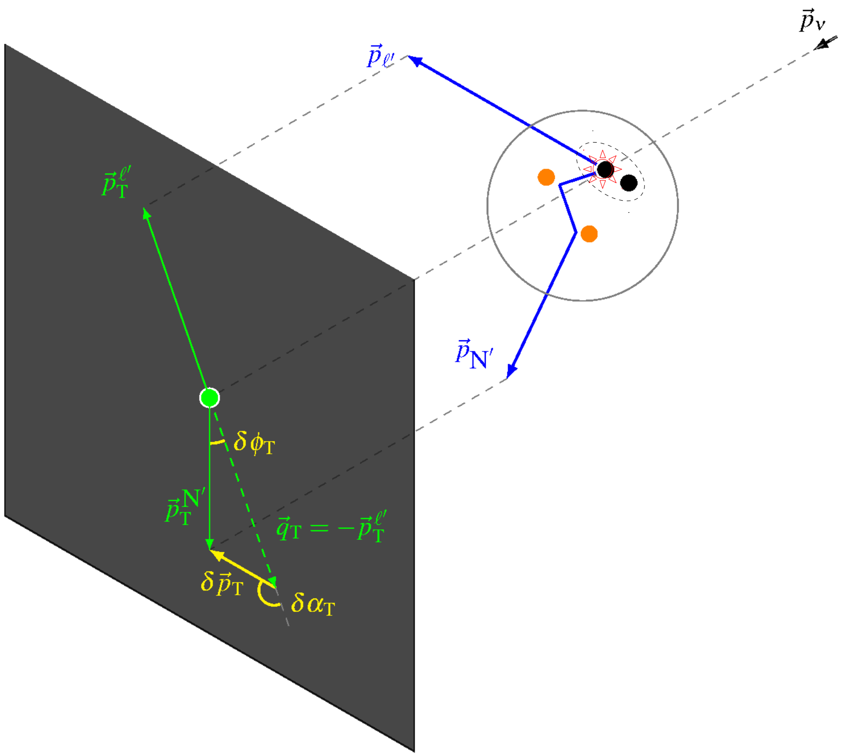
Transverse Kinematic Imbalance (TKI)

– Precisely identify intranuclear dynamics and the absence thereof

Phys. Rev. D92, 051302 (2015), Phys. Rev. C94, 015503 (2016)



Stationary nucleon target

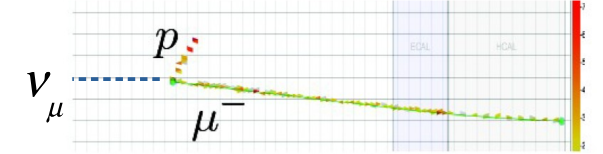


Nuclear target (A>1)

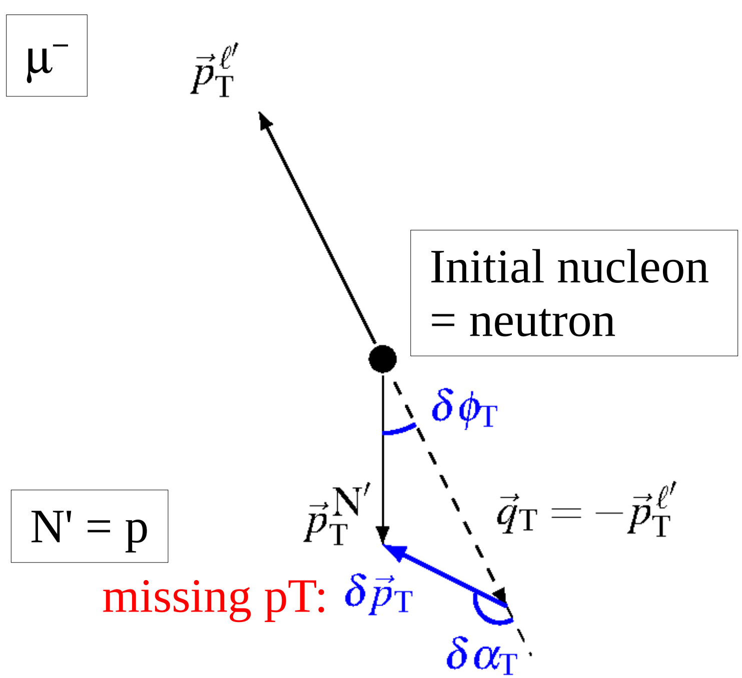
Fermi motion
Final-state interactions
Pion absorption
2p2h
...

TKI measurements @ MINERvA

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



ν n→μ⁻ p

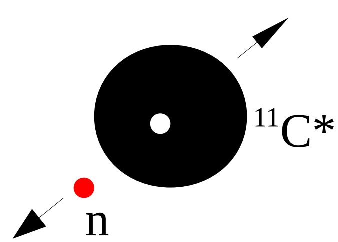


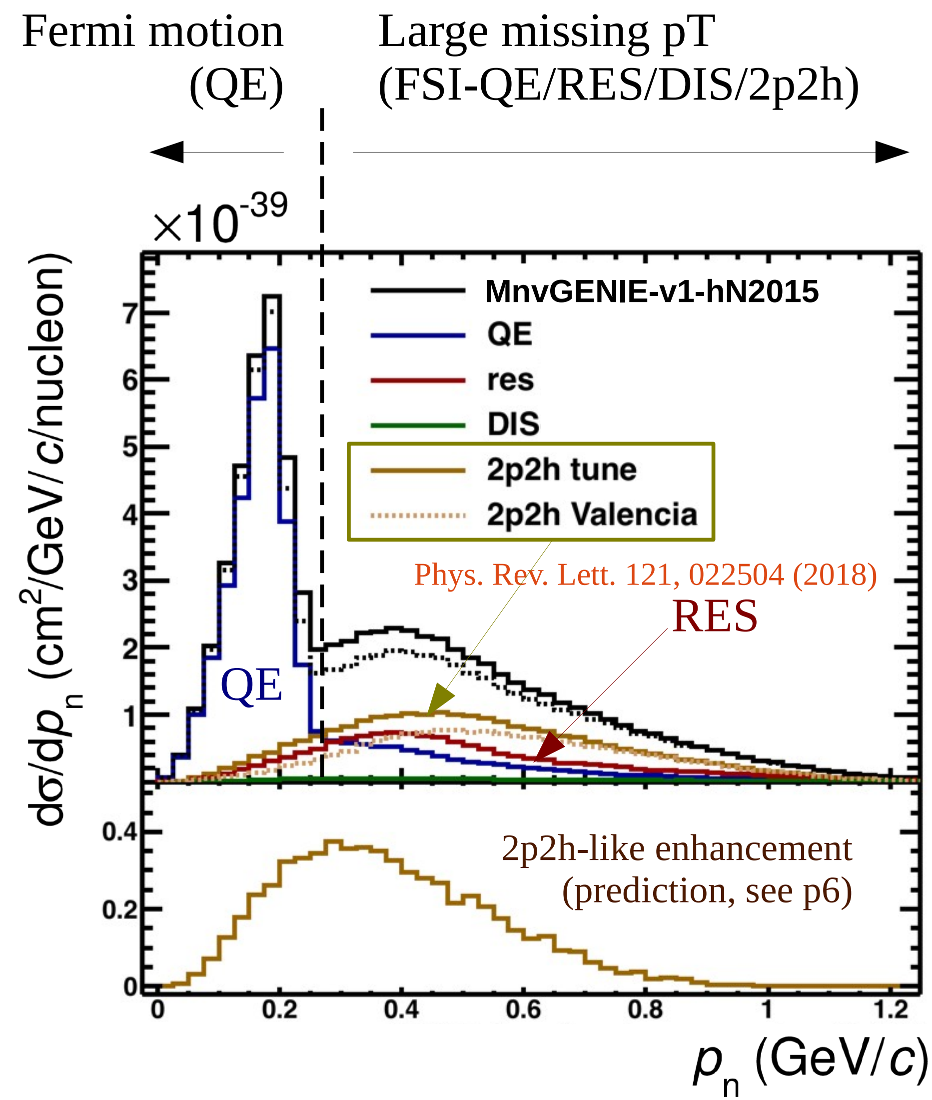
Assuming target remnant $^{11}C^*$

$$p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$$

~ [1 + O(10%)] ×δp_T

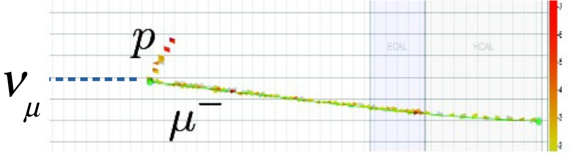
Phys.Rev. C95, 065501 (2017)



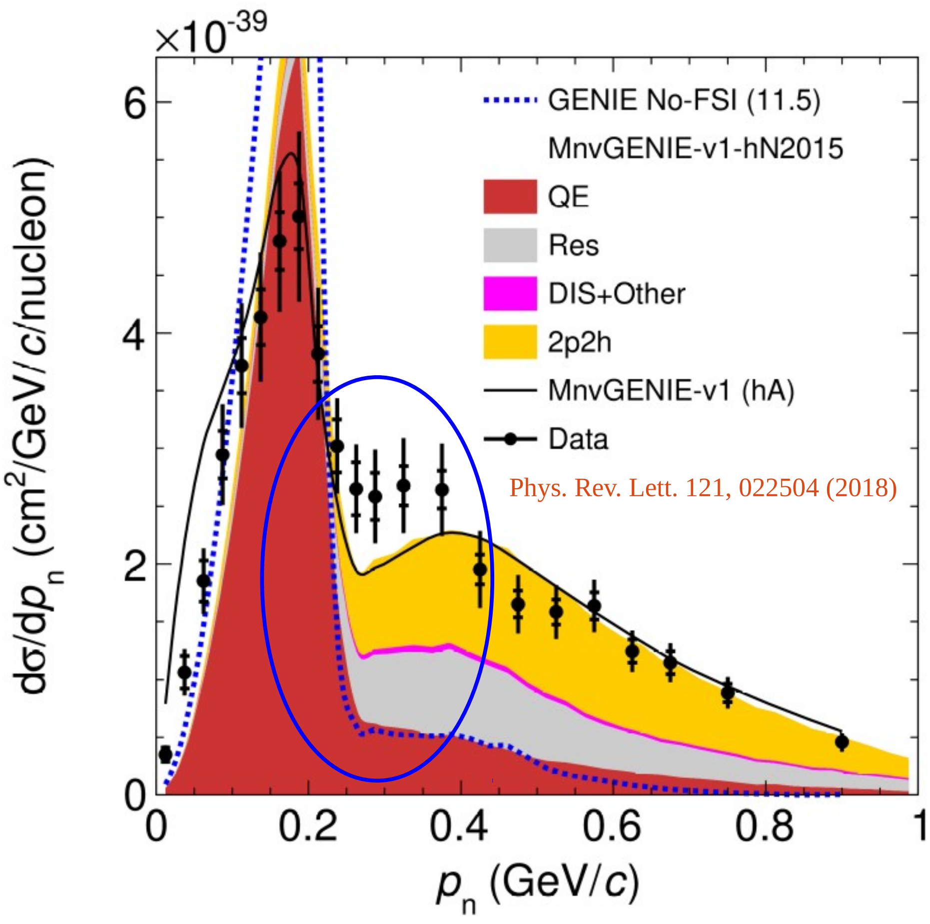


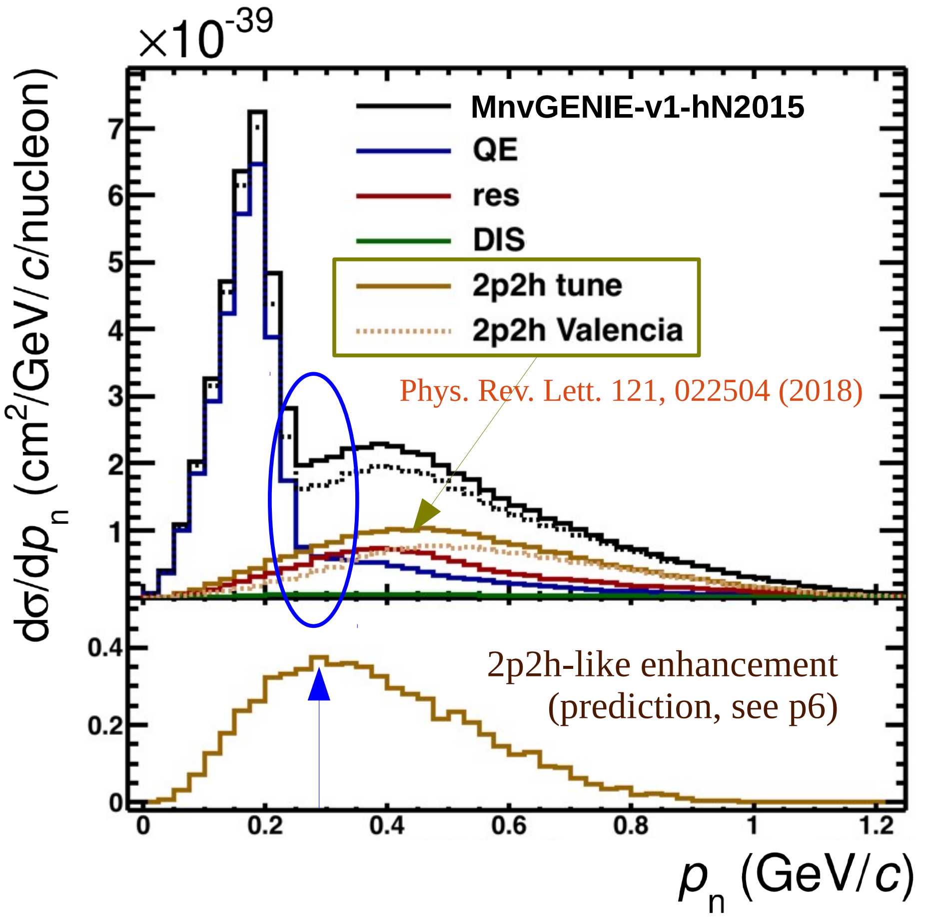
TKI measurements @ MINERvA

– QE-like measurement on C probing $\nu\, n \rightarrow \mu\, p$



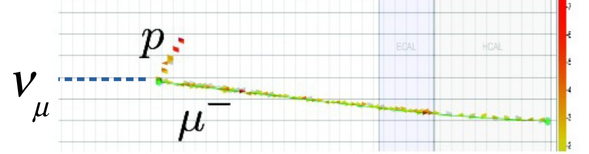
2p2h-like enhancement needs to be even stronger to fill the dip



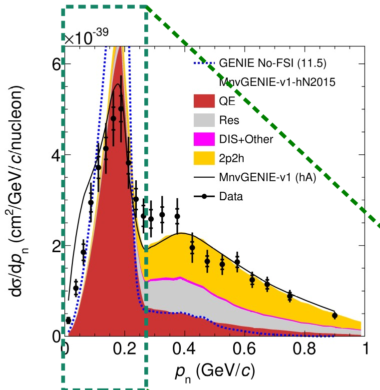


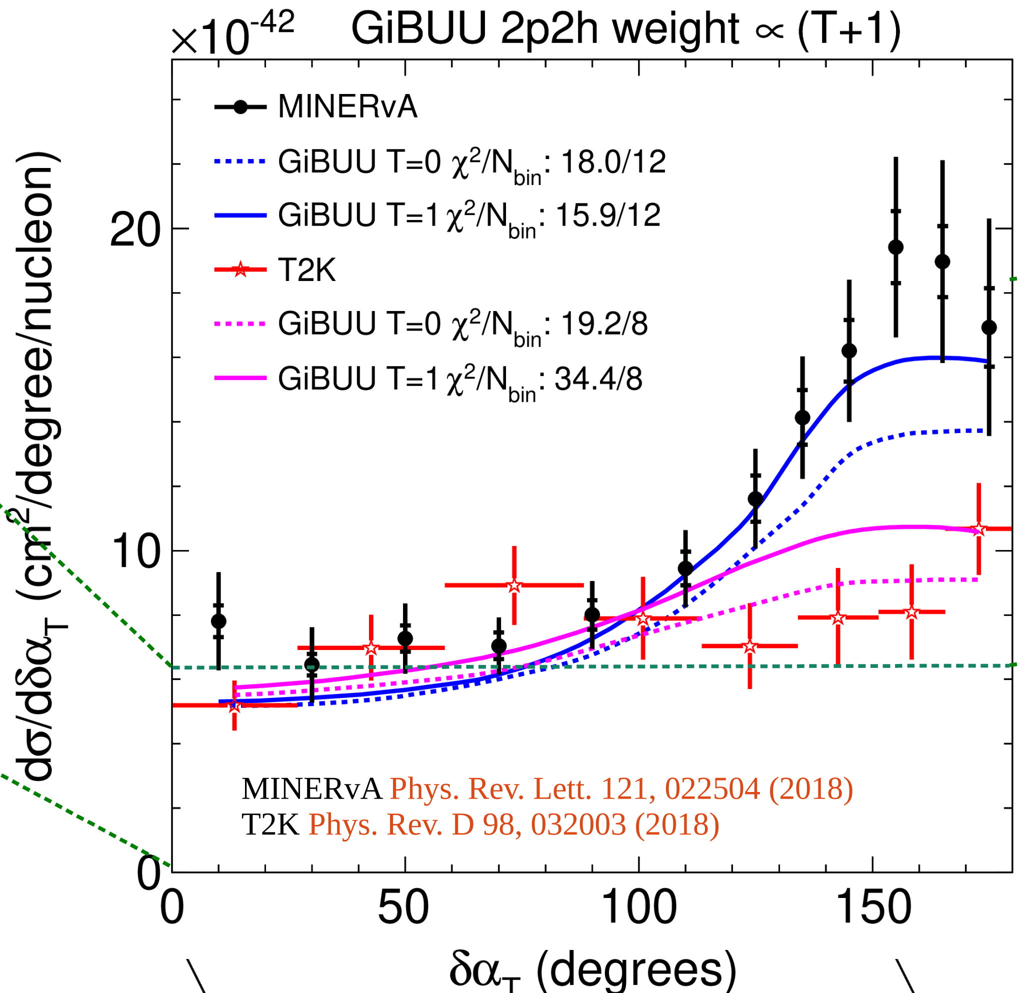
TKI measurements @ MINERvA

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



Fermi motion (QE)

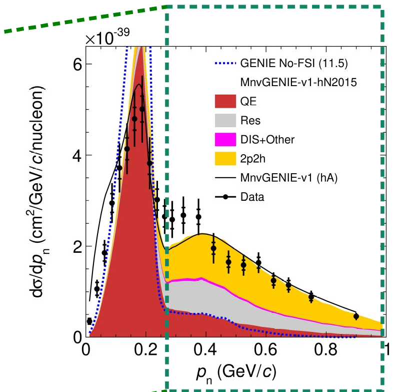




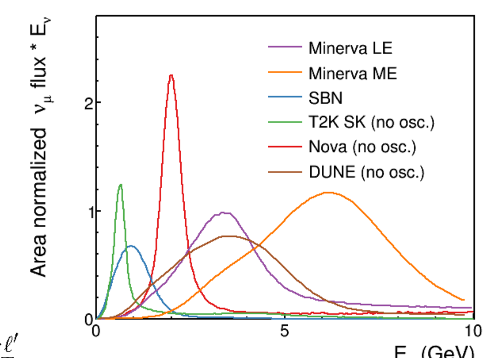
Large missing pT

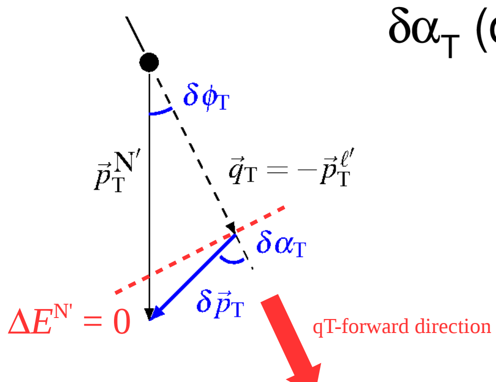
“**Dissipative**” processes:

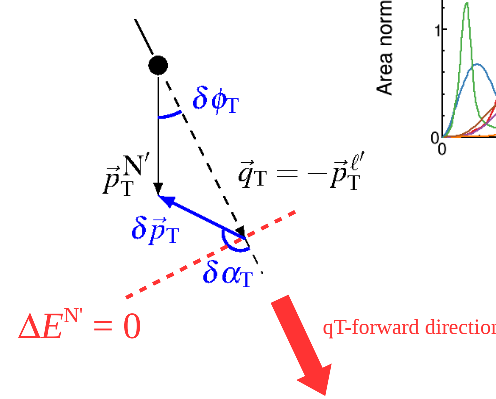
FSI-QE/RES/DIS/2p2h



→ Energy-dependent

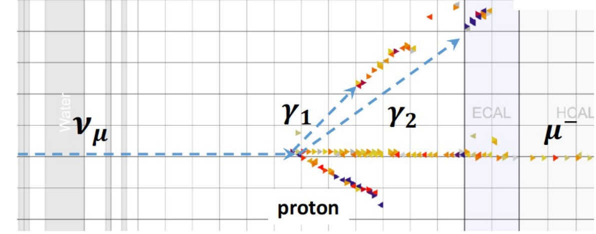






TKI measurements @ MINERvA

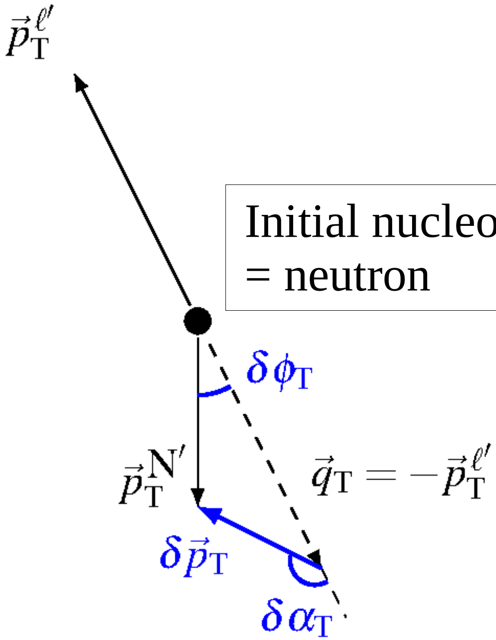
– Inclusive π^0 production on C probing $\nu\, n \rightarrow \mu\, p\, \pi^0$



NEW

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

μ⁻



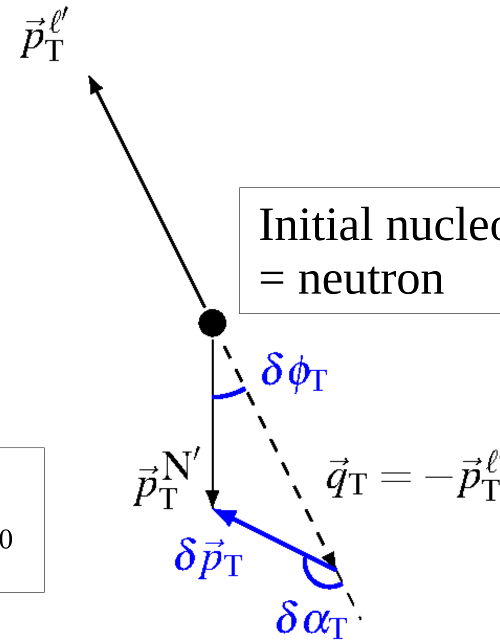
Initial nucleon = neutron

N' = p

via QE-like measurement

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

μ⁻



Initial nucleon = neutron

N' = Δ

$\Delta \rightarrow p\, \pi^0$

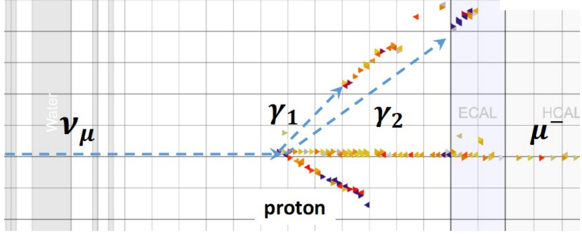
via inclusive π^0 production

*Generally, $\nu/\bar{\nu}\ n/p \rightarrow \mu\ p\ \pi^{+/-/0}$

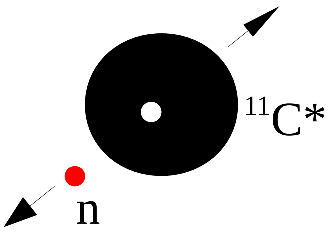
Phys.Rev.C 99, 055504 (2019)

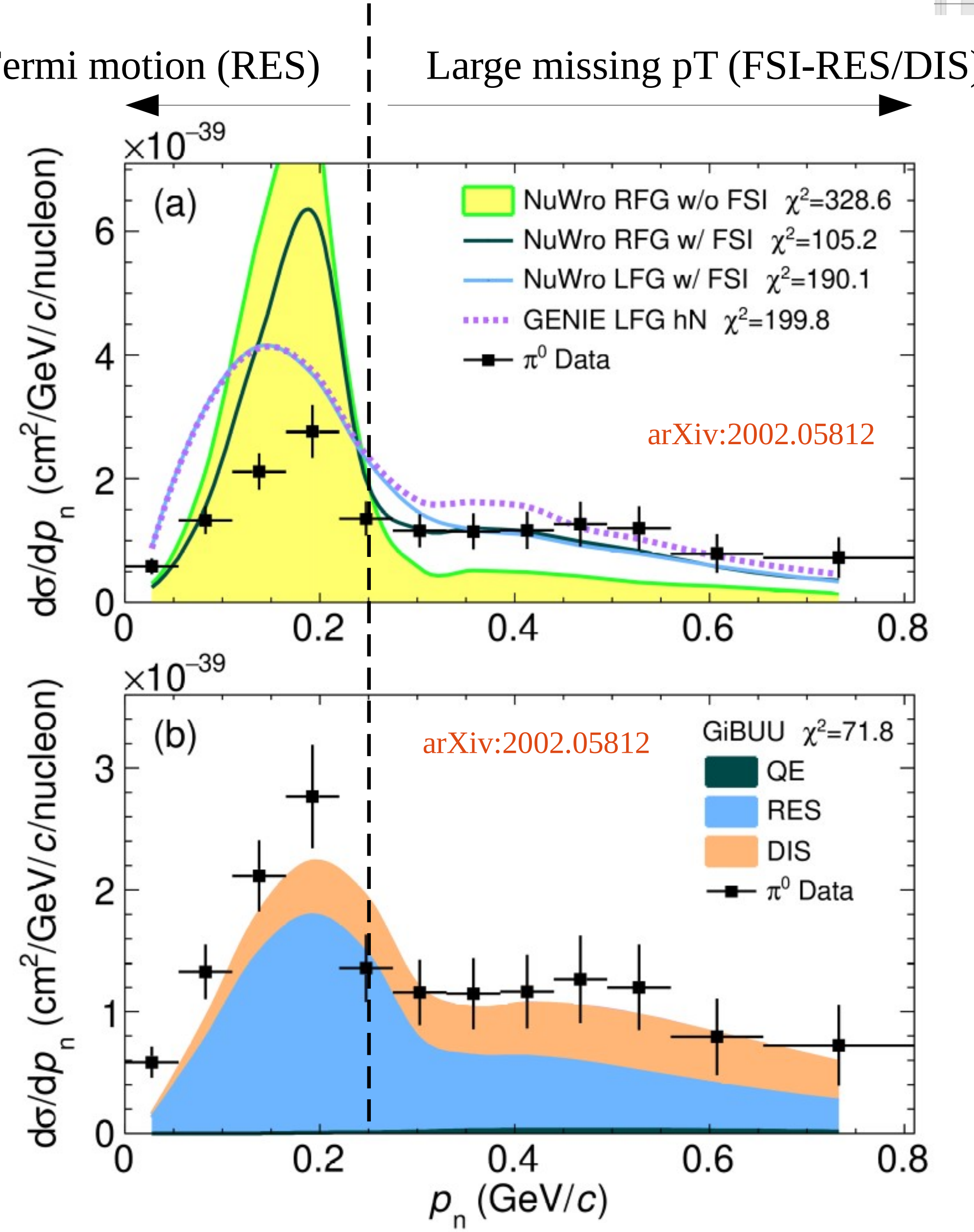
TKI measurements @ MINERvA

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



NEW

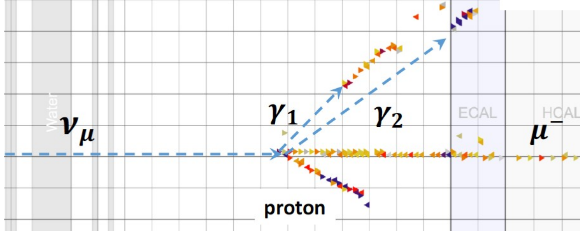




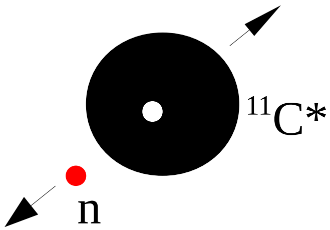
- ✗ Fermi motion peak in pion production worse modeled than in QE
- ✓ Large missing pT region reasonably modeled

TKI measurements @ MINERvA

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

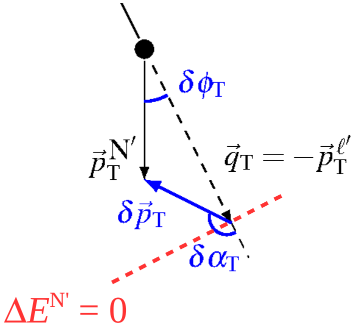


NEW

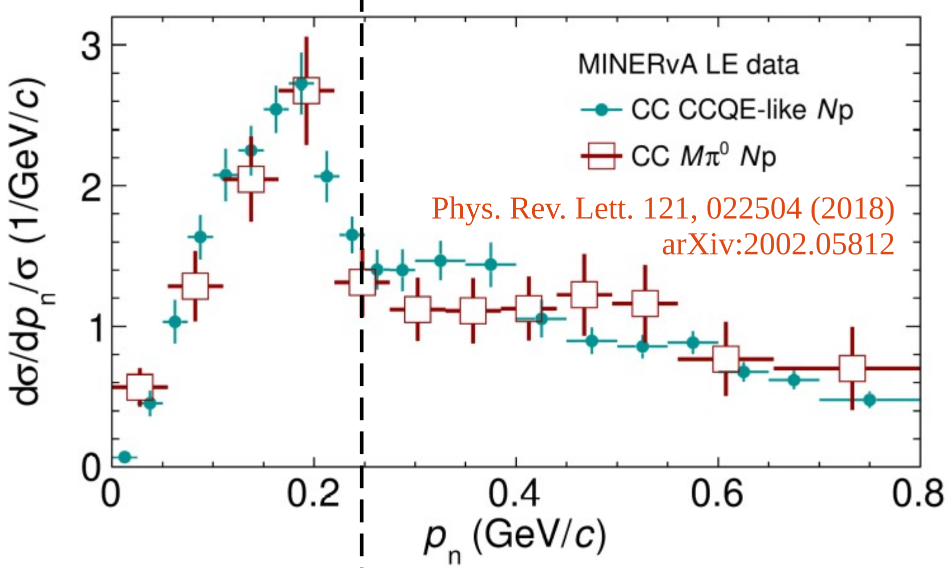


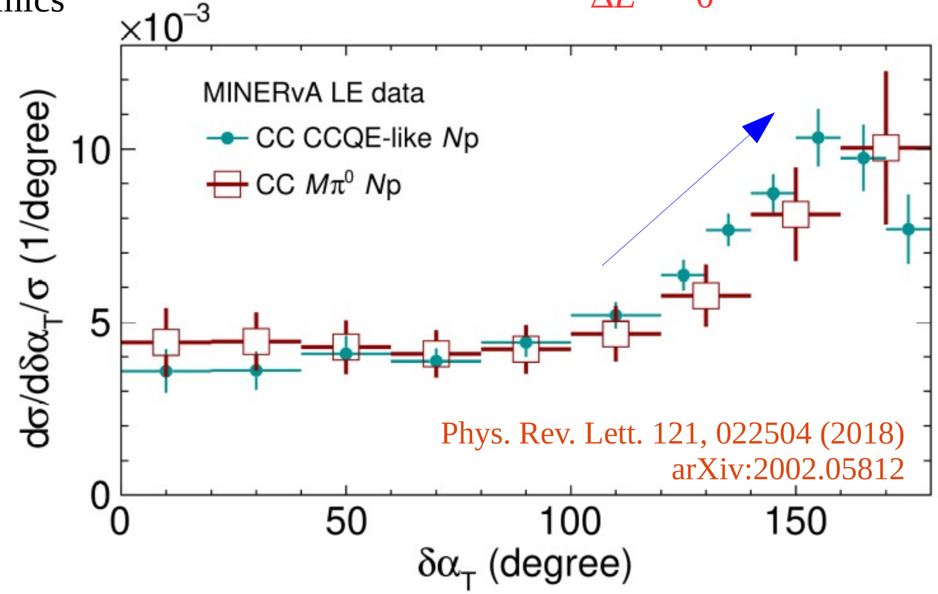
Shape comparison between QE-like and pion production

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



Large missing pT (δp_T)
Dissipative dynamics





Large missing pT: pion absorption
Open π (pion production)

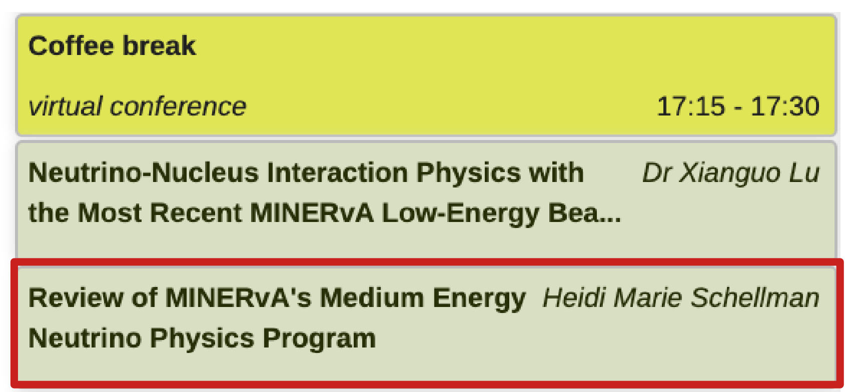
absorbed π (QE-like)

Summary

Selected MINERvA results using Low-Energy data set ($\langle E_\nu \rangle \sim 3$ GeV)

- TKI (Transverse Kinematic Imbalance) in QE-like and inclusive π^0 measurements
  a) QE-like
     → Suggests even larger 2p2h-like enhancement is needed
  b) Inclusive π^0 production
     → Mis-modeling at Fermi motion peak
     → Reasonable model description at large missing pT
  c) Shape comparison between QE-like and inclusive π^0 production
     → Similar dissipative dynamics at large missing pT
  d) More TKI: MINERvA analysis on binding energy Phys.Rev.D 101, 092001 (2020)

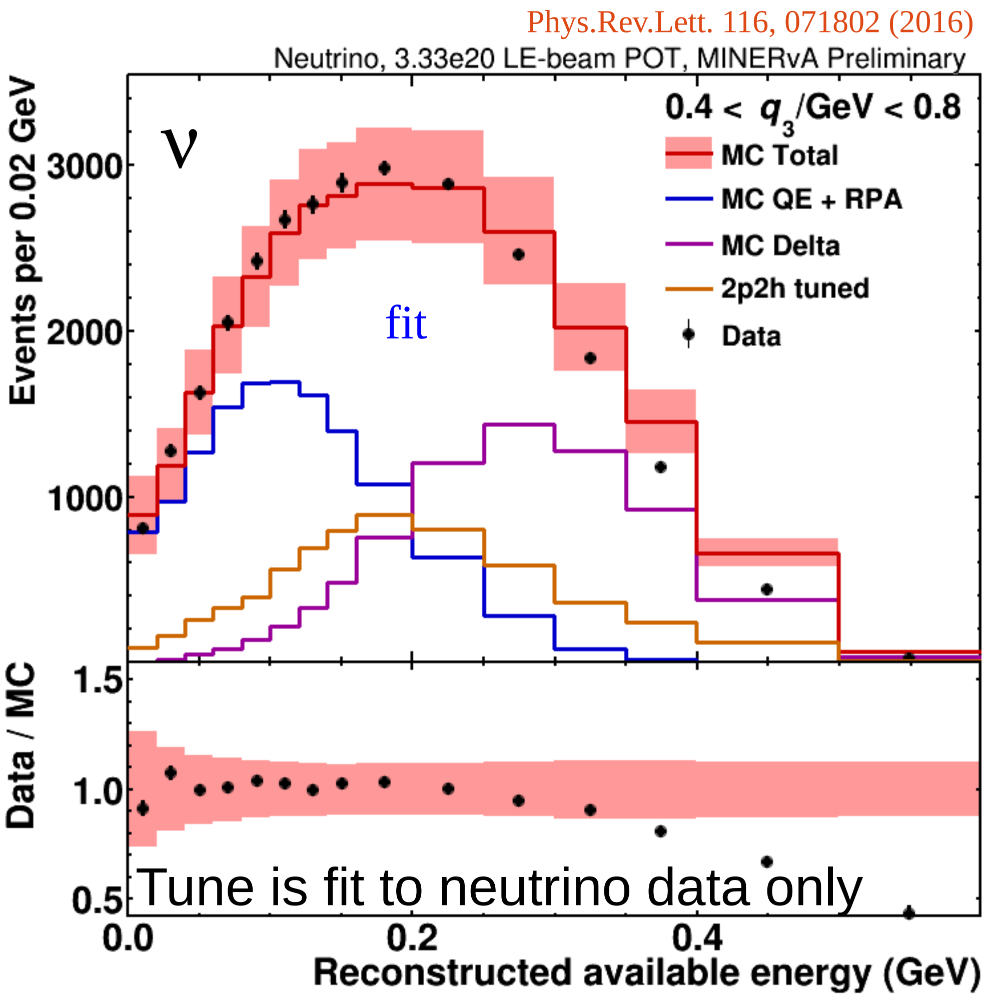
Follow Medium-Energy results:

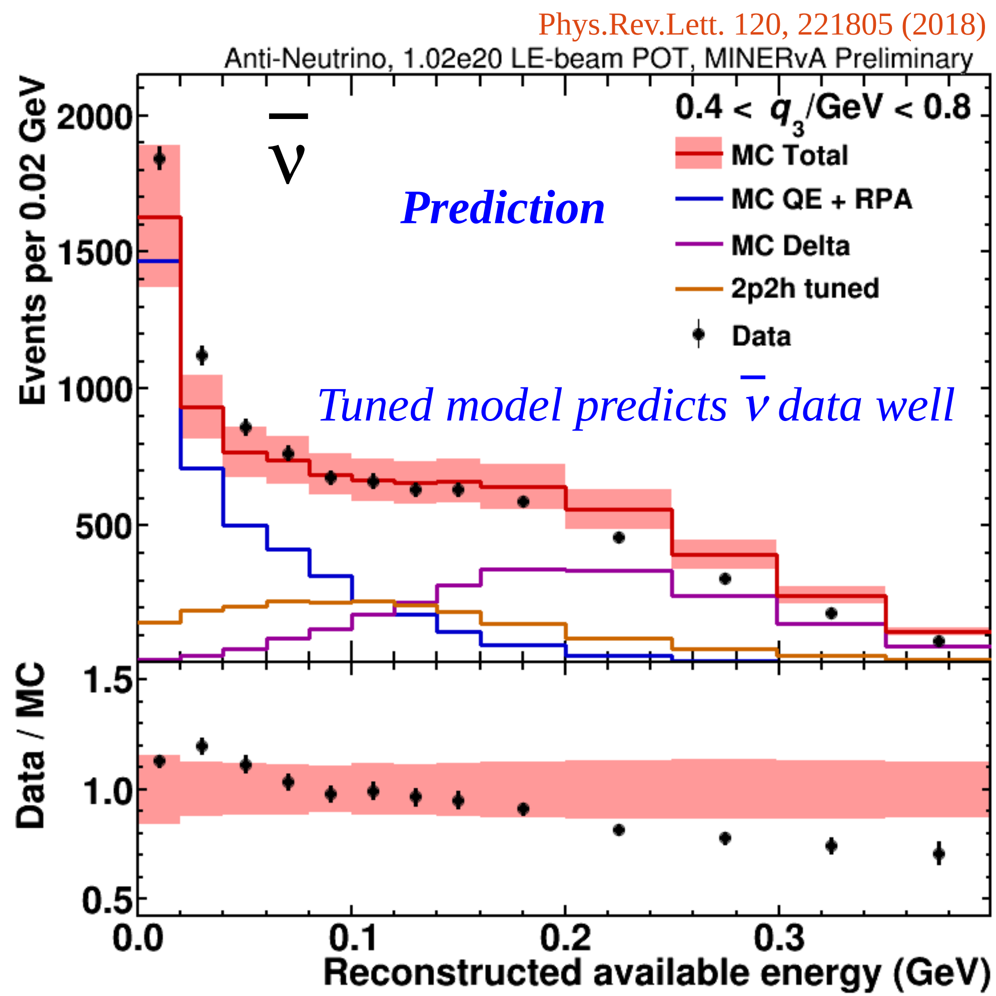


Thank you!

BACKUP

2p2h-like enhancement in νA and $\bar{\nu}$A

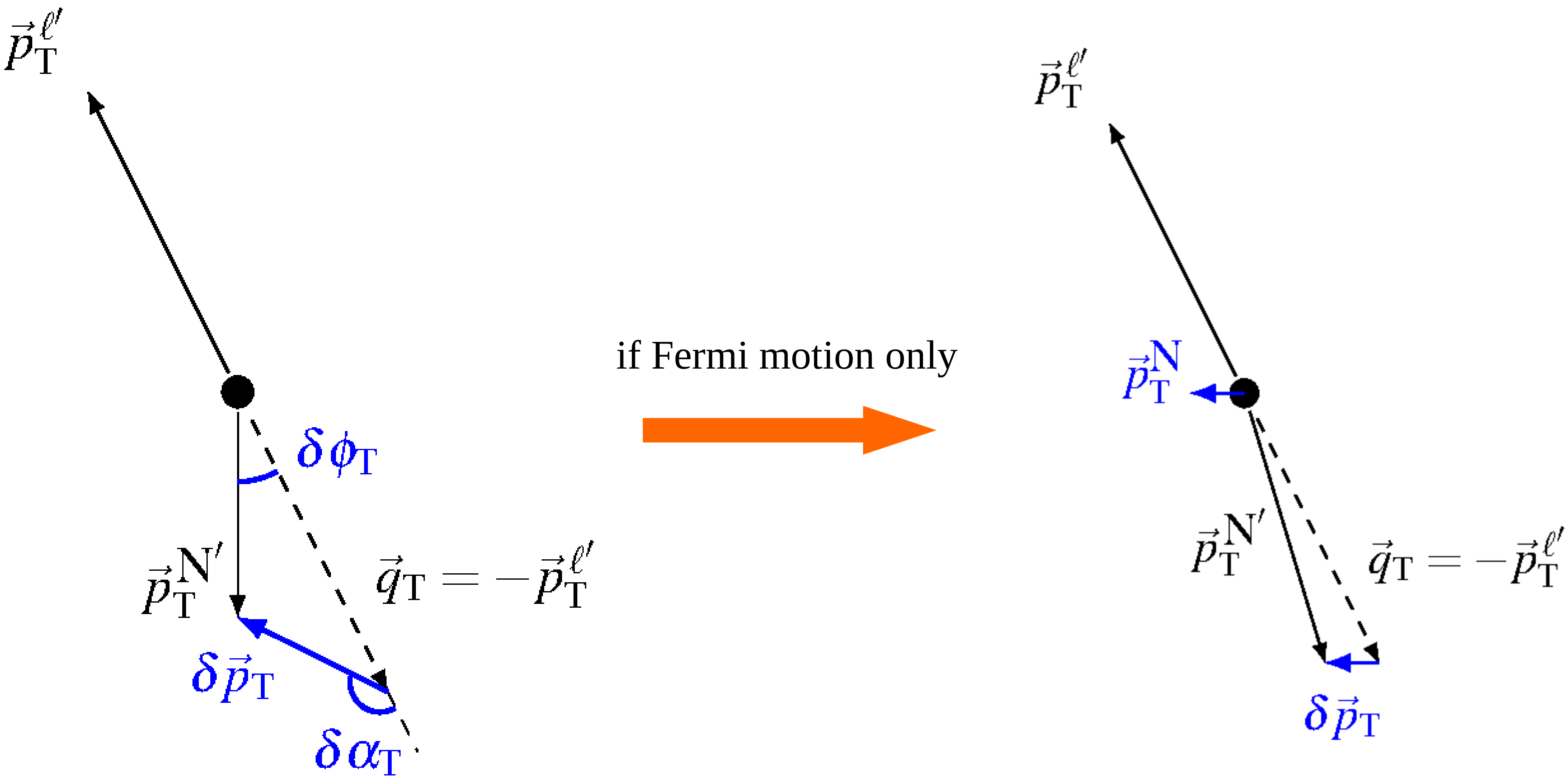




GENIE [Nucl.Instrum.Meth. A614 (2010) 87-104]

- 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]

Transverse Boosting Angle $\delta\alpha_T$

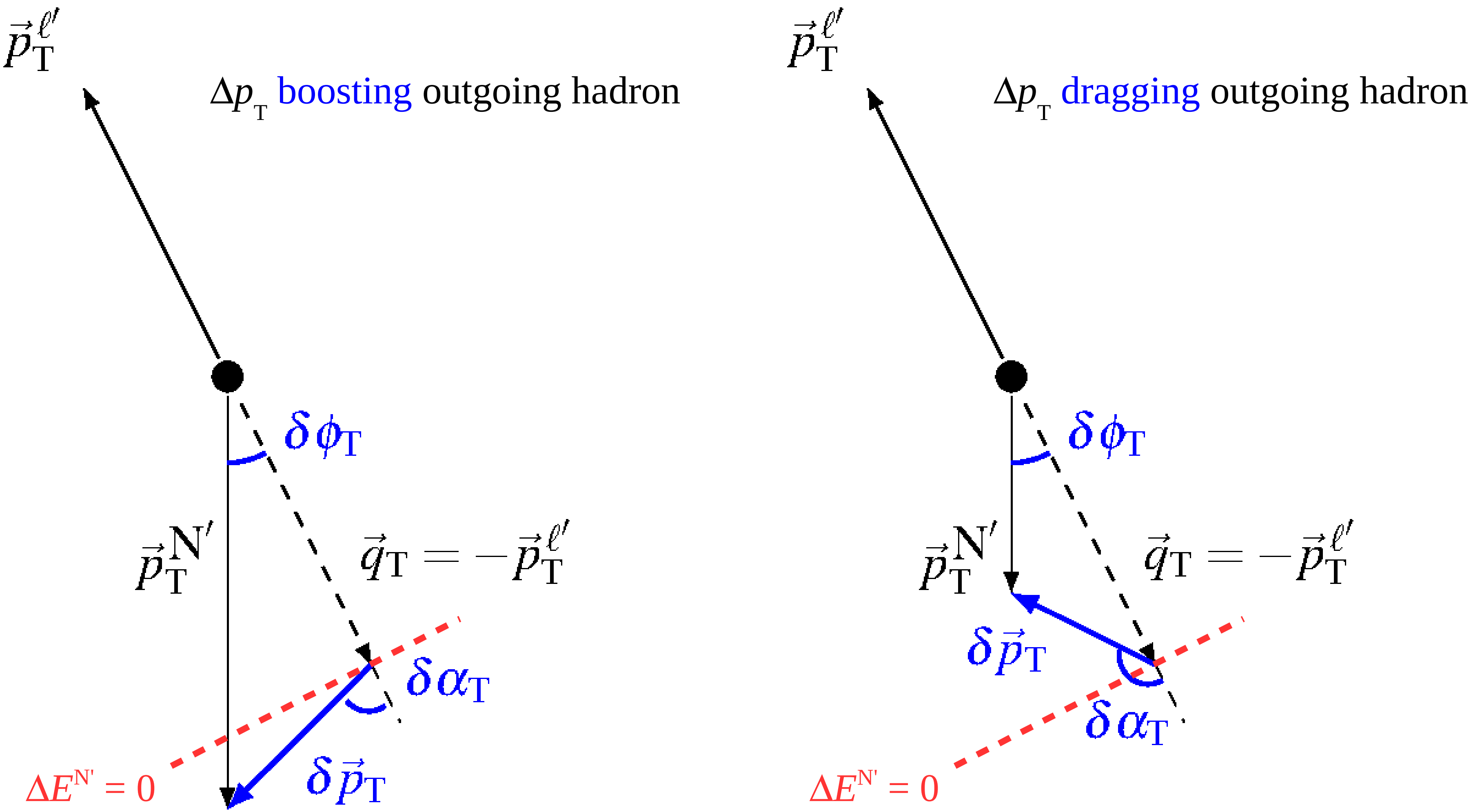


$$\delta\vec{p}_T = \vec{p}_T^{N}$$

Total transverse momentum
Transverse momentum imbalance
Missing pT ...

$\delta\alpha_T$ is Fermi motion direction → isotropic

Transverse Boosting Angle $\delta\alpha_T$



Full nuclear effects

$$\delta\vec{p}_T = \vec{p}_T^{N} - \Delta\vec{p}_T$$

- FSI
- Momentum sharing with extra particles (non-exclusive channels)
  - pion absorption
  - 2p2h

Emulated Nucleon Momentum p_N

A more general analysis of kinematic imbalance

Transverse: $0 = \vec{p}_T^{\,\ell'} + \vec{p}_T^{\,N'} - \delta\vec{p}_T$

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

New variable: $p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$

[A. Furmanski, J. T. Sobczyk, Phys.Rev. C95, 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

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

$$E_{A'} = \sqrt{m_{A'}^2 + p_n^2}$$

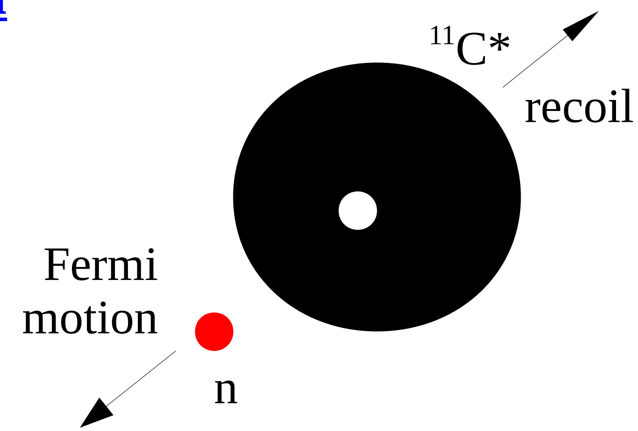
p_n: recoil momentum of the nuclear remnant

final-state

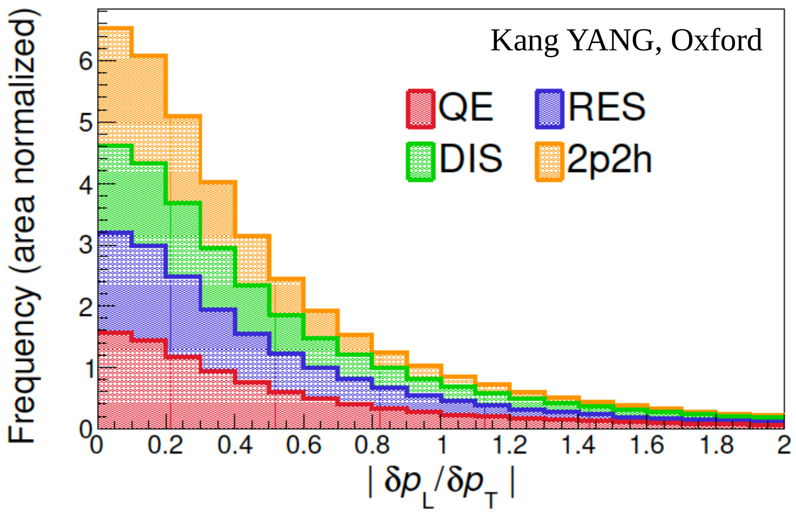
Dual Interpretation

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

initial-state



Emulated Nucleon Momentum p_N



TL;DR:

$\delta\vec{p}_T = \vec{p}_T^{\,N} - \Delta\vec{p}_T$

δp_T is promoted to p_N by ~ 10% correction

$p_N \sim [1 + O(10\%)] \times \delta p_T$

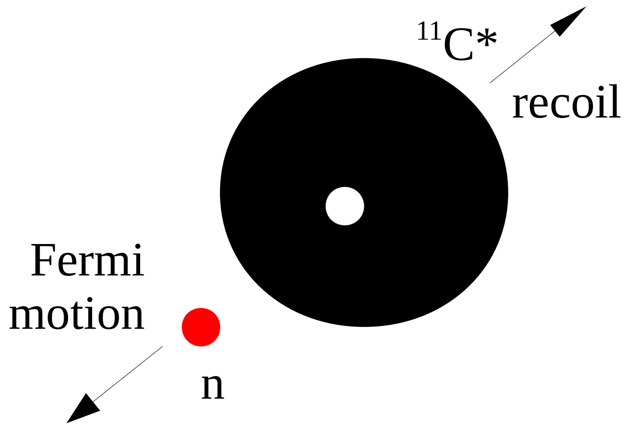
p_n: recoil momentum of the nuclear remnant

final-state

Dual Interpretation

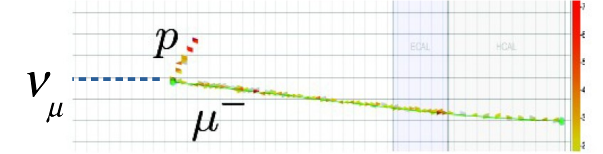
For CCQE, A' = $^{11}C^*$
No more unknowns
p_n: neutron Fermi motion

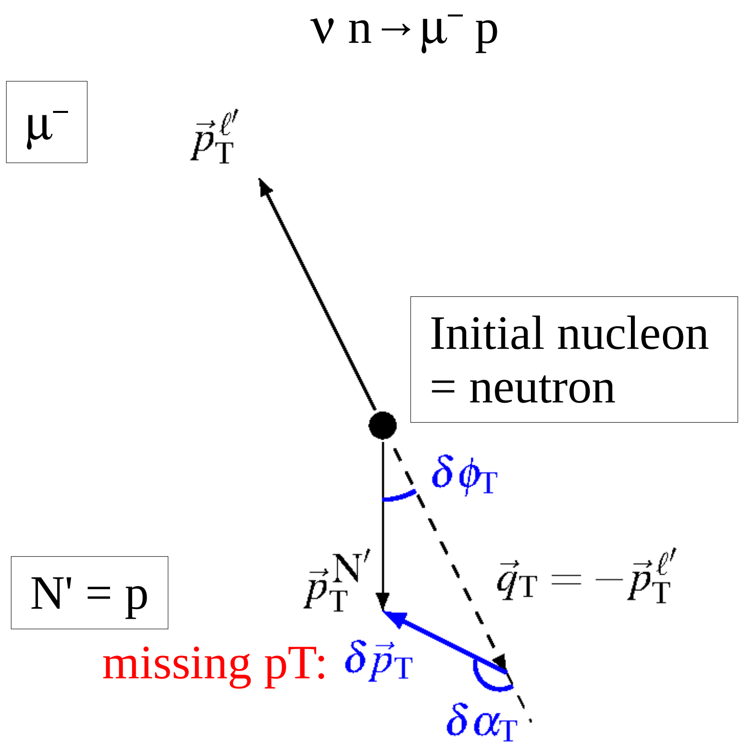
initial-state

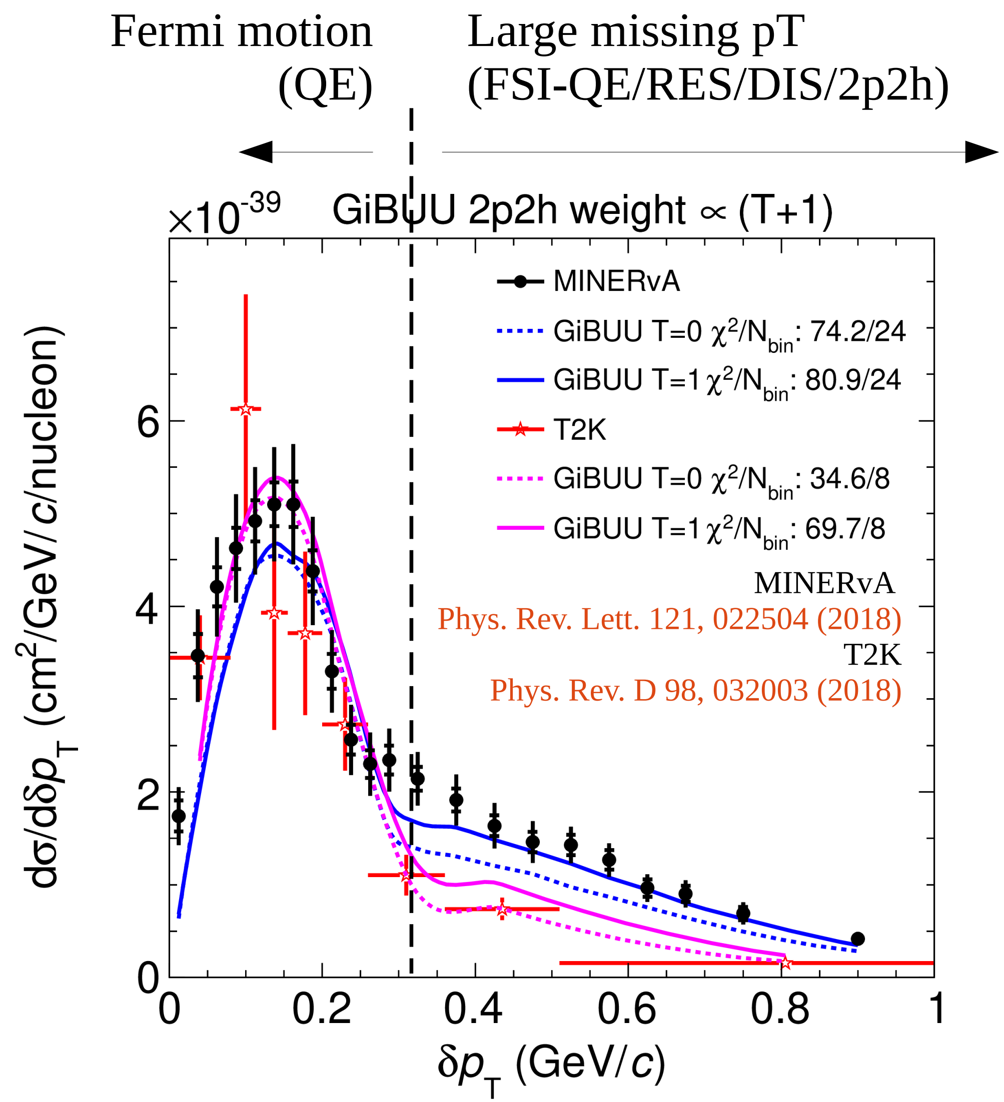


TKI measurements @ MINERvA

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







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