

# Transverse kinematic imbalance in neutrino interactions

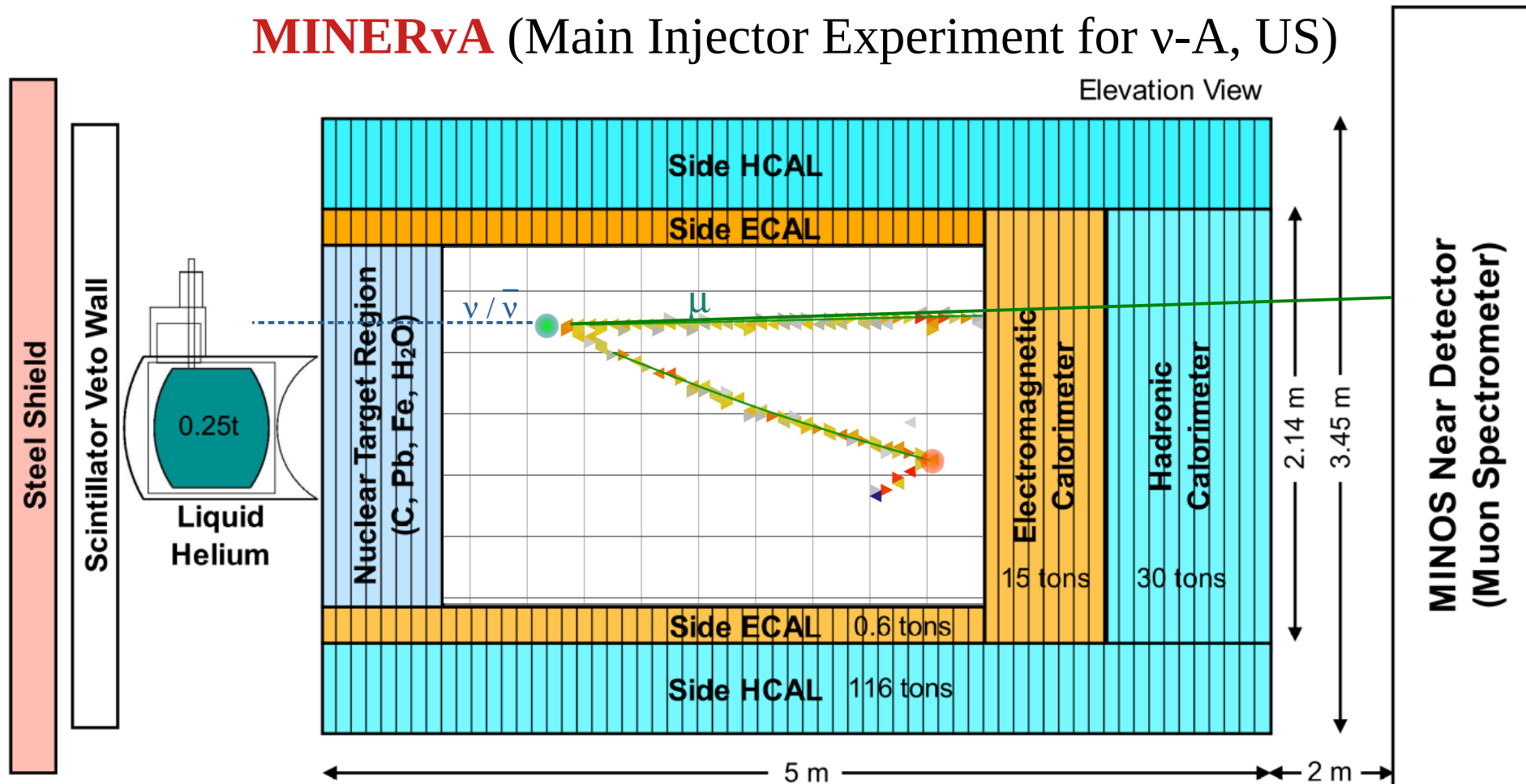
Xianguo LU/ 卢显国 University of Oxford

Mini-workshop on study of sub-multi GeV neutrino interactions with hadrons  
15 December 2020

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

– Constrain models used in oscillation measurements

## MINERvA (Main Injector Experiment for $\nu$ -A, US)



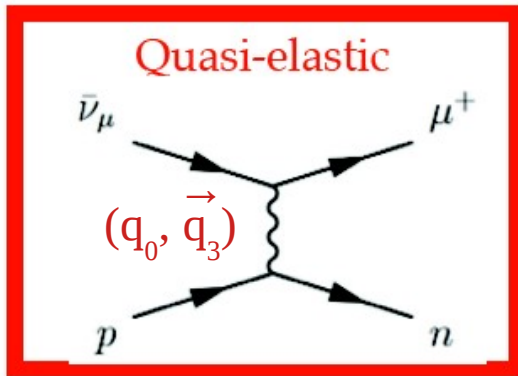
Active scintillator target:

- Homogeneous non-magnetized tracker
- EM shower reconstruction

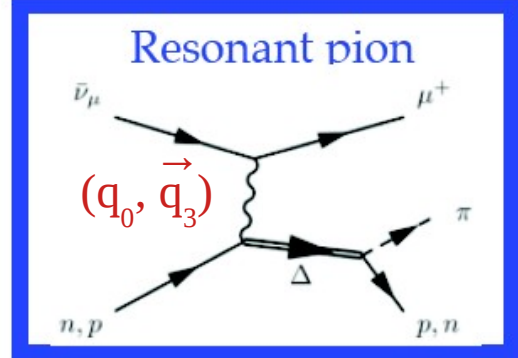
MINOS Near Detector:

- Muon spectrometer

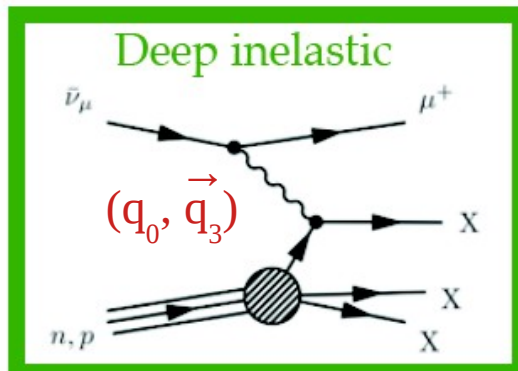
# $\nu$ and $\bar{\nu}$ interactions @ MINERvA



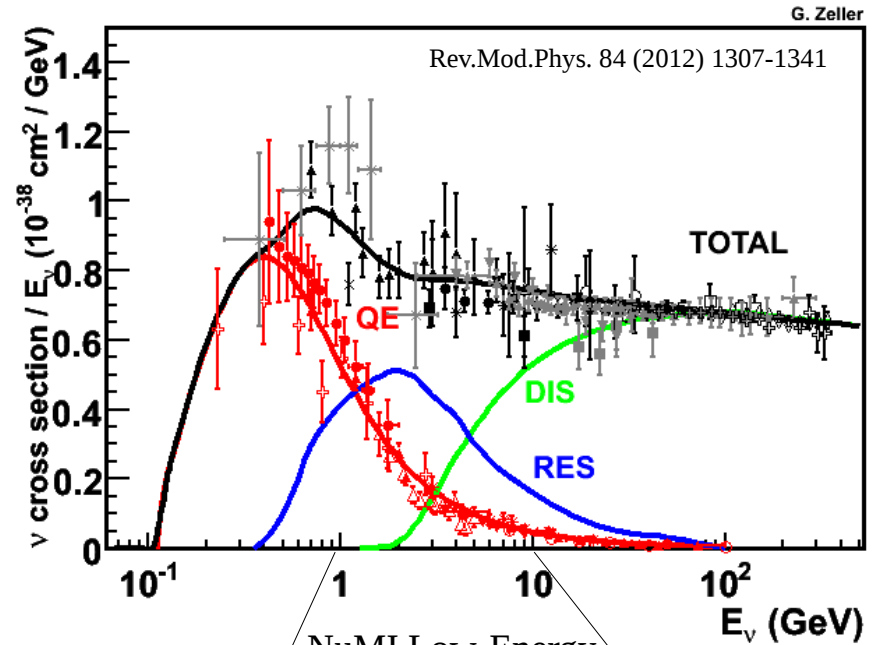
**QE**



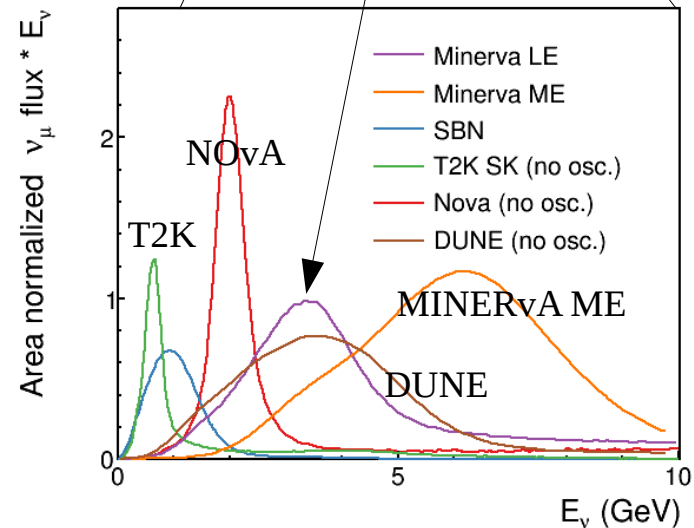
**RES**



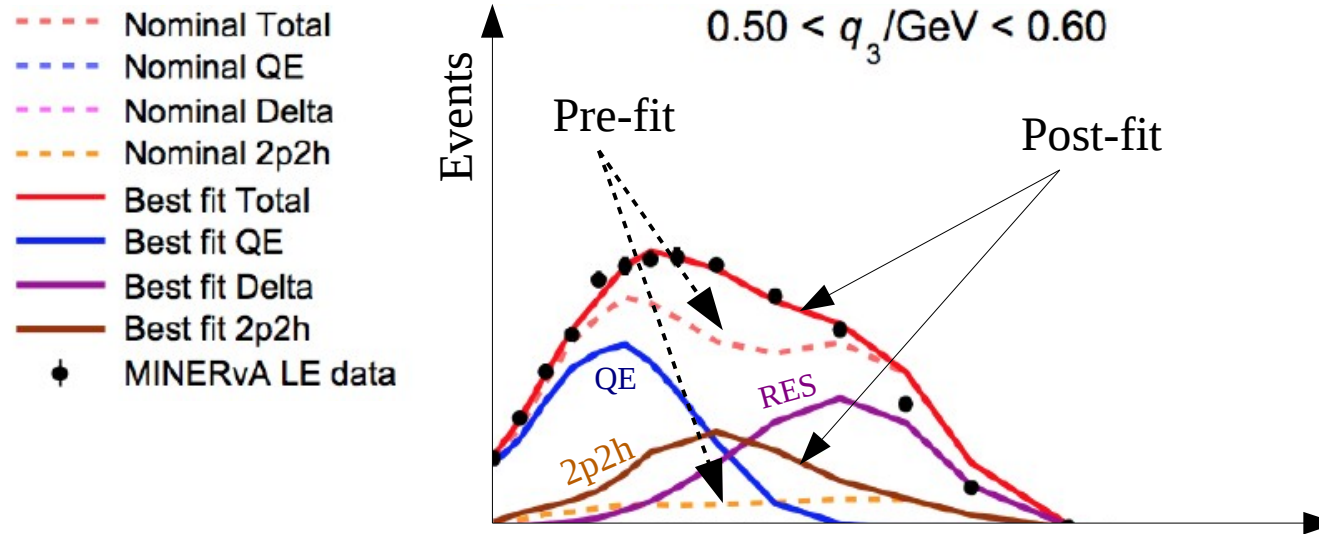
**DIS**



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



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



Available energy as energy transfer ( $q_0$ ) proxy

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

“Low-recoil” fit:

- Enhance Valencia\* 2p2h cross section as a function of ( $q_0$ ,  $q_3$ )
- Enhanced by 50% overall, by up to 200% in dip region
- Fit to neutrino; prediction for antineutrino

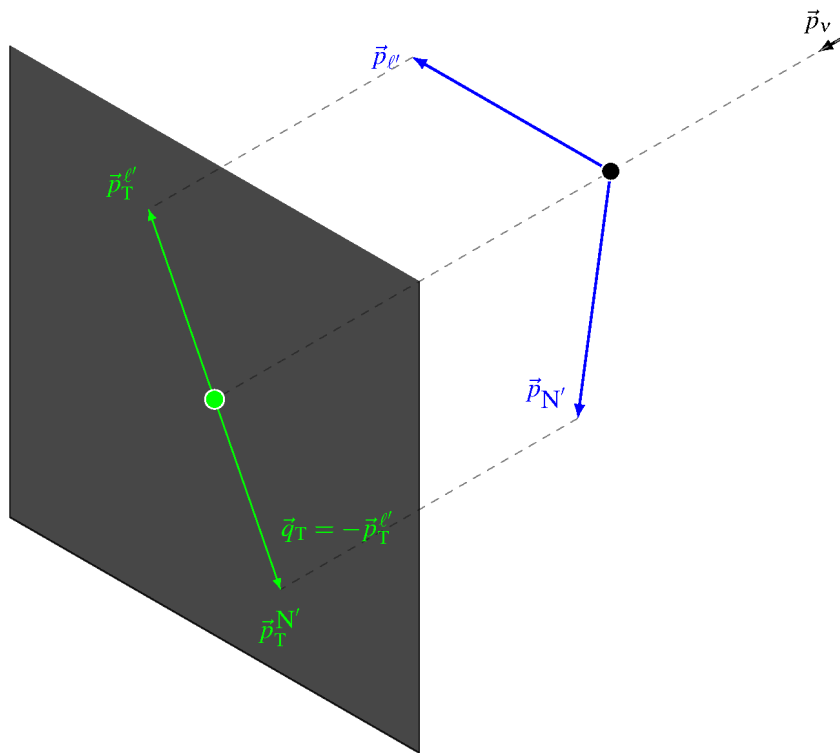
Phys.Rev.Lett. 116, 071802 (2016), Phys.Rev.Lett. 120, 221805 (2018)

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

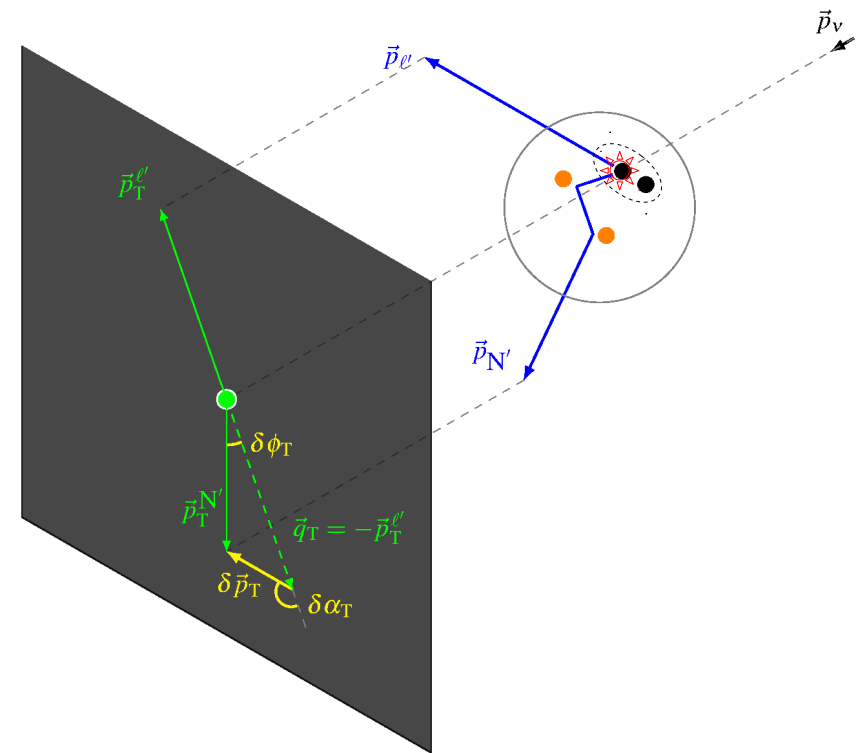
# Transverse Kinematic Imbalance (TKI)

– Precisely identify intranuclear dynamics or the absence thereof

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



Stationary nucleon target

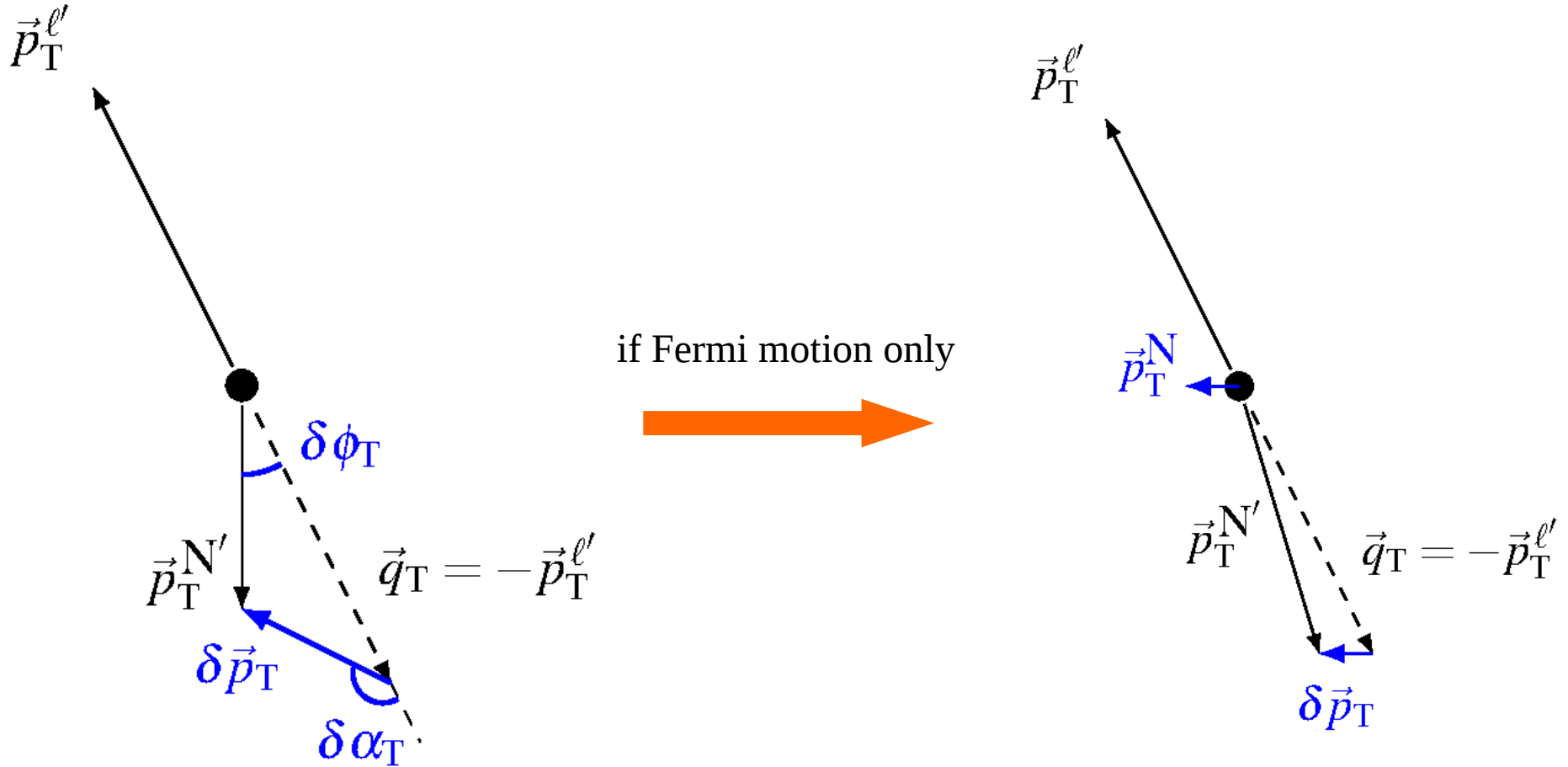


Nuclear target  
( $A > 1$ )

Fermi motion  
Final-state interactions  
Pion absorption  
2p2h

...

# Transverse Boosting Angle $\delta\alpha_T$

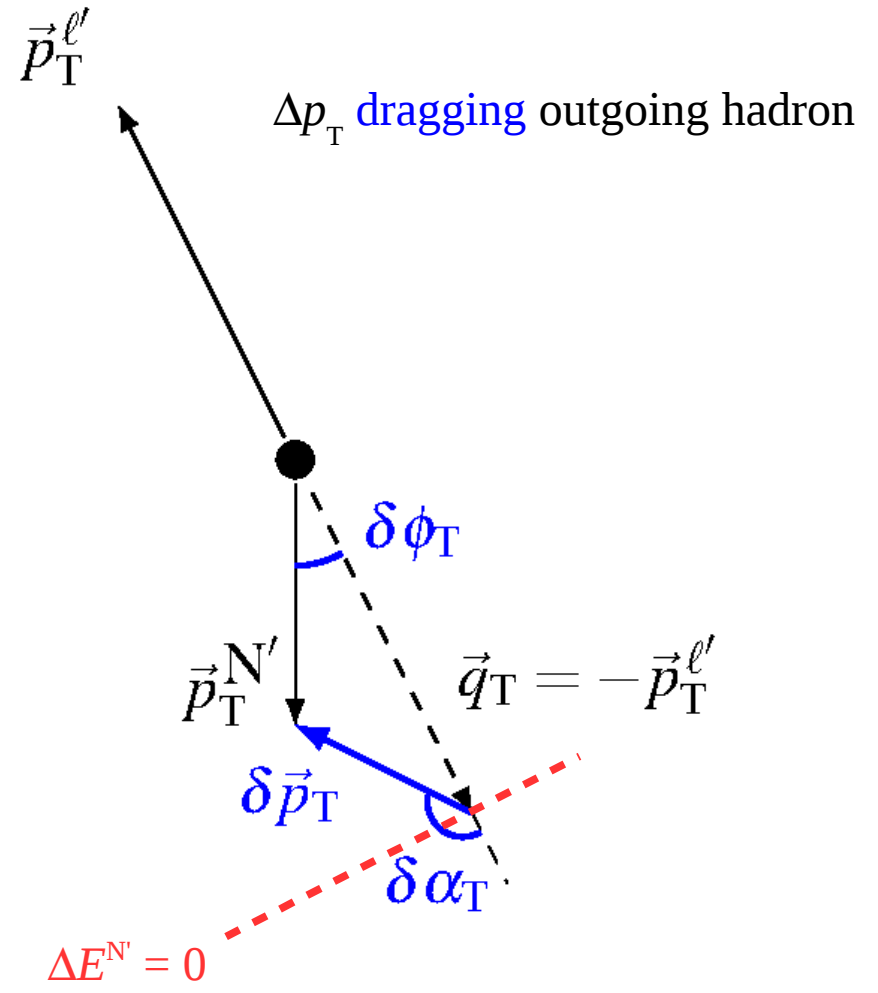
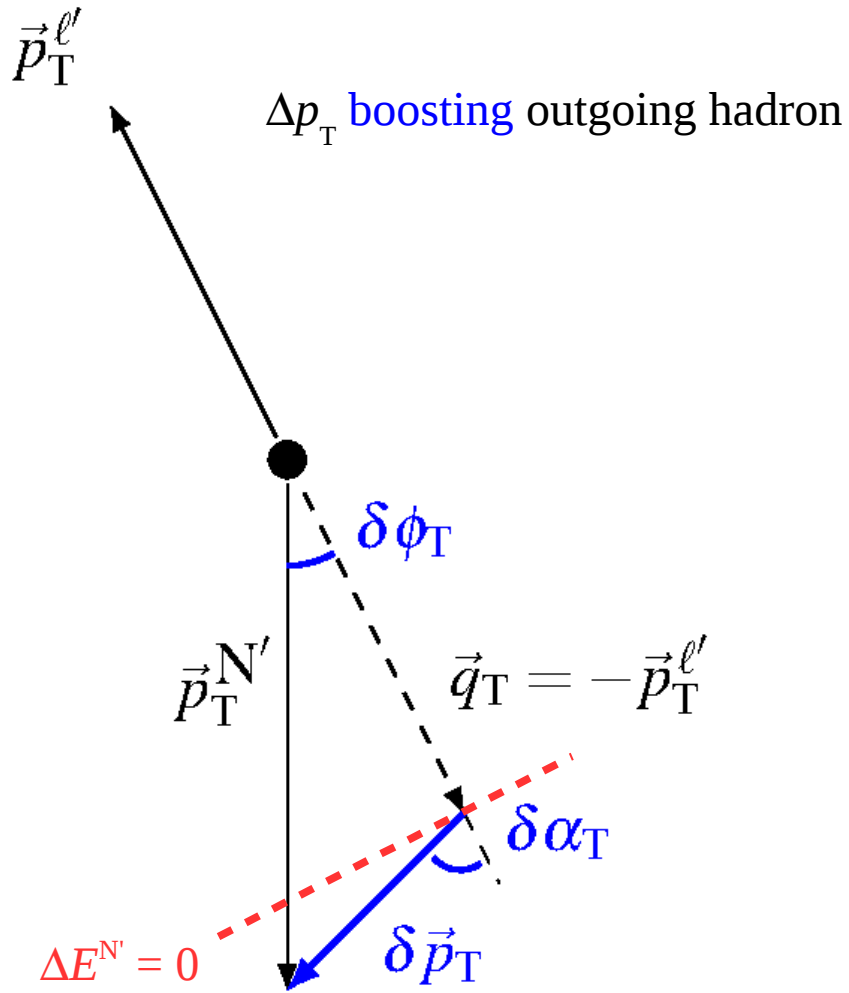


$$\delta\vec{p}_T = \vec{p}_T^N$$

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

Total transverse momentum  
 Transverse momentum imbalance  
 Missing  $p_T$  ...

# 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  $\mu$ -p-A' final states  
Use energy conservation to close the equations

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

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

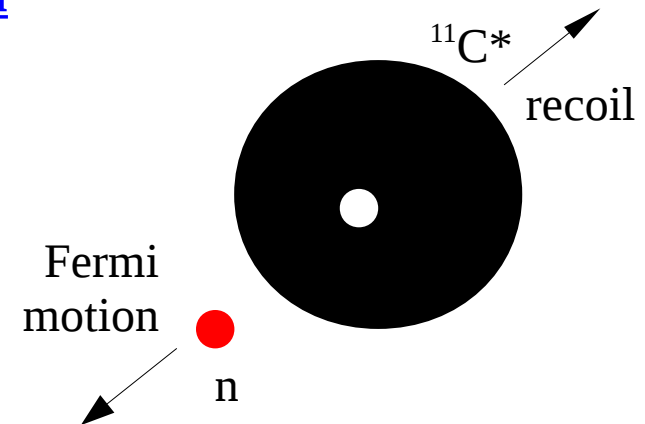
$p_n$ : recoil momentum of the nuclear remnant

final-state

**Dual Interpretation**

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

initial-state



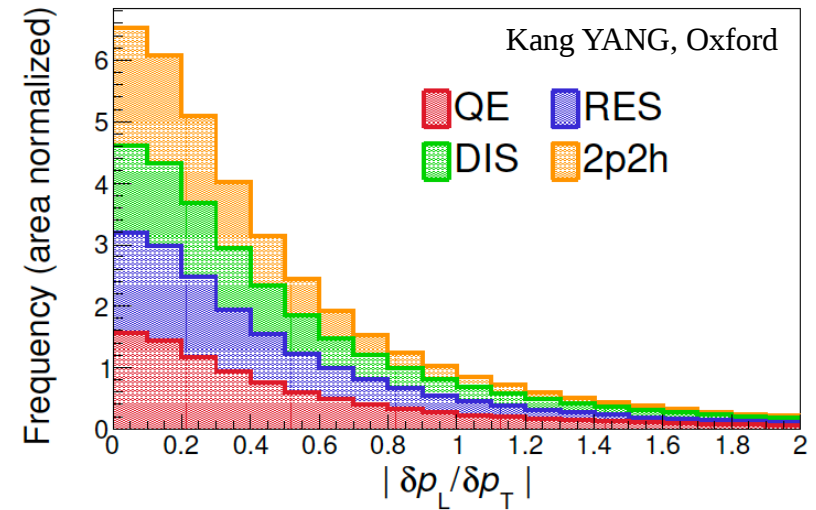
# Emulated Nucleon Momentum $p_N$

**TL;DR:**

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

$\delta p_T$  is promoted to  $p_N$  by  $\sim 10\%$  correction

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



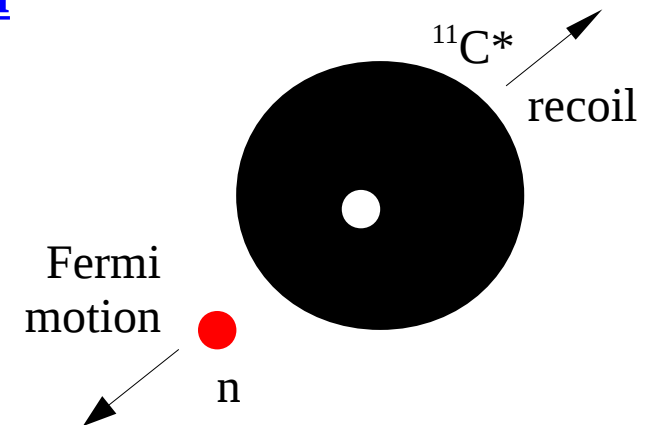
$p_n$ : recoil momentum of the nuclear remnant

final-state

Dual Interpretation

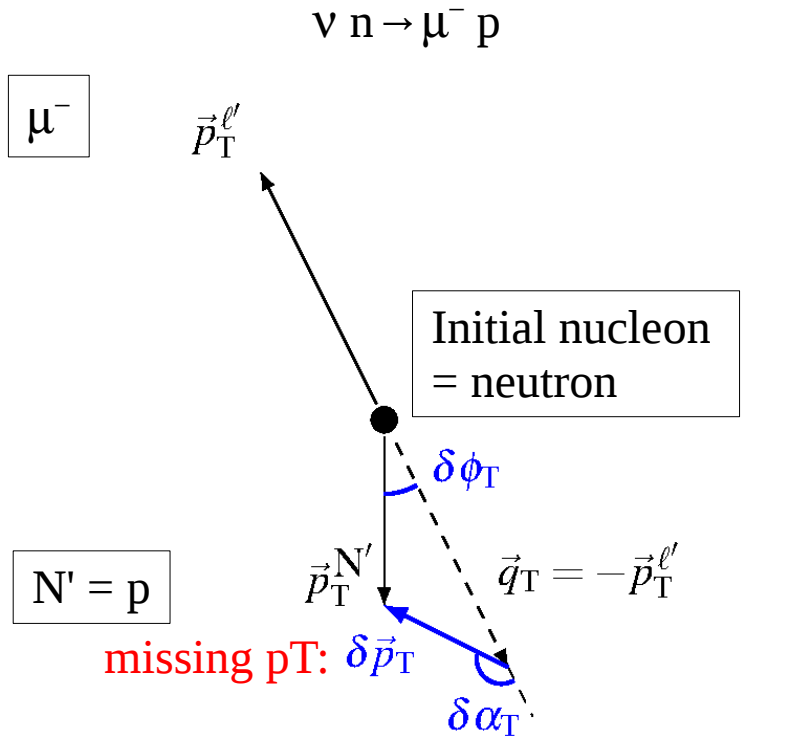
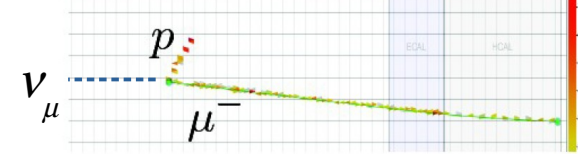
For CCQE,  $A' = {}^{11}\text{C}^*$   
 No more unknowns  
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initial-state



# TKI measurements @ MINERvA

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

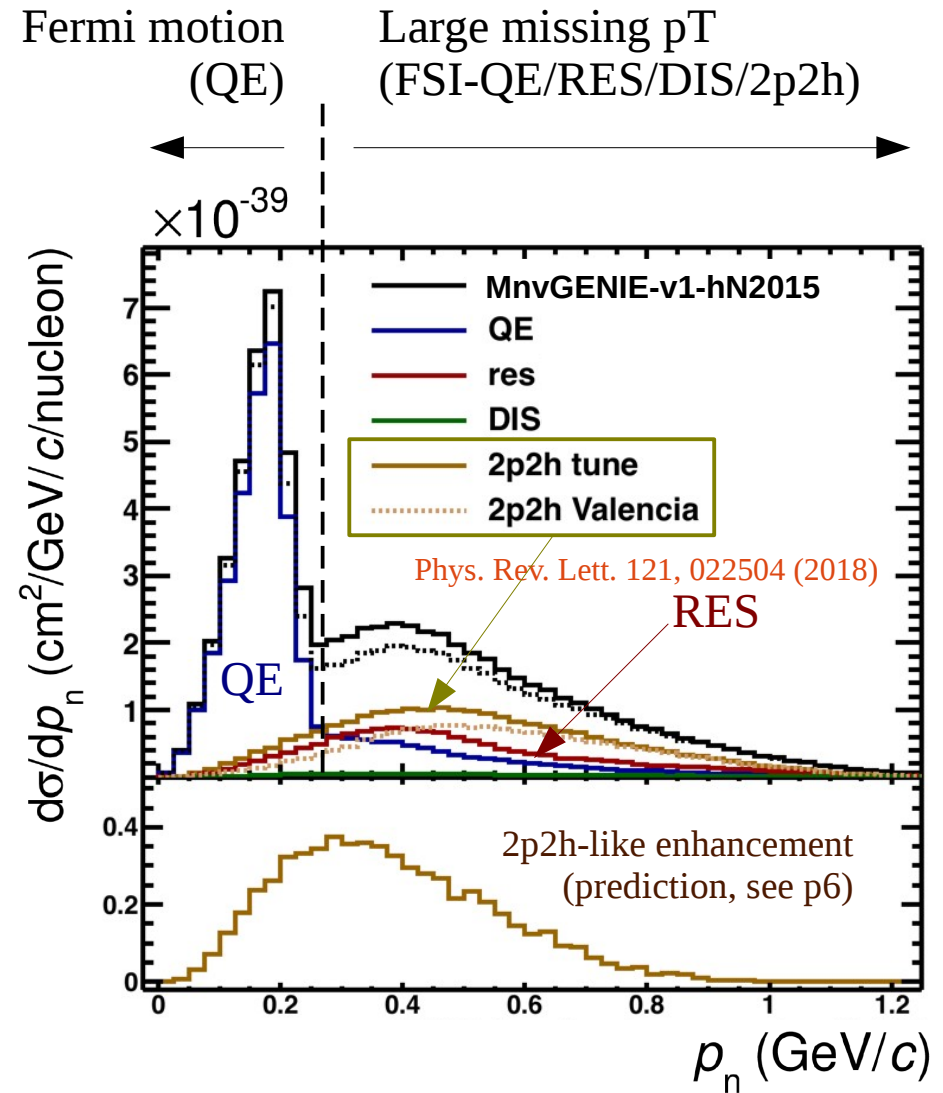
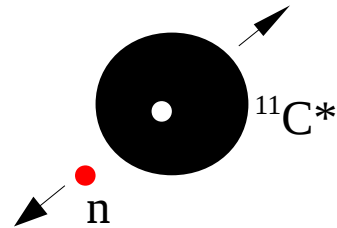


Assuming target remnant  $^{11}\text{C}^*$

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

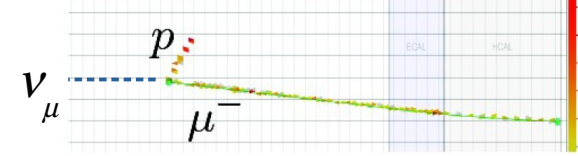
$$\sim [1 + O(10\%)] \times \delta p_T$$

Phys.Rev. C95, 065501 (2017)

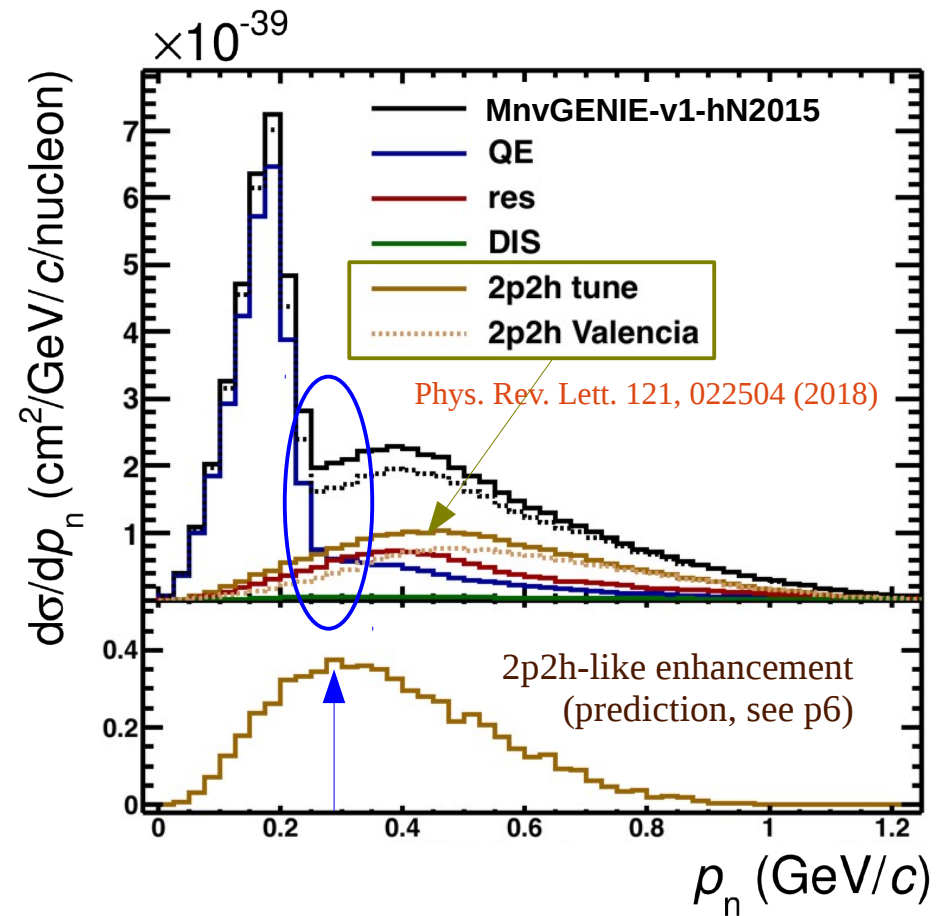
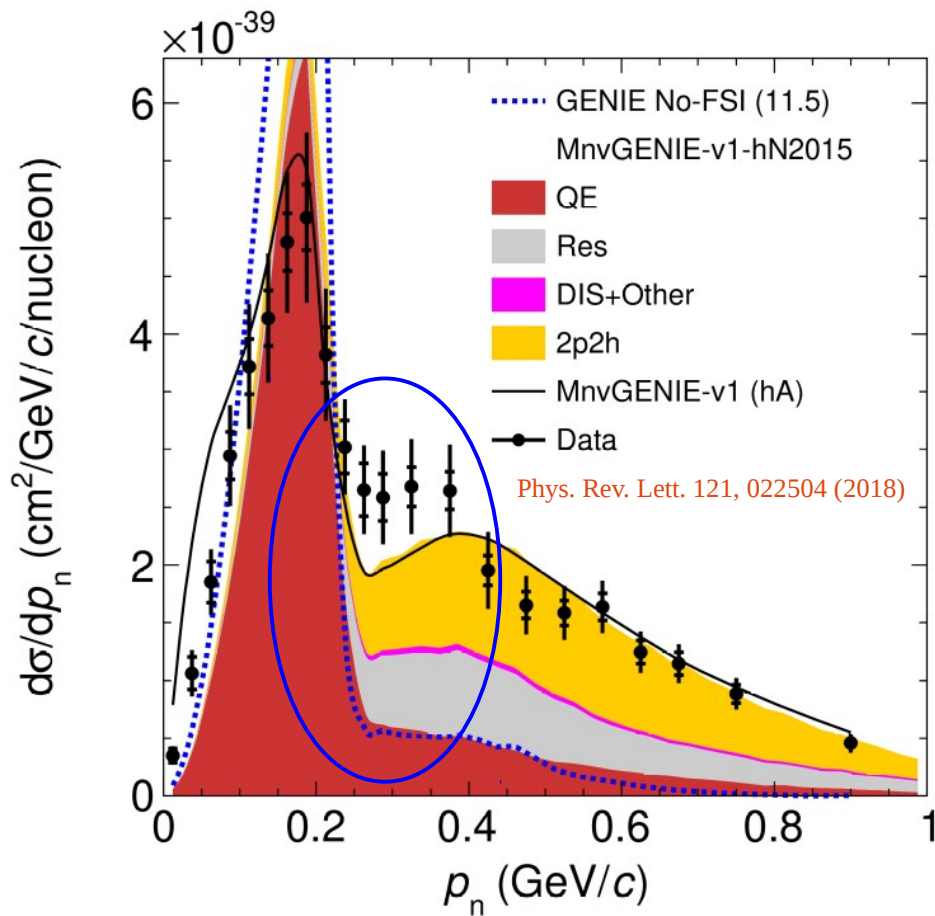


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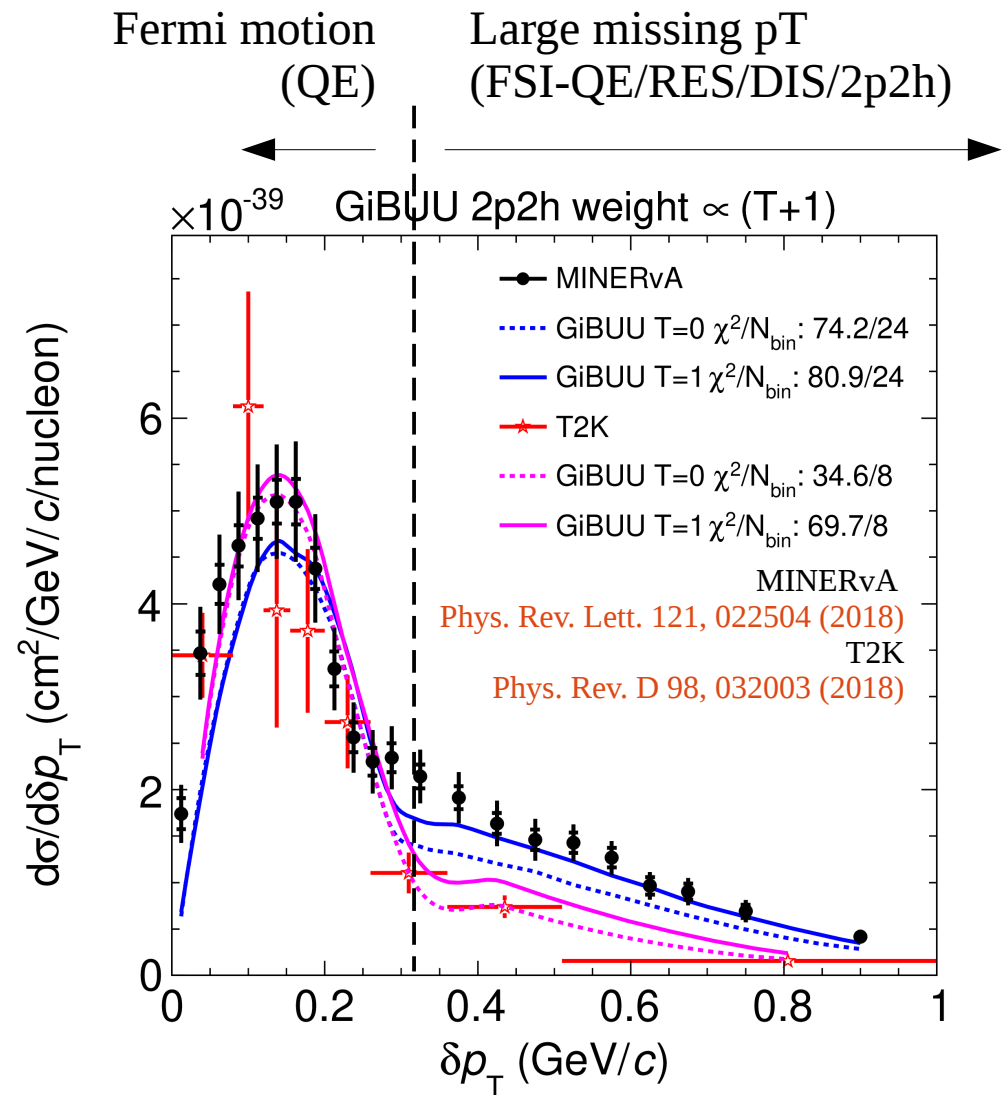
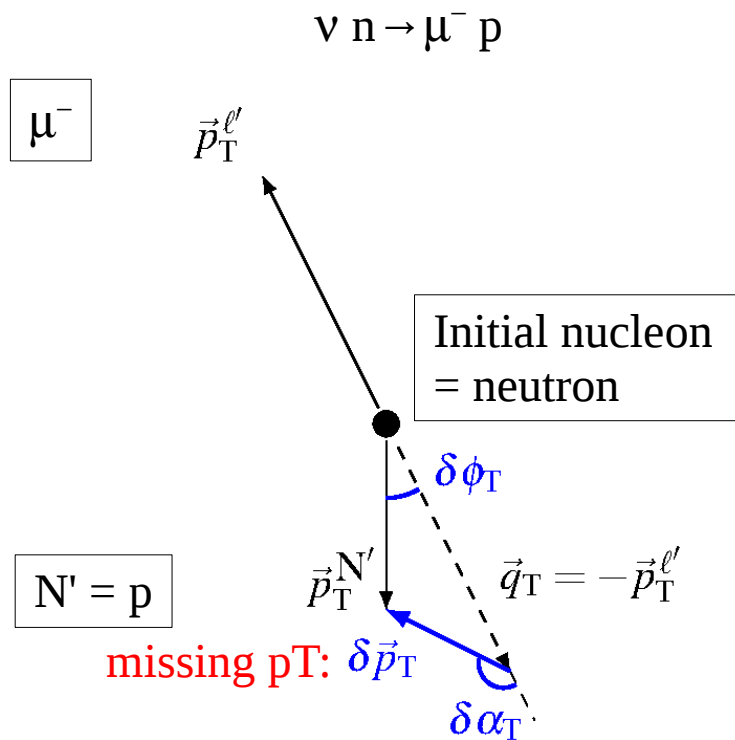


2p2h-like enhancement needs to be even stronger to fill the dip



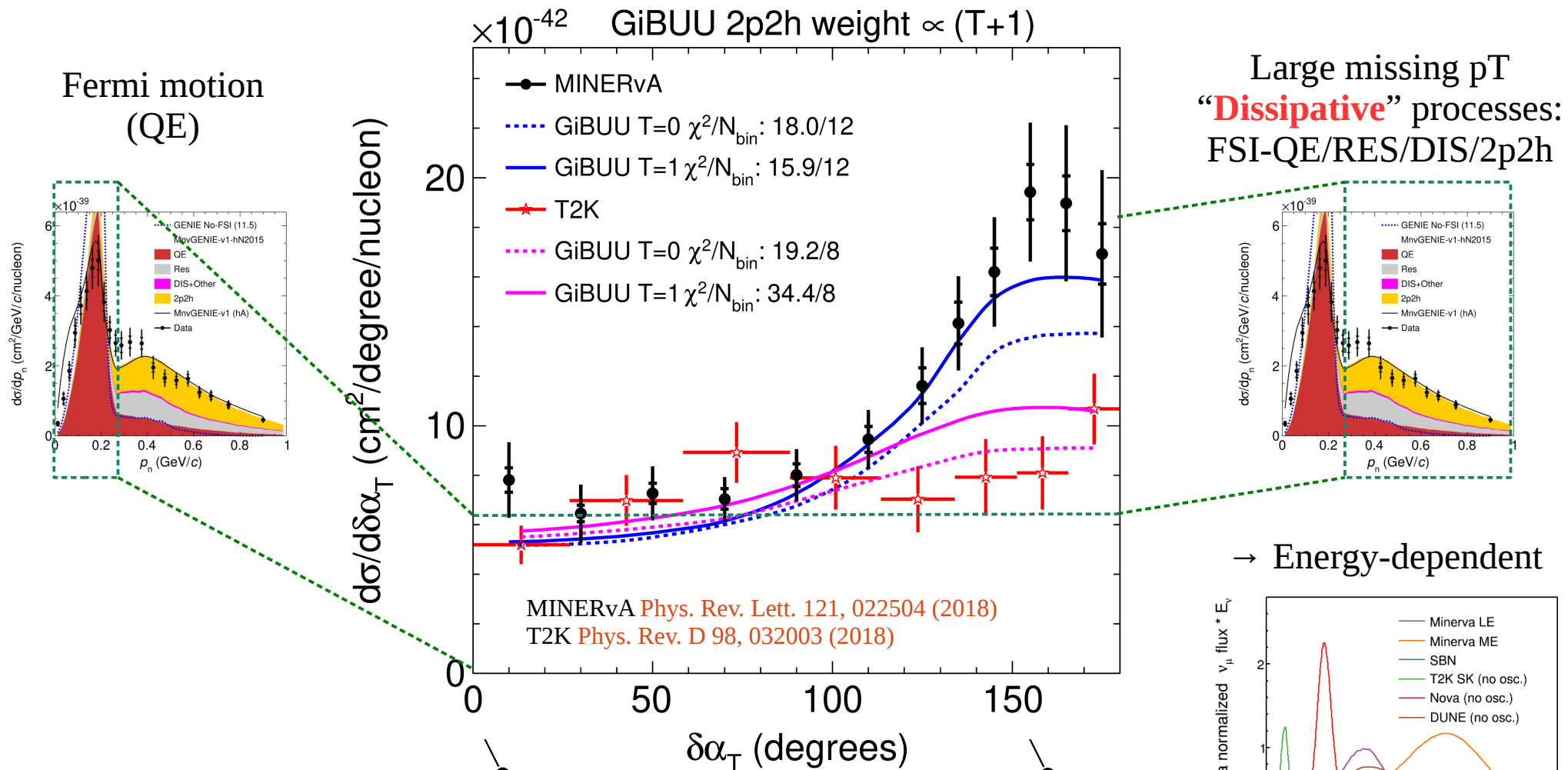
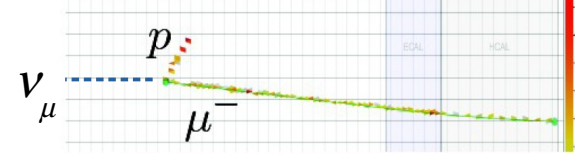
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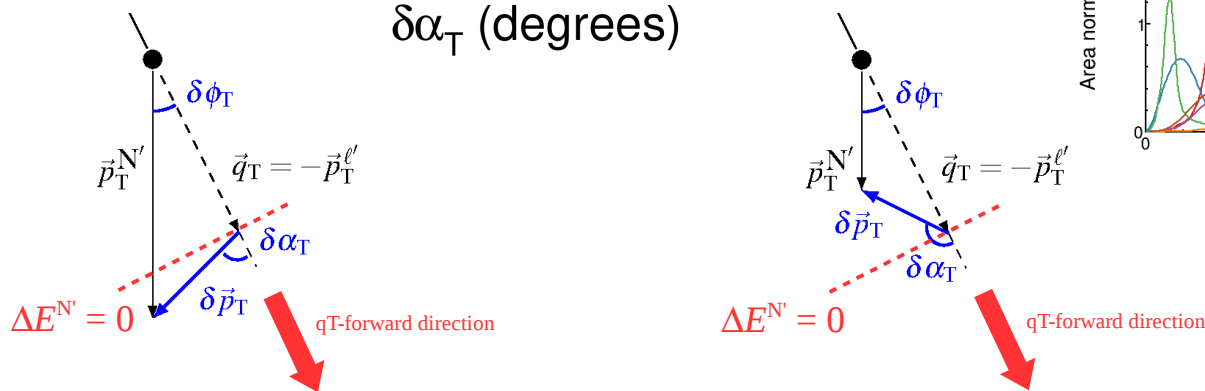
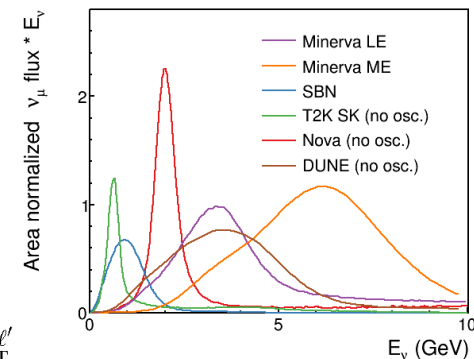


# TKI measurements @ MINERvA

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

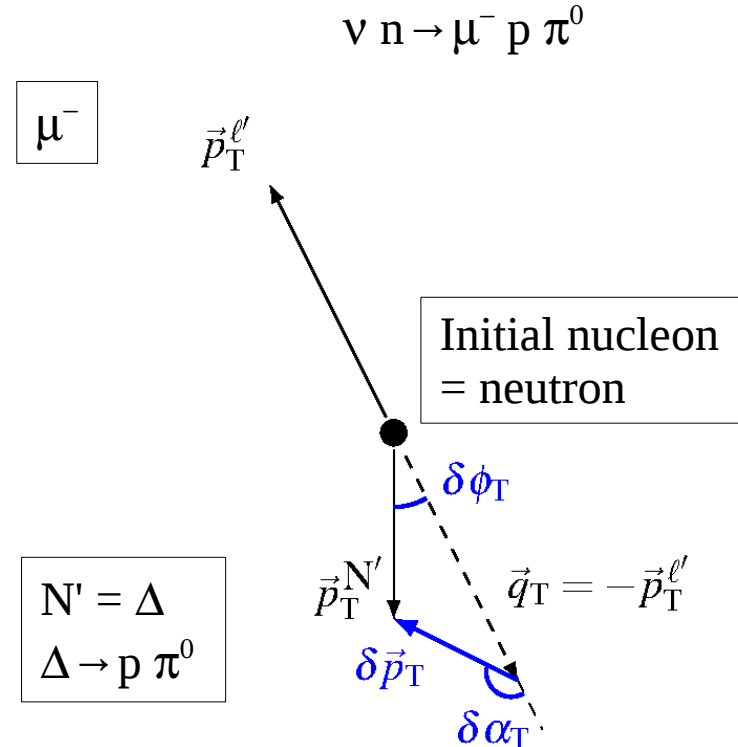
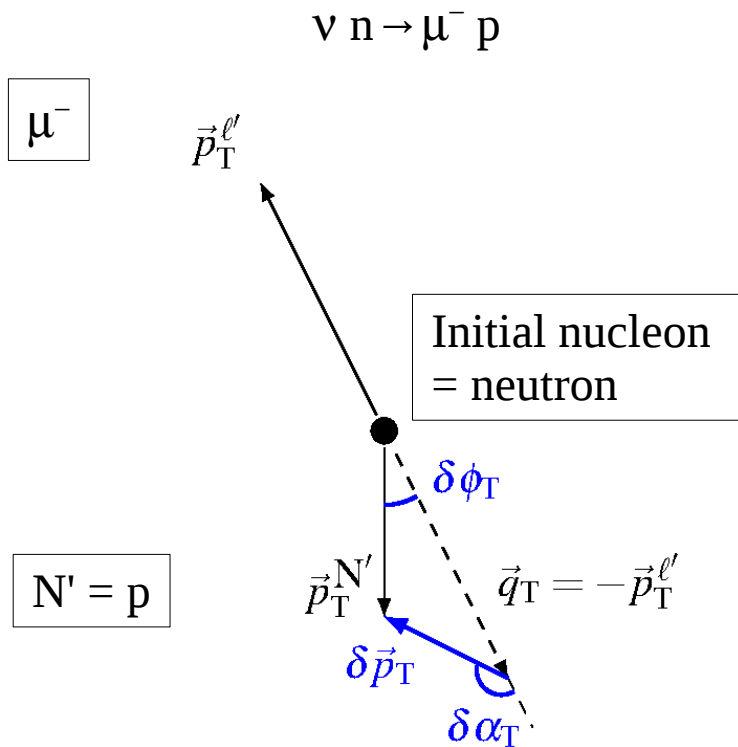
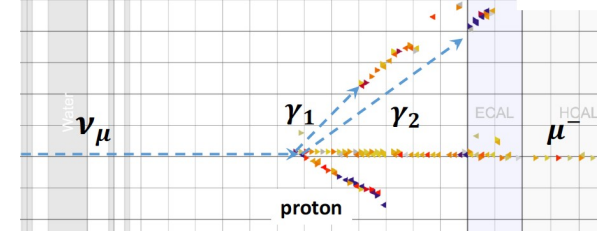


→ Energy-dependent



# TKI measurements @ MINERvA

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

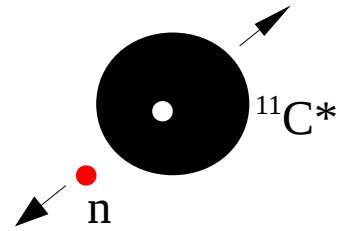
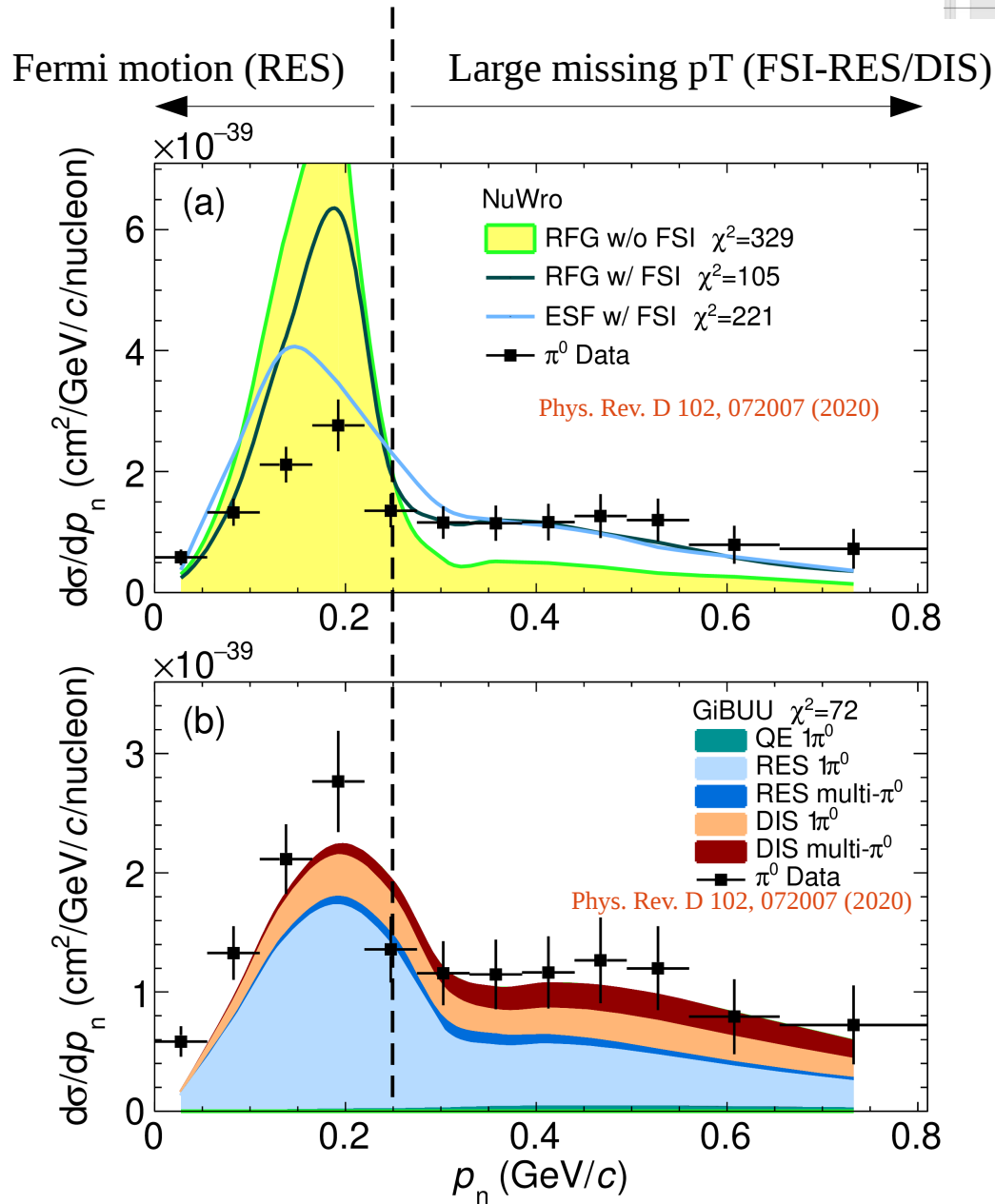
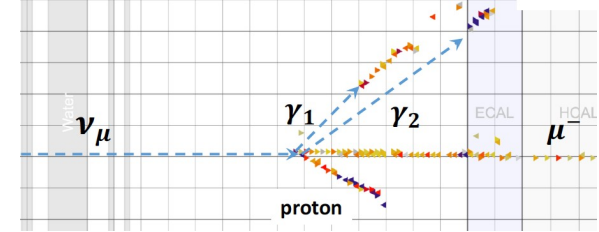


\*Generally,  $\nu/\bar{\nu} n/p \rightarrow \mu p \pi^{+/-/0}$

Phys.Rev.C 99, 055504 (2019)

# TKI measurements @ MINERvA

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

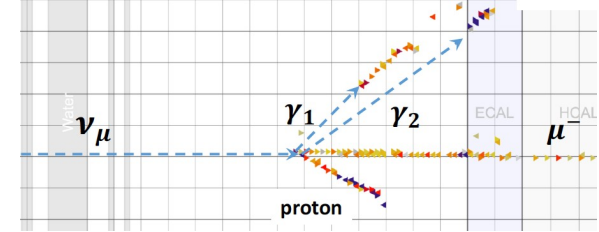


× Fermi motion peak in pion production worse modeled than in QE

✓ Large missing pT region reasonably modeled

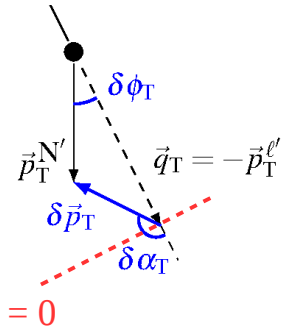
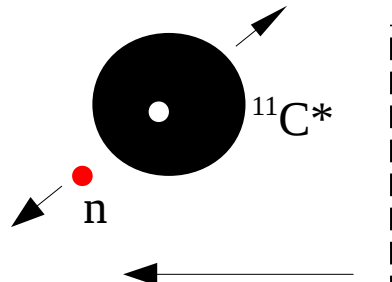
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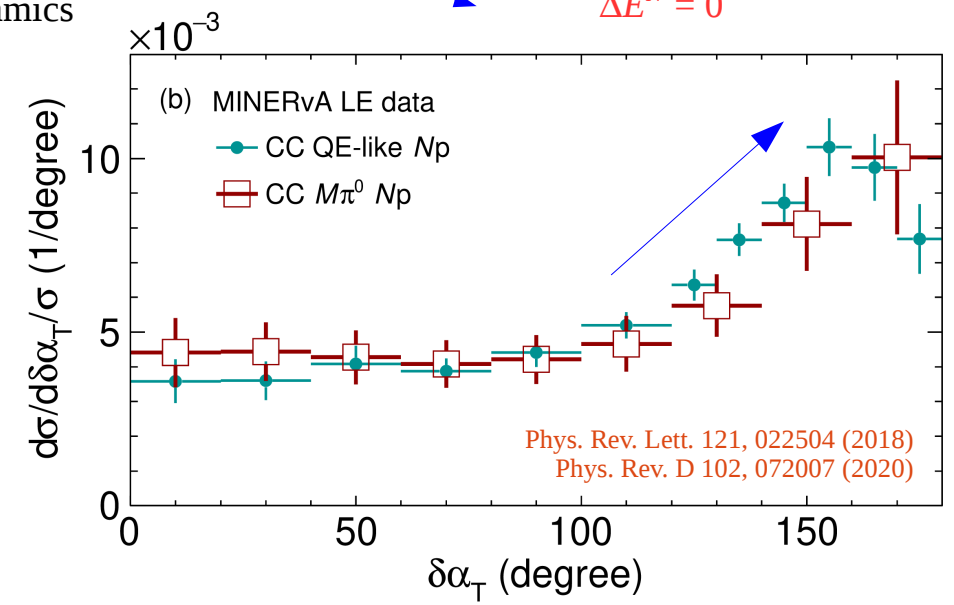
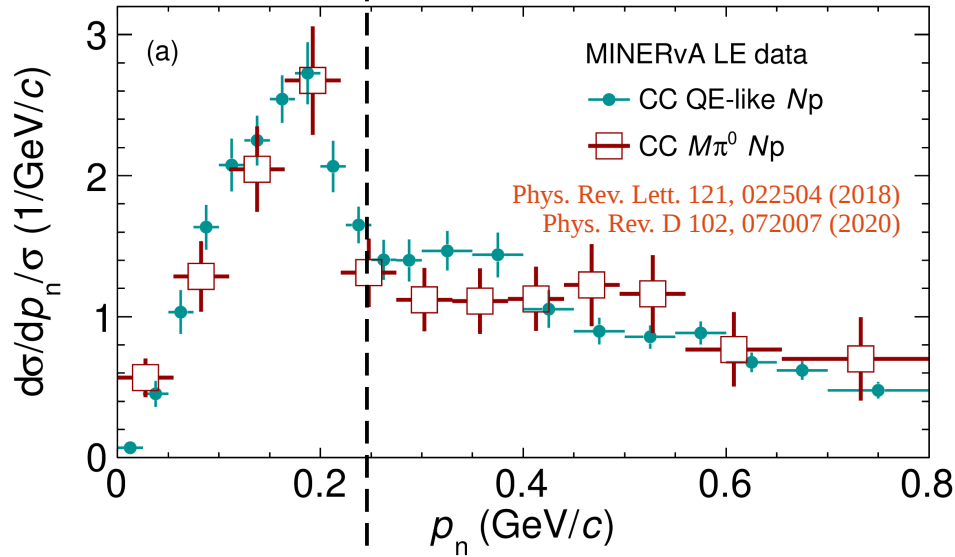


Shape comparison between QE-like and pion production

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



Large missing  $p_T$  ( $\delta p_T$ )  
Dissipative dynamics



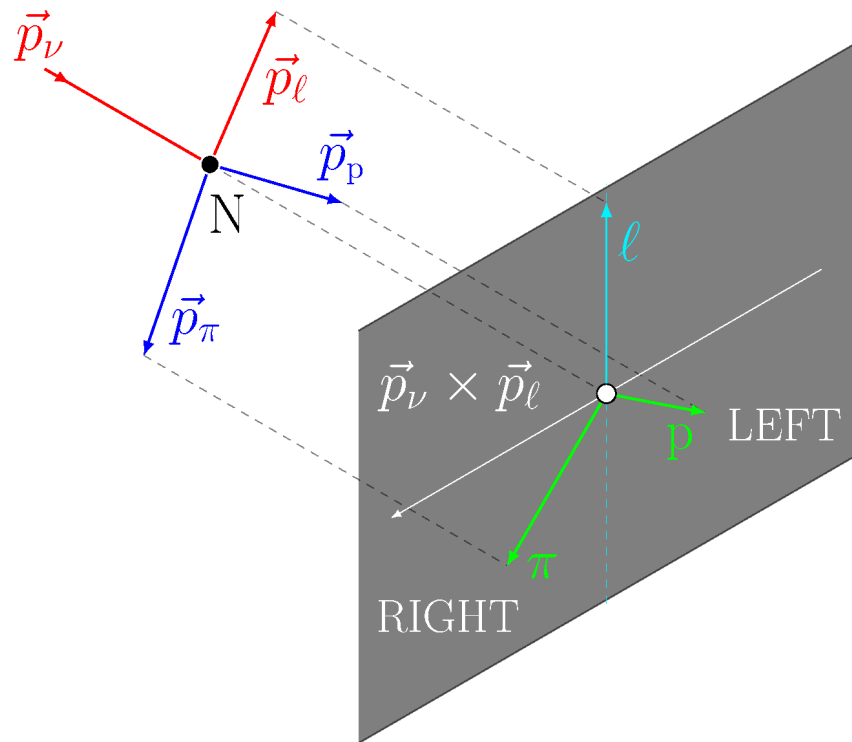
Large missing  $p_T$ : pion absorption  
Open  $\pi$  (pion production)

↕  
absorbed  $\pi$  (QE-like)

# TKI measurements @ MINERvA

– Left-right asymmetry in pion production

Phys. Rev. D 100, 073010 (2019)



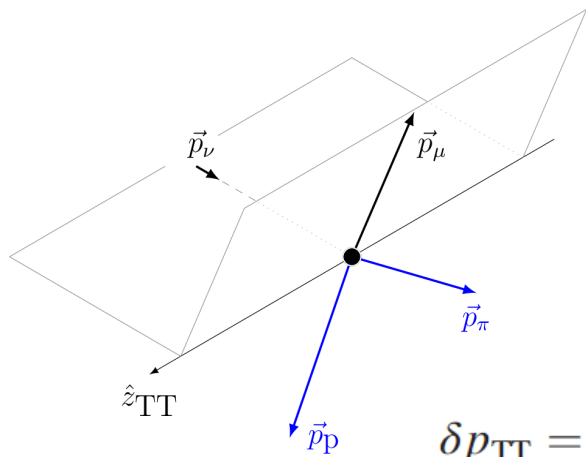
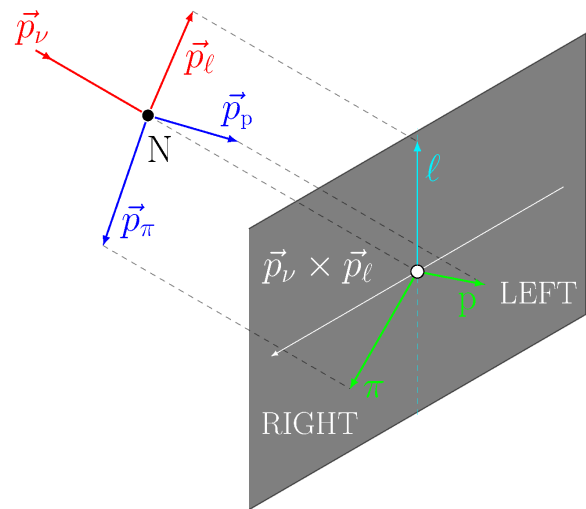
Measurement	Beam energy (GeV)	ALR	Error
ANL	0.9	0.053	0.035
MINERvA	3	0.15	0.10
T2K	0.6	0.038	0.046

- The (pion) asymmetry seems to be increasing with energy: pion prefers left, proton right
- Previous measurements have large errors  
[for full review, see [Phys. Rev. D 100, 073010 \(2019\)](#)]

$$A_{\text{LR}} \equiv \frac{N_{\text{L}} - N_{\text{R}}}{N_{\text{L}} + N_{\text{R}}}$$

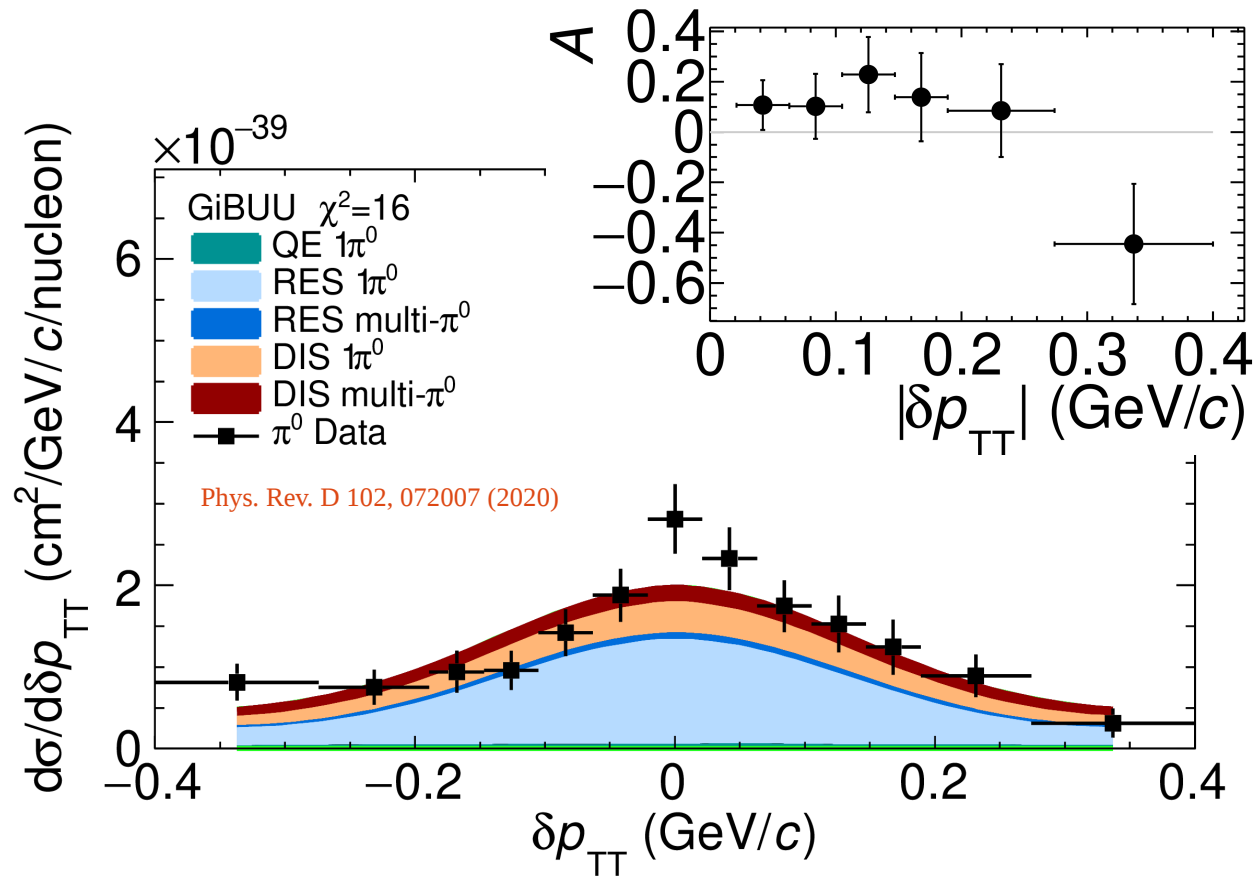
# TKI measurements @ MINERvA

– Double-transverse kinematic imbalance in pion production



$$\delta p_{\text{TT}} = \delta \vec{p}_{\text{T}} \cdot \hat{z}_{\text{TT}}$$

$$= \vec{p}_{\text{h}} \cdot \hat{z}_{\text{TT}},$$

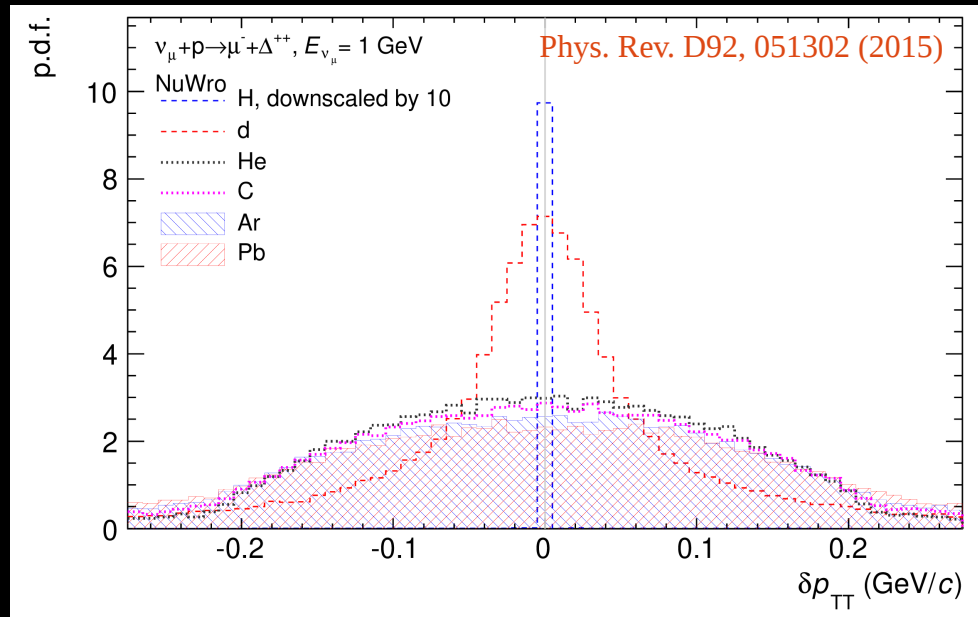


- If proton prefers right, that is  $z_{\text{TT}} > 0$

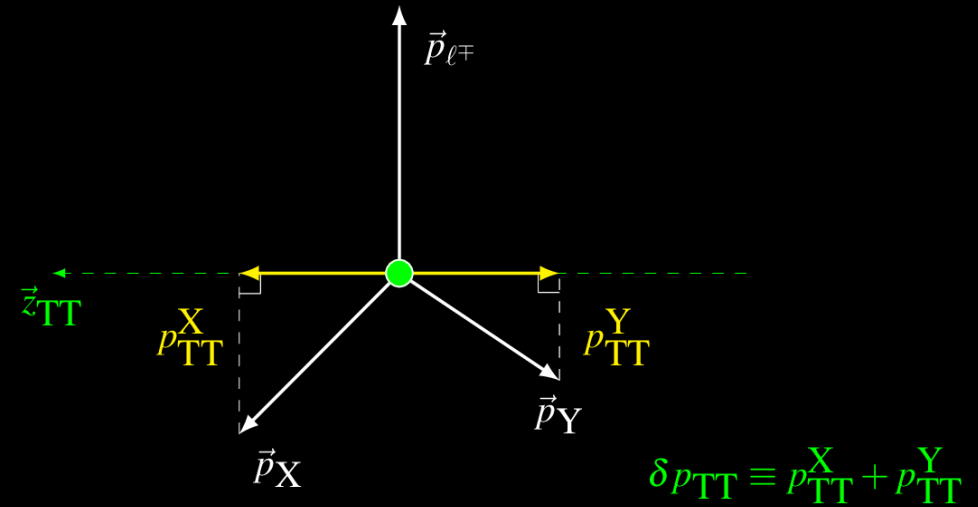
$$\delta p_{\text{TT}} = |\vec{p}_{\text{p}} \cdot \hat{z}_{\text{TT}}| - |\vec{p}_{\pi^0} \cdot \hat{z}_{\text{TT}}|$$

- dpTT asymmetry affected by proton and pion FSI
- No such asymmetry in models; observed mild ones

# Neutrino-Hydrogen Interactions



$\{X, Y\}$   
 $= \{p, \pi^+\}$  for  $\nu + p \rightarrow \ell^- + \Delta^{++}$   
 or  $\{p, \pi^-\}$  for  $\bar{\nu} + p \rightarrow \ell^+ + \Delta^0$



Double-transverse momentum imbalance  $\delta p_{TT}$

- H: 0
- Heavier nuclei: irreducible symmetric broadening
  - by Fermi motion  $O(200 \text{ MeV})$  and FSI
- $\text{CH}_n$ :  $\nu\text{H}$  interaction can be extracted
  - $\nu\text{H } \delta p_{TT} \sim O(<10\text{MeV})$  after detector smearing
  - $\nu\text{C } \delta p_{TT} \sim 200 \text{ MeV}$

**Might be feasible in NINJA?**

**Similar proposal in DUNE**

**Phys. Rev. D 102, 033005 (2020)**

# Discussion on application on NINJA

MINERvA and T2K are reporting interesting results on Transverse Kinematic Imbalance, or TKI, and there are more to come

- Require exclusive measurement of final-state particles: muon-proton, or muon-proton-pion system
  - PID
  - Momentum resolution better than  $\sim 3\%$
- Production rate depends on beam energy
  - For MINERvA, both QE and RES have large statistics
  - For T2K ND280, QE dominant, very few RES
  - NINJA: on-axis, energy between T2K and MINERvA, might well have enough statistics past the RES onset
- TKI @ NINJA
  - Intranuclear dynamics: Fermi motion, FSI, 2p2h
  - Nucleon level production cross section for QE and RES
  - Direct measurement of neutrino-hydrogen interaction → novel beam flux constraint

Thank you!

# BACKUP

# 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]

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