皮影 Shadow play
Source: http://www.cnhubei.com/ztmjys-pyts

Neutrino Shadow Play
– Neutrino interactions for oscillation measurements

Xianguo LU / 卢显国 University of Oxford

INT-18-1a: Nuclear ab initio Theories and Neutrino Physics
Seattle, 9 March 2018

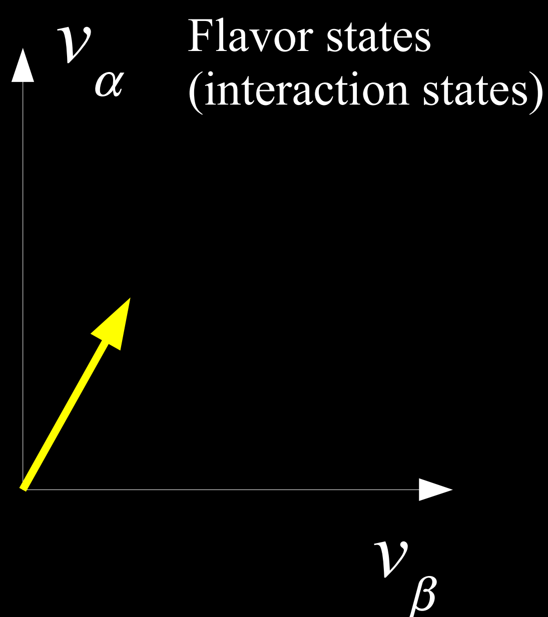
THE Universe

– Matter & very little antimatter (matter-antimatter asymmetry)

CP-Symmetry violation (CP violation)

Neutrino

– Oscillation



The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

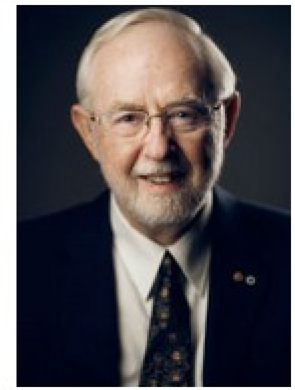


Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

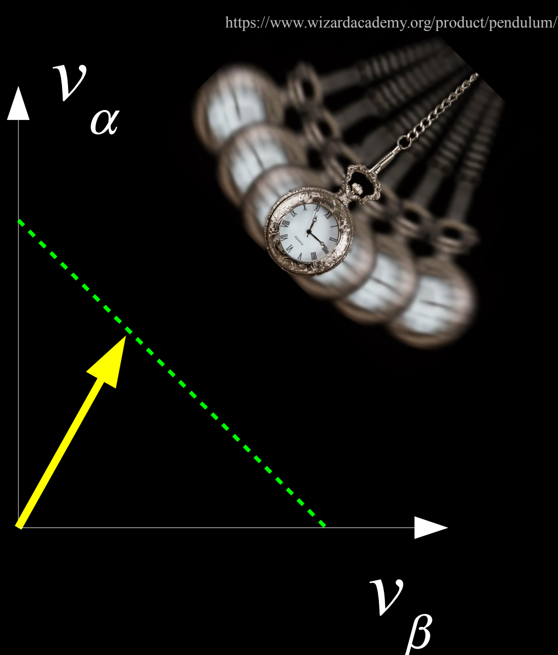
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

https://www.nobelprize.org/nobel_prizes/physics/laureates/2015/

Neutrino mass:
shift between interaction and propagation states

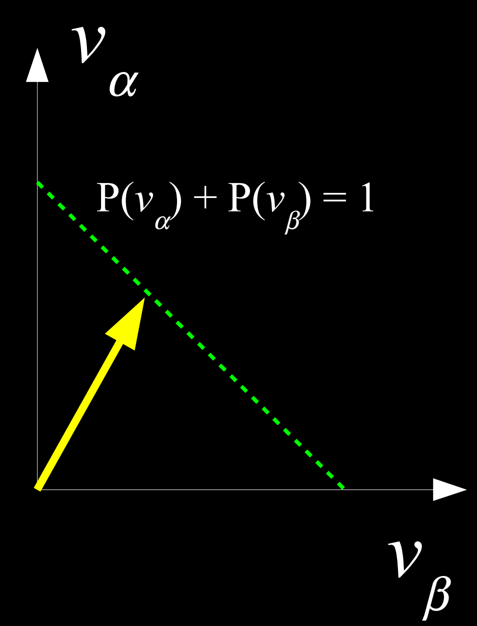
Neutrino

– Oscillation



oscillation between flavor states as a function of time

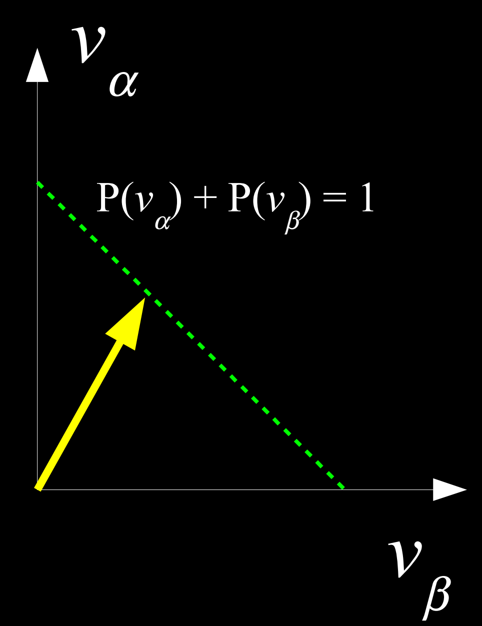
Neutrino
– Oscillation



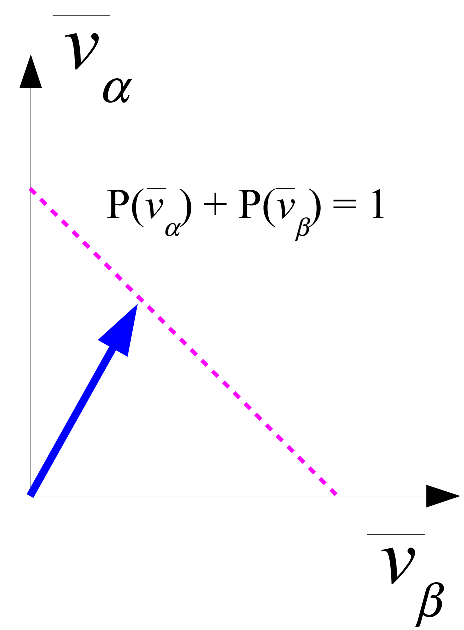
oscillation between flavor states as a function of time

Neutrino

– Oscillation



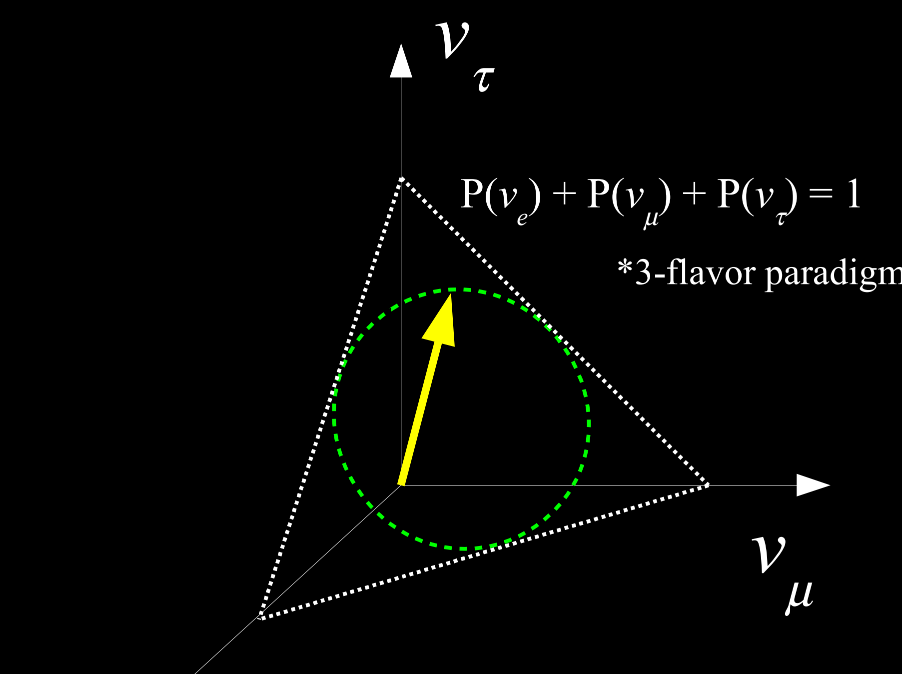
oscillation between flavor states as a function of time



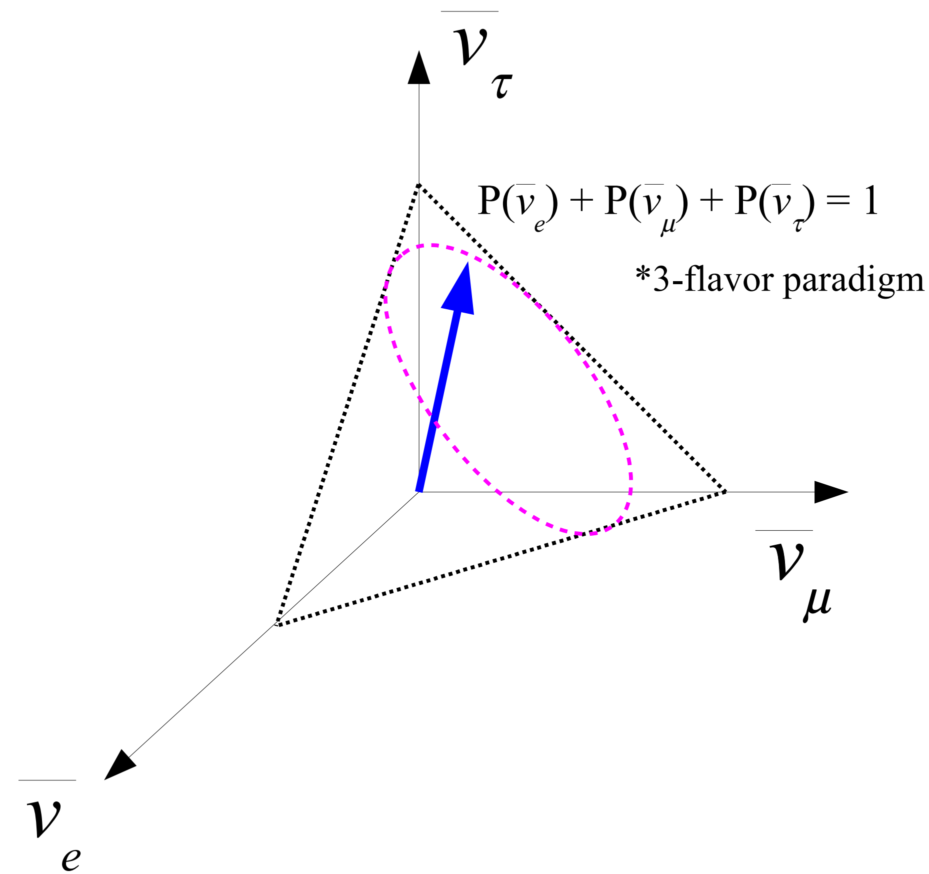
If only 2 flavors, same oscillation behavior
→ CP violation not observed

Neutrino

– CP violation



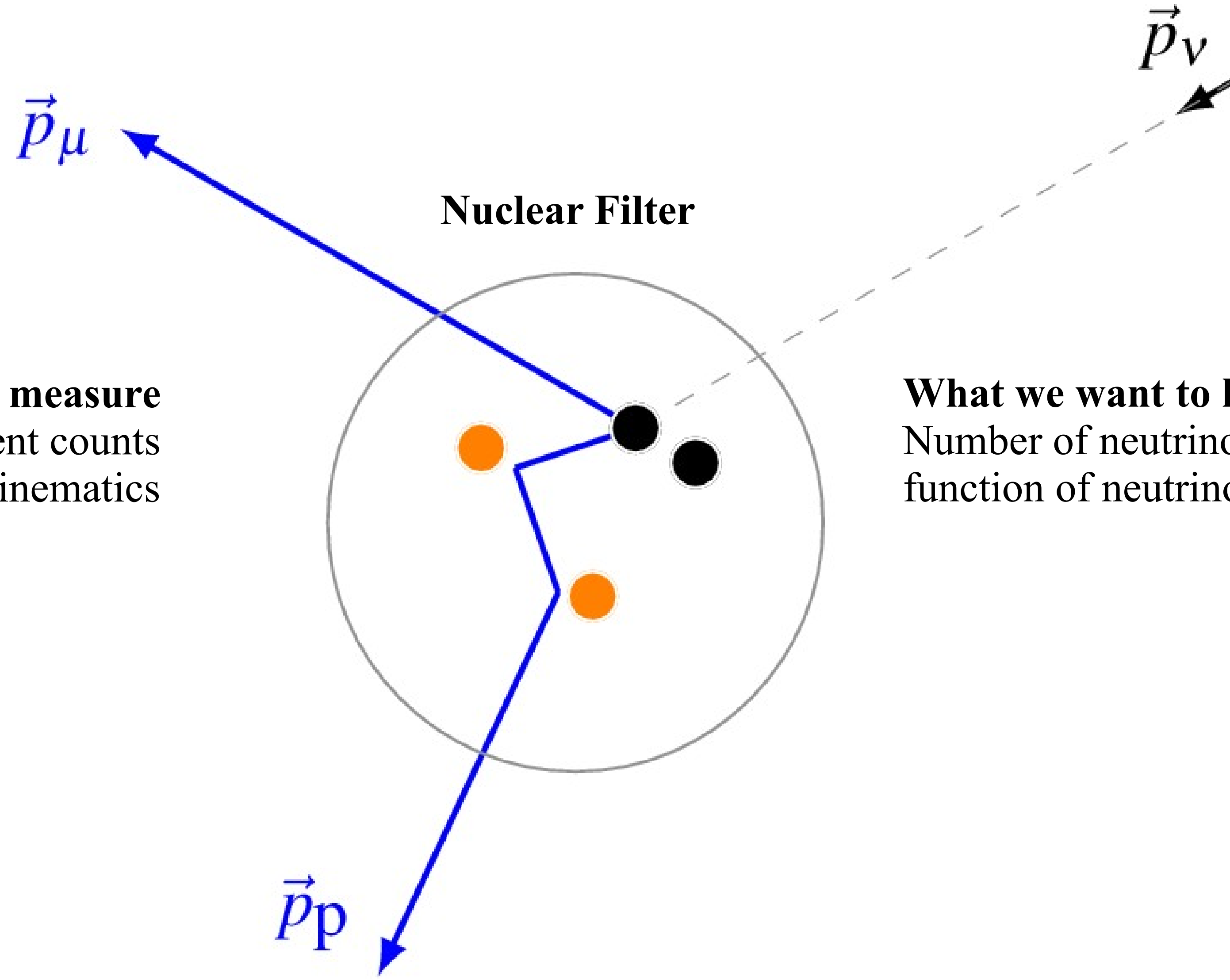
oscillation between flavor states as a function of time ~distance/energy



Oscillation property difference
→ CP violation

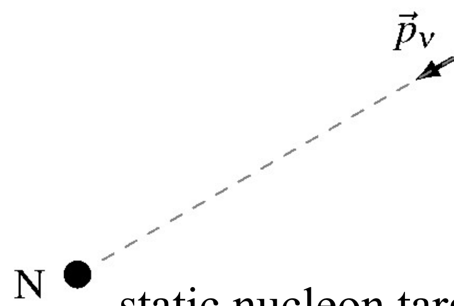
The big picture of neutrino detection in oscillation measurements

What we measure
Event counts
Final-state kinematics



What we want to know about
Number of neutrinos as a function of neutrino energy

Neutrino energy in GeV regiem

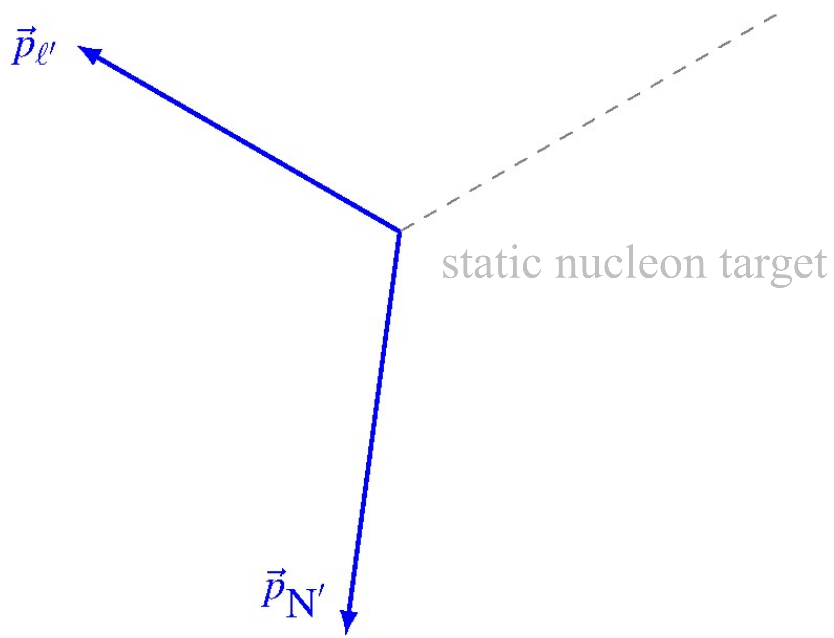


static nucleon target

Quasi-elastic scattering (QE)

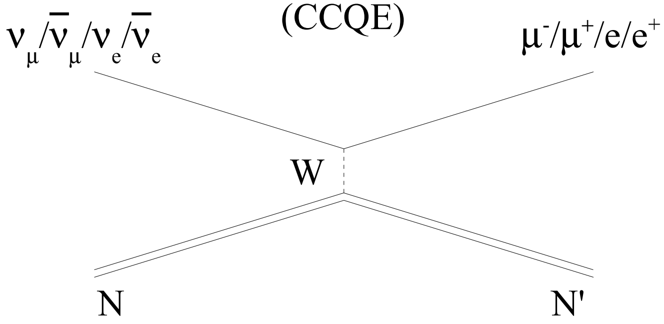
$\nu \mathrm{n} \to \ell^{-} \mathrm{p}$

charged current (CC) ν → *l′*

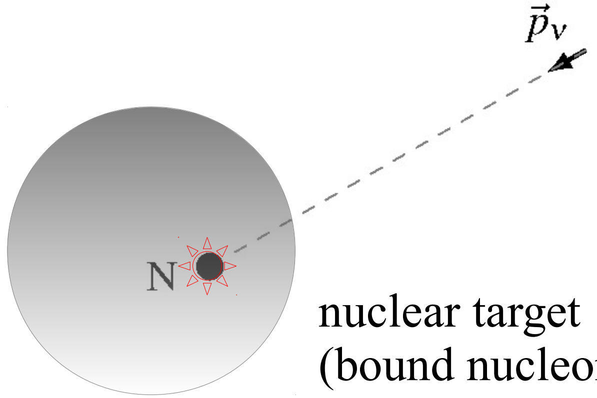


quasi-elastic (QE) N → N'

Charged-Current Quasi-Elastic (CCQE)



Fermi motion biases E_ν reconstruction

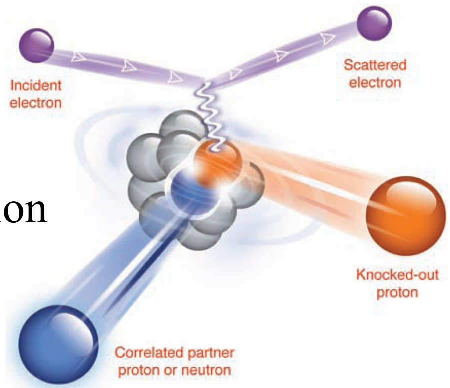


nuclear target
(bound nucleon)

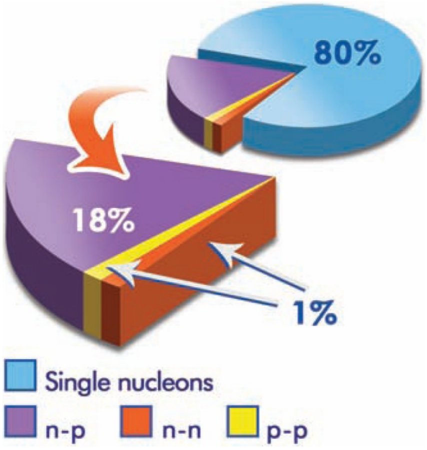
Fermi motion biases E_ν reconstruction

Multinucleon correlations:

initial correlation
large relative motion

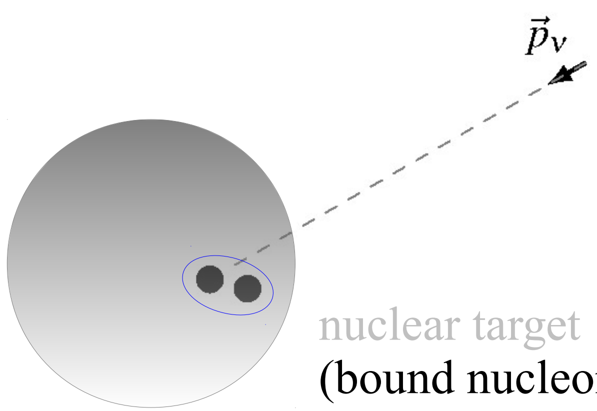


Science 320 (2008) 1476-1478



Fermi motion biases E_ν reconstruction

Multinucleon correlations:
cross section unknown, strong bias to *all* final-state kinematics



nuclear target
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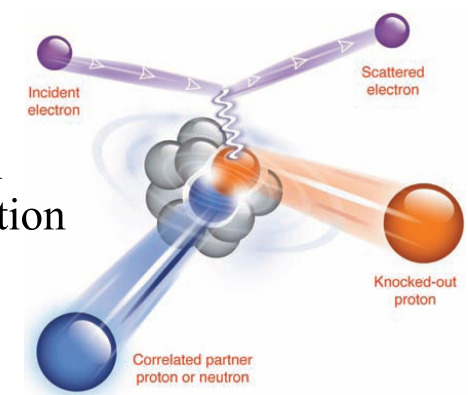
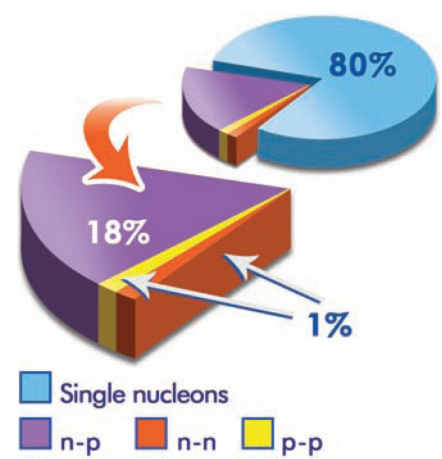


Science 320 (2008) 1476-1478



In particle-hole excitation:

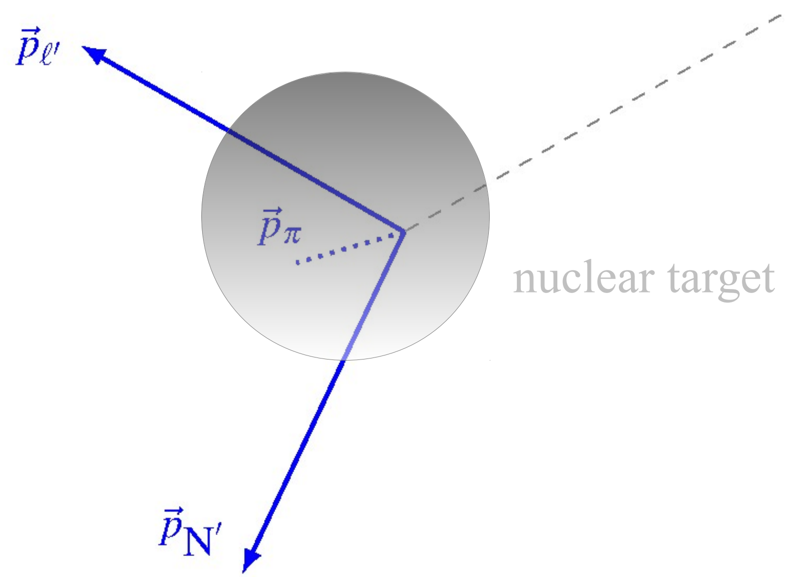
- Impulse approximation: independent particles (1p1h)
- RPA (random phase approximation): sum of 1p1h excitation (over all pairs) → "screening effect"
- npnh (n≥2): sub-leading terms in ph expansion → short range correlations, meson exchange currents *etc.*

Fermi motion biases E_ν reconstruction

Multinucleon correlations:
cross section unknown, strong bias to *all* final-state kinematics

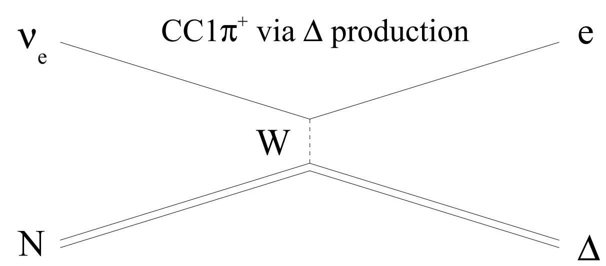
QE-like: π absorbed in nucleus ← final-state interaction (FSI)

charged current (CC) ν → *l'*



Resonance production (RES)

$$\nu p \to \ell^- \Delta^{++} \to \ell^- p \pi^+$$



QE-like N → N'
including resonance production (RES) Δ → N'π followed by π absorption

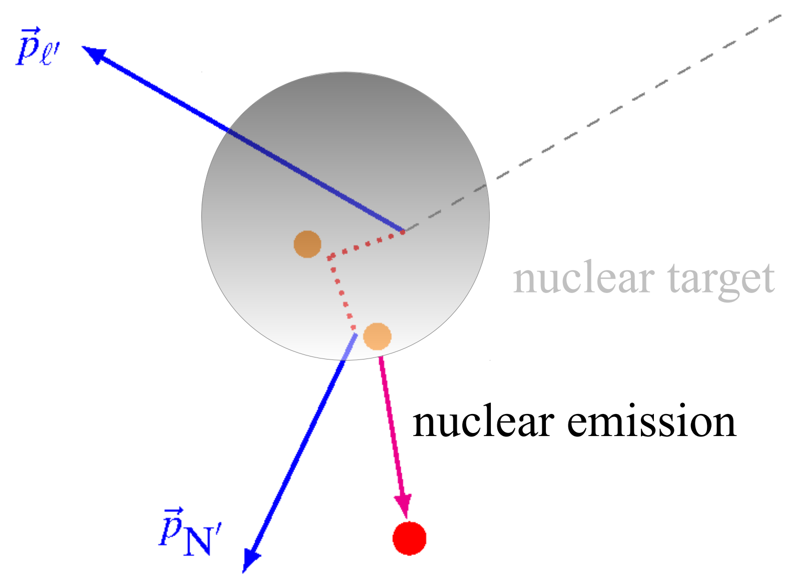
Fermi motion biases E_ν reconstruction

Multinucleon correlations:
cross section unknown, strong bias to *all* final-state kinematics

QE-like: π absorbed in nucleus ← final-state interaction (FSI)

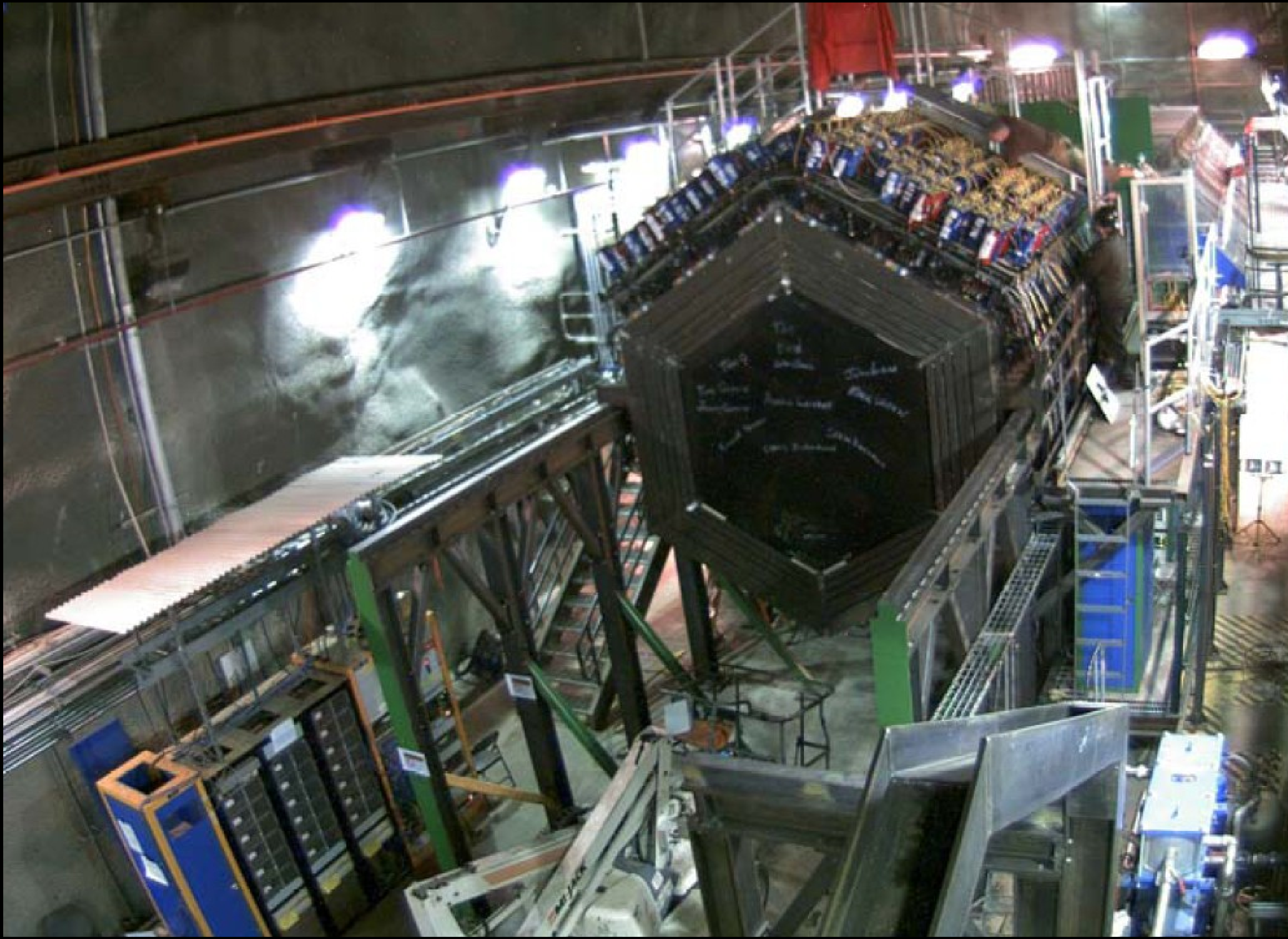
FSI → energy-momentum transferred in nucleus, possible nuclear emission

charged current (CC) $\nu \rightarrow l'$



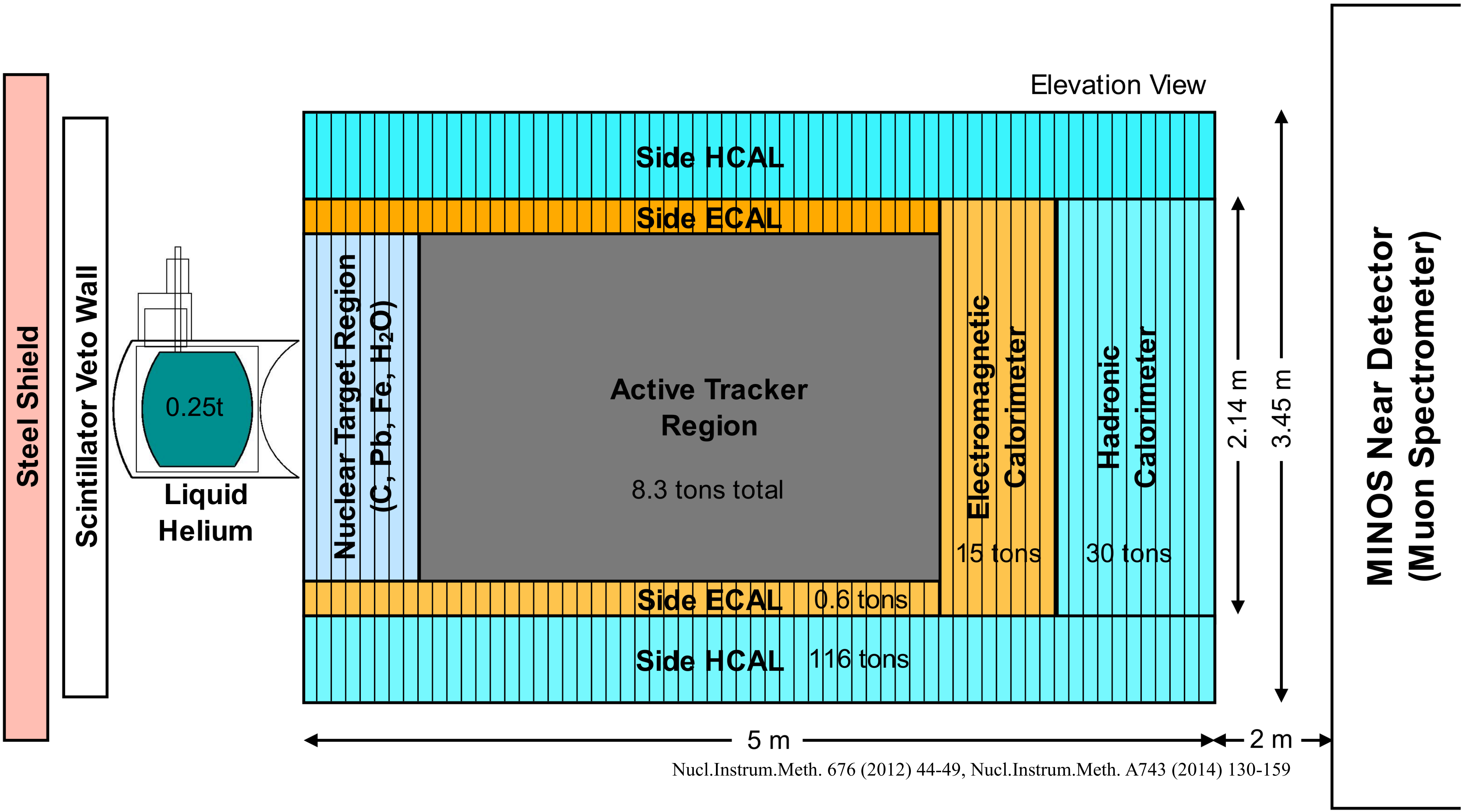
QE-like N → N'
including resonance production (RES) Δ → N'π followed by π absorption

MINERvA



Source: http://vmsstreamer1.fnal.gov/VMS_Site_03/VMSFlash/090924Minerva/index.htm

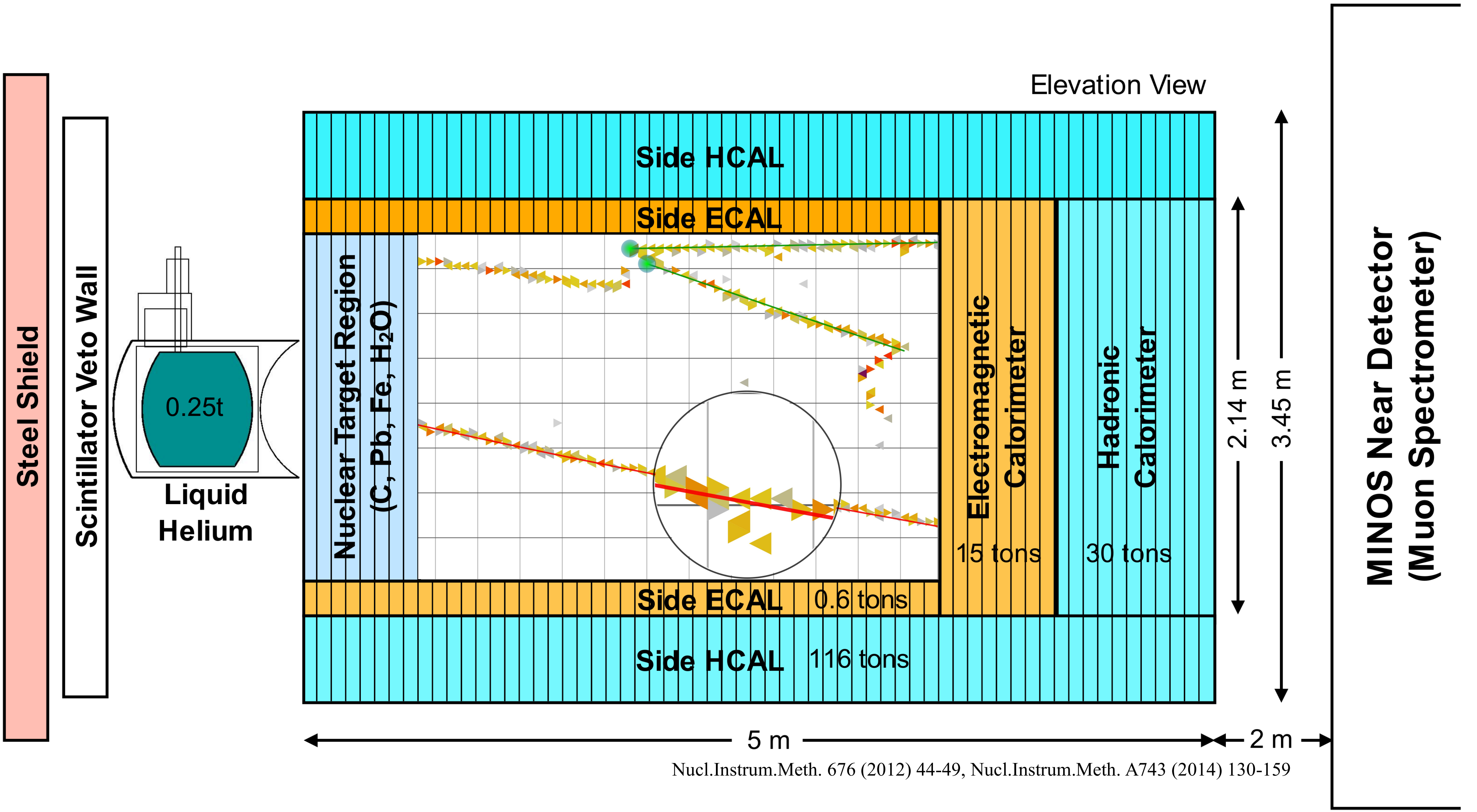
MINERvA



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

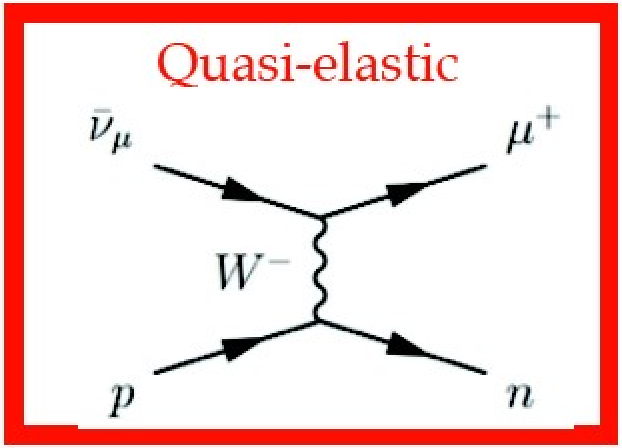
Scintillator tracker

MINERvA

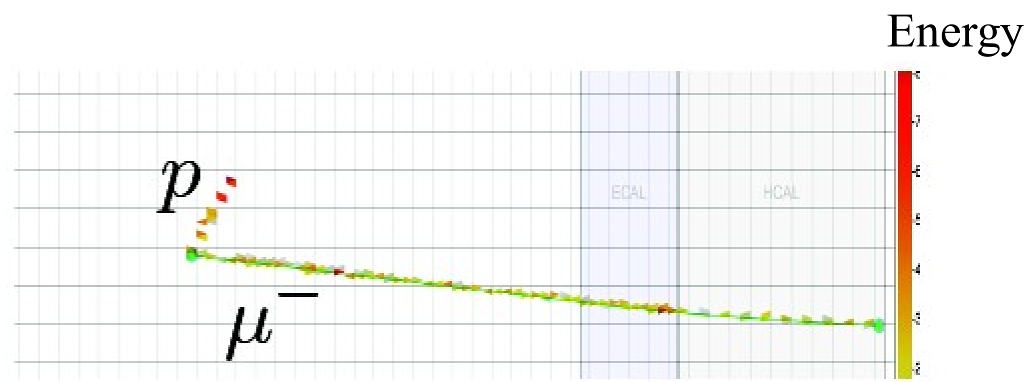


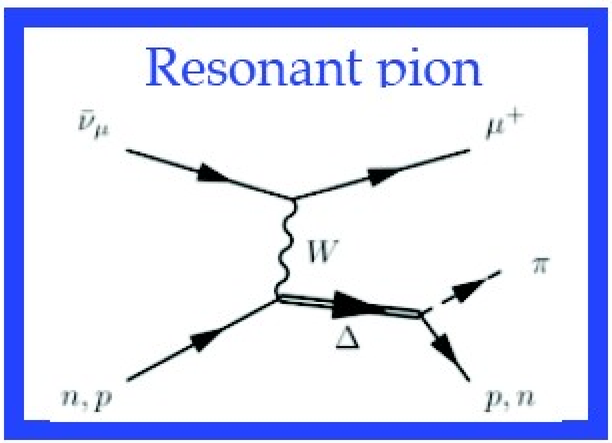
Nucl.Instrum.Meth. 676 (2012) 44-49, Nucl.Instrum.Meth. A743 (2014) 130-159

Scintillator tracker:
Hydrocarbon (CH) target
Homogeneous non-magnetized active tracker

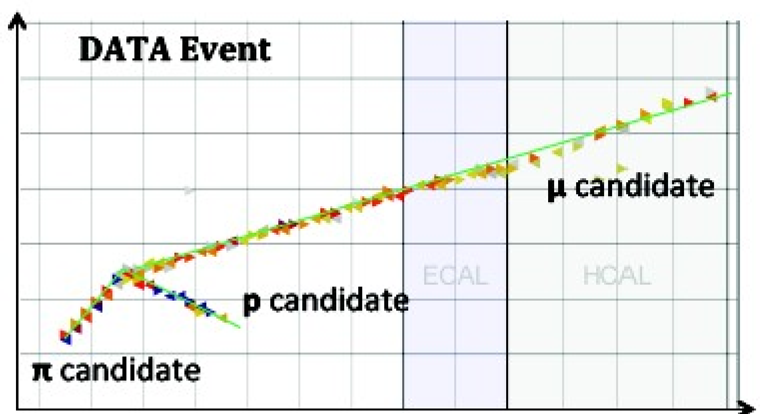


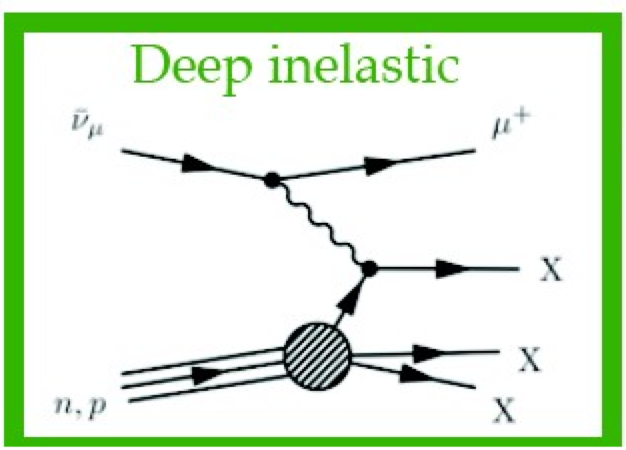
QE





RES





DIS

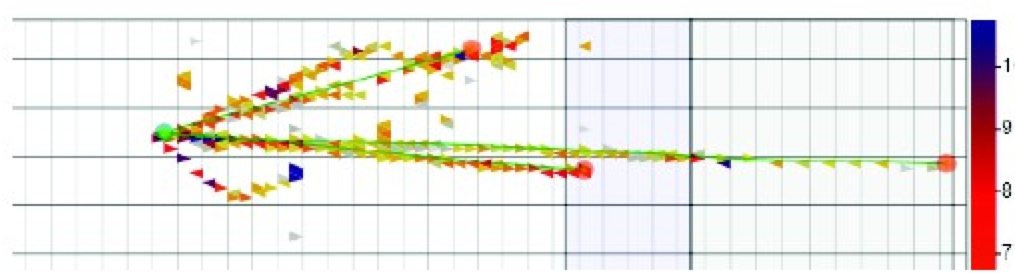
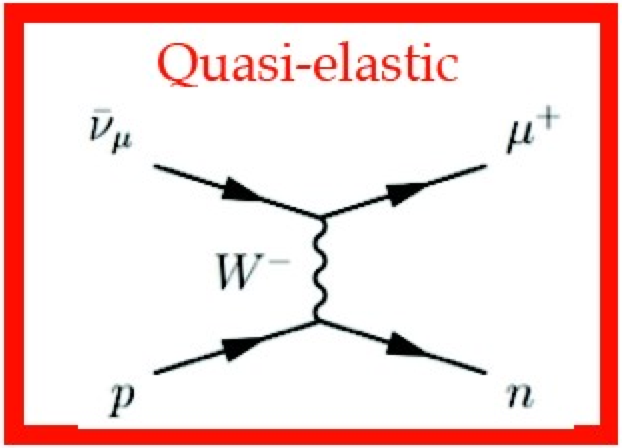
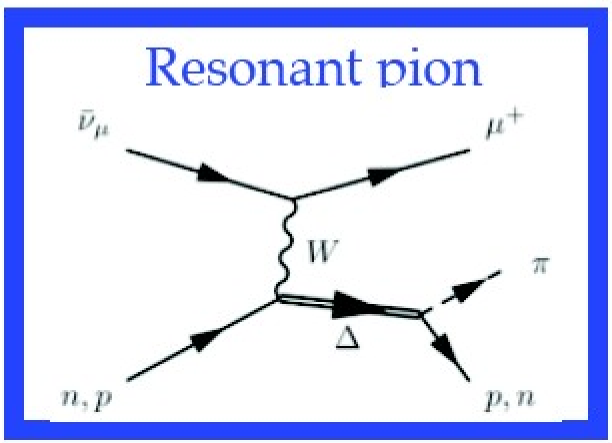


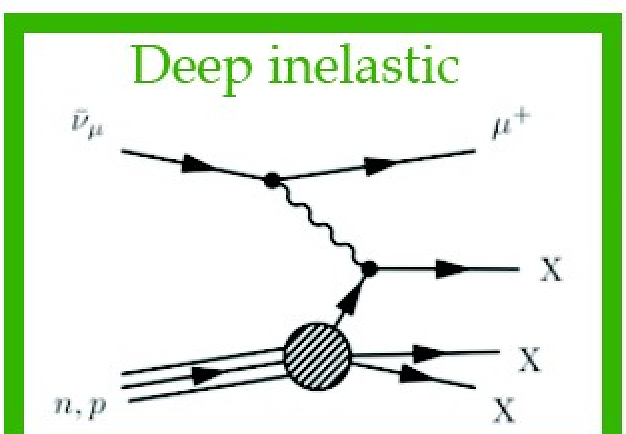
Diagram by M. Betancourt


Quasi-elastic
$\bar{\nu}_\mu$
μ^+
W^-
p
n

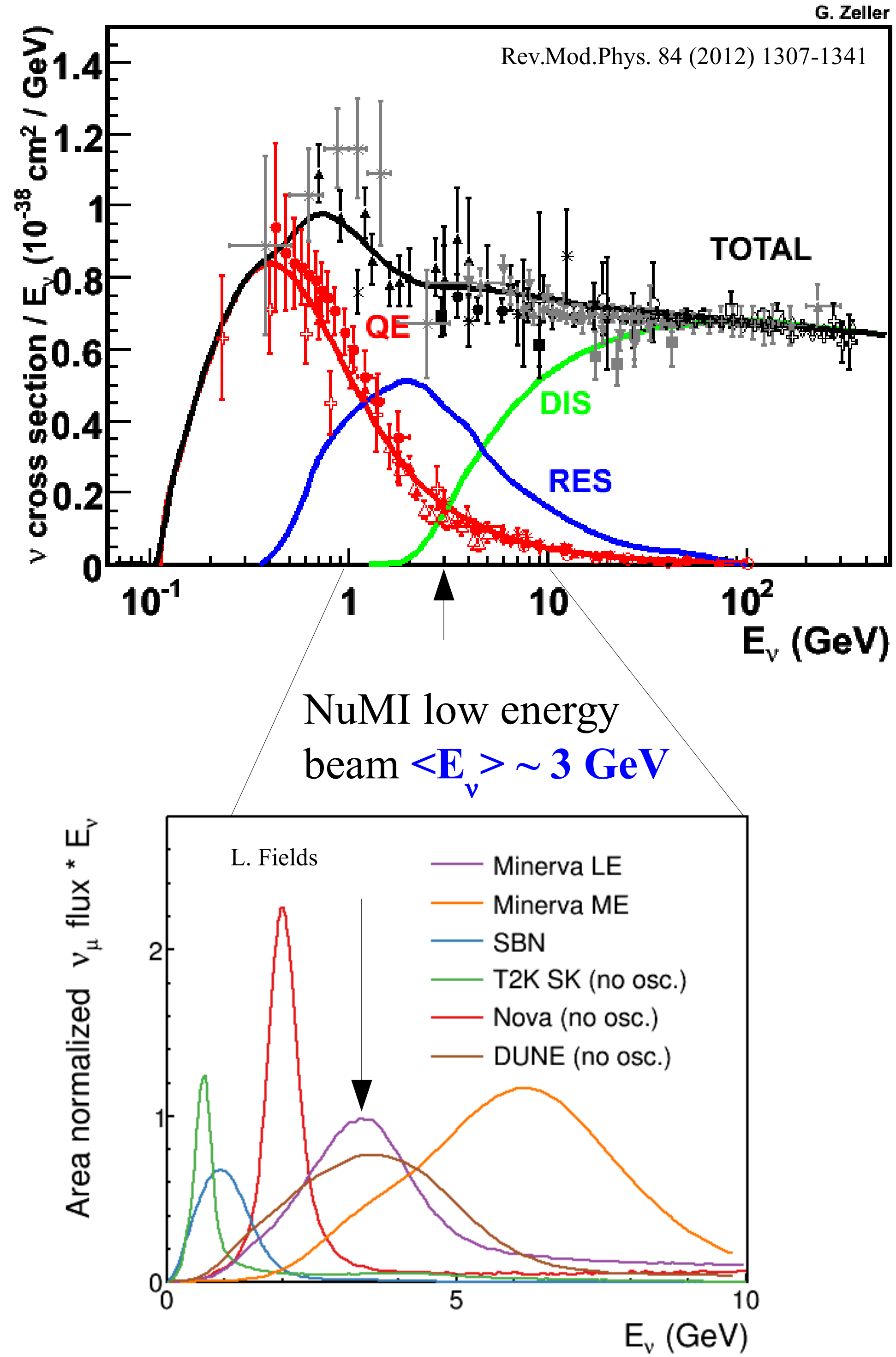
QE


Resonant pion
$\bar{\nu}_\mu$
μ^+
W
π
Δ
n, p
p, n

RES

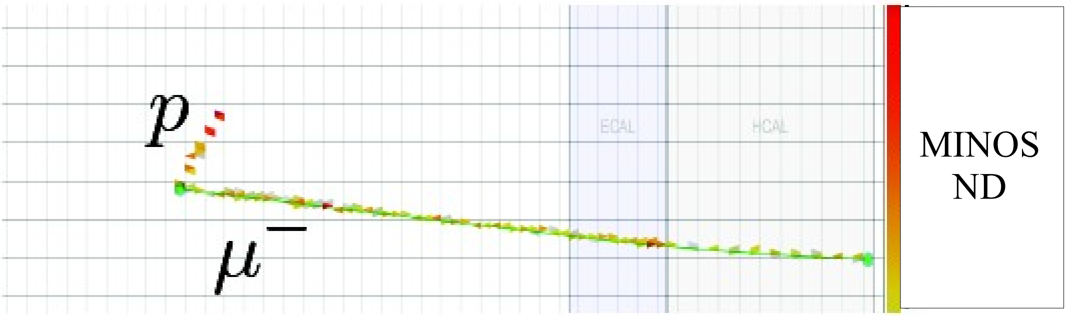

Deep inelastic
$\bar{\nu}_\mu$
μ^+
X
X
X
n, p

DIS


G. Zeller
Rev.Mod.Phys. 84 (2012) 1307-1341
ν cross section / E_ν (10^{-38} cm^2 / GeV)
TOTAL
QE
DIS
RES
E_ν (GeV)
NuMI low energy beam $<E_\nu> \sim 3$ GeV
L. Fields
Minerva LE
Minerva ME
SBN
T2K SK (no osc.)
Nova (no osc.)
DUNE (no osc.)
Area normalized ν_μ flux * E_ν
E_ν (GeV)

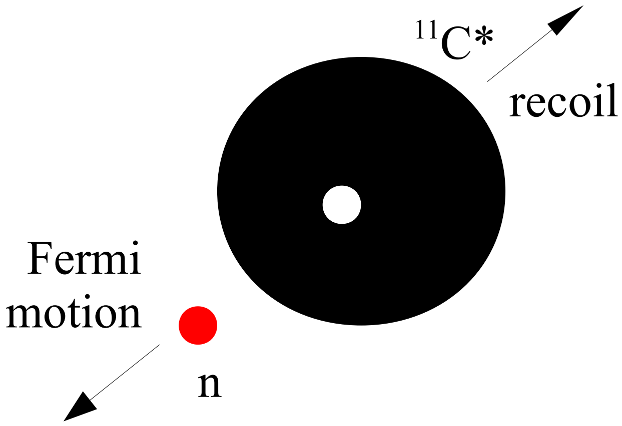
Today's topic:

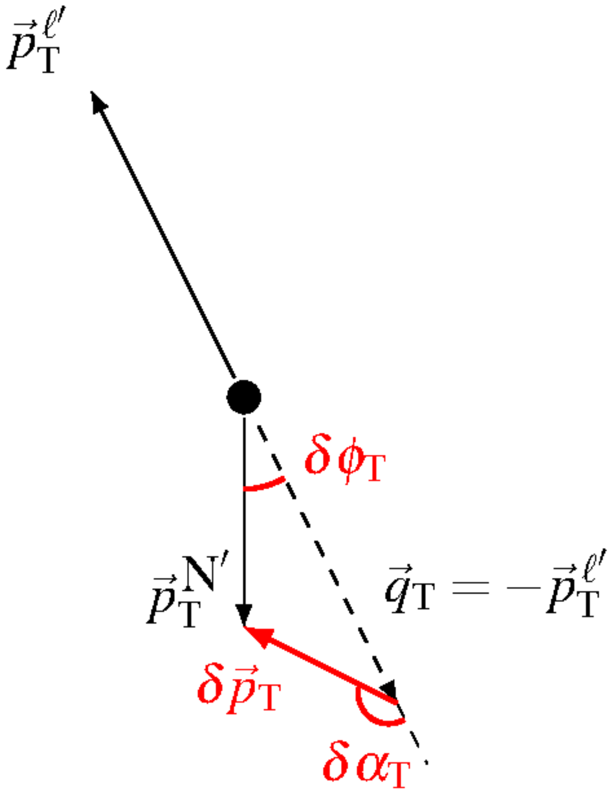
μ-p mesonless production



Observables:

- **Transverse kinematics imbalances**
  [XL, L. Pickering, S. Dolan *et al.,* Phys.Rev. C94 (2016) no.1, 015503]
- **Initial neutron momentum**
  [A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501]





A brief history of Shadow Art

https://en.wikipedia.org/wiki/Cave_painting

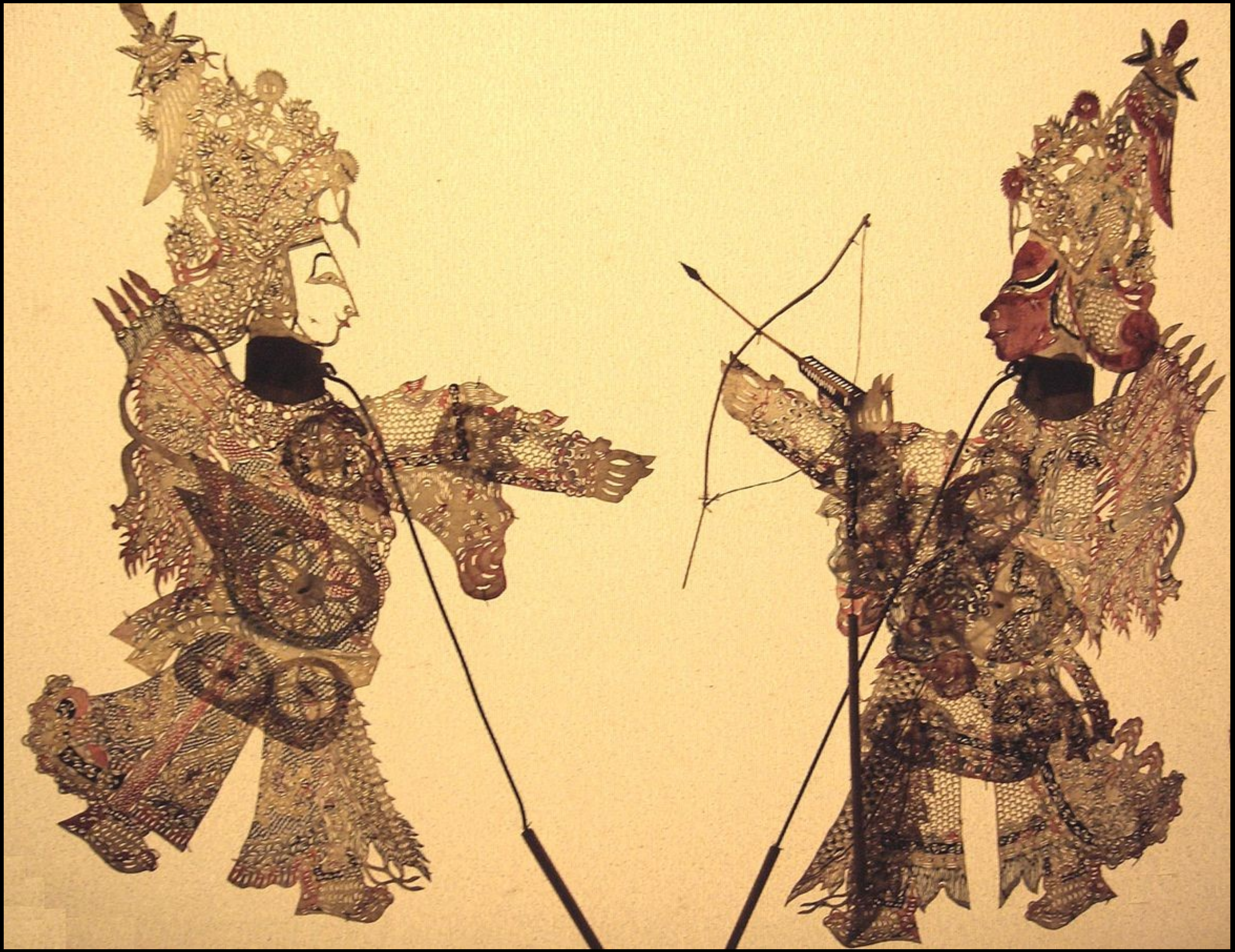
Cave of Pettakere, Bantimurung district (kecamatan), South Sulawesi, **Indonesia**. Hand stencils estimated between **35,000-40,000 BP**

A brief history of Shadow Art

https://en.wikipedia.org/wiki/Cave_painting

Cueva de las Manos located Perito Moreno, **Argentina**.
The art in the cave dates between **13,000-9,000 BP**

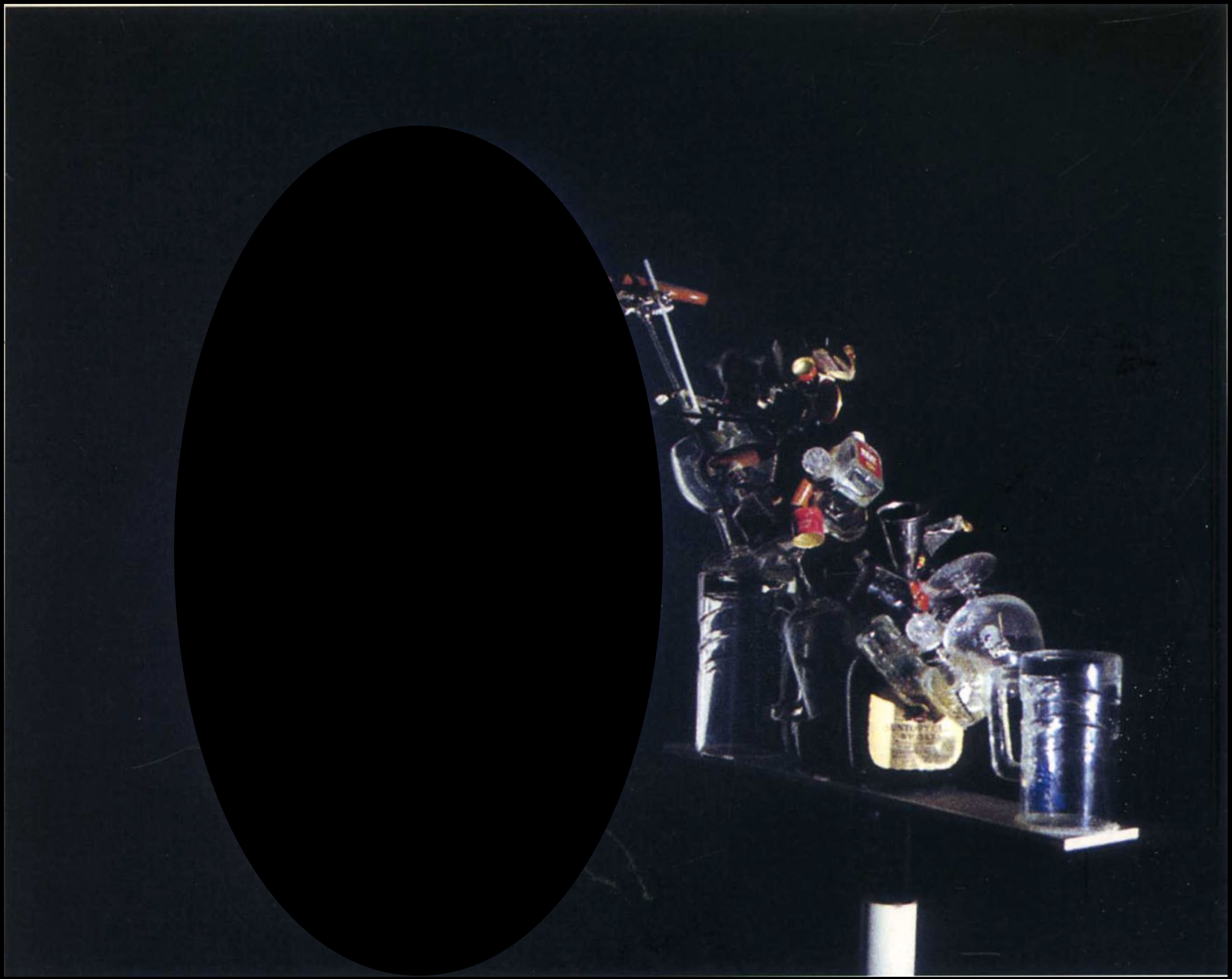
A brief history of Shadow Art



https://zh.wikipedia.org/wiki/%E7%9A%AE%E5%BD%B1%E6%88%B2

Traditional Chinese "movie"

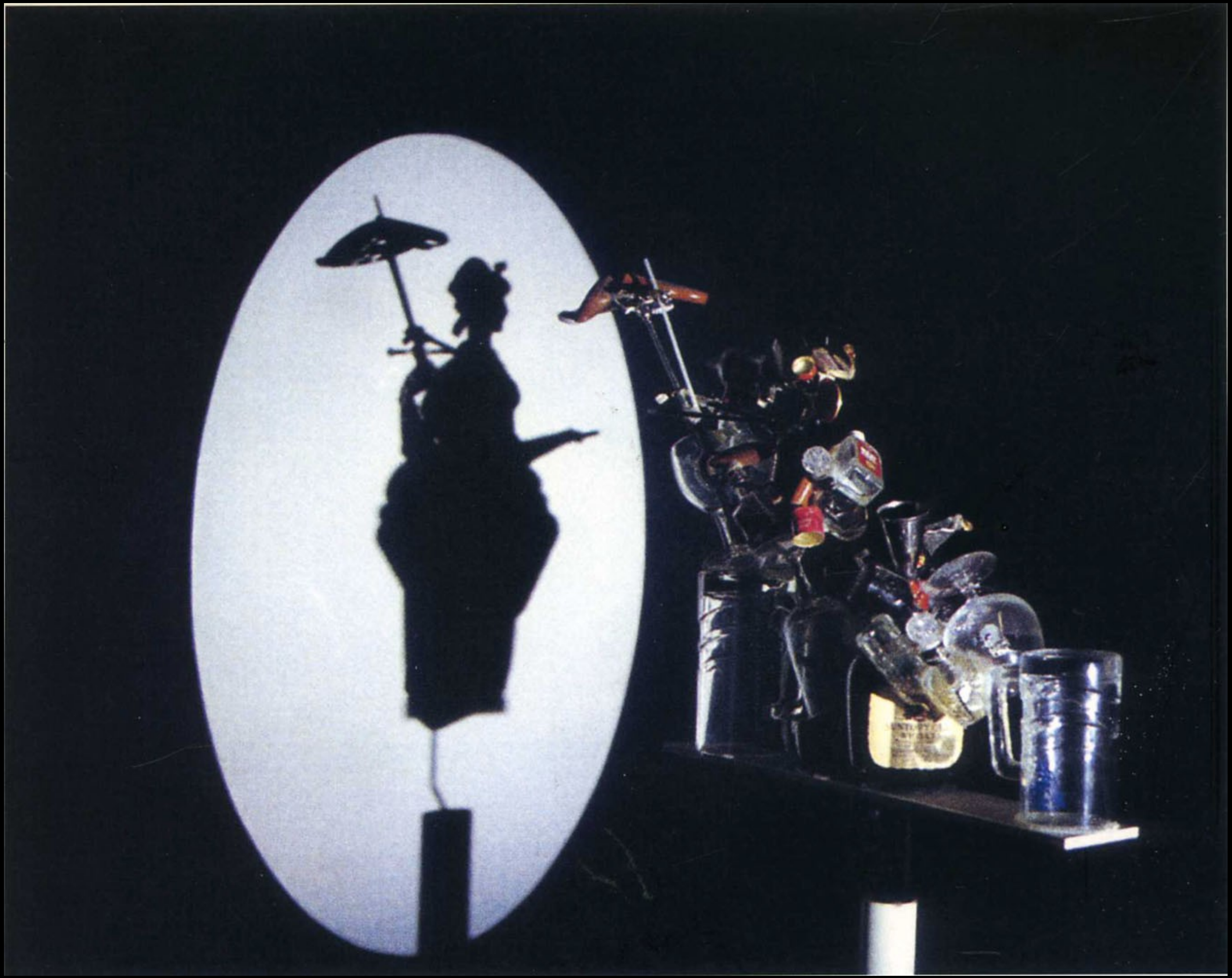
A brief history of Shadow Art



http://www.spoon-tamago.com/2015/08/03/illusionistic-shadow-art-by-shigeo-fukuda/

Japanese modern art

A brief history of Shadow Art



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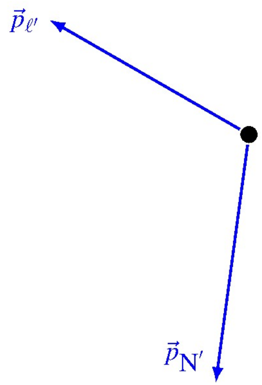
Japanese modern art

Transverse kinematic imbalances
– *a neutrino shadow play*



Transverse kinematic imbalances
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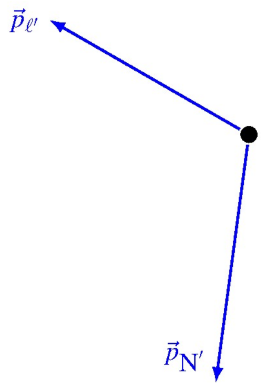
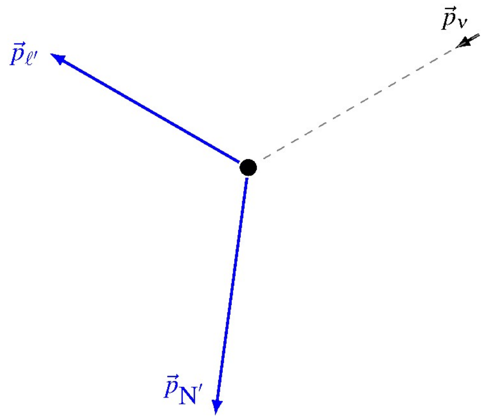


Xianguo Lu, Oxford

Source: http://zhejiangpiying.sokutu.com/tupian.html

To make *Neutrino Shadow Play*, we need
- ✓ beam of light
- ✓ screen

Transverse kinematic imbalances
– *a neutrino shadow play*



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To make *Neutrino Shadow Play*, we need
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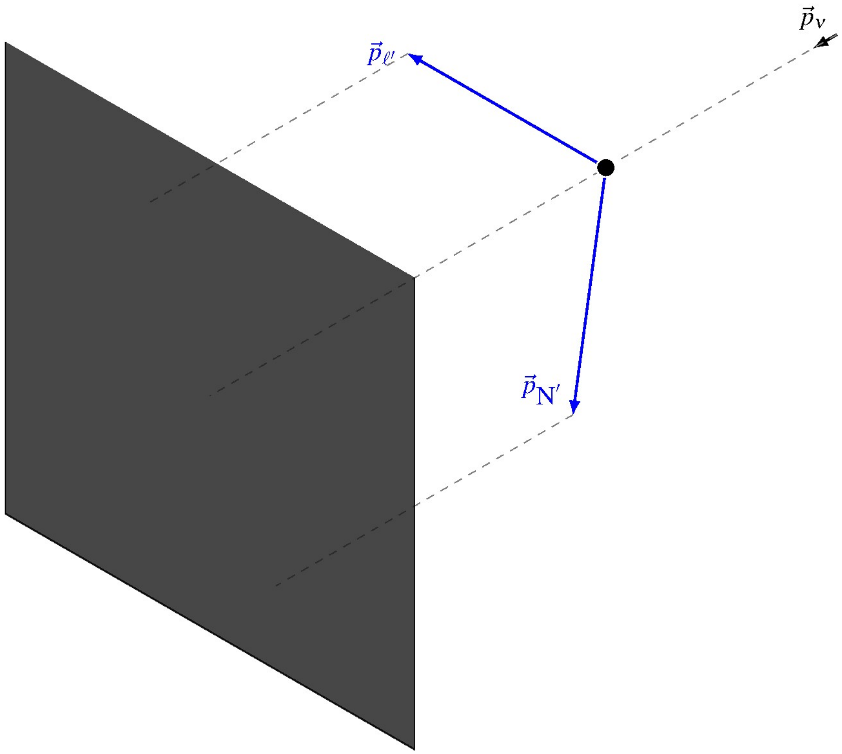
- ✓ screen

Xianguo Lu, Oxford

Transverse kinematic imbalances – *a neutrino shadow play*



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To make *Neutrino Shadow Play*, we need

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Xianguo Lu, Oxford

Transverse kinematic imbalances
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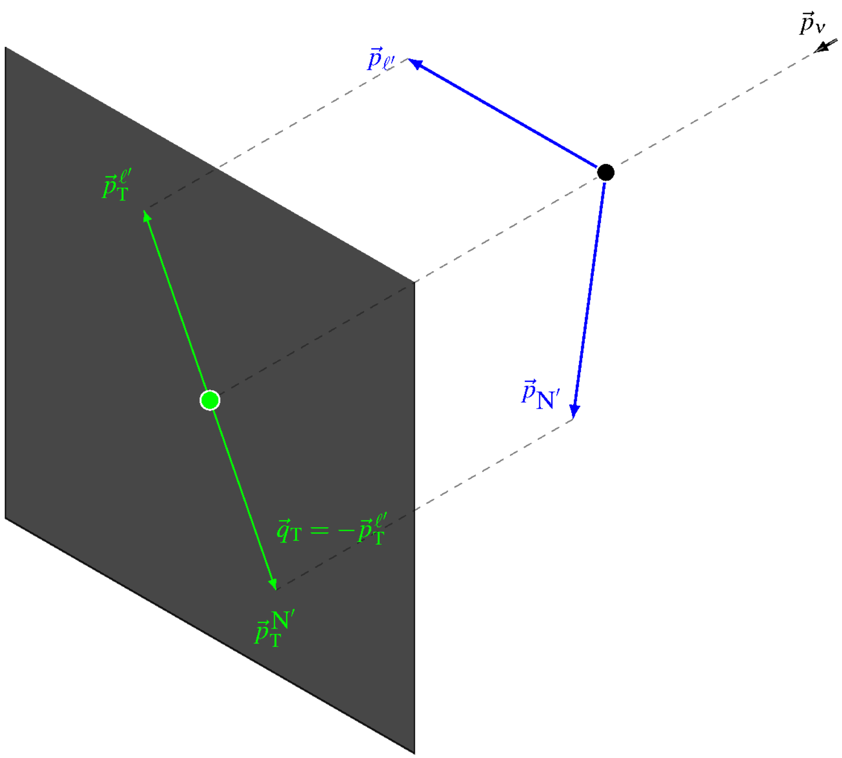

Static nucleon target

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Xianguo Lu, Oxford

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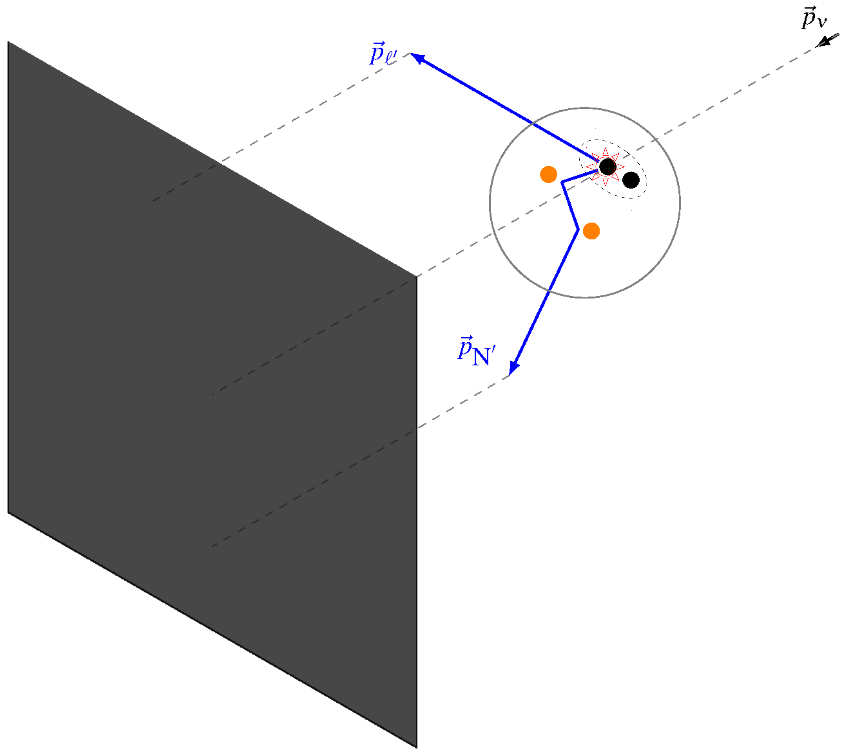

Nuclear target

Xianguo Lu, Oxford

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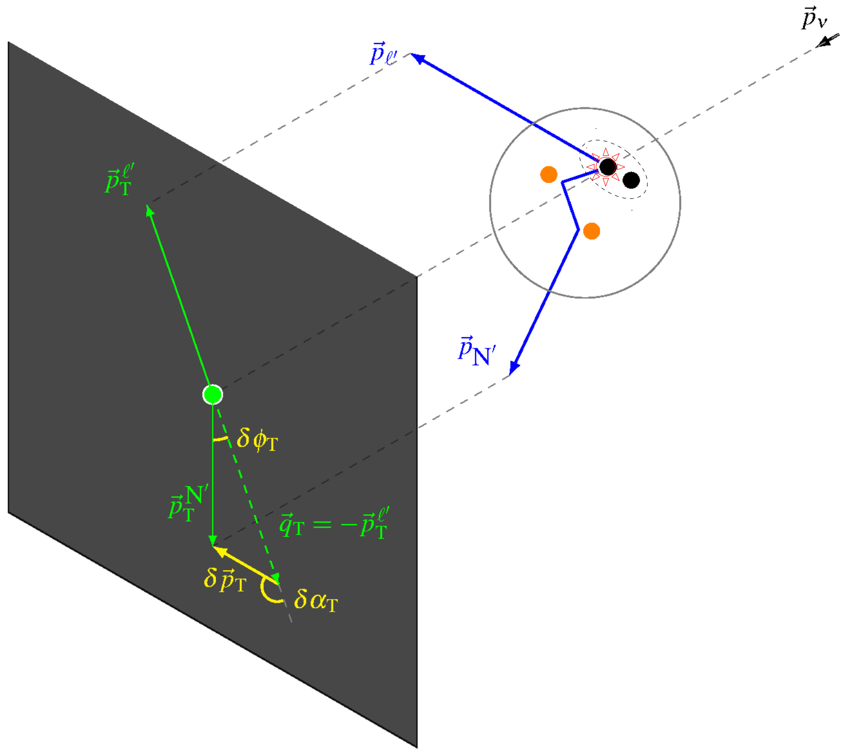

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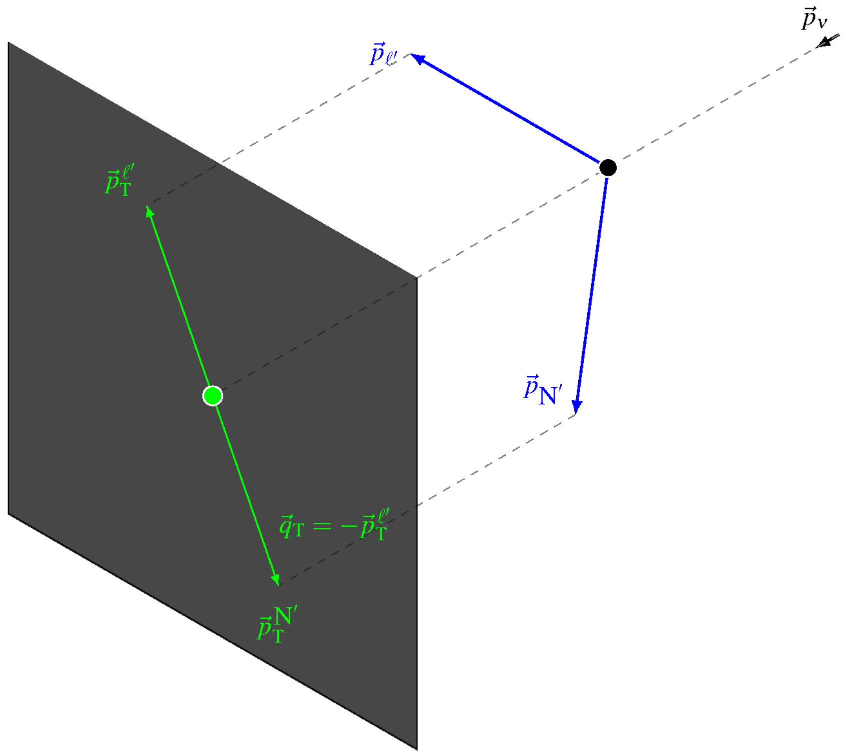
Xianguo Lu, Oxford

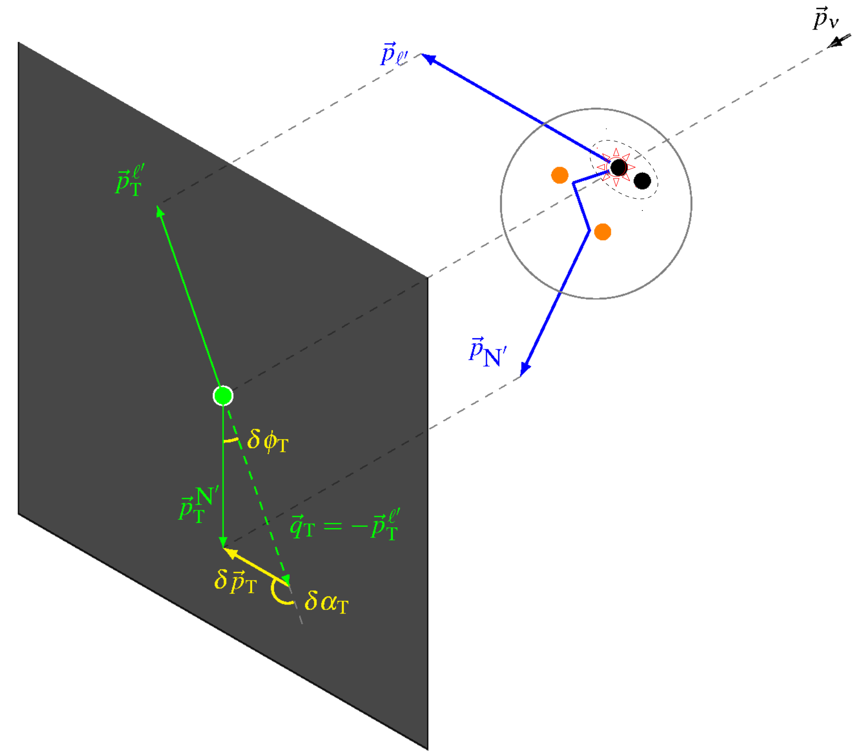
Transverse kinematic imbalances
– *a neutrino shadow play*

$$\delta\vec{p}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\mathrm{N}} - \Delta\vec{p}_{\mathrm{T}}$$

Convolution of Fermi motion and intra-nuclear momentum transfer due to FSI, resonance production, 2p2h etc.



Static nucleon target



Nuclear target

XL, L. Pickering, S. Dolan *et al.,* Phys.Rev. C94 (2016) no.1, 015503

Transverse kinematic imbalances
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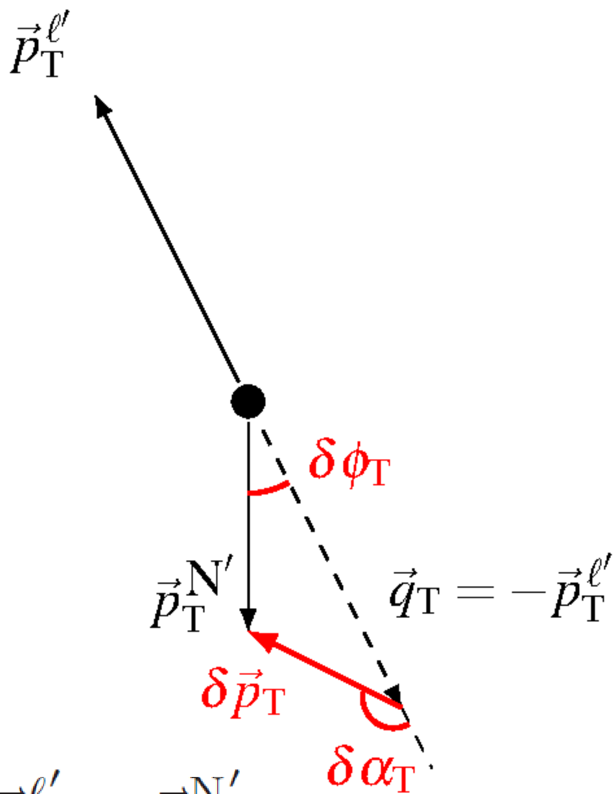
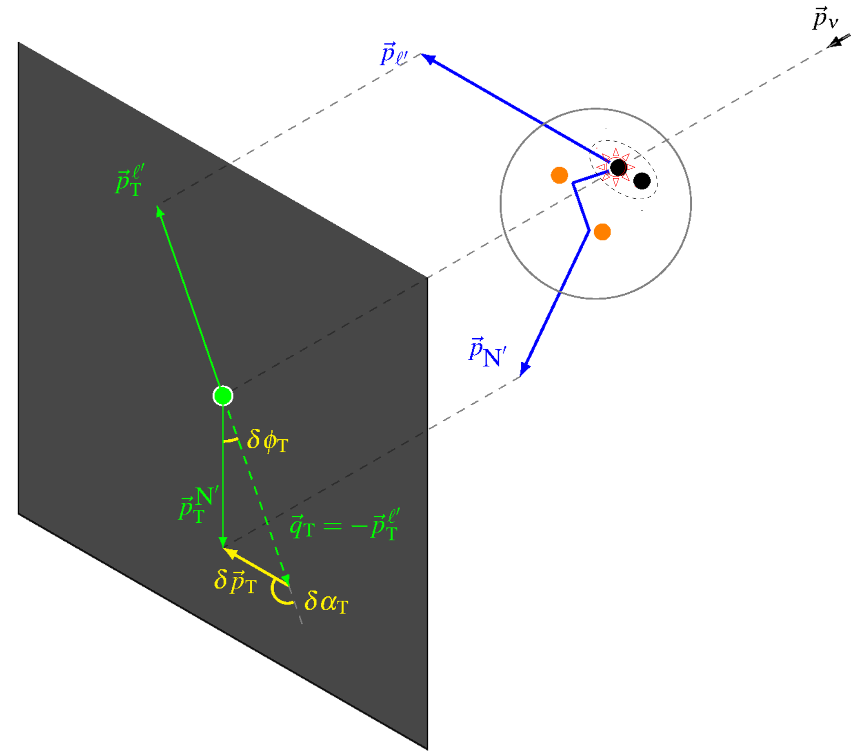


$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\ell'} + \vec{p}_{\mathrm{T}}^{\mathrm{N}'}$$



Nuclear target

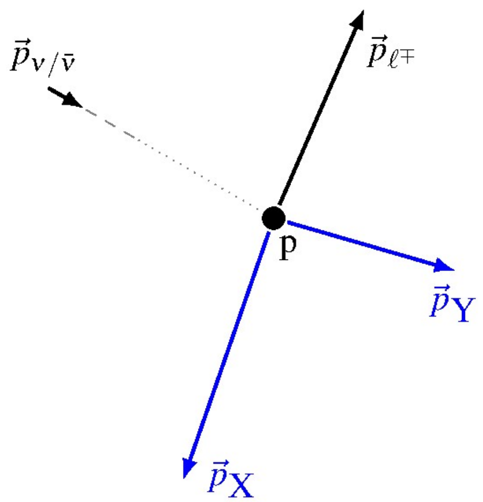
XL, L. Pickering, S. Dolan *et al.,* Phys.Rev. C94 (2016) no.1, 015503

EXTENSION: RADICAL SOLUTION TO NUCLEAR EFFECT PROBLEM

Lepton-proton interaction → 3 charged particles: l p → l' X Y

- Leading order realization in standard model:

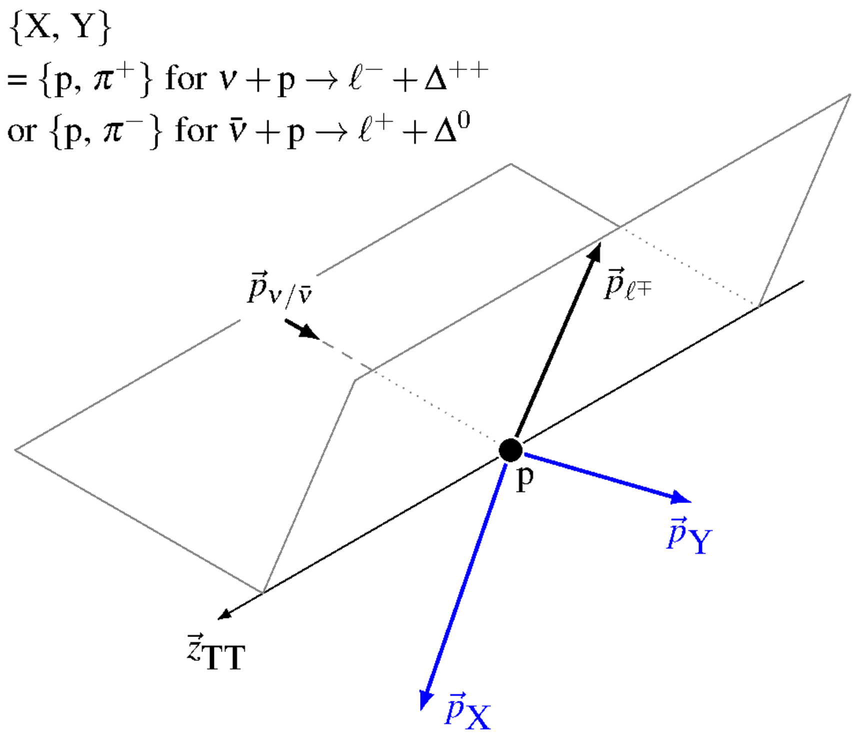
{X, Y}
= $\{p, \pi^+\}$ for $\nu + p \to \ell^- + \Delta^{++}$
or $\{p, \pi^-\}$ for $\bar{\nu} + p \to \ell^+ + \Delta^0$



XL *et al.*, Phys.Rev. D92 (2015) no.5, 051302

Lepton-proton interaction → 3 charged particles: l p → l' X Y

- Leading order realization in standard model:

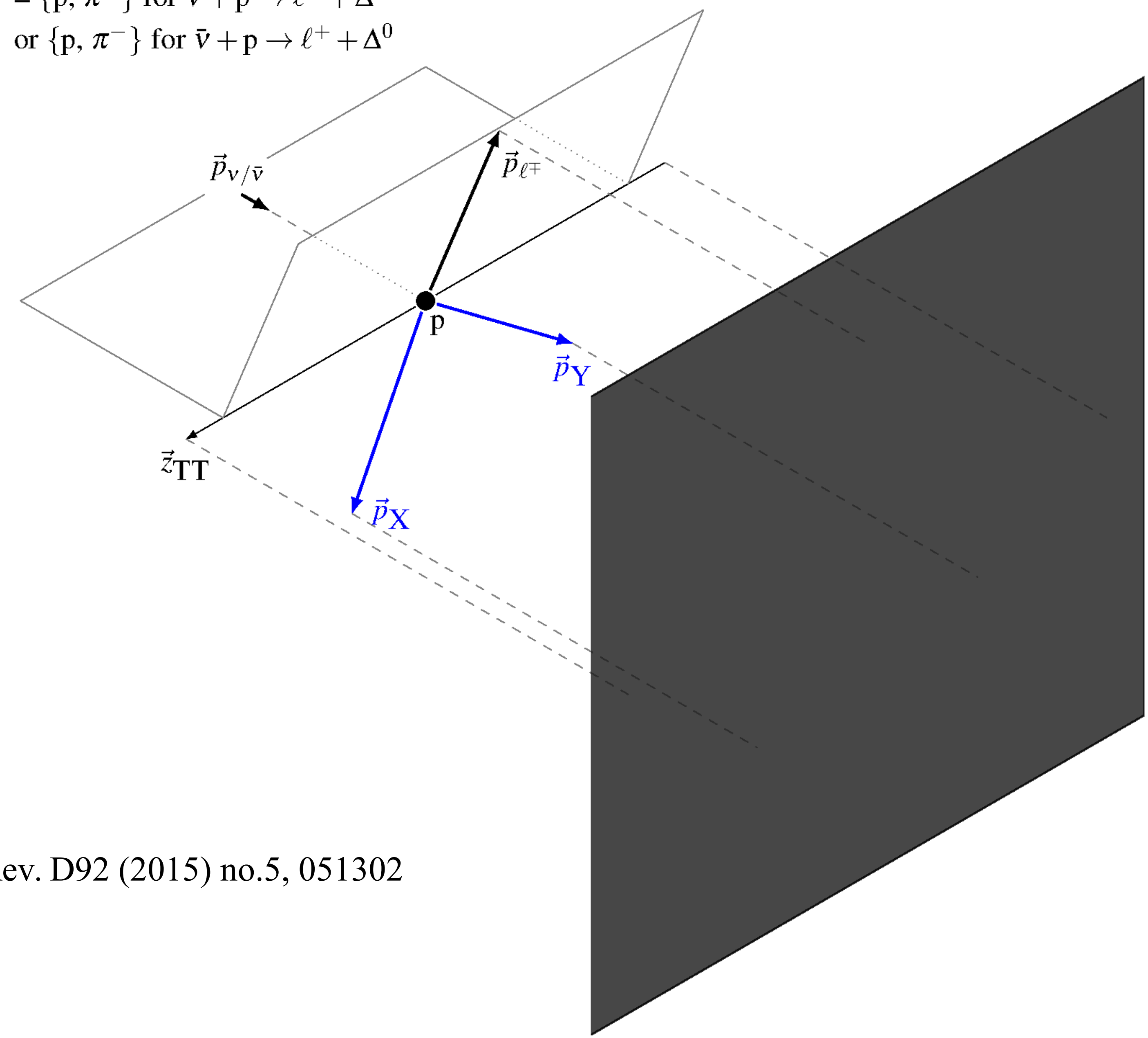


XL *et al*., Phys.Rev. D92 (2015) no.5, 051302

Lepton-proton interaction → 3 charged particles: l p → l' X Y

- Leading order realization in standard model:

{X, Y}
= {p, π^+} for $\nu + \mathrm{p} \to \ell^- + \Delta^{++}$
or {p, π^-} for $\bar{\nu} + \mathrm{p} \to \ell^+ + \Delta^0$



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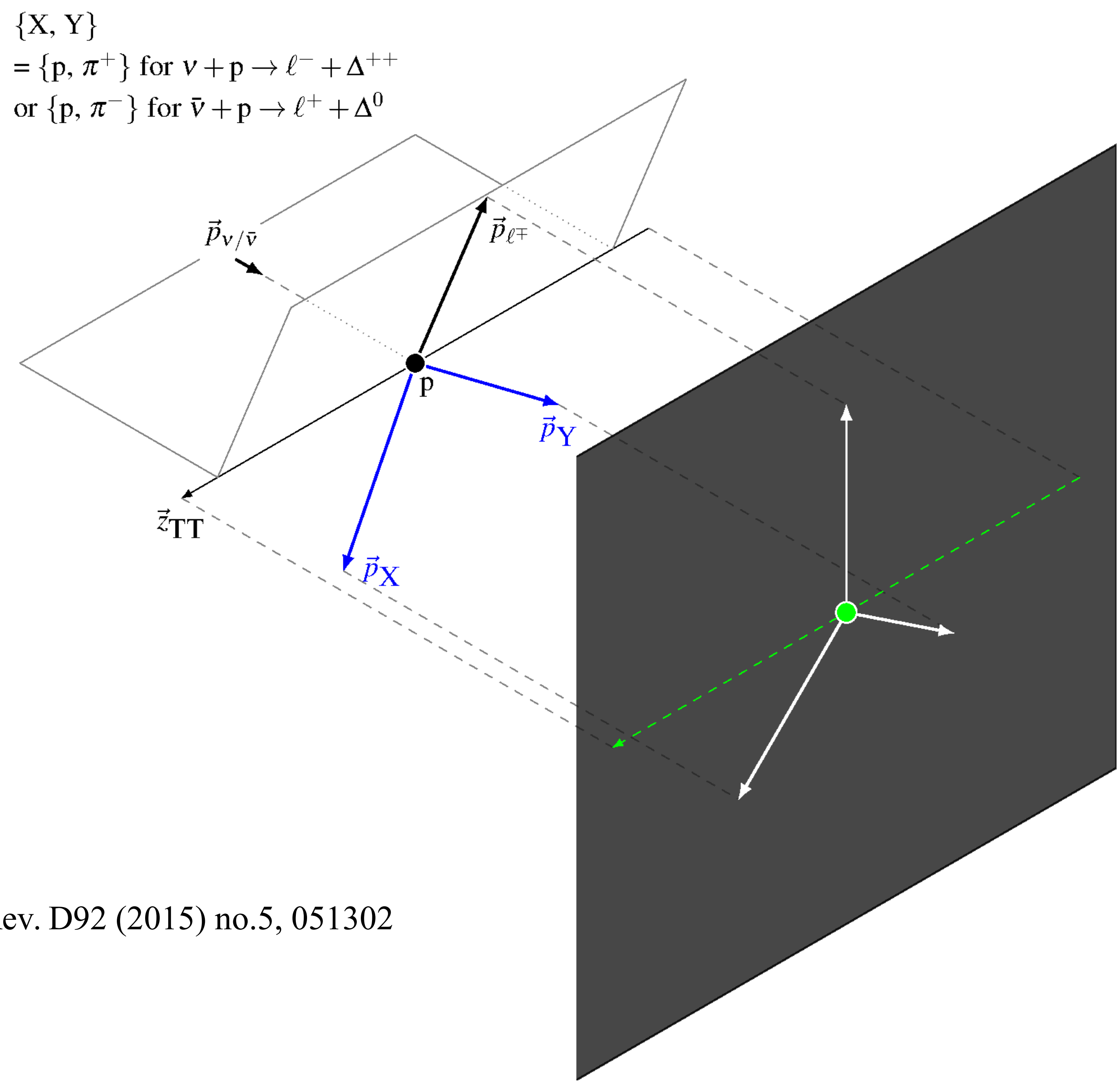

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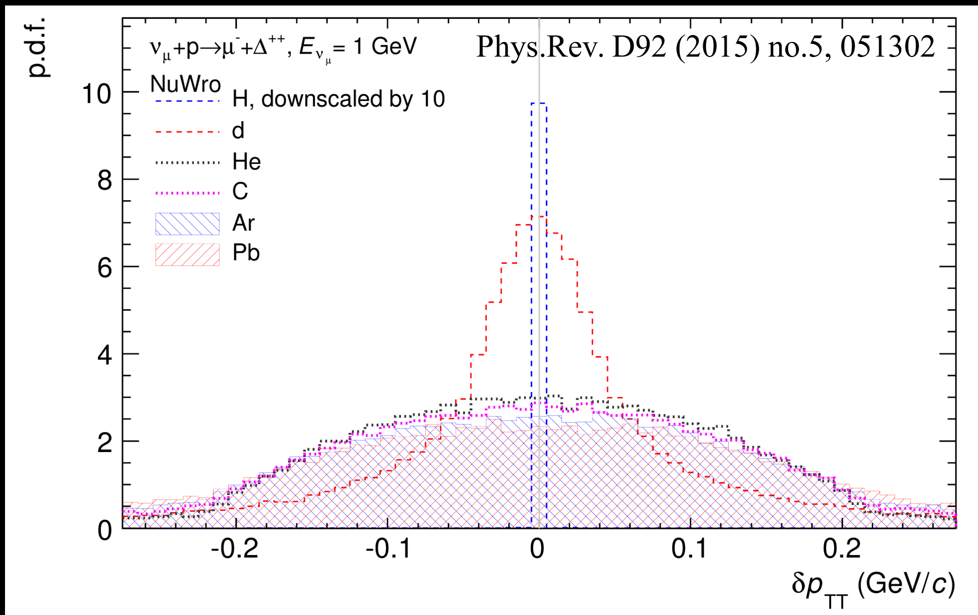
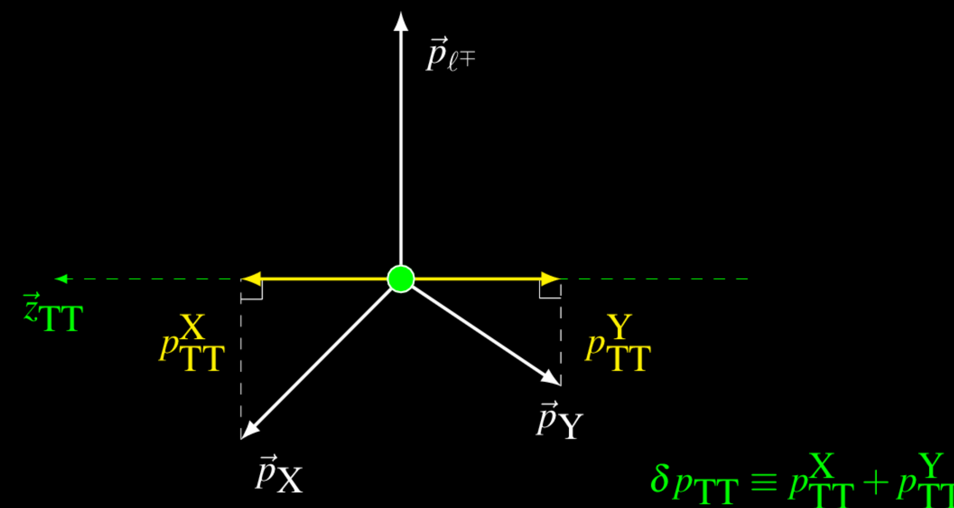


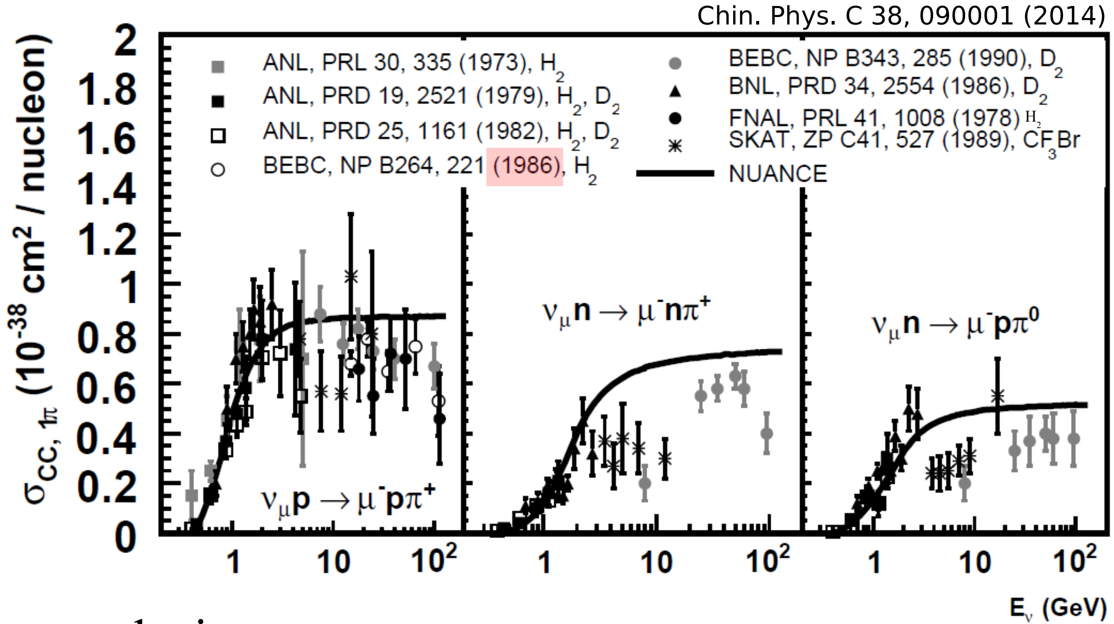


Double-transverse momentum imbalance δp_{TT}

- H: 0
- Heavier nuclei: irreducible symmetric broadening
  - by Fermi motion O(200 MeV)
  - further by FSI
- CH_n: Hydrogen shape is only detector smearing.
  - With good detector resolution, hydrogen yield can be extracted.
  - With very good res., event-by-event selection of ν-H interaction is possible.

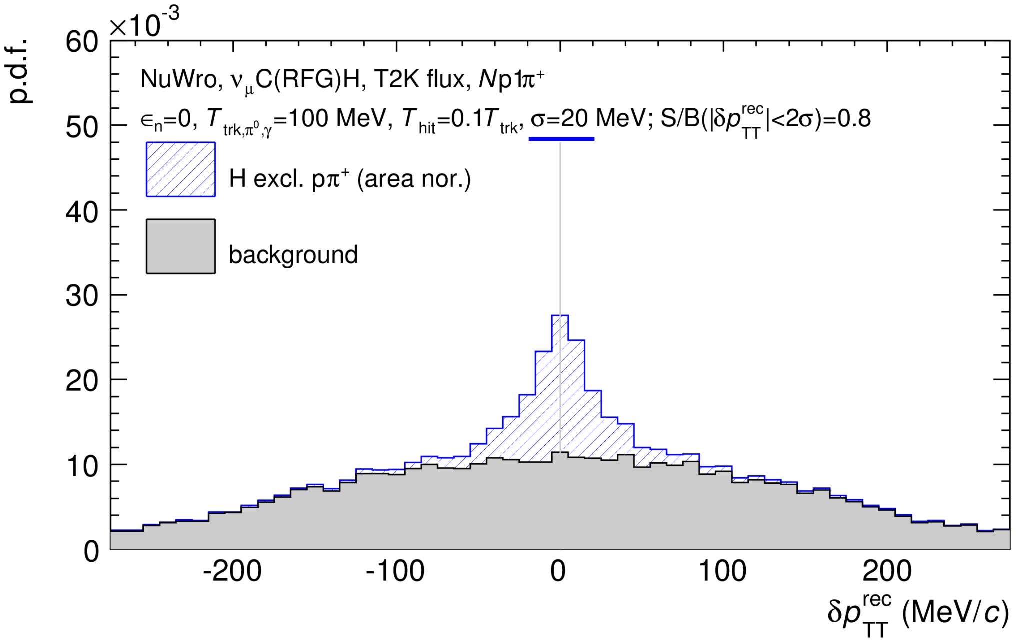
XL *et al*., Phys.Rev. D92 (2015) no.5, 051302

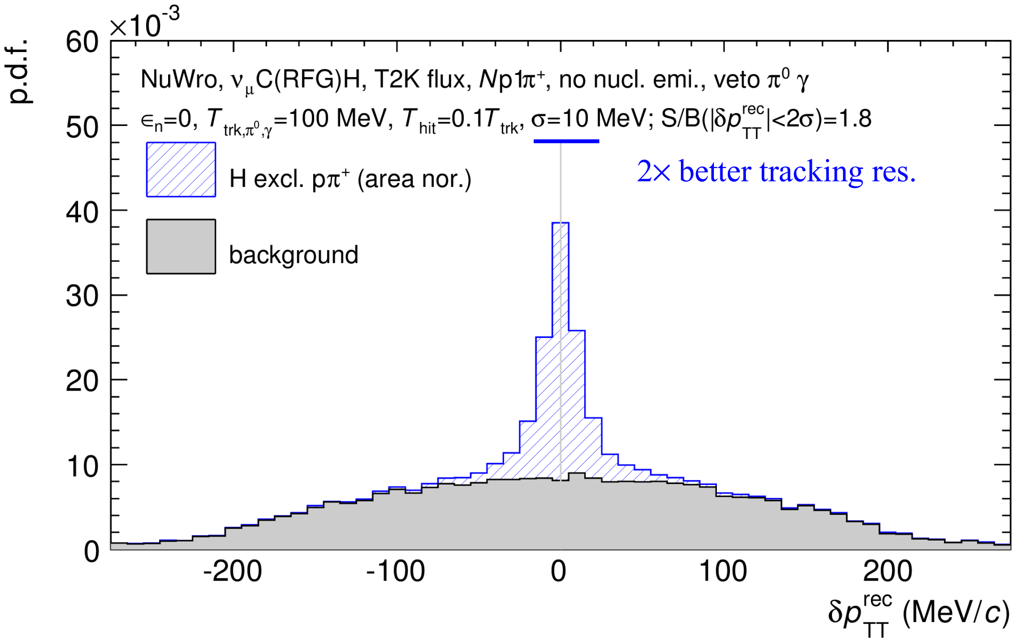
- Pure hydrogen
  - Technical requirement: bubble chamber (historical: 73, 79, 78, 82, 86)



  - Safety issue: explosive
    - "*Since the use of a liquid H2 bubble chamber is excluded in the ND hall **due to safety concerns**, ...*" [FERMILAB-PUB-14-022]
- Neutrino interactions on hydrogen:
  - In the last ~30 years there has been no new measurement
  - Nuclear-effect independent measurement of neutrino energy

Extracting neutrino-hydrogen events from CH targets





arXiv:1512.09042

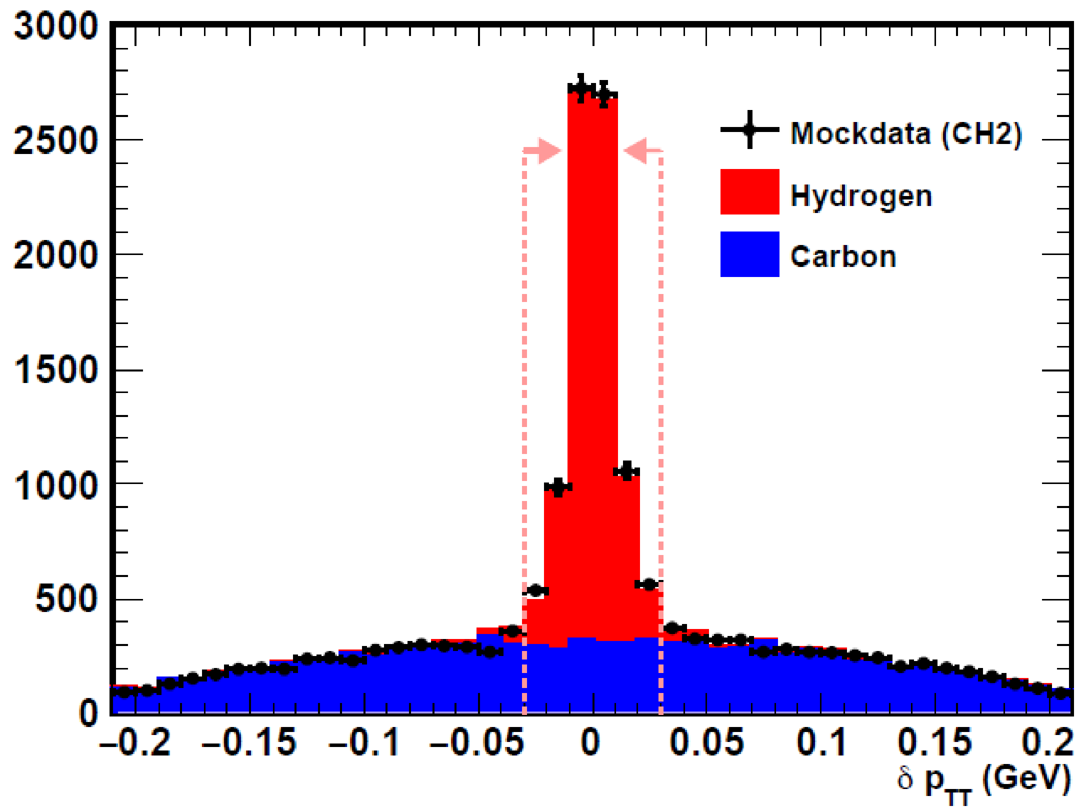
Toy simulation of T2K performance

- T2K neutrino flux on CH target
- Realistic detector resolution

ν-Hydrogen Interactions in STT

Hydrogen Events Selection and Background Normalization

Slide from
Hongyue Duyang
U. of South Carolina



- Select 3-track ($\mu^- p \pi^+$) events with $W_{rec} < 1.4$ GeV (RES region).
- Signal region: $|\delta p_{TT}| < 0.03$ GeV. Background region: $|\delta p_{TT}| > 0.03$ GeV.
- Normalize signal and background to mockdata.
- Purity is $\sim$77% in signal region.

ν-Hydrogen Interactions in STT

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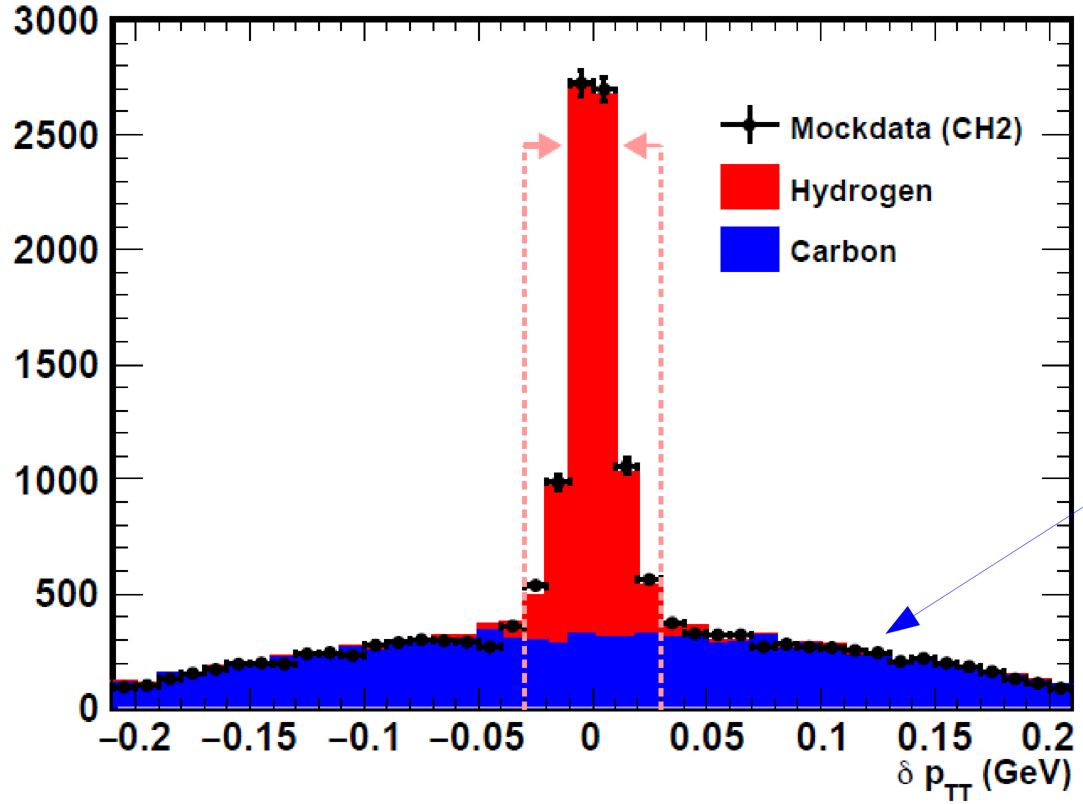

Background shape: constrained by **multiple nuclear targets**, especially carbon (graphite)

- Select 3-track ($\mu^- p \pi^+$) events with $W_{rec} < 1.4$ GeV (RES region).
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6 / 11

https://indico.fnal.gov/event/16205/contribution/3/material/slides/0.pdf

END OF EXTENSION
BACK TO
NUCLEAR EFFECT MEASUREMENT

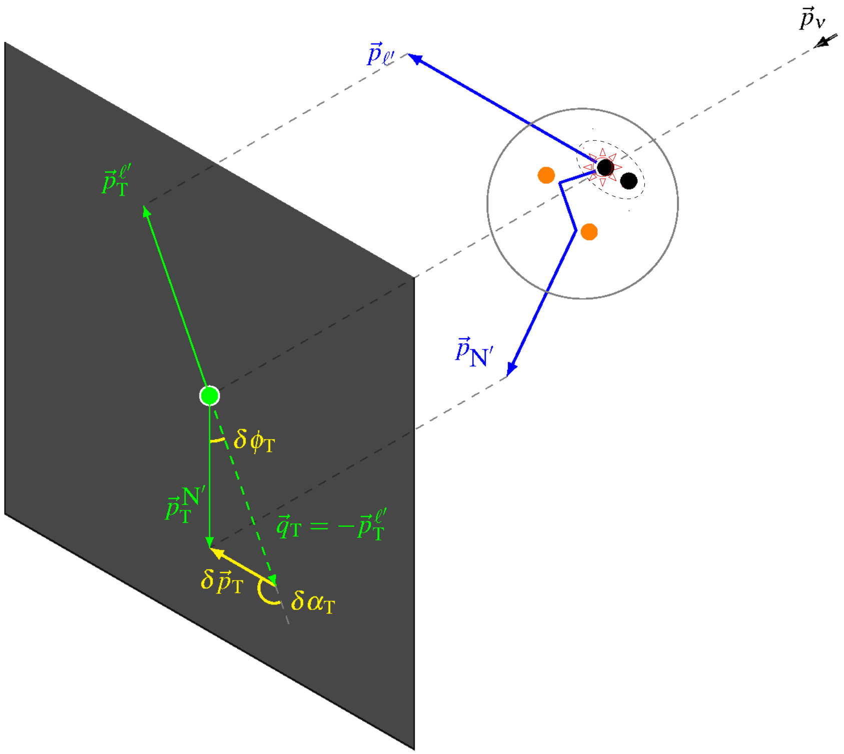
A more general analysis of kinematic imbalance

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

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

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

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



A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501

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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

A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501

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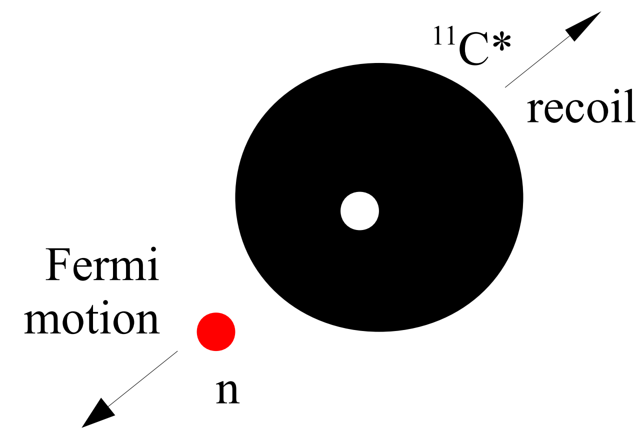

For CCQE, A' = ^{11}C*
No more unknowns
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A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501

Measurement of final-state correlations in neutrino charged-current muon-proton mesonless production on hydrocarbon at $\langle E_\nu \rangle = 3$ GeV

Signal definition:

- Charged current
- One muon and at least one proton in the restricted final-state phase space
- No mesons

$$1.5\ \mathrm{GeV}/c < p_\mu < 10\ \mathrm{GeV}/c,\ \theta_\mu < 20^\circ,$$
$$0.45\ \mathrm{GeV}/c < p_\mathrm{p} < 1.2\ \mathrm{GeV}/c,\ \theta_\mathrm{p} < 70^\circ$$

Measurement:

Data sample: NuMI low energy neutrino data, 3.28×10^{20} POT

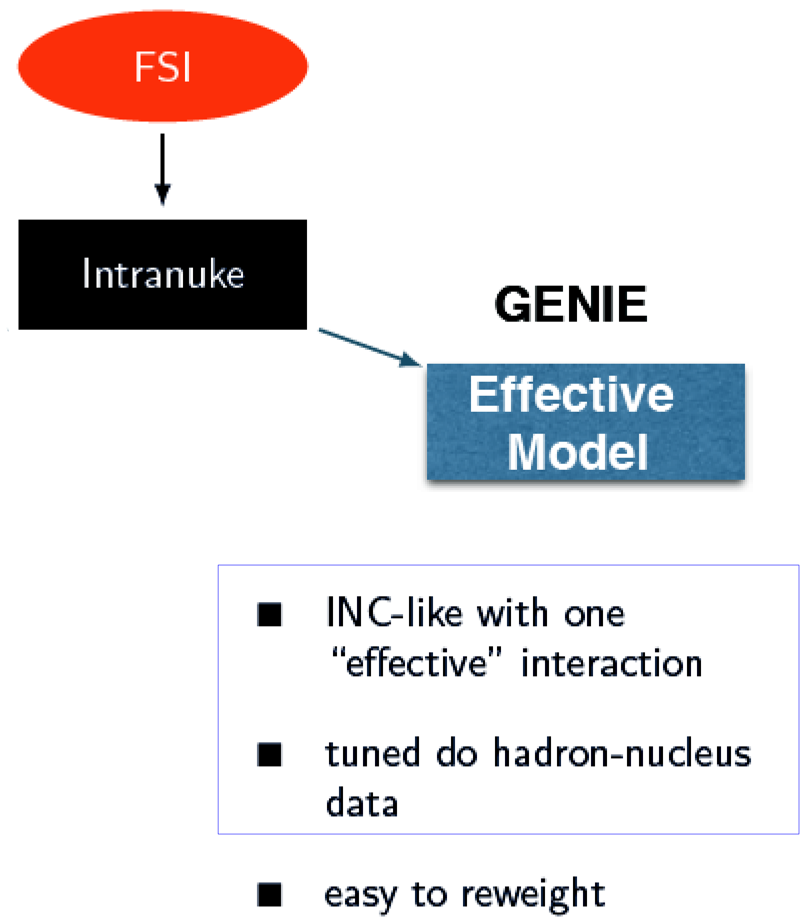
Interaction target: tracker (mostly CH)

- Event selection
- Background estimation and subtraction
- Unfolding
- Efficiency correction

➢ Flux integrated cross section as results → Focus today

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

- **Nominal**: 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]
- **No-FSI**: Nominal without FSI



courtesy of Tomasz Golan

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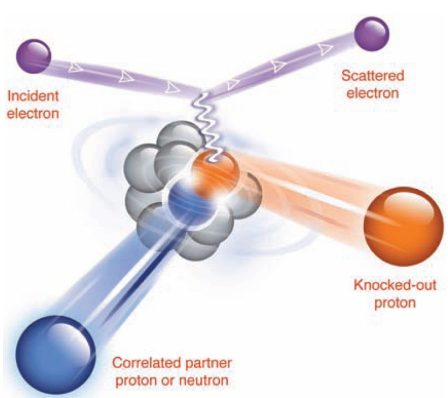
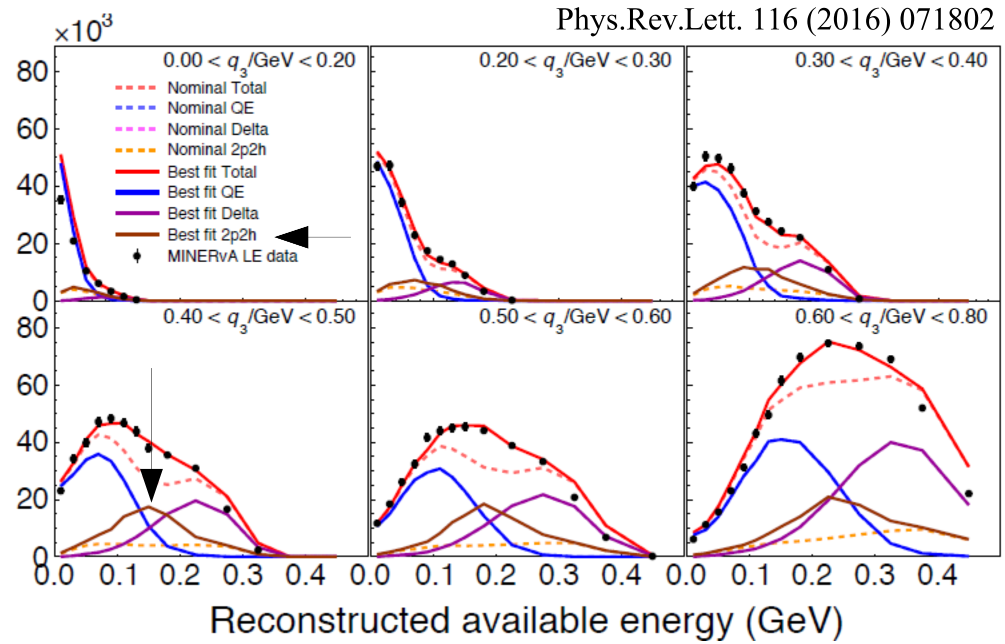
  - ➢ Added Random Phase Approximation (RPA) [Phys.Rev. C70 (2004) 055503]
  - ➢ Non-resonance pion production scaled down by 75% [Phys.Rev. D90 (2014) no.11, 112017]
  - ➢ Valencia 2p2h [Nieves *et al.*, Phys.Lett. B707 (2012) 72-75, Phys. Rev. C 86, 015504 (2012), Phys.Rev. D88 (2013) no.11, 113007, arXiv:1601.02038]
    - ✓ tuned to MINERvA inclusive data → significant enhancement in small 4-momentum transfer region [Phys.Rev.Lett. 116 (2016) 071802]



Science 320 (2008) 1476-1478

Phys.Rev.Lett. 116 (2016) 071802



→ representing energy transfer from the neutrino to the target

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Detector simulation: GEANT4 (4.9.2)

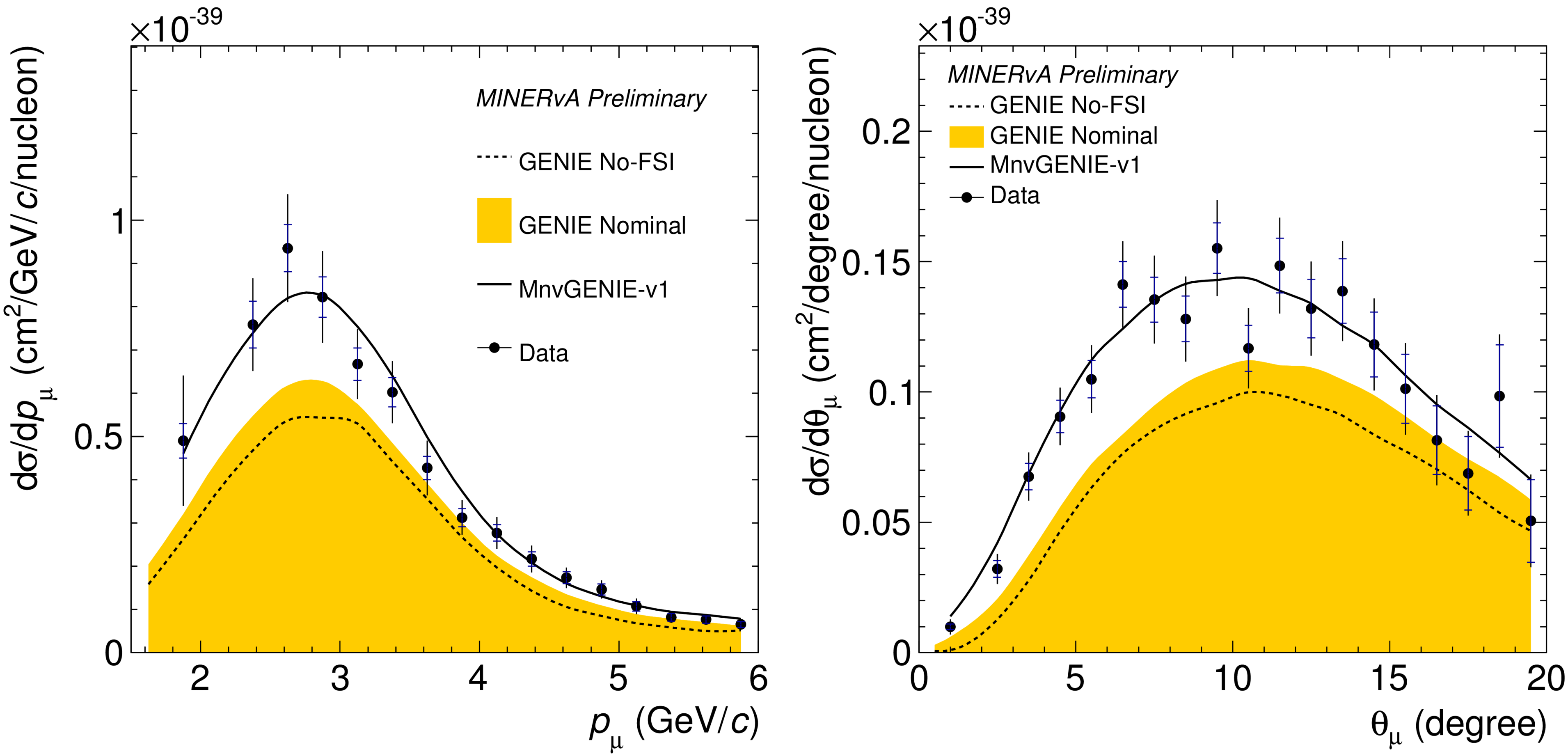
GENIE used in other experiments (e.g. NOvA, T2K, μBooNE, DUNE)

This analysis:
GENIE MINERvA Tune (v1) used in cross section extraction

RESULTS: Flux integrated cross section

Single-Particle Kinematics

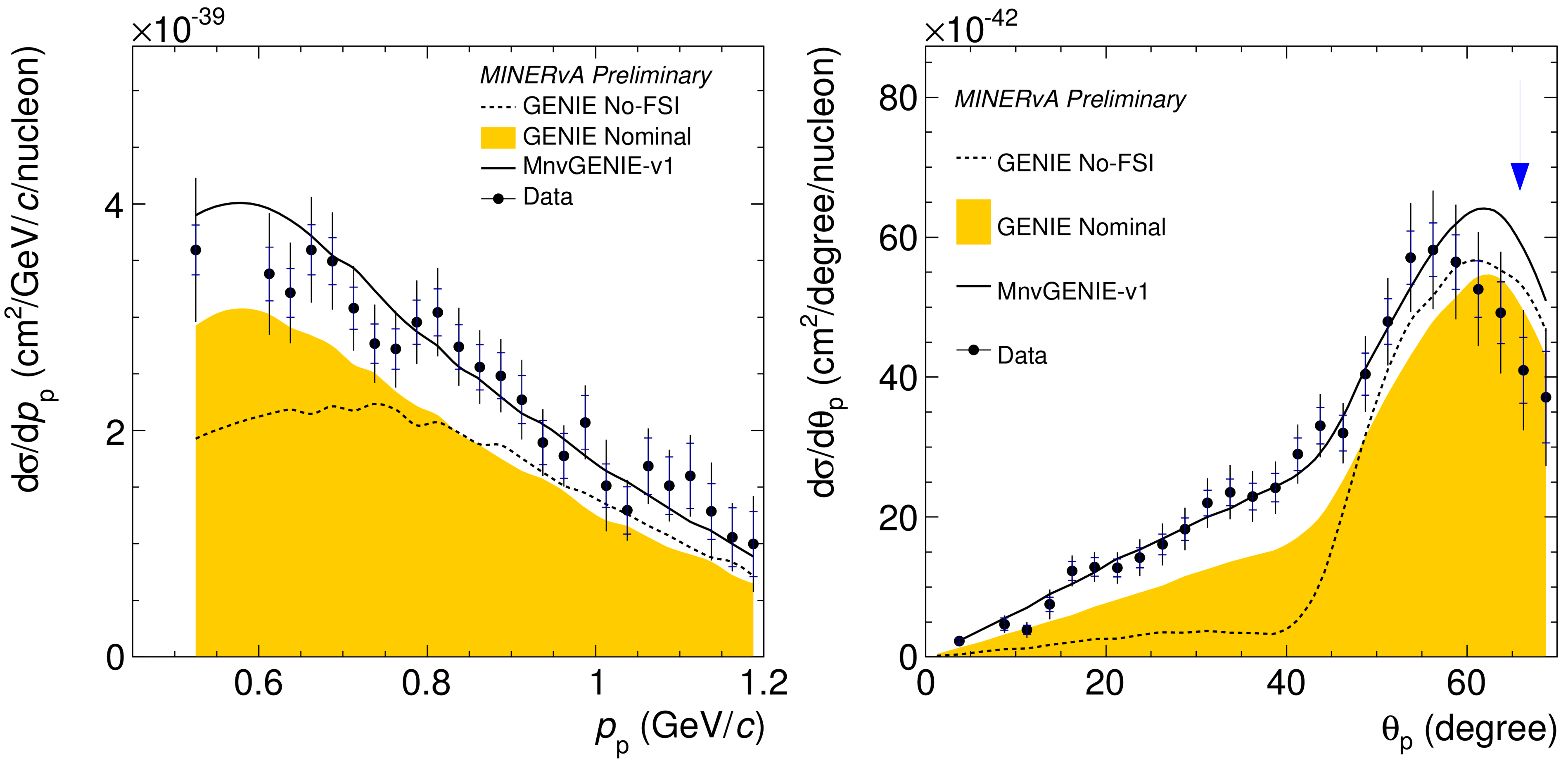
- Muon momentum, angle



- Good description by GENIE MINERvA Tune (v1)
- All predictions have same shape

Single-Particle Kinematics

- Muon momentum, angle
- Proton momentum, angle

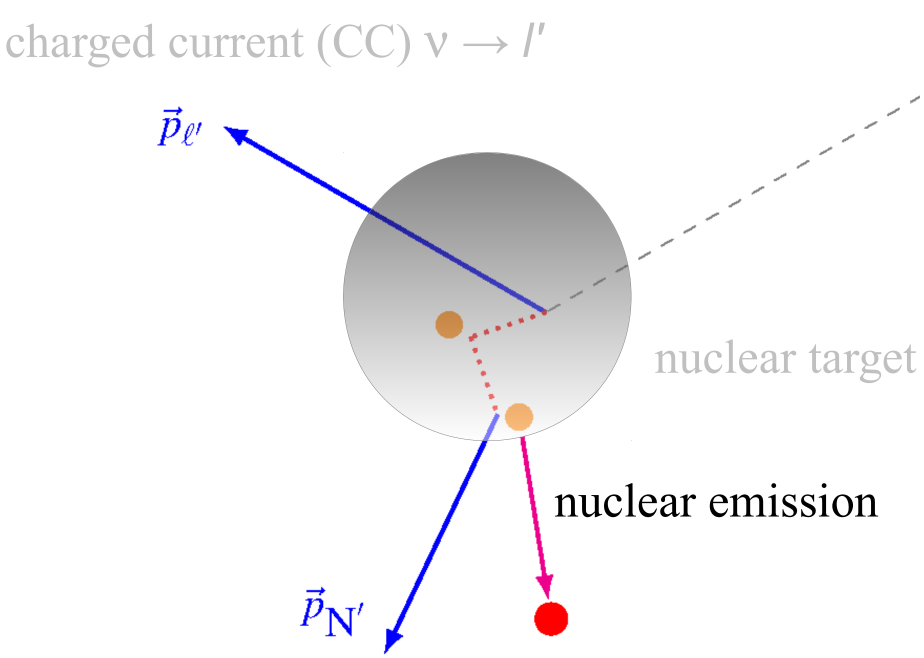


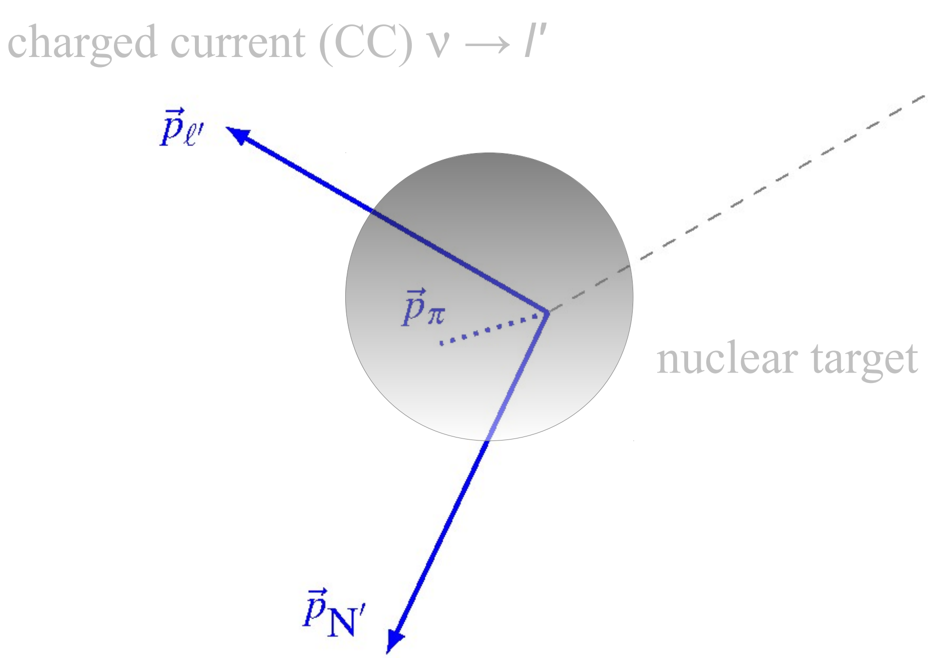
- GENIE Nominal and No-FSI have different shape
- GENIE MINERvA Tune (v1) excess at high angle

FSI decomposition in mesonless proton production:

Proton FSI:
- Non-interacting (no change of energy and direction of the proton)
- Acceleration: energy of proton increased after FSI
- Deceleration: energy of proton decreased after FSI

Pion FSI: pion absorption





Single-Particle Kinematics

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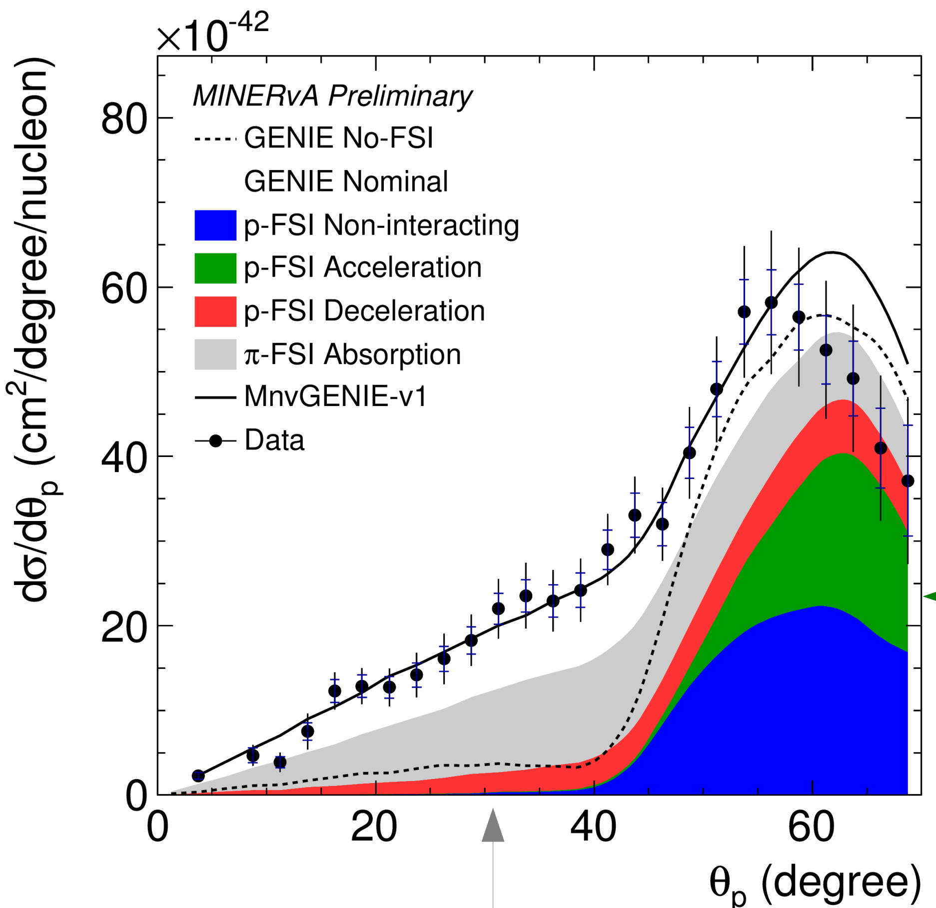

Proton FSI acceleration localized at high angle

Pionless resonant production dominates low angle

NUCLEAR EFFECT DIAGNOSTICS

A more general analysis of kinematic imbalance

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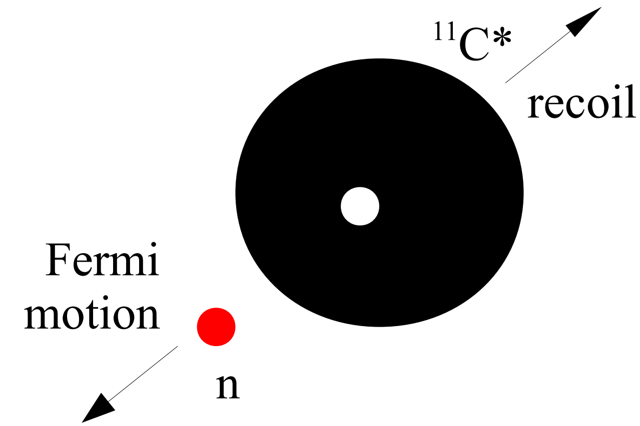

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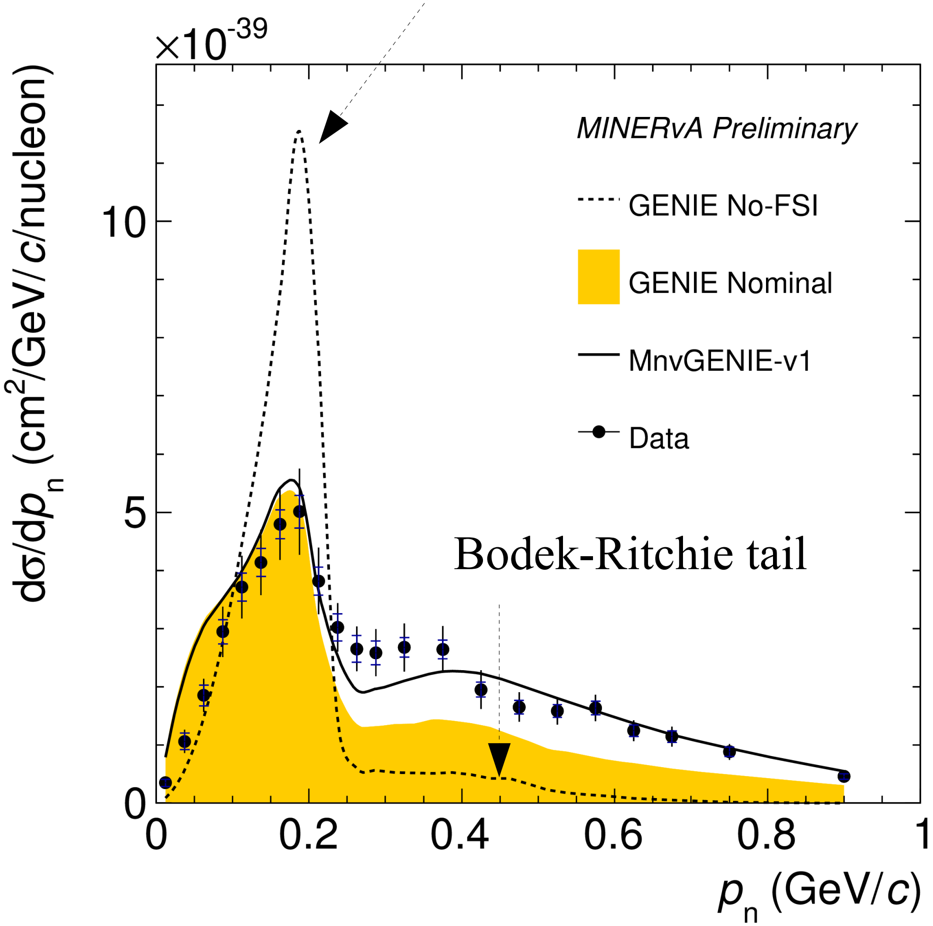
A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501

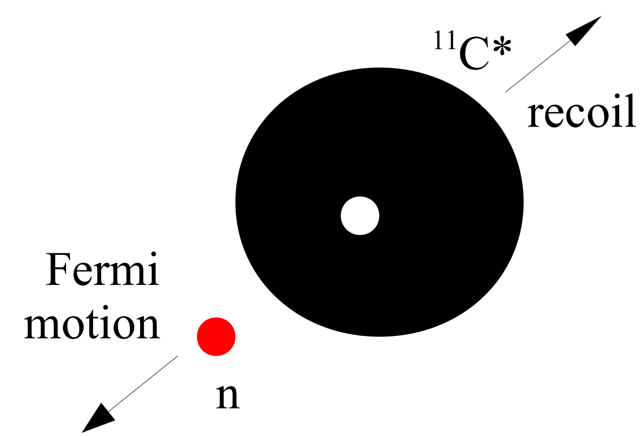
Nuclear Effect Diagnostics

- CCQE with Fermi motion

Fermi Gas model prediction

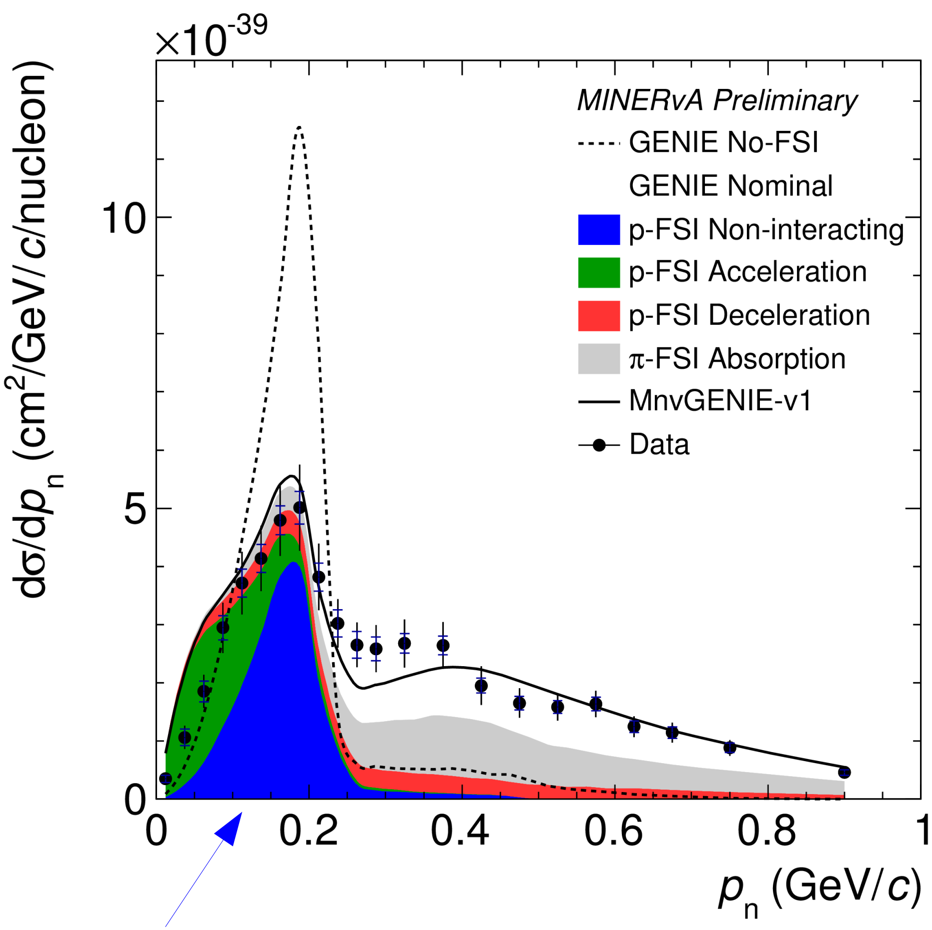


p_n is Fermi motion magnitude → "QE peak"
– GENIE No-FSI



Nuclear Effect Diagnostics

- CCQE with Fermi motion



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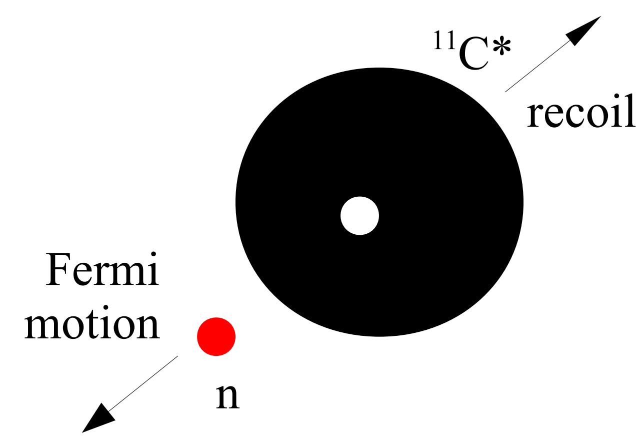
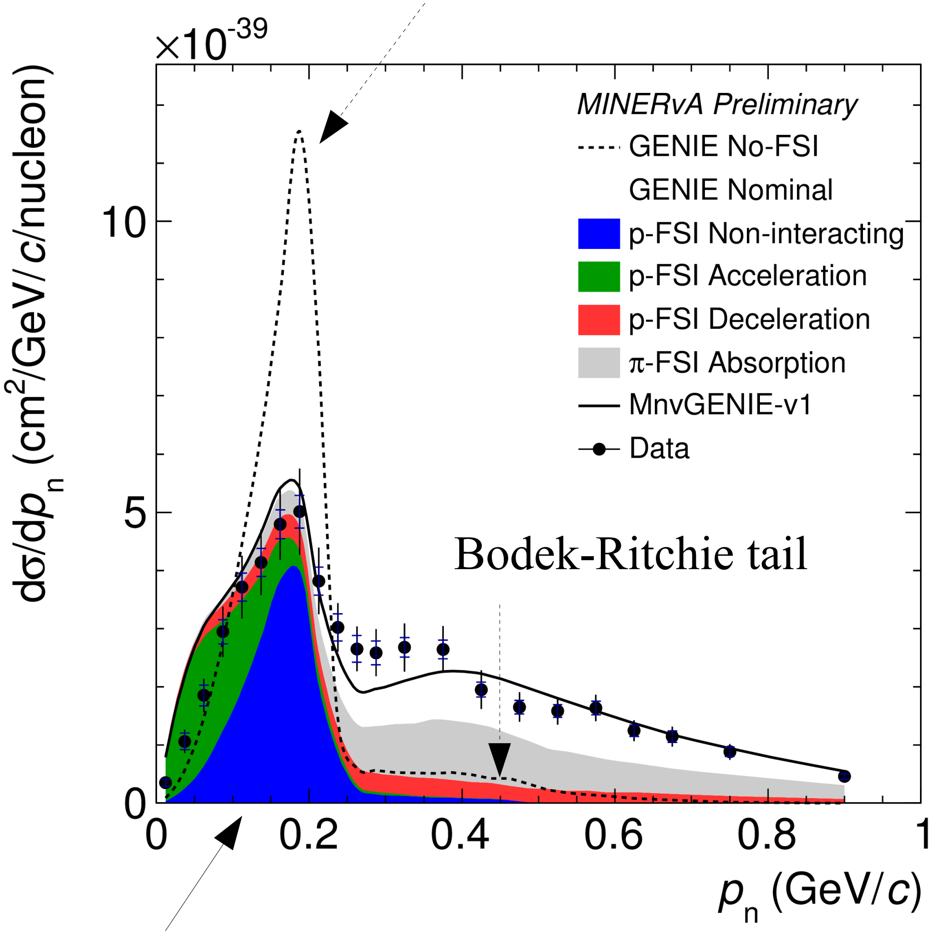


Nuclear Effect Diagnostics

- CCQE with Fermi motion

Fermi Gas model prediction



Bodek-Ritchie tail

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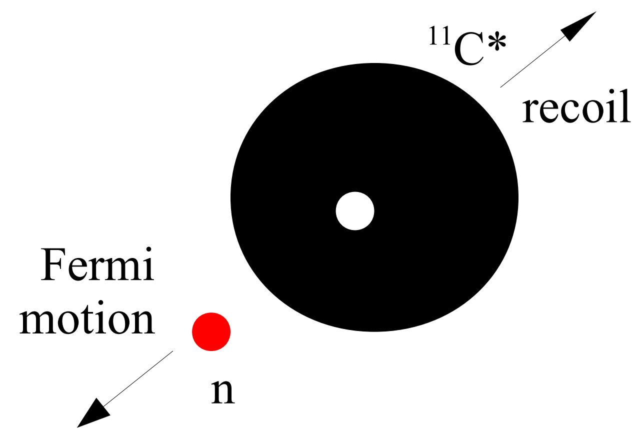
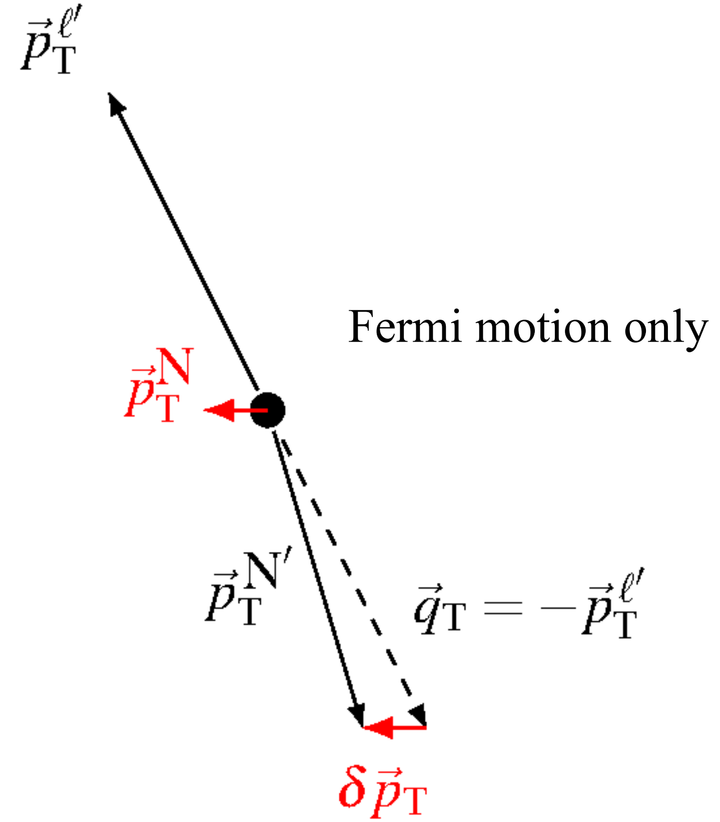


QE peak dominated by CCQE without FSI
Direct constraint of Fermi motion



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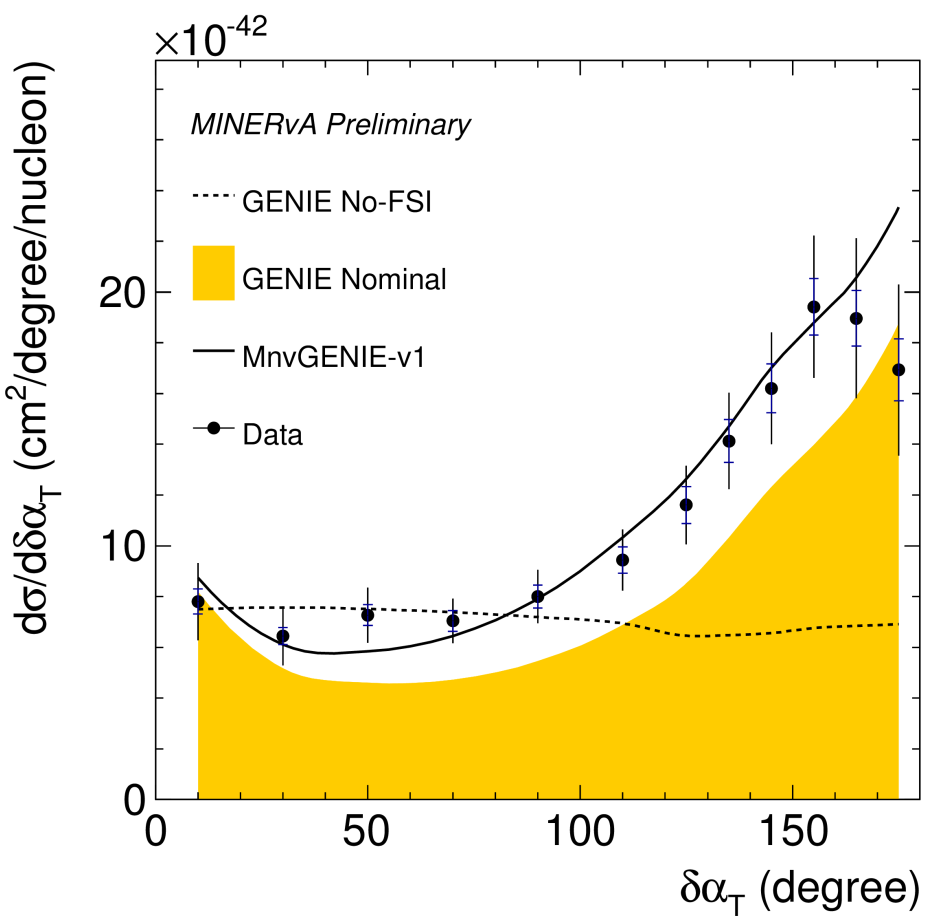
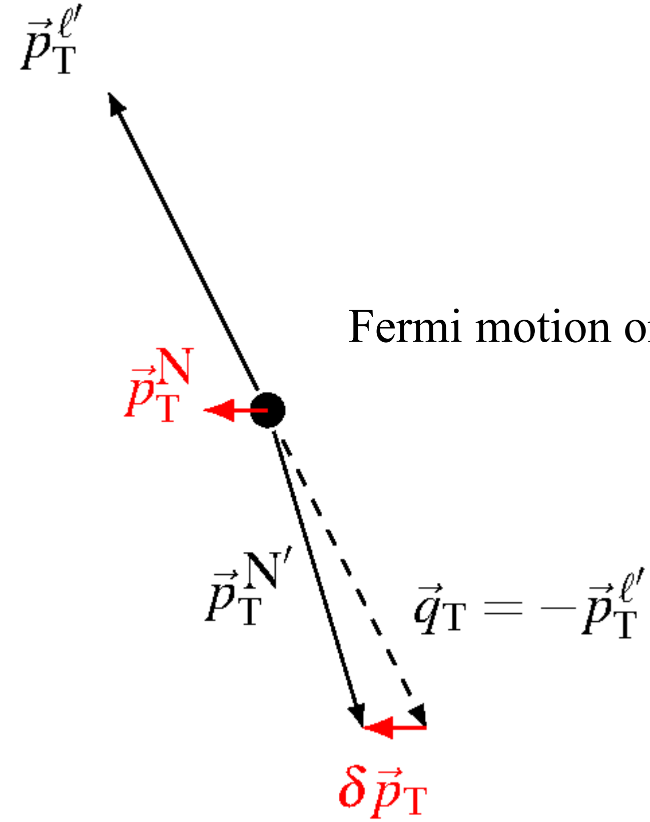
$$\delta\vec{p}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\mathrm{N}}$$

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

Nuclear Effect Diagnostics

- CCQE with Fermi motion





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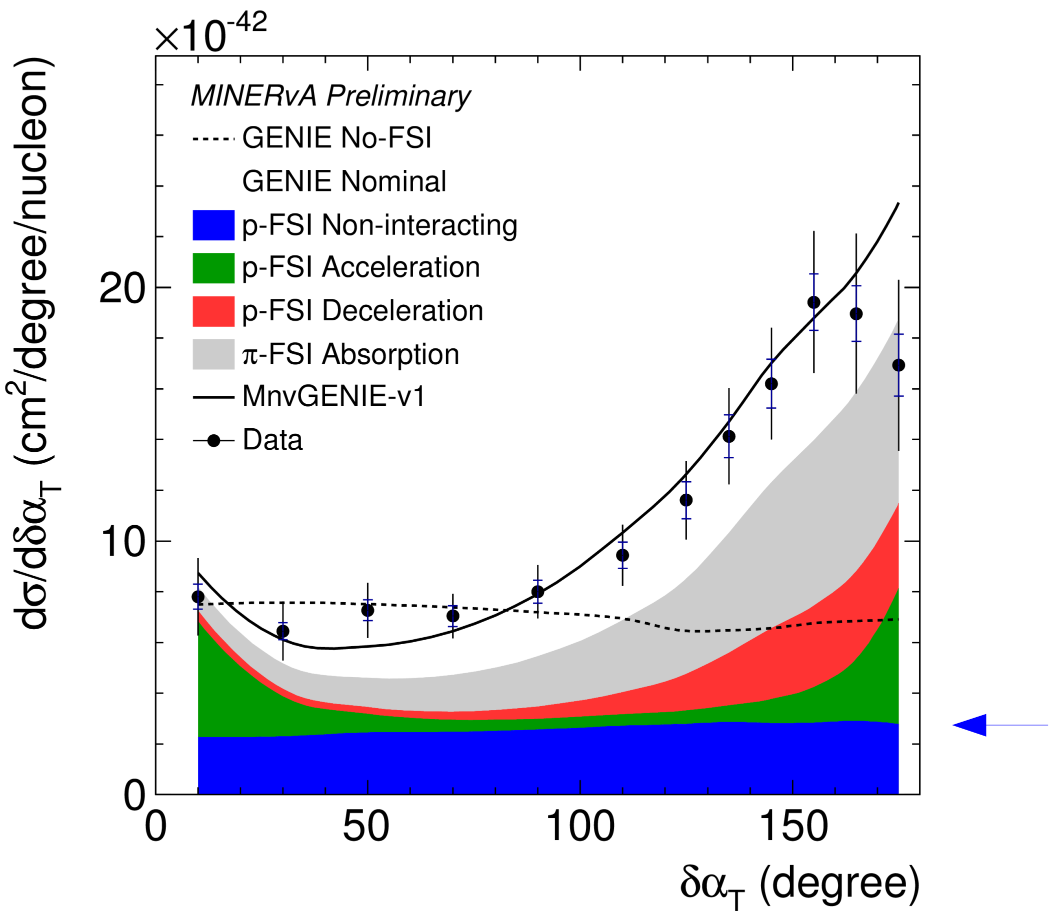

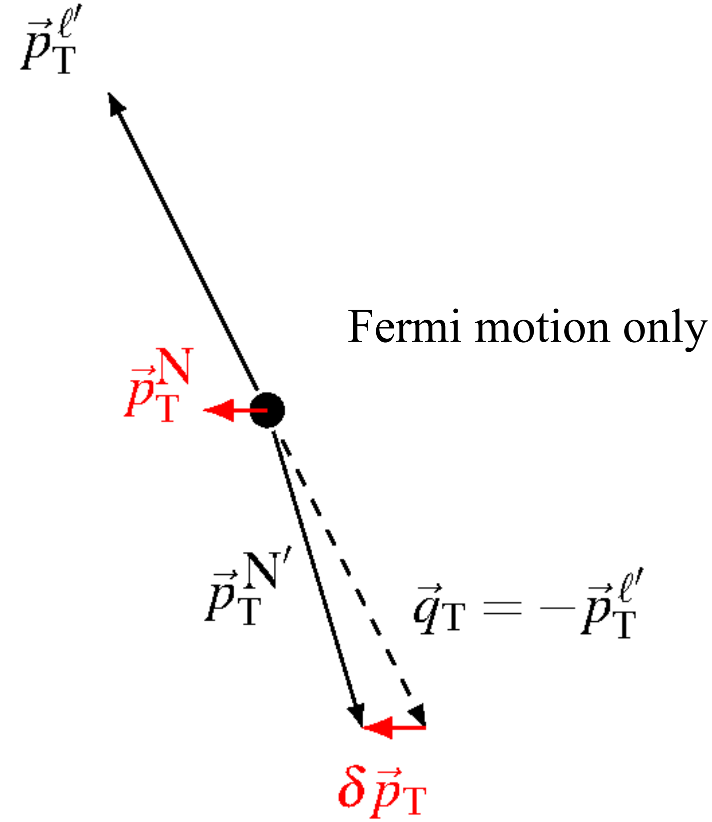

$\delta\alpha_T$ is Fermi motion direction → isotropic

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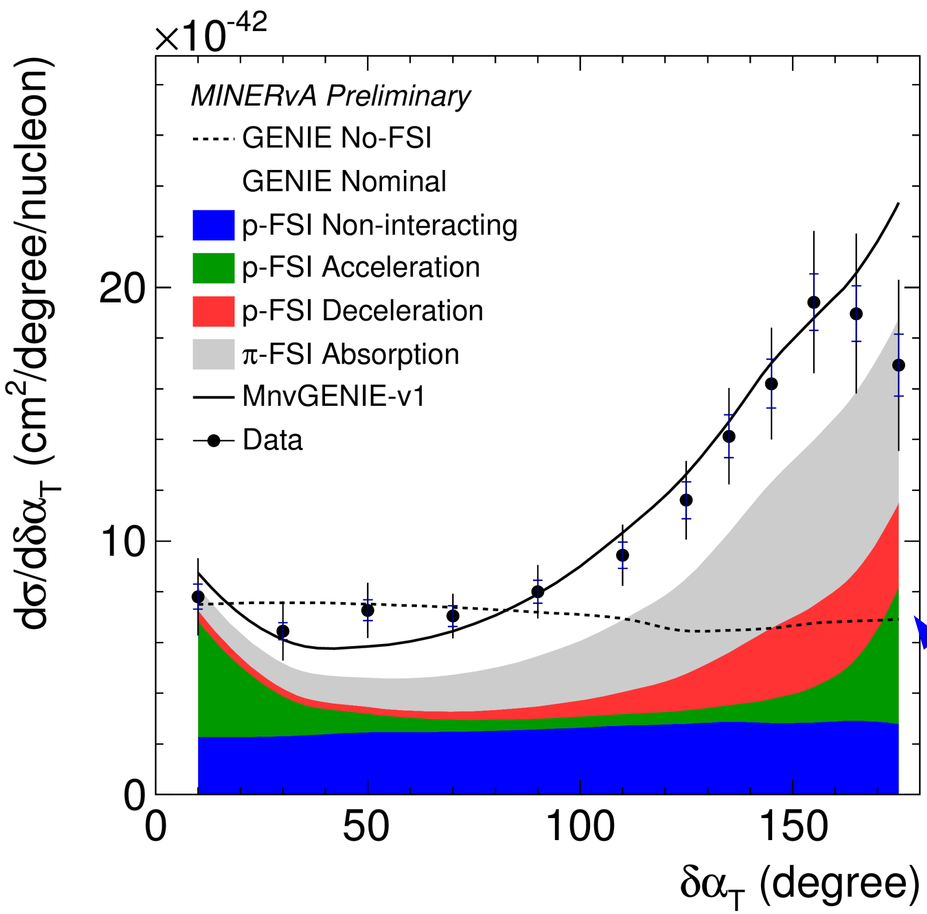
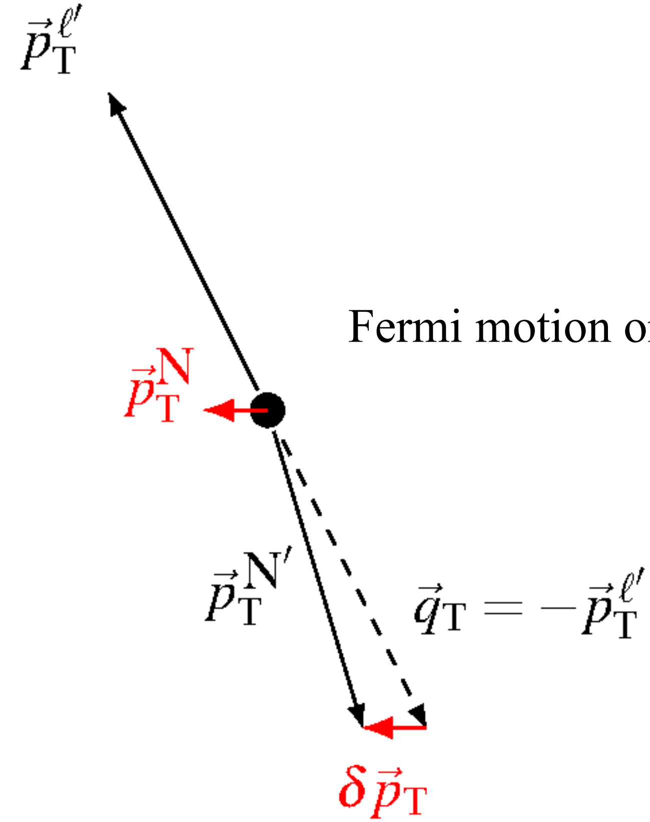
– p-FSI Non-interacting

Nuclear Effect Diagnostics

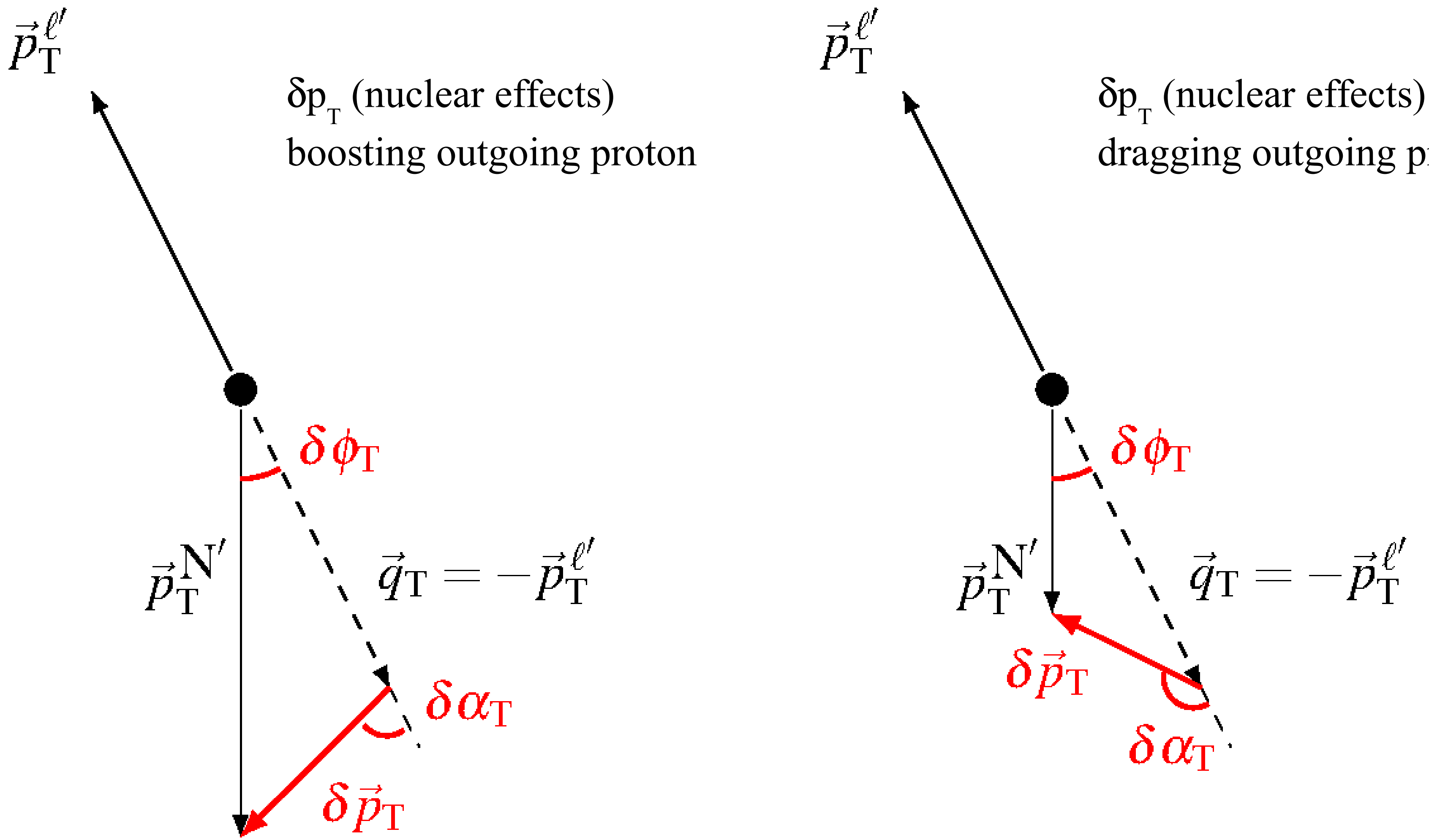
- CCQE with Fermi motion





$\delta\alpha_T$ is Fermi motion direction → isotropic
– GENIE No-FSI
– p-FSI Non-interacting

Baseline for all non-Fermi motion effects
Factor out Fermi motion uncertainty
Complementary to p_n



With full nuclear effects

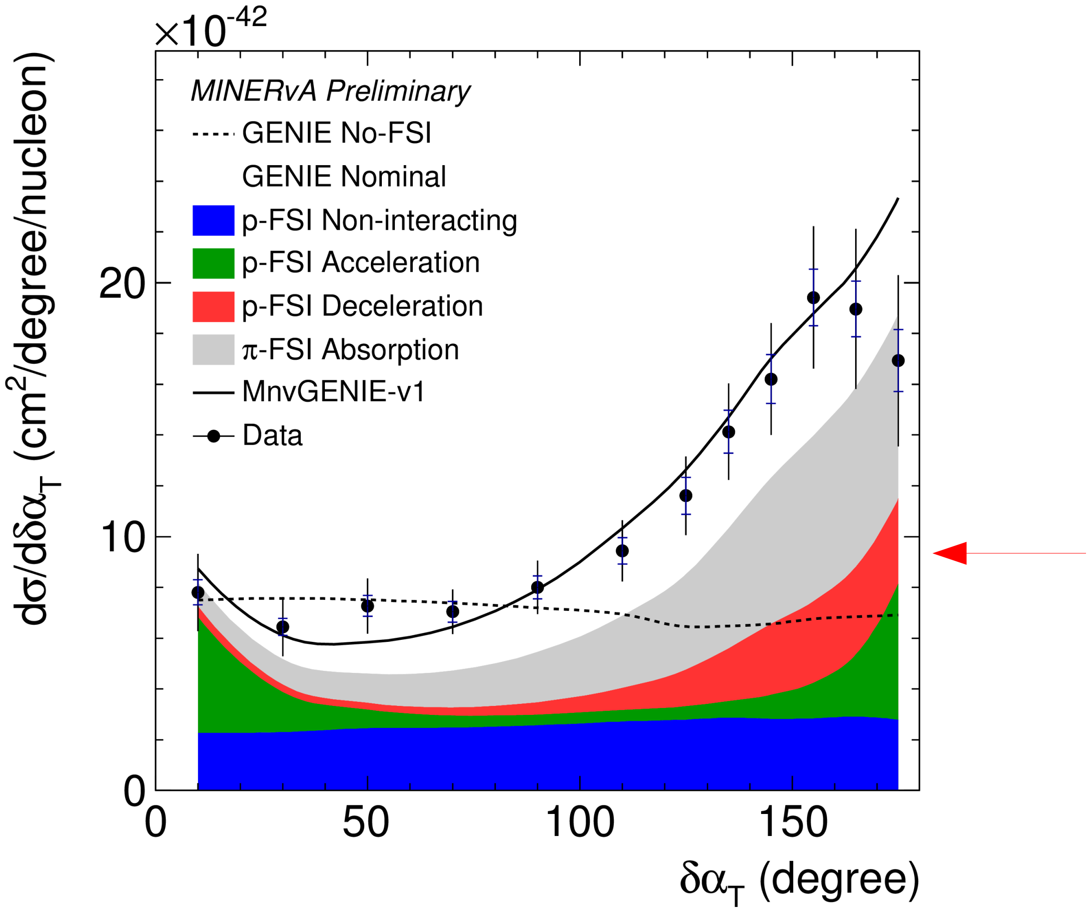
$$\delta\vec{p}_T = \vec{p}_T^{N} - \Delta\vec{p}_T$$

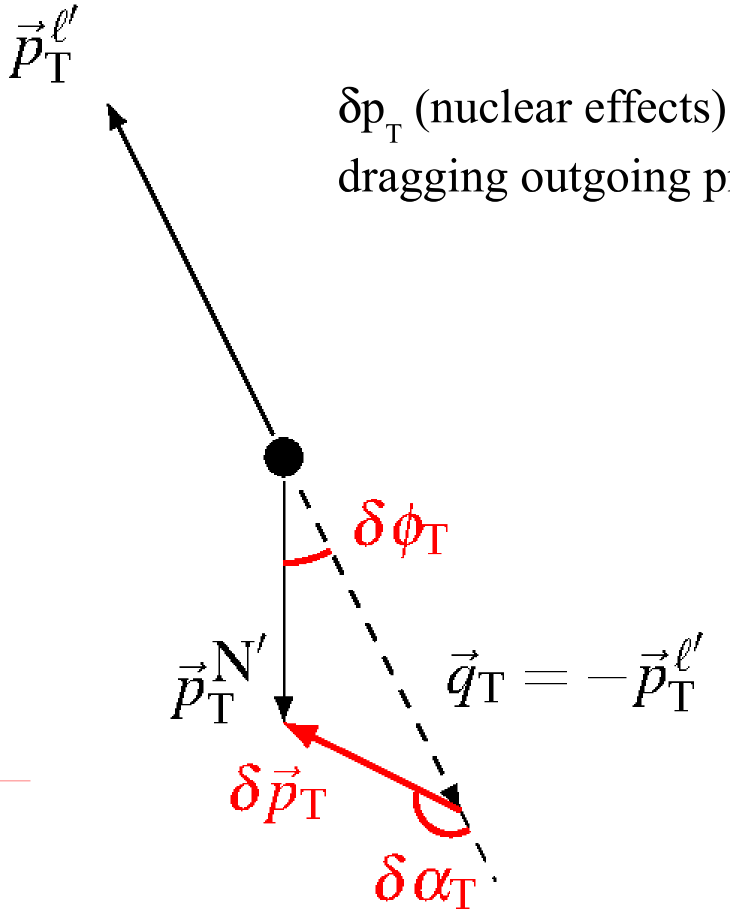
Intranuclear momentum transfer

Baseline for all non-Fermi motion effects
Factor out Fermi motion uncertainty
Complementary to p_n

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration

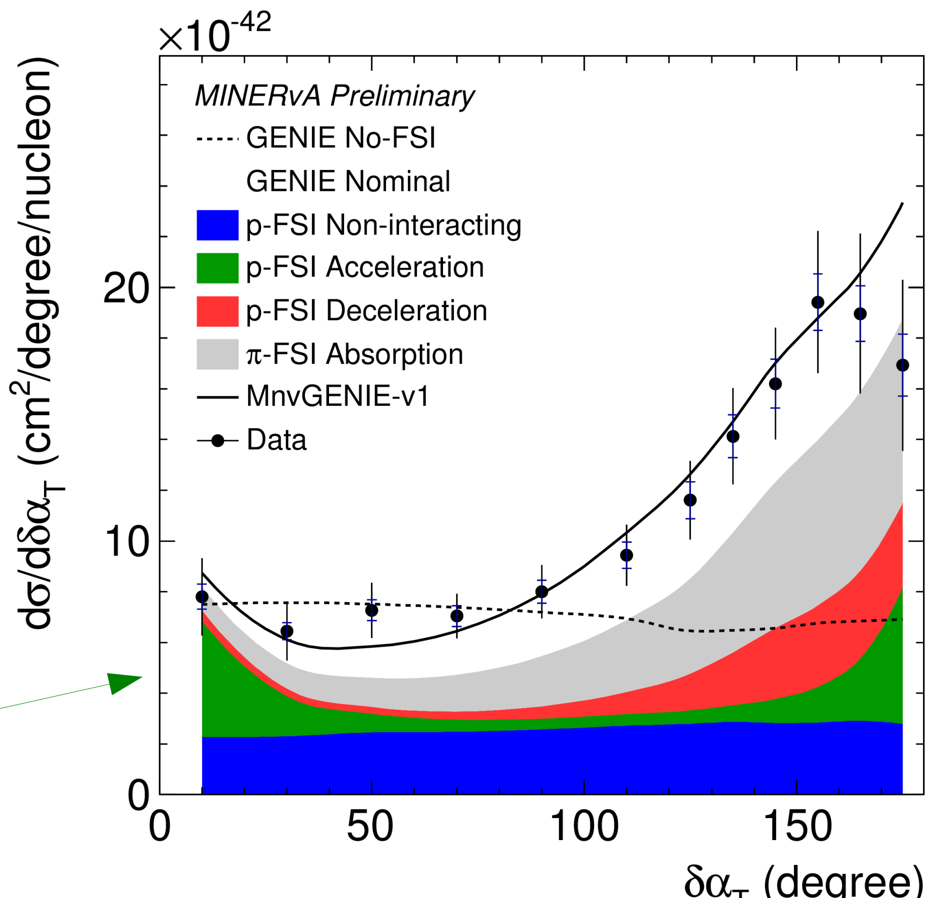


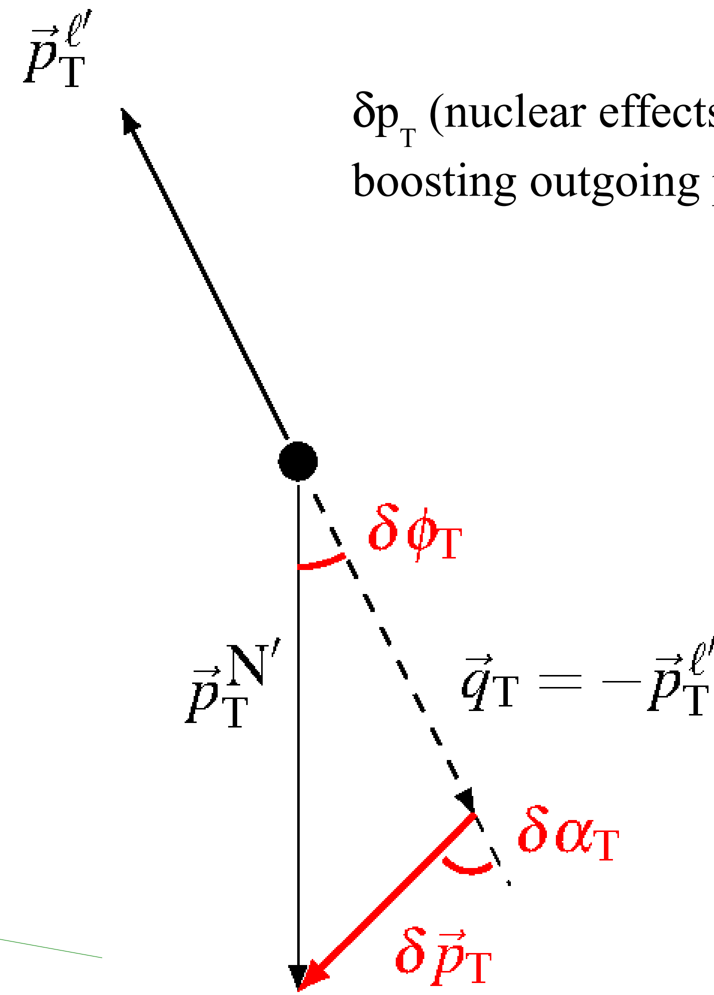


Deceleration at large $\delta\alpha_T$

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration





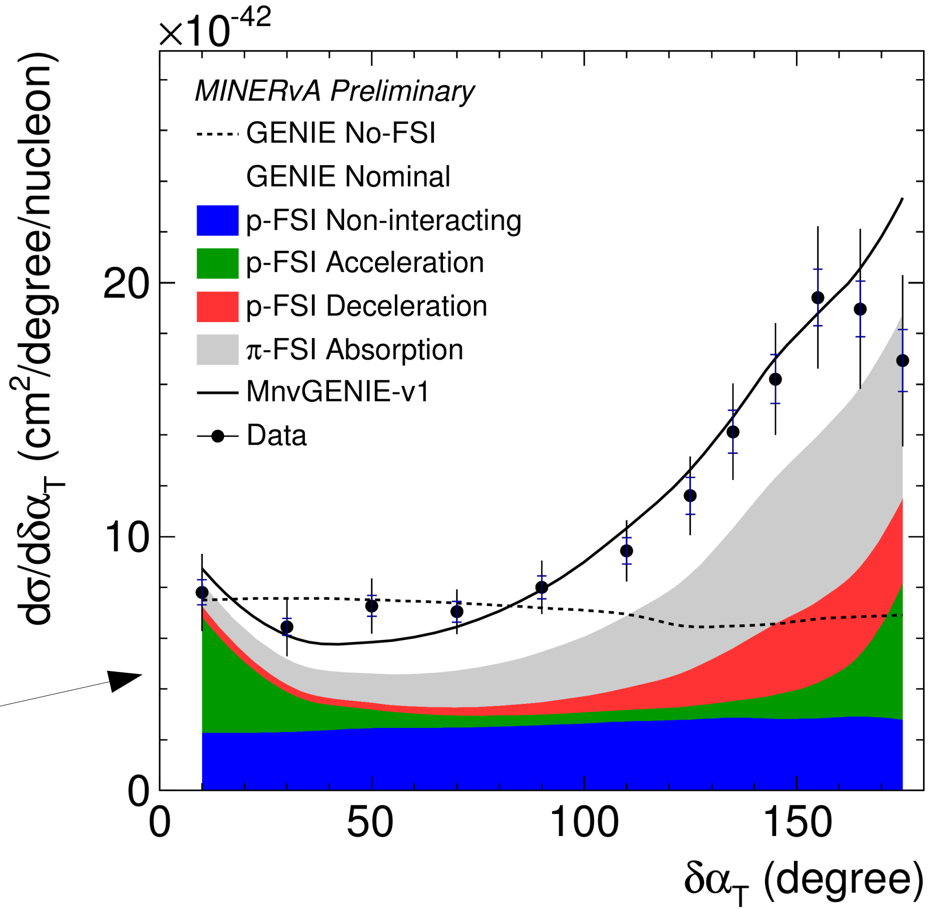
δp_T (nuclear effects) boosting outgoing proton

Deceleration at large $\delta\alpha_T$

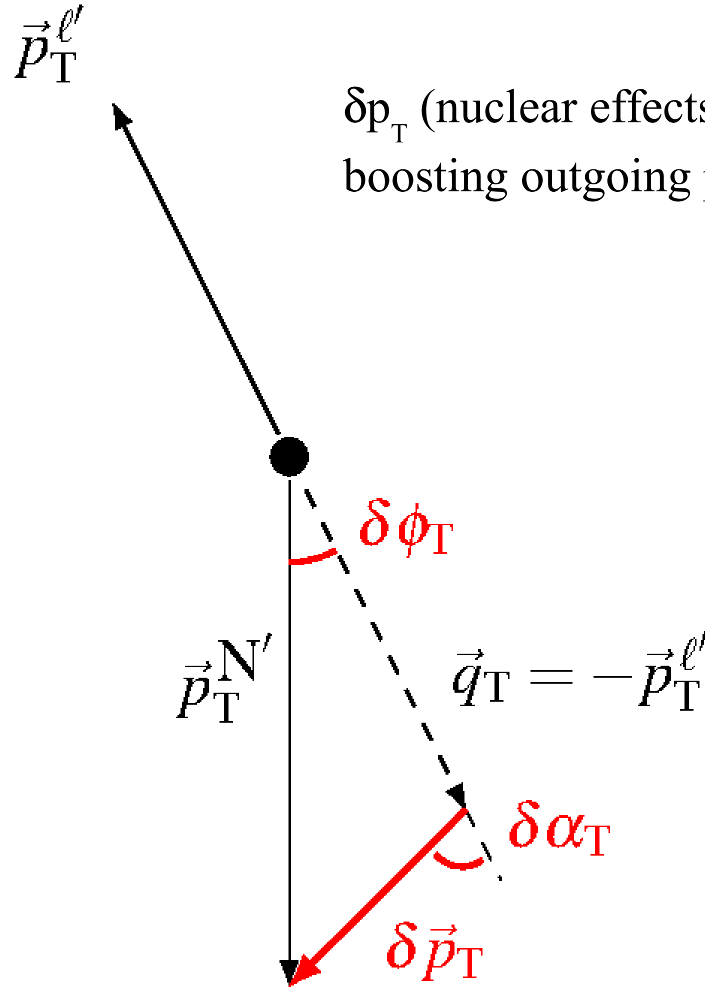
Acceleration at both small and (due to transverse projection) large $\delta\alpha_T$

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration



Only acceleration can enter small $\delta\alpha_T$



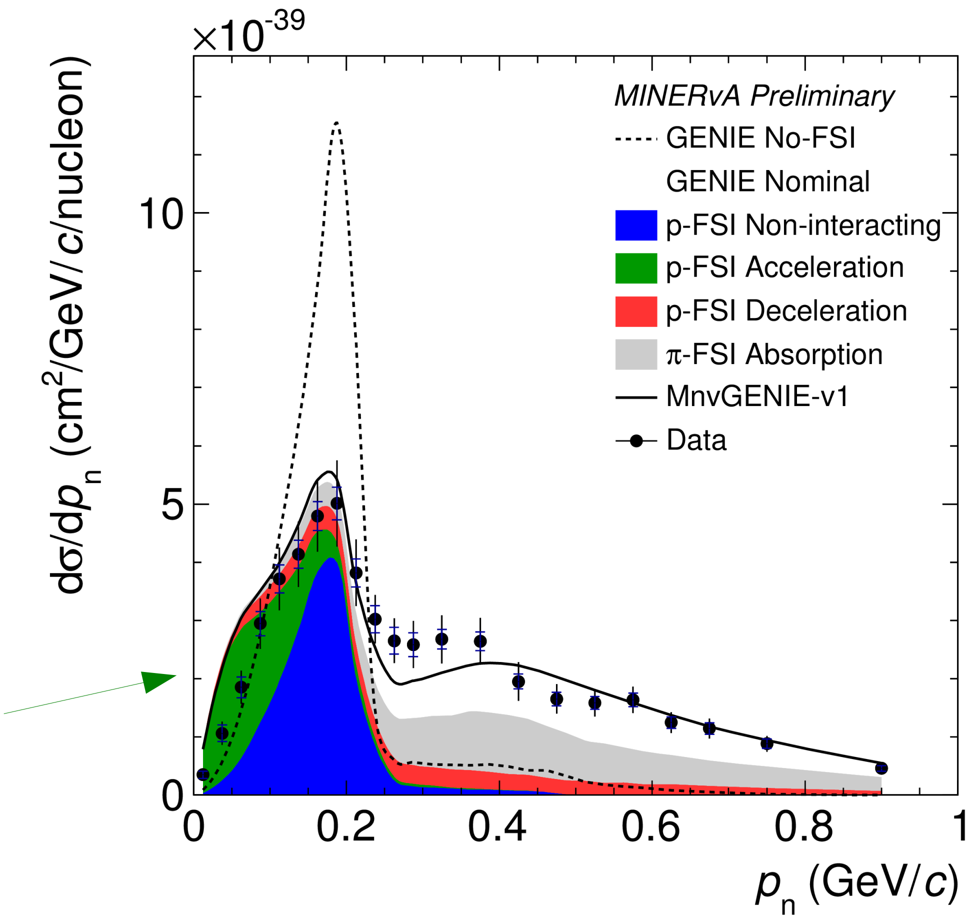
δp_T (nuclear effects) boosting outgoing proton

Deceleration at large $\delta\alpha_T$

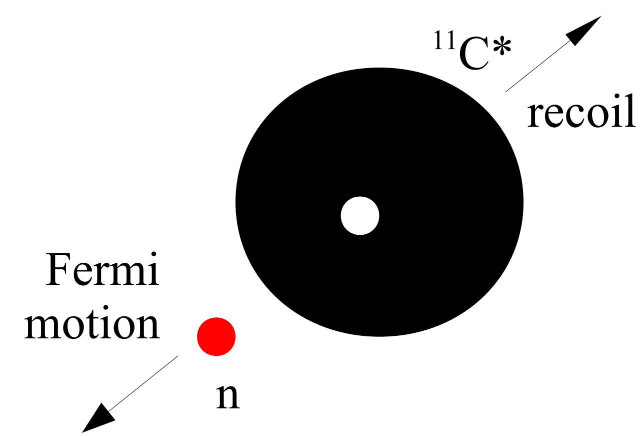
Acceleration at both small and (due to transverse projection) large $\delta\alpha_T$

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration



Acceleration to the left of QE peak
Strongly distort QE peak



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

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

For RES, DIS, 2p2h, no longer exclusive μ-p-A' final states

$$p_{\mathrm{n}} = |\vec{p}_{\mathrm{N}} - \Delta\vec{p}|$$

Fermi motion Intranuclear momentum transfer

A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501

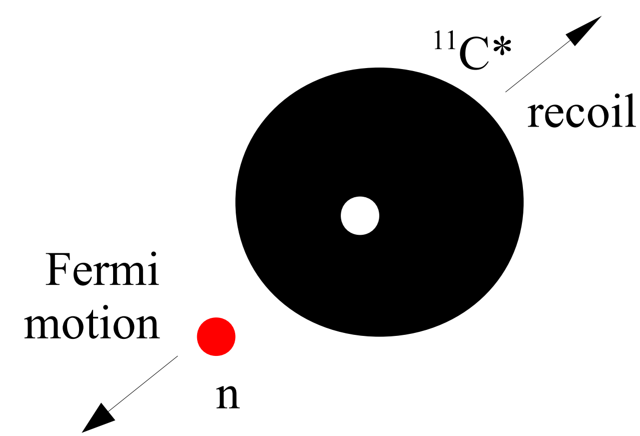
Assuming exclusive μ-p-A' final states

Use energy conservation to close the equations

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

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

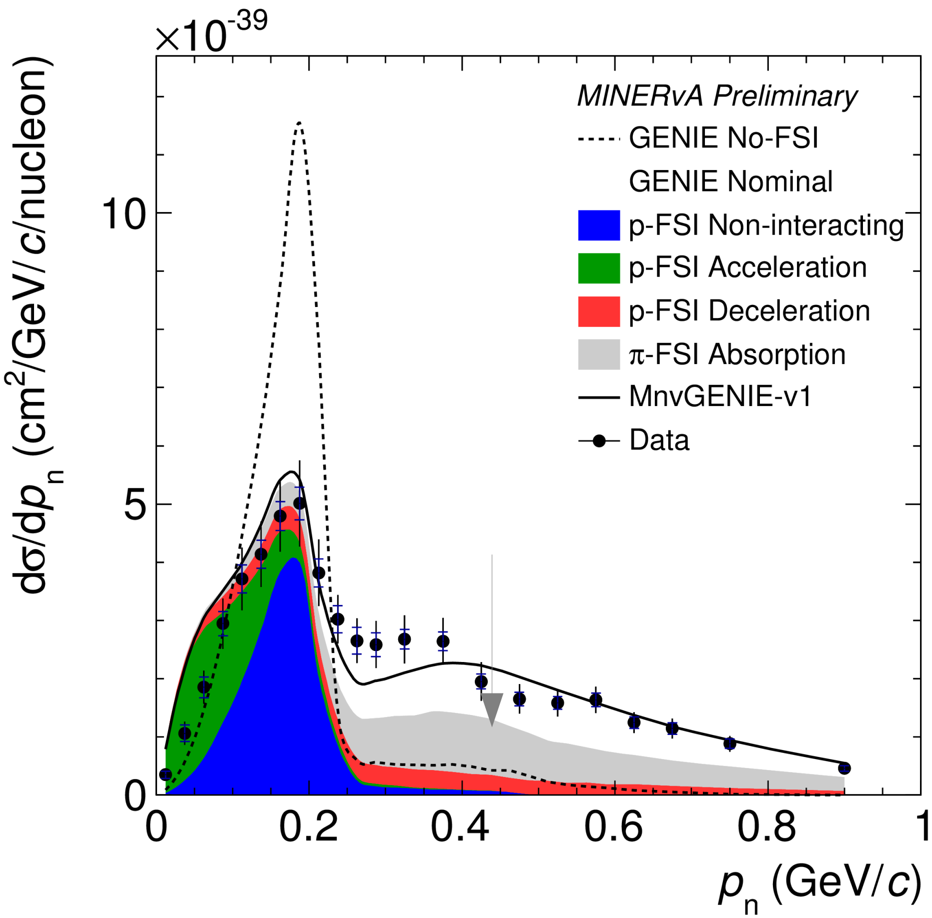
p_{n}: recoil momentum of the nuclear remnant



$$p_L = \frac{1}{2}(M(A) + k'_L + p'_L - E' - E_{p'}) - \frac{p_T^2 + M^*(A-1)^2}{2(M(A) + k'_L + p'_L - E' - E_{p'})}$$

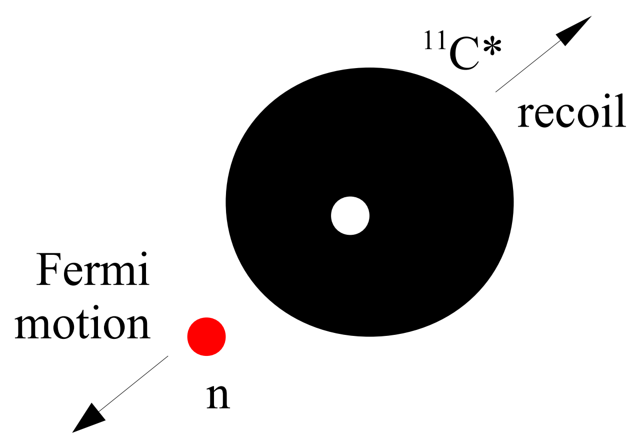
Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration
- Pionless resonant production, pion absorption FSI, and 2p2h



Δ*p* small → Δ*p* large

p_n: smeared δp_T beyond QE peak → tail
– π-FSI Absorption



Pion production and 2p2h process: strong intra-nuclear momentum transfer due to momentum sharing with proton

Nuclear Effect Diagnostics

- CCQE with Fermi motion
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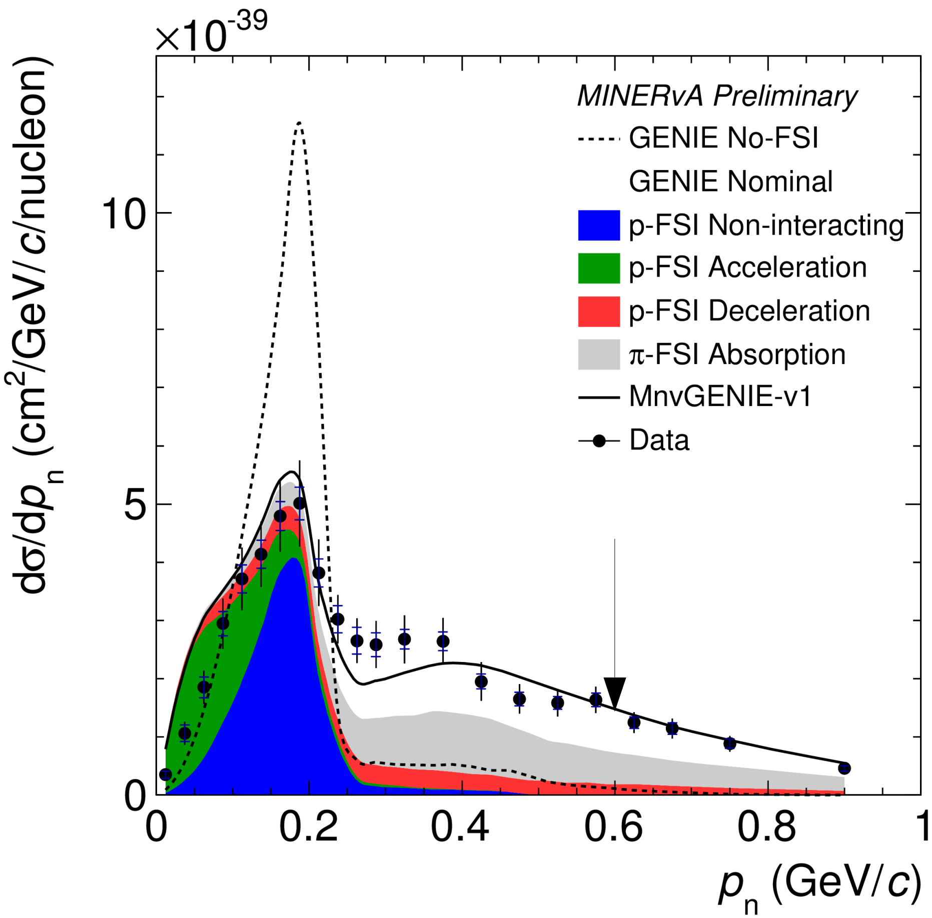
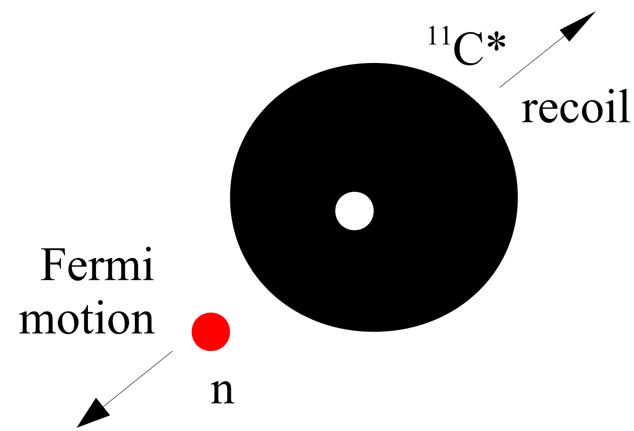


Δ*p* small → Δ*p* large

p_n: smeared δp_T beyond QE peak → tail

– π-FSI Absorption

– 2p2h
(= MnvGENIE-v1 – GENIE Nominal)



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Nuclear Effect Diagnostics

- CCQE with Fermi motion
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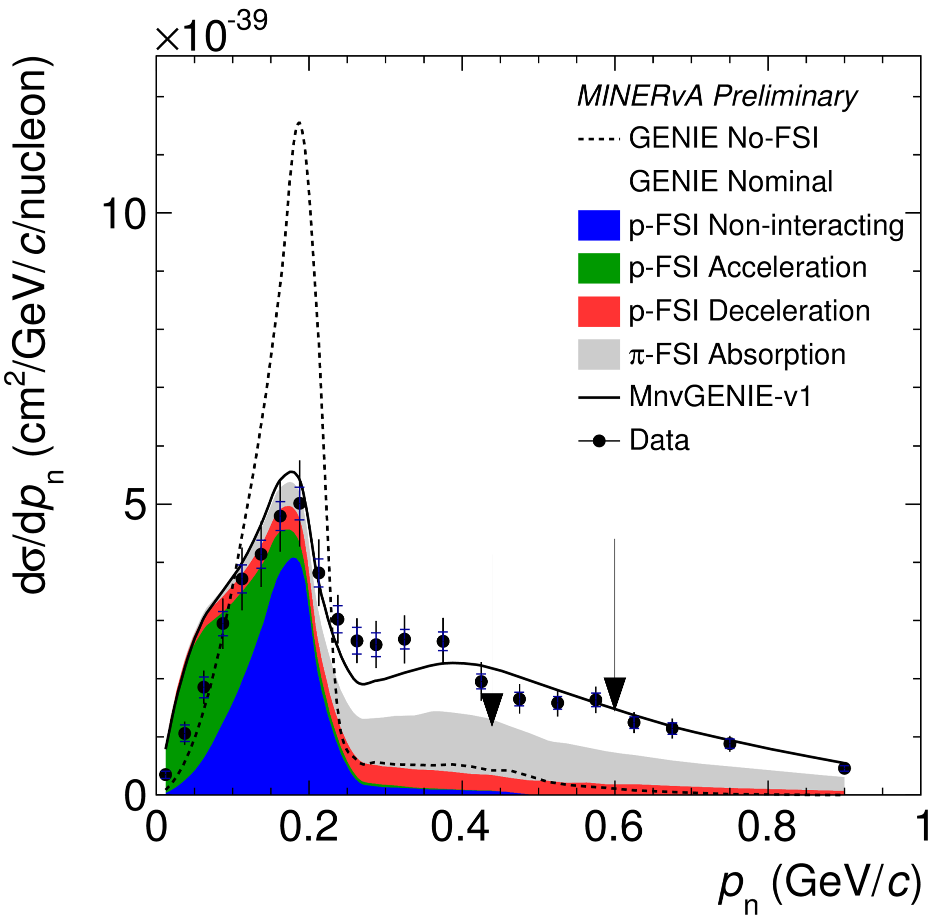


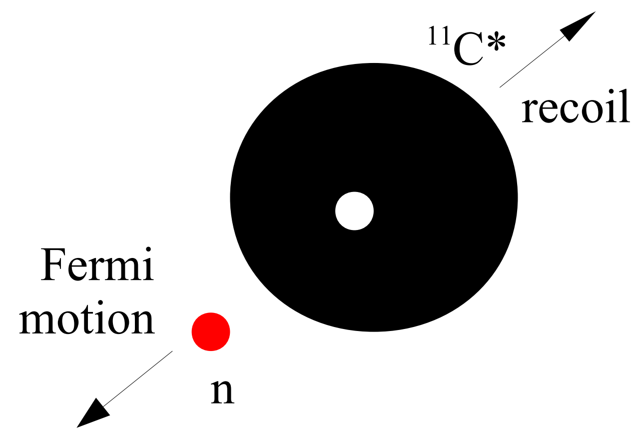
Δp small → Δp large

GENIE describes the tail reasonably well due to large contribution from 2p2h tuned to MINERvA inclusive measurements

p_n: smeared δp_T beyond QE peak → tail

– π-FSI Absorption

– 2p2h
(= MnvGENIE-v1 – GENIE Nominal)



Pion production and 2p2h process: strong intra-nuclear momentum transfer due to momentum sharing with proton

Nuclear Effect Diagnostics

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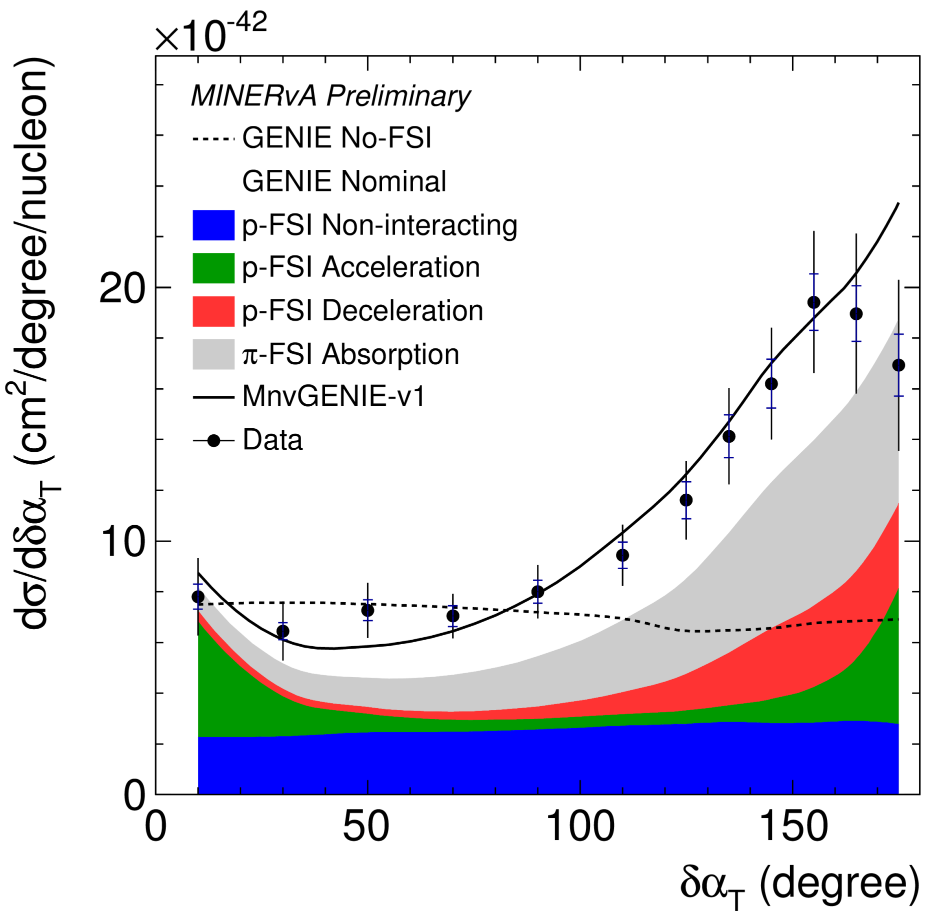
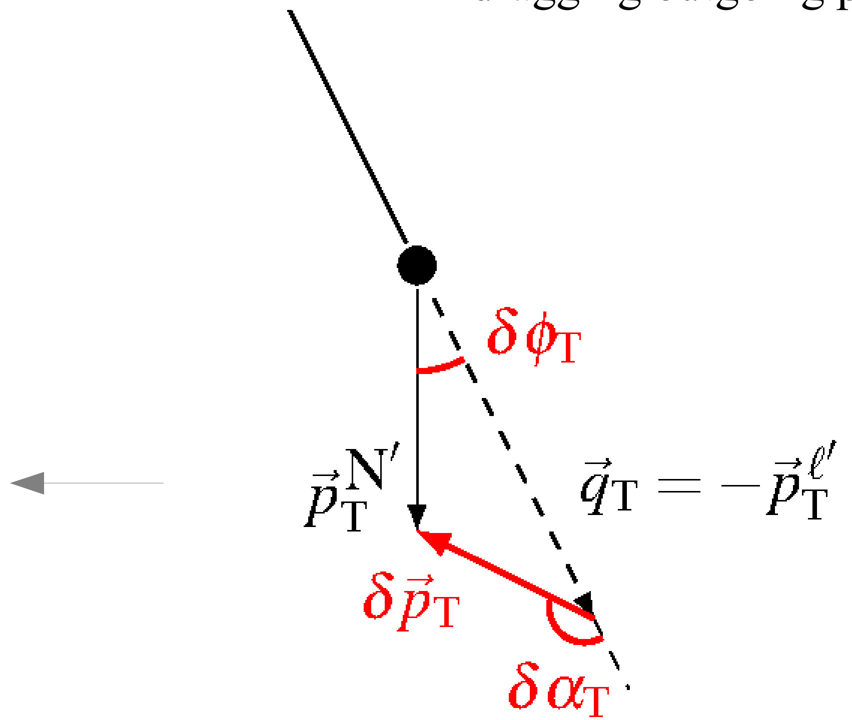
- Pionless resonant production, pion absorption FSI, and 2p2h



δp_T (nuclear effects) dragging outgoing proton



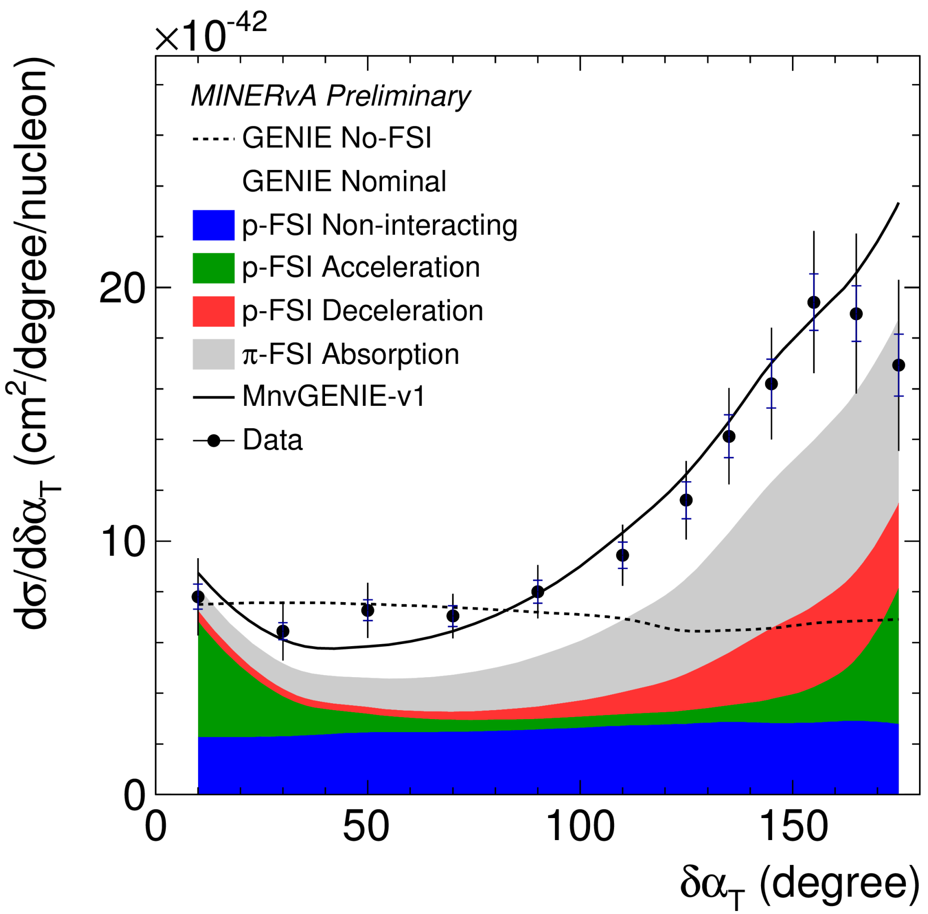
Proton momentum shared by others, decelerated → large $\delta\alpha_T$ region

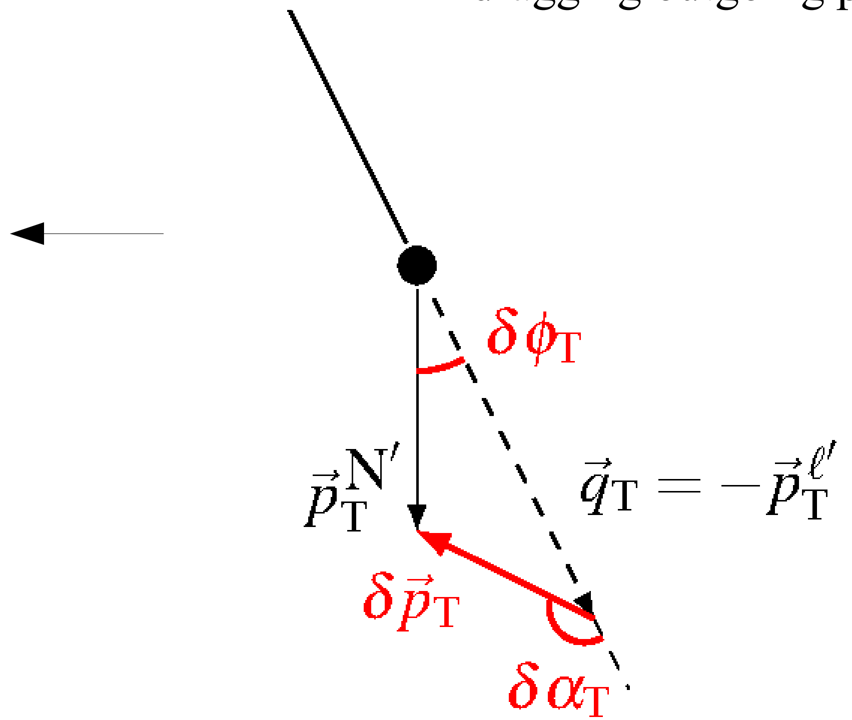
– π-FSI Absorption

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration
- Pionless resonant production, pion absorption FSI, and 2p2h

δp_T (nuclear effects) dragging outgoing proton





Proton momentum shared by others, decelerated → large $\delta\alpha_T$ region

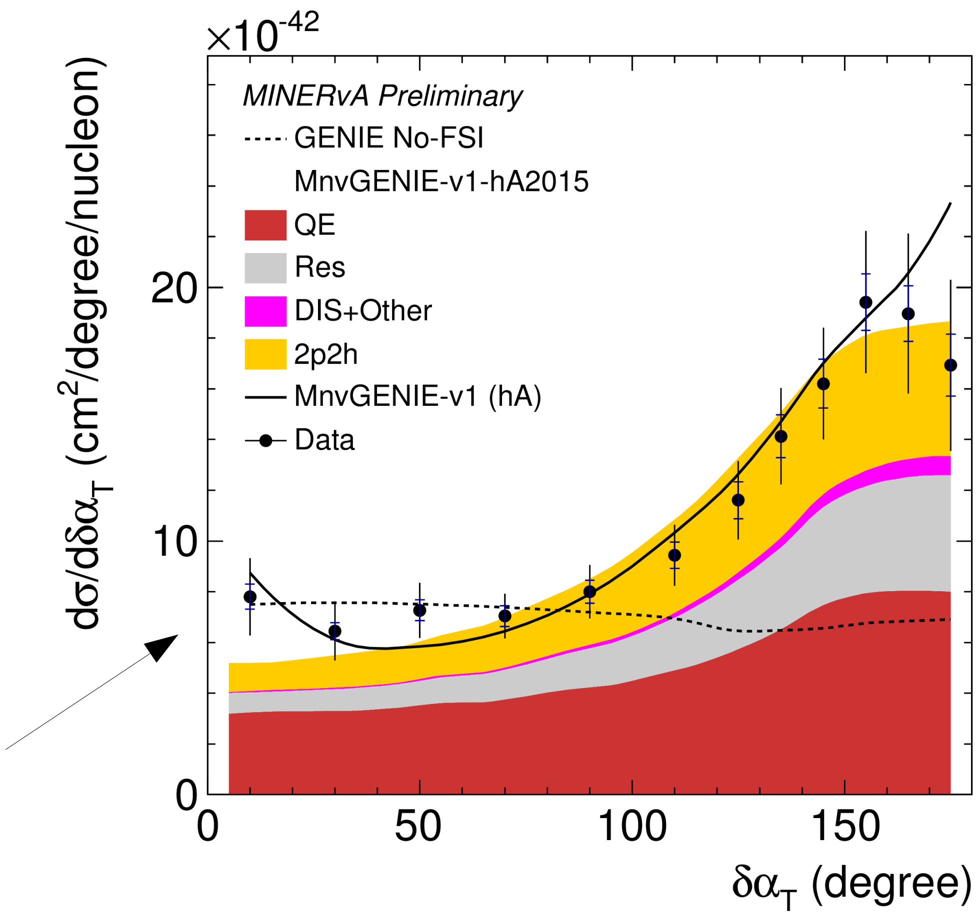
– π-FSI Absorption

– 2p2h (= MnvGENIE-v1 – GENIE Nominal)

ADVANCED TOPICS: GENIE FSIs

Advanced Topics: GENIE FSIs

- (pre2015) hA: effective model, include “elastic component” in intranuclear scattering, used in GENIE MINERvA Tune (v1)
- hA2015: removed “elastic component”, replacing hA in MnvGENIE-v1-hA2015



No p-FSI acceleration

Advanced Topics: GENIE FSIs

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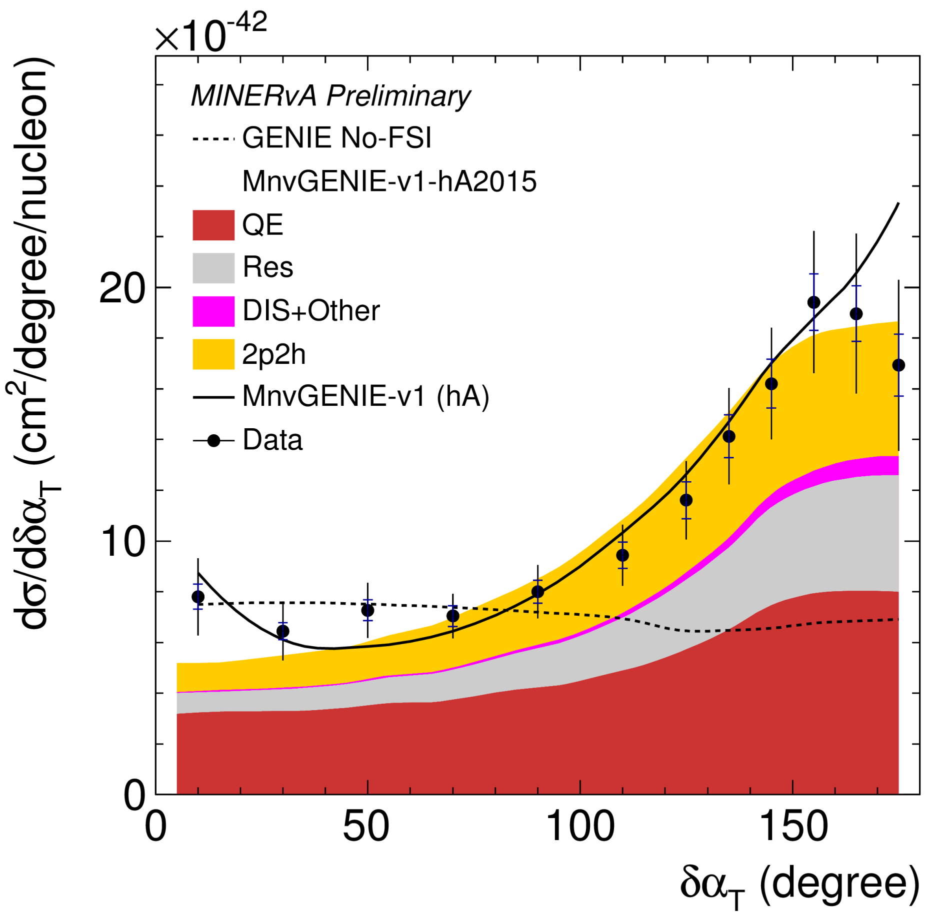
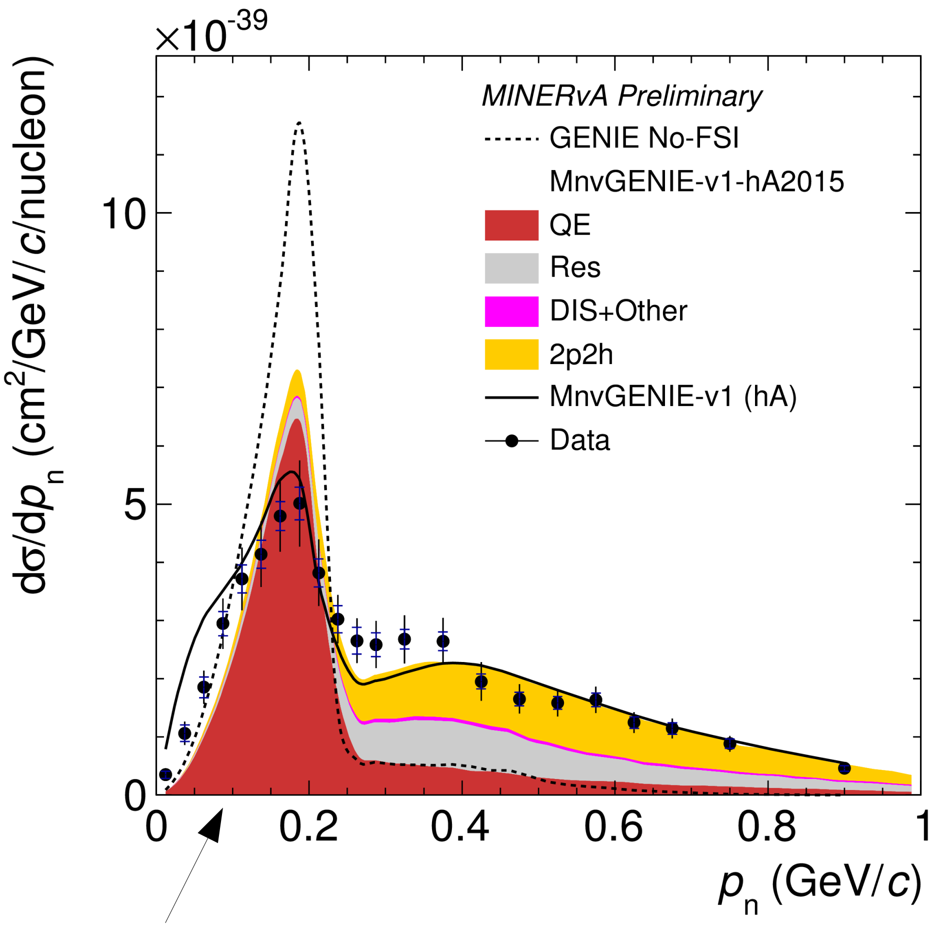


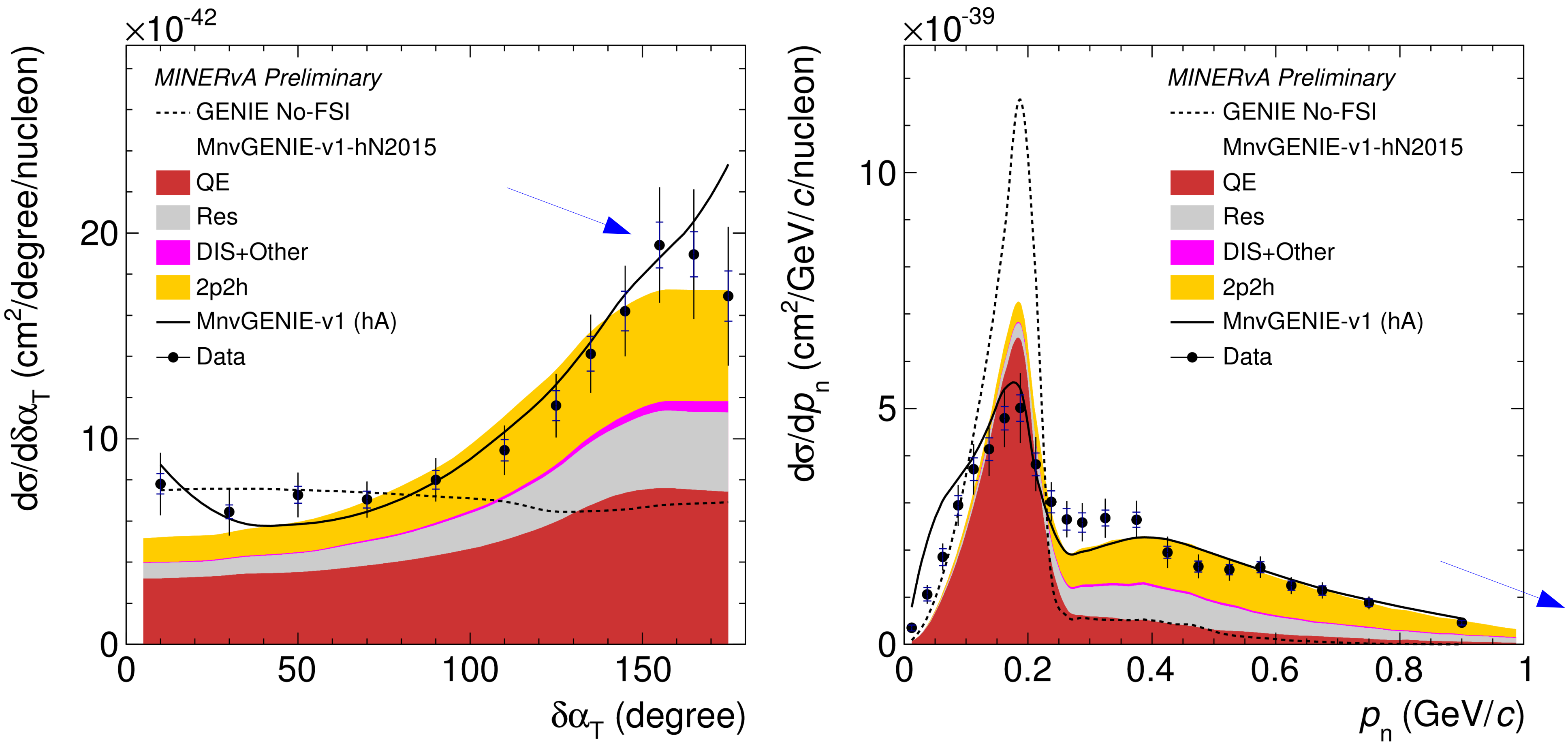


No p-FSI acceleration

QE peak not distorted, but much narrower

Advanced Topics: GENIE FSIs

- (pre2015) hA: effective model, include "elastic component" in intranuclear scattering, used in GENIE MINERvA Tune (v1)
- hA2015: removed "elastic component", replacing hA in MnvGENIE-v1-hA2015
- hN2015: full cascades + Oset, replacing hA in MnvGENIE-v1-hN2015



hA2015 and hN2015 difference in
- Large $\delta\alpha_T$ (concentrated)
- p_n tail (diluted)

ADVANCED TOPICS: NUWRO

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

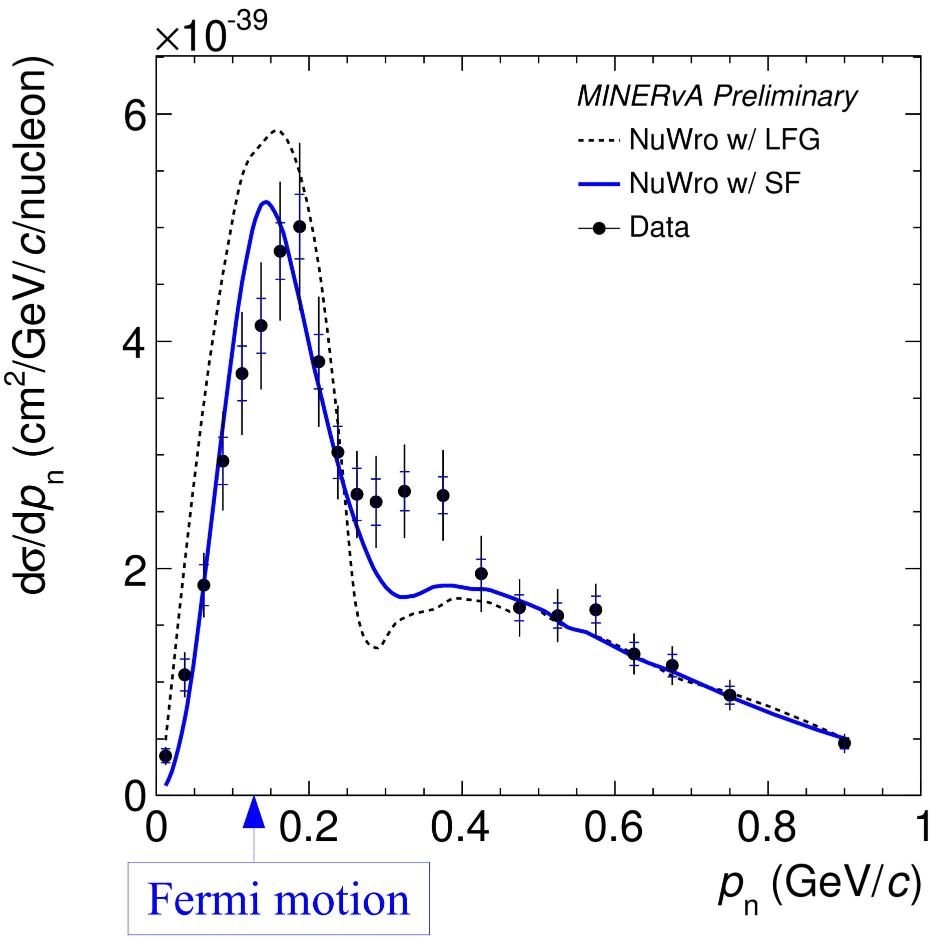
- **Nominal**: version 2.8.4
  - global Fermi Gas (RFG) model with Bodek-Ritchie (BR) tail [Phys. Rev. D 23, 1070 (1981)]
  - hA FSI [AIP Conf.Proc. 1405 (2011) 213-218]
- **No-FSI**: Nominal without FSI
- **MnvGENIE-v1: GENIE MINERvA Tune (v1) [only 2p2h relevant for this analysis]**
  - Added Random Phase Approximation (RPA) [Phys.Rev. C70 (2004) 055503]
  - Non-resonance pion production scaled down by 75% [Phys.Rev. D90 (2014) no.11, 112017]
  - 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]
    - tuned to MINERvA inclusive data → significant enhancement in small 4-momentum transfer region [Phys.Rev.Lett. 116 (2016) 071802]

Simulation: NuWro [Phys.Rev. C86 (2012) 015505]

- Version: 11q
  - Local Fermi Gas (LFG) or Spectral Function (SF) [Benhar *et al.*, Nucl.Phys. A579 (1994) 493-517]
  - FSI: intranuclear cascades of hadronic interactions + Oset model [Nucl.Phys. A484 (1988) 557-592]
- Valencia 2p2h [Nieves *et al.*, Phys.Lett. B707 (2012) 72-75, Phys. Rev. C 86, 015504 (2012)]

Advanced Topics: NuWro

- Fermi motion



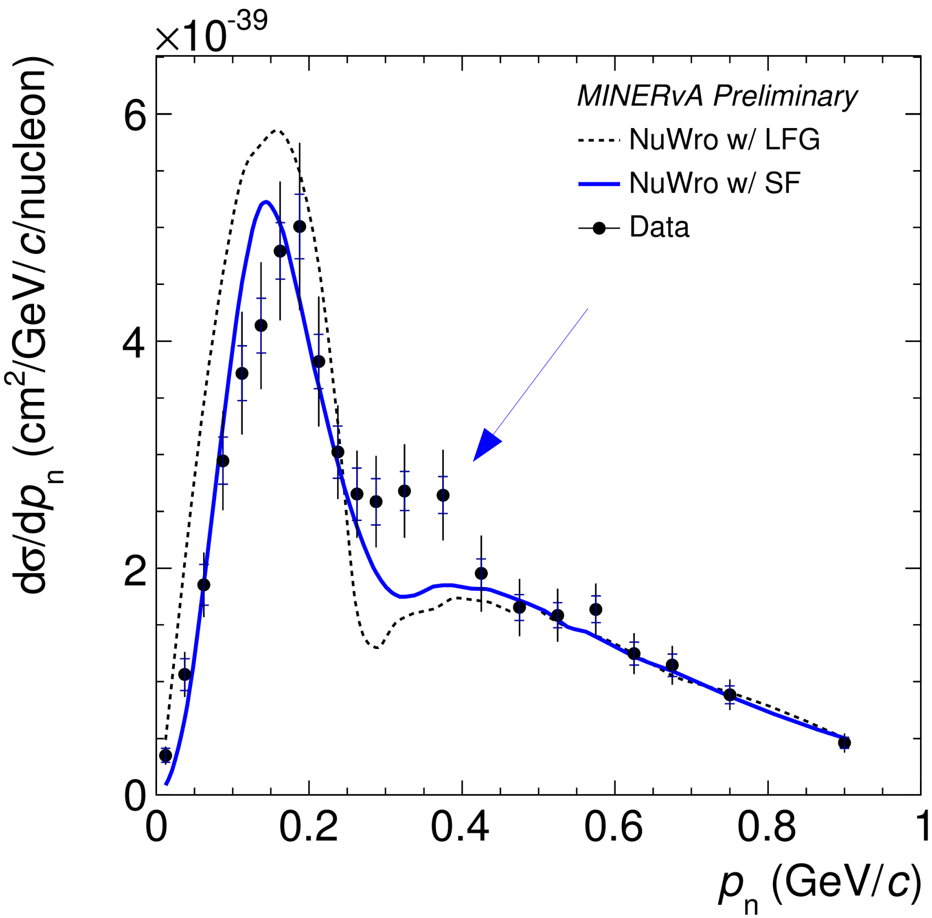
Δp small → Δp large

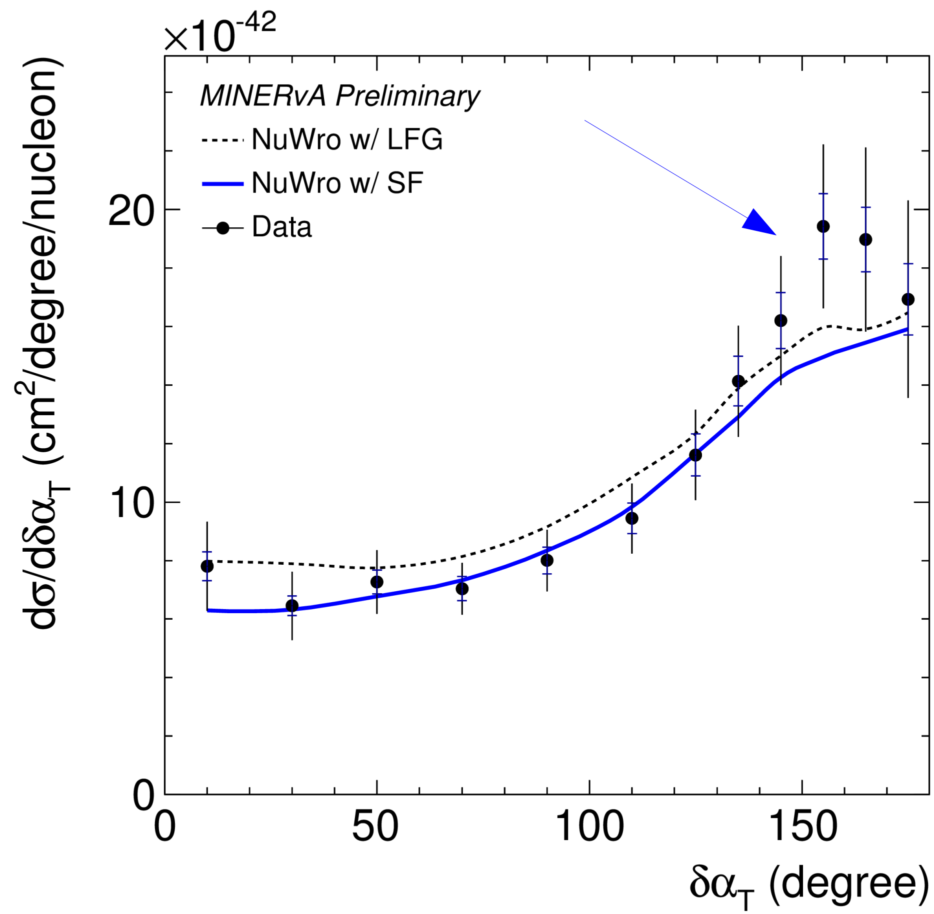
(intranuclear momentum transfer)

SF describes Fermi motion very well

Advanced Topics: NuWro

- Fermi motion
- Resonance / 2p2h strength





Δp small → Δp large
(intranuclear momentum transfer)

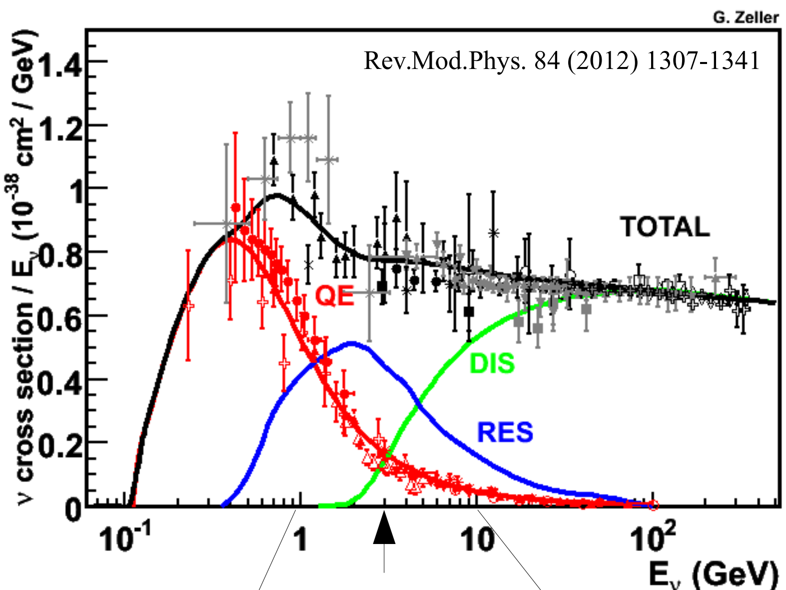
SF describes Fermi motion very well
Resonance / 2p2h lacks of local strength

ADVANCED TOPICS: COMPARISON TO T2K

Advanced Topics: Comparison to T2K

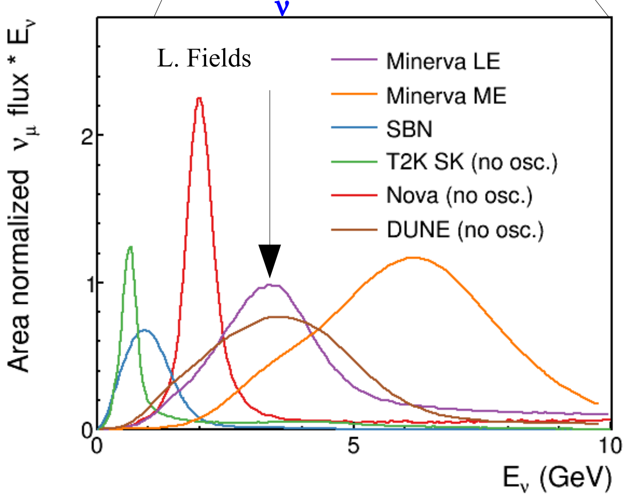
[arXiv:1802.05078] *same target, slight difference in signal phase space definition

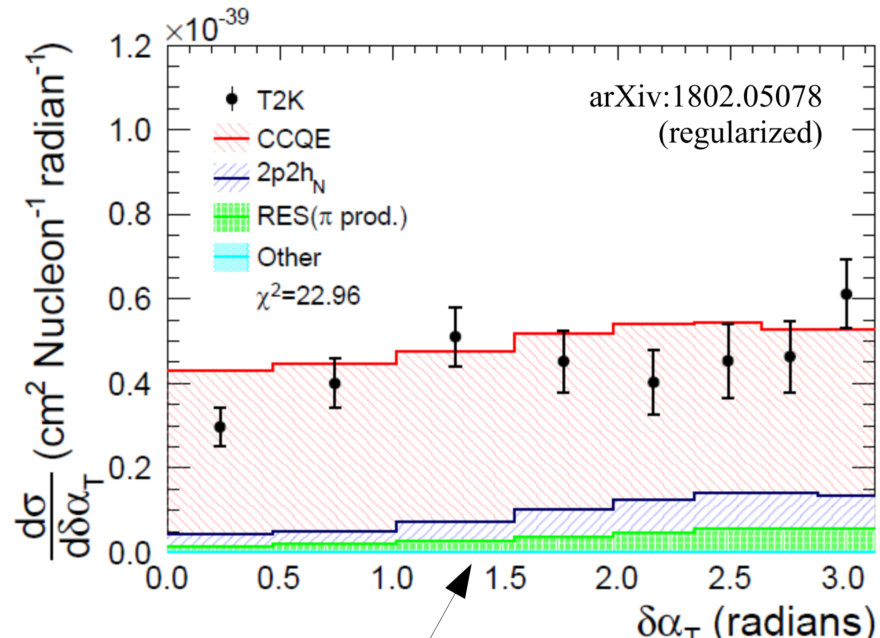
- $\delta\alpha_T$



NuMI LE

<E_ν> ~ 3 GeV



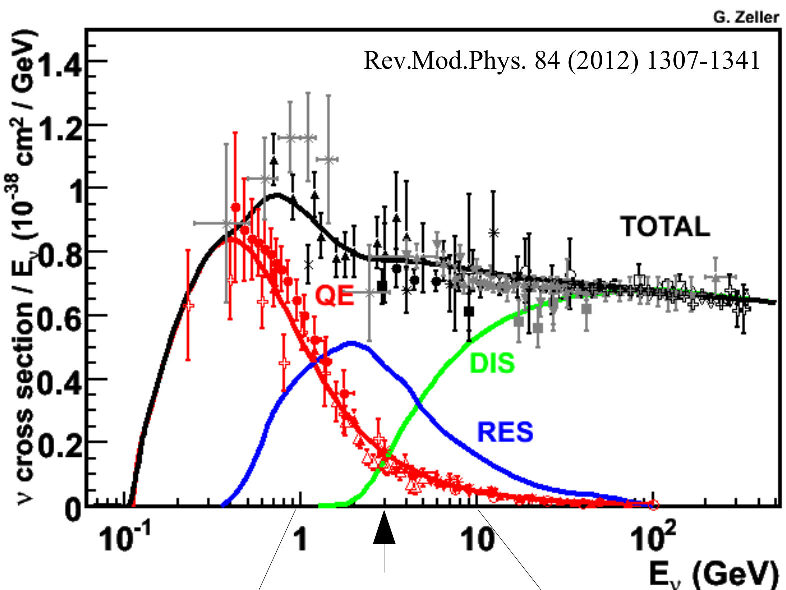


MINERvA-T2K difference mainly due to RES:
Very small resonance contribution at T2K

Advanced Topics: Comparison to T2K

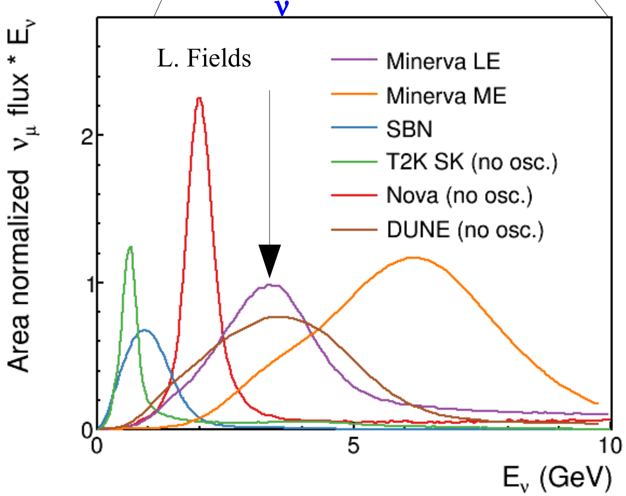
[arXiv:1802.05078] *same target, slight difference in signal phase space definition

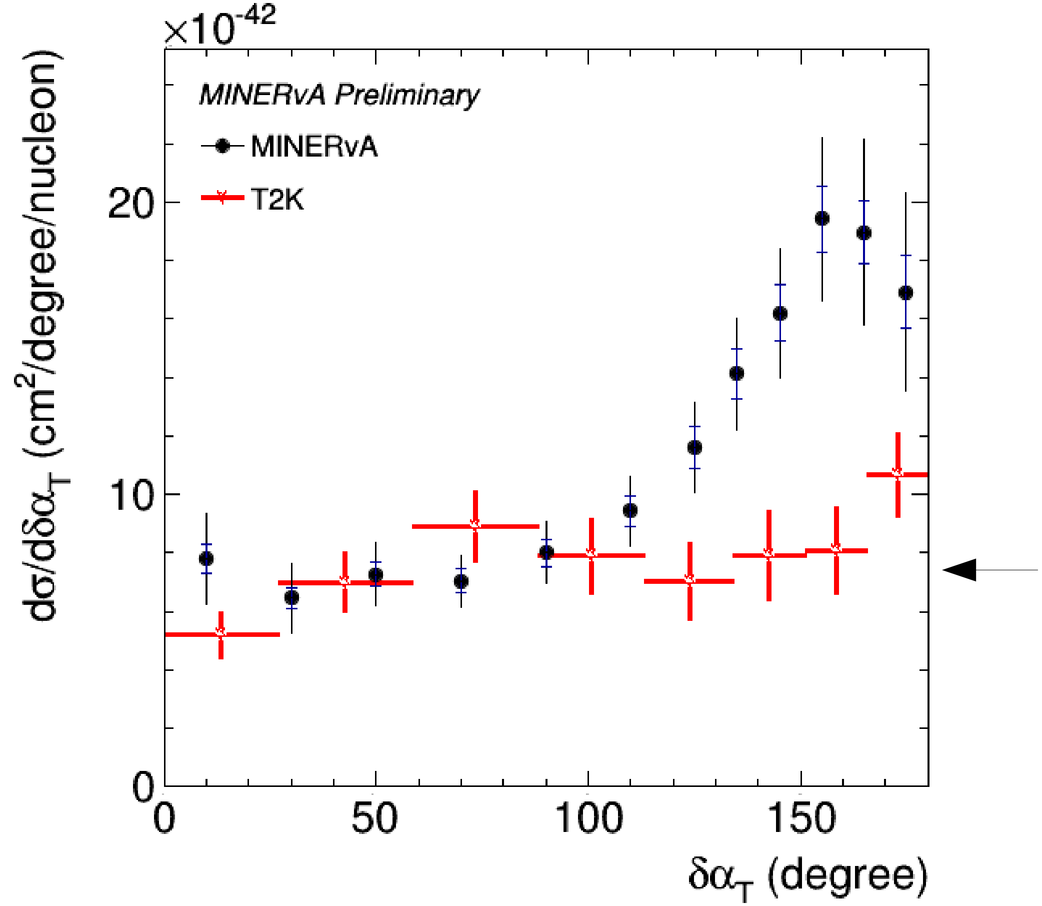
- $\delta\alpha_T$



NuMI LE

$\langle E_\nu \rangle \sim 3$ GeV





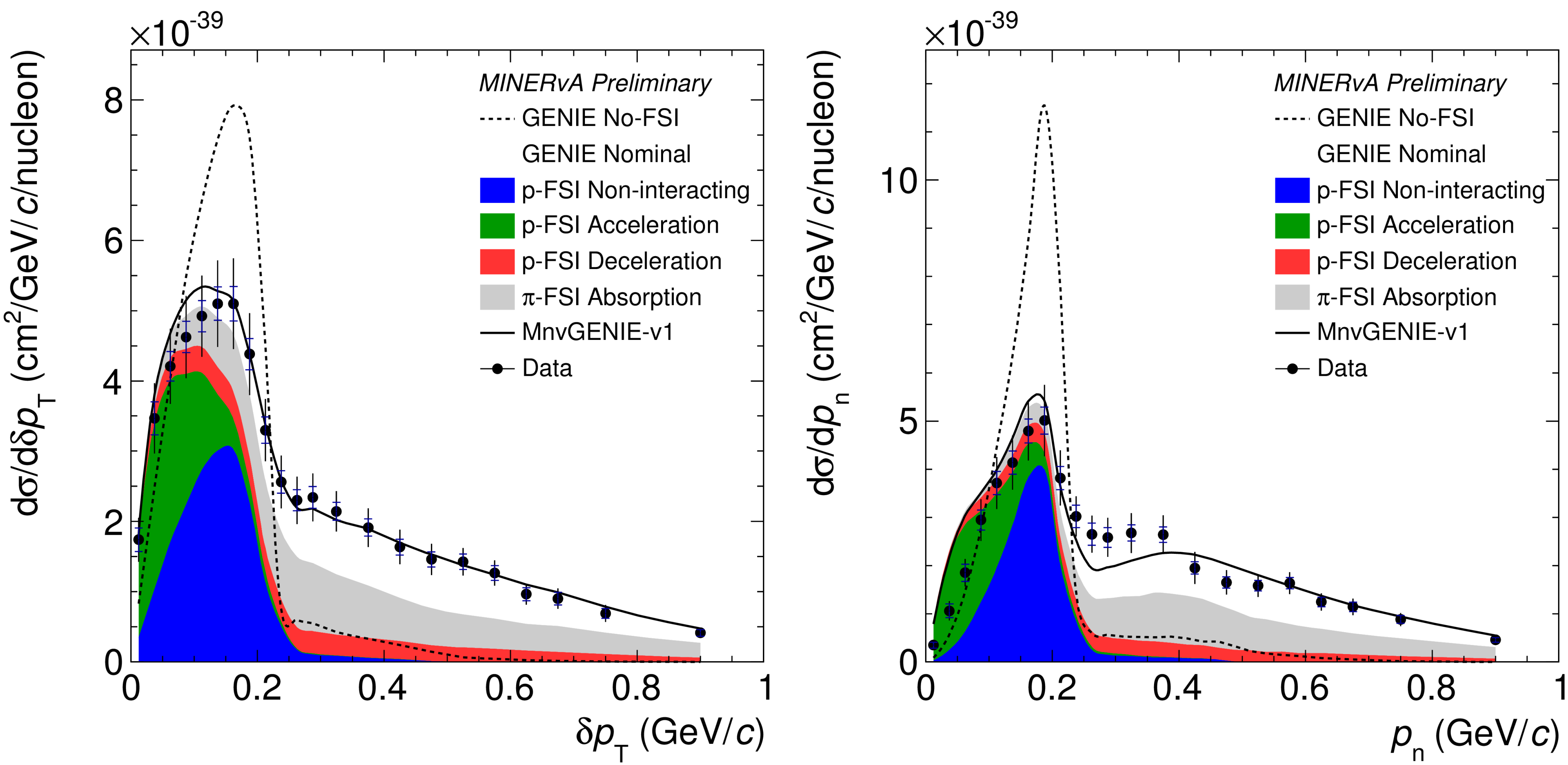
MINERvA-T2K difference mainly due to RES

Fermi motion (isotropic) baseline consistent

Advanced Topics: Comparison to T2K

[arXiv:1802.05078] *same target, slight difference in signal phase space definition

- $\delta\alpha_T$
- δp_T



$$\delta\vec{p}_{\rm T} = \vec{p}_{\rm T}^{\rm N} - \Delta\vec{p}_{\rm T}$$

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

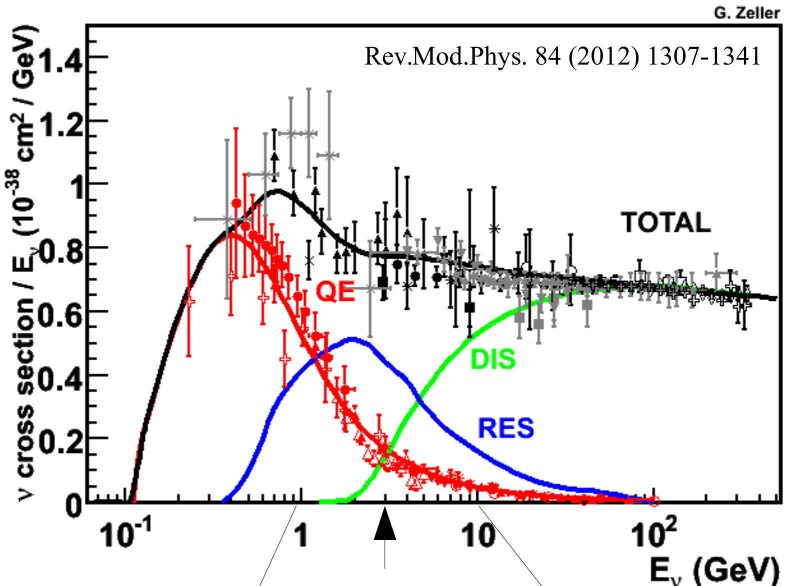
Only differ by longitudinal momentum imbalance

p_n has better resolution

Advanced Topics: Comparison to T2K

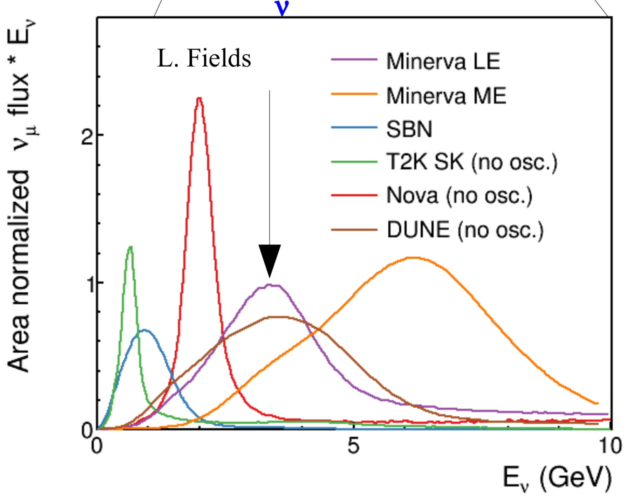
[arXiv:1802.05078] *same target, slight difference in signal phase space definition

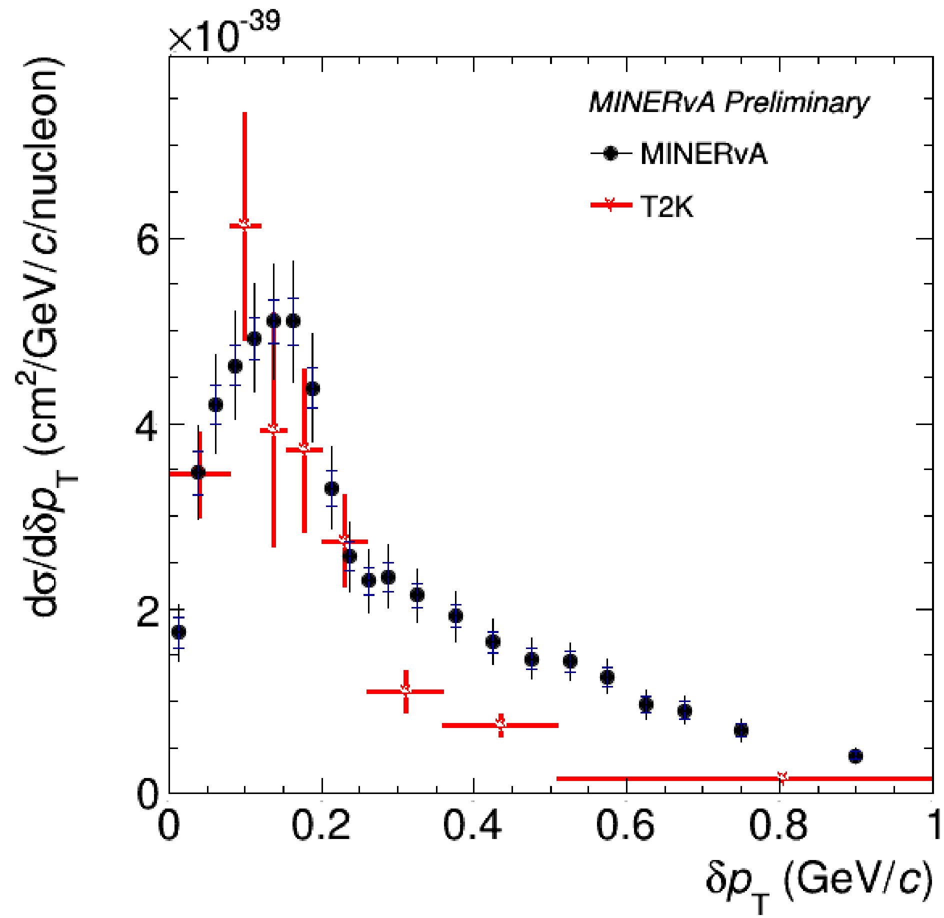
- $\delta\alpha_T$
- δp_T



NuMI LE

$<E_\nu> \sim 3$ GeV

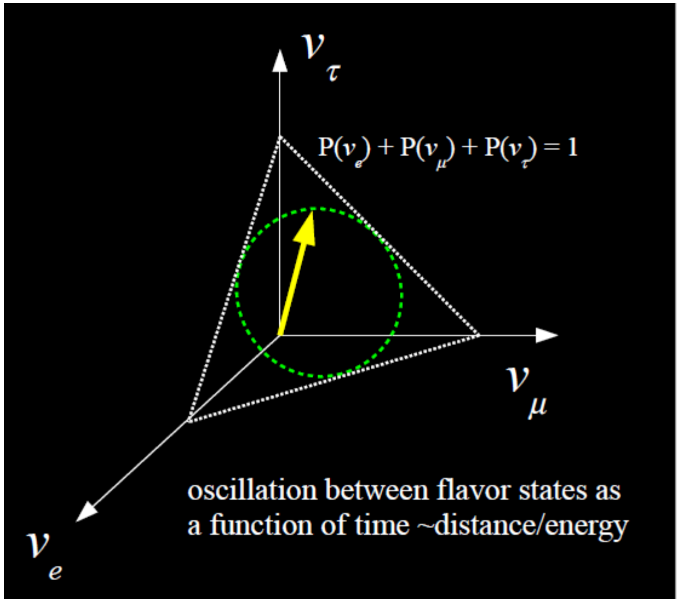


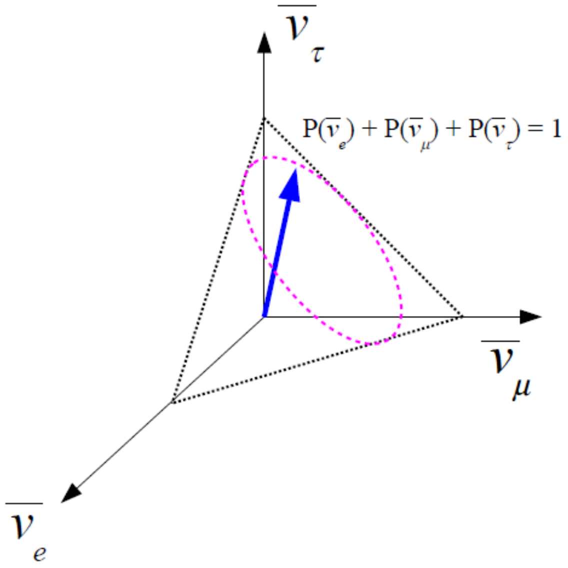


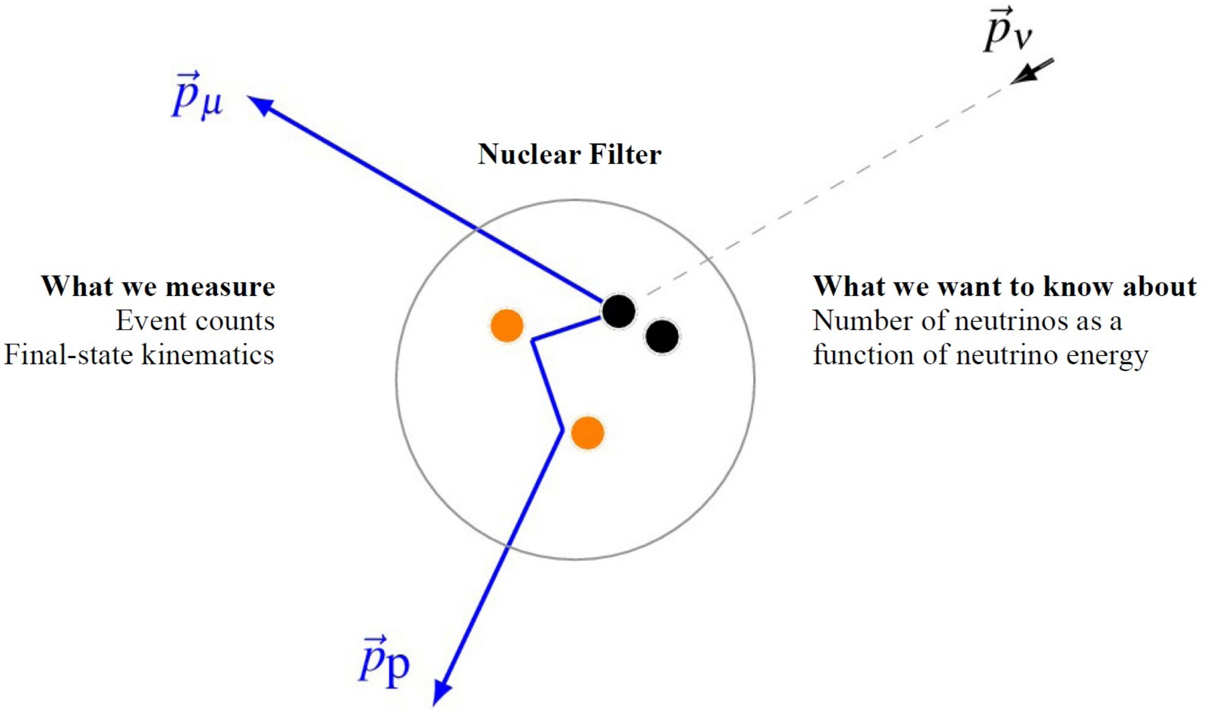
MINERvA-T2K difference mainly due to RES

The QE peaks are consistent

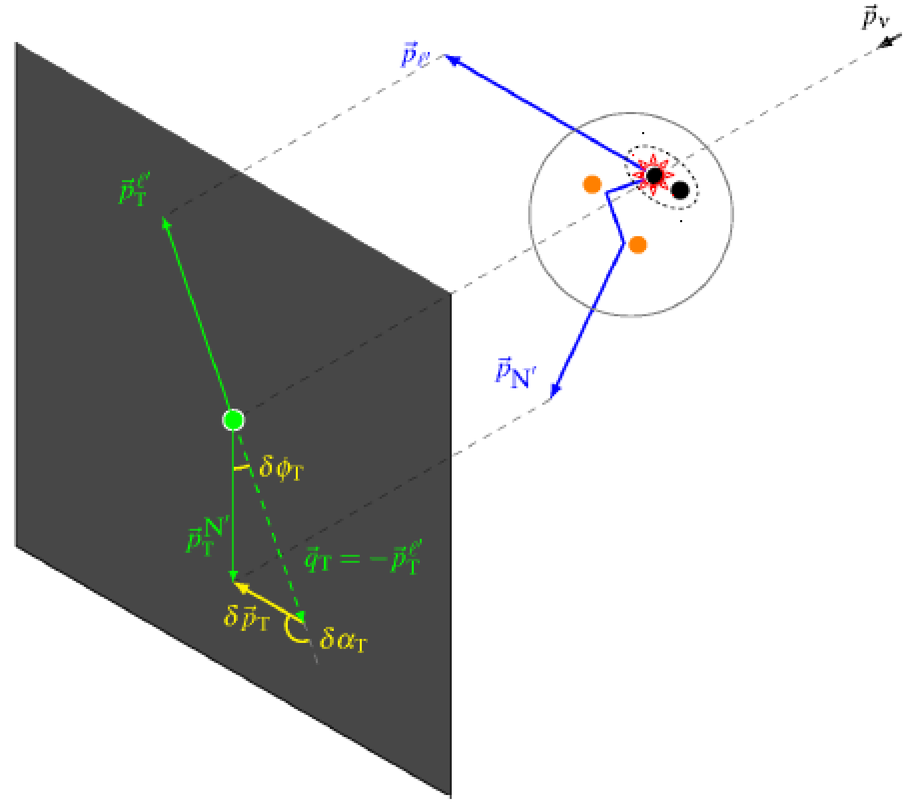
Summary and Outlook

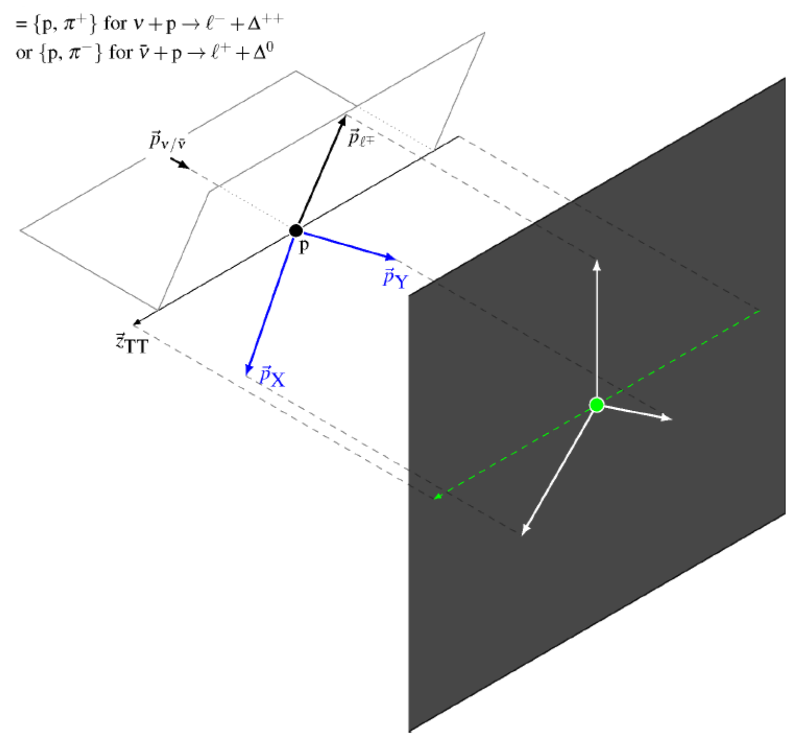






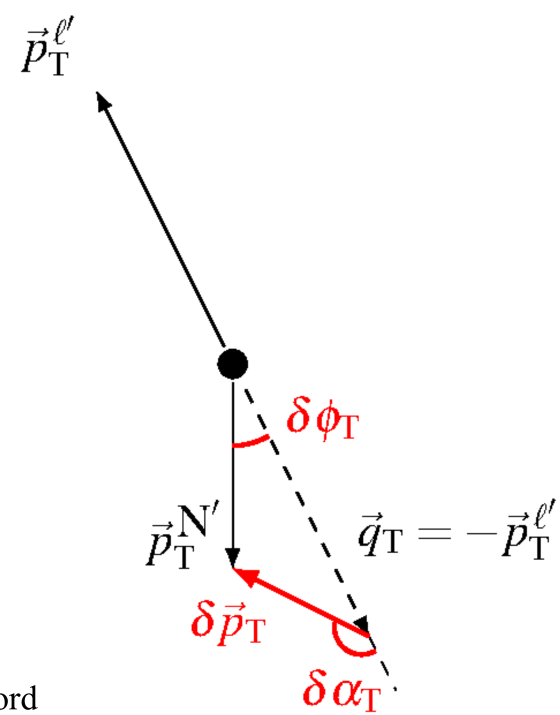
Summary and Outlook

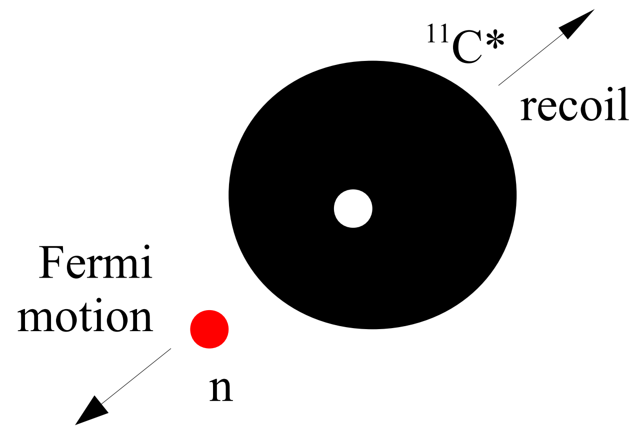




Summary and Outlook

- Muon-proton mesonless production at MINERvA
  - 2014: LE neutrino beam, CH target
  - 2016: LE neutrino beam, CH + nuclear targets
  - **This analysis**: LE neutrino beam, CH (3.28×10^{20} POT)
  - **Future: medium energy neutrino beam CH + nuclear targets** ($E_\nu \sim 6$ GeV, 12×10^{20} POT)
- In this analysis, we have shown
  - Single-particle kinematics (muon and proton momentum and angle)
  - Transverse kinematic imbalances ($\delta\alpha_T$, δp_T)
  - Initial neutron momentum (p_n)





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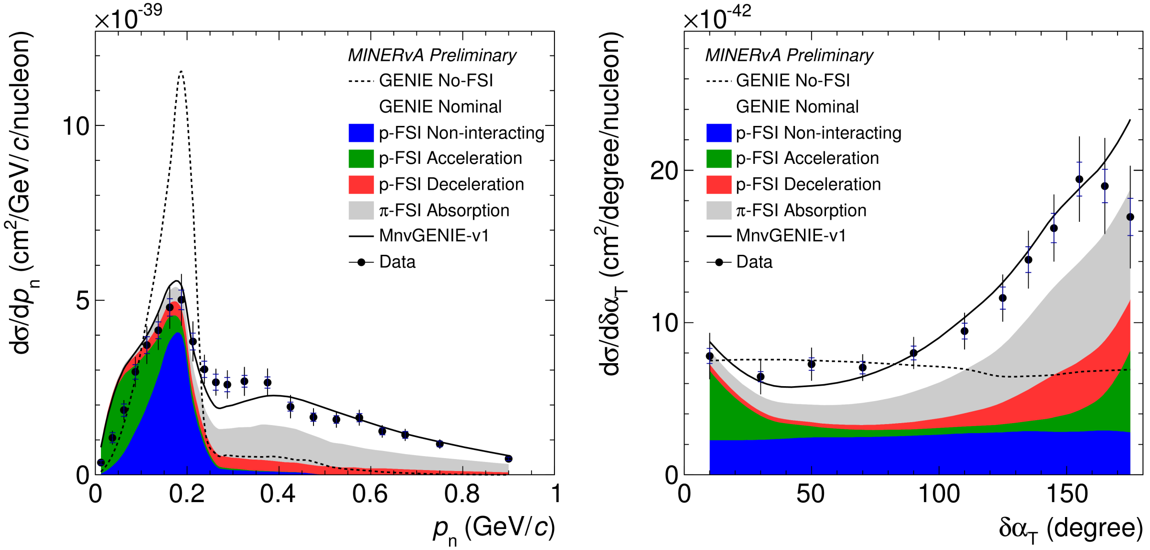
By rearranging final-stat kinematics, nuclear effects can be diagnosed:

- ✓ p_n strong constraint to Fermi motion
- ✓ $\delta\alpha_T$ factors out Fermi motion uncertainty and have direct sensitivity to FSI



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By rearranging final-stat kinematics, nuclear effects can be diagnosed:

- p_n strong constraint to Fermi motion
- $\delta\alpha_T$ factors out Fermi motion uncertainty and have direct sensitivity to FSI

Interesting observation:

- GENIE MINERvA Tune (v1)
  - Describes data well to first order
  - Critical component is Valencia 2p2h tuned to MINERvA inclusive data
- NuWro
  - SF provides very good description of data

Summary and Outlook

- Muon-proton mesonless production at MINERvA
  - 2014: LE neutrino beam, CH target
  - 2016: LE neutrino beam, CH + nuclear targets
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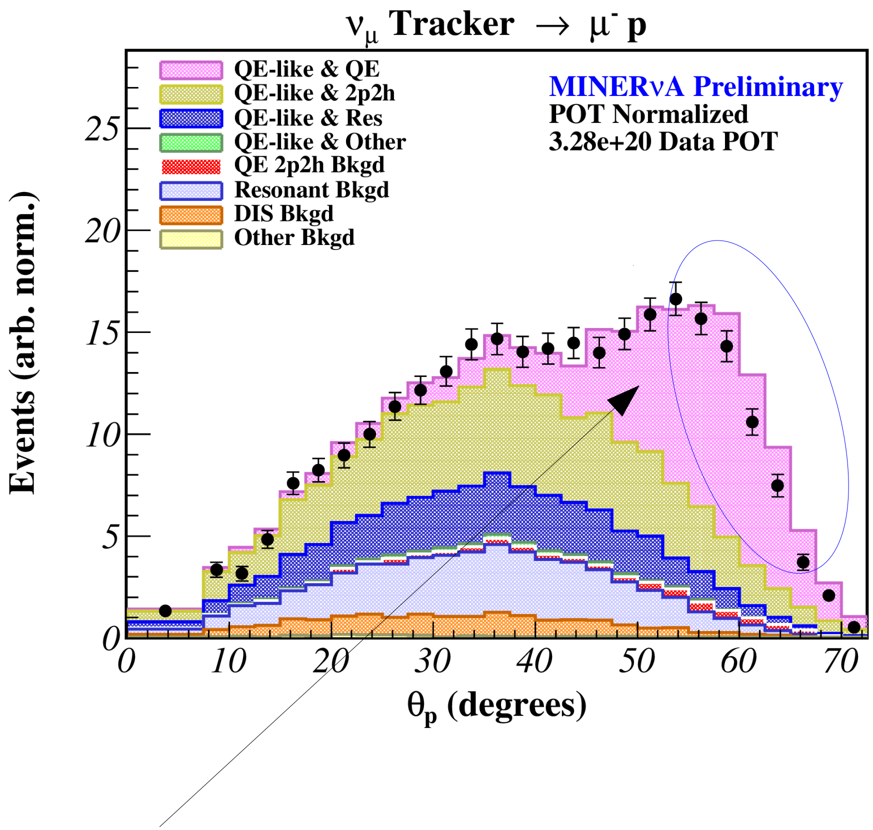
  - ✓ Single-particle kinematics (muon and proton momentum and angle)
  - ✓ Transverse kinematic imbalances ($\delta\alpha_T$, δp_T)
  - ✓ Initial neutron momentum (p_n)
- **New developments**
  - Transverse kinematic imbalances
    - ✓ New system to solve the nuclear effect problem in neutrino interaction most relevant for oscillation measurements
    - ✓ Radical approach → double transverse kinematic imbalance [Phys. Rev. D 92, 051302(R)]
  - First measurement of Furmanski-Sobczyk initial neutron momentum
    - ✓ diagnostic power
    - Practically efficient way to select pure CCQE events (beyond the scope of this talk)

Source: http://www.cnhubei.com/ztmjys-pyts

BACKUP

Selected Sample

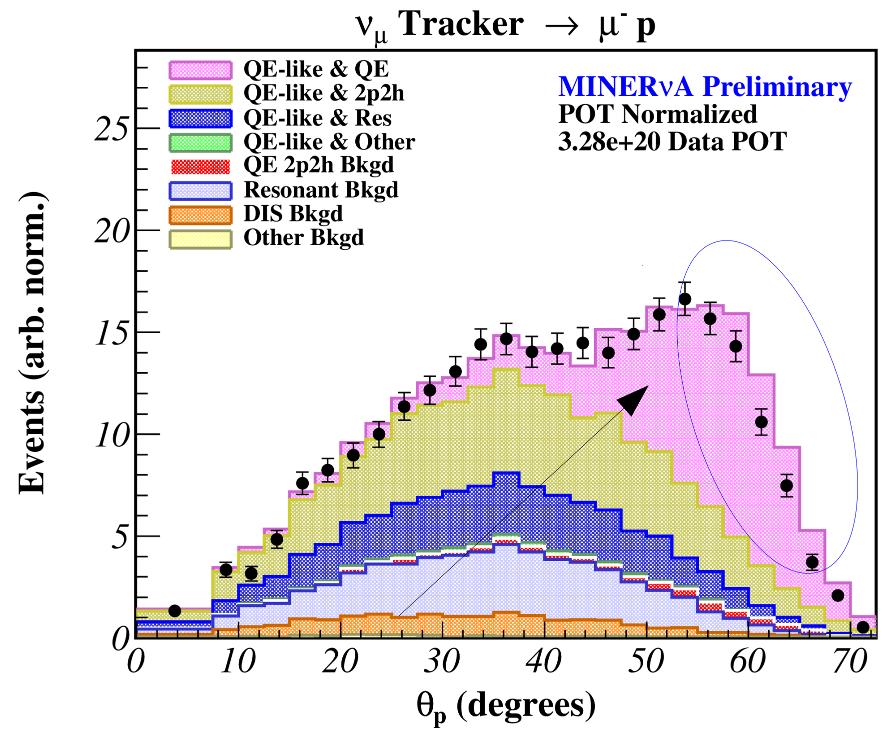
- Data-MC comparison at reconstructed level after sideband fit

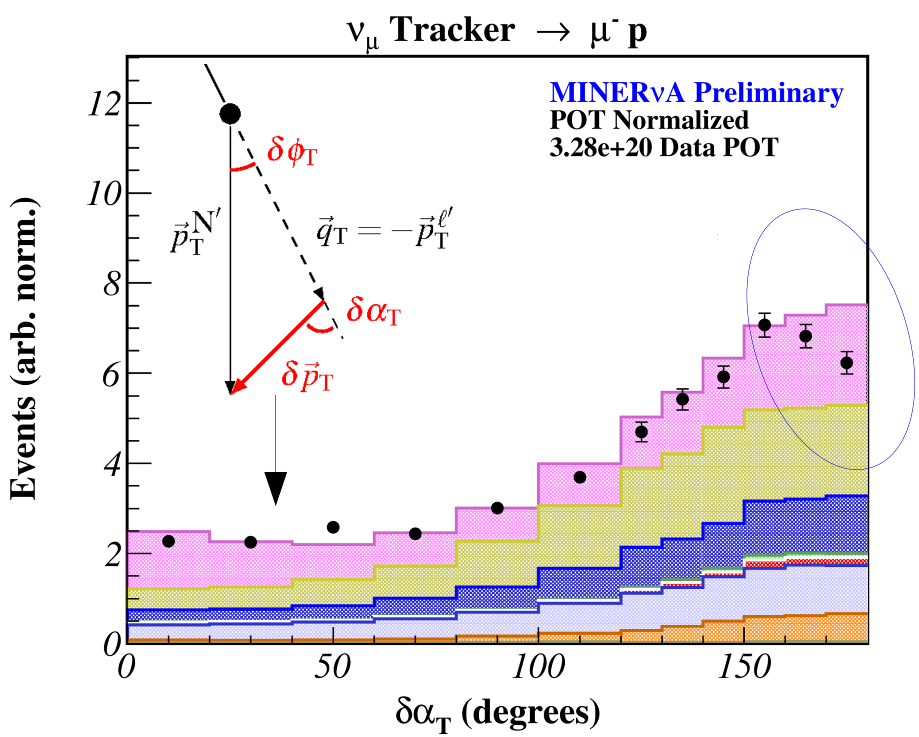


GENIE MINERvA Tune (v1) describes data well (to first order)
Large concentration of pure QE at high angle
GENIE excess above data beyond 60 deg (see discussion later slides)

Selected Sample

- Data-MC comparison at reconstructed level after sideband fit

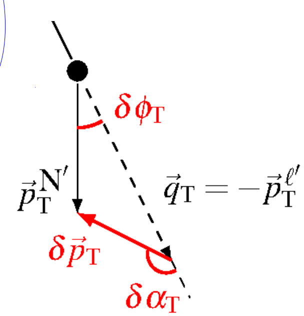




GENIE MINERvA Tune (v1) describes data well (to first order)

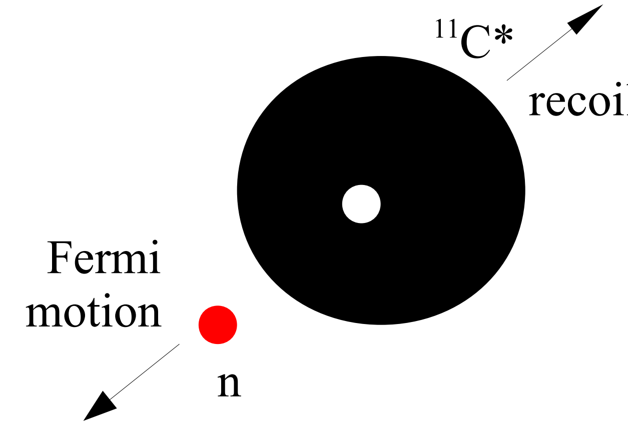
Depletion at small $\delta\alpha_T$

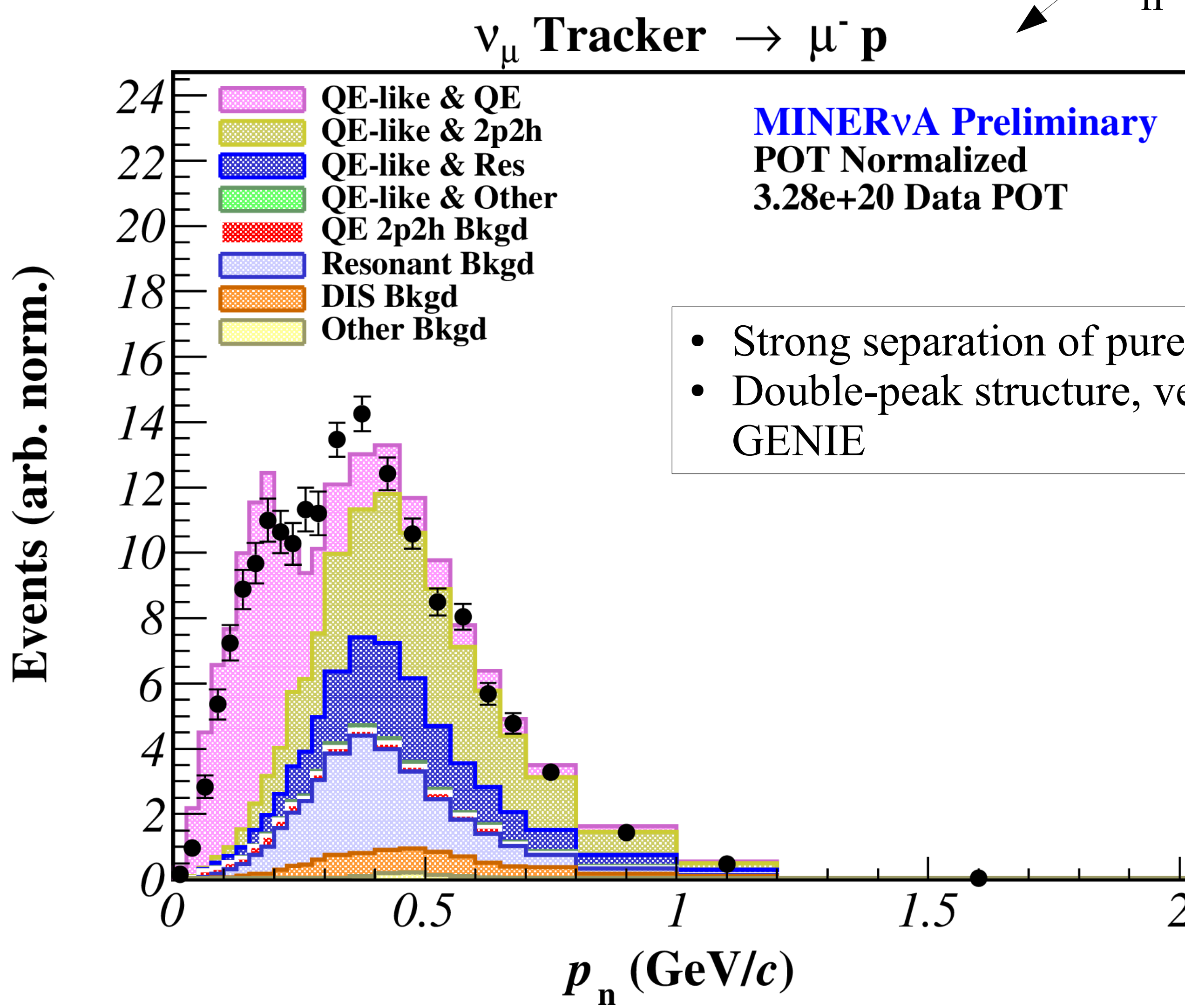
GENIE excess at $\delta\alpha_T \rightarrow 180$ deg.



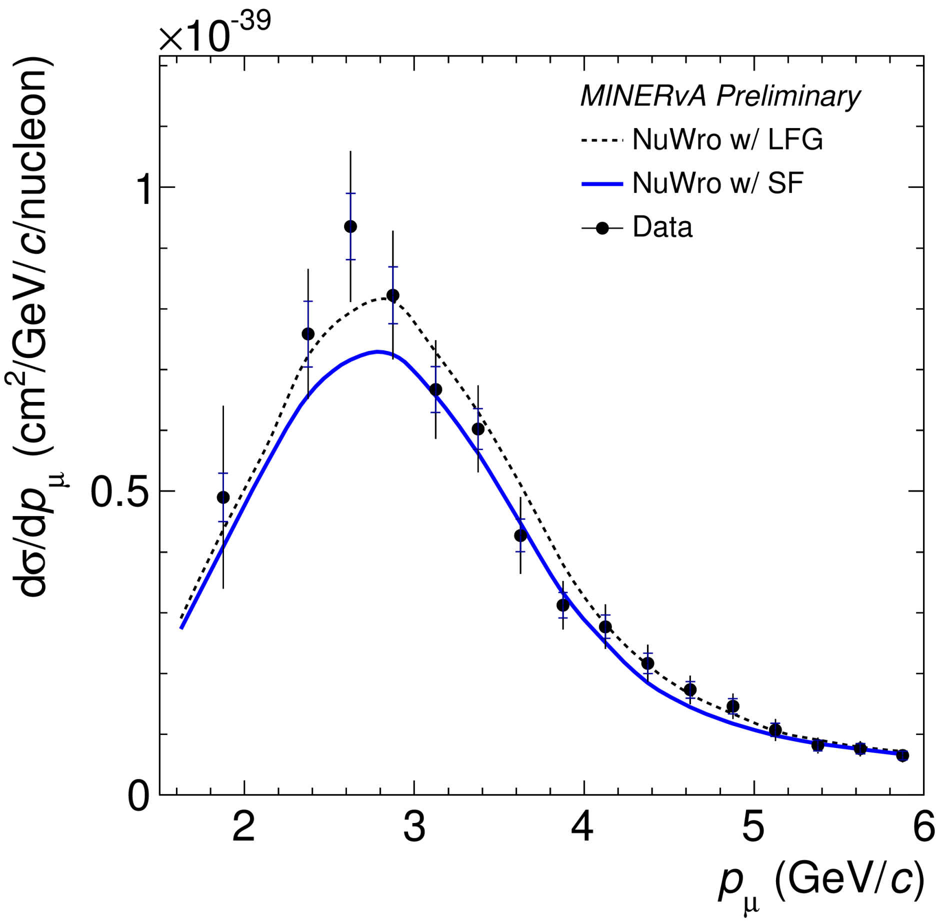
Selected Sample

- Data-MC comparison at reconstructed level after sideband fit

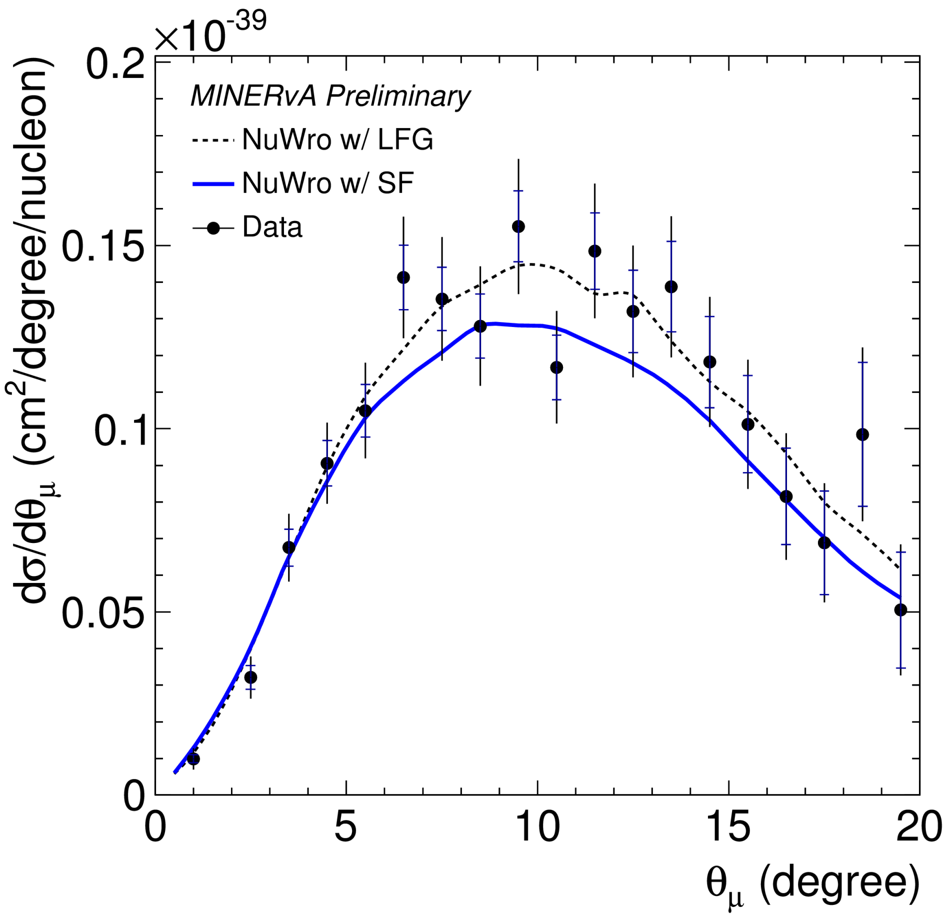




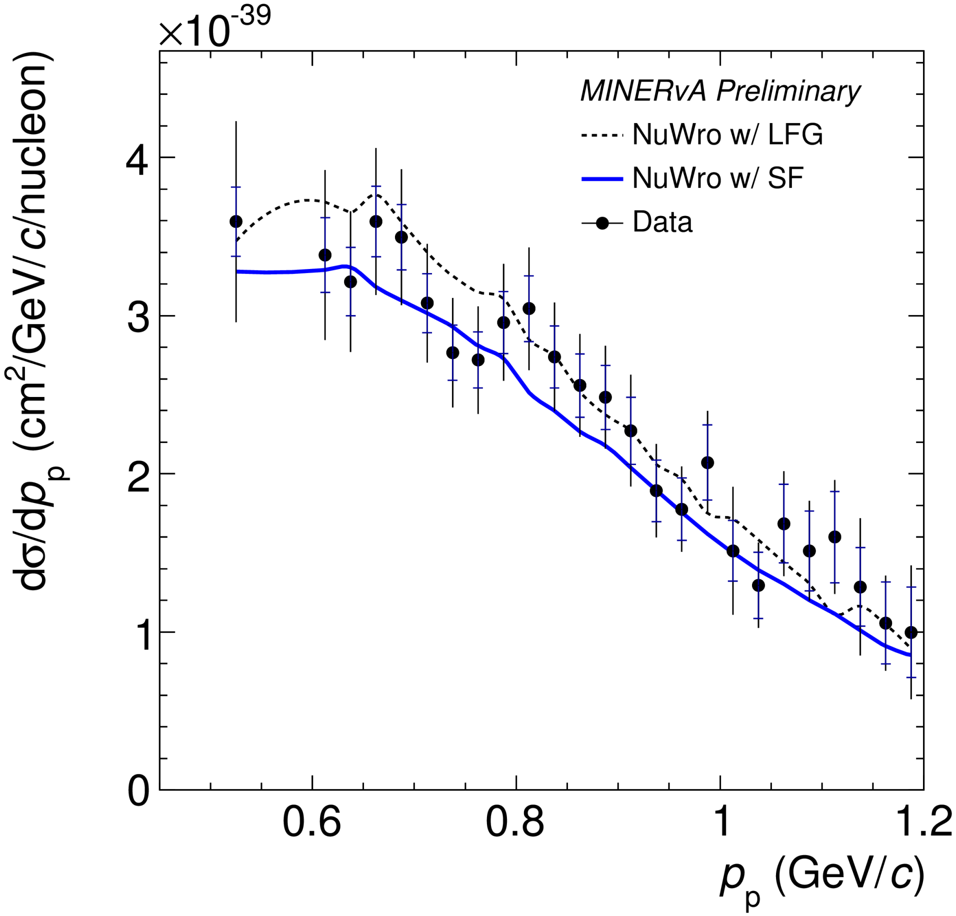
- Strong separation of pure QE
- Double-peak structure, very strong in GENIE

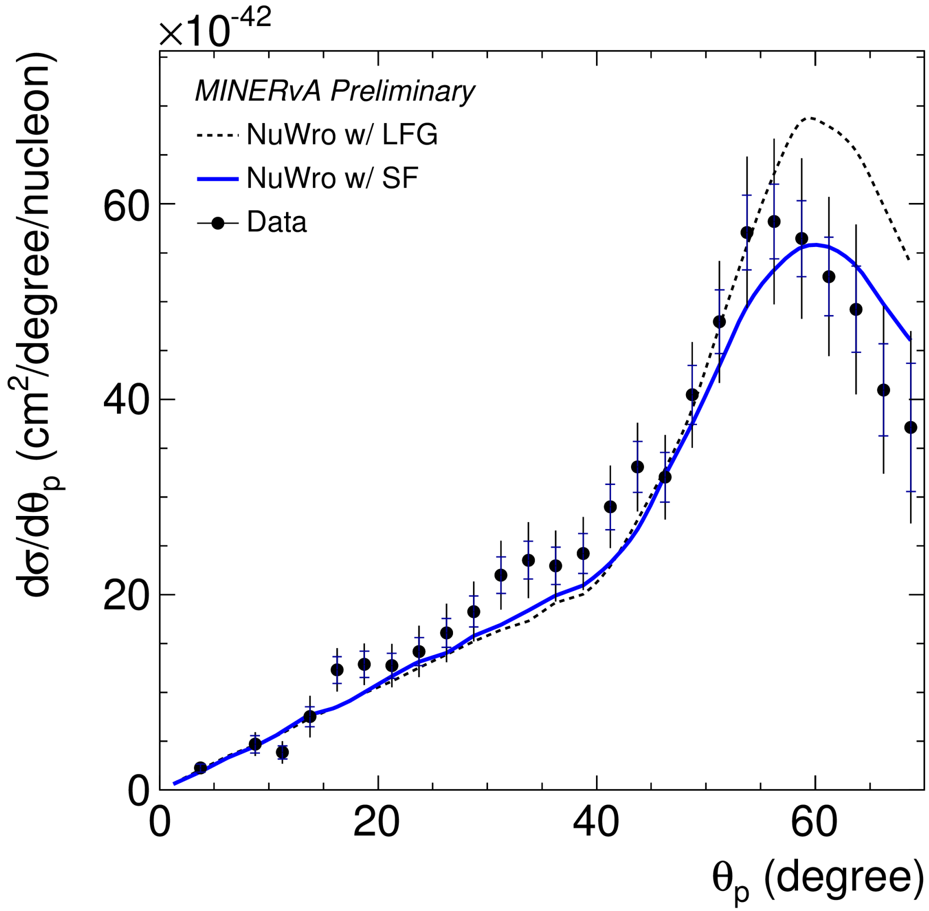


$\times 10^{-39}$
MINERvA Preliminary
NuWro w/ LFG
NuWro w/ SF
Data
$d\sigma/dp_\mu$ (cm^2/GeV/c/nucleon)
0
0.5
1
2
3
4
5
6
p_μ (GeV/c)



$\times 10^{-39}$
MINERvA Preliminary
NuWro w/ LFG
NuWro w/ SF
Data
$d\sigma/d\theta_\mu$ (cm^2/degree/nucleon)
0
0.05
0.1
0.15
0.2
0
5
10
15
20
θ_μ (degree)


×10^-39
MINERvA Preliminary
NuWro w/ LFG
NuWro w/ SF
Data
dσ/dp_p (cm²/GeV/c/nucleon)
p_p (GeV/c)


×10^-42
MINERvA Preliminary
NuWro w/ LFG
NuWro w/ SF
Data
dσ/dθ_p (cm²/degree/nucleon)
θ_p (degree)

66.4 deg

Analysis	p_p	$cos\theta_p$	p_μ	$cos\theta_\mu$
Multi-dimensional	> 500 MeV	-	-	-
STV	450-1000 MeV	> 0.4	> 250 MeV	> -0.6
Inferred kinematics	> 450 MeV	> 0.4	-	-

TABLE I. Signal phase space restrictions for the three analyses.

arXiv:1802.05078

END