皮影 Shadow play

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

Neutrino Shadow Play

– Kinematic determination of nuclear effects at MINERvA

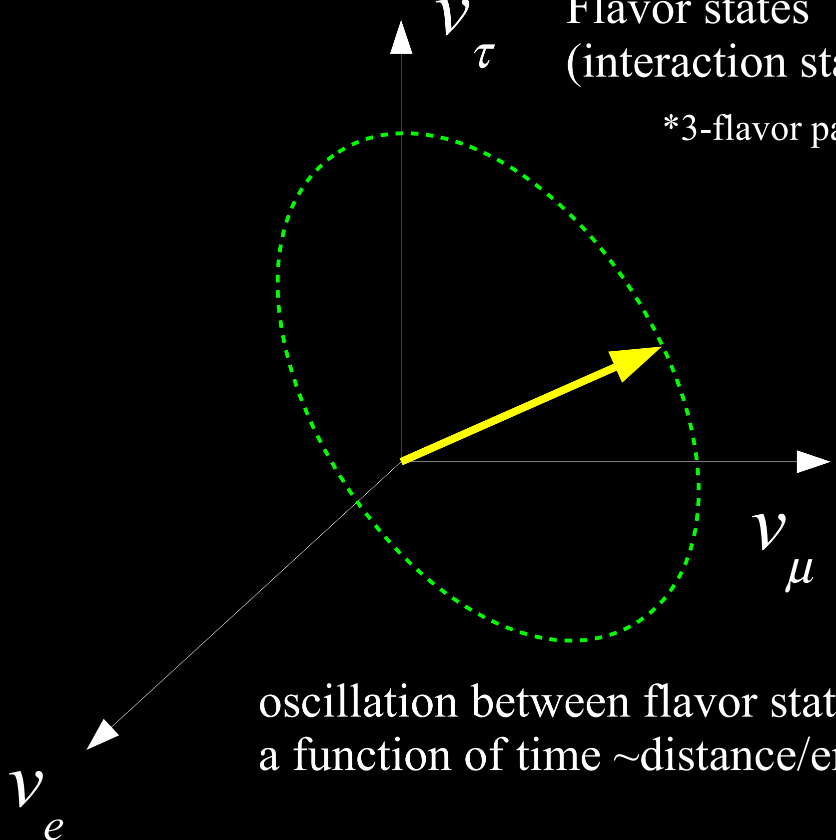
Xianguo LU/ 卢显国 University of Oxford

on behalf of MINERvA Collaboration

Joint Experimental-Theoretical Physics Seminar

FNAL, 2 March 2018

Neutrino
– Oscillation



Flavor states
(interaction states)

*3-flavor paradigm

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

The Nobel Prize in Physics 2015

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

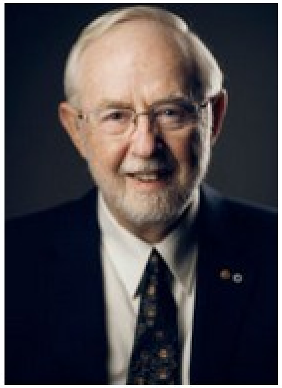


Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

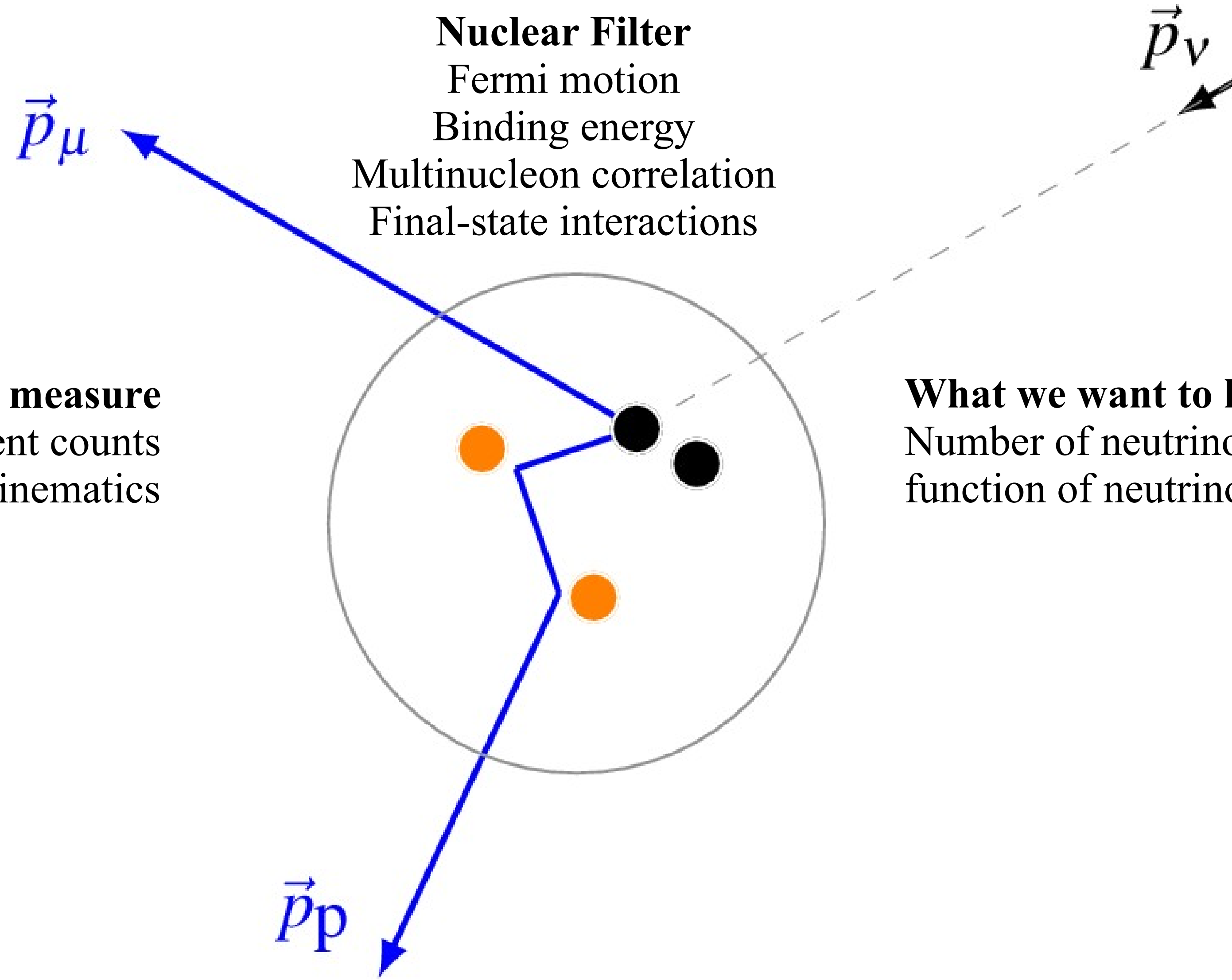
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

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

Neutrino mass:
shift between interaction and propagation states

The big picture of neutrino detection in oscillation experiment

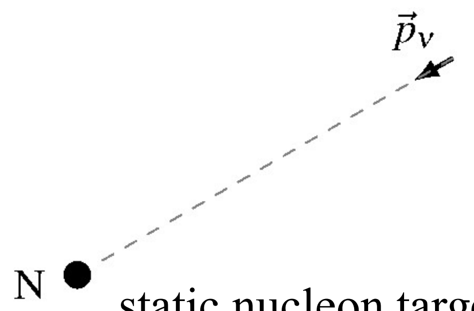
Nuclear Filter
Fermi motion
Binding energy
Multinucleon correlation
Final-state interactions



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

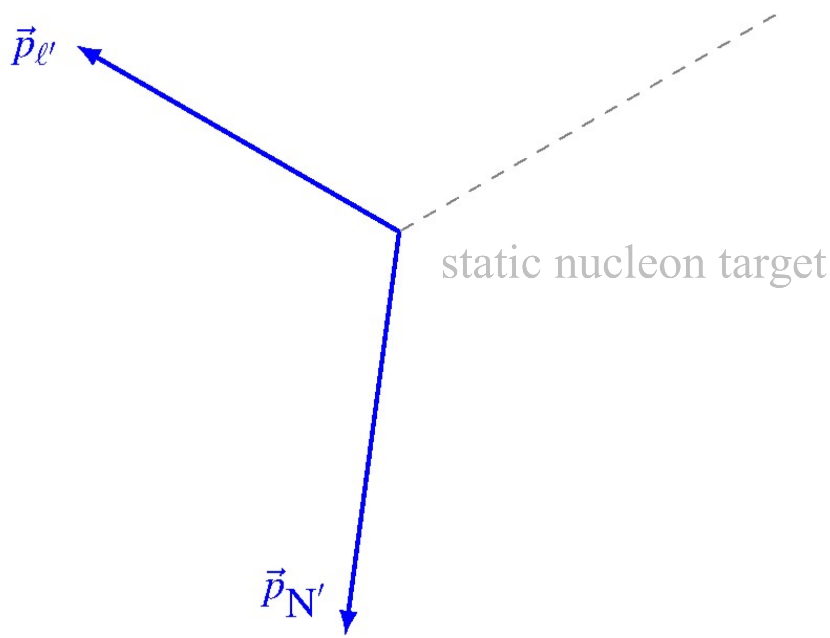


static nucleon target

Quasi-elastic scattering (QE)

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

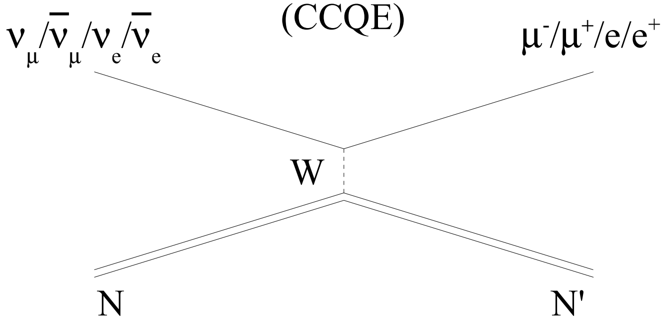
charged current (CC) $\nu \rightarrow l'$



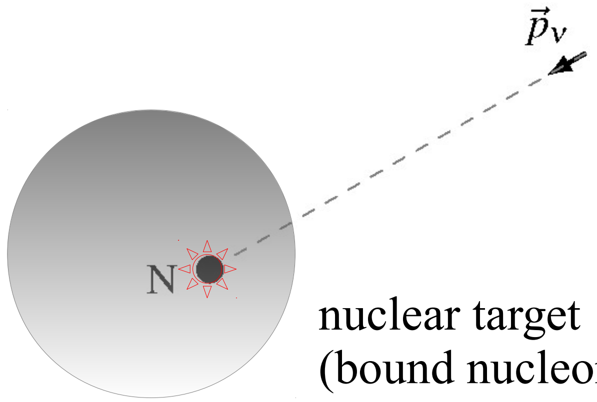
quasi-elastic (QE) $\mathrm{N} \rightarrow \mathrm{N}'$

Charged-Current Quasi-Elastic

(CCQE)



Fermi motion (FM) biases E_ν reconstruction

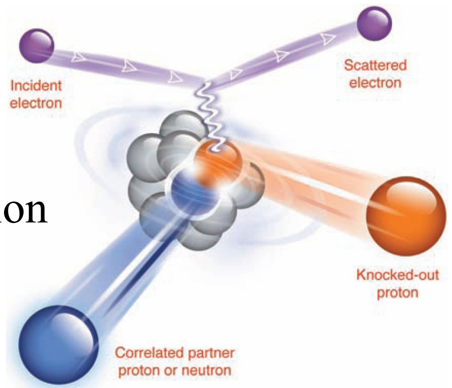


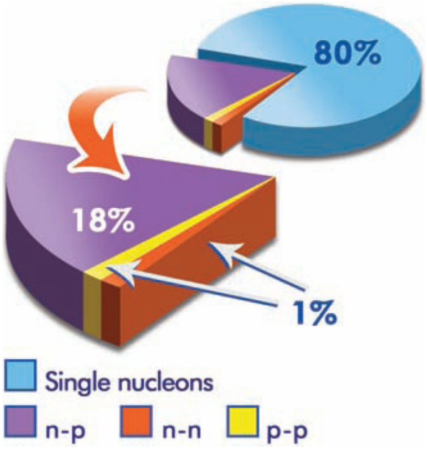
nuclear target
(bound nucleon)

Fermi motion (FM) biases E_ν reconstruction

Multinucleon correlations:

initial correlation
large relative motion

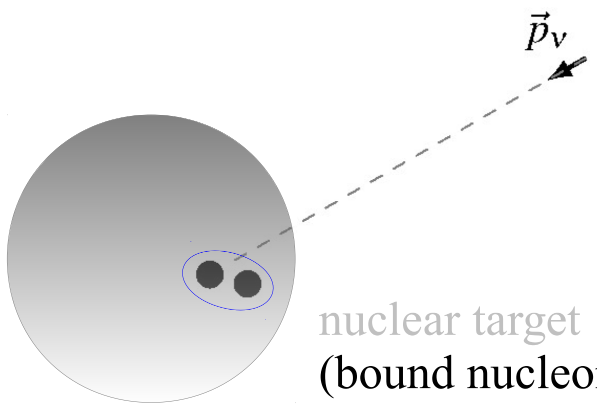




Science 320 (2008) 1476-1478

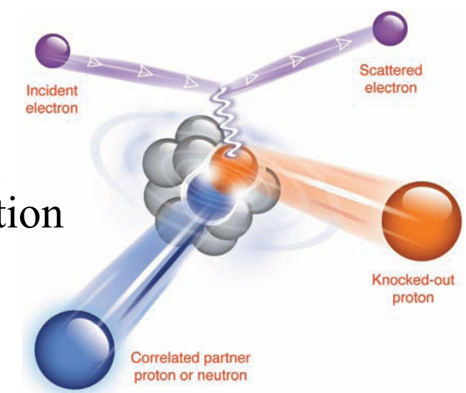
Fermi motion (FM) biases E_ν reconstruction

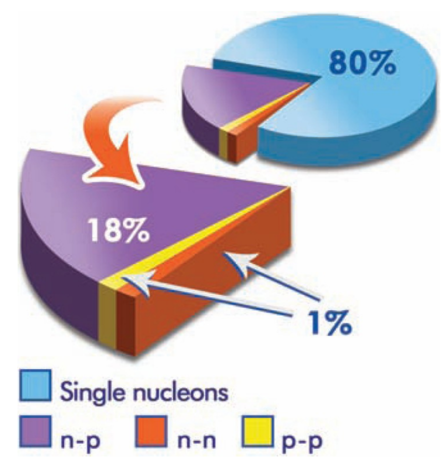
Multinucleon correlations:
cross section unknown, strong bias to *all* final-state kinematics



nuclear target
(bound nucleons)

initial correlation
large relative motion





Science 320 (2008) 1476-1478

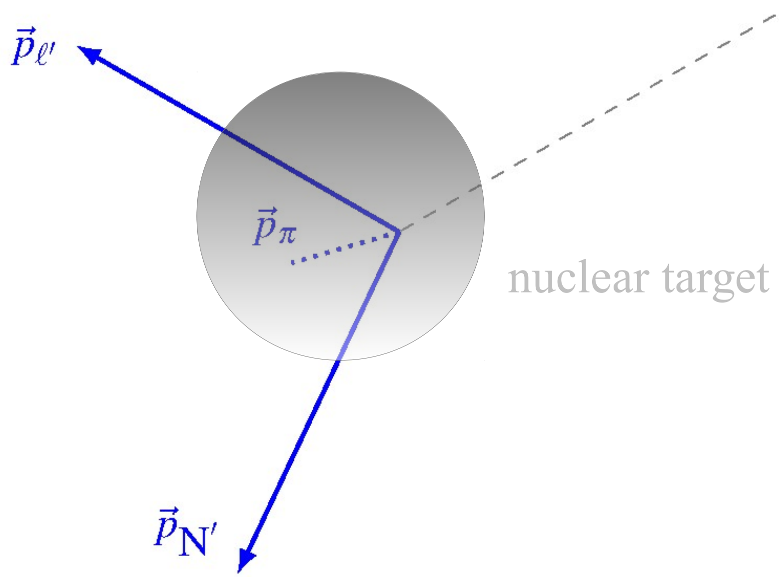
- Impulse approximation: independent particles
- In particle-hole excitation:
  - RPA (random phase approximation): sum of 1p1h excitation (over all pairs) ~ ground state correlations (long range)
  - npnh (n≥2): sub-leading terms in ph expansion ~ multinucleon correlations (short range)

Fermi motion (FM) biases E_ν reconstruction

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

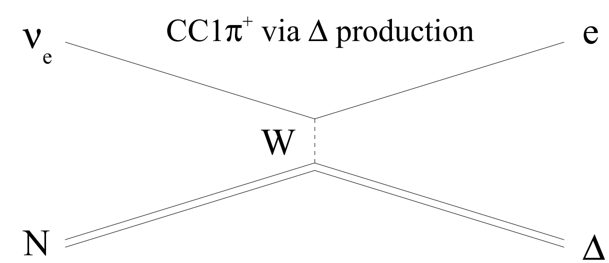
QE-like: π absorbed in nucleus ← final-state interaction (FSI)

charged current (CC) ν → *l'*



Resonance production (RES)

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



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

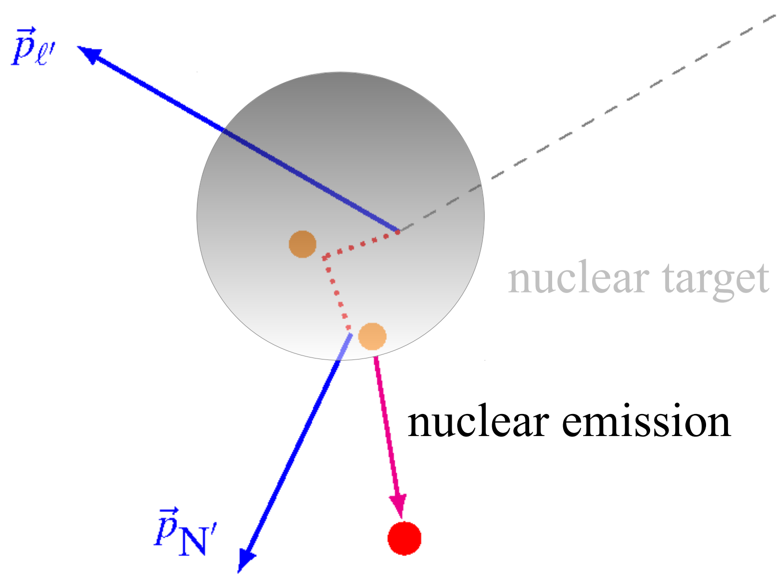
Fermi motion (FM) biases E_ν reconstruction

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) ν → *l'*



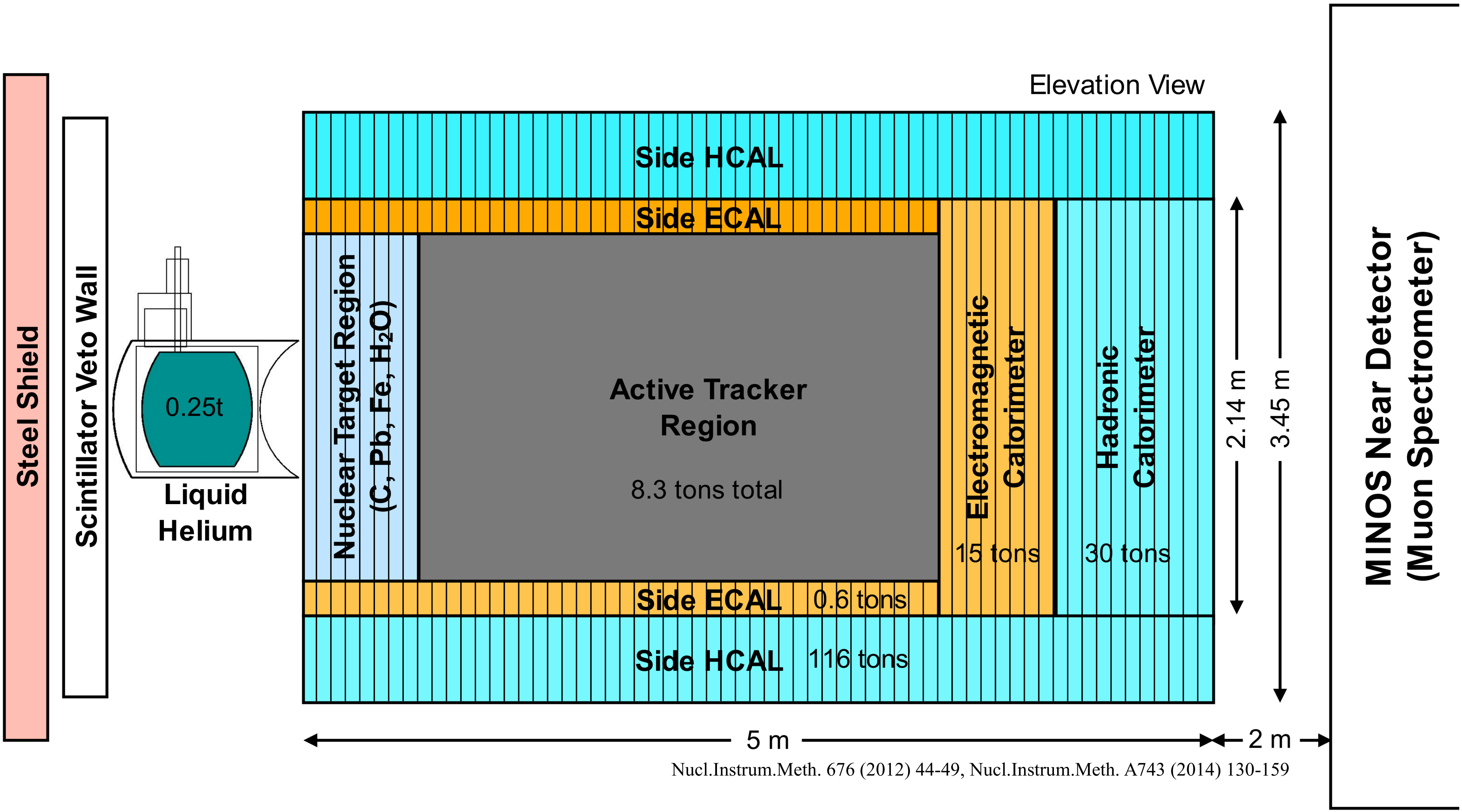
QE-like N → N'
including resonance production (RES) Δ → N'π followed by π absorption

MINERvA

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

MINERvA

Thanks to MINOS!

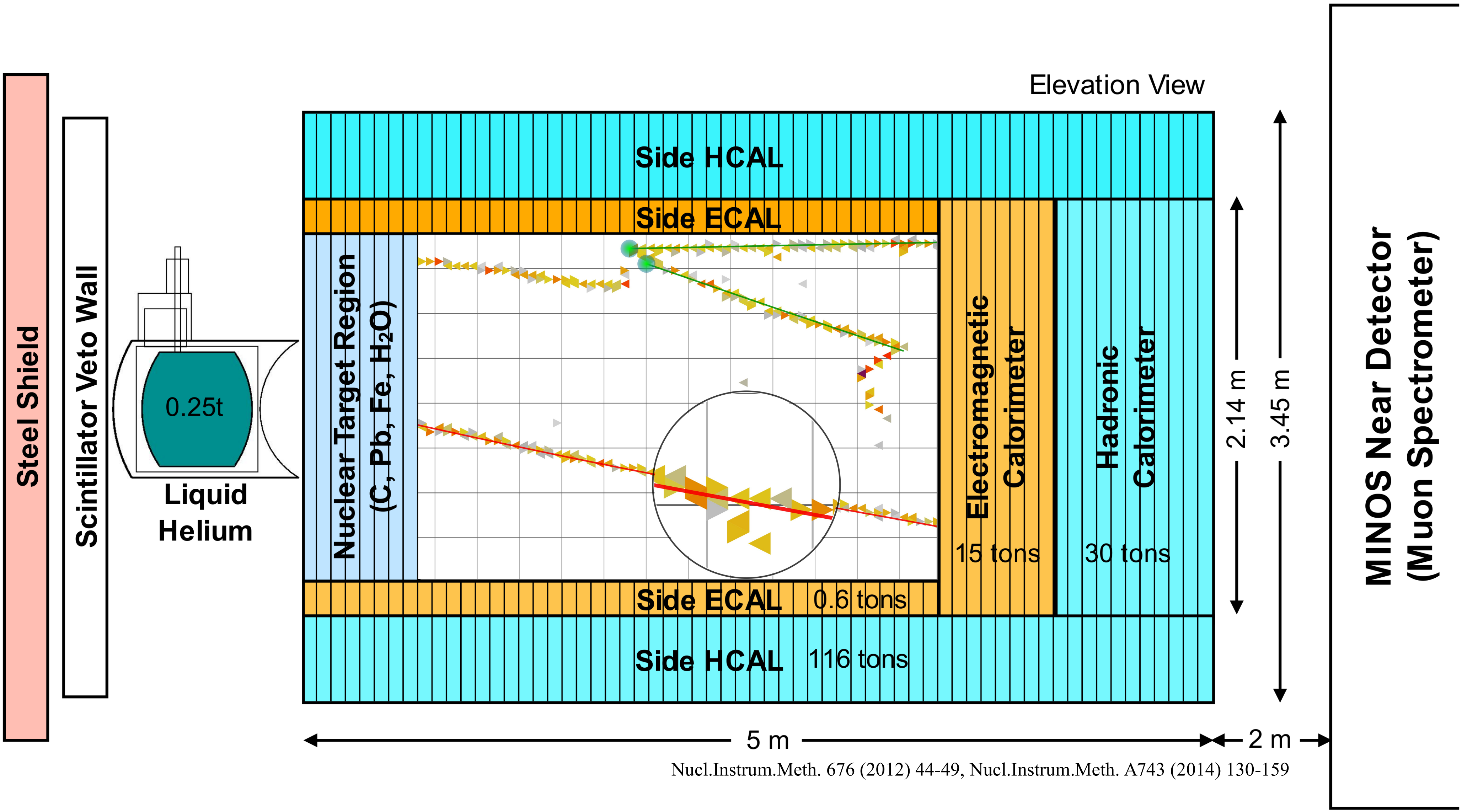


Nucl.Instrum.Meth. 676 (2012) 44-49, Nucl.Instrum.Meth. A743 (2014) 130-159

Scintillator tracker

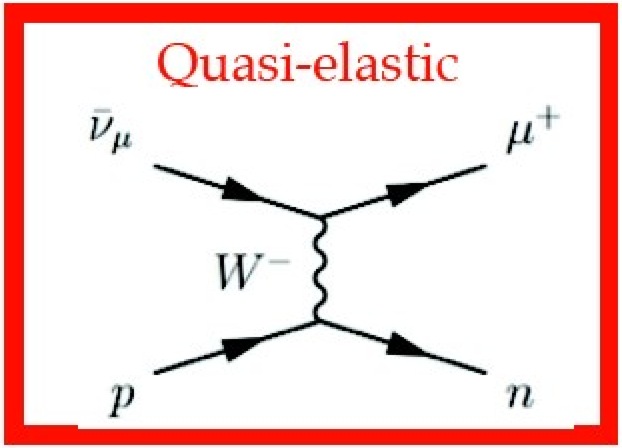
MINERvA

Thanks to MINOS!

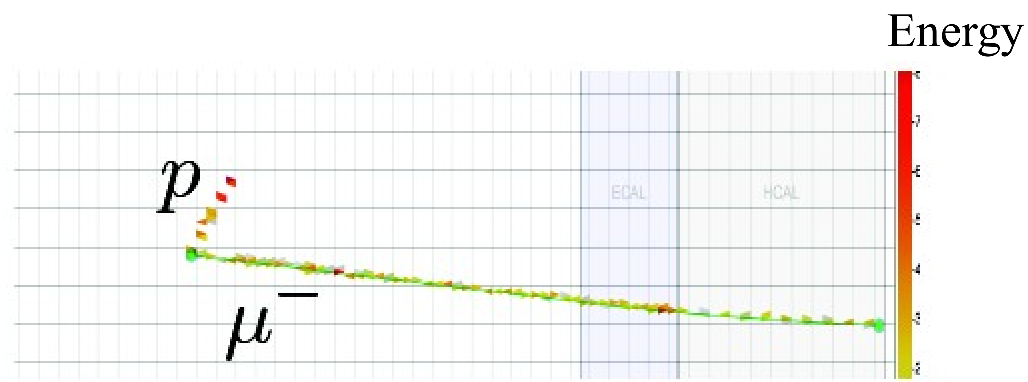


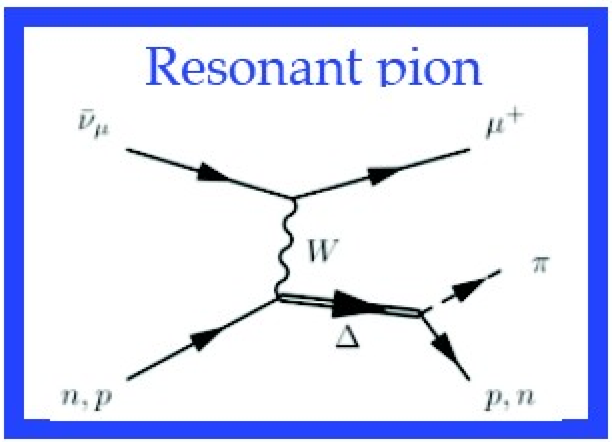
Nucl.Instrum.Meth. 676 (2012) 44-49, Nucl.Instrum.Meth. A743 (2014) 130-159

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

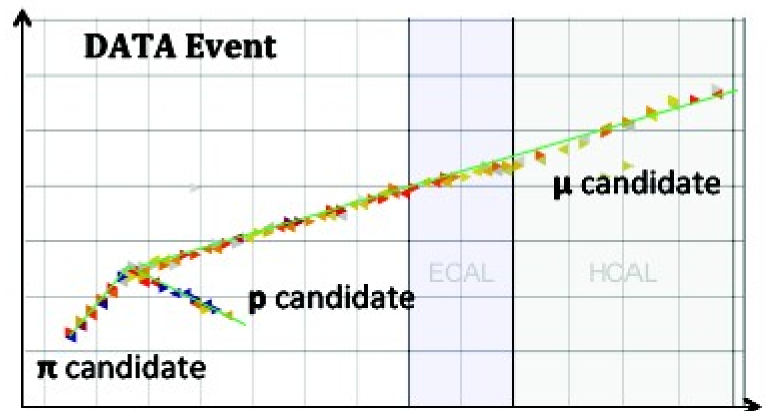


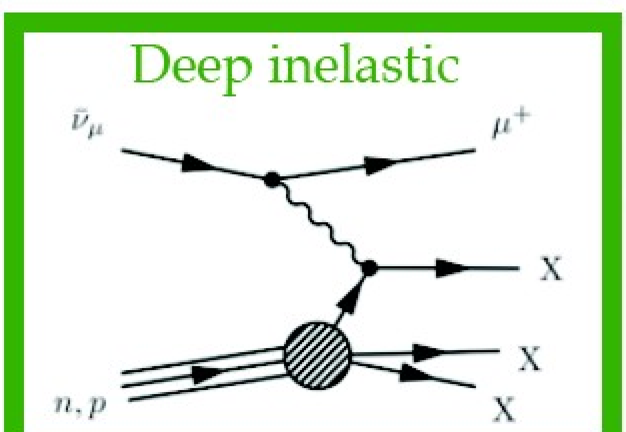
QE





RES





DIS

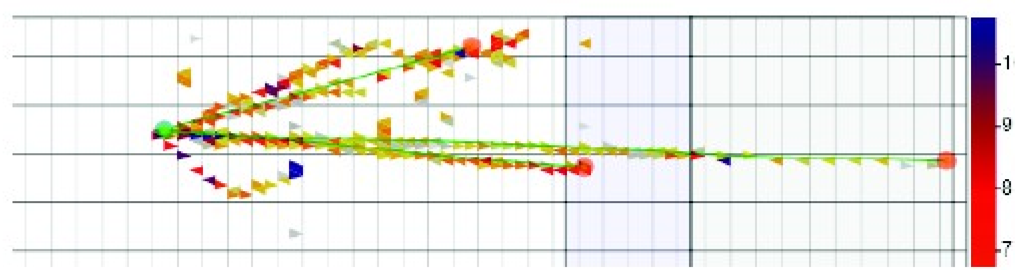
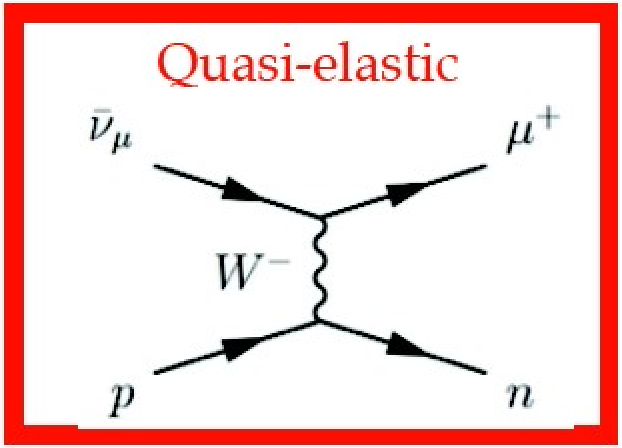
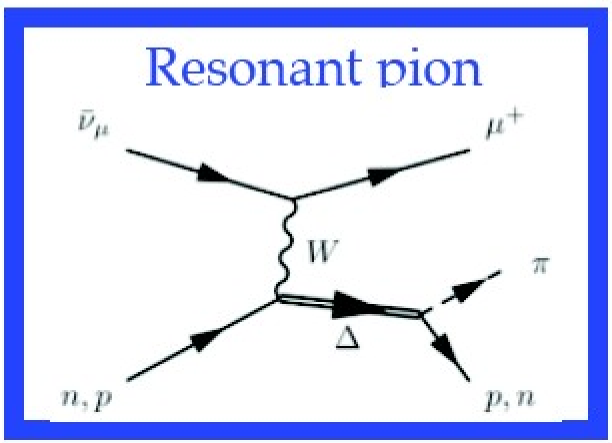


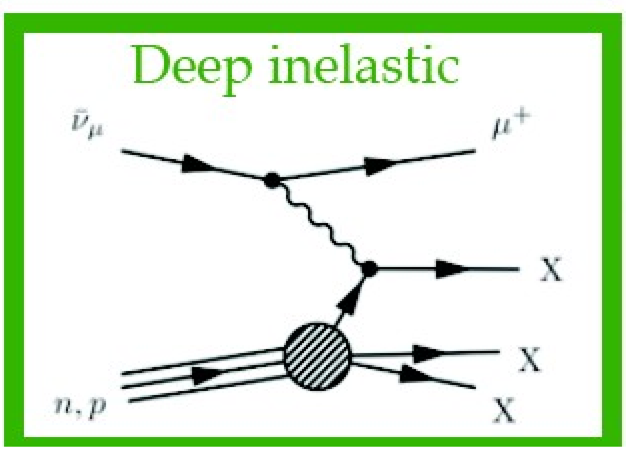
Diagram by M. Betancourt



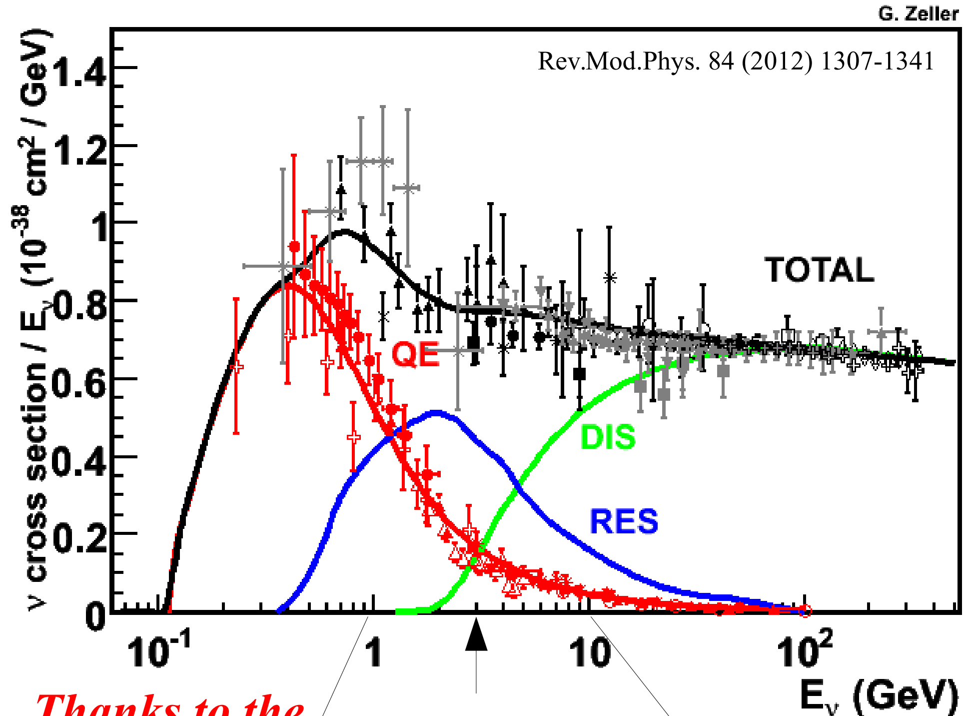
QE



RES

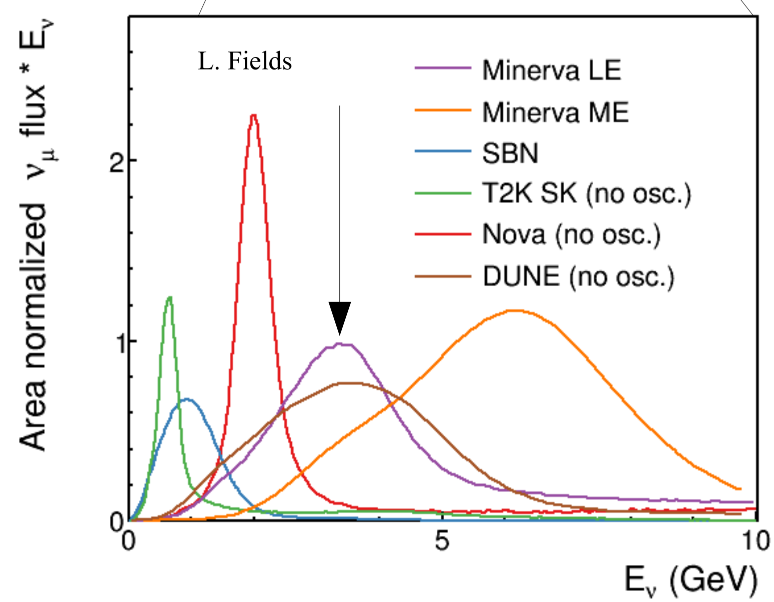


DIS



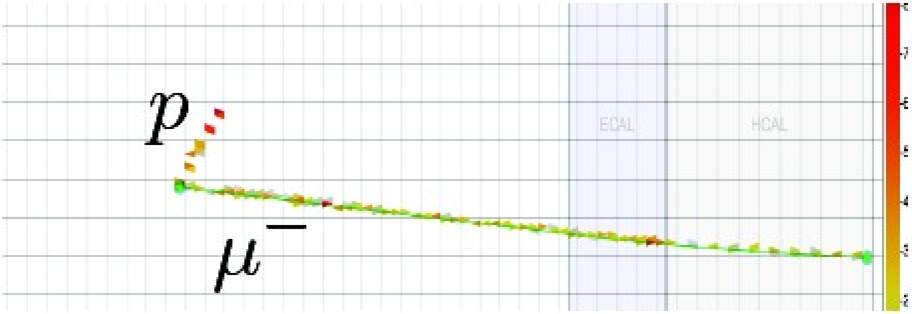
Thanks to the accelerator division!

NuMI low energy beam **$\langle E_\nu \rangle \sim 3$ GeV**



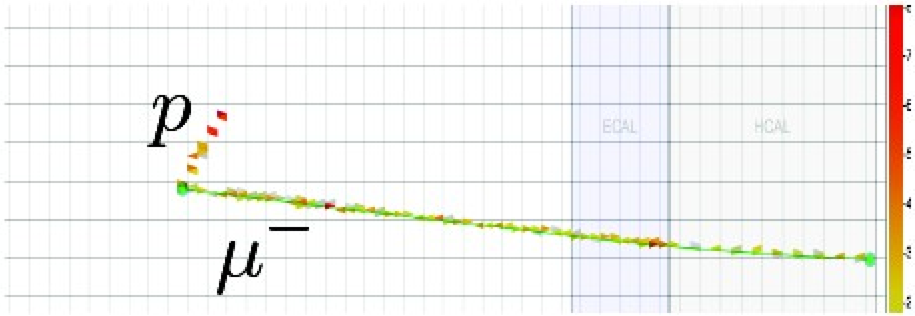
Today's topic:

μ-p mesonless production



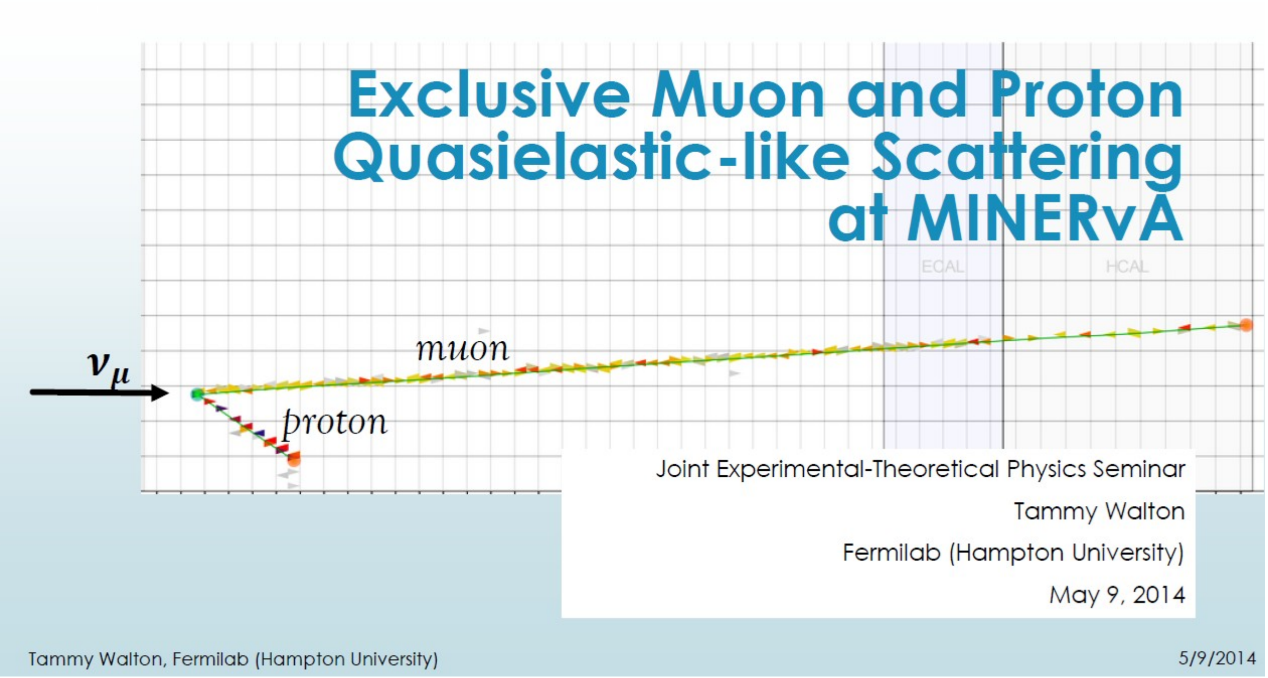
Today's topic:

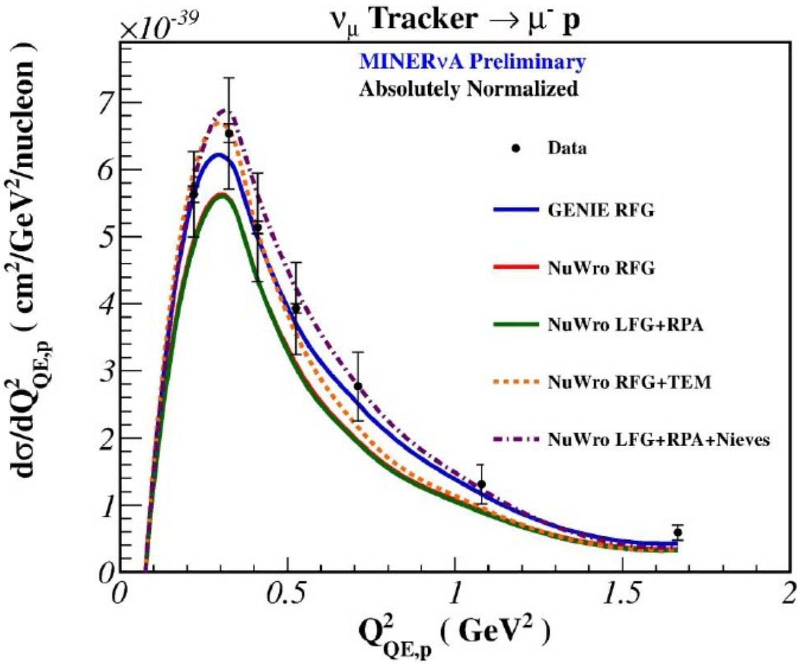
μ-p mesonless production



First presented by Tammy Walton in 2014 [Phys. Rev. D 91, 071301(R)]

- Hydrocarbon target
- NuMI low energy (LE) neutrino beam
- Foundation of further MINERvA μp analyses

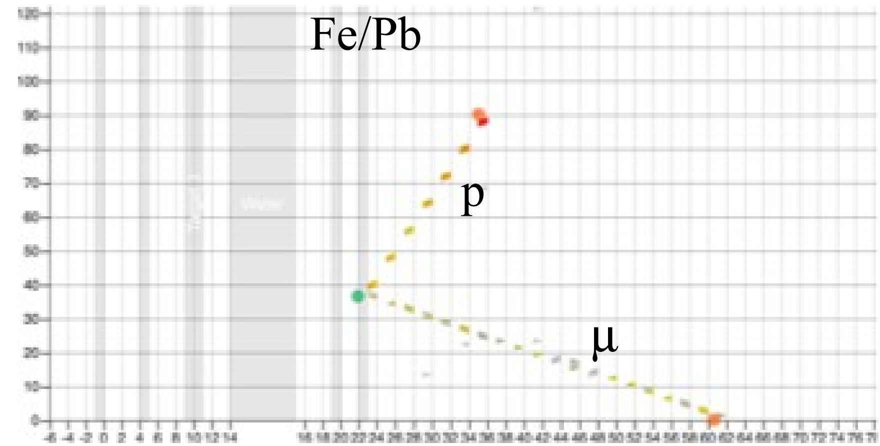




http://minerva-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=9895;filename=twalton_wine_cheese_05092014.pdf;version=5

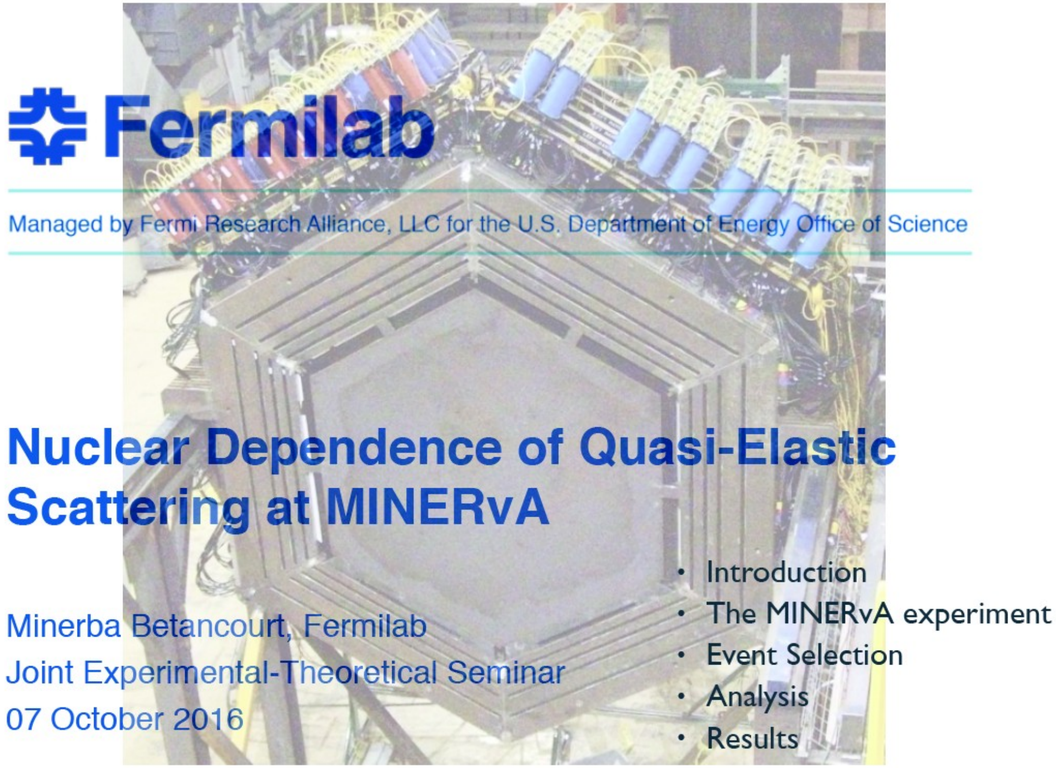
Today's topic:

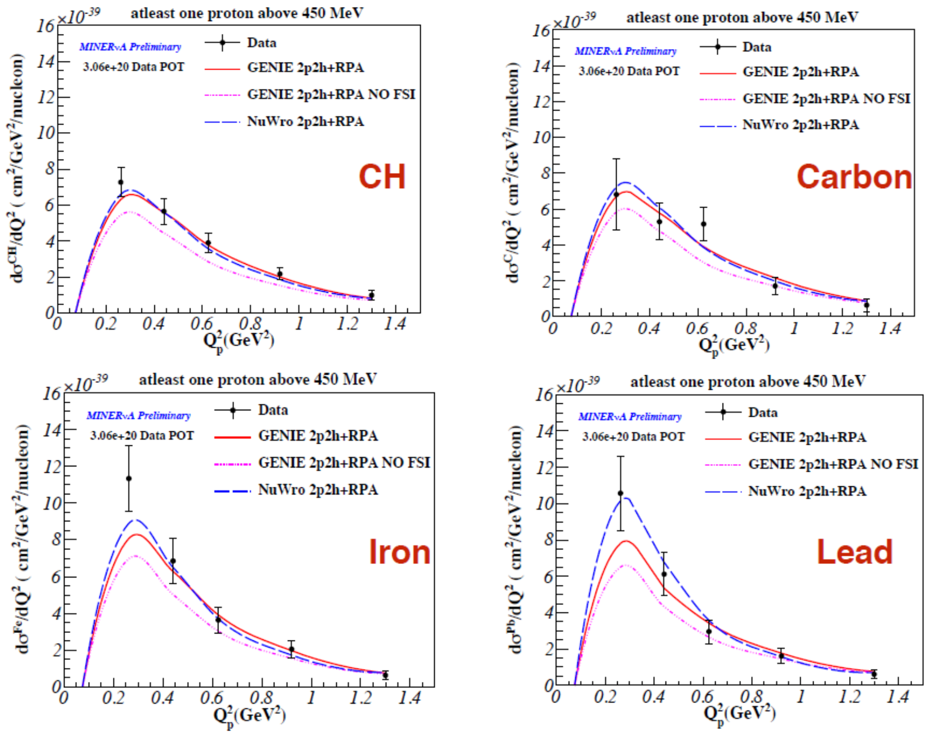
μ-p mesonless production



Extension to nuclear targets presented by Minerba Betancourt in 2016 [Phys. Rev. Lett. 119, 082001]

- Extended previous framework
- Challenging analysis

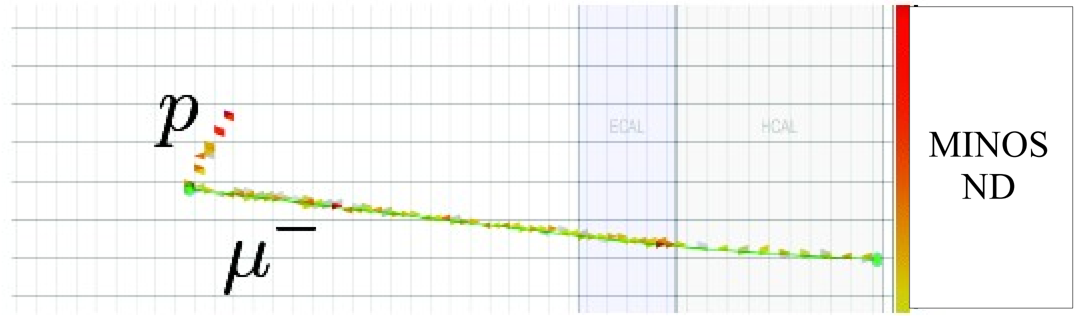




https://web.fnal.gov/organization/theory/_layouts/15/WopiFrame.aspx?sourcedoc=/organization/theory/JETP/2016/Betancourt_wine_and_cheese.pdf&action=default

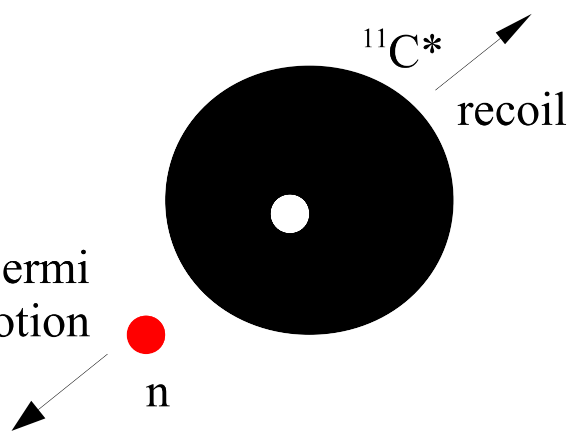
Today's topic:

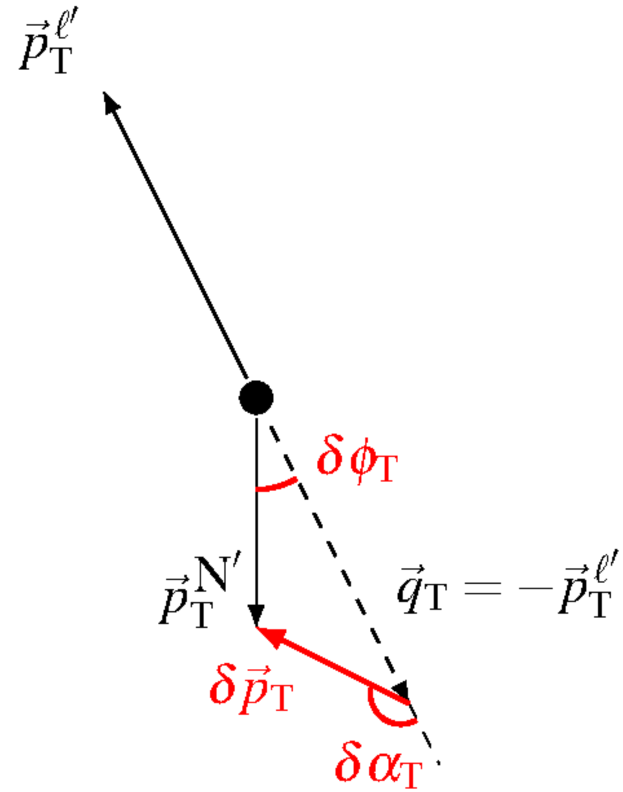
μ-p mesonless production



This analysis

- Subsample of 2014 analysis
  - Muon matched to MINOS
  - Proton kinematics measurement significantly better
- New 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

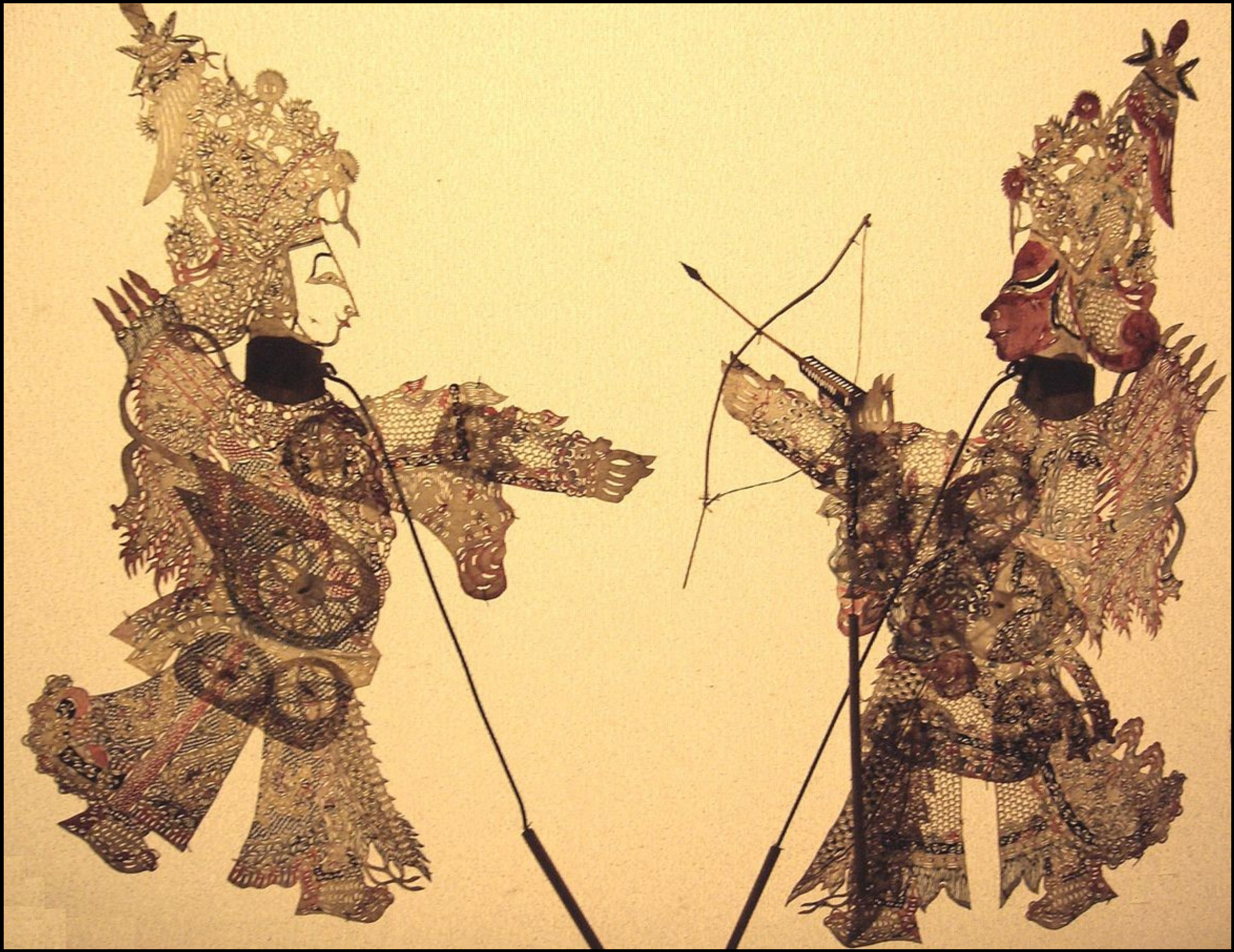
Cave of Pettakere, Bantimurung district (kecamatan), South Sulawesi, **Indonesia**. Hand stencils estimated between **35,000-40,000 BP**

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**

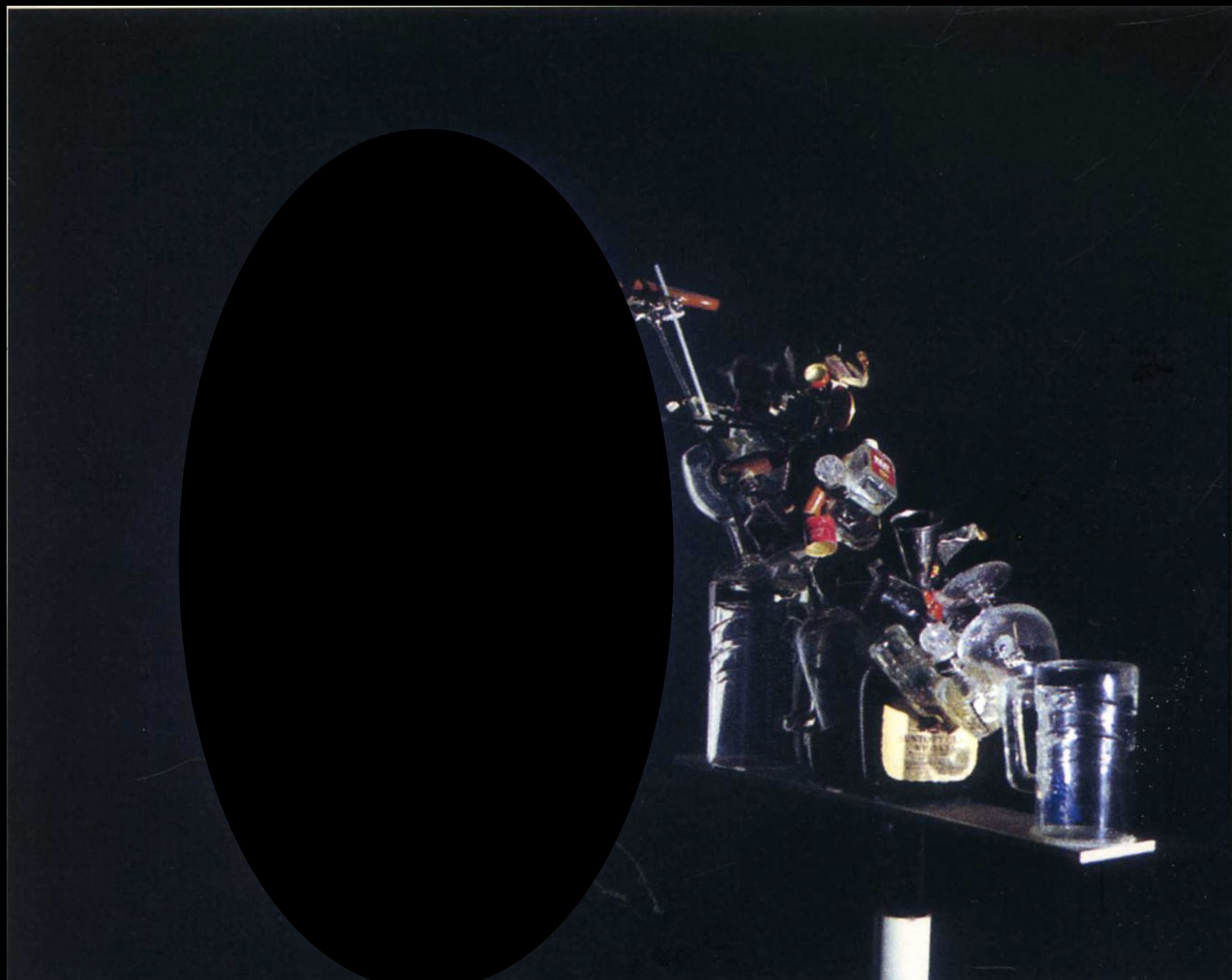
A brief history of Shadow Art



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

Traditional Chinese “movie”

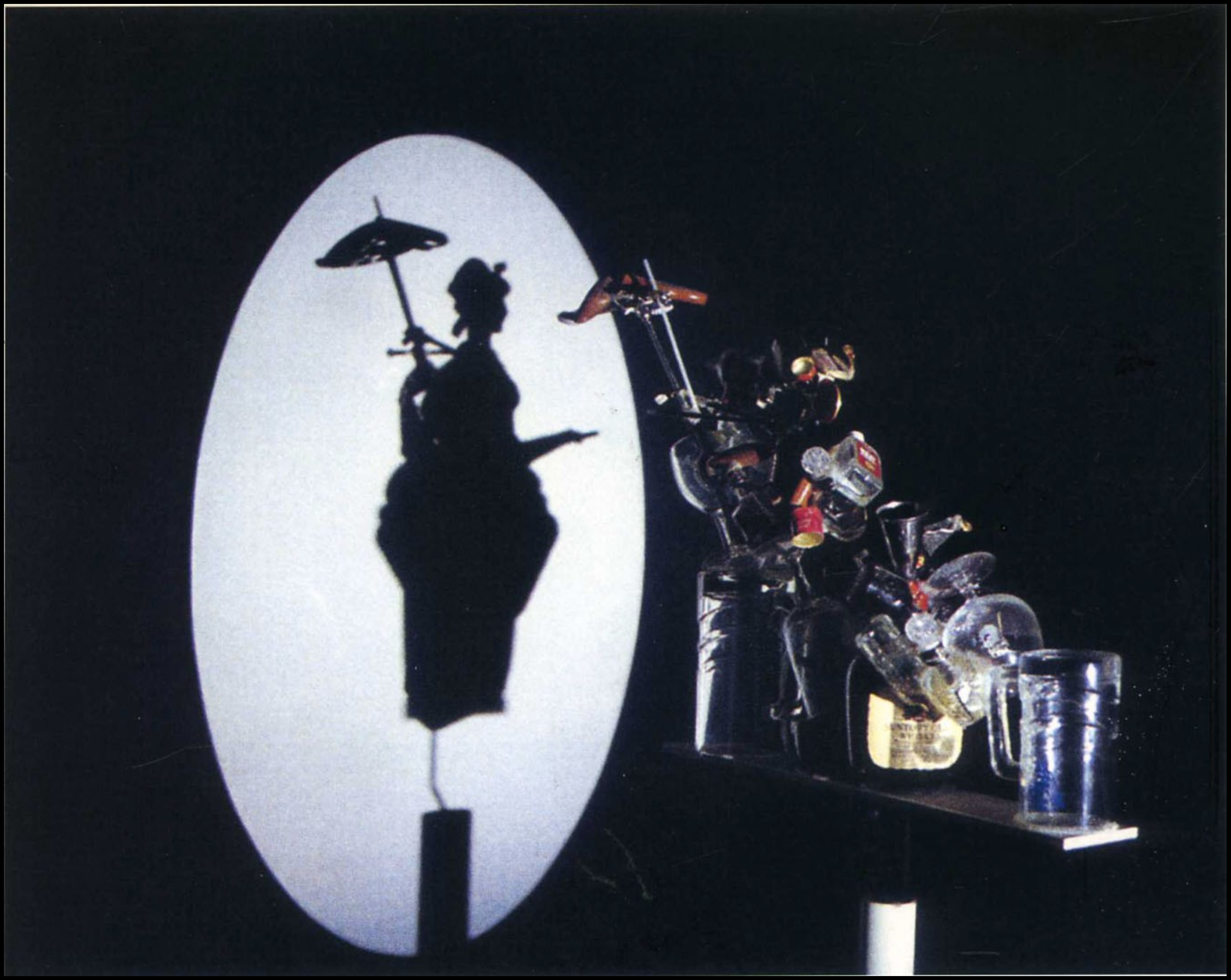
A brief history of Shadow Art



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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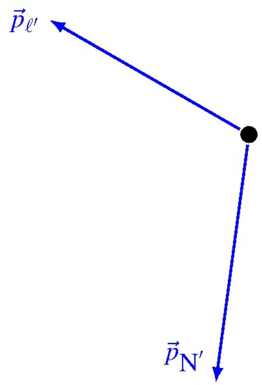
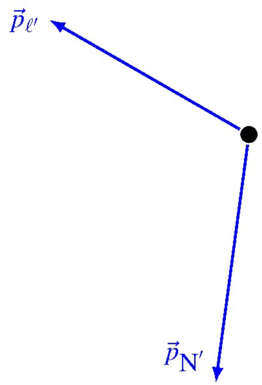
Japanese modern art

Transverse kinematic imbalances
– a neutrino shadow play



Transverse kinematic imbalances
– *a neutrino shadow play*

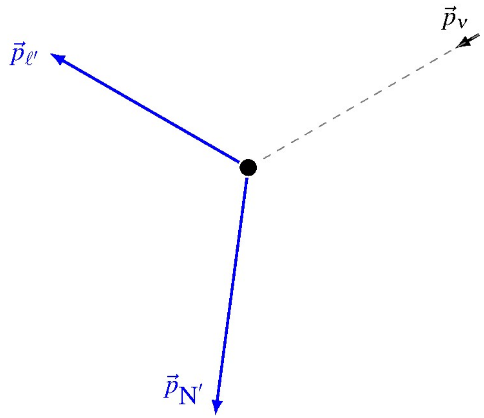


Source: http://zhejiangpiying.sokutu.com/tupian.html

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

Xianguo Lu, Oxford

Transverse kinematic imbalances
– *a neutrino shadow play*



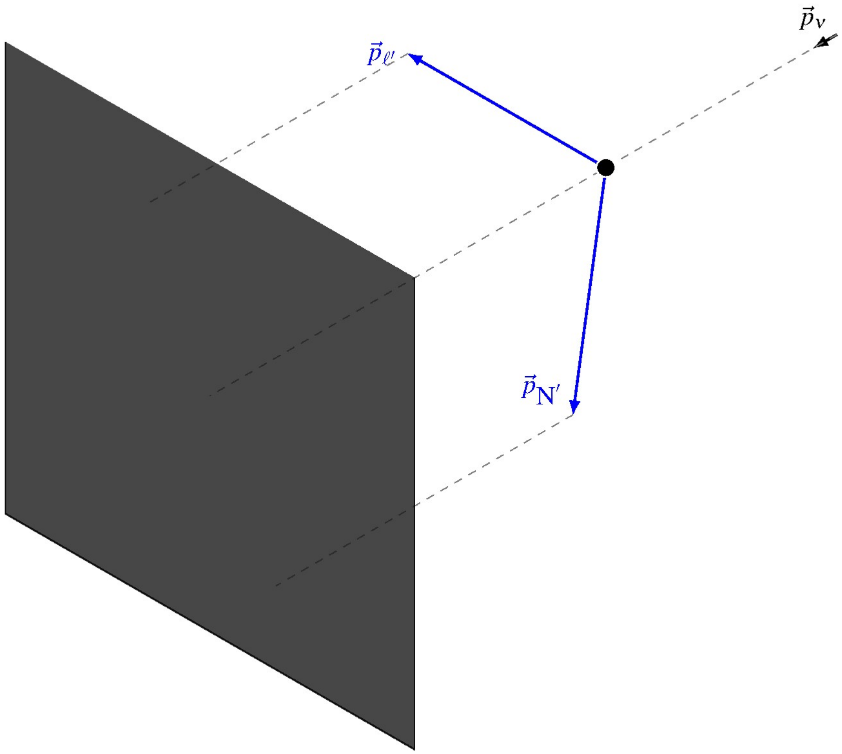
Xianguo Lu, Oxford

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

To make *Neutrino Shadow Play*, we need

- ✓ beam of light → accelerator
- ✓ screen

Transverse kinematic imbalances
– *a neutrino shadow play*

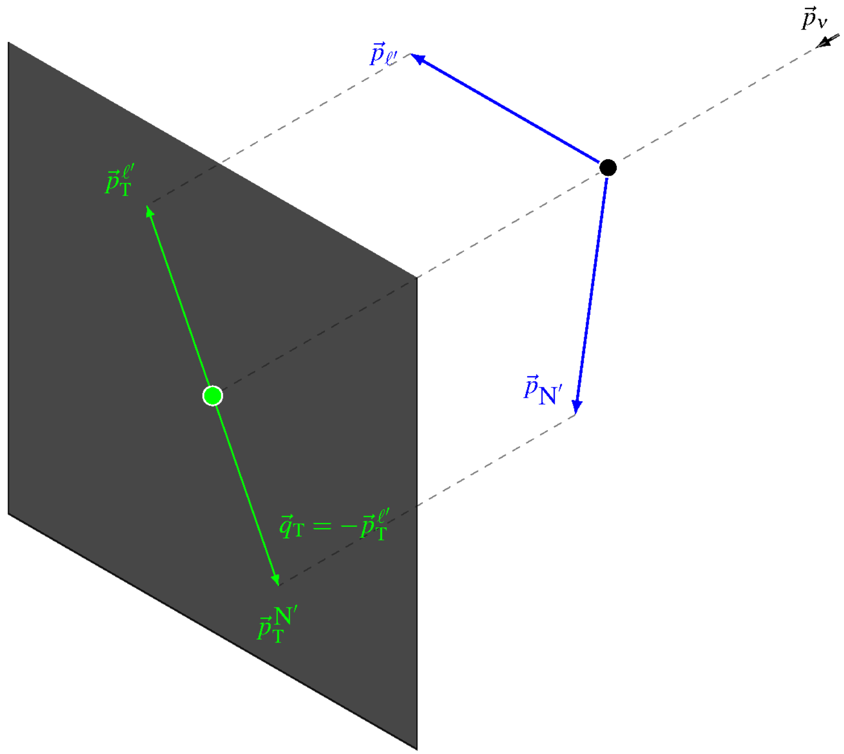


Source: http://zhejiangpiying.sokutu.com/tupian.html

To make *Neutrino Shadow Play*, we need
- ✓ beam of light → accelerator
- ✓ screen → transverse plane

Xianguo Lu, Oxford

Transverse kinematic imbalances
– *a neutrino shadow play*



Static nucleon target

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

To make *Neutrino Shadow Play*, we need

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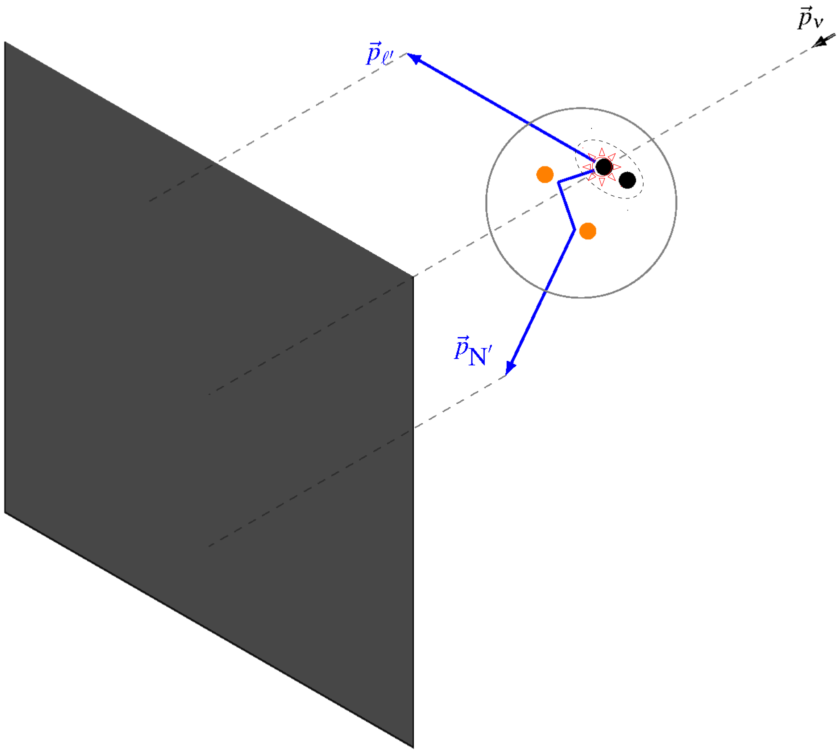
- ✓ screen → transverse plane

Xianguo Lu, Oxford

Transverse kinematic imbalances
– *a neutrino shadow play*



Nuclear target

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

To make *Neutrino Shadow Play*, we need
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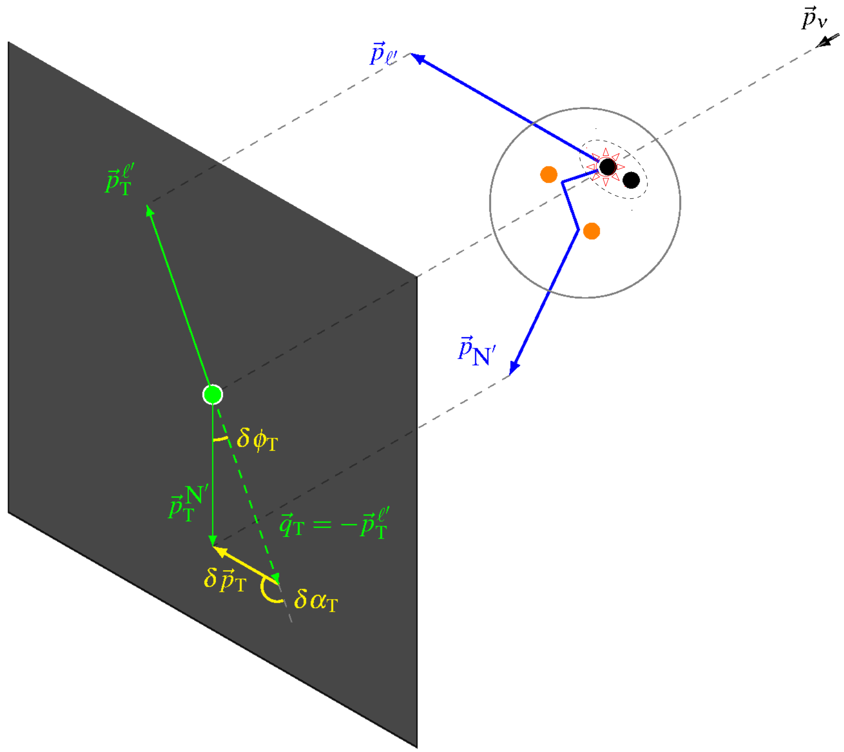
✓ screen ⟶ transverse plane

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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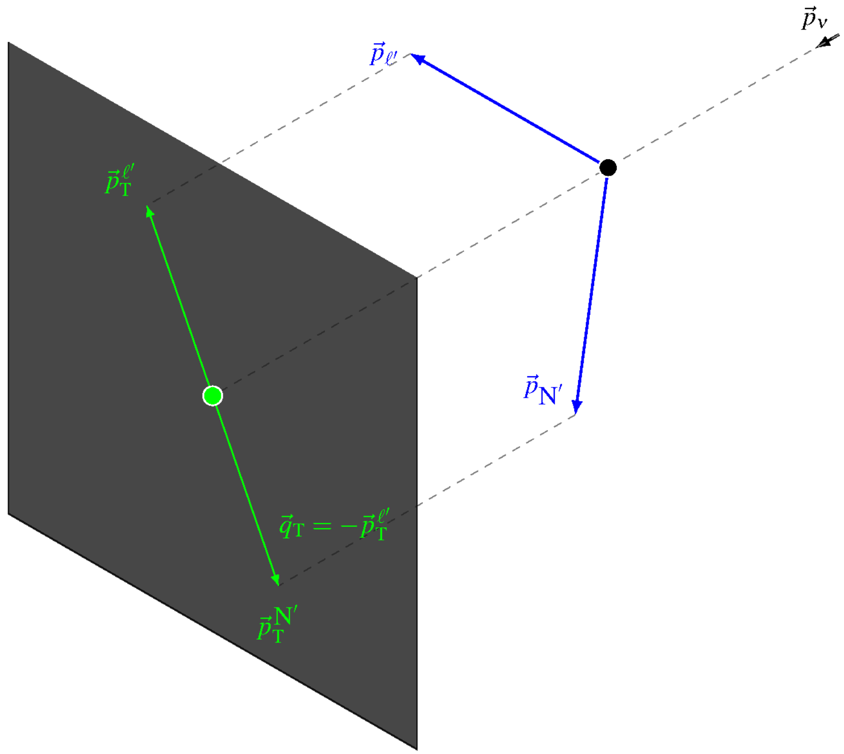
Xianguo Lu, Oxford

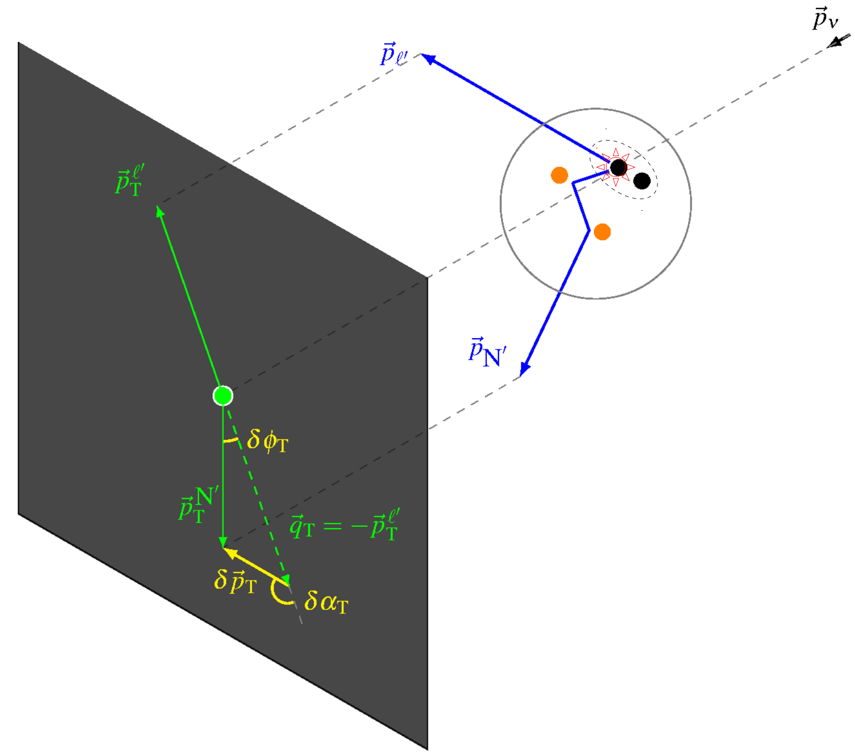
Transverse kinematic imbalances
– *a neutrino shadow play*

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

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



Static nucleon target



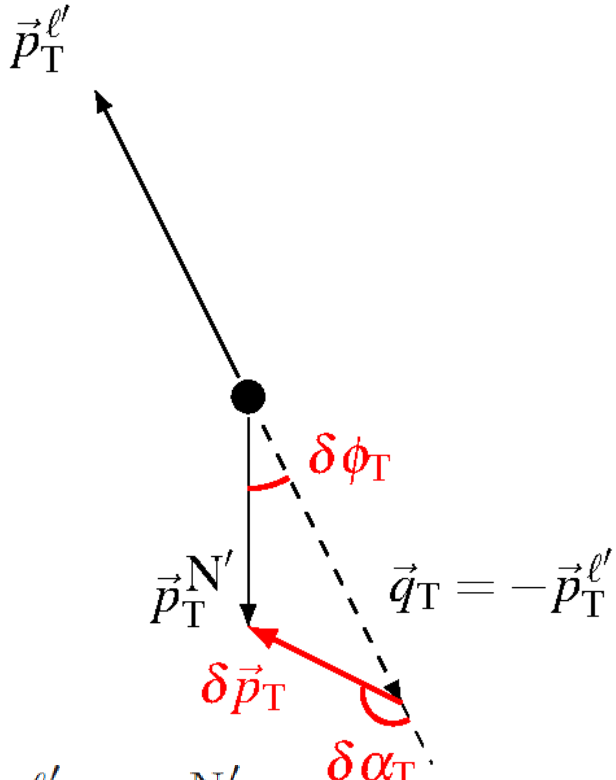
Nuclear target

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

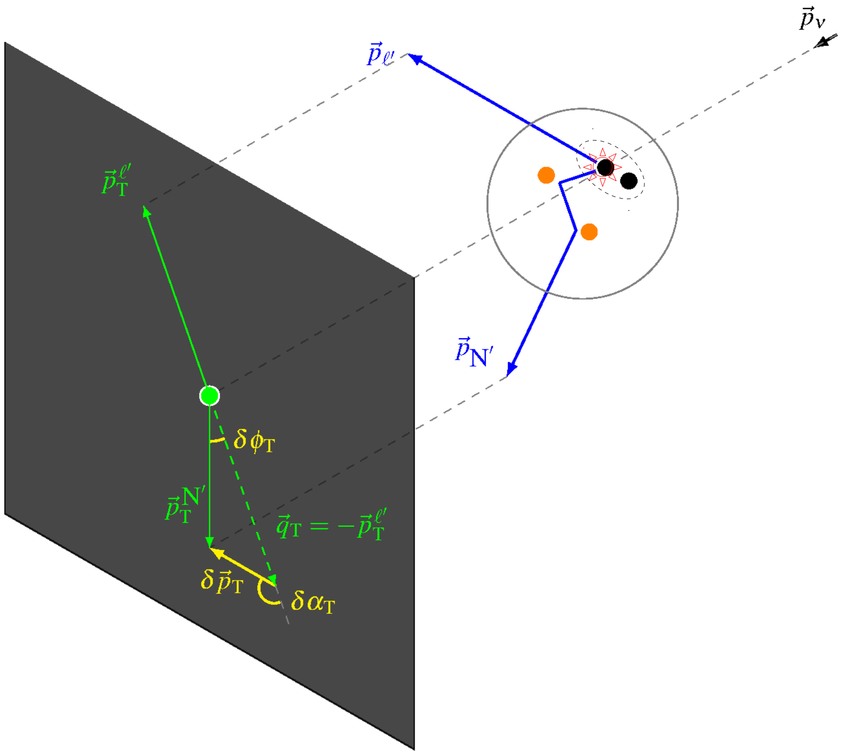
Transverse kinematic imbalances
– *a neutrino shadow play*

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

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



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



Nuclear target

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

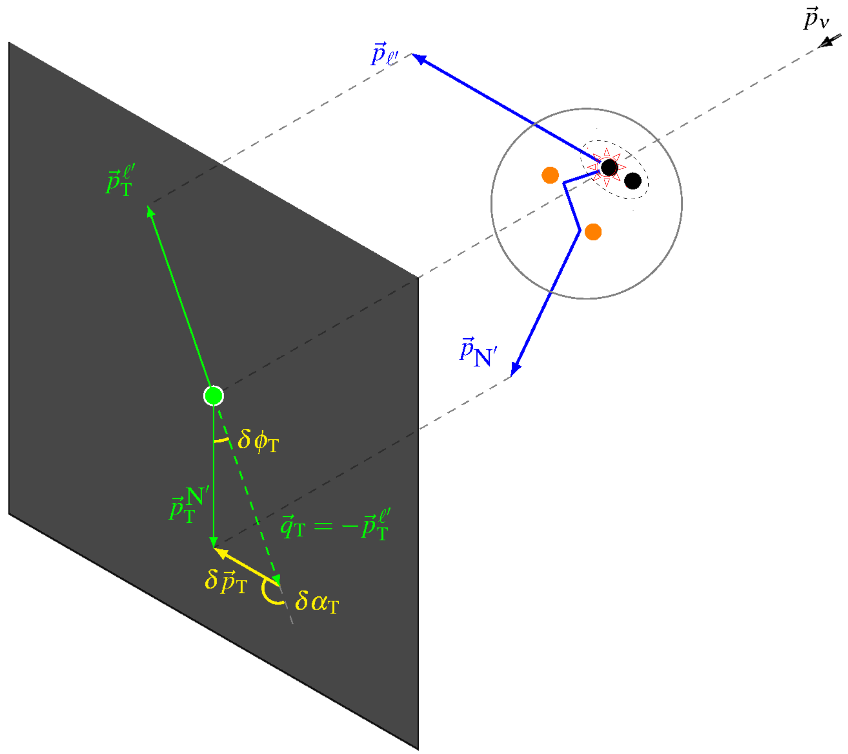
A more general analysis of kinematic imbalance

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.



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

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.

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

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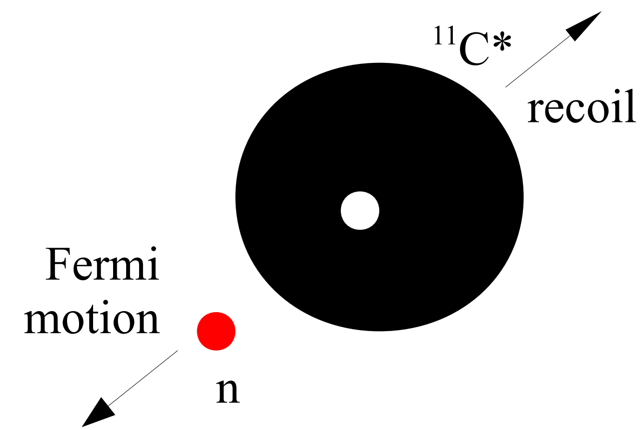
p_n: recoil momentum of the nuclear remnant

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



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

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

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)

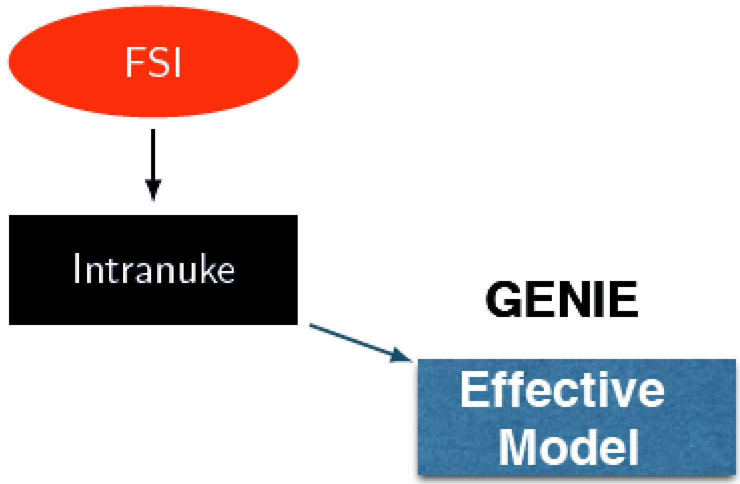
- Event selection
- Background estimation and subtraction
- Unfolding
- Efficiency correction

Focus today

➢ Flux integrated cross section as results

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



- INC-like with one "effective" interaction
- tuned do hadron-nucleus data
- easy to reweight

courtesy of Tomasz Golan

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

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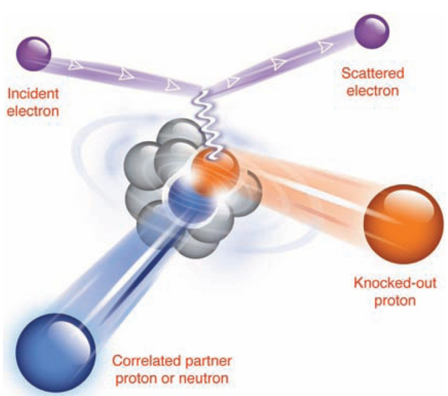
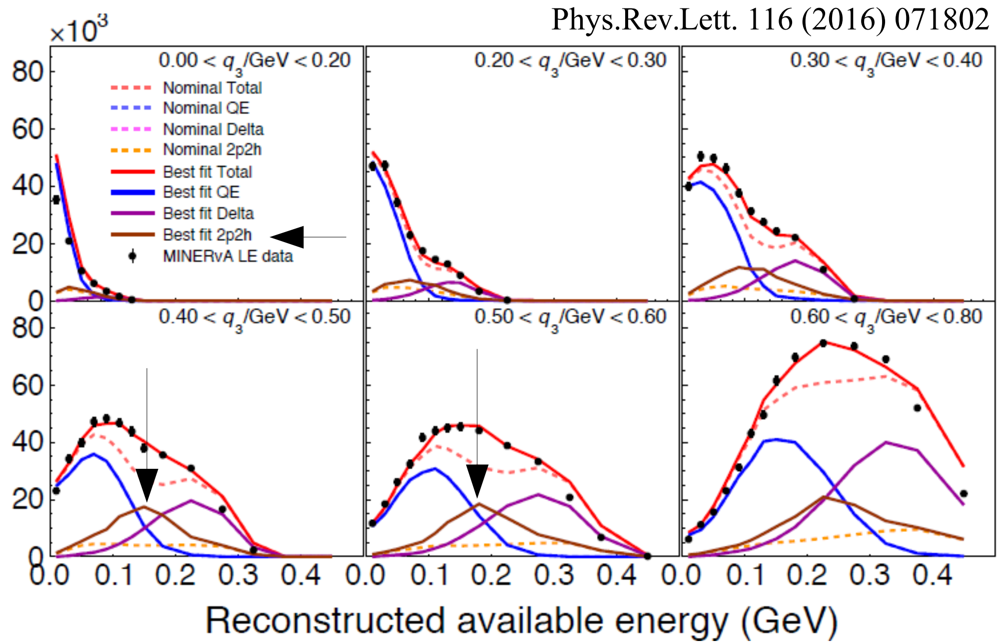
- **MnvGENIE-v1: GENIE MINERvA Tune (v1) [only 2p2h relevant for this analysis]**
  - Added Random Phase Approximation (RPA) [Phys.Rev. C70 (2004) 055503]
  - Non-resonance pion production scaled down by 75% [Phys.Rev. D90 (2014) no.11, 112017]
  - Valencia 2p2h [Nieves *et al.*, Phys.Lett. B707 (2012) 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]



Science 320 (2008) 1476-1478

Phys.Rev.Lett. 116 (2016) 071802



→ representing energy transfer from the neutrino to the target

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

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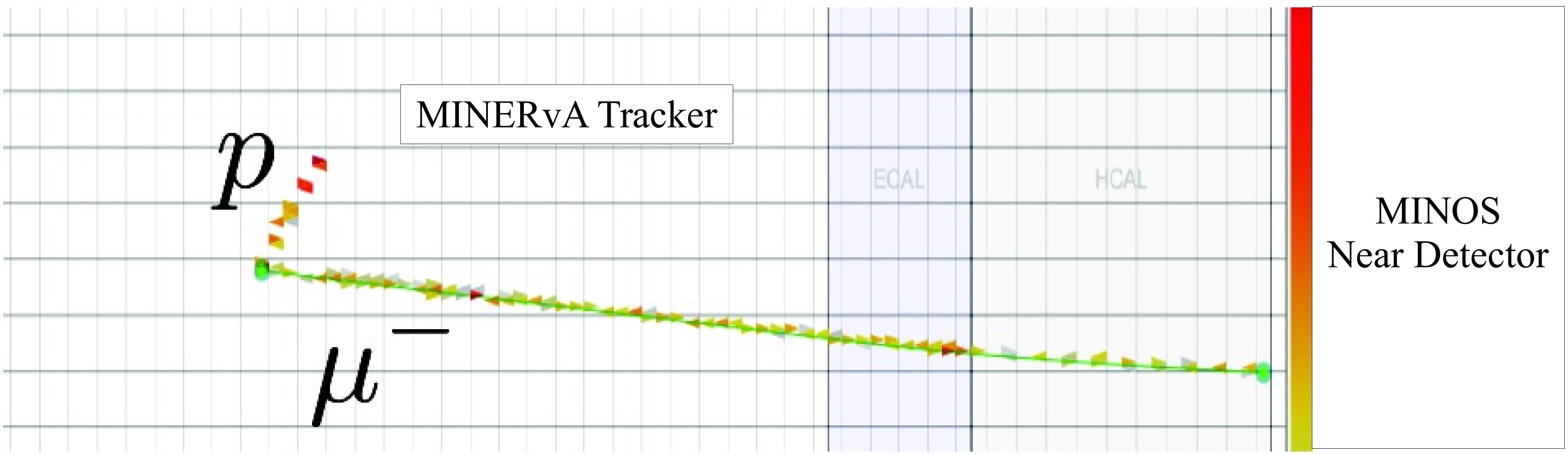
Detector simulation: GEANT4 (4.9.2)

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

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

Event Selection

- One muon candidate track matched to a MINOS track
- At least one proton candidate (particle identification using dE/dx along the track)
  - Elastically Scattered Contained (ESC) proton selection
- Vertex in tracker
- Michel electron (from pion-muon-electron decay chain) tag to remove pion production
- Cut on energy far from vertex (unattached visible energy) to remove events with untracked pions



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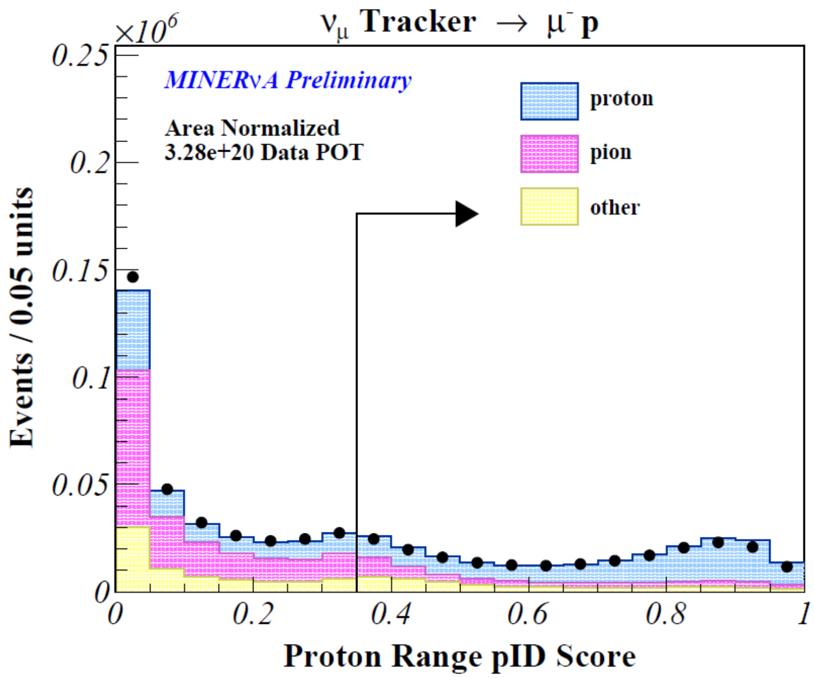

Based on dE/dx profile along the track

Event Selection

- One muon candidate track matched to a MINOS track
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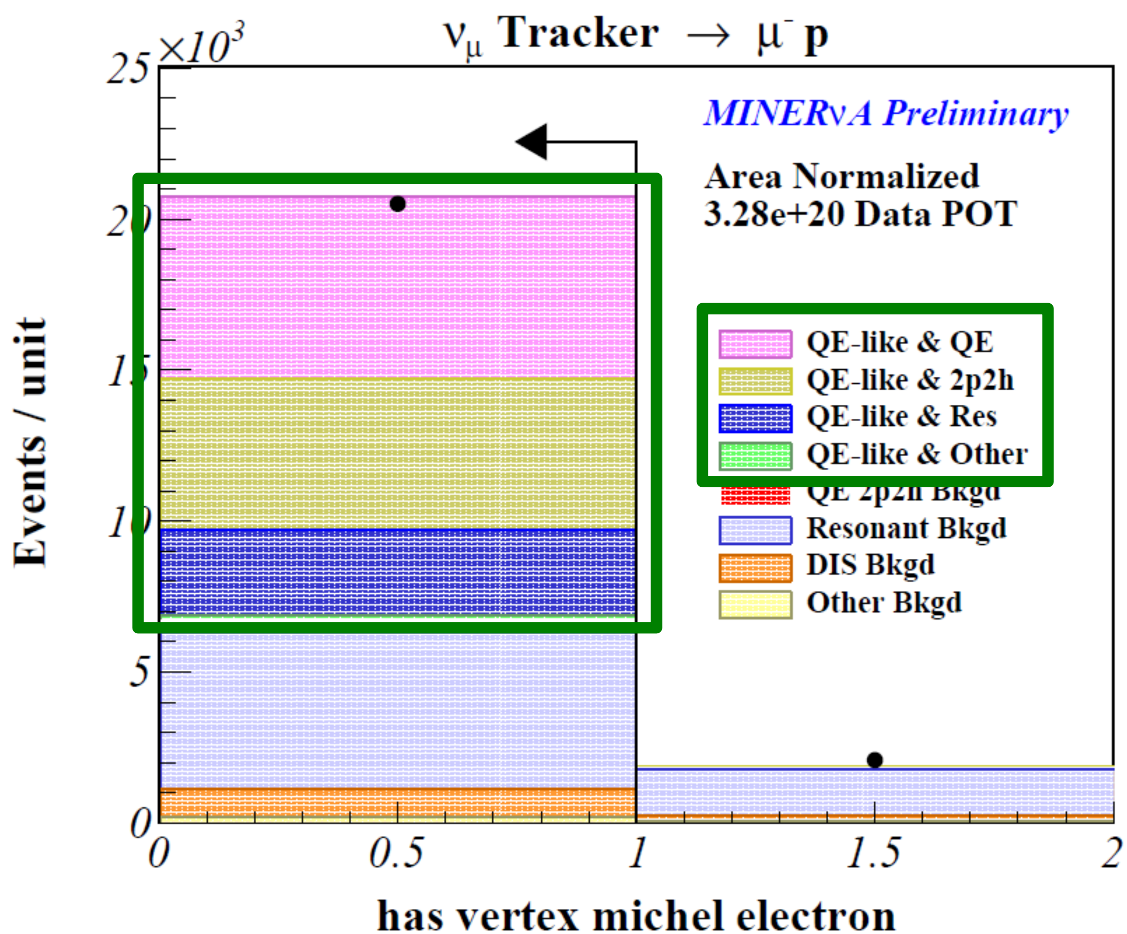

Signal:
QE-like events

Event Selection

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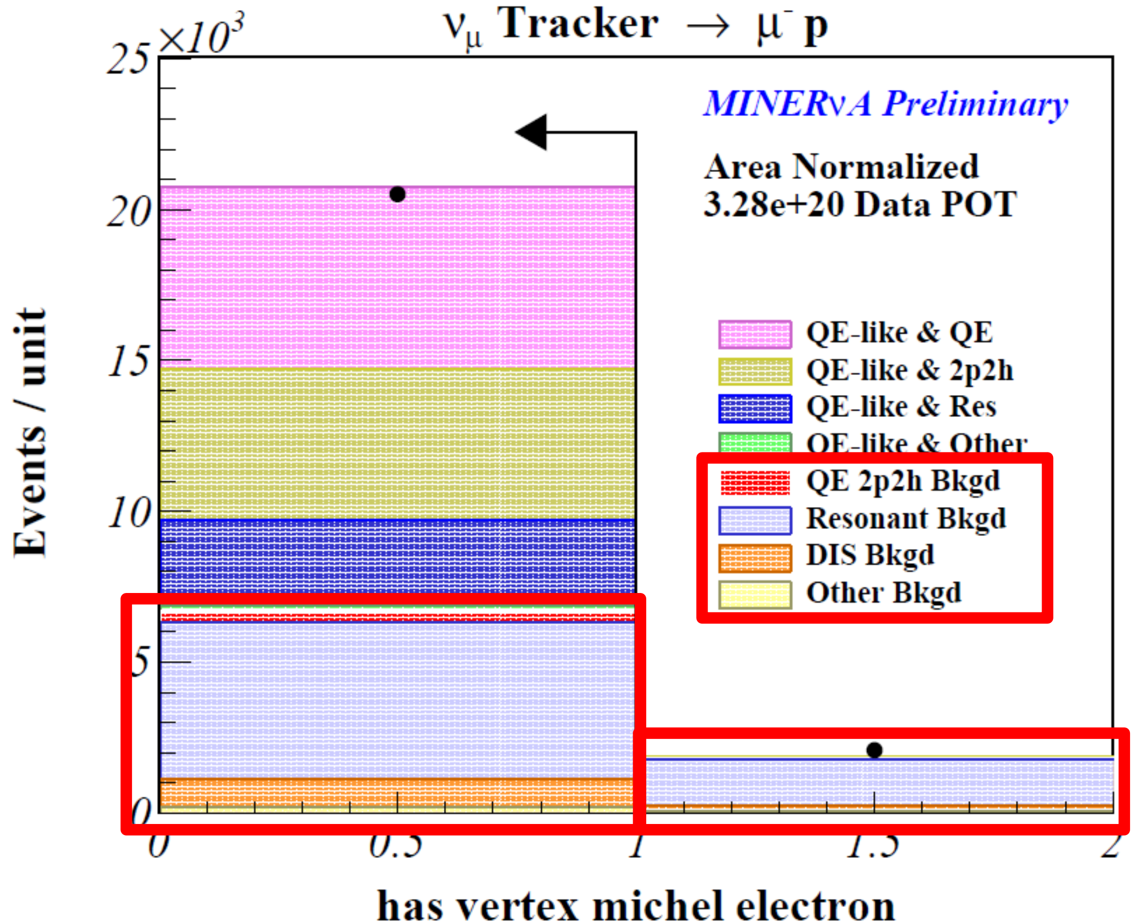

Background

Event Selection

- One muon candidate track matched to a MINOS track
- At least one proton candidate (particle identification using dE/dx along the track)
  - Elastically Scattered Contained (ESC) proton selection → new development
- Vertex in tracker
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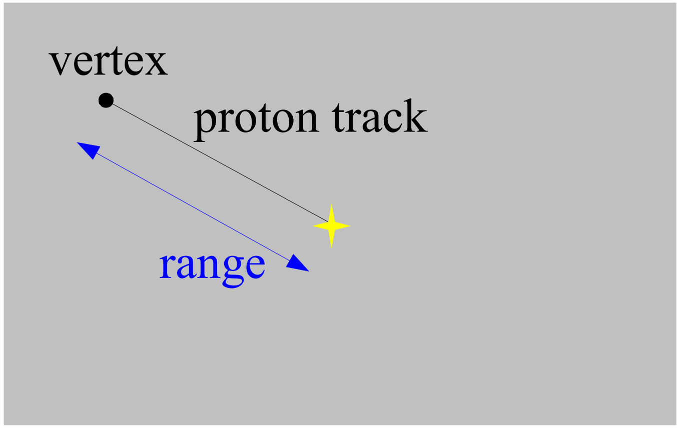
Homogeneous non-magnetized tracker
Momentum by range



Momentum-range correlation best known when the track has "peaceful" end: stopped elastically

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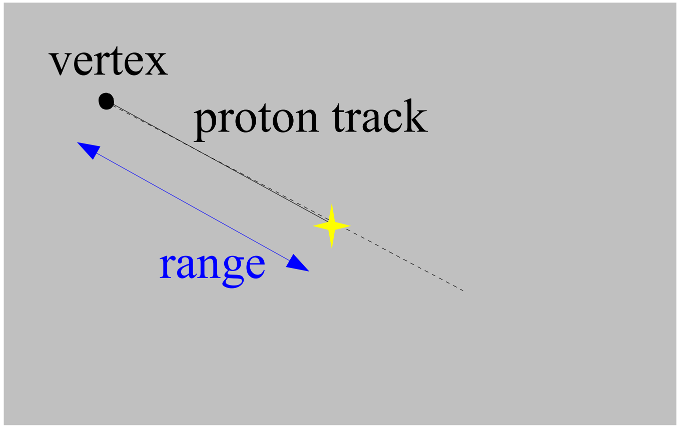

Momentum-range correlation best known when the track has "peaceful" end: stopped elastically

If track ends on the fly due to inelastic interaction in detector (e.g. p A → n A')
Range can only be measured prematurely → large bias in momentum estimation

Event Selection

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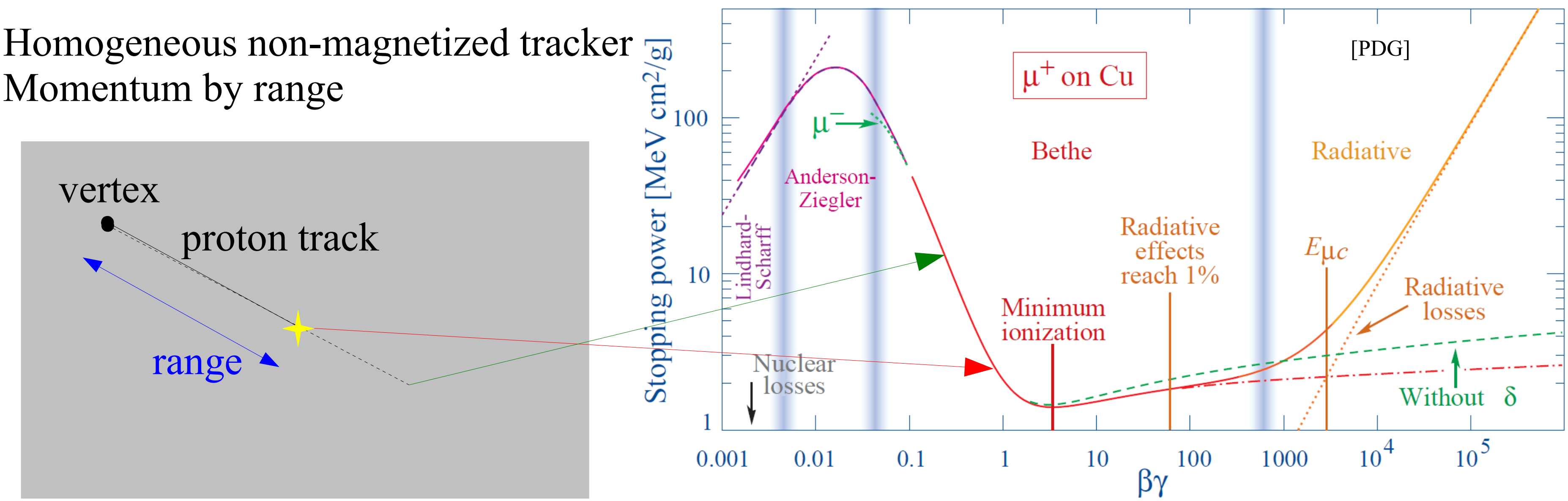

Proton stopped on the fly have smaller dE/dx
→ Cut on dEdx from track end point

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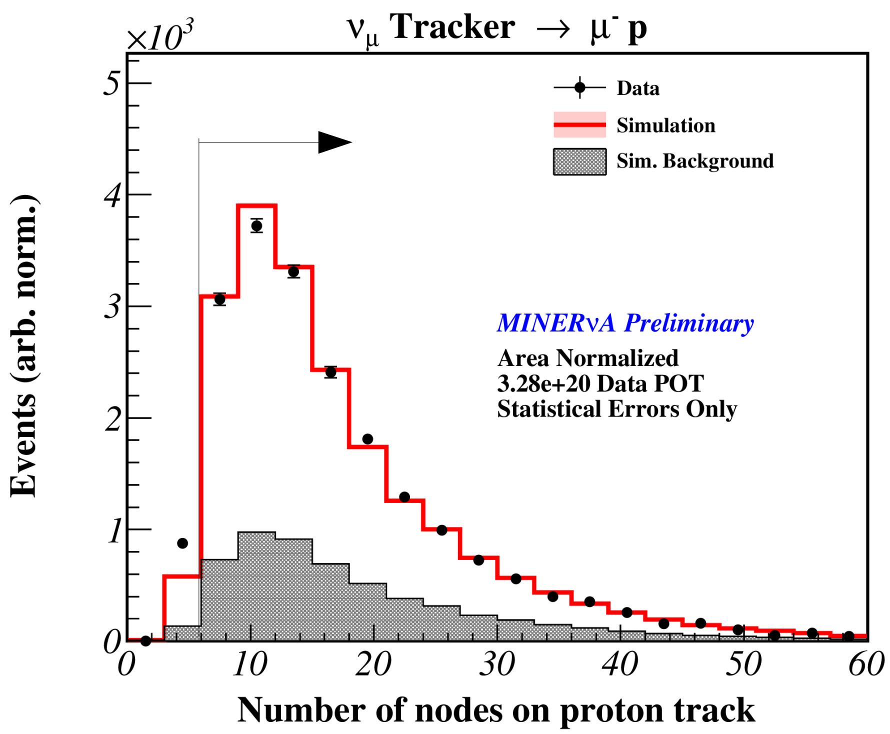
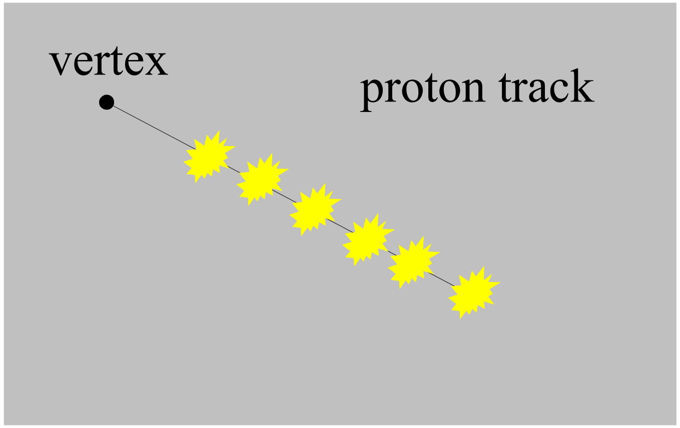


- Require at least 6 dE/dx nodes from track end point



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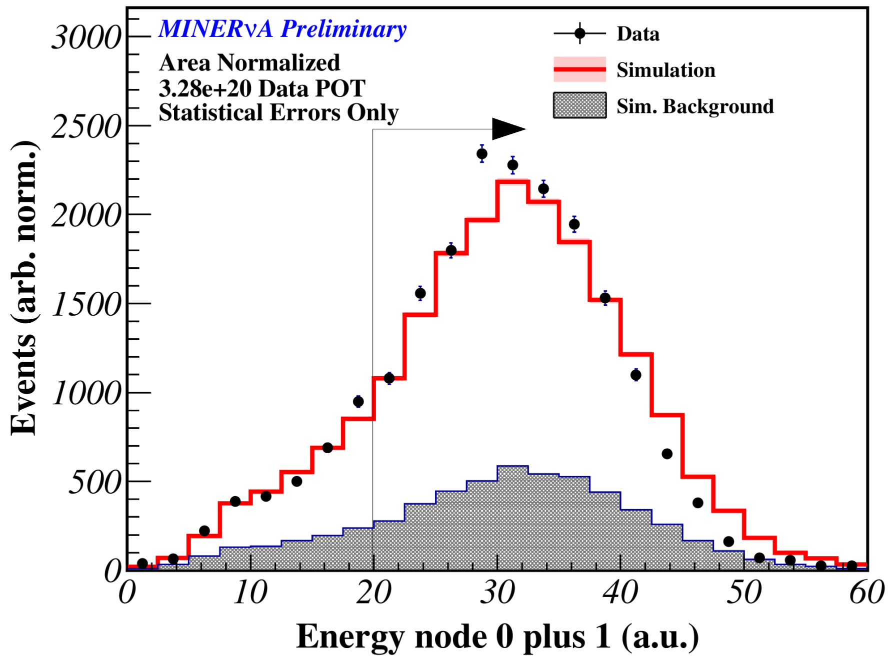
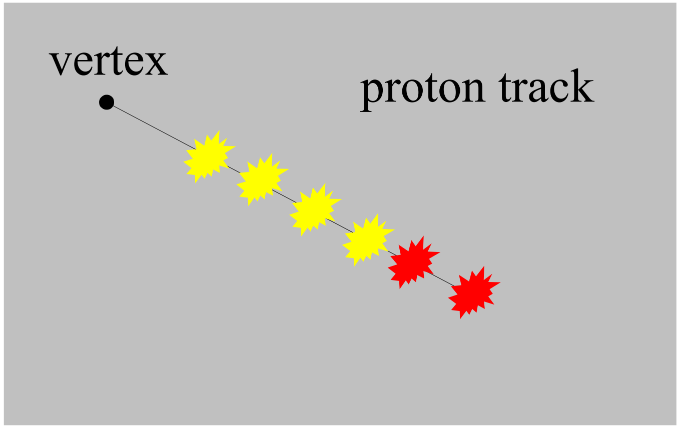


- Require at least 6 dE/dx nodes from track end point
- Cut on summed dE/dx of last two nodes (node 0 and 1 correlated)



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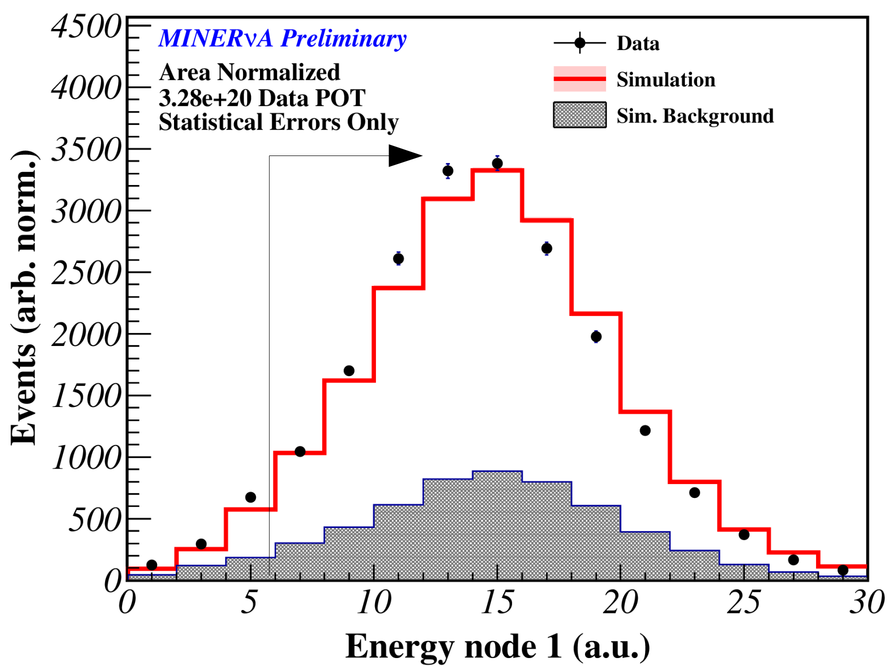
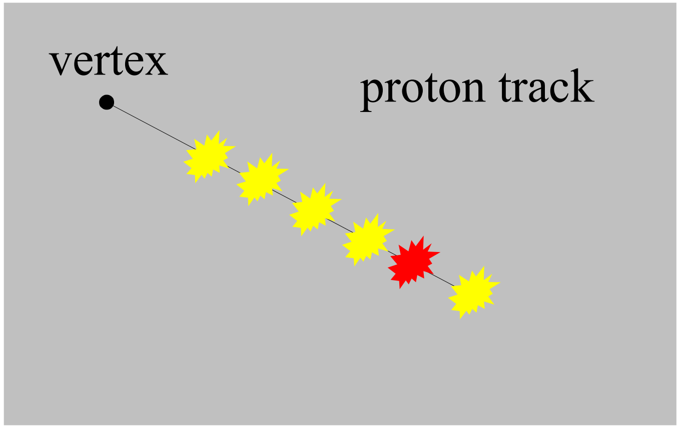


- Require at least 6 dE/dx nodes from track end point
- Cut on summed dE/dx of last two nodes (node 0 and 1 correlated)
- Cut on individual nodes (node 1-5)



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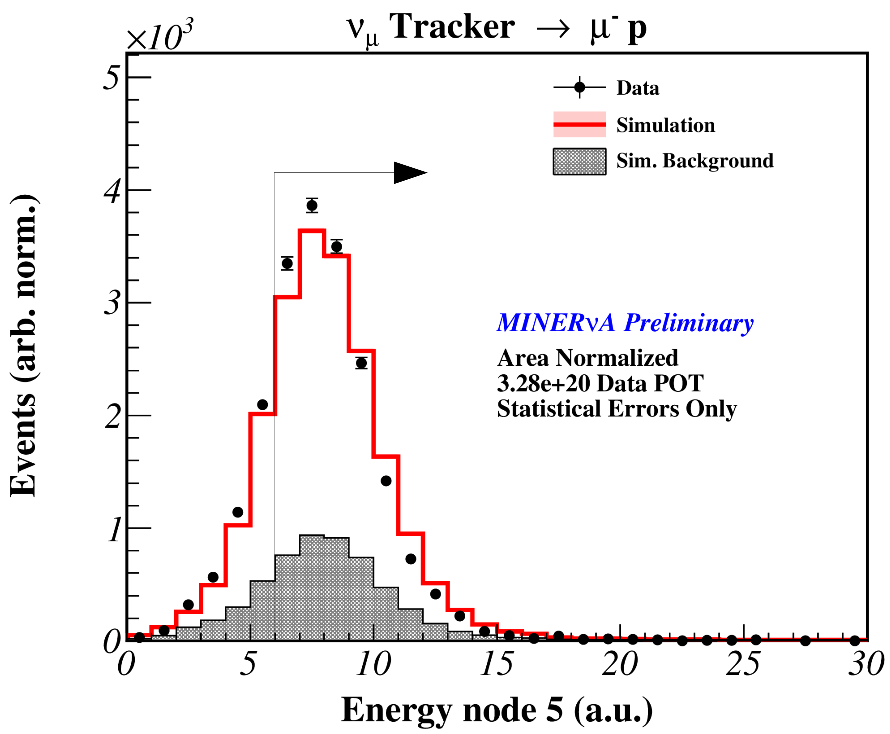

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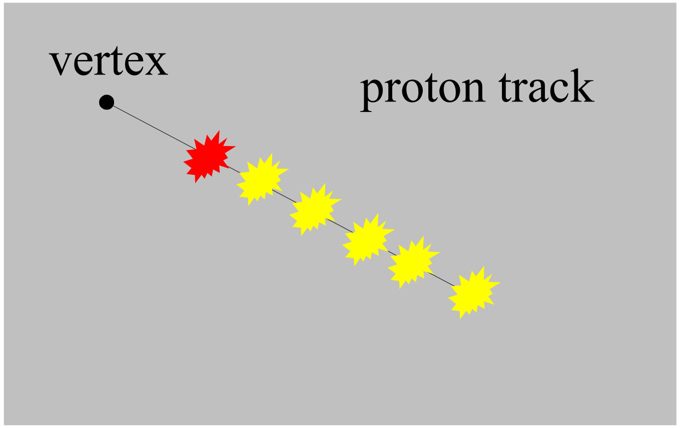

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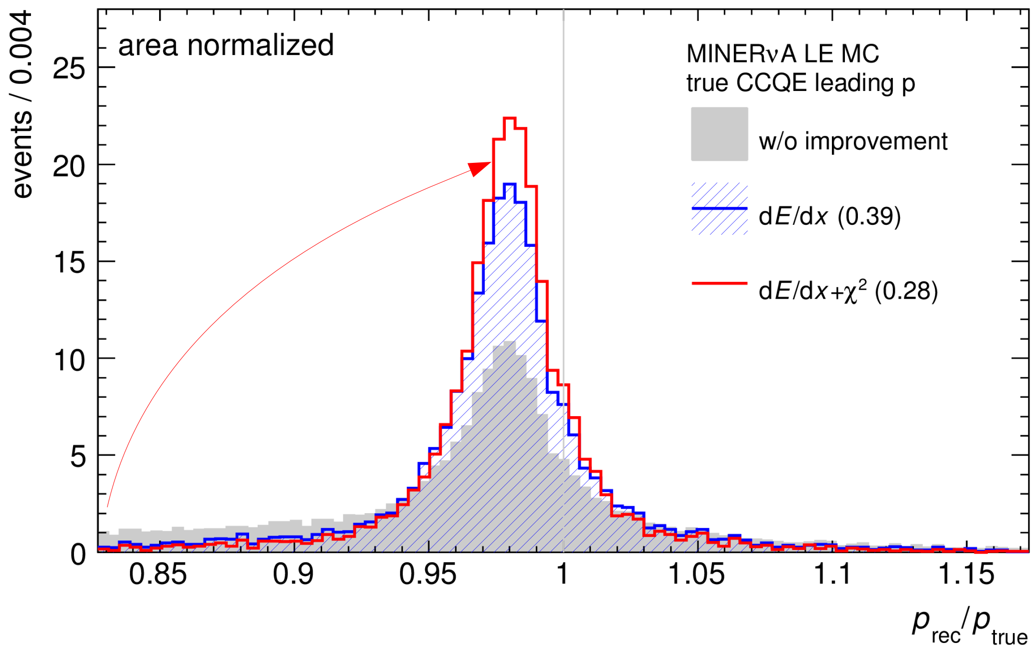

*dE/dx+cleanup cut efficiency 30-40-20%@0.6-0.75-1 GeV/c

ESC proton selection:

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

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

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

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

Event Selection

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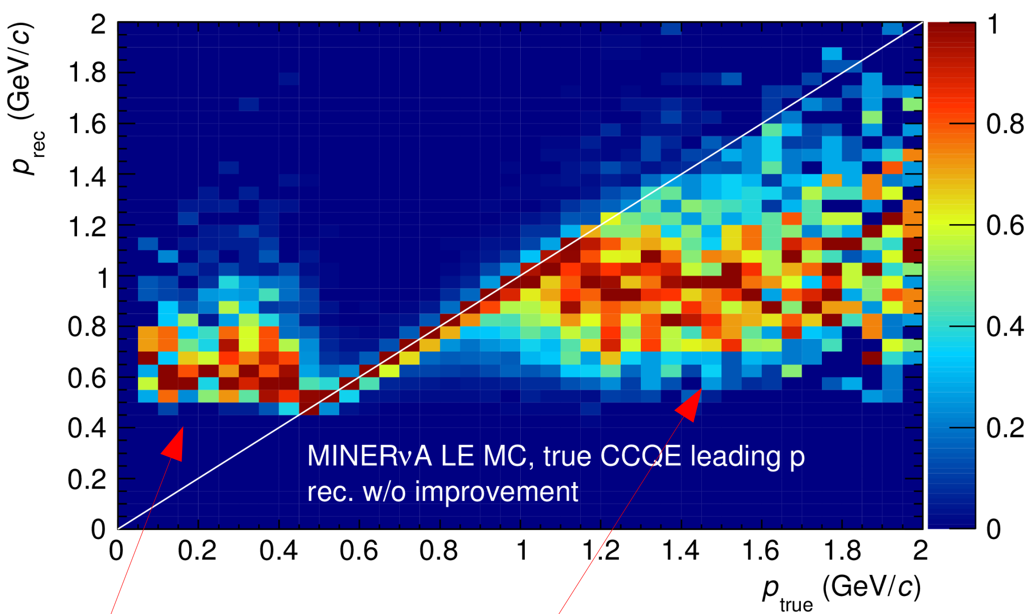
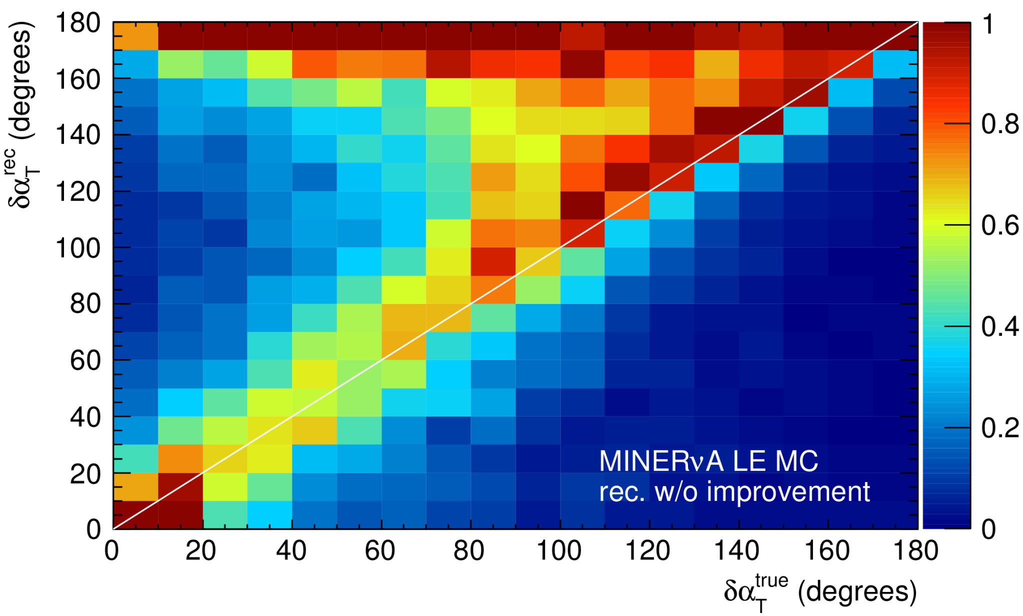
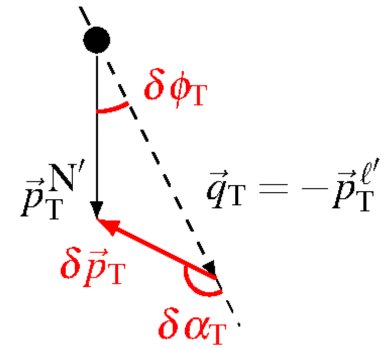




Short track around vertex

Inelastic scattered protons

Reconstructed as a function of true quantity before ESC proton selection for proton momentum and $\delta\alpha_{\rm T}$



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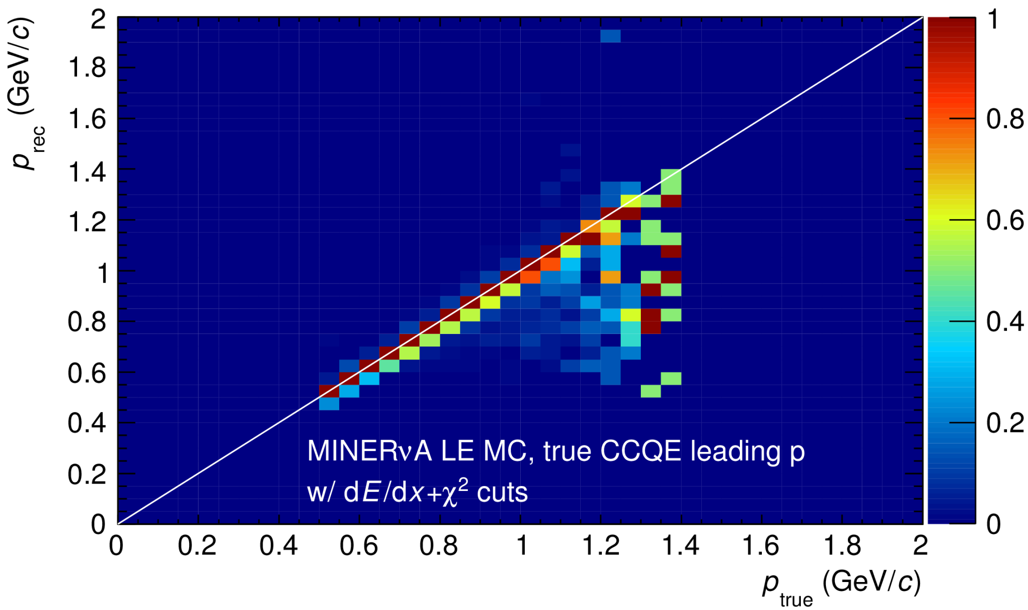
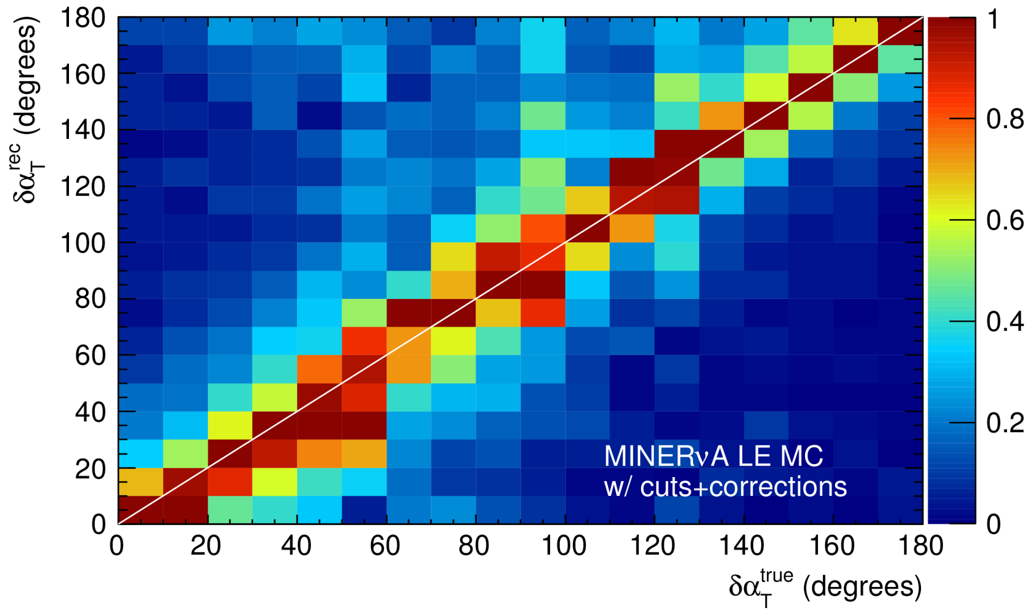
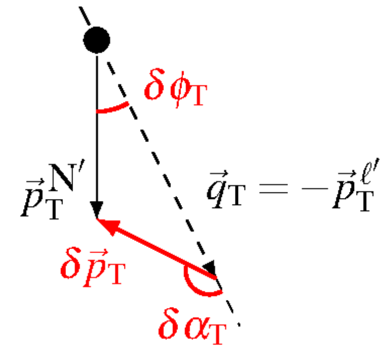




Reconstructed as a function of true quantity after ESC proton selection and pT-scale correction (only applied to derived variables) for proton momentum and $\delta\alpha_T$



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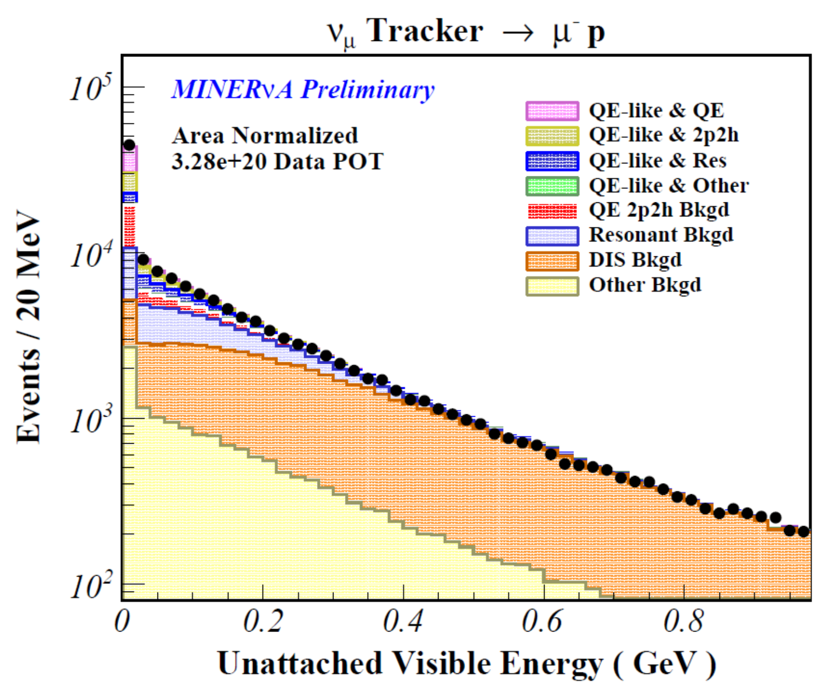

Large unattached visible energy dominated by background.

Event Selection

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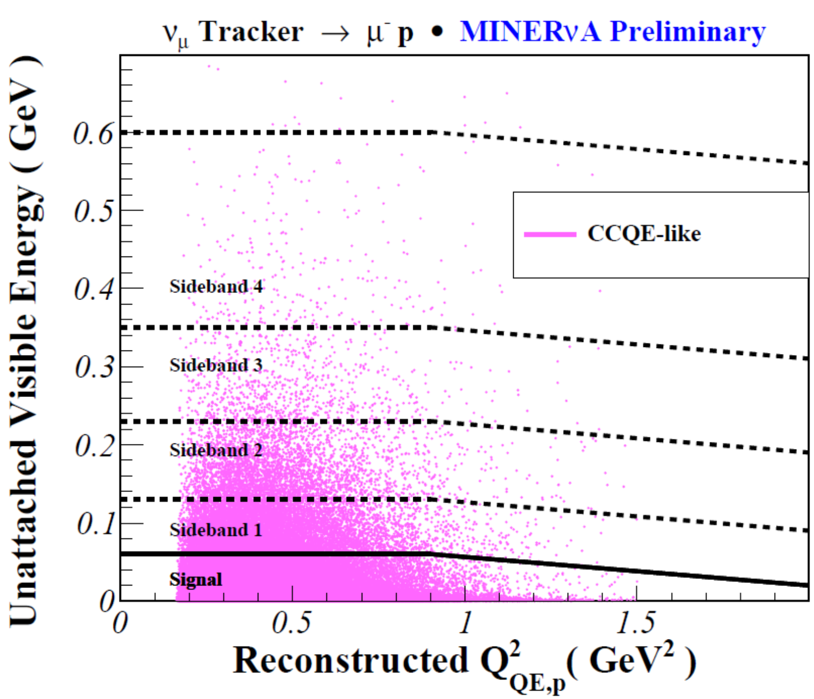

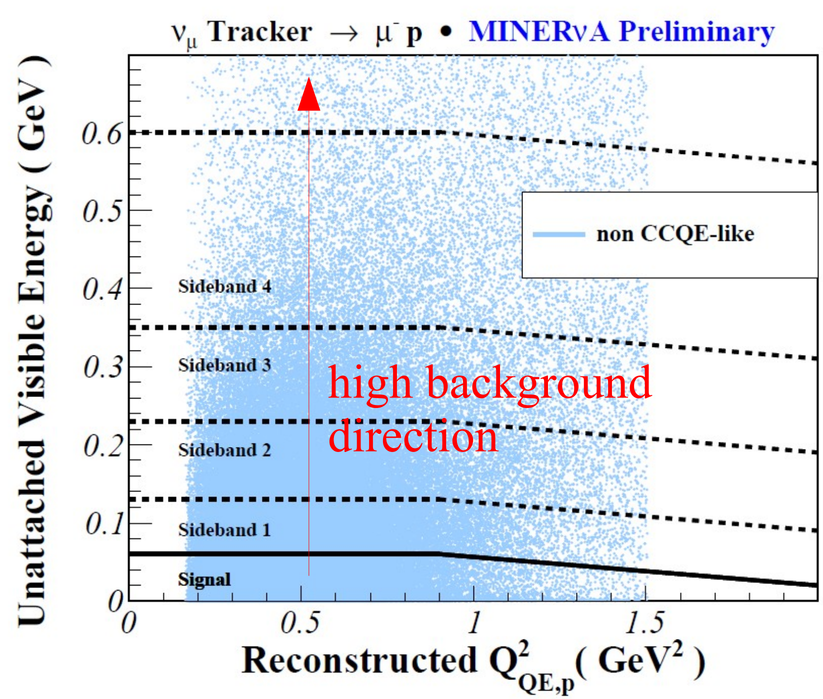

Signal and sidebands are defined

Event Selection

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  - Elastical ... (ESC) proton selection
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- Michel ele ... electron decay chain) ta
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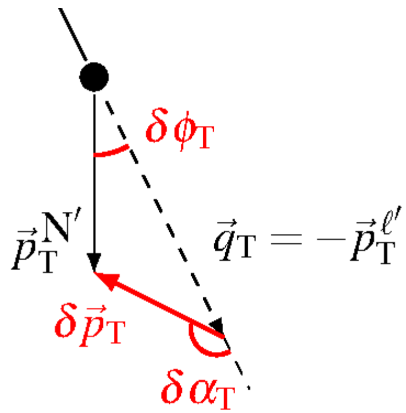
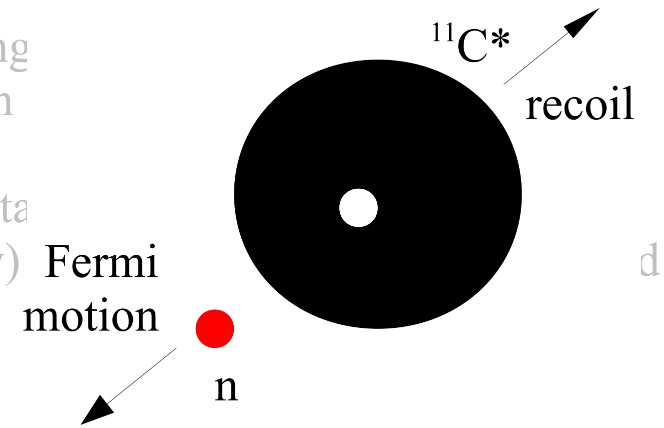
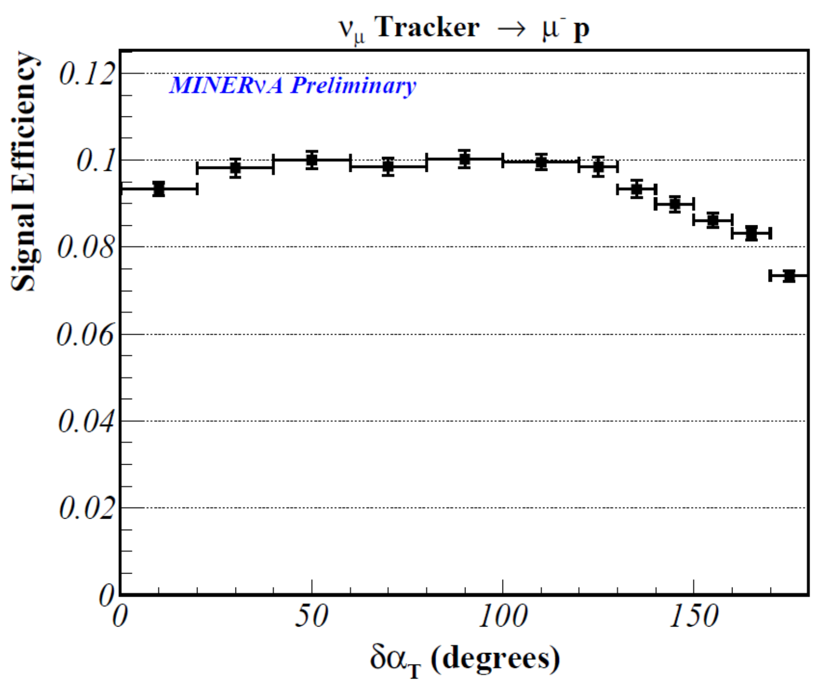
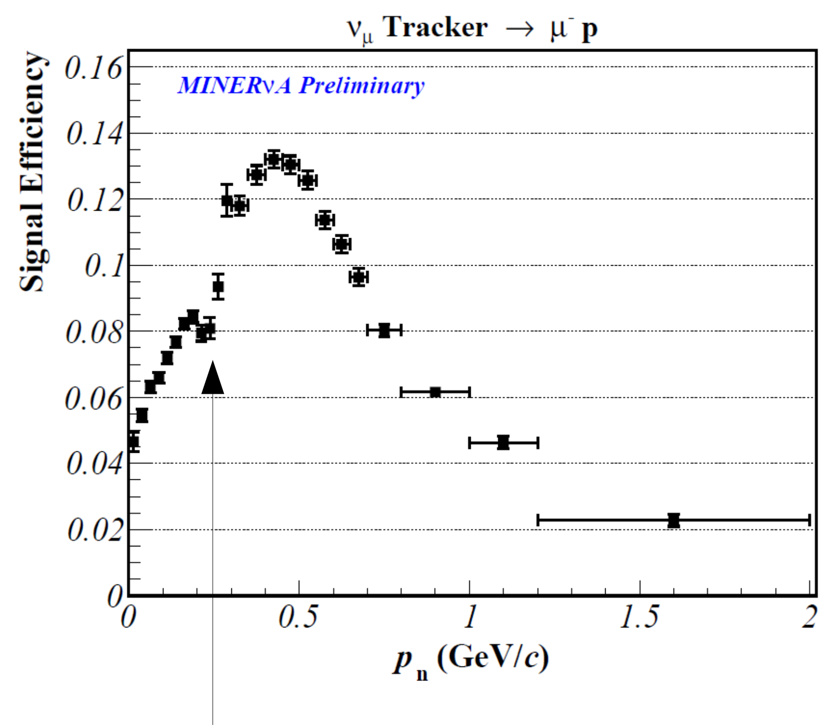
  pions







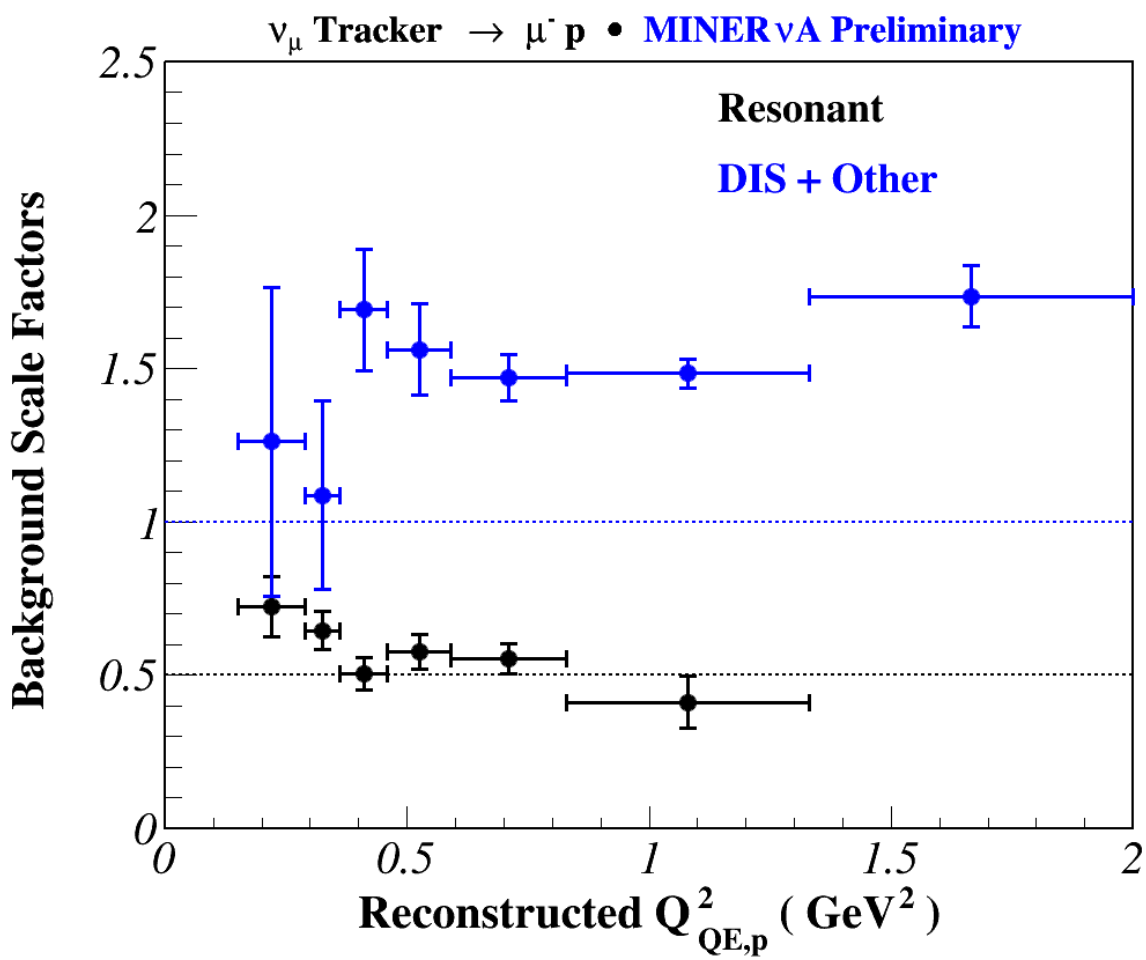


Overall efficiency: ~ 9%

Peak region (see later slides)

Background Estimation

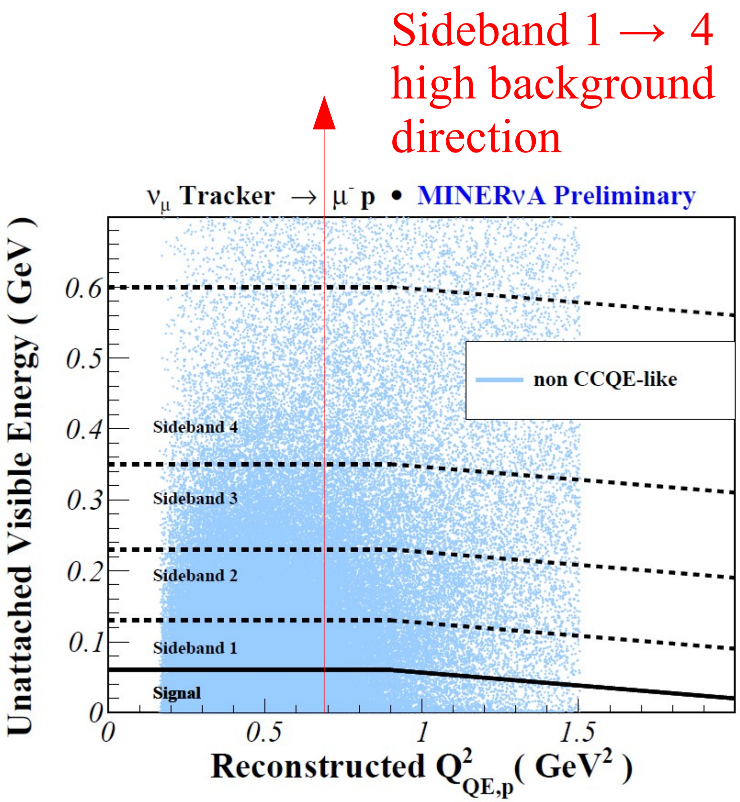
- Data driven sideband fit

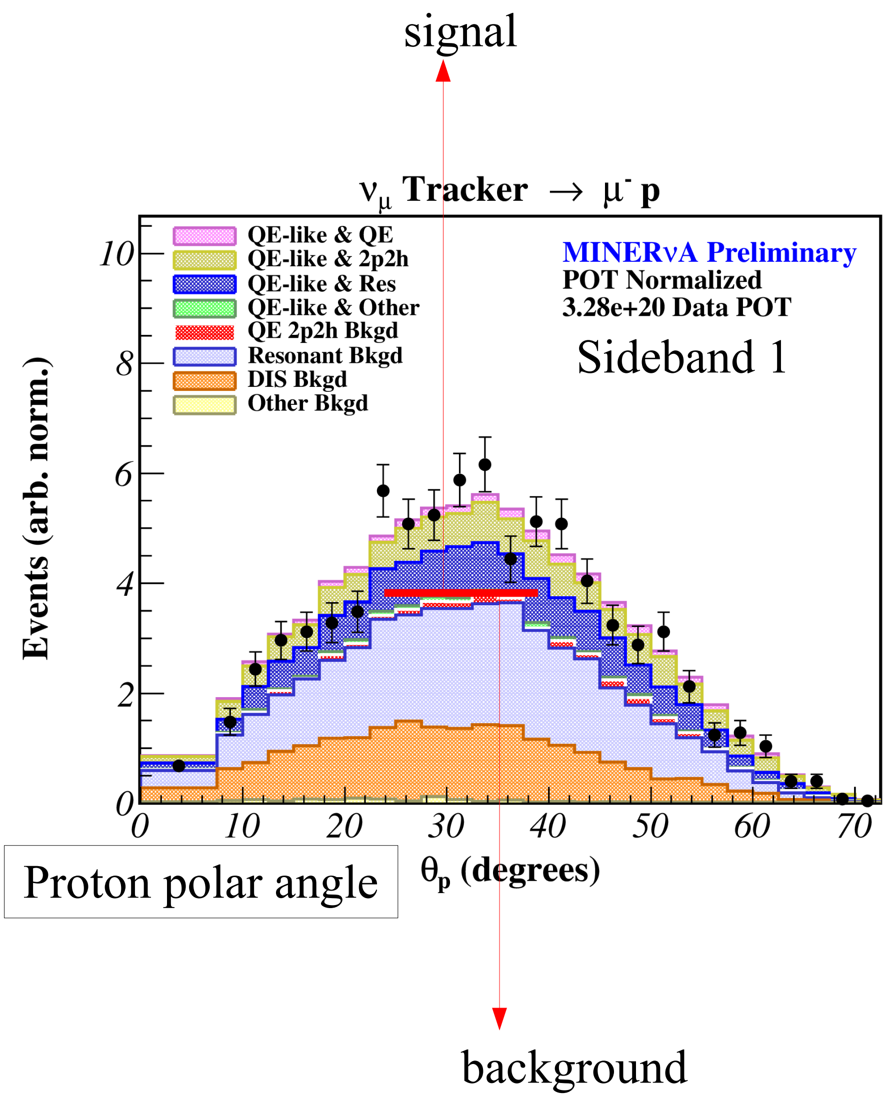


Background in MC are rescaled according to data driven sideband fit

Background Estimation

- Data-MC comparison at reconstructed level after sideband fit

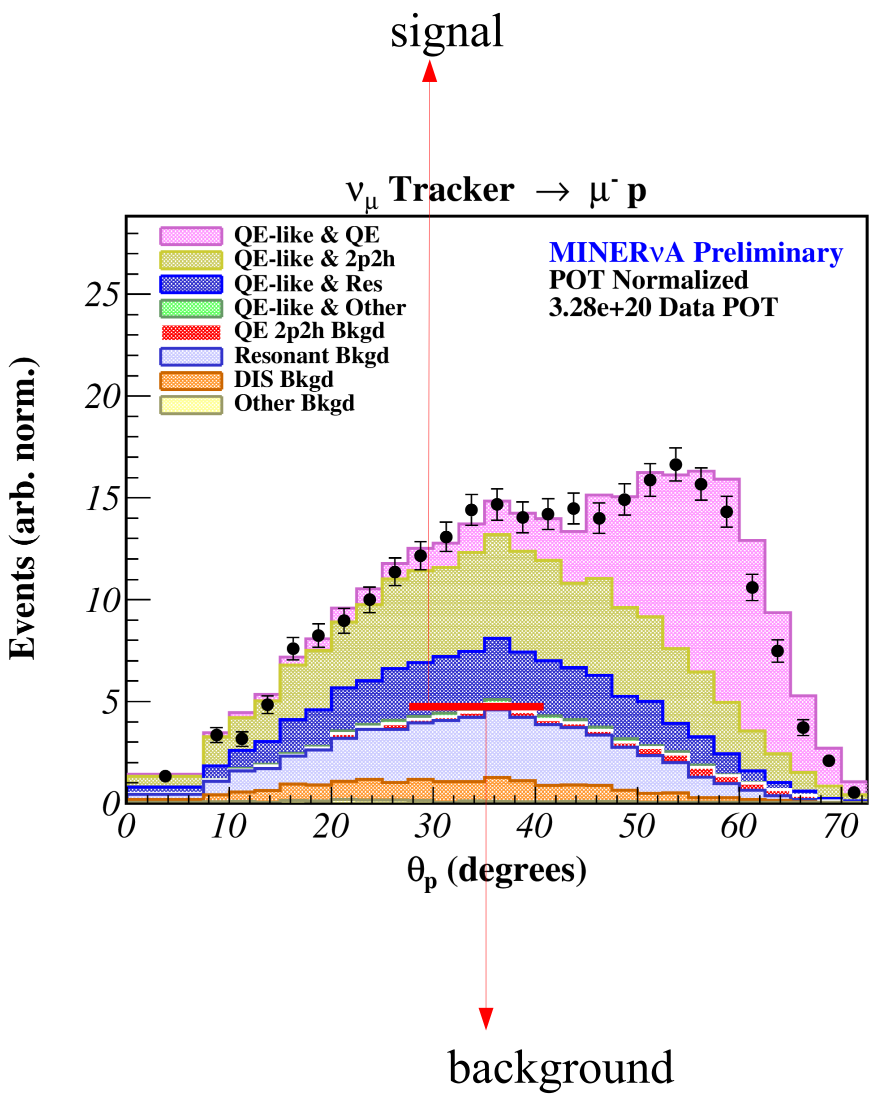




Selected Sample

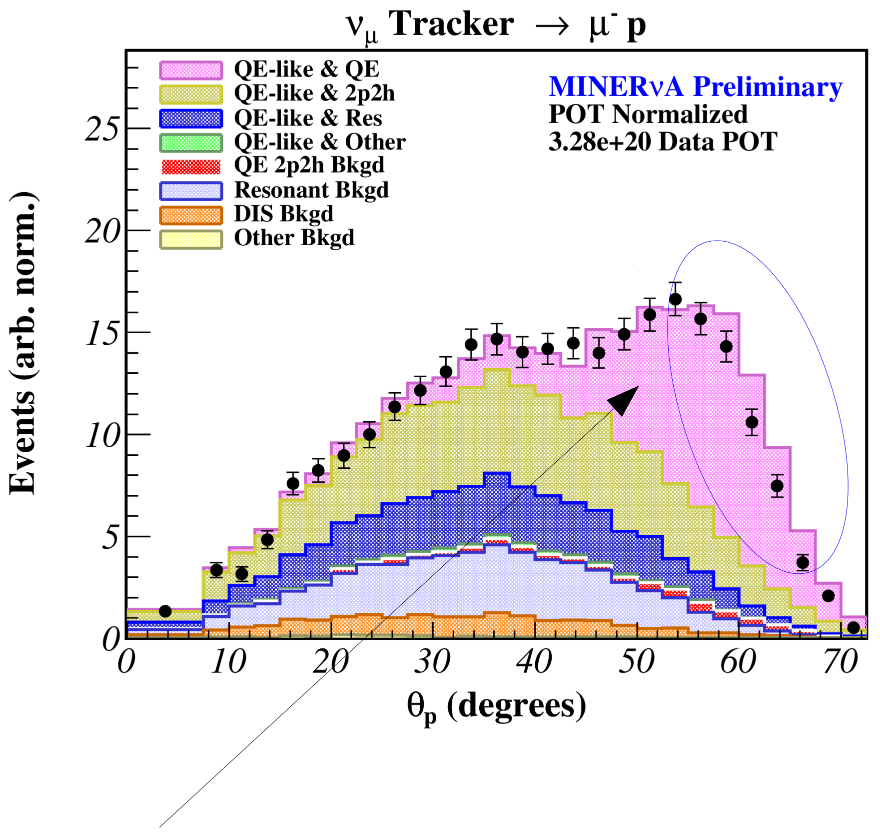
- Data-MC comparison at reconstructed level after sideband fit

Selected sample
Overall purity: 78%
Overall QE-2p2h bkgd fraction: 3%
Overall RES bkgd fraction: 13%
Overall DIS bkgd fraction: 5%
Overall Other bkgd fraction < 1%



Selected Sample

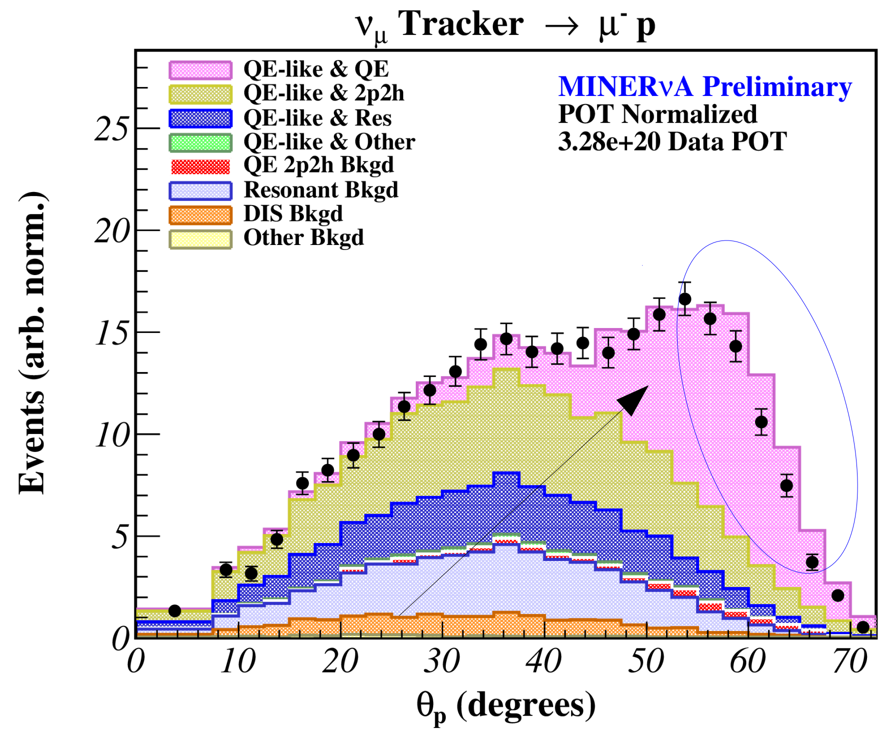
- Data-MC comparison at reconstructed level after sideband fit

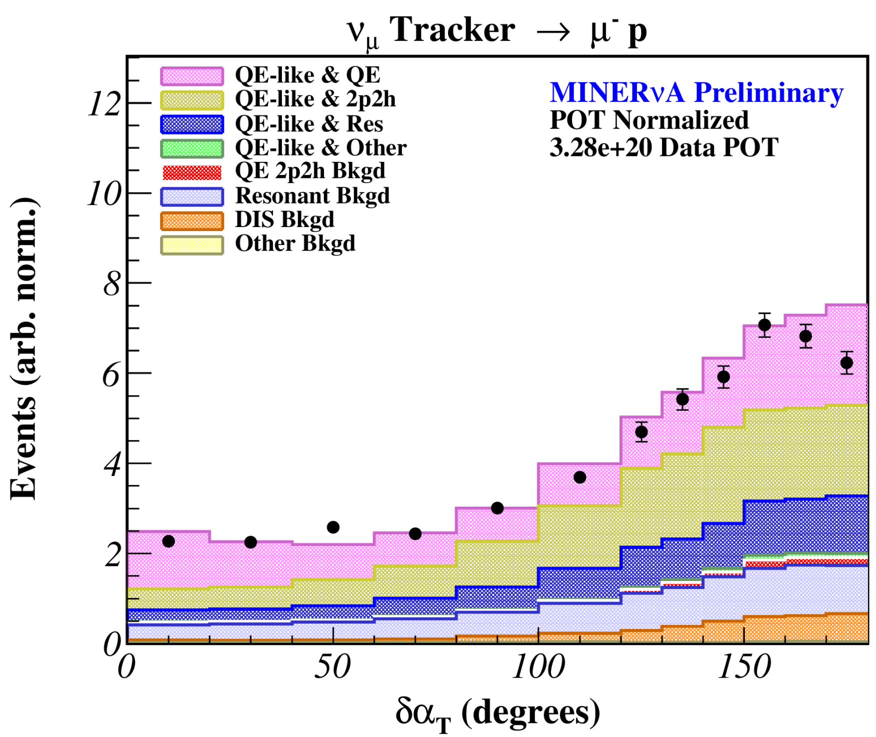


GENIE MINERvA Tune (v1) describes data well (to first order)
Large concentration of pure QE at high angle
GENIE excess above data beyond 60 deg (see discussion later slides)

Selected Sample

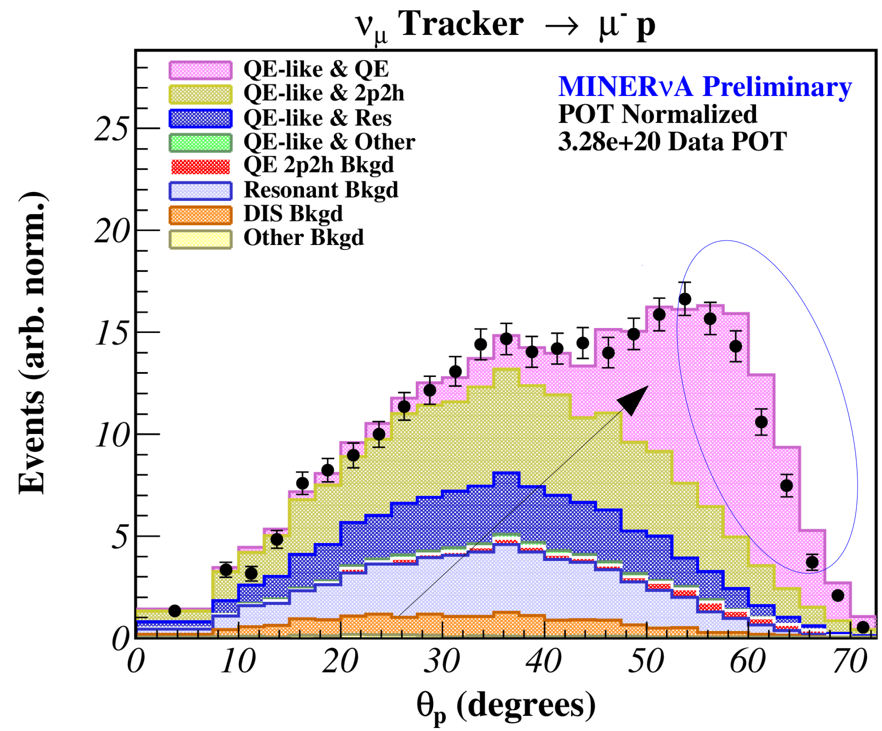
- Data-MC comparison at reconstructed level after sideband fit

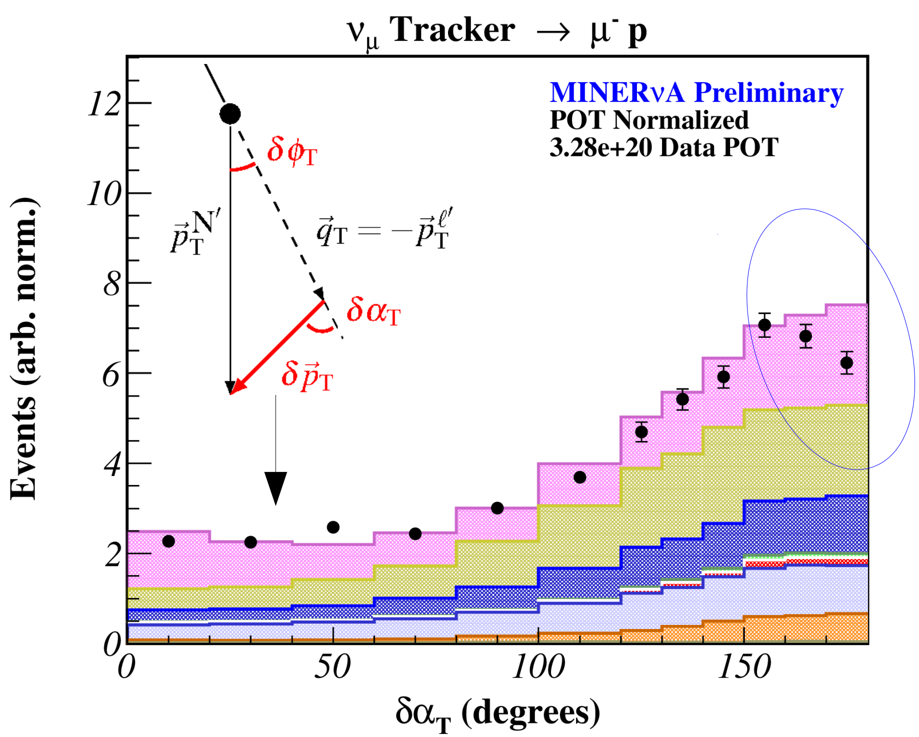




Selected Sample

- Data-MC comparison at reconstructed level after sideband fit

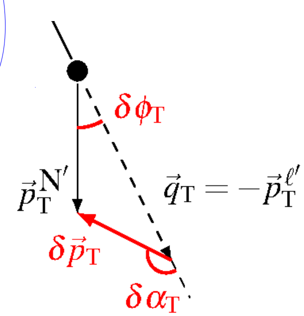




GENIE MINERvA Tune (v1) describes data well (to first order)

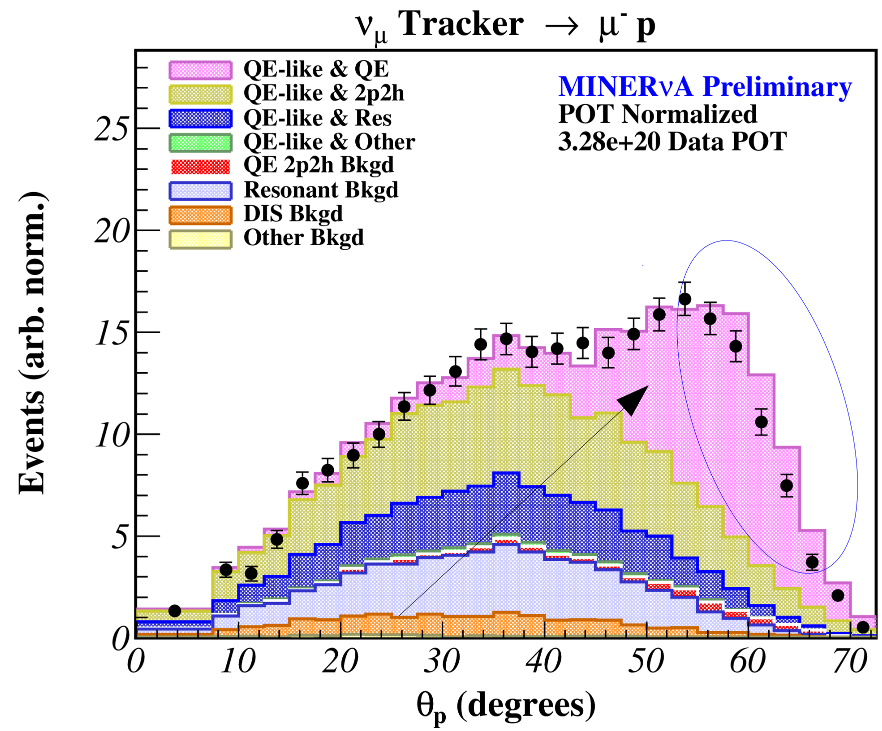
Depletion at small $\delta\alpha_T$

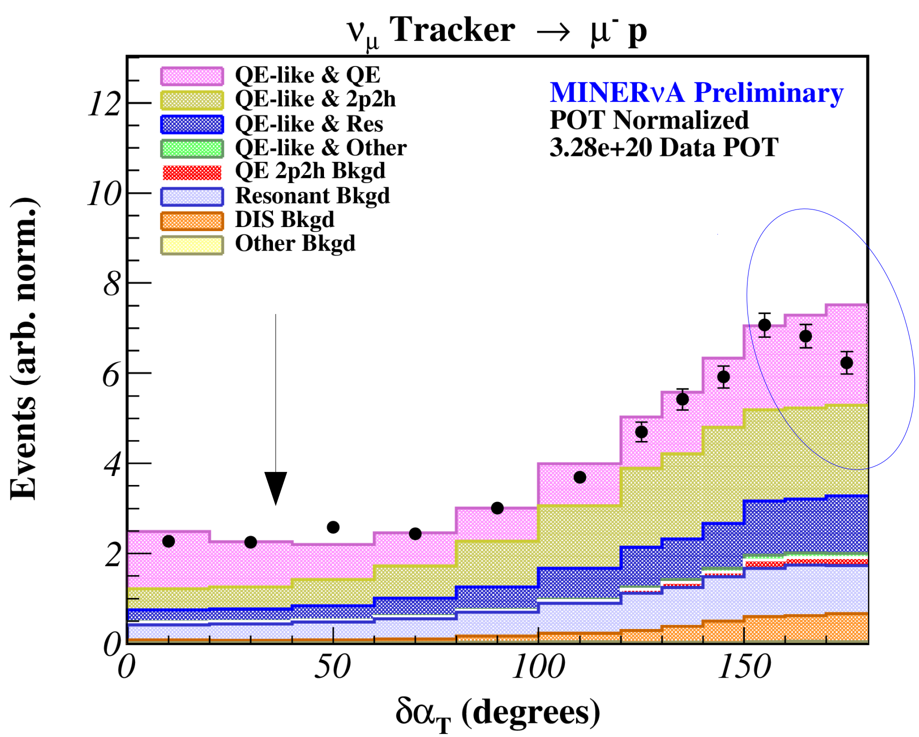
GENIE excess at $\delta\alpha_T \rightarrow 180$ deg.

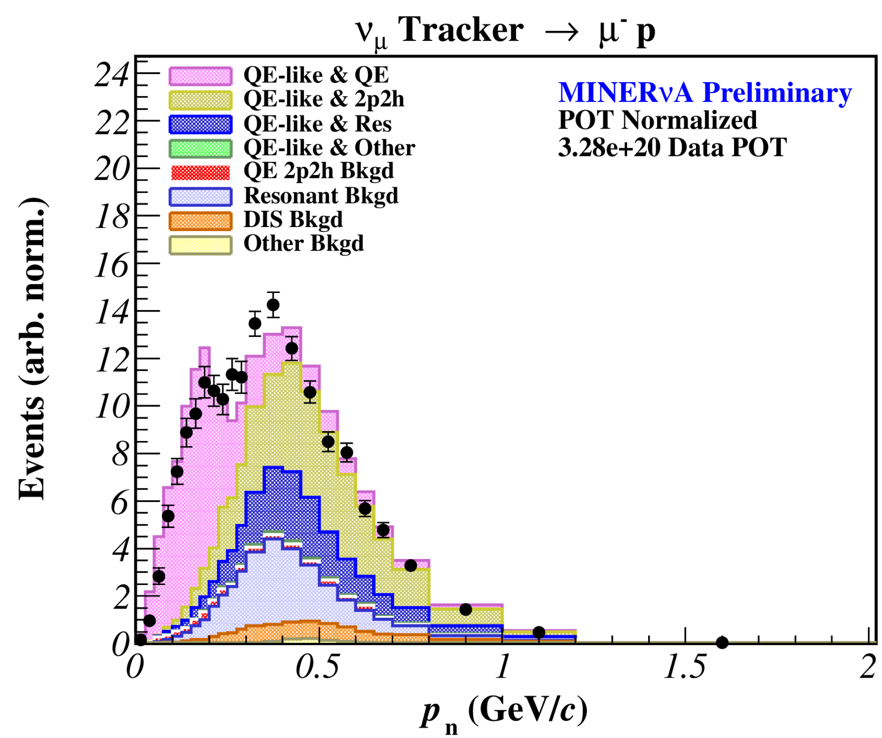


Selected Sample

- Data-MC comparison at reconstructed level after sideband fit

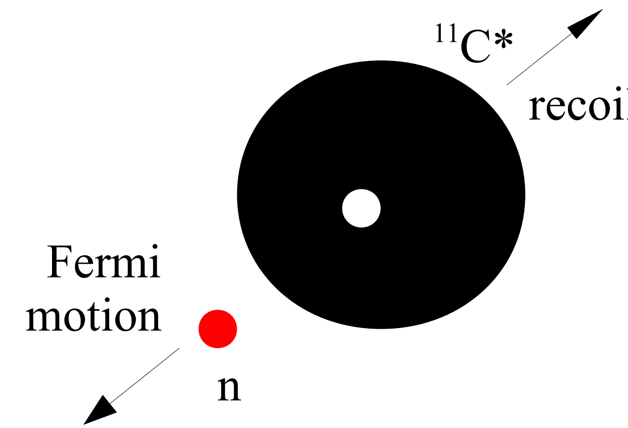


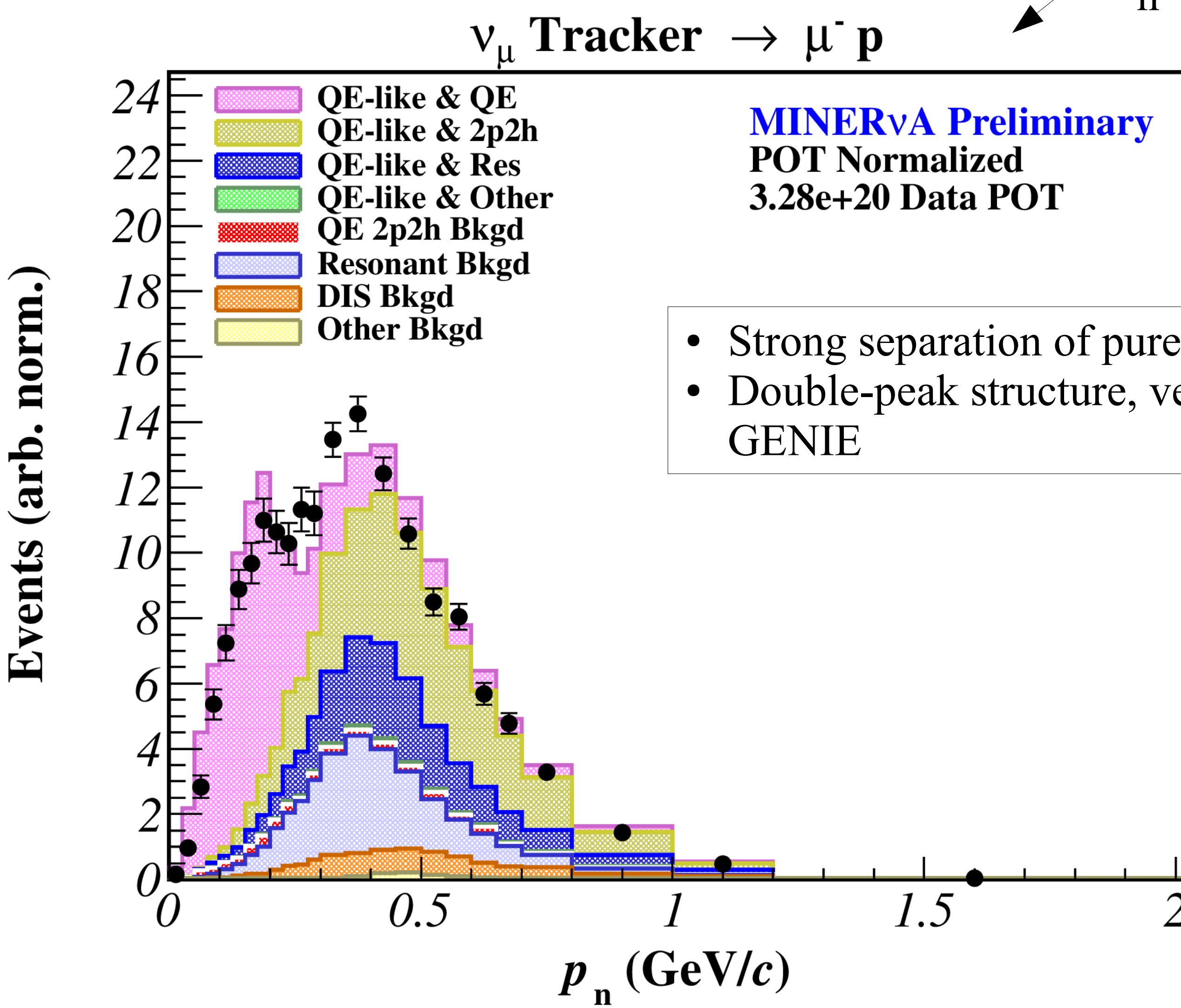




Selected Sample

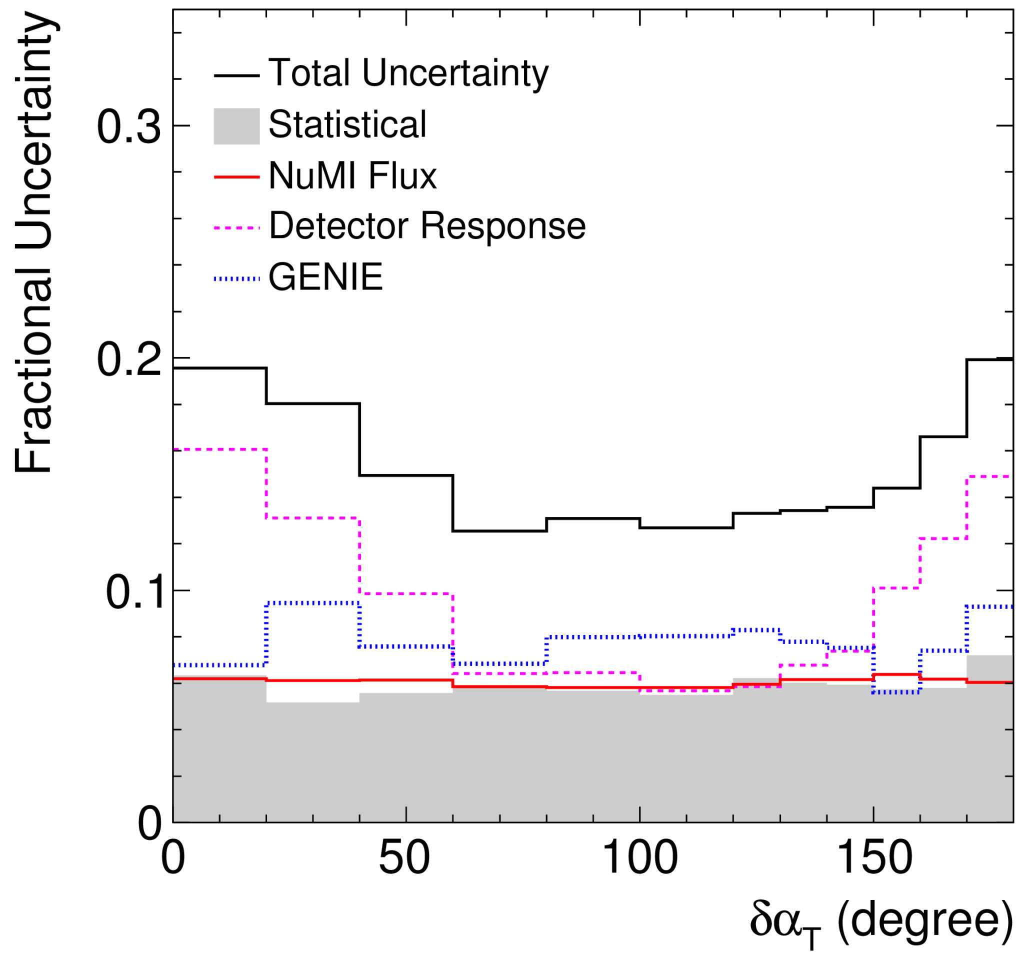
- Data-MC comparison at reconstructed level after sideband fit





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

Systematic Uncertainties



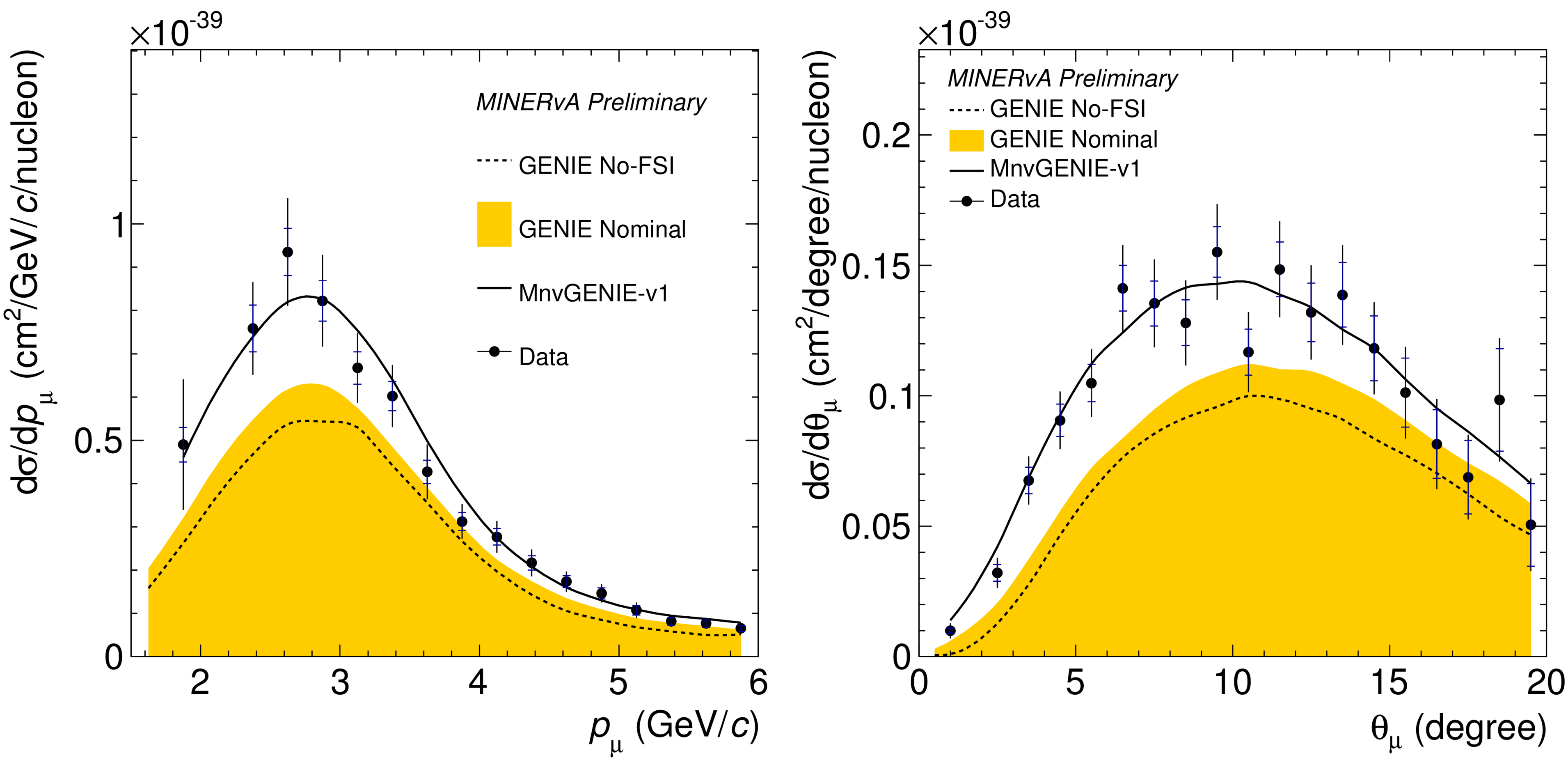
Total uncertainty = 12-20%
~ 6% (stat) + 6% (flux, mostly normalization) + 8% (GENIE) + 6-16% (detector)

Detector systematics dominated by transverse projection and ESC proton selection uncertainties.
GENIE systematics dominated by 2p2h model uncertainties.

RESULTS

Single-Particle Kinematics

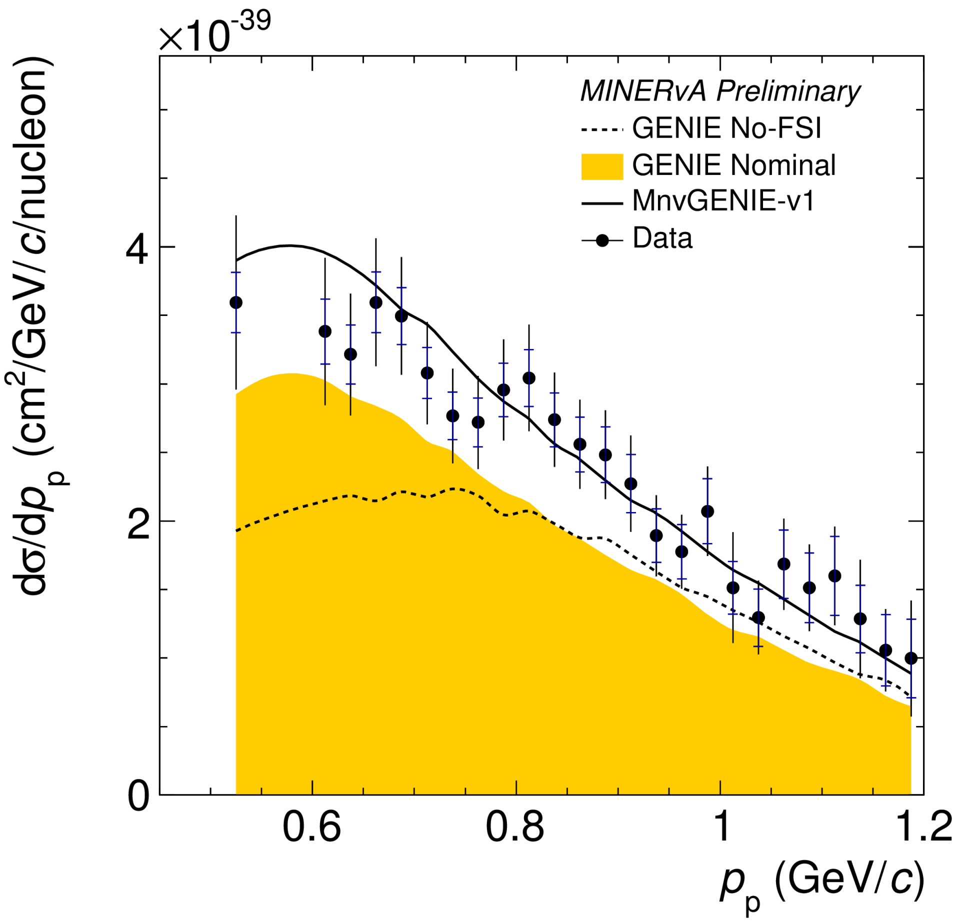
- Muon momentum, angle

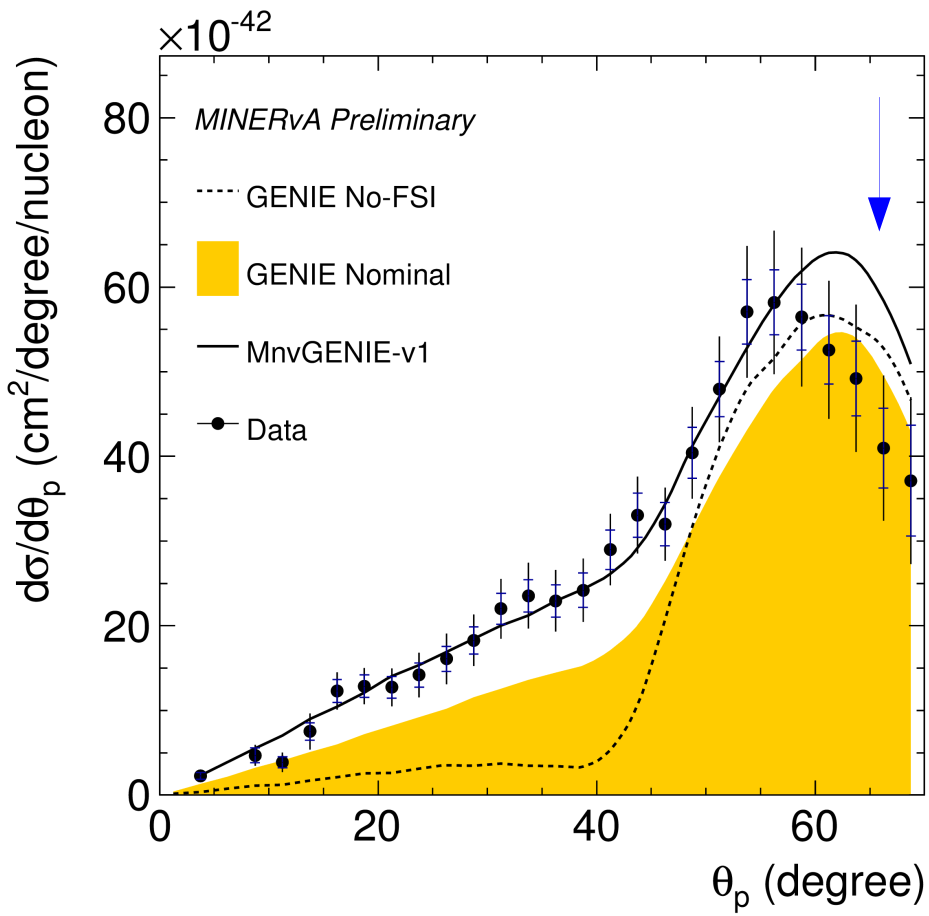


- Good description by GENIE MINERvA Tune (v1)
- All predictions have same shape

Single-Particle Kinematics

- Muon momentum, angle
- Proton momentum, angle



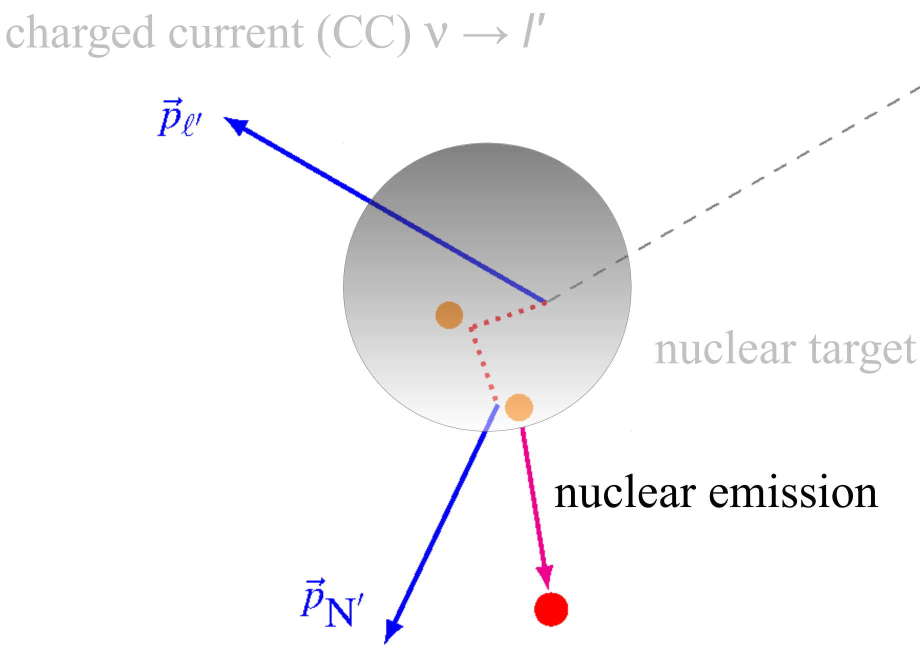


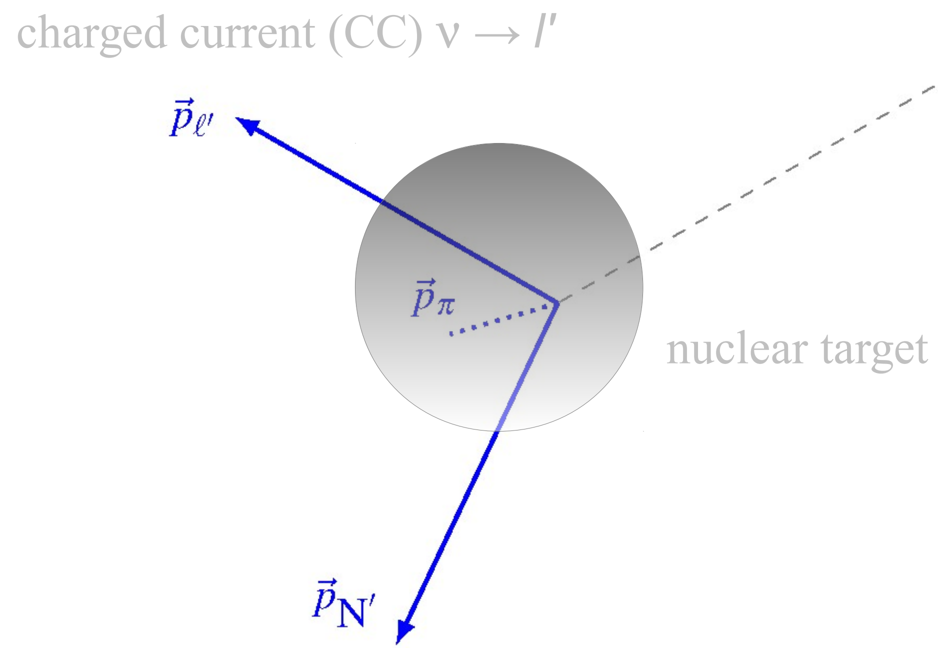
- GENIE Nominal and No-FSI have different shape
- GENIE MINERvA Tune (v1) excess at high angle

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

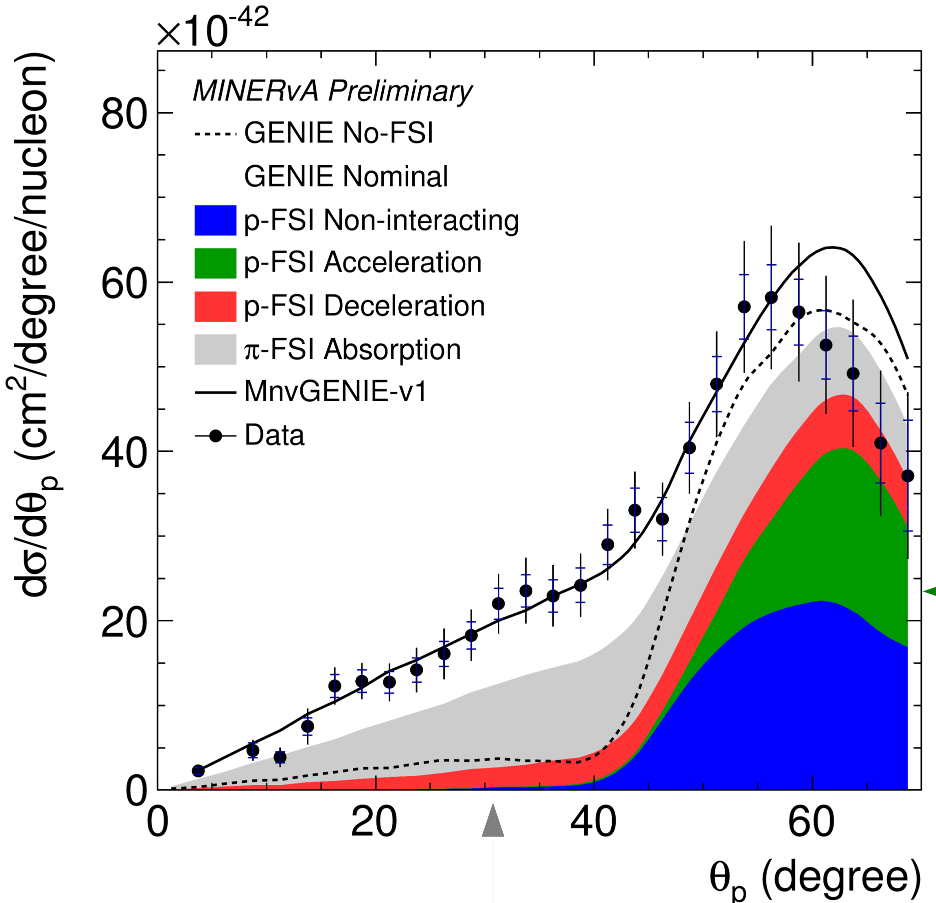
Pion FSI: pion absorption





Single-Particle Kinematics

- Muon momentum, angle
- Proton momentum, angle



Proton FSI acceleration localized at high angle

Pionless resonant production dominates low angle

NUCLEAR EFFECT DIAGNOSTICS

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.

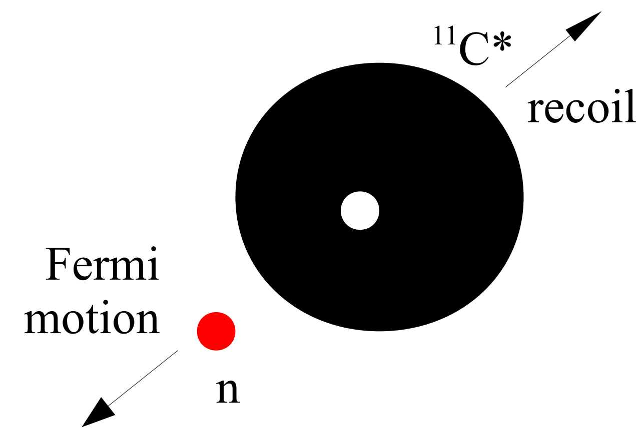
Assuming exclusive μ-p-A' final states
Use energy conservation to close the equations

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

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

p_{n}: recoil momentum of the nuclear remnant

For CCQE with elastic FSI, A' = ^{11}C*
No more unknowns
p_{n}: neutron Fermi motion *weakly smeared

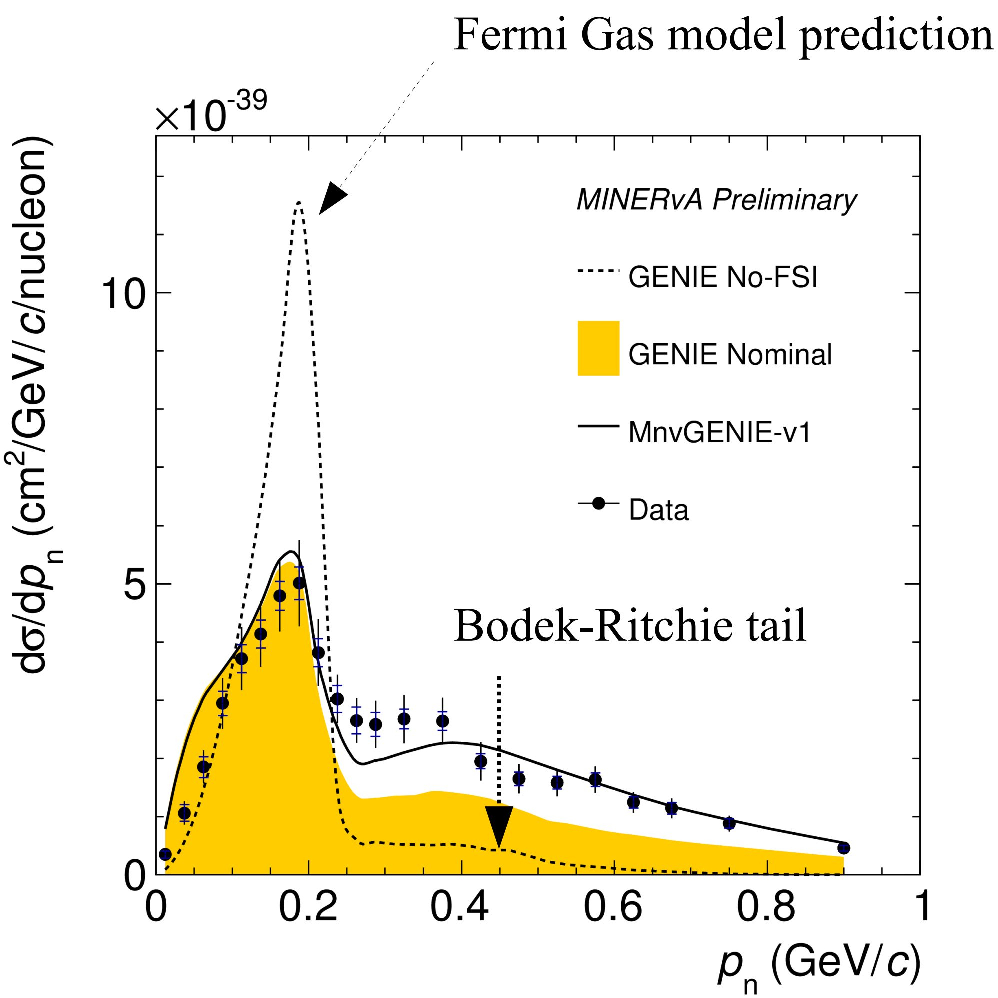


A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501

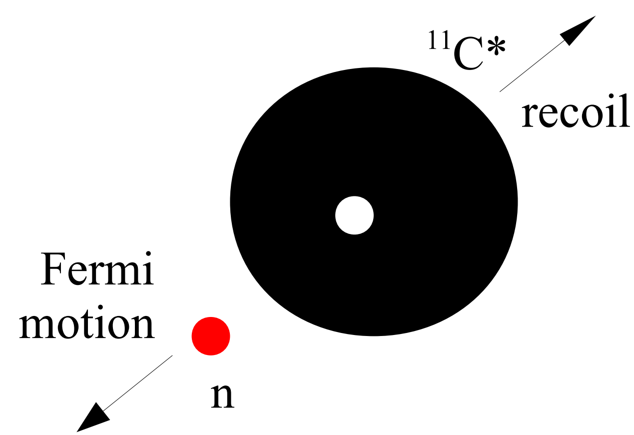
$$p_L = \frac{1}{2}(M(A) + k'_L + p'_L - E' - E_{p'}) - \frac{p_T^2 + M^*(A-1)^2}{2(M(A) + k'_L + p'_L - E' - E_{p'})}$$

Nuclear Effect Diagnostics

- CCQE with Fermi motion

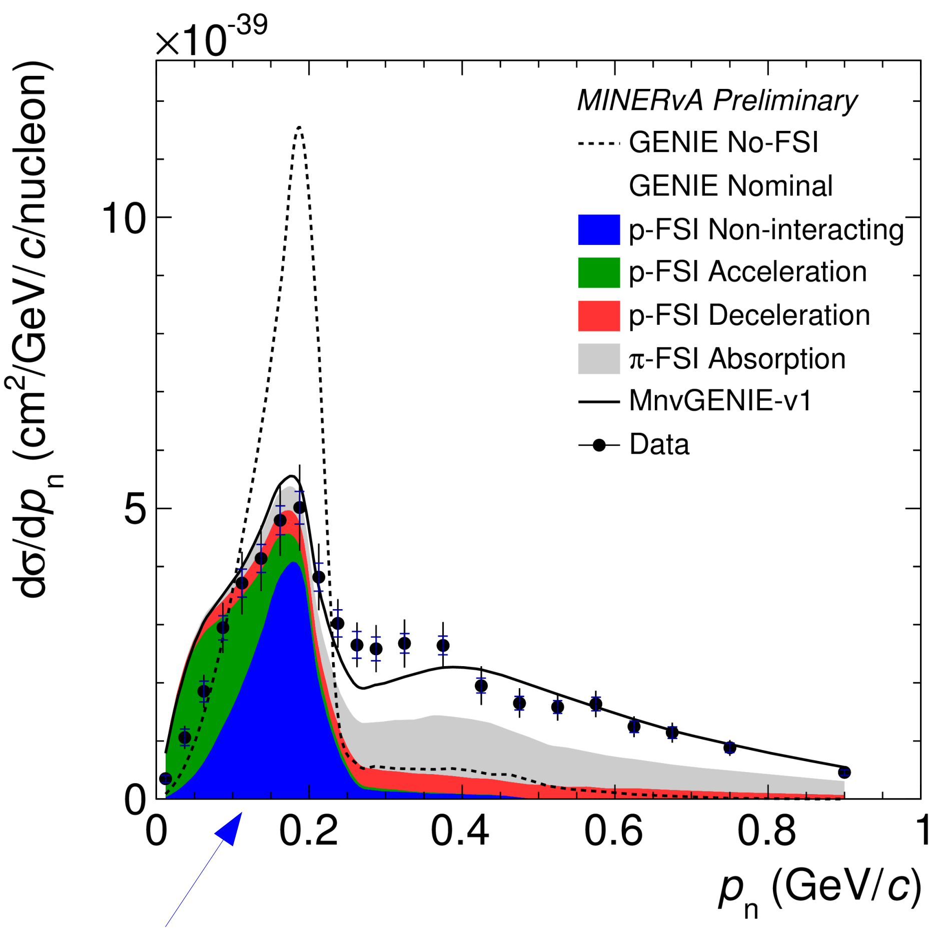


p_n is Fermi motion magnitude → “QE peak”
– GENIE No-FSI



Nuclear Effect Diagnostics

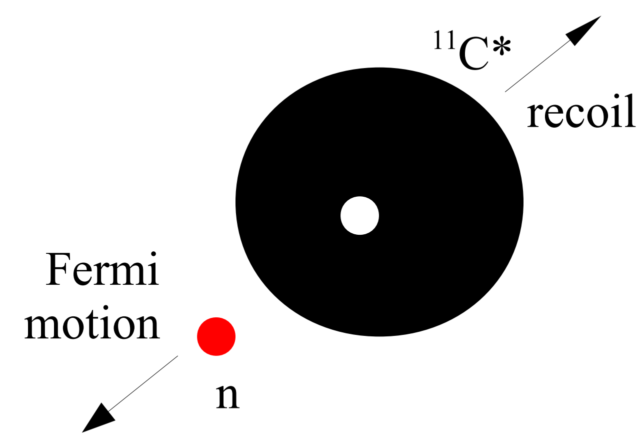
- CCQE with Fermi motion



p_n is Fermi motion magnitude → "QE peak"

– GENIE No-FSI

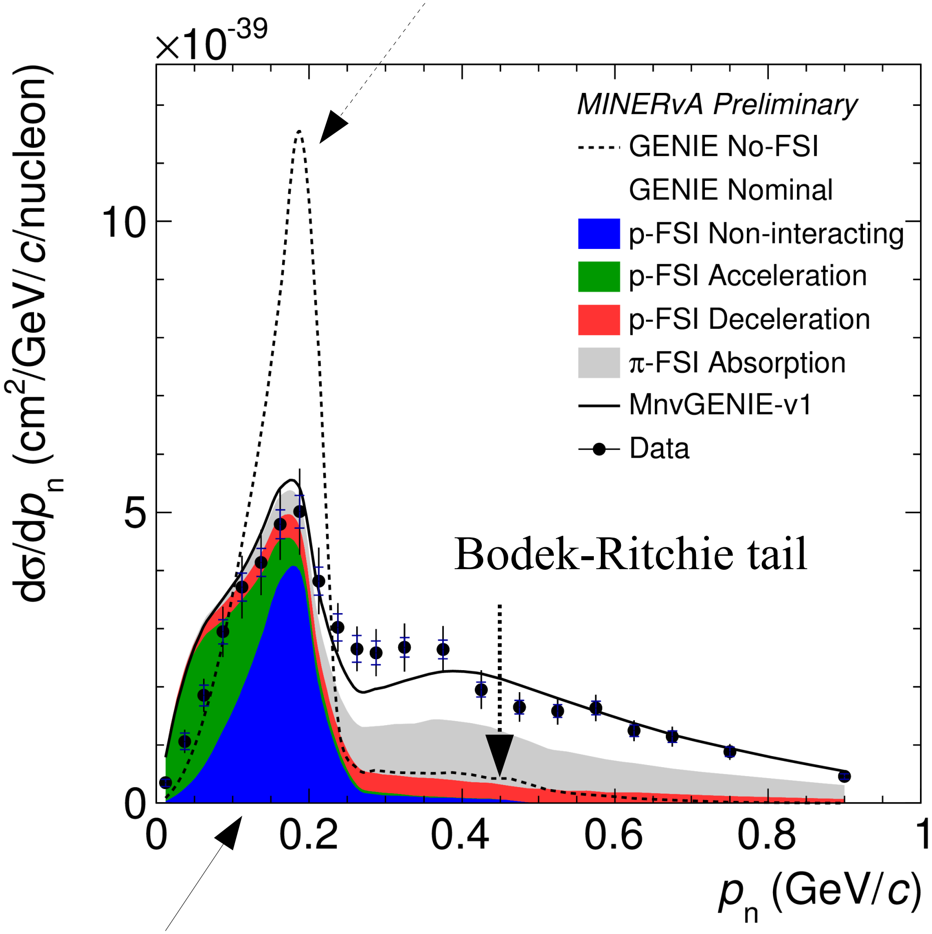
– p-FSI Non-interacting



Nuclear Effect Diagnostics

- CCQE with Fermi motion

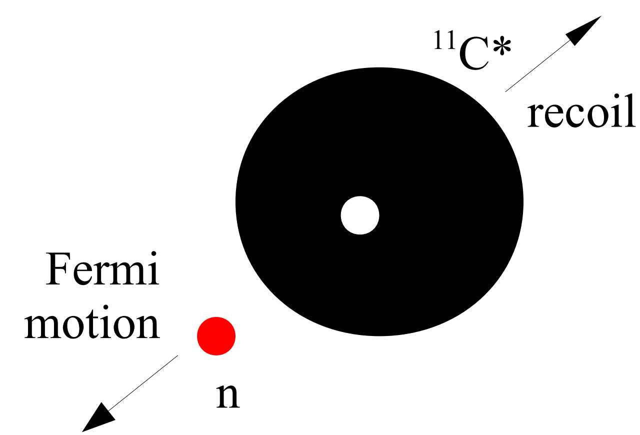
Fermi Gas model prediction

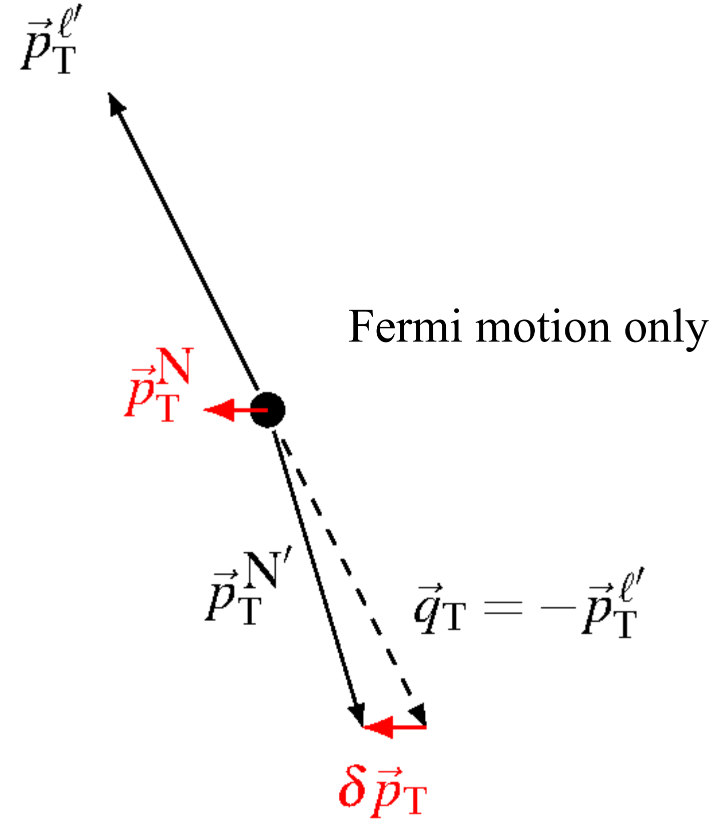


Bodek-Ritchie tail

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

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





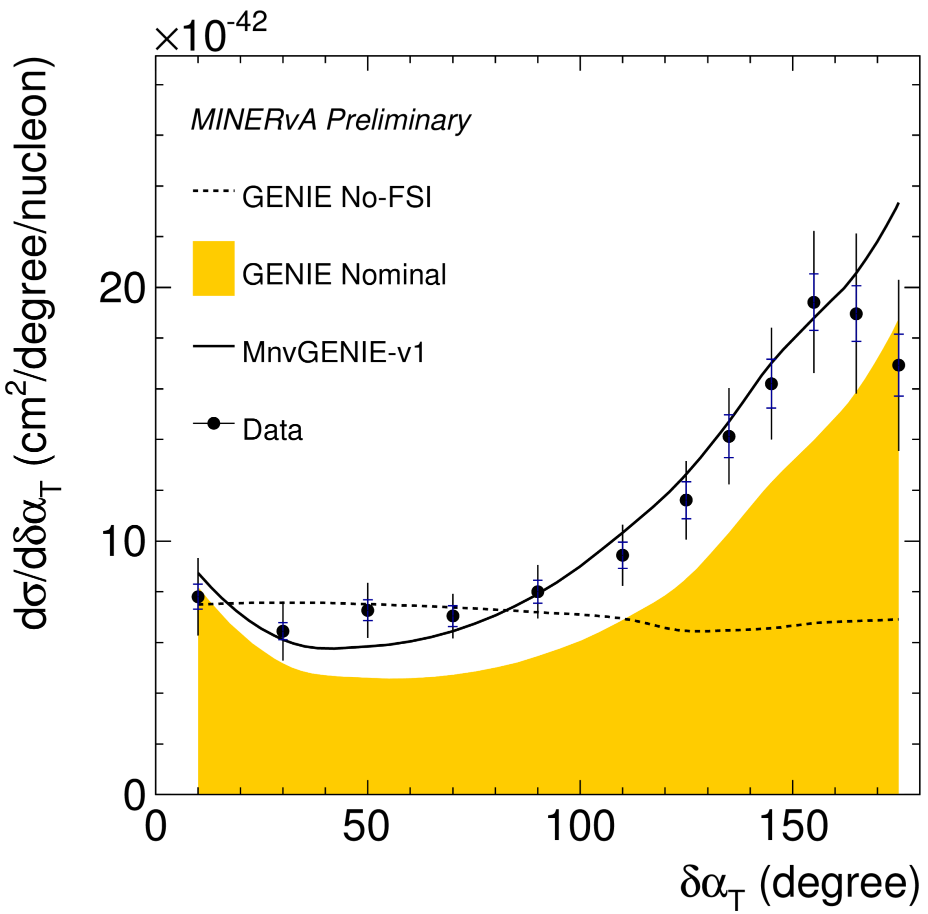
For CCQE with elastic FSI, A' = $^{11}C^*$
No more unknowns
p_n: neutron Fermi motion *weakly smeared

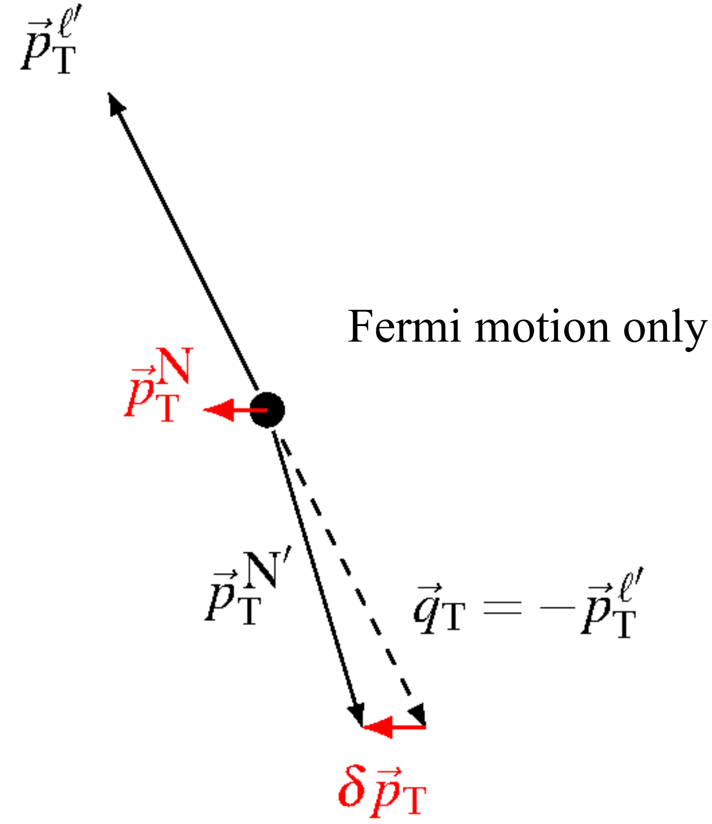
$$\delta\vec{p}_T = \vec{p}_T^{N}$$

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

Nuclear Effect Diagnostics

- CCQE with Fermi motion

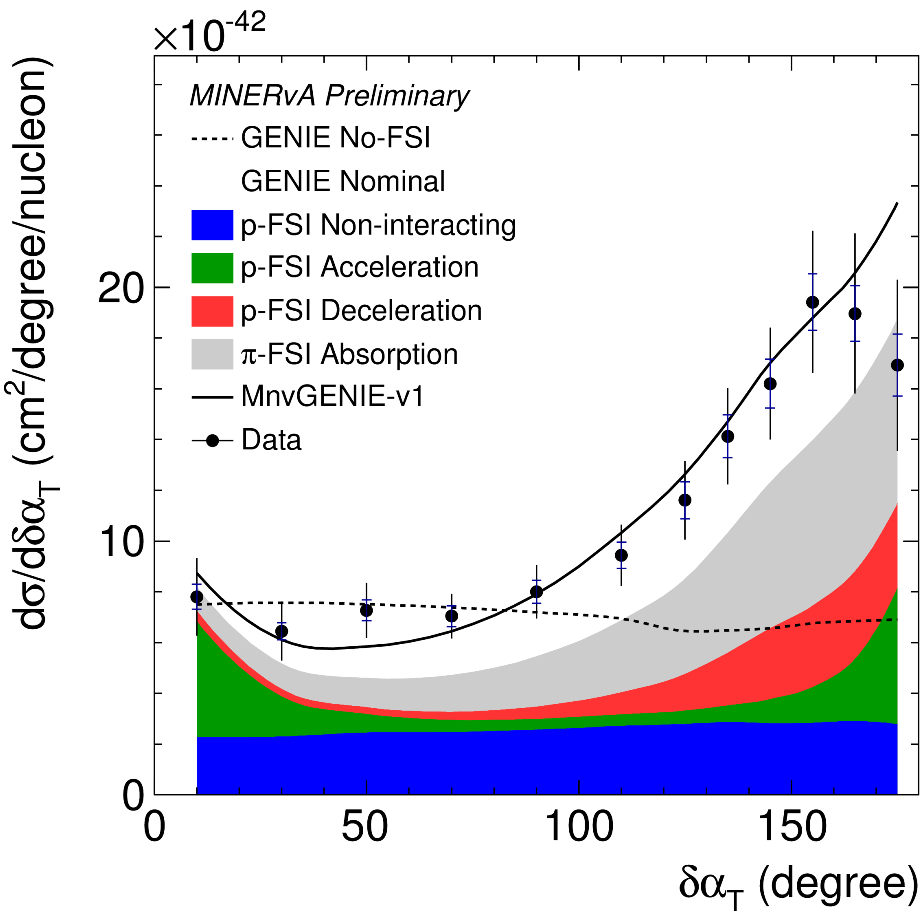


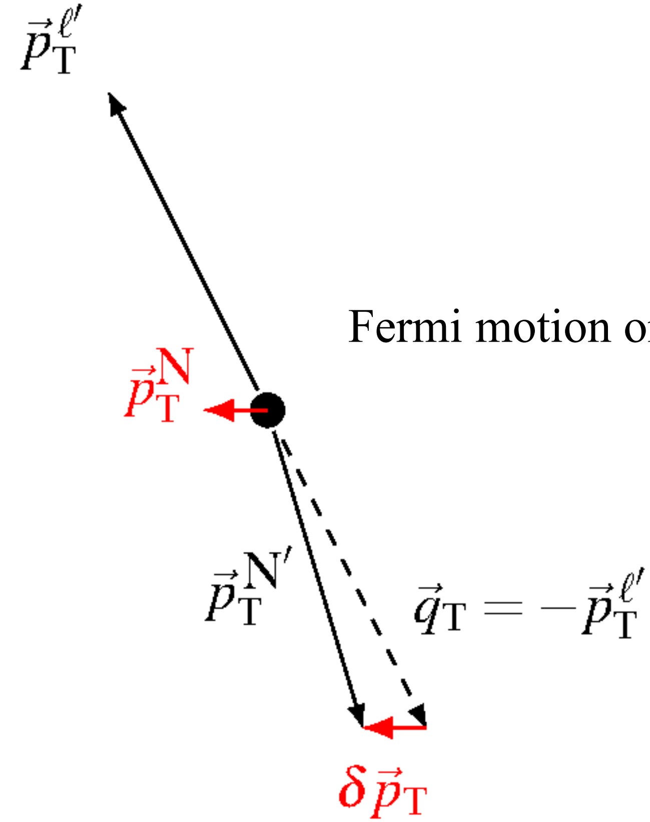


$\delta\alpha_T$ is Fermi motion direction → isotropic – GENIE No-FSI

Nuclear Effect Diagnostics

- CCQE with Fermi motion





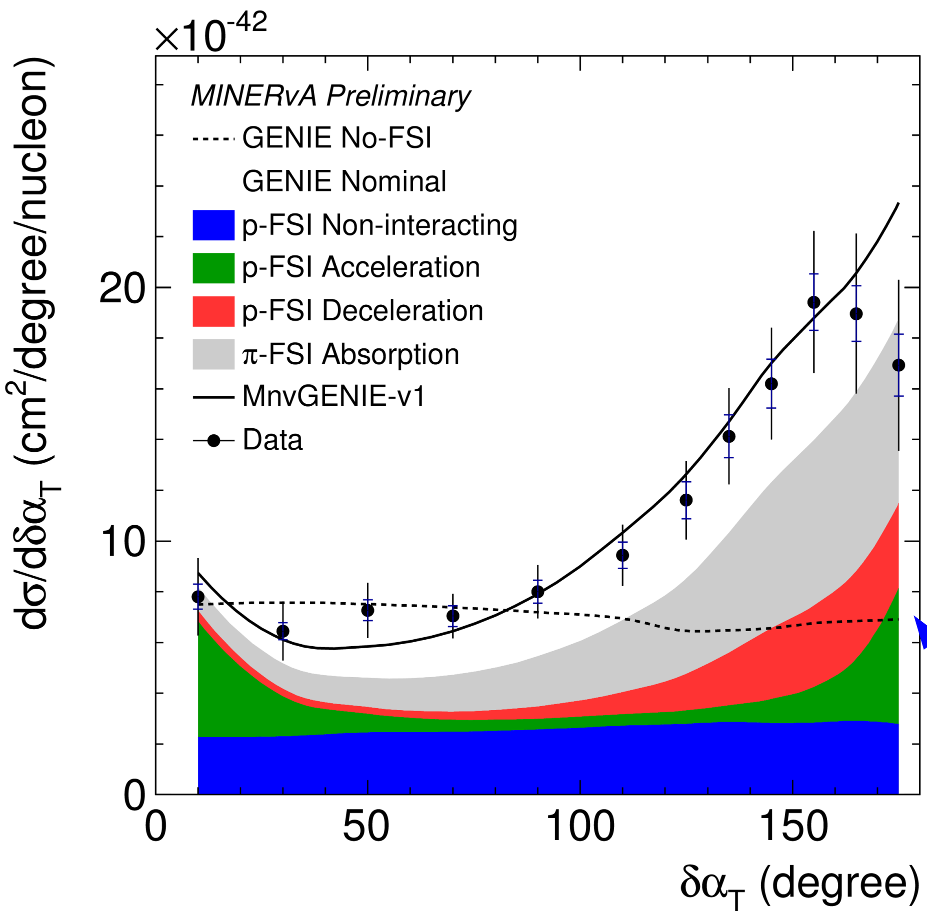
$\delta\alpha_{\mathrm{T}}$ is Fermi motion direction → isotropic

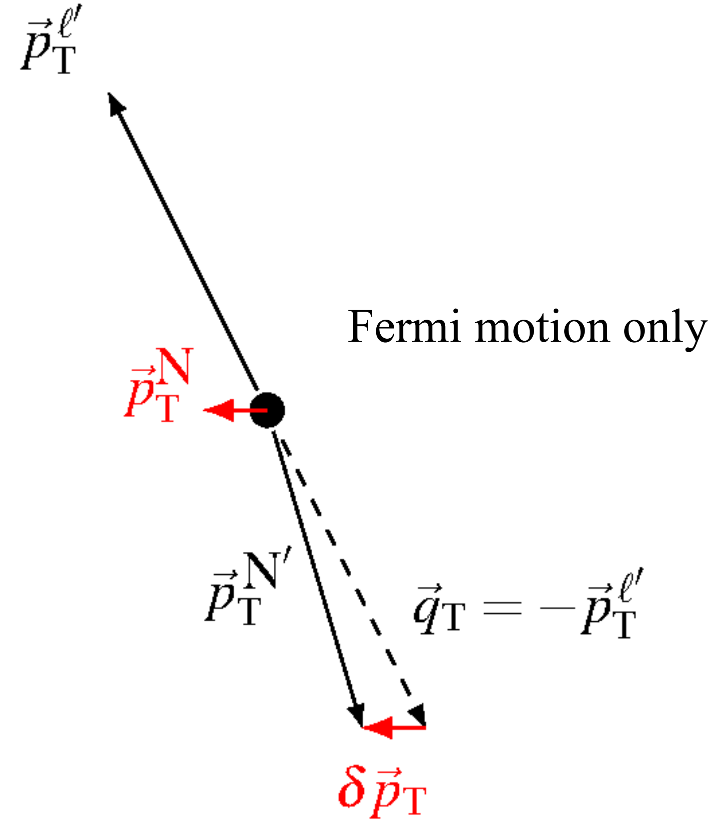
– GENIE No-FSI

– p-FSI Non-interacting

Nuclear Effect Diagnostics

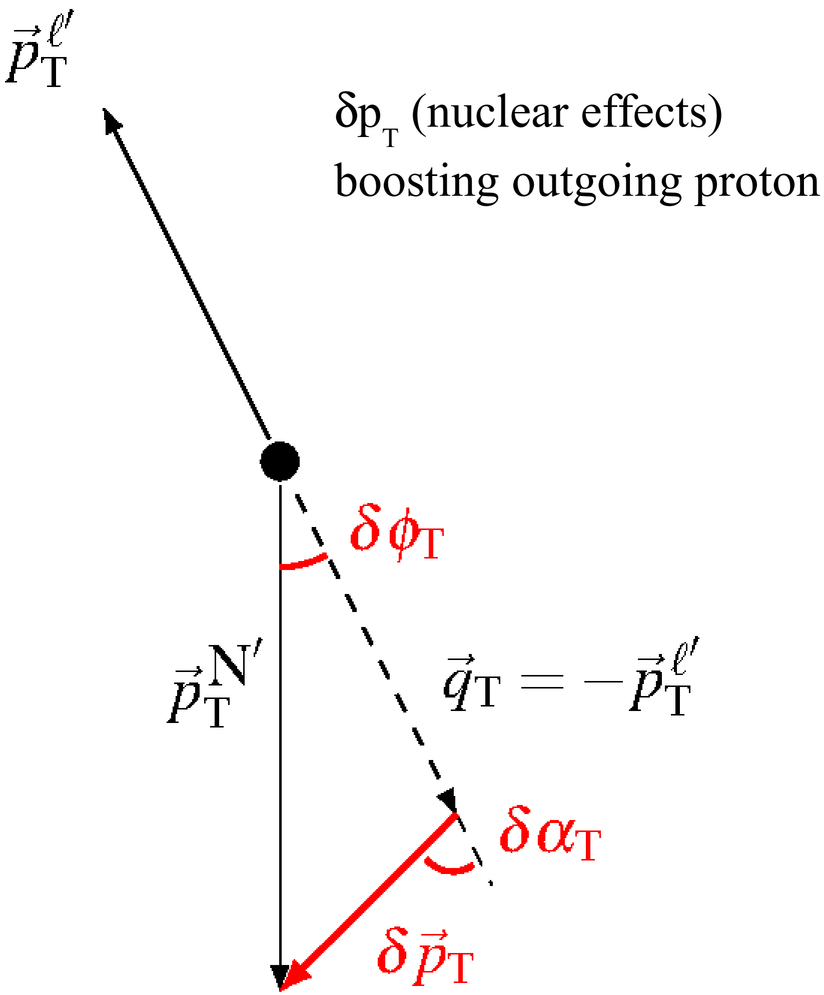
- CCQE with Fermi motion

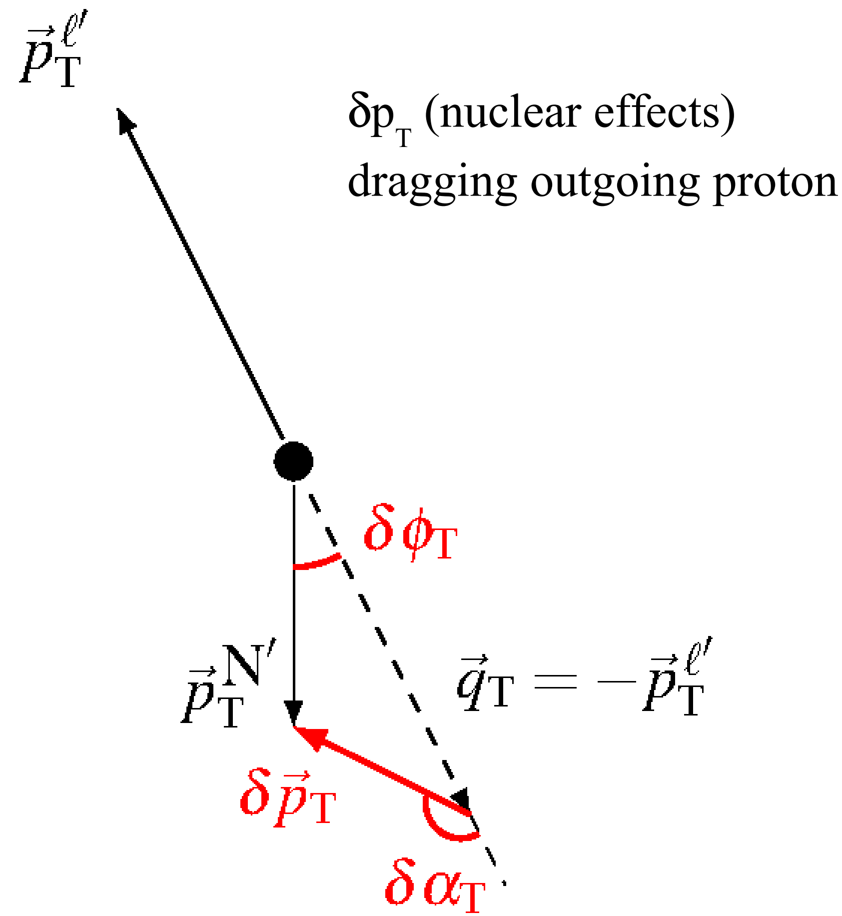




$\delta\alpha_T$ is Fermi motion direction → isotropic
– GENIE No-FSI
– p-FSI Non-interacting

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





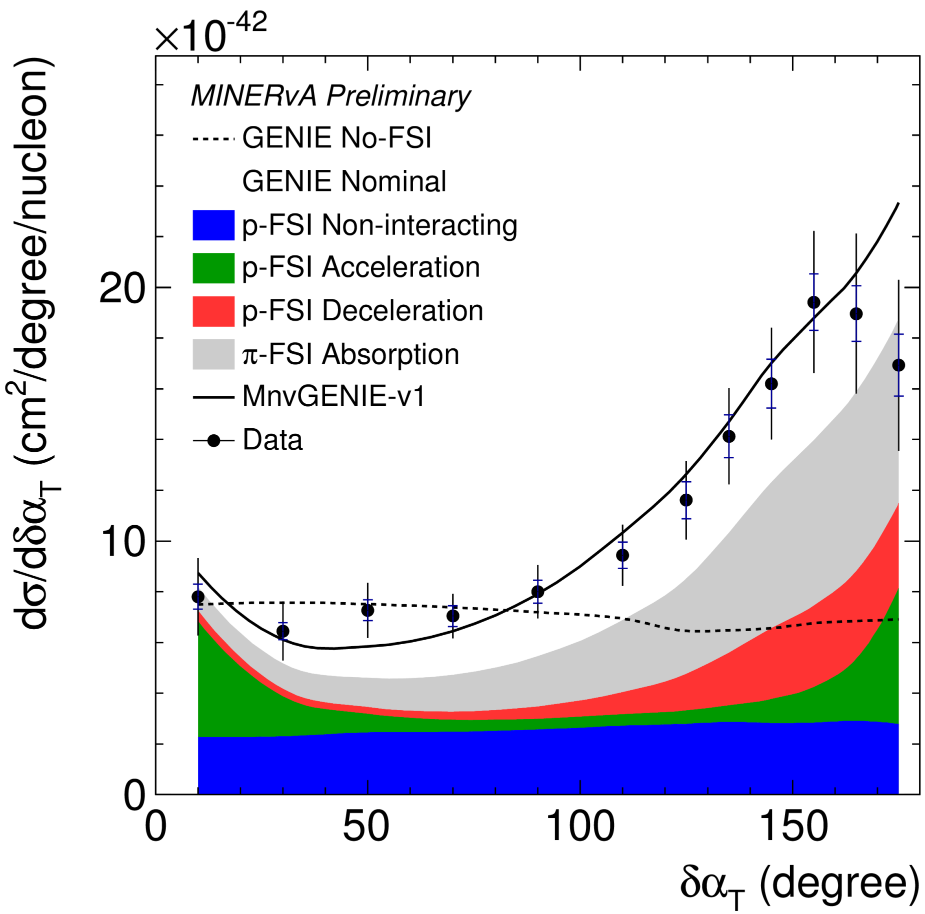
With full nuclear effects

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

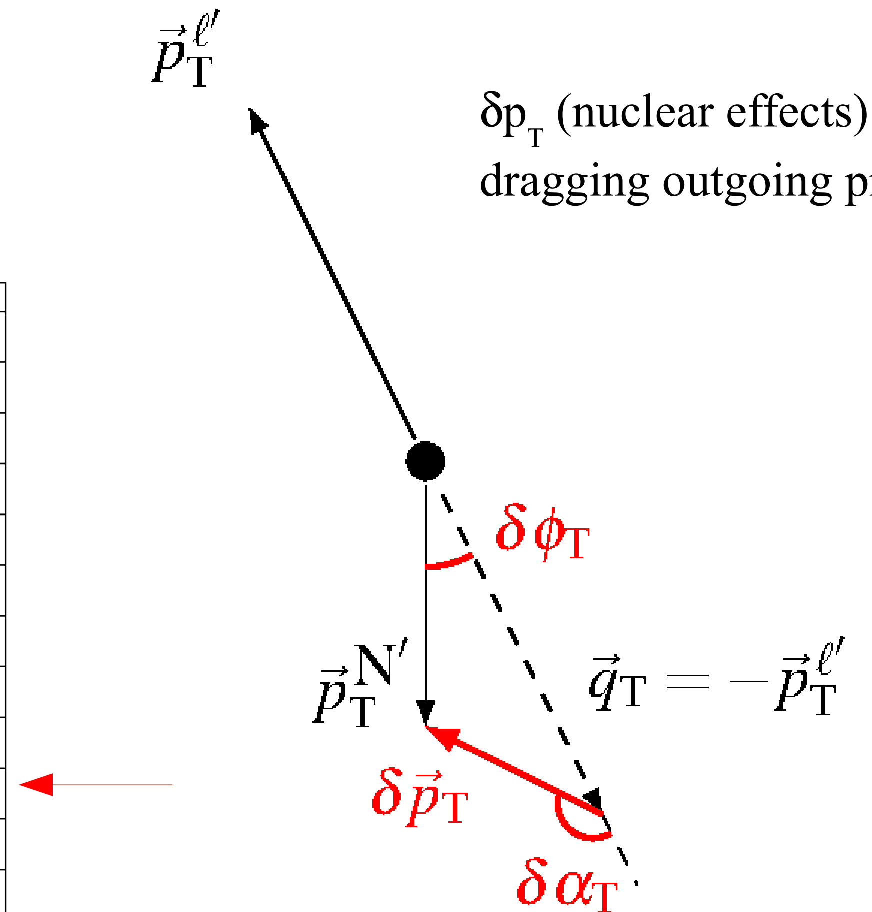
Baseline for all non-Fermi motion effects
Factor out Fermi motion uncertainty
Complementary to p_n

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration



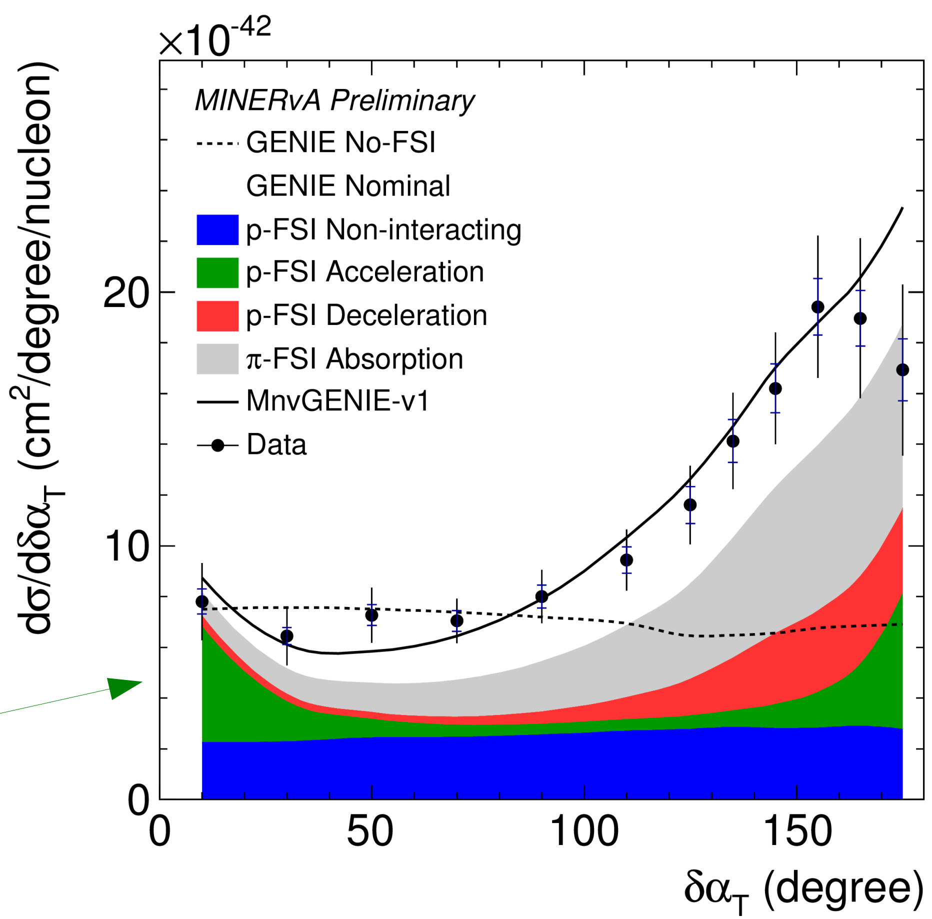
δp_T (nuclear effects) dragging outgoing proton

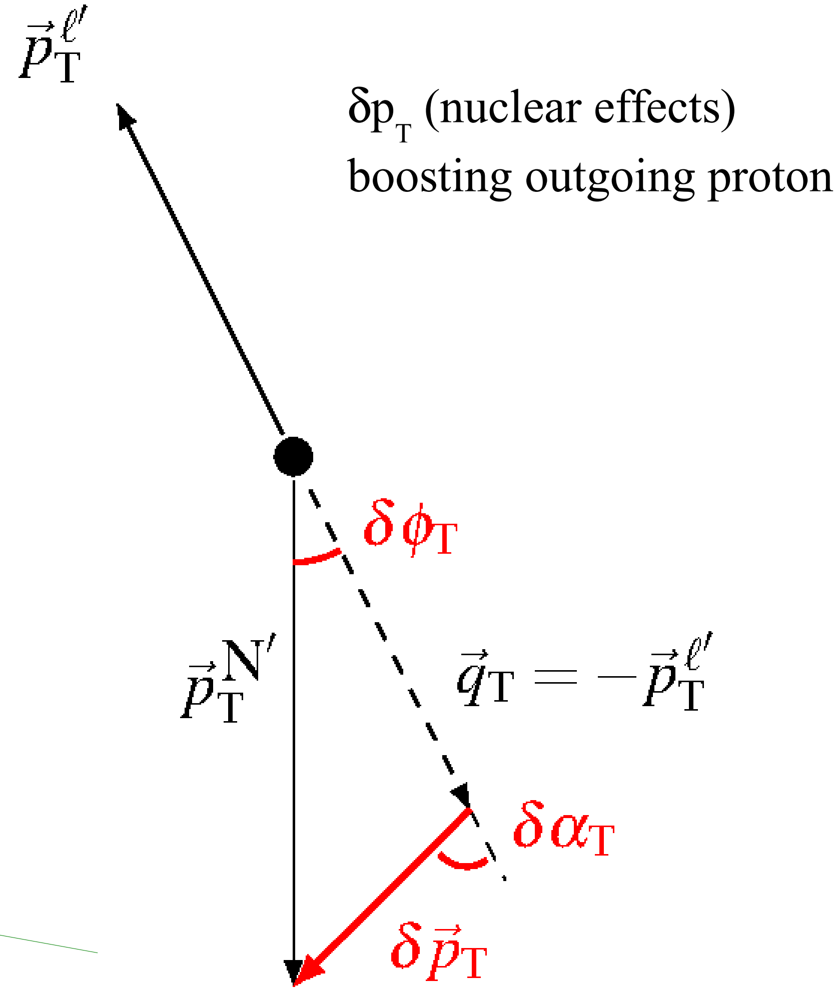


Deceleration at large $\delta\alpha_T$

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration



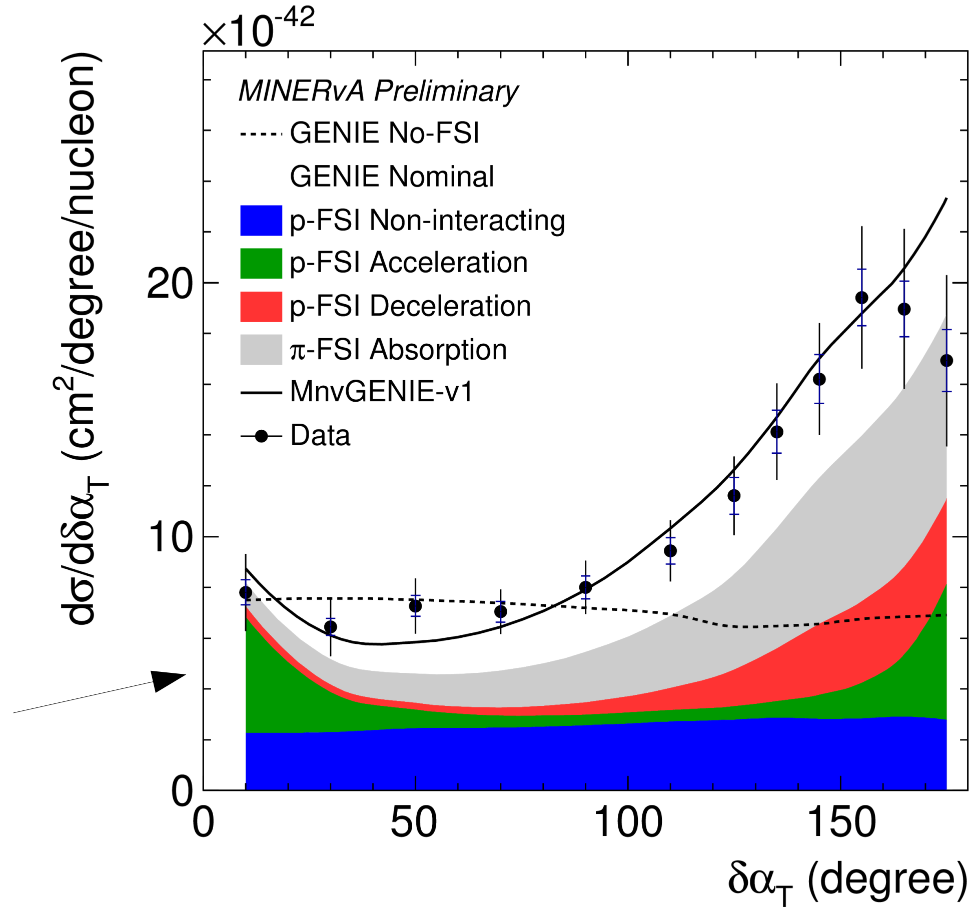


Deceleration at large $\delta\alpha_T$

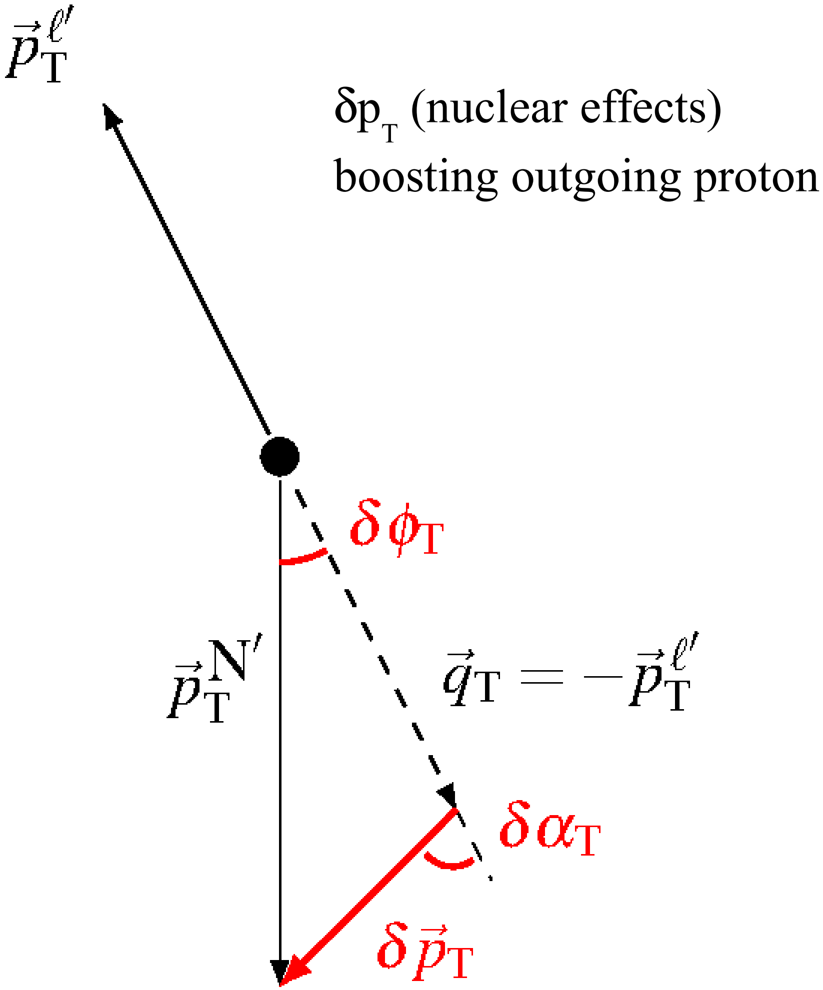
Acceleration at both small and (due to transverse projection) large $\delta\alpha_T$

Nuclear Effect Diagnostics

- CCQE with Fermi motion
- FSI deceleration vs. acceleration



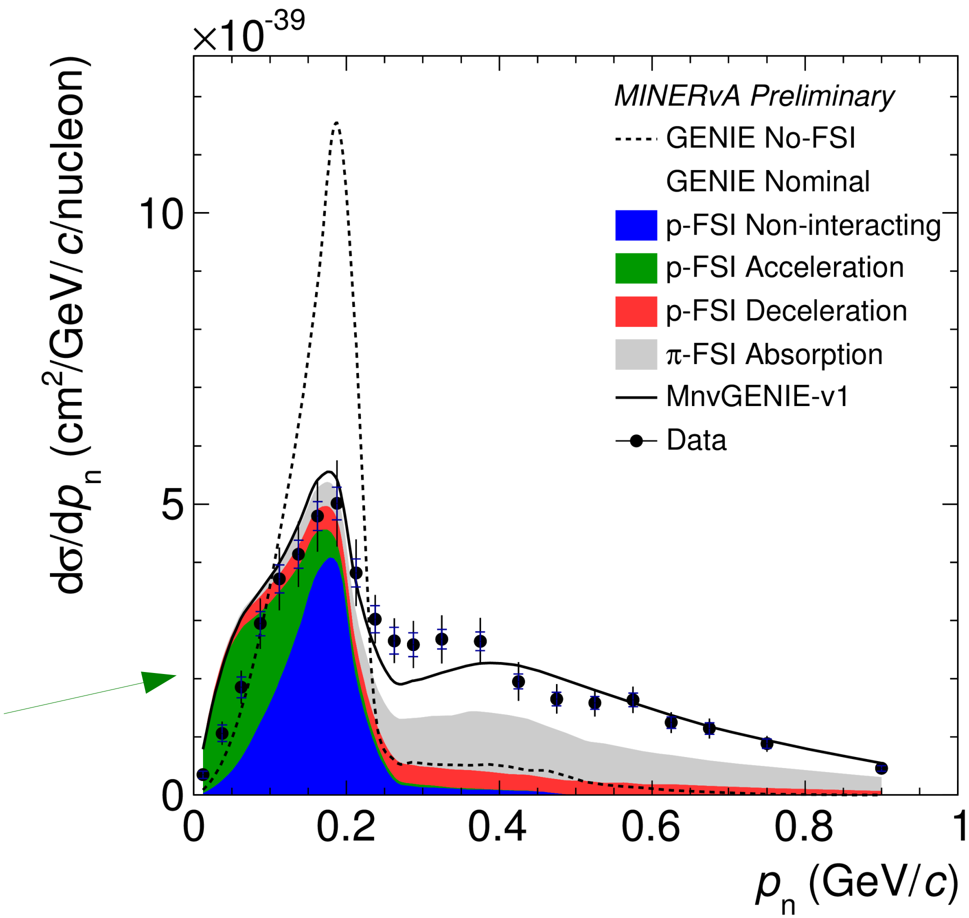
Only acceleration can enter small $\delta\alpha_T$



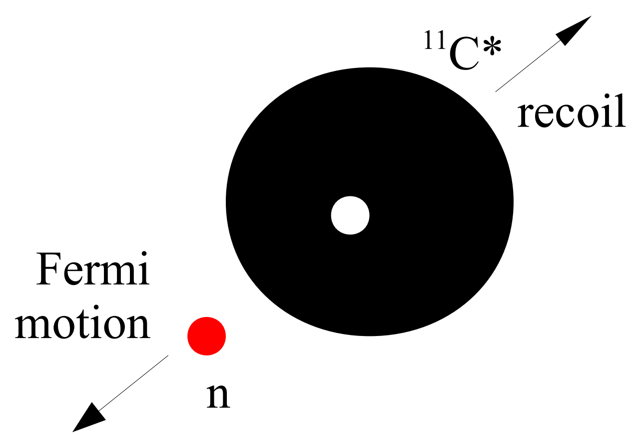
Deceleration at large $\delta\alpha_T$
Acceleration at both small and (due to transverse projection) large $\delta\alpha_T$

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_n: smeared δp_T beyond QE peak

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

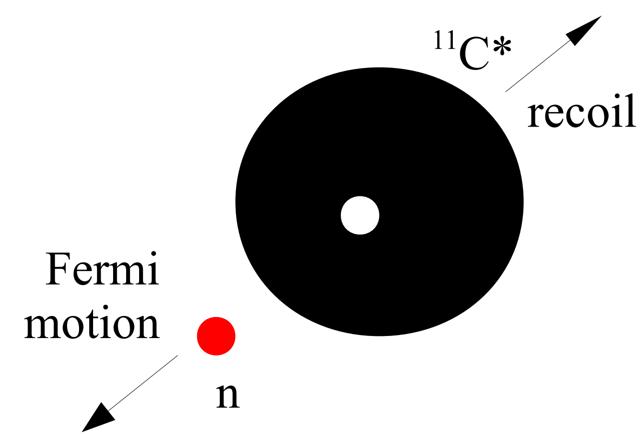
Assuming exclusive μ-p-A' final states

Use energy conservation to close the equations

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

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

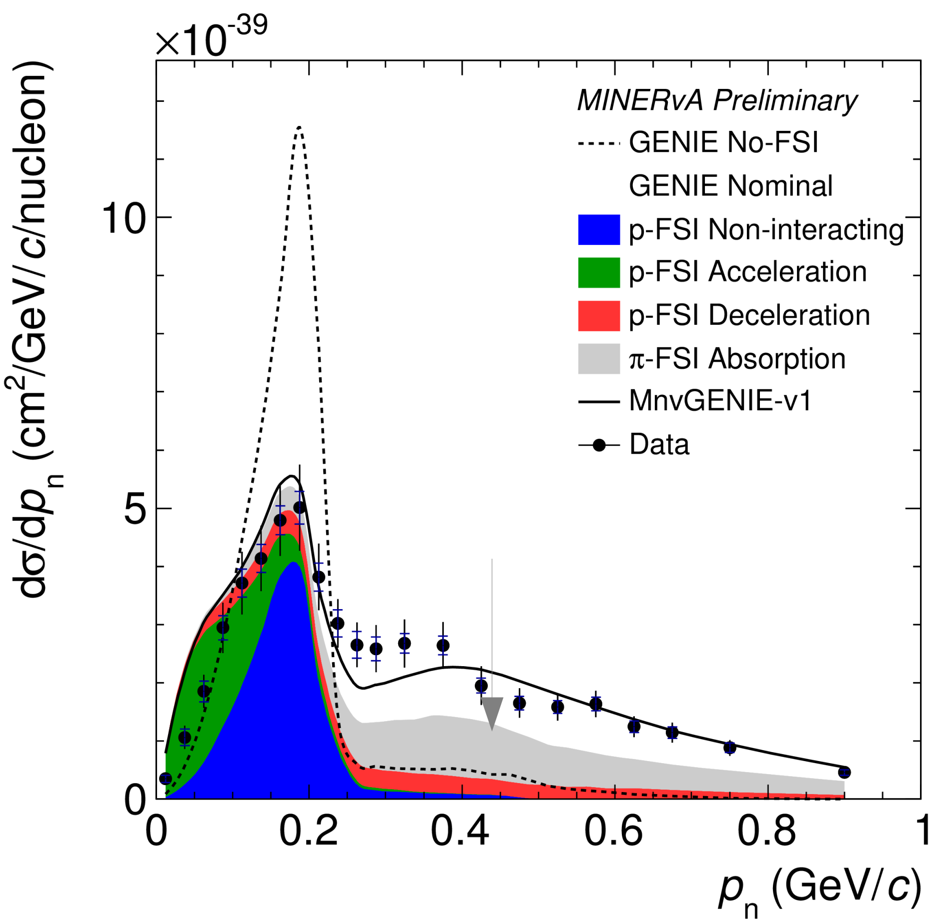
p_n: recoil momentum of the nuclear remnant



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

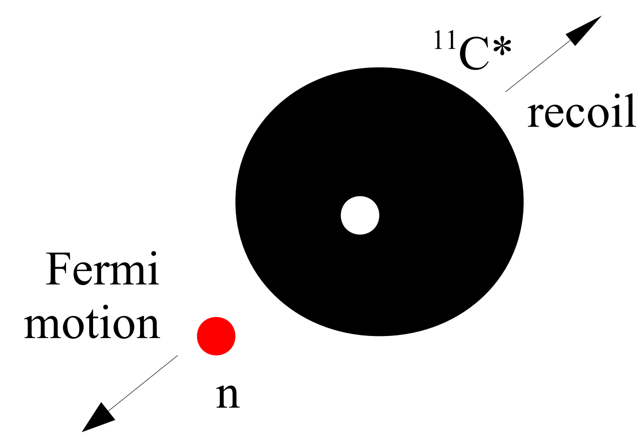
Nuclear Effect Diagnostics

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



p_n: smeared δp_T beyond QE peak → tail

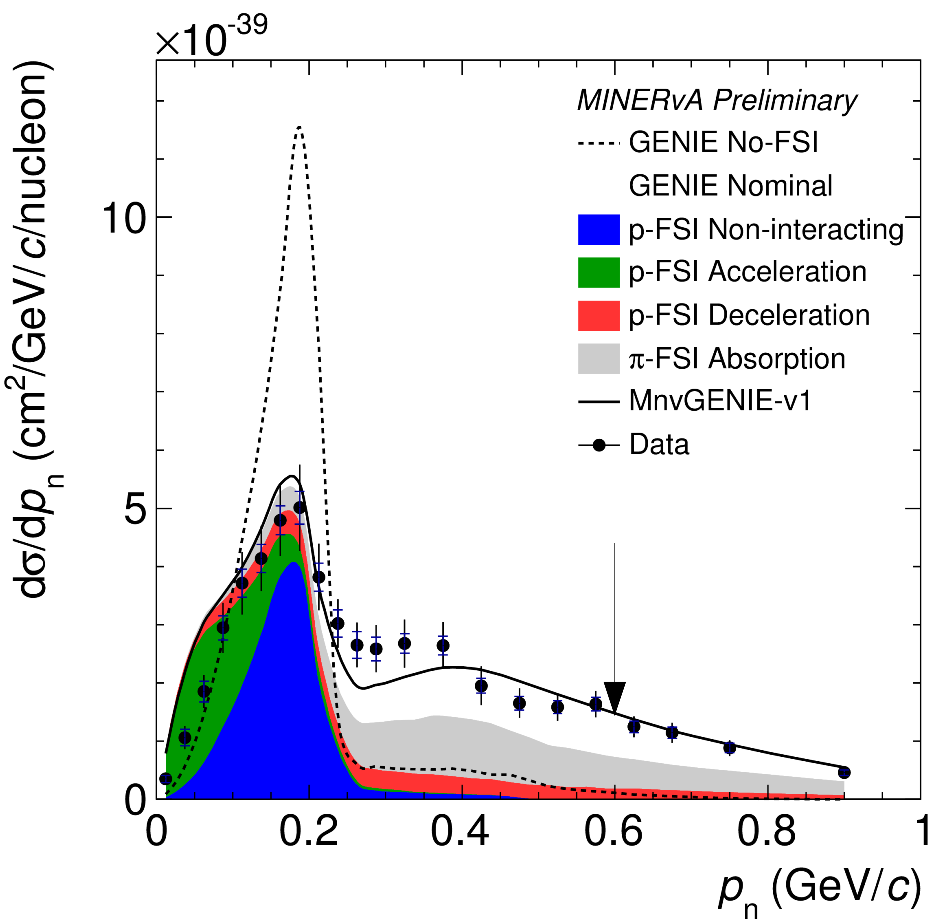
– π-FSI Absorption



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

Nuclear Effect Diagnostics

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

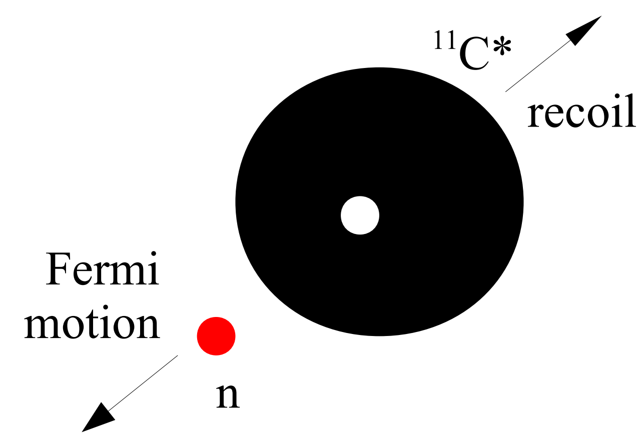


p_n: smeared δp_T beyond QE peak → tail

– π-FSI Absorption

– 2p2h

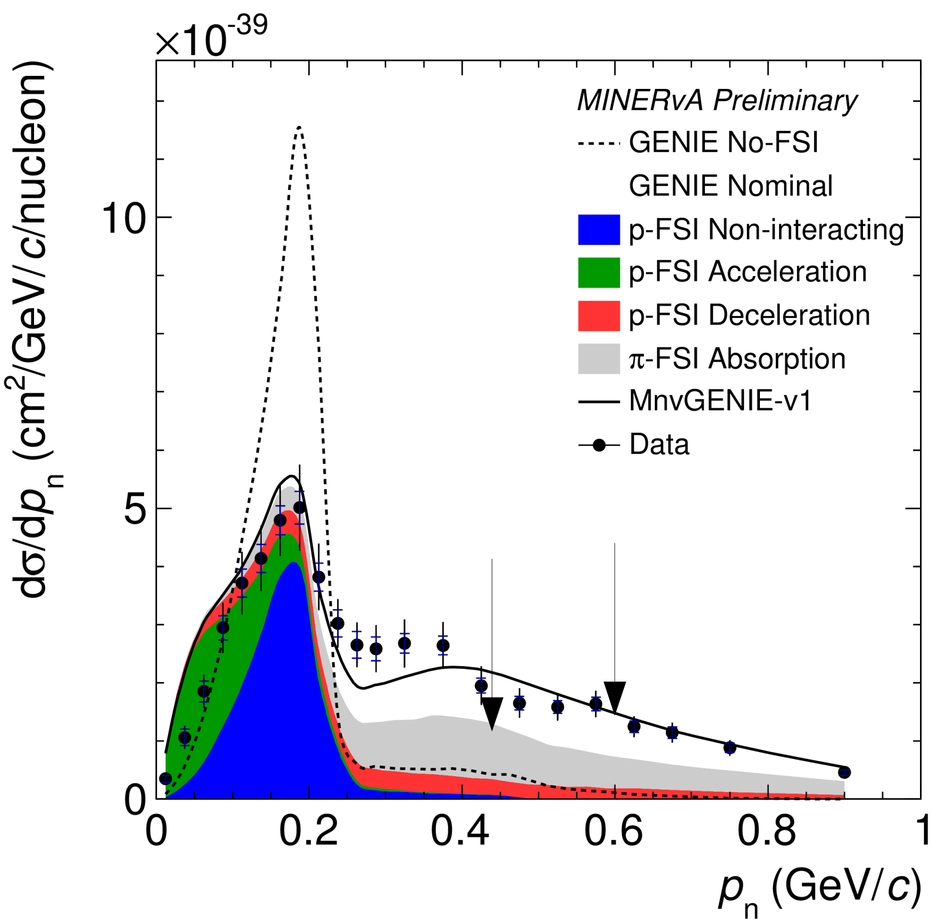
(= MnvGENIE-v1 – GENIE Nominal)



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

Nuclear Effect Diagnostics

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



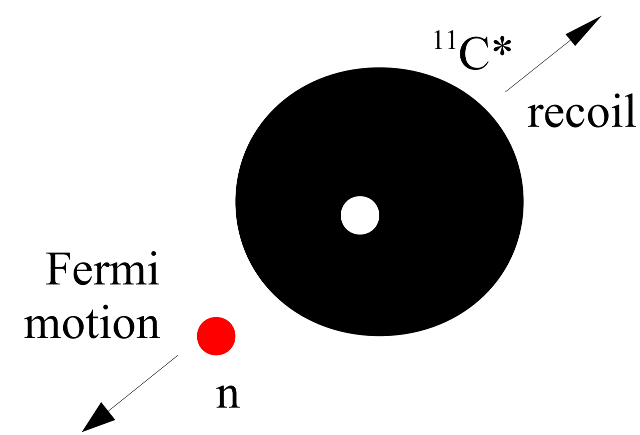
GENIE describes the tail reasonably well due to large contribution from 2p2h tuned to MINERvA inclusive measurements

p_n: smeared δp_T beyond QE peak → tail

– π-FSI Absorption

– 2p2h

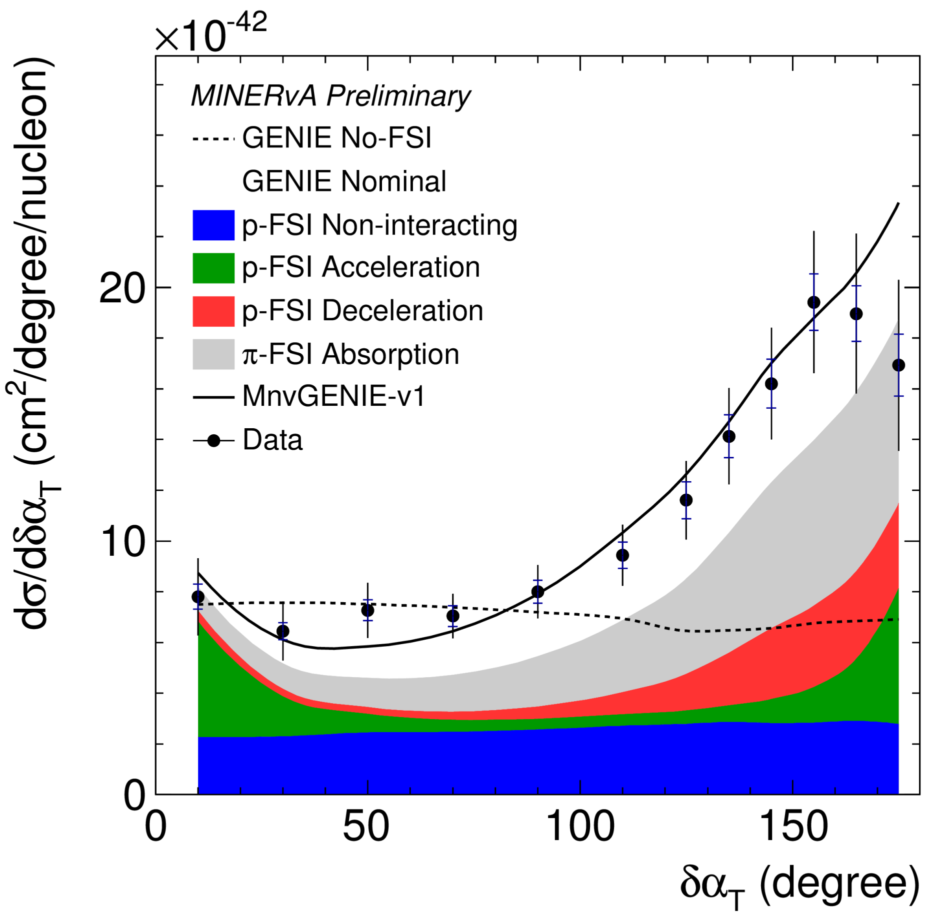
(= MnvGENIE-v1 – GENIE Nominal)



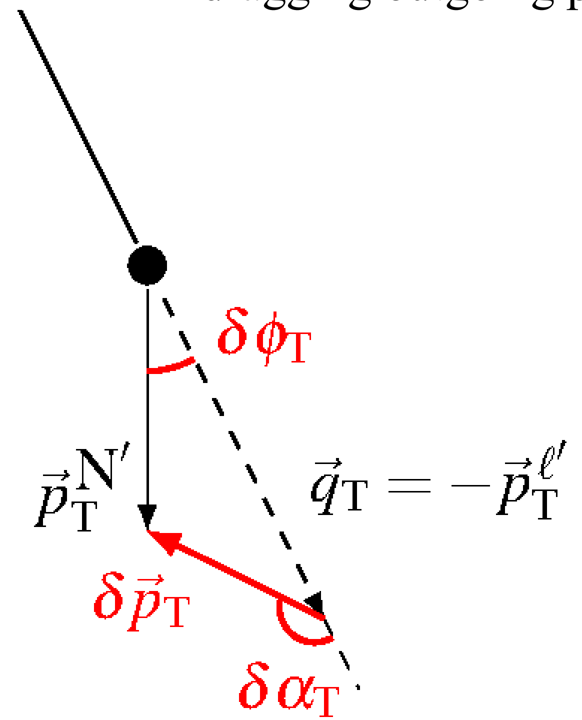
Pion production and 2p2h process: strong intra-nuclear momentum transfer due to momentum sharing with proton

Nuclear Effect Diagnostics

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



δp_T (nuclear effects) dragging outgoing proton

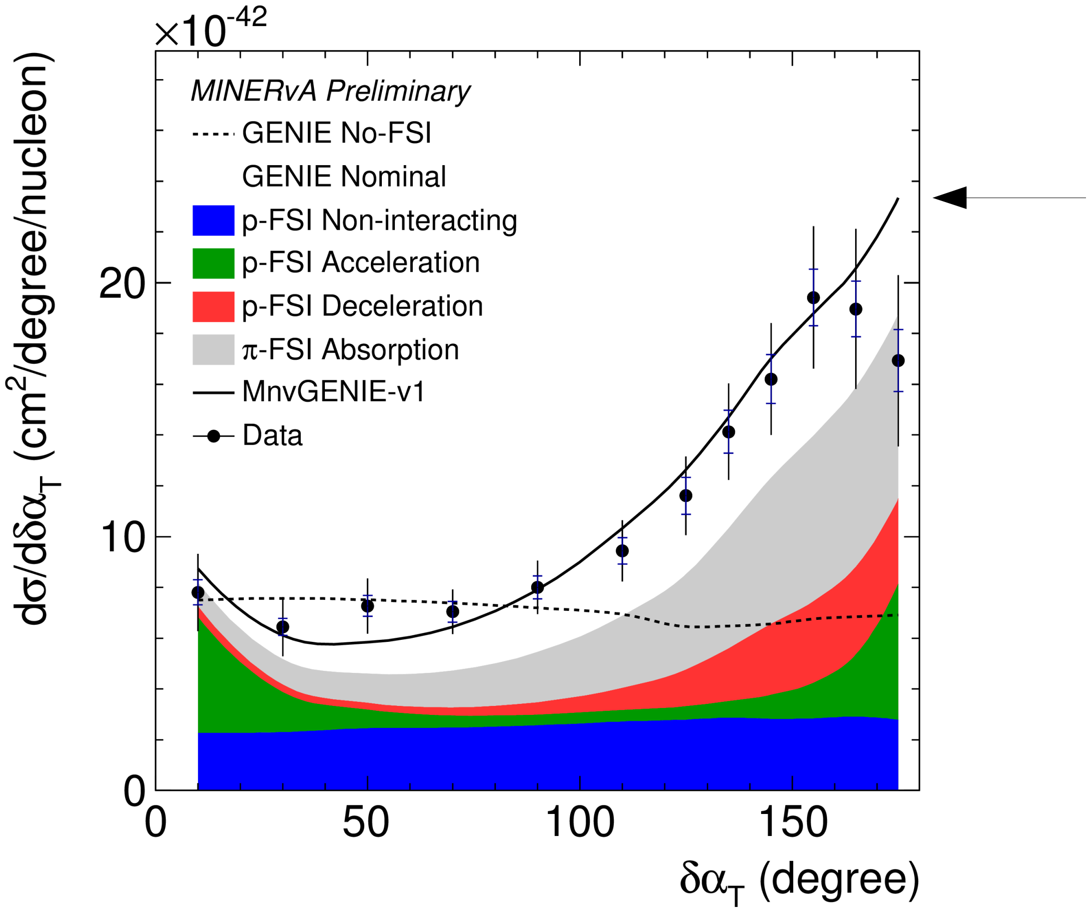


Proton momentum shared by others, decelerated → large $\delta\alpha_T$ region

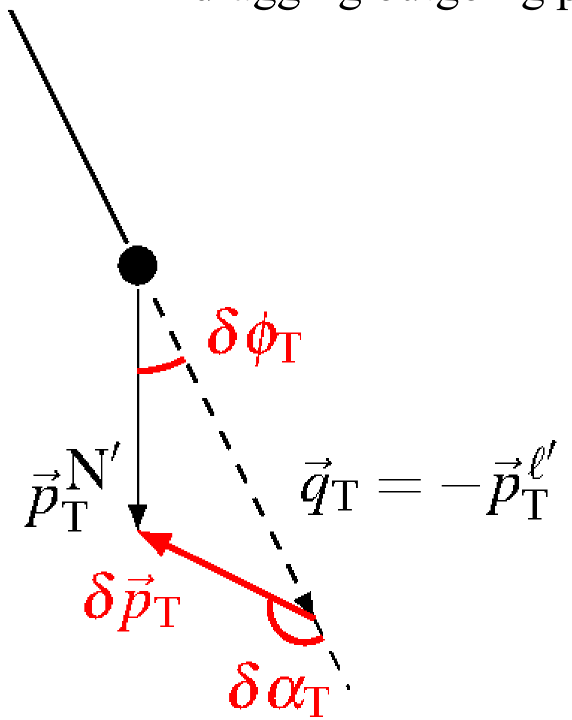
– π-FSI Absorption

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

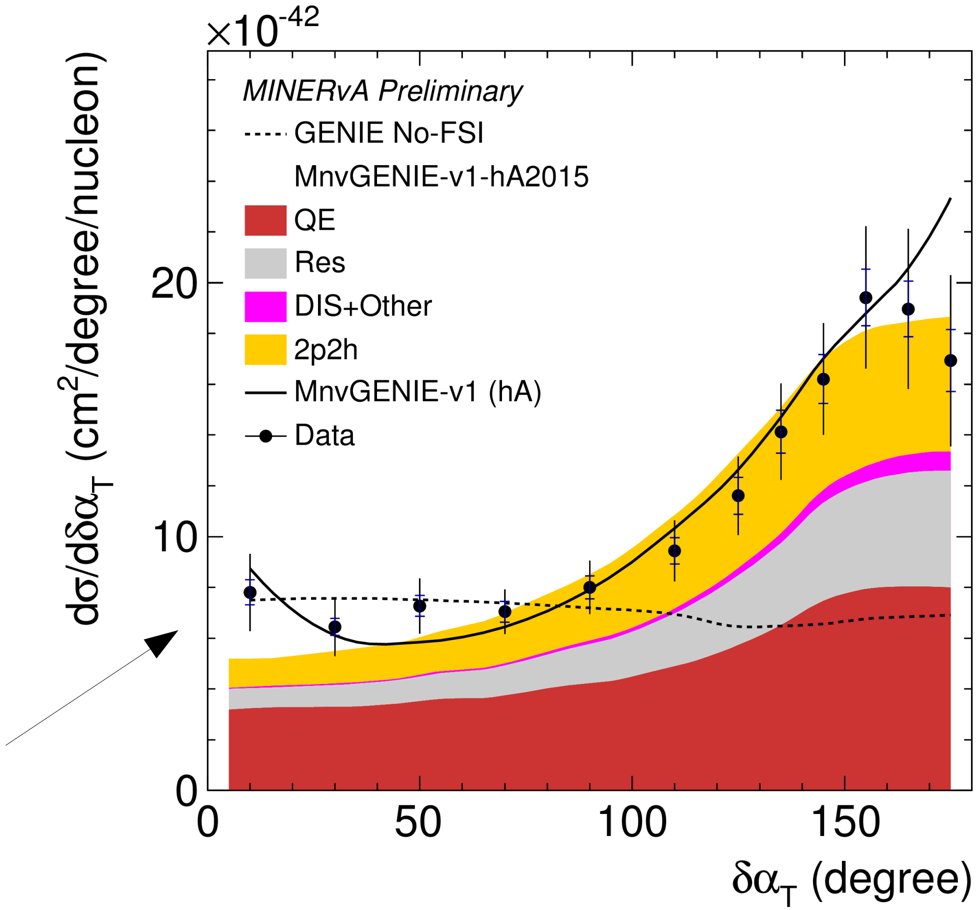
– π-FSI Absorption

– 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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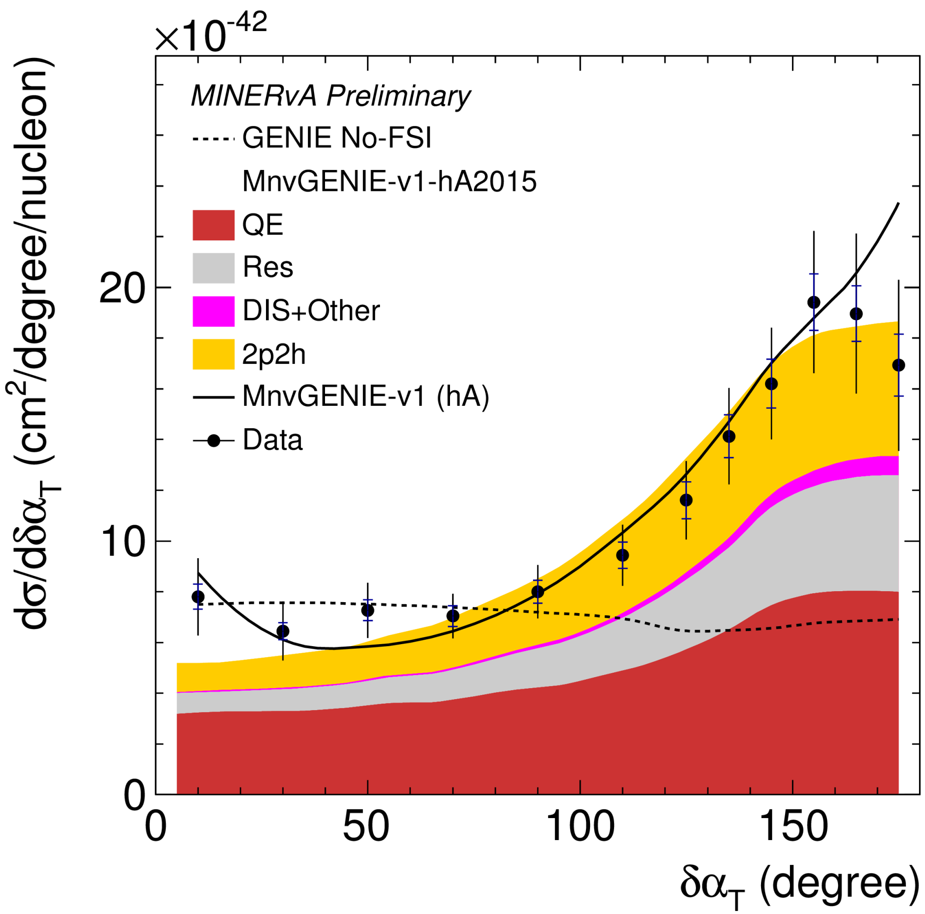
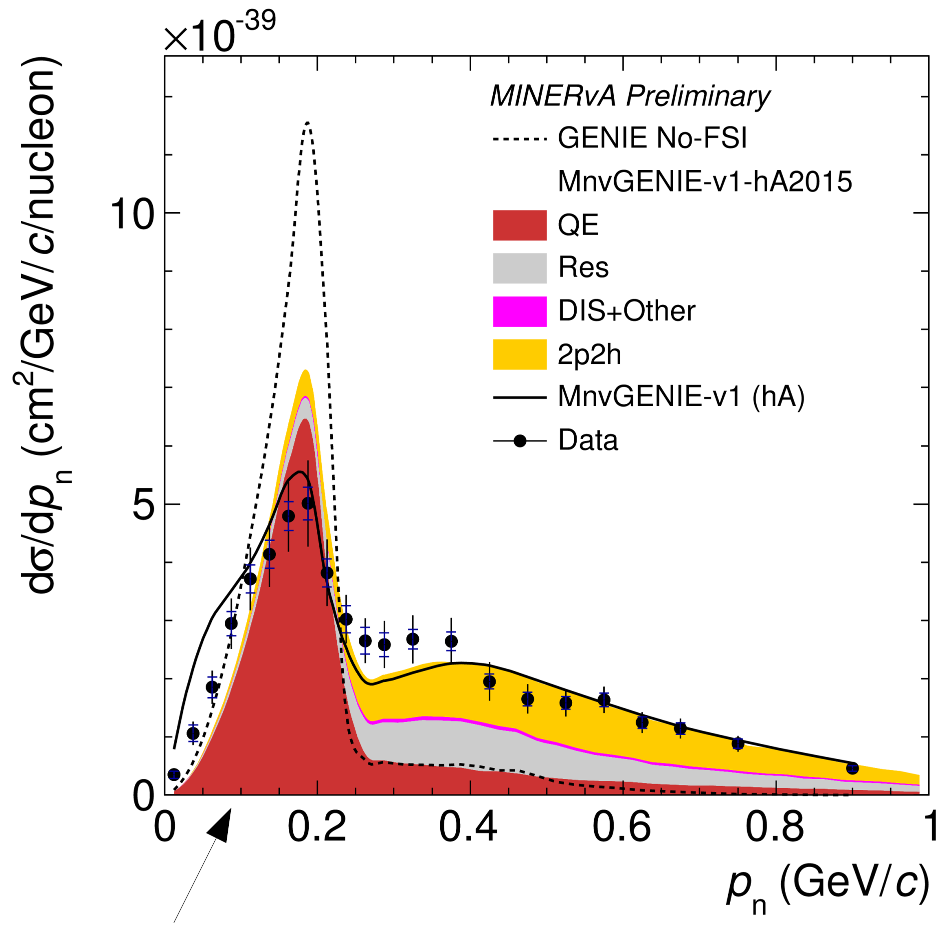


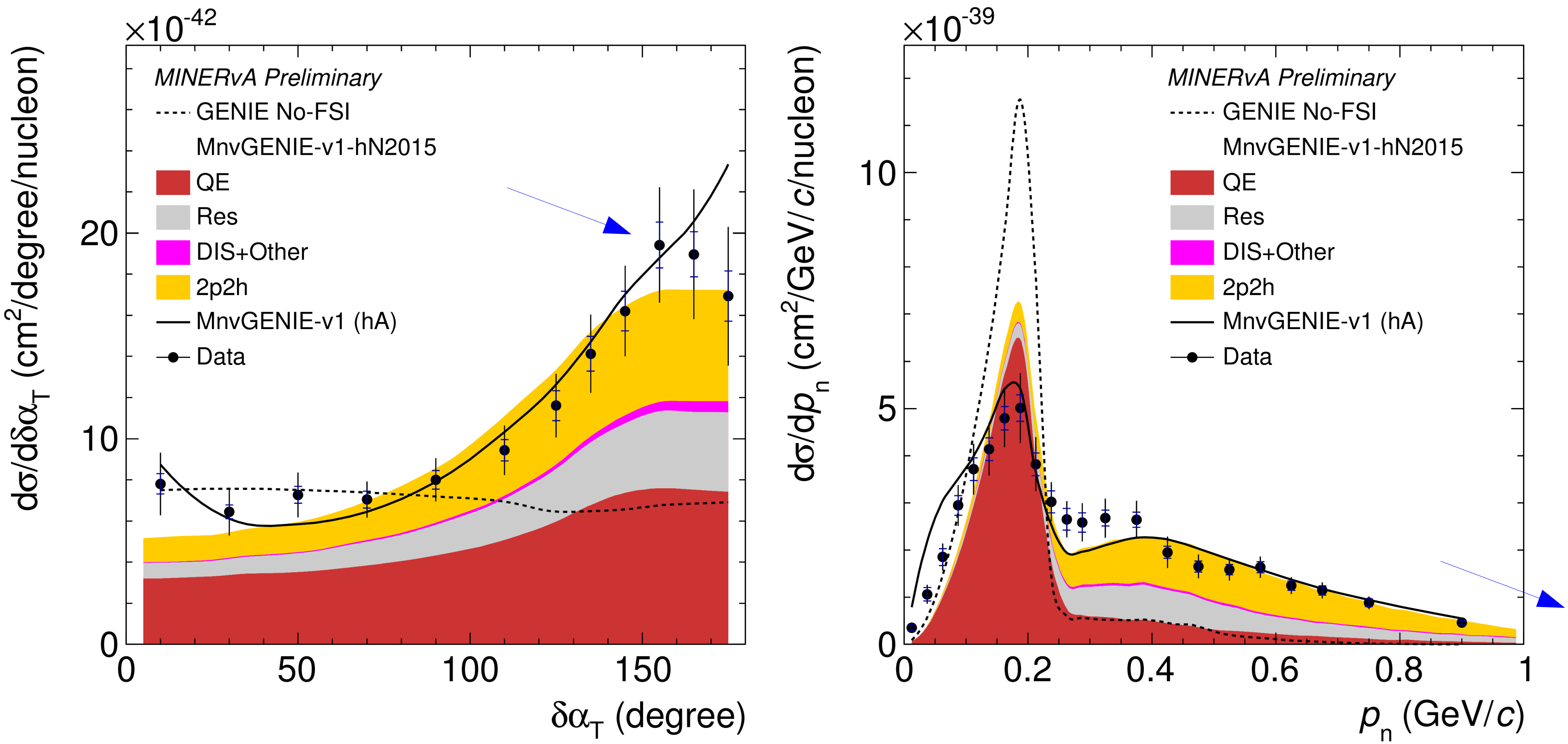


No p-FSI acceleration

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]

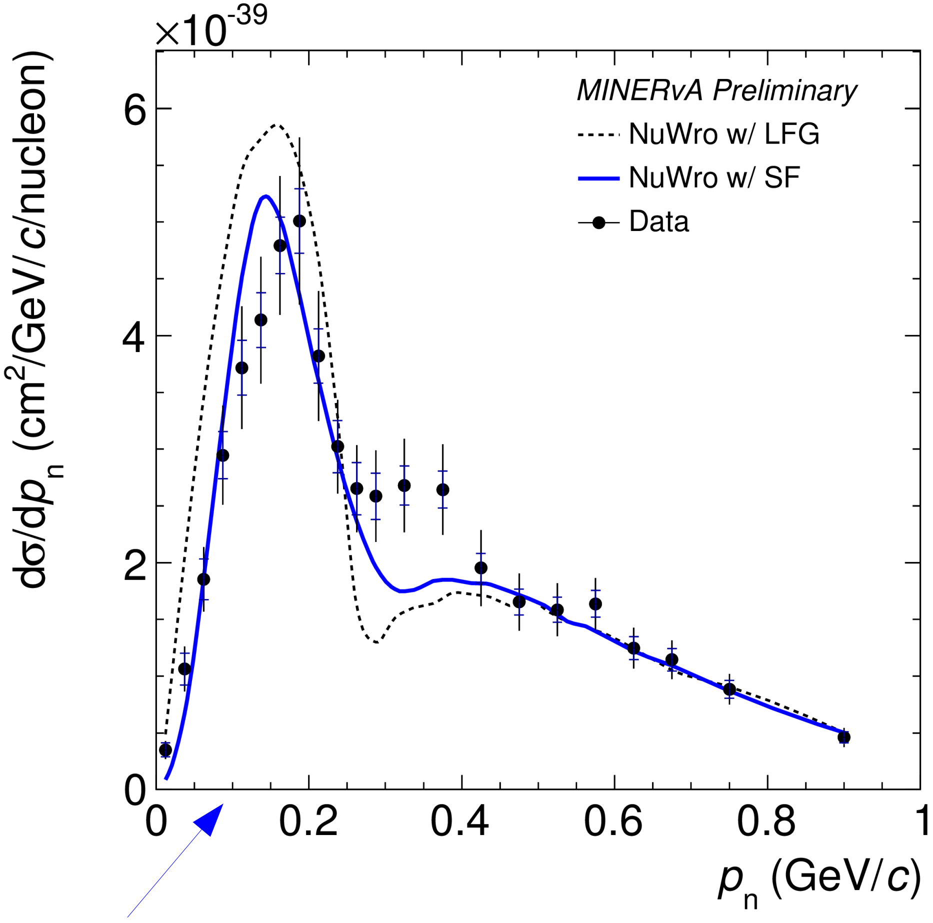
- **Nominal**: version 2.8.4
  - global Fermi Gas (RFG) model with Bodek-Ritchie (BR) tail [Phys. Rev. D 23, 1070 (1981)]
  - hA FSI [AIP Conf.Proc. 1405 (2011) 213-218]
- **No-FSI**: Nominal without FSI
- **MnvGENIE-v1: GENIE MINERvA Tune (v1) [only 2p2h relevant for this analysis]**
  - Added Random 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

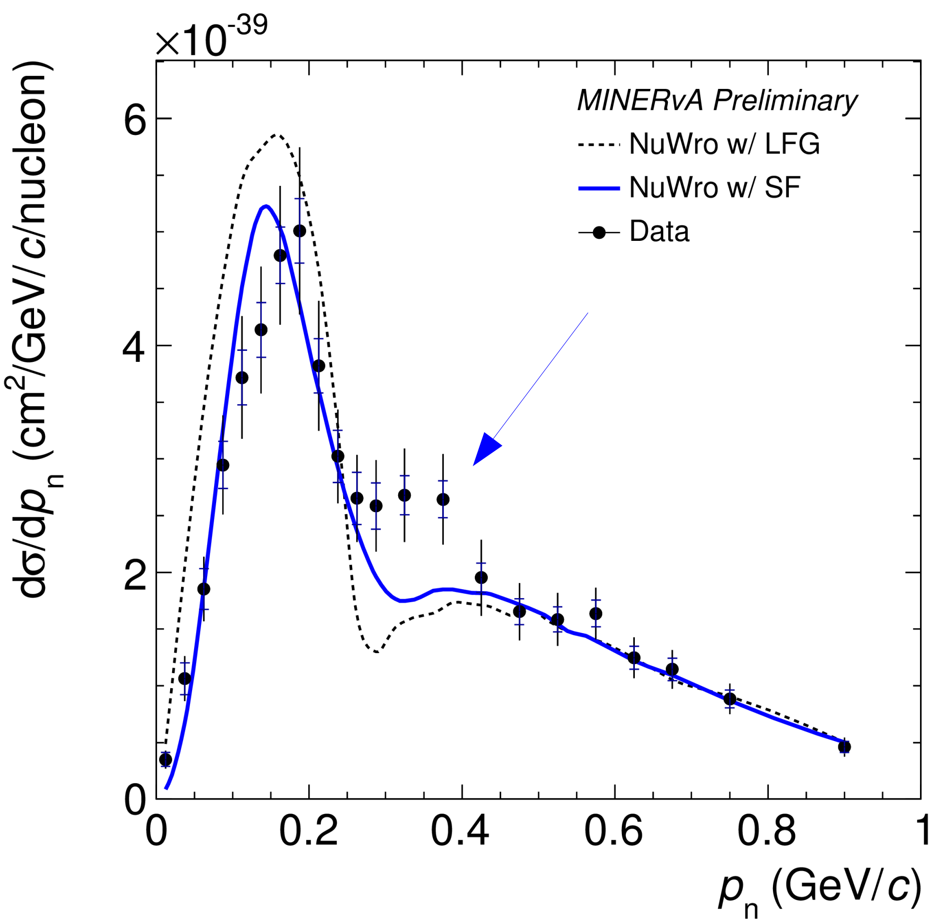
- Fermi motion

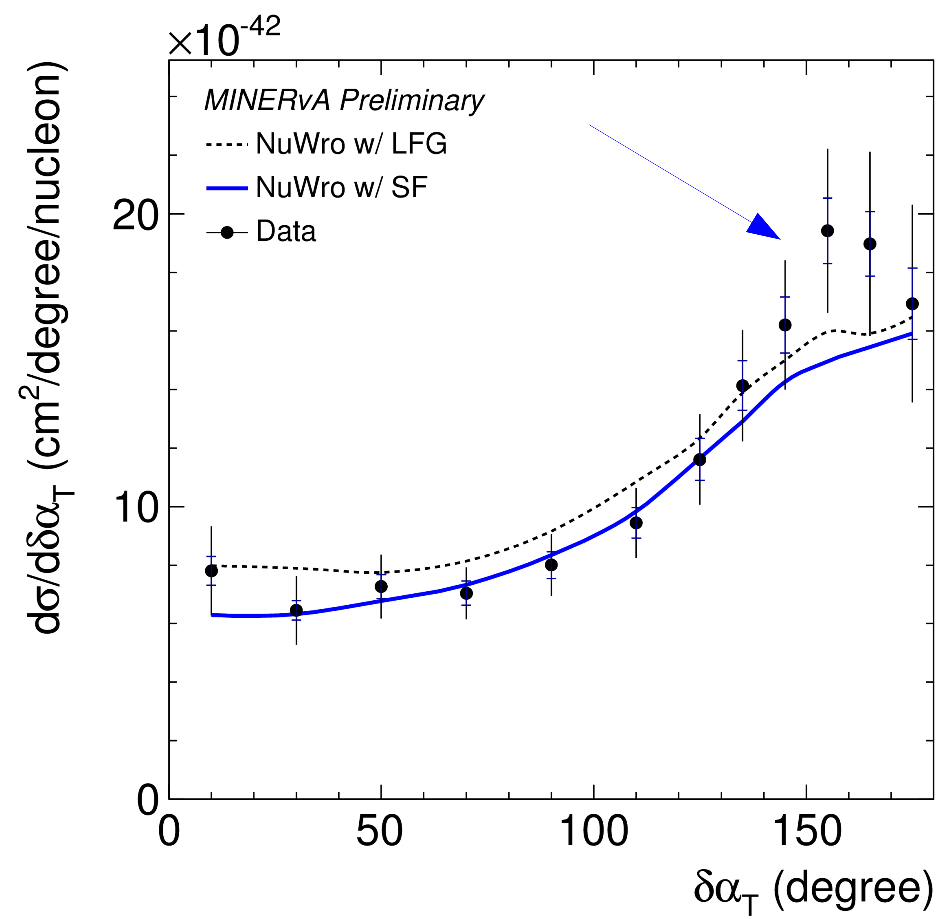


SF describes Fermi motion very well

Advanced Topics: NuWro

- Fermi motion
- Resonance / 2p2h strength





SF describes Fermi motion very well

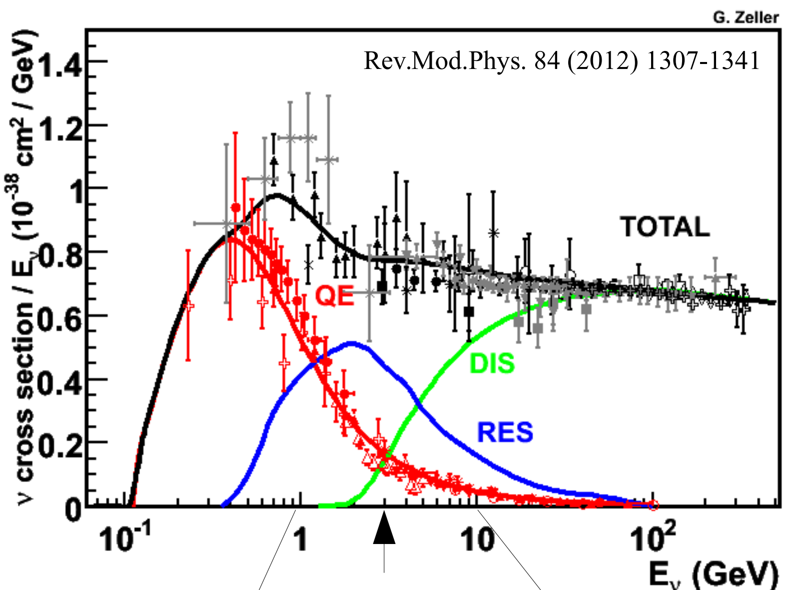
Resonance / 2p2h lacks of strength in small regions

ADVANCED TOPICS: COMPARISON TO T2K

Advanced Topics: Comparison to T2K

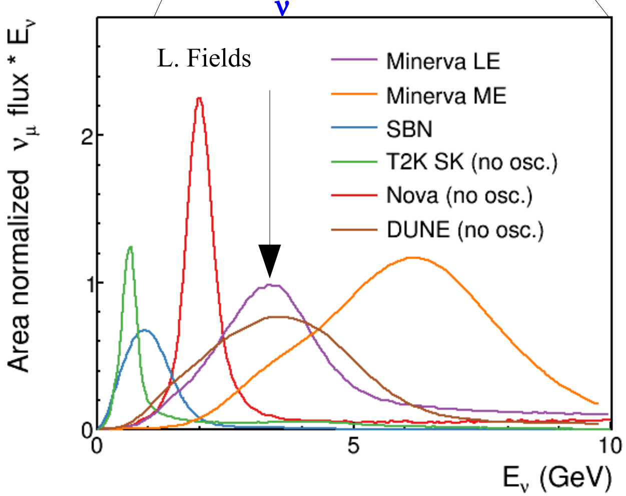
[arXiv:1802.05078] *same target, slight difference in signal phase space definition

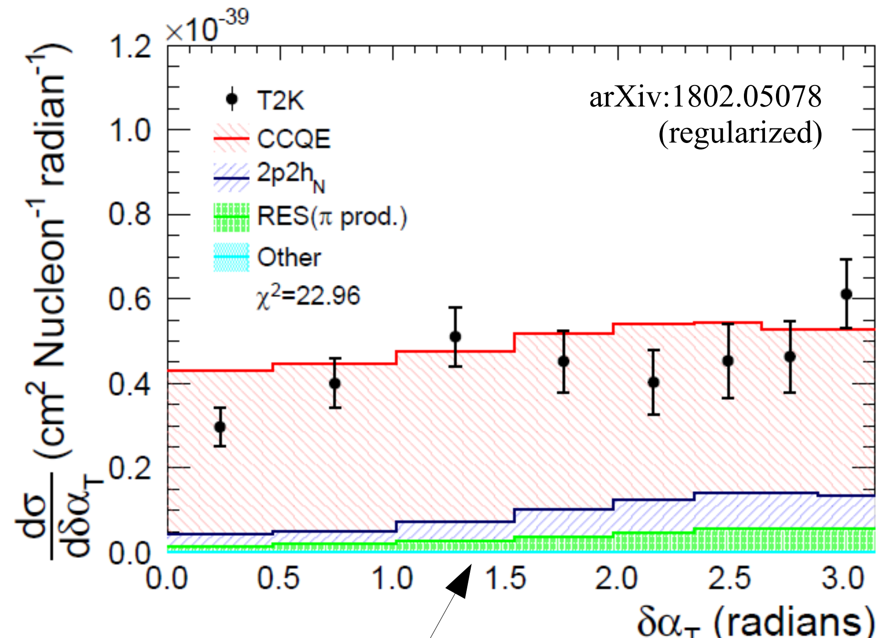
- $\delta\alpha_T$



NuMI LE

$<E_\nu> \sim 3$ GeV



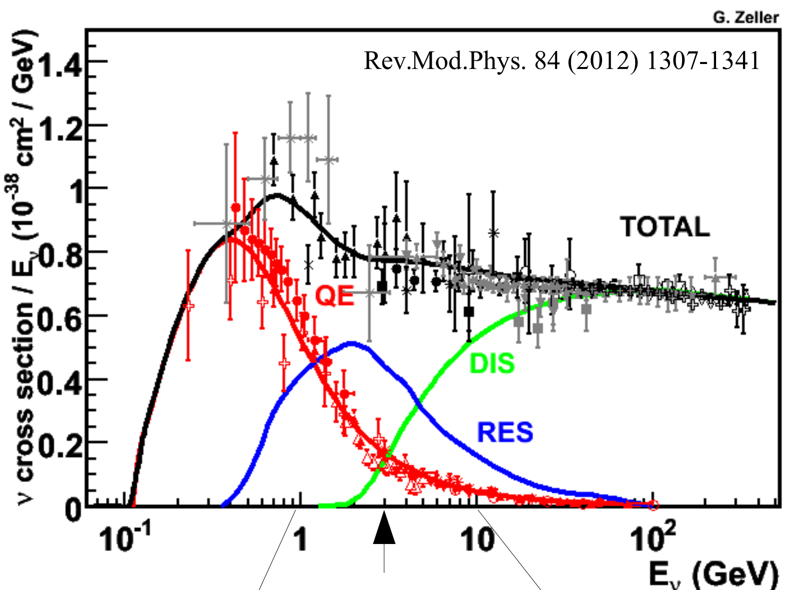


MINERvA-T2K difference mainly due to RES:
Very small resonance contribution at T2K

Advanced Topics: Comparison to T2K

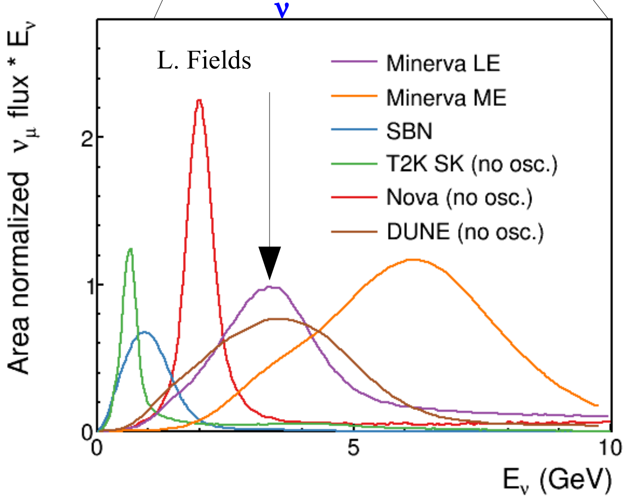
[arXiv:1802.05078] *same target, slight difference in signal phase space definition

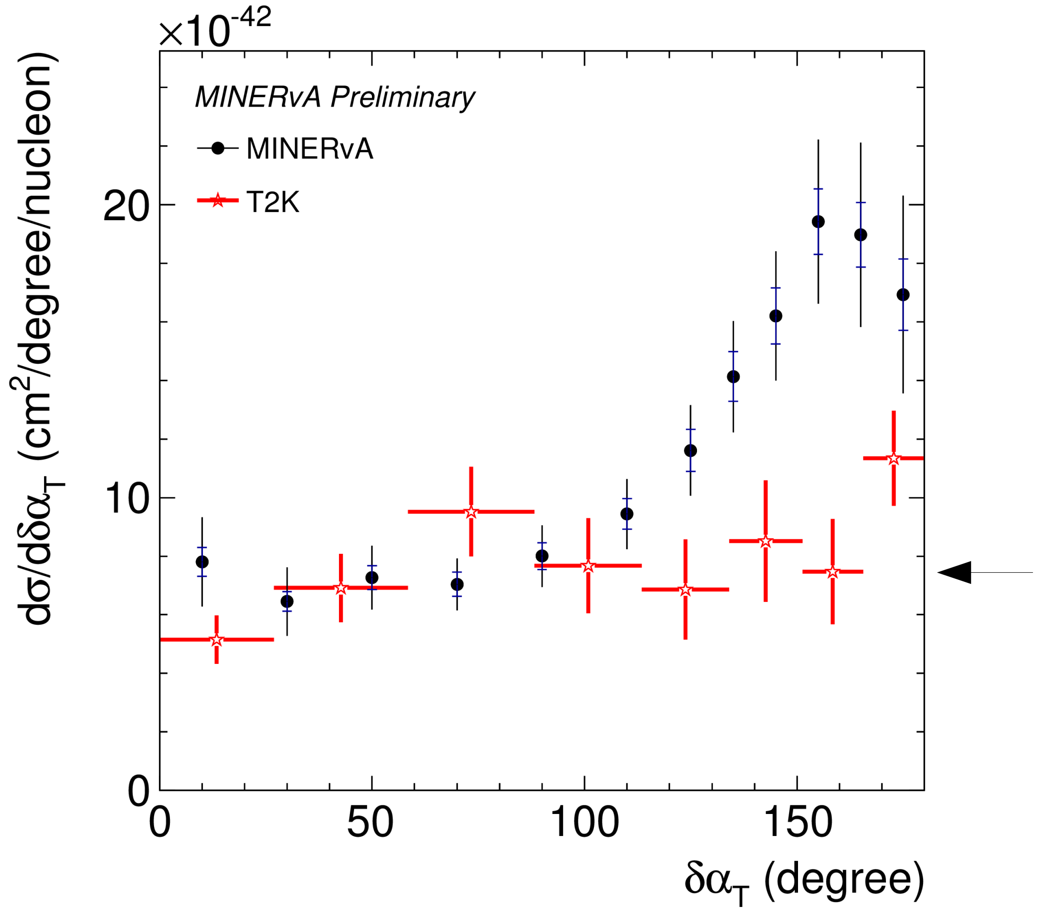
- $\delta\alpha_T$



NuMI LE

<E$_\nu$> ~ 3 GeV





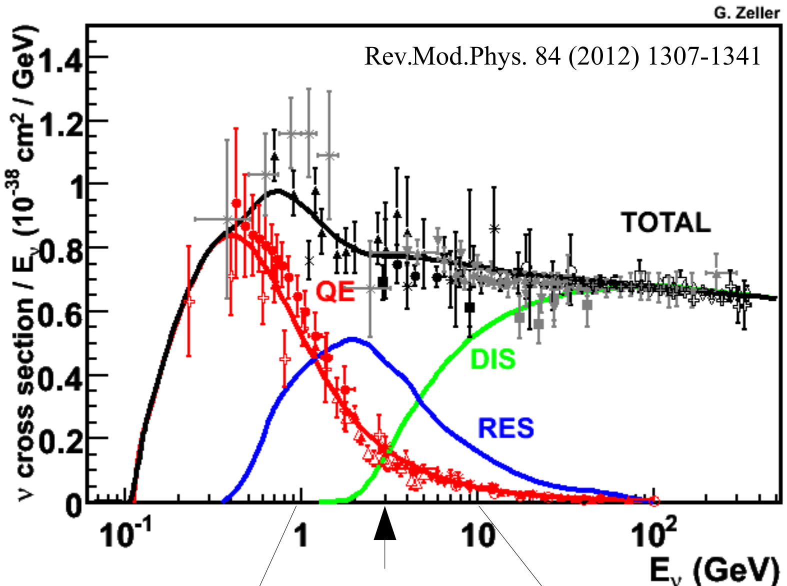
MINERvA-T2K difference mainly due to RES

Fermi motion (isotropic) baseline consistent

Advanced Topics: Comparison to T2K

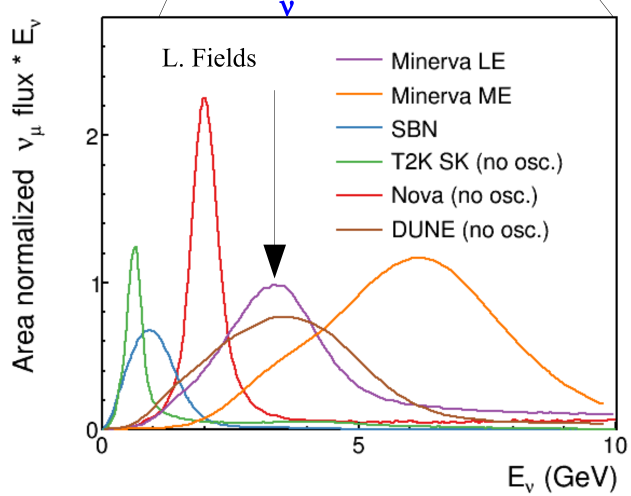
[arXiv:1802.05078] *same target, slight difference in signal phase space definition

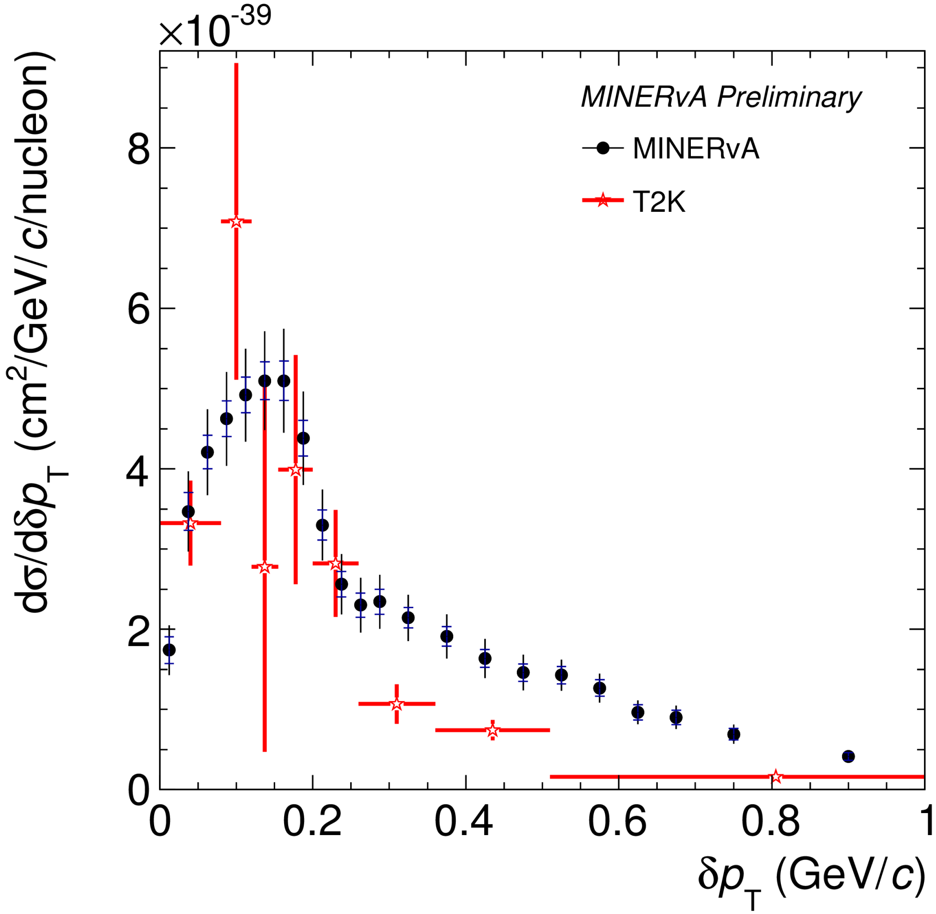
- $\delta\alpha_T$
- δp_T



NuMI LE

<E_ν> ~ 3 GeV



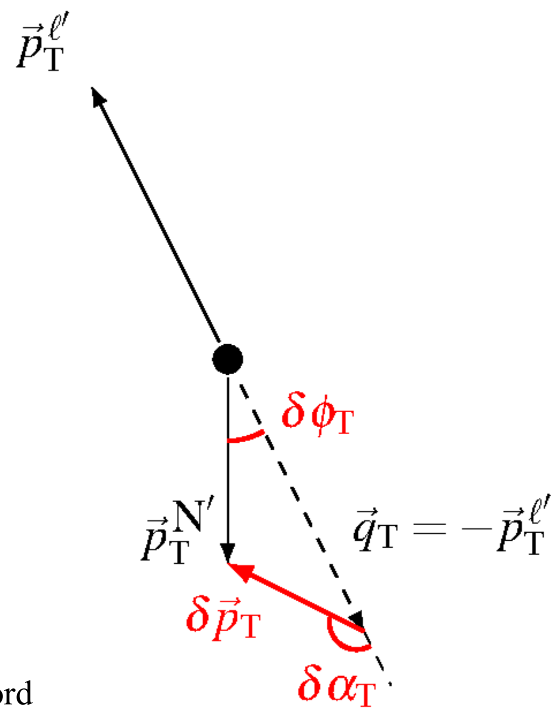


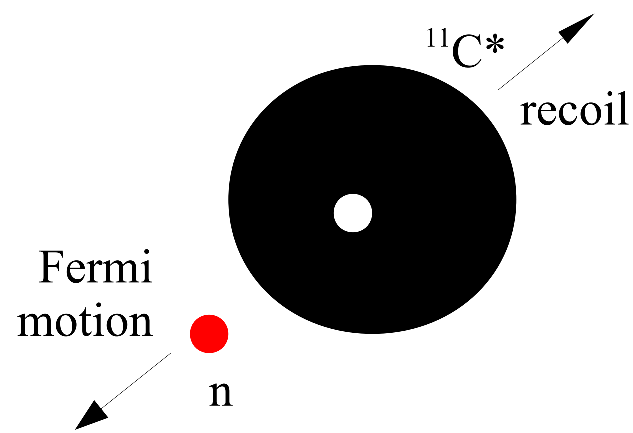
MINERvA-T2K difference mainly due to RES

The QE peaks are consistent

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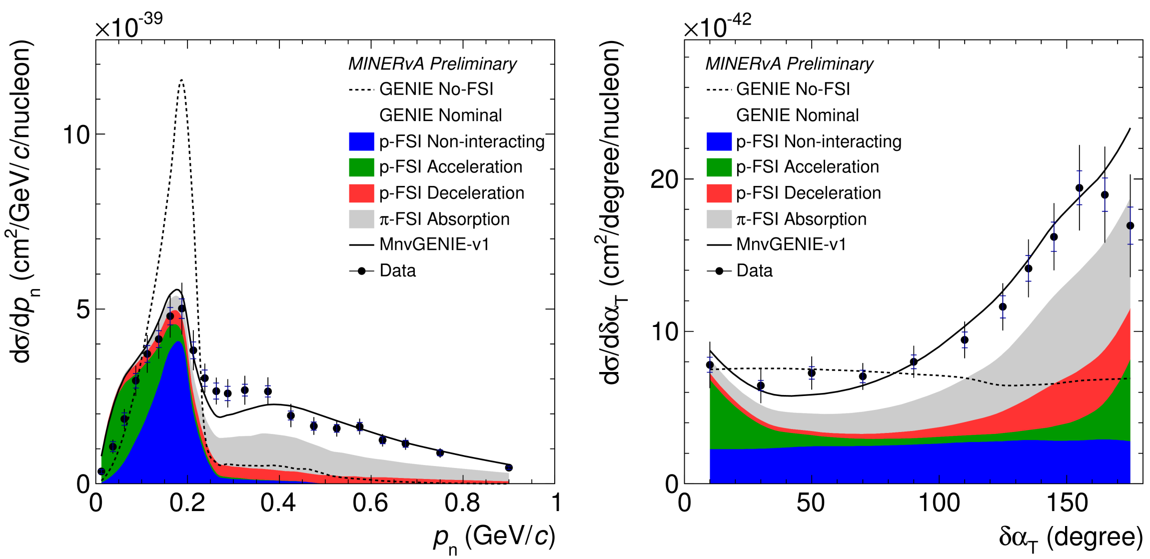
By rearranging final-stat kinematics, nuclear effects can be diagnosed:

- ✓ 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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✓ $\delta\alpha_T$ 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

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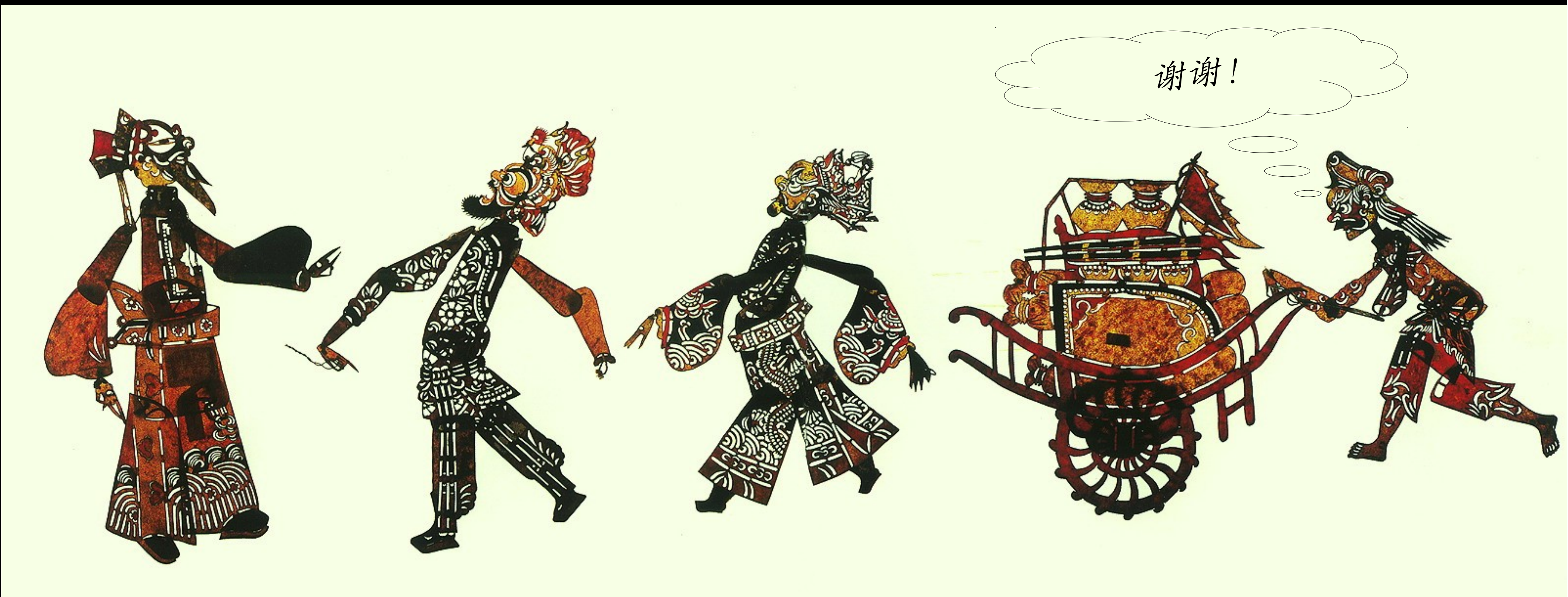
  - Initial neutron momentum (p_n)
- **New developments**
  - Transverse kinematic imbalances
    - New system to solve the nuclear effect problem in neutrino interaction most relevant for oscillation measurements
    - Radical approach → double transverse kinematic imbalance [Phys. Rev. D 92, 051302(R)]
  - First measurement of Furmanski-Sobczyk initial neutron momentum
    - diagnostic power
    - Practically efficient way to select pure CCQE events (beyond the scope of this talk)
  - ESC (Elastically Scattered Contained) proton selection
    - Powerful to enhance the proton reconstruction quality
    - Application in other homogeneous non-magnetized detectors, e.g. LAr

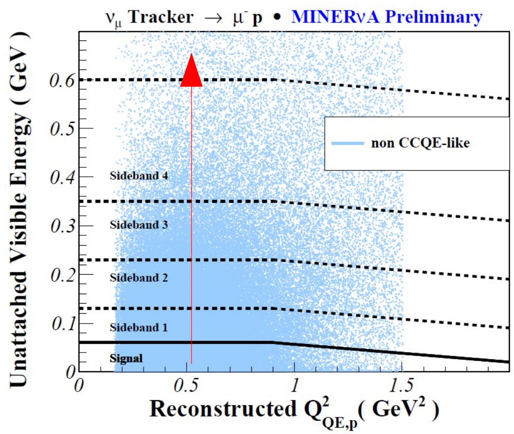


Source: http://www.cnhubei.com/ztmjys-pyts

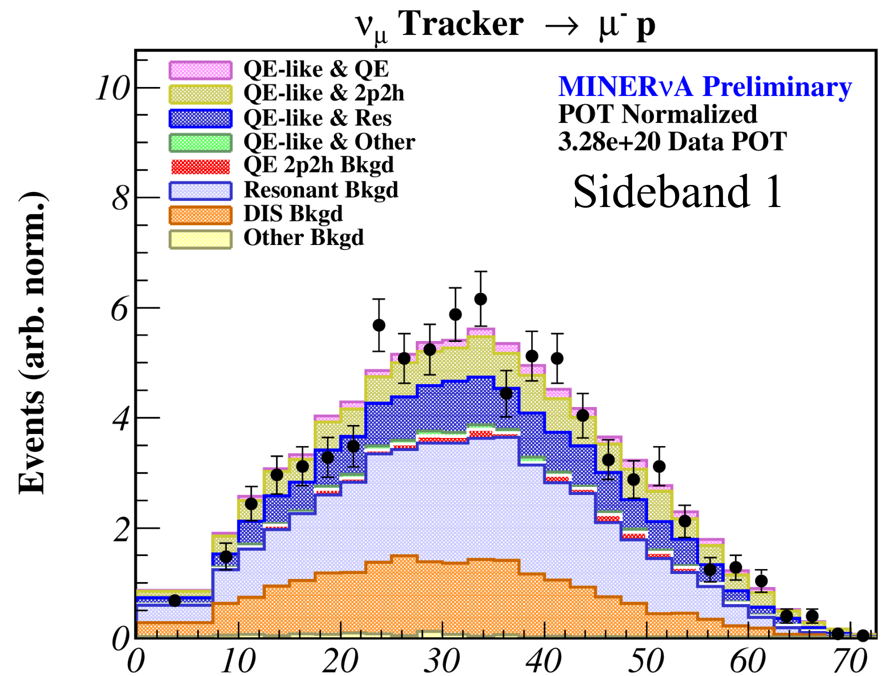
BACKUP

Background Estimation

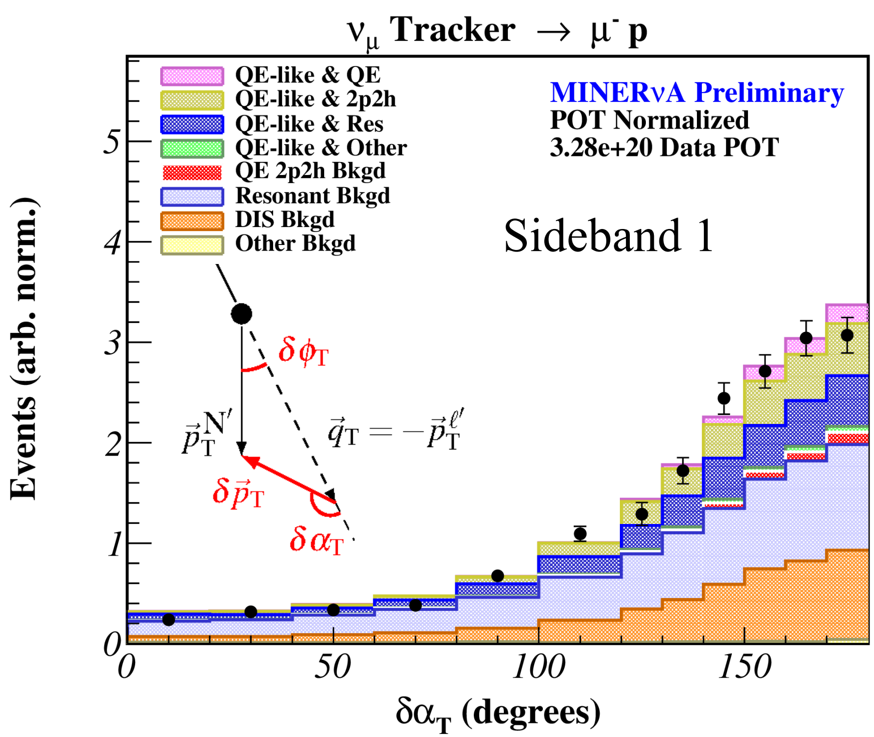
- Data-MC comparison at reconstructed level after sideband fit

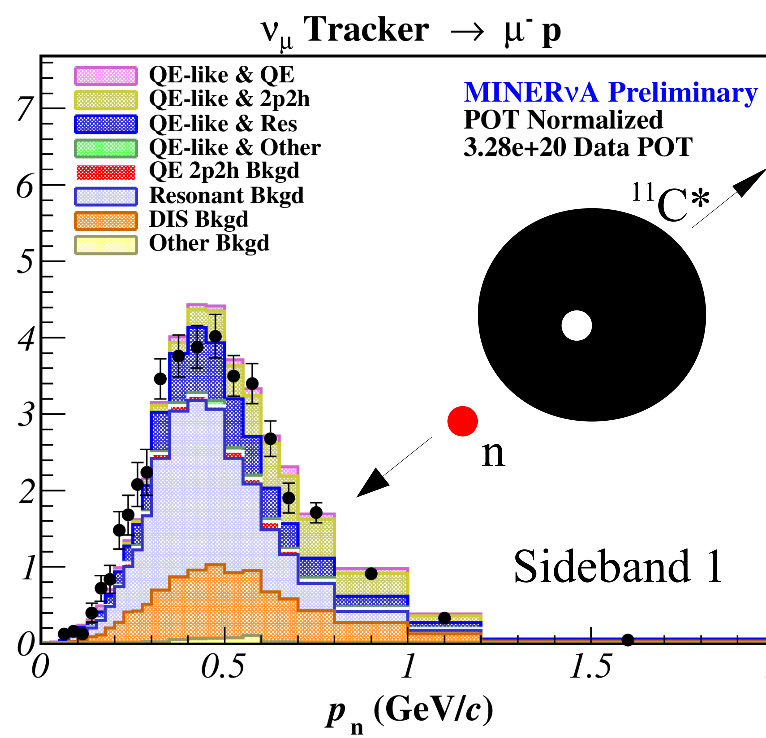


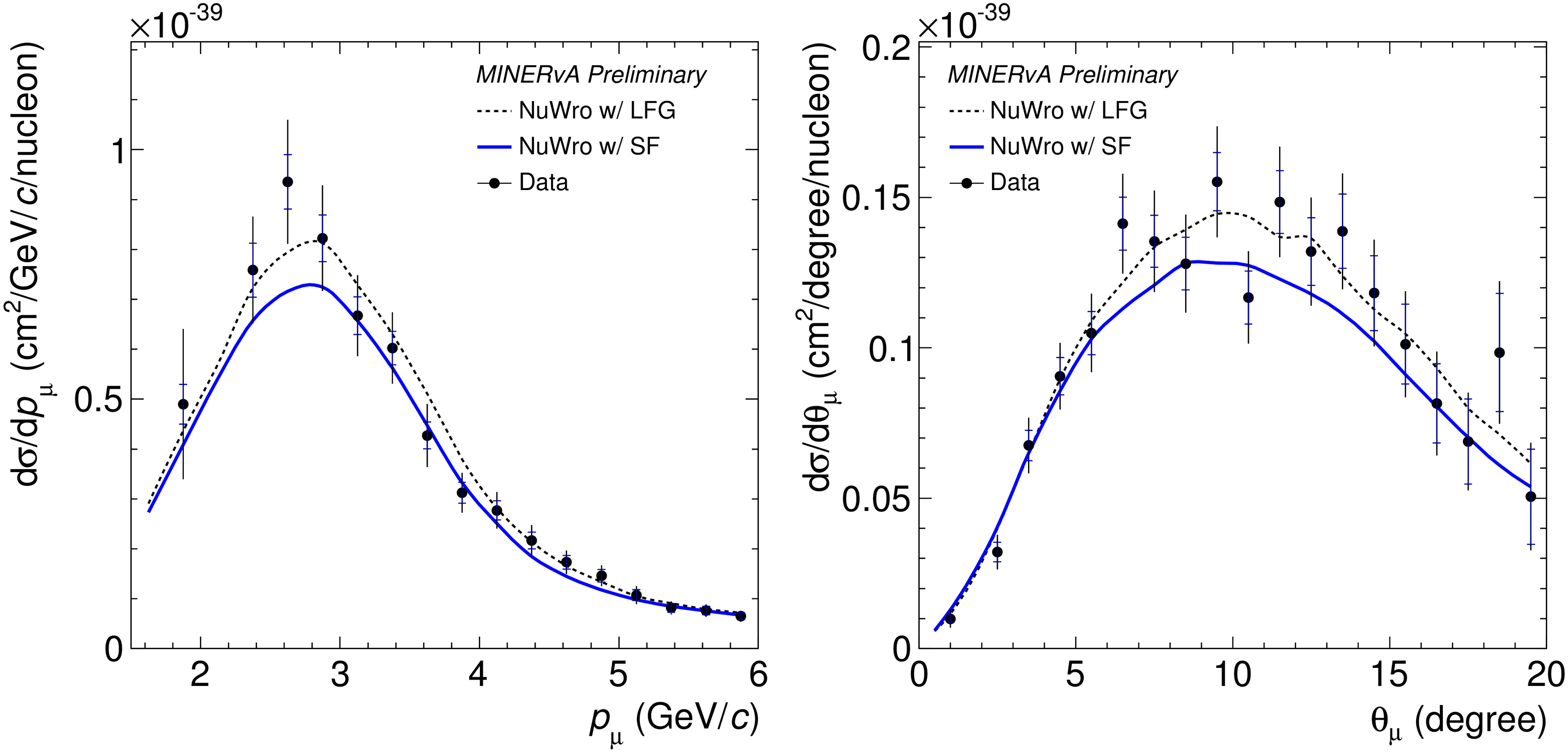
Sideband 1 → 4 high background direction



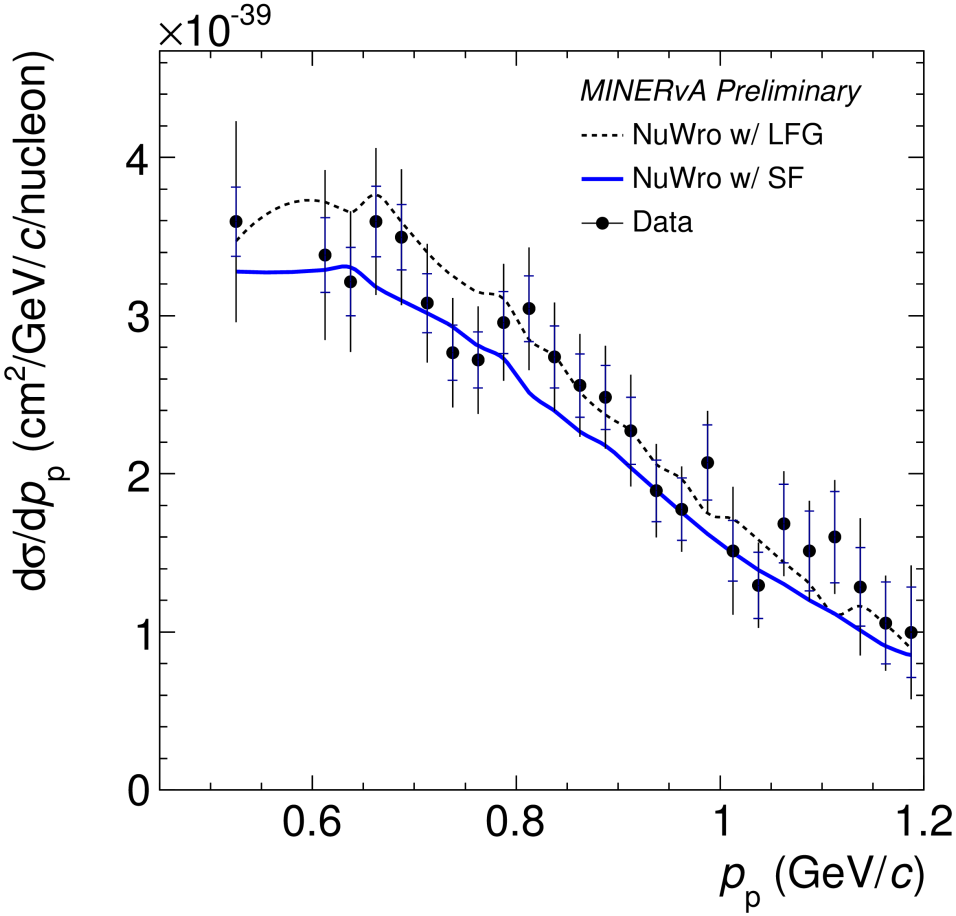
Proton polar angle

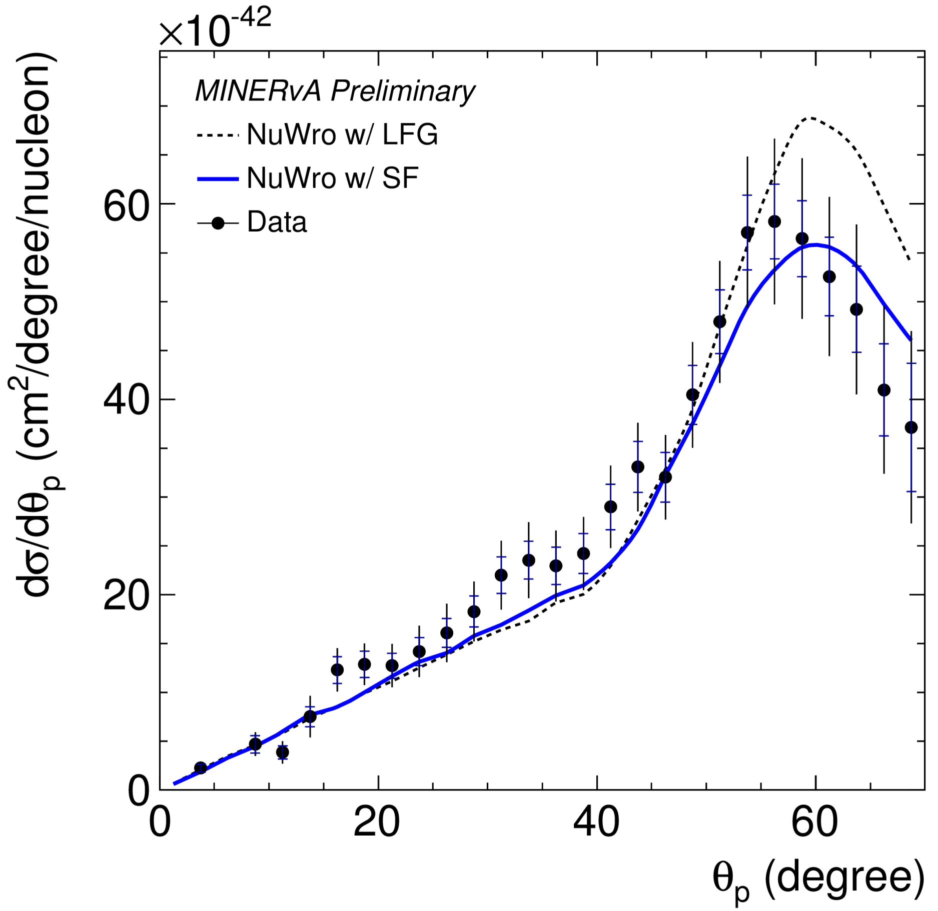




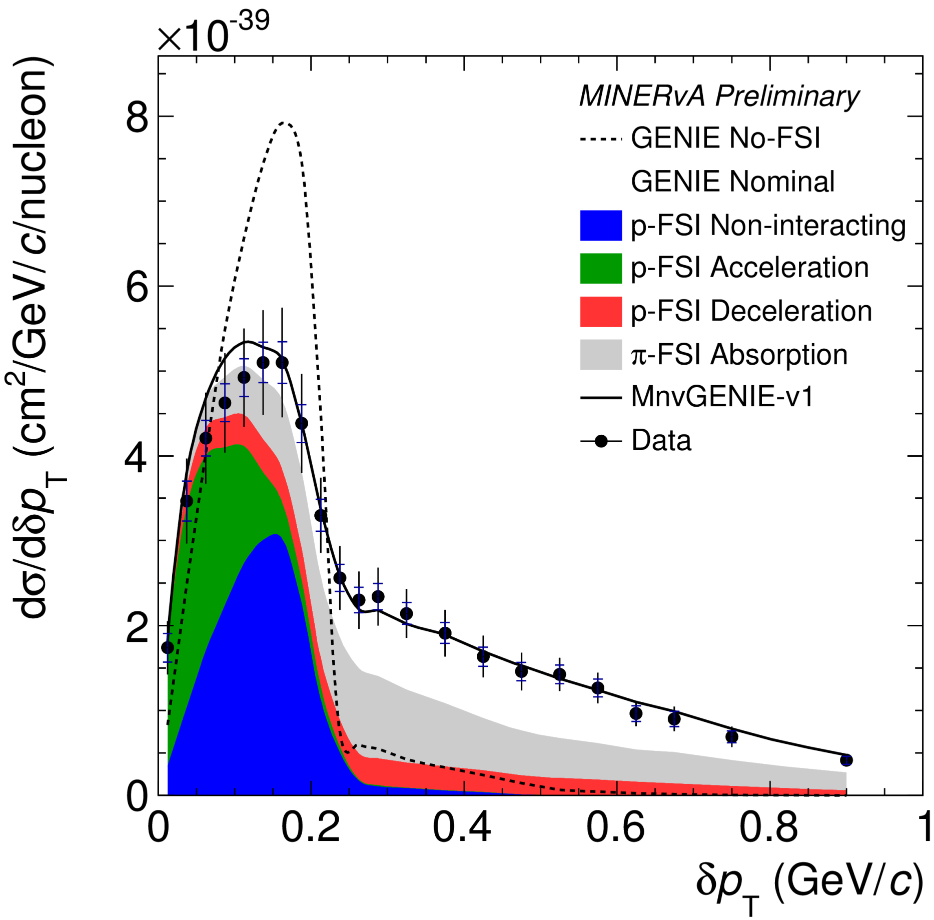


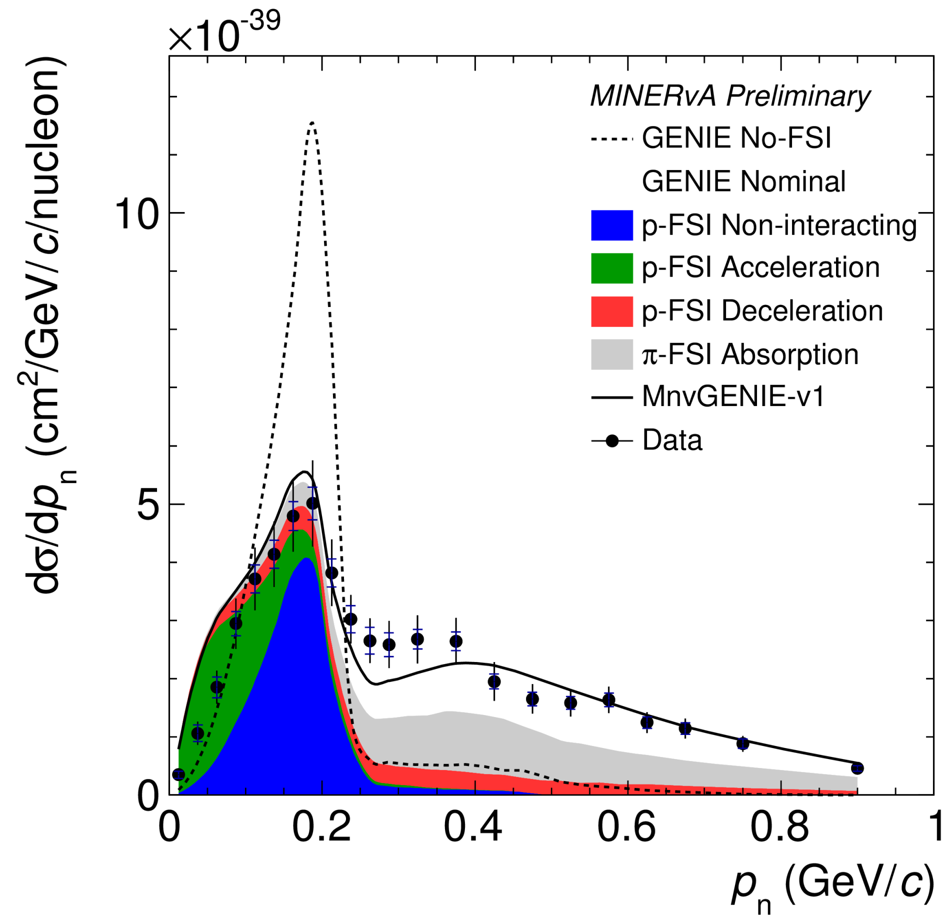
MINERvA Preliminary
NuWro w/ LFG
NuWro w/ SF
Data
×10^-39
dσ/dp_μ (cm²/GeV/c/nucleon)
p_μ (GeV/c)
MINERvA Preliminary
NuWro w/ LFG
NuWro w/ SF
Data
×10^-39
dσ/dθ_μ (cm²/degree/nucleon)
θ_μ (degree)


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


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

Interpretation of δp_T





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

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

Only differ by longitudinal momentum imbalance

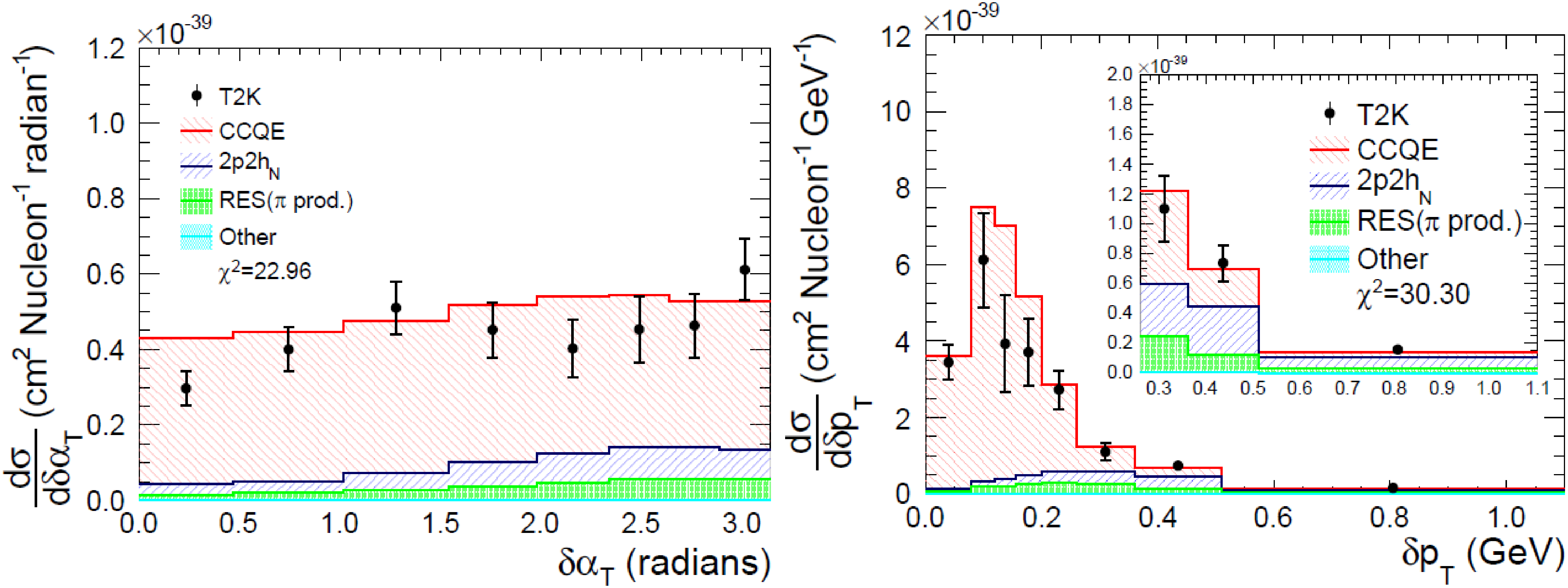
p_n has better resolution

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.

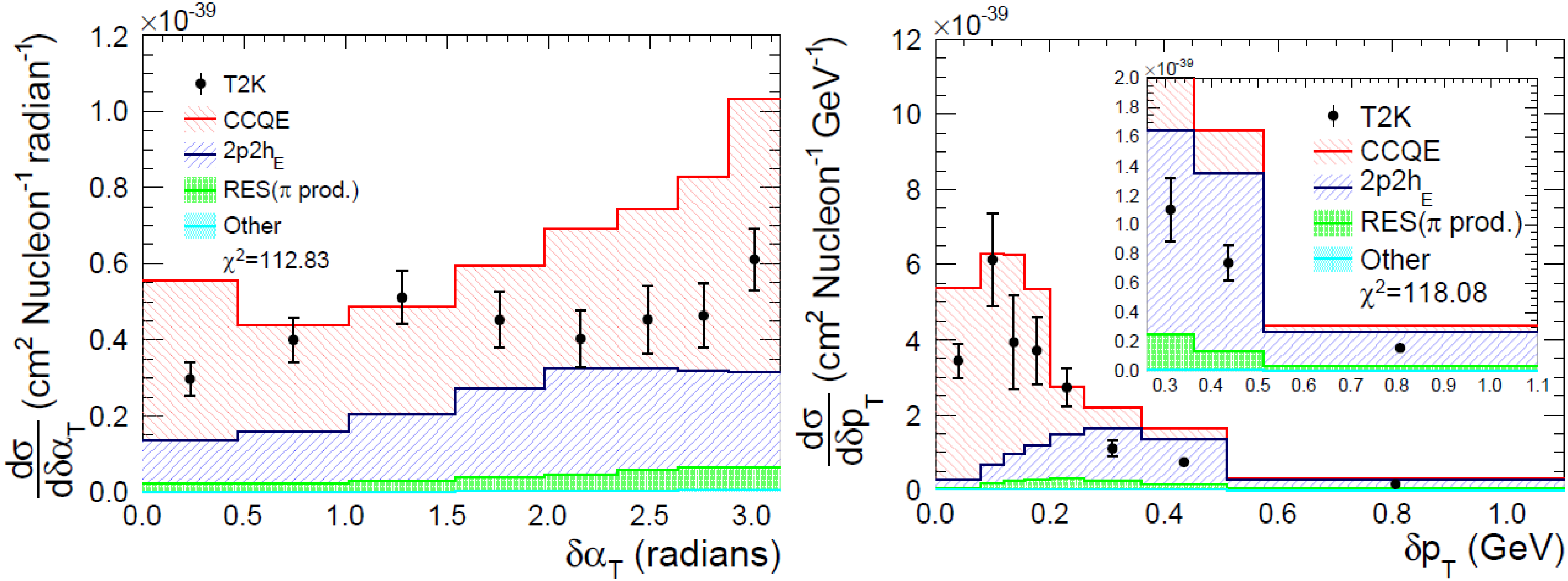
arXiv:1802.05078



NEUT for T2K has very small RES

FIG. 16. The extracted differential cross section as a function of the single transverse variables compared to: the NEUT 5.3.2.2 simulation with the SF initial state model and an ad hoc 2p2h model (**left**); the same NEUT simulation with various scalings of the mean free path of nucleons undergoing FSI processes to simulate different FSI strengths (**right**). $2p2h_N$ indicates the Nieves et. al. model of Ref. [76] implemented in NEUT. A comparison of the NEUT prediction without a 2p2h contribution is also shown. More details of these models can be found in Sec. IV A. The 'N' subscript after LFG indicates that the model is using both a 1p1h and 2p2h prediction from the aforementioned model of Nieves et. al. The inlays on the left plots show a close-up of the tail regions of δp_T and $\delta\alpha_T$ whilst those on the right show the same comparisons on a logarithmic scale.

arXiv:1802.05078



GENIE for T2K has very small RES

FIG. 17. The extracted differential cross section as a function of the single transverse variables compared to: the GENIE 2.12.4 simulation (**left**) and the GiBUU 2016 simulation (**right**). GENIE uses the Bodek and Richie RFG initial state model and this prediction also includes GENIE's empirical 2p2h prediction ($2p2h_E$). This GENIE prediction is similar that used as a starting point for the NOνA experiment's oscillation analyses. More details of these models can be found in Sec. IV A. The inlays on the plots show a close-up of the tail regions of δp_T and $\delta\alpha_T$.

Both GENIE taken from left column

arXiv:1802.05078

END