On the measurements of neutrino energy spectra and nuclear effects in neutrino-nucleus interactions

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Kyoto HE Seminar
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Outline

1. Introduction
2. Measuring nuclear effects w/ minimal dependence on neutrino energy
3. Measuring neutrino energy independent of nuclear effects
4. Theory predictions
5. Measurement in MINERvA
6. Measurement in T2K
7. Summary

References: arXiv:1512.05748 and 1507.00967, unless otherwise specified.

1. Probing the antimaterial world with neutrino interactions

material world

antimaterial world

violation of CP-symmetry

(to be found)

⇑

leptonic CP violation

1. Probing the antimaterial world with neutrino interactions

material world

antimaterial world

violation of CP-symmetry

(to be found)

$\Uparrow$

ν

$\bar{\nu}$

leptonic CP violation

$P\left(\nu_\mu \to \nu_e\right)$ $=, \neq, \neq$ $P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$

1. Probing the antimaterial world with neutrino interactions

material world

antimaterial world

violation of CP-symmetry

(to be found)

accelerator

ν

$\bar{\nu}$

detector

$P\left(\nu_{\mu} \to \nu_{e}\right)$

$=, \neq, \neq$

$P\left(\bar{\nu}_{\mu} \to \bar{\nu}_{e}\right)$

1. Probing the antimaterial world with neutrino interactions

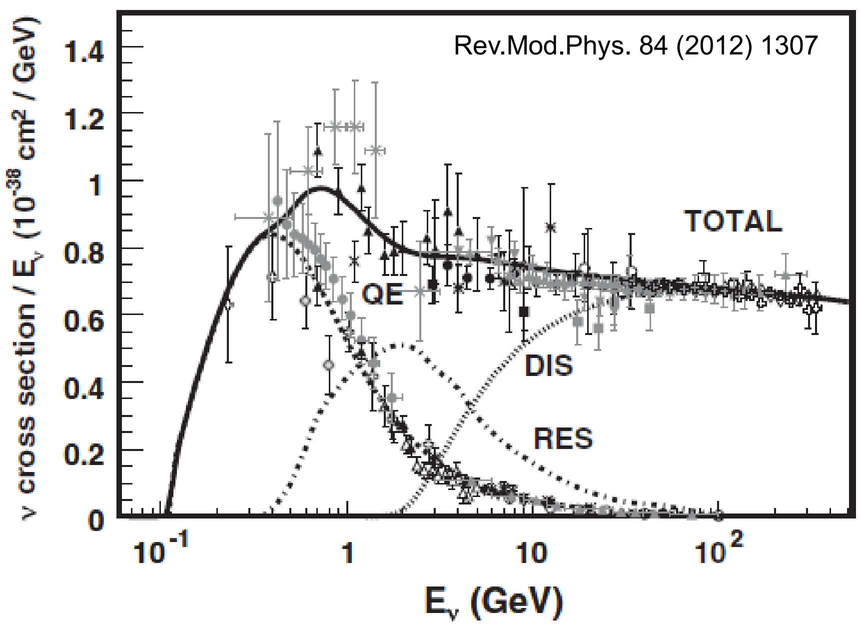
ν → detector ← $\bar{\nu}$

Quasi-elastic scattering (QE):

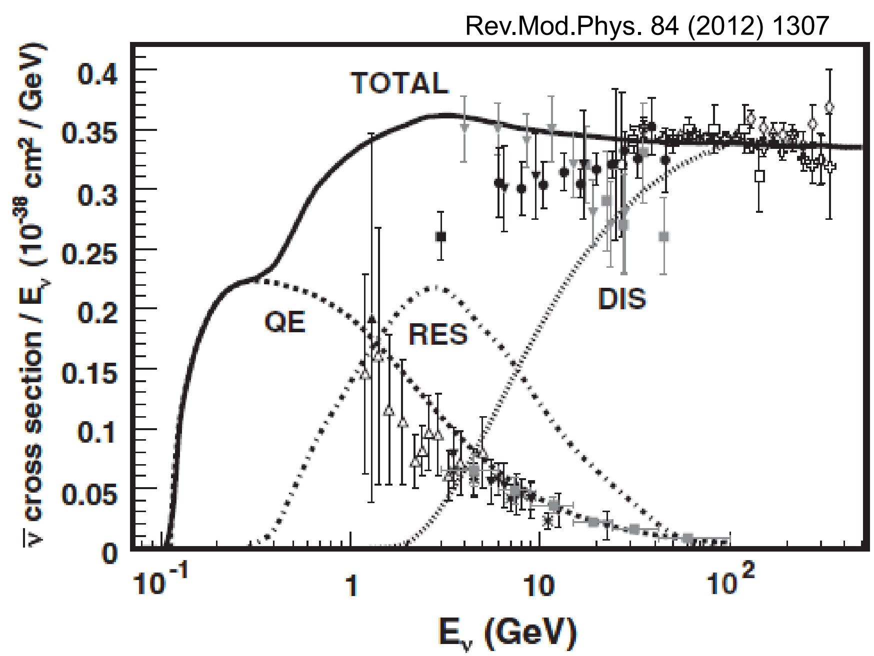
$$\nu \mathrm{n} \rightarrow \ell^- \mathrm{p}$$

Resonance production (RES):

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



$\neq$



Charged-current cross section per nucleon

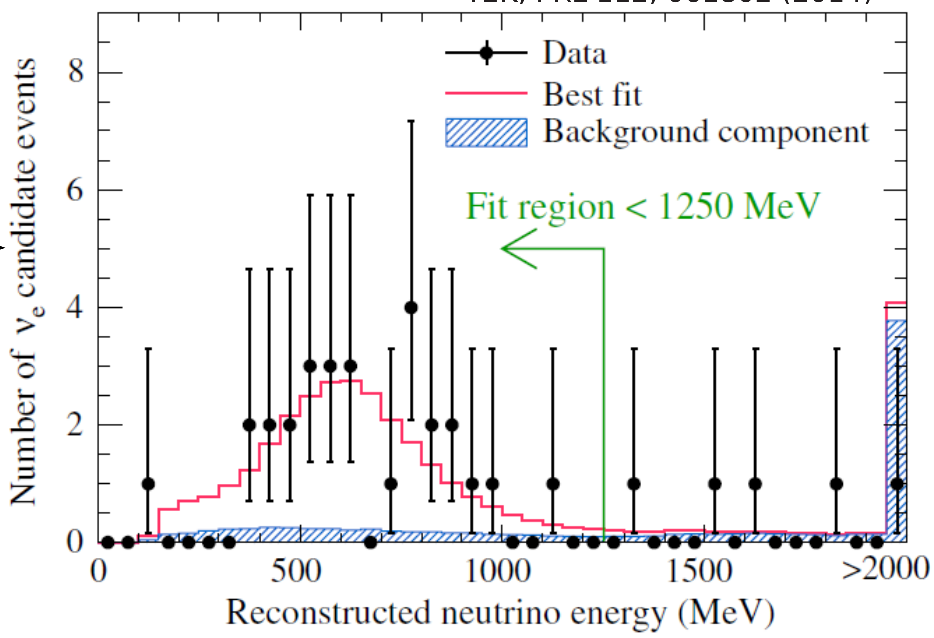
1. Probing the antimaterial world with neutrino interactions

detector

$$P\left(\nu_\mu \rightarrow \nu_e\right)$$

$$P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$$

T2K, PRL 112, 061802 (2014)

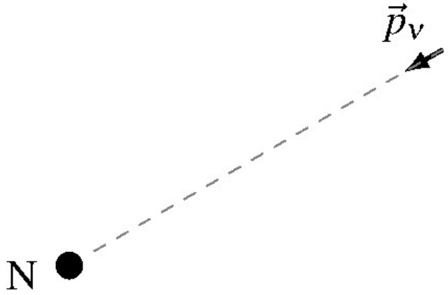


Neutrino energy reconstruction

Convert to flux via cross section

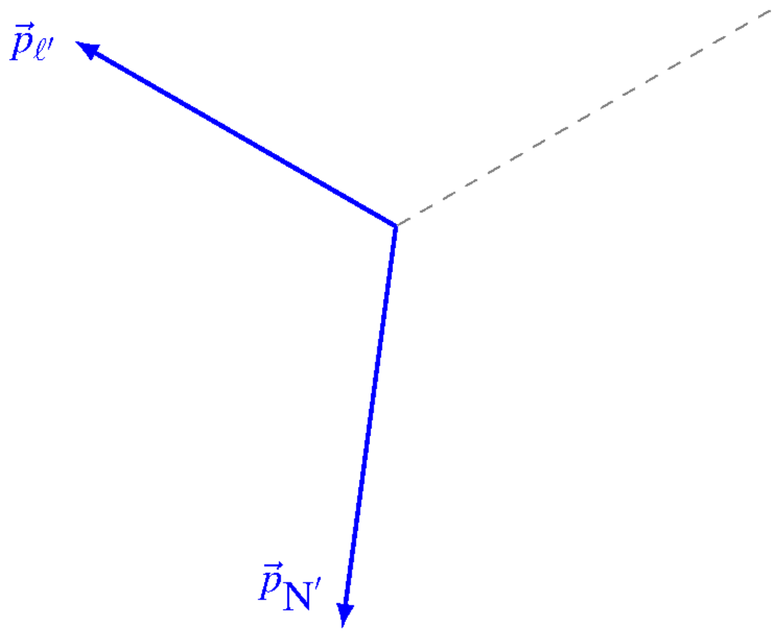
1. Neutrino interactions on static nucleon

- Static nucleon target



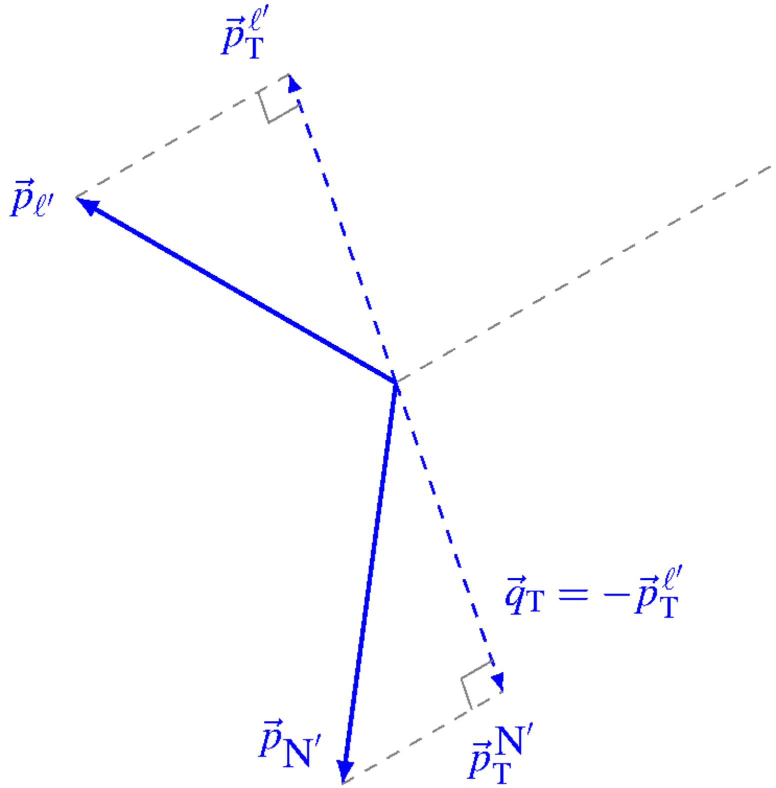
1. Neutrino interactions on static nucleon

- Static nucleon target, charged current (CC) ν → *l'*, quasi-elastic (QE) N → N'
  - Detection via charged lepton
  - Neutrino energy ← charged lepton kinematics



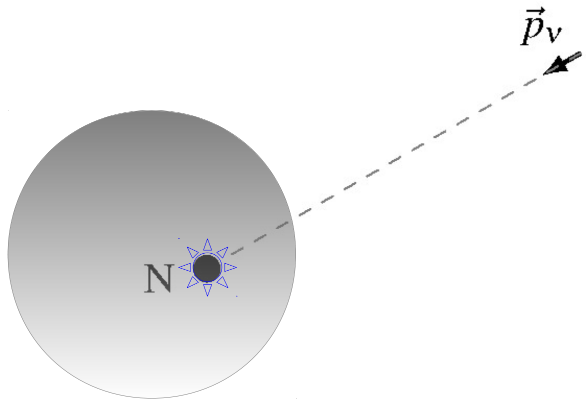
1. Neutrino interactions on static nucleon

- Static nucleon target, charged current (CC) ν → *l′*, quasi-elastic (QE) N → N'
  - Detection via charged lepton
  - Neutrino energy ← charged lepton kinematics
  - Lepton and hadron transversely balanced



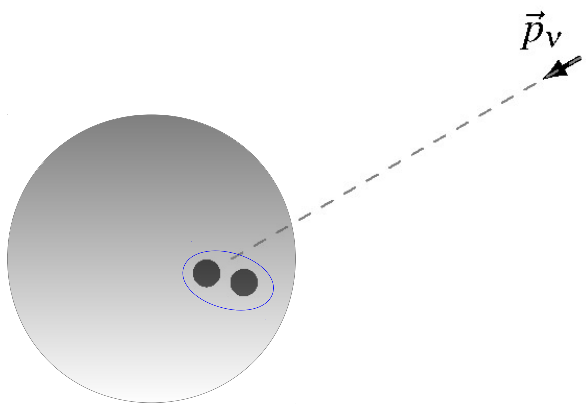
1. Neutrino interactions on bound nucleon

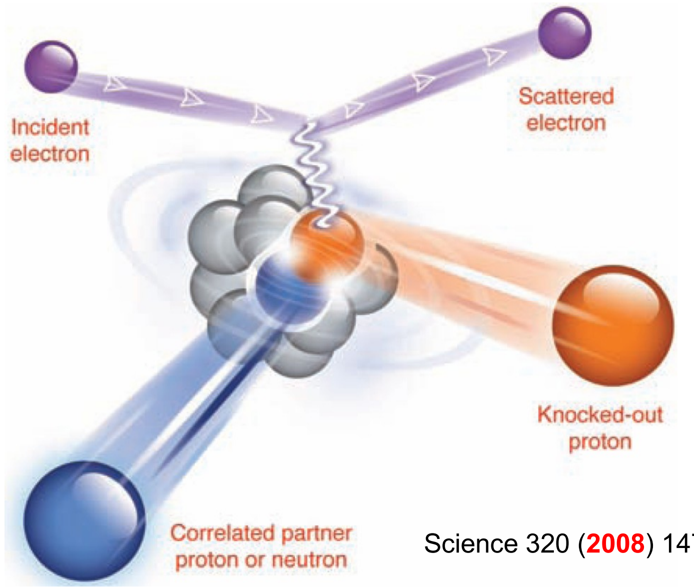
- Nucleus (bound nucleon) target
  - Fermi motion (FM) biases neutrino energy reconstruction



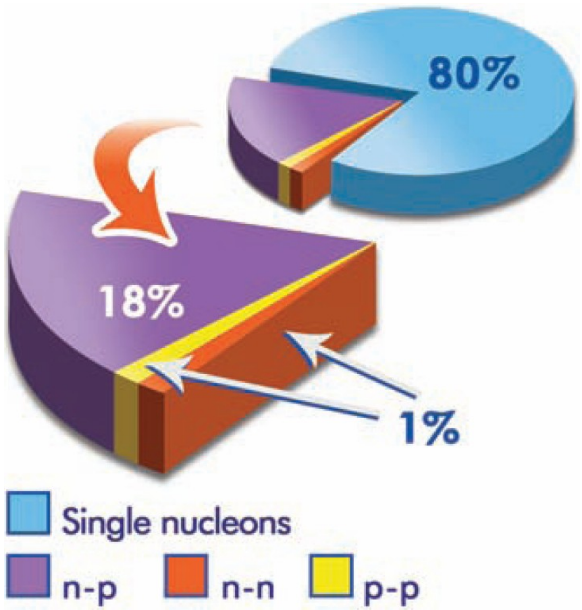
1. Neutrino interactions on bound nucleon

- Nucleus (bound nucleon) target
  - Fermi motion (FM) biases neutrino energy reconstruction
  - Multinucleon correlations: cross section unknown, strong bias to *all* final state kinematics





Science 320 (**2008**) 1476-1478



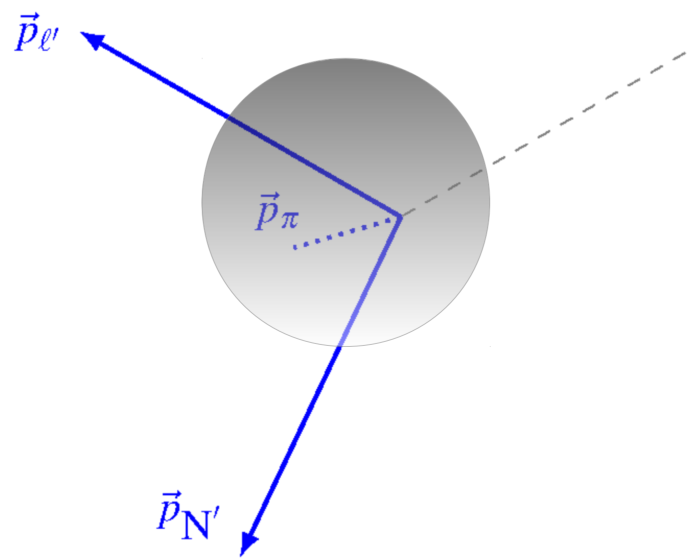
initial nucleon in correlation with another in large relative motion

Properties largely unknown, for simplicity no further discussion here. See more detail in arXiv:1512.05748.

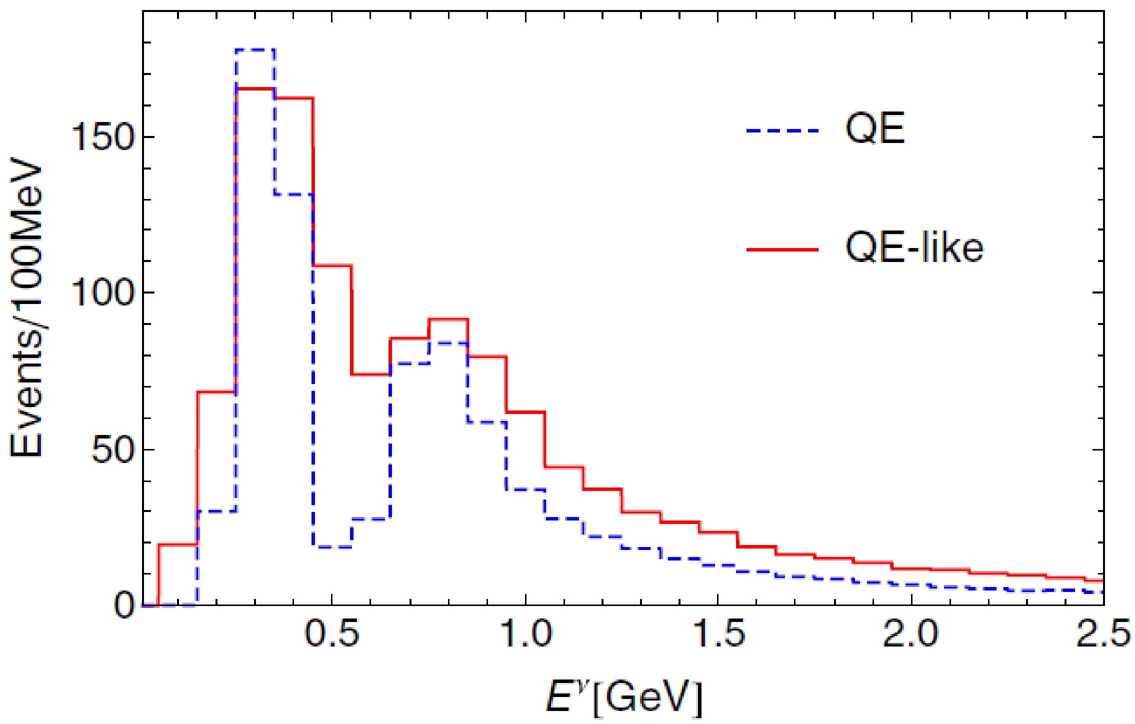
1. Neutrino interactions on bound nucleon

- Nucleus (bound nucleon) target, CC $\nu \to l'$, QE $N \to N'$
  - Fermi motion (FM) biases neutrino energy reconstruction
  - Multinucleon correlations: cross section unknown, strong bias to *all* final state kinematics
  - QE-like: QE faked by resonance production (RES) $\Delta \to N'\pi$

    π absorbed in nucleus $\leftarrow$ final state interaction (FSI)

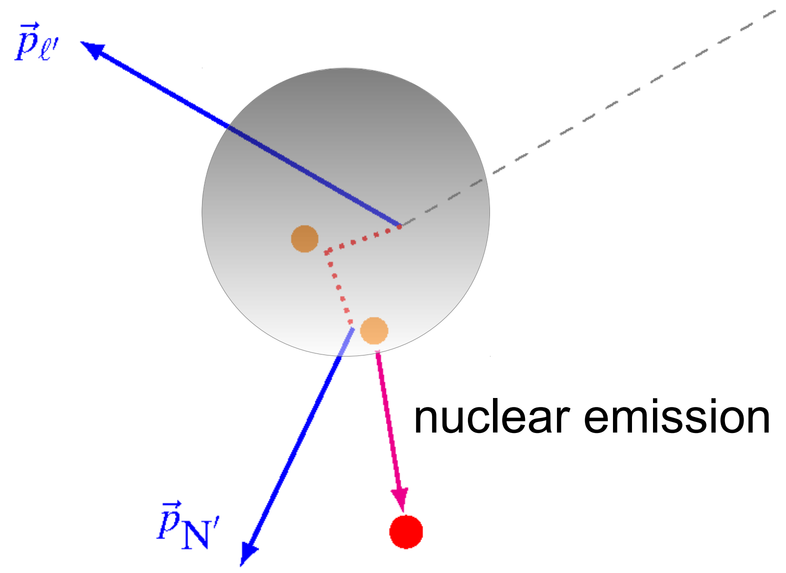


PRL 111, 221802 (2013)



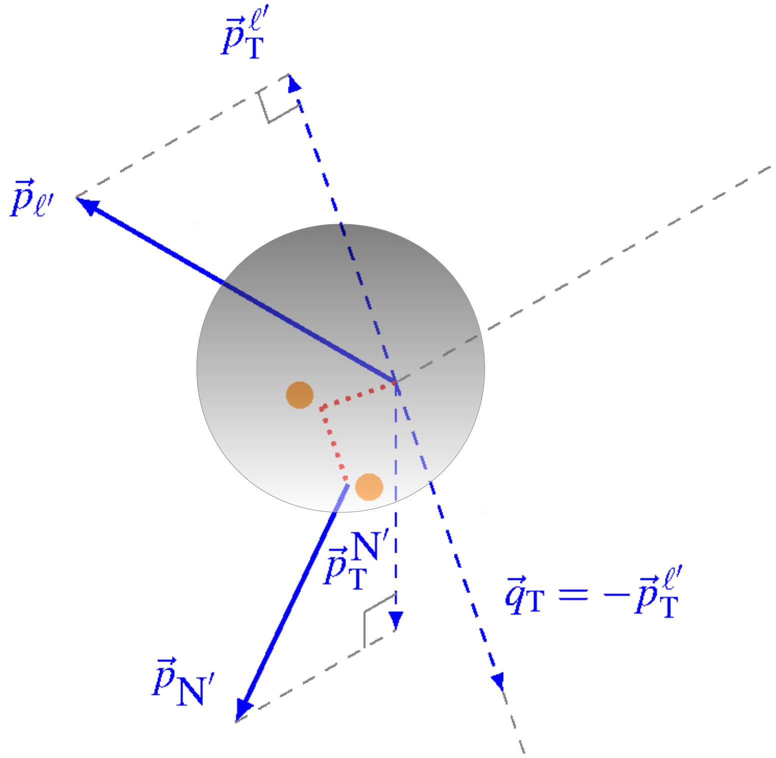
1. Neutrino interactions on bound nucleon

- Nucleus (bound nucleon) target, CC $\nu \rightarrow l'$, QE N → N'
  - Fermi motion (FM) biases neutrino energy reconstruction
  - Multinucleon correlations: cross section unknown, strong bias to *all* final state kinematics
  - QE-like: QE faked by resonance production (RES) $\Delta \rightarrow N'\pi$
    π absorbed in nucleus ← final state interaction (FSI)
  - FSI → energy-momentum transferred in nucleus, possible nuclear emission



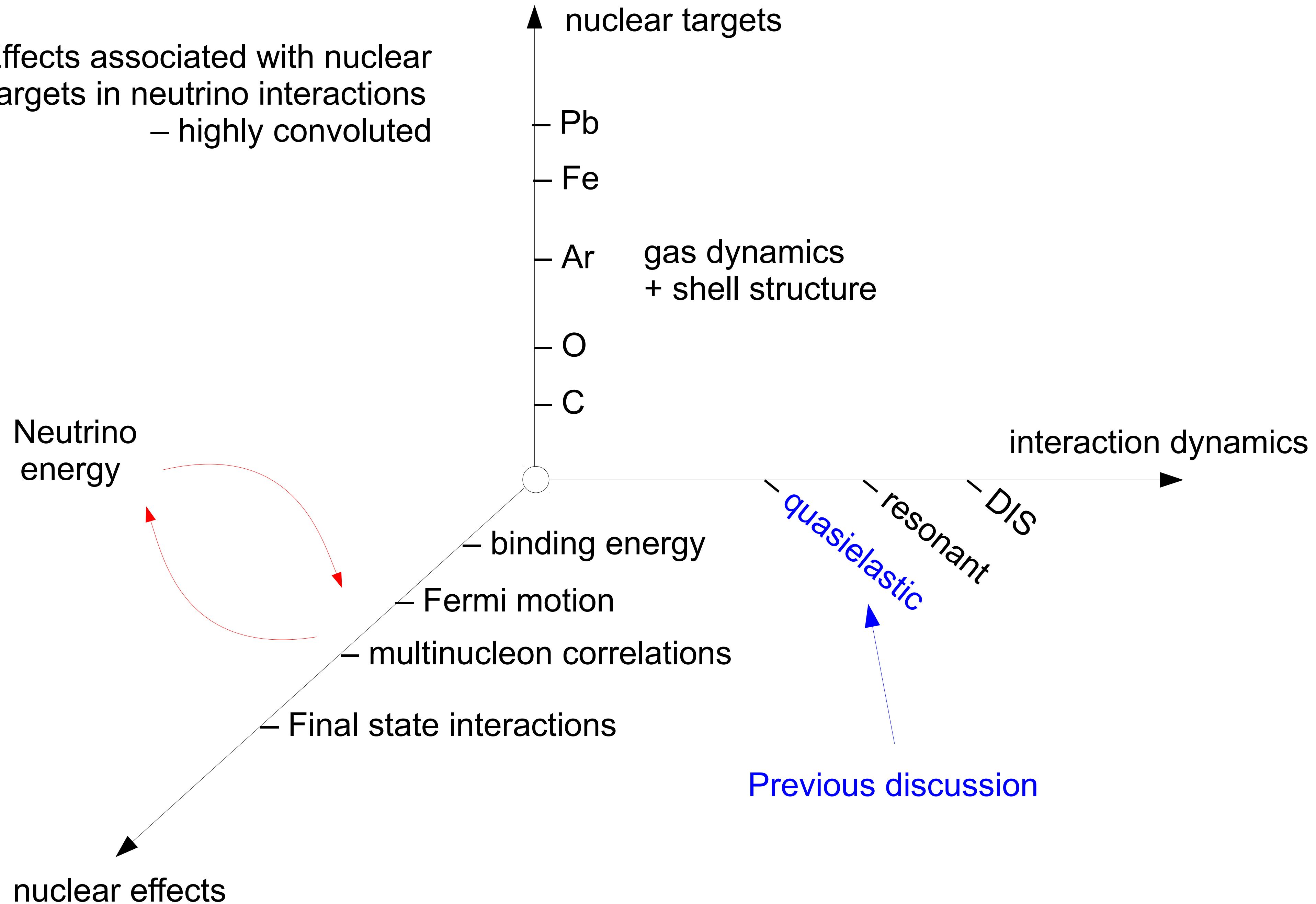
1. Neutrino interactions on bound nucleon

- Nucleus (bound nucleon) target
  - Nuclear effects: FM, multinucleon correlations, FSI, etc.
  - Transverse momenta **NOT** balanced



1. Nuclear effects in neutrino interactions

Effects associated with nuclear targets in neutrino interactions – highly convoluted

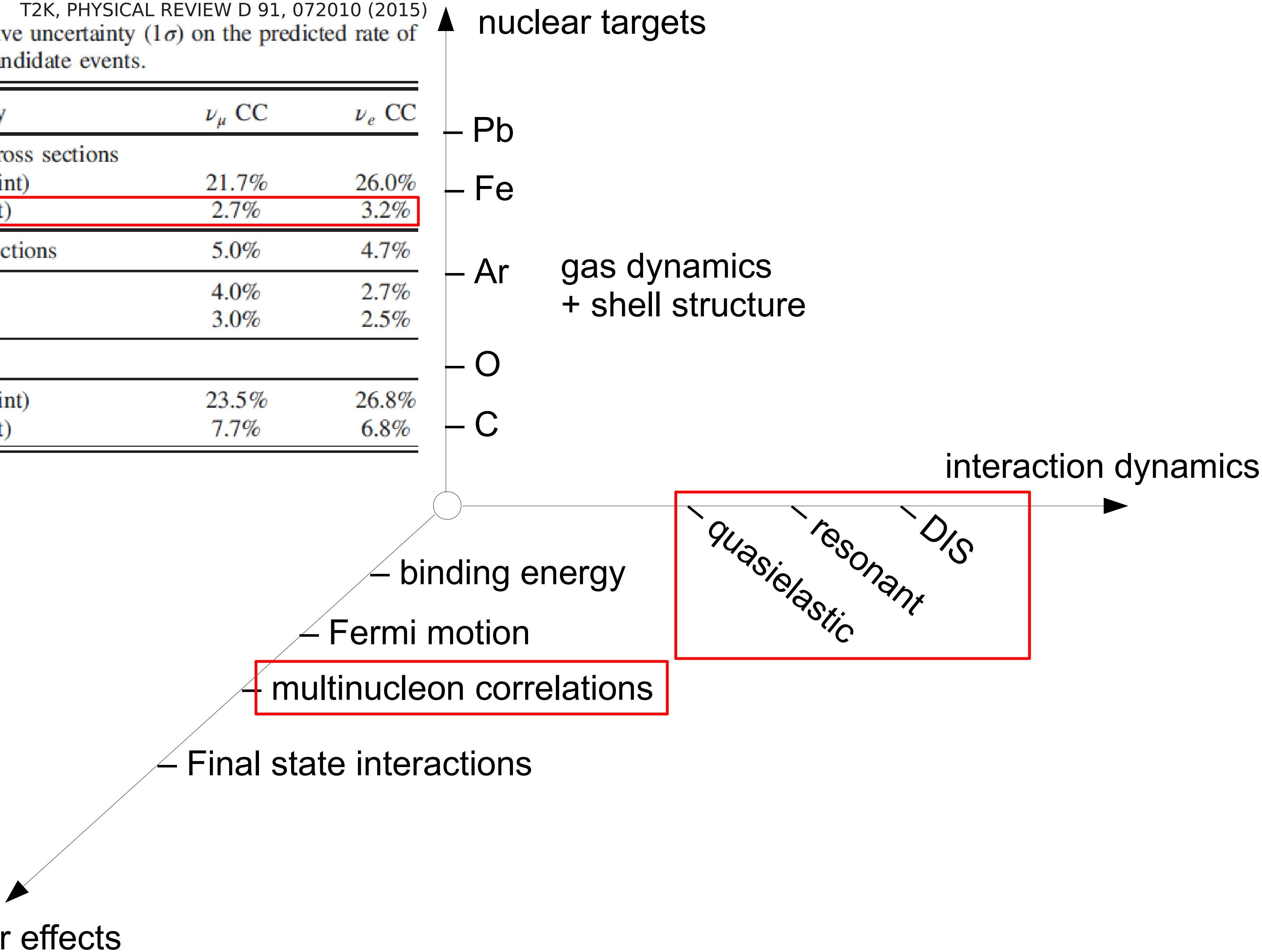


1. Nuclear effects in neutrino interactions

T2K, PHYSICAL REVIEW D 91, 072010 (2015)

TABLE XX. Relative uncertainty (1σ) on the predicted rate of ν_μ CC and ν_e CC candidate events.

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI + SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%



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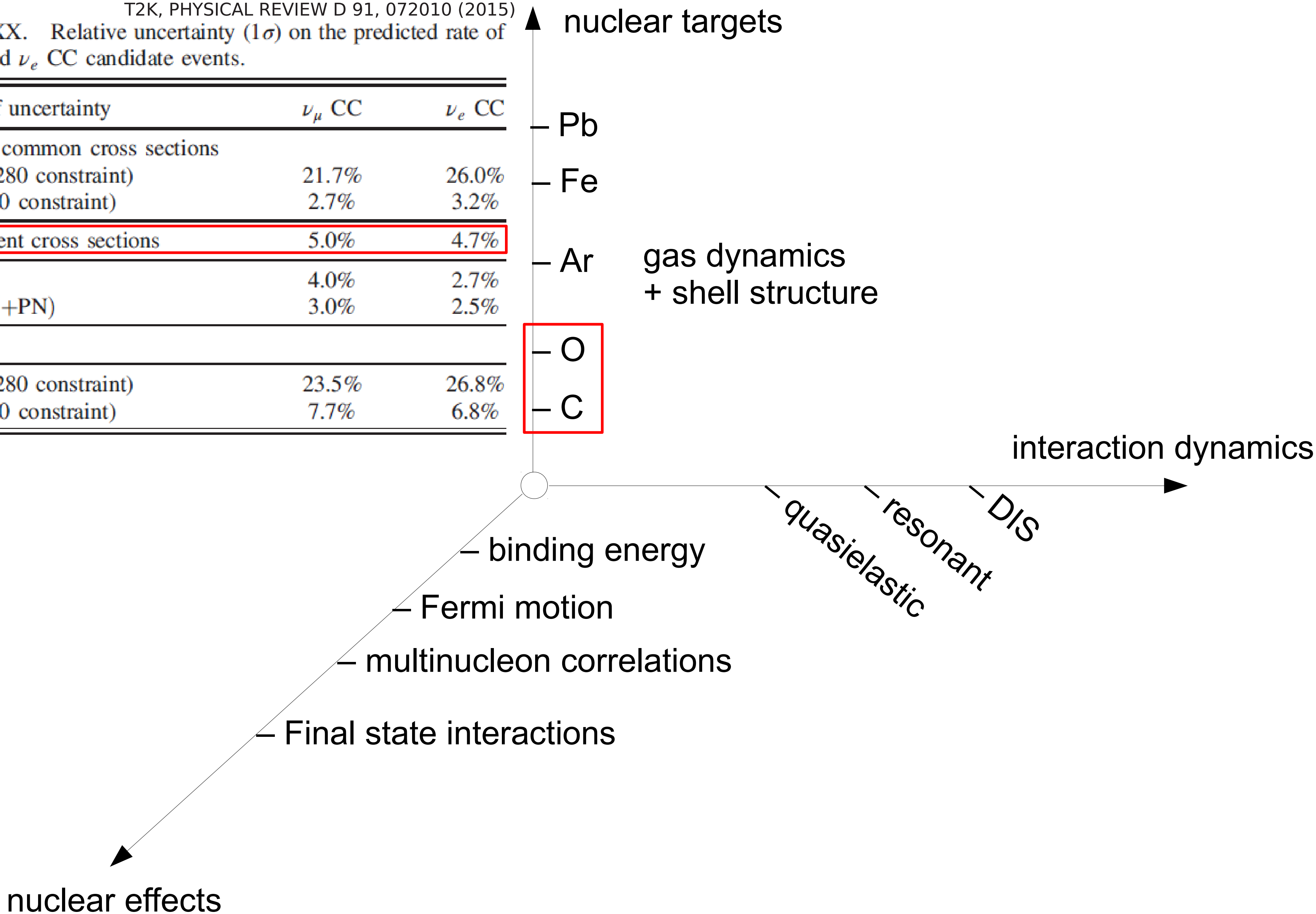

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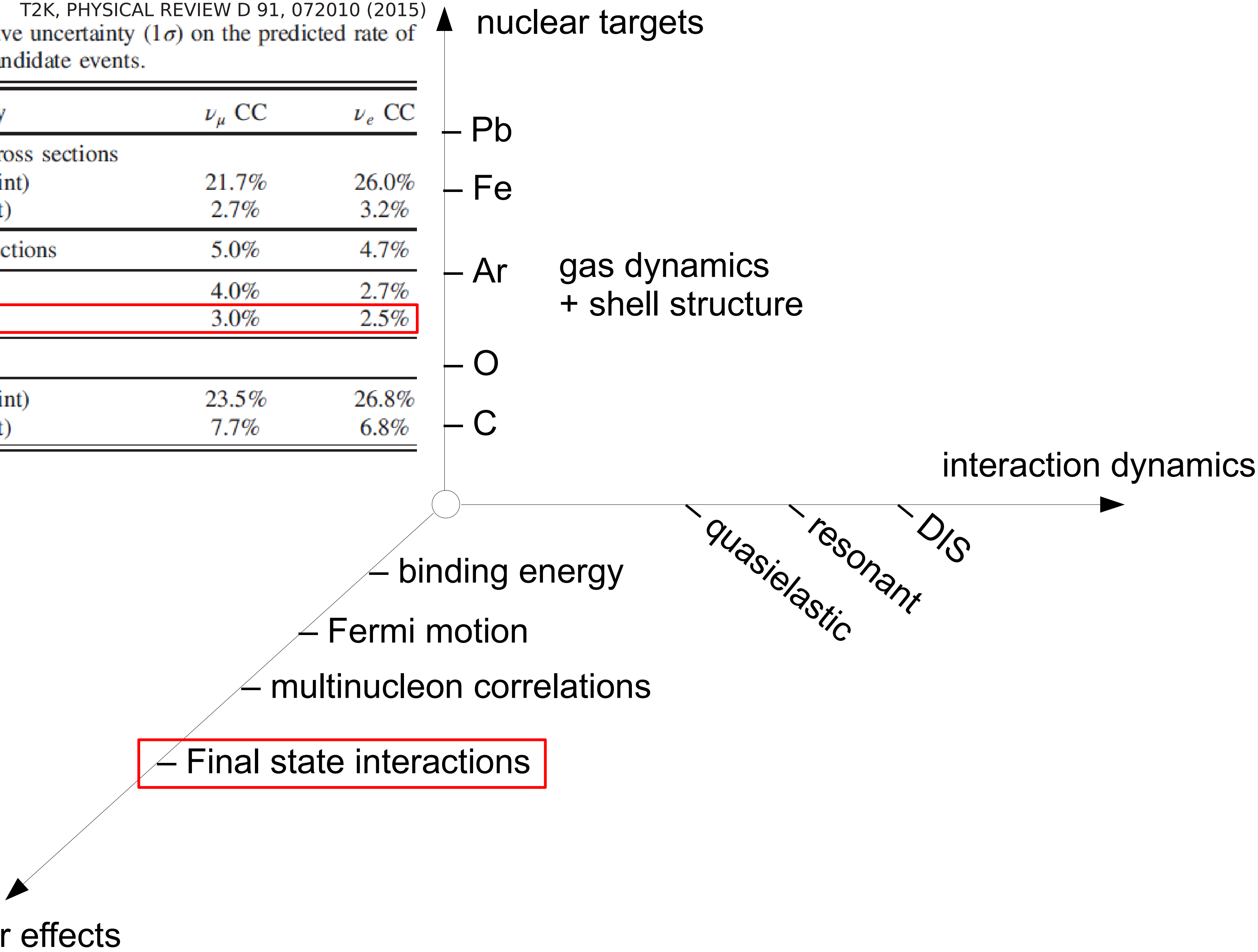
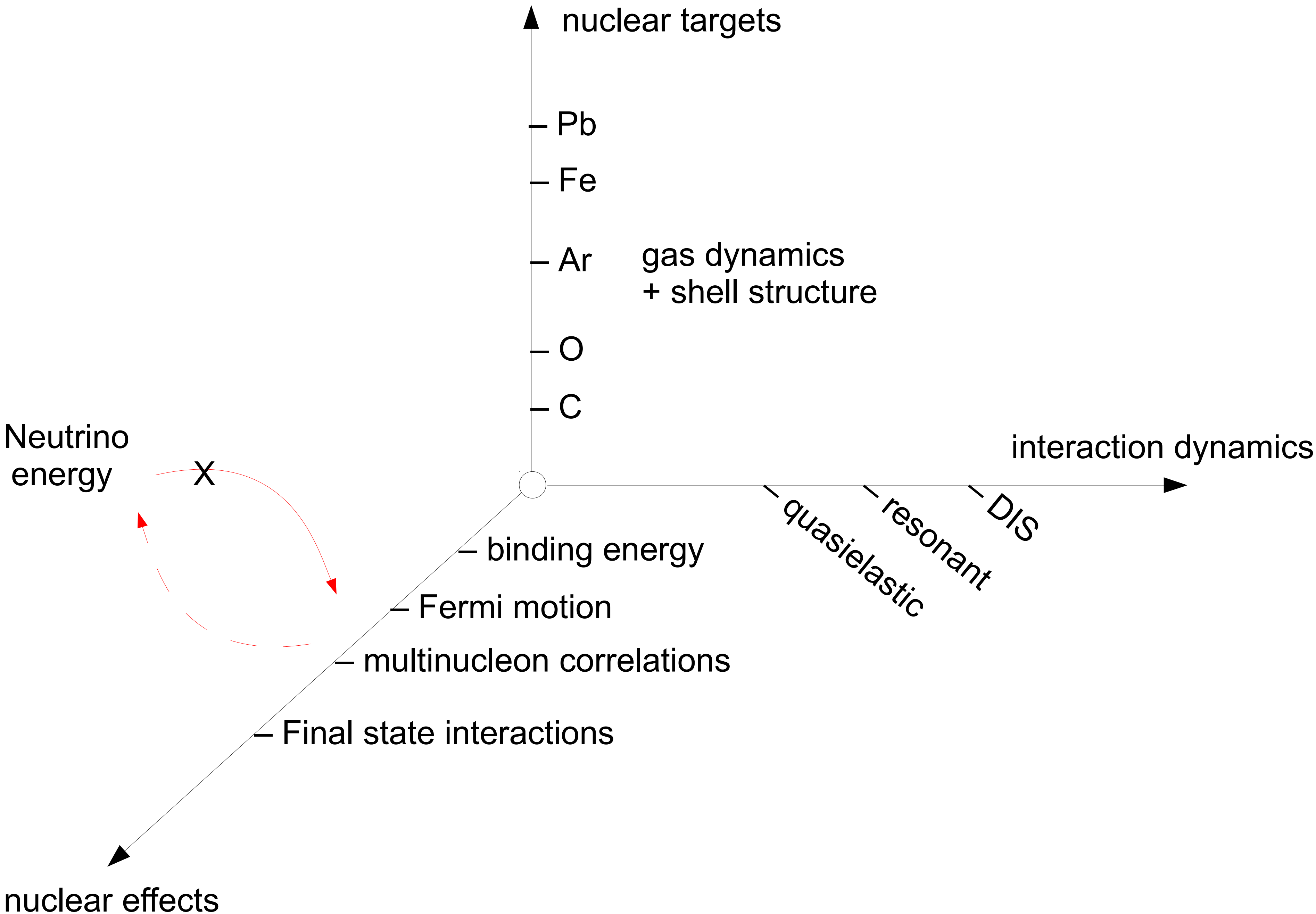
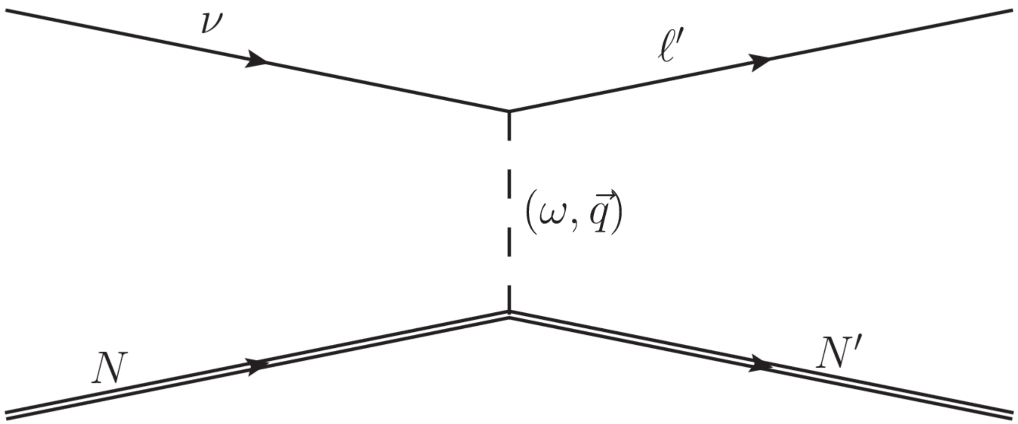


Outline

2. Minimal energy dependent measurement of nuclear effects



2. Energy dependence of final state kinematics



4-momentum transfer: Q^2
Invariant mass of N': W
Ignoring binding energy,

$$\omega \sim \frac{Q^2 + W^2 - m_{\rm N}^2}{2\sqrt{m_{\rm N}^2 + p_{\rm N}^2}}$$

($p_{\rm N}^2/2m_{\rm N}^2 \simeq 2\%$ effect of Fermi motion)

Quasi-elastic scattering (QE):

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

Resonance production (RES):

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

For QE and RES, $Q^2 << m_N^2$ (interaction length)
W is nucleon or resonance mass.
ω "saturates" when $E_\nu > O(m_N/2)$

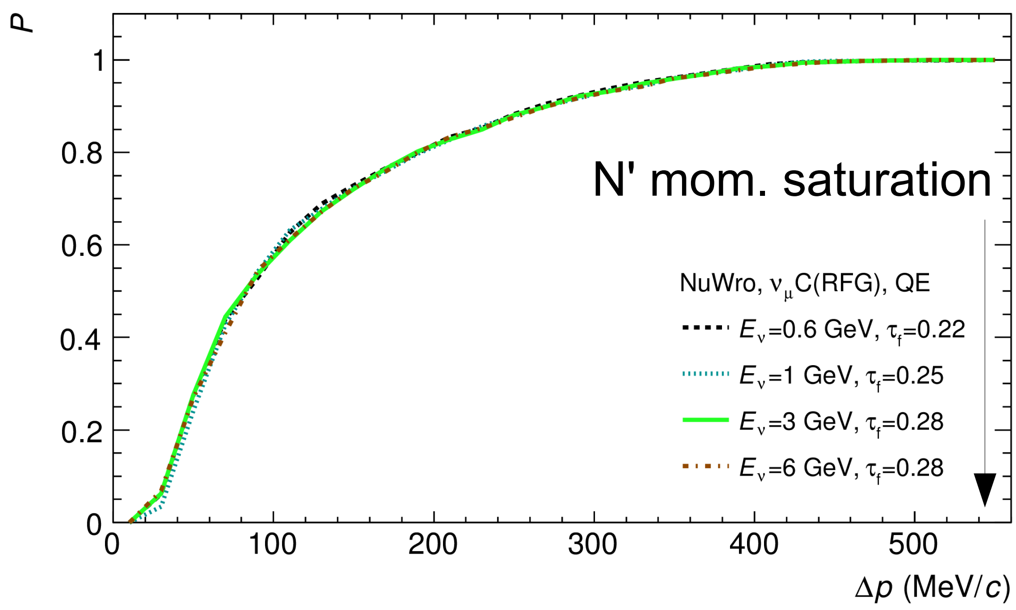
- Lepton retains most of the increase of neutrino energy
- Hadronic kinematics much less E_ν-dependent than leptonic ones

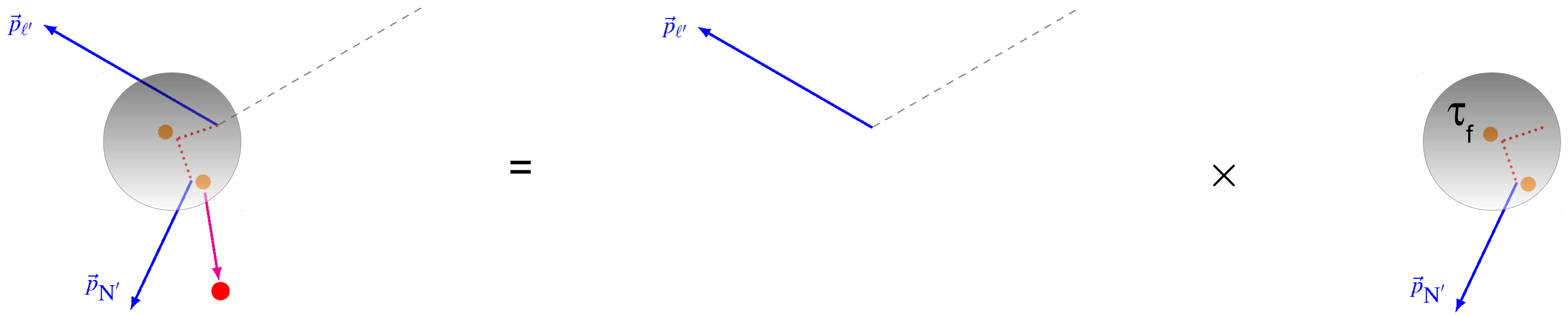
2. Energy dependence of nuclear medium response

N' mom. saturates with large neutrino energy.

FSI all determined by N' momentum:

1. In-medium interaction probability τ_f saturates





2. Energy dependence of nuclear medium response

N' mom. saturates with large neutrino energy.

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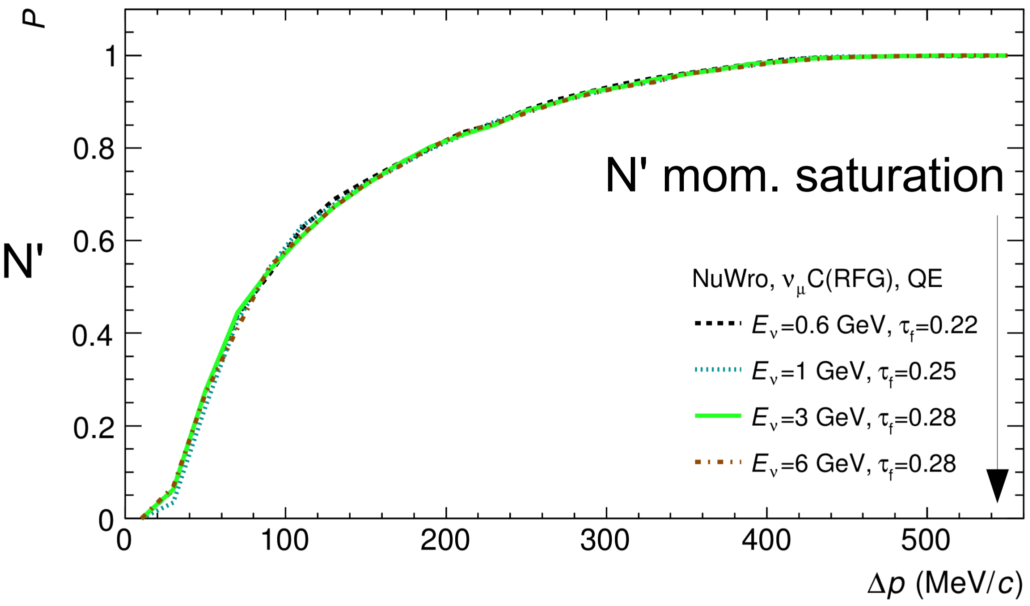
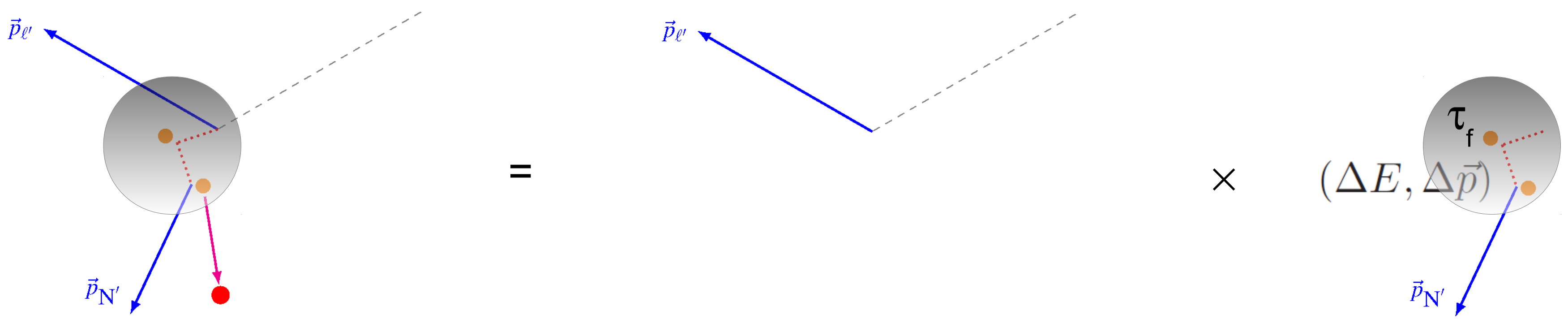
1. In-medium interaction probability τ_f saturates
2. Energy-momentum transfer $(\Delta E, \Delta \vec{p})$ from N' to the nucleus also saturate





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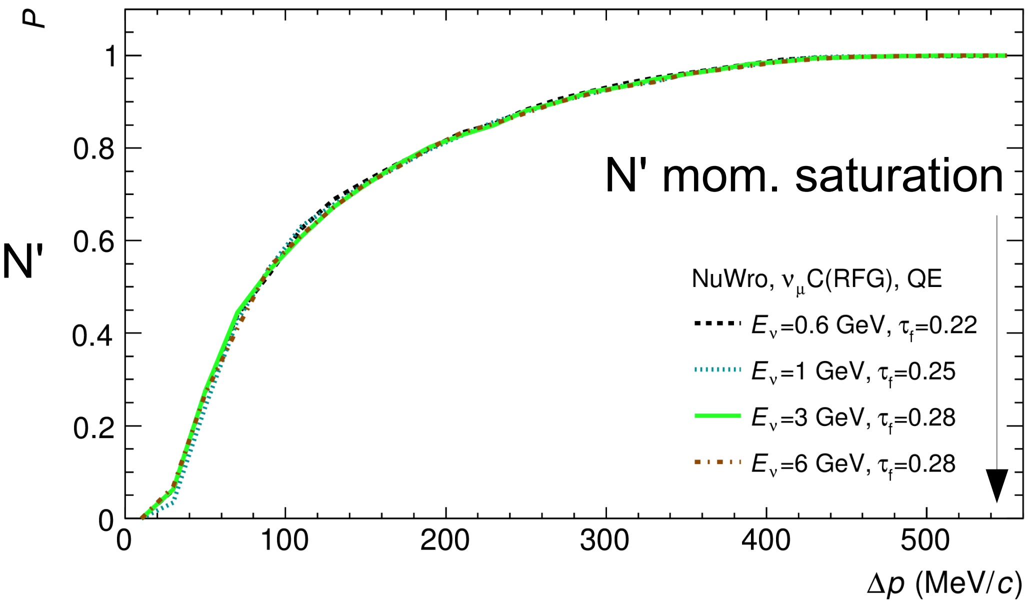
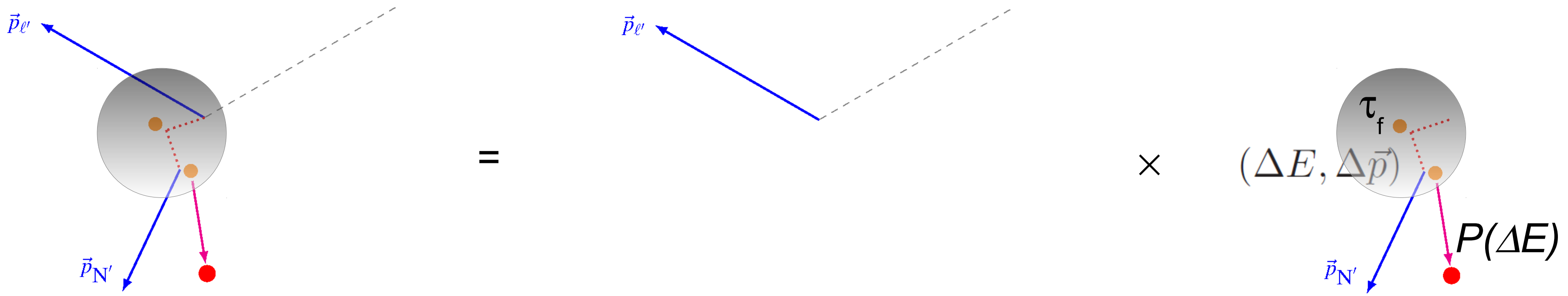
Medium response:
Nuclear emission: nucleus being excited or broken-up, emitting particles.
Probability: *P(ΔE)*





2. Energy dependence of nuclear medium response

N' mom. saturates with large neutrino energy.

FSI all determined by N' momentum:

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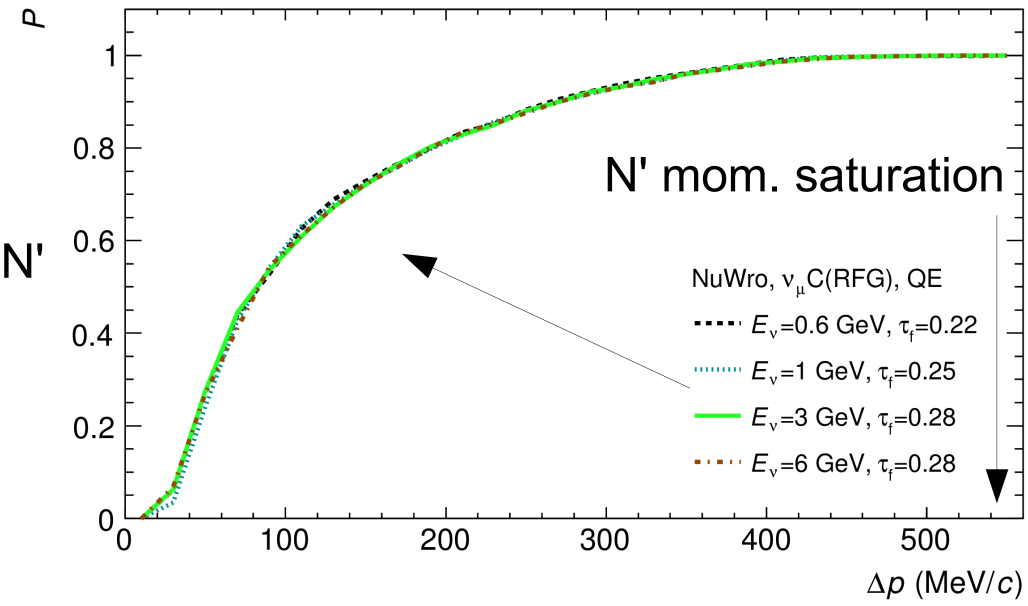
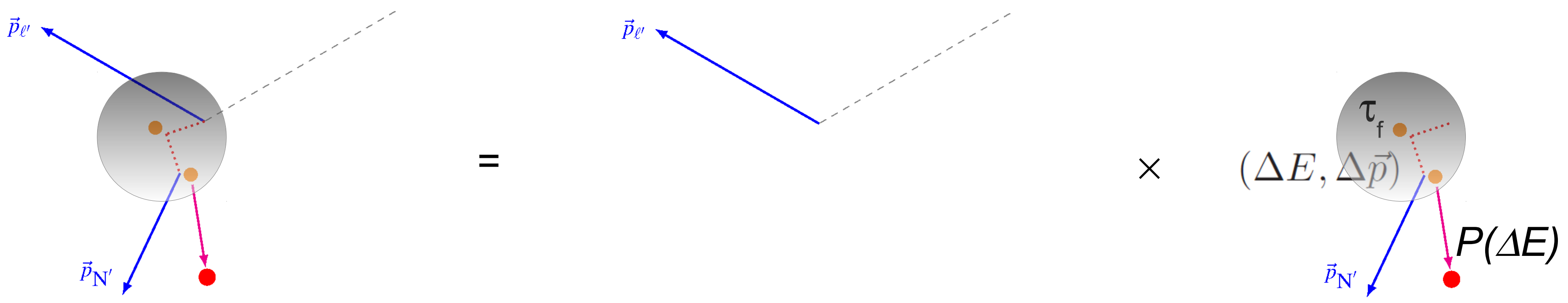


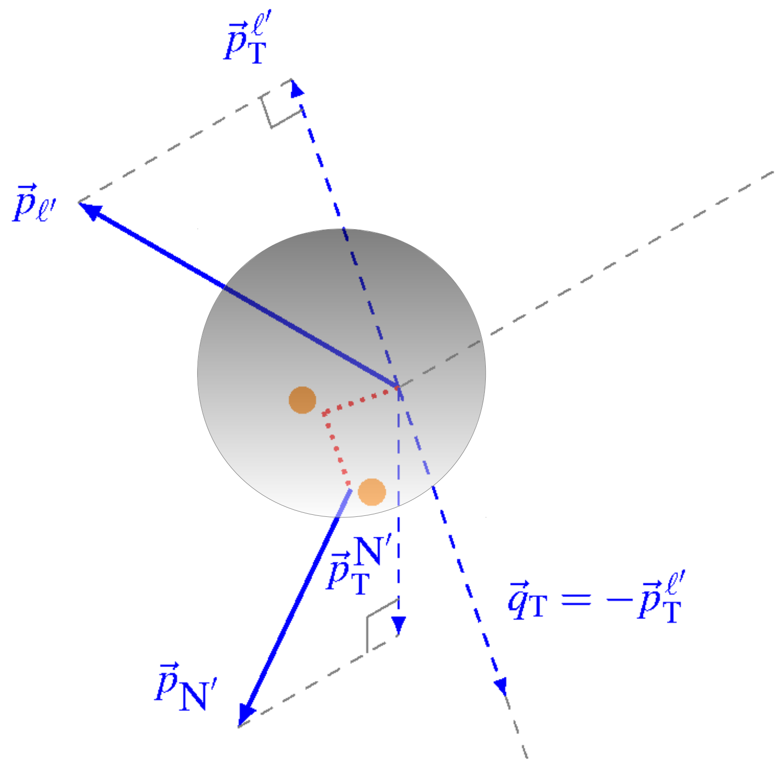
- $(\Delta E, \Delta\vec{p})$ fully determine nuclear response – ideal variables to characterize FSI.



2. State-of-the-art probes of nuclear effects

- Neutrinos produced by accelerators have well understood directions.
- Momentum conservation applies in all directions of the neutrino-**nucleus** interaction system.

→ neutrino-**nucleon** kinematic imbalance
=
nuclear effects



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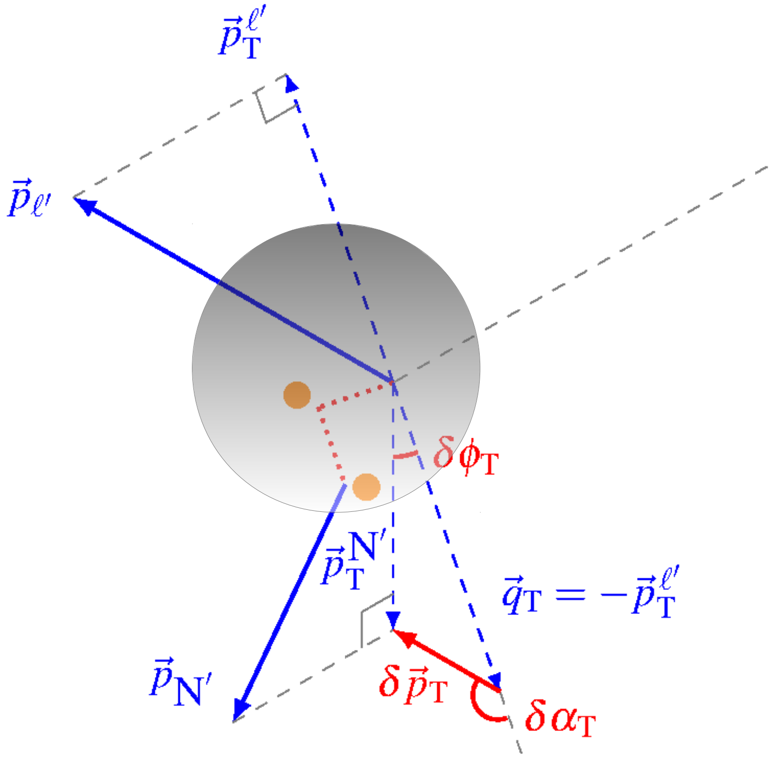
→ neutrino-**nucleon** kinematic imbalance
=
nuclear effects

- Neutrino energy unknown, use transverse projection

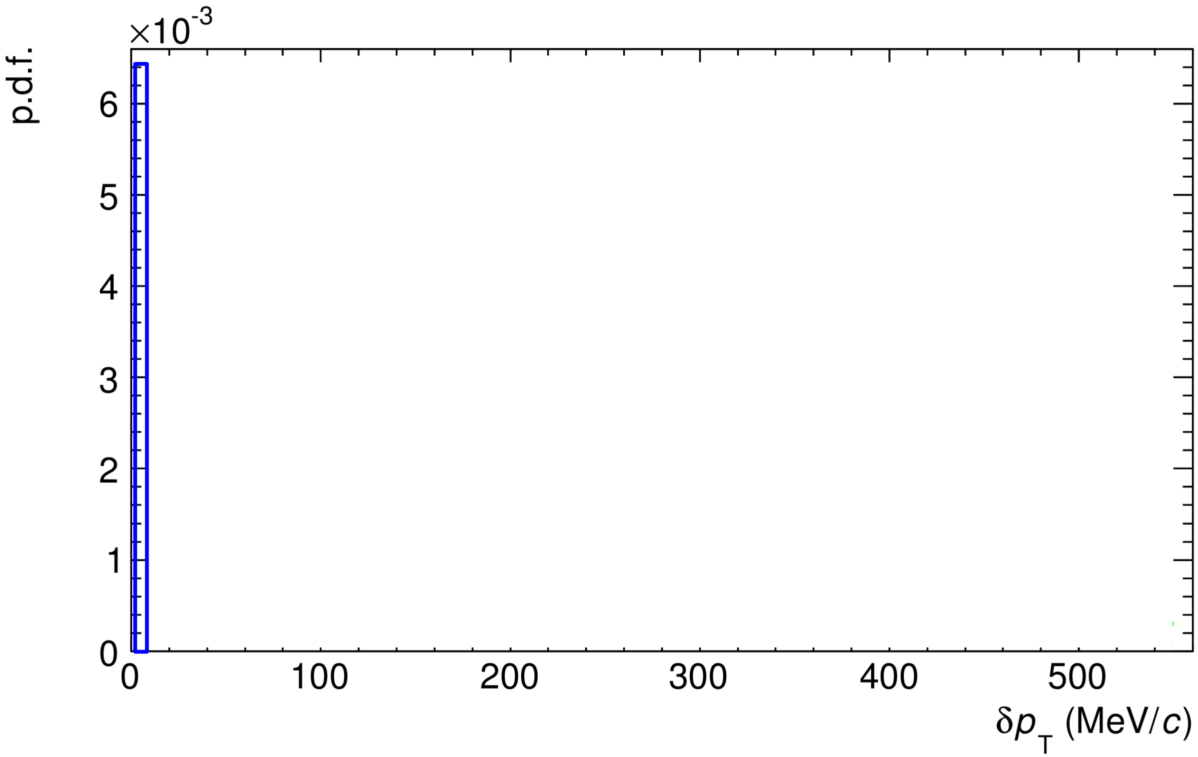
$$\rightarrow \delta\vec{p}_\mathrm{T} = \vec{p}_\mathrm{T}^{\mathrm{N}} - \Delta\vec{p}_\mathrm{T}$$

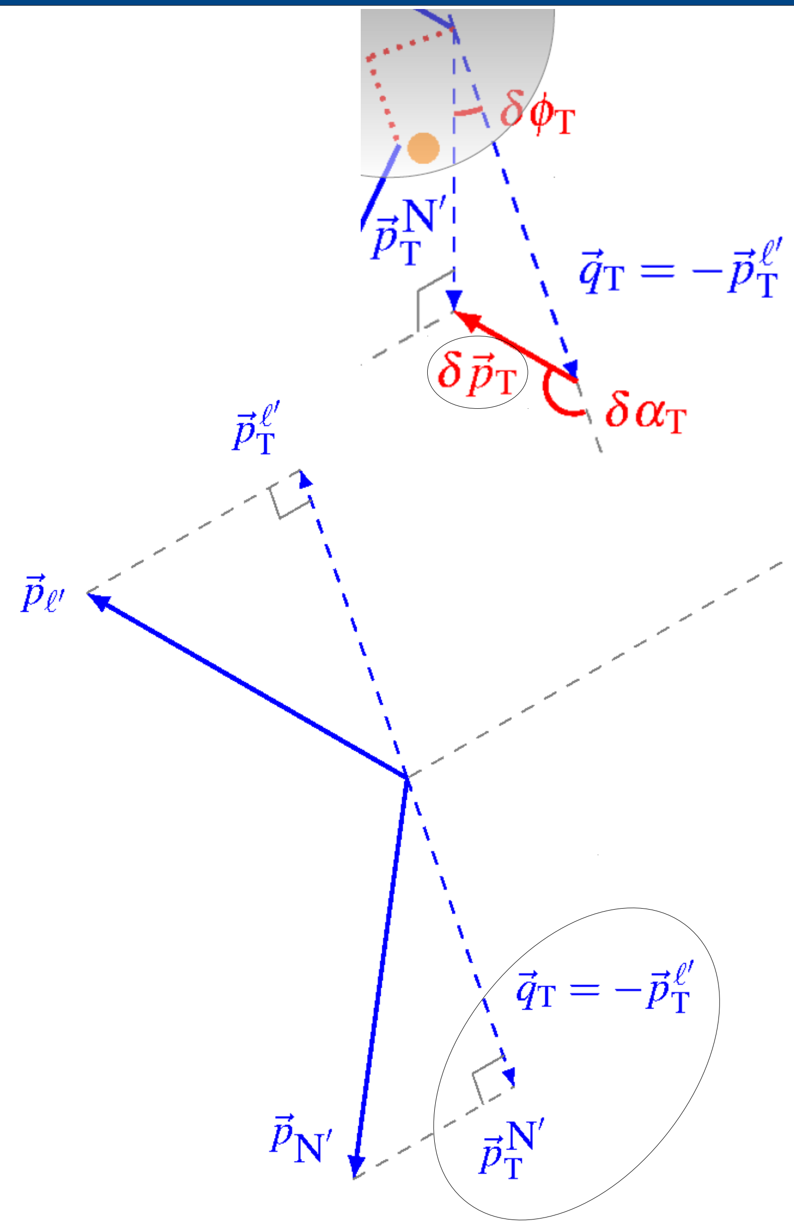
To first order, nuclear effects can be determined independently on neutrino energy.



2. State-of-the-art probes of nuclear effects

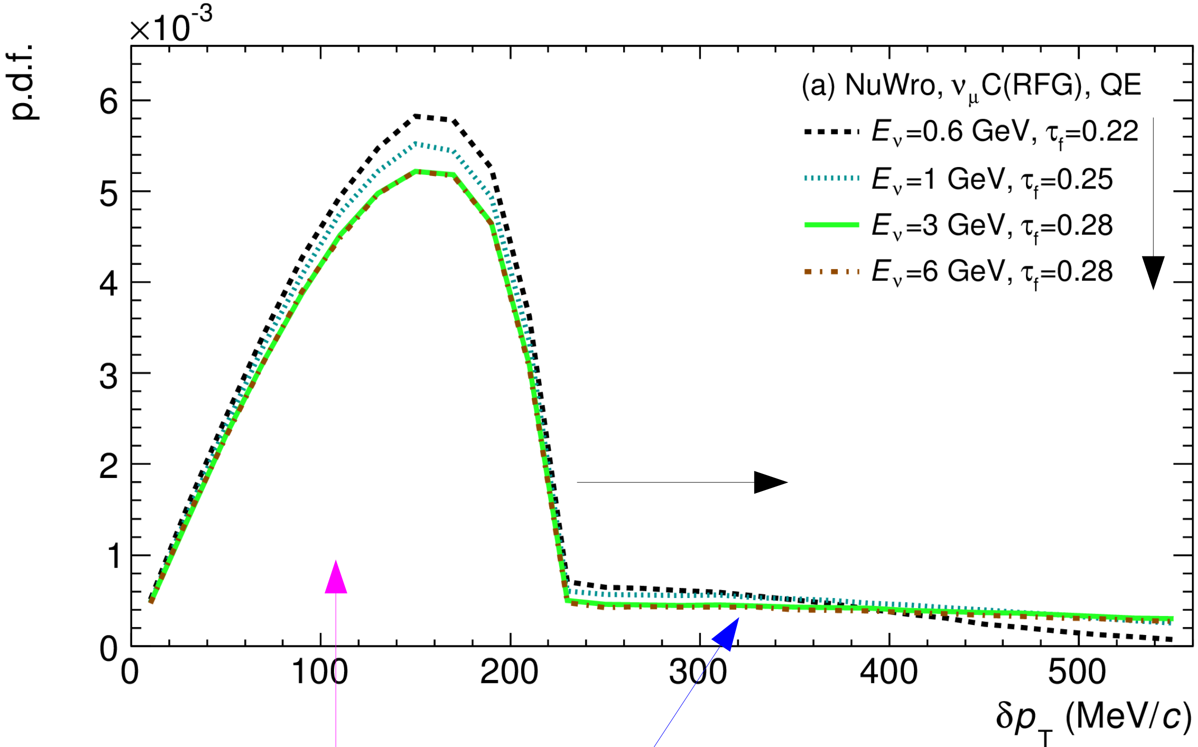
No nuclear effects

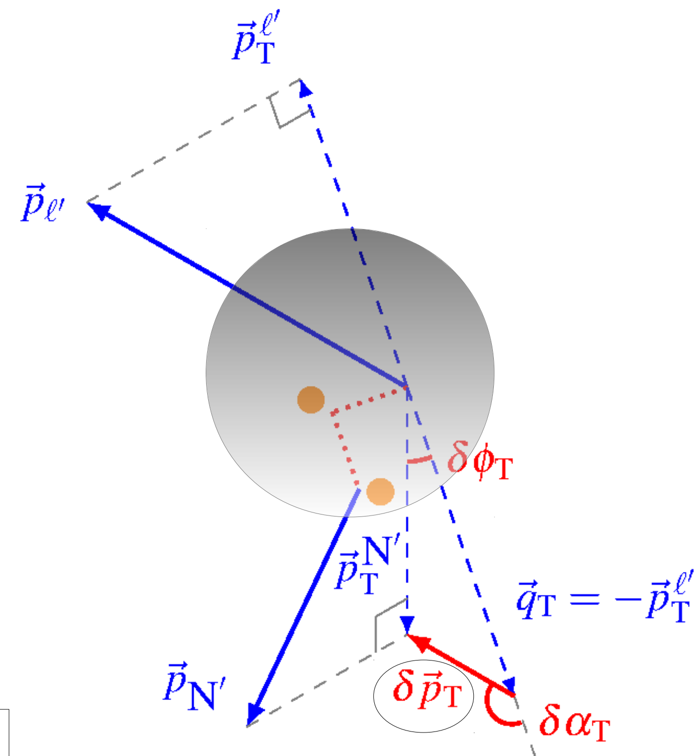




2. State-of-the-art probes of nuclear effects

Limited energy evolution with FSI strength





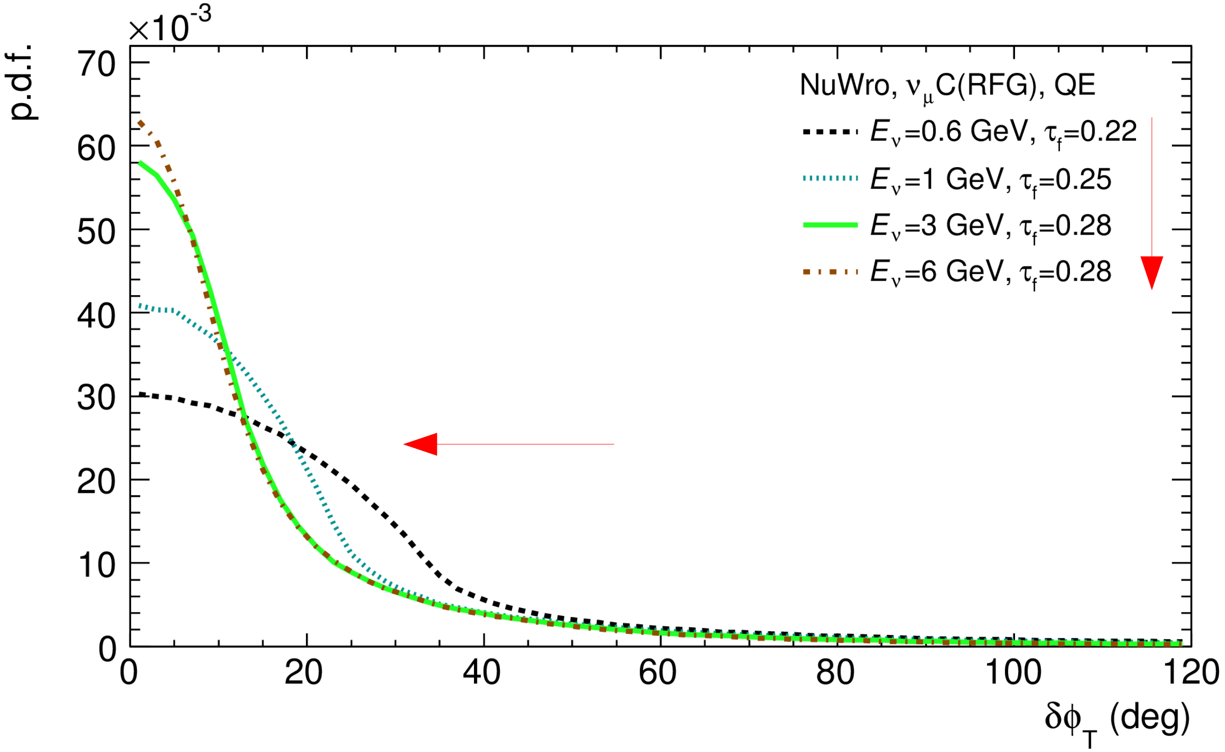
$\delta\vec{p}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\mathrm{N}} - \Delta\vec{p}_{\mathrm{T}}$ *invariant w/* ***neutrino energy***

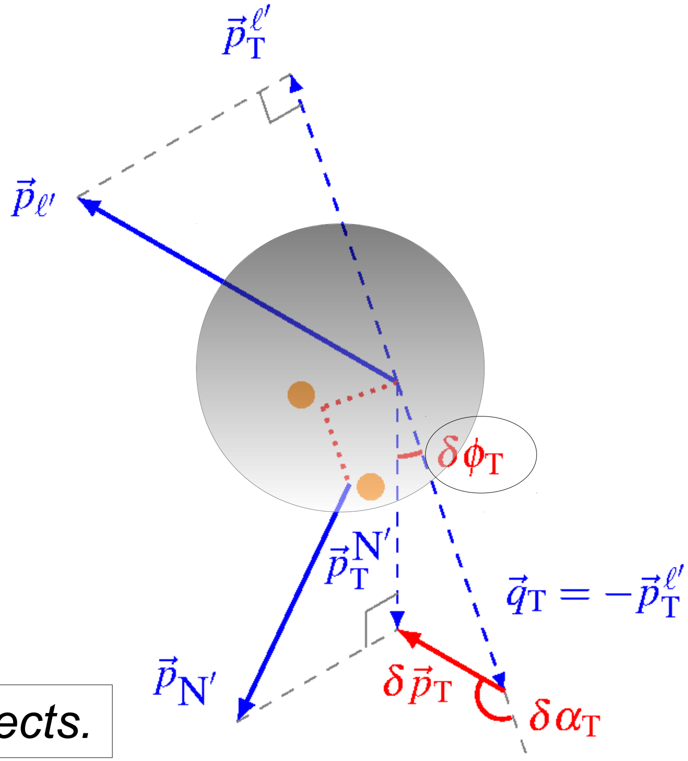
FM

FSI

Counterexample

Strong – inverted – energy evolution contains lepton kinematics $\delta\phi_T \sim \delta p_T/q_T$

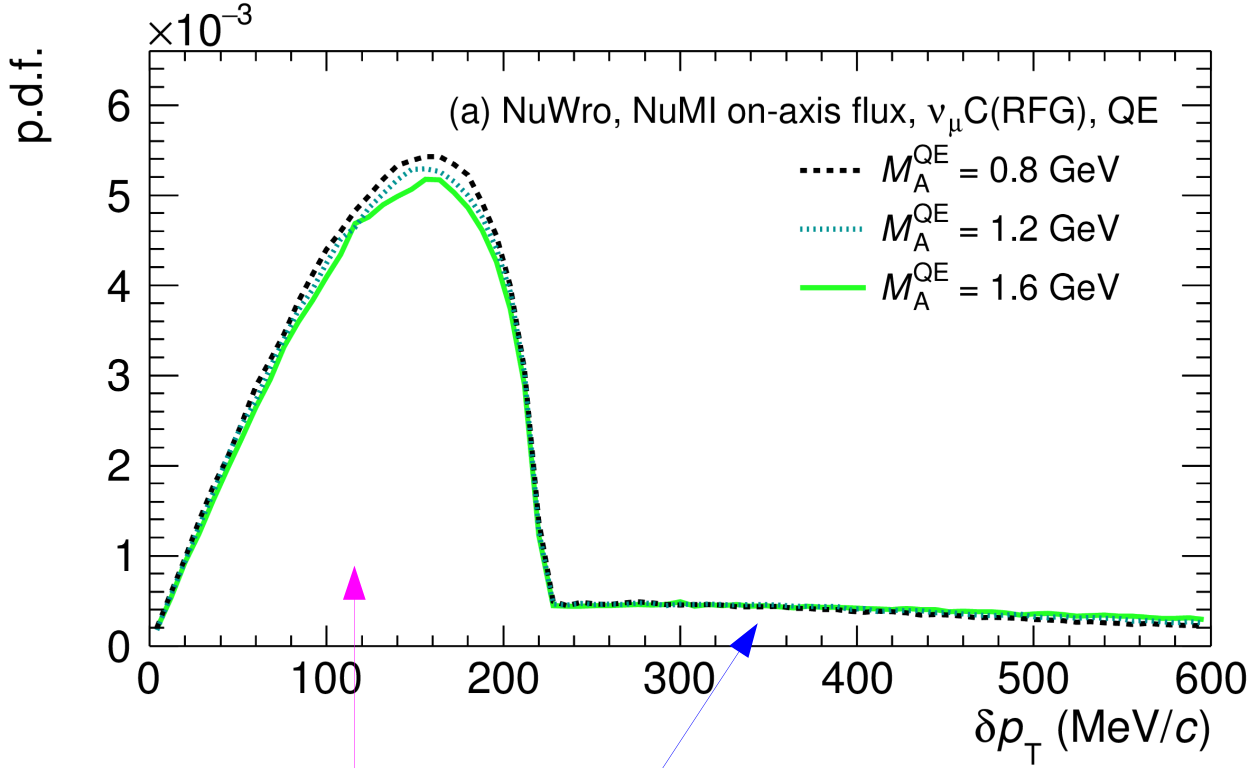


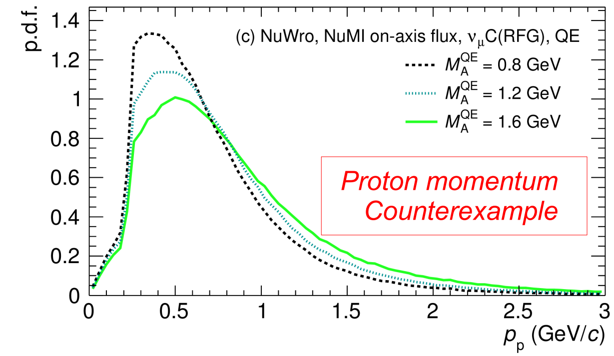


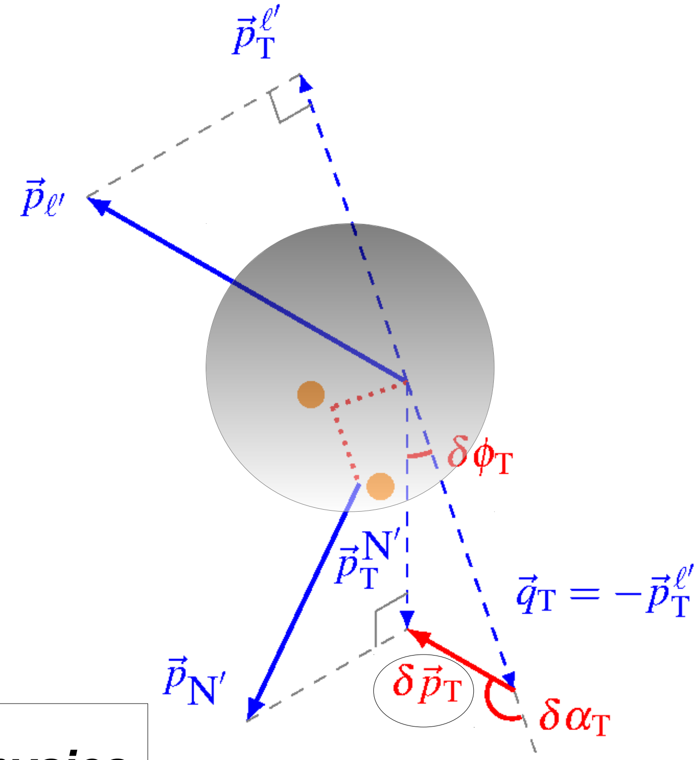
Neutrino energy dependence can ***counteracts*** *nuclear effects.*

2. State-of-the-art probes of nuclear effects

Extension







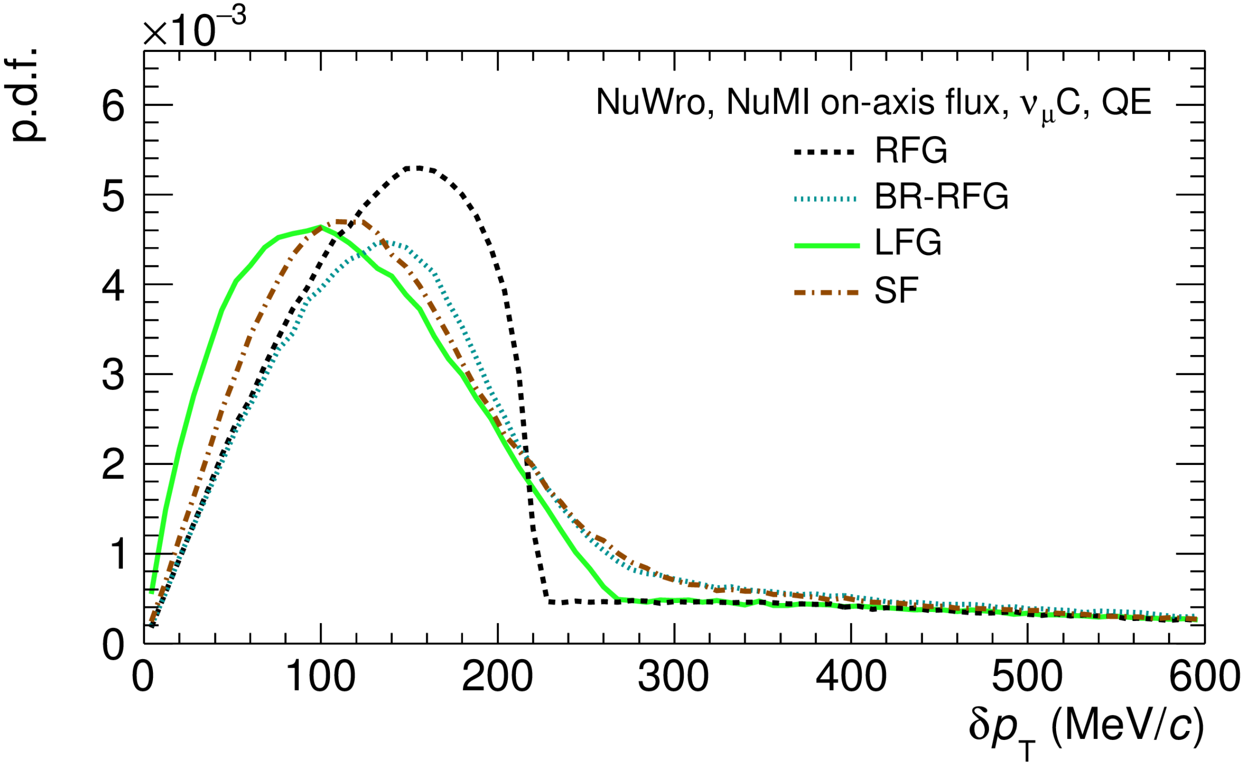
$\delta\vec{p}_T = \vec{p}_T^{\,N} - \Delta\vec{p}_T$ *invariant w/* ***nucleon-level physics***

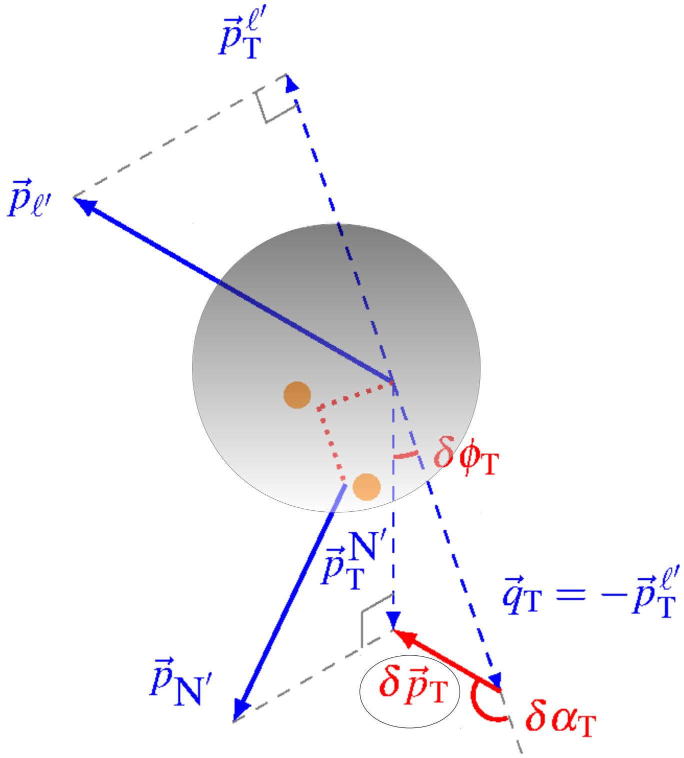
FM

FSI

2. State-of-the-art probes of nuclear effects

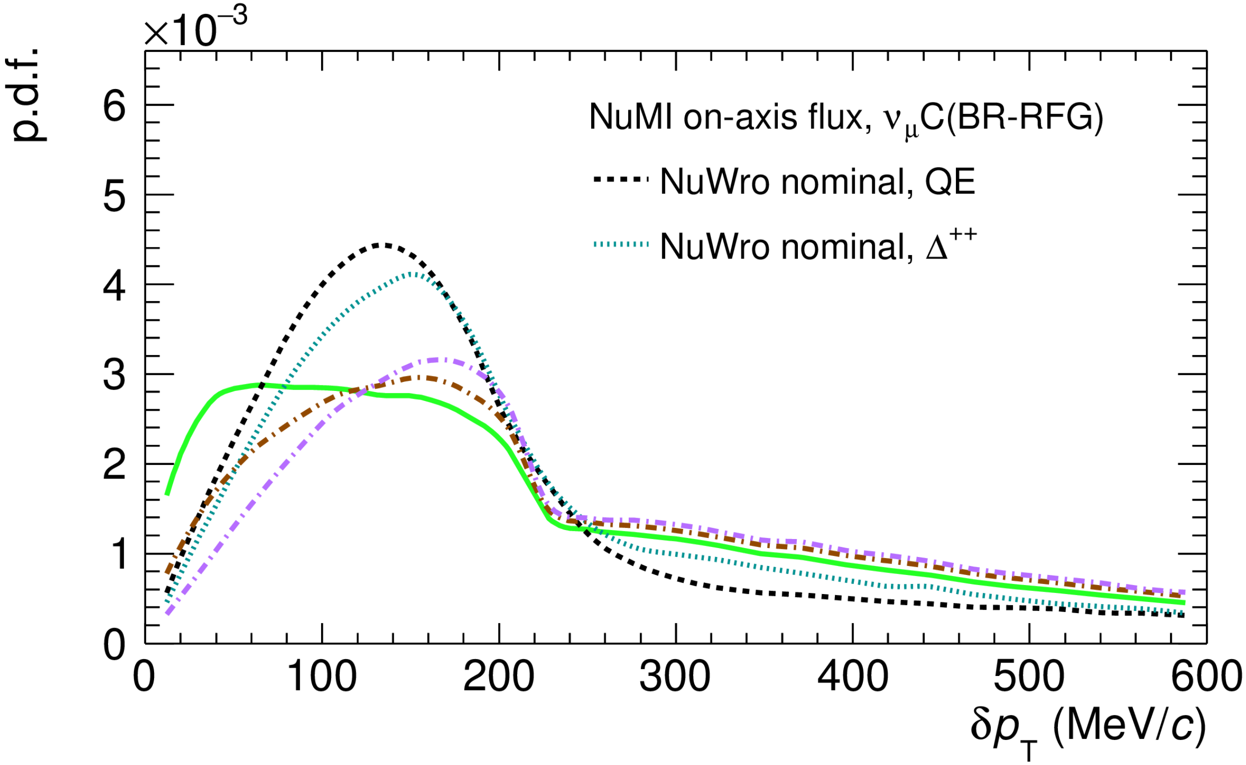
Application

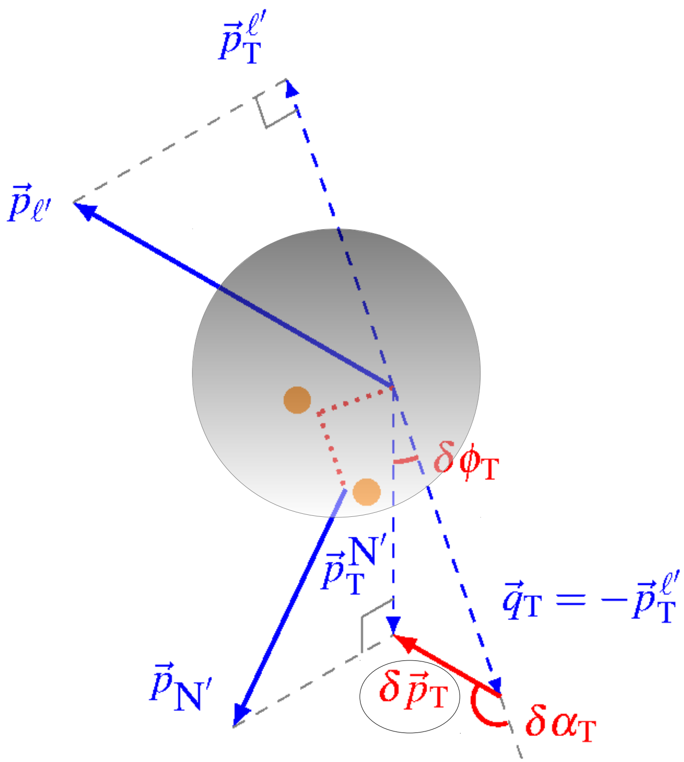




- Directly showing initial state, useful to study new target material

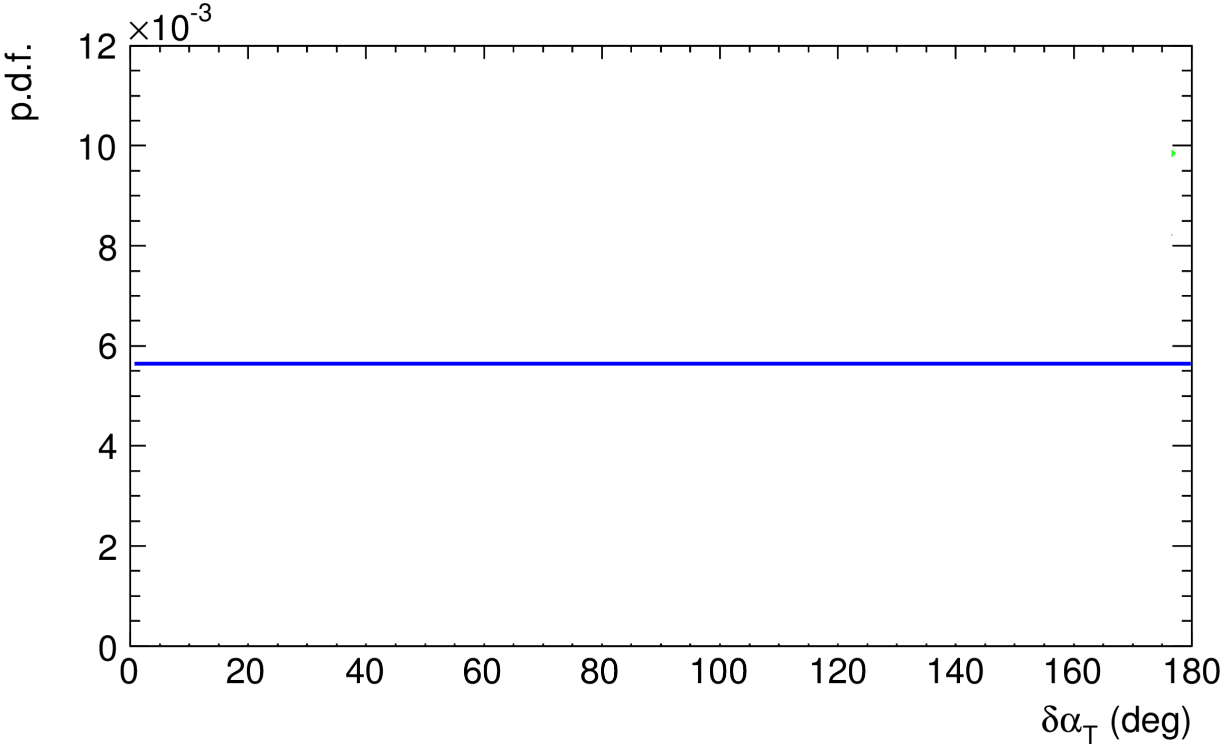
Application

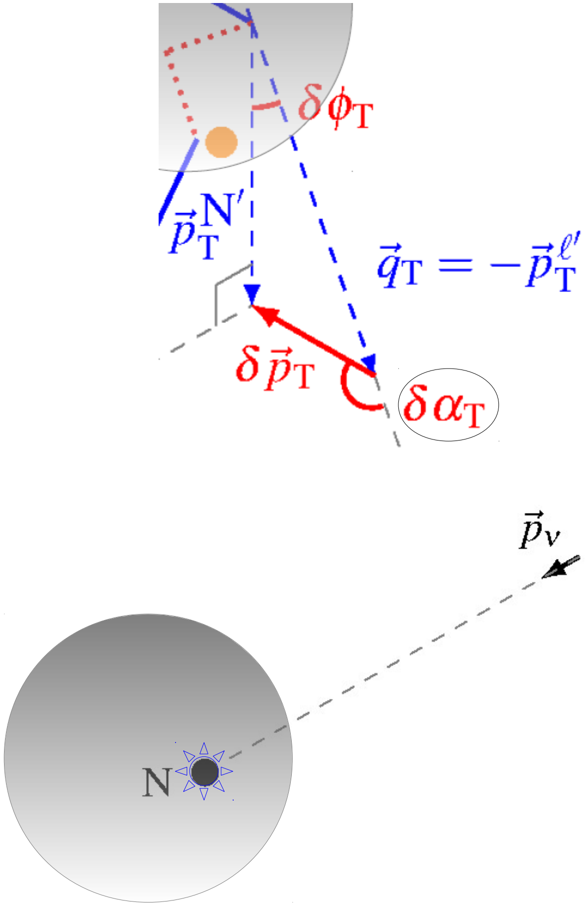




- In RES, N' = proton + pion, sensitive to pion FSI
- Useful to study FSI in anti-neutrino interaction (anti-nu CCQE N'=neutron)

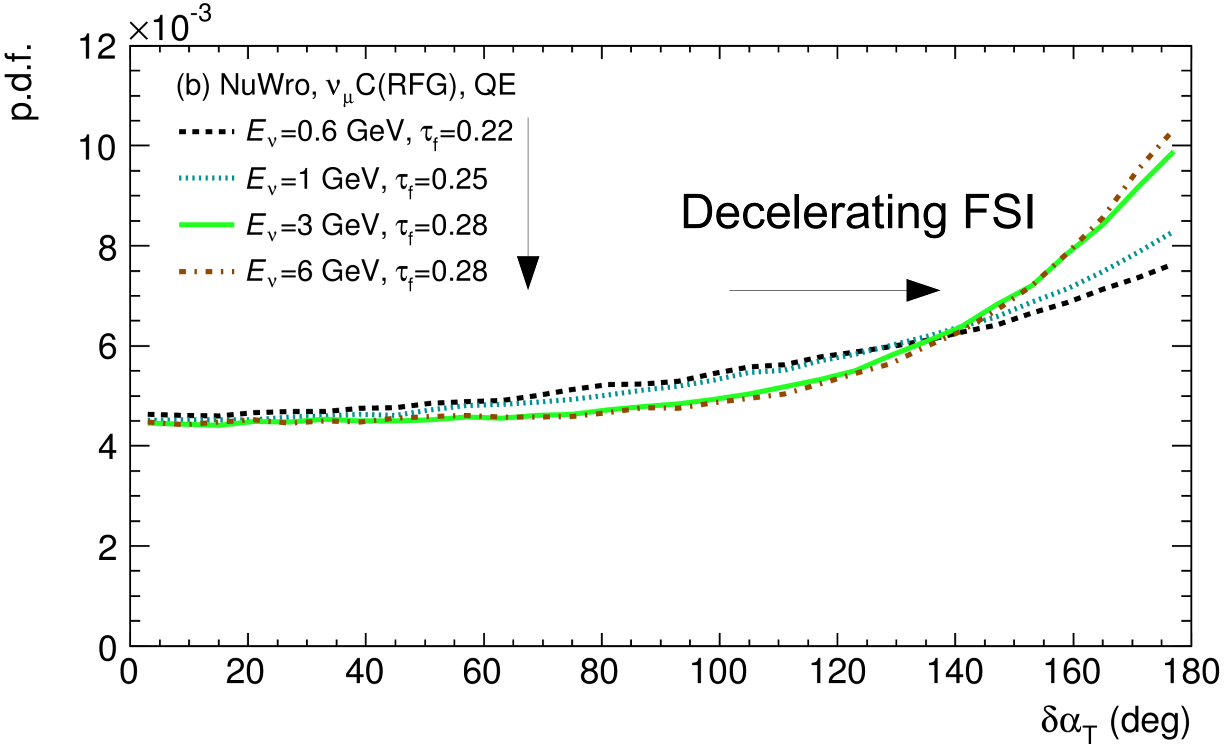
No FSI (i.e. FM only)

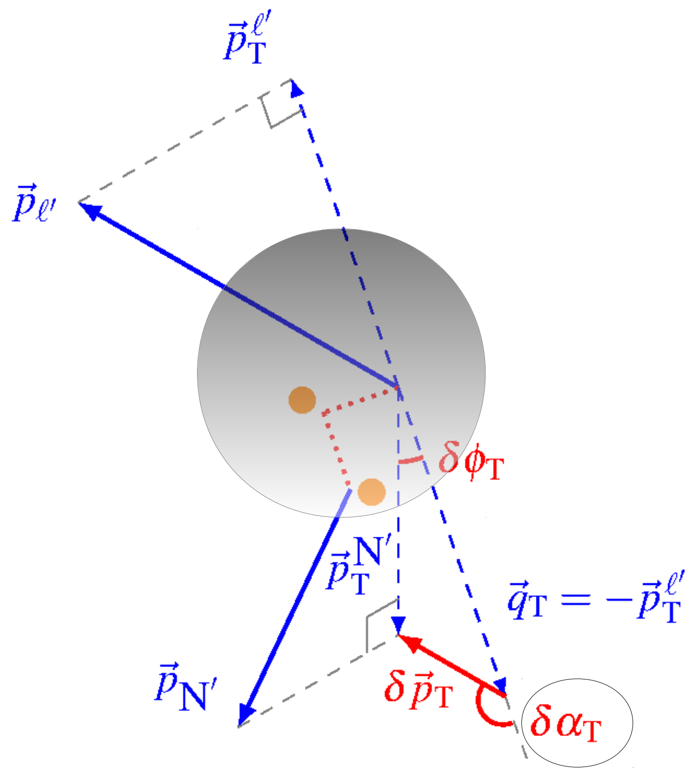




Isotropic FM

2. State-of-the-art probes of nuclear effects





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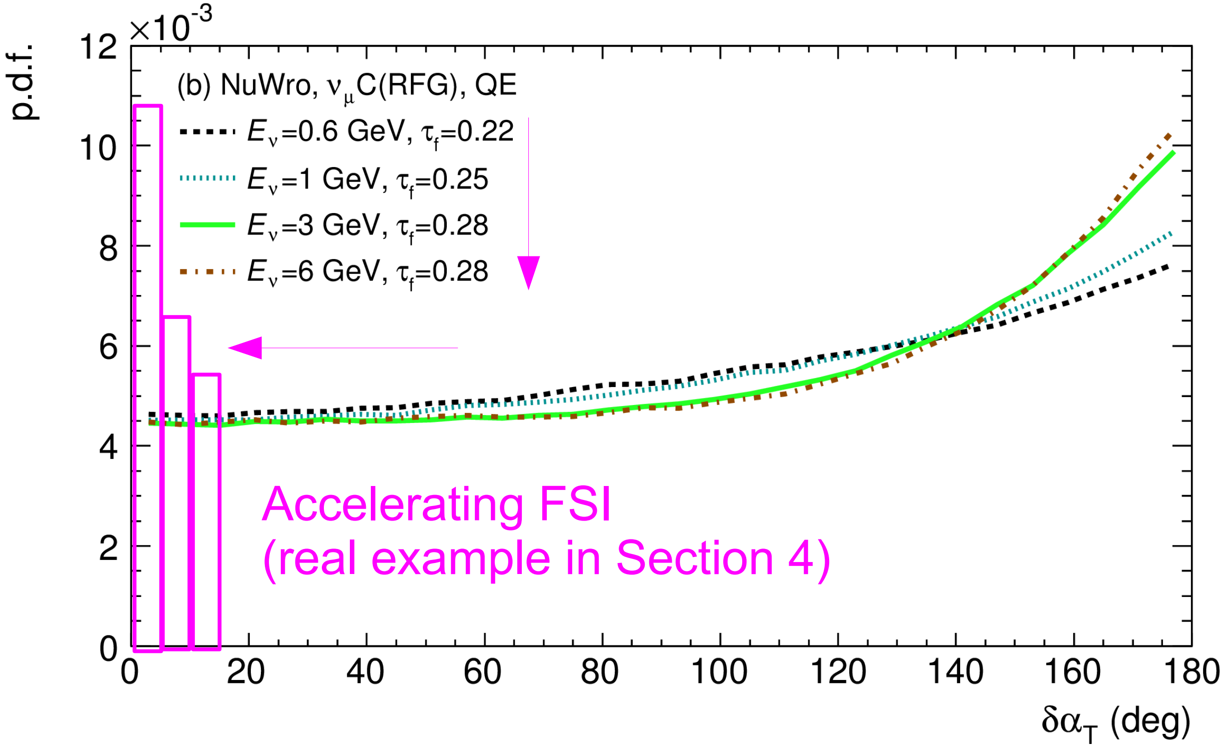

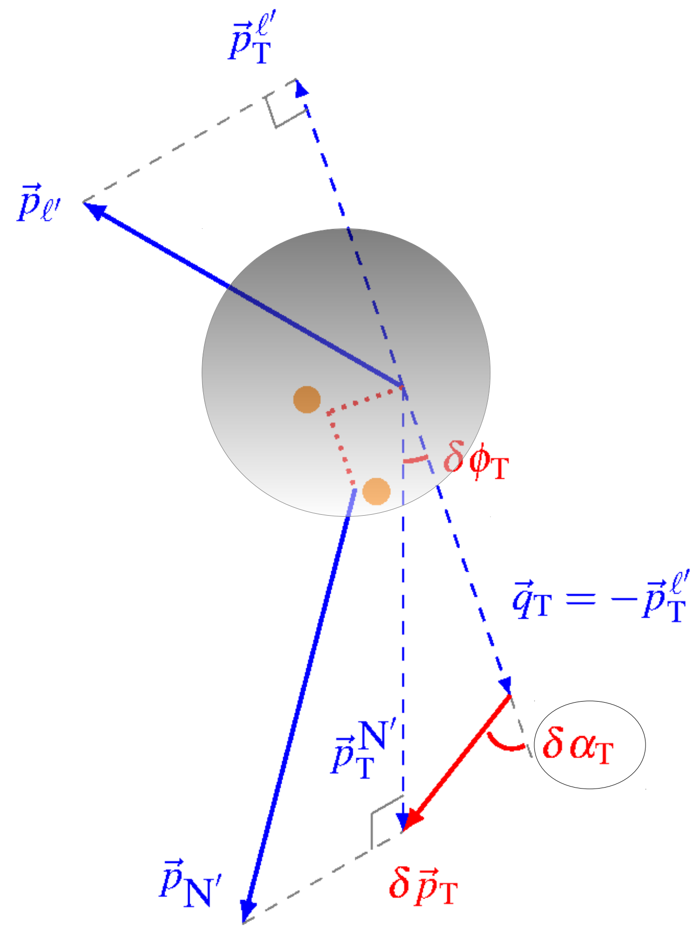

Outline

1. Introduction
2. Measuring nuclear effects w/ minimal dependence on neutrino energy
3. Measuring neutrino energy independent of nuclear effects
4. Theory predictions
5. Measurement in MINERvA
6. Measurement in T2K
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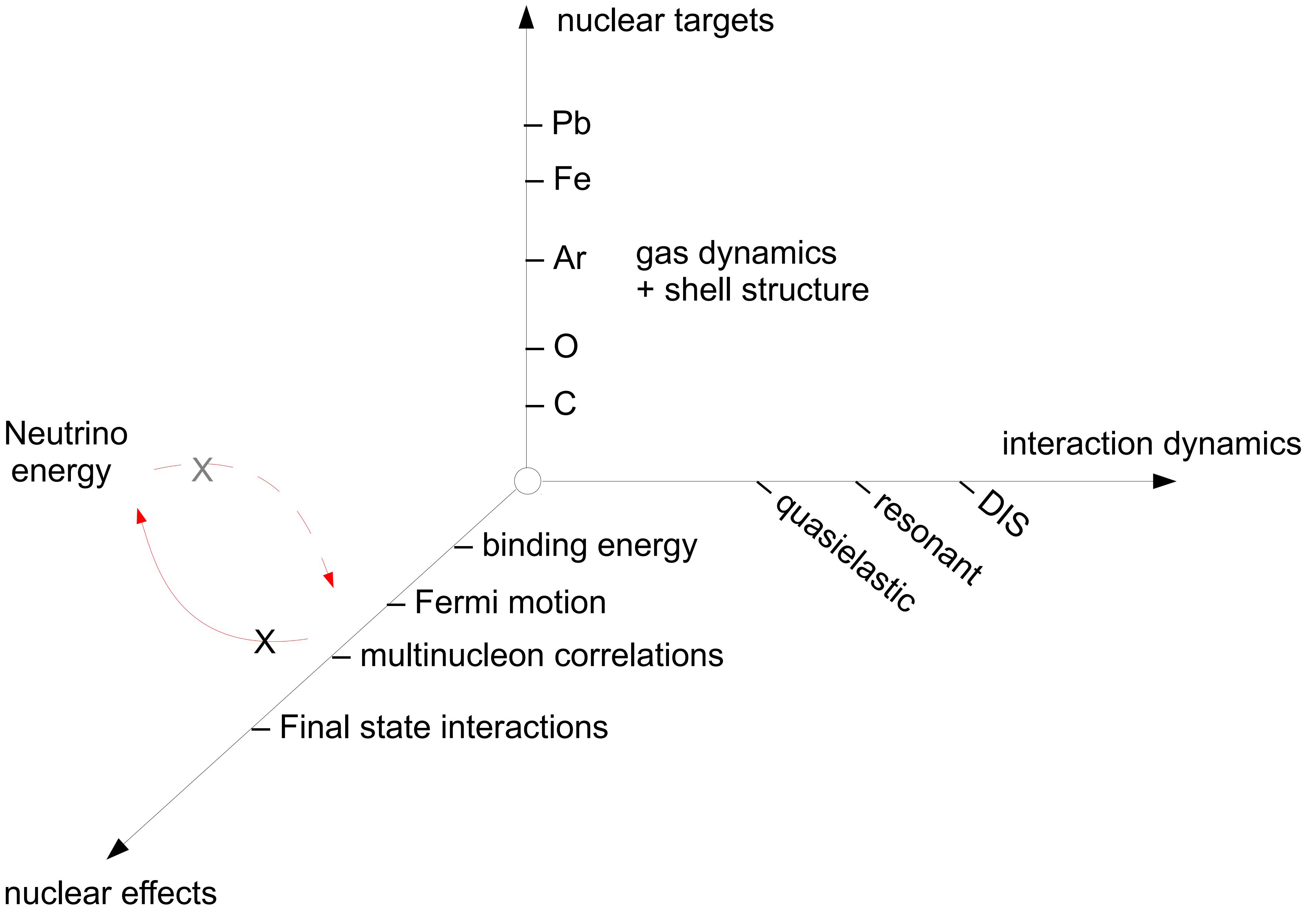
3. Nuclear effect-independent reconstruction of neutrino energy

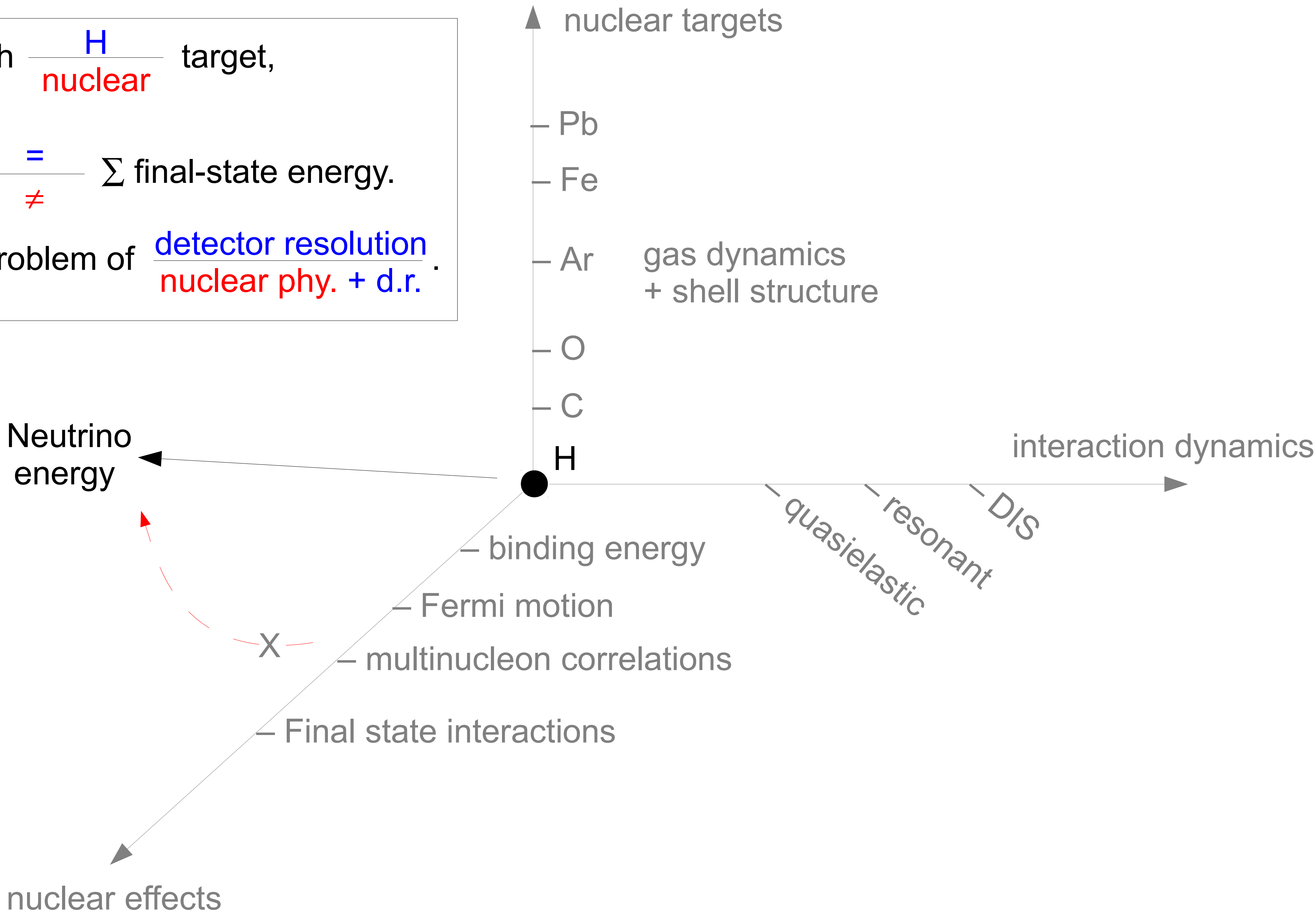


3. Hydrogen as neutrino interaction target

With $\frac{\text{H}}{\text{nuclear}}$ target,

$E_\nu \frac{=}{\neq} \sum$ final-state energy.

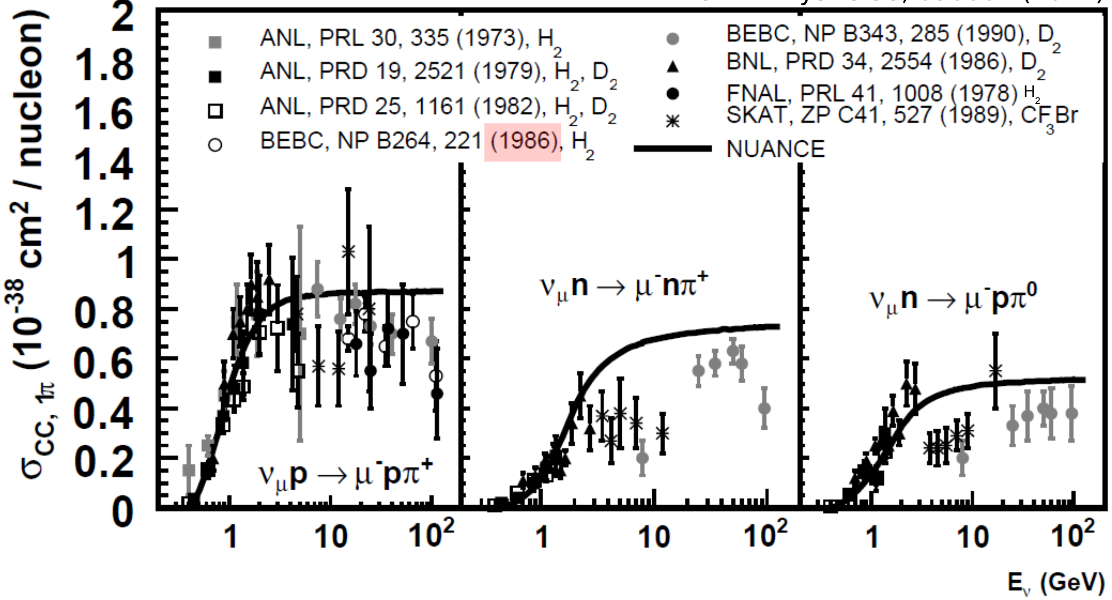
A problem of $\frac{\text{detector resolution}}{\text{nuclear phy. + d.r.}}$.



3. Hydrogen as neutrino interaction target

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

Chin. Phys. C 38, 090001 (2014)



  - Safety issue: explosive

LBNE design report, FERMILAB-PUB-14-022

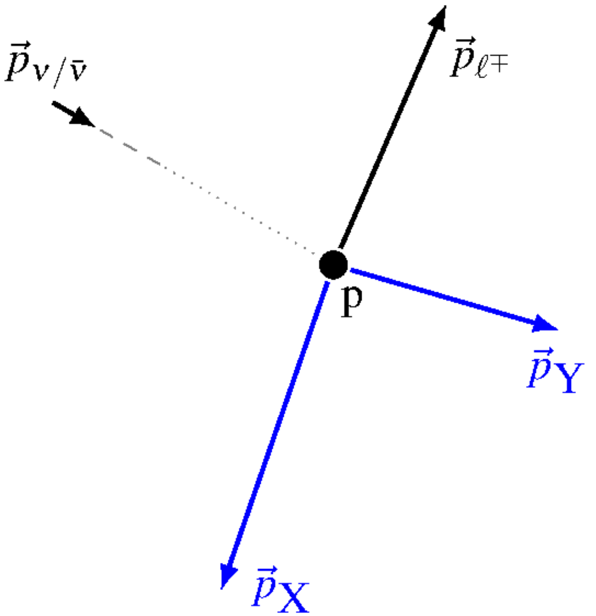
    - "*Since the use of a liquid H2 bubble chamber is excluded in the ND hall* ***due to safety concerns****, ...*"
- In the last ~30 years there has been no new measurement of neutrino interactions on pure hydrogen.

3. Double-transverse kinematic imbalance

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

- Leading order realization in standard model:

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



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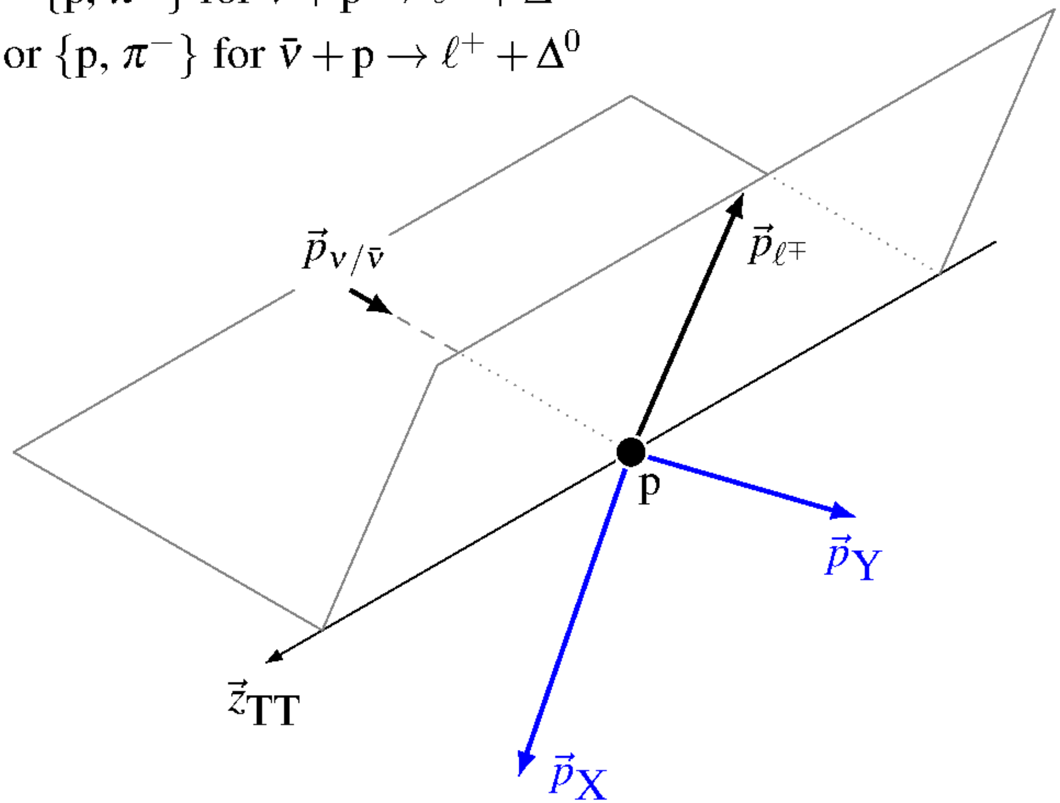

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Lepton-proton interaction → 3 charged particles: l p → l' X Y

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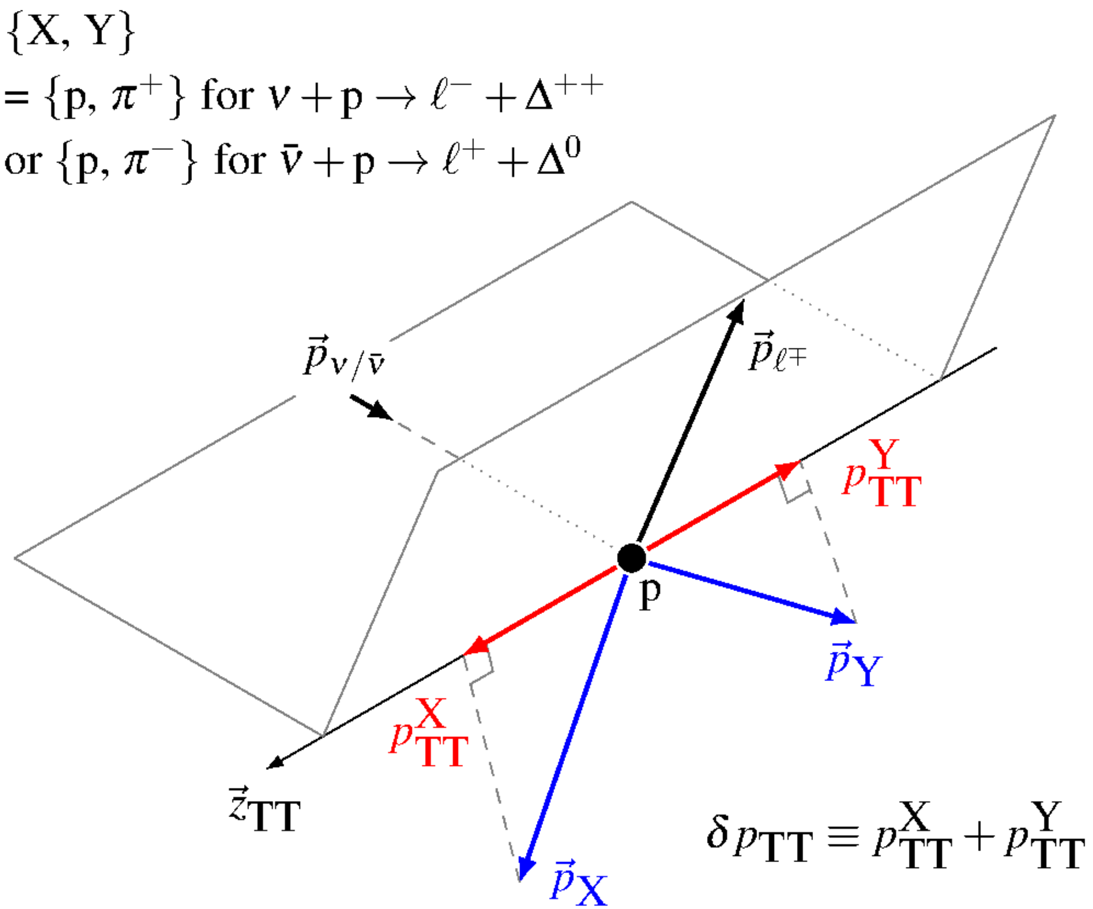
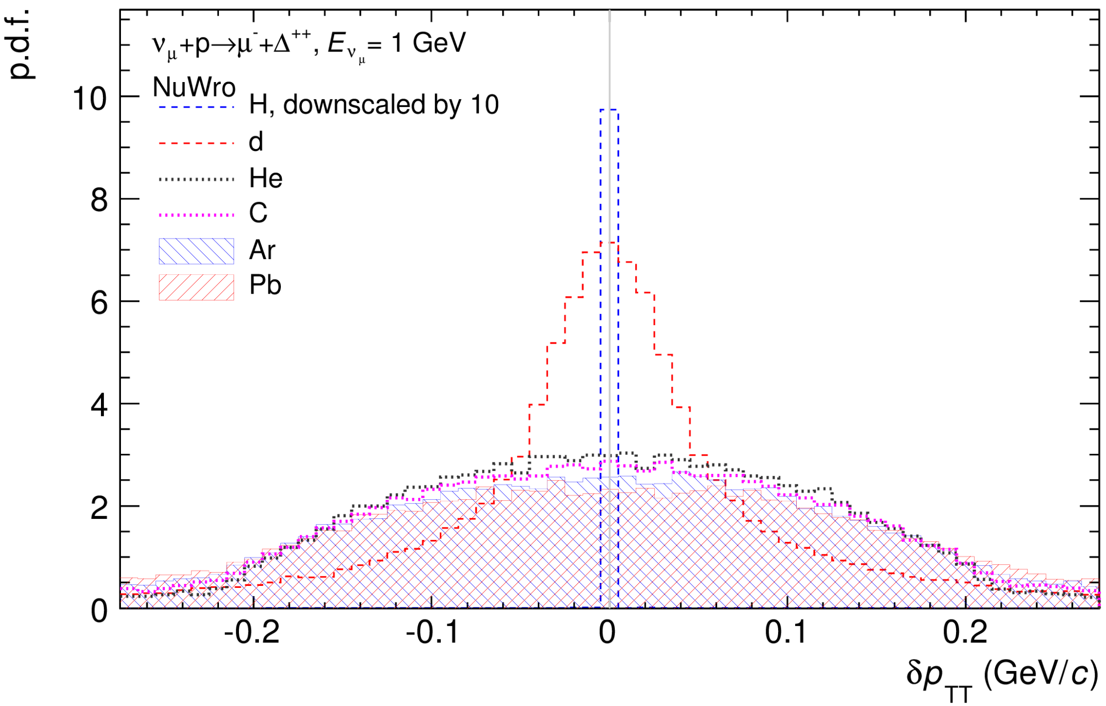


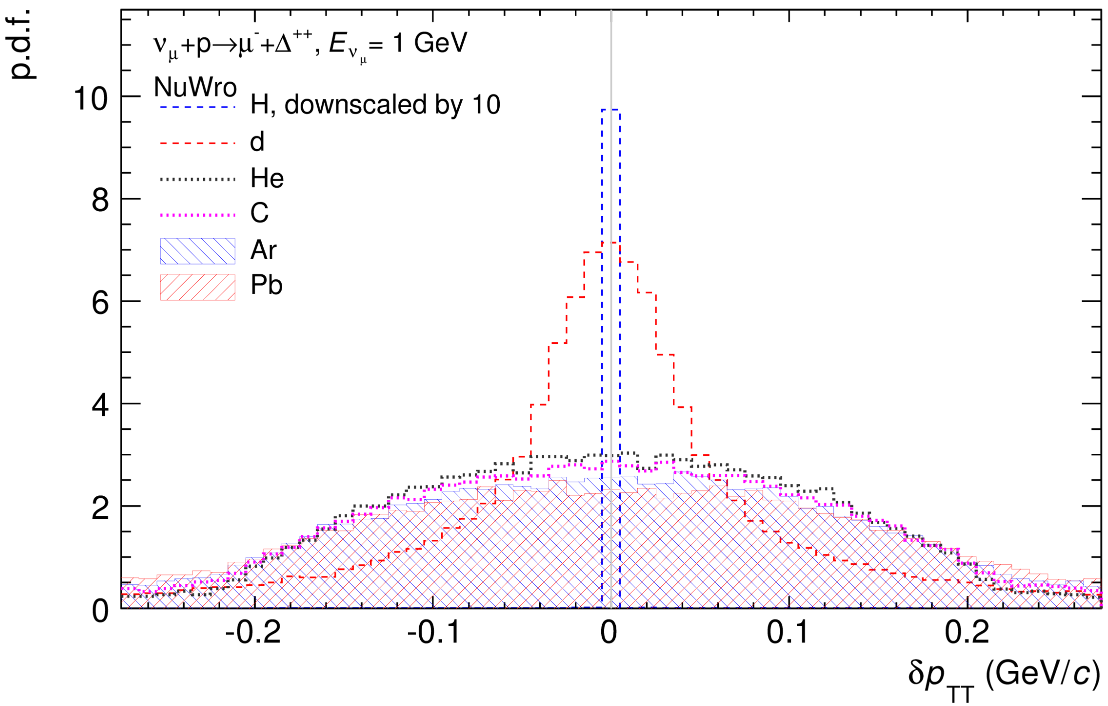


Double-transverse momentum imbalance

$$\delta p_{\mathrm{TT}} \equiv p_{\mathrm{TT}}^{\mathrm{p}} + p_{\mathrm{TT}}^{\pi}$$

- Hydrogen: 0
- Heavier nuclei: irreducible symmetric broadening
  - by Fermi motion O(200 MeV)
  - further by FSI

3. Hydrogen doping



Double-transverse momentum imbalance

$$\delta p_{\rm TT} \equiv p_{\rm TT}^{\rm p} + p_{\rm TT}^{\pi}$$

- Hydrogen: 0
- Heavier nuclei: irreducible symmetric broadening
  - by Fermi motion *O*(200 MeV)
  - further by FSI
- **Hydrogen doping**: adding hydrogen atoms in target material.
- Hydrogen shape is only detector smearing.
  - With good detector resolution, hydrogen yield can be extracted.
  - With very good res., event-by-ev. selection of nu-H interaction is possible.
- *In situ* nuclear-free flux measurement with current technology is possible via "*bin-and-fit"* method (arXiv:1512.09042, see *new* demonstration in Section 6).

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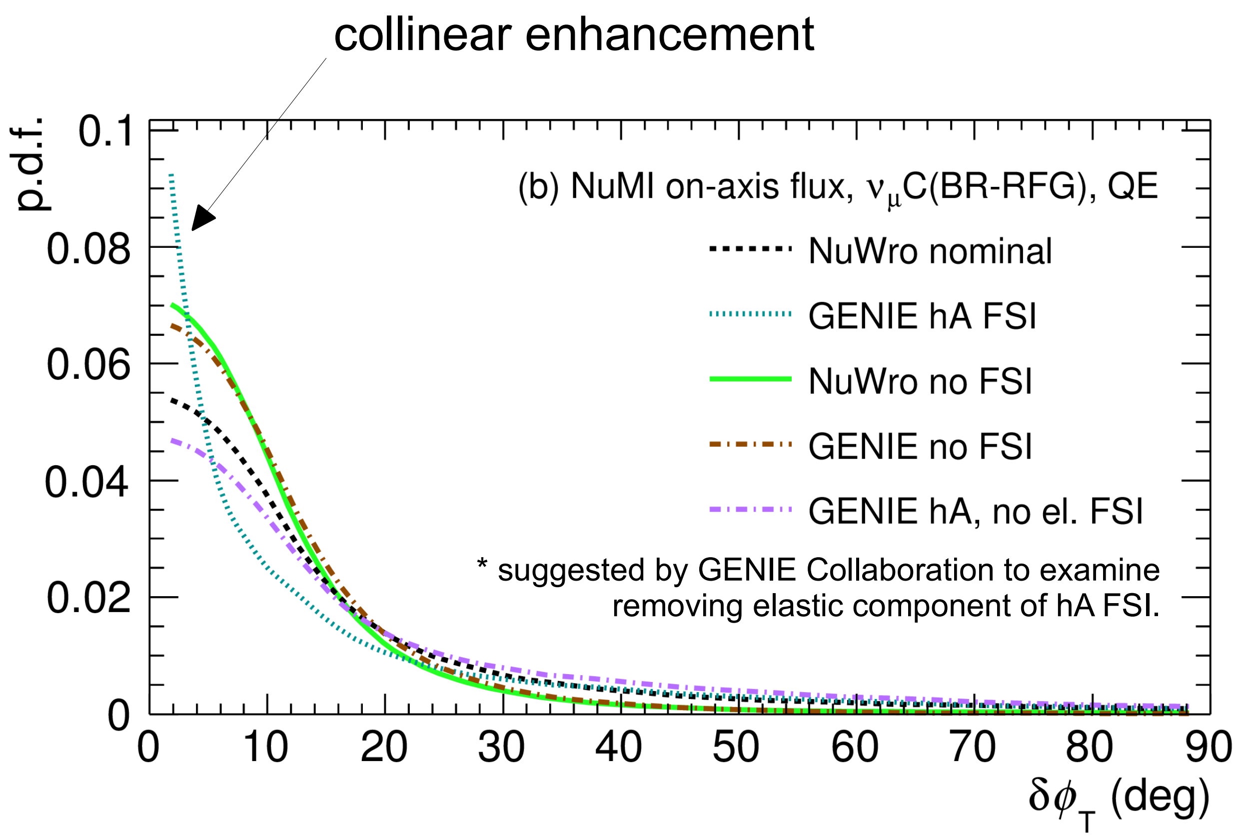
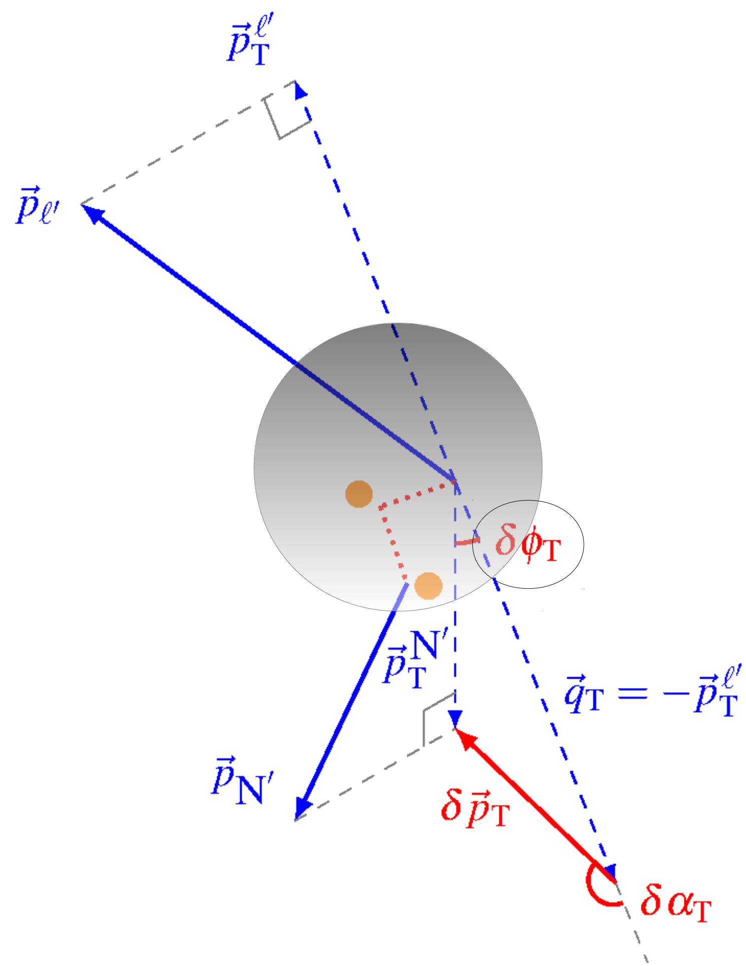
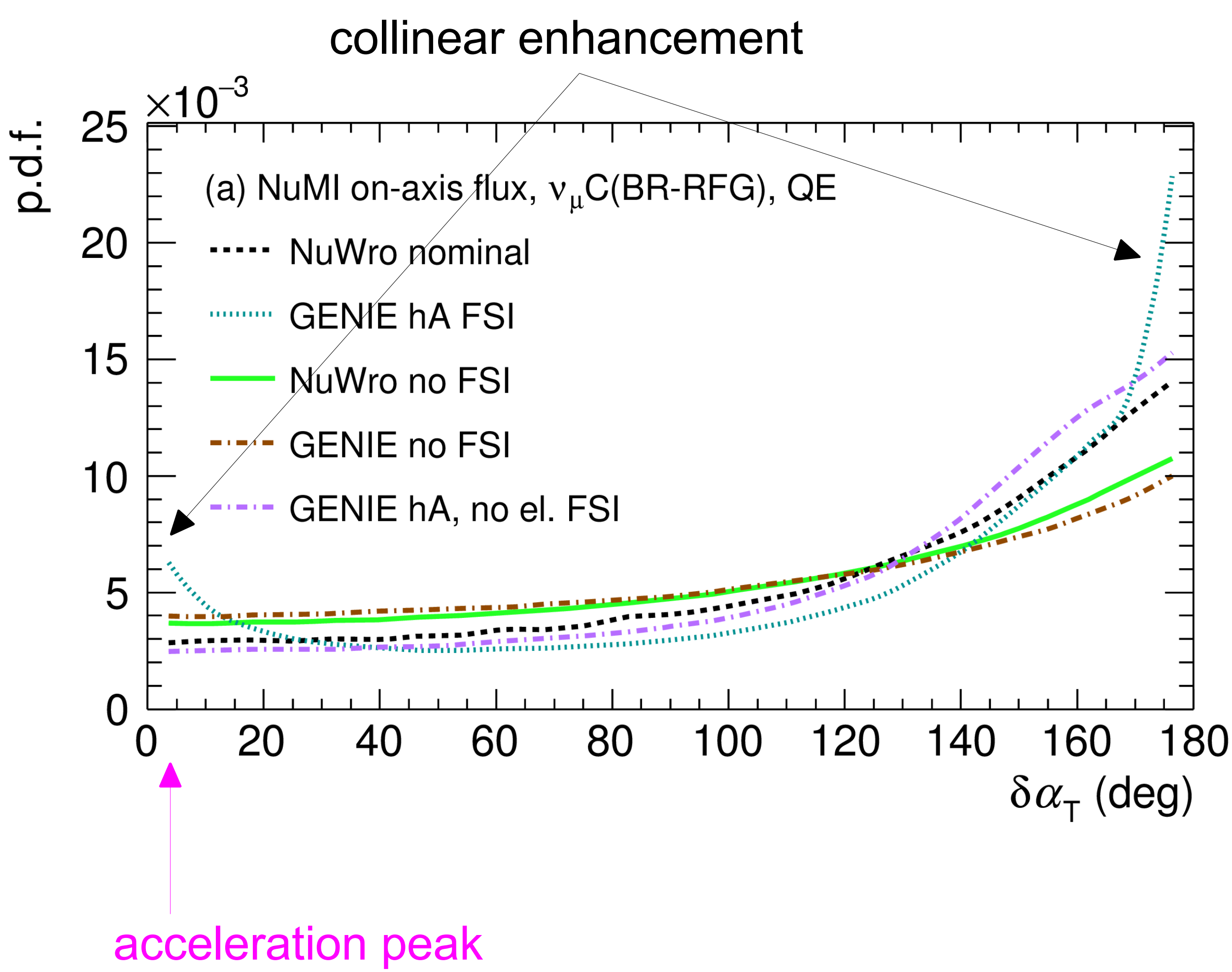
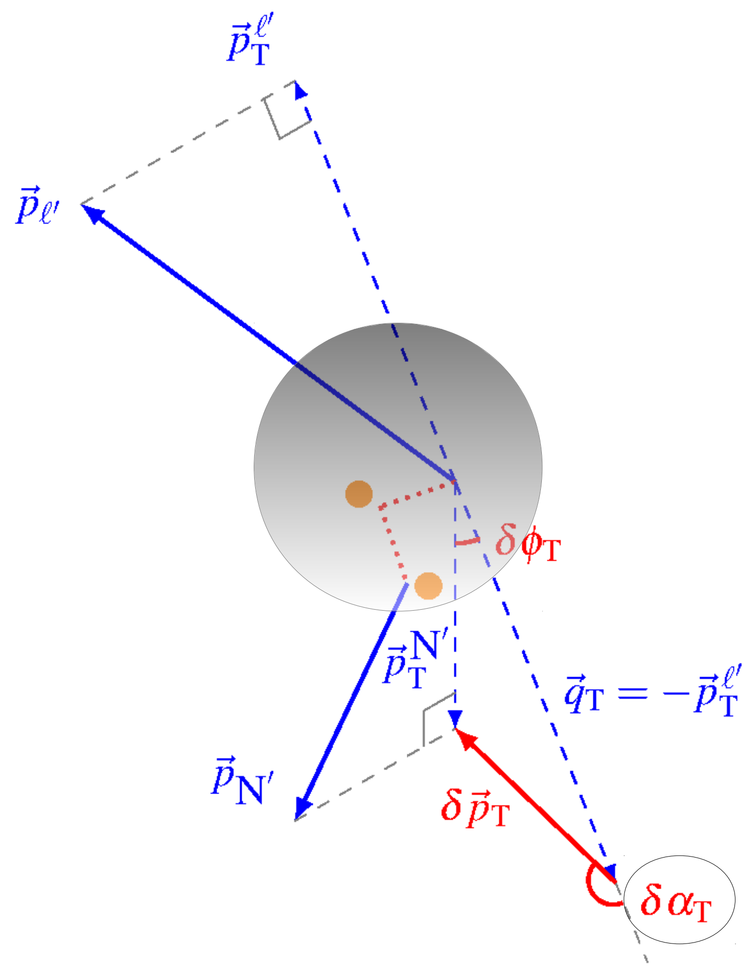
4. Theory predictions for transverse kinematic imbalance

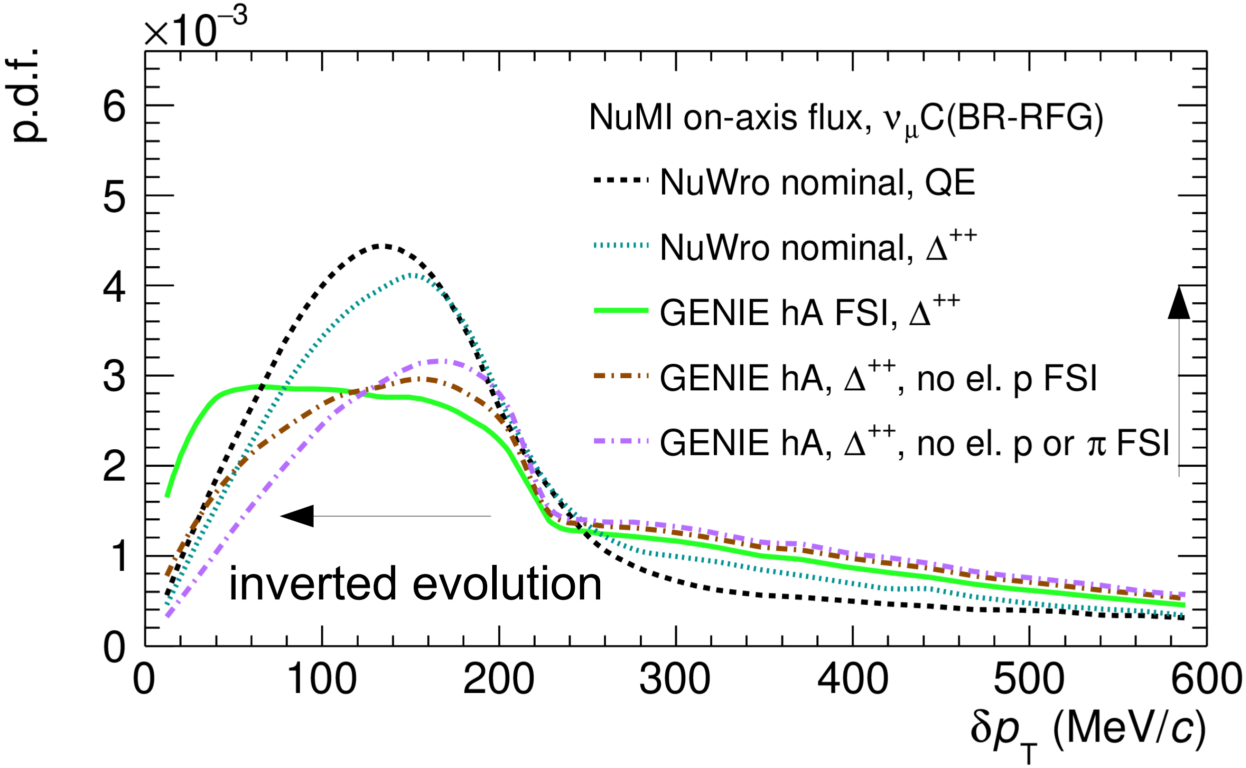




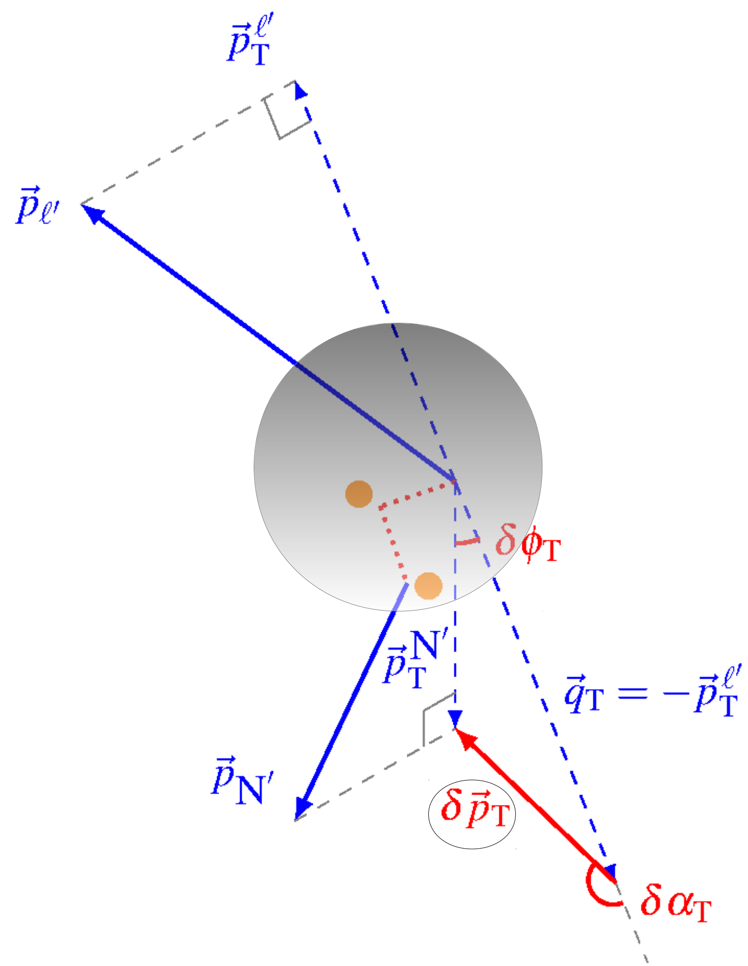
4. Theory predictions for transverse kinematic imbalance





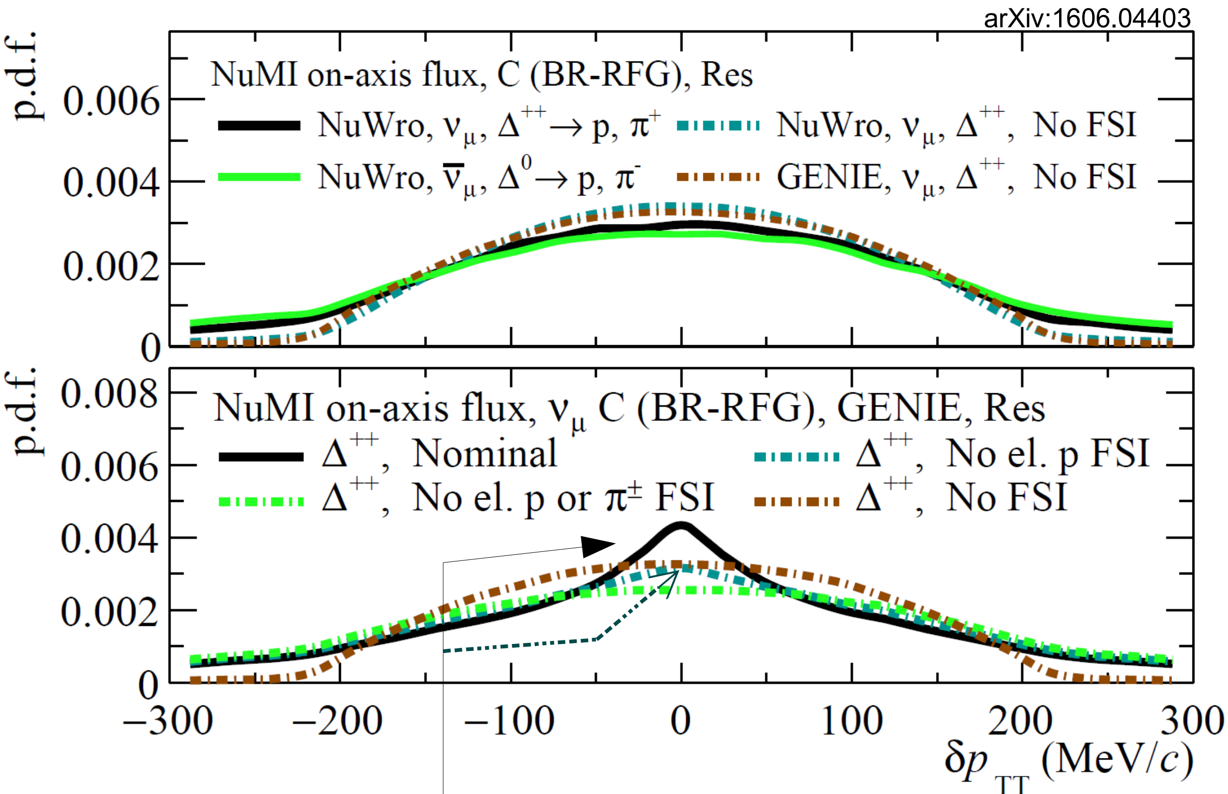


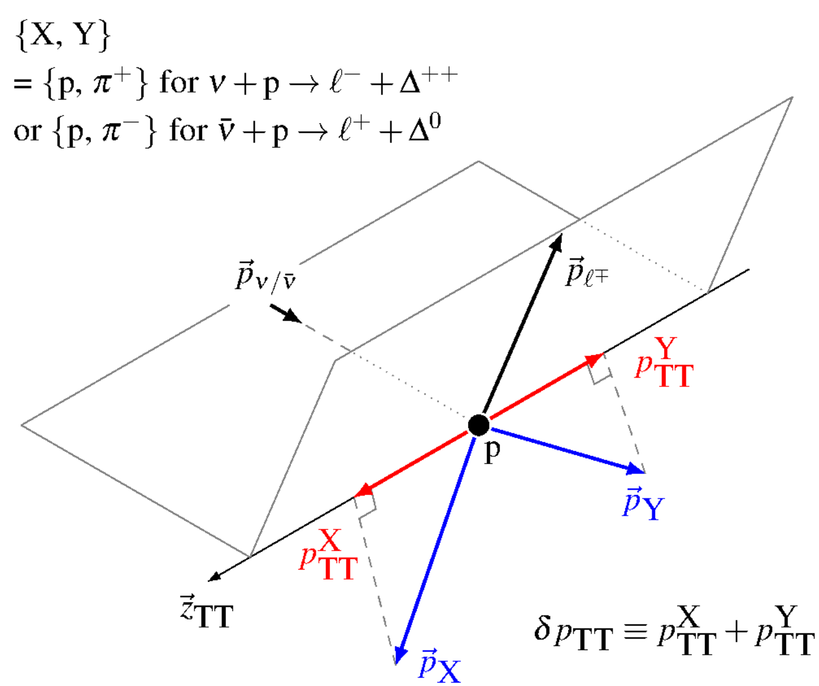
p.d.f.
×10^-3
NuMI on-axis flux, ν_μC(BR-RFG)
NuWro nominal, QE
NuWro nominal, Δ^{++}
GENIE hA FSI, Δ^{++}
GENIE hA, Δ^{++}, no el. p FSI
GENIE hA, Δ^{++}, no el. p or π FSI
inverted evolution
δp_T (MeV/c)
0
100
200
300
400
500
600
1
2
3
4
5
6



$\vec{p}_T^{\ell'}$
$\vec{p}_{\ell'}$
$\delta\phi_T$
$\vec{p}_T^{N'}$
$\vec{q}_T = -\vec{p}_T^{\ell'}$
$\vec{p}_{N'}$
$\delta\vec{p}_T$
$\delta\alpha_T$

4. Theory predictions for transverse kinematic imbalance





collinear enhancement
similar in $p\pi^-$ and $p\pi^0$ systems

Conclusion: large room to improve theories

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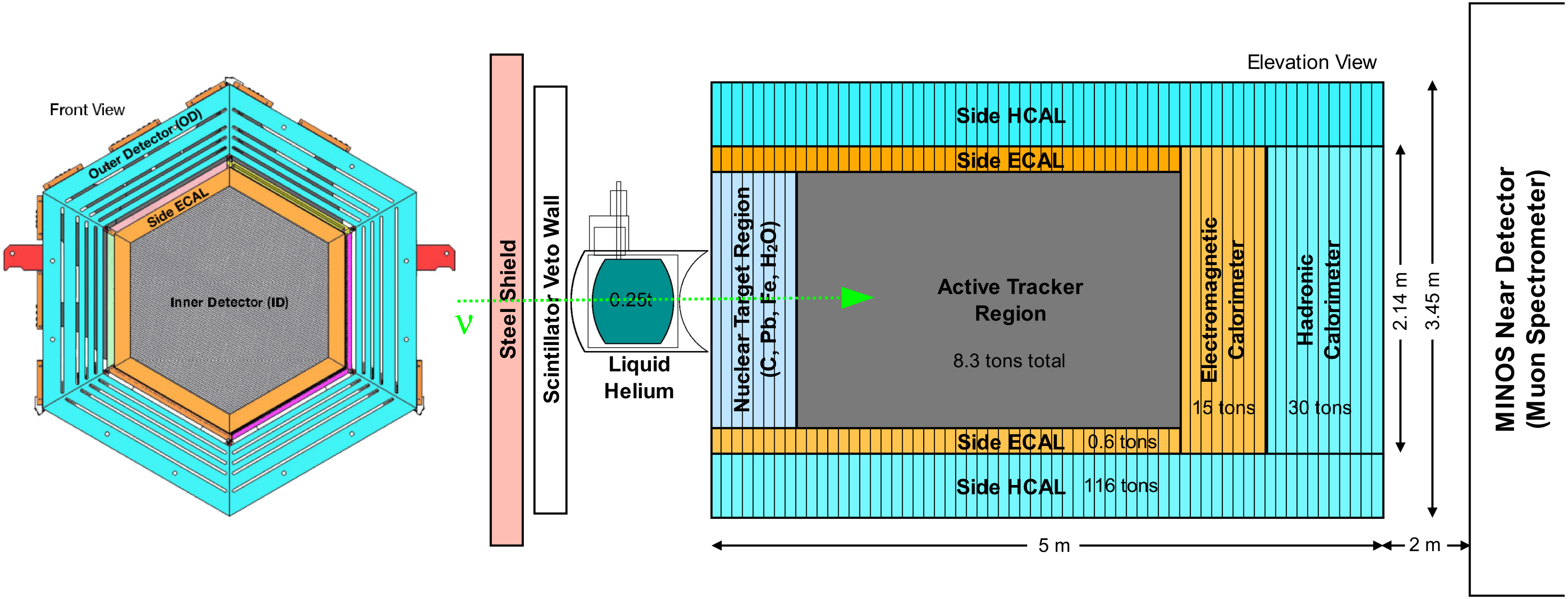
5. Measurement in MINERvA

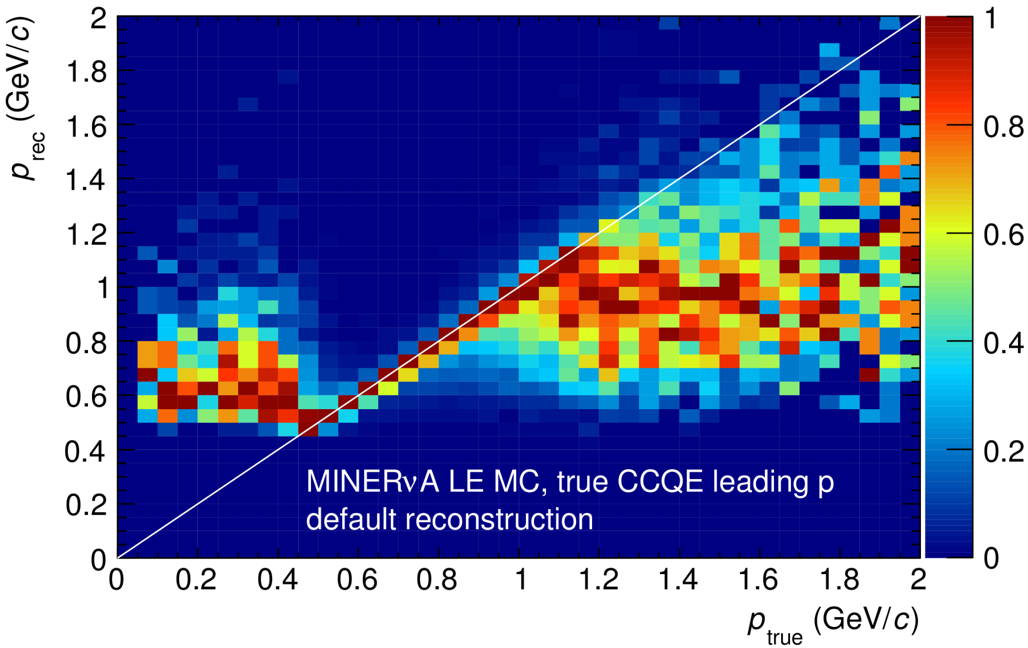
Nucl.Instrum.Meth. A743 (2014) 130-159

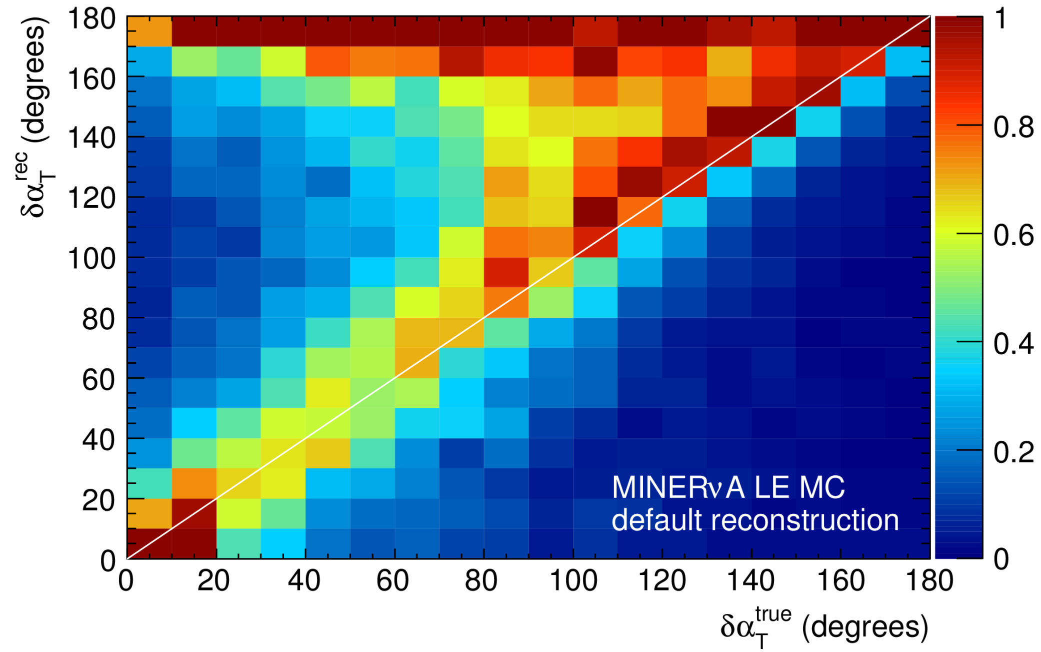


Phys.Rev. D91 (2015) no.7, 071301

- NuMI on-axis neutrino beam, 3 GeV peak energy
- Fine grained scintillator tracker as target
- Event selection: 1 μ, ≥ 1 p, 0 π (CCQE-like)
  - μ reconstruction: tracker, matched to MINOS ND, momentum by range and curvature
  - p reconstruction: ID and momentum by tracker dE/dx profile, momentum threshold 450 MeV
  - π veto: cut on untracked energy and Michel electrons

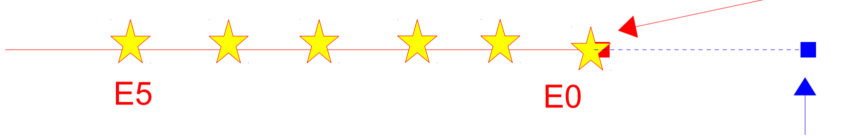
5. Measurement in MINERvA – selecting ESC protons





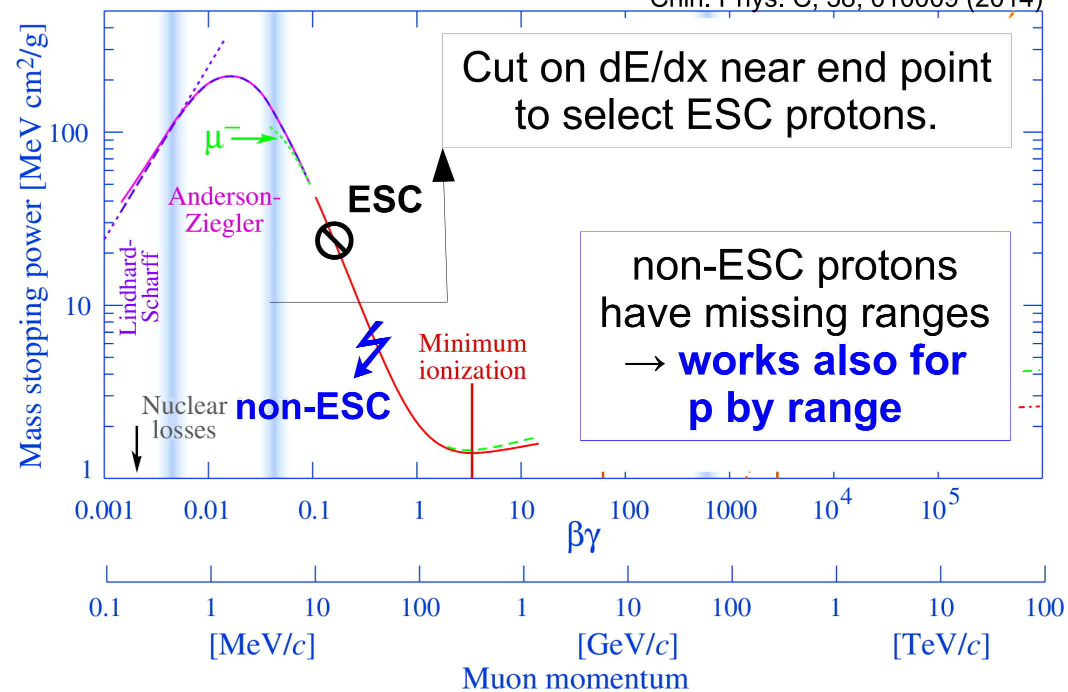
Elastically scattering contained = ESC

Nominal end point:
ESC protons true end point (p → 0)
or exiting or inelastic interaction
(p ≠ 0 w/ different dE/dx profile)



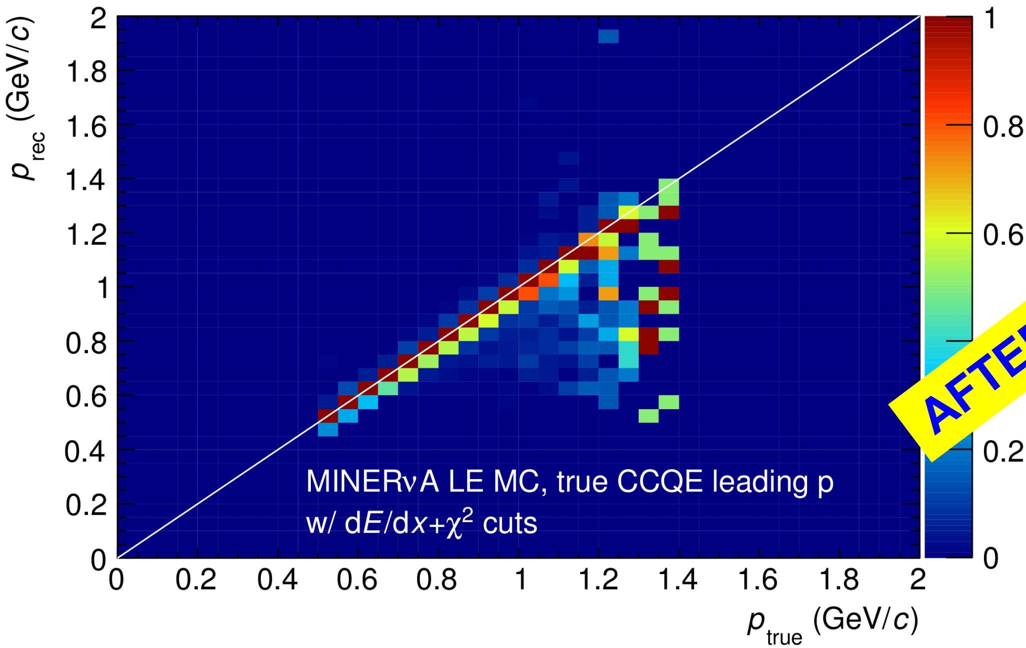
Non-ESC true end point (p → 0)

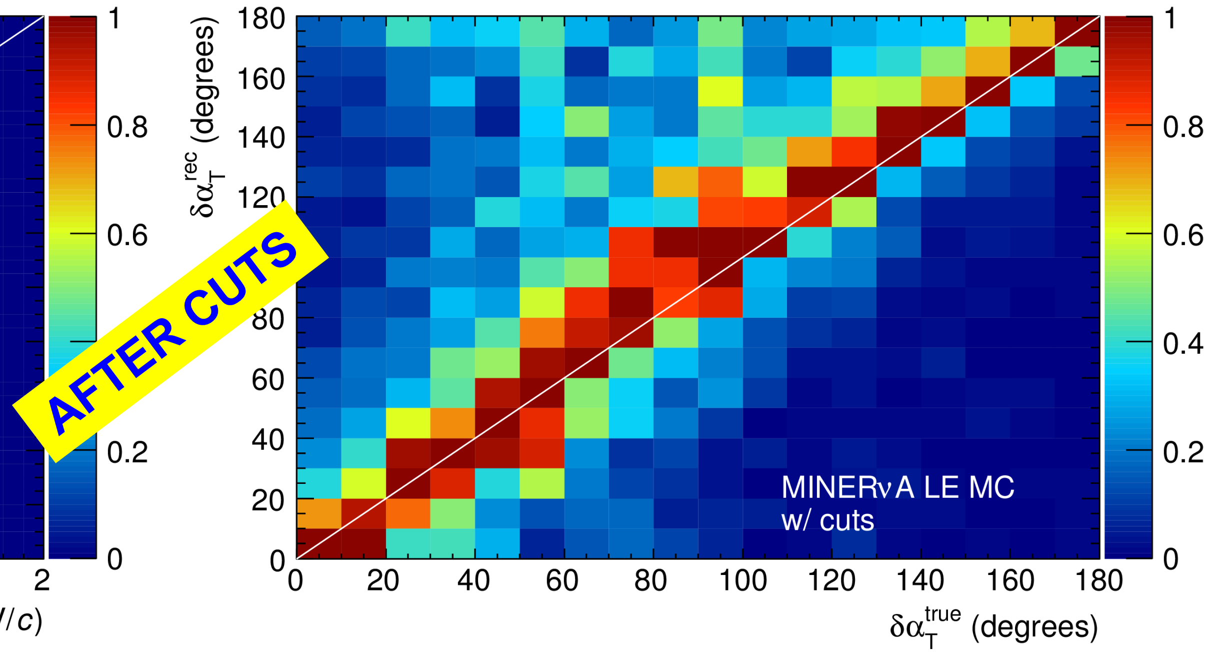
Chin. Phys. C, 38, 010009 (2014)

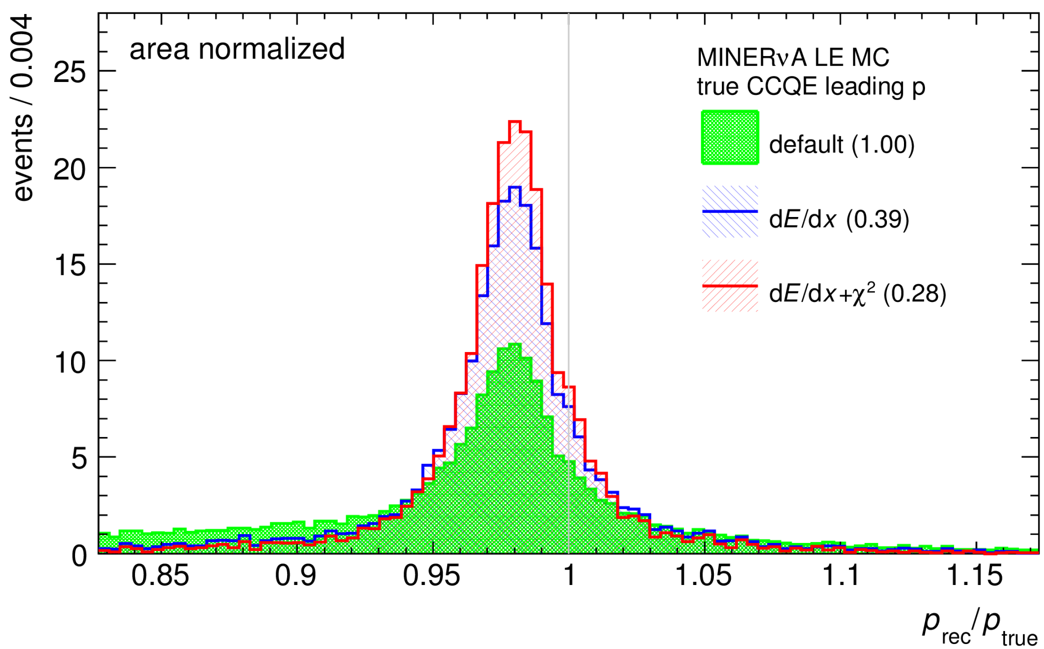


Neutrino2016 P2.043

5. Measurement in MINERνA – selecting ESC protons



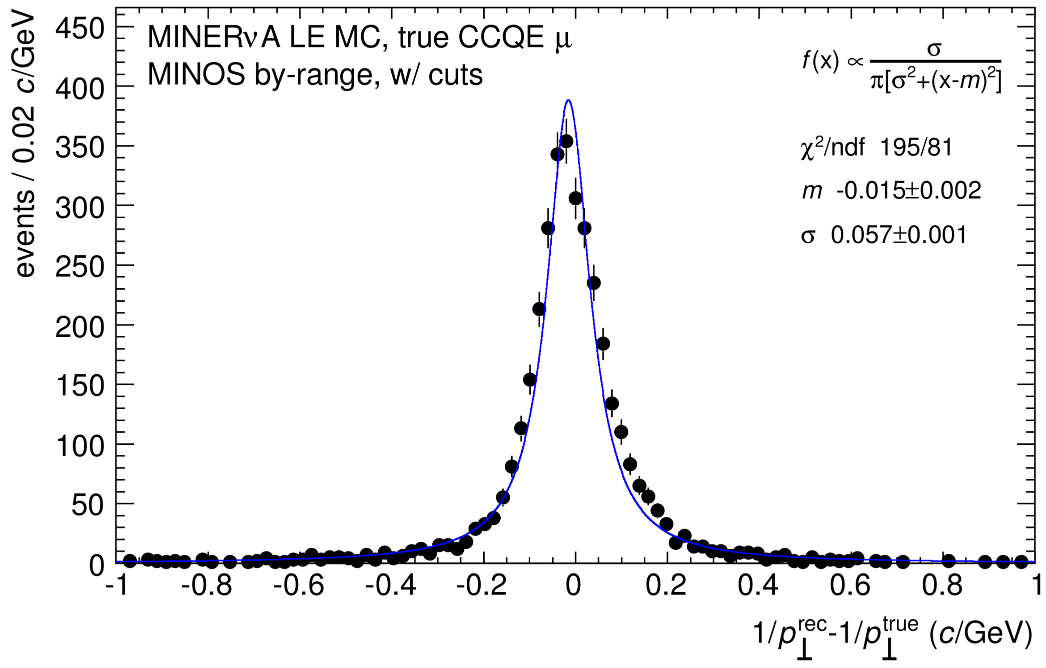


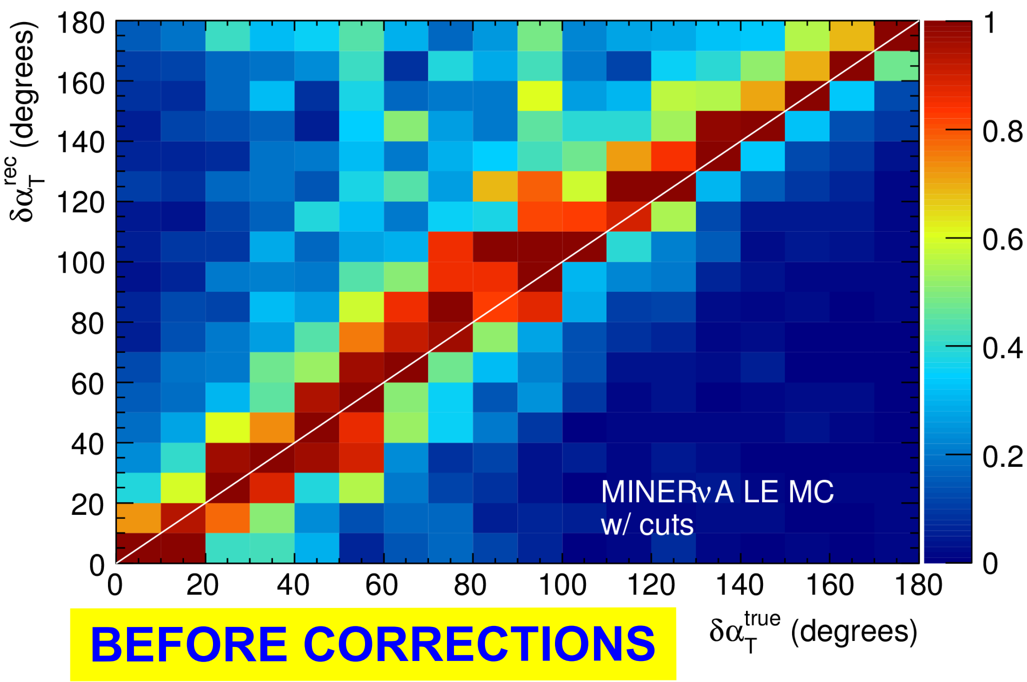


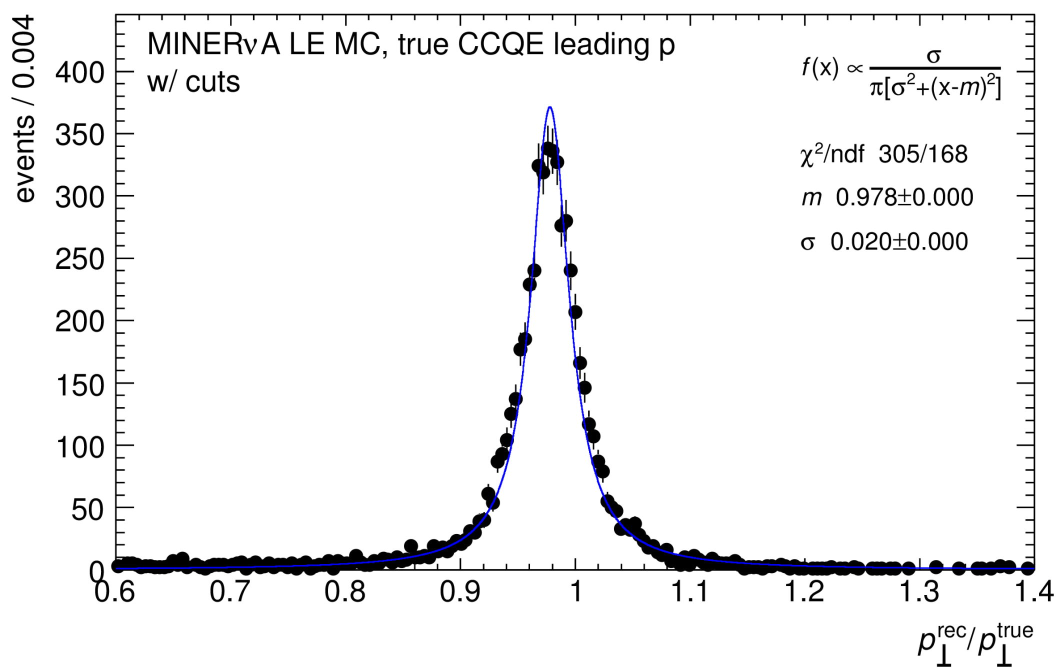
	Spread	Statistics
default	100%	100%
dE/dx	60%	40%
χ^2	70%	60%
dE/dx + χ^2	50%	30%

Neutrino2016 P2.043

5. Measurement in MINERvA – p_T scale corrections







Non-unity p_T scales:
instrumental apparent acceleration or deceleration of the final-state particles.

Correction recipe: find a p_T-scale related distribution that can be described analytically.

Neutrino2016 P2.043

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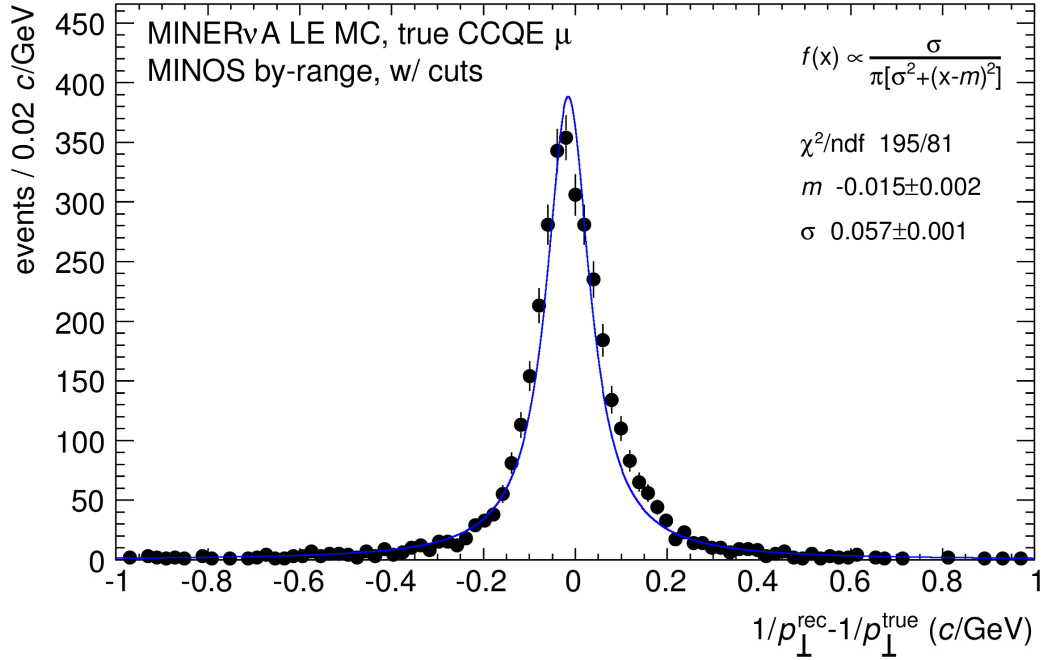
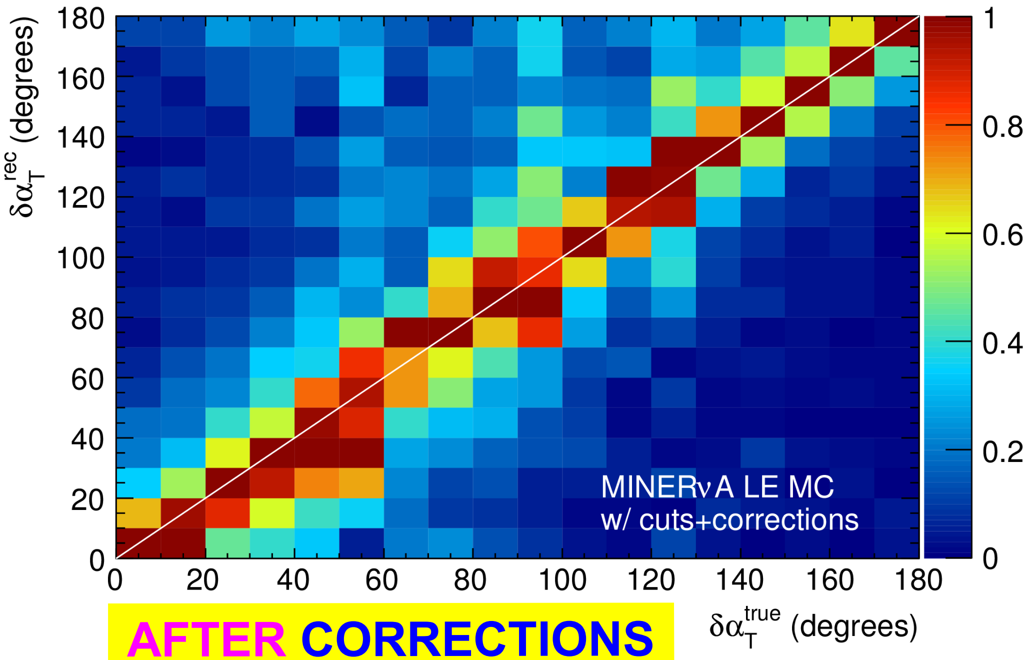
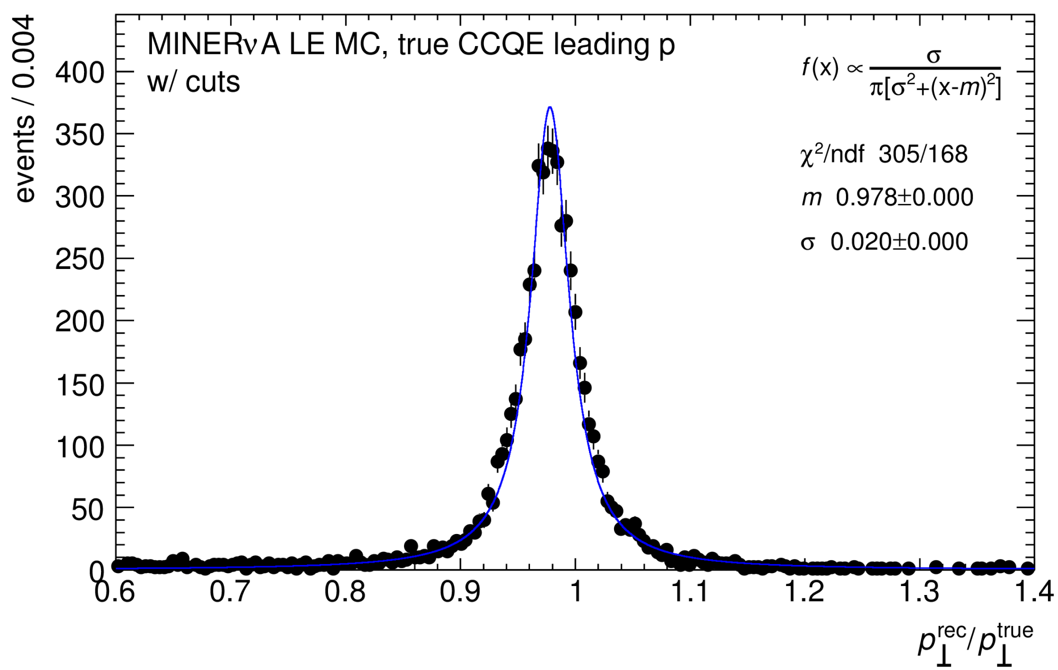




AFTER CORRECTIONS

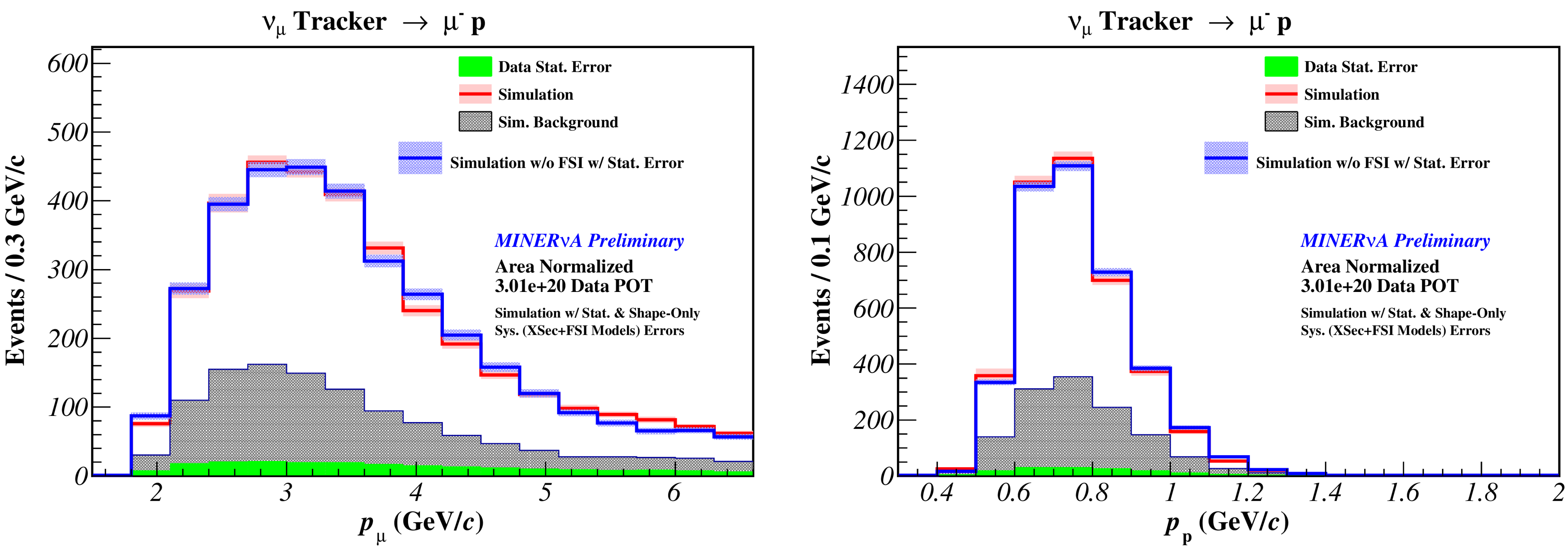


Non-unity p_T scales:
instrumental apparent acceleration or deceleration of the final-state particles.

Correction recipe: find a p_T-scale related distribution that can be described analytically.

Neutrino2016 P2.043

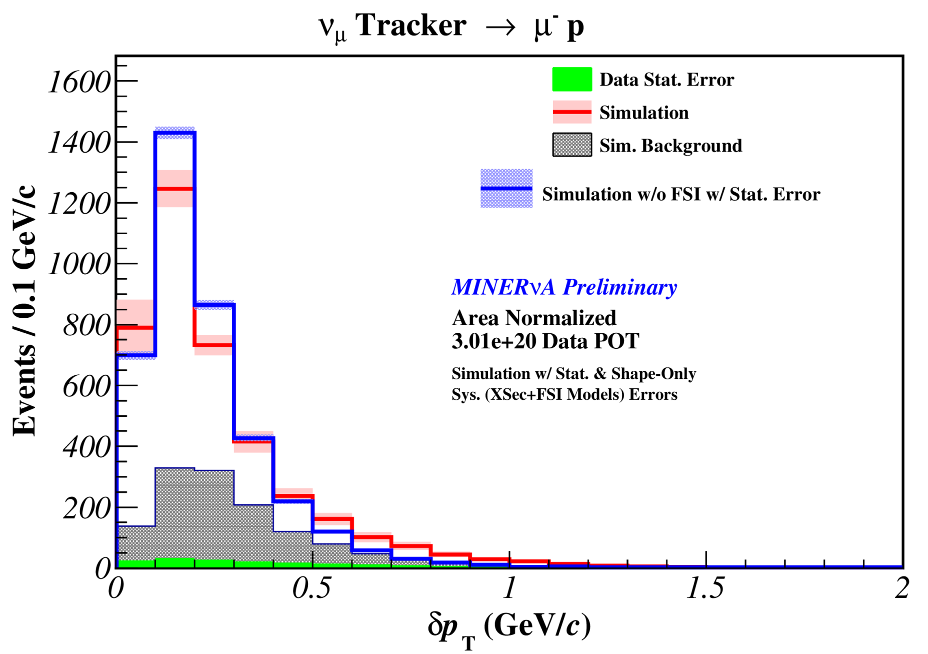
5. Measurement in MINERvA – final-state momentum spectra

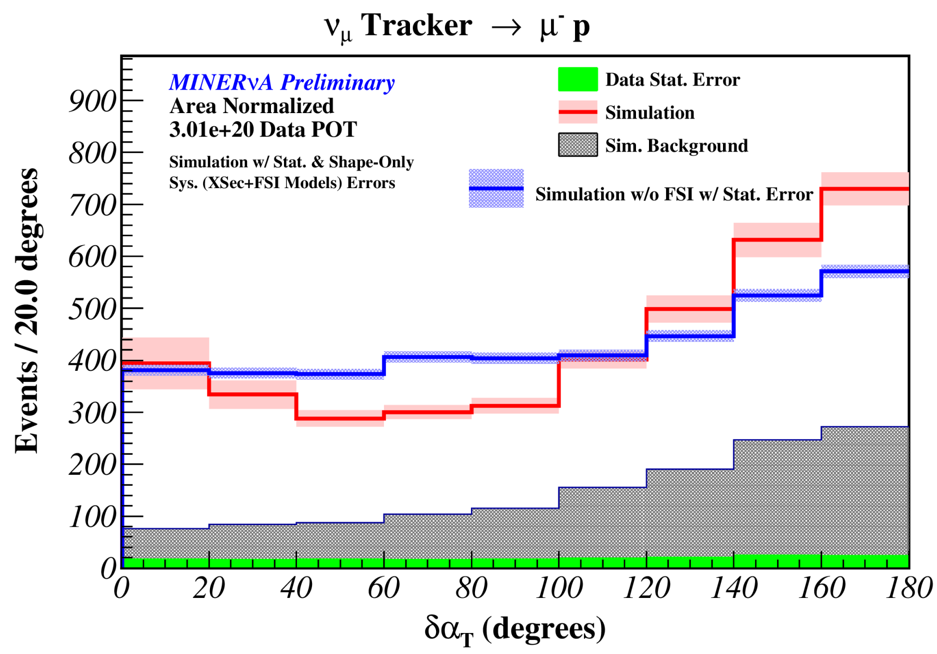


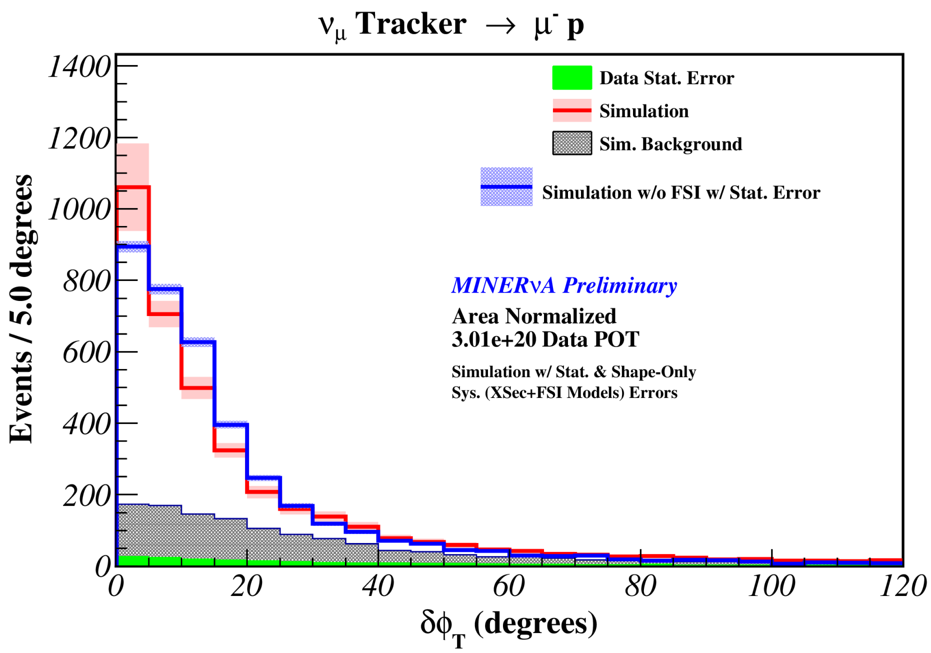
- In given acceptance, overall spectral shapes not sensitive to FSIs.
- Nuclear effects are difficult to observe on top of kinematics originating from neutrino-nucleon interaction level. Direct observables are therefore needed.

Neutrino2016 P2.043

5. Measurement in MINERvA – single-T kinematic imbalance







- GENIE predictions in MINERvA acceptance show collinear enhancement discussed previously (Section 4).
- Sensitivity achieved by momentum improvement cuts and corrections.

Neutrino2016 P2.043

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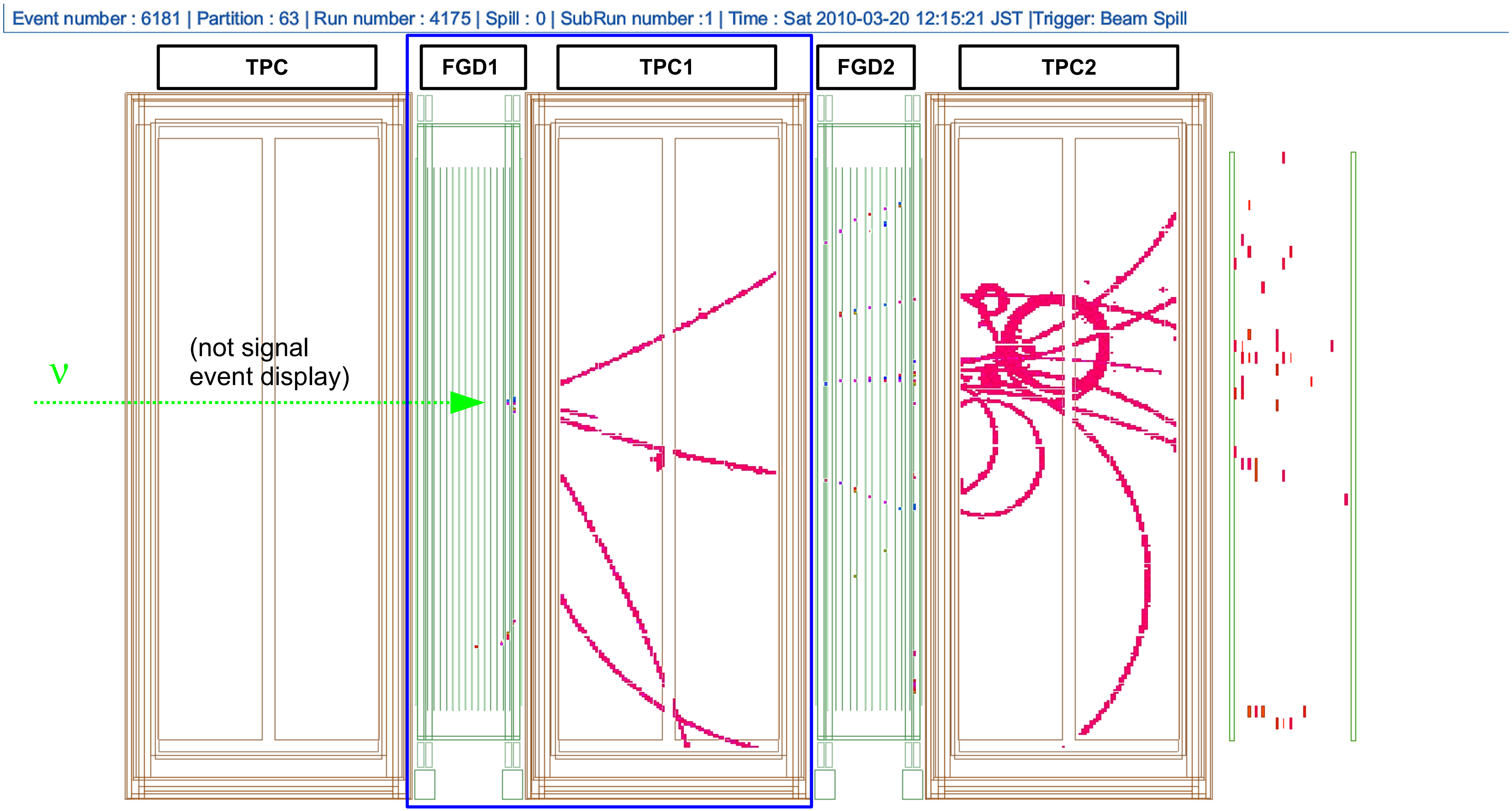
6. Measurement in T2K

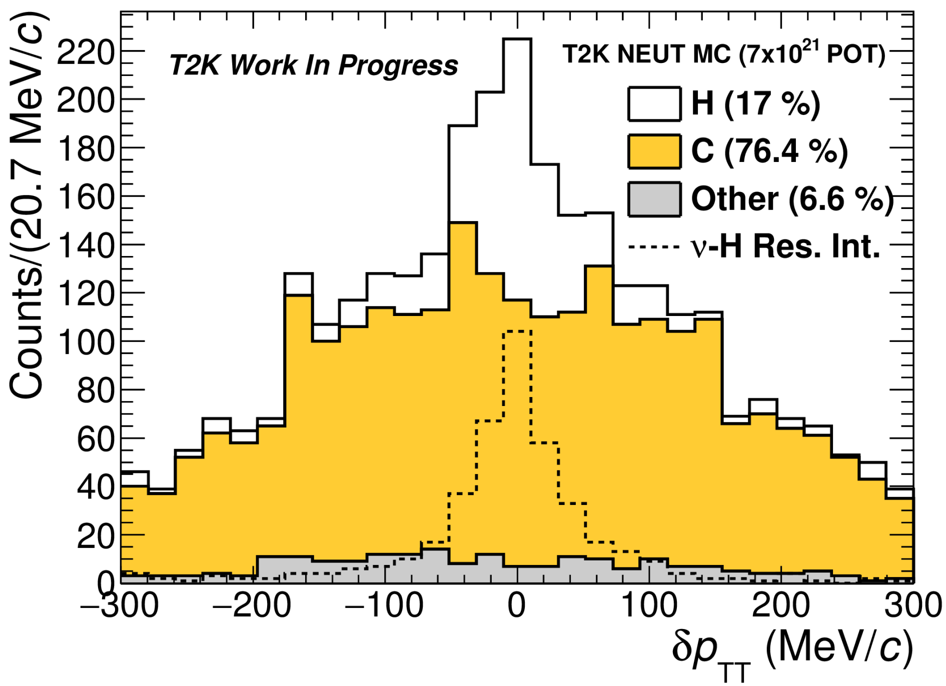
Nucl.Instrum.Meth. A659 (2011) 106-135

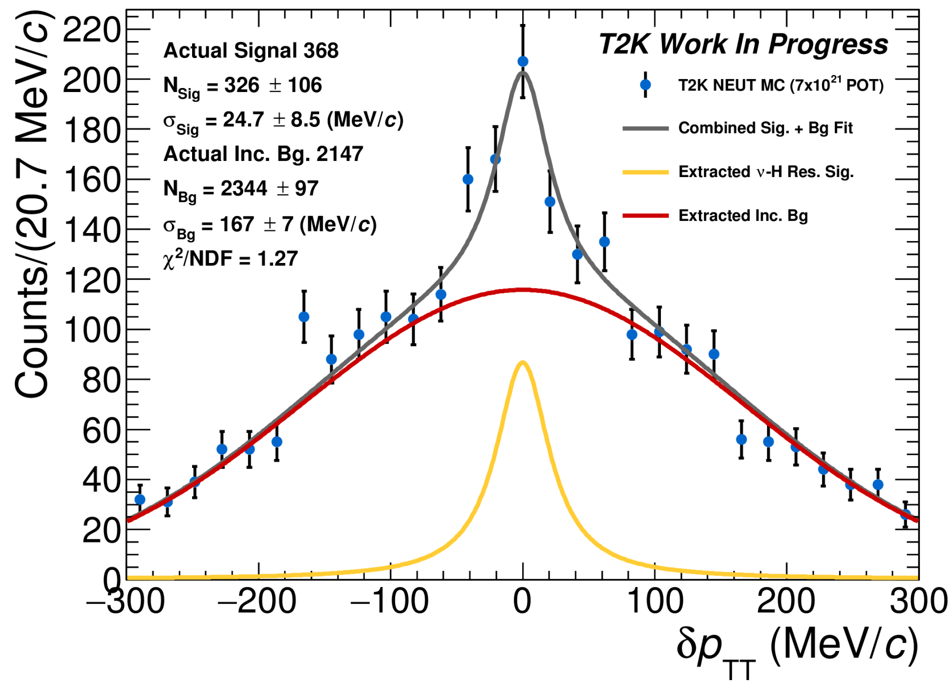


- J-PARC off-axis neutrino beam, 600 MeV peak energy
- Fine Grained Detector (FGD1) as CH target
- Event selection: 1 μ, $\geq$1 p, 1 π^+
  - PID and tracking: TPC1

arXiv:1605.00154

6. Measurement in T2K – double-T kinematic imbalance

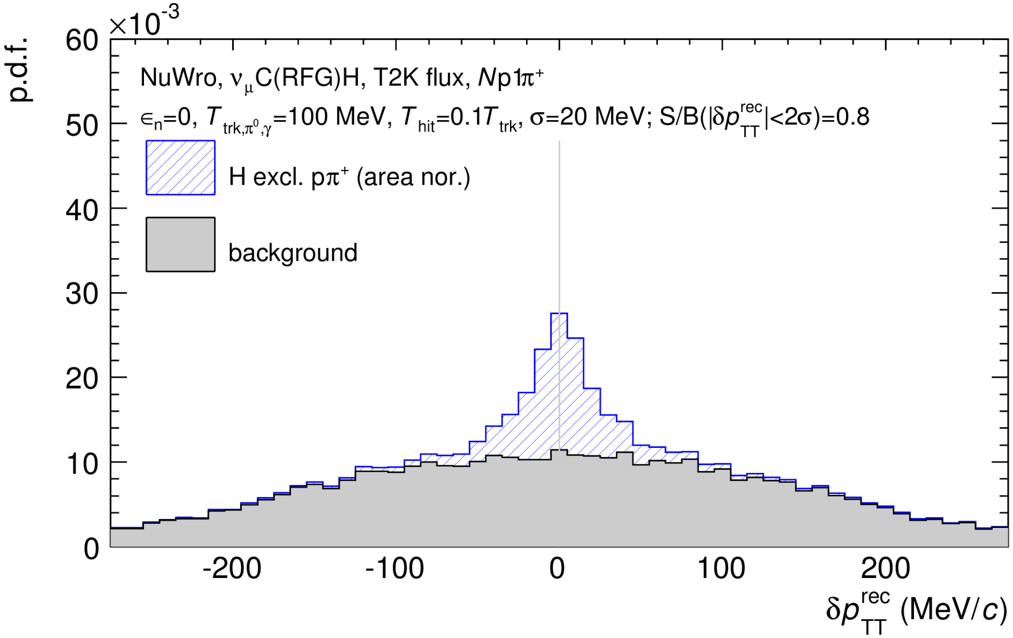




Current objective:
Develop signal extraction techniques;
Measure ν-H cross section – first one since 30 years.

arXiv:1605.00154

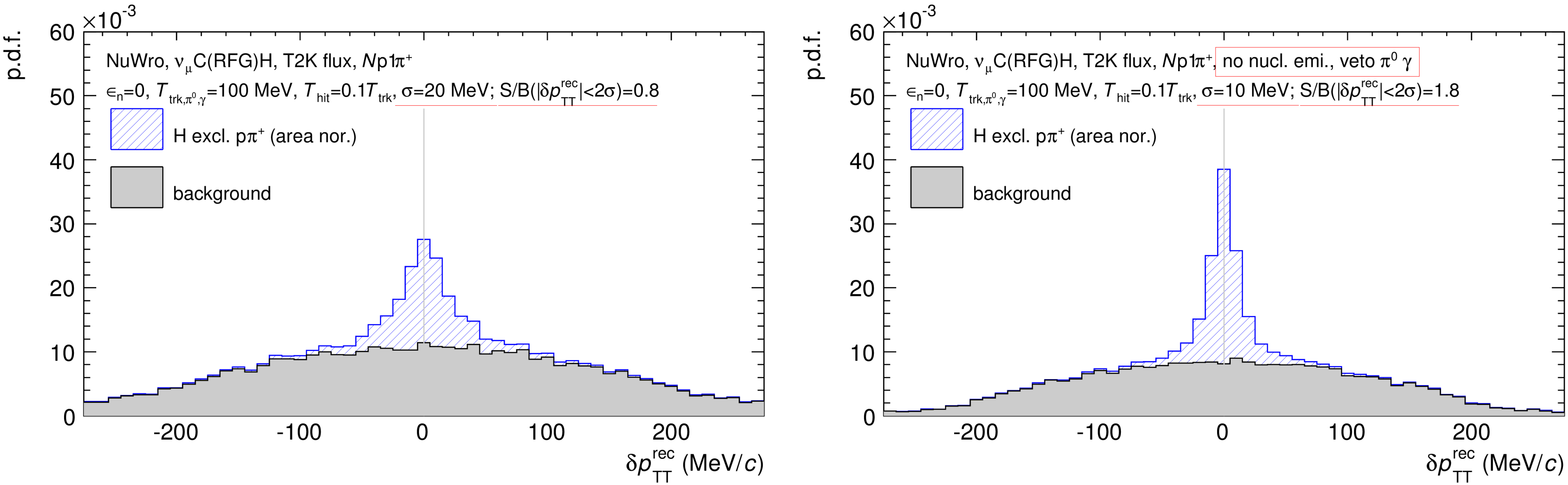
6. Prospects for Current Experiments



Simple performance projection of T2K-like detector using NuWro+T2K flux on CH (ideal acceptance)

arXiv:1512.09042

6. Prospects for Current Experiments



Simple performance projection of T2K-like detector using NuWro+T2K flux on CH (ideal acceptance)

The hydrogen event selection can be improved by

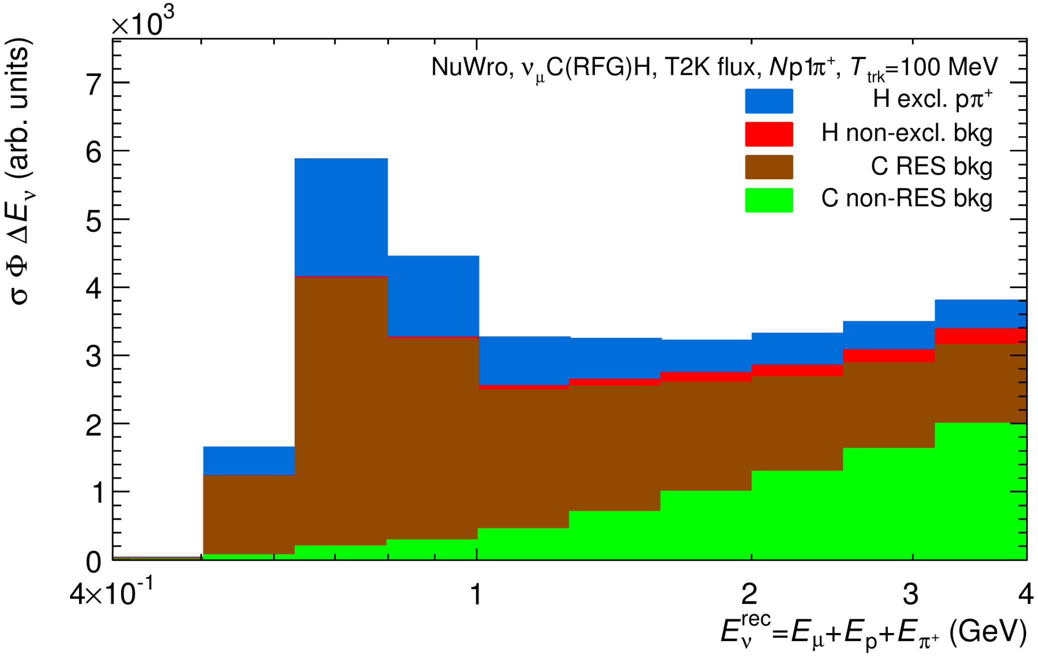
- Veto nuclear emission
- Veto π^0, γ background
- Improve tracking resolution → most critical

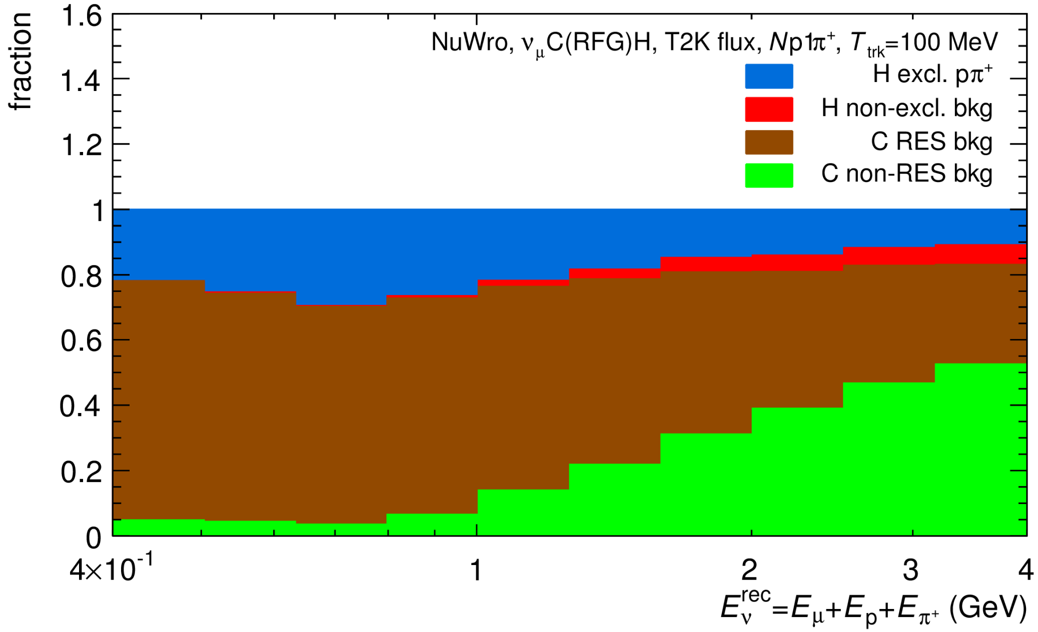
Requirement on nuclear physics decreases as resolution improves!

- ✓ Now only need to look at $|\delta p_{TT}|<O(10\text{ MeV})$ region.
- ✓ In future even a less burden; can be measured w/ pure nuclear target, e.g. graphite.

arXiv:1512.09042

6. *In situ* nuclear-free flux measurement via "bin-and-fit"





Previous setting (ideal accpt.) but w/ ideal tracking+PID

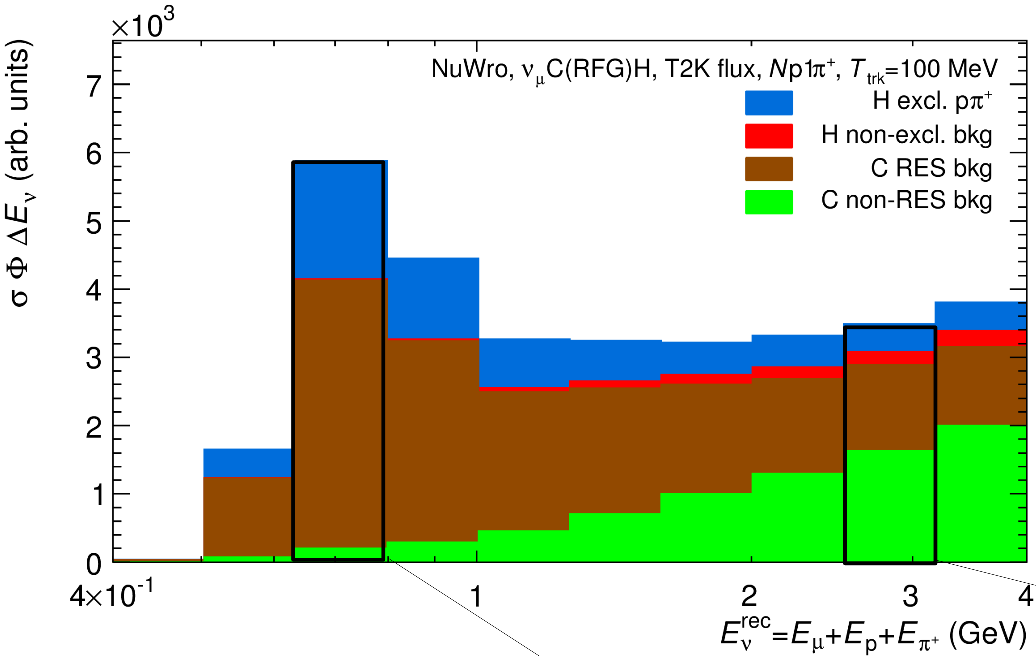
3-particle final state: μ, p, π^+

E_ν reconstructed as sum of final-state energy

H excl. pπ^+ signal

- Fraction: ~ 20% (blue-shifted peak) – 10% (tail)

6. *In situ* nuclear-free flux measurement via “bin-and-fit”



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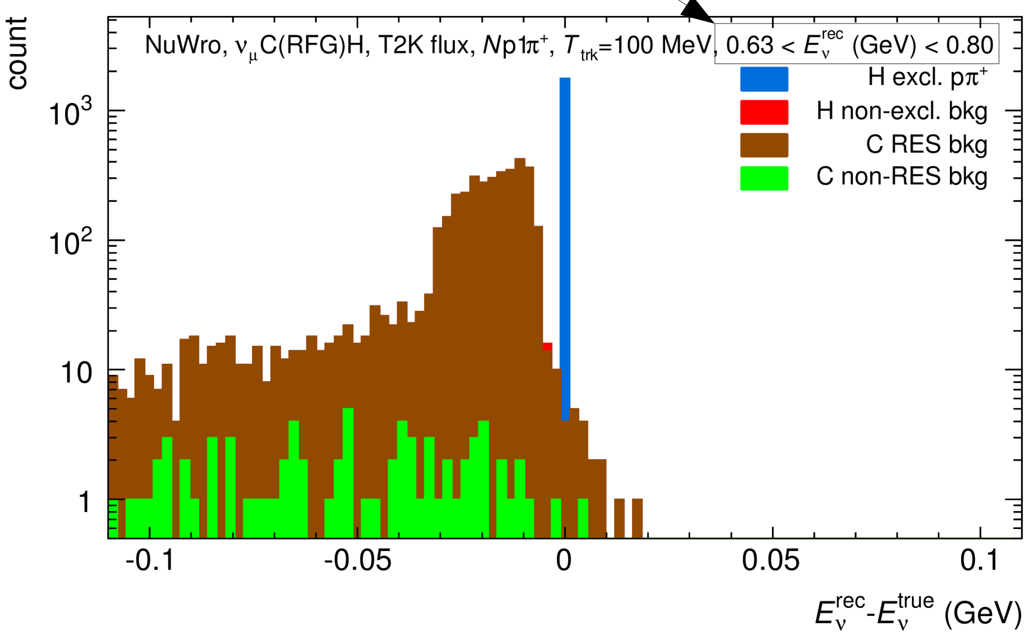
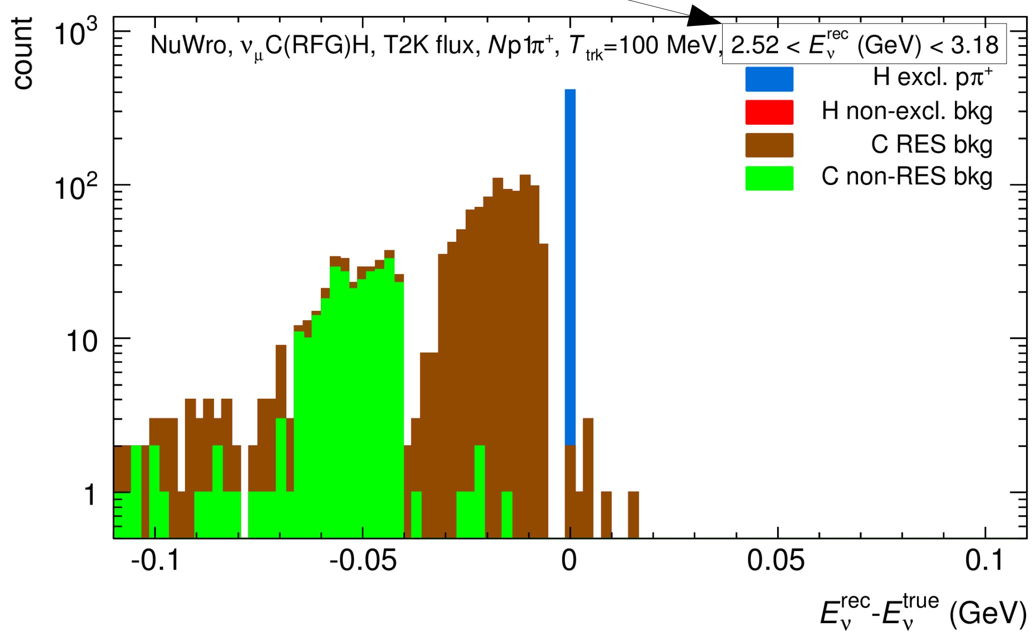
E_ν reconstructed as sum of final-state energy

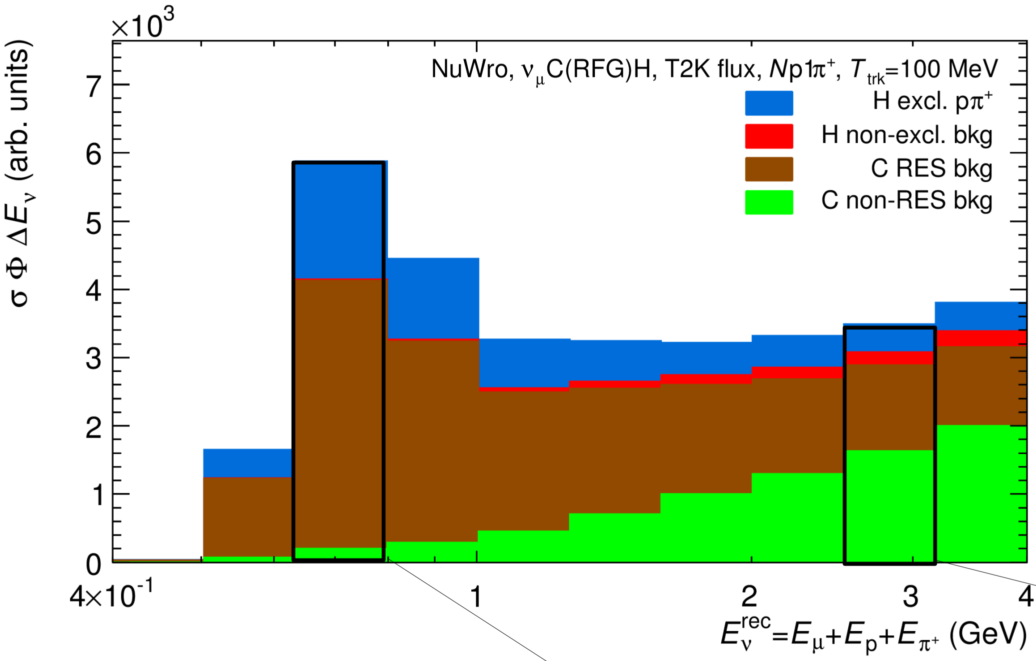
H excl. pπ^+ signal

- Fraction: ~ 20% (blue-shifted peak) – 10% (tail)
- No (nuclear) bias in reconstructed E_ν





6. *In situ* nuclear-free flux measurement via "bin-and-fit"

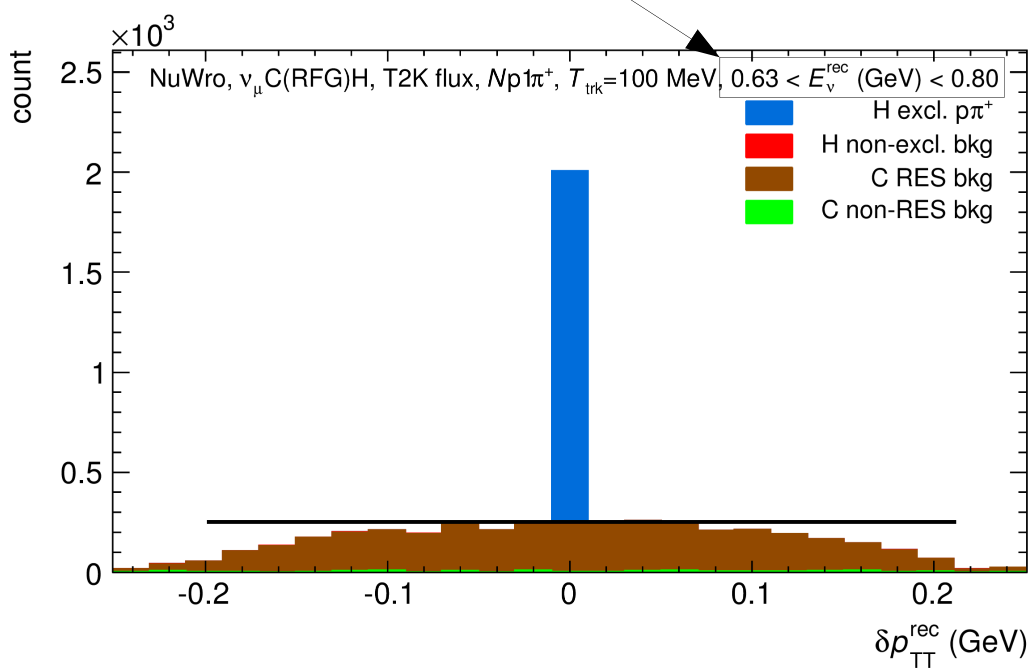


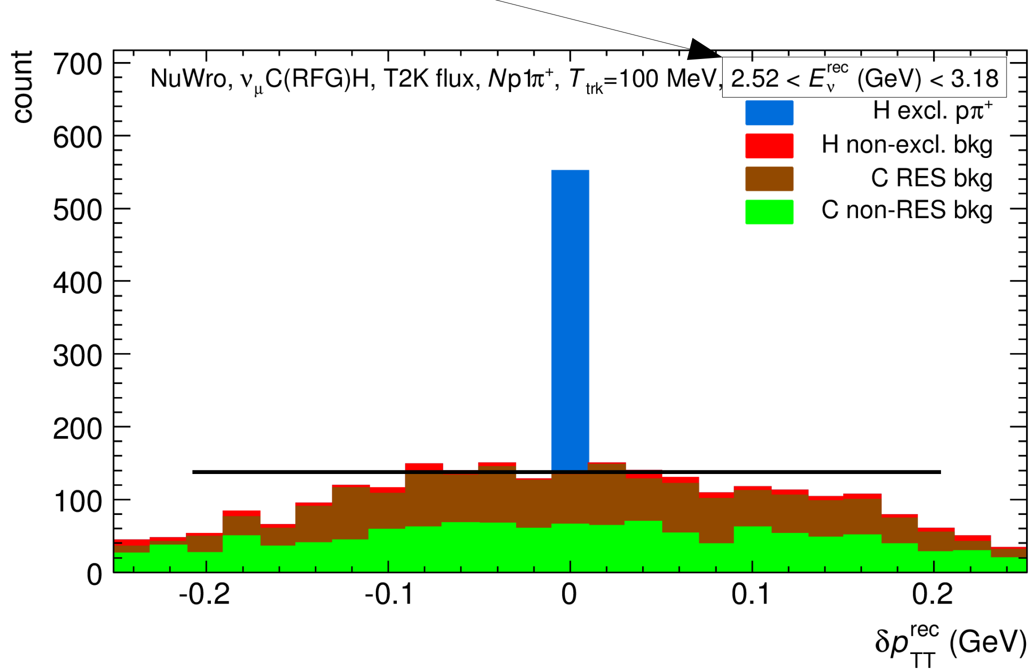
Previous setting (ideal accpt.) but w/ ideal tracking+PID

3-particle final state: μ, p, π^+
E_ν reconstructed as sum of final-state energy

H excl. pπ^+ signal

- Fraction: ~ 20% (blue-shifted peak) – 10% (tail)
- No (nuclear) bias in reconstructed E_ν
- Can be extracted (statistically in realistic case)





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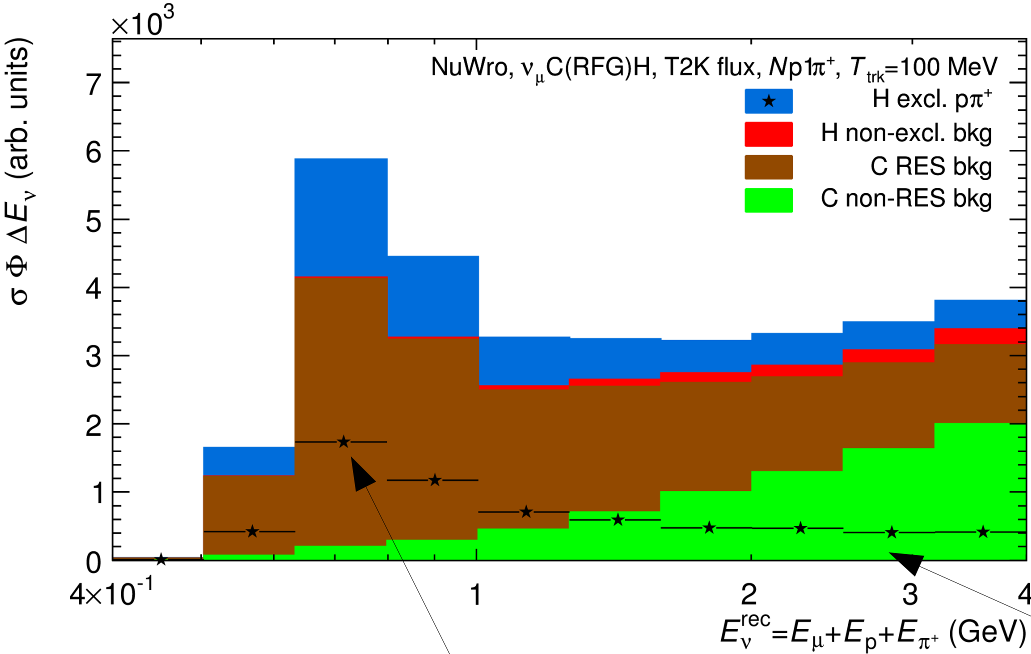


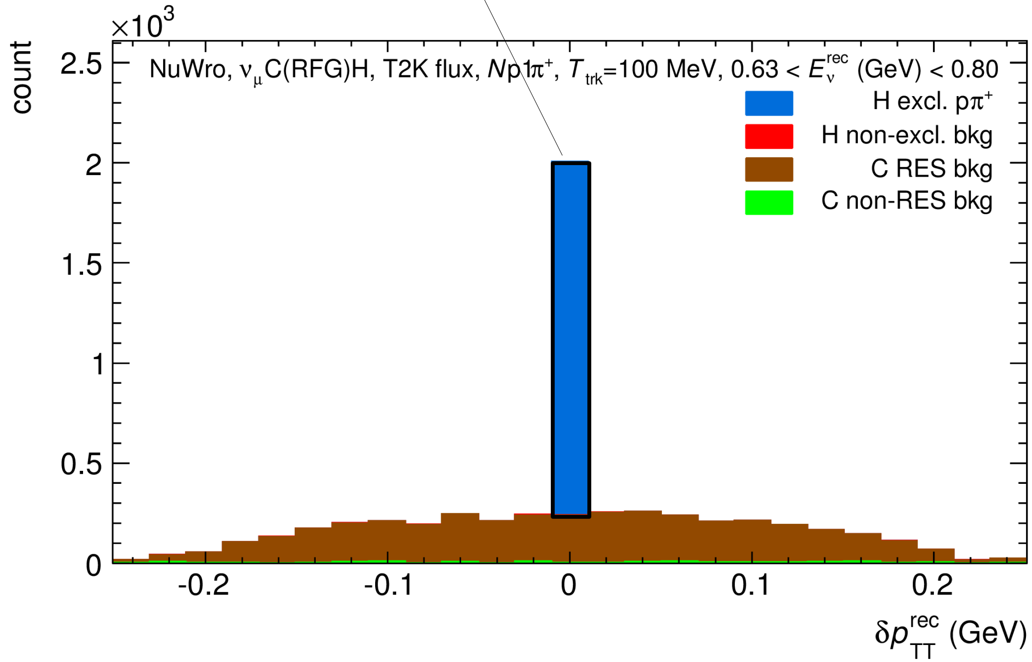
Previous setting (ideal accpt.) but w/ ideal tracking+PID

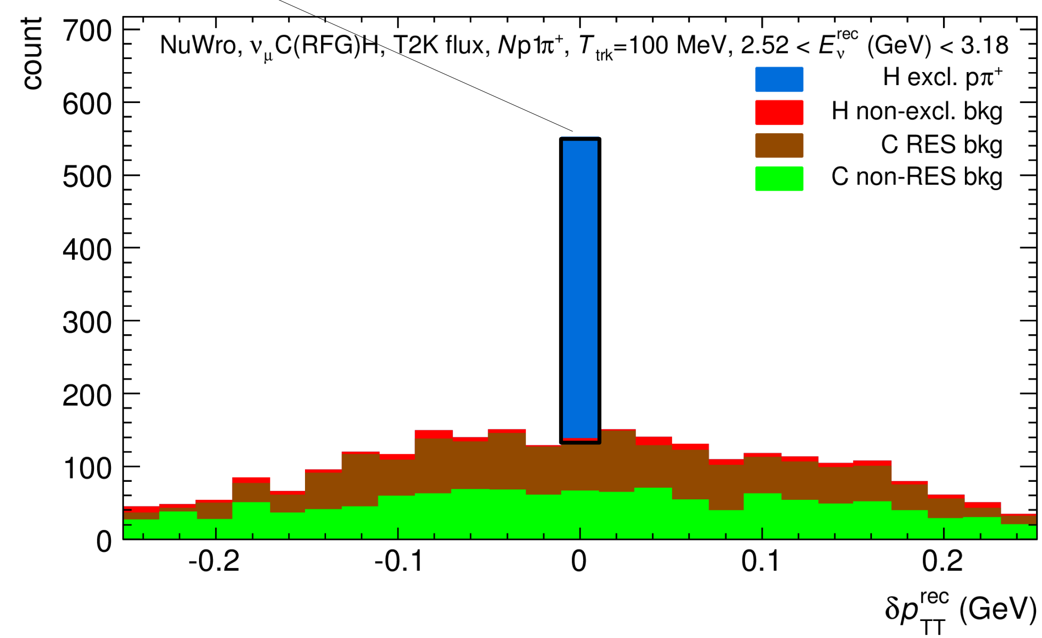
3-particle final state: μ, p, π^+

E_ν reconstructed as sum of final-state energy

H excl. pπ^+ signal

- Fraction: ~ 20% (blue-shifted peak) – 10% (tail)
- No (nuclear) bias in reconstructed E_ν
- Can be extracted (statistically in realistic case)
- σ only nucleon cross section, $\Phi = N/(\sigma\ \Delta E_\nu)$
  - → both Φ and E_ν ***nuclear-free***
  - → require tracking, PID (only needed for E_ν calculation), νH excl. pπ^+ x-sec





6. Potentials in Near-Future Experiments

- **T2K-II ND for *in situ* nuclear-free flux measurement**
  - Has free hydrogens (CH and H_2O)
  - Capable of momentum and PID measurement of muons, protons, pions
  - Need to optimize configuration for momentum resolution, and for acceptance for high statistics. A higher B-field is a more expensive but very effective way to improve the resolution.
  - Calorimetry capability to veto nuclear emission and electromagnetic background.
  - Nuclear physics in $|\delta p_{TT}|<O(10\text{ MeV})$ can be measured *in situ* with embedded graphite target.

Outline

1. Introduction
2. Measuring nuclear effects w/ minimal dependence on neutrino energy
3. Measuring neutrino energy independent of nuclear effects
4. Theory predictions
5. Measurement in MINERvA
6. Measurement in T2K
7. Summary

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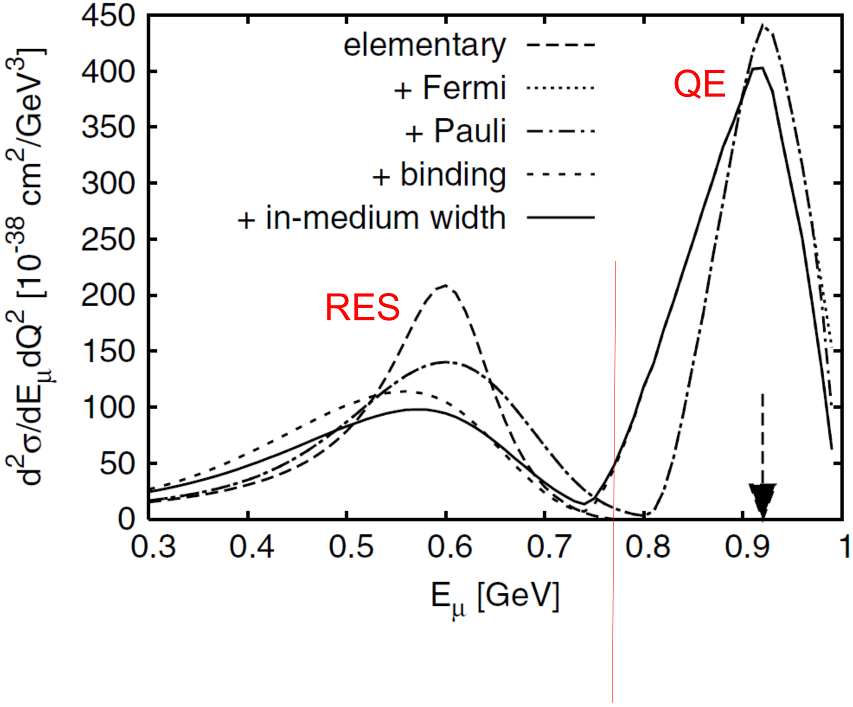
- Understanding nuclear effects is crucial for neutrino physics at GeV regime, deeply related to solving matter-antimatter asymmetry of our current universe.
- For neutrinos provided by accelerators, one can use transverse kinematic imbalance to maximally disentangle nuclear effects and neutrino energy uncertainty.
- Experimental efforts are under way. By exploring this new technique, we aim to provide critical physics input in neutrino interactions, and demonstrate/apply novel flux constraining techniques for future experiments.
- Outlook
  - Current measurements:
    - T2K-ND, MINERνA
  - Potential measurements in current experiments:
    - TK2-INGRID, T60, NOνA, μBooNE
  - Potential measurements in future experiments:
    - T2K-II-ND, DUNE-ND

BACKUP

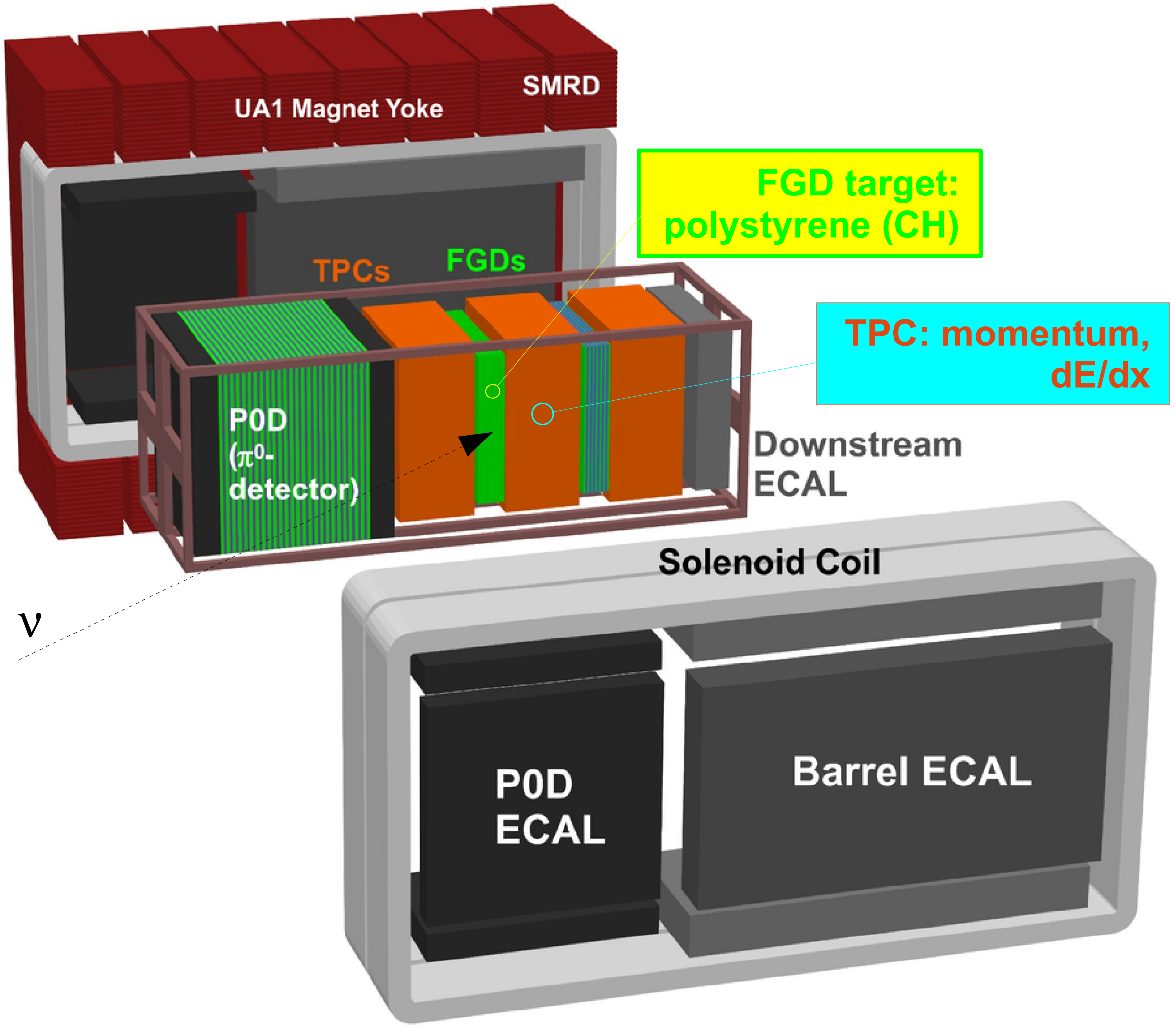
Neutrino energy 1 GeV

PHYSICAL REVIEW C 73, 065502 (2006)



6. Measurement in T2K

Nucl.Instrum.Meth. A659 (2011) 106-135



ν beam: off-axis, peak ~ 600 MeV

END

4785; 4948