Neutrino-nucleus interactions
Current understanding

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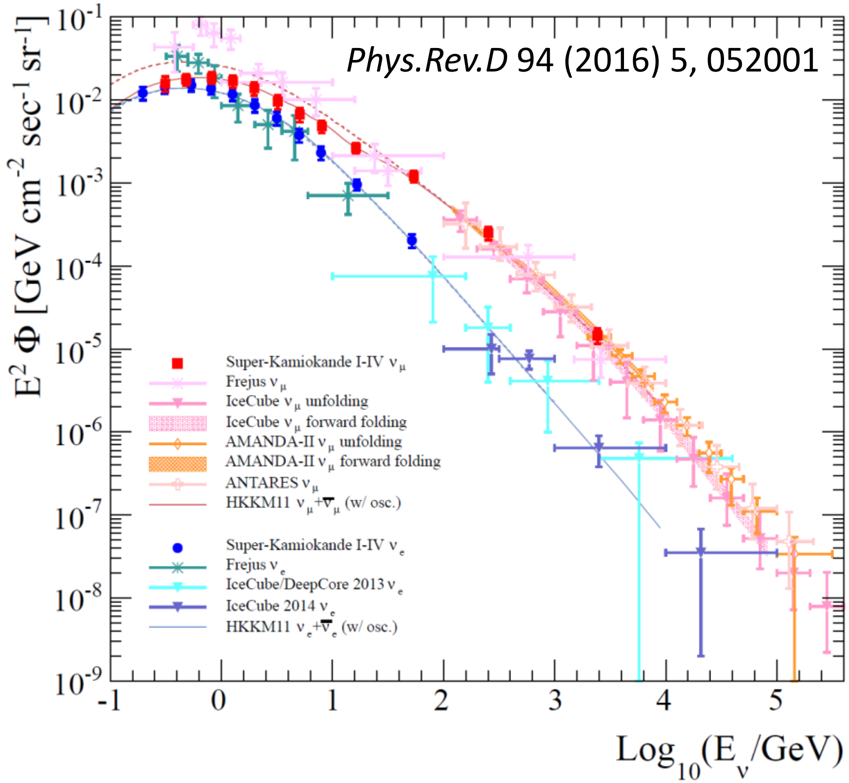
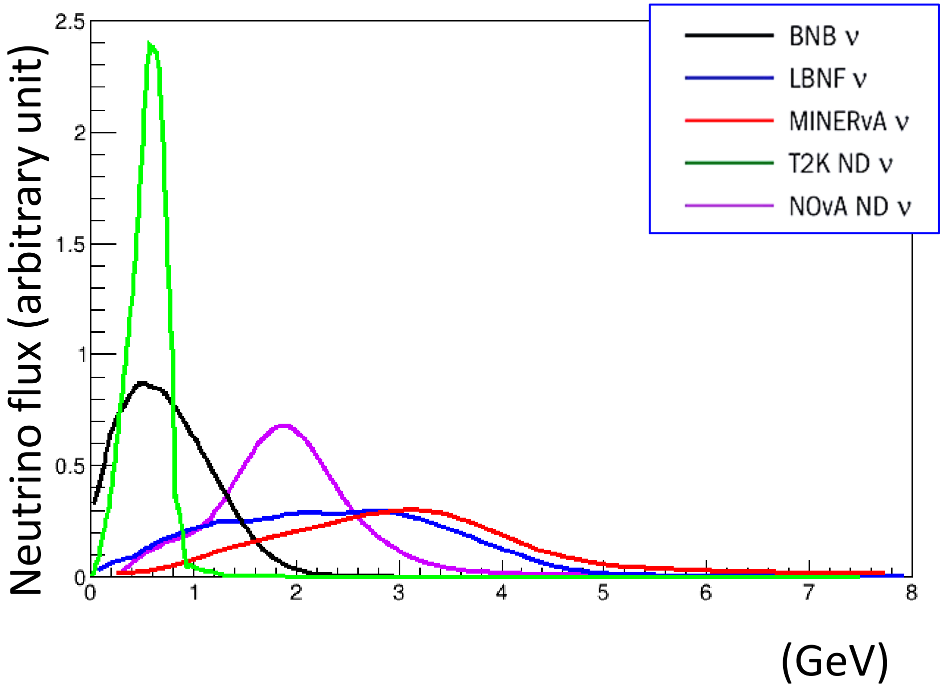
Introduction

- The energy of atmospheric neutrino spans from ~100 MeV to TeV.
- The energy of accelerator neutrino spans from ~100 MeV to GeV.



Phys.Rev.D 94 (2016) 5, 052001



- Current and next generation atmospheric- and accelerator-based neutrino oscillation experiments uses nuclear targets, like scintillator (Carbon), water (Oxygen), Argon, etc.

Detect particles from "neutrino-nucleus scattering".

Neutrino-nucleon/nucleus interactions above 100 MeV

Charged current quasi-elastic scattering (CCQE)

$$\nu + N \rightarrow l^{-} + N'$$

Neutral current elastic scattering

$$\nu + N \rightarrow \nu + N'$$

Single meson productions (RES)

$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi\ (\,\eta, K\,)$$

Single photon productions

$$\nu + N \rightarrow l^{-}(\nu) + N' + \gamma$$

(radiative decay of resonance)

Deep inelastic scattering (DIS)

$$\nu + N \rightarrow l^{-}(\nu) + N' + n \times \pi$$

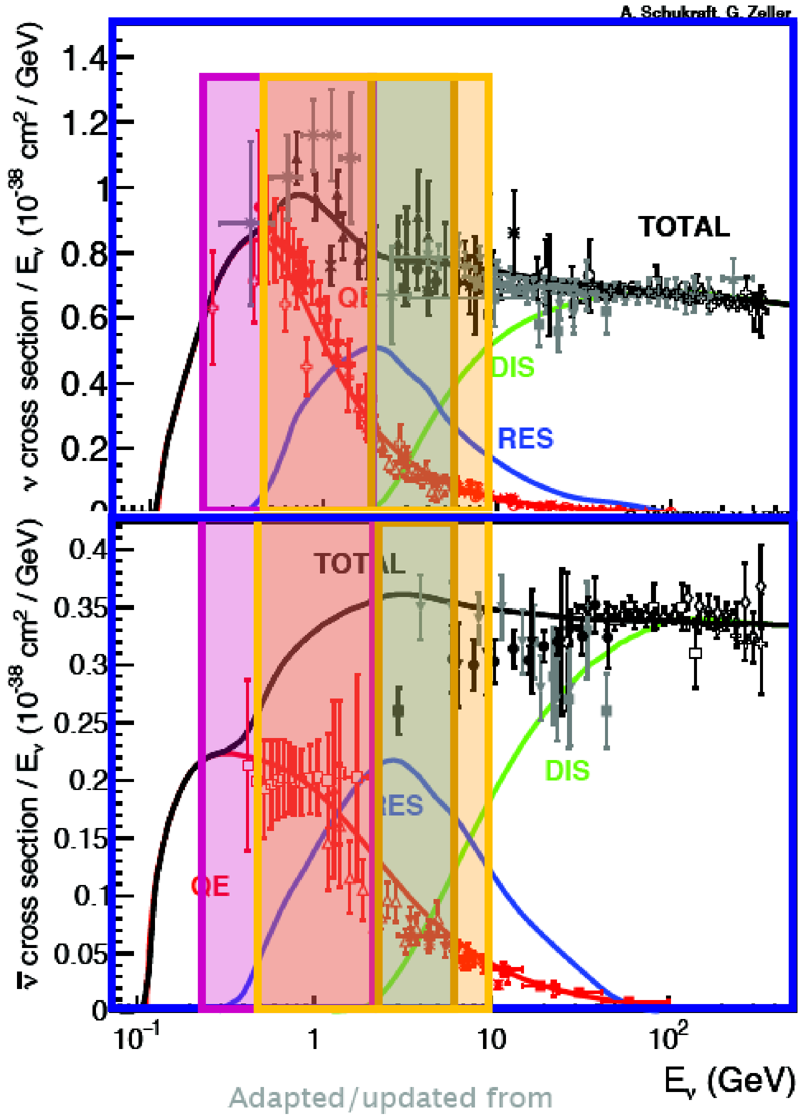
$$(\,\eta, K\,)$$

Coherent Single meson productions

$$\nu + A \rightarrow l^{-}(\nu) + A' + \pi^{+}(\pi^{0})$$

Neutrino detectors ~ nucleus target

Various “nuclear effects”

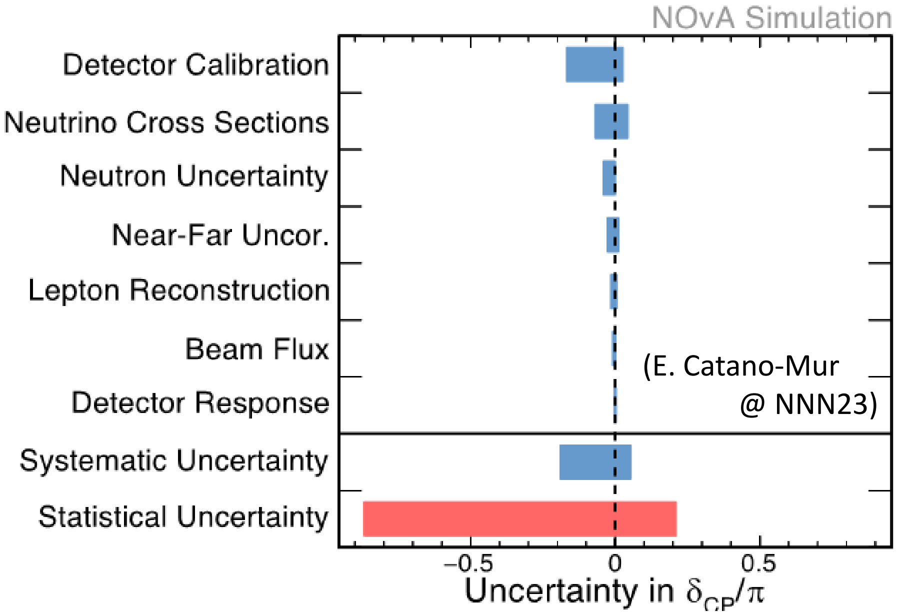


Adapted/updated from
I.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Introduction

Uncertainty of neutrino-nucleus interactions became one of the dominant sources of systematic errors.

NOνA Uncertainty on δ_{CP}



(E. Catano-Mur @ NNN23)

T2K uncertainty on the number of events in FD (SK)

	1 ring e (ν)	**1 ring e with 1 decay e (single π) (ν)**	**1 ring e ($\bar{\nu}$)**
Flux	2.8 %	2.8 %	2.9 %
Interaction	3.2 %	4.2 %	3.1 %
FD + SI + PN	3.1 %	13.4 %	3.9 %

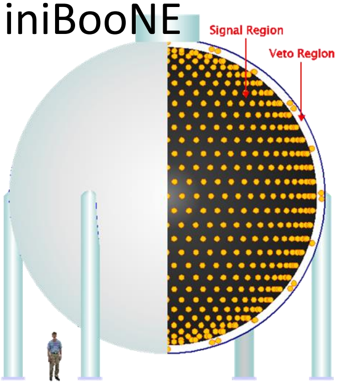
FD	Uncertainty from the far detector
SI	Uncertainty from the secondary interactions in the detector
PN	Uncertainty from Photo-nuclear effects

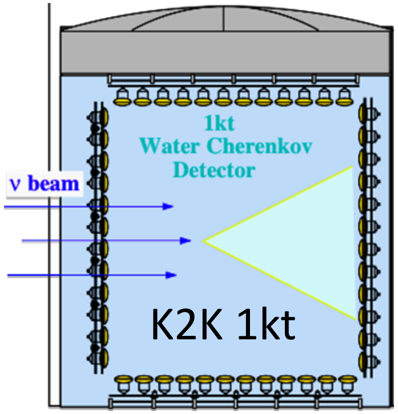
We must minimize the uncertainty of νA interactions.

Neutrino-nucleon/nucleus scattering experiments

Cherenkov detectors (Mineral Oil, Water)

MiniBooNE

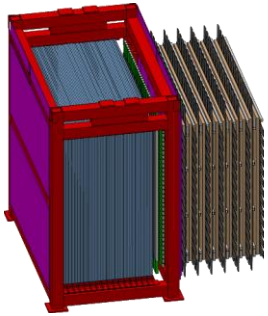




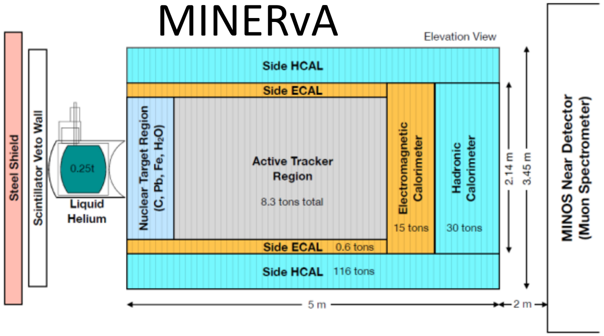
K2K 1kt

Scintillator tracking detectors with Calorimeters, mu tracker (+gas TPC)

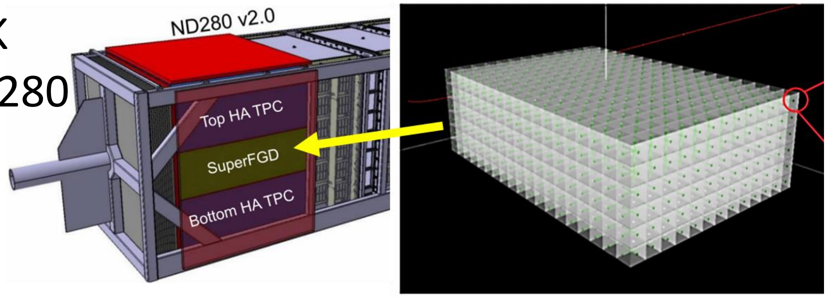
K2K SciBar



MINERvA

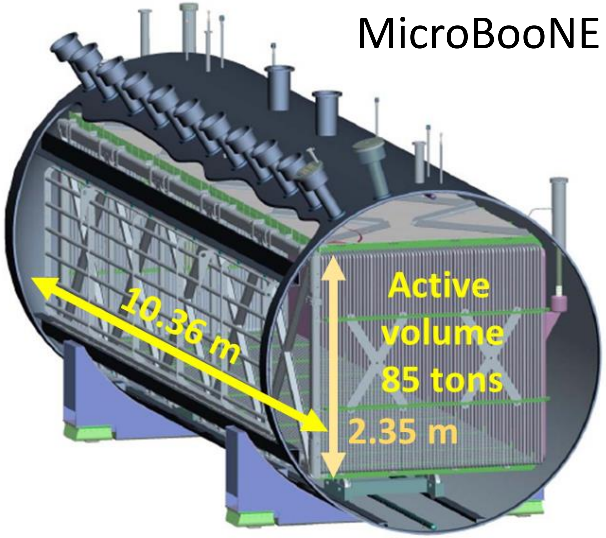


T2K
ND280

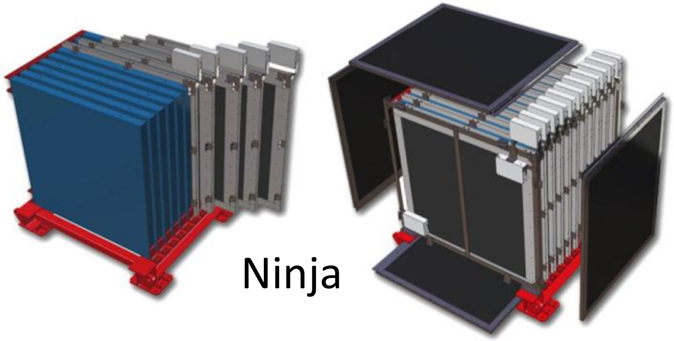


Liquid argon TPC

MicroBooNE



Nuclear emulsion detector



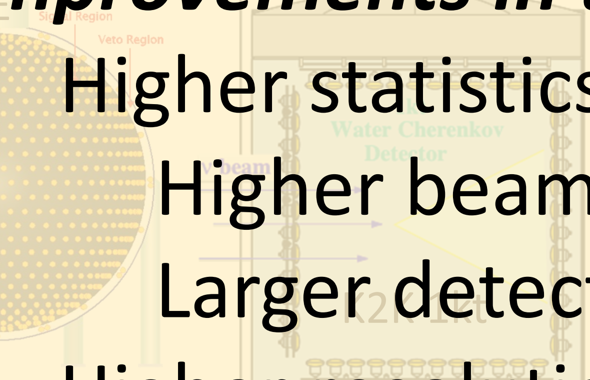
Ninja

Neutrino-nucleon/nucleus scattering experiments

Cherenkov detectors (Mineral Oil, Water)

Scintillator tracking detectors with Calorimeters, mu tracker (+gas TPC)

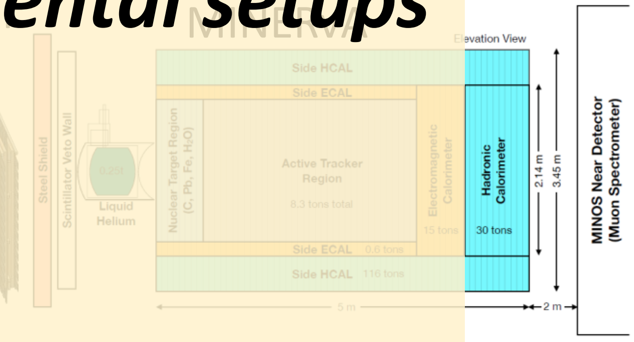
MiniBooNE



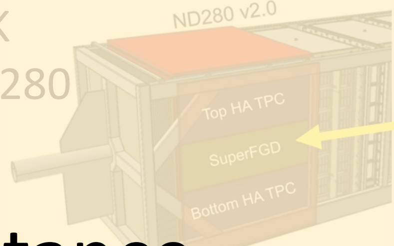
K2K 1kt

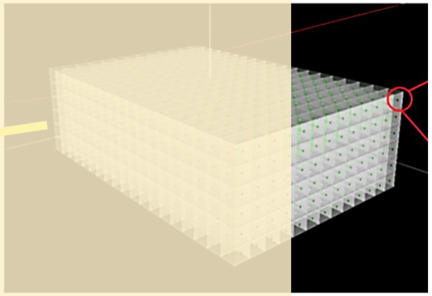
K2K SciBar

MINERvA



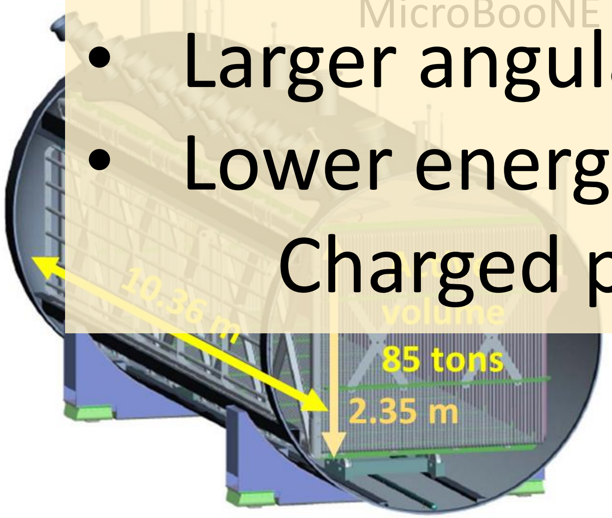
T2K ND280



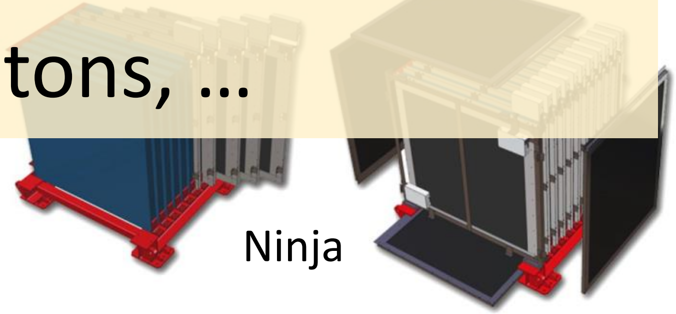


Liquid argon TPC

MicroBooNE



Nuclear emulsion detector



Ninja

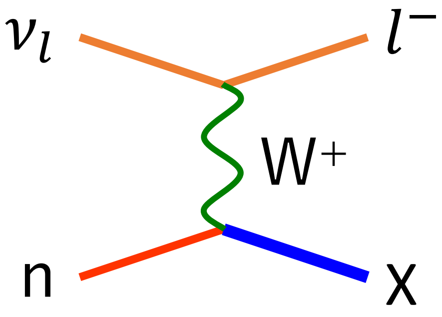
Improvements in the experimental setups

- Higher statistics
  - Higher beam intensity
  - Larger detectors
- Higher resolution
  - Finer granularity
- Larger angular acceptance
- Lower energy thresholds
  - Charged pions, protons, …

Charged current quasi-elastic scattering

Dominant interaction in a few hundred MeV.

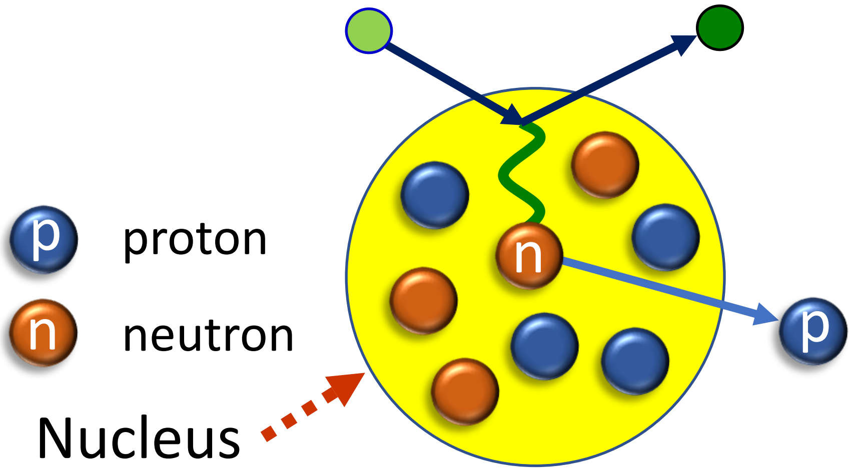
$$\boxed{\begin{array}{l} \nu\, n \rightarrow l^-\, p \\ \bar{\nu}\, p \rightarrow l^+\, n \end{array}}$$



Experiments after the late 1990's found some discrepancies.

- Fraction of forward going charged leptons in ***CCQE-like events*** is **smaller** than expected.
- # of ***CCQE-like*** events is **larger** than expected.

Modern neutrino experiments use "nuclear target."



Initial "nucleon" is bound in the target nucleus.

Scattered (produced) nucleon is in the nuclear medium.

"Nuclear effects"

Charged current quasi-elastic scattering

Dominant interaction in a few hundred MeV.

$$\boxed{\begin{array}{l} \nu\, n \rightarrow l^{-}\, p \\ \bar{\nu}\, p \rightarrow l^{+}\, n \end{array}}$$

Experiments after the late 1990's found some discrepancies.

Possible sources of discrepancies

1) Nuclear modeling (binding effects)
   - Changes the allowed kinematical ranges and distributions.
2) Neutrino-nucleon interaction modeling (axial vector form factor)
   - Changes the expected event rates and distributions.
   - Parameter is determined (mainly) by the old bubble chamber neutrino experiments in the 70's and 80's.

Axial vector form factor (dipole) $F_A(q^2) = -\frac{1.276}{(1-(q^2/{M_A}^2))^2}$

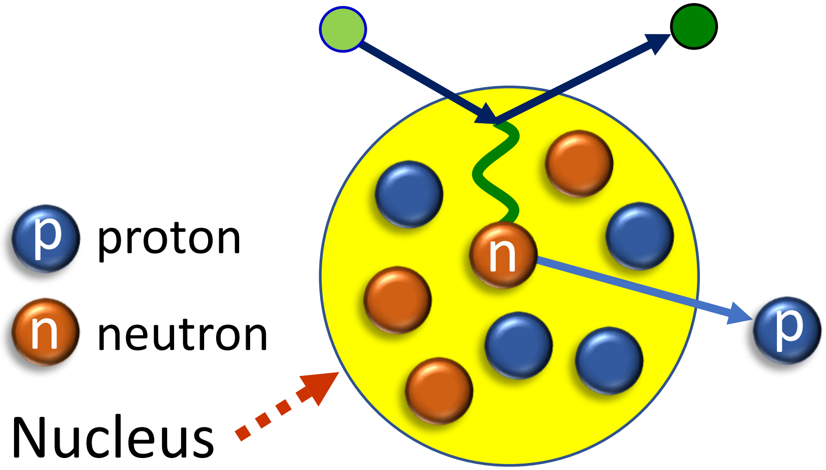
It is easy to change M_A, gives reasonable agreements with data, and thus, is used as an "effective" parameter.

3) Missing interactions which are observed as CCQE-like
   - Easily change the expected event rates and distributions.

Charged current quasi-elastic interaction

$$\begin{gathered} \nu\, n \rightarrow l^{-}\, p \\ \bar{\nu}\, p \rightarrow l^{+}\, n \end{gathered}$$

1) Nuclear modeling (binding effects)



Differential cross-section is large at small 4-momentum transfer (q^2).

Sensitive to various "nuclear" binding effects.

Outgoing nucleon is also re-scattered in the nucleus.

Several models have been proposed and are being tested.

- Fermi-gas
  Considering nucleon-nucleon correlations
- Spectral function
  Considering nuclear medium effects
- Relativistic mean-field (RMF) approaches
- Super-scaling model with RMF
- ...

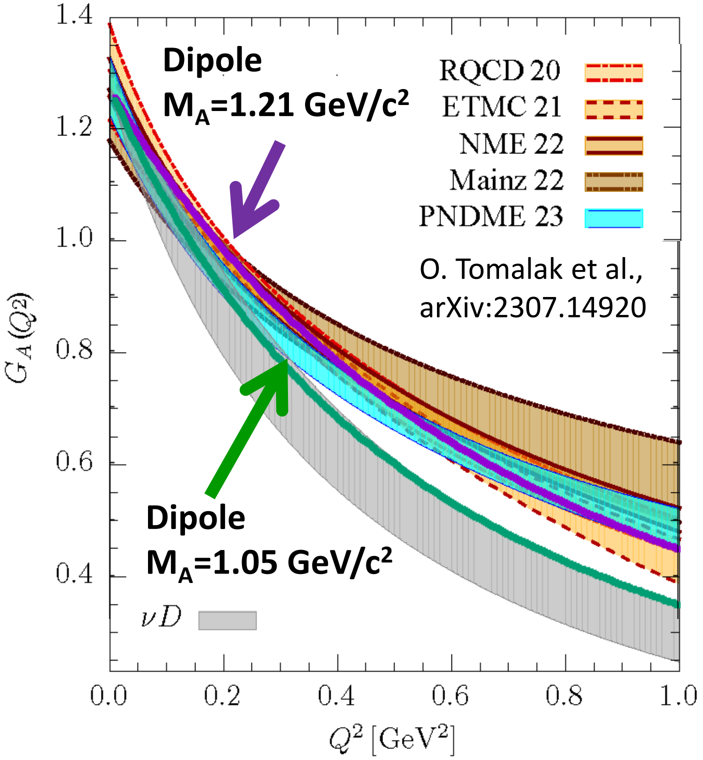
Charged current quasi-elastic interaction

2) Neutrino-nucleon interaction modeling

Axial vector form factor (dipole) $F_A(q^2) = -\frac{1.276}{(1-(q^2/{M_A}^2))^2}$

Recent lattice QCD (LQCD) results suggest the larger M_A from bubble chamber data fit and non-dipole.

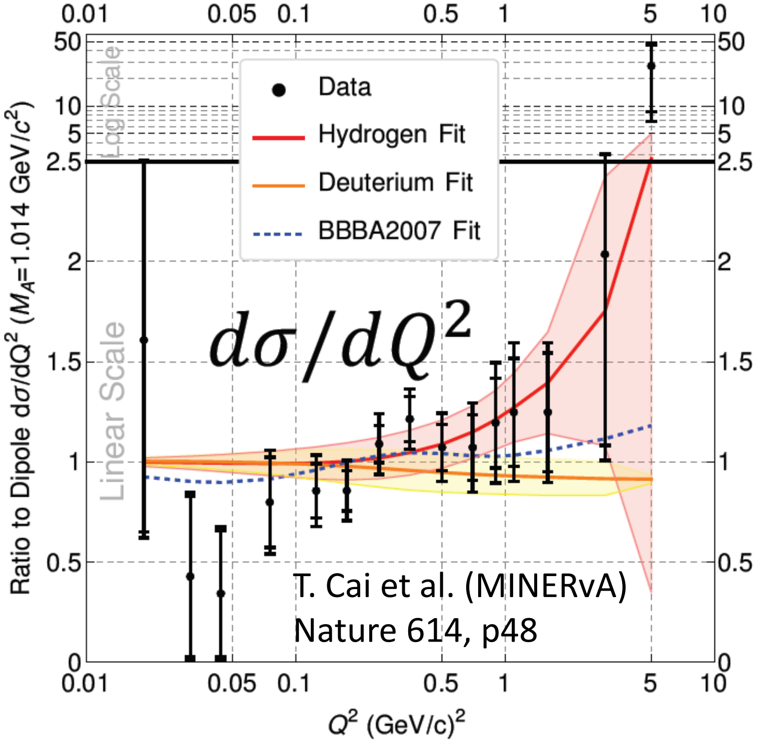
MINERvA measured ds/dQ^2 of $\overline{\nu_\mu}\,\mathrm{p} \rightarrow \mu^+\mathrm{n}$ scattering. Enhance in the large Q^2.



Dipole
M_A=1.21 GeV/c^2

Dipole
M_A=1.05 GeV/c^2

O. Tomalak et al., arXiv:2307.14920

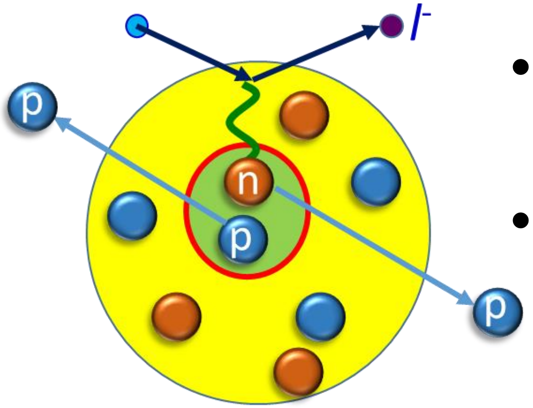


T. Cai et al. (MINERvA) Nature 614, p48

Charged current quasi-elastic-like events

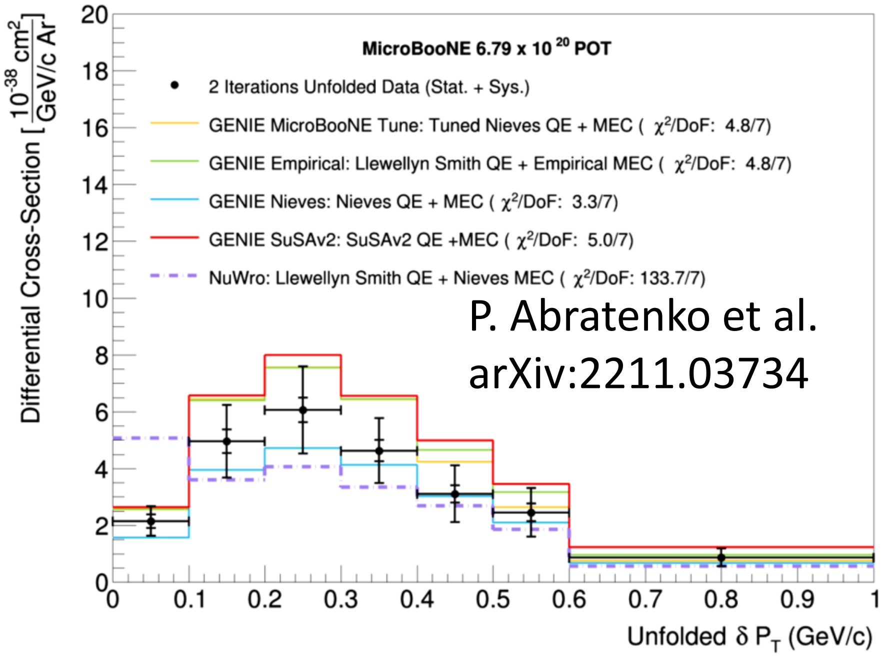
3) Missing "CCQE-like" interaction

"multi-nucleon" scattering $\nu\, N_1 N_2 \rightarrow l^{\pm}\, N_1' N_2'$



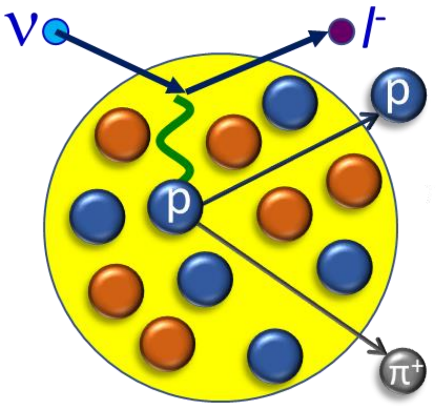
- Known to exist from the electron scattering experiments.
- Some models were proposed and implemented in simulation programs. (But it is difficult to implement models completely.)

- It has been difficult to "identify" this interaction experimentally.
- *New experiments (detectors) have started publishing results.*
  - MicroBooNE did the first differential cross-section measurement of 1 μ + 2 protons + 0 pion.



P. Abratenko et al.
arXiv:2211.03734

Single pion production

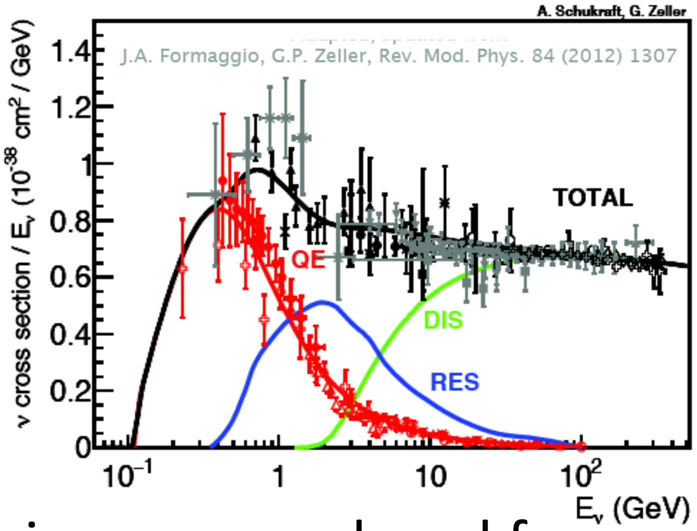


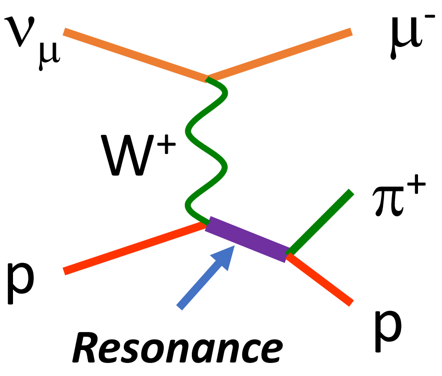
Charged and neutral single π production

$$\nu + N \rightarrow l^-(\nu) + N' + \pi$$

Dominant interaction around 1 to a few GeV.

- Dominant interaction in medium energy or wide band ν experiments, like NOvA and DUNE.
- Background when selecting "CCQE" as a signal, like T2K.
- Background of "proton decay" searches

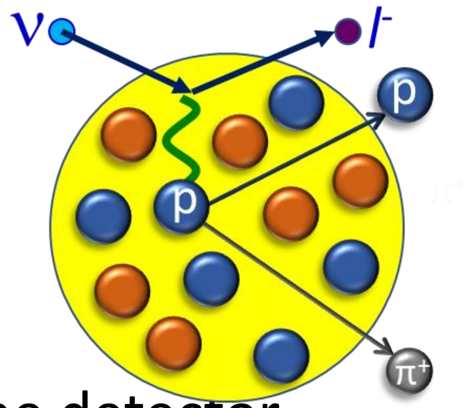




- A large fraction of pions are produced from the decay of the intermediate resonance.
  Re-interaction probability is high.
- Non-resonant contribution also exists.

Complicated process

Single pion production



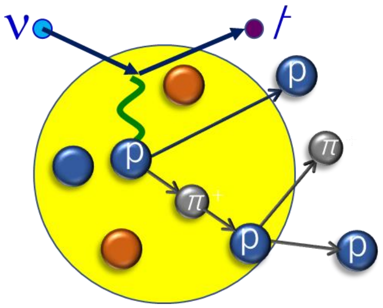
Charged and neutral single π production

$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

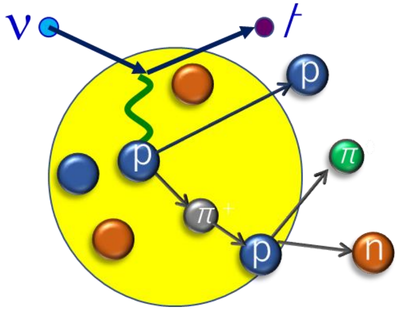
High probabilities of pion interactions

in the nucleus and secondary interaction in the detector

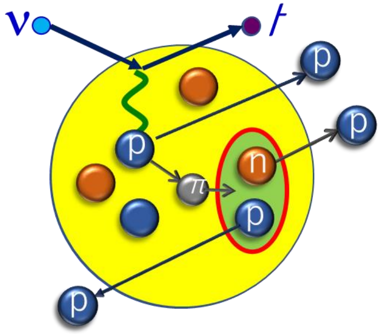
Inelastic scattering



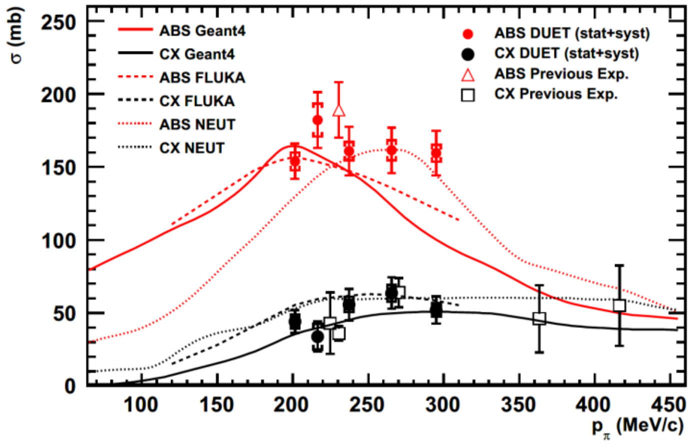
Charge Exchange



Absorption



(Additional pions may be produced.)



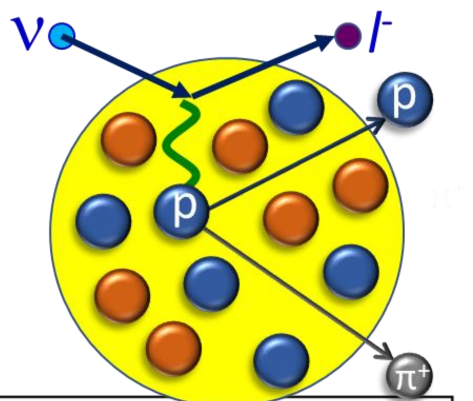
Available pion scattering data sets are limited.

Few data above Δ region

(p_π > 350 MeV/c).

Source of uncertainty.

Single pion production

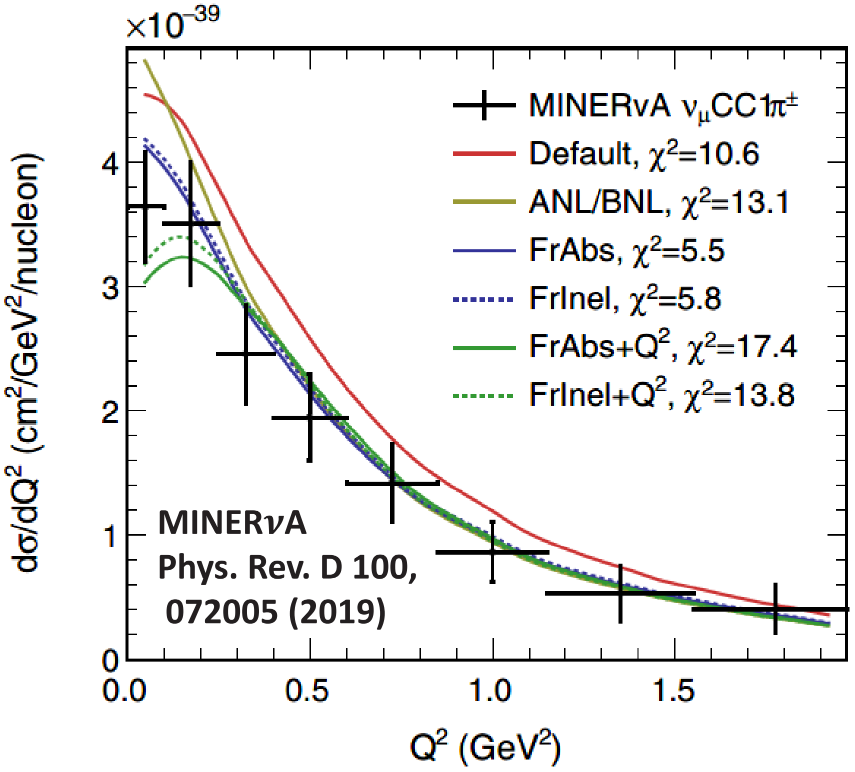


Charged and neutral single π production

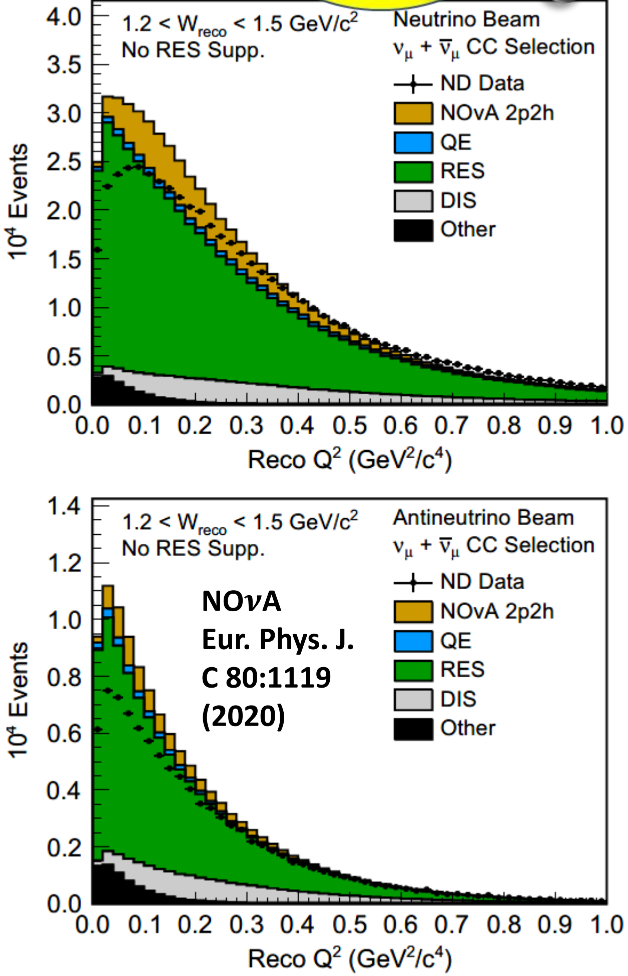
$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Discrepancies between the observation and simulation results

Suppression in small q^2 region

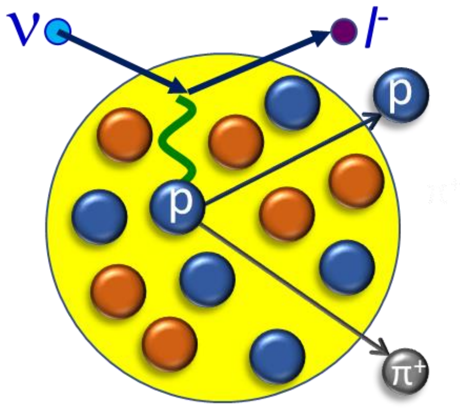


MINERνA Phys. Rev. D 100, 072005 (2019)



NOνA Eur. Phys. J. C 80:1119 (2020)

Single pion production



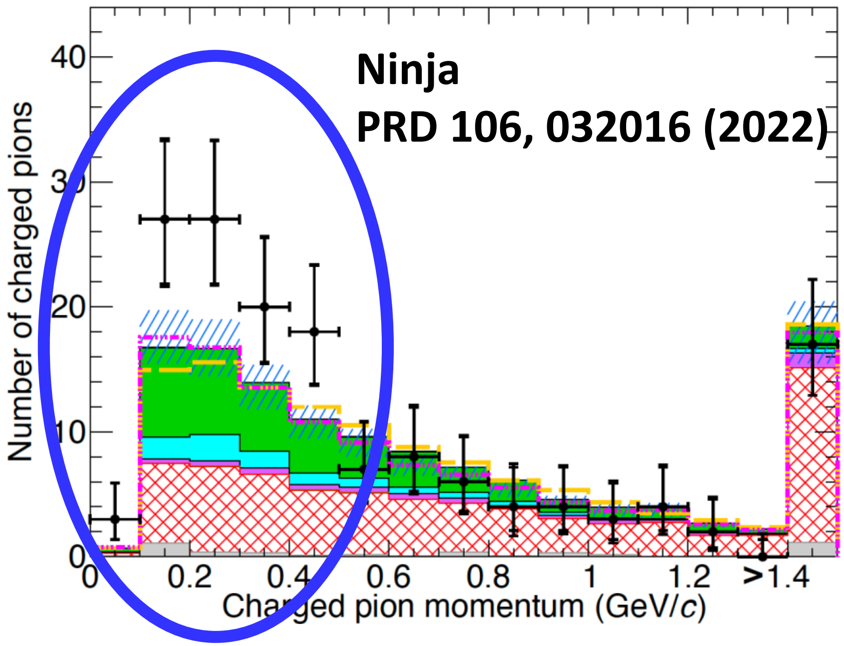
Charged and neutral single π production

$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Discrepancies between the observation and simulation results

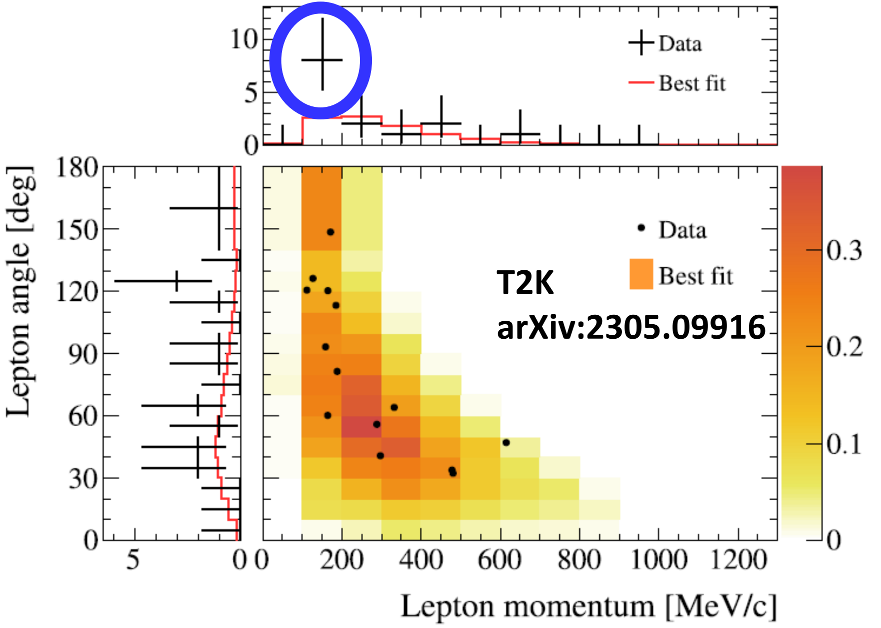
Low-momentum charged pion events excess in the data

($\bar{\nu} + Fe$@Ninja)



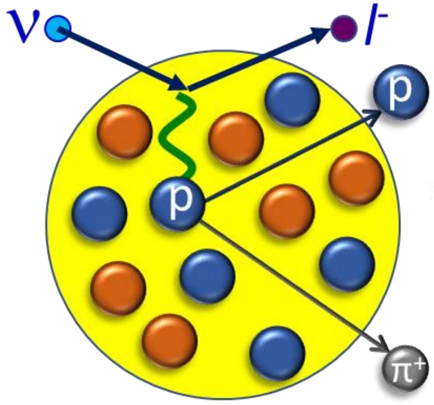
Ninja
PRD 106, 032016 (2022)

Low-momentum lepton + pion events excess in the data (e-like 1 ring with decay-e@SK = pion momentum < therehsold)



T2K
arXiv:2305.09916

Single pion production



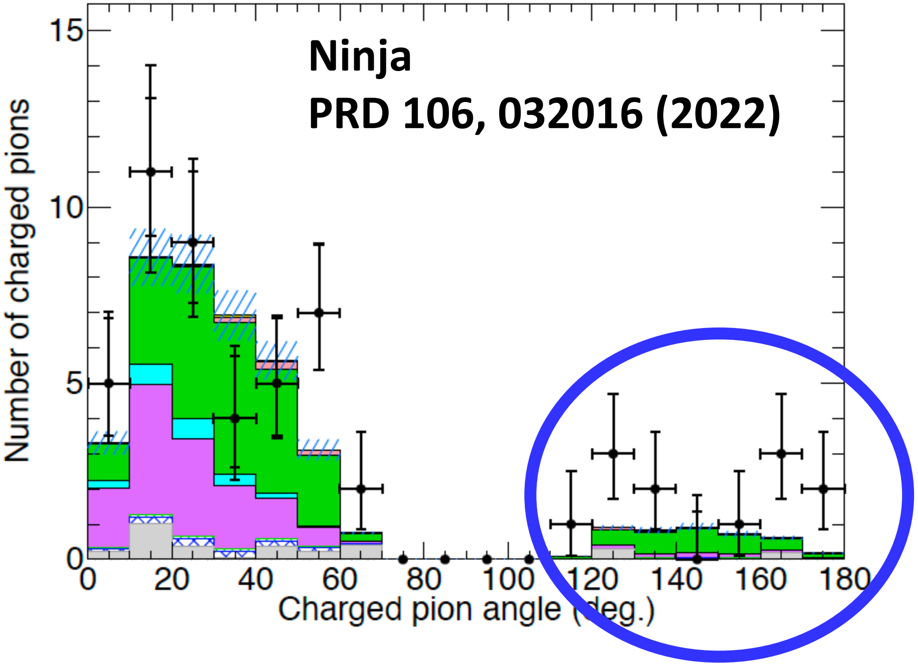
Charged and neutral single π production

$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Discrepancies between the observation and simulation results

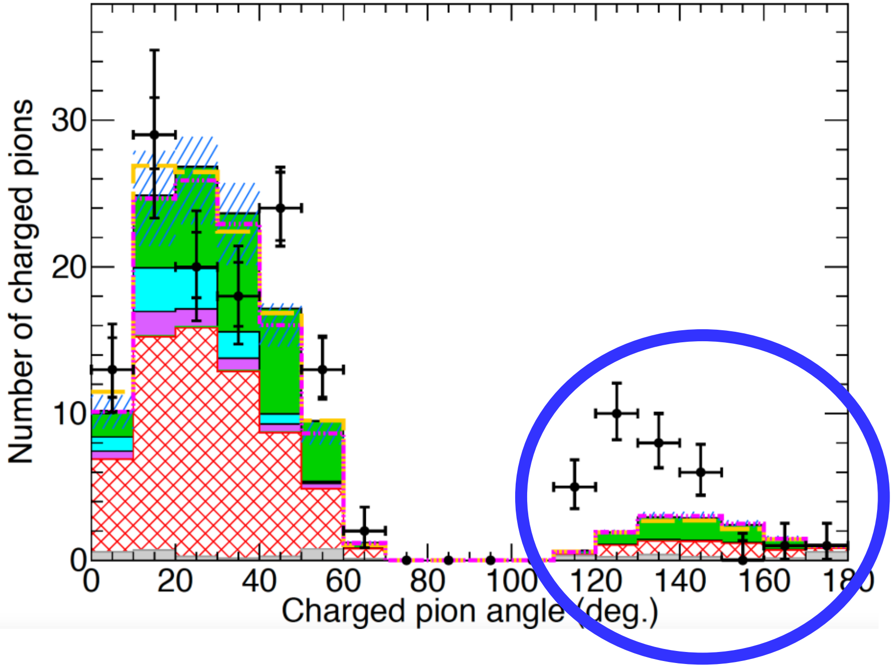
Larger # of charged pions in the backward direction.

($\nu + Fe$@Ninja)



Ninja
PRD 106, 032016 (2022)

($\bar{\nu} + Fe$@Ninja)



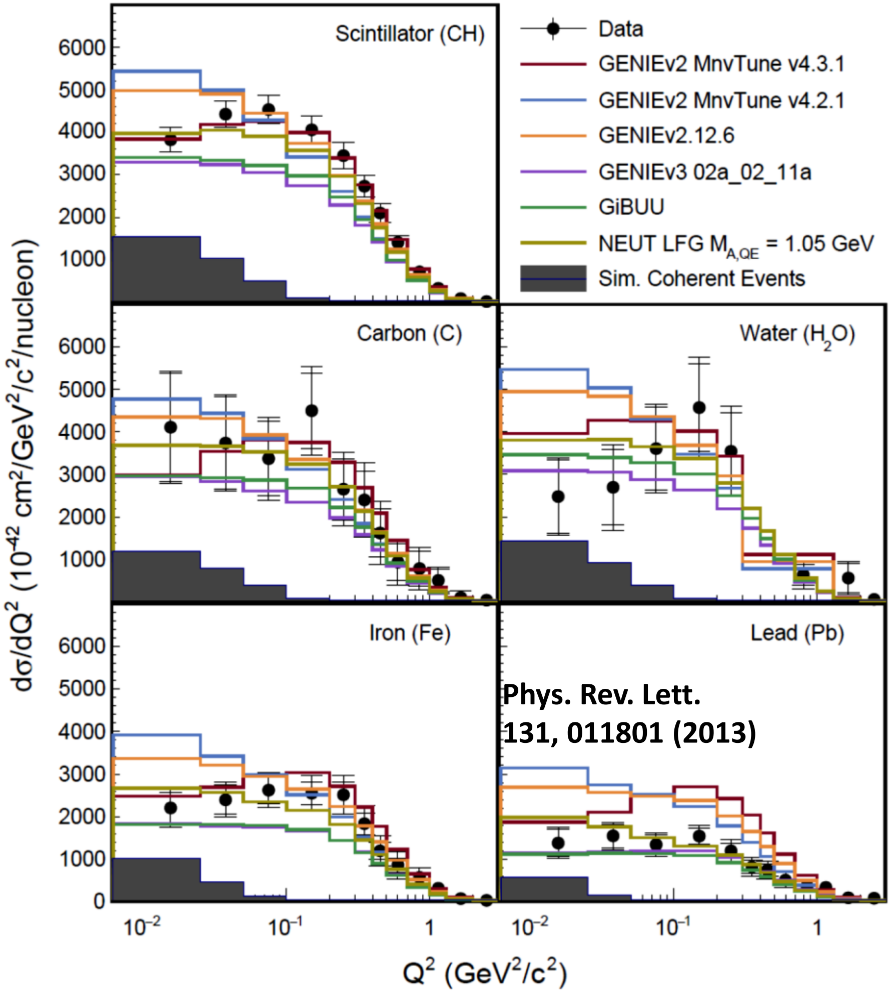
Single pion production

Charged and neutral single π production

$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

Nuclear dependence

- Primary ν interaction
  - Nuclear binding effects
- Final state interactions



Phys. Rev. Lett. 131, 011801 (2013)

- ✓ MINERvA reported the nuclear dependence of differential cross-sections.
- ✓ High precision and high statistics Carbon and Argon data sets will be available from various experiments.

Single pion production

Charged and neutral single π production

$$\nu + N \to l^{-}(\nu) + N' + \pi$$

Primary neutrino-nucleon interaction models in simulation programs

Rein and Sehgal model
- Relativistic harmonic oscillator quark model (FKR)
- Existing resonances and their interferences.
- Extensively used because it is straightforward in implementing the model and the reference code was provided by authors.

MK model (M. Kabirnezhad)
- Various enhancement introduced to the original Rein-Sehgal model
  - Graczyk-Sobczyk form-factors, HNV model based non-resonant contribution, fit to the electron scattering data sets.

Dynamical coupled-channels model (Nakamura, Sato et al.)
- Interferences are under control
- Coupling strengths are determined by experimental data analysis

Adler-Rarita-Schwinger formalization
- Treat final hadronic state (3/2-spin resonance state) as Rarita-Schwinger field. (Applicable to Δ)

Shallow and Deep Inelastic scattering (SIS/DIS)

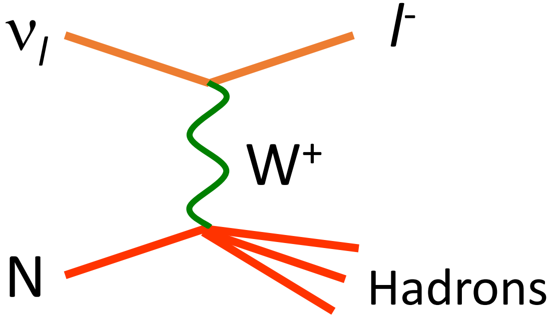
Charged and neutral SIS & DIS

$$\nu + N \rightarrow l^{-}(\nu) + N' + X\ (X = hadrons)$$

Dominant interaction above a few GeV.

Described as neutrino-quark interactions.

- Rather simple cross-section equations with parton distribution functions.
- Parton distribution functions (PDF) are extracted from various high energy experiments.

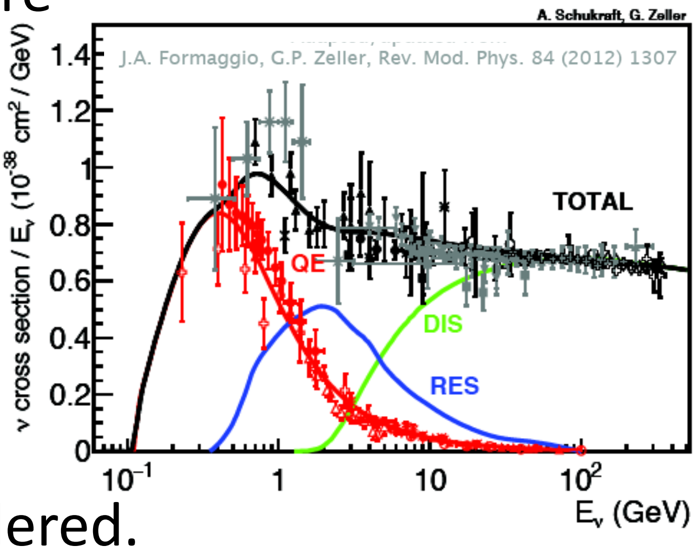


Issues

Existing PDF does not cover the entire kinematic regions as-is. (Covers large q^2 and W regions.)

No nuclear dependences are considered.

➡ Careful treatments (corrections) are required to for the interactions from a few to 10 GeV.


A. Schukraft, G. Zeller

J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Shallow and Deep Inelastic scattering (SIS/DIS)

Charged and neutral SIS / DIS

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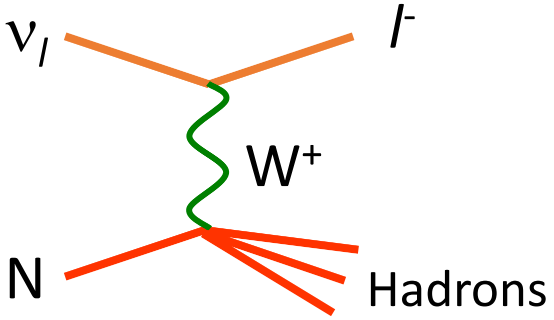
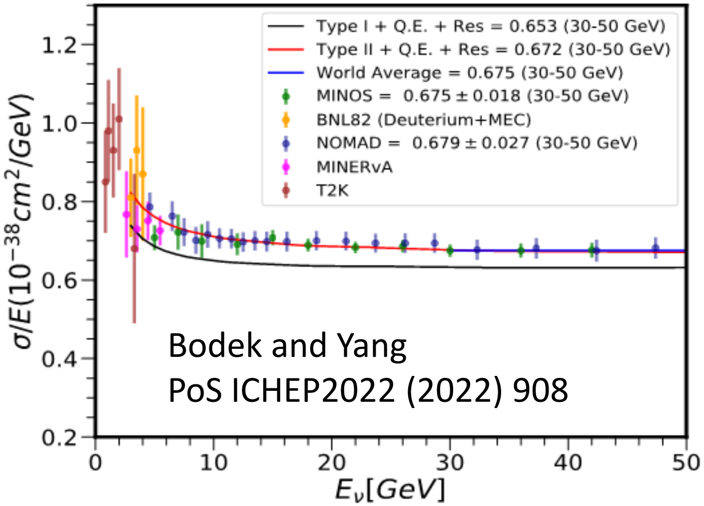
Dominant interaction above a few GeV.

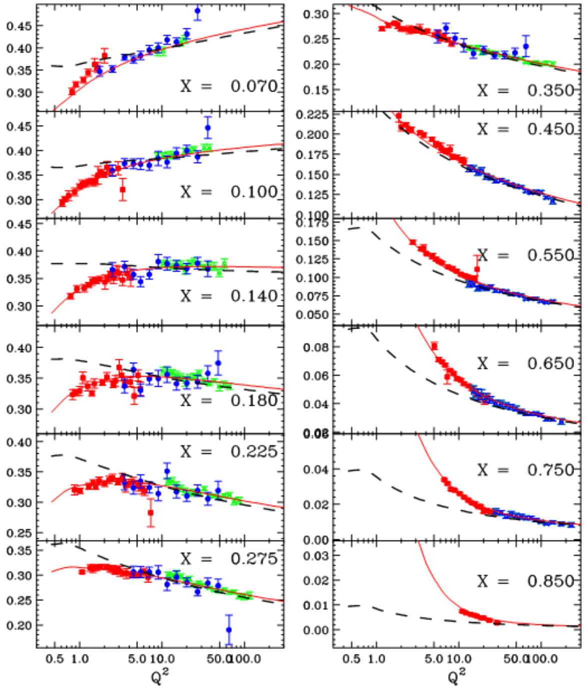


Model for “low energy” SIS / DIS

Prescriptions by Bodek and Yang are commonly used. Their model provide the way to extend the PDF to low q2, low W region. (Model parameters are extracted by fitting various data.)



Bodek and Yang
PoS ICHEP2022 (2022) 908



Bodek and Yang PoS ICHEP2022 (2022) 908

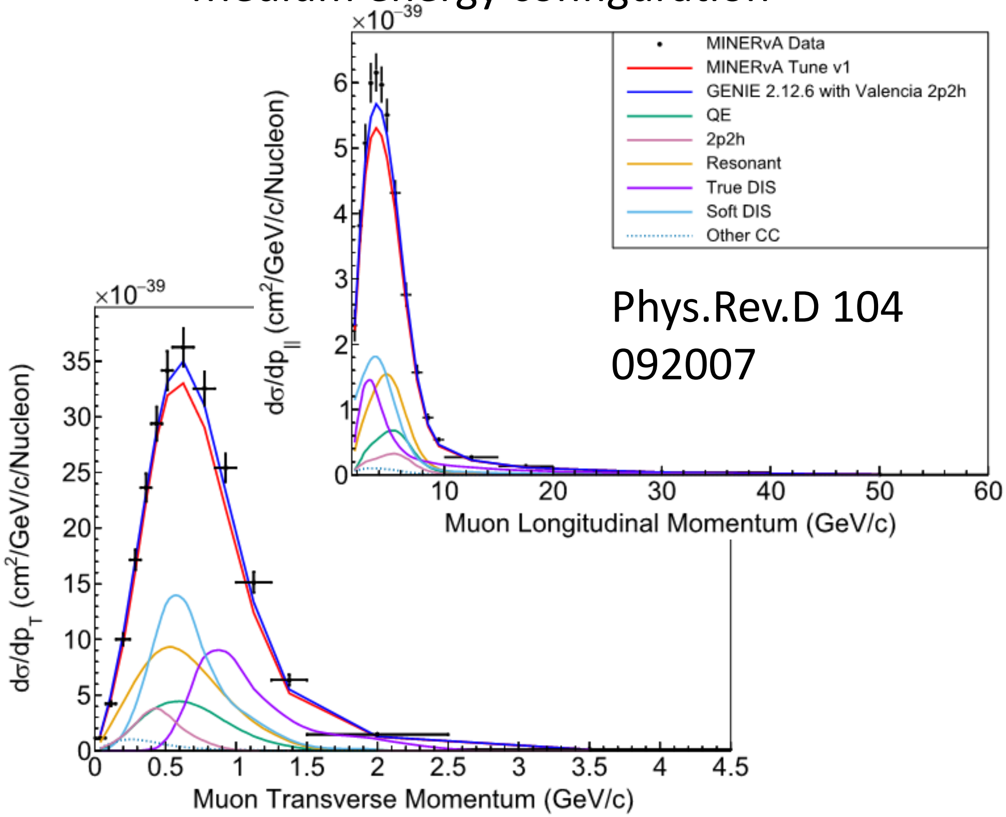
Shallow and Deep Inelastic scattering (SIS/DIS)

Charged and neutral SIS / DIS

$$\nu + N \rightarrow l^{-}(\nu) + N' + X \ (X = hadrons)$$

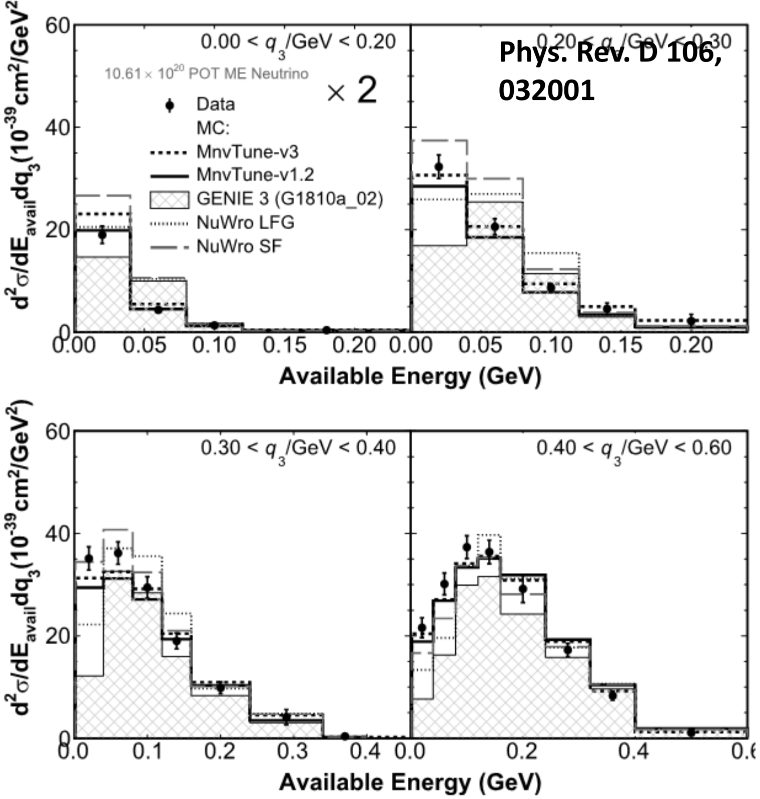
MINERvA experiment published various results,
both lepton momenta and hadron energies.

Lepton kinematics
Medium energy configuration



Phys.Rev.D 104
092007

Available energy (Hadron energy)
Medium energy configuration



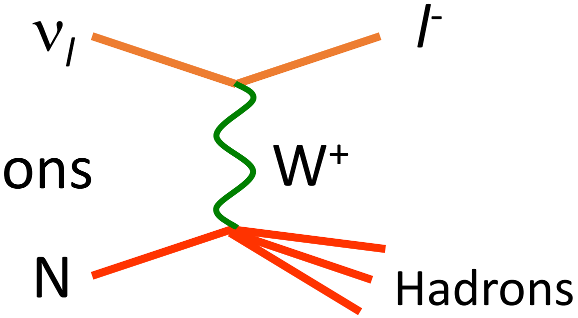
Phys. Rev. D 106, 032001

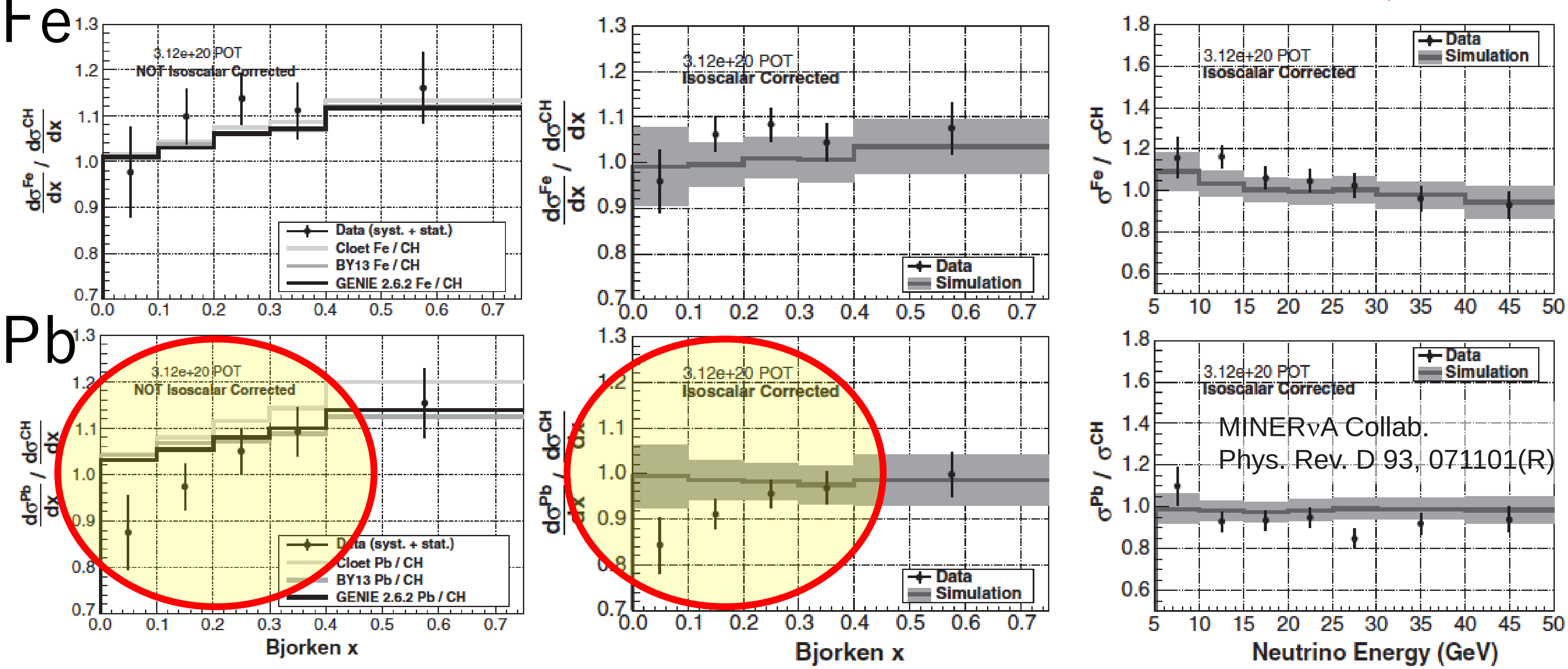
Shallow and Deep Inelastic scattering (SIS/DIS)

Charged and neutral SIS & DIS

$$\nu + N \rightarrow l^{-}(\nu) + N' + X \ (X = hadrons)$$

MINERvA experiment also published nuclear dependence of differential cross-sections





MINERνA Collab.
Phys. Rev. D 93, 071101(R)

Neutrons from neutrino interactions

Neutron provides useful information
to improve various physics sensitivities

- Neutrino / anti-neutrino discrimination
  - Identification of supernova(SN) diffuse ν signal
    $$\bar{\nu_e} + p \rightarrow e^+ + n$$
  - Accelerator and atmospheric neutrino signal separation
    $$\nu + n \rightarrow l^- + p \text{ or } \overline{\nu_x} + p \rightarrow l^+ + n$$

- Interaction channel discrimination
  - Pointing accuracy improvement in SN burst.
    $$\bar{\nu_e} + p \rightarrow e^+ + n \text{ or } \nu + e^- \rightarrow \nu + e^-$$

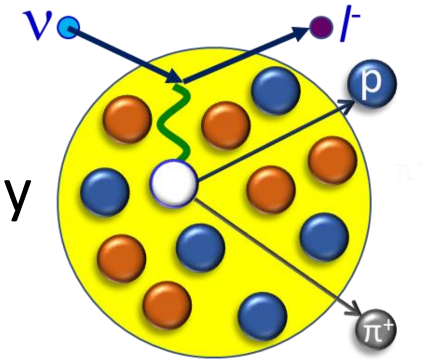
- Nucleon decay background rejection
  - Nucleon decay itself does not produce neutron, but background atmospheric neutrino interactions do.

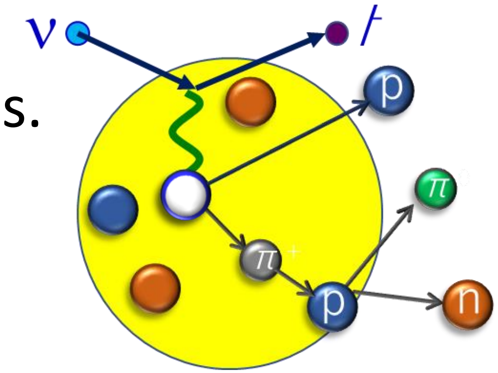
Neutrons from neutrino interactions

Neutron provides useful information
to improve various physics sensitivities

Various interactions produce neutrons.

- Nuclear de-excitation after primary neutrino interaction (= Remaining unstable nucleus may emit neutron),
- Final state interactions of hadrons in nucleus, and
- Secondary interactions of hadrons in nucleus. (meson-nucleus scattering, π^- absorption, nucleon-nucleon scatterings etc.)



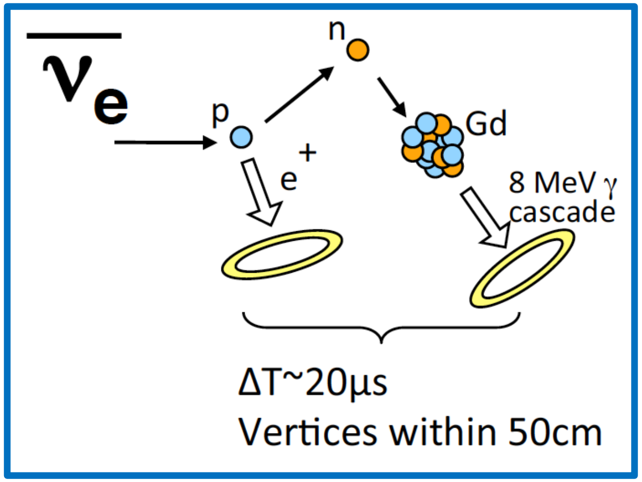


All these channel must be understood at certain level.

Neutrino-nucleus interaction simulation programs

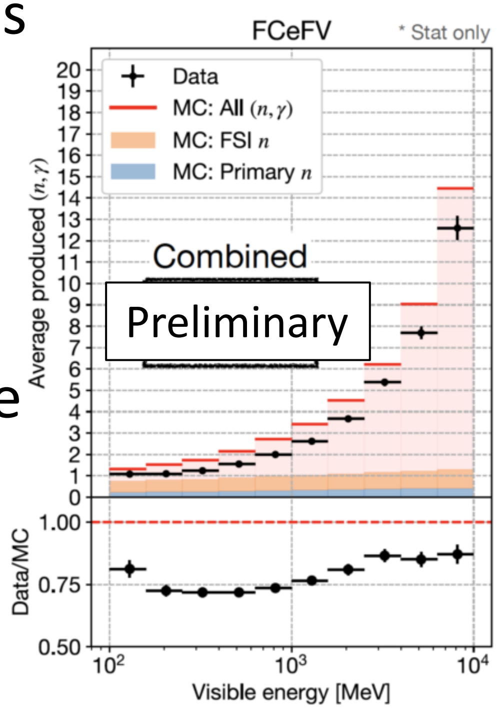
Super-Kamiokande loaded Gd to the water.
(In 2020, concentration was 0.01% and now 0.03 % from 2022.)

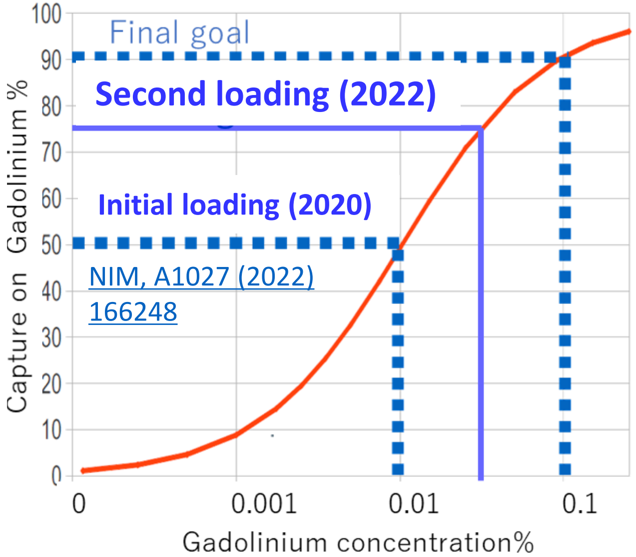
- Gd captures neutron and emit 8 MeV γ cascade.
- SK can detect γ emitted from Gd at high efficiency.



Observed # of neutrons was systematically **lower** than predicted.

Same tendencies were observed with the pure water phase (SK IV) atmospheric and T2K data. (n detection efficiency was ~25%.)



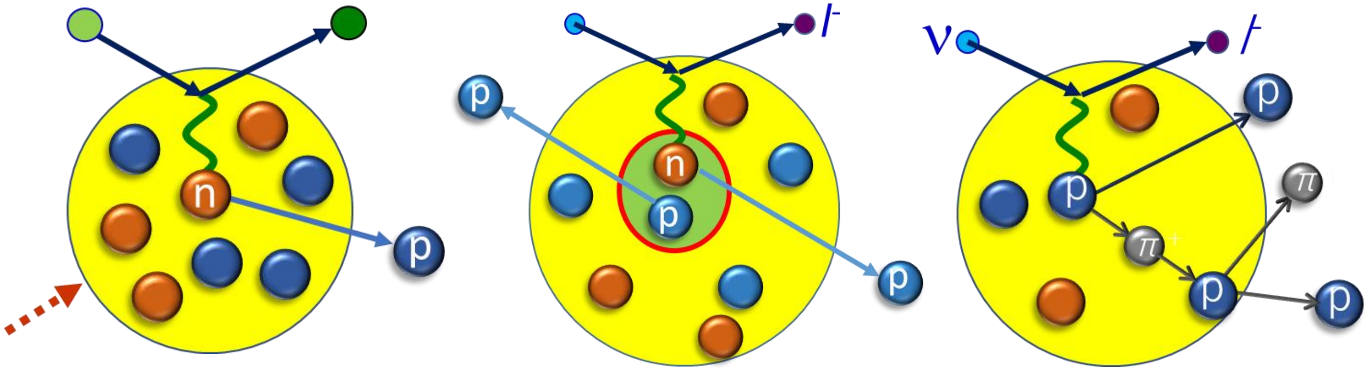


Neutrino-nucleus event generators
(Neutrino-nucleus interaction simulation programs)

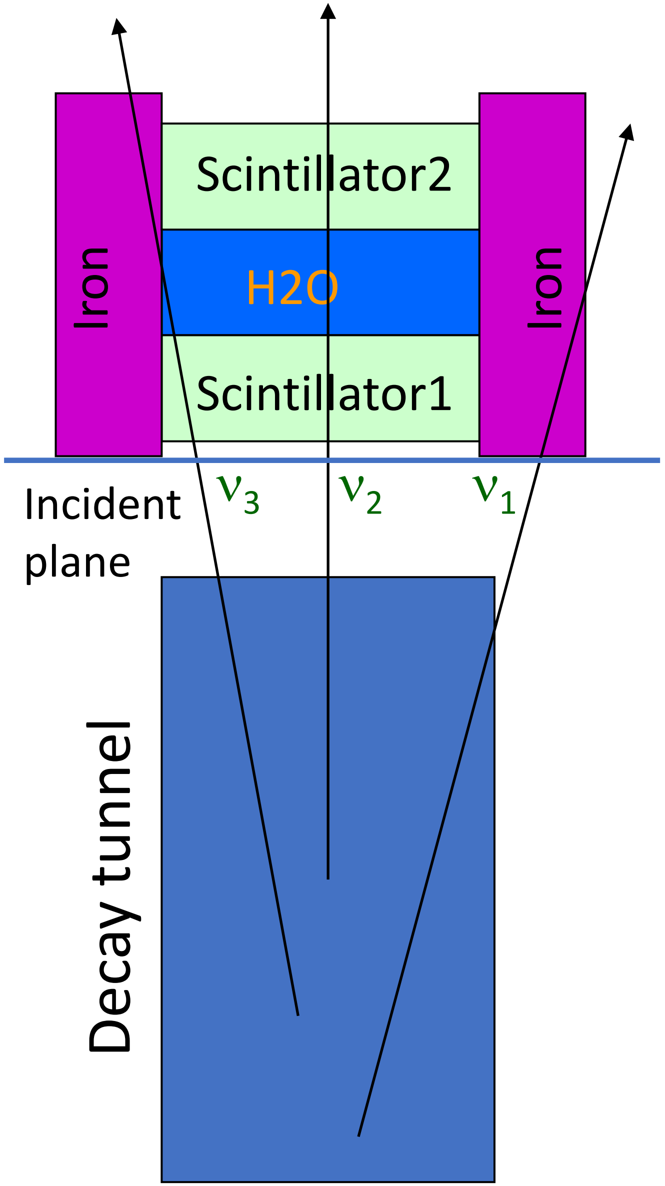
Simulation programs play critical roles in neutrino experiments.

Physics process simulation

- Neutrino-nucleon/nucleus interactions
  Various initial state nuclear (binding) effects
- Final state interactions of hadrons
- Treatments of the remaining nucleus



Neutrino-nucleus event generators (Neutrino-nucleus interaction simulation programs)



- Handlings of neutrino detector geometry

  Appropriate treatment of interaction in each detector (target medium).

  Neutrino detectors have complex structures and contain various kinds of material.

- Handlings of neutrino (beam) flux

  Position dependence of the accelerator neutrino direction.

  The correct location and geometry of detectors must be considered.

There are various detector geometry data formats, and the neutrino beam flux data formats.

Neutrino-nucleus event generators
(Neutrino-nucleus interaction simulation programs)

Several generators are available in the market
- Widely used in the experiments
  - GIBUU, GENIE, NEUT and NuWro
- New generator
  - Achilles Fully factorized and highly modular design

- Low energy dedicated ($E_\nu < 100\mathrm{MeV}$, Argon target)
  - MARLEY (Model of Argon Reaction Low Energy Yields)

- Nuclear de-excitation simulator
  - NucDeex Used with the any event generators
    Currently supports ^{12}C and ^{16}O.

Future directions of neutrino event generators

It is useful to compare the outputs from the different neutrino-nucleus interaction simulation program outputs.

However, it has been difficult to “compare” because

  - the neutrino beam flux data formats are different and
  - different neutrino-nucleus interaction simulation programs have been using different data output formats.

- “NUISANCE” tries to solve this issue by making a framework to compare outputs from different simulation programs, but it is not an easy task to maintain.
- Attempt to define the common data format (NuHepMC) based on the HepMC (HepMC3) to make direct comparisons easier.
- Also, the discussion has started to realize the common “neutrino flux driver” to interchange the simulation programs.

Summary and prospects

- Precise understanding of neutrino-nucleus interactions is essential to archive the physics goals of current, near-future and future neutrino oscillation and nucleon decay experiments.
- Unfortunately, current our understanding turns out to be not precise enough to satisfy the requirements in the future experiments.
- There are various unsolved problems remaining even in the simplest quasi-elastic scattering ($\nu\, n \rightarrow l^{-}\, p, \bar{\nu}\, p \rightarrow l^{+}\, n$). More difficult situation for more complicated interactions, like single meson productions, shallow/deep inelastic scatterings and hadron re-interactions in the nucleus or in the detector.
- Neutron emission from various processes in the detector became crucial subject to be studied.
- Nuclear de-excitation is another interesting topic to be studied.

Summary and prospects

- Several new neutrino scattering experiments have started providing new information (MicroBooNE, MINERνA, Ninja, NOVA-ND, T2K-ND280) and further information will be published in coming years from existing and new detectors/experiments (ICARUS, SBND, T2K-ND280 upgraded.)
- Collaboration with electron scattering community has been started and this will also give useful insights.
- Lattice QCD gives interesting new information and will be interesting to compare with the neutrino scattering data.
- Developments of new models by theorists and collaboration with theorists are expanding. These activities have to be accelerated further.

Summary and prospects

- Real and simulated data comparisons will be more crucial in evaluating the models and their implementation in simulation program libraries.
    - Efforts to define the “community standard” particle data formats to realize the direct comparisons of simulation outputs have been started. This also includes the work to improve the interoperability of the simulation software in different beamline (accelerator). This work has to be accelerated.