MC generators ~ overview

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Before starting,

Not a review ~ remind you how experimentalists use,
what we need and what we are doing ~

1) Some examples ~ analyses of neutrino experiments
2) Brief introduction of (some of the) generators

Detailed comparisons and discussions
will be covered in the following talks

In this session,

1) Introduction	S. Dytman
2) Inter-generator Comparisons	T. Golan & N. Mayer
3) Pion production ~ Data / Monte-Carlo comparisons	P. Rodrigues
4) Implementation of meson exchange current	T. Katori

Also, there are lots of talks related to the generators, of course.

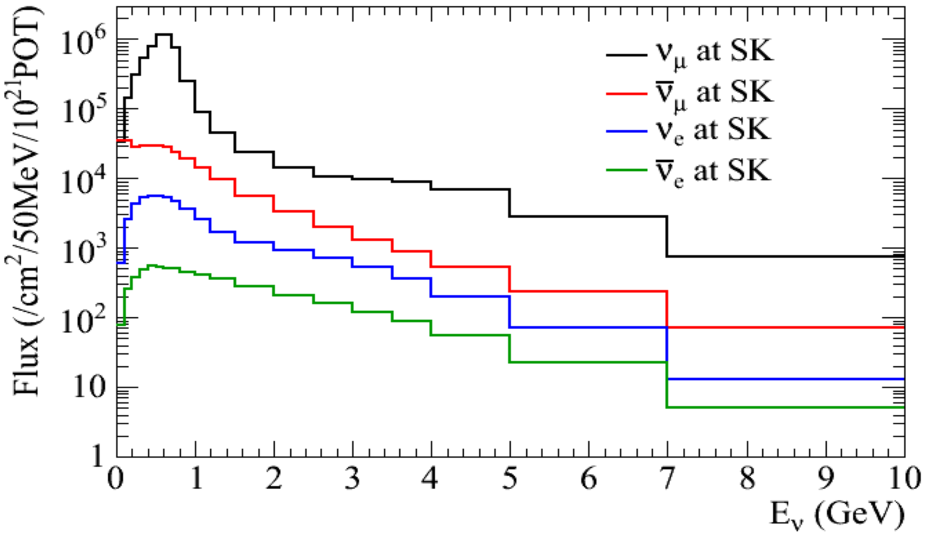
Neutrino spectrum measurements

Neutrino oscillation studies using accelerator neutrino beams
~ need to measure energy spectrum precisely

No usable “monochromatic beams” available
for the neutrino oscillation studies

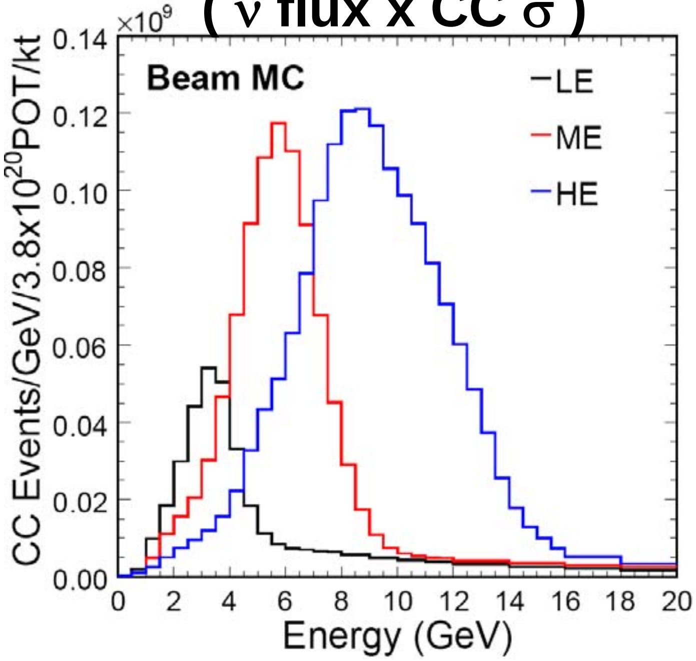
T2K ν energy spectrum

(ν flux)



NuMI ν_μ energy spectrum

(ν flux x CC σ)



→ Need to use “observed particles” in the detectors
to “reconstruct” incoming neutrino energy

Neutrino spectrum measurements

Precision of the ν energy spectrum measurements
= precision of the ν energy reconstruction.

→ Precise “prediction” of observed particles in the detector

→ Extensive use of neutrino event generators

There exists various ways to reconstruct neutrino energy
Depends on the energy of neutrinos and
characteristics of the detectors.

Case 1: Eν = 100 ~ 1 GeV

Charged current quasi-elastic scattering events

Use direction and momentum of lepton

Case 2: Eν > several GeV

Charged current deep inelastic scattering events

Calorimetric measurements

Requirements are different for
the different energies and detectors.

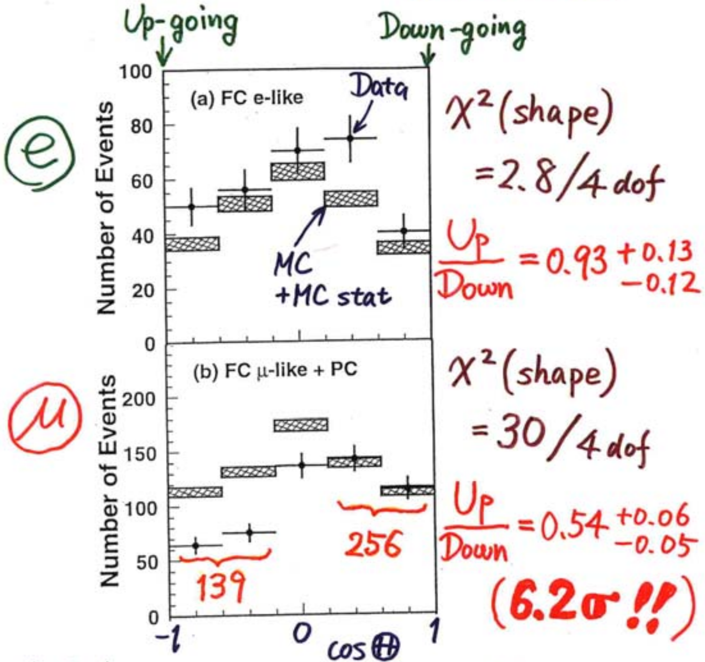
Atmospheric neutrino oscillation analysis in SK

up/down asymmetry for different flavors

~ Most of the uncertainties are canceled

Atmospheric ν analysis (1998)

Zenith angle dependence
(Multi-GeV)



χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

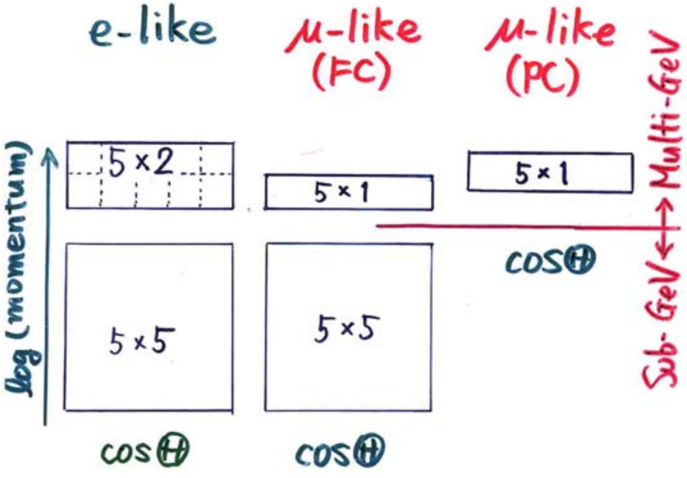
(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%
1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7%
Non ν Background …..< 2%) 2.1%

Definition of χ^2 for $\begin{cases}\Delta m^2 \\ \sin^2 2\theta\end{cases}$



$$\chi^2(\sin^2 2\theta, \Delta m^2) = \sum \frac{(N_{data} - N_{exp'd})^2}{\sigma^2} + \sum_i \left(\frac{\alpha_i}{\sigma_i}\right)^2$$ ← syst. error

$$N_{exp'd} = N_{exp'd}(\sin^2 2\theta, \Delta m^2, \alpha_1, \alpha_2 \cdots)$$

Just 5 categories (70 bins)

Atmospheric neutrino oscillation analysis

High statistics atmospheric neutrino data

~ Possibility in observing small distortion in ν_e

- Matter effect ~ from mass hierarchy

  Possible ν_e enhancement in several GeV passed through the earth core

- Solar term ~ from θ_{23} octant degeneracy

  Possible ν_e enhancement in sub-GeV

- Interference

  CP phase could be studied.

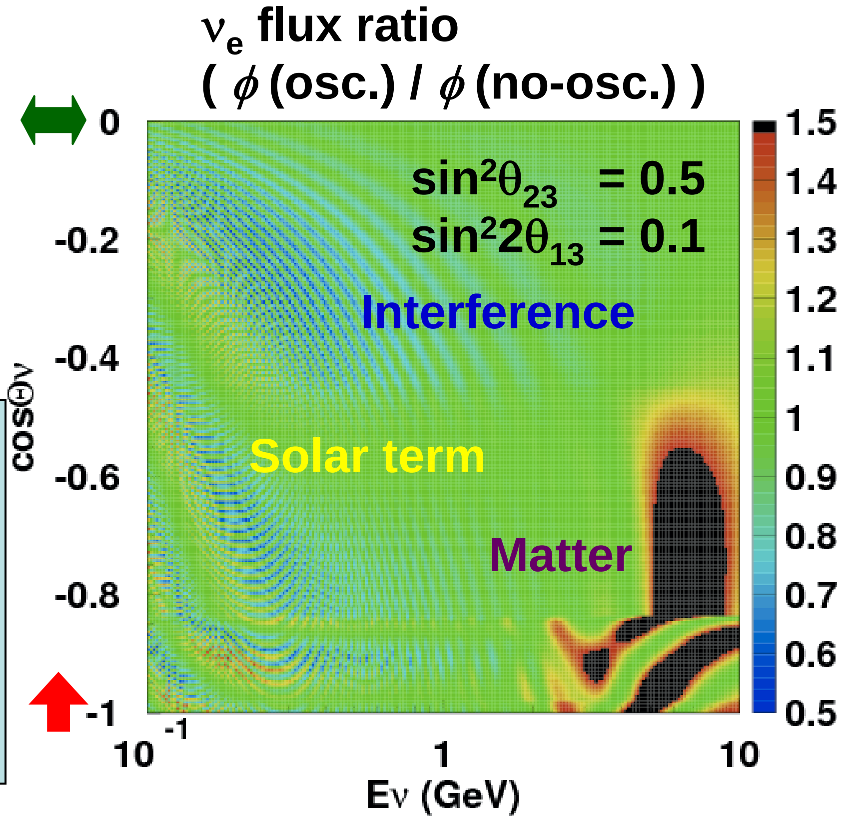
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m^2_{12}) + \Delta_3(\theta_{13}, \Delta m^2_{12}, \underline{\delta})$$

Matter effect

Solar term

Interference

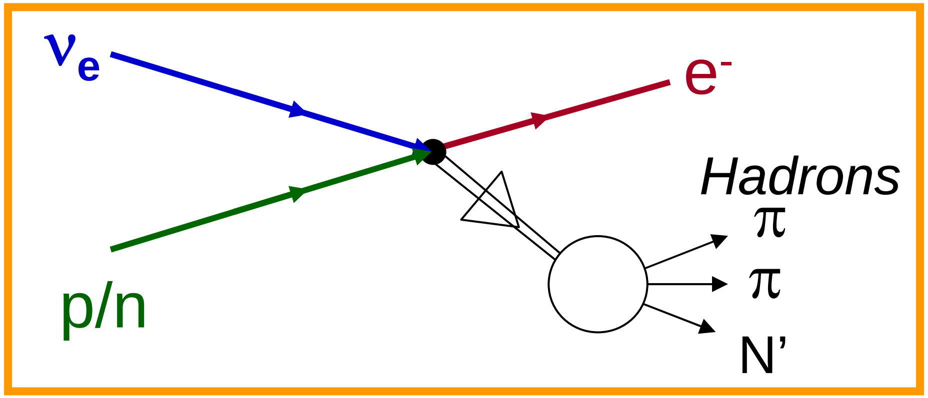


Three flavor oscillation analysis using atmospheric ν in SK

ν_e / $\bar{\nu}_e$ difference is expected to be visible in ***a few ~ 10 GeV*** region

→ Dominant interaction : Deep inelastic scattering

Use cross-section difference
(energy transfer dependence)
between ν and $\bar{\nu}$.



Observables	***ν_e CC***	***$\bar{\nu}_e$ CC***
Energy fraction of the most energetic ring	**Smaller**	**Larger**
Number of rings	**More**	**Fewer**
Transverse momentum	**Larger**	**Smaller**
# of decay electrons	**More**	**Fewer**

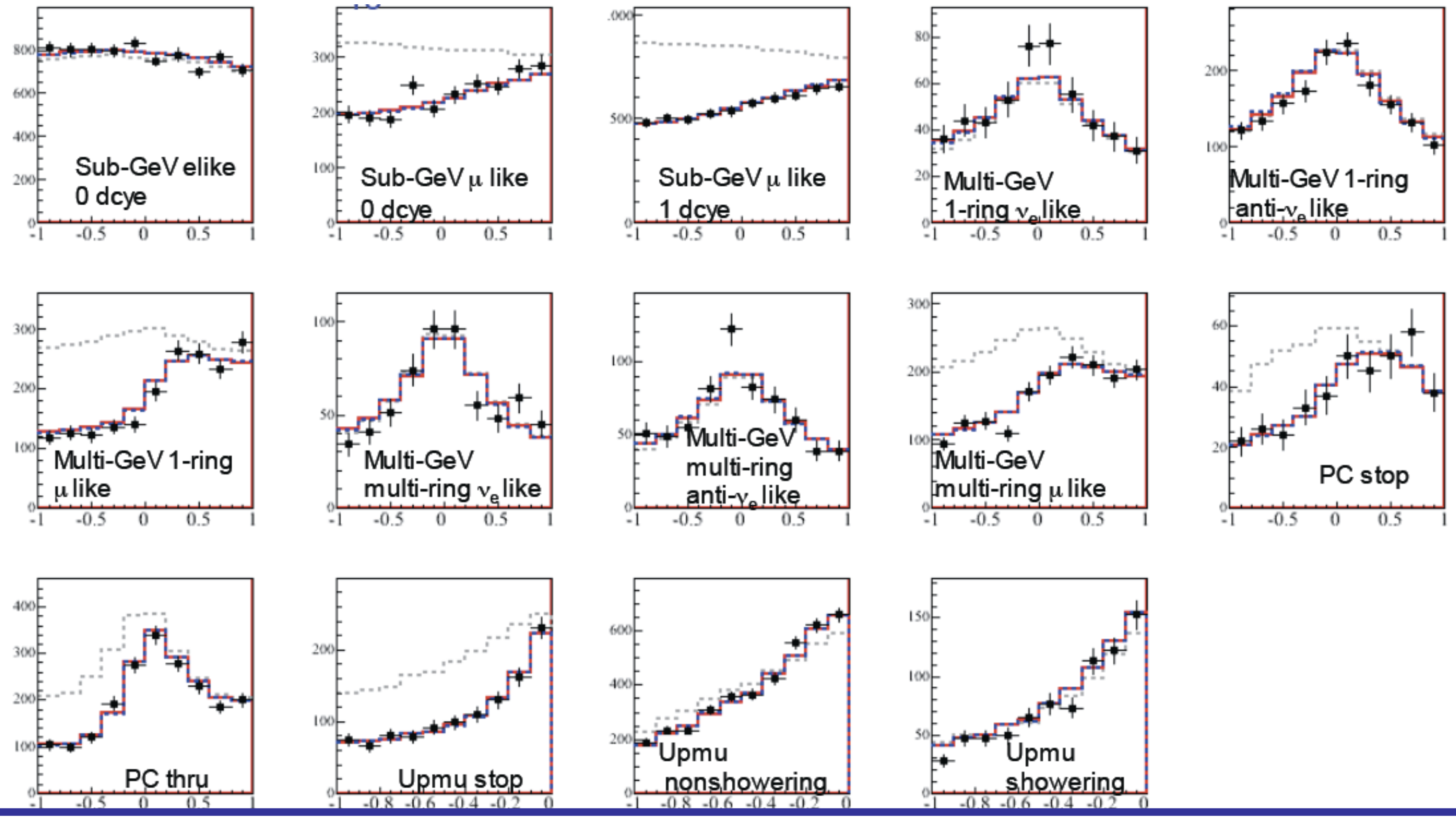
Purity of selected samples 59% 32%

Atmospheric neutrino oscillation analysis in SK

Latest analyses has ***18*** categories (~ ***480*** bins)

combinations of
fully / partially contained, μ-like, e-like, single / multi-ring,
with / without decay-e, upward going stop / thru,
showering / non-showering …

Atm. ν zenith angle distributions



Atmospheric neutrino oscillation analysis in SK

We don’t know where the neutrinos are coming from.

Oscillation analysis
~ fit distributions of particle momentum and direction
using the simulation results
assuming oscillations (or the other possibilities).

Observables

- particle type (μ-like, e-like)
- Direction and momentum ***~ $d^2\sigma/d\theta_l dE_l$***
- # of rings ~ multiplicity
  # of generated particles in primary ν interactions
  Interactions in the target (Oxygen)
- # of decay electrons (muons, pions, etc..)
  Interactions in the target and in the detector

ν interaction, hadronization, nuclear effects
from E_ν ~ a few hundreds of MeV ~ TeV

Precisions of neutrino mixing parameters

Already, uncertainties of neutrino interactions
(incl. final state interactions) became
one of the major sources of systematic error.
*) Error of T2K analyses are still statistically limited.
But the systematic errors may limit our sensitivities
before the T2K finished.

θ_{13} is known to be rather large. Good news!

→ Next goal : CP violated or not?

1) Much higher precision is required.
Total systematic uncertainties < a few ~ 5 %
2) Need to know the characteristics of anti-ν
and differences between ν and anti-ν

Generators are necessary to be improved
to be used in those “next generation” experiments.

What we need to know?

- Neutrino energy spectrum measurements
  - Correct estimation of
    - signal efficiencies and purities
      - (contamination from the backgrounds),
    - kinematics of particles visible in the detectors
- Neutrino flavor identification without magnetic field
  - Differences in charge multiplicities (y distributions)
    - for both neutrino and anti-neutrino

→ x & y dependence around a few to 10 GeV
Visible particle multiplicities
Hadronization ~ formation zone effects

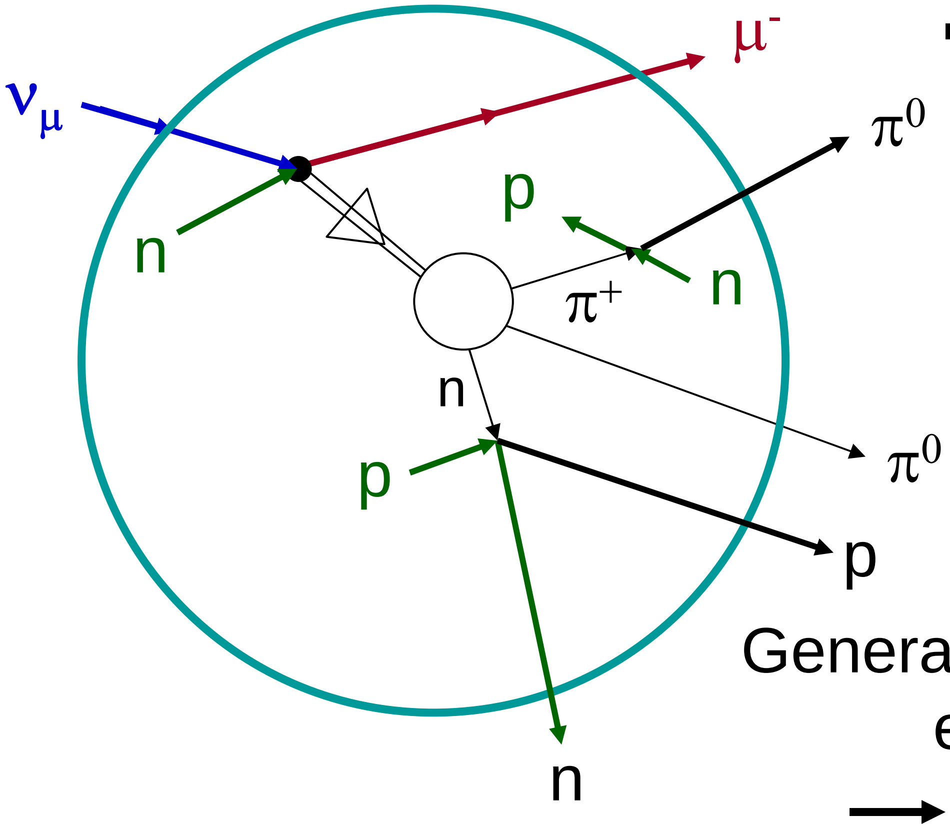
- tau neutrino related studies

→ Cross-section of ν_τ
(lepton mass effects, pseudo scalar term etc.)
DIS of ν_μ and ν_e (charge multiplicities, c productions)

- Evaluation of the systematic uncertainty

How event generators are used?

1) Provide information how signal and background events are observed in the detectors



→ # of signal & backgrounds
Signal efficiency
Background contamination

Output {
# of particles
particle types
direction
momentum

Generators have to cover entire “allowed” kinematic range

→ Not all the “models” are usable in the generators.

Sometimes, extrapolation is necessary.
Sometimes, used model is simplified in the actual code.

How event generators are used?

2) Provide information for the evaluation of the systematic errors in extracting the results (physics parameters)

Usually, shift parameters by (usually) 1σ (one by one)
and check how the results are changed.

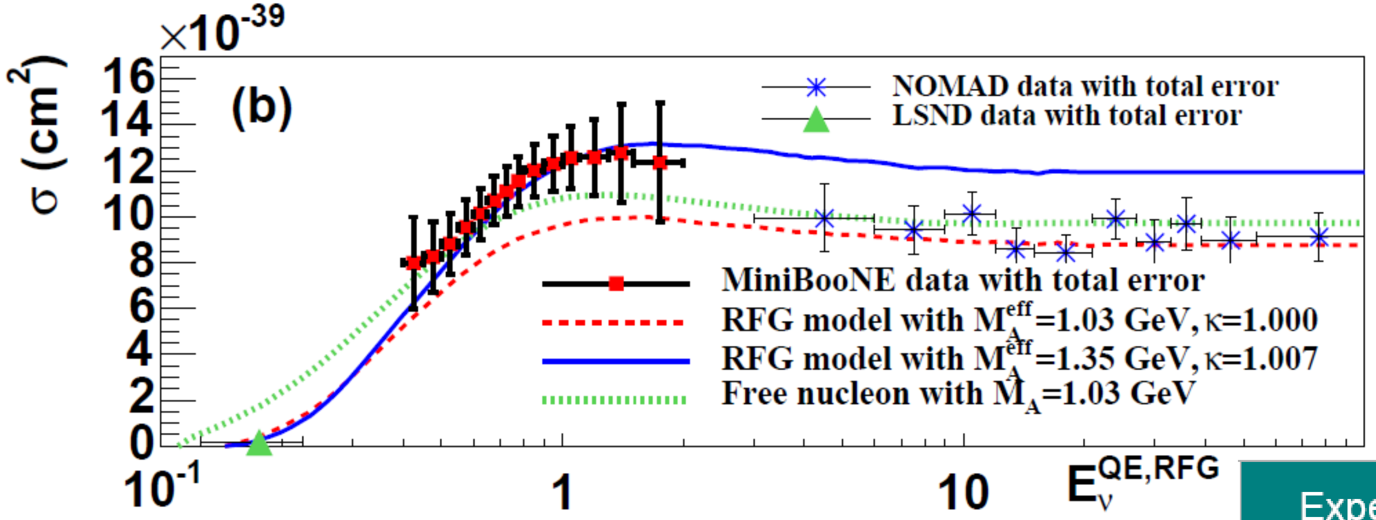
case a) Re-run the simulation
Generate events with shifted parameters,
do the same analysis, and check the difference.

case b) reweighting scheme
If it is possible to obtain (calculate)
the change of the probability (cross-section)
for an event if a parameter is shifted by 1σ,
use this “weight” to estimate errors.
(quick but **not always** possible…)

Most of the times, predefined parameters in the generation are not the best. Search for the best parameter sets.

Remaining issues ~ one example ~

Charged current quasi-elastic scattering



(T. Katori et al.)

K2K / MiniBooNE / MINOS data
can be reproduced
with rather large M_A values
with simple CCQE model.
NOMAD data seems to be consistent
with small M_A value.

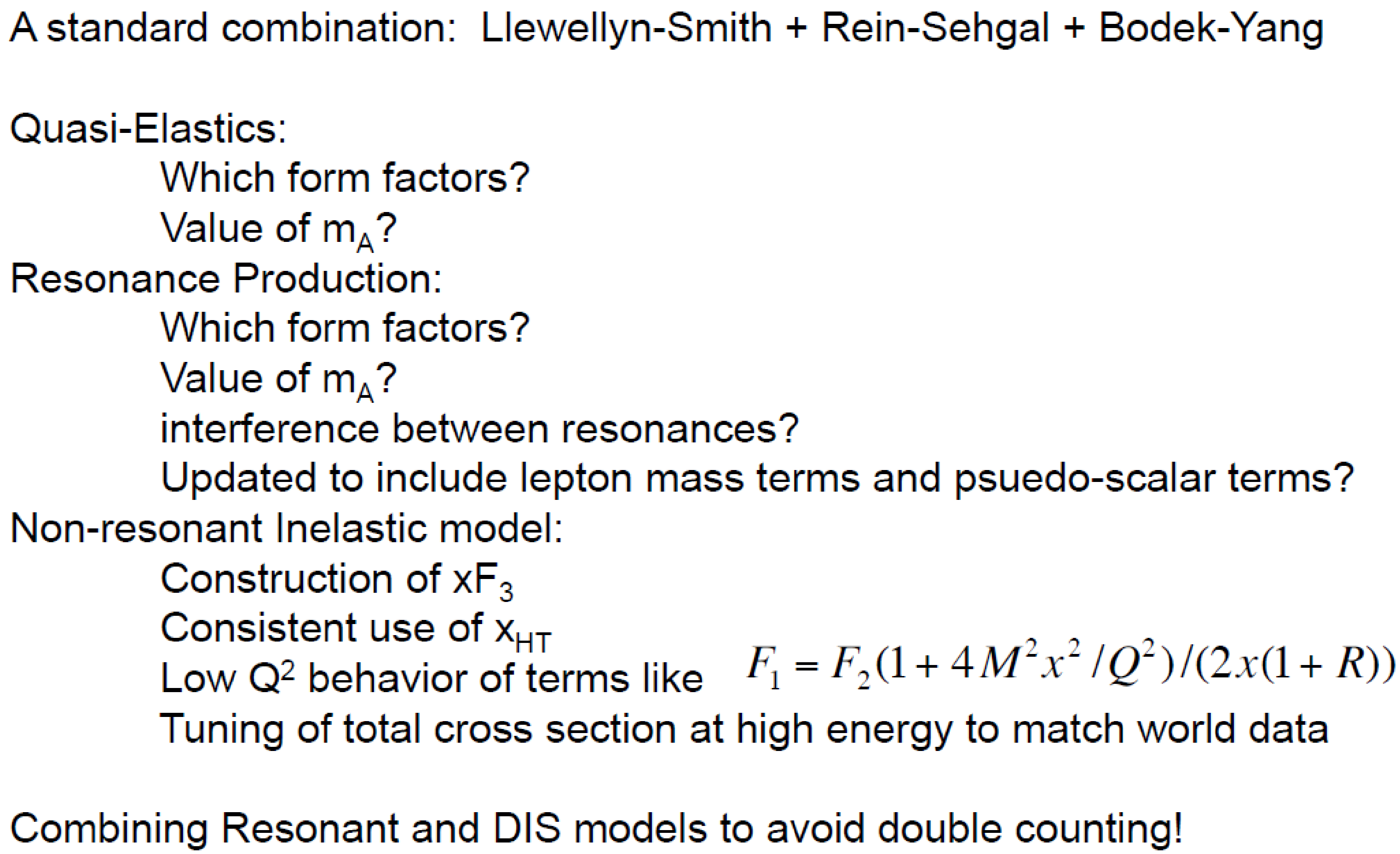
→ Source of systematic uncertainty
Need to be understood!

Experiment	M_A Value (GeV)
World Average (n,p)	1.03±0.03
K2K SciFi (O)	1.20±0.12
K2K SciBar (C)	1.14±0.10
MiniBooNE (C)	1.35±0.17
MINOS (Fe)	1.19±0.17
NOMAD (C)	1.05±0.06

Compiled by K. McFarland

Standard framework of the generators

Taken from a talk by H. Gallagher in NuINT 09.



A standard combination: Llewellyn-Smith + Rein-Sehgal + Bodek-Yang

Quasi-Elastics:
- Which form factors?
- Value of m_A?

Resonance Production:
- Which form factors?
- Value of m_A?
- interference between resonances?
- Updated to include lepton mass terms and psuedo-scalar terms?

Non-resonant Inelastic model:
- Construction of xF_3
- Consistent use of x_{HT}
- Low Q^2 behavior of terms like $F_1 = F_2(1+4M^2x^2/Q^2)/(2x(1+R))$
- Tuning of total cross section at high energy to match world data

Combining Resonant and DIS models to avoid double counting!

Still quite similar in 2012 (for some of the generators .)
BUT several important improvements and suggestions
new models and parameterizations are included.

GENIE Universal Object-Oriented Neutrino Generator

(http://www.genie-mc.org)

arXiv(0905.2517)

Intended to provide new “universal” generator
for the next generation experiments.
Used in ArgoNeut, MicroBooNE, MINOS,
MINERνA, Nova, T2K and more.

- Fully extensible, configurable.
  Continuous efforts to incorporate up-to-date models
- Includes flux and geometry handling functionalities.
- Includes framework to support event reweighting.
- Includes data and validation / tuning tools.
- Extensive documentation and Users’s Manual

GENIE Universal Object-Oriented Neutrino Generator

Primary interactions relevant for neutrino + A interactions

- (Quasi-) elastic scattering
- Resonance excitations (meson productions)
  Rein-Sehgal (W < 1.7 GeV/c^2)
- Coherent pion productions
- Deep inelastic scattering
  Custom build hadronization model (AGKY)
  (for transition region W = 2.3 ~ 3 GeV/c^2)
  KNO + JETSET

Nuclear effects

Relativistic Fermi-Gas model with **NN correlation** and **Spectral function** can be used, also.

About Multi-nucleon correlation, wait T. Katori’s talk.

INTRANUC – hA model as default

Full nuclear cascade simulation is also available

Formation time (in hadronization)

GENIE Universal Object-Oriented Neutrino Generator

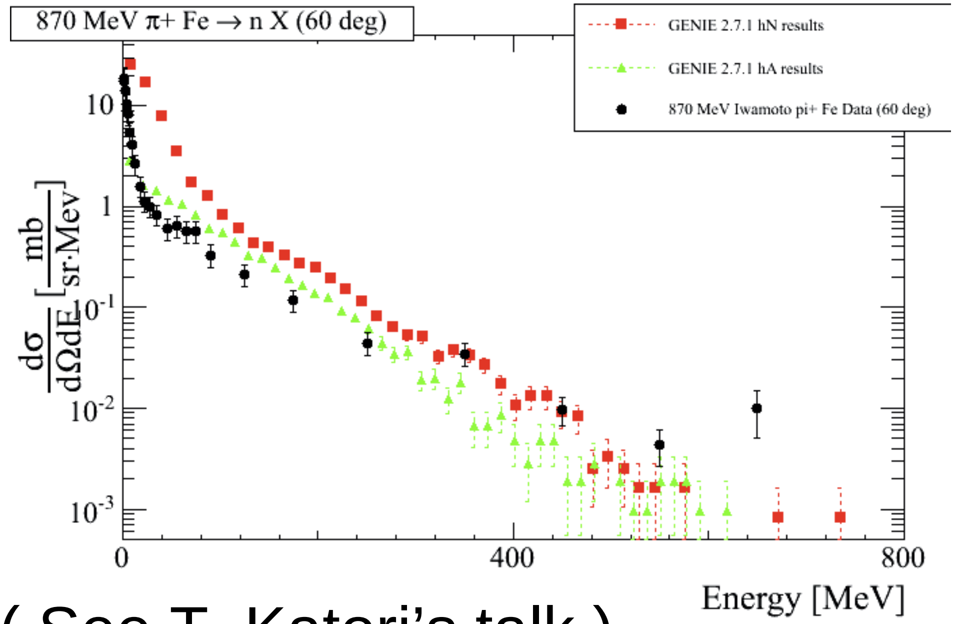
~ Recent improvements ~

Full intra-nuclear cascade

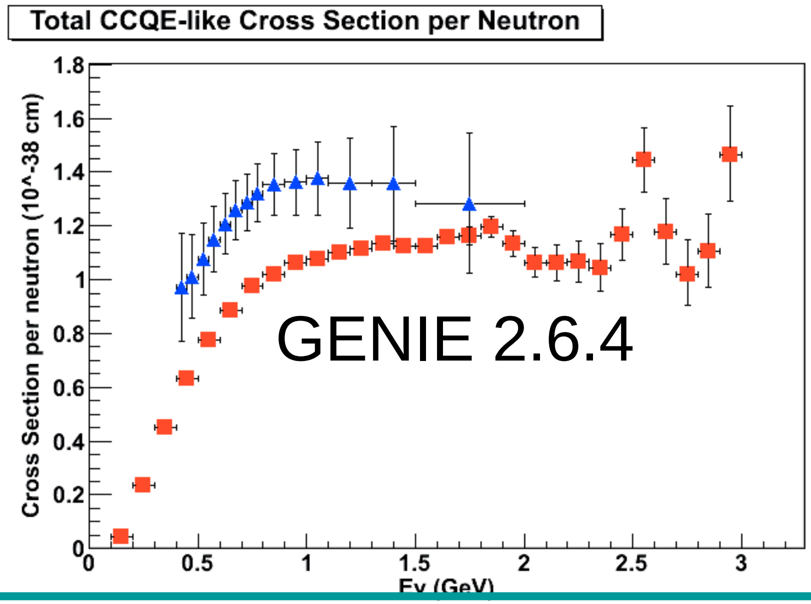
" Intranuke-hN "

(S. Dytman)

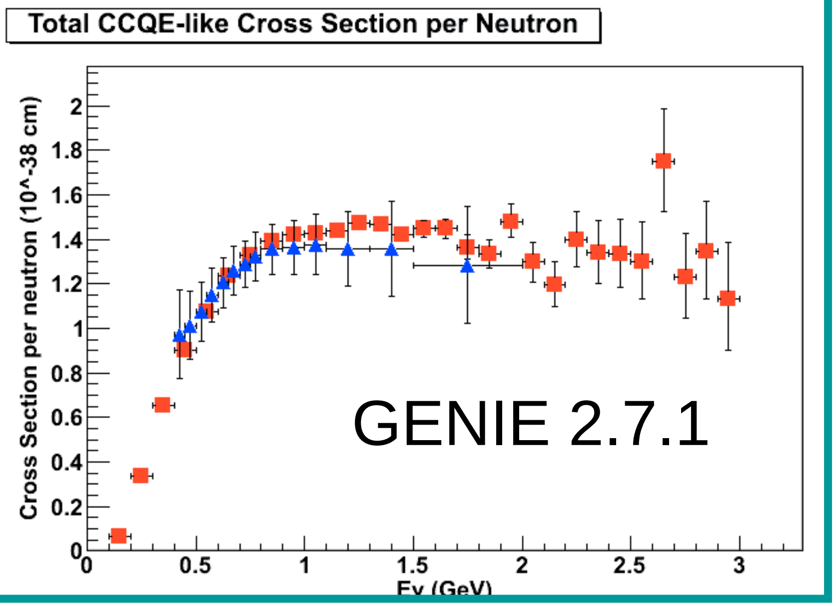
Validation with π + Fe data



Multi-nucleon correlation effects (See T. Katori's talk)



GENIE 2.6.4



GENIE 2.7.1

NEUT

Initially develop for the Kamiokande.
Major updates for Super-Kamiokande.
Continuous updates not only for SK
but for the other new experiments,
K2K, SciBooNE and T2K…

Recently, reweighting, geometry and flux handling packages
are also prepared by the T2K members.

Rather old and simple models are selected / used as default
compared to the other “new” generators.
Now, we are working hard
to include newer (better) models.

NEUT

Physics models

- (Quasi-) elastic scatterings (Relativistic Fermi Gas)
  dipole vector/axial-vector form factors as default.
  (Testing BBBA07 with transverse corrections)
- Resonance decay 1 meson and coherent π productions
  Rein & Sehgal model ($W < 2\mathrm{GeV}/c^2$)
  Radiative decays of resonances are also included.
  (mainly for the ν_e appearance studies)
- Deep inelastic scatterings
  GRV98 with Bodek-Yang correction
  PYTHIA + custom KNO scaling
- Nuclear cascade model
  (simulates hadron interactions in nucleus)
  Initially, based on the model by Oset et. al,
  parameters tuned with the experimental data.

NUANCE

Main Author : D. Casper
Originally developed for IMB, used in Super-K and MINOS.
Then, extensively used and had been updated / maintained
by the members of the MiniBooNE collaboration.
But now they (basically) stopped further development.

But still, this generator is still useful
because many tunings and comparisons have been done.

Physics models

(Quasi-) elastic scatterings with BBBA(03) form factor
  with additional Pauli-blocking suppression
Resonance productions
  Rein & Sehgal with ***tuned form factor***
Coherent and diffractive scatterings
Deep inelastic scatterings
  with Bodek-Yang prescriptions and LUND + KNO
Intra nuclear cascade for hadrons

GIBUU The Giessen Blotzmann – Uehling - Uhlenbeck Project

(http://gibuu.physik.uni-giessen.de/GiBUU/)

Physics Reports 512 (2012) 1–124

Dedicated talk : O. Lalakulich (Oct. 23 10:40 ~)

Aiming to provide an unified transport framework
in the MeV and GeV energy regimes for
elementary reactions on nuclei as e.g.
electron + A, **photon** + A, **neutrino** + A,
hadron + A (especially **pion** + A and **proton** + A)
and for **heavy-ion collisions.**

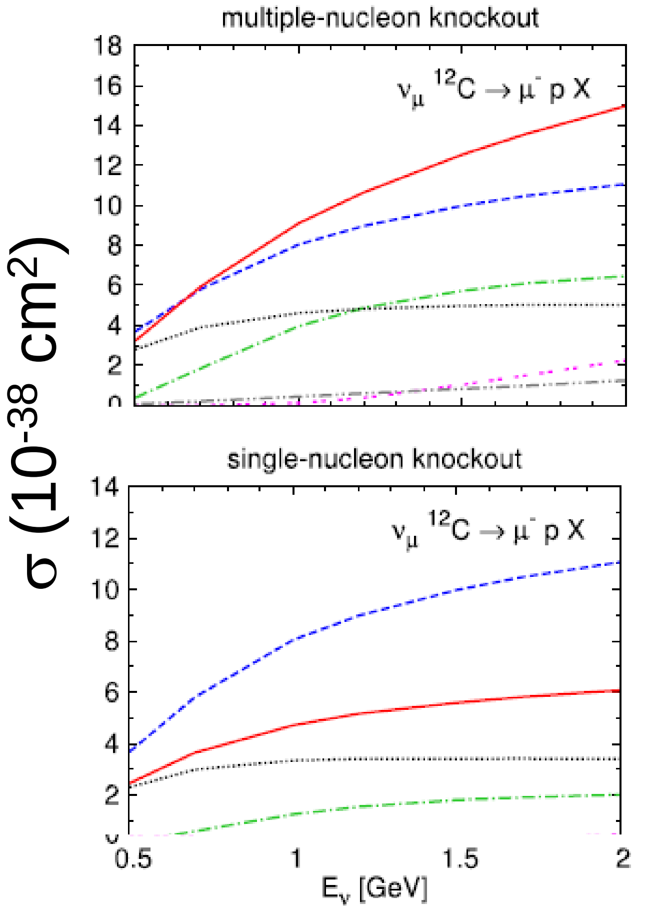
Primary interactions relevant for neutrino + A interactions

- (Quasi-) elastic scattering
- 2p-2h excitation
- Resonance excitations (meson productions)
  Resonances below 2GeV are considered.
  Also, background term is taken into account.
- Deep inelastic scattering with PYTHIA

GIBUU The Giessen Blotzmann – Uehling - Uhlenbeck Project

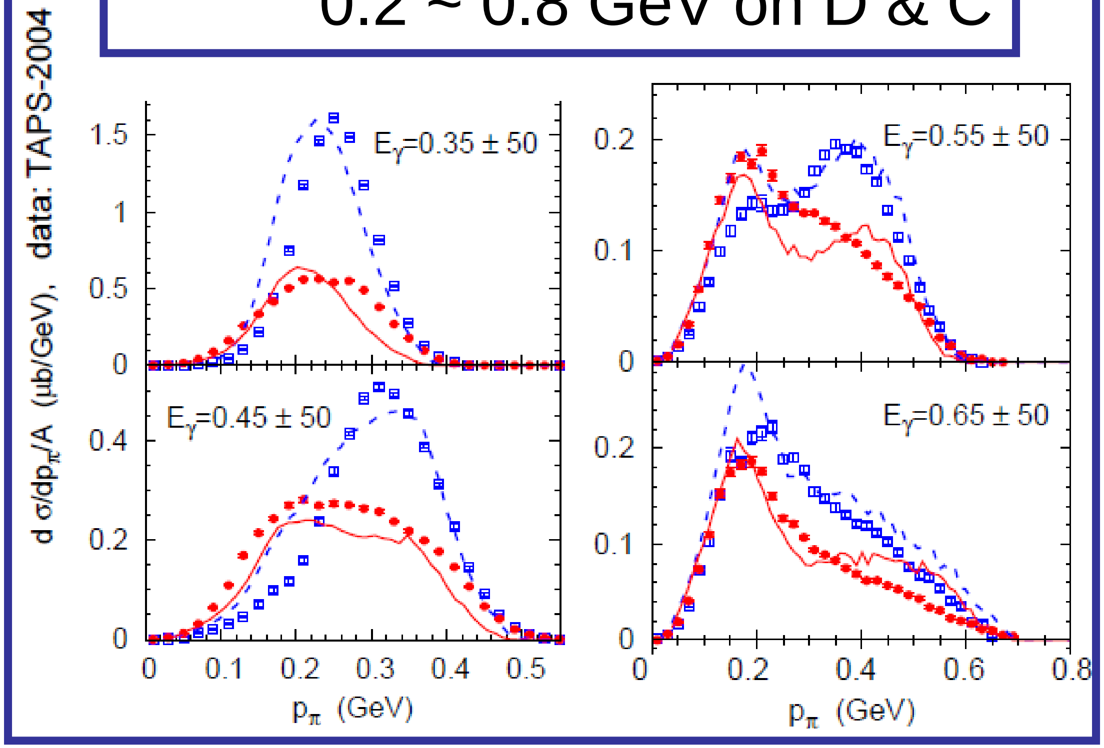
Particle transportation in nucleus
with numerous nuclear effects with up to date models

ν_μ ^{12}C scattering



Mean field potentials
and in-medium spectrum functions,
Local density approximation

Photo π^0 production
0.2 ~ 0.8 GeV on D & C



NuWro

NuWro - Wroclaw Neutrino Event Generator

(http://borg.ift.uni.wroc.pl/nuwro/)

Phys. Rev. C **86**, 015505 (2012)

“The main motivation for the NuWro authors was to have a tool to investigate the impact of nuclear effects on directly observable quantities, with all the FSI effects included.”

Primary interactions

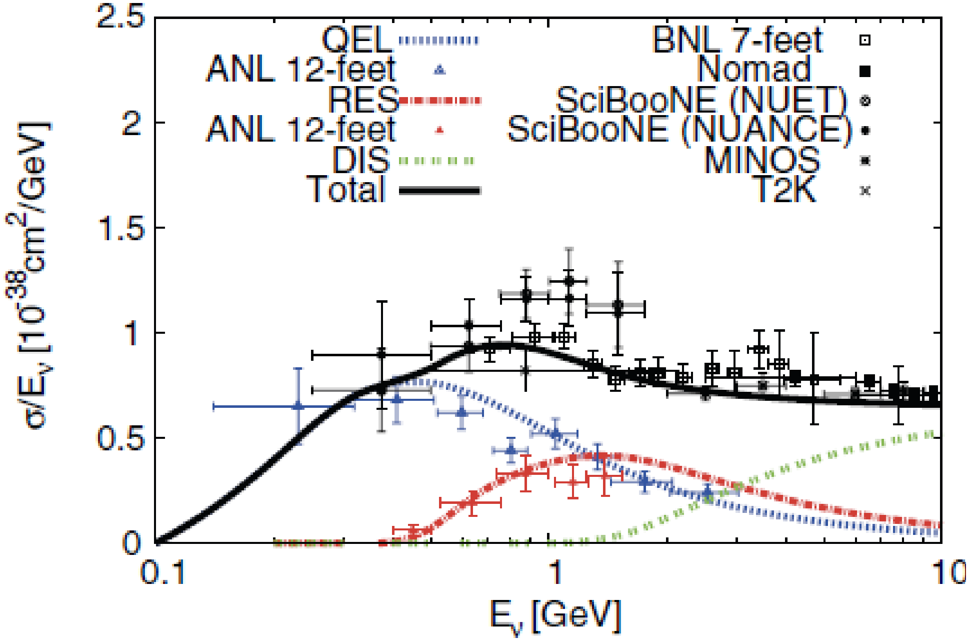
- (Quasi-) elastic scatterings,
- Resonance productions
  - (not Rein-Sehgal) W < 1.6 GeV/c^2),
- Deep inelastic scatterings (W > 1.6 GeV/c^2)
  - (PYTHIA Bodek-Yang prescriptions)
- Coherent pion productions

Nuclear effects

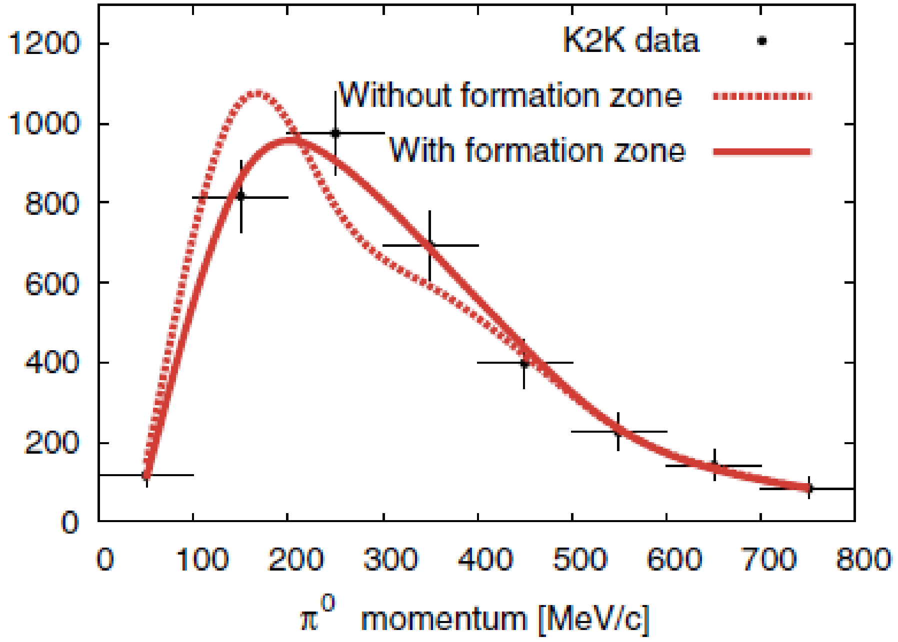
- Spectral function with local density approximation
- Nuclear cascade simulation
- Formation time (in hadronization)

NuWro NuWro - Wroclaw Neutrino Event Generator

Cross-section in NuWro



K2K π^0 momentum w/ and w/o formation zone



Also, both spectral function
and simple Fermi-gas models are implemented
~ interesting comparisons

Effects of multi-nucleon correlations are also studied.

Summary

Generators are one of the most important components
in the experiments.

Also, understanding of the limitations of each model
is also essential in evaluating the systematic uncertainties.

The generators developed by the theorist groups
are really useful and informative.
*) One advertisement
Theorists in Japan form a new group
to develop new generator :)
(See poster by Nakamura-san et al.)

Recent “closer communications” with the theorists
and experimentalists help us a lot:
the better understandings of the data and,
the improvements of the generators.

fin.