WG 1.3
Requirements from experiments and short term plan of generators

contributions from

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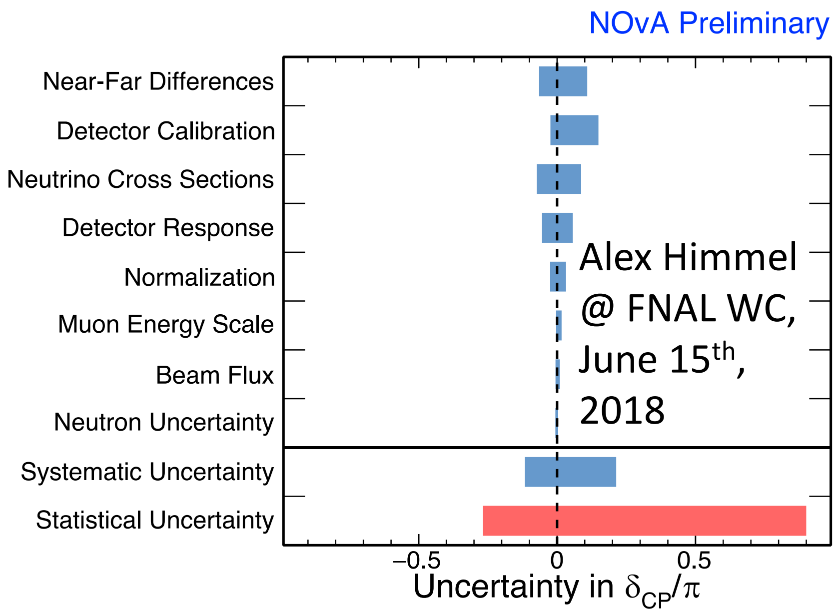
Introduction

Uncertainties from neutrino-nucleus interactions
became one of the dominant sources of the systematic error
in various neutrino experiments.

Uncertainty of δ_{CP} in the NOνA experiment



Uncertainty of observed # of events in the T2K experiment

% Errors on Predicted Event Rates

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03

M. Friend @ KEK seminar, Jan. 10th, 2019

Near future, the total systematic error
is required to be reduced to a few %.
→ Uncertainties from neutrino-nucleus interactions < a few %.

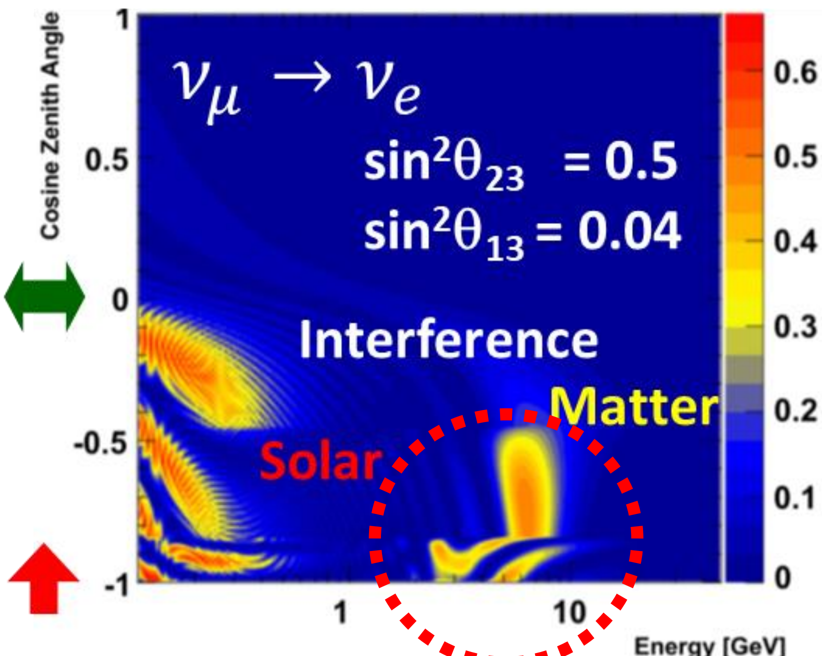
Introduction

T2K & FNAL Booster neutrino beams

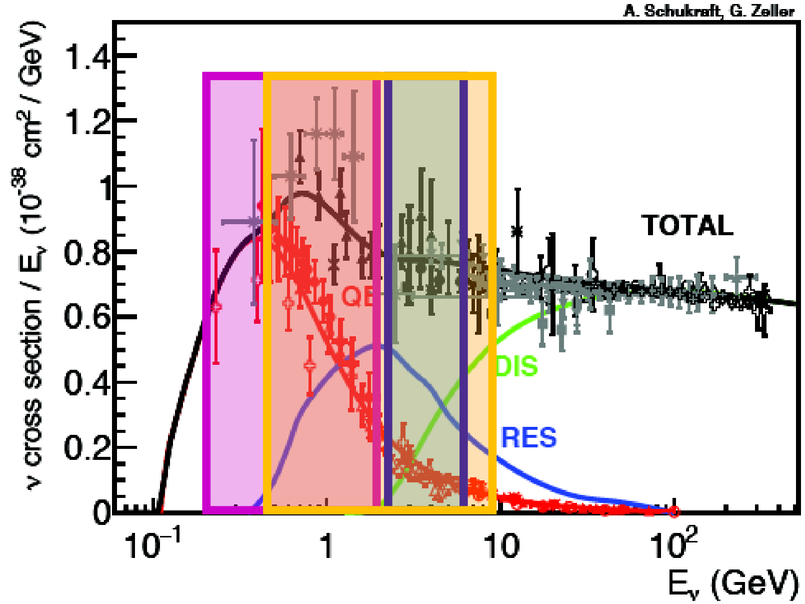
NOνA neutrino beam

DUNE neutrino beam

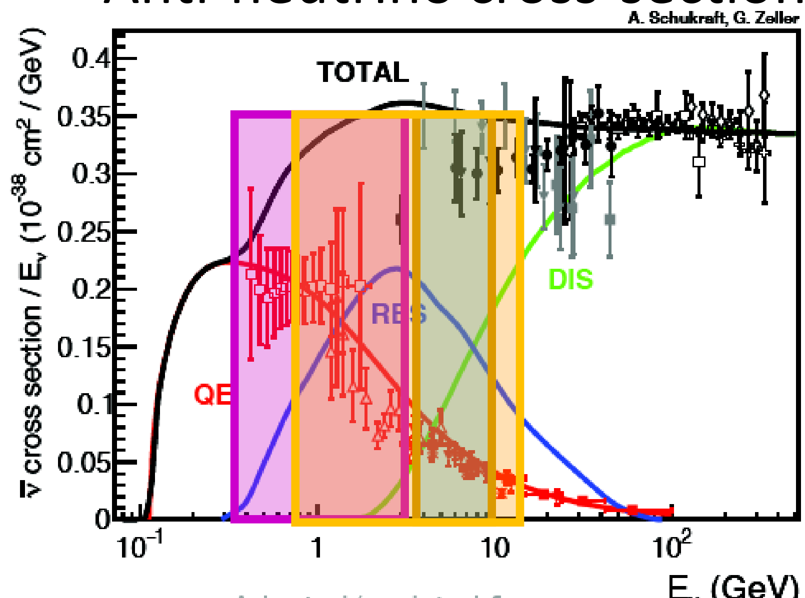
Atmospheric neutrino oscillogram (for normal hierarchy)



Neutrino cross-section



Anti-neutrino cross-section



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

Requests to the event generators from experiments

1) Standardization among generators

"This would facilitate comparisons of generators by experiments, which would naturally feed back to improvements in models, alternative evaluations of systematics, etc." (From NOνA)

- Tools to do the translations among generators
- Common interface (output)
- Common interface (input)
- Common enumerations for interactions

NUISANCE group has been working to provide possible solution:

https://nuisance.hepforge.org/

Requests to the event generators from experiments

2) Characteristics, limitations and size of the errors of the implemented models

"We'd also like to better understand what goes into a model, to best understand its limitations and how much faith to put into the systematics knobs provided.
As an example in Genie, there is a desire to better understand the fitting system that Genie authors use to create the central tunes and the systematics. There was a call to make that system public." (From NOνA)

Requests to GENIE from experiments

1) Improved handling of systematic knobs

"NOvA would like to have, particularly those that are non-reweightable or have hard thresholds."

As an example, once you set the formation zone, there are no events below that limit to reweight, so you can not easily probe the effect of smaller formation zones.
Another example is the DIS systematics that has a hard cutoff at 1.7GeV. It would be nice to have an interpolated transition region.

"As a first step, more documentation of the systematic knobs and potential problems would mean that experiments wouldn't rediscover these sticky issues at inconvenient times in the analysis timeline."

Requests to the event generators from experiments

3) Treatments of DIS (Deep inelastic scattering)
and SIS (Shallow inelastic scattering)

"We know there are problems with ***DIS+SIS*** modeling and the determination of its uncertainties.
Getting consensus on
what should be in a generator for ***DIS+SIS*** and
what the uncertainties are on that process now
would be important near term goals.
There is little to no theoretical input on the region between ***DIS+SIS*** and ***resonance***.
Improving the theory in this poorly constrained region will help many experiments to come."
(MINERνA, NOνA and DUNE)

Requests to the event generators from experiments

3) Pion production and re-interaction in nucleus

"The highest priority needs that MINERvA has from a generator have to do with ***pion production.***
Because what we measure there is
a convolution of FSI and primary interaction,
being able to understand and consider
different FSI models is a near term need,
as is the need to consider
various primary interaction models of pion production."

Requests to the event generators from experiments

3) Pion production and re-interaction in nucleus

"Neutrino mass hierarchy is studied using the electron and anti-electron neutrinos in Super-Kamiokande.
The discrimination of flavors are done by event topology.
(= $d\sigma/dq^2$ and hadron multiplicity)
Therefore, understandings of ***DIS/SIS interactions***, ***single pion productions*** and ***final state interactions of pions*** become crucial."

Requests to the event generators from experiments

4) Neutron multiplicity

"Super-Kamiokande is starting Gd phase quite soon.
Then, *the number of neutrons* is expected to be used extensively, for example

neutrino / anti-neutrino discrimination,
neutrino energy estimation,
background rejection of proton decay and so on."

"Therefore, we need to know

the accuracy of prediction of neutron multiplicity,

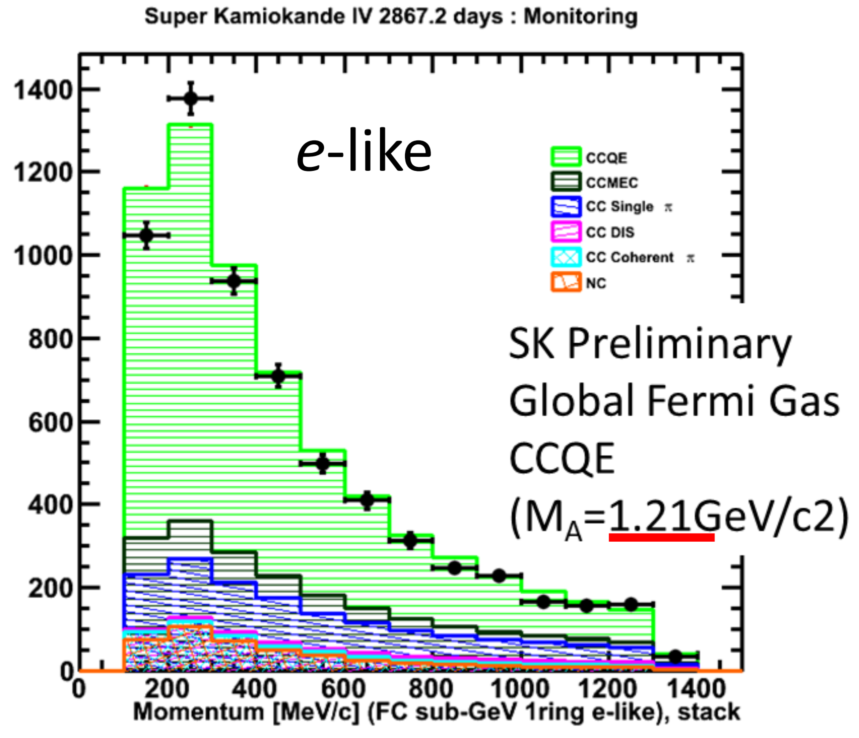
which includes the production of neutrons

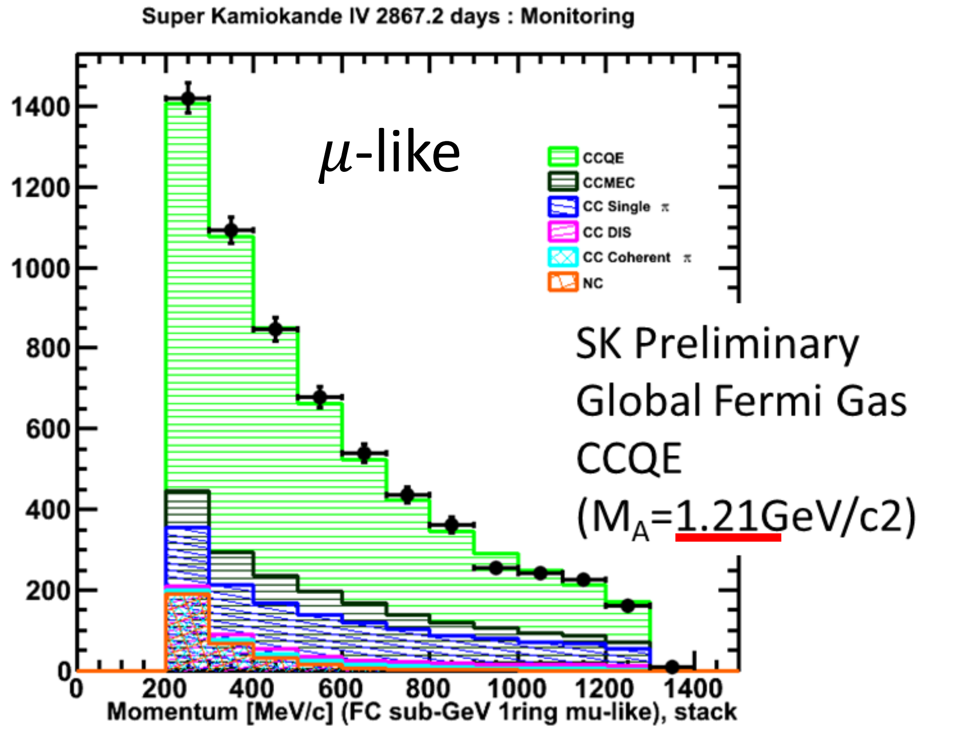
from the *primary neutrino interactions* and also
from the *(re-) scattering of hadrons in nucleus*."

Requests to the event generators from experiments

5) Low energy (<1GeV) CCQE-like(?) cross-section

"The number of 1-ring events (single lepton observed without additional decay electrons) seems to be larger than the predictions with "nominal" M_A especially around a few hundreds of MeV even with 2p2h."





Requests to the event generators from experiments

5) Relation between the neutrino energy and lepton kinematics

"Relation and uncertainty between the true energy and lepton kinematics is largest and urgent topic in T2K."

Which CCQE and 2p2h models are most appropriate?
How to validate?
How to assign "reasonable" uncertainty?

How large the contributions from 1π production are?
(both NC and CC)
How large the single γ production cross-section is?

NCEL (~1GeV/c protons) has to be understood further.

Requests to generators from experiments

9) Models to be implemented / improved

- New 1p1h QE models (specifically to NEUT)
  SuSA etc., especially for energy below 1GeV.
- New 2p2h models
  SuSA etc.
- Improved single pion production models
  Minoo's model, ANL-Osaka DCC model etc.
- Improved SIS/DIS models
  $d\sigma/dq^2$ and hadron multiplicity
- Improved pion FSI
- Improved nucleon FSI

Requests to GENIE from experiments

1) Improved handling of systematic knobs

“How the tool developed for the GENIE tuning system can be exploited to support reweight as well.
This should overcome the problem related to non-reweightable parameters, to some extent.

“It would be interesting to understand if the new features is worth the effort of the development.”
(Booster Neutrino experiments)

Requests to NEUT from experiments

1) Portability issue

"The code being in Fortran is a significant barrier to it being used more widely."
"There was also a request for more documentation on their flux driver."

- NEUT heavily relies on CERNLIB and this is the main cause of the portability issue.
  NEUT uses PYTHIA 5.7 / JETSET 7.4 comes with CERNLIB,
  which is capablevin simulating neutrino-quark scattering.
  However, it is not easy to compile CERNLIB.
- NEUT does not have generic (portable) flux driver.
  Only available ones are dedicated for SK (atmospheric)
  and T2K.
  Also possible to handle simple 1D flux histogram
  in the root format.

The NuWro current activities and plans for near future

- An attempt to create a "phenomenological 2p-2h" model based on the Valencia theoretical model and T2K and MINERvA CC0π data.
  - Preliminary results were shown at T2K internal meetings.
  - MINERvA data lead to PP puzzle.
  - The problem seems to be overcome but new results are not yet ready.
- Implementation of Ghent pion production model
  - To replace a phenomenological model which is as old as NuWro itself.
  - It will also become a part of eWro, an electron scattering NuWro branch.
- Implementation of CCQE strange hadron production in antineutrino scattering.
- Implementation of Ghent model as still another option for 2p-2h.

Neut current activities and plans for near future

- New single pion models
  1) Minoo’s model
  2) ANL-Osaka DCC model (Sato & Nakamura)
- New or improvements of CCQE/multi-nucleon scattering models
  1) SuSA
  2) Improvements in Local Fermi-gas model
  3) **Neutral current** multi-nucleon scattering model
- Improvements in the NC and CC SIS & DIS.
- Improvements in the nucleon re-scattering.

- Reorganization of the code
- Standard event (data) format?

  It is a good time to think about the `common’ data format to make it easy to compare events from different simulation program libraries.

GENIE3 (Bear series)

- **First major release in 10-yrs**:
- **Culmination of a 5-yr development cycle** by tens of authors **- Far surpassed original scope of GENIE3**
- **Change in philosophy**
  - No longer a single "Default" comprehensive model, and unsupported / optional modelling elements enabled at user's risk (and almost always breaking consistency and global tune)
  - **Running <u>out of the box</u>: Several comprehensive models, characterised against data + tuned!**
- Important changes in the Generator framework and code structure.
- **Improved support for non-neutrino event simulation** (boosted dark matter, nucleon decay, n-nbar etc)
- **New GENIE products** (Comparisons, Tuning, Continuous Integration, Unit testing, +)
- **Expansion into new and distinct areas of work**: GENIE not just a "Generator group"
  - Development of the **GENIE global analysis of scattering data,** in collaboration with LHC physicists.
    - Enables emphasis on construction and characterisation of comprehensive models, physics tuning, uncertainties.
  - **Balancing of service** (Generator support) and **proprietary research** (global analysis / Generator tuning) tasks
  - **Open-source Generator a vehicle for deploying GENIE global analysis results / tunes.**

New infrastructure and proven development paradigm: Accelerated product release cycles

- **Substantial new infrastructure** (Comparisons, Tuning, Continuous Integration): **<u>Accelerated major release cycles</u>.**
- **Capacity for producing new comprehensive models and tunes <u>surpasses</u> the capacity of experiments to consume / evaluate our tunes.**
  - Closer direct communication between experiments and the core GENIE team (this Forum)
  - Talk directly to us to make sure we prioritise your need for a model development, a systematic study, a tune or a new tool.

- **Enhancing a development paradigm that proved very successful:**
  - **Community contributions** in the implementation of new theoretical models
    - Under core GENIE team supervision (GENIE Working Groups and Executive Board):
      - Ensure GENIE standard of design, efficiency, consistency, integration, validation, documentation
  - **Continued core GENIE team effort in development of crucial empirical models (hadronization, FSI)**
  - **Integration by core GENIE team**
    - Development of comprehensive models, resolving model stitch up / extrapolation and double-counting issues.
    - Comprehensive model characterization and production of tunes

Scope of future major GENIE Generator releases

GENIE4 (Cheetah series) - Planned for ~Q1-Q2/2020

- Release of an **expanded set of GENIE Comprehensive Model Configurations**, including several new microscopic / theoretical calculations and improved empirical hadronic models.
- **Full deployment of new physics tuning results from the GENIE Global Analysis**, including hadronization tunes and nuclear cross-section data tunes.
- **Revamp the GENIE Reweight product, aiming to provide full support for all GENIE tunes**
  - including support for intrinsically non-reweightable systematic parameters (hadronic and nuclear simulations) considered in new GENIE global fits / tunes

GENIE5 (Dugong series) - Planned for ~end of 2022

- **First release of explicit Argon tunes** produced from a combined analysis of folded data distributions from the SBND experiment —> **Modelling work to underpin the early physics exploitation effort in DUNE**

GENIE4 roadmap

Have launched a series of new incubator projects by:

Reviewing needs for the GENIE4 tunes

- Reassessment of the uncertainties included in some of our data archives (Hadronization)
- Upgrades of existing data/MC comparisons to interface with our Professor tuning infrastructure (Hadronization)
- Implementation of missing data/MC comparisons (MINERvA, Hadronization)
- Misc technical upgrades in Tuning and Comparison products

Planning Reweight upgrades to support new tunes

Planning upgrades and new standardized interfaces to underpin new model implementation

Reviewing community physics modelling needs / identifying low-hanging fruits

In addition, we **review the status of several existing projects** that missed GENIE3 and stalled in recent months

The community can influence GENIE4!
Send us your ideas/views and help us launch and define new projects.
Contribute to incubator projects included in the GENIE roadmap

GENIE4/5 - development priorities

Neutrino interaction cross-section and nuclear models:

- **NLO DIS (up to 1E+10 GeV)**
- **Valencia - Aligarh DIS model**
- **SuSAv2**
- **SuSAM***
- **LANL 0π**
- **Kabirnezhad 1π**
- **Alvarez-Ruso NC 1γ**
- **Valencia - Aligarh single-Kaon model for anti-neutrinos** (already implemented for neutrinos)
- **Valencia - Aligarh hyperon production model** (alternative to existing)
- **Correlated Fermi Gas model**
- **Improvement and validation of electron scattering mode**
- **Implementation of radiative corrections in electron scattering mode**

GENIE4/5 - development priorities

<u>Hadronics:</u>

- **GENIE interface to INCL++**
- **GENIE / GEANT4 interface**
- **New hN processes from Sato-Lee - Grace Chu, Harry Lee**
  - **Includes $\pi N \to \pi\Lambda$, $\pi N \to \pi\Delta$, $NN \to N\Delta$**
- **GENIE / PYTHIA8 interface**
  - **incl improved treatment of initial state radiation**

GENIE4/5 - development priorities

Tuning and corresponding tools

- **Extend and deploy nuclear cross-section model tunes**
  - Only bare-nucleon cross-section model tunes were released in v3
- **Implement new tunes of neutrino-induced hadronization models**
- **ReWeight support out of the box for all GENIE tunes**
  - ReWeight / Professor interface
  - Richer metadata in output event files
  - Public releases of covariance matrices and systematic response functions

Fin.

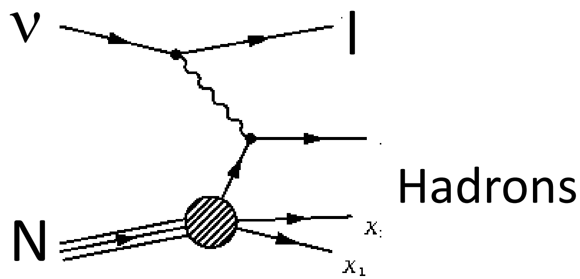
Importance of SIS/DIS in the atmospheric neutrino studies

Compare appearance probabilities of ν_e and $\overline{\nu_e}$

Statistically separate ν_e and $\overline{\nu_e}$

Dominant interaction (a few ~ 10 GeV)

→ Deep inelastic scattering



Differential cross-sections are different

Observables	ν_e CC	$\overline{\nu_e}$ CC
Number of rings	More	Fewer
Transverse momentum	Larger	Smaller
# of decay electrons	More	Fewer
Signal efficiency	52.9%	71%
Purity	58.4%	27.5%

Normal hierarchy