2p2h in Neut and experimental interests

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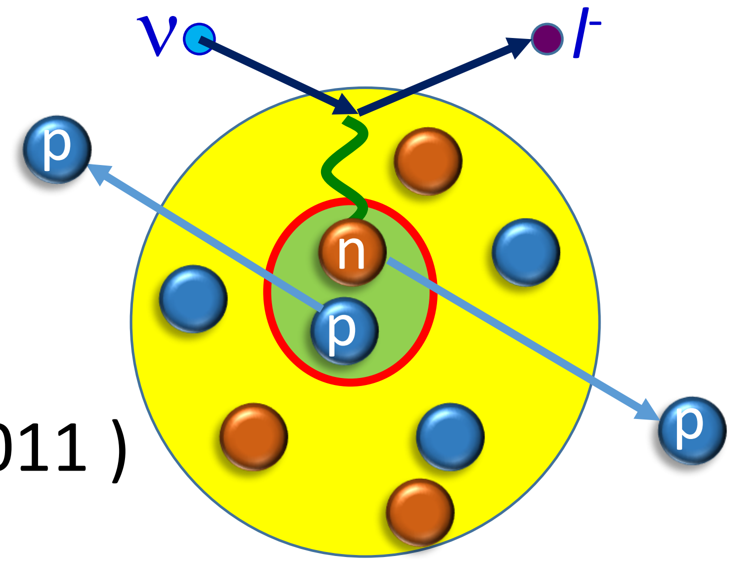
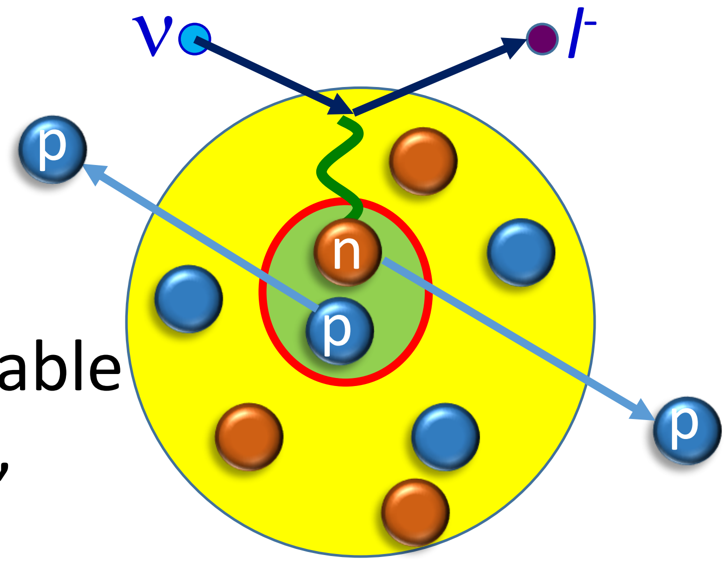
2p2h model in NEUT



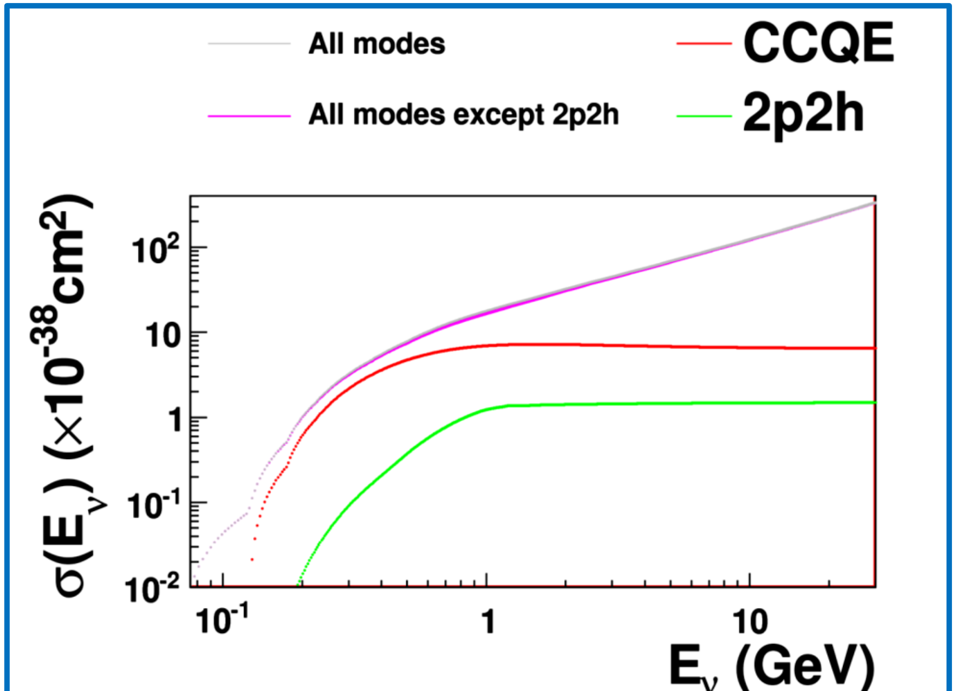
- Reference model
  - J. Nieves et al.
  - Phys. Rev. C. 83 045501 (2011)

  High energy extension
  - ~ R. Gran et al. Phys. Rev. D88 113007 (2013)
- Nucleon scattering handling
  - ~ based on prescription by J. Sobczyk
    - Phys. Rev. C86 015504 (2011)
- Only for ^{12}C, ^{16}O and ^{40}Ca

2p2h model in NEUT



- Total cross-sections ($\sigma(E_\nu)$)
  Use pre-calculated lookup table
  In order to use E_ν > 1.0 GeV,
  $|q_3|$ < 1.2 GeV/c constraint
  is applied.

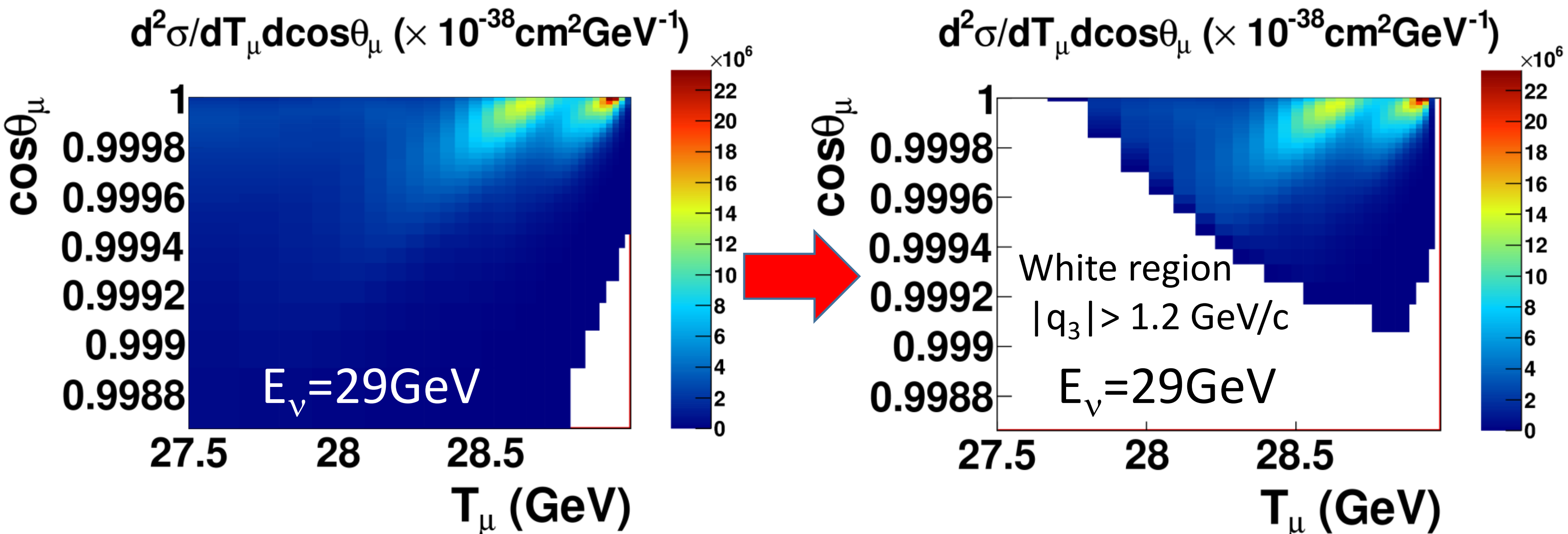


Cross-section saturates
~ 1 GeV
owing to the $|q_3|$ cutoff.

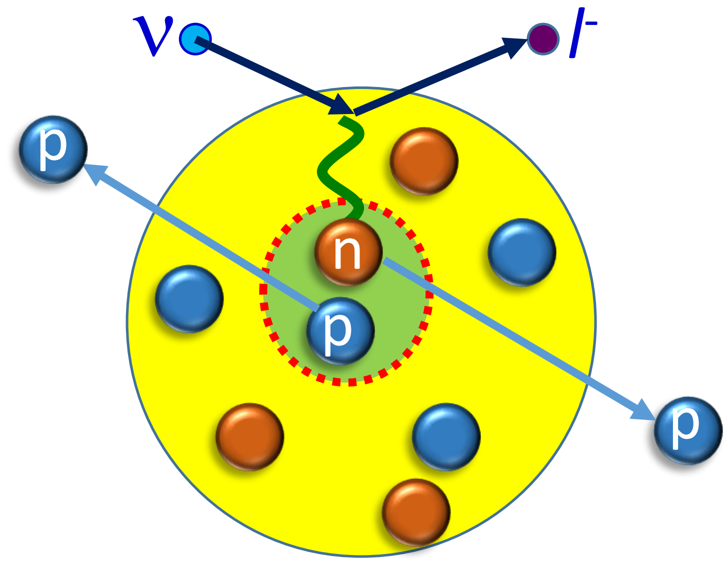
2p2h model in NEUT

- Lepton kinematics (T_μ, $\cos\theta_\mu$)
  Use pre-calculated 2D lookup table.
  (Because of this,
  only ^{12}C, ^{16}O and ^{40}Ca are included.)

Apply $|q_3| < 1.2$ GeV/c constraint

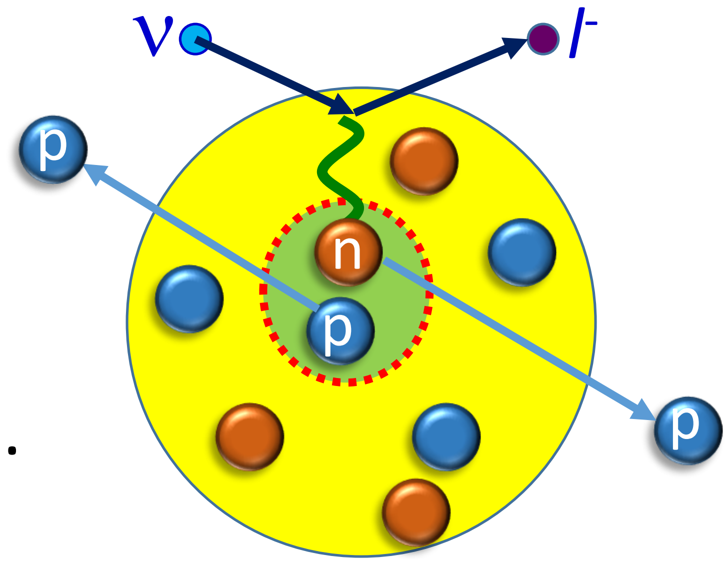


2p2h model in NEUT



- Hadron (nucleon) kinematics
  - Initial state nucleons
    - Uncorrelated two nucleons
    - Momentum distribution is same as 1p1h
  - Final state nucleons
    - Transferred energy is shared equally between two outgoing nucleons
    - Energy is conserved
    - Additional re-scattering is handled just as same as the other interactions.

2p2h model in NEUT



- Hadron (nucleon) kinematics
  0) Calculate energy transfer to the hadron system.
  1) Fix two uncorrelated nucleon momenta.
  2) Boost CMS frame of nucleon system.
  3) Give half of the transfer energy to each nucleon.
  4) Eject direction of two nucleon isotropically.
  5) Boost back to the LAB frame.
  6) Check the Pauli-blocking condition. (If not satisfied, go to 1)

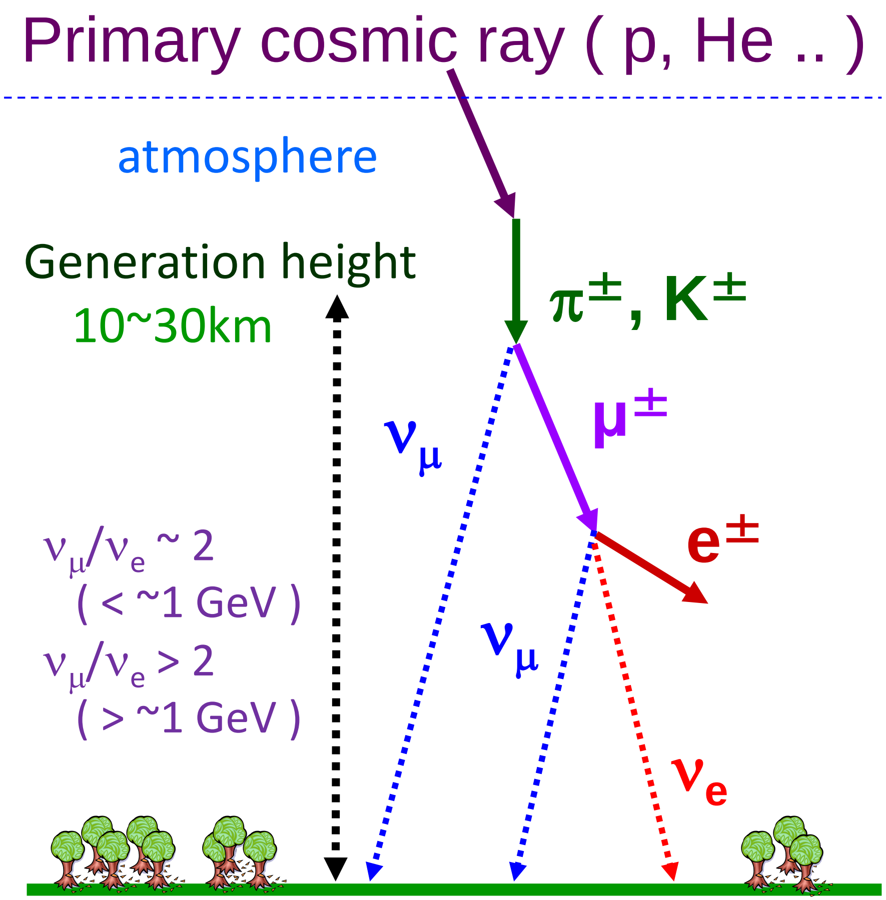
2p2h model in Neut
Necessary improvements

- More generic implementation
  - non-isotropic nucleus
  - replace `differential cross-section lookup tables'
    - with the hadronic tensor tables
  - better (more appropriate) hadron kinematics
    - initial momenta distribution
      and their correlations
    - nuclear binding effects

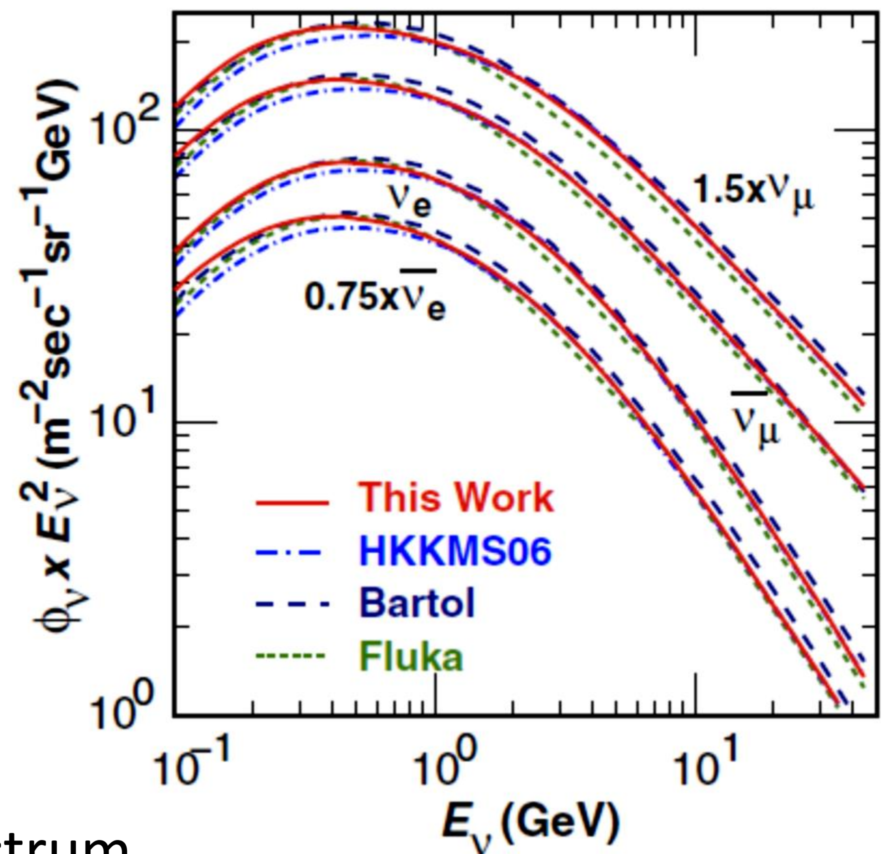
- Nucleon re-scattering
  - Not only for this interaction
  - Need better implementation.

atmospheric neutrino

Characteristics of atmospheric neutrino



Atmospheric ν energy spectrum



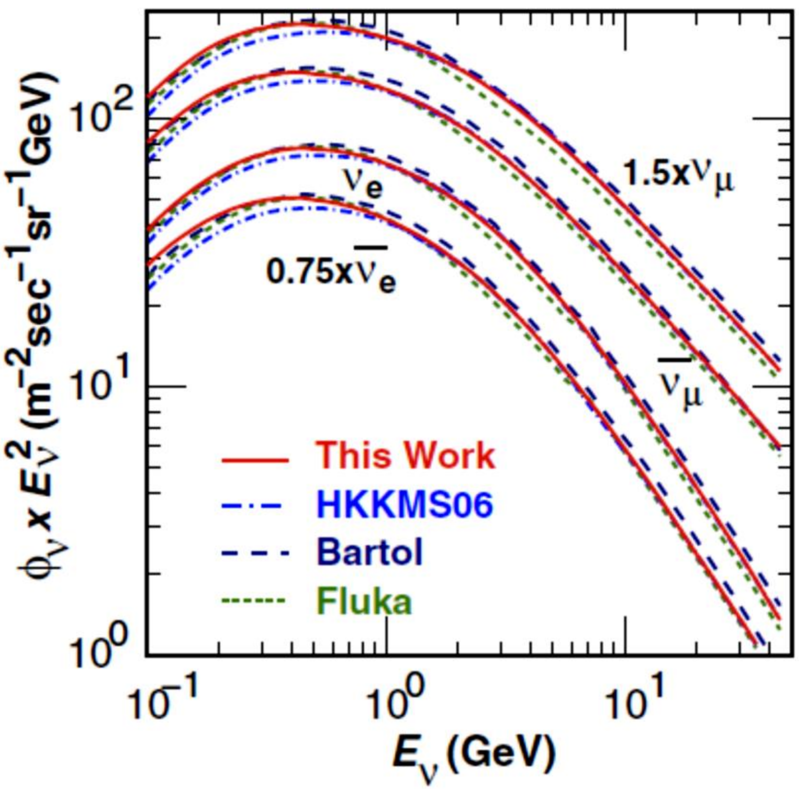
Atmospheric neutrino energy spectrum

Peaked at ***~ several hundreds of MeV, Extended > TeV***

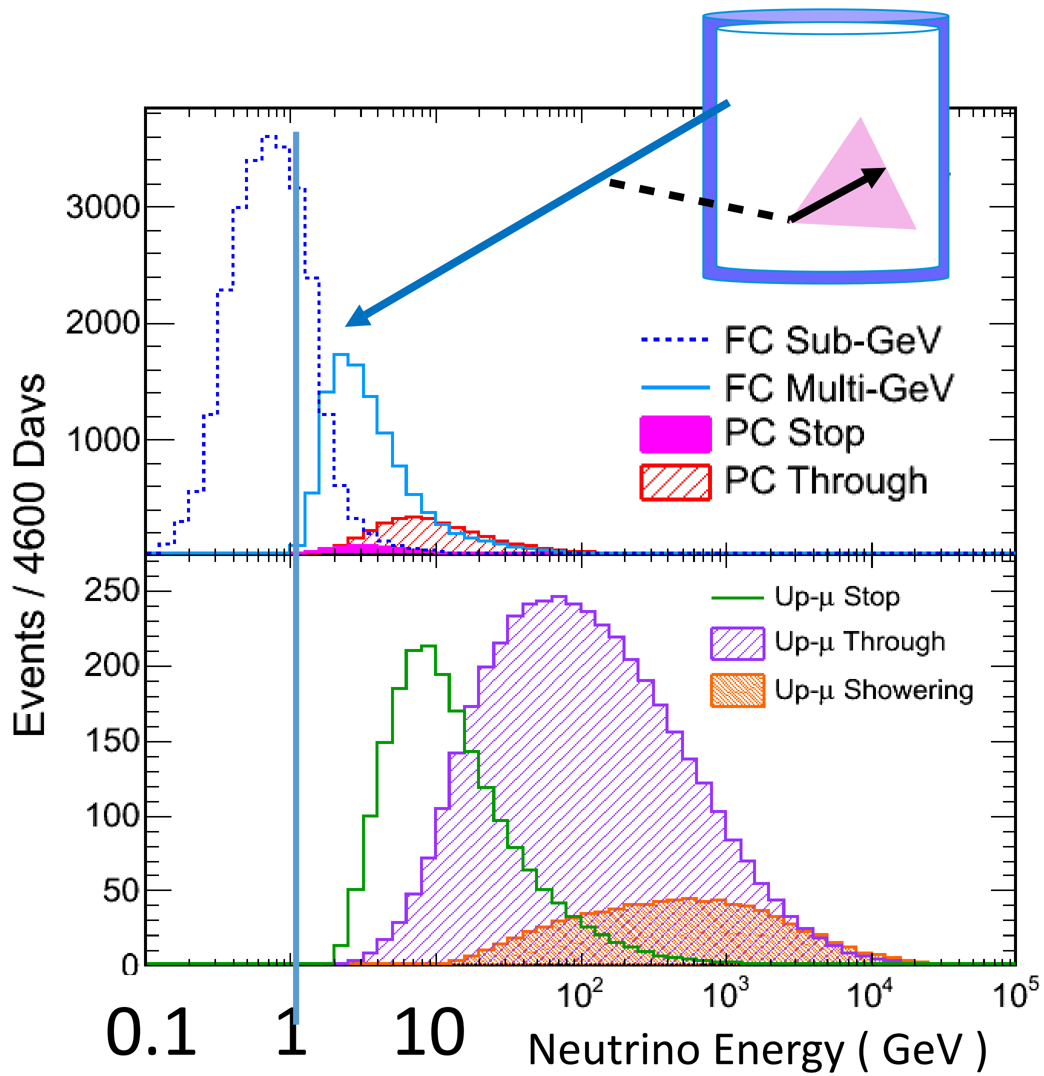
Neutrino travel length from ***~ 10 km to 13,000 km***

Zenith angle corresponds to travel length of neutrinos.

Atmospheric neutrino
SK Event category

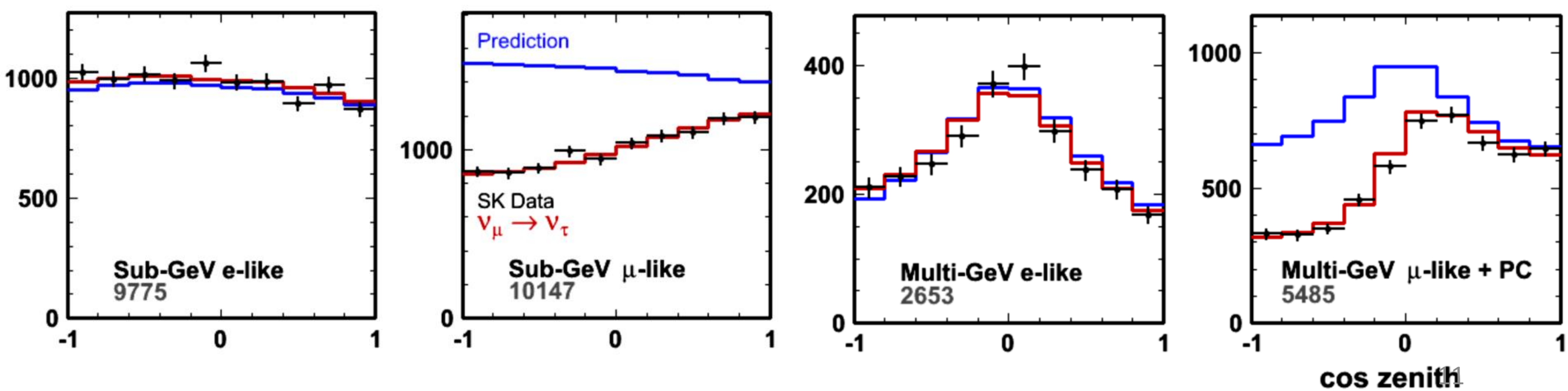


Fully Contained (FC)



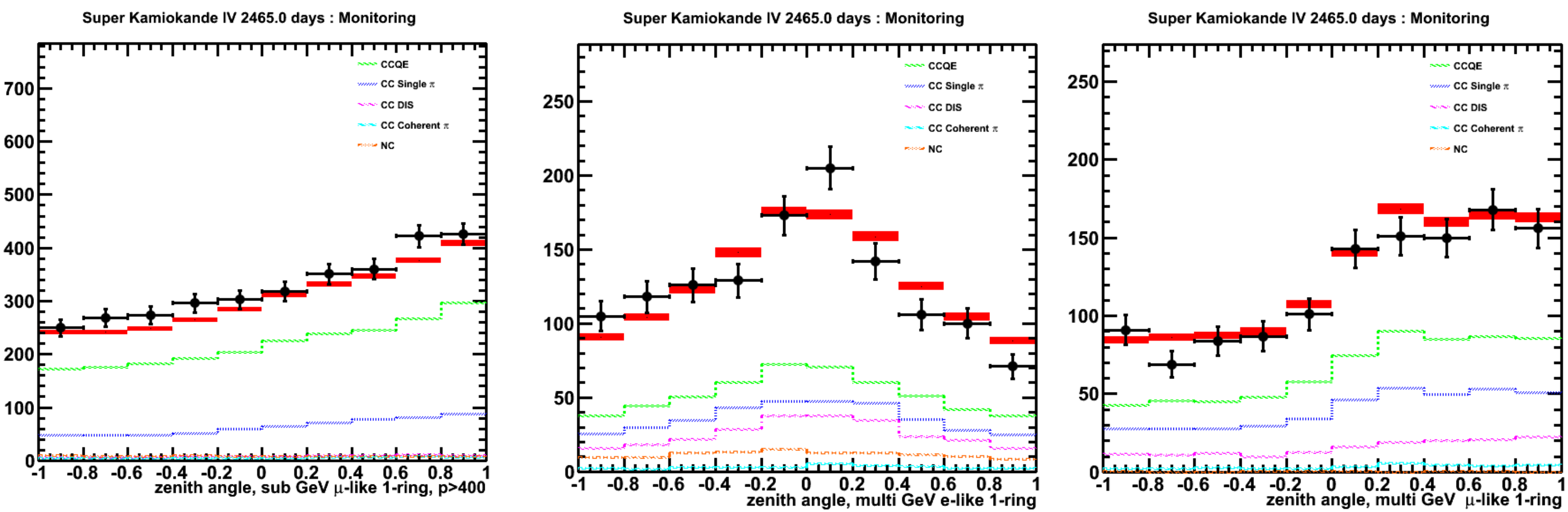
Atmospheric neutrino Oscillation analysis in SK

- In total 19 analysis samples
  (classified by ν flavors, event topologies, energies, ...)
- *Fit to the data in bins of* ***$\cos\theta_{zenith}$ and momentum***
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in sub-dominant contributions
  Three-flavor effects, Sterile Neutrinos, LIV, ...



Atmospheric neutrino
~ lepton zenith angle distribution ~

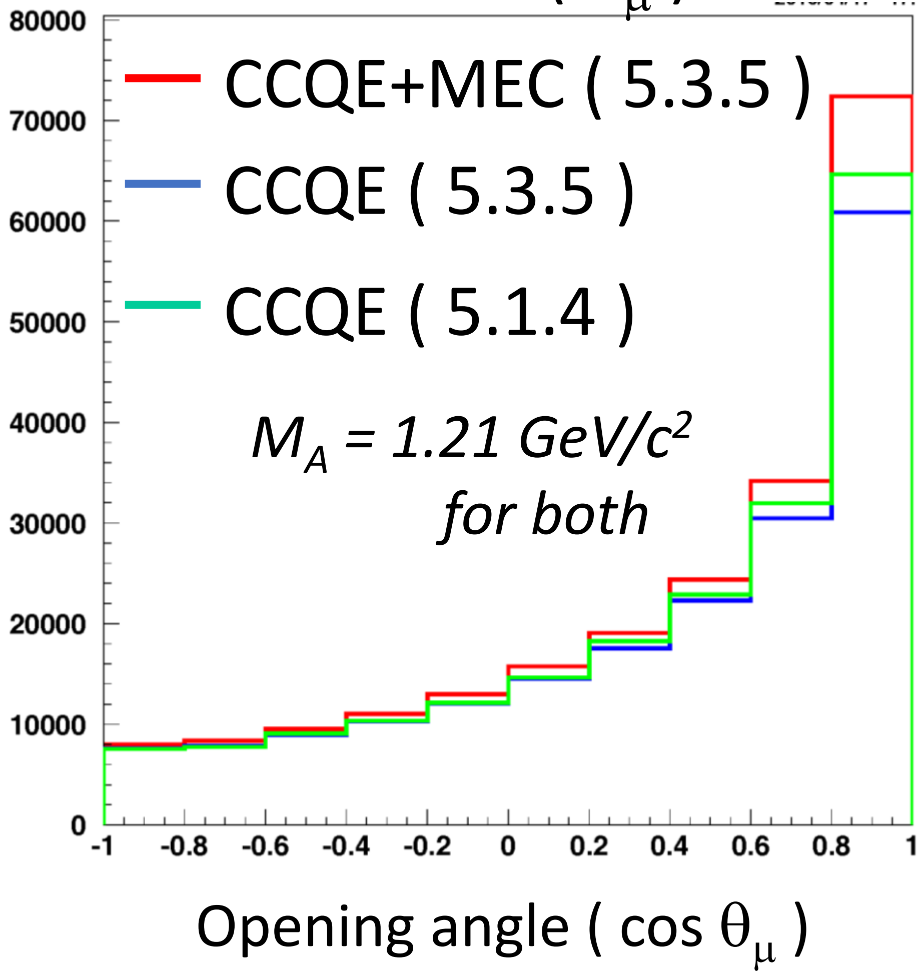
Atmospheric neutrino oscillation analysis fits
the momentum distributions and
the zenith angle distributions of charged leptons.



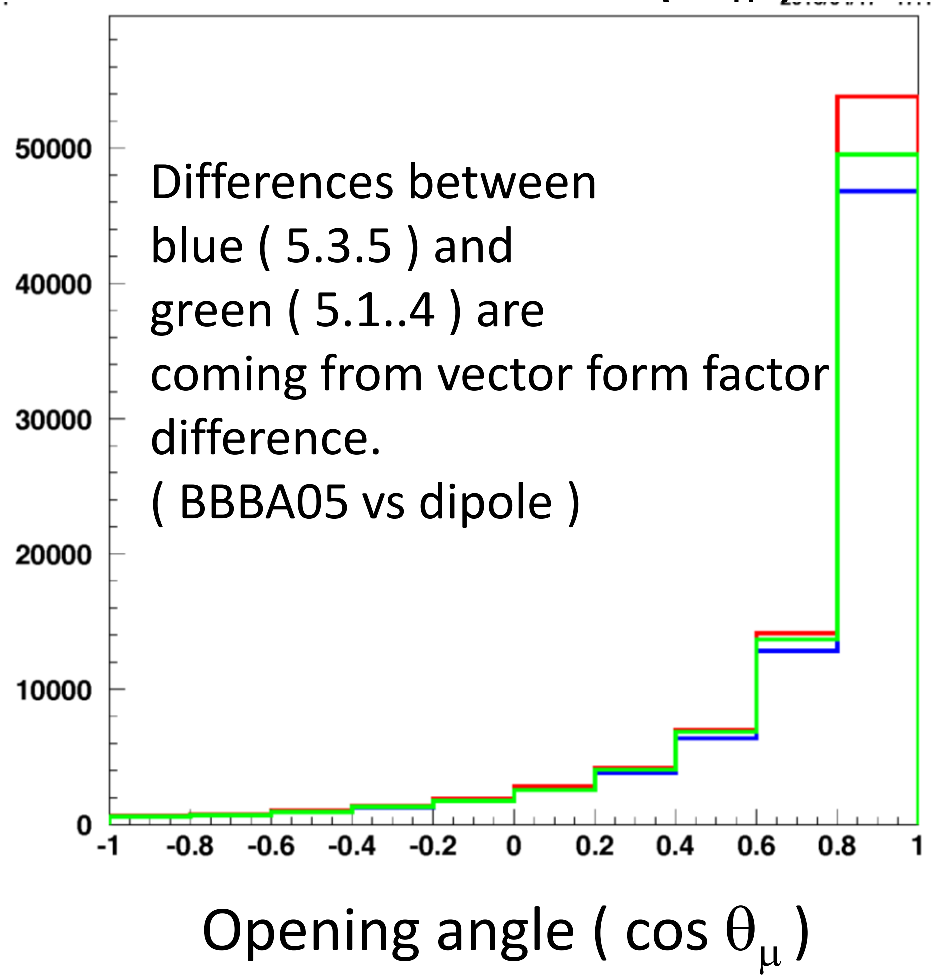
Relation between neutrino and lepton is also important.

Lepton direction
with atmospheric neutrino flux

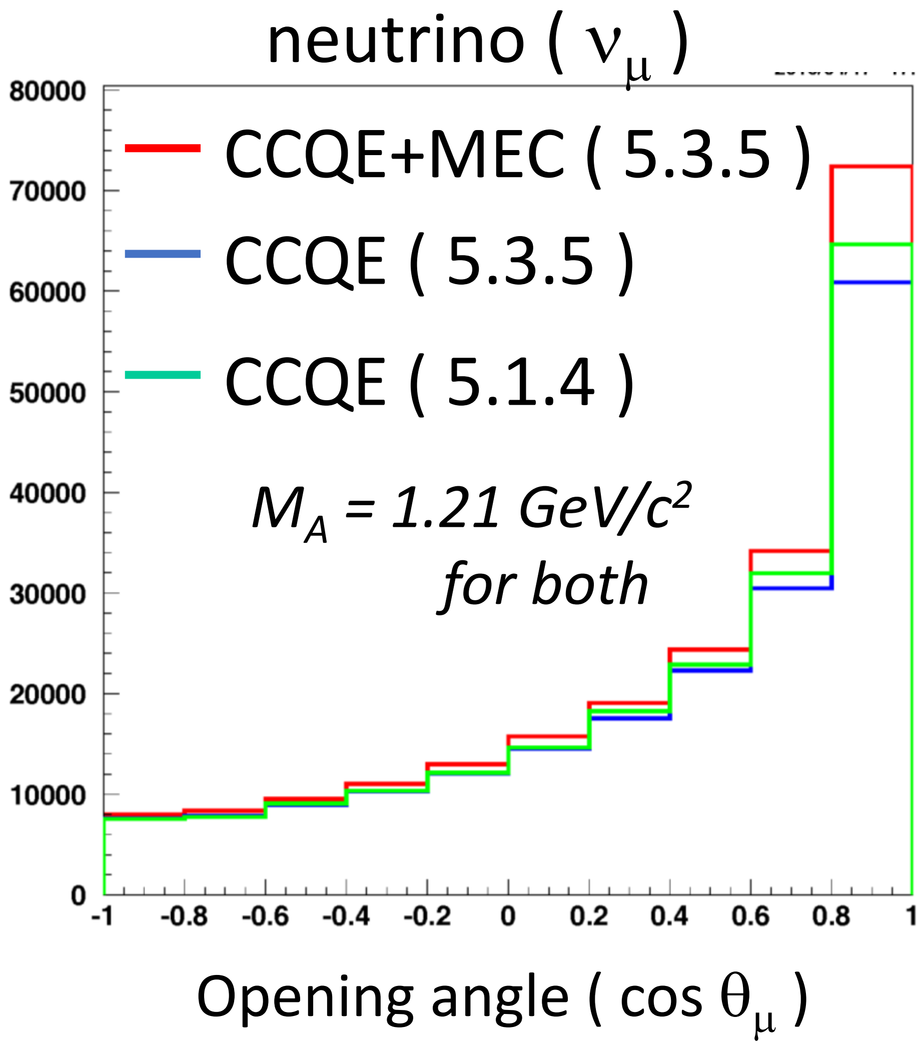
neutrino (ν_μ)



anti neutrino ($\bar{\nu}_\mu$)



Lepton direction with atmospheric neutrino flux



2p2h : sharper peak in forward.

RPA effect needs to be taken into account.

The effect in the atmospheric neutrino oscillation analysis may not be so large but need to be understand the effect.
~ We have started the study using the latest Neut.

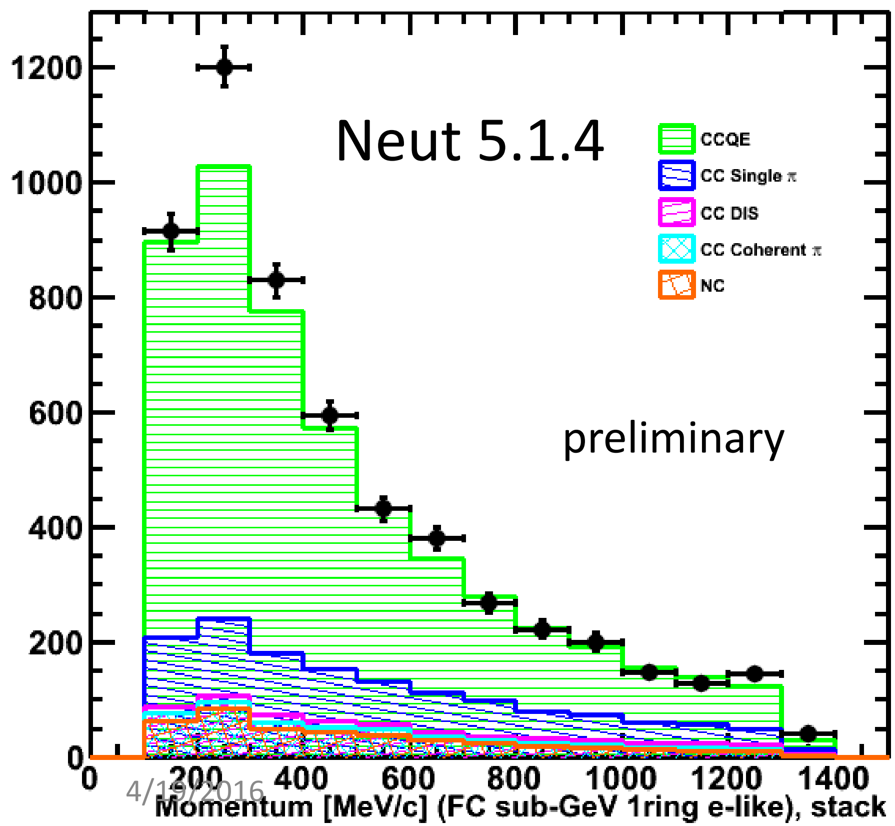
Atmospheric neutrino
Charged lepton momentum

Old Neut (5.1.4)

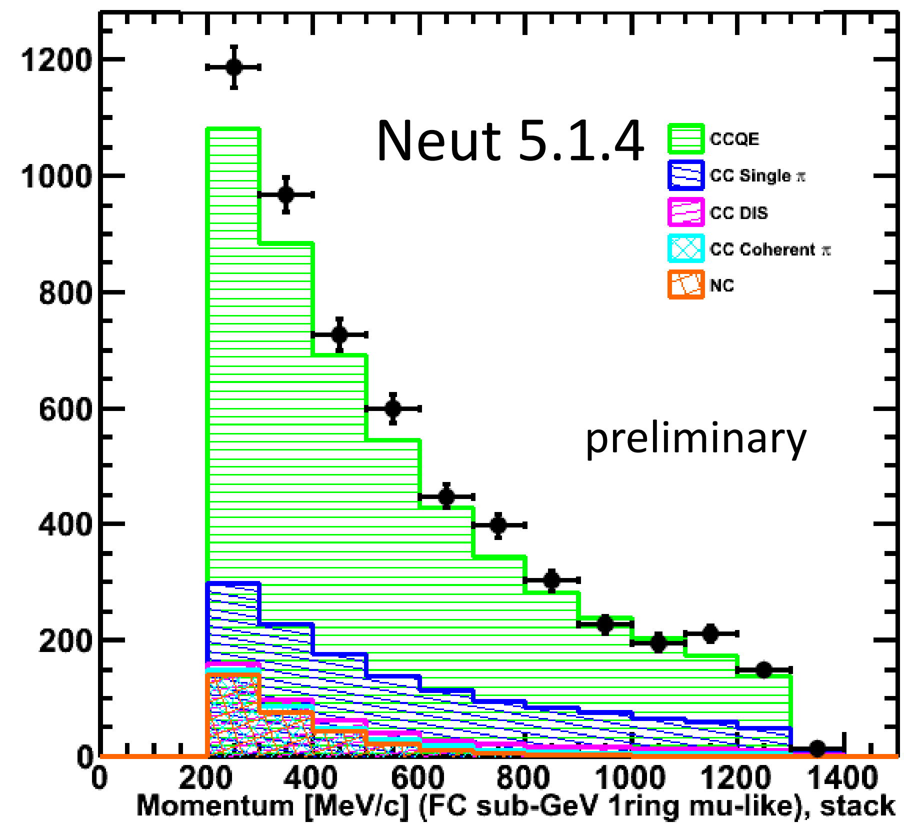
Simple relativistic Fermi gas (Smith-Moniz) CCQE ($M_A = 1.2$ GeV/c^2)

Rein-Sehgal single p production ($M_A = 1.2$ GeV/c^2)

Super Kamiokande IV



Super Kamiokande IV



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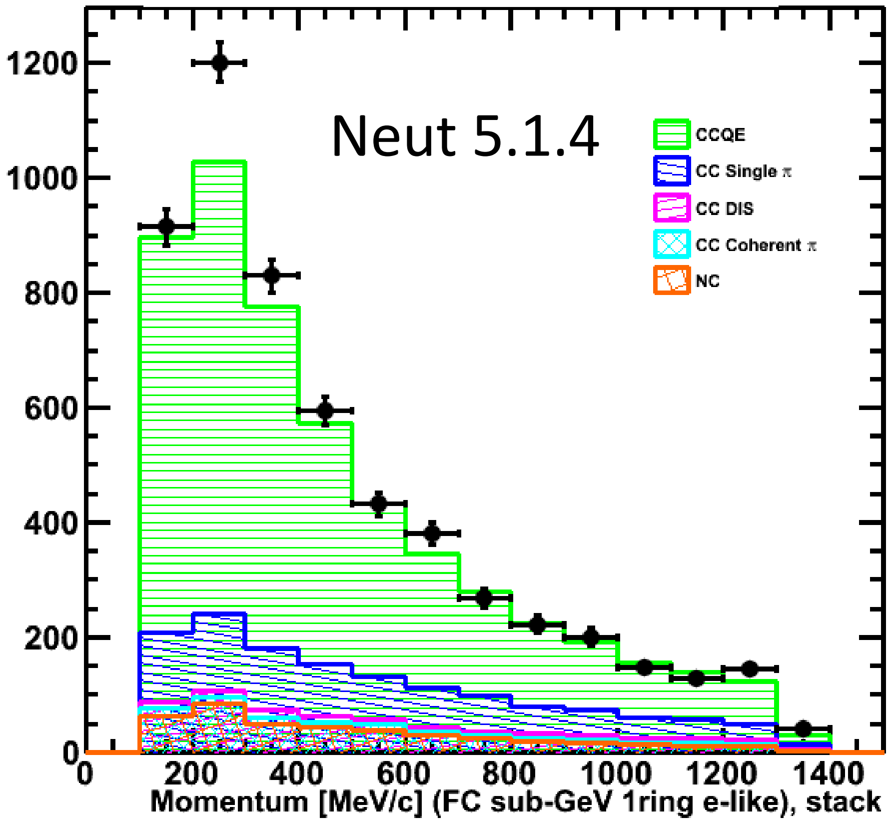


Numbers of observed events are always larger than MC prediction.

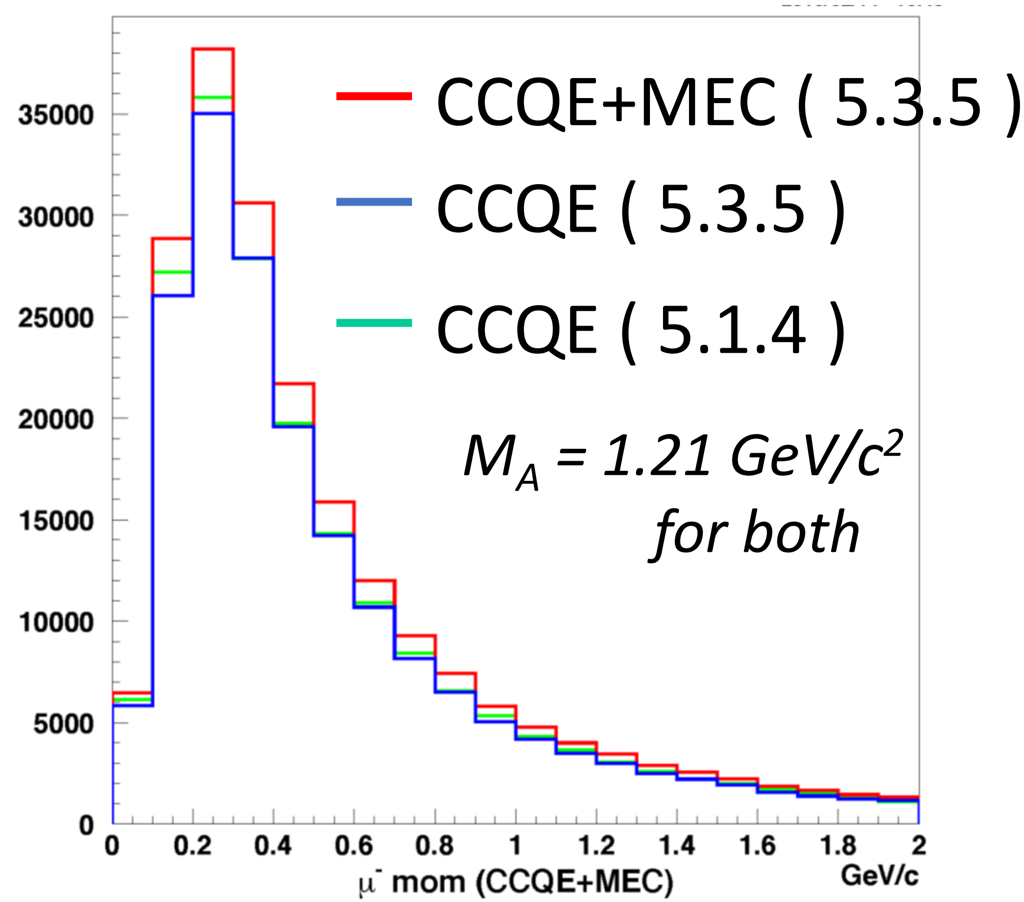
Even with larger M_A value.

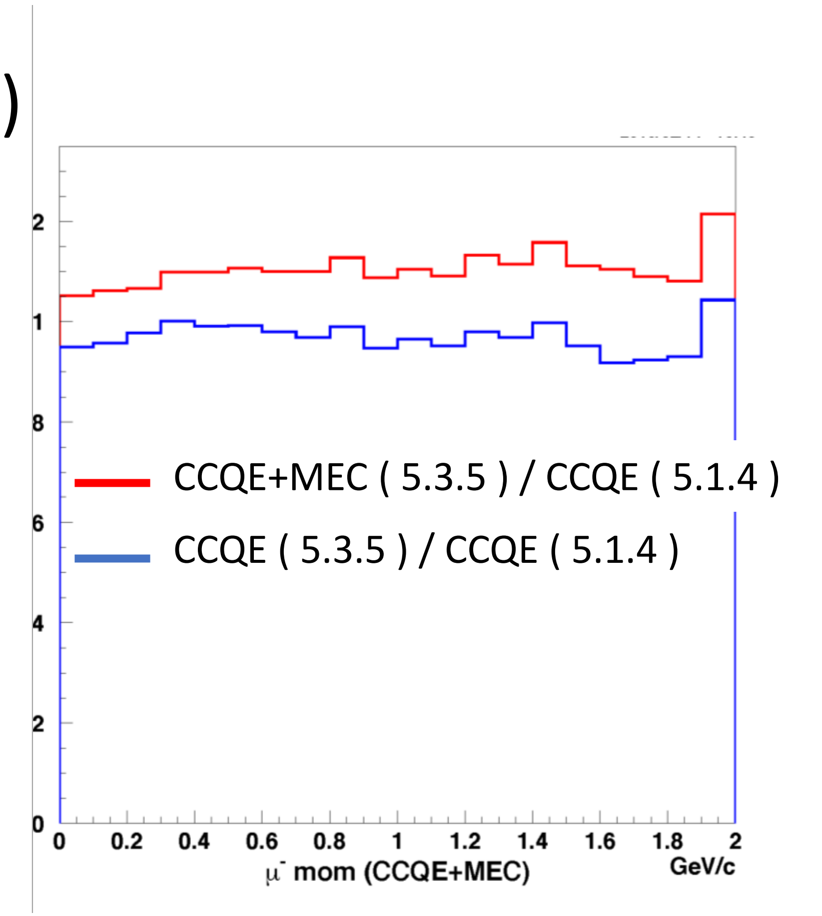
Absolute normalization of neutrino flux has ~10% uncertainty.

If we set M_A smaller, the discrepancy becomes larger.

Can 2p2h explain this discrepancy?

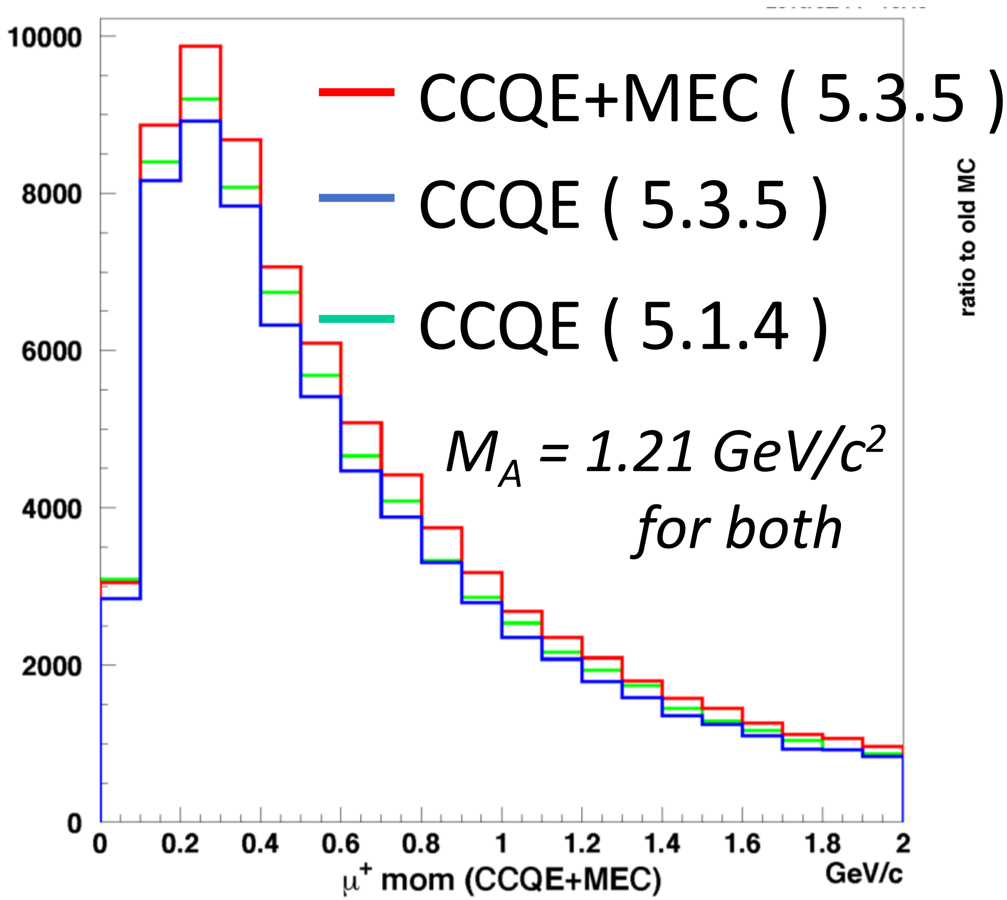
Atmospheric neutrino
Charged lepton momentum

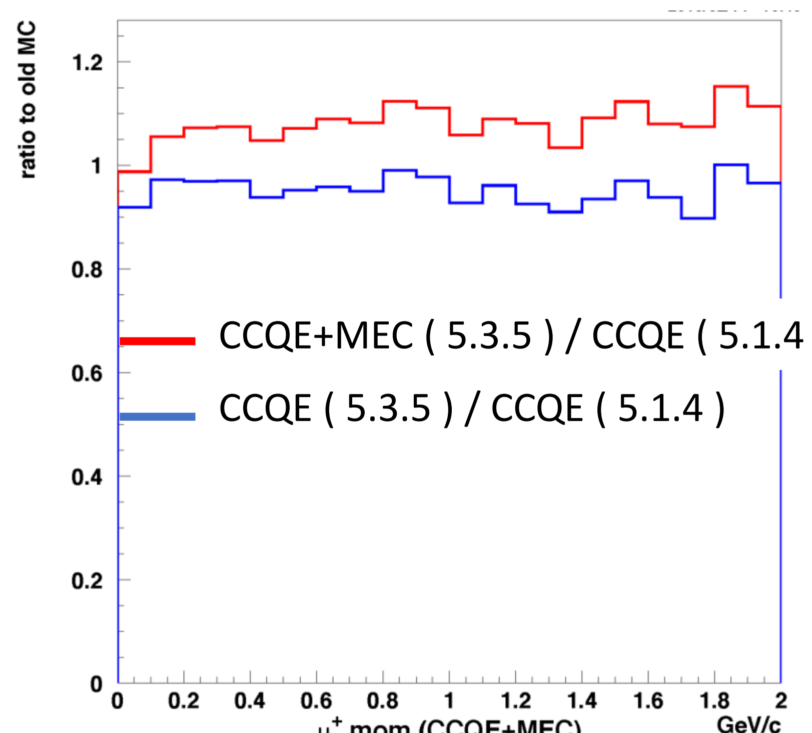




CCQE difference is coming from the difference of vector form factor (BBBA05 vs dipole)

Atmospheric neutrino
Charged lepton momentum



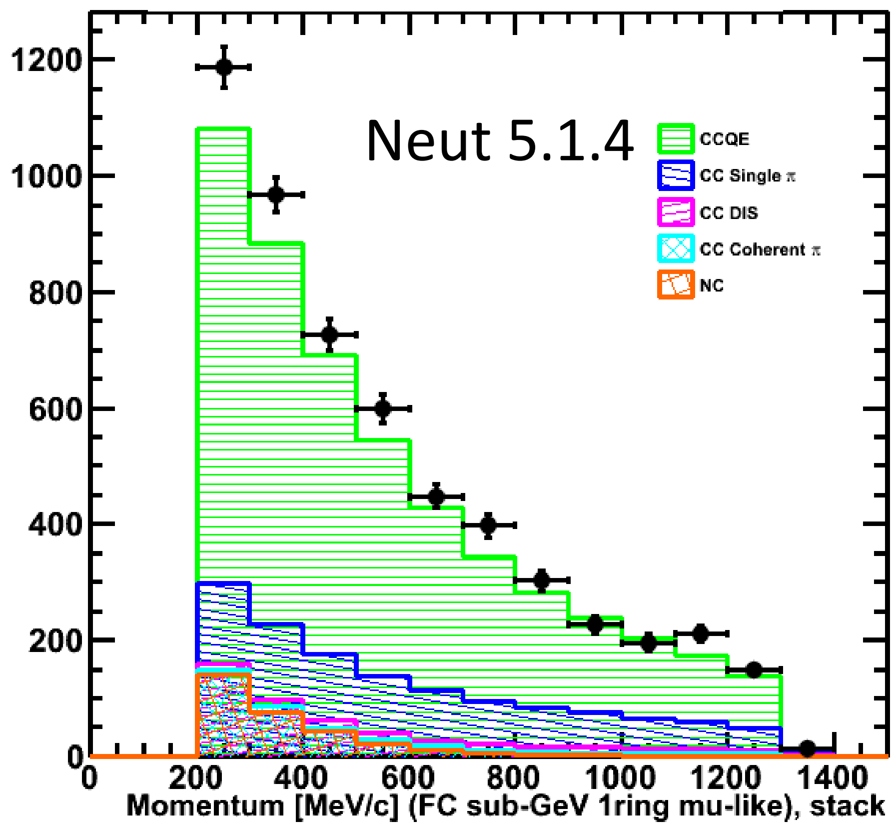


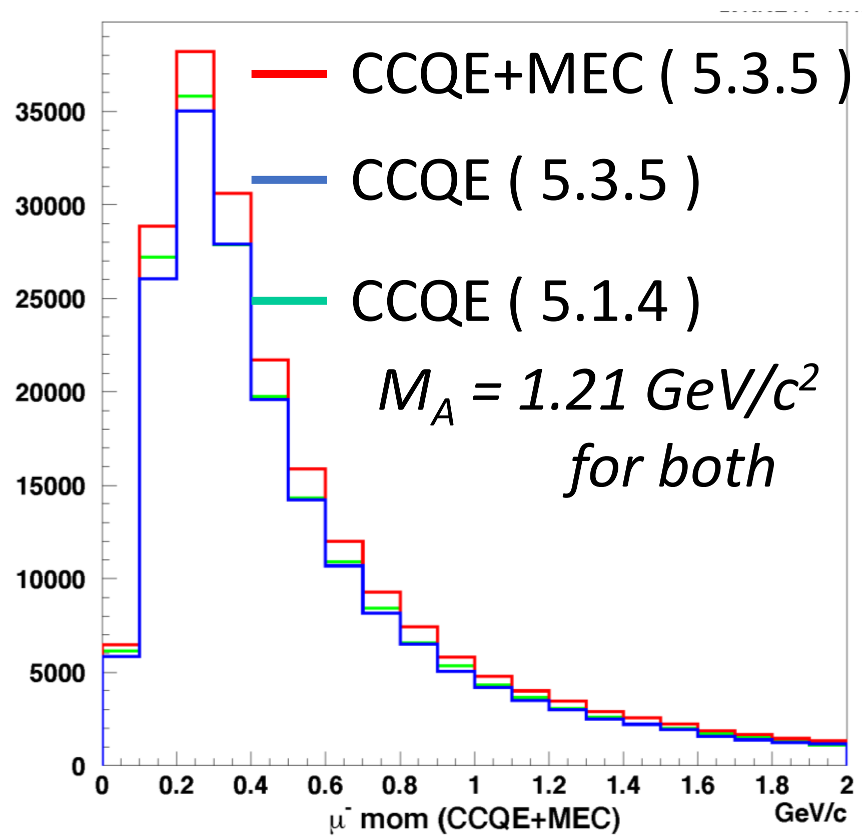
CCQE difference is coming from the difference of vector form factor (BBBA05 vs dipole)

Atmospheric neutrino
Charged lepton momentum

Simple RFG CCQE (M_A = 1.2 GeV/c^2) + 2p2h (MEC)
seems to have better agreements in the low momentum region.
However, this combination may give larger # of events in high momentum region.

Super Kamiokande IV





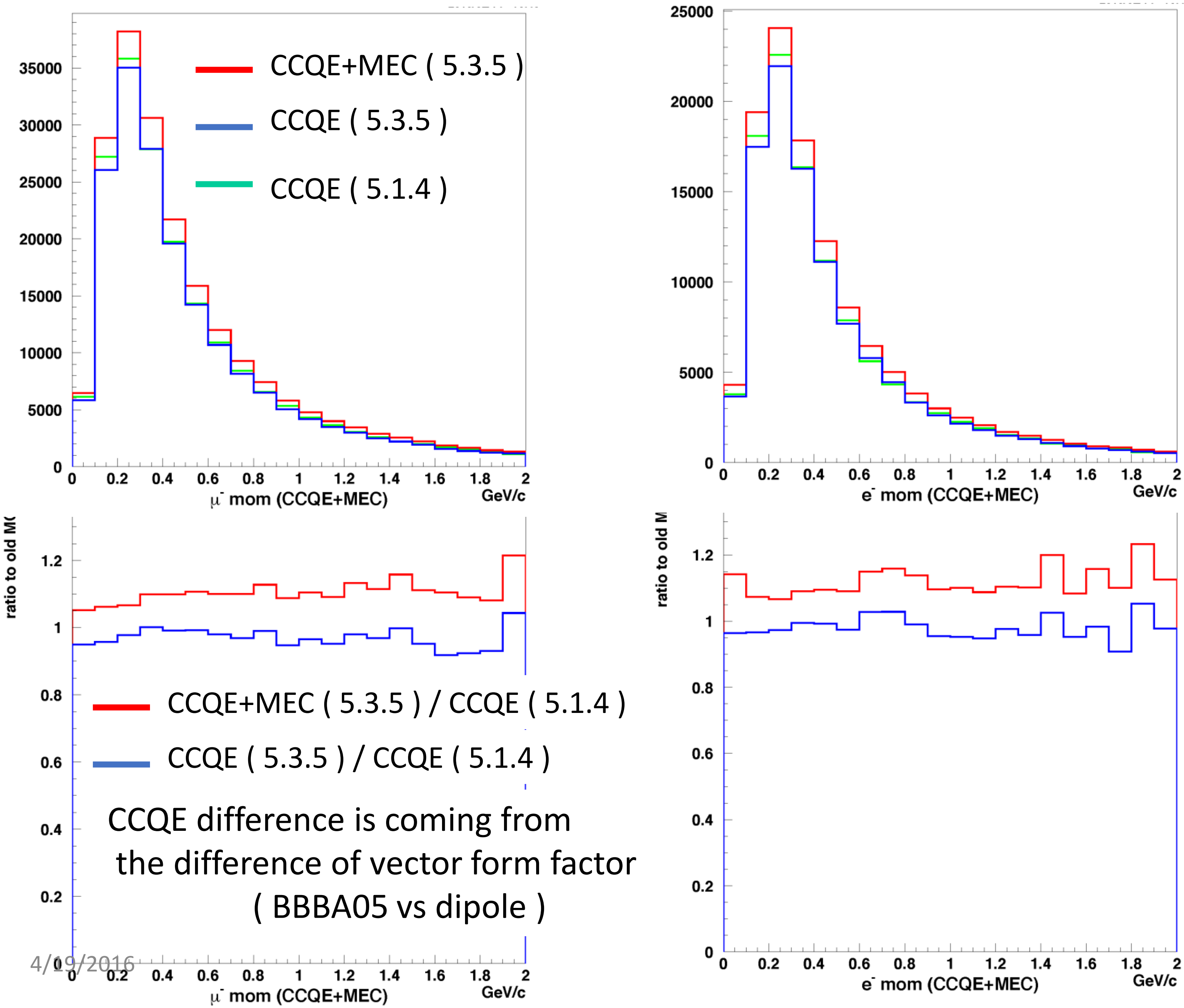
Atmospheric neutrino
Charged lepton momentum

Simple RFG CCQE ($M_A = 1.2\ GeV/c^2$) + 2p2h (MEC)
seems to have better agreements
in the low momentum region.
However, this combination may give larger # of events
in high momentum region.

If we apply RPA correction on the CCQE,
# of events are expected to be reduced,
especially in the low energy region.

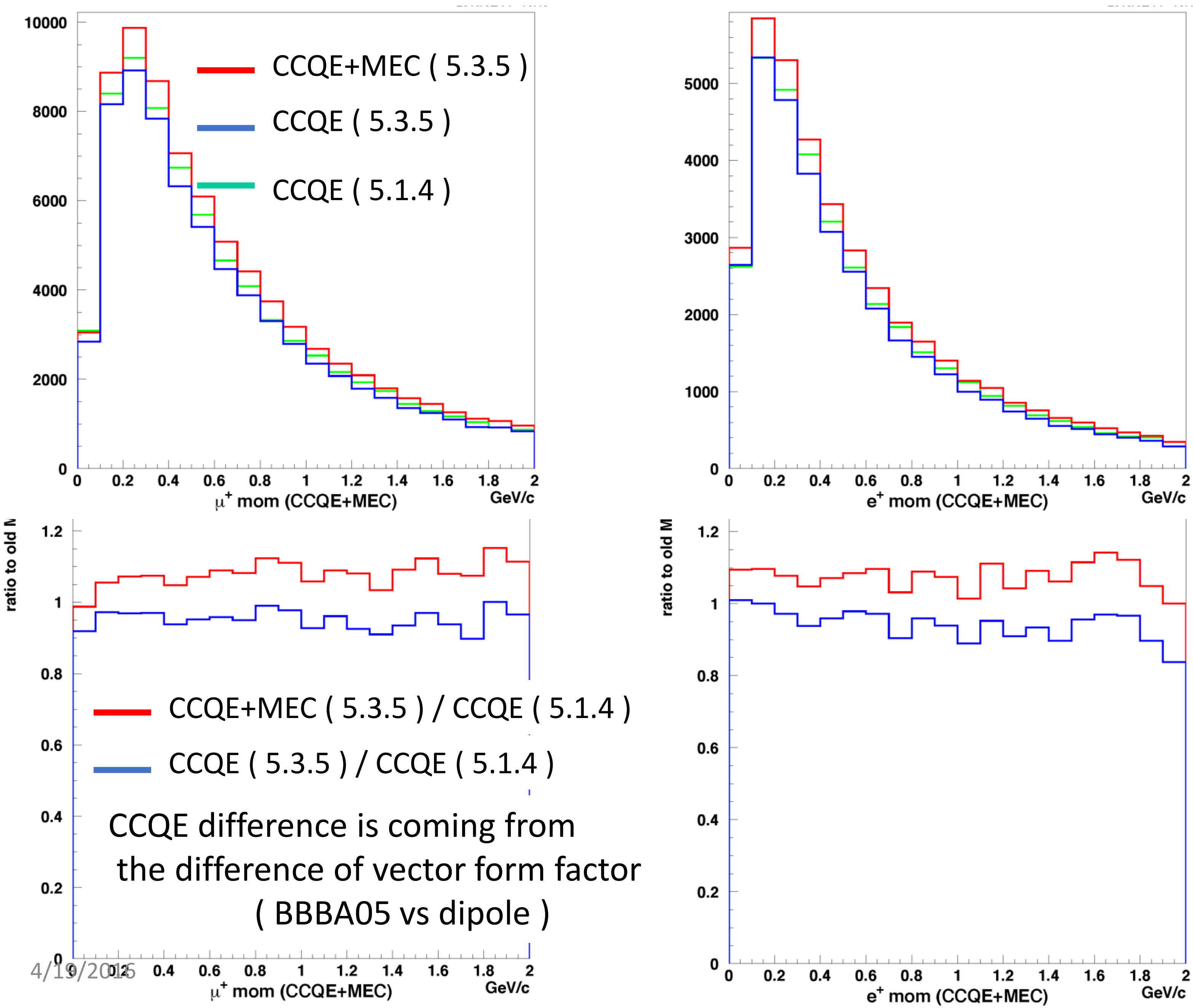
We need further studies.

Lepton momentum comparisons (CCQE + MEC, neutrino mode)



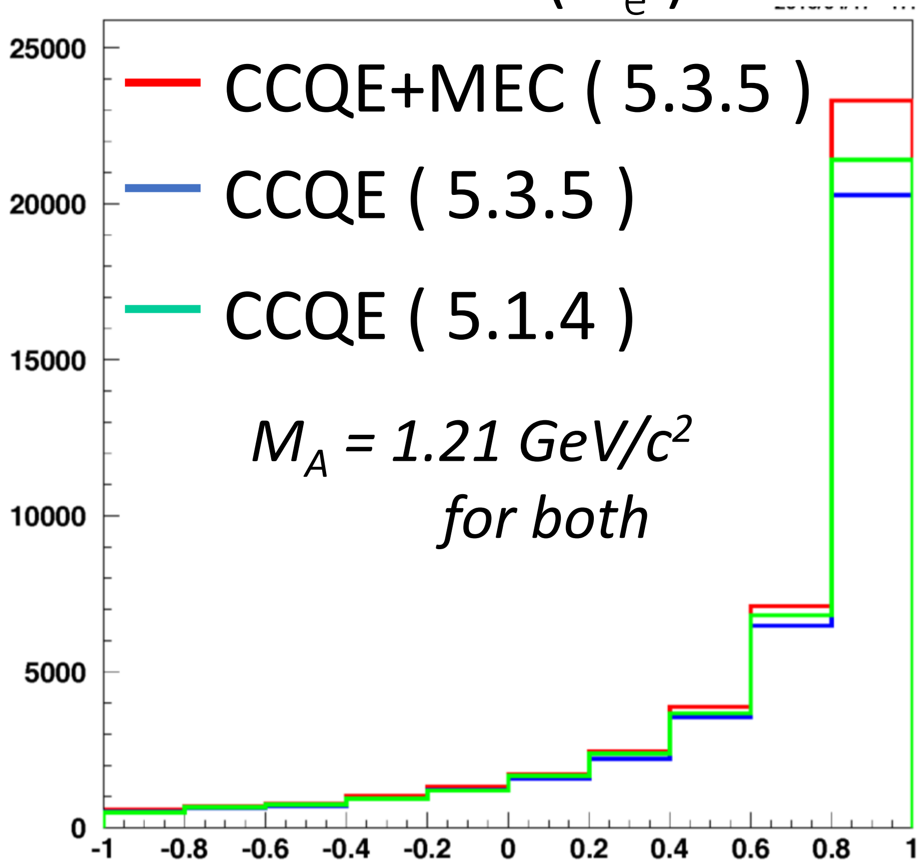
CCQE difference is coming from
the difference of vector form factor
(BBBA05 vs dipole)

Lepton momentum comparisons (CCQE + MEC, anti neutrino mode)



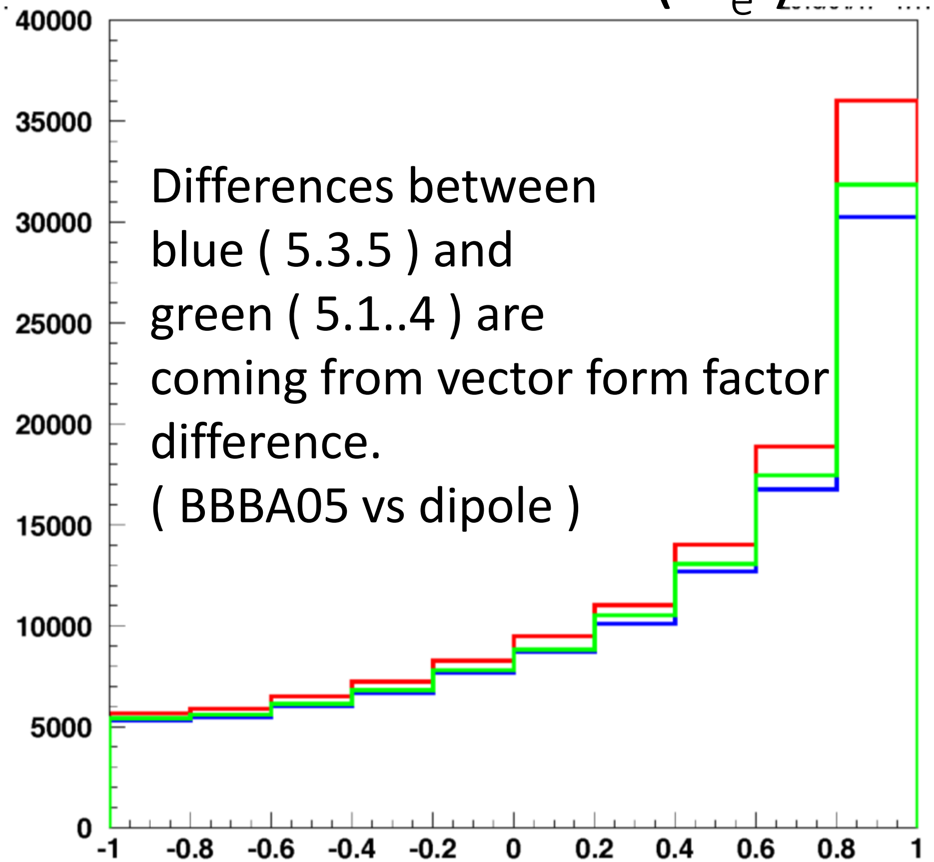
Lepton direction with atmospheric neutrino flux

neutrino (ν_e)



Opening angle ($\cos\theta_e$)

anti neutrino ($\bar{\nu}_e$)



Opening angle ($\cos\theta_e$)