Introduction
~ Experimental point of view ~

Yoshinari Hayato (Kamioka, ICRR, Univ. of Tokyo)

Neutrino experiments

What we do in the experiments

Most of the times, we need to

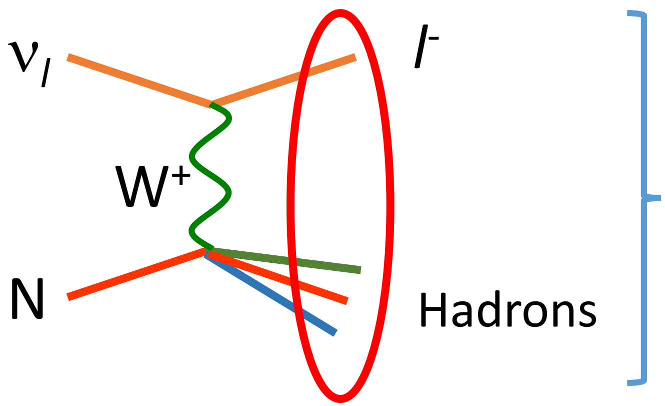
reconstruct of energy and direction of a neutrino,

and

identify the flavor of a neutrino.

What we can observe in the detectors are

only some fraction of the particles produced.



Some of these particles

are invisible (not detected)

in the detectors.

Need “precise” simulation

to “reconstruct” neutrino information.

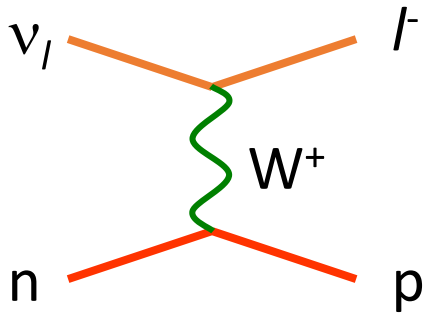
Neutrino experiments ~ examples ~

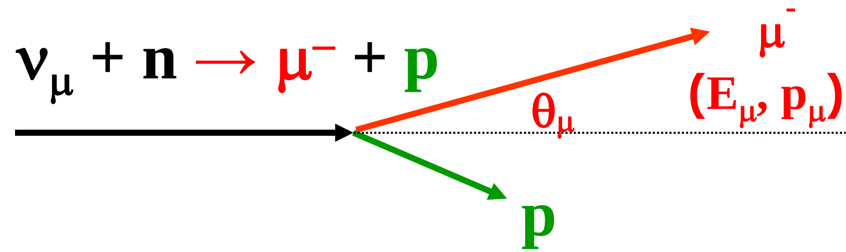
Accelerator based experiment

Direction of neutrino is known

Case 1: $E\nu$ = 100 ~ 1 GeV

$\nu + N \rightarrow l + N'$ Charged current quasi-elastic scattering events





Use direction and momentum of lepton
to reconstruct energy of neutrino

- Purity of the selected events
- Binding effects of target nucleon
- Fermi momentum, Binding energy etc.
- Contamination ~ Impurity
- Interactions other than genuine CCQE
- Multi-nucleon interaction?

Neutrino experiments ~ examples ~

Accelerator based experiment

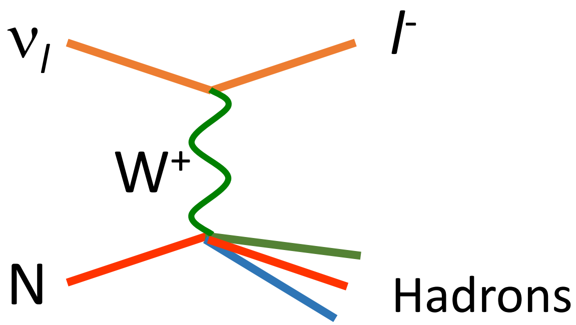
Direction of neutrino is known

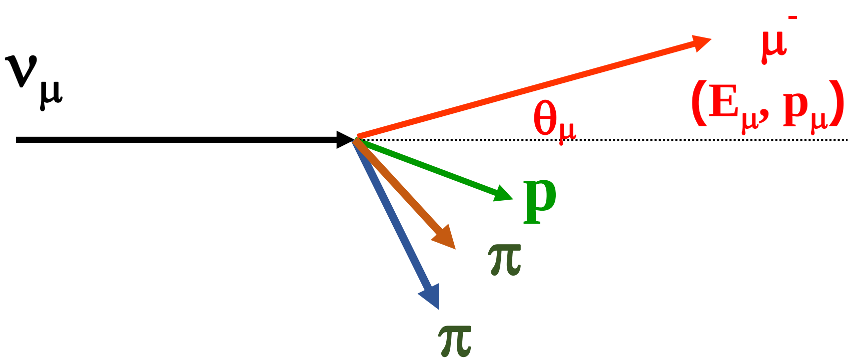
Case 2: $E\nu$ > several GeV

Charged current interactions,

mainly ν + N → *l* + N' + **hadrons**

(Charged current deep inelastic scattering evens)





Use direction and momentum of lepton

together with the observed energy of hadrons

to estimate the energy of neutrino

Neutrino experiments ~ examples ~

Accelerator based experiment

Direction of neutrino is known

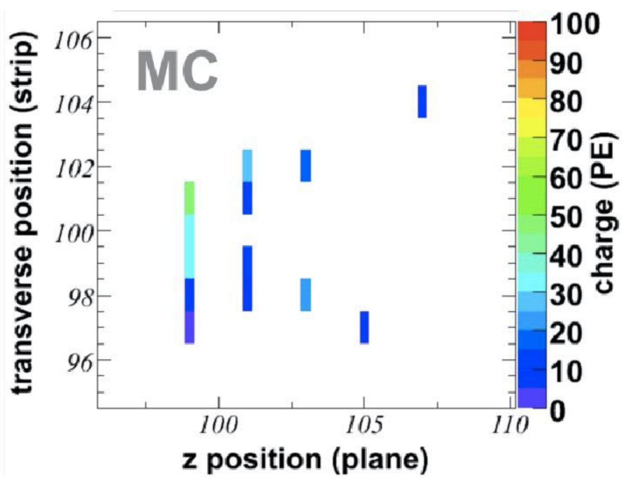
Case 2: Eν > several GeV

Pattern recognition ~ using event topology (MINOS experiment)

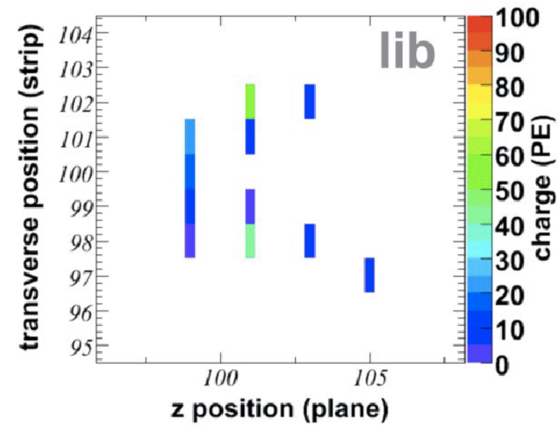
Compare the recorded “real” event

with the simulated events (catalog) for the interaction ID.

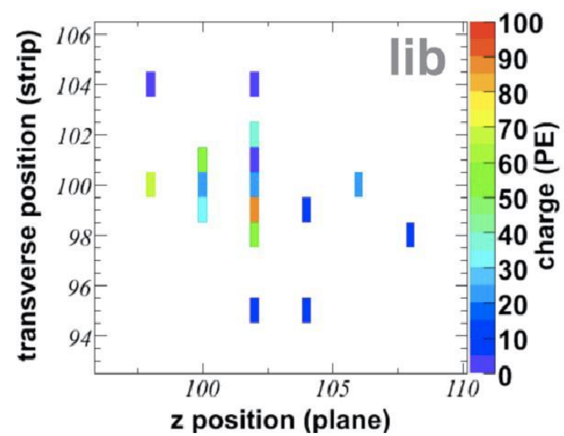
Example



Similar



Different



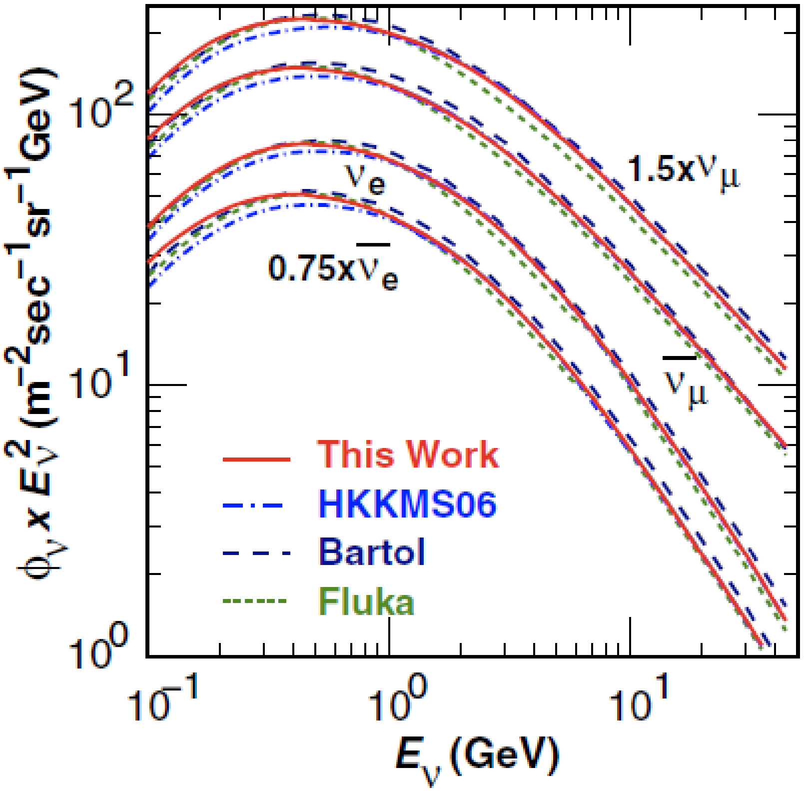
Reproducibility of the “simulation”

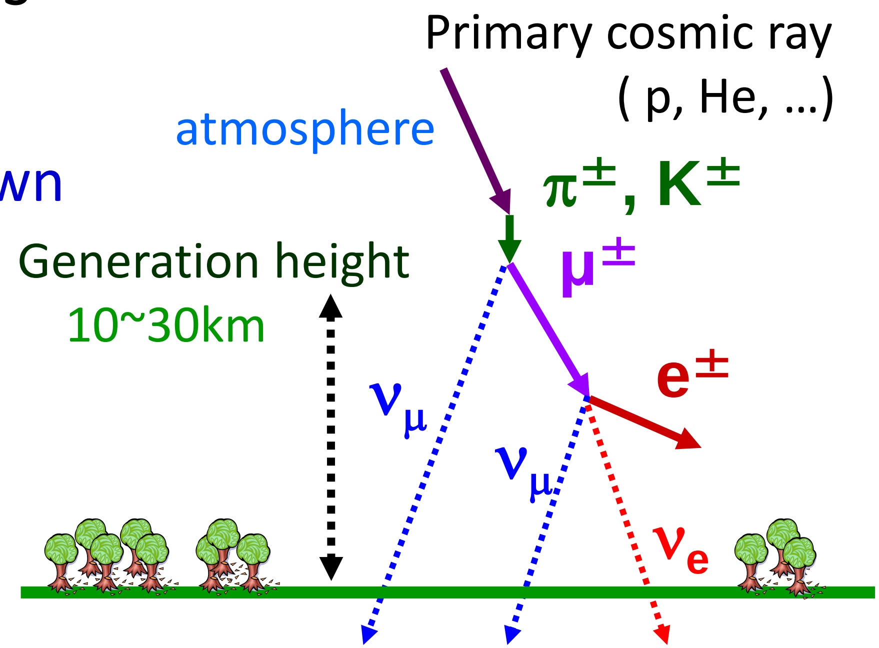
is really crucial.

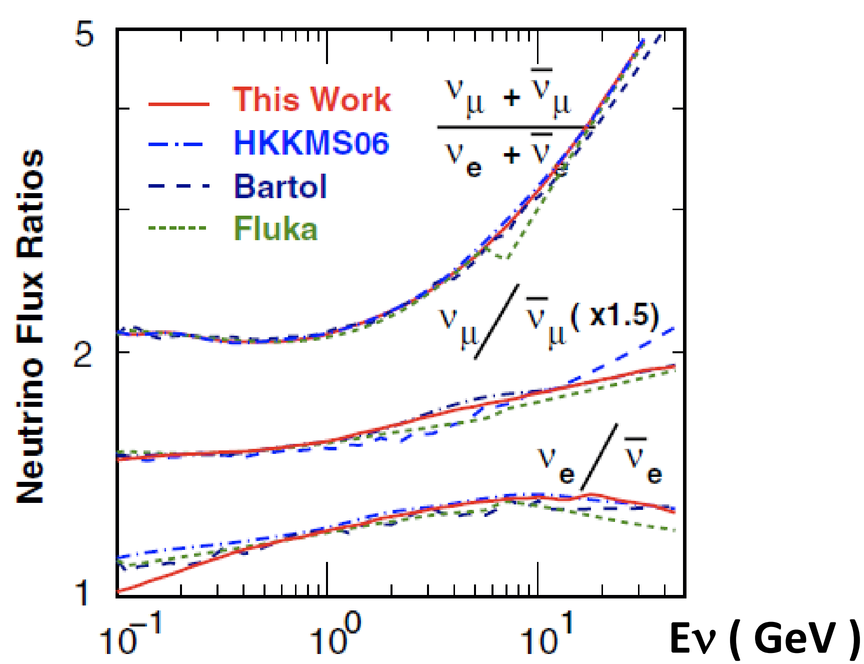
Neutrino experiments ~ examples ~

Atmospheric ν experiments

neutrino direction is unknown



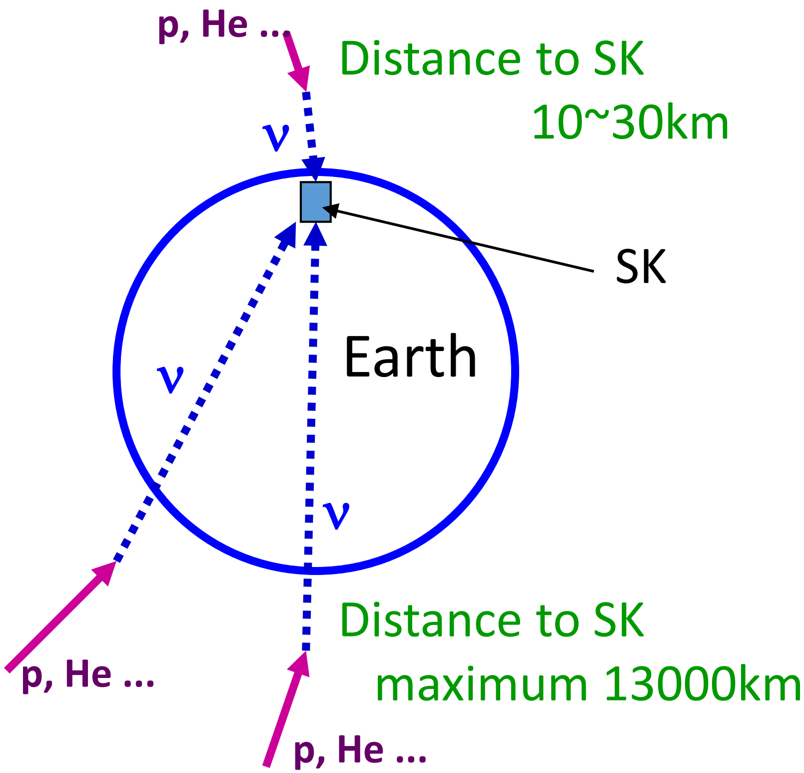




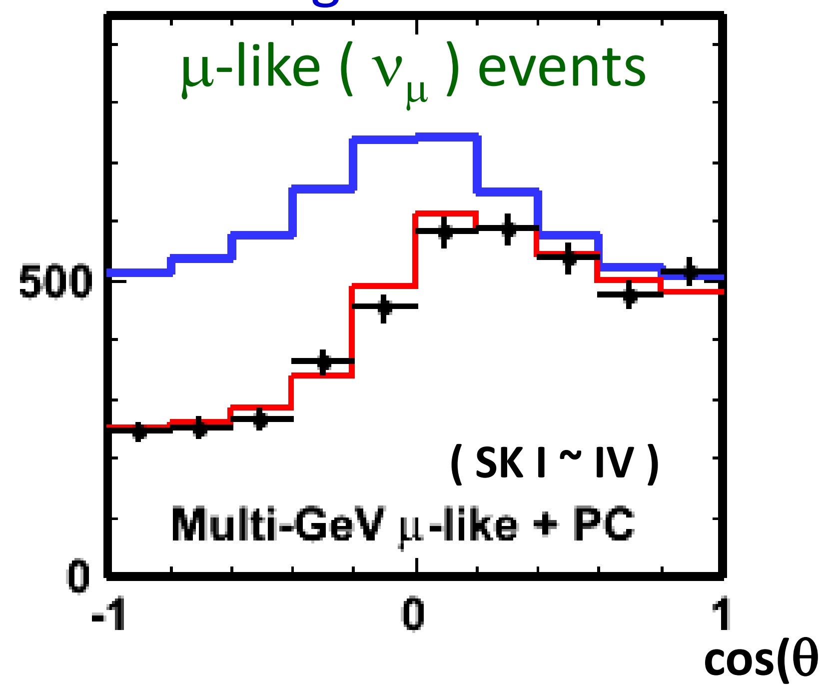
- Broad energy spectrum
  a few tens of MeV ~ TeV
- ν_μ/ν_e ~ 2 (< ~1 GeV)
- ν_μ/ν_e > 2 (> ~1 GeV)

Neutrino experiments ~ examples ~

Atmospheric ν experiments ~ neutrino direction is unknown



zenith angle distribution



- Neutrino oscillation base line from ~ 10 km to 13,000 km
- Zenith angle corresponds to travel length of neutrinos.

Large up-down asymmetry

↓

ν_μ disappearance

First evidence of ν oscillation

(1998)

Neutrino experiments ~ examples ~

Atmospheric ν experiments ~ neutrino direction is unknown

Oscillation analysis

Fit observed distributions of particle momentum and direction using the simulation results assuming oscillations with various parameters.

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

Necessary to understand

ν interactions, hadronization, nuclear effects from E_ν ~ 100 MeV ~ TeV

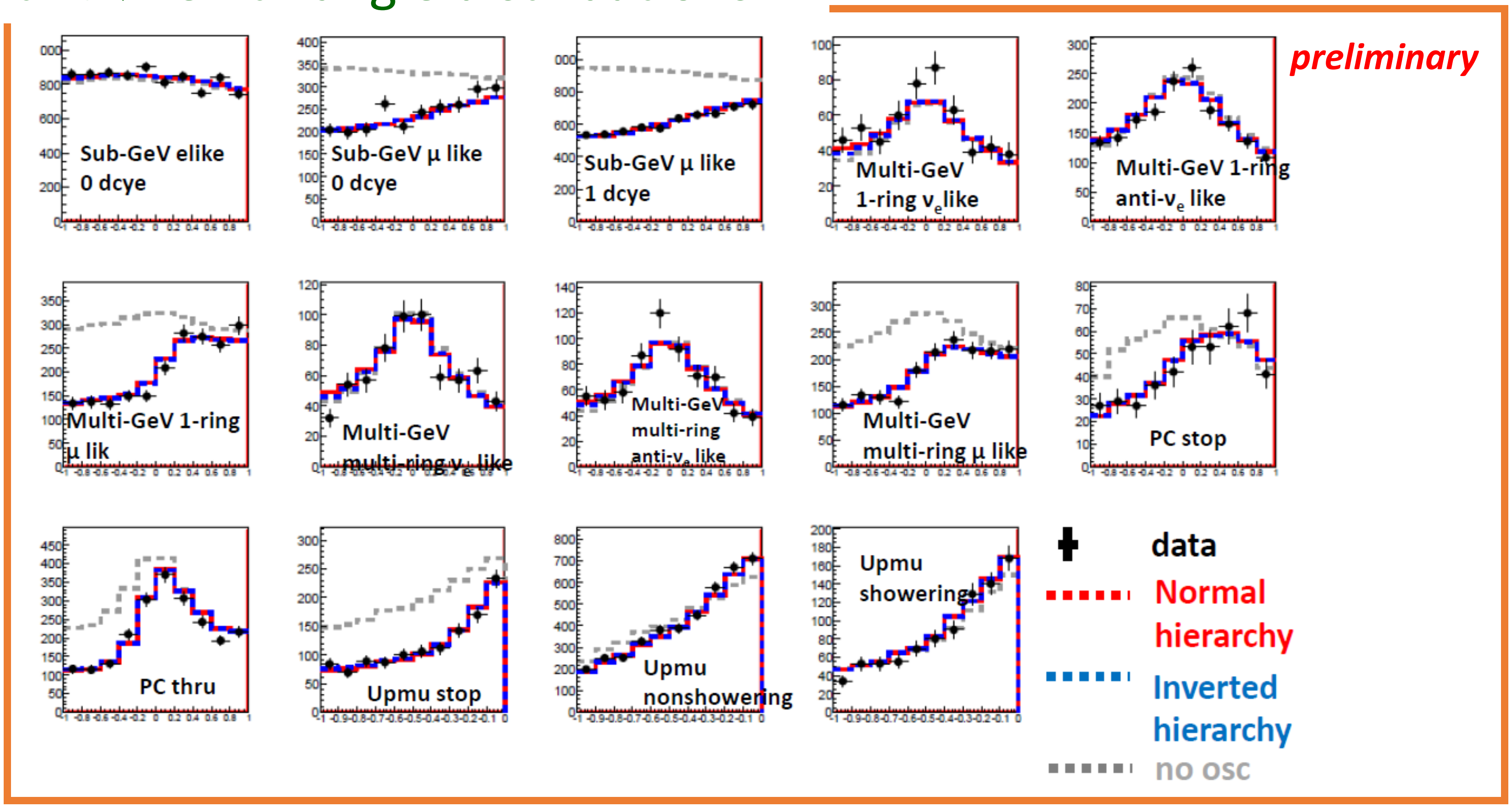
Neutrino experiments ~ examples ~

Atmospheric ν experiments ~ neutrino direction is unknown

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



Neutrino experiments ~ examples ~

Atmospheric ν experiments ~ neutrino direction is unknown

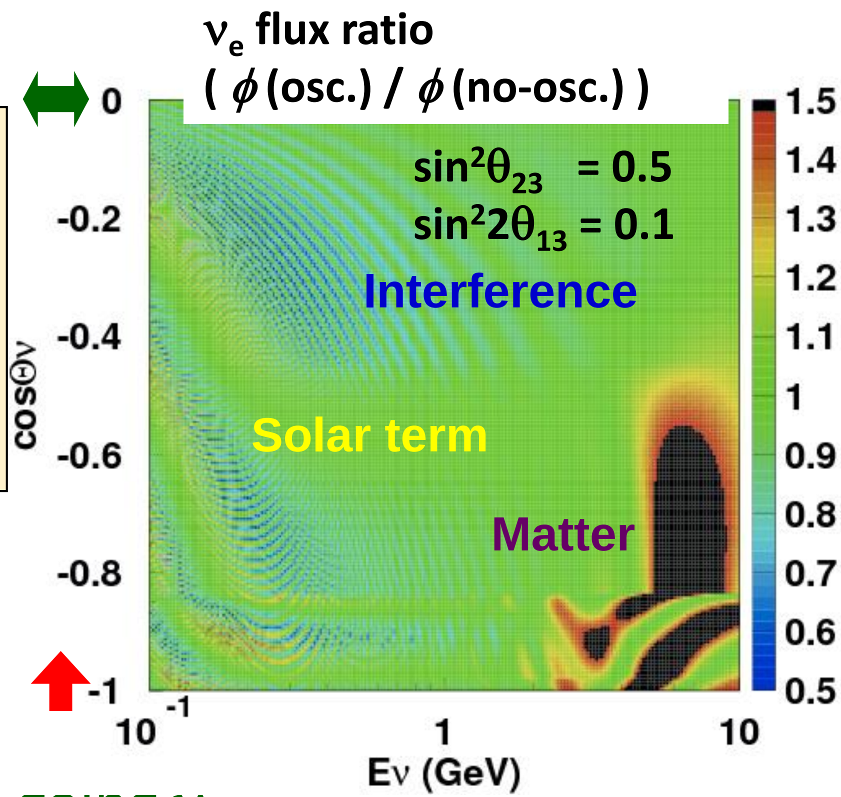
High statistics atmospheric neutrino data

Study small distortion in ν

Difference in # of electron events:

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

⬅ **Matter effect** ($\Delta_1(\theta_{13})$)
⬅ **Solar term** ($\Delta_2(\Delta m_{12}^2)$)
⬅ **Interference** ($\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$)



- Matter effect

  from mass hierarchy

  Possible enhancement

  in several GeV upward going ν_e .

- Solar term from θ_{23} octant degeneracy

  Possible ν_e enhancement in sub-GeV

- Interference term affected by CP phase

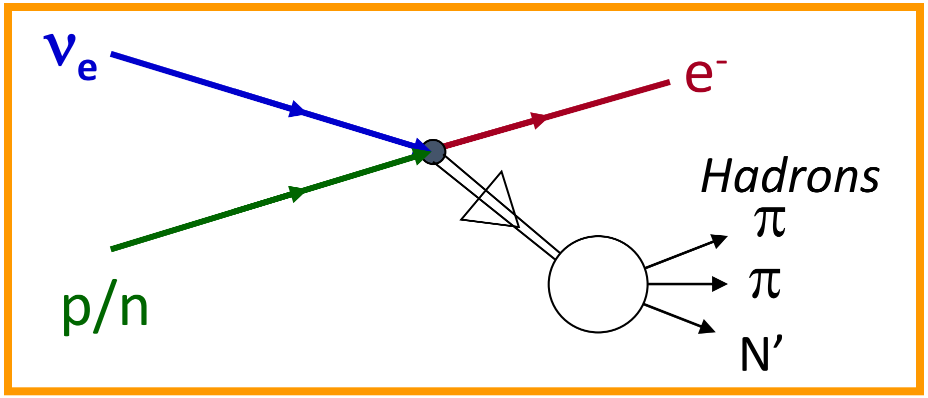
Neutrino experiments ~ examples ~

Atmospheric ν experiments ~ neutrino direction is unknown

Study ν_e / $\bar{\nu}_e$ difference 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	**58%**	**31%**

Neutrino experiments ~ examples ~

Atmospheric ν experiments ~ neutrino direction is unknown

ν_e / $\bar{\nu}_e$ difference in ***a few ~ 10 GeV*** region

Used to the matter effect and CP violation.

- Precise understanding of the interaction

  1) interaction probabilities (cross-sections)

  Fraction of CCQE-like, 1π productions, and multi-hadron productions

  2) $d\sigma/dq^2$ for each interactions

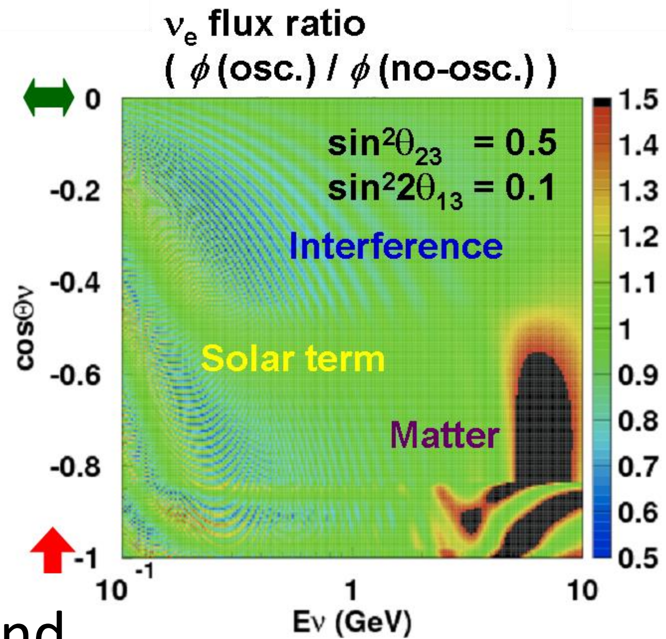
  3) hadron (esp. π) multiplicities

  for both neutrinos and anti-neutrinos ***with large angle acceptance***

- Interactions of π in Oxygen & detector
- Interactions of ν_τ (Cross-section)

  ~ hadronic decays of τ

  another source of background

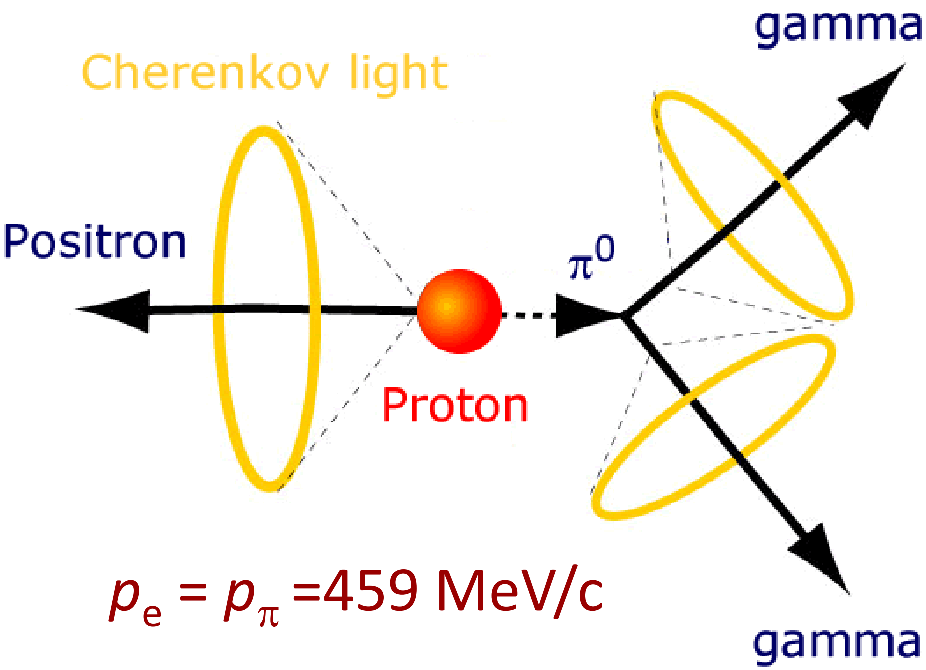


Proton decay experiments ~ examples ~

GUT models predicts proton decays ~ experimental confirmation

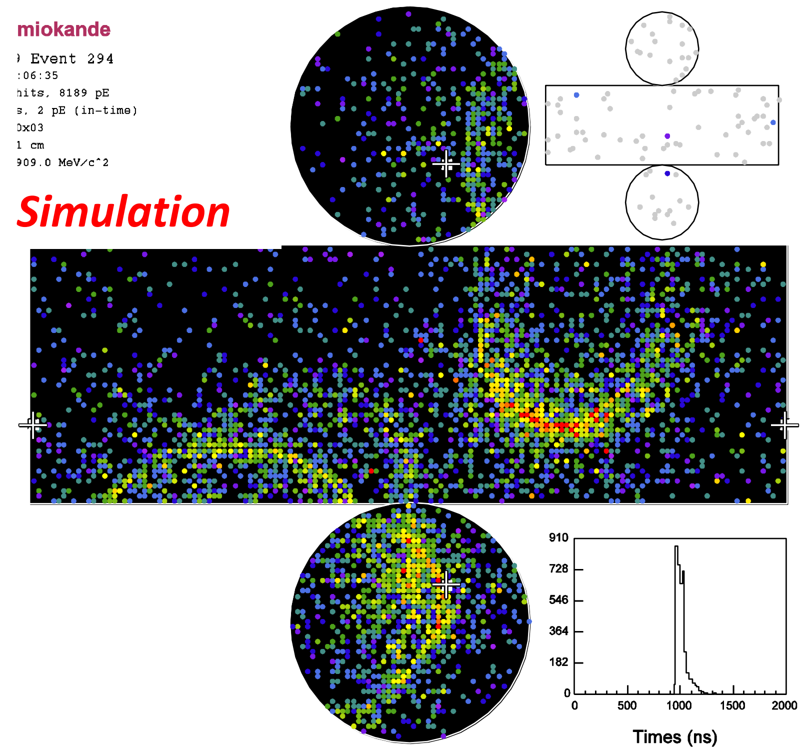
$p \to e^{+} + \pi^{0}$

Ring imaging water Cherenkov detectors
have very high efficiency in identifying both e^{+} and π^{0}



$p_e = p_\pi = 459$ MeV/c

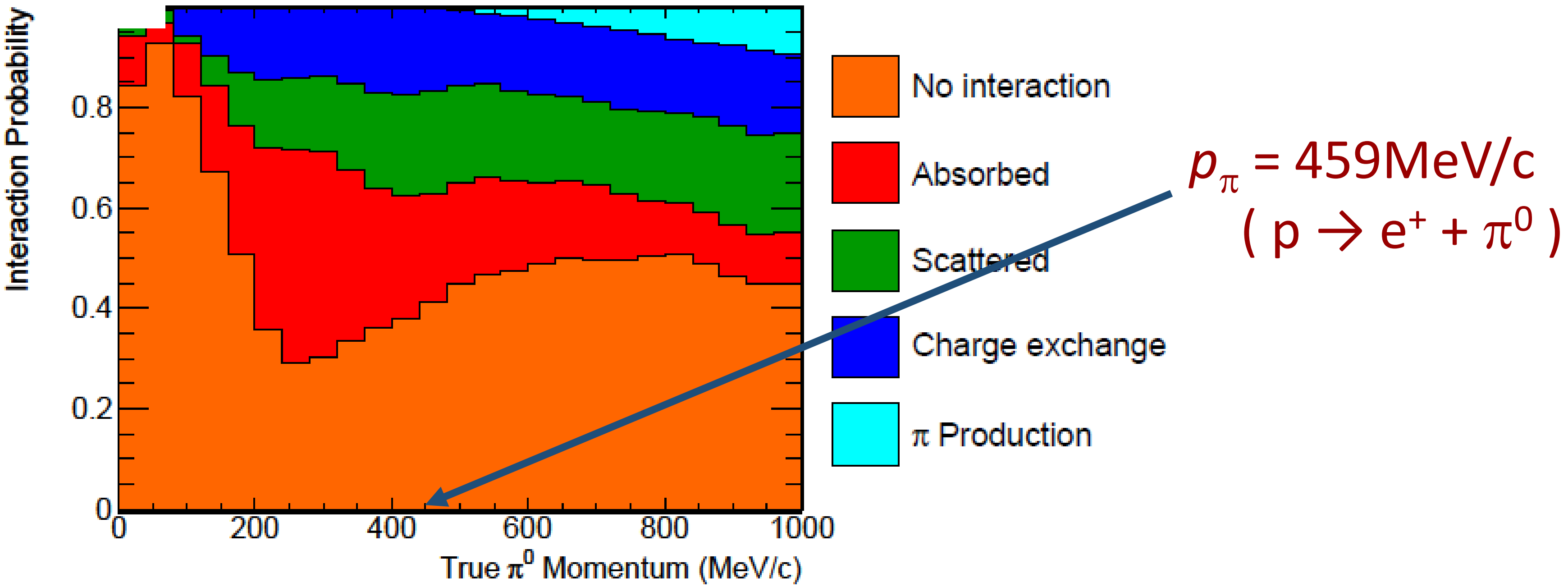
SK event display
$p \to e^{+} + \pi^{0}$ (simulation)



Clear 3 e-like rings
are expected to be observed.

Proton decay experiments ~ examples ~

Interaction probability of π^0 in ^{16}O (MC)



Interaction probability of π in ^{16}O is so high.

Only ~ 40 % of π^0 escape from Oxygen without interactions

Less than ~ 15 % of scattered π^0 (no charge exchange) can be identified as signal.

The uncertainty of π interactions

~ important in estimating efficiency of nucleon decay

Summary

Current and next generation high-statistics, high-precision neutrino and nucleon decay experiments require much precise understandings of neutrino-nucleus interactions and hadron interactions in nucleus.

Predictions of "exclusive channels" are necessary.

Not only the low energy region (CCQE dominant region) but Intermediate energy region (a few ~ 10 GeV) is also getting important.

Hadronic interactions in nucleus are also very important.

Various new experiments are studying neutrino interactions. Theoretical guidance ("what should be measured") will be also useful.