Implementations
pion production

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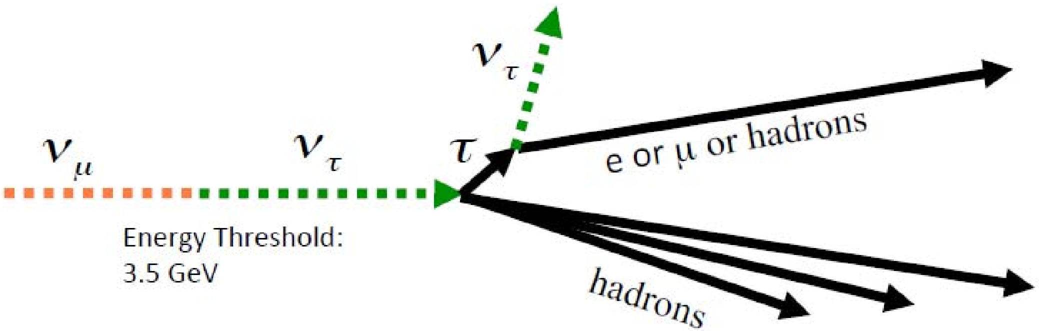
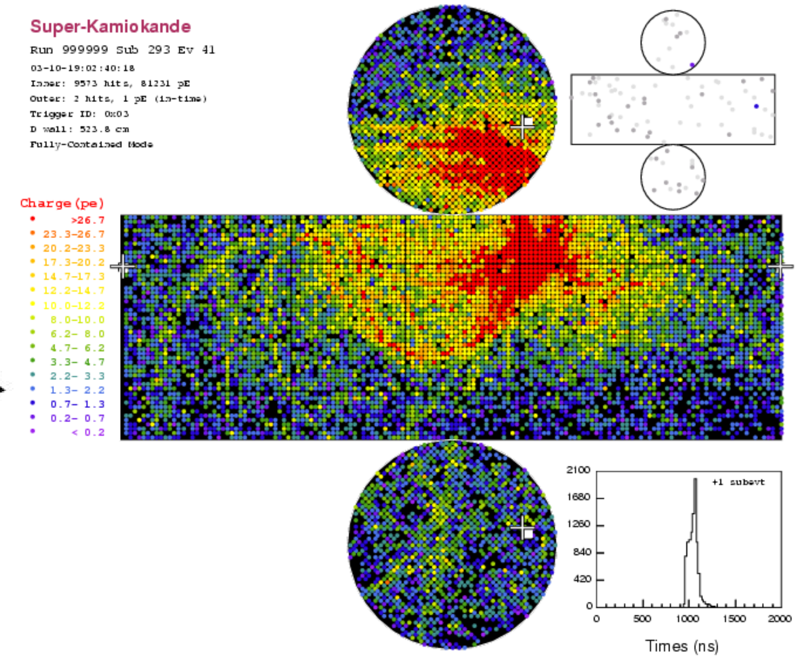
0. Example ~ Atmospheric neutrino oscillation analysis

ν_τ appearance search





DIS, Tau daughters:

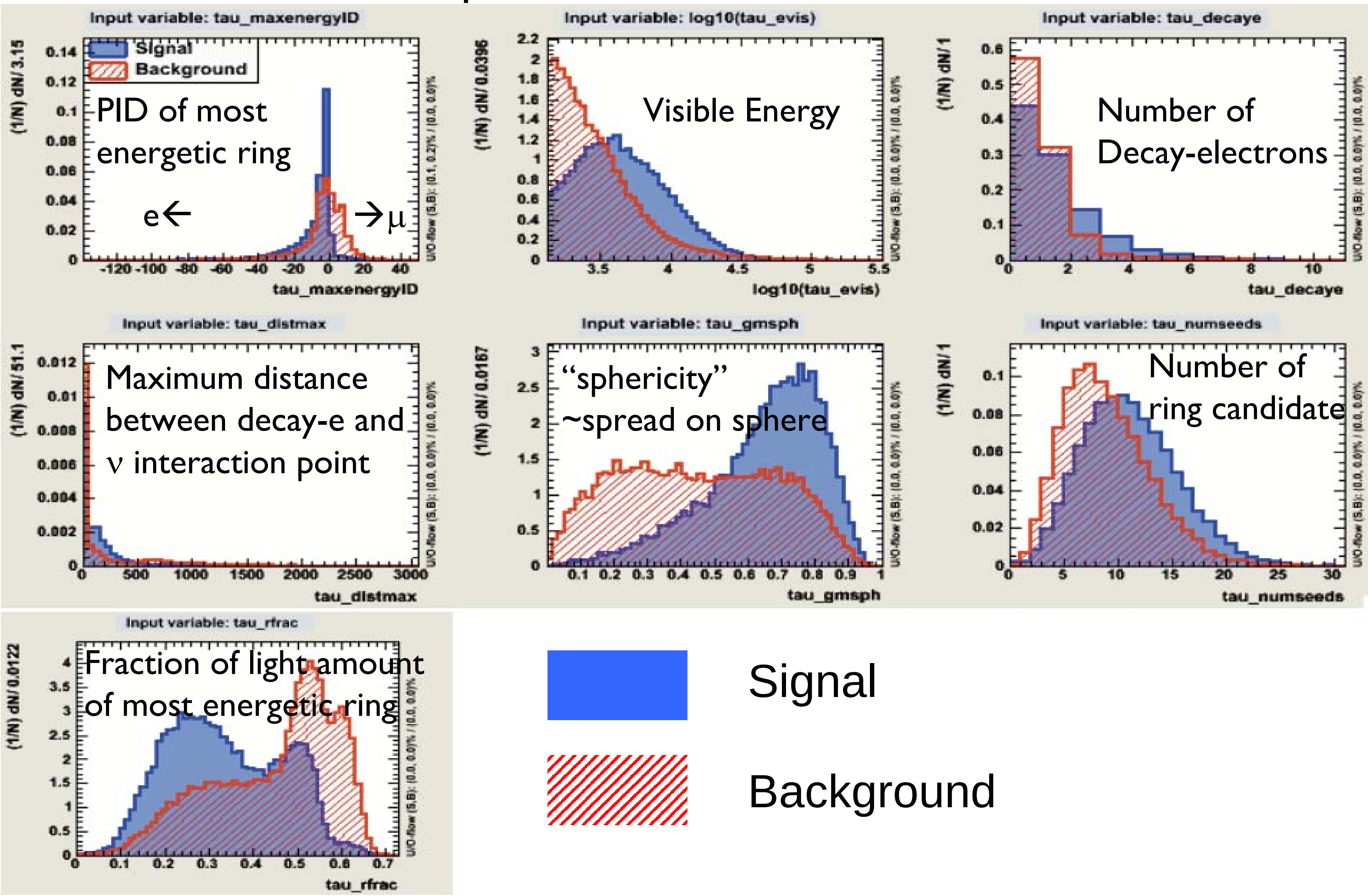
- Tend to be high energy event, multiple rings
- Decay electrons from π-μ-e decay
- Analyze with neural net

Appear by oscillation

1. Only in upward-going events
2. Downward-going events are used to evaluate backgrounds

0. Example ~ Atmospheric neutrino oscillation analysis

Inputs of the neural network



0. Example ~ Atmospheric neutrino oscillation analysis

Possible enhancement in several GeV (1 ~ 10 GeV)
induced by θ_{13}

Want to identify ν_e

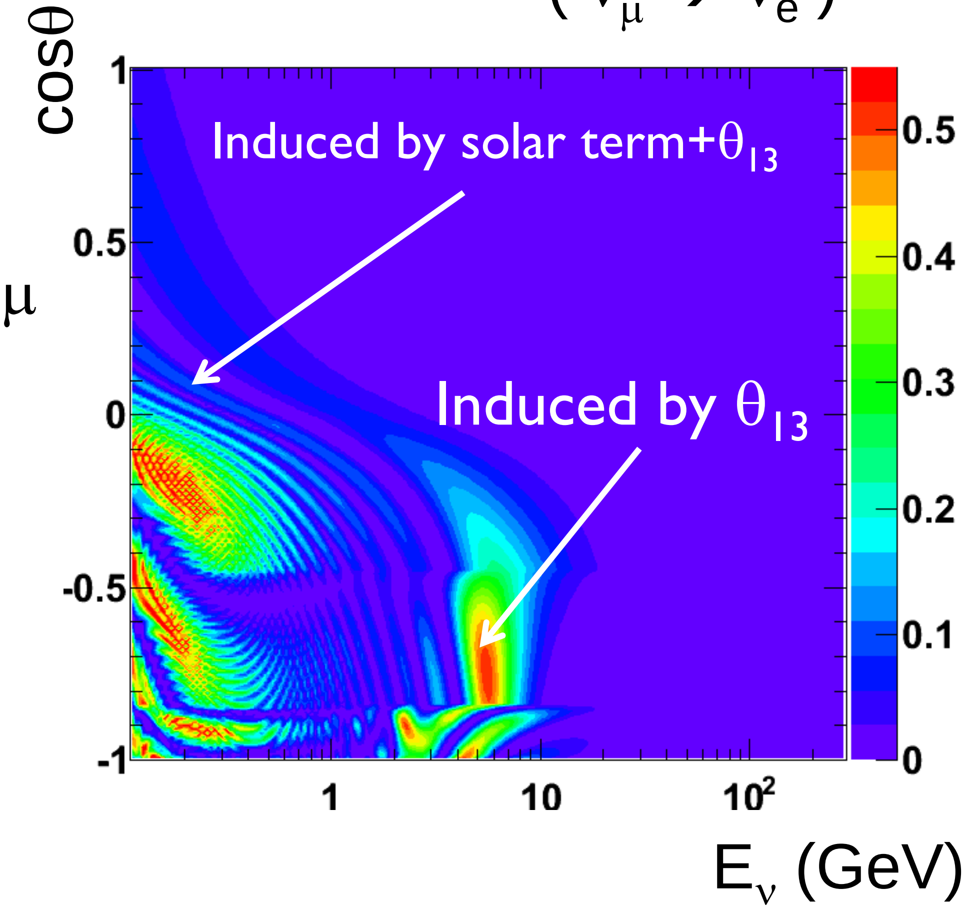
Background

- neutral current
- ν_μ CC with low momentum μ

Dominant interactions

- 1 pion production
- DIS

Oscillation probability ($\nu_\mu \rightarrow \nu_e$)



0. Example ~ Atmospheric neutrino oscillation analysis

Even e-like (electron, positron or γ)

a) ν_e CC

b) Neutral if all the rings are current (γ from π^0 s)

Possible difference between ν_e charged current and neutral current events

1) PID of most energetic ring

e-like for charged current ν_e

2) transverse momentum of particles

NC has larger (observed) transverse momentum

3) # of decay electrons (from μ, charged π etc.)

ν_μ CC events is expected to have larger # of decay e.

4) Distance between decay electron vertex and event vertex

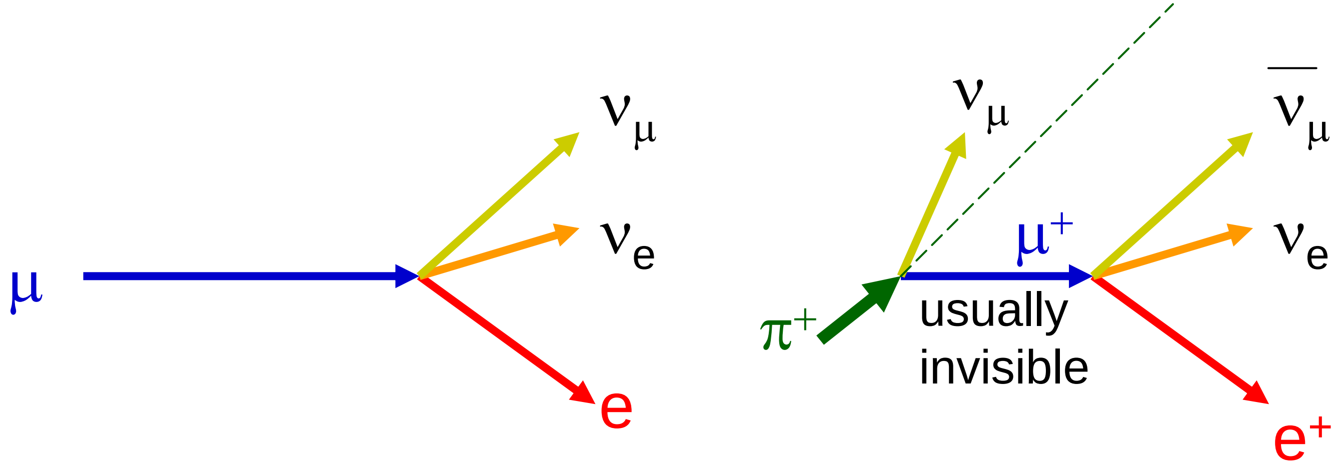
~ next page ~

0. Example ~ Atmospheric neutrino oscillation analysis

There might be μ-like ring from charged π

How to select (enhance) events from ν_e ?

Use location of decay electron.



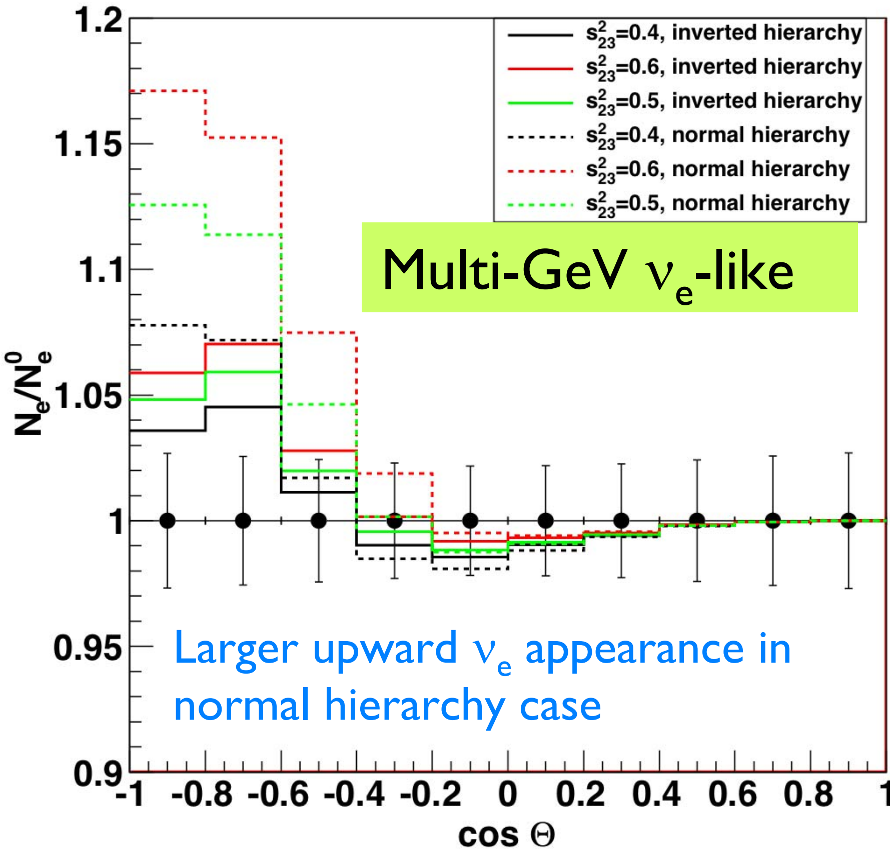
Use distance from the primary vertex

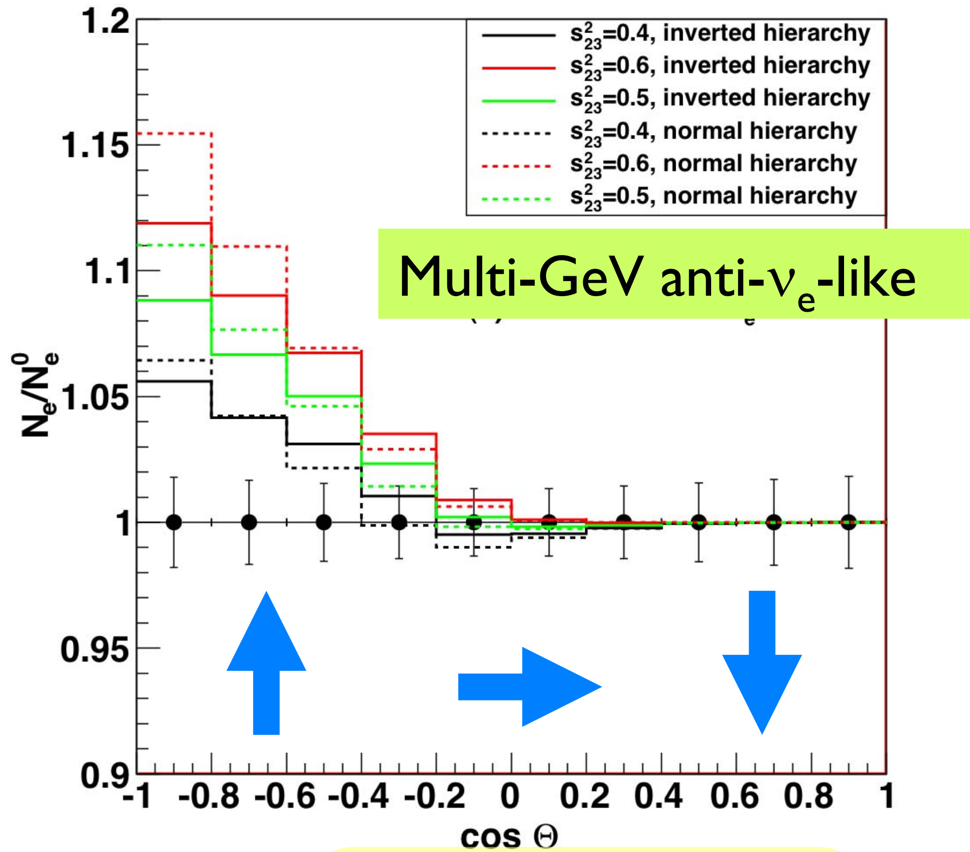
to the vertex of decay electron

Usually, momentum of π is smaller

0. Example ~ Atmospheric neutrino oscillation analysis

~ Mass hierarchy ~ (next generation exp.)





$\sin^2\theta_{23} = 0.4$ ——— Inverted hierarchy

$\sin^2\theta_{23} = 0.5$ - - - - - Normal hierarchy

$\sin^2\theta_{23} = 0.6$

$\Delta m^2_{12} = 7.6 \times 10^{-5}$ eV^2

$\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2

$\sin^2\theta_{12}=0.31$

$\sin^2\theta_{13}=0.025$

$\delta_{CP}=40°$

Error bars are for 10 HK year exposure

~250 SK year exposure

0. Example ~ Atmospheric neutrino oscillation analysis

Study of CP violation and matter effects.
Study of CPT violation

→ Need neutrino and anti-neutrino enhanced sample

- Use y distribution difference
  between neutrino and anti-neutrino

$$\frac{d^2\sigma^\nu}{dxdy} = \frac{G_F^2 m_N E_\nu}{\pi}\left[(1-y+\frac{1}{2}y^2+C_1)F_2(x) \pm y(1-\frac{1}{2}y+C_2)[xF_3(x)]\right]$$

$y = (E_\nu – E_{lep}) / E_\nu$

→ Differences in
Transverse momentum
Total energy to hadrons

- Use difference in # of decay electrons
  π^+ produce decay electron. Not for π^-.

0. Example ~ Atmospheric neutrino oscillation analysis

Need to understand the interactions
and to estimate uncertainties

Interaction cross-section and differential cross-sections
1) single pi
2) Deep inelastic scattering (low energy)

Hadron multiplicity

Difference between neutrino and anti-neutrinos
From low energy interactions
to high energy interactions.

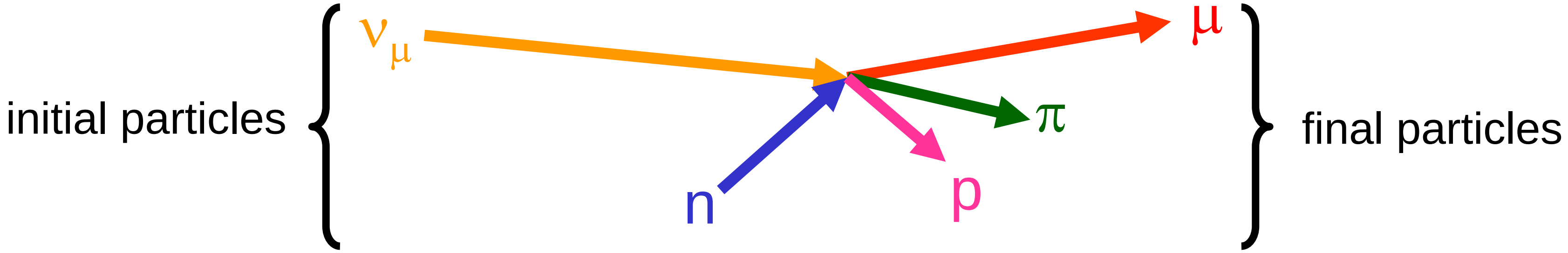
1. Introduction ~ simulation procedure ~

- **Simulate primary interaction**

  Fix interaction position of neutrino
  Fix the number of particles in the finals state
  Fix the types and 4-momenta (direction) of each particle.

Example) single π production

Input : Neutrino energy and direction



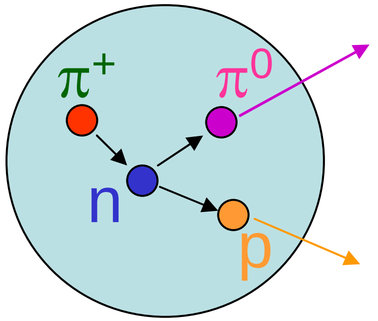
- Leptons are generated at the interaction point
- Starting point of hadrons are
  slightly moved from the original interaction point.

Formation zone model

$$L = p / \mu^2$$

p : Momentum of hadron
μ^2: fitted constant = 0.08 $\pm$ 0.04 GeV^2 Ammosov et al.

1. Introduction ~ simulation procedure ~



- **Simulate secondary interaction in nucleus**

Simulate the interaction in the target nucleus and fix the properties of each particle outside of the target nucleus.

Generated hadrons in nucleus are traced until the particles exit from the nucleus using cascade model.

Interaction probability (mean free paths)

- Low momentum π (p_π < 500MeV/c)

Density and momentum dependent

Model by Oset et al.

** scaled to fit experimental data

- High momentum of π (p_π > 500MeV/c) and other hadrons (K, p, n)

momentum dependent mean free paths are extracted from (old) experimental data

2. Primary interaction in Neut ~ single pion ~

Primary neutrino interactions

1) Single pion production $\nu + N \rightarrow l + N' + \pi$

Used modeled : Rein and Sehgal.

Original paper ~ lepton mass was ignored
Annals Phys. 133 (1981) 79-153
Update ~ consider lepton mass
Phys.Rev. D76 (2007) 113004

- Split into two steps

$$\nu + N \rightarrow l + N^*$$

$$N^* \rightarrow N' + \pi$$

- Consider resonances with $W < 2\mathrm{GeV}/c^2$

$W \equiv$ Mass of the intermediate resonance (N^*)

3. Primary interaction in Neut ~ DIS ~

Primary neutrino interactions

2) Deep inelastic scattering

$\nu + N \rightarrow l + N' + \text{mesons}$

$$\frac{d^2\sigma^\nu}{dxdy} = \frac{G_F^2 m_N E_\nu}{\pi}\left[(1 - y + \frac{1}{2}y^2 + C_1)F_2(x) + y(1 - \frac{1}{2}y + C_2)[xF_3(x)]\right]$$

$$C_1 = \frac{m_\ell^2(y-2)}{4m_N E_\nu x} - \frac{m_N xy}{2E_\nu} - \frac{m_\ell^2}{4E_\nu^2},$$

$$C_2 = -\frac{m_\ell^2}{4m_N E_\nu x},$$

**** To calculate cross-sections for neutral current simply multiply factors to CC cross-section obtained from old experiments.**

- Used PDF : GRV98
  with correction by Bodek and Yang
- Special treatment applied for the overlap region
  (W < 2GeV/c^2) ~ next page

3. Primary interaction in Neut ~ DIS ~

Corrections suggested by Bodek and Yang (For GRV98)

1. Modified scaling variable

$$\xi_w = x \frac{Q^2 + B}{0.5Q^2(1 + [1 + (2Mx)^2/Q^2]^{1/2}) + Ax}$$

2. Correction factor for the PDF (K-factor) to describe low q^2

$$K_{valence} = \frac{[1 - G_D^2(Q^2)][Q^2 + C_{2v}]}{Q^2 + C_{1v}}$$

$$1 - G_D^2(Q^2) = \frac{Q^2}{Q^2 + C}$$

$$K_{sea} = \frac{Q^2}{Q^2 + C_{sea}}$$

A = 0.419

B = 0.223

C_{1v} = 0.544

C_{2v} = 0.431

C_{sea} = 0.380

3. Correction to Callan-Gross relation

$$2xF_1 = F_2 \frac{1 + 4Mx^2/Q^2}{1 + R}$$

R: Fitted function

4. d/u ratio

$$u_v \rightarrow u'_v(d_v, u_v) \quad d_v \rightarrow d'_v(d_v, u_v)$$

3. Primary interaction in Neut ~ DIS ~

Avoid double counting : the resonance region to the DIS region

W < 2GeV : Restrict # of mesons to be larger than 1

Exclude 1 meson production

by using multiplicity function <n>(W)

Because non-resonant background is already included

in the single π production.

Multiplicity is determined based on the experimental result.

Current version: S. J. Barish et al. Phys. Rev D.17,1 (1978)

(There are recent reports from CHORUS collaboration.

Eur.Phys.J.C51:775-785,2007)

$$\langle n_\pi \rangle = 0.09 + 1.83 \ln(W^2)$$

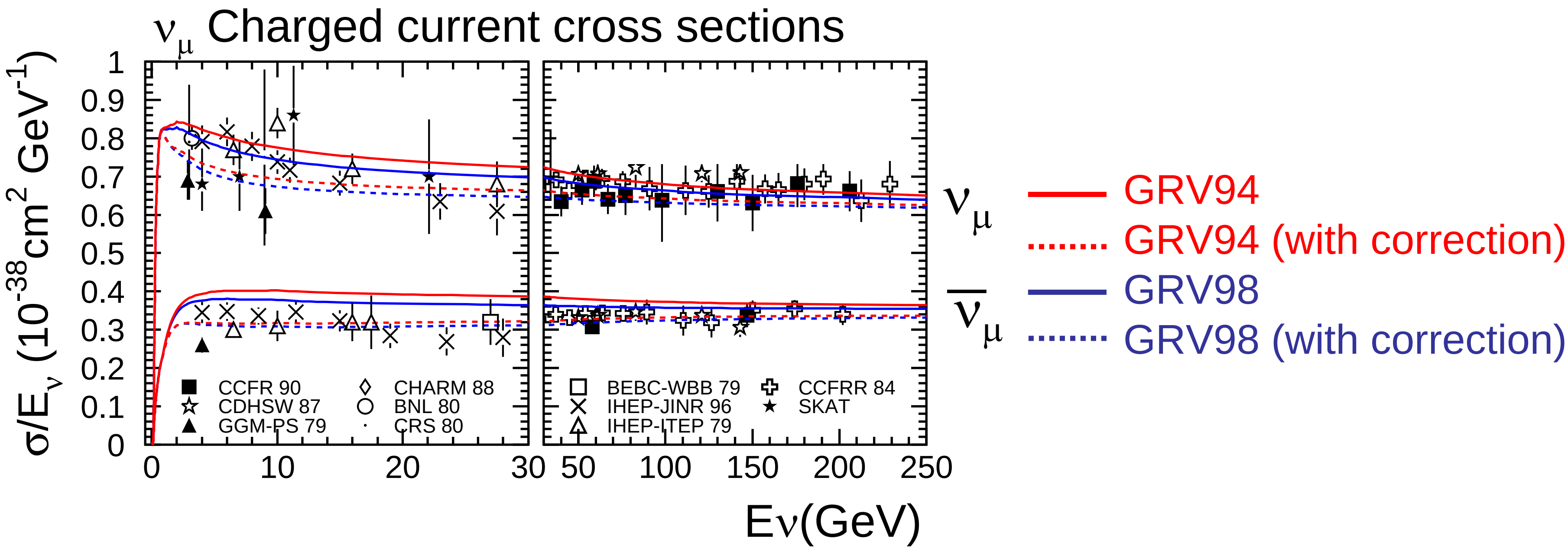
W > 2GeV : Use PYTHIA to generate vectors.

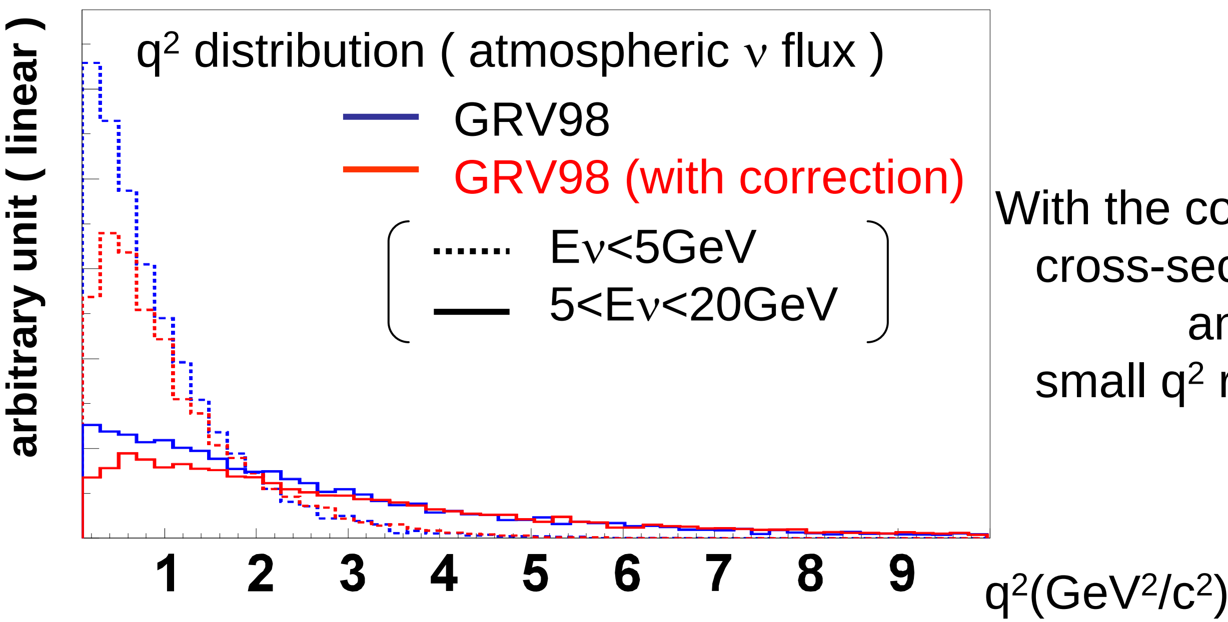
	W < 2GeV	W > 2GeV
# of π = 1	Rein & Sehgal	PDF + Custom kinematics (Bodek & Yang Corr.)
# of π > 1	Use PDF + PYTHIA (Bodek & Yang Corr.)	Use PDF + PYTHIA (Bodek & Yang Corr.)

As for the parton distribution function,

we use the correction suggested by Bodek and Yang.

3. Primary interaction in Neut ~ DIS ~





With the correction,
cross-section is suppressed
and
small q^2 region is also suppressed.

4. Nuclear effects ~ Final state interaction in Neut

re-scattering of pion, kaon, eta, omega and nucleon in nucleus

Different models are used in each simulation program.

Implementation in NEUT

Cascade model is used.

Each particle is tracked in the nucleus until it escapes from the nucleus.

For low momentum pion (< 500MeV/c , so-called Δ region)

Mean free paths of absorption and inelastic-scattering are calculated based on a model by L.Salcedo et al. .

(Nucl. Phys. A484(1998) 79)

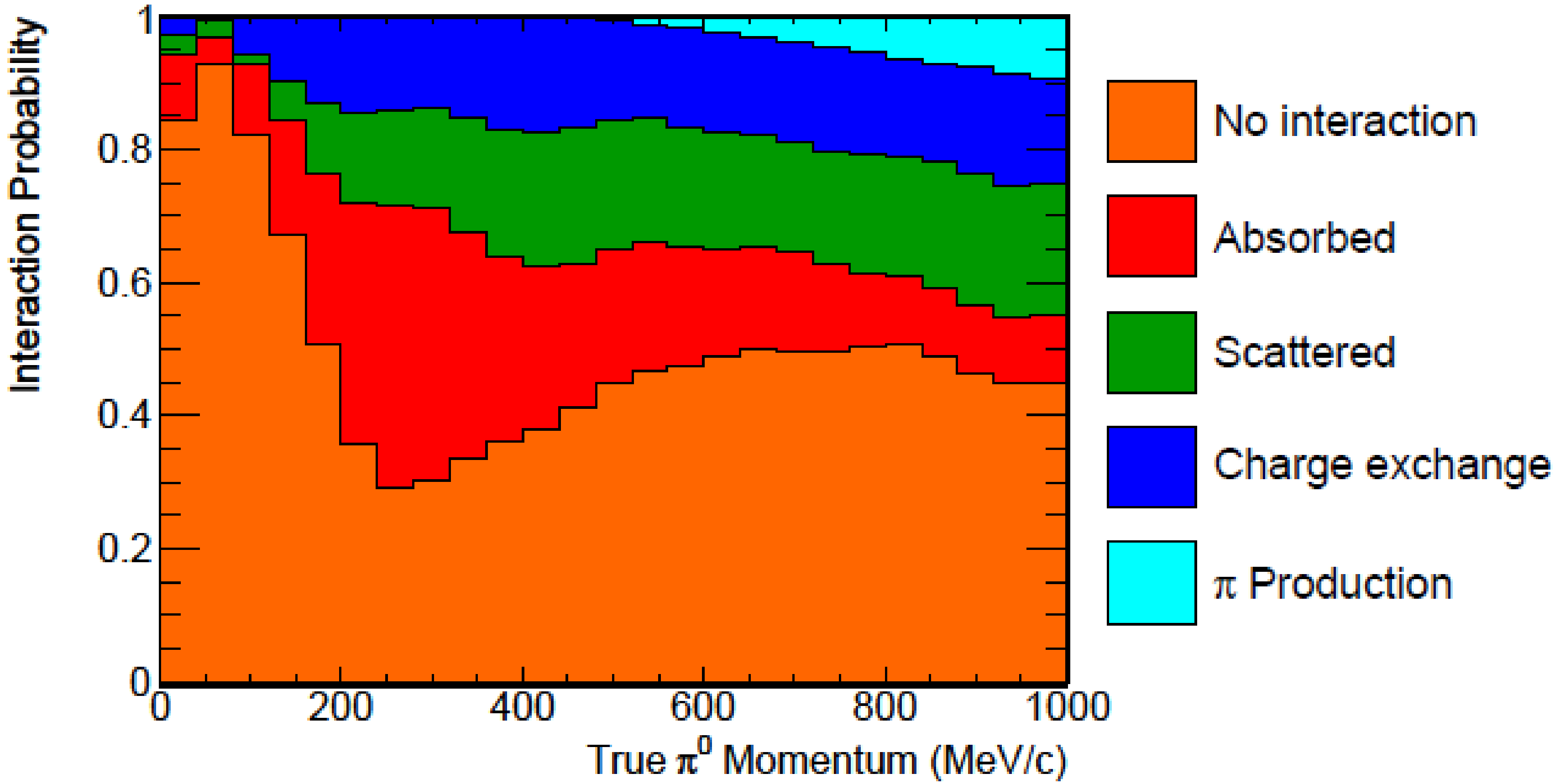
* These mean free paths are position and momentum dependent.
* The Fermi surface momentum also has radius dependence.

For the higher momentum pion (> 500MeV/c), kaons, eta, omega and nucleons

Parameters are taken from various experiments.

4. Nuclear effects ~ Final state interaction in Neut

Interaction probability of π^0 generated in Oxygen



4. Nuclear effects ~ Final state interaction in Neut

Kinematics of the scattered particles

Use the results of phase shift analysis of π-N scattering

Also, the medium correction is applied to each phase shift.
(R.Seki et al., Phys. Rev. C27 (1983) 2817)

$$f=\sum_T C_T \sum_l \{[lf^l_{2T,2l-1}+(l+1)f^l_{2T,2l+1}] \times P_l(\cos\theta)-i\boldsymbol{\sigma}\cdot\boldsymbol{n}[f^l_{2T,2l-1}-f^l_{2T,2l+1}] \times P'_l(\cos\theta)\}.$$

Here, $f^l_{2T,2J}$ is an amplitude with orbital angular momentum l, isospin T, and total angular momentum J. C_T is the isospin factor written with Clebsch-Gordan coefficients,

$$C_T=\left(1t_{\pi'}\frac{1}{2}t_{N'}\,|\,Tt_\pi+t_N\right)\left(1t_\pi\frac{1}{2}t_N\,|\,Tt_\pi+t_N\right),$$

(t_N, t_π, $t_{N'}$, $t_{\pi'}$ are initial and final Z component of π, N isospin.)
$\boldsymbol{\sigma}$ is the Pauli matrix and $\boldsymbol{n}=(\boldsymbol{k}\times\boldsymbol{k}')/(|\boldsymbol{k}\times\boldsymbol{k}'|)$, with $\boldsymbol{k}$, $\boldsymbol{k}'$ being pion initial and final momenta. We consider 8 resonances, S_{11}, S_{31}, P_{11}, P_{13}, P_{31}, P_{33}, D_{13}, D_{15} for this amplitude. The resonance parameters are taken from the phase shift analyses of $\pi-N$ scattering.[25] Pion interaction in oxygen is

$$f_{2T,2J}(^{16}\mathrm{O})=f_{2T,2J}\times\left\{1-\frac{2f^l_{2T,2J}}{\pi}\times C\times\int k^2\,dk\,Q_0(k,K)G_0(k,E)\right\}^{-1}.$$

$$C=1+(k^2+m_\pi^2)^{1/2}/(k^2+m_N^2)^{1/2},$$

$$Q_0(k,K)=\begin{cases}1 & \text{if } \xi K+k<P_F,\\ 0 & \text{if } |\xi K-k|>P_F,\\ [P_F^2-(\xi K-k)]/4\xi Kk & \text{otherwise,}\end{cases}$$

$$G_0^{-1}(k,E)=\left(E-\frac{k^2}{2M}\right)^2-k^2-m_\pi^2+i\varepsilon,$$

$$\xi=1\Big/\left(1+\frac{W}{m_N}\right),$$

4. Nuclear effects ~ Final state interaction in Neut

Nucleon re-scattering

Originally prepared by the members of IMB group. (W. Gajewski for K2K)

Nucleon re-scattering is also simulated by using the cascade model.

Elastic scattering, single π and two π productions are considered.

(Original ref. S.J.Lindenbaum and R.M.Sternheimer, Phys.Rev. 105 (1957),
Modifications in MECC7 and GCALOR have been taken into account.)

$N + N \rightarrow N + N$

$N + N \rightarrow N^{*} + N$

$N + N \rightarrow N^{*} + N^{*}$

$N^{*} \rightarrow N' + \pi$

Interaction probabilities (tables of each interaction mean free path)
and direction of nucleons or intermediate resonances
are taken from MECC7 and GCALOR.
(Basic parameters are taken from various experiments.)

Decay of the intermediate resonances
Isotropic in the resonance rest frame.

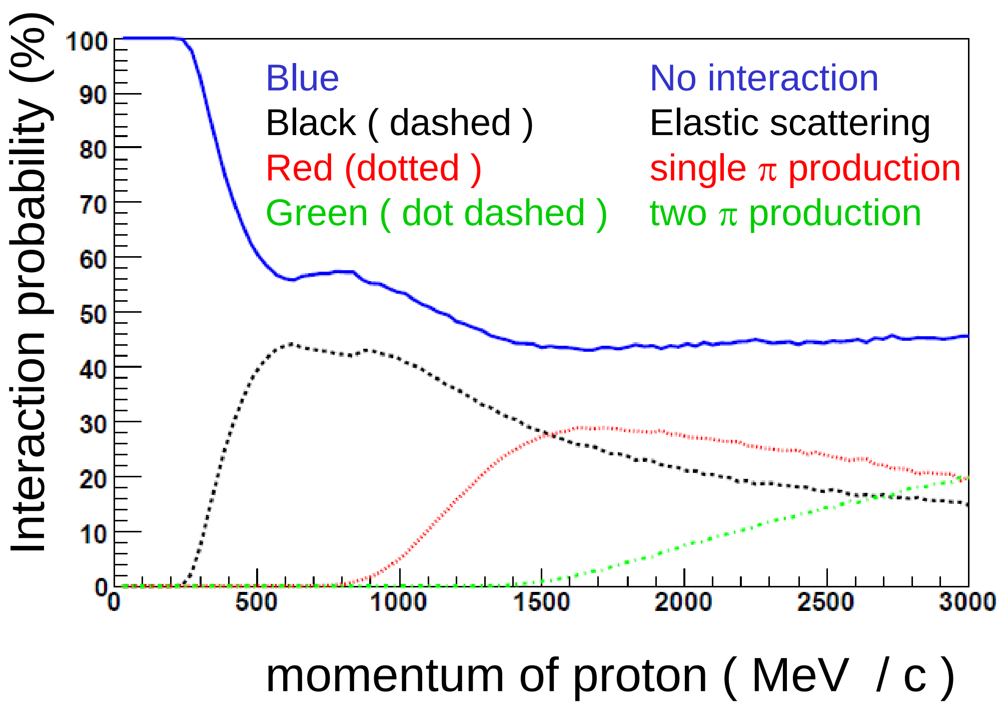
4. Nuclear effects ~ Final state interaction in Neut

Nucleon re-scattering

Some distributions (results of the simulation)

Target : ^{16}O

Momentum dependence of the interaction probabilities of proton



Scattering angle of the outgoing nucleon (most energetic one)

Incident momentum of proton 0.5 ~ 1.0 GeV / c (uniform)