ν_μ appearance measurement in a SK-like detector for a beta-beam

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2009 Mar. 23

EUROnu Annual meeting @ CERN, Geneva

introduction

- Pure ν_e or $\overline{\nu_e}$ beam could be produced at the Beta-beam facility.
- The golden signal is a ν_μ appearance channel.
- Because the beam contains only one type neutrino, it is not necessary to identify the charge. Therefore, a very massive Water Cherenkov detector could be a good candidate as the far detector.

- Here, we studied the efficiencies and the backgrounds of ν_μ appearance in a Water Cherenkov detector with the proposed beta beams, based on our experiences of the Super-Kamiokande (SK) analysis.

Beta-beam facility

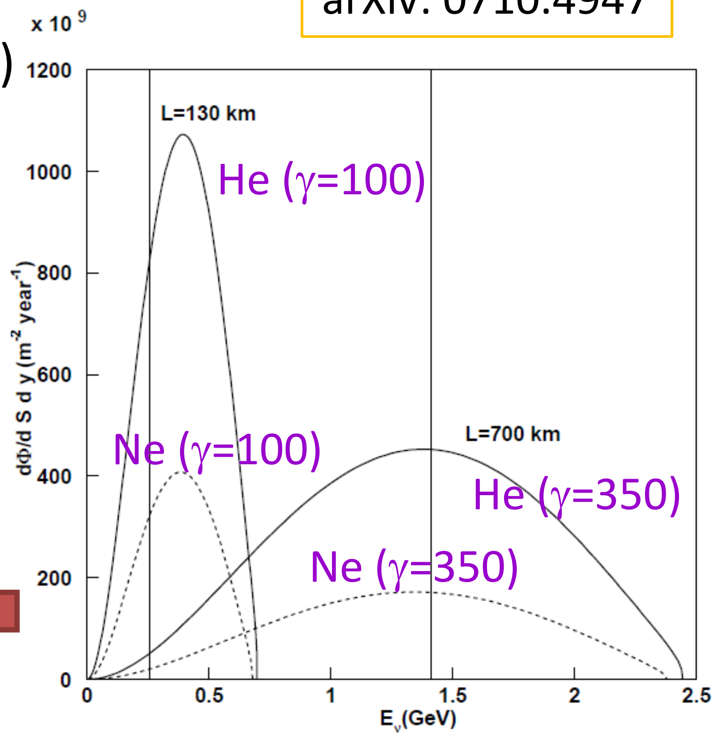
- Beta-beam facility is determined by following;
  - Type of ion (E_0)
  - Relativistic γ(=E/m) of ion
  - Baseline L
- L/Eν should be near the oscillation maximum
  - LE: γ=100, L=130km (ex. CERN→Frejus)
  - HE: γ=350, L=700km (ex. CERN→Gran-Sasso)
- Choice of isotope
  - CERN-SPS : γ(He) ≤ 150, γ(Ne) ≤ 250
  - Refurbished SPS: γ(He) ≤ 350, γ(Ne) ≤ 580

  → choose He and Ne

  1 year operation= 2.9 x 10^{18} decays (He)

  = 1.1 x 10^{18} decays (Ne)

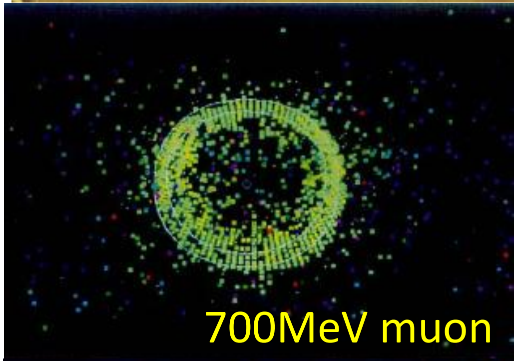
arXiv: 0710.4947

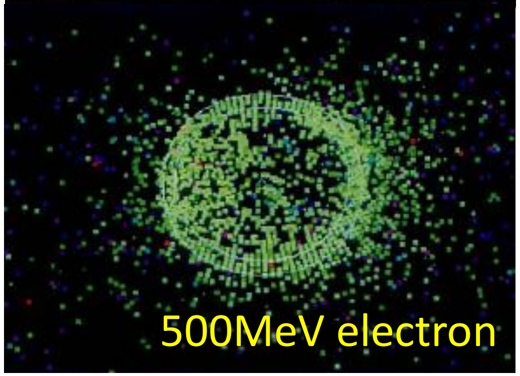


We assume these 4 beta-beam setups

Neutrino measurement in Super-Kamiokande

1. Detection of a Cherenkov ring of a lepton produced by the neutrino interaction
2. Identification of particle type (e or μ) by the ring pattern
3. Reconstruction of the lepton momentum with the observed charge



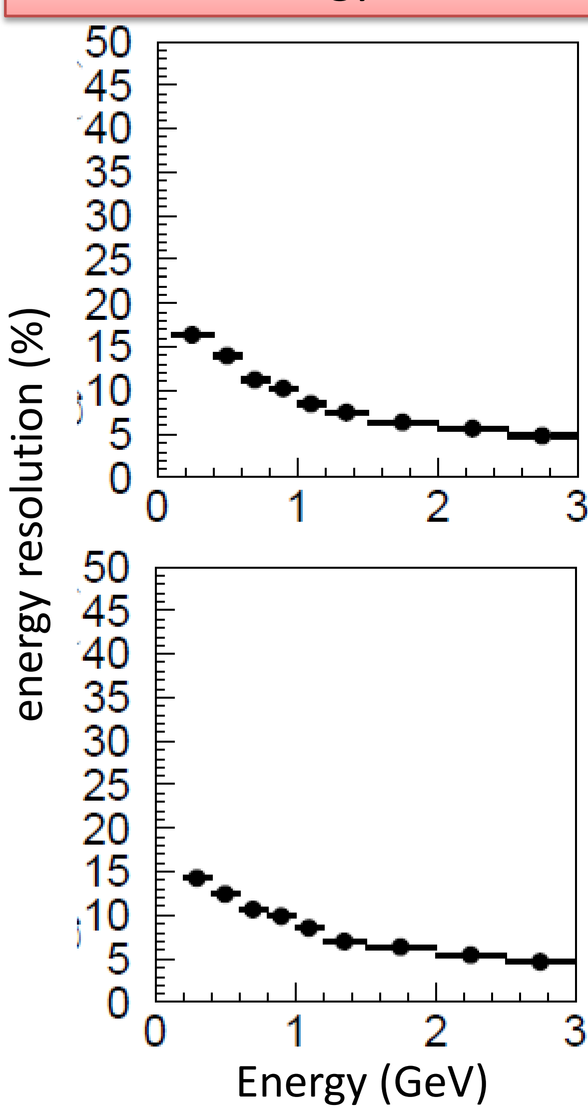


Momentum threshold

	Cherenkov radiation	Analysis threshold
electron	0.57 (MeV/c)	100 (MeV/c)
muon	118 (MeV/c)	200 (MeV/c)
proton	1 (GeV/c)	

Performance of the detector

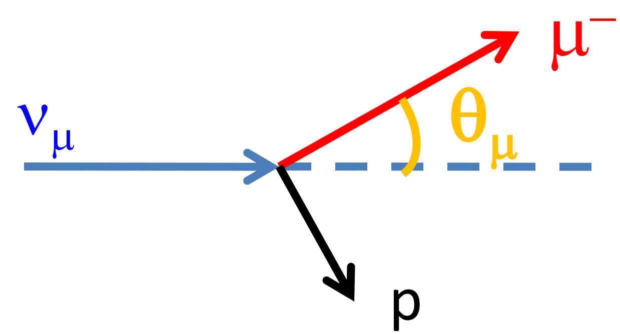
Neutrino energy resolution for CCQE



ν_e
(1-ring, e-like, CCQE)

ν_μ
(1-ring, μ-like, CCQE)

CCQE (ν_μ+n→μ^-+p)



$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta_\mu}$$

m_N: nucleon mass
E_μ : muon energy
m_μ: muon mass
P_μ : muon momentum

Overview of this study

This study aims to understand the detection efficiencies and the backgrounds of ν_μ appearance from beta-beam in the Water Cherenkov detector.

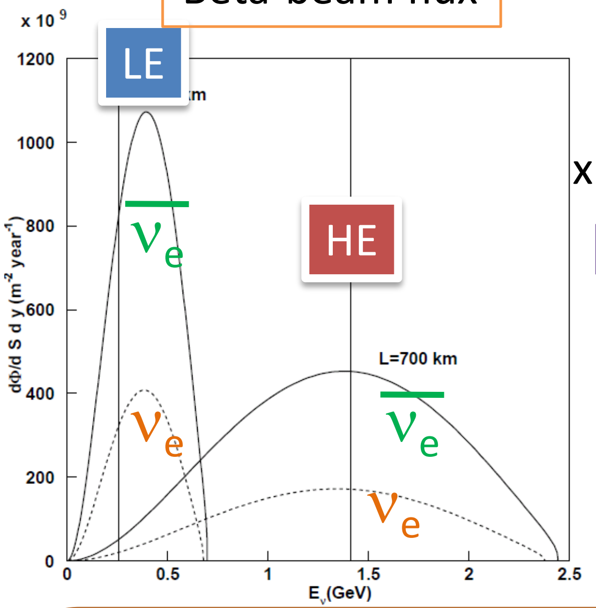
The study is based on the current SK Monte-Carlo simulation and the analysis tools.

contents

- Expected ν flux from beta-beam
- Event selection's performance
  - single-ring selection
  - Particle identification selection (PID)
  - Decay electrons selection
- About background

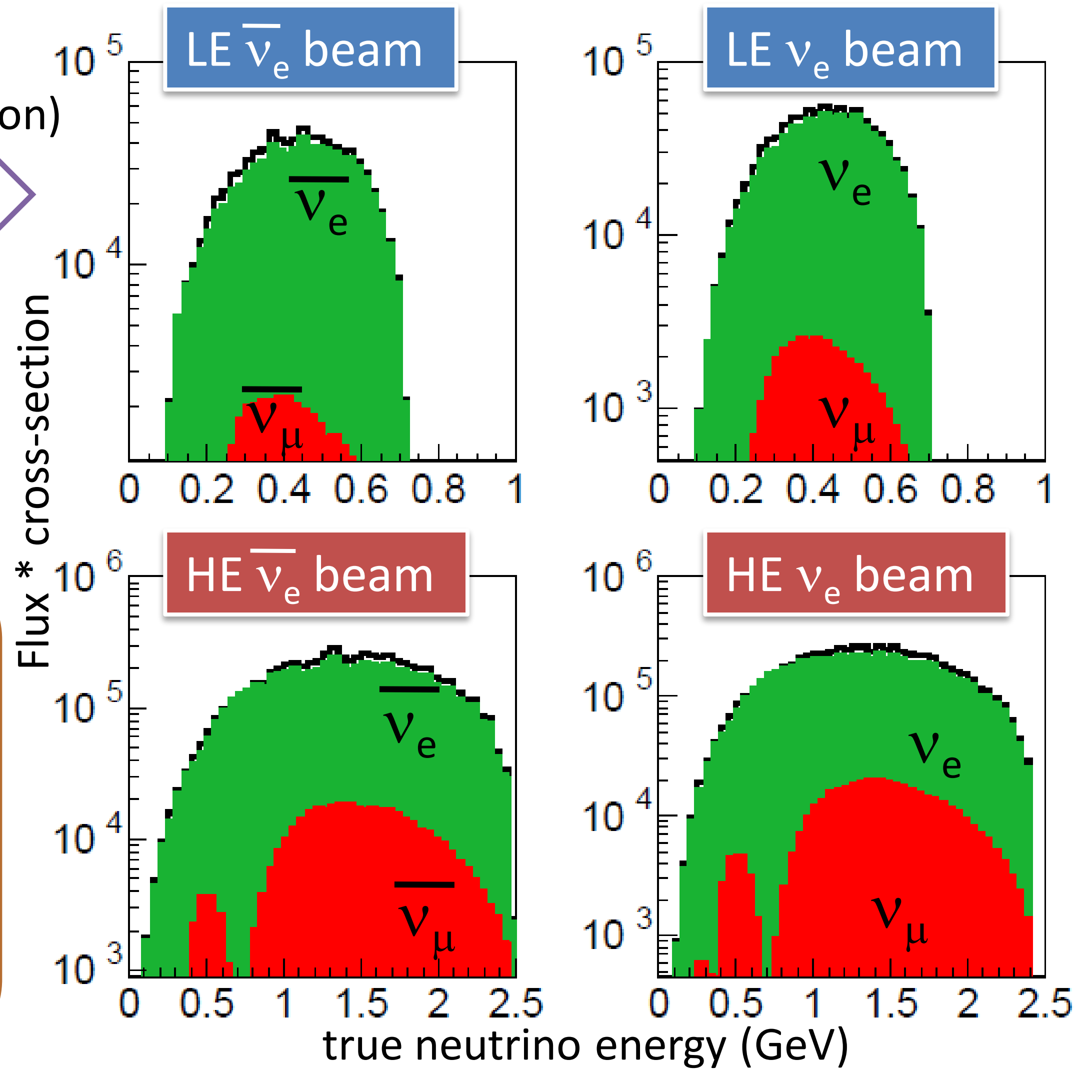
Expected neutrino energy spectra in WC 1Mton-year (flux*cross-section)

Beta-beam flux



x (cross section)

interacted neutrino spectra from beta-beam



Assuming oscillation probabilities :

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2 \Delta$$

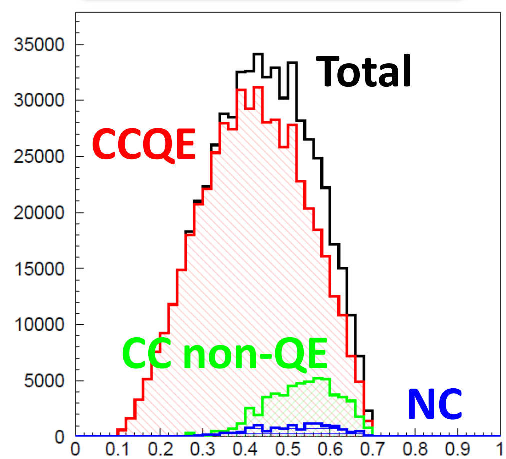
$$P(\nu_e \to \nu_\mu) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta$$

$\sin^2 2\theta_{13} = 0.15$, $\sin^2\theta_{23} = 0.5$
$\Delta = (1.27 * \Delta m^2 * L)/E\nu$
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2
($\theta_{12} = 0$, $\delta = 0$, no matter effect)

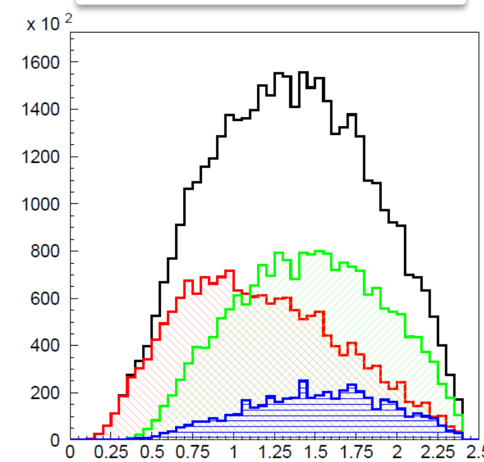
Event selection

- To reject cosmic-ray and low energy events, applying the standard selections (FVFC):
  - Fully-contained selection
  - vertex in the fiducial volume
  - visible energy > 30MeV

from LE ν_e beam



from HE ν_e beam

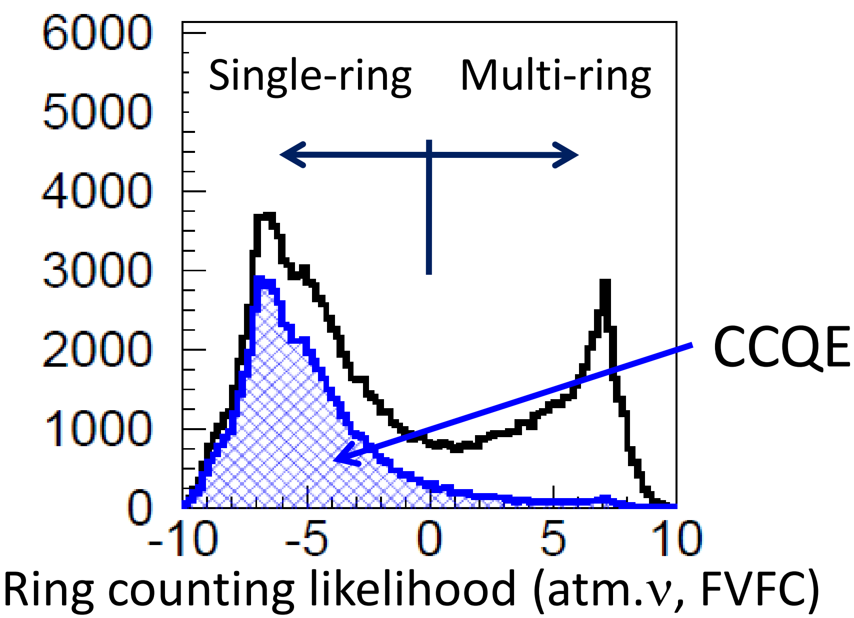


true neutrino energy (GeV) after FVFC selection

- the selection to find CCν_μ events:
  1. single-ring
  2. μ-like ring
  3. with 1 decay electron

Event selection 1: single-ring

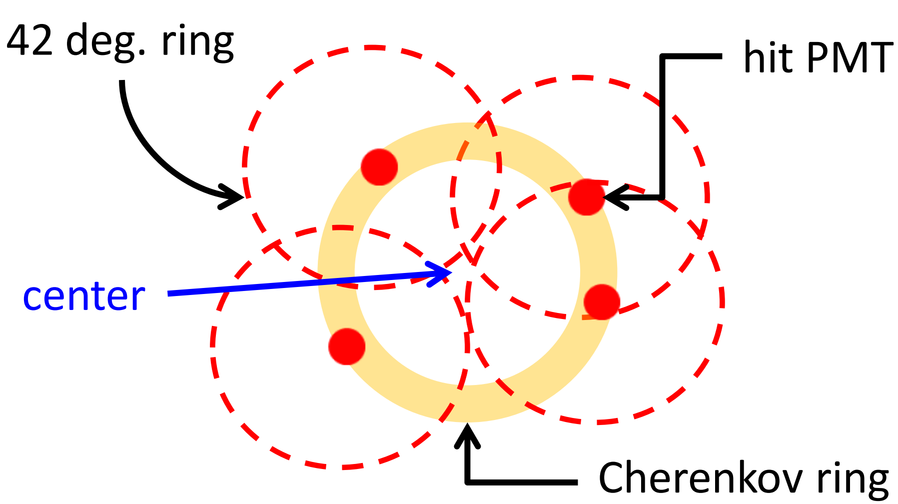
- "single-ring" selection is to select CCQE events.
- The efficiency for identifying CCQE events as single-ring is 94.2% for atm ν.



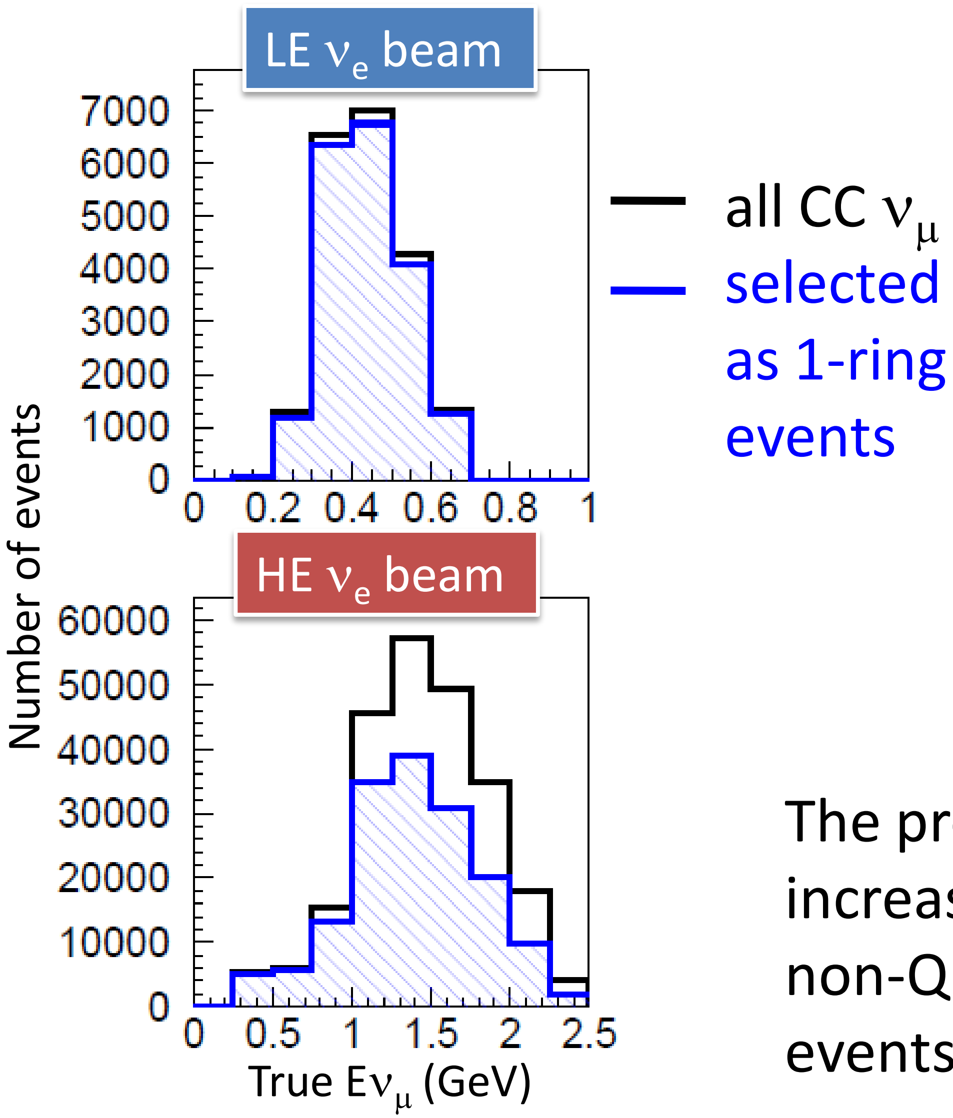
Ring counting technique

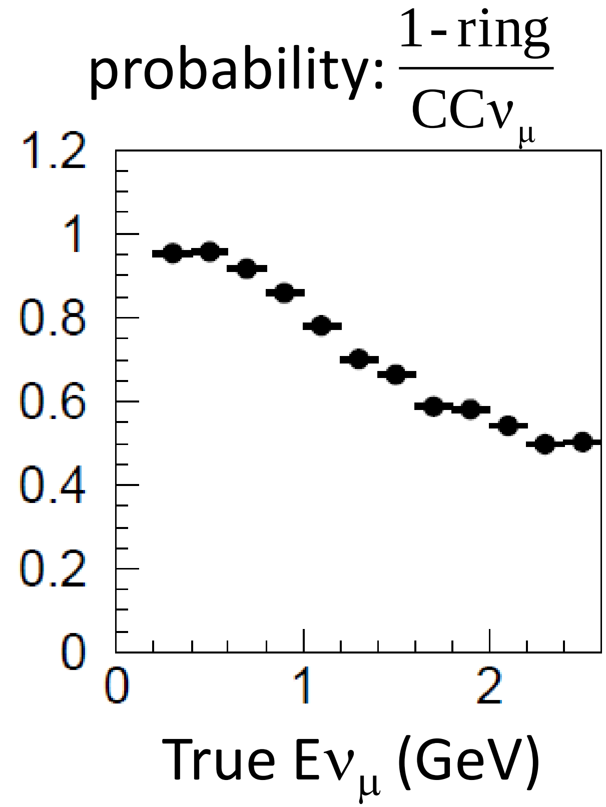
- Ring candidate search
  - Hough transformation method
- Ring candidate test
  - likelihood method

Hough transformation method



single-ring selection probability



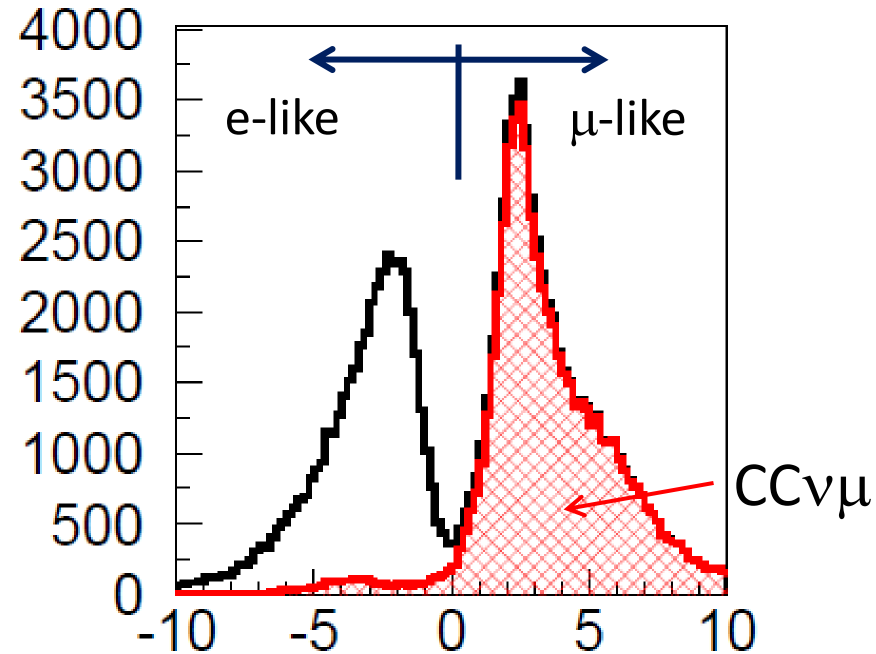


The probability goes down with increasing neutrino energy. Because CC non-QE neutrino interactions (multi-ring events) are getting larger over ~1GeV.

Event selection 2: μ-like ring

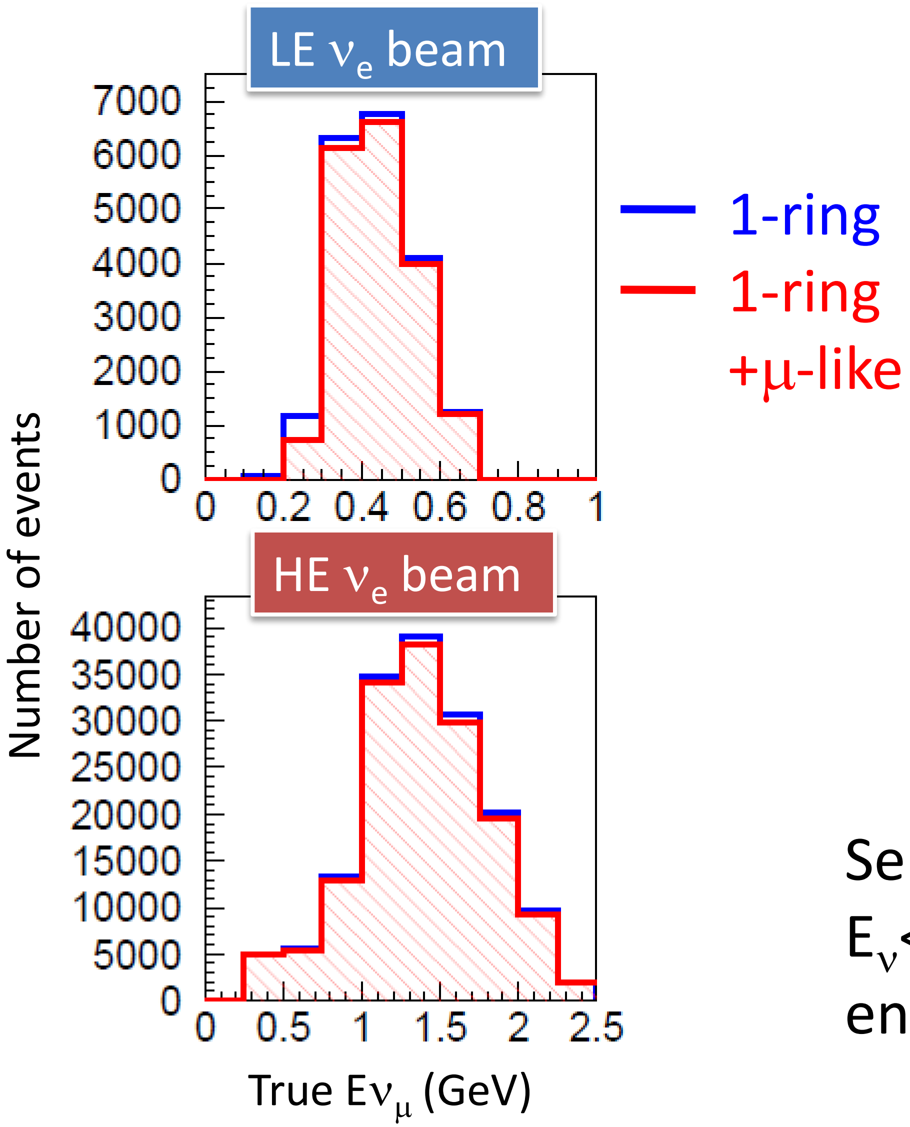
- Classification of the rings to two types by the likelihood method using the differences in the patterns and the opening angles

- The misidentification probabilities are ~1% for atmospheric ν_e and ν_μ CCQE events.

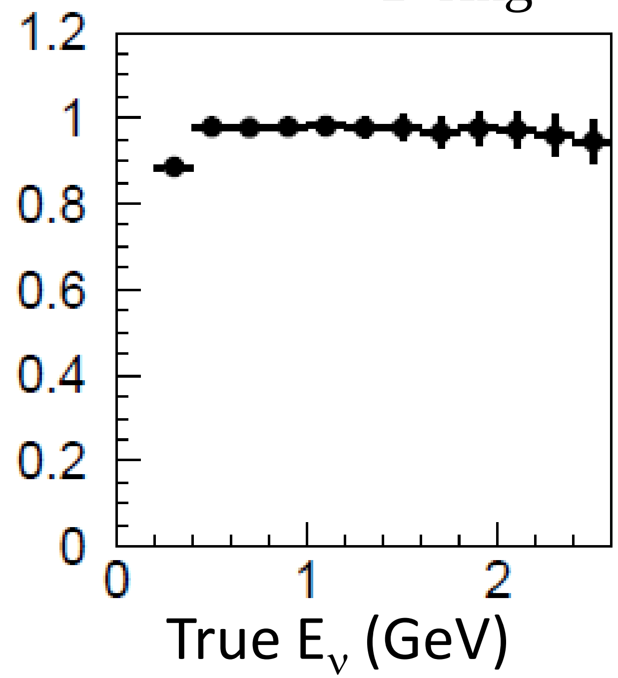


PID likelihood
(atm.ν, FVFC, 1-ring)

μ-like selection probability



probability : $\frac{\text{1-ring \& } \mu\text{-like}}{\text{1-ring}}$

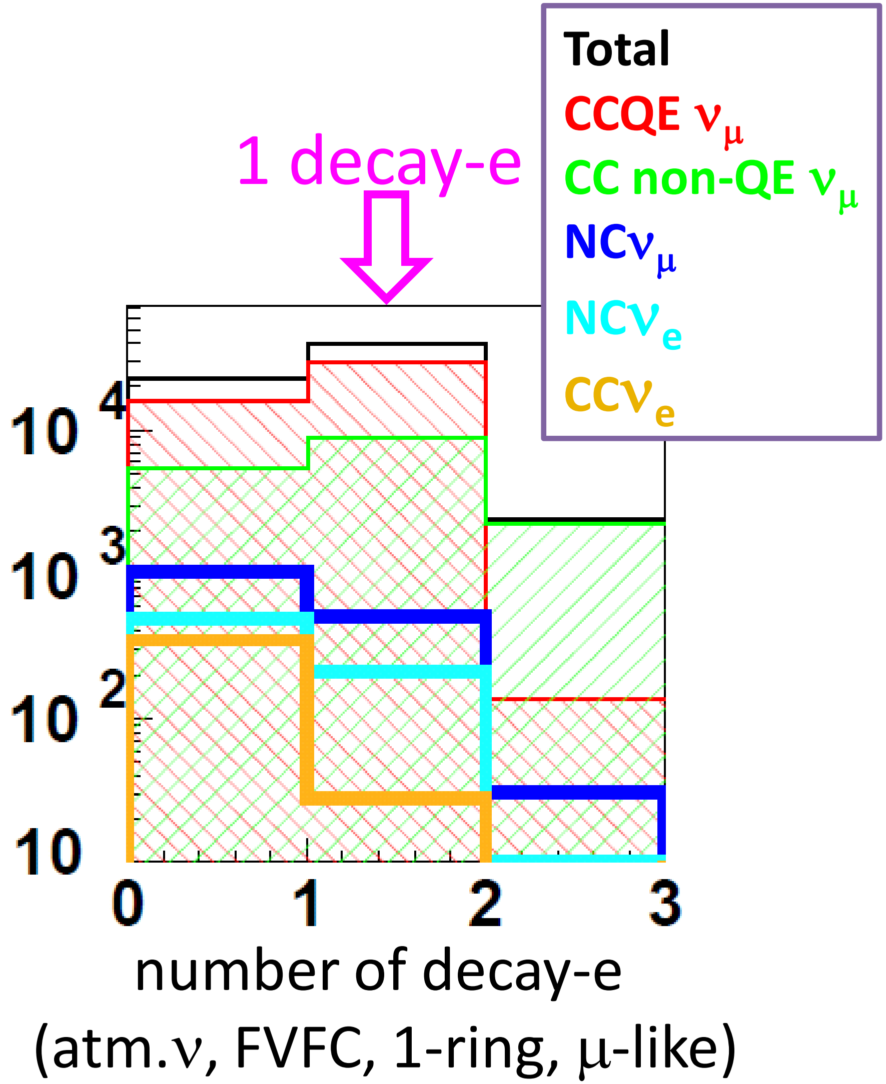


Selection probability is ~90% for E_ν<400MeV, ~95% for E_ν >400MeV energy region.

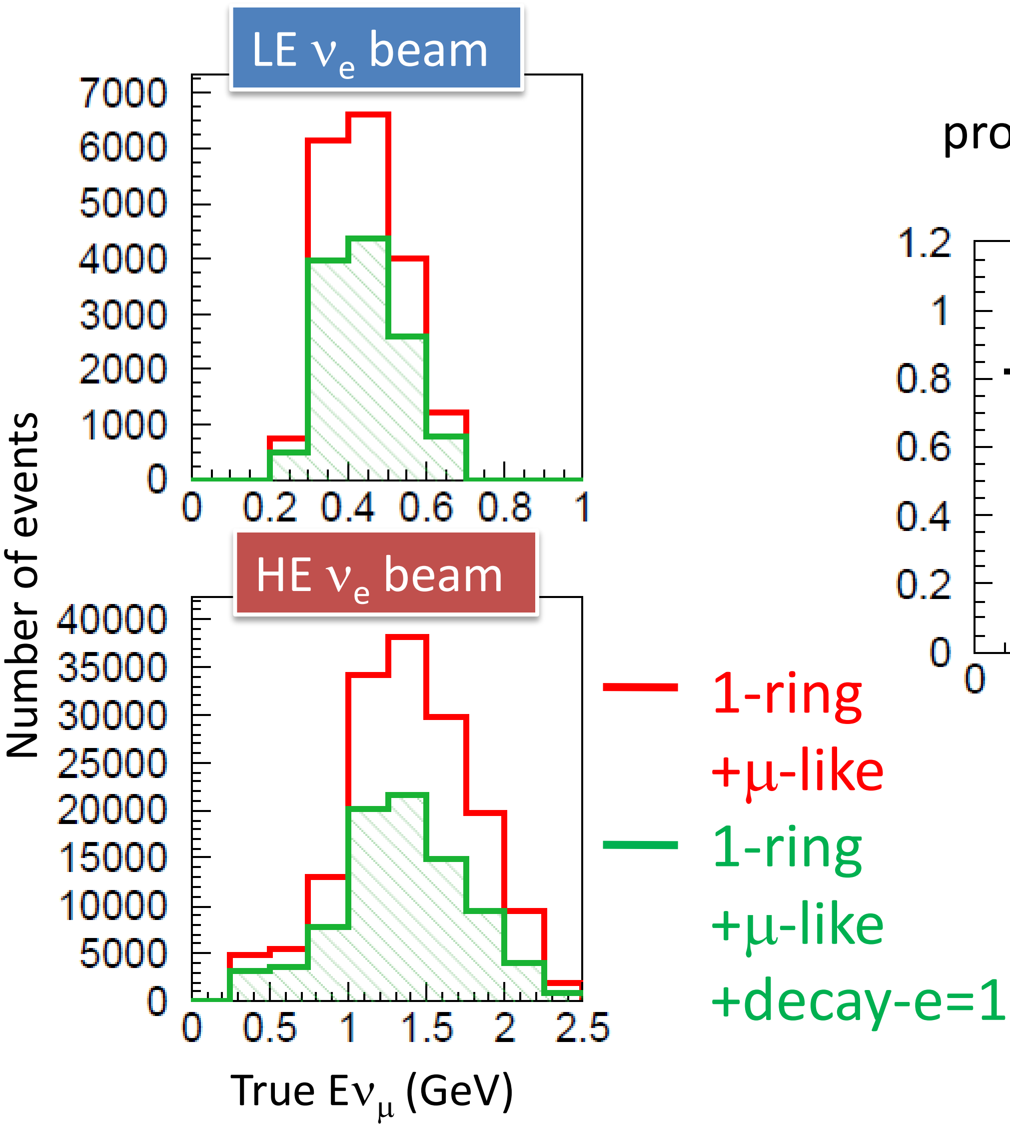
Event selection 3: with 1 decay electron

- Selection of with 1 decay-e is to increase the fraction of CCQE interactions and to reduce backgrounds, $NC\nu_\mu$, $NC\nu_e$ and $CC\nu_e$.

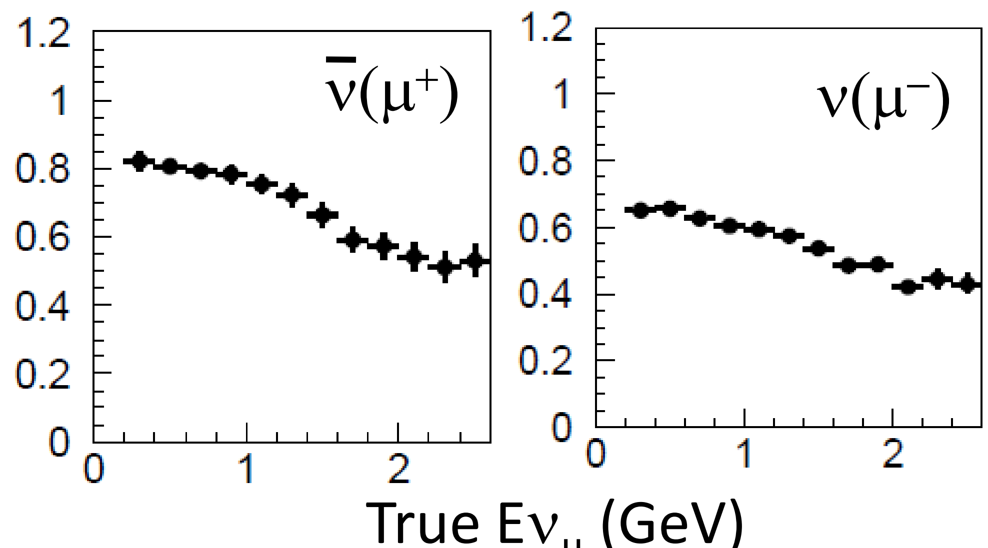
- The efficiency of detecting decay-e are 80% for μ^+ and 63% for μ^- .



Decay electron selection probability



probability: $\dfrac{1\text{-ring} \,\&\, \mu\text{-like} \,\&\, 1\text{-dcaye}}{1\text{-ring} \,\&\, \mu\text{-like}}$



Summary of event selection

Summary of the event selection efficiencies(probabilities) for CC ν_μ in each beam

event selection efficiencies (probabilities)

	LE beam		HE beam	
	CC $\bar{\nu}_\mu$	CC ν_μ	CC $\bar{\nu}_\mu$	CC ν_μ
FC,FV,evis	100 %	100 %	100 %	100 %
1-ring	96.6	95.8	79.6	68.0
μ-like	95.7	95.1	98.8	97.6
1 decay-e	81.4	65.2	66.7	54.8
Final sample	75.3	59.4	52.5	36.4

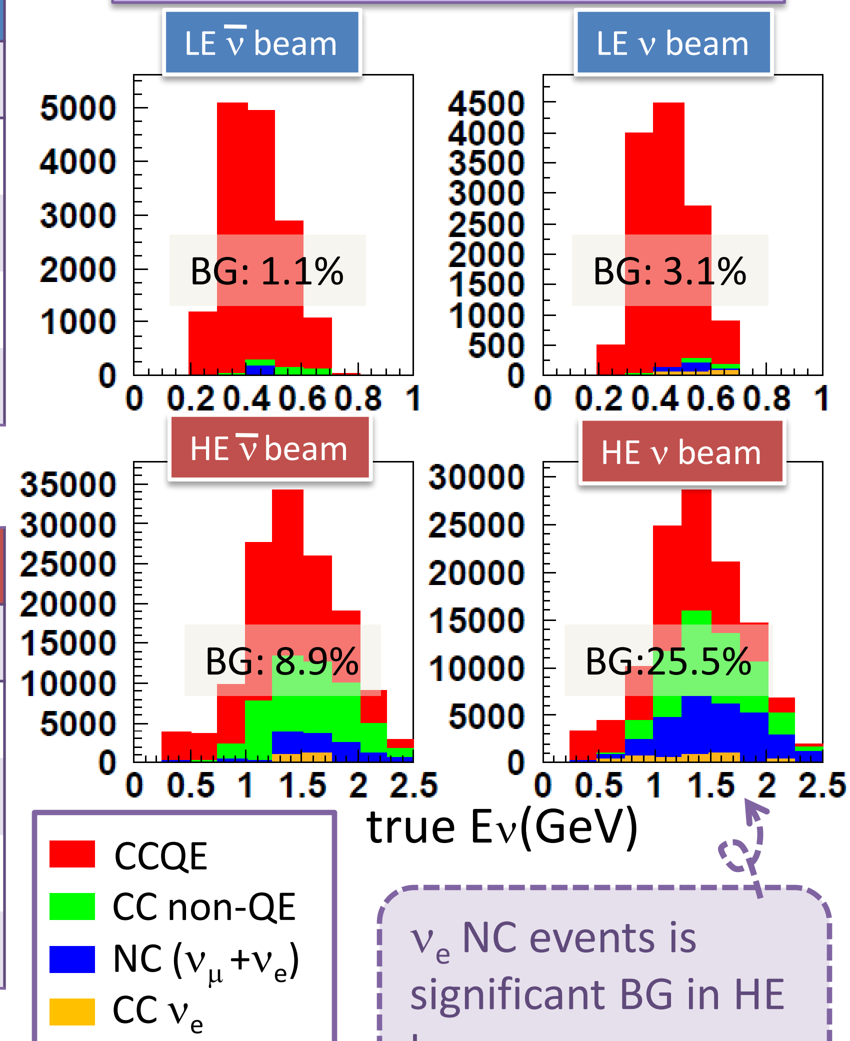
Backgrounds in final sample

Number of backgrounds after the selections

	LE $\overline{\nu}_e$ beam		LE ν_e beam	
	NC	CC ν_e	NC	CC ν_e
FVFC	100%	100%	100%	100%
+1-ring	30.46	94.60	30.17	92.85
+μ-like	4.37	1.19	6.43	1.03
+dcy-e	0.92	0.00	1.79	0.04

	HE $\overline{\nu}_e$ beam		HE ν_e beam	
	NC	CC ν_e	NC	CC ν_e
FVFC	100%	100%	100%	100%
+1-ring	36.31	81.37	39.69	72.95
+μ-like	10.35	0.72	16.75	54.21
+dcy-e	1.99	0.08	5.05	0.08

Neutrino spectra of final sample ($\sin^2 2\theta_{13} = 0.15$)

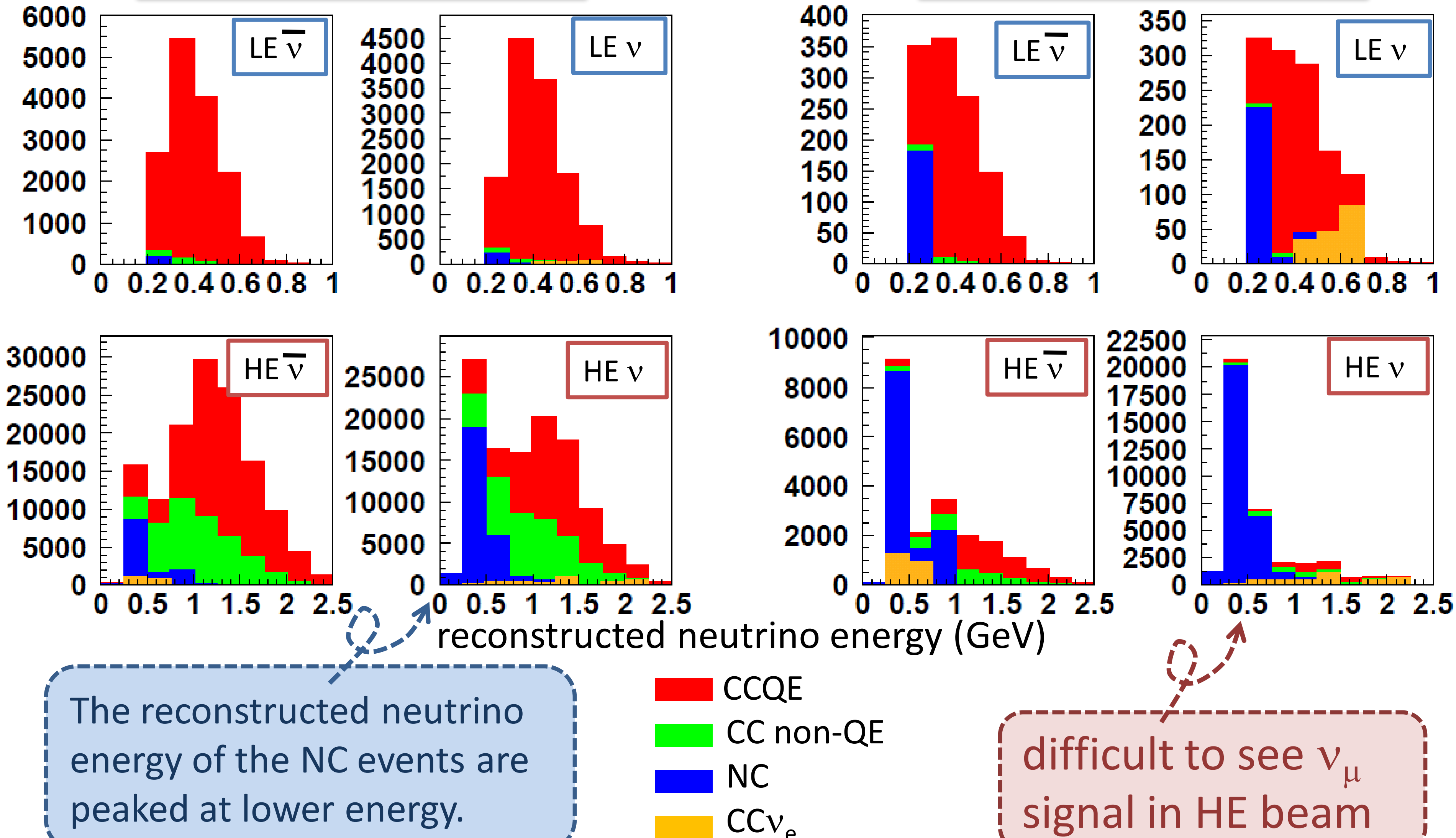


ν_e NC events is significant BG in HE beam.

Reconstructed neutrino energy distribution

In case of $\sin^2 2\theta_{13} = 0.15$

In case of $\sin^2 2\theta_{13} = 0.01$



The reconstructed neutrino energy of the NC events are peaked at lower energy.

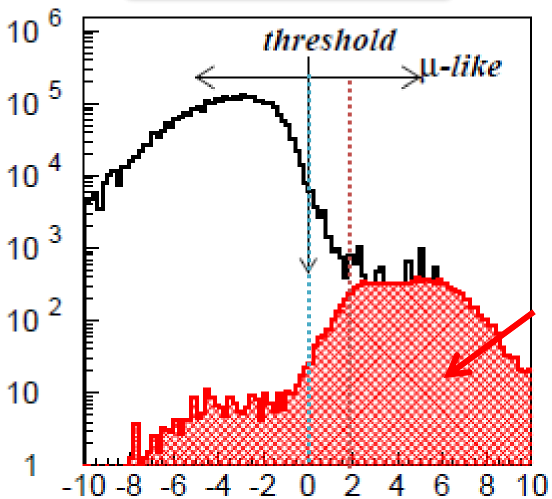
difficult to see ν_μ signal in HE beam

Optimization of PID selection

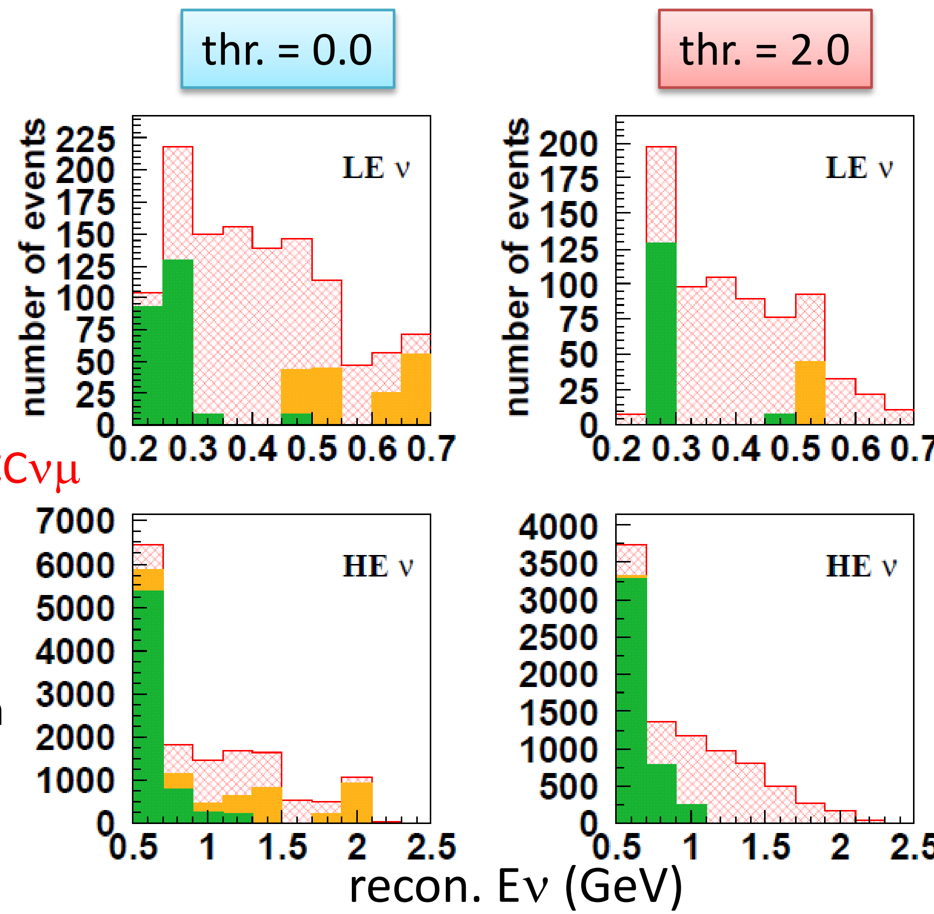
The current cut parameter on PID is for classification for atmospheric neutrino, ν_e and ν_μ.

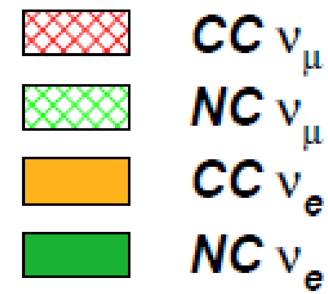
→ change the threshold to maximize the signal to BG ratio

PID likelihood



1-ring,CCν from HE νe beam
In case of $\sin^2 2\theta_{13} = 0.01$



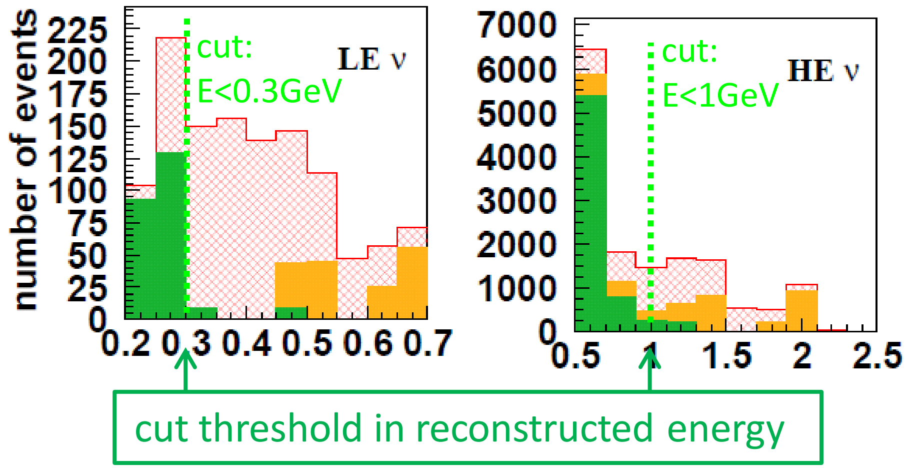


It's possible to distinguish BG from signal even if $\sin^2 2\theta_{13} = 0.01$.

Reconstructed energy & new PID selection

The selection efficiency and the ratio signal to BG in each cut:

1. SK selection only
2. 1 & Reconstructed Energy cut (E<0.3GeV for LE, E<1GeV for HE)
3. 1 & New PID cut (threshold = 2.0)
4. 2 & 3



	LE ν_e beam		HE ν_e beam	
cut	Eff. (%)	SIG/BG	Eff. (%)	SIG/BG
1	59.4	2.0	36.4	0.2
2	52.1	4.0	22.1	1.2
3	40.8	3.1	32.3	0.3
4	35.3	9.0	21.0	* 1550

($\sin^2 2\theta_{13} = 0.01$)

* due to the limited statistics of Monte-Carlo simulation, these values have ~60% statistical errors

→ The recon.E cut added new PID cut is effective for SIG/BG.

summary

- The selection efficiencies for CC ν_μ are :
  - 75.3% ($\bar{\nu}$), 59.4% (ν) from LE beam
  - 52.5% ($\bar{\nu}$), 36.4% (ν) from HE beam.

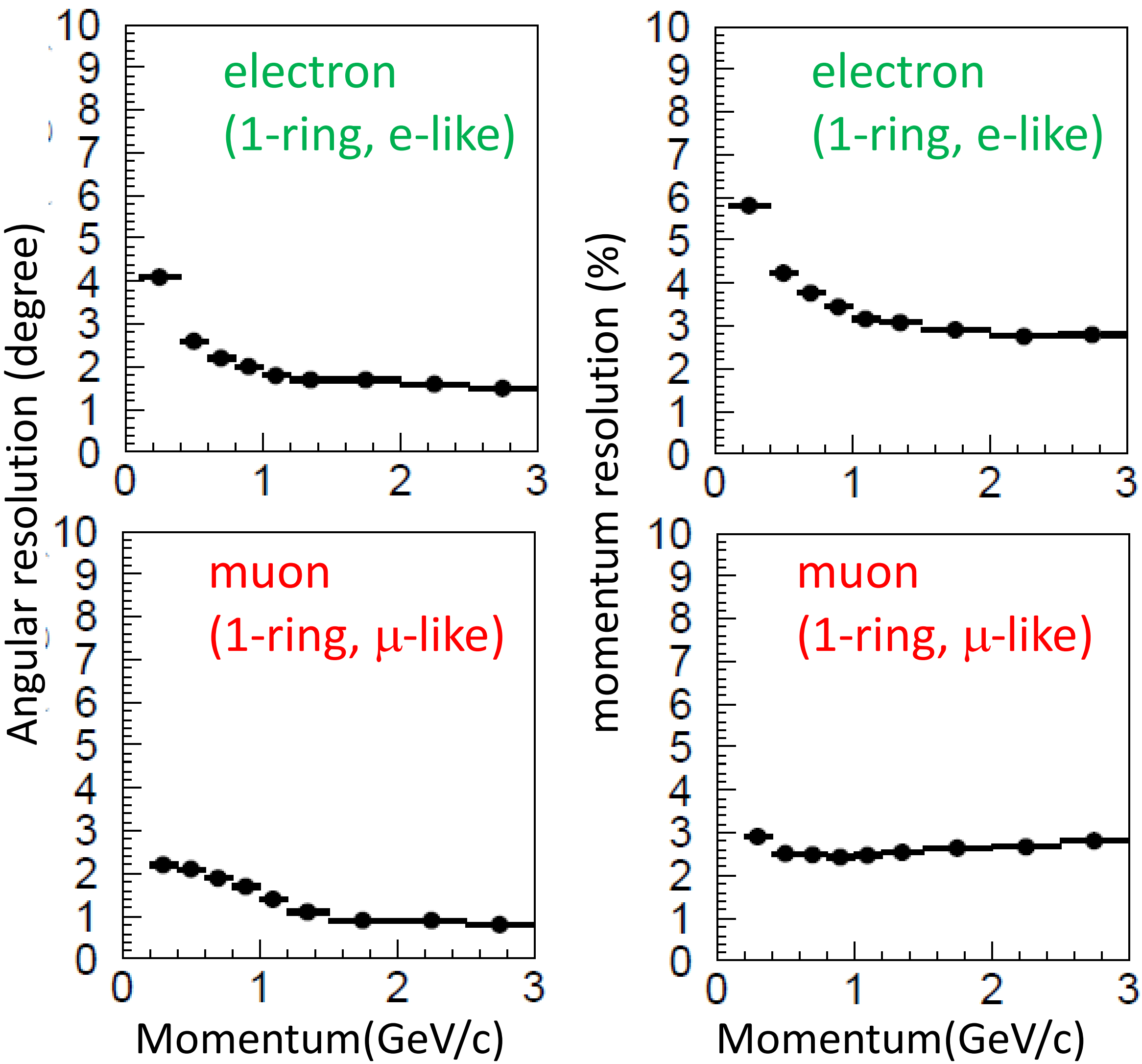
- Small fraction of BG in the LE beams is expected.
- For HE beams, NCν_e (mainly NC charged π production) could be the dominant background. The remaining events after the selection are :
  - 0.92% ($\bar{\nu}$), 1.79% (ν) from LE beam
  - 1.99% ($\bar{\nu}$), 5.05% (ν) from HE beam.
- CC ν_e BG events after the selection for all beam sets are less than 0.1%.
- If the statistics of ν_μ signal is low like in case of $\sin^2 2\theta_{13}=0.01$, the ratio of signal to BG is very low.
- There is much possibility to distinguish the signal from BG by using optimized PID selection and reconstructed energy.

Backup

Performance of the detector (1)

Angular resolution

momentum resolution



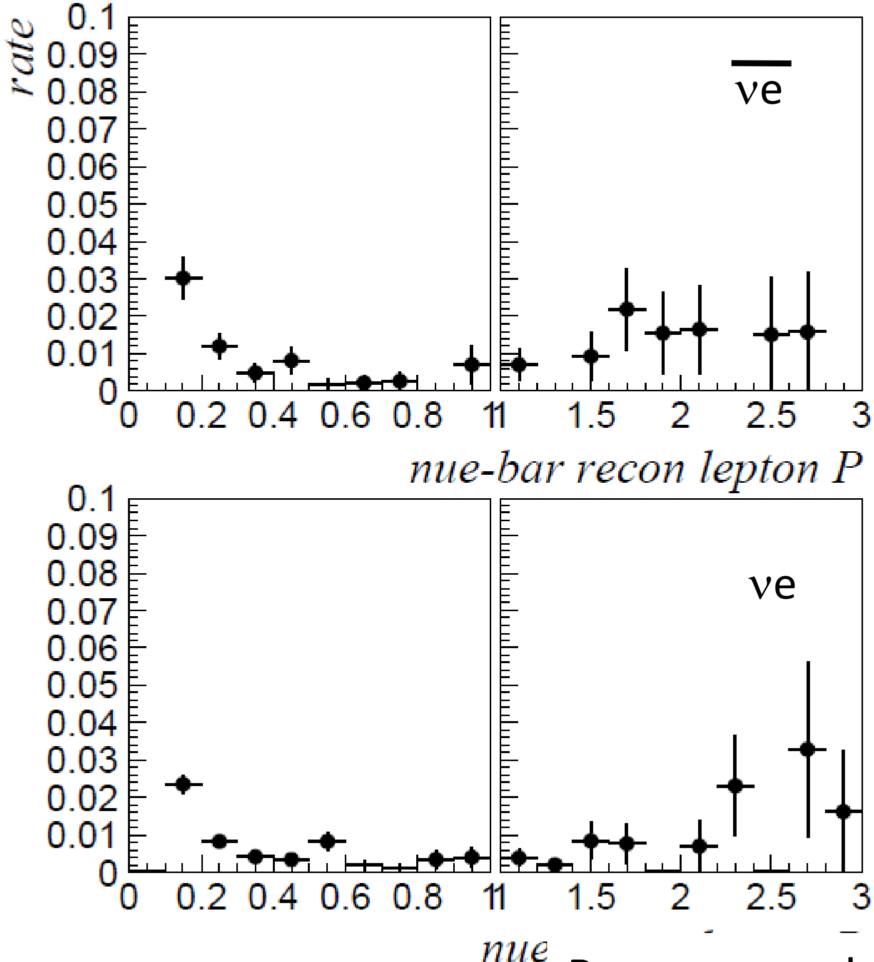
vertex resolution

[cm]

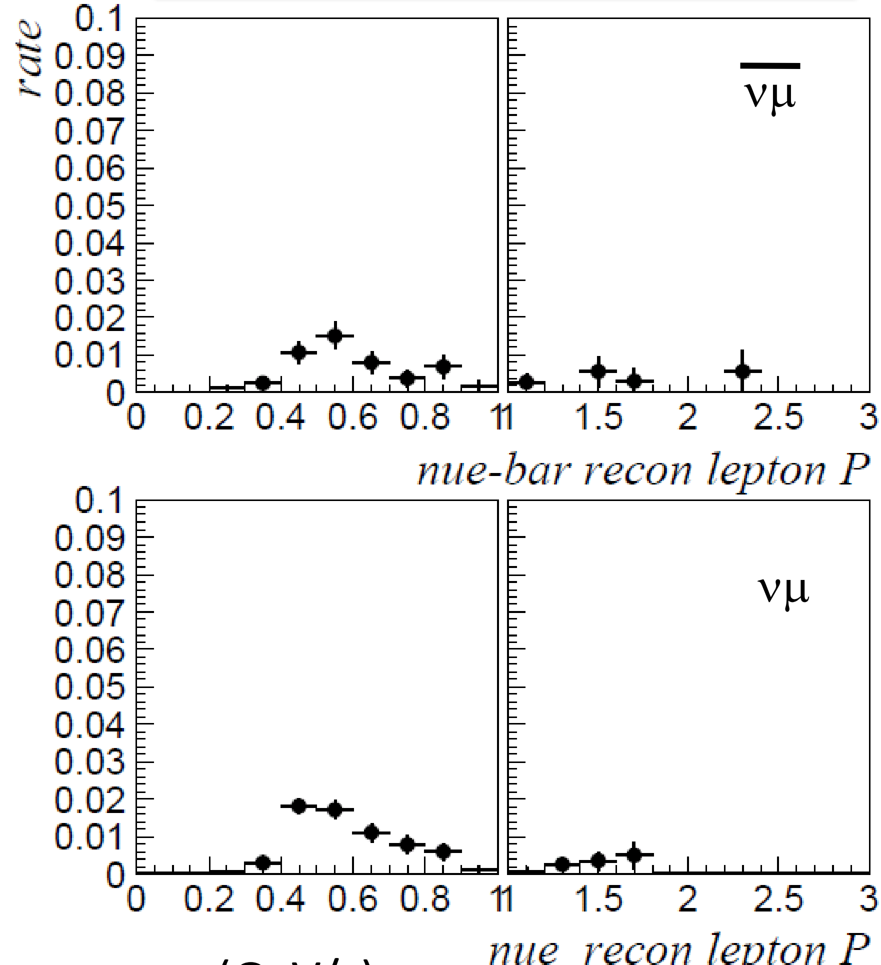
	electron	muon
<1GeV	27.3	23.9
>1GeV	48.9	23.8

Mis-ID (for atm. ν)

Probability mis-ID νe as μ-like

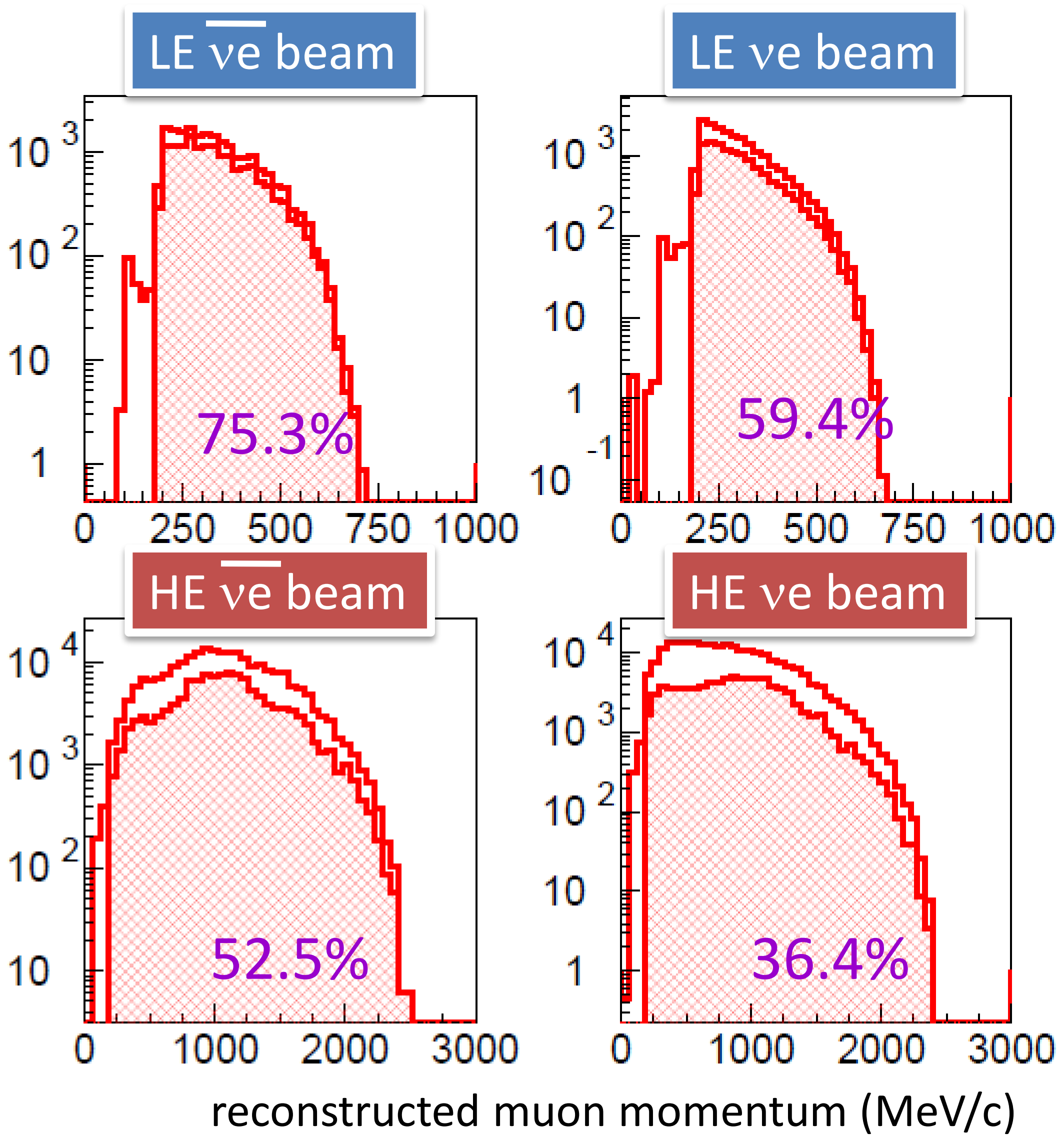


Probability mis-ID $\nu\mu$ as e-like



Recontructed momentum (GeV/c)

Expected CC signal and selections



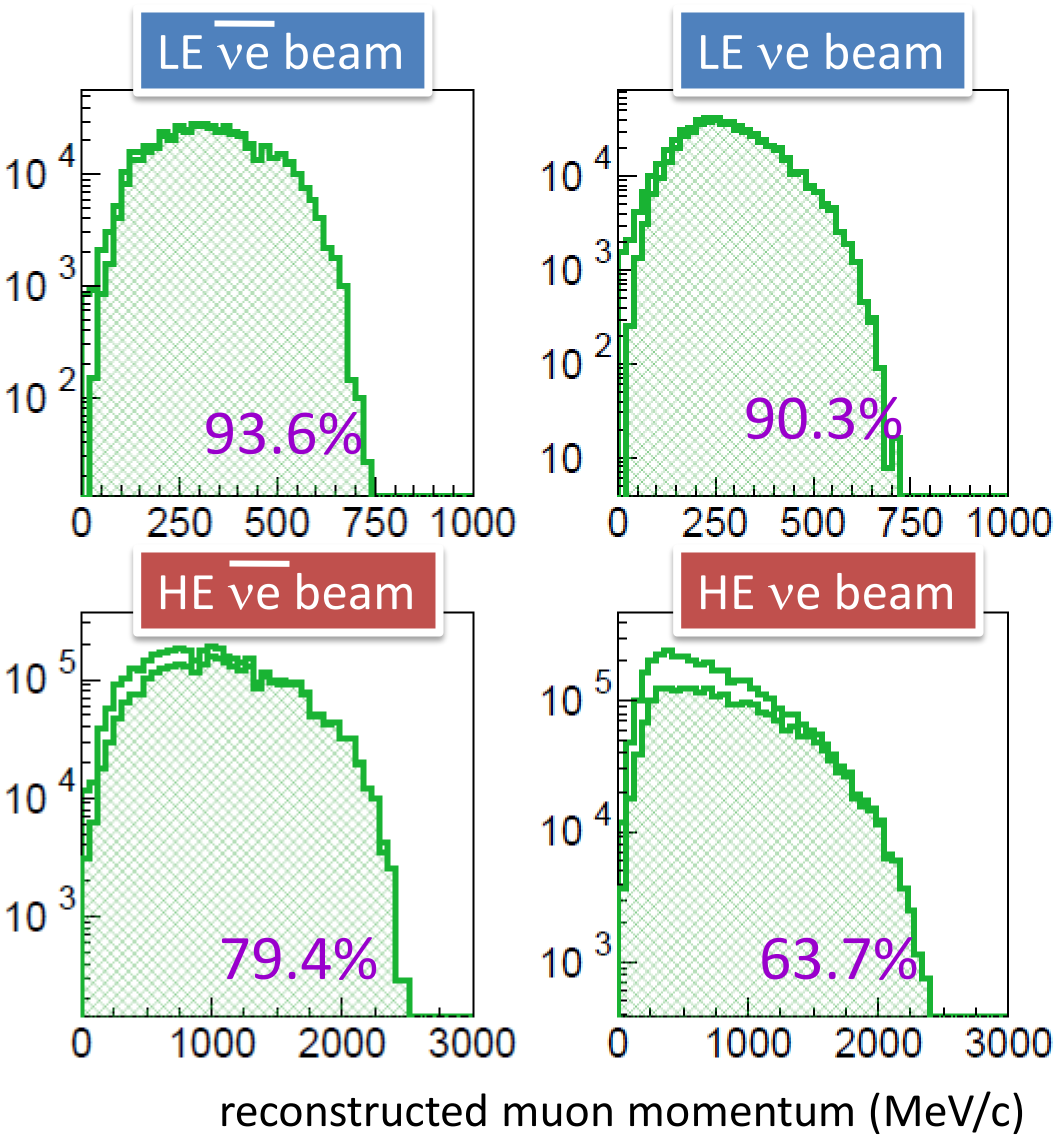
Open reconstructed muon momentum (CC events, FVFC)

Hatch after selection

Selection criteria;

1. single-ring
2. μ-like ring
3. with 1-decay electron

Expected electron spectrum



Open reconstructed e momentum (Fiducial Volume)

Hatch after selection

Selection criteria;

- 1-ring
- e-like ring
- Decay-e=0

Reconstructed energy & new PID selection

The selection efficiency and the ratio signal to BG in each cut:

1. SK selection only
2. 1 & Reconstructed Energy cut (E<0.3GeV for LE, E<1GeV for HE)
3. 1 & New PID cut (threshold = 2.0)
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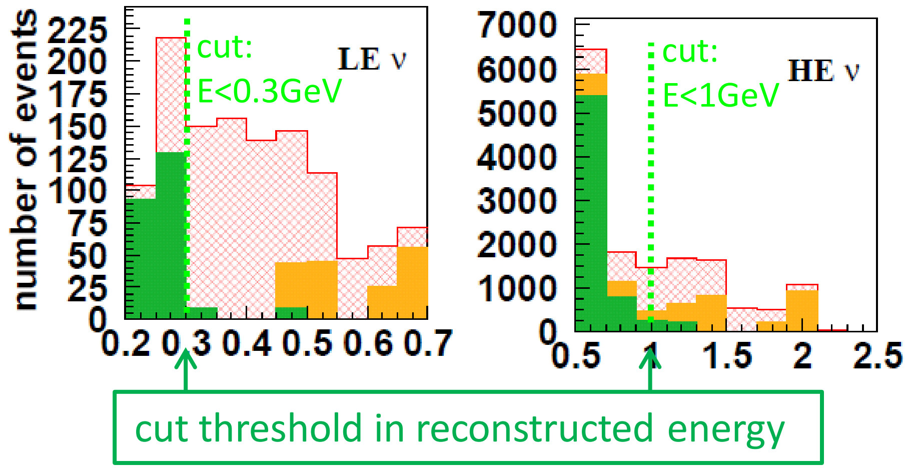

($\sin^2 2\theta_{13} = 0.01$)

	LE $\overline{\nu}_e$ beam		LE ν_e beam		HE $\overline{\nu}_e$ beam		HE ν_e beam	
cut	Eff. (%)	SIG/BG	Eff. (%)	SIG/BG	Eff. (%)	SIG/BG	Eff. (%)	SIG/BG
1	75.3	5.5	59.4	2.0	52.5	0.7	36.4	0.2
2	62.5	** $\sim 10^4$	52.1	4.0	37.0	* 2044	22.1	1.2
3	49.7	3.6	40.8	3.1	48.6	1.4	32.3	0.3
4	40.7	** $\sim 10^6$	35.3	9.0	35.9	* 1980	21.0	* 1550

*(**) due to the limited statistics of Monte-Carlo simulation, these values have ~60(400)% statistical errors

→ The recon.E cut added new PID cut is effective for SIG/BG of HE beam.

Cross-sections