Possibilty of CC inclusive measurement w/ INGRID

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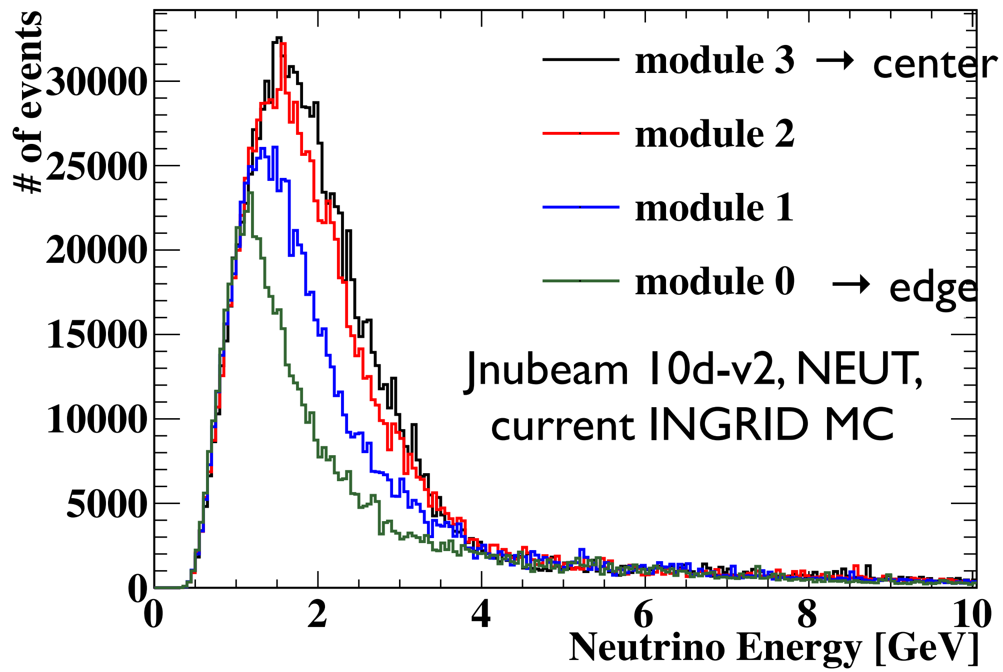
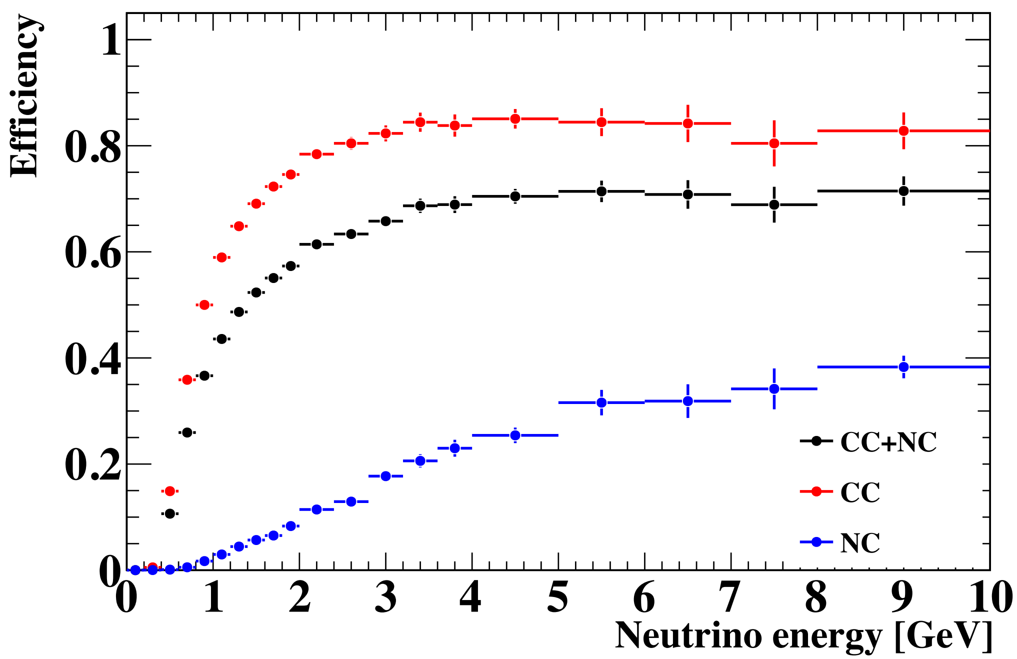
Motivation

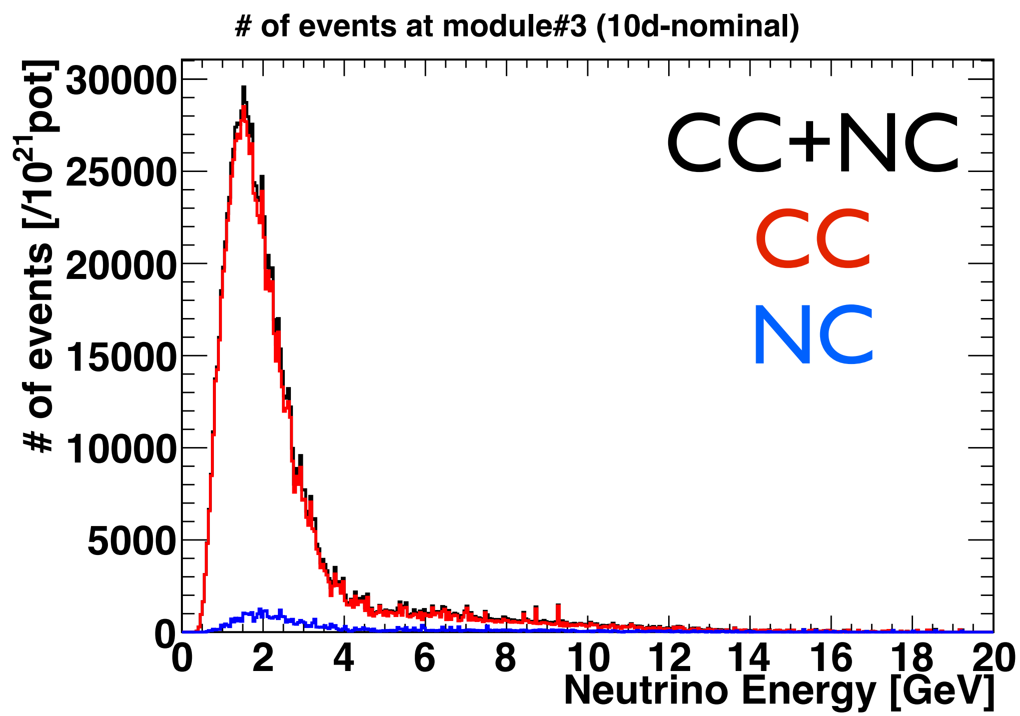
- Neutrino energy distribution is expected to be different at each module.
    - Because each modules is set with different off-axis angle.
- Flux at each module is almost same for Enu<1GeV and Enu>4GeV, but different at 1<Enu<4GeV
- I try to measurement the inclusive neutrino cross-section at 1~4GeV (hopefully 1~3GeV) by using the flux difference among modules.

νμ true energy distribution after neutrino selection



INGRID Efficiency to neutrino interaction in FV

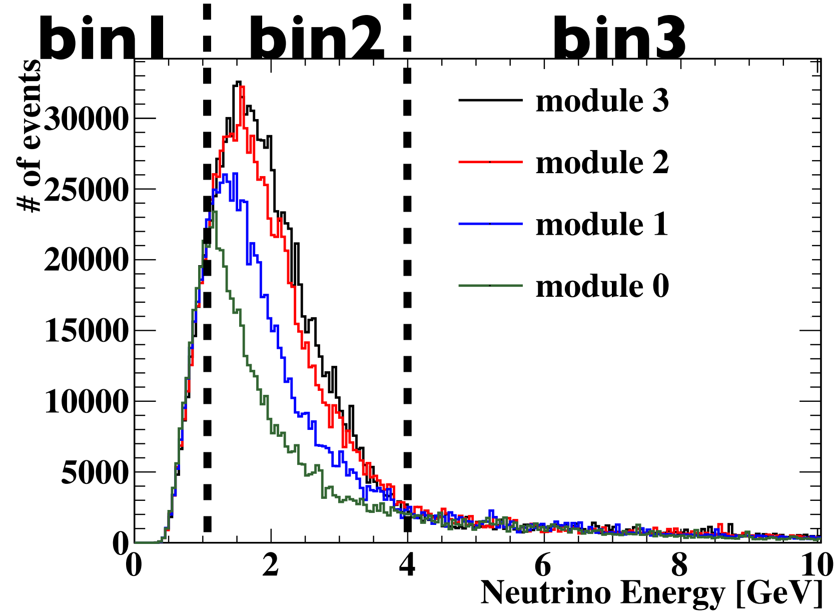


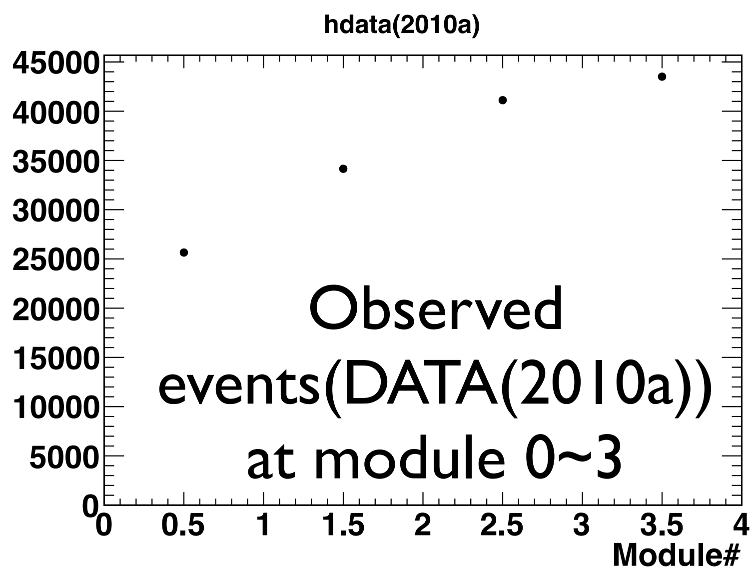


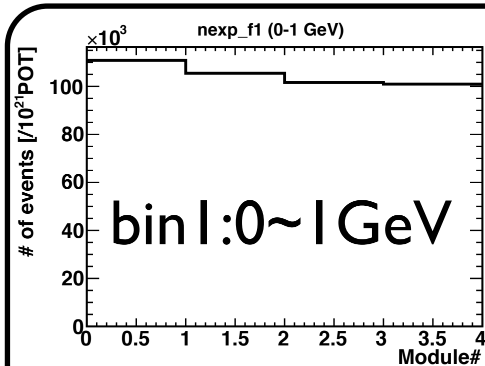
- More than 90% of remained events after current neutrino selection is events of CC interaction mode.
  - High CC interaction purity.

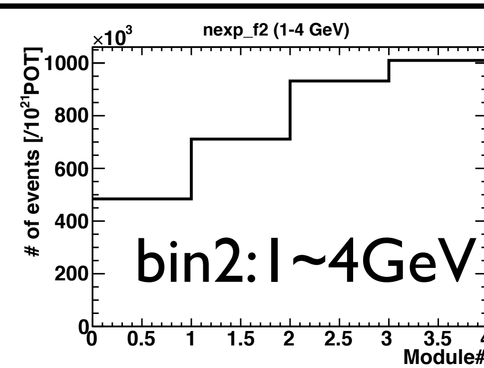
Motivation

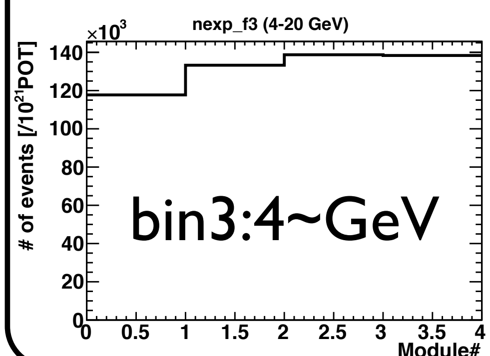
- Divide true neutrino energy into some bins
- Cross section is obtained as the normalization factor(f_i) at each bin(i) common to all modules.
- Get f_i which reproduce Data/MC for all modules.
- Measured Cross section = Cross section(MC) x (1+f_i)











Expected events(MC) at module0~3

Fit function

Maximum the following likelihood:

$$L = \prod_{module} Gauss(N^{obs}_{mod} | N^{exp}_{mod}, \sqrt(N^{exp}_{mod}))$$ (stat. error)

$$\times \frac{1}{2\pi^{n/2}\sqrt(det\Sigma_{sys})} exp(-\frac{1}{2}(f_1, f_2, f_3 ...)\Sigma^{-1}_{sys}(f_1, f_2, f_3, ...)^T)$$ (syst. error)

$$N^{exp}_{mod} = \Sigma_{bins} \int_{bin\#i} \phi(E)\sigma(E)\epsilon(E) \times (1 + f_i)dE$$

- $(f_1, f_2, f_3, ...)$ are fitting parameters (normalization at each energy bins)
- At first step, consider only stat. error term
  - Fitting parameters is constrained : $1+f_i > 0$.
  - I tried some division of energy bins.

Fitting demonstration

- Check whether fitting is valid or not by using Fake MC ($N^{exp,fake}$) as N^{obs}.
  - Fake MC is changed from MC expectation by design as like the following formula:

$$N_{mod}^{exp,fake} = \Sigma_{bins} \int_{bin\#i} \phi_{mod}(E)\sigma(E)\epsilon(E)(1+\delta_i)dE$$

$\delta_i = 0.1 * i$ → Use this $N^{exp,fake}_{mod}$ as N^{obs}_{mod}

- Check if obtained parameters (f_i) by fitting are consistent to given δ_i, my fitting analysis is valid.
- Normalization parameters I want to measure have few ten % error at this time with only stat. error, this analysis method needs to be change.

Analysis configuration

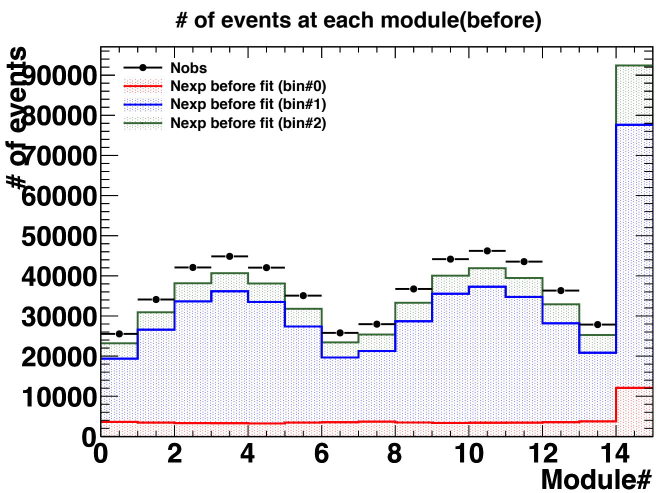
- Used modules for analysis : #0~3, #7~10, #14(shoulder module)
- MC configuration
  - Flux : Jnubeam 10d-v2 (by weighting based on energy)
  - Neutrino interaction : NEUT 5.0.6
  - Detector MC : current INGRID MC (not nd280 software)
- MC stat. is normalized according to the followings:
  - #0~3, #7~10 : RunI p.o.t. (update RunI & RunII soon)
  - #14 : RunII p.o.t.
- Try two cases for binning as first trial
  - Case 1 : <1GeV(bin#1), 1~4GeV,(bin#2), >4GeV(bin#3)
  - Case 2 : <1GeV(bin#1), 1~3GeV(bin#2), >3GeV(bin#3)
- In both case, cross-section in 2nd bin is expected to be measured and there would not be sensitivity to dissolve 1st and 3rd bin because of the flux difference of among modules.

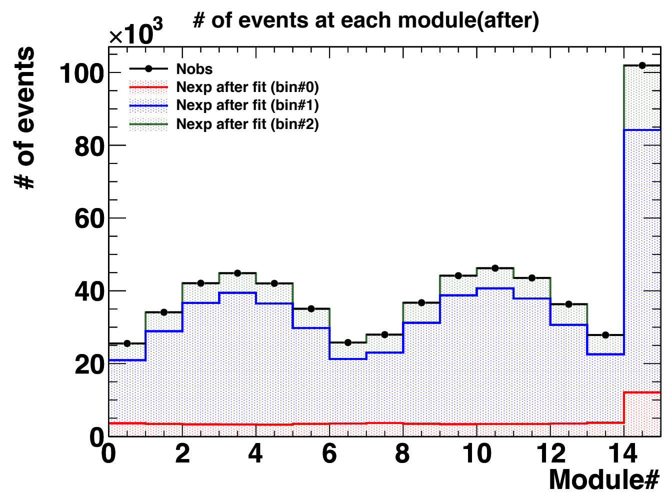
Case 1

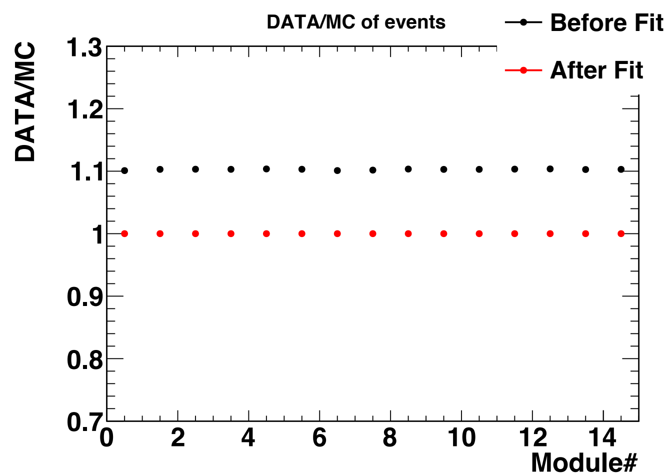
NAME	VALUE	ERROR
f1	9.99417e-01	3.51683e-01
f2	1.09996e+00	1.87102e-02
f3	1.20058e+00	3.70212e-01

```
=== INPUT Fake MC ===
    bin#:0 = 1
    bin#:1 = 1.1
    bin#:2 = 1.2
```

- Equal to input Fake MC.
- Fitting error of parameter I want to measure is ~2% → Good







→ Data(Fake MC) / MC become closer to 1.

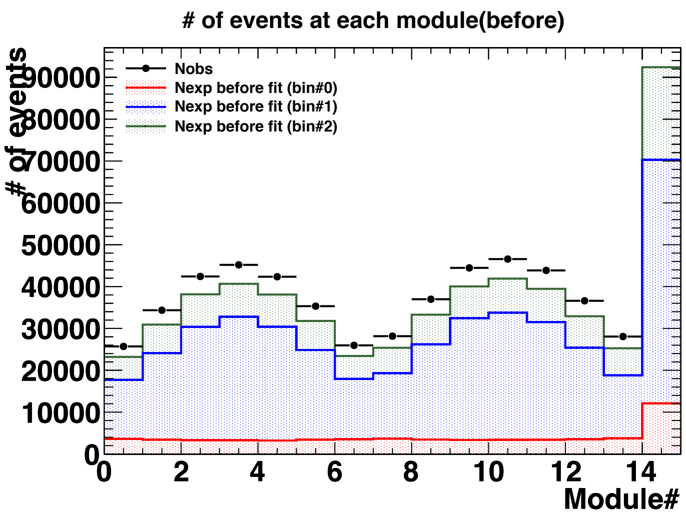
This fitting seems to be valid.

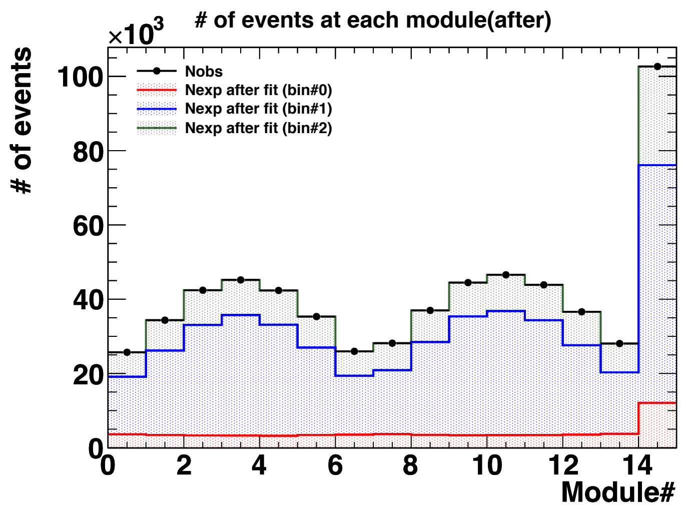
Case 2

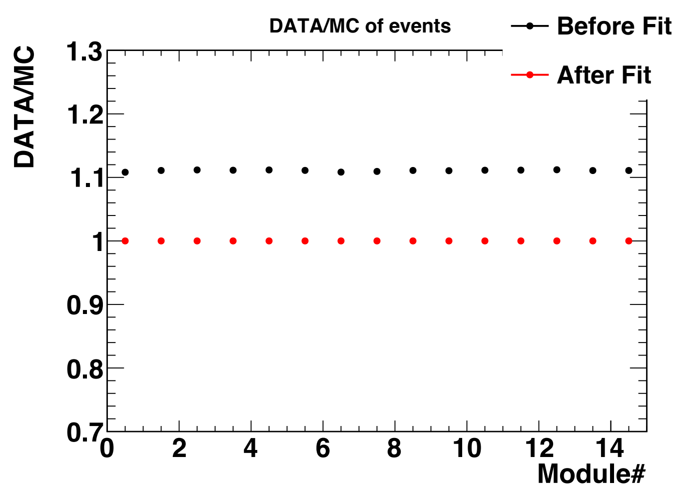
NAME	VALUE	ERROR
f1	9.99515e-01	2.66557e-01
f2	1.09992e+00	3.96428e-02
f3	1.20044e+00	2.52056e-01

```
=== INPUT Fake MC ===
    bin#:0 = 1
    bin#:1 = 1.1
    bin#:2 = 1.2
```

- Equal to input Fake MC.
- Fitting error of parameter I want to measure is ~4% → More than first, but small.







This fitting seems to be valid.

List of systematic uncertainty

- Detector systematic uncertainty
  - Otani-san, Christophe, other people have studied. Need to consider treatment of uncertainty in my analysis.
- Flux uncertainty
  - Due to hadron production, proton beam parameter, off-axis, etc.
- Uncertainty of GEANT4 physics models
- Uncertainty related neutrino interaction
  - Events in interacted in scintillator is expected to account for 5% of in iron. I would treat the interaction in scintillator as a uncertainty.
  - Use the current uncertainty studied by NIWG.

➡At first step, I consider about well-known detector systematic

Detector systematic

- Two kinds of error : detector common / dependent.
- At current study, detector systematic errors are considered as common (according to TN-040)).
  - Deference of each module is estimated to be small against error size.
- At first step, I consider this error as common in all modules. This part of likelihood can be defined as the followings:

$$L^{det.\ syst.} = \prod_{module} Gauss(N^{exp}_{mod} | N^{exp}_{0,mod}, \sigma^{det.}_{N^{exp}_{0,mod}}))$$

$$N^{exp}_{0,mod} = \Sigma_{bins} \int_{bin\#i} \phi(E)\sigma(E)\epsilon(E)dE \ (MC\ init\ prediction)$$

$$N^{exp}_{mod} = \Sigma_{bins} \int_{bin\#i} \phi(E)\sigma(E)\epsilon(E)(1+f_i)dE$$

$$\sigma^{det.}_{N^{exp}_{0,mod}} = N^{exp}_{0,mod}\sigma^{det.},\ \sigma^{det}\ : common\ among\ modules$$

Next step

- Proceed this analysis with Fake MC (to understand fitting).
- Consider treatment of some systematic errors in the analysis.
  - Detector systematic.
  - Flux systematic
- Current analysis, the main of neutrino interaction mode is CC int. (~90%). But NC int. remains ~10%.
  - Measured CC int. Cross section in bin#i = Cross section(MC)_i x (1+f_i) x Purity_i(=CC/(CC+NC) in bin#i).
  - Need to consider the uncertainty of Purity_i (related to neutrino interaction model).

Back up

Energy dependence of CC Purity

(10d-nominal, NEUT5.0.6)