T2KK sensitivity as a function of off-axis angle

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2nd T2KK workshop, July 13, 2006

Outline

Motivation

Likelihood analysis:

- Analysis strategy
- Likelihood variables
- Efficiency results
- Future plans

Oscillation analysis

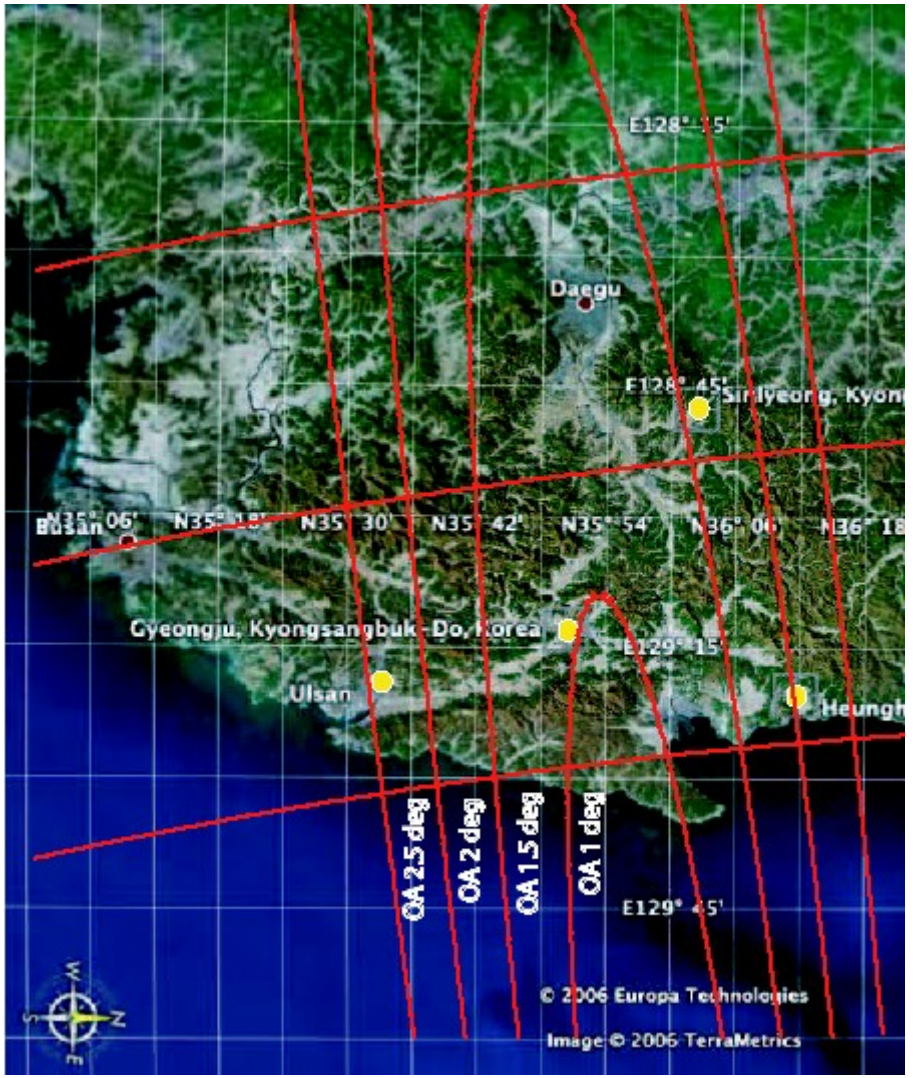
- Introduction
- Spectrum (each off-axis angle)
- χ^2 analysis
- Sensitivity curves
- Conclusions

Overview

Study the sensitivity to CP violation and mass hierarchy as a function of the off-axis angle.

Axis considered:

- 1°Off-Axis (OA)
- 1.5°Off-Axis (OA)
- 2°Off-Axis (OA)
- 2.5°Off-Axis (OA)



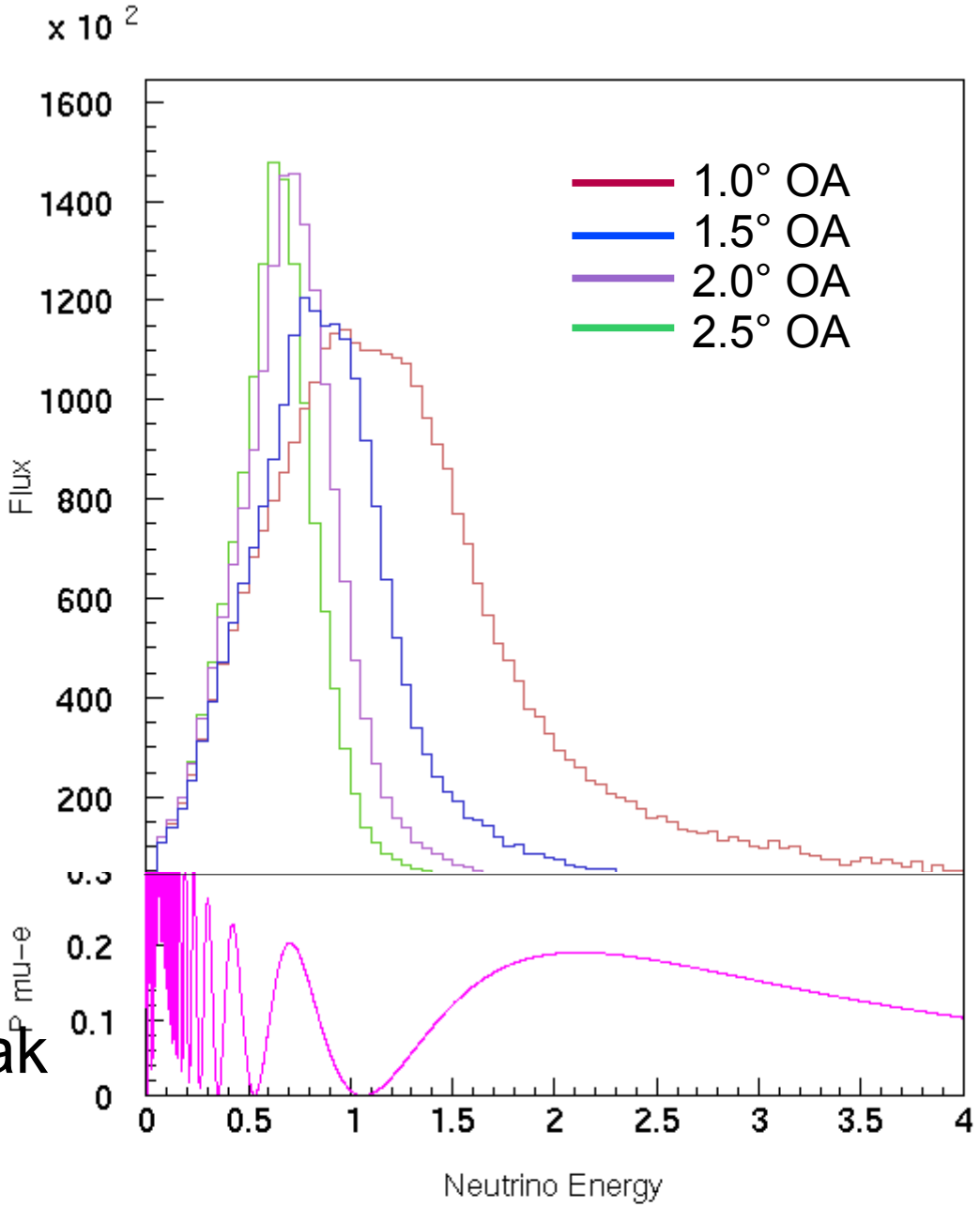
Pros & cons

Small off-axis angle:
(high energy tail)

- ✔ 1st appearance peak
- ✗ more NC background

Big off-axis angle:
(narrow peak)

- ✔ Low background
- ✗ Low statistics at high E
- ✗ Only 2nd appearance peak



Likelihood analysis strategy

Based on the T2K ν_e appearance analysis

- Apply following precuts:
  FCFV, Evis <100 MeV
  Single ring
  e-like
  no decay electron
- In this study, I used the T2K Monte Carlo.
- Combine Super-K variables into a likelihood to discriminate electrons from π^0.

8 Variables

Standard SK variables:

Ring parameter
PID parameter

Special π^o fitter variables: (POLfit, Pattern Of Light)

π^o mass
π^o likelihood
Energy fraction of 2nd ring

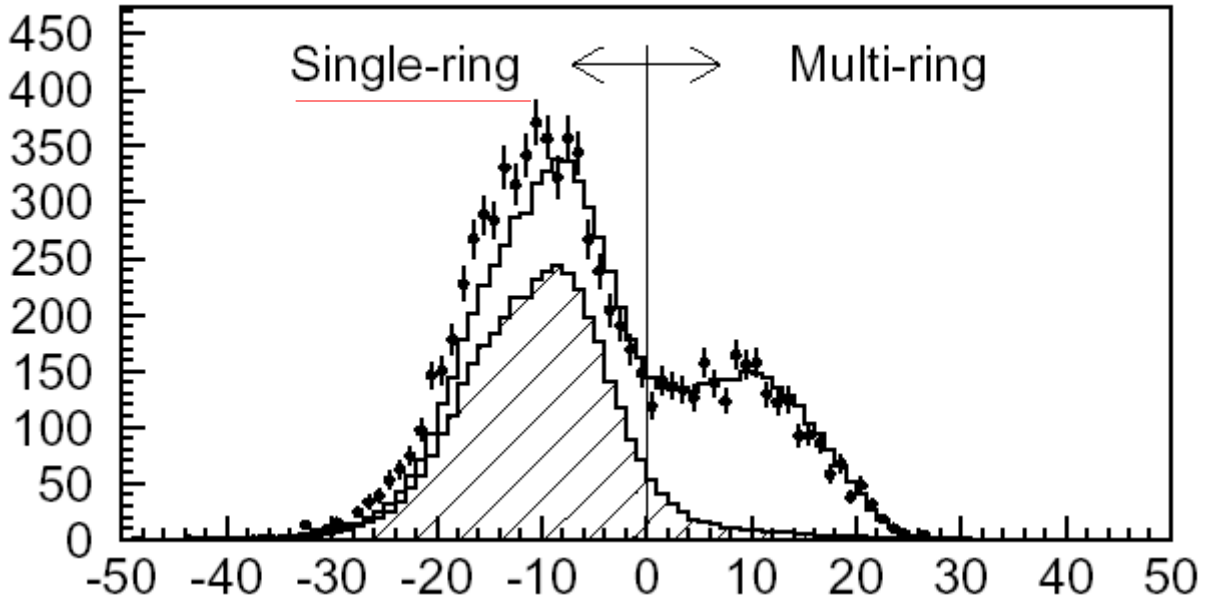
New variables, defined for this analysis:

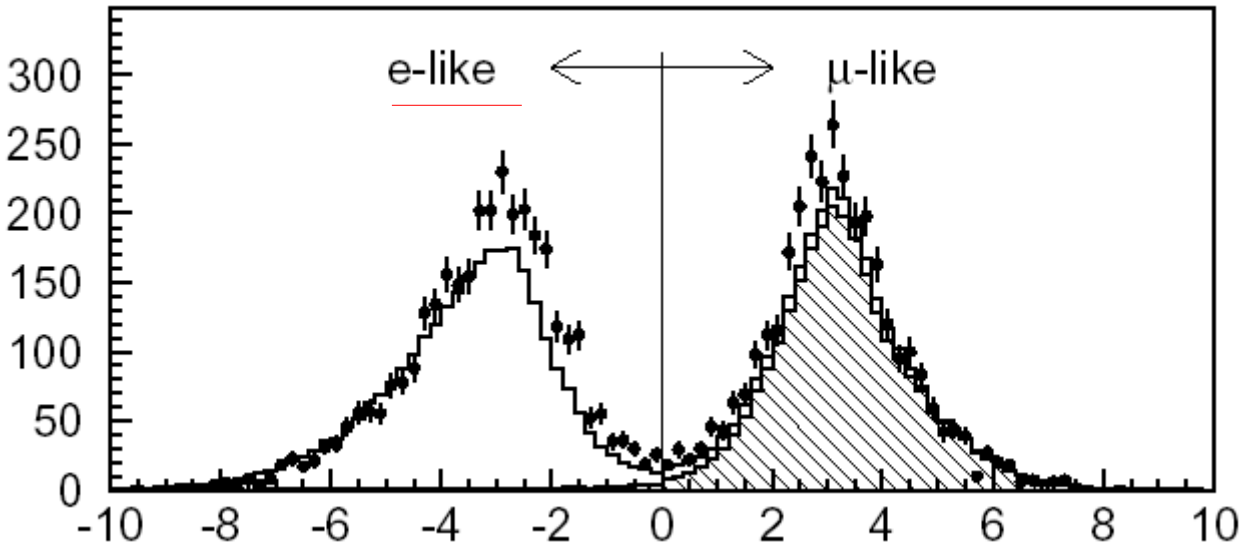
Chi_Xalong
Chi_cos(open)

Beam related variable:

$\text{Cos}\theta_{ve}$

Ring and PID Parameter:





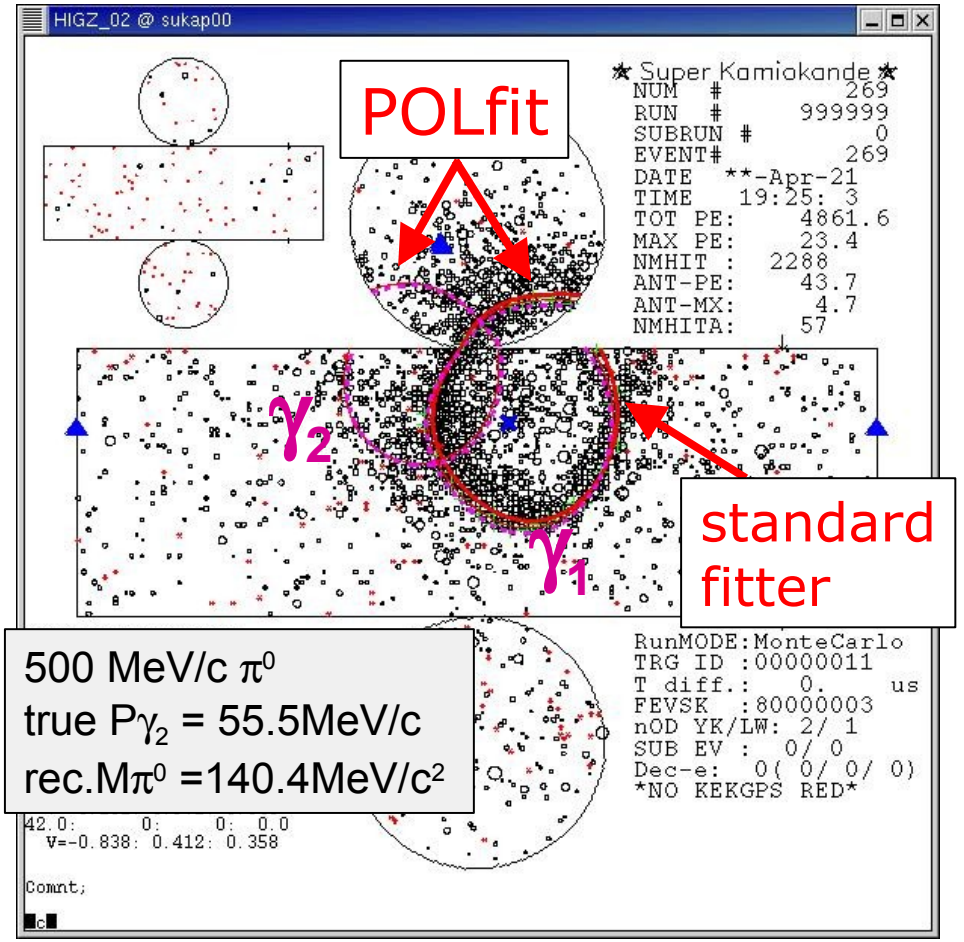
Those variables are not only precuts, (keep single-ring, e-like)

we also use the variables themselves in the likelihood.

— MC
▨ CCQE
● SK data

POLfit

S.Nakayama's talk
1st T2KK Workshop
November 2005



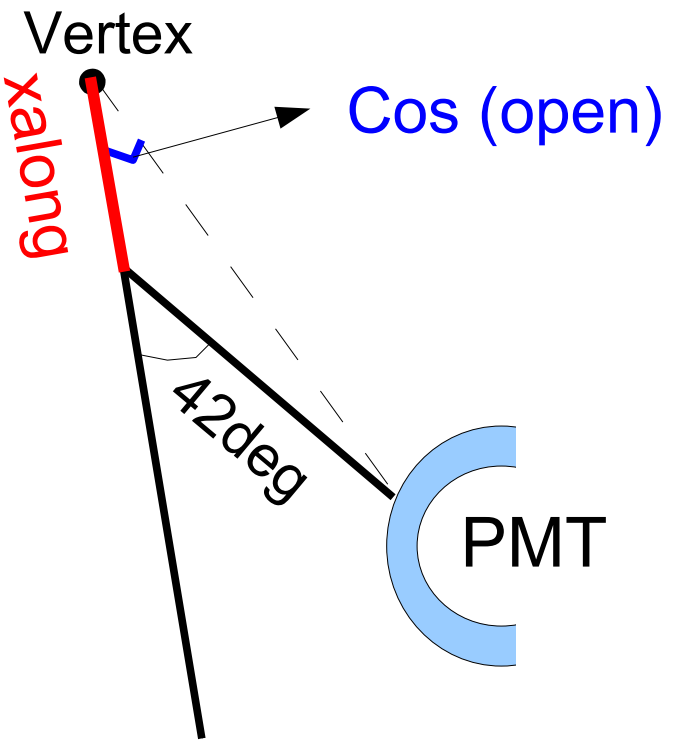
- Target: FCFV 1R-elike events
- $\Delta L \equiv$ Likelihood(2γ assump.) – Likelihood(electron assump.)
- Try to reconstruct two γ rings
- Input: vertex, visible energy, and the 1st γ direction by the standard fitter
- Compare observed & expected (direct+scatter) charge
- Vary the 2nd γ direction and the energy fraction until the best match found

I use : π^o mass
π^o ΔLikelihood
Energy fraction of 2nd ring

Xalong & Cos(open)

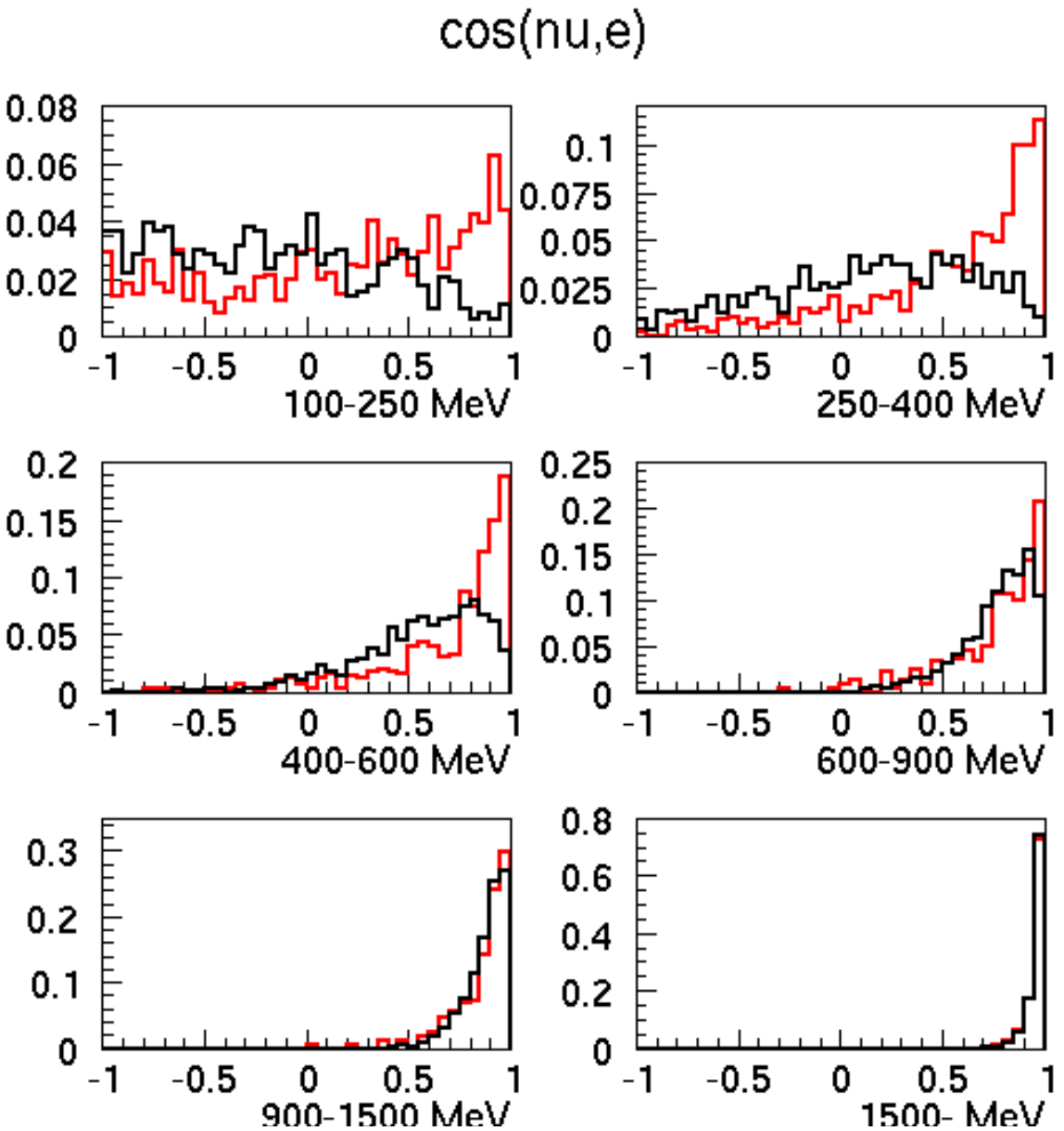
Xalong: Distance between vertex and emitting point of Cherenkov light.

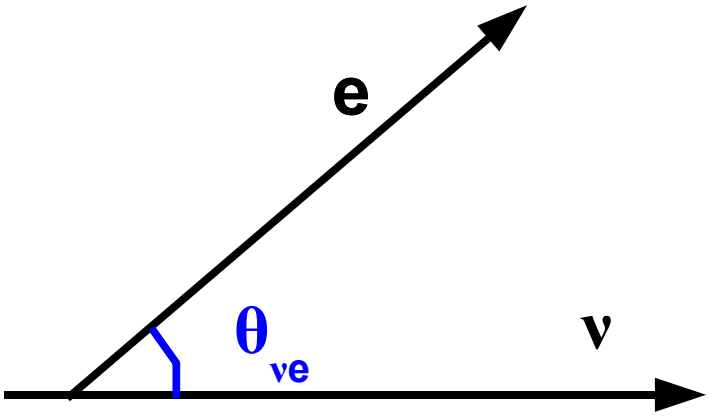
Cos(open): Angle between vertex-pmt vector & direction of neutrino



- I compute those values for each hit pmt, plot distributions.
- Using part of the MC I create templates of those distributions.
- For each event, I assign a χ^2 value comparing the event against the templates.
- The χ^2 value is added to the likelihood.

Example of distribution (1)



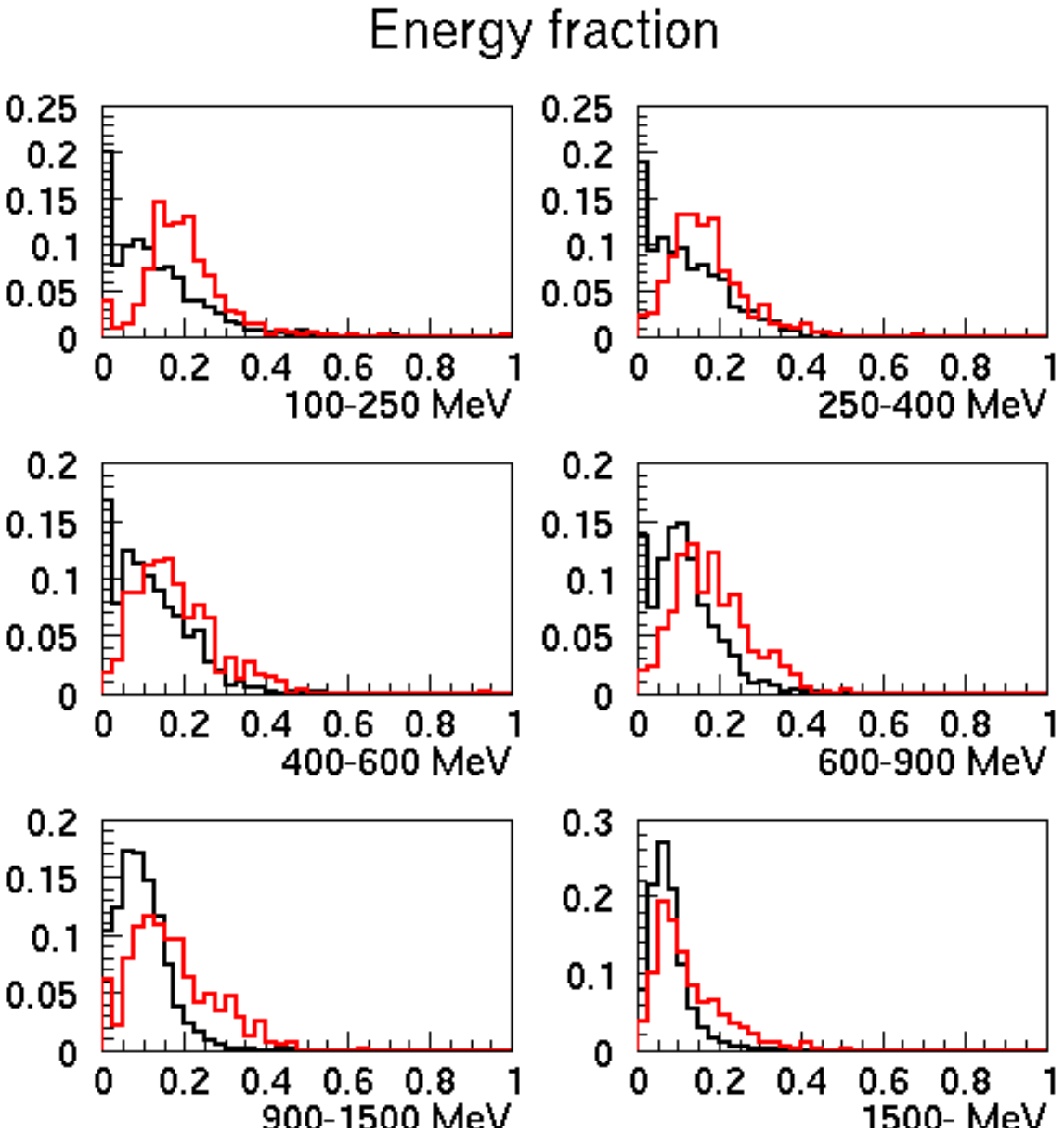


Bad at high energy

Background

Signal

Example of distribution (2)



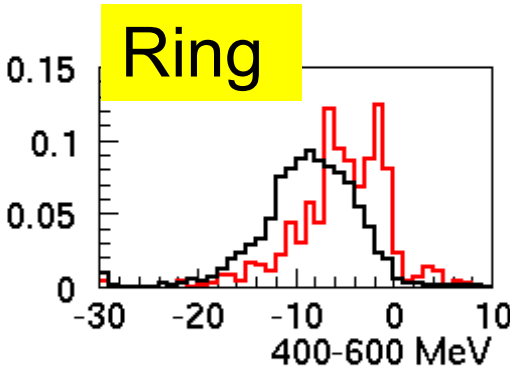
Energy fraction of the 2nd ring.

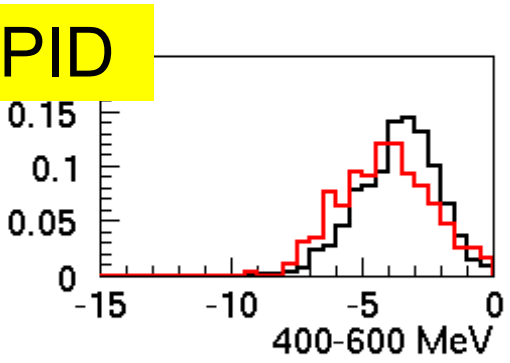
OK at high energy

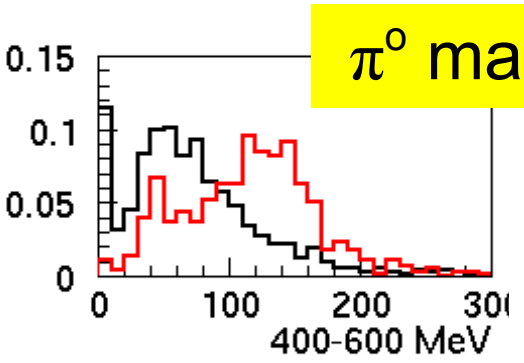
Background

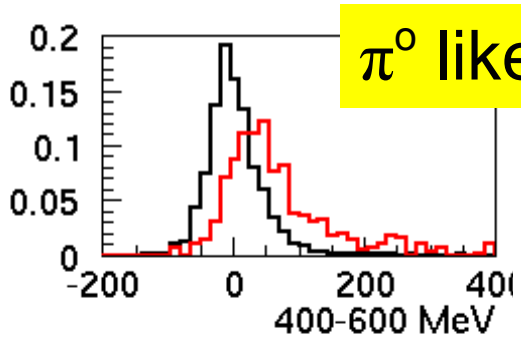
Signal

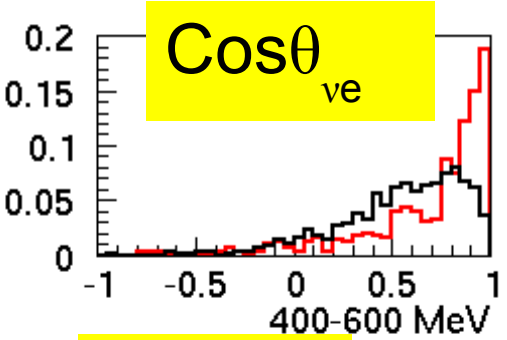
Overview of distributions:

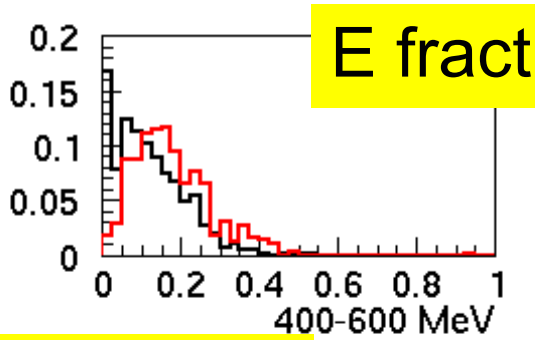


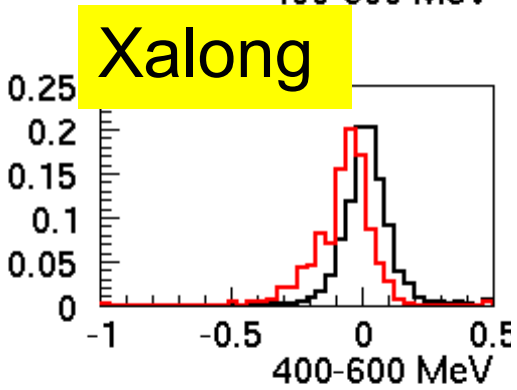


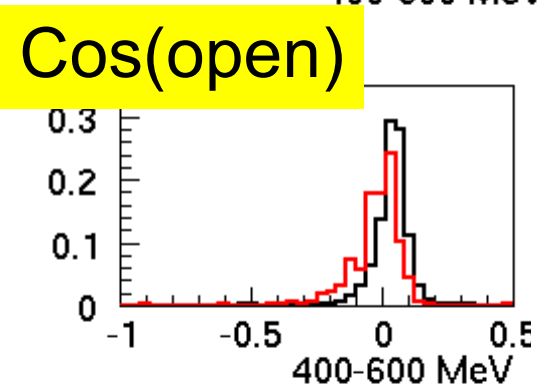










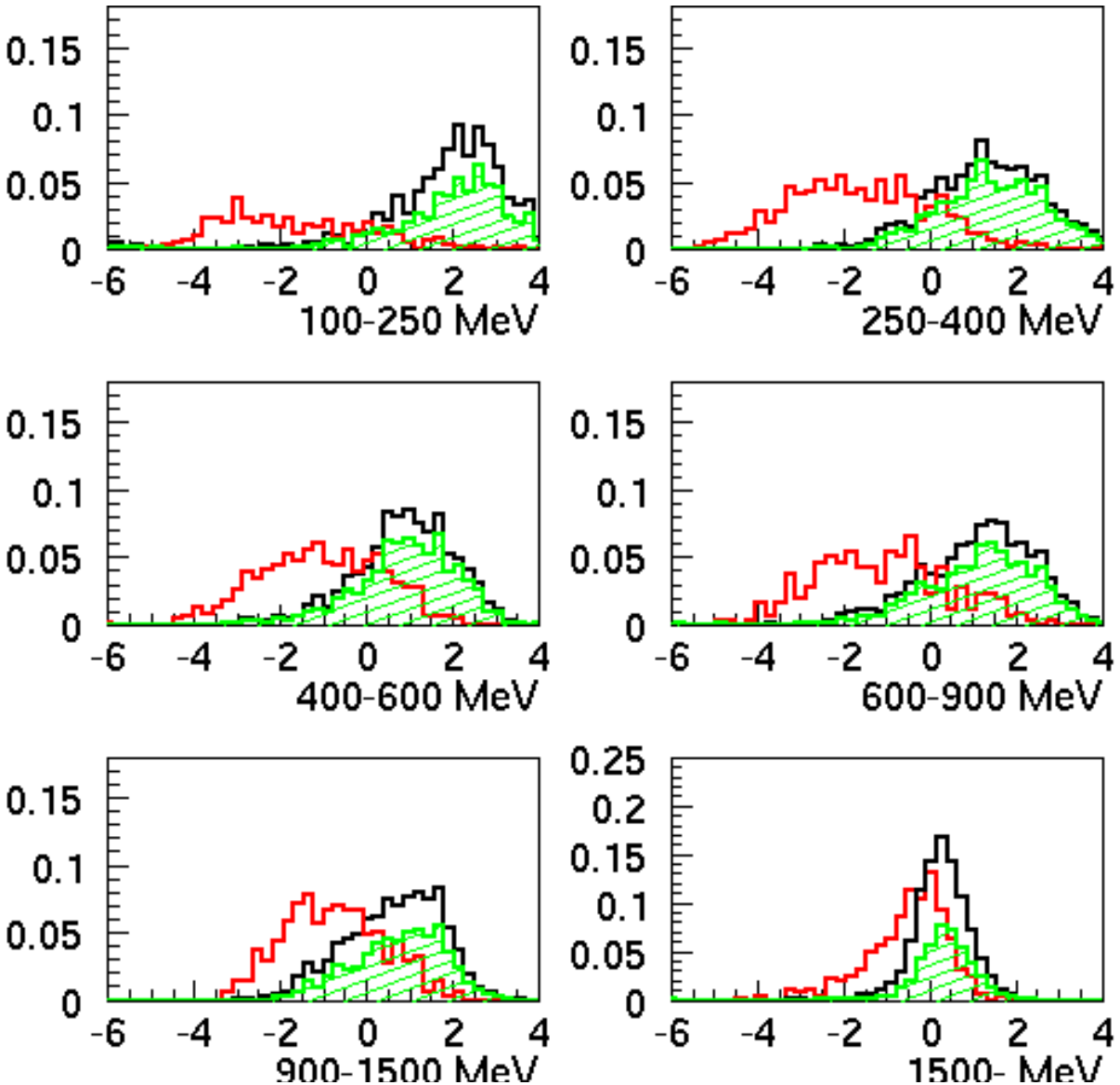


At peak energy

Background

Signal

final likelihood



Background
Signal
ν_e CCQE

Final efficiency

E_{rec} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-
ν_μ CC	fcfv	286.9	415.7	370.4	995.0
	1ring	170.2	220.8	146.3	433.6
	e-like	3.6	4.5	5.3	25.4
	nodecay-e	1.4	1.5	1.9	11.9
	likelihood	0.2	0.5	0.6	2.2
	efficiency	14.6%	31.4%	32.0%	18.7%
NC	fcfv	422.0	229.6	86.0	83.6
	1ring	89.0	66.2	26.0	41.1
	e-like	53.4	57.2	24.9	39.6
	nodecay-e	50.4	53.1	20.8	32.6
	likelihood	5.1	10.9	4.0	11.1
	efficiency	10.1%	20.5%	19.5%	34.0%
ν_e	fcfv	12.2	36.7	33.7	73.3
	1ring	5.7	21.6	16.9	37.4
	e-like	5.6	21.3	16.8	37.2
	nodecay-e	4.7	18.9	14.5	30.8
	likelihood	4.0	15.4	11.3	22.1
	efficiency	85.4%	81.8%	78.3%	71.7%

NB: arbitrary numbers

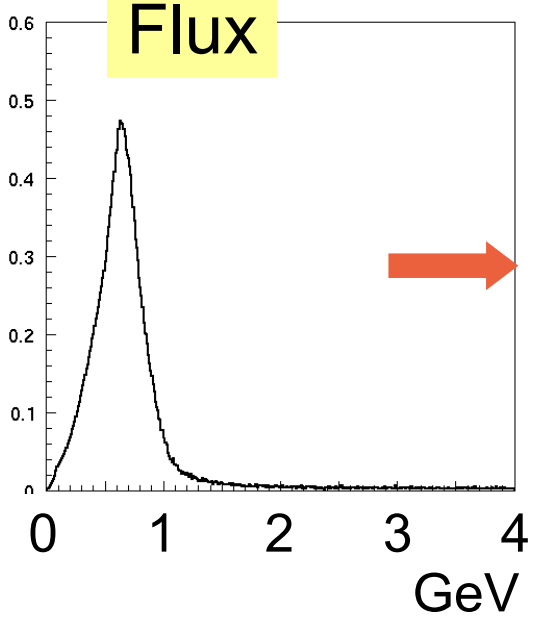
Likelihood future

There is room for improvement:

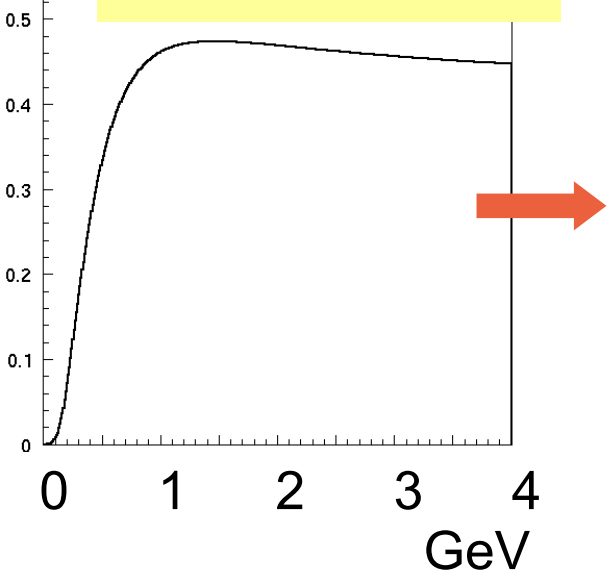
- Add new variables (Total pe charge/Evis, SK-II software variables, etc)
- Use different set of variables for different energies
- Extend analysis to higher energy bins
- Test Neural Network analysis
- Compare with atmospheric data
  → Check how well the variables are reproduced by MC.

Oscillation analysis

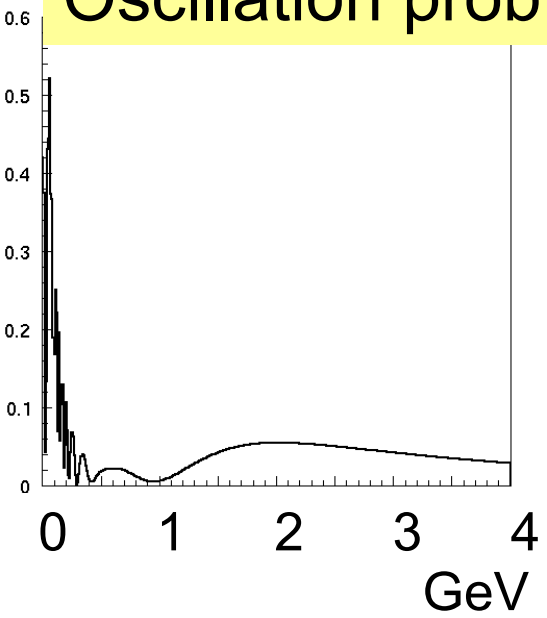
Flux



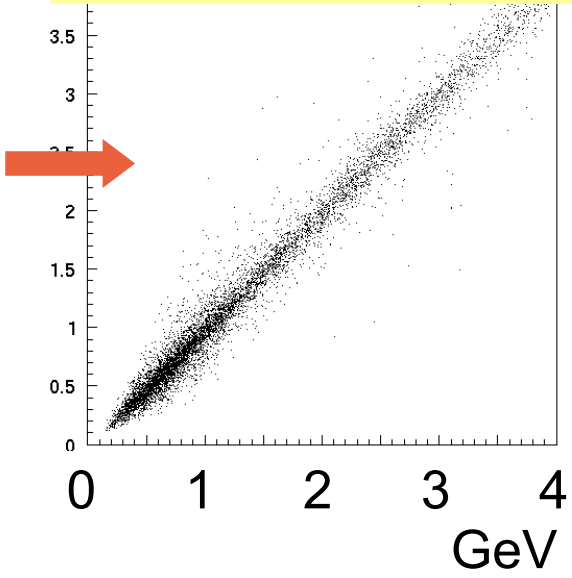
Cross-section



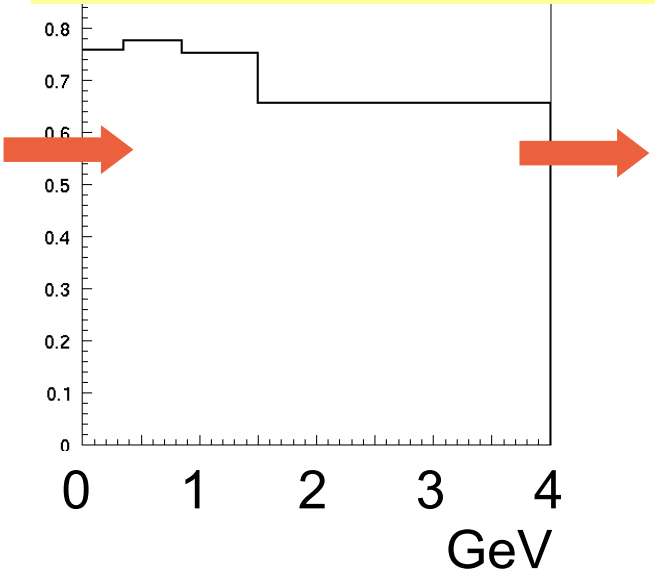
Oscillation prob



Energy smearing

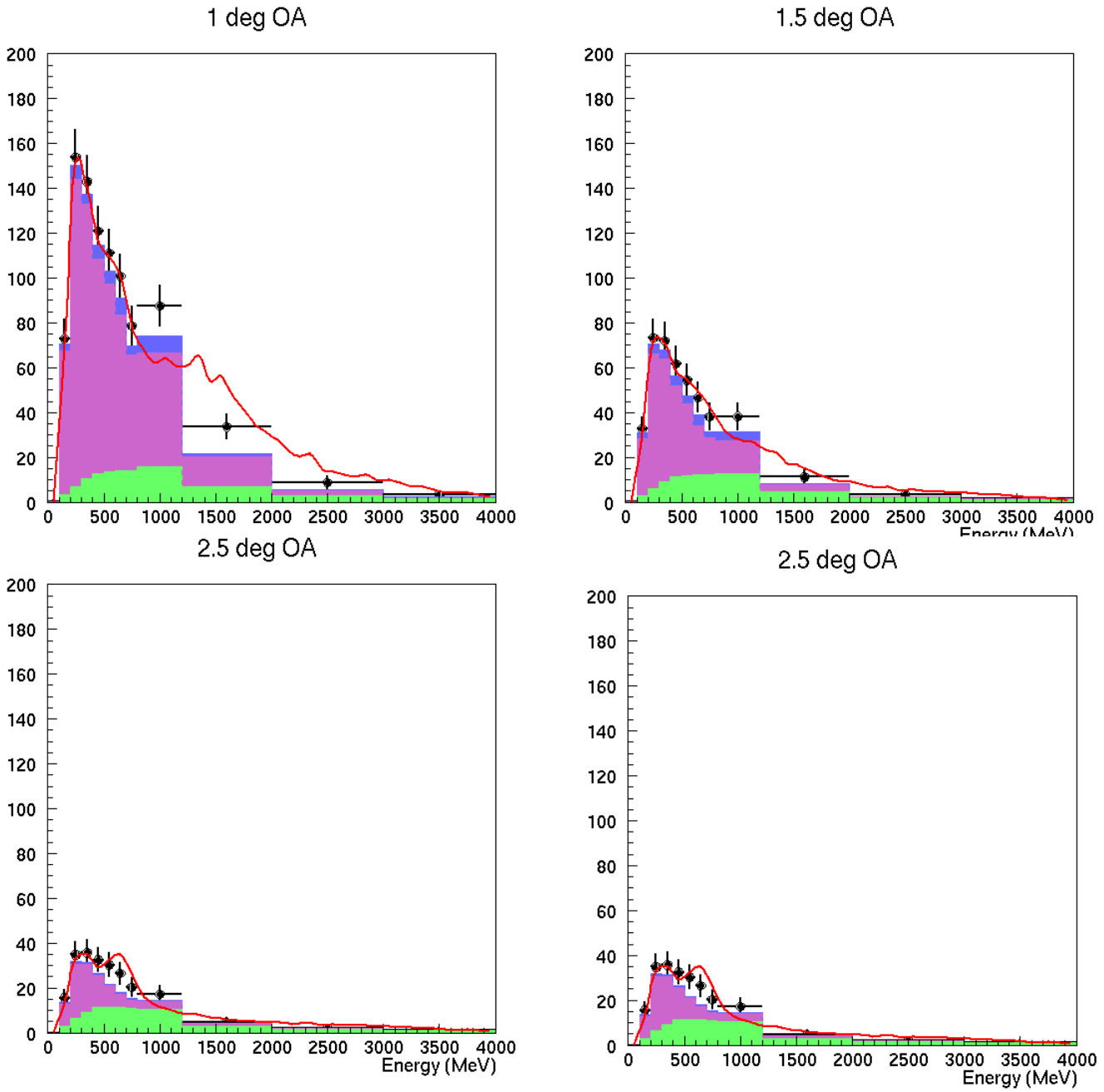


Likelihood efficiency



Input spectrum for χ^2 analysis

Spectrum for each OA



0.27 Mton (FV)
4 yr ν run
4MW
$\sin^2 2\theta_{13}=0.1$
$\delta = \pi/2$

Background:
- beam ν_e
- NC
- ν_μ mis-ID

Signal+Background:
- Without detector effect
- With detector effect

χ^2 Definition

The oscillation analysis was done for: 4MW beam

k=1,4

- 0.27Mton at Kamioka or 0.54Mton in Kamioka
- 0.27Mton in Korea
- 4 years running of neutrino
- 4 years running of antineutrino

When Kamioka only

With the following energy bins (MeV):

i=1,7

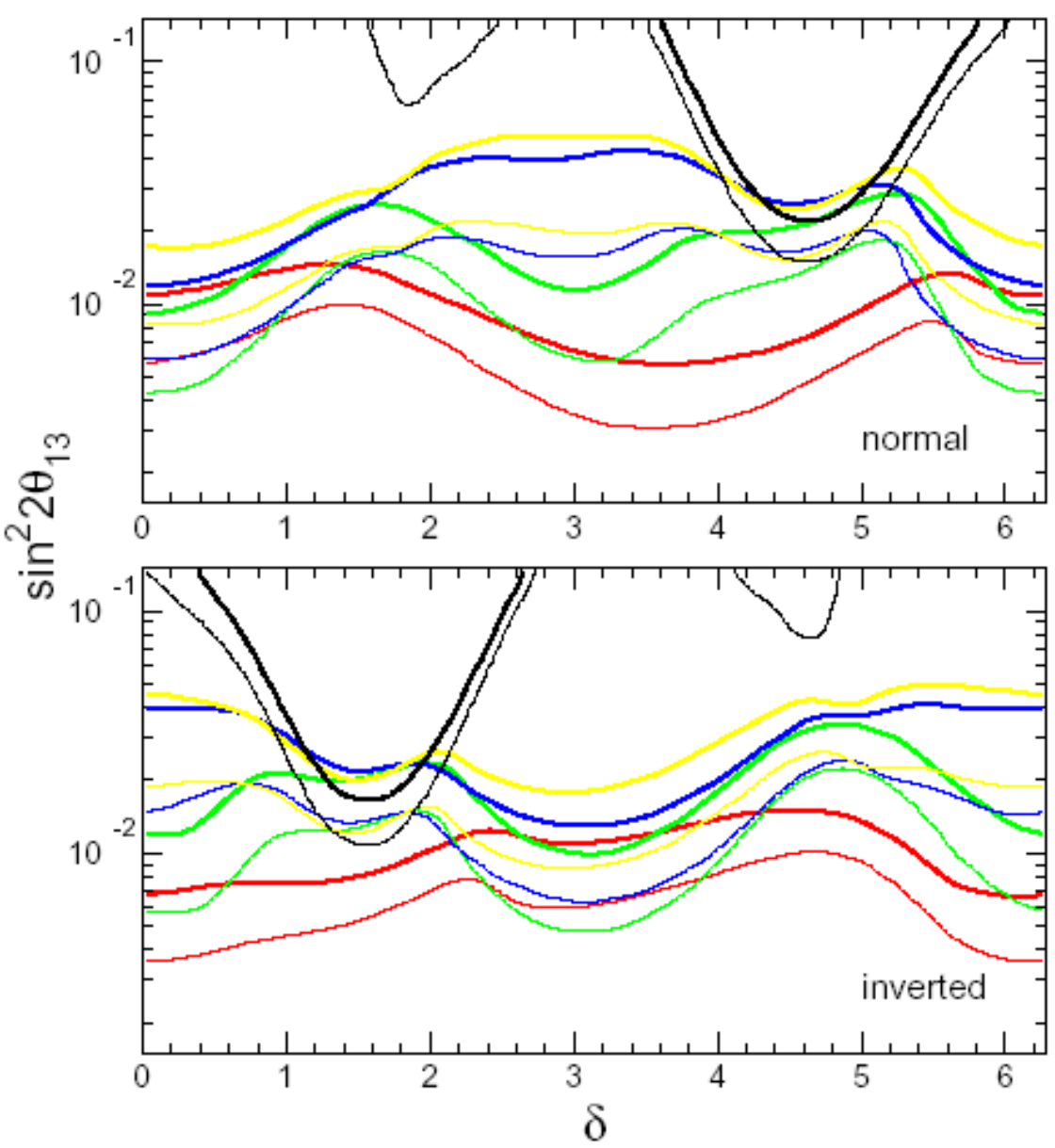
400-500, 500-600, 600-700, 700-800,
800-1200,1200-2000, 2000-3000

$$\chi^2 = \sum_{k=1}^{4} \left(\sum_{i=1}^{7} \frac{\left(N(e)_i^{\rm obs} - N(e)_i^{\rm exp}\right)^2}{\sigma_i^2} \right) + \sum_{j=1}^{3} \left(\frac{\epsilon_j}{\tilde{\sigma}_j} \right)^2$$

$$N(e)_i^{\rm exp} = N_i^{\rm BG} \cdot (1 + \sum_{j=1}^{2} f_j^i \cdot \epsilon_j) + N_i^{\rm signal} \cdot (1 + f_3^i \cdot \epsilon_3) \quad .$$

hep-ph 0604026 eq 3) and 4)

Sensitivity mass hierarchy



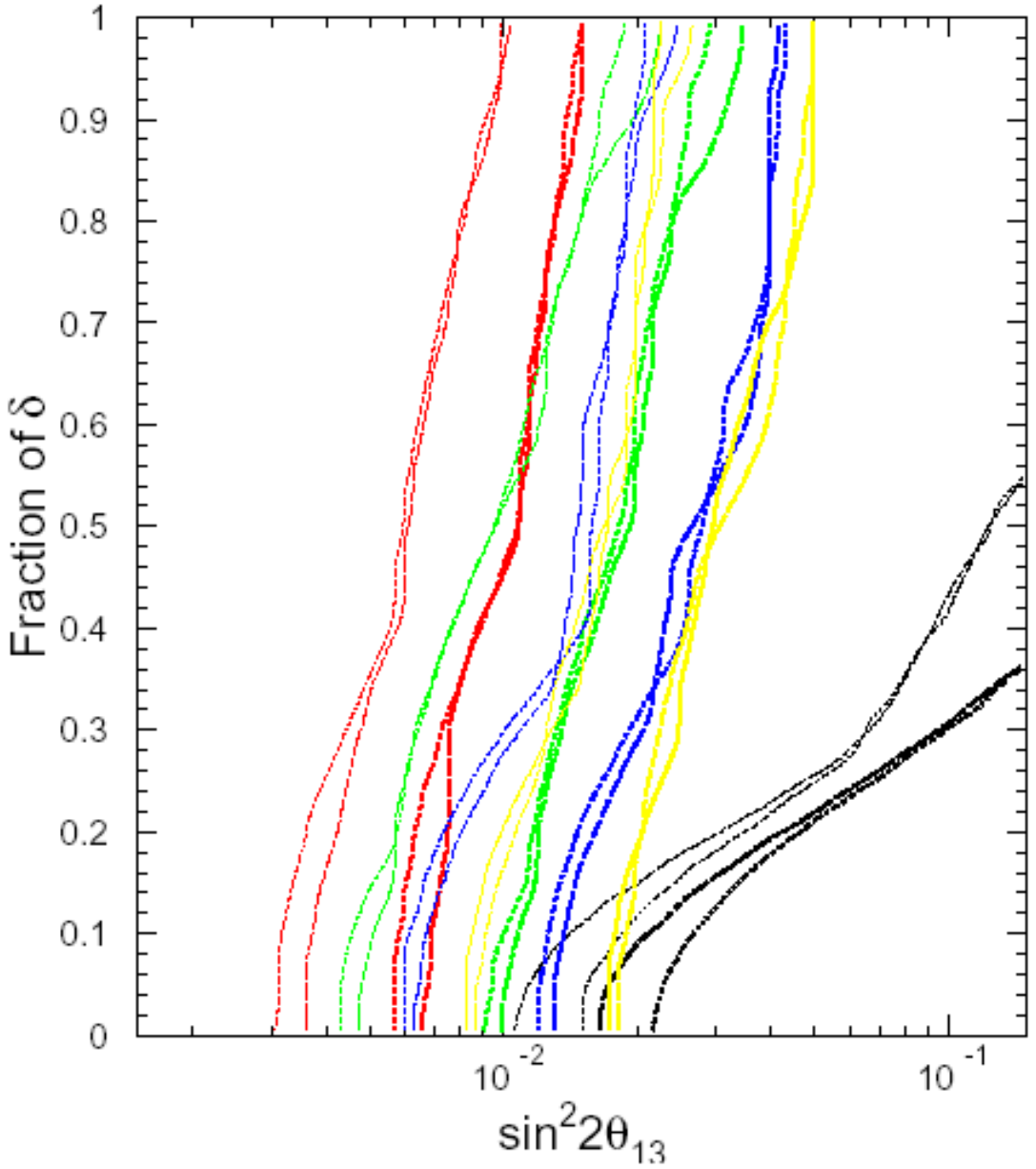
Kamioka+Korea (4yr+4yr)
- 1.0° OA
- 1.5° OA
- 2.0° OA
- 2.5° OA

Kamioka only
- 2σ
- 3σ

2 detectors always better

Best sensitivity when OA= 1.0°

Sensitivity mass hierarchy



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- 1.0° OA
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- 2.0° OA
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Kamioka only
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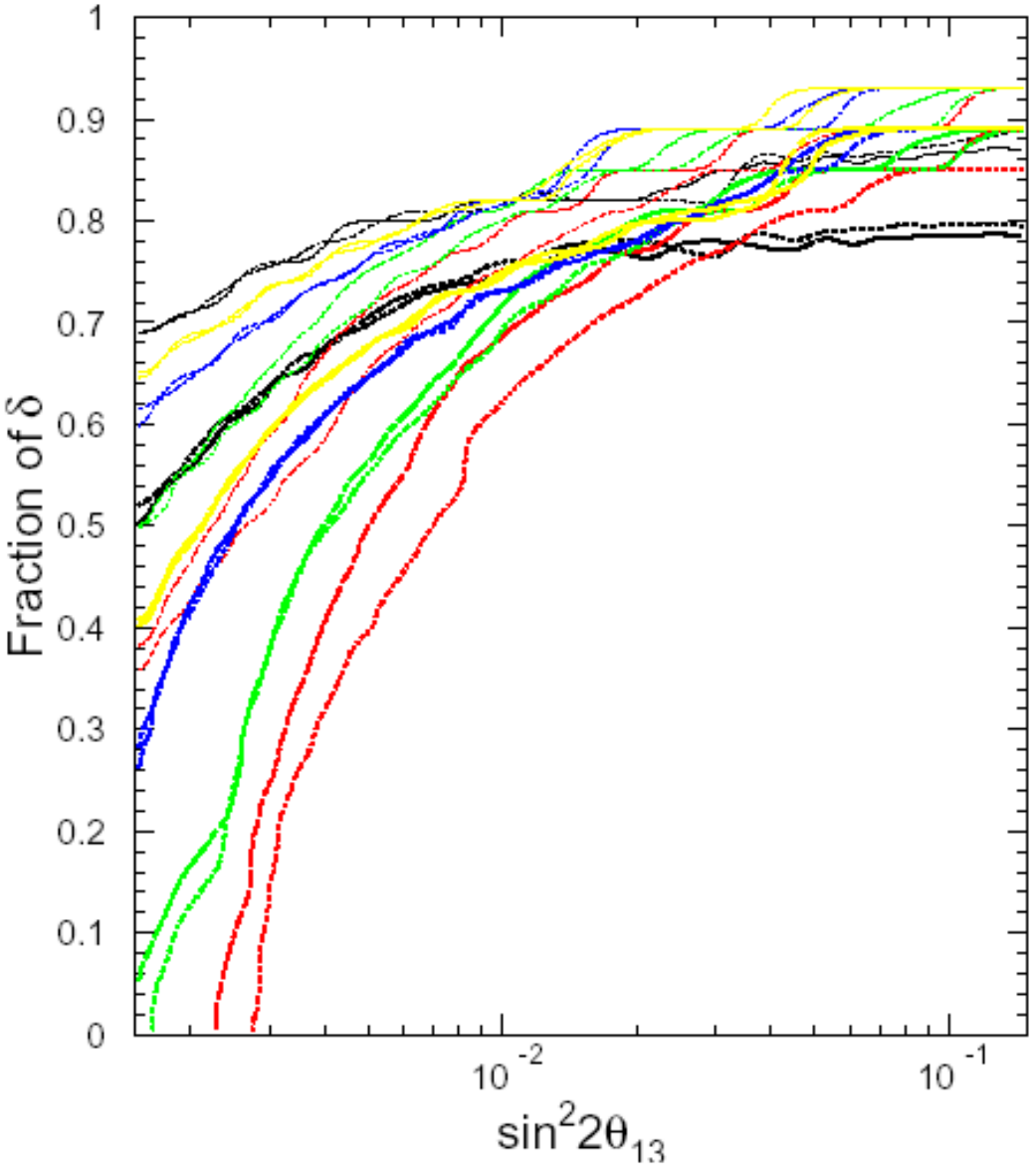
2 detectors always better

Best sensitivity when OA= 1.0°

Sensitivity CP violation



If $\sin^2 2\theta_{13}$ is big:

Best sensitivity with 2 detectors (& big OA)

If $\sin^2 2\theta_{13}$ is small:

Best sensitivity with Kamioka only

Conclusions

Likelihood analysis developed for ν_e appearance:

ε = 82% / BG = 21% ⟶ ε = 72% / BG = 34%

Oscillation analysis conclusions:

For mass hierarchy:

Best set up is when OA is small (= 1.0°)

1^{st} osc maximum ➡ matter effect

For CP violation study:

Best set up is Kamioka only (for small $\sin^2 2\theta_{13}$)

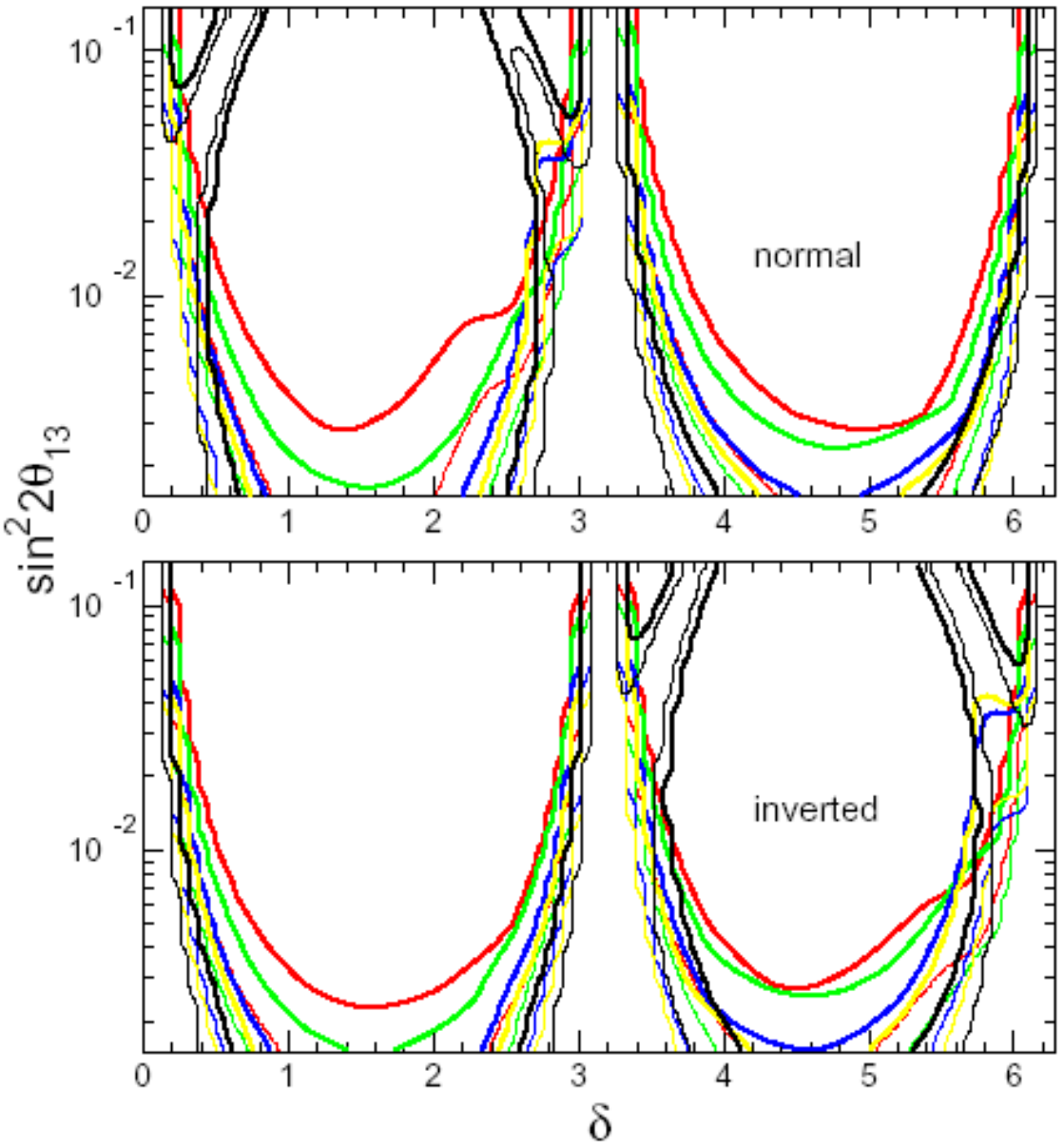
or OA big (= 2.5°) if 2 detectors (for big $\sin^2 2\theta_{13}$)

2^{nd} osc maximum ➡ bigger CP effect

Future plan: Extend analysis to higher energies (especially for 1° OA)

Backups:

Sensitivity CP violation



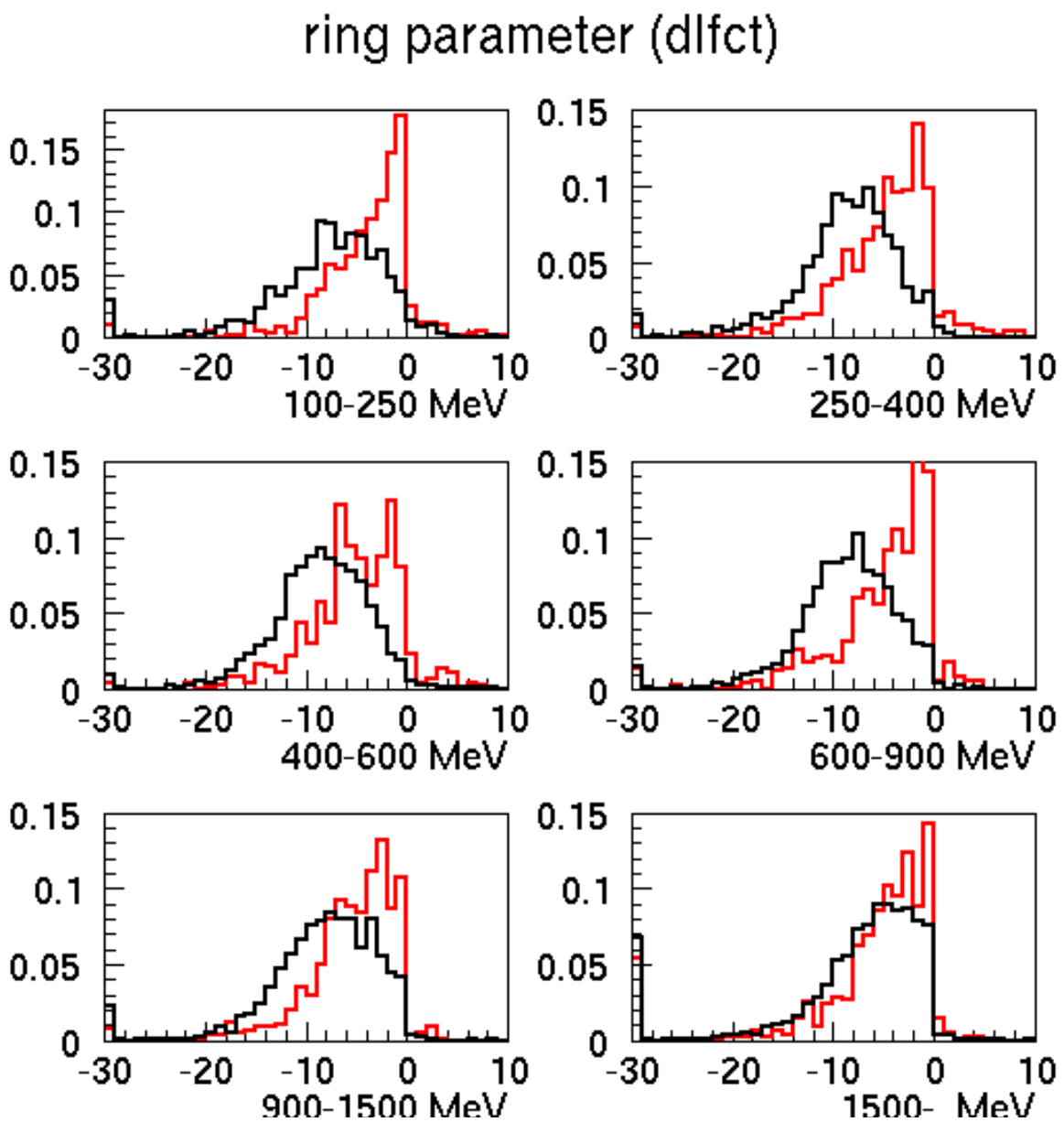
If $\sin^2 2\theta_{13}$ is big:

Best sensitivity with 2 detectors (big OA)

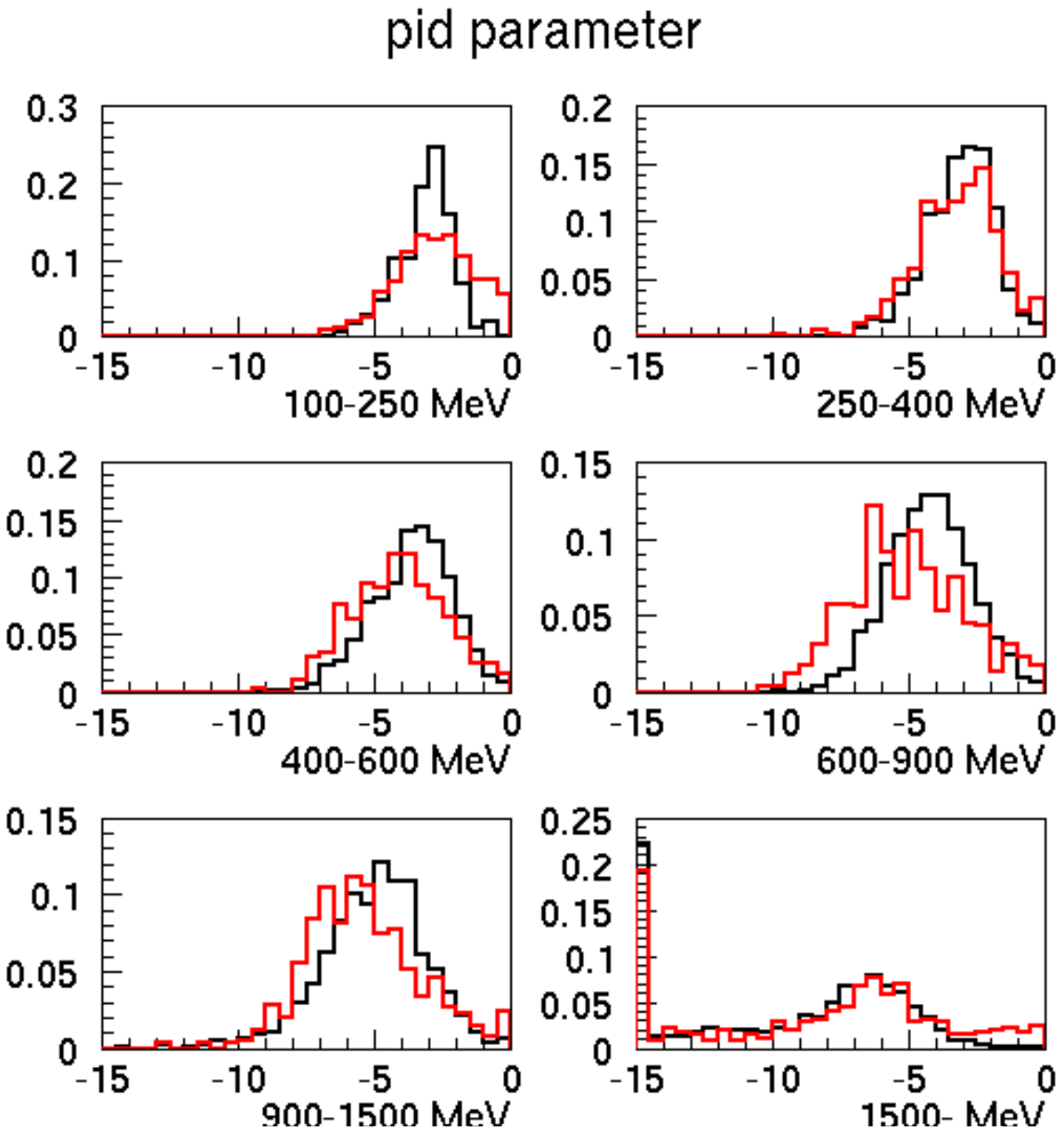
If $\sin^2 2\theta_{13}$ is small:

Best sensitivity with Kamioka only

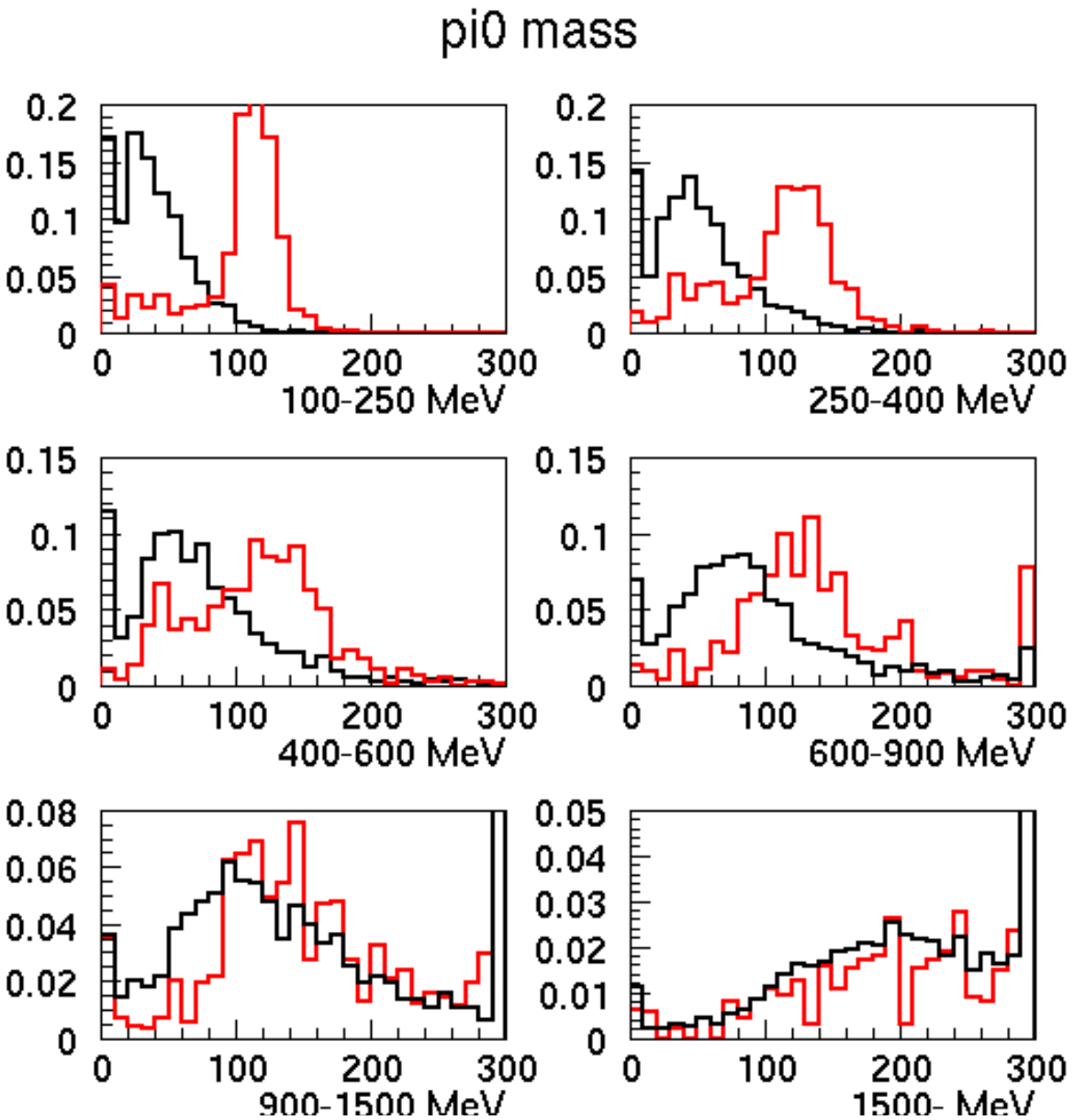
ring param


ring parameter (dlfct)
0.15
0.1
0.05
0
-30
-20
-10
0
10
100-250 MeV
250-400 MeV
400-600 MeV
600-900 MeV
900-1500 MeV
1500- MeV

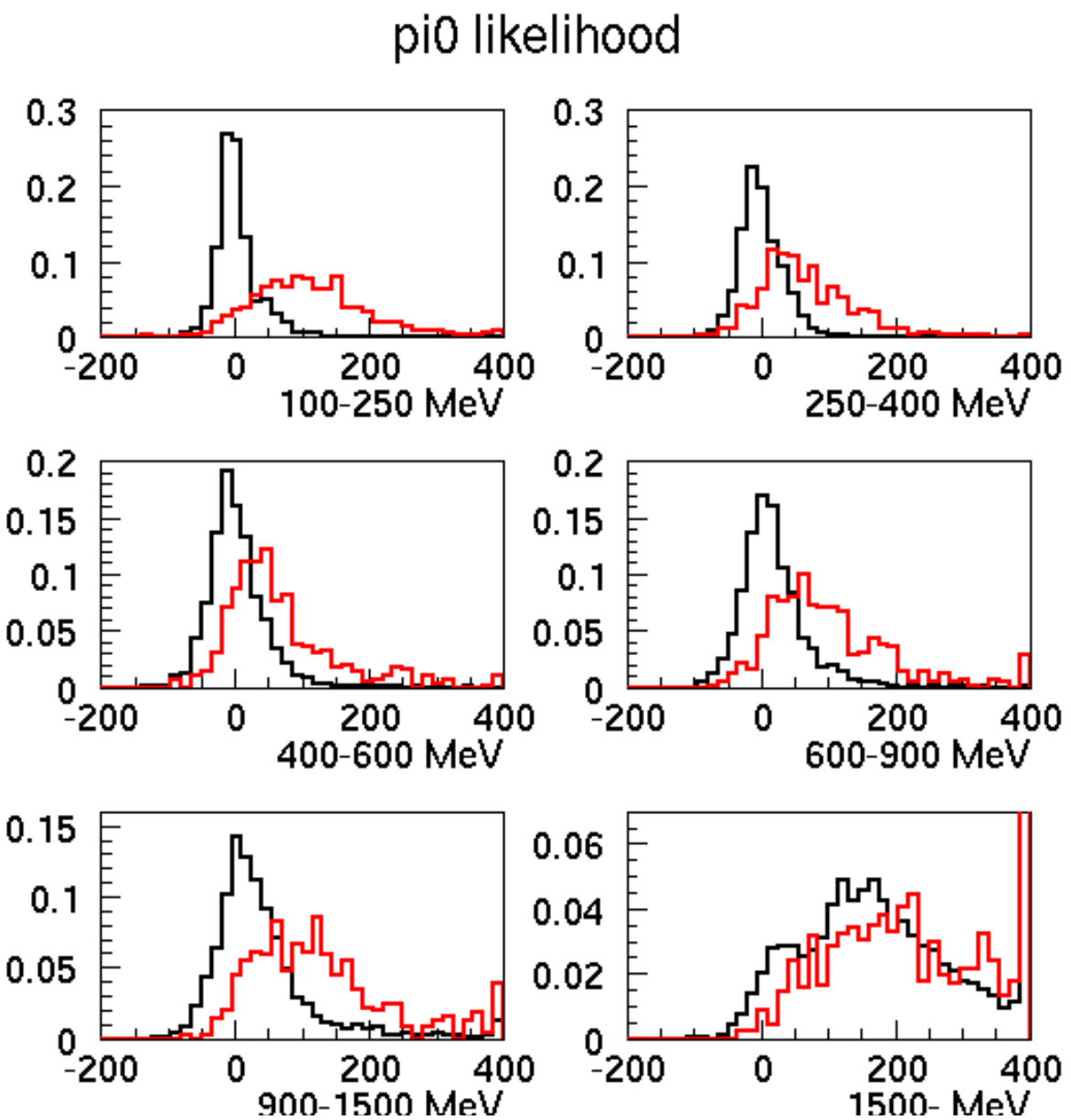
pid


pid parameter
100-250 MeV
250-400 MeV
400-600 MeV
600-900 MeV
900-1500 MeV
1500- MeV

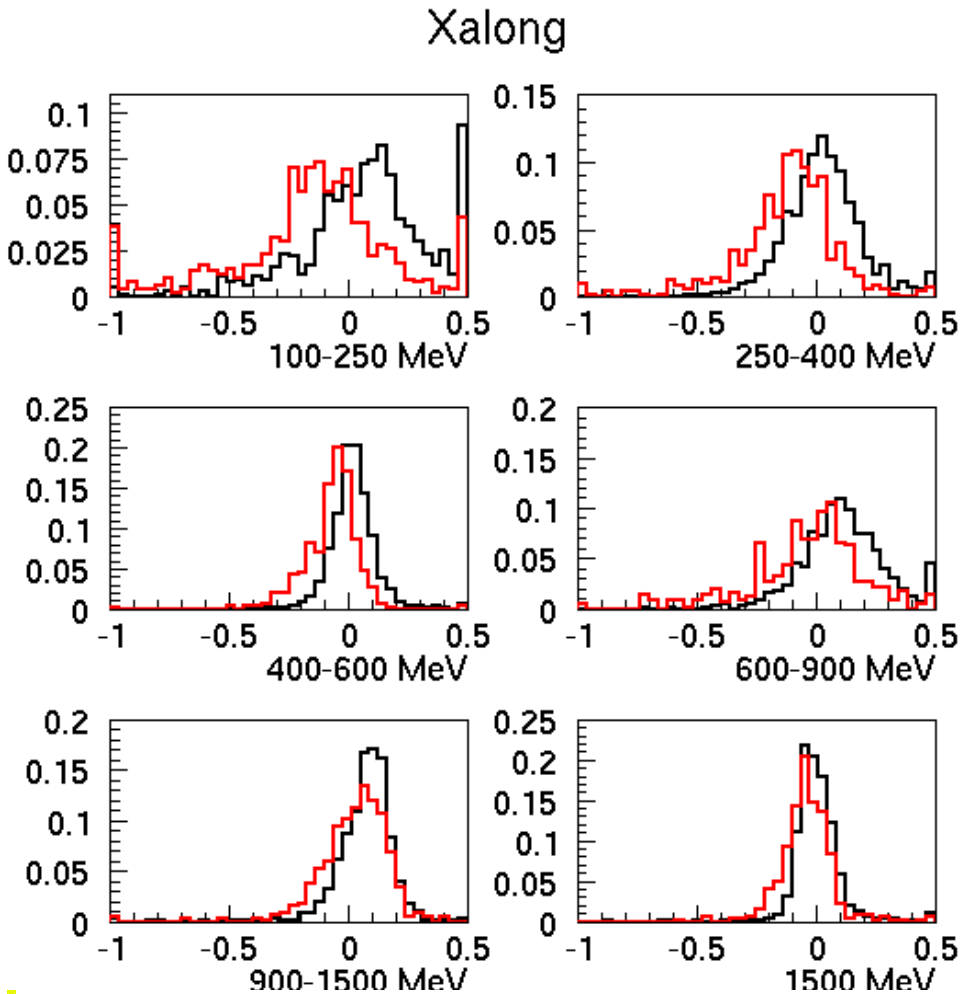
pi0mass

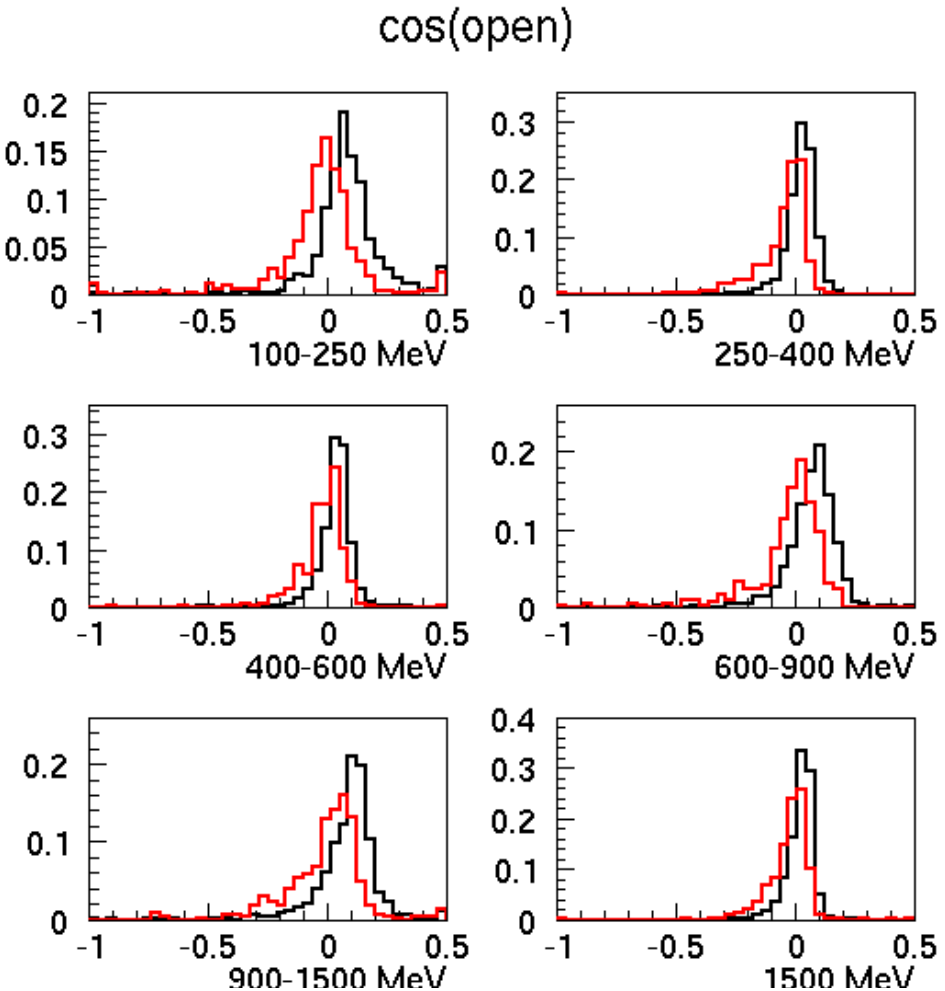

pi0 mass
100-250 MeV
250-400 MeV
400-600 MeV
600-900 MeV
900-1500 MeV
1500- MeV

pi0like


pi0 likelihood
100-250 MeV
250-400 MeV
400-600 MeV
600-900 MeV
900-1500 MeV
1500- MeV

xalong cosopen (distribution)





usefulness of variables

add/remove variables
eff tables